

Proceedings of the Third
ICFA Mini-Workshop on
High Intensity, High Brightness
Hadron Accelerators

CONF-9705197-Summ.

May 7-9, 1997, Brookhaven National Laboratory

RECEIVED

NOV 10 1997

OSTI

MASTER

u

Disclaimer Statement

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Government, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency, contractor, or subcontractor thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency, contractor or subcontractor thereof.

BNL-64754
Informal Report

Proceedings of the Third ICFA Mini-Workshop on
High Intensity, High Brightness Hadron Accelerators

T. Roser, et. al.

May 7-9, 1997

AGS Department

Brookhaven National Laboratory
Associated Universities, Inc.
Upton, Long Island, New York 11973

Under Contract No. DE-AC02-76CH00016 with the

UNITED STATES DEPARTMENT OF ENERGY

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

Preface

The 3rd mini-workshop on high intensity, high brightness hadron accelerators was held at Brookhaven National Laboratory on May 7-9, 1997 and had about 30 participants.

The workshop focussed on rf and longitudinal dynamics issues relevant to intense and/or bright hadron synchrotrons. A plenary session was followed by four sessions on particular topics. This document contains copies of the viewgraphs used as well as summaries written by the session chairs.

M. Blaskiewicz
Scientific Secretary

Contents

T. Roser	Summary of Plenary Session	1
J.M. Brennan	AGS/RHIC Status and Plans	3
R. Garoby	CERN Status and Plans	25
D. Wildman	FNAL Status and Plans	38
C. Ohmori	KEK Status and Plans	61
A. Thiessen	LANL Status and Plans	75
M. Blaskiewicz	Summary of Barrier Cavity Session	93
M. Yoshii	AGS Barrier Cavity Upgrade	94
C. Ohmori	KEK Barrier Cavity Results and Plans	107
R. Garoby	Summary of Longitudinal Emittance Control Session	123
S. Hancock	CERN Experiences	125
E. Jensen	LHC Issues	131
J.M. Brennan	High Brightness in RHIC	137
K.Y. Ng	Space Charge Effects and Ferrite Compensation	142
J. Wei	RHIC Operation with Increased Bunch Area (I)	160
J. Kewisch	RHIC Operation with Increased Bunch Area (II)	169
K.Y. Ng	Summary of Longitudinal Instabilities Session	175
Y.H. Chin and H. Tsutsui	Longitudinal Instabilities in a Barrier Rf System	176
M. Blaskiewicz	Fast Particle-Particle Update Schemes	191
J. Rose	Stability in RHIC	195
J.M. Brennan	Summary of Beam Loading and Rf Stability Session	203
E. Onillon	State Vector Techniques	205
M. Blaskiewicz	The NSNS Rf System	223
R. Garoby	PS Phase Measurement System	228
	List of Participants	231

Plenary Session

T. Roser

During the plenary session summary and status talks from the four organizing laboratories (BNL, CERN, FNAL, and KEK) and also from LANL were presented.

Mike Brennan reported on the various high intensity and high brightness efforts at BNL. In preparation for RHIC operation the AGS needs to produce very bright Gold beams with 10^9 ions per bunch and a bunch area of 0.2 eVs/u . The present performance has reached already 0.4×10^9 ions per bunch with a bunch area of 0.6 eVs/u . This intensity was achieved by merging 8 bunches into one which is most effectively done early in the acceleration cycle.

High intensity proton beams are accelerated in the Booster and AGS. With second harmonic cavities more than 2×10^{13} protons on two bunches each with a bunch area of about 1.5 eVs were accelerated in the Booster. The beam performance is very sensitive to the relative phase of the first and second harmonic rf system. Four Booster beam batches are accumulated in the AGS for a maximum intensity of 6×10^{13} protons. Stability during accumulation can only be achieved by diluting the bunches to about 4 eVs using a high frequency cavity.

To avoid excessive blow-up and also to allow for the accumulation of more than four Booster batches a Barrier bucket system is being developed. With such isolated sine waves gaps in the debunched beam can be manipulated in such a way as to stack successive loads from the Booster. So far with two 12 kV cavities an intensity of 3×10^{13} protons was achieved by stacking six Booster loads. The development goal is to build 80 kV cavities to produce 250 ns long sine waves.

The development and upgrade plans for the CERN PS and PS Booster in the LHC era were presented by Roland Garoby. With only one bunch accelerated per Booster ring two Booster loads can be accumulated in the PS. Before extraction to the SPS the beam will be debunched and rebunched into 84 bunches with a new 140 MHz rf system. Each bunch will have to contain 10^{11} protons in a bunch area of 0.3 eVs . The goal is to send nominal LHC beam to the SPS in 1998.

The status and plans for high intensity beams at FNAL was summarized by David Wildman. The next Tevatron collider run will make use of the new Main Injector with increased production and stacking rate for antiprotons. High proton intensity will also be required for the long baseline neutrino experiment and in the future for even higher Tevatron luminosity. Presently longitudinal coupled

bunch instabilities driven by higher order modes of the rf cavities in the Booster, Main Ring, and Tevatron are limiting intensity unless a number of active and passive dampers are used. A permanent magnet 8 GeV Recycler ring has recently been made part of the Main Injector project. This ring will be used to store and cool anti-protons both remaining from the previous store and directly from the Antiproton Accumulator ring. Wide band ferrite loaded barrier cavities with a peak voltage of 2 kV will be used to manipulate the antiprotons in the Recycler.

Chihiro Ohmori reported on the plans for the Japanese Hadron Facility. It will consist of a 200 MeV Linac, a 3 GeV Booster accelerating 5×10^{13} protons at 25 Hz and a 50 GeV Main ring accelerating 2×10^{14} protons. The Main ring lattice will be transition-free. A development program is underway to use Finemet (Fine-Crystal High μ Metal) in the main ring cavities. This material has high permeability, a low Q factor ($Q < 1$) and performs well even for large rf fields. These cavities will be used for acceleration as well as Barrier Cavities.

Arch Thiessen gave an overview of the LANSCE PSR status and upgrade plans. The intensity at 800 MeV is limited to 4×10^{13} protons by a fast transverse instability which is believed to be caused by electrons. Clearing gaps in the beam help suppress this instability and an upgrade of the rf system including a second harmonic system is underway to improve the situation. Potential well distortion from space charge is typically overcome by using much larger rf gap voltage. Alternatively the vacuum pipe impedance could be modified to cancel the space charge effects. A test is planned this year at the PSR of such an impedance tuner.

**Workshop on High Intensity-
High Brightness Beams: RF Issues**

BOOSTER/AGS/RHIC

J. M. Brennan

● **High Brightness for RHIC**

J. Rose - stability
E. Omiolon - Beam
Control

● **High Intensity Protons**

M. Blaskiewicz -
NSNS

● **Barrier Cavity, Development**

M. Yasaki

Issues for Discussion

● **Phase modulation for emittance blow-up**

● **Higher brightness for...e.g. g-2 experiment**

● **Very high brightness for a proton driver**

● **More accumulation for higher average current**

➔ **Barrier Cavities**

High Brightness for RHIC ($^{179}\text{Au}^{+79}$, $\gamma=12$)

I. Specifications

Bunch Intensity = 10^9 ions
 Longitudinal Emittance = 0.2 eVs/u

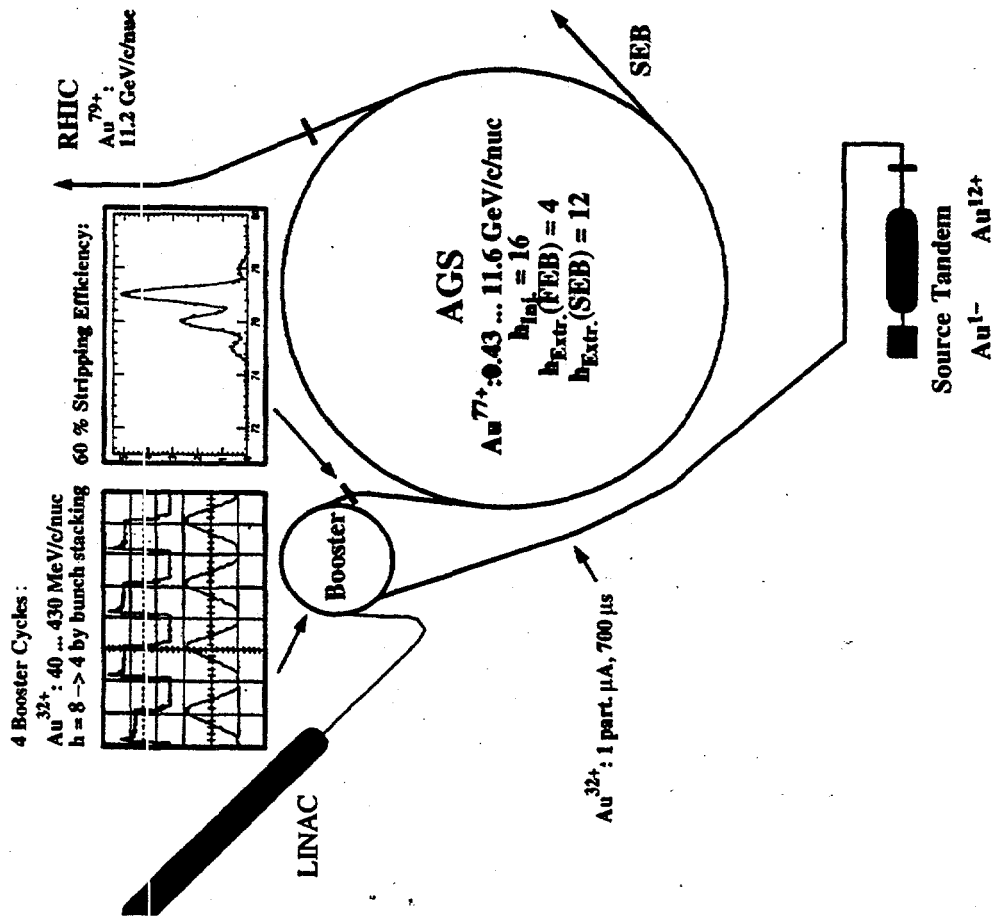
II. Performance to date (Jan. 97)

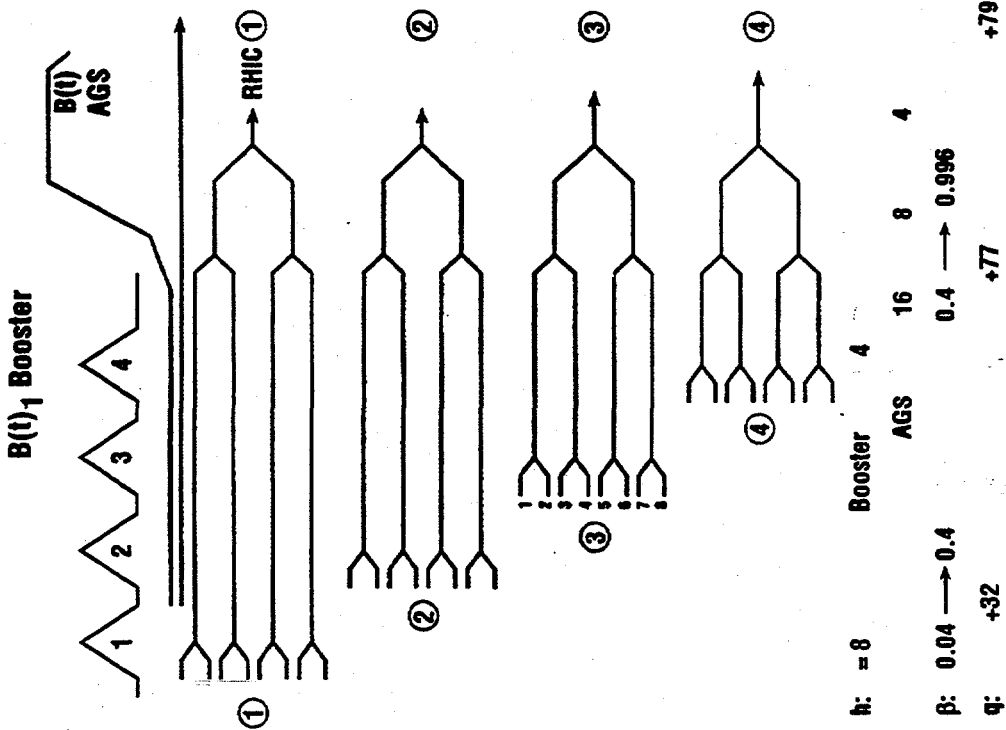
Bunch Intensity = 0.4×10^9 ions
 Longitudinal Emittance = 0.6 eVs/u

III. Operating Mode

Bunch merging, $2 \times 2 \times 2$
 Accumulation in AGS at 430 MeV/c/u
 Motivations

Gold Acceleration at the AGS





1. luminosity formula

$$L = 3/2 f_{rev} B (\beta\gamma) N_B^2 / \epsilon_N \beta^*$$

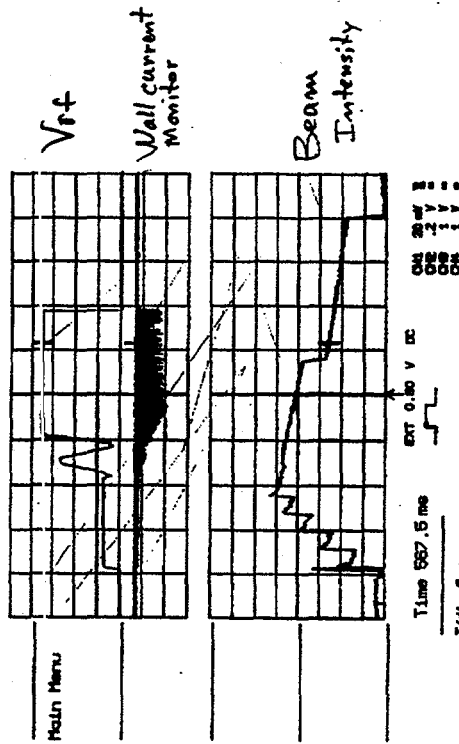
→ intensity per bunch is paramount

2. transverse emittance must be low

- 3. longitudinal emittance is not in the formula,**
- i. chromatic non-linearities at transition, → growth
 - ii. leakage into adjacent buckets at re-bucketing to 197 MHz
 - d. filling time, IBS at low energy, blows up longitudinal emittance

Acceleration in the AGS

30-Jan-97
13:52:02

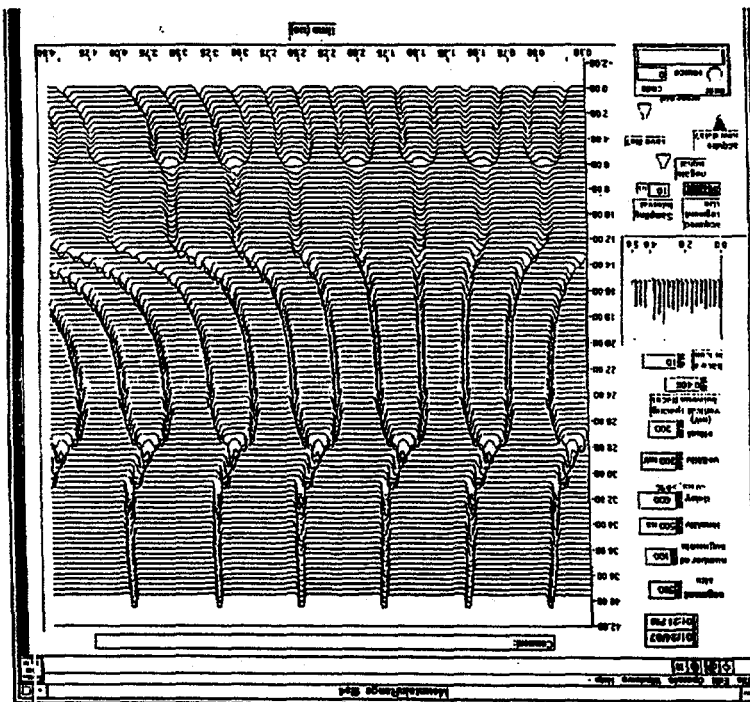


● The loss rate was a surprise!

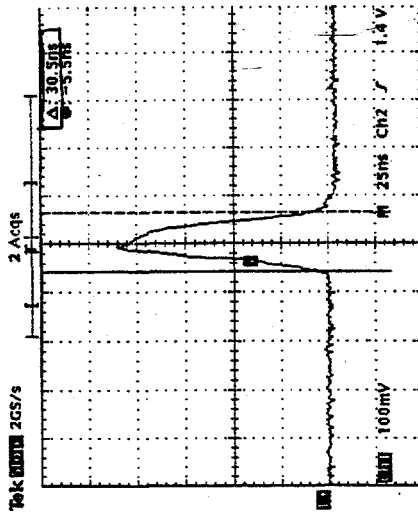
● Same rate with rf on or off.

● Vacuum?

- a. not predicted
- b. capture? Au⁴⁷⁷
- c. problem for RHIC? Au⁴⁷⁹



Longitudinal Emittance
After Three Bunch Mergings



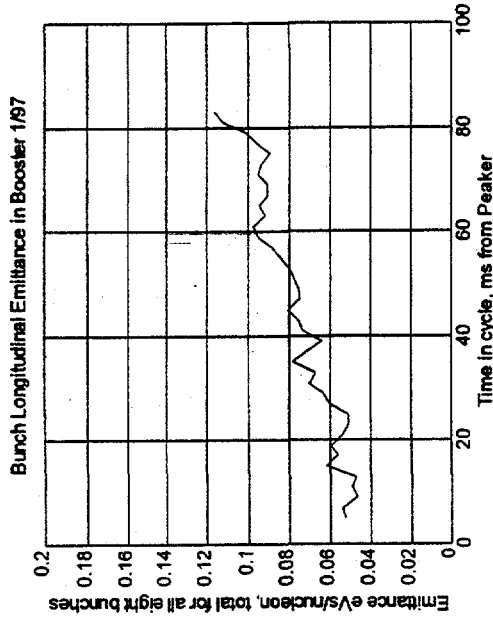
$$V_H = 220 \text{ kV}$$

$$\dot{B} = 0, h = 8$$

$$l = 28 \text{ ns}$$

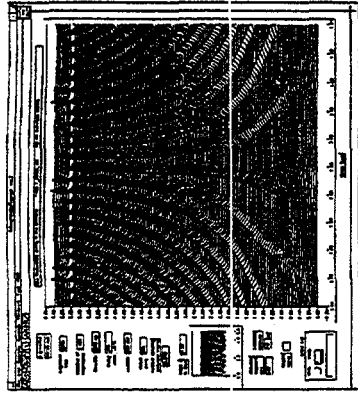
$$\Rightarrow \epsilon = 0.60 \text{ eVs}/\mu$$

The Booster Emittance is Small Enough.

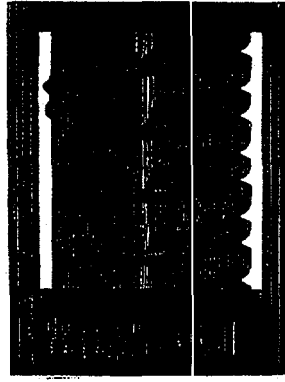


● If we put all the Booster beam into one RHIC bunch we still have a factor of two head room.

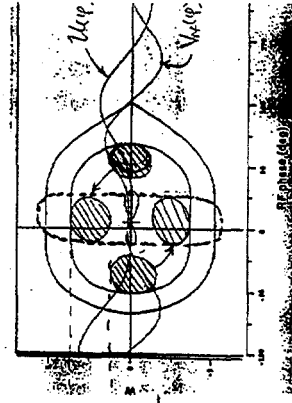
● There is 100% growth in the Booster



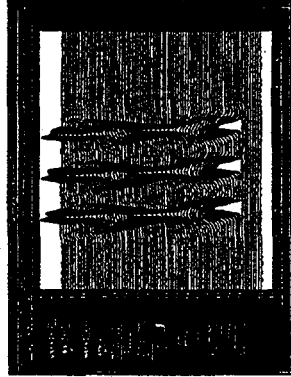
Booster Cycle



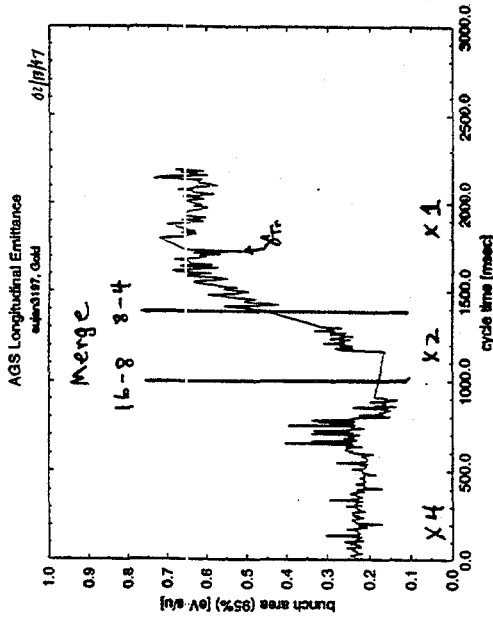
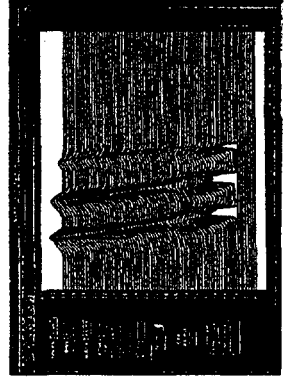
$n = 8 \rightarrow 4 \Delta T \approx 100 \mu s$



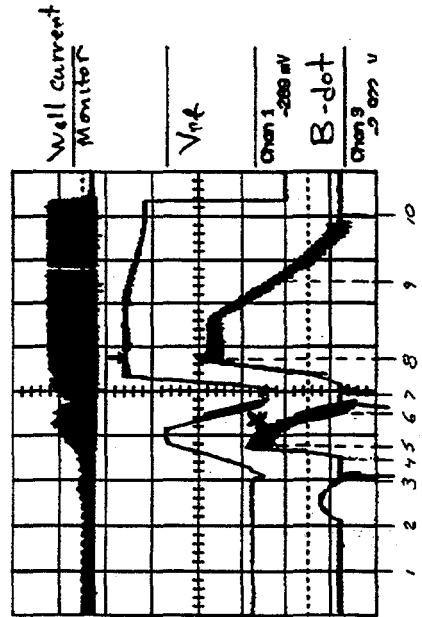
Merge in Double rf



In AGS, after
+32 \rightarrow +77 stripping



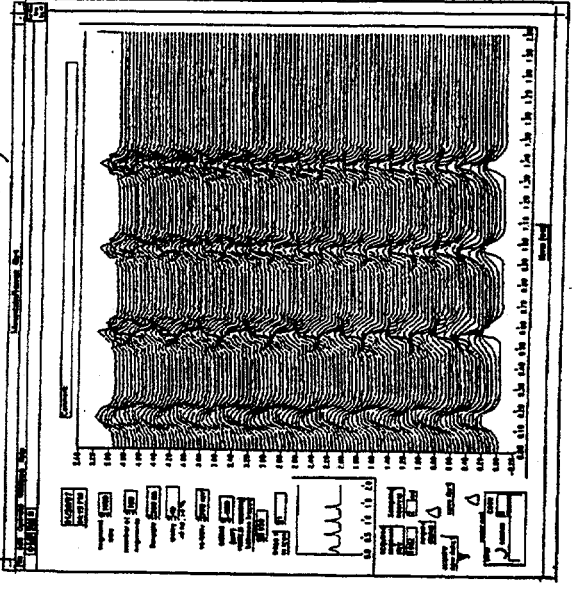
1-Feb-87
16:20:06



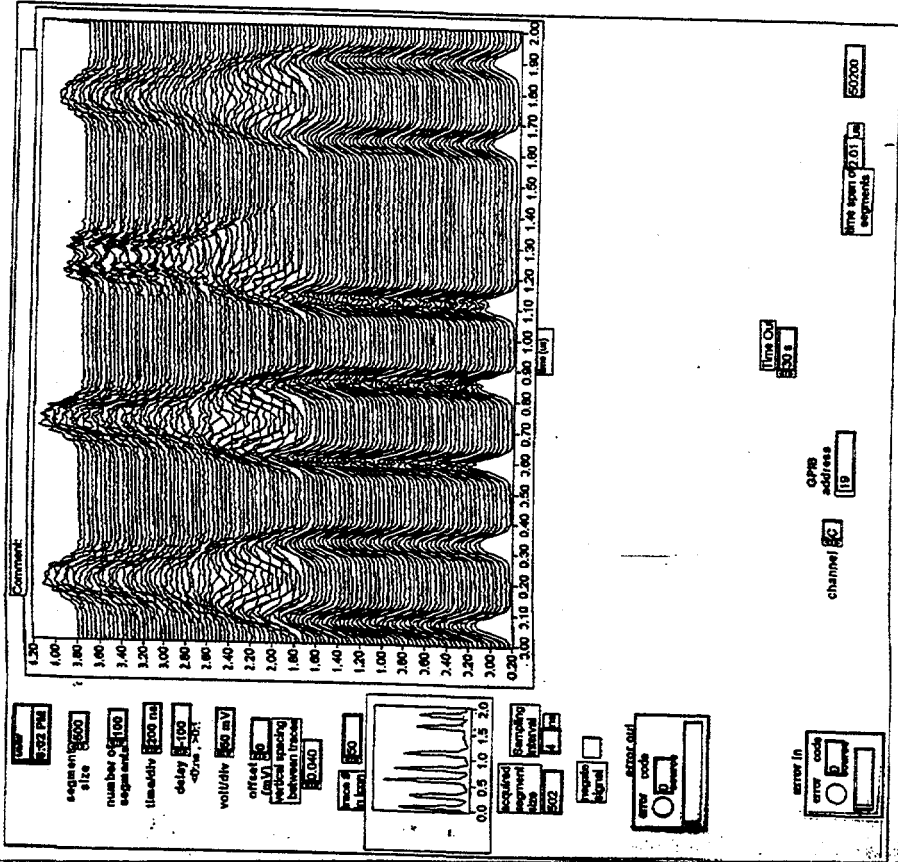
* $\delta \left(\frac{B}{V_{rf}} \right)$ is large + fast!

Mismatch at AGS Injection

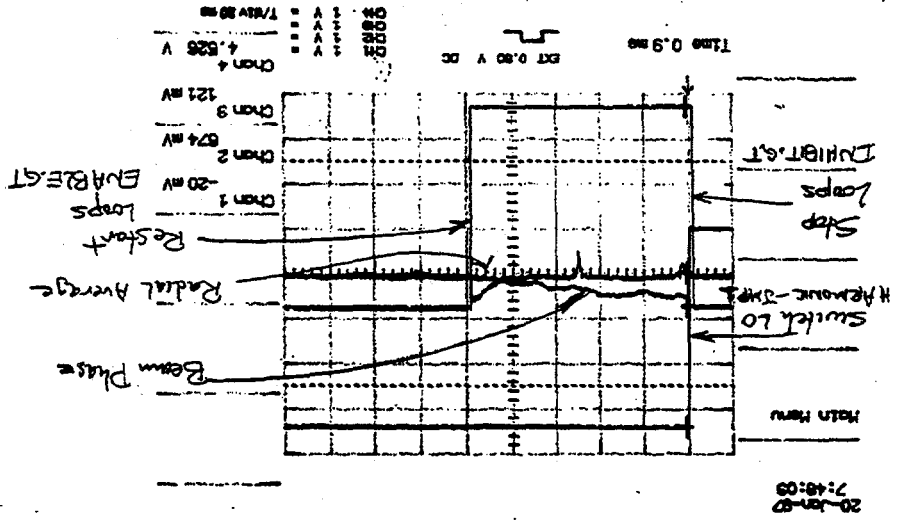
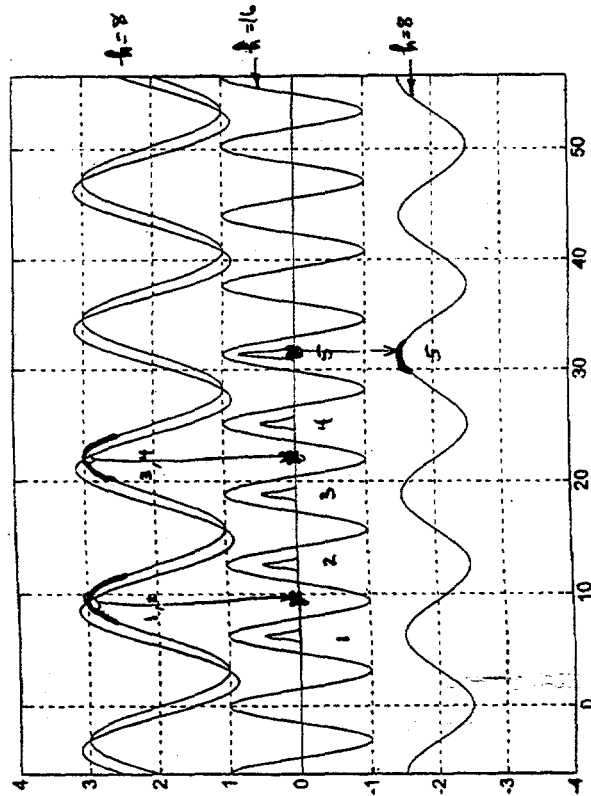
- Momentum Error
- Bucket shape mismatch, need more Vrf for ΔE
- New batch perturbs old batch via phase loop
- Batch-by-batch phase loop, bunch shape damper



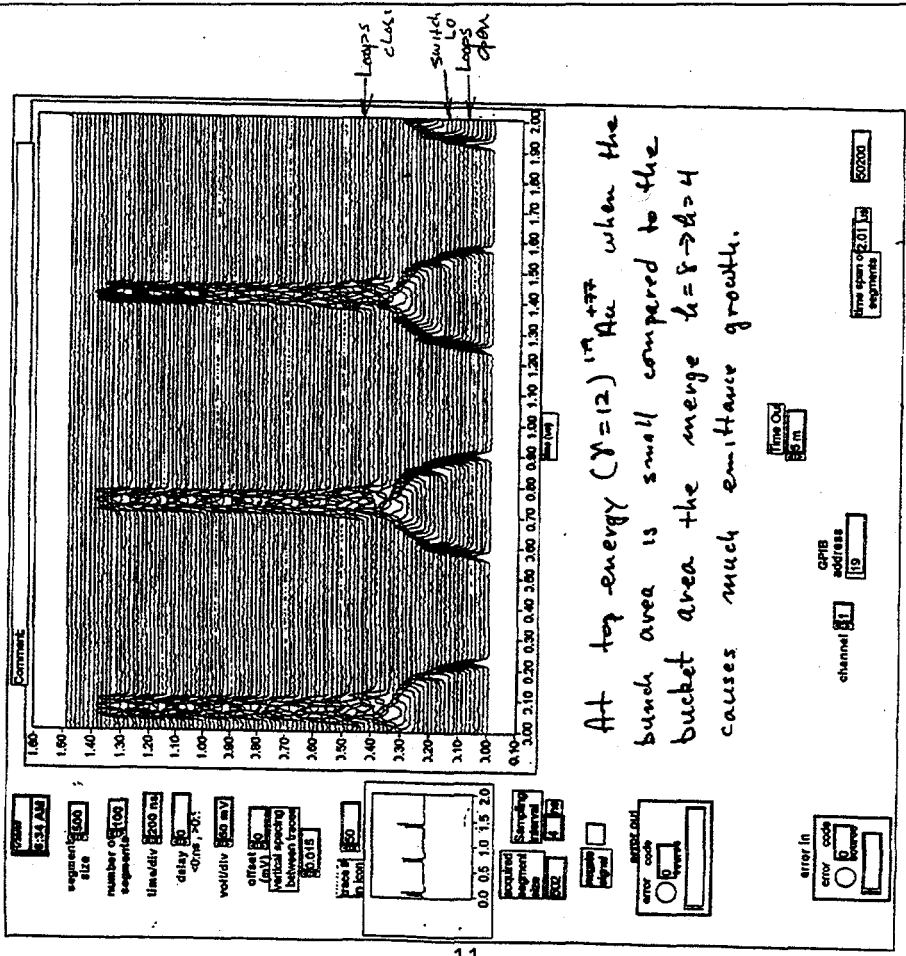
MRange_ch3
Last modified on 1/9/97 at 8:09 PM



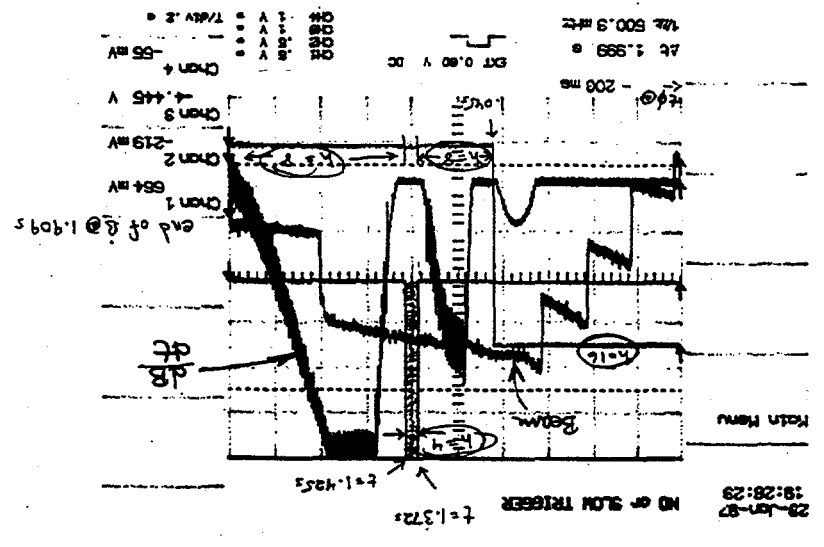
With odd number of bunches
 phase of $h=8$ is not equal
 to phase of $h=16$. This causes
 transient (glitch) in phase loop
 during $16 \rightarrow 8$ merge.



MountainRange_jmb
 Last modified on 1/20/97 at 6:34 AM



2048 turns per trace $T_{rev} = 2.7 \text{ ns}$



Booster
(200 Mev to 1.9 GeV, 2×10^{13} ppp)

I. Parameters

1. Frequency range: 1.6 to 2.8 MHz, $h=2$
2. Voltage: 2 x 45 kV, $h=2$
 2 x 15 kV, $h=4$
3. Beam Current: 8 - 10 Amps, rf
4. Power: $h=2$ 2 x 120 kW to beam
 2 x 60 kW to ferrite
 2 x 120 kW tetrodes

II. Current transformer plot

III. Second harmonic

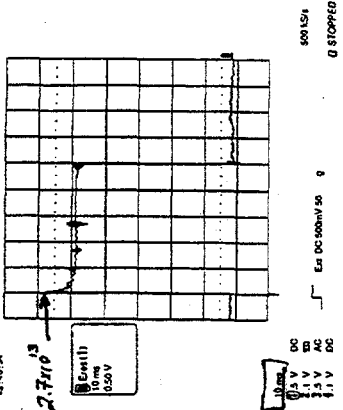
1. Bucket area
2. Bunching factor

Issues for Discussion

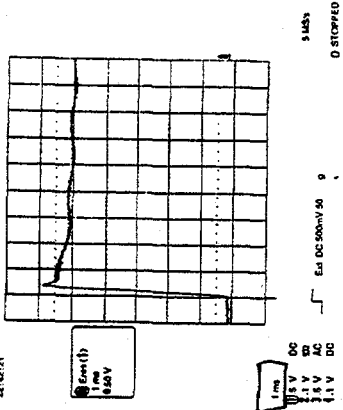
- Preserving the phase feedback during merge
- "Vacuum loss"?
- Using larger emittance in RHIC
- Bunch stability in RHIC
- RF Noise during 10 hour store

Booster Beam Current
 2.1×10^{13} P/P

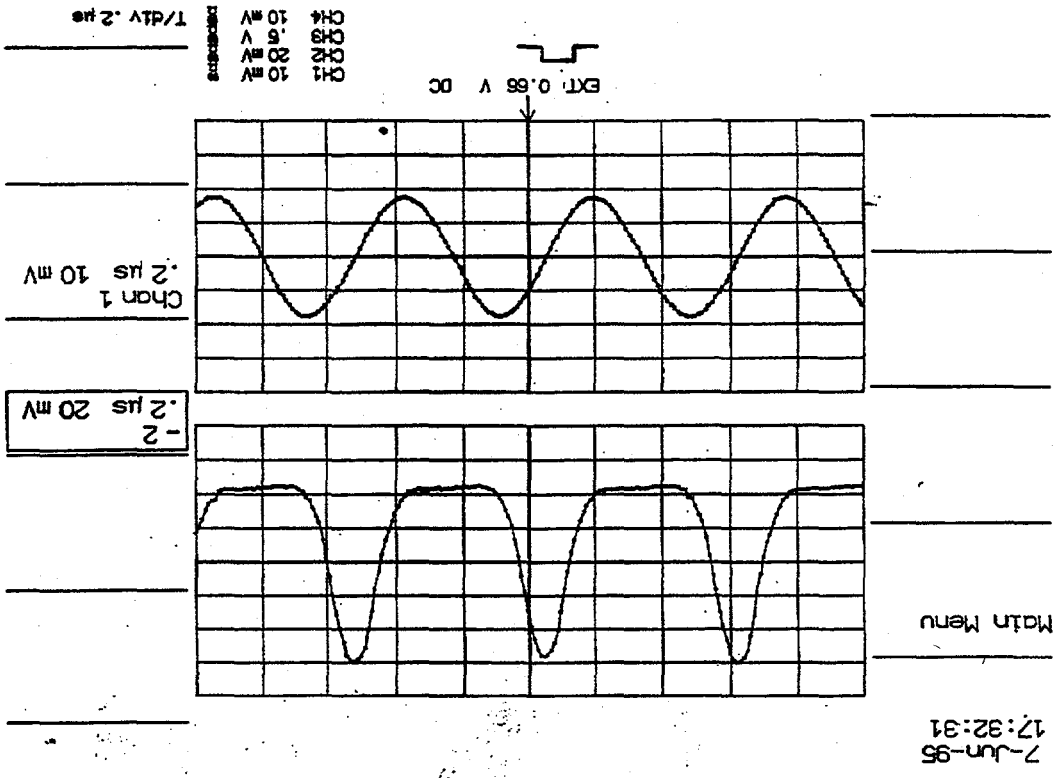
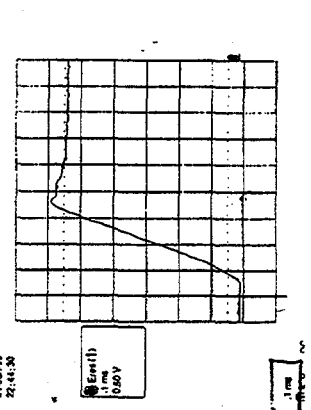
Complete Cycle



Early Loss
 2 ms - stopbands
 10 ms - bucket area



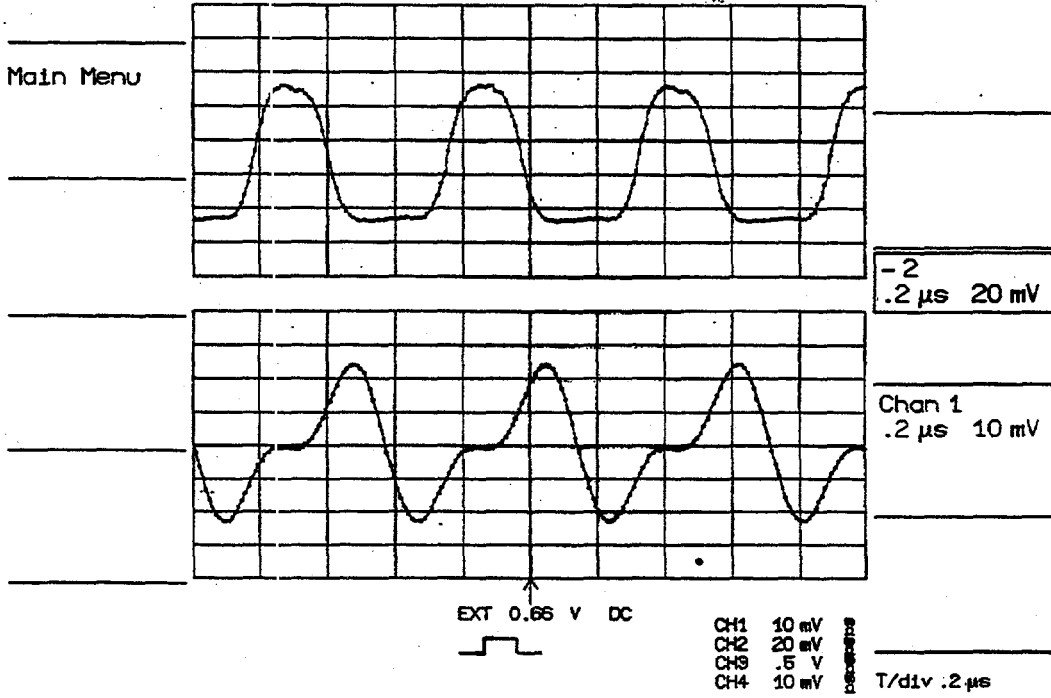
RF "capture" loss
 200 μs



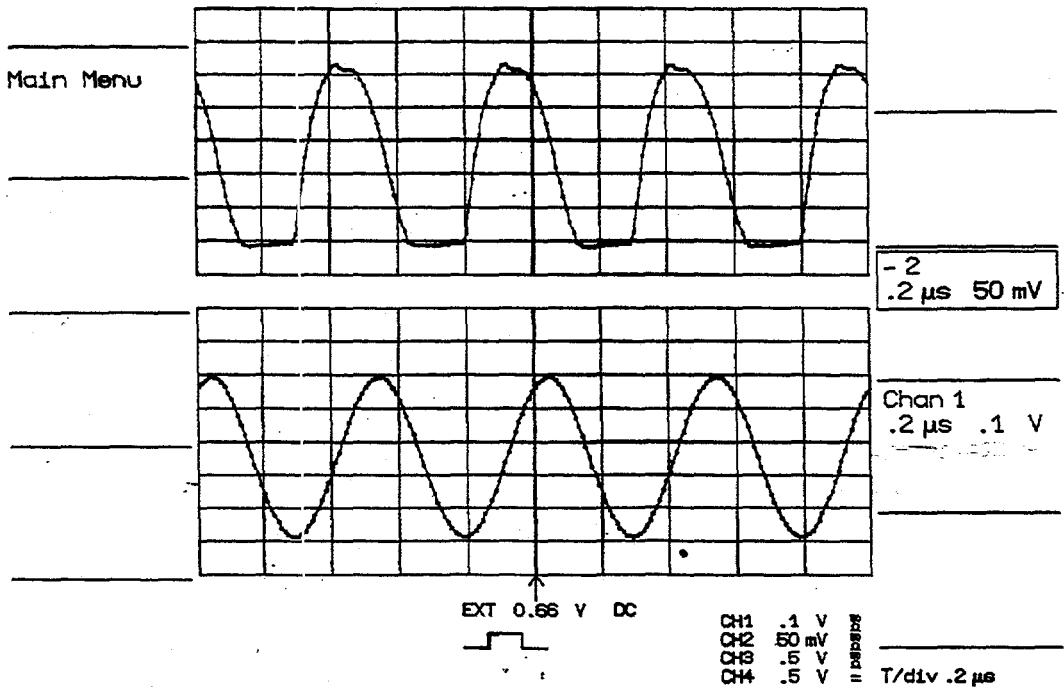
$V_{avg} = 90 \text{ kV}$
 $V_1 = 19\% V_{max}$
 $k_1 = 2$

$V_{max} = 90 \text{ kV}$
 $V_1 = 19\% V_{max}$
 $V_2 = 9.1\% V_{max}$
 $n_1 = 2$
 $n_2 = 4$

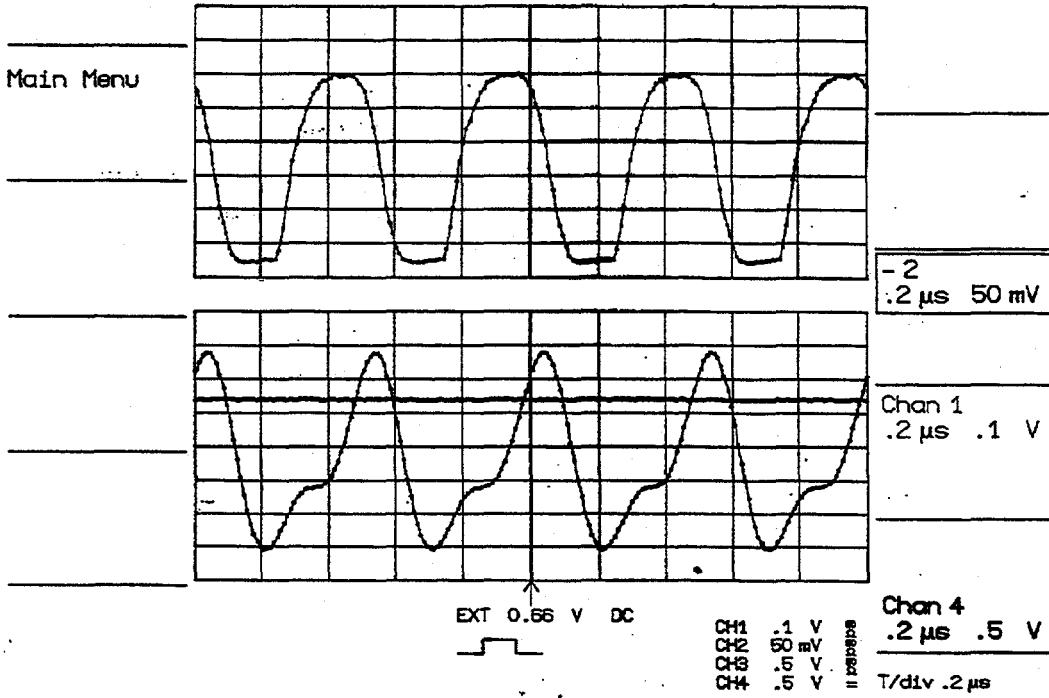
7-Jun-95
17:45:04



7-Jun-95
18:11:23



7-Jun-95
18:04:40



BOOSTER MODE - LEBI FAST CHOPPER
 Mad May 5 13:17:43 1993 37
 V Error: 0.51 kV/turn B dot: 3.2 1/sec Inj turns: 200 L beam: 20:000 mA
 K.E.: 200.0 MeV F dot: 35.2 MHz/ms phi_1: 110.0 deg
 Moving Bkt Bunch Stationary Bkt
 Area: 1.28 eVns 1.14 eVns 1.62 eVns phi_stable: 5.96 deg
 Height: 2.95 MeV 2.83 MeV 3.22 MeV
 Height: 13.05 kHz 12.50 kHz 14.22 kHz delta R: 0.01 cm
 Injection time: 236.7 usec Synch freq: 7.089 kHz 8Synch osc: 1.68
 fill fraction: 31.2 % of bunch height dInj particles: 1.95e+12

$\left\{ \begin{array}{l} 85 \text{ kV @ } h=2 \\ 30 \text{ kV @ } h=4 \end{array} \right.$

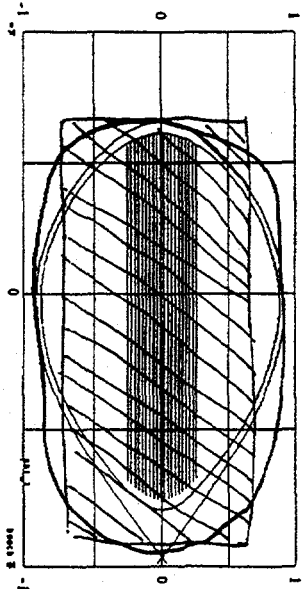
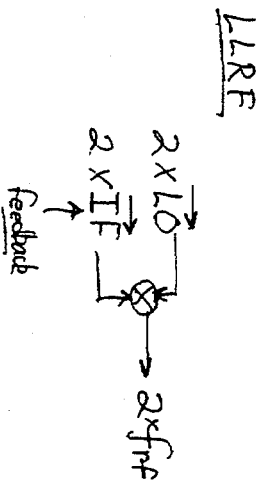


Figure 4. Longitudinal phase space: "dilute" population of 20 turns injected over the period of 200 turns.



Issues for Discussion

- Near Beam-loading limit
 1. Rf feedback
 2. Feedforward compensation
 3. Low-level drive feedback

- Optimize use of second harmonic
 1. Programming the phase $h=4/h=2$
 2. Stability in double rf bucket

AGS (1.9 GeV to 23 GeV, 6×10^{13} ppp)

I. Parameters

1. Frequency range: 2.8 to 2.9 MHz, $h=8$
2. Voltage: 10 x 40 kV (4 gaps each)
3. Beam Current: 5 to 7 Amps, rf
4. Power:
 - 10 x 60 kW to beam
 - 10 x 50 kW to ferrite
 - 10 x 190 kW in tetrode

II. Description of cycle

1. Four batches, 450 ms accumulation
2. Low voltage at injection, transition, and de-bunching for slow spill
3. Power booster at key points
4. Emittance blow-up via "VHF", 93 MHz

22-Apr-96
14:59:46

55.36 TP

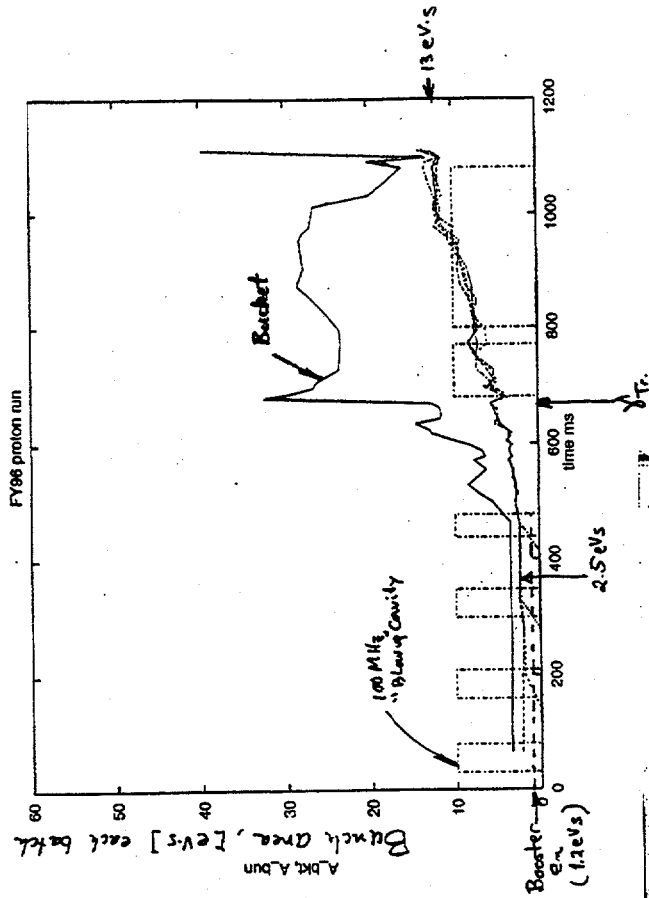
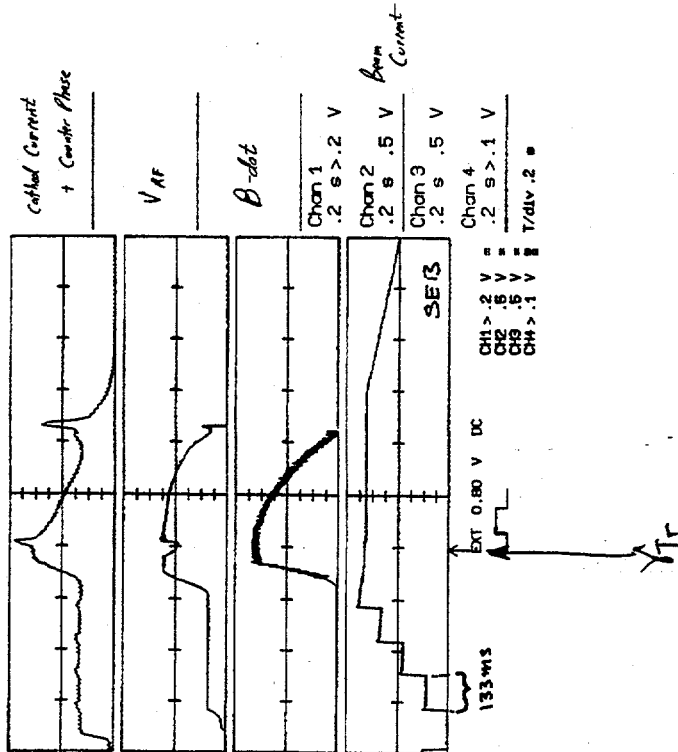
Main Menu

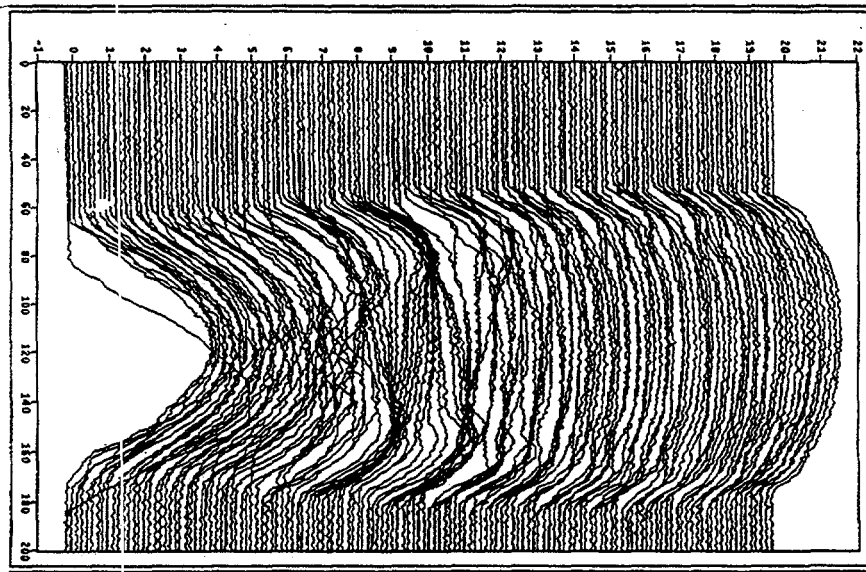
I cathode

V_{AF}

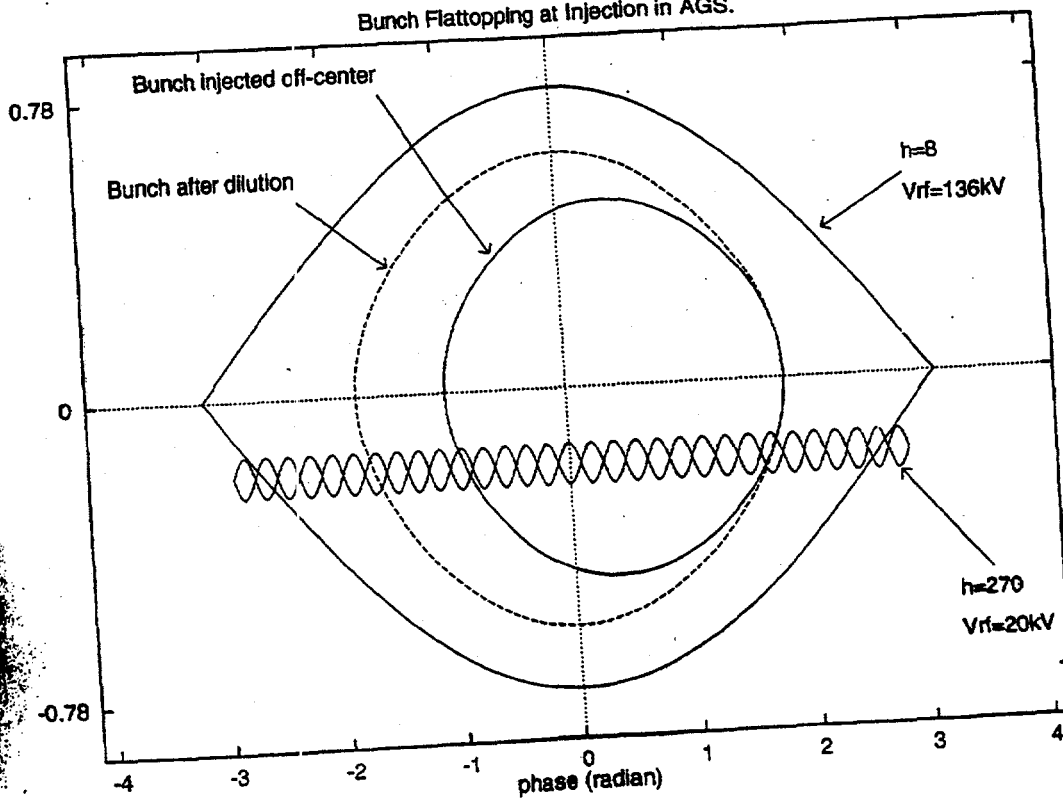
$\frac{dB}{dt}$

Beam Current





Bunch Flattopping at Injection in AGS.



Barrier Cavity Development

I. Motivation

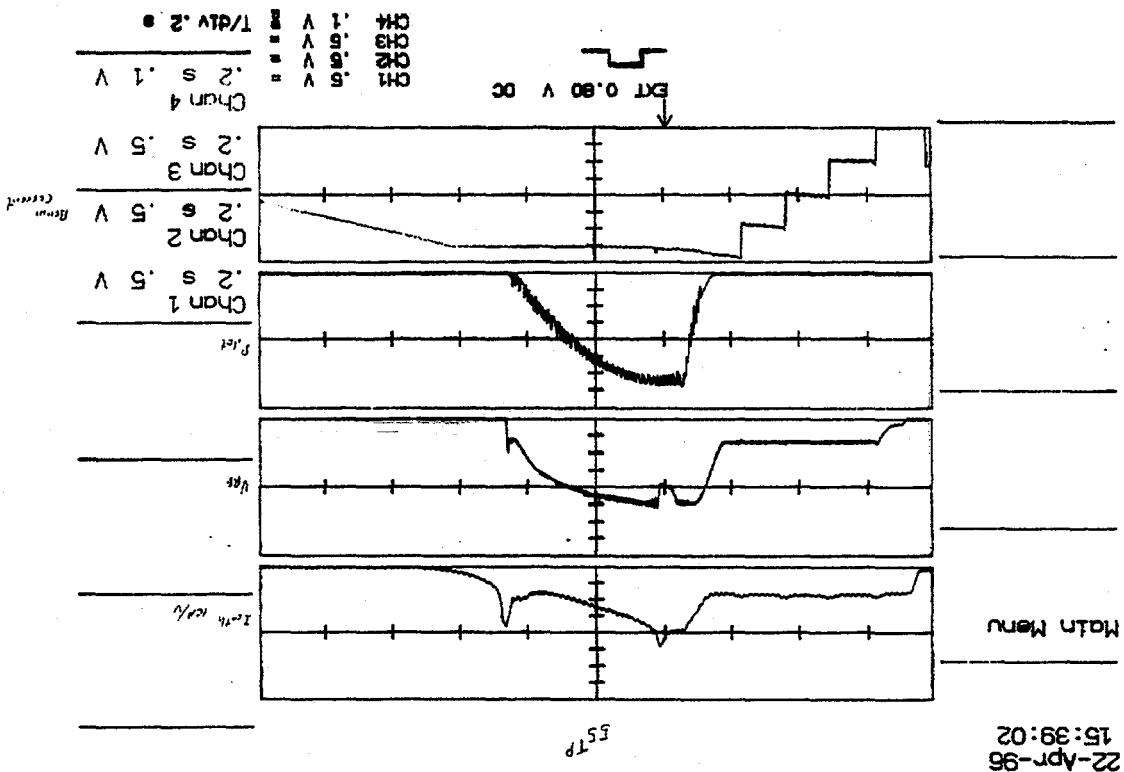
1. Slow loss during accumulation, AGS
2. Accumulate more than 4 loads
3. Prospects for a dedicated accumulator

II. Our approach

1. Isolated sine waves
2. High-Q cavities
3. Two cavities, two barriers

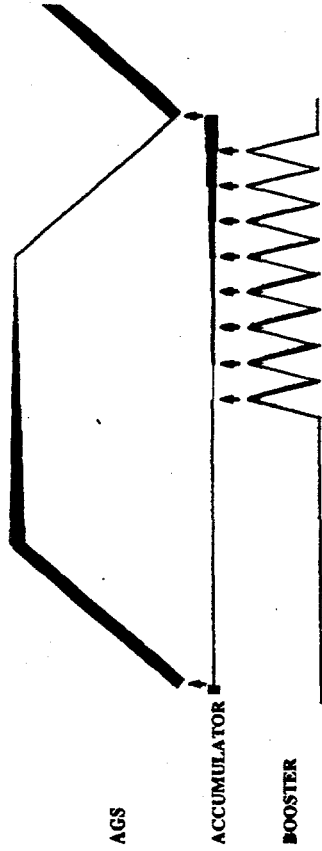
III. Development goals

1. 80 kV per cavity
2. 250 ns sine wave, 3 μ s rep. rate

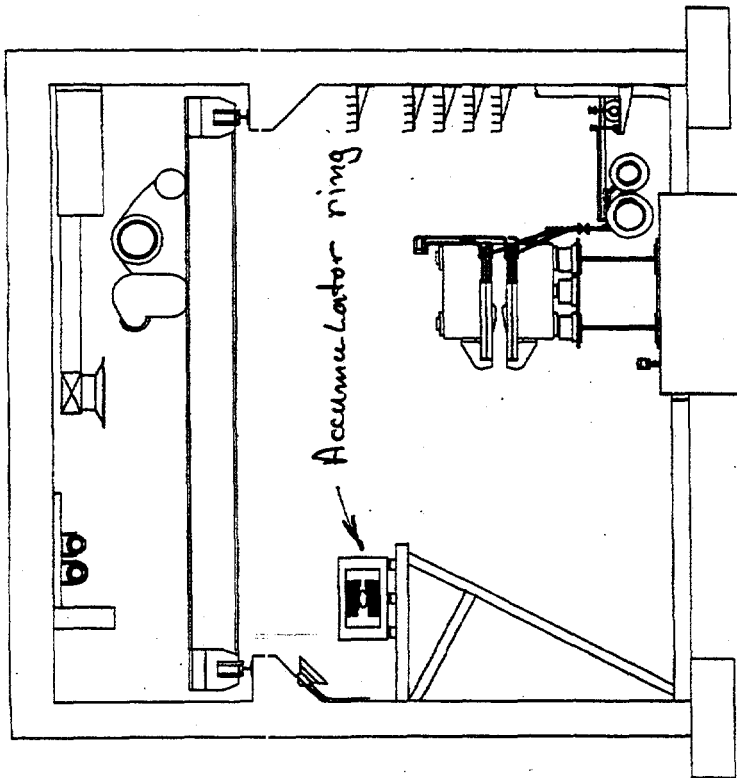
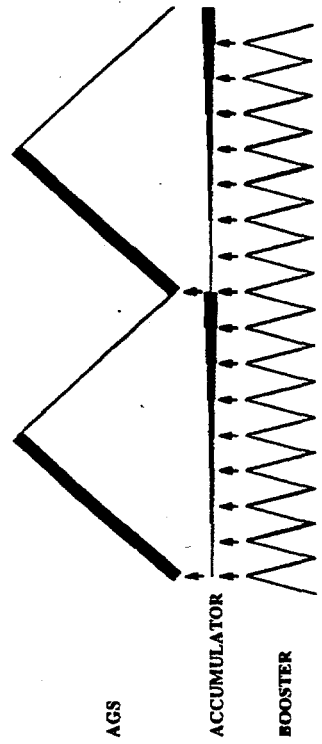


AGS WITH ACCUMULATOR RING

SLOW EXTRACTED BEAM:

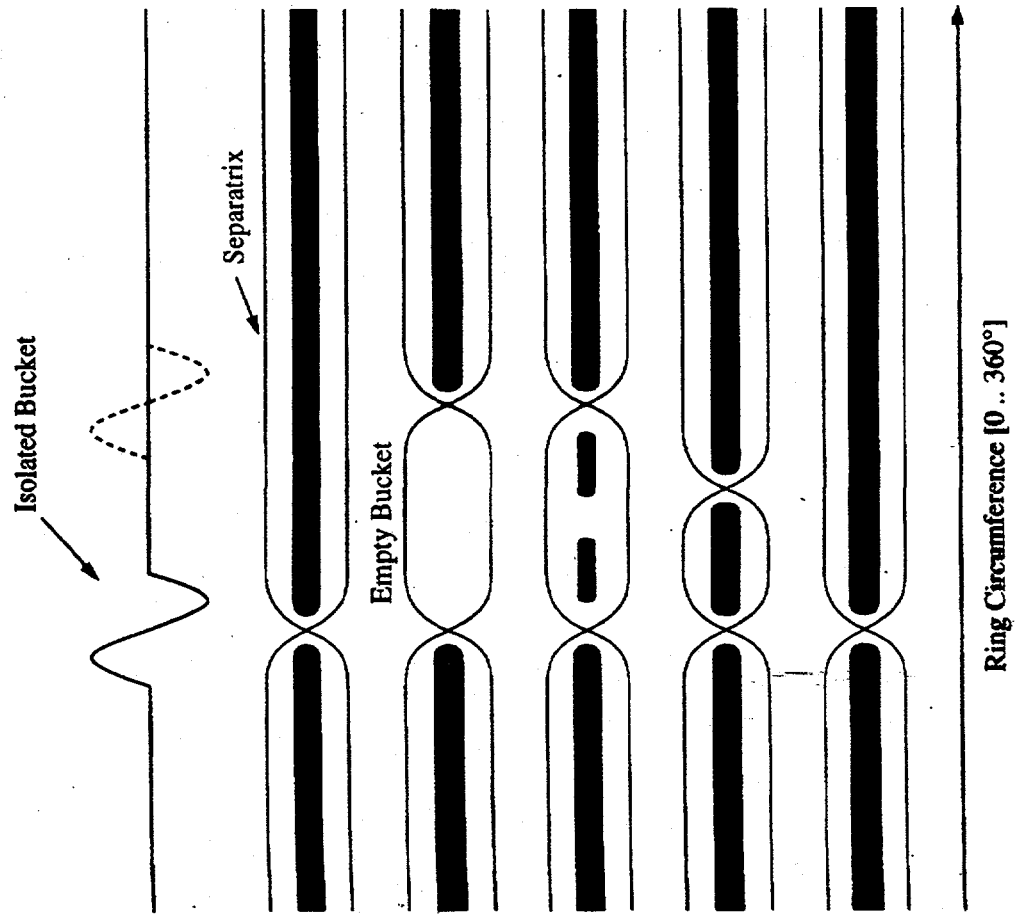


FAST EXTRACTED BEAM:



An accumulator could be added to the AGS tunnel

Time Domain Stacking with Barrier Bucket Cavity

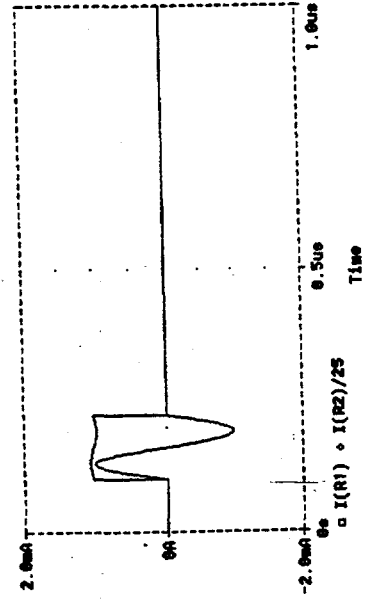


$$I(t) = \frac{V}{R} + C \frac{dV}{dt} + \frac{1}{Z} \int V(t) dt$$

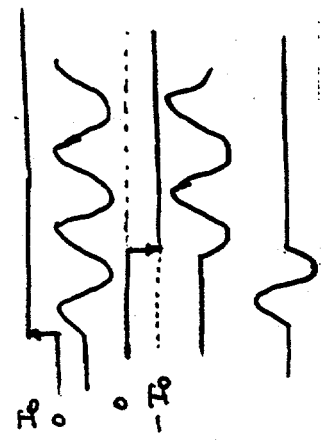
$$V(t) = V_0 \sin \omega t \quad 0 < \omega t < 2\pi$$

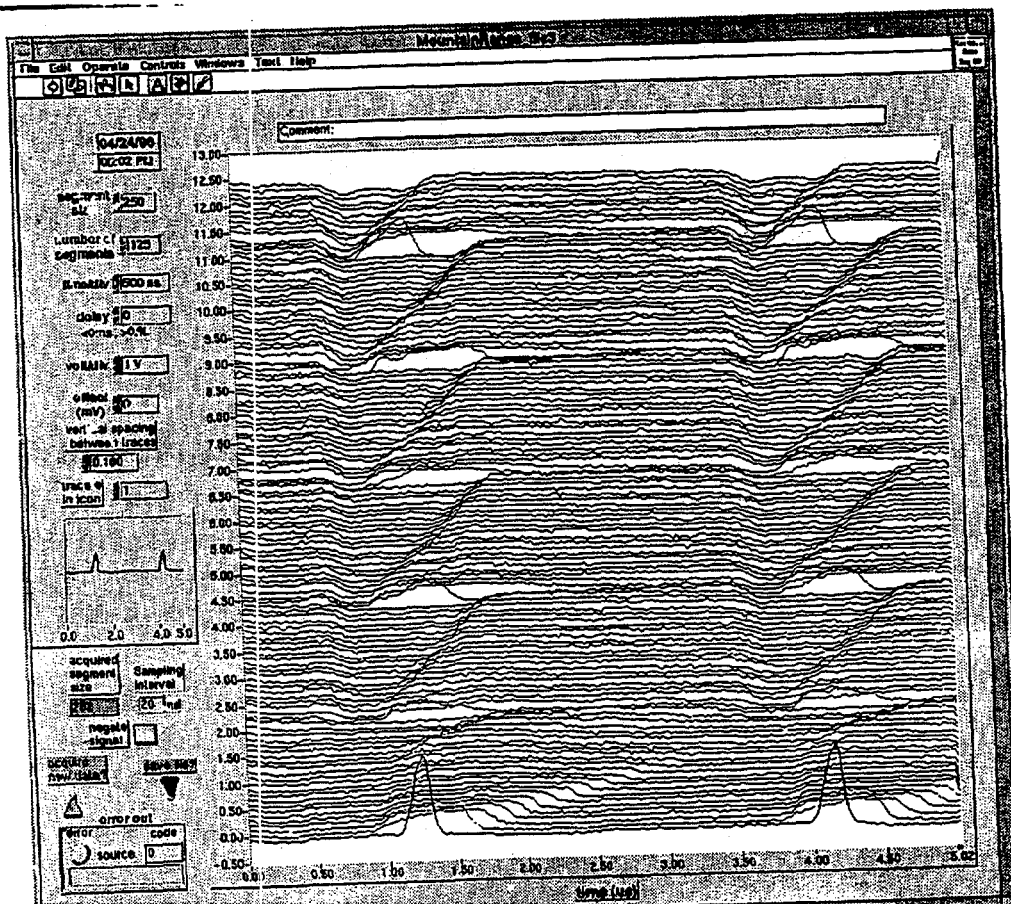
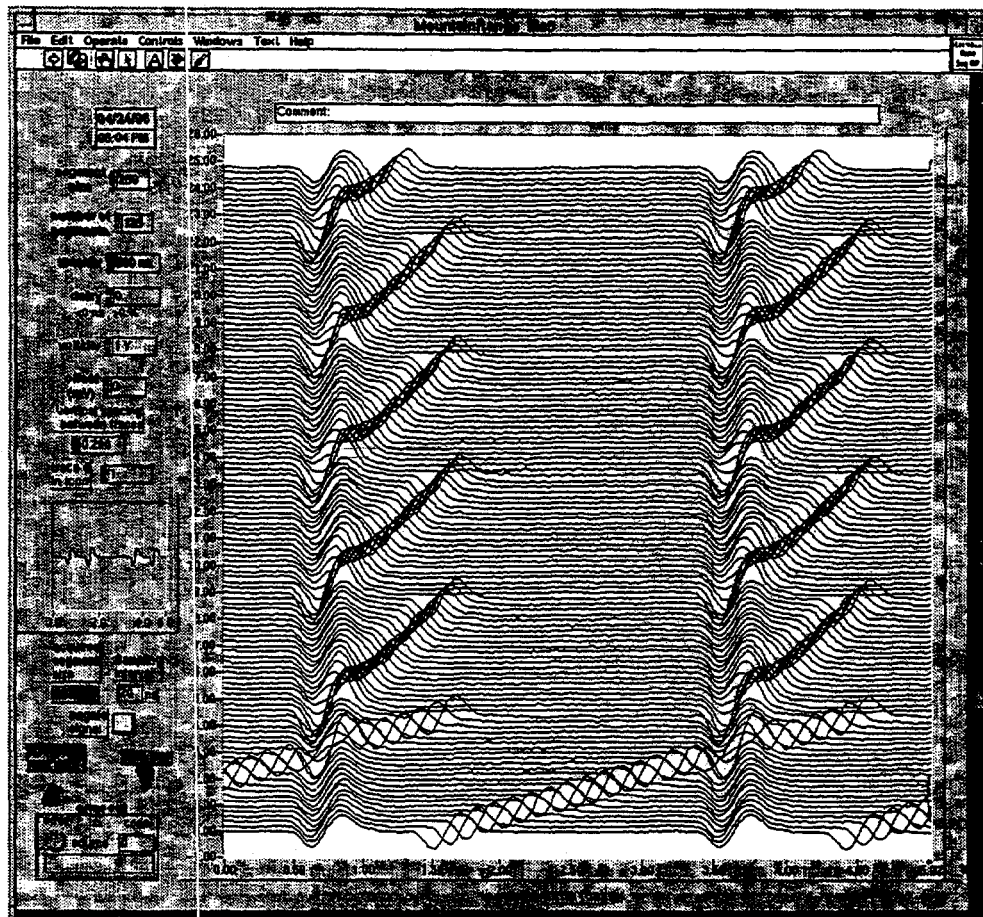
$$I(t) = \frac{V_0}{R} \sin \omega t + \frac{V_0}{\omega Z} + V_0 C \omega \cos \omega t \left(\omega C - \frac{1}{\omega Z} \right)$$

RF Waveform for Barrier Bucket (below transition)



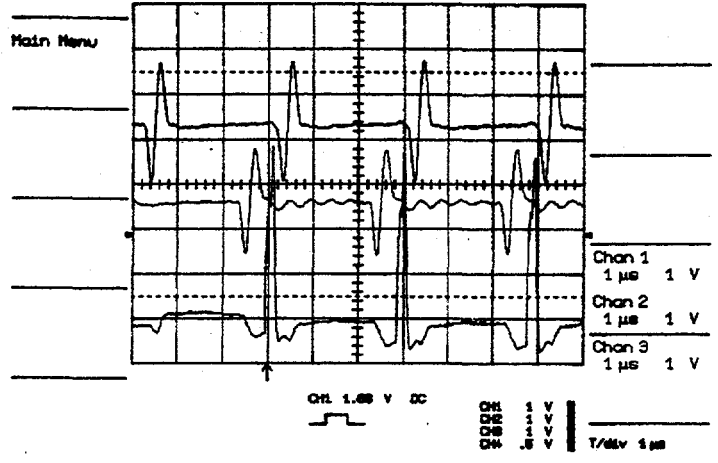
Cavity Voltage and Current for Q = 25





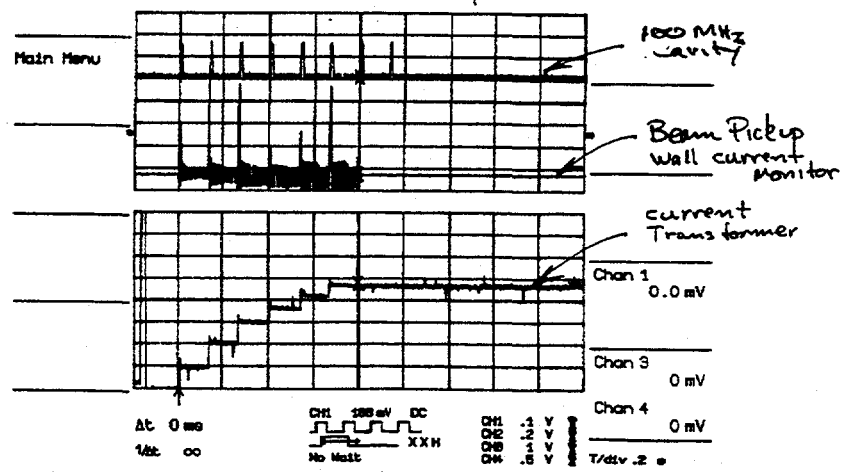
Barrier Buckets (12kV each)

24-Apr-96
17:29:14



24-Apr-96
16:45:40

¹³
3 X 10¹³ protons



**STATUS OF THE CERN PS INJECTOR COMPLEX
IN VIEW OF LHC**

References:

- Beams in the PS Complex during the LHC era, CERN/PS 93-08 (DI) - Revised -
- Proceedings of the 3rd International Workshop on High Brightness Beams for Large Hadron Colliders (LHC96), Montreux, Switzerland, 13-18 October 1996 (to be published as a special issue of Particle Accelerators):
 1. The PS Booster as Pre-Injector for LHC, K. Schindl
 2. The PS in the LHC injection chain, R. Cappi
 3. Bunched beam longitudinal instabilities in the PSB, F. Pedersen
 4. Longitudinal limitations in the PS complex for the generation of the LHC proton beam, R. Garoby
 5. Microwave instability and impedance measurement in the SPS, E. Chapirochikova, T. Linnecar
 6. And plenty more ...

Third ICFA Mini-Workshop on High Intensity High Brightness Hadron Accelerators
May 7 - 9 1997, Brookhaven National Laboratory (USA)

②

1. INTRODUCTION

The big picture ...

The Injectors' complex

This talk analyzes issues in the PS complex

2. REMINDER

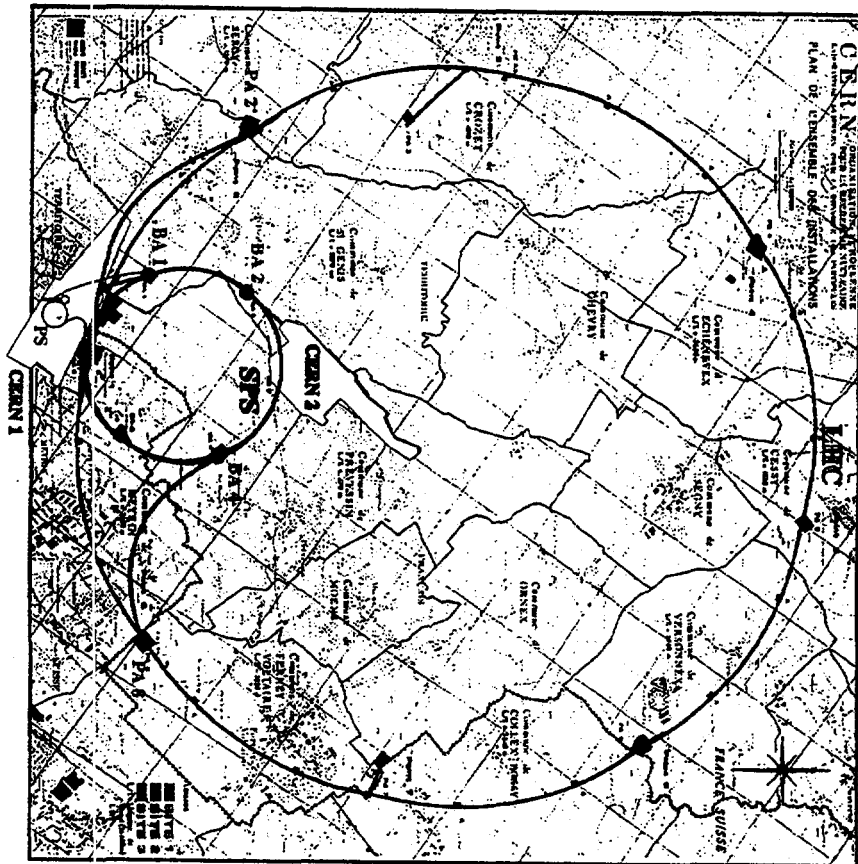
The injectors' chain for protons

Conclusion no. 1: the transverse emittance budget is tight

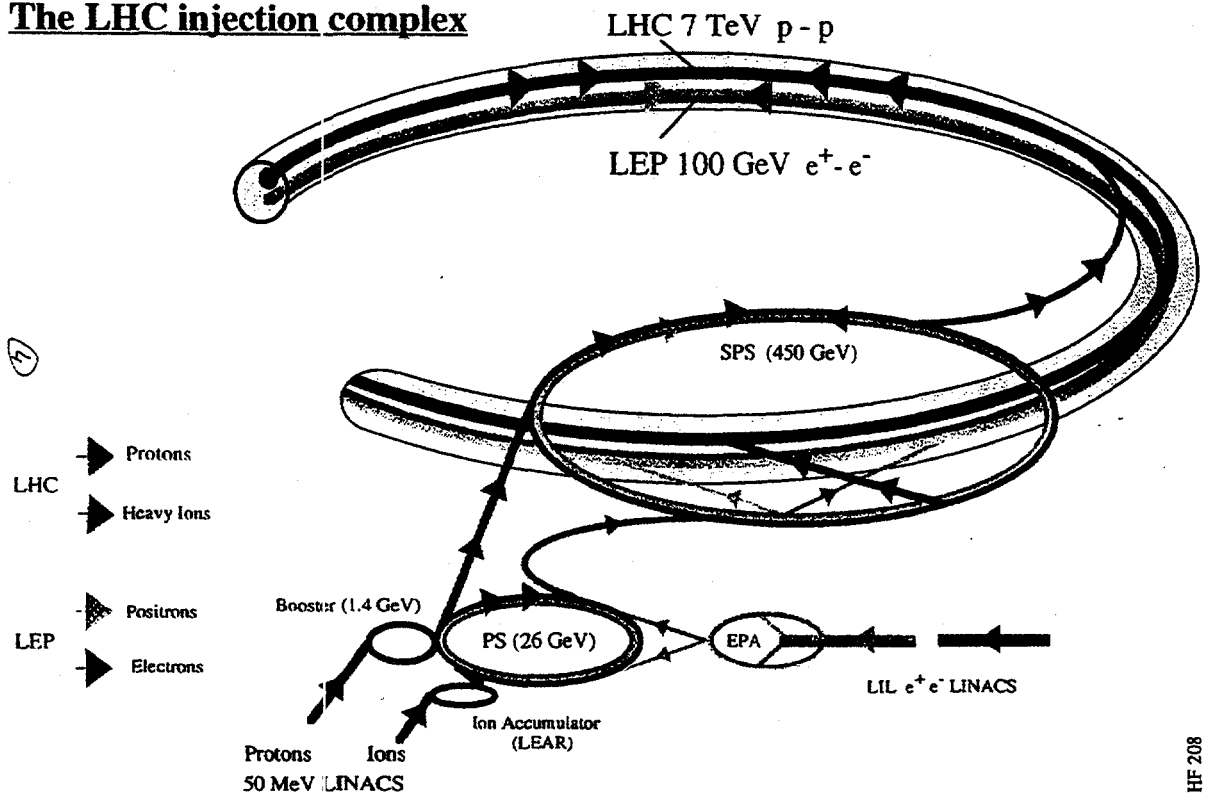
Operations in the longitudinal phase plane

Conclusion no. 2: the longitudinal emittance budget is also tight

②



The LHC injection complex



HF 208

The LHC Proton Injector Chain

	NOMINAL	BEAM-BEAM
LHC	T [TeV] B (T) 1 (m) (1)	7.5 9.0 2.5 10 ¹⁴
1.2 pulses 14.4 sec	p/bunch e* [µm]	1.7 10 ¹¹
450 GeV		3.75
SPS	p/pulse p/bunch e* [µm]	4.0 10 ¹³ 1.7 10 ¹¹
3 pulses 3.6 sec		3.5
26 GeV/c		
PS	p/pulse e* [µm]	1.4 10 ¹³
2 pulses 1.2 sec		3.0
1.4 GeV		
PS	p/ing e* [µm]	1.8 10 ¹²
Booster (4 rings)		2.5
50 MeV		
L. linac 2	[mA] e* [µm]	180 1.2
750 keV		
RFQ	[mA] e* [µm]	200 0.5...1

New Hardware
e* (normalised r.m.s. emittance) = (β²)⁻¹σ²/β

K.Schindl/PS 19/02/97

RF systems
40/80 MHz
25 ns spacing
Beam control
h=8, h=16

RF systems
1 to 1.4 GeV
RF systems
h=1, h=2

Two (warm)
transfer lines
New ejection
to T1.8
400 MHz RF
6 MV (s.c.)

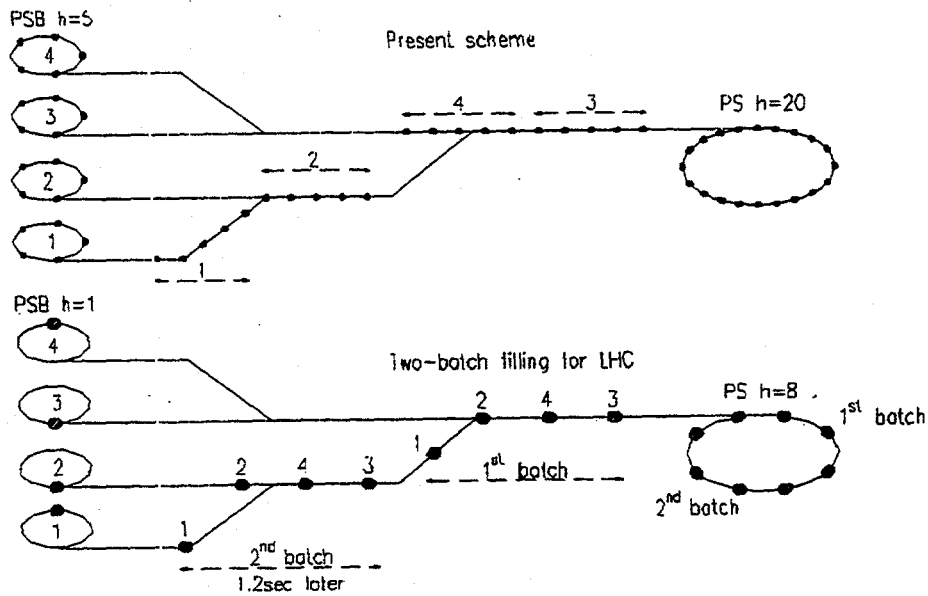
25 ns spacing
filling 3rd/ring

LHC96 - October 96
R. Garoby

LONGITUDINAL LIMITATIONS OF THE PS FOR THE LHC PROTON BEAM

1. NOMINAL OPERATING SCHEME ([1, 2] and R. Capii at LHC96)

Id.	DESCRIPTION	COMMENT
1	1 bunch / ring in the PSB, reduction of peak line density with second harmonic cavity	~ OK (under test)
2	Controlled blow-up of longitudinal emittance during acceleration in the PSB: aim for hollow particle distribution	~ OK (under test)
3	Bunch to bucket transfer PSB to PS of 2 PSB batches	OK
4	Bunch splitting in the PS (8 → 16 bunches) at low energy	OK
5	Controlled longitudinal blow-ups during PS flat-tops	OK
6	Acceleration up to 26 GeV	OK
7	Debunching (h=16) & rebunching (h=84)	MARGINAL
8	Fast ejection	MARGINAL



LHC'96 - October 96
R. Garoby

2. DELICATE PROCESSES (items 1, 2, 7 and 8)

2.1 Dual harmonic operation in the PSB (1)

- ⊙ Lots of experience with $h=5$ & 10 in the PSB since > 10 years
- ⊙ Thoughts and experiments with $h=1$ & 2 presented by F. Pedersen at this workshop

2.2 Blow-up during acceleration in the PSB (2)

- ⊙ The defocusing $h=2$ spoils the "normal" operation of the blow-up process. Understood after the test in 12/93 but experimental demonstration is still to be done. (Presented at EPAC94 [3])

2.3 Debunching (h=16) and rebunching (h=84) at 26 GeV in the PS

⊖ Tight longitudinal emittance budget (following figures from low intensity simulation):

- Total initial beam emittance (h=16): 16 eVs
- Emittance of debunched beam: 26 eVs
- Emittance of compressed bunches: 30 eVs

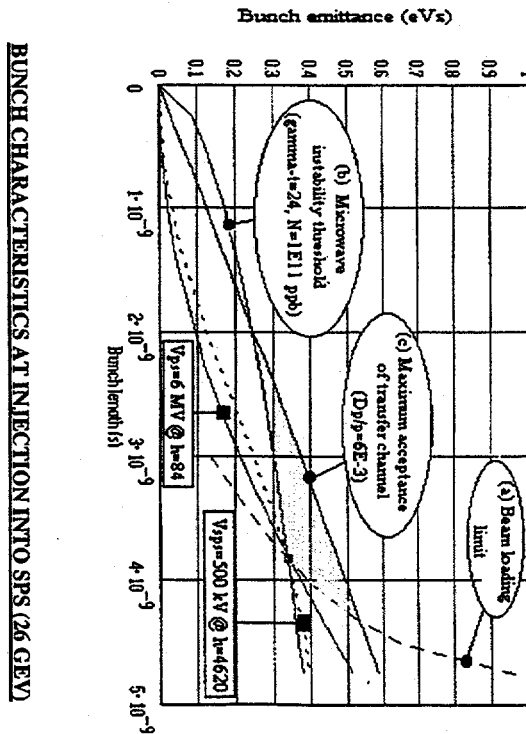
⊖ Bunch dimensions (lb, Dp) marginally satisfying for capture and stability in SPS, although with an already very large voltage for the PS

⊖ Non-adiabatic beam gymnastics prior to ejection (=> phase and energy drift of the beam w.r.t. reference)

2.4 Fast ejection at 26 GeV from the PS

⊖ Kicker rise-time longer than distance between bunches:

- 3 bunches will be lost in the PS extraction system,
- 1 (2 ?) bunch(es) will be incorrectly deflected and will end up with a tail at large transverse amplitudes



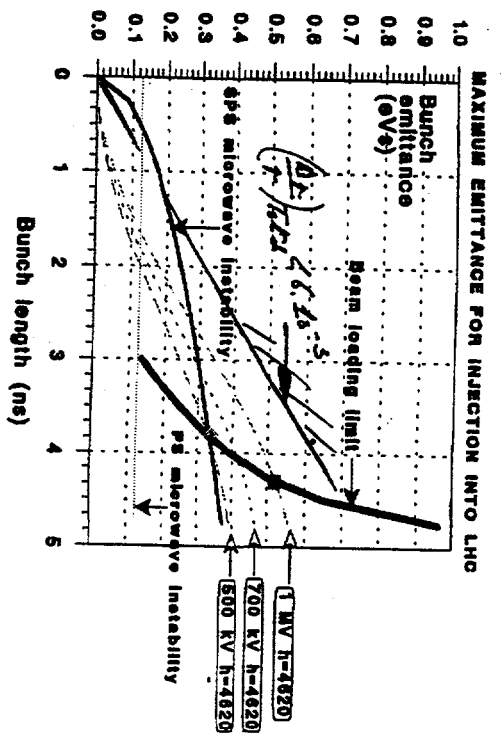


Figure 1 : Bunch parameters

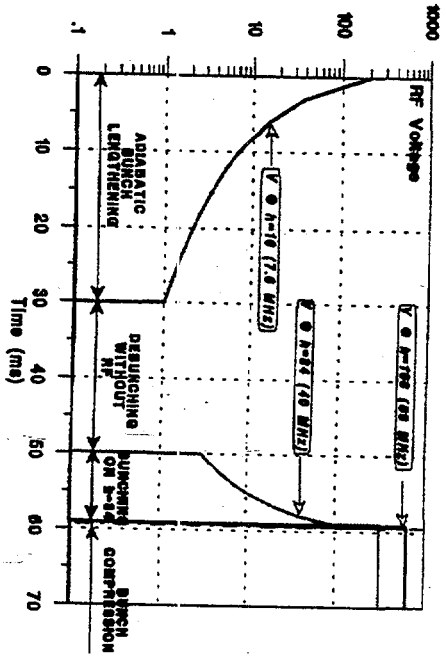


Figure 2 : Voltage programmes

FF

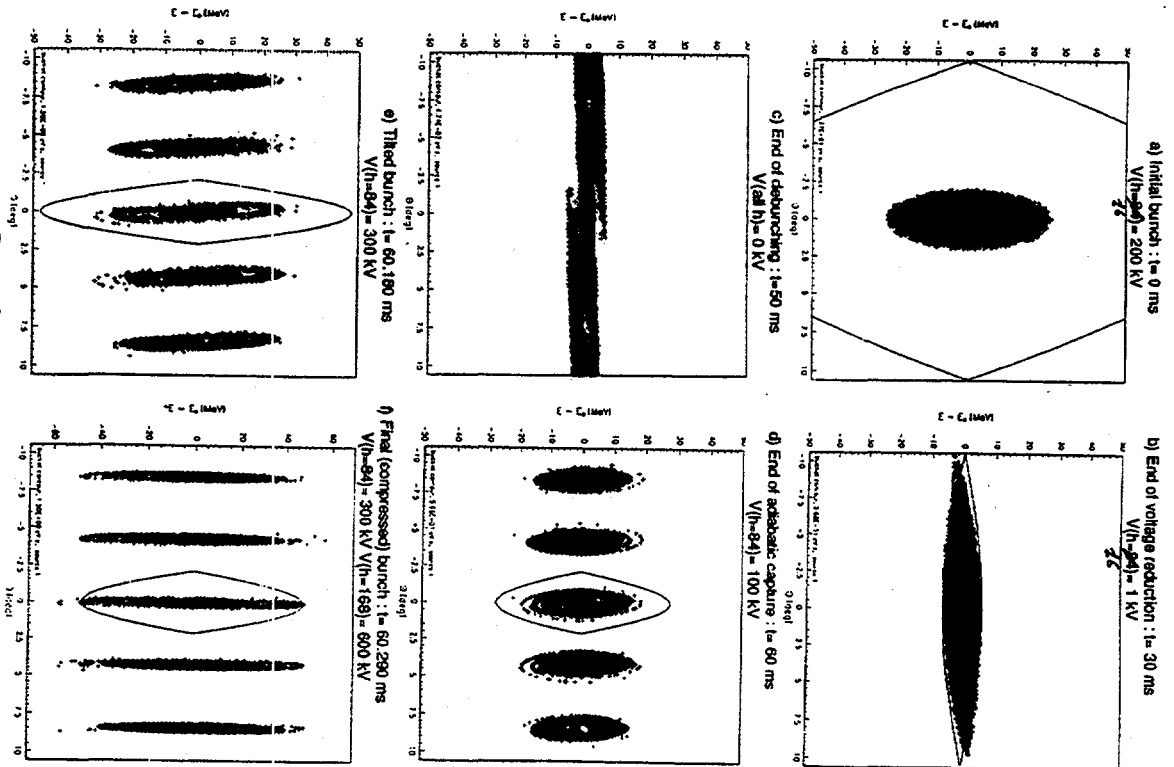


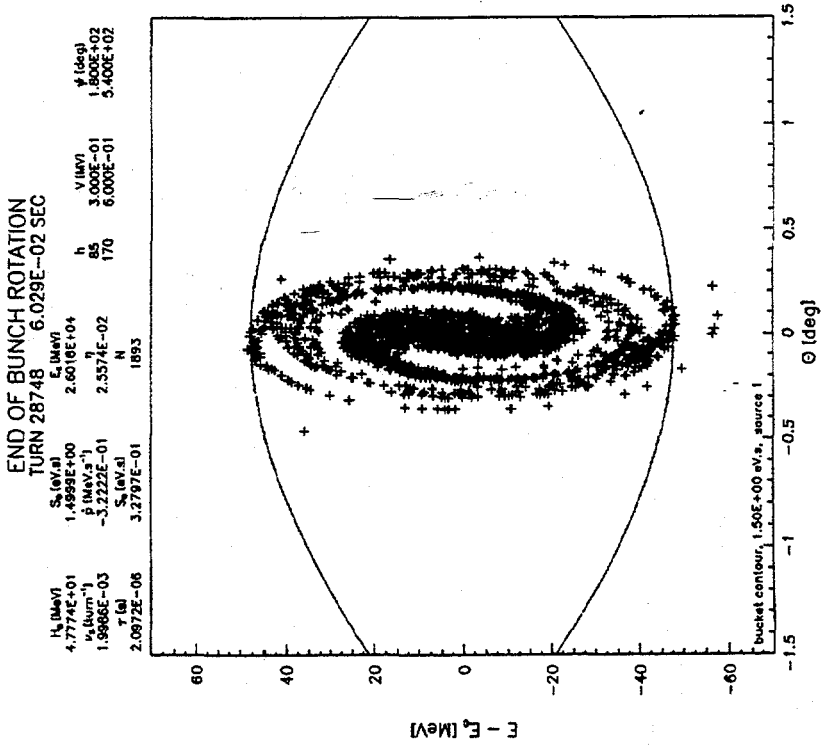
Figure 3 : Results of longitudinal tracking

FF

3. RECENT RESULTS

3.1 Hardware

- Prototype 40 MHz system for the PS ("C40"):
 - built and ready on time for first installation in the PS (week 40 / 1996)
 - Nominal performance achieved {V range: 3 to 300 kV pulsed, V rise-time < 20 μ s, Closed loop bandwidth: ~ 400 kHz, Gap short-circuit active, H.O.M. dampers installed}
- Prototype 0.6 - 1.8 MHz system for the PSB ("C02"):
 - built and tested on bench in 1996
 - Nominal performance achieved {V range: up to 8 kV CW, Open loop gain of fast feedback: ~ 20 dB} installed on ring 3 during the 96 winter shut-down
- 1.2 - 3.6 MHz systems for the PSB ("C04"):
 - operationally available (modification of present C08 systems)



(21)

(23)



bulletin



Semaine du lundi 21 avril

no 17/197

Week Monday 21 April

Le synchrotron à protons du CERN apprend de nouveaux tours

Lorsqu'il le LHC prendra ses premiers faisceaux de protons en 2005, ceux-ci auront été accélérés dans le PS et le SPS exactement comme les faisceaux d'électrons et de positrons du LEP aujourd'hui. Mais auparavant, il faudra encore beaucoup de travail, et pour être prêt à temps il faut commencer dès maintenant.

Le LHC fonctionnera avec une fréquence de répétition des paquets de 40 MHz, ce qui revient à dire que les paquets de particules qui circuleront dans la machine seront espacés que de 25 milliards de seconde (nanosecondes, ns). C'est beaucoup plus rapproché que les paquets du LEP, et c'est un chiffre qui a été choisi pour fournir aux expériences un maximum de données sans surcharger leurs systèmes d'acquisition de données. Mais c'est également un chiffre qui signifie que le PS, qui est déjà la machine la plus habile au monde à jongler avec les particules, devra apporter de nouveaux tours à son répertoire.

Dans la chaîne des accélérateurs qui préparent les faisceaux pour le LHC, le PS est le meilleur endroit pour grouper les particules en paquets courts et intenses. On ambitionne pour cela de nouvelles cavités radiofréquence (RF), sensibles à celles qui servent à accélérer les particules. La différence est qu'elle servira uniquement au groupage. Lorsque le PS aura fini d'accélérer les faisceaux de protons pour le LHC, une cavité à 40 MHz se mettra en service et comprimera les paquets en appliquant un bref mais changeant de tension. Les paquets seront alors devenus si courts qu'il ne leur faudra

CERN's Proton Synchrotron learns new tricks

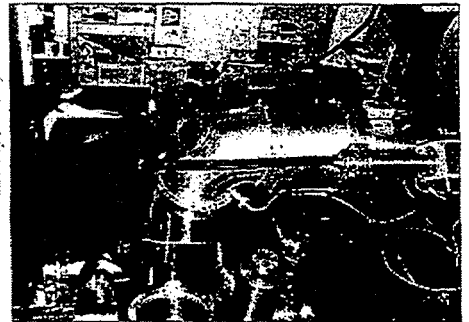


A delicate operation during the assembly of the new 40 MHz cavity as the mission-critical electrode is carefully installed.

Une opération délicate lors de l'assemblage de la nouvelle cavité à 40 MHz: l'électrode, en forme de champagne, est installée prudemment.

When the LHC enters its first proton beams in 2005, they will have been precisely selected through the PS and SPS just like LEP's electron and positron beams today. But before that can happen, there's much work to be done, and in order to be ready on time, it has to start now. The LHC will operate at a bunch repetition frequency of 40 MHz, or to put it another way, the bunches of particles travelling around the machine will be just 25 billionths of a second apart. That's a lot closer together than LEP's bunches, and it's a figure which has been chosen to provide the experiments with as much data as possible without overloading their data acquisition systems. But it's also a figure which means that the PS, already the world's most versatile particle juggler, will have to add new tricks to its repertoire.

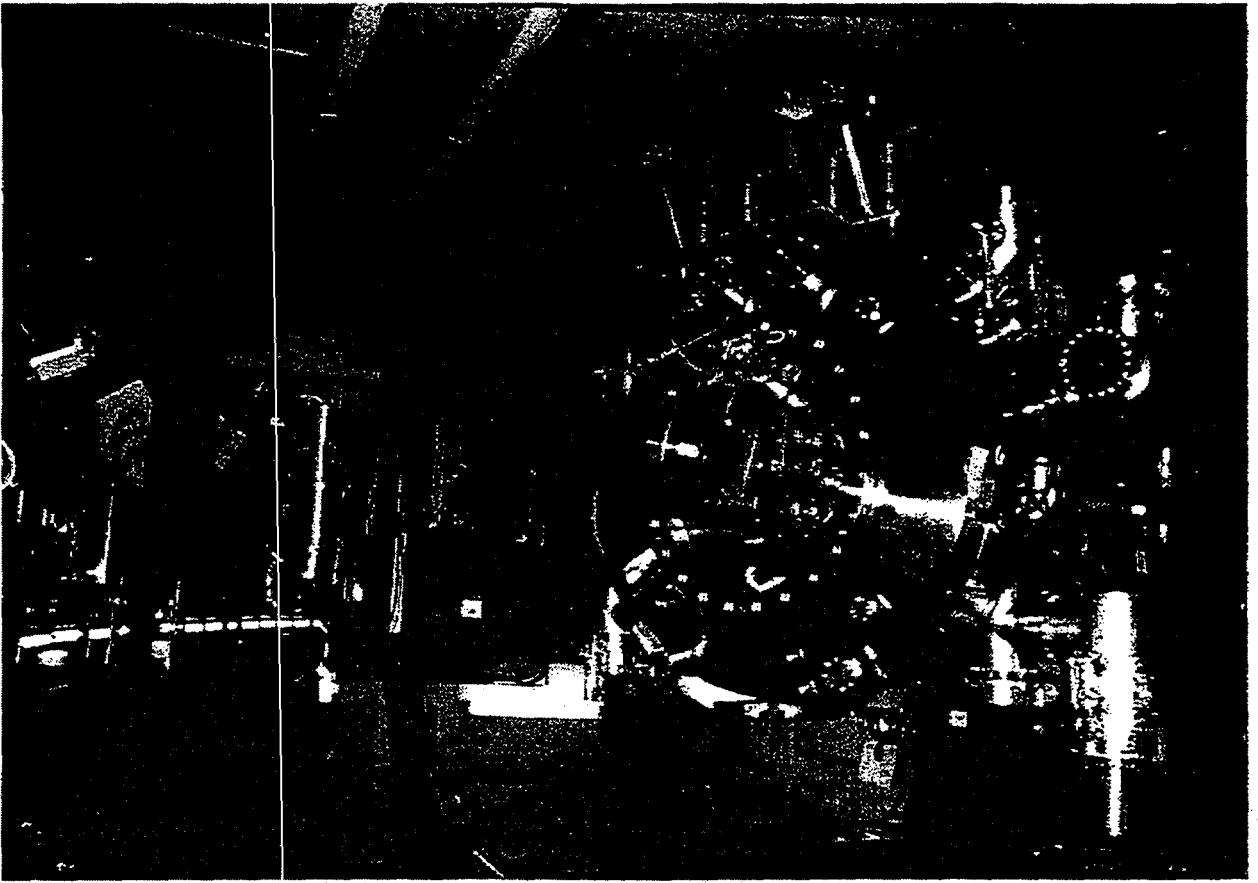
The PS is the best place in the chain of accelerators preparing particles together into short intense bunches. The way this will work is by using new radio frequency, RF, cavities similar to the ones used for accelerating particles. The difference is that these ones will be used just for bunching. When the PS has finished accelerating the proton beams for the LHC, a 40 MHz cavity will switch on and squeeze the bunches together by applying a rapid change in voltage. This will only take 10 ns to pass any given point. But that is still not quite short enough because the SPS will operate



The new 40 MHz cavity installed in the PS. The jiggler governing the array can clearly be seen in the foreground.

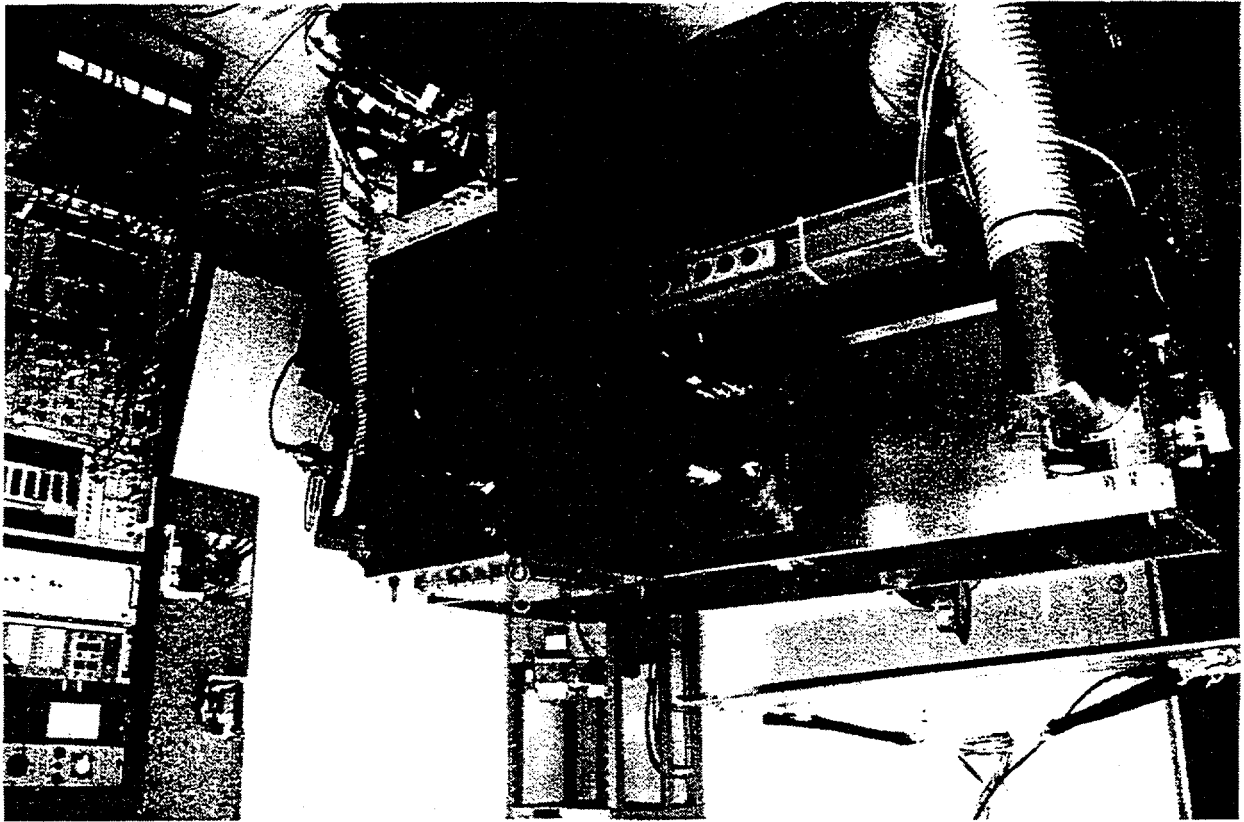
Y Cette nouvelle cavité est installée au PS. L'amplificateur qui aligne la cavité est clairement visible au premier plan.

La nouvelle cavité à 40 MHz: le joggler qui gouverne l'ensemble est nettement visible en premier plan.

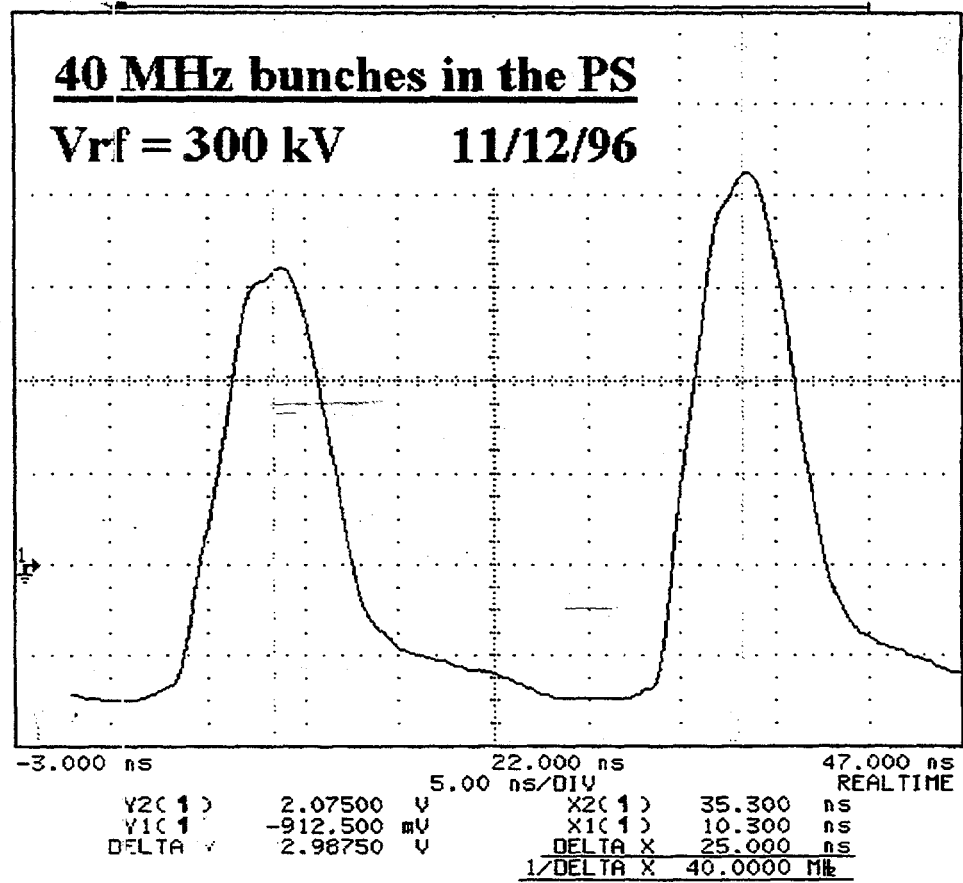


3.2 Beam experiments

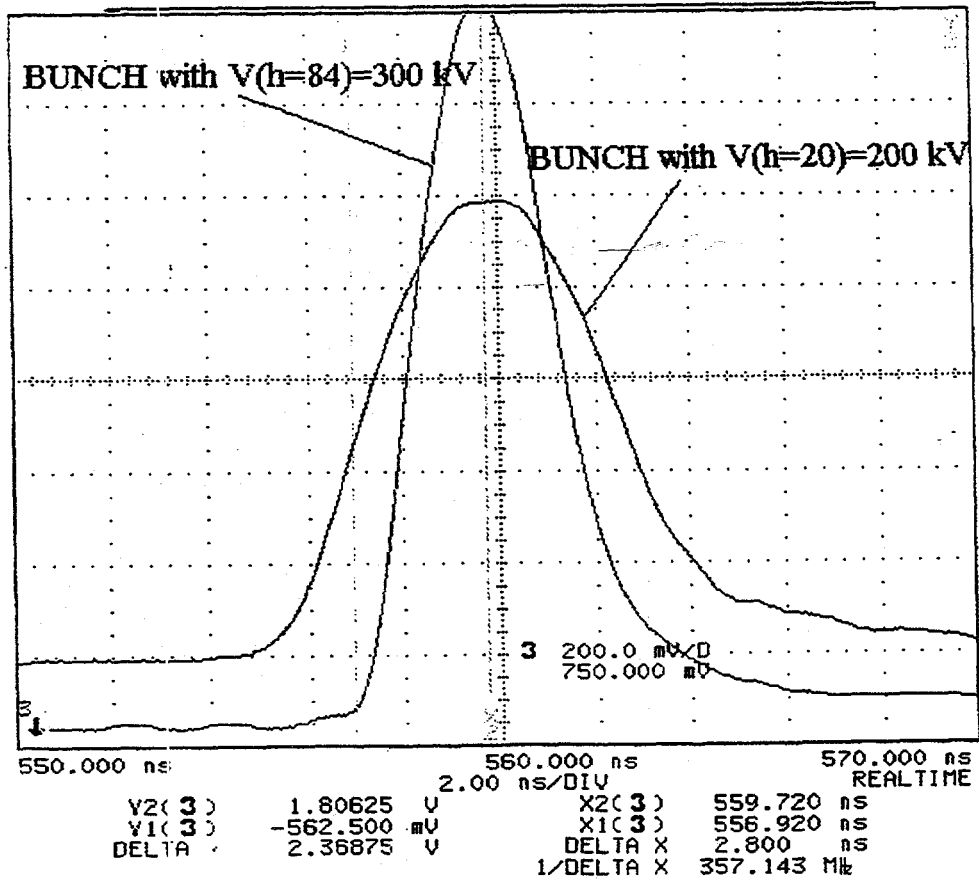
- Rebunching at 40 MHz in the PS (12/96):
 - no problem has been observed on any of the PS beam with the short-circuit open (neither with leptons (HOM) nor with high intensity protons).
 - Multi-pactor at low field was very helpful (but unreliable over the long term).
 - Debunching ($h=20$) / rebunching ($h=83$) could be achieved up to 10^{13} ppp and provided bunches of quasi-nominal emittance (~ 0.4 eVs, 9 ns)
 - Nominal voltage range measured on the beam
- Single bunch compression in the PS (4/97):
 - a single bunch of $1.5 \cdot 10^{11}$ ppp was accelerated on $h=20$ without blow-up up to 26 GeV, and synchronized to SPS revolution frequency
 - bunch to bucket transfer into $h=84$ worked OK
 - bunch compression \rightarrow 5.1 ns (adiabatic) & 3.8 ns (non-adiabatic)
- Acceleration with $h=1$ in the FSB (ring 3):
 - successful demonstration test (4/97) with $\sim 2 \cdot 10^{12}$ ppp and check of ppm compatibility

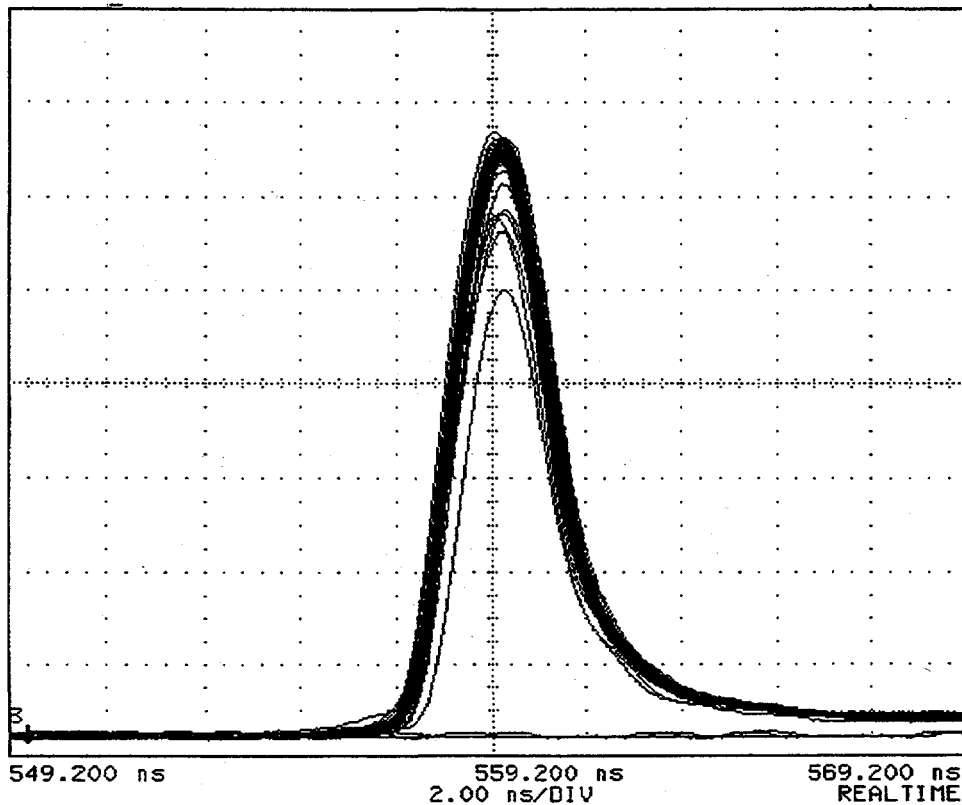


18



19





SYNCHRONISATION JITTER ON COMPRESSED BUNCH
capture up to 60 kV & Step to 300kV . - 4/4/97)

4. WORK PLAN

4.1 Short term aims (till end 97)

- Build and test the hardware required for the 97-98 shut-down (4 CO2 RF systems for the PSB, 2 C80 RF systems for the PS, low level RF and beam controls for all new modes of operation, specification of control's software for 98)
- As far as reasonably achievable (☺ : bnl internal joke), test prototypes and check all modes of operation during 97
- Beam studies (analysis of longitudinal instabilities, understanding of controlled blow-up mechanism with dual harmonics RF system in the PSB, minimization of longitudinal emittance in the PS, etc.)
- Provide test beams to SPS
- Feasibility study for a 2 GeV Supraconducting Linac
- Define & begin work for the Anti-proton Decelerator ("AD")

4.2 Medium term aims (till end 98)

- Resume operation for physics for the start-up in March 98
- Provide nominal LHC proton beam to SPS for the summer 98
- Build / modify hardware and begin beam studies for the AD

4.3 Long term aims (after 98)

- Start & run the AD
- Implement modifications (if any) for proper handling of the nominal LHC beam in the SPS
- Design and implement a technique to create a void of a few bunches in the PS 40 MHz bunch train
- Prepare Ions injectors' complex for LHC
- Define (implement ?) a scheme to attain the ultimate luminosity in LHC...

05/06/97
R. Garoby

2. PS

SPS test beams	<ul style="list-style-type: none"> 1 to 20 bunches on h=20 @ 26 GeV with freq synchro. on SPS Recaptured beam on h=84 @ 26 GeV (10¹³ ppp, 0.4 eVs, 9.5 ns) 1 bunch on h=84 (from 1 bunch on h=20) (5 to 15x10¹⁰ ppp, 0.14 eVs, 3.8 ns) 	<p>Week 16: beam to SPS</p> <p>Weeks 17 Week 18: beam to SPS Weeks 15-22 Week 23: beam to SPS</p>
LHC H+	<ul style="list-style-type: none"> Capture on h=8 Splitting on h=16 Blow-up and acceleration on h=16 	Weeks 35-40 (Sept.)
SFTPRO	<ul style="list-style-type: none"> High beam intensity capture / splitting and acceleration on h=16 Analysis & damping (!) of instabilities 	Weeks 40-46 (Oct.)
SFTION	<ul style="list-style-type: none"> Capture & acceleration of Pb³⁺ on h=16 	Weeks 47-48 (End Nov.)

3. OTHER TASKS ON THE MACHINES

- Test of new 200 MHz blow-up hardware (200 MHz phase-shifter with digital control by GFAS)
- Check phase stabilisation loop for 40 MHz system
- Build and test 40 MHz phase loop
- Set-up and exercise tuning loop for the 40 MHz cavity
- Monitor effects induced by the 40 MHz cavity on the beam. track evolution of multipactor levels.

Domain	Action	Benefits	Comments
PS longitudinal parameters	<ul style="list-style-type: none"> increase V_{RF} reduce I_{RF} 	better bunch compression	<ul style="list-style-type: none"> expensive and of limited effect to be investigated but no clear solution yet
Gap in the beam	<ul style="list-style-type: none"> "killer" kicker "barrier-bucket" bunch splitting 	no badly deflected bunches	<ul style="list-style-type: none"> beam losses to be investigated needs high energy Linac or rebuilt PSB ejection kickers
SPS longitudinal parameters	<ul style="list-style-type: none"> reduce IZ/nI increase I_{RF} 	improved stability in SPS => relaxed requirements on the PS	<ul style="list-style-type: none"> under investigation (source of dominant impedance localised) deserves investigation
New PS ("PS-XXI")	<ul style="list-style-type: none"> increase transfer energy imaginary variable %_{PS} 	<ul style="list-style-type: none"> improved stability in SPS better bunch compression improved reliability simplified operation 	<ul style="list-style-type: none"> major investment needs upgrade of the transfer channel to SPS needs further studies
High energy Linac ("SPL")	<ul style="list-style-type: none"> increased injection energy in the PS (2 GeV) no waiting time at PS injection energy chopped injected beam 	<ul style="list-style-type: none"> minimal long-blow-up better bunch compression no badly deflected bunches reduced transverse emittances improved reliability simplified operation 	<ul style="list-style-type: none"> major investment most effective solution to increase LHC beam brightness needs further studies

LONG TERM THEMES OF INVESTIGATION

(26)

(25)

Intensity Related RF Issues at Fermilab

David Wildman
Fermilab

Acknowledgments

Joe Dey
Kathy Harkay
Gerry Jackson
Ioanis Kourbanis
Dave McGinnis
Jim Steimel

Future Plans Requiring Higher Intensities

Collider Run II (1999)

Increase number of colliding bunches from 6×10^6 to 36×10^6
Multi-Batch Coalescing
Increase Pbar production and stacking rate
Higher Main Injector Intensity of 6×10^{10} ppb
Recycler Ring Barrier Bucket RF system

Tev 33 (before LHC)

Increase Collider luminosity to 1×10^{33}
Slip stacking ?
Additional Main Injector RF ?
A higher frequency RF system for the Tevatron ?

NUMI = NeUtrinos at the Main Injector(2000+)

High intensity fixed target experiments to detect neutrino oscillations

Muon Collider (?)

A fast cycling high intensity proton driver

Booster Resistive Wall Monitor

5

Three Topics for Discussion

Longitudinal Coupled Bunch Instabilities

Multi-Batch Coalescing (transient beam loading)

Wideband Recycler Ring RF (barrier buckets)

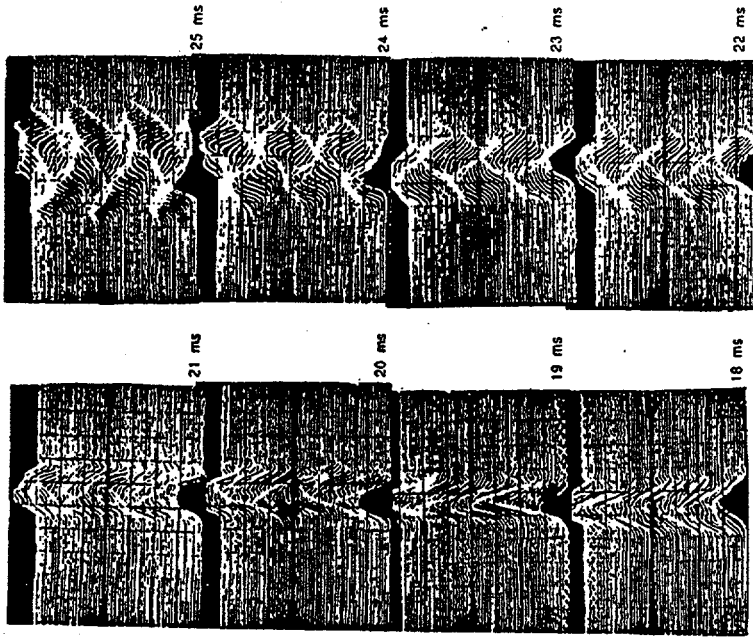


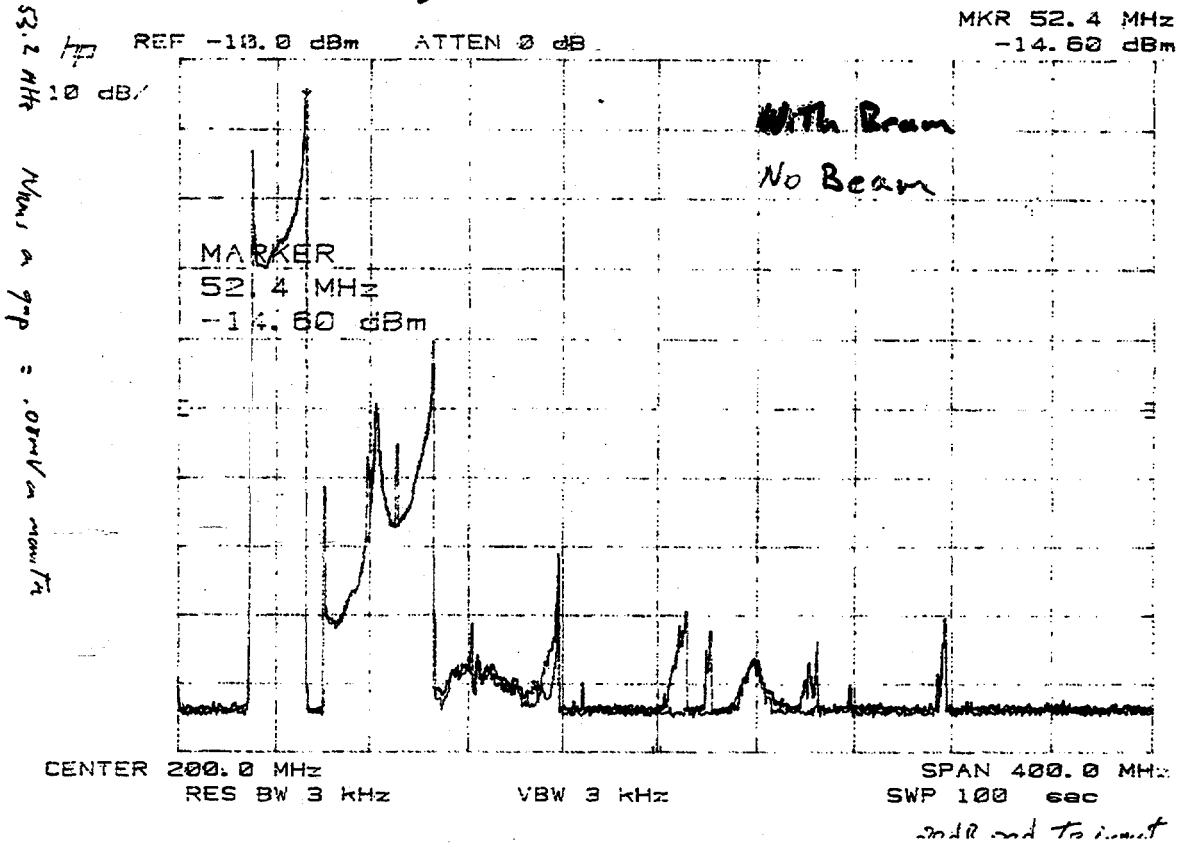
Figure 1.1 Time Evolution of the Bunch Phase (Mountain Range Plots) Through a Portion of the Booster Cycle. Growing dipole oscillations indicative of the coupled-bunch instability are clearly seen. The beam intensity is 1.5×10^{10} protons per bunch, the transition jump system is off, and the RF cavity dampers are out. The horizontal scale is 2 nsec per division. [Ref. 43]

Booster RF Cavity

Upstream Monitor STA 12 Mod: No beam

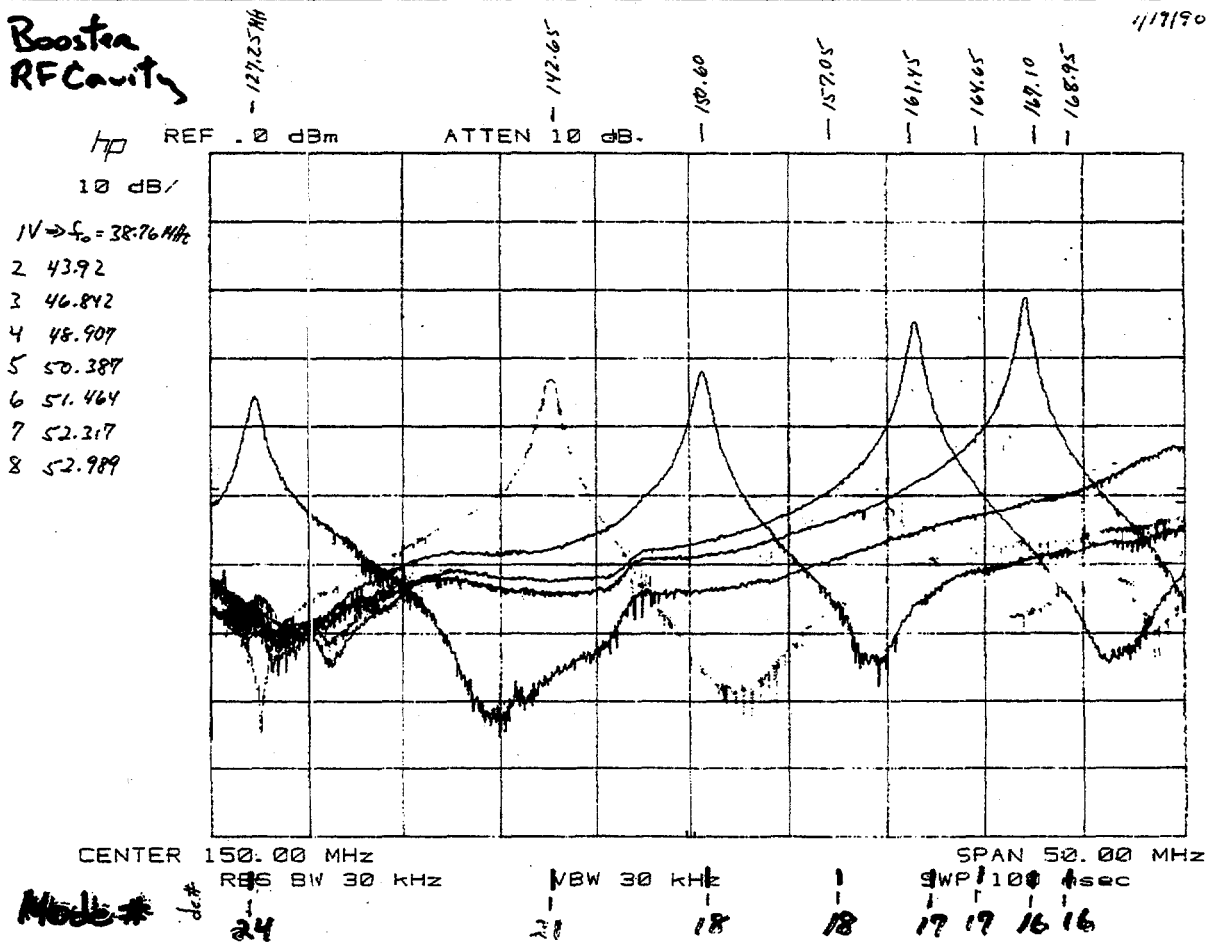
6/17/90

Black: with beam



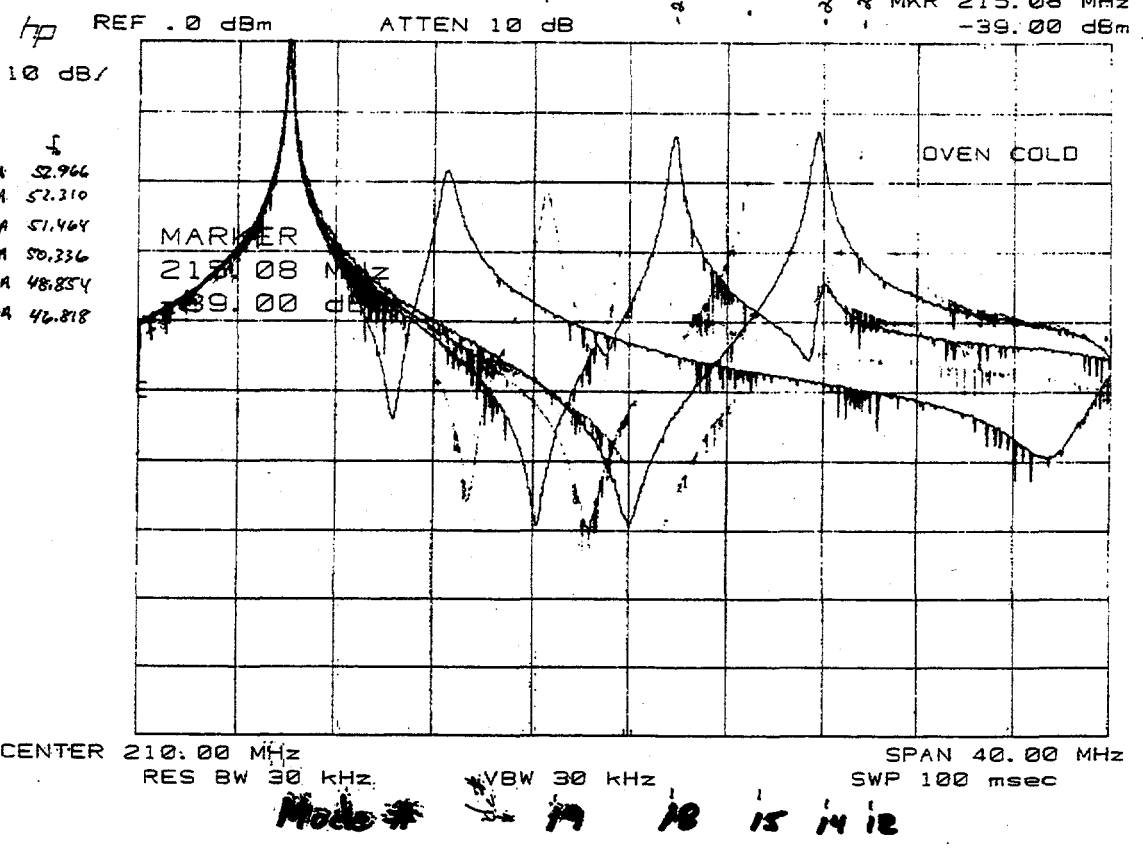
Booster RF Cavity

6/17/90



Booster RF Cavity

1/18/70



$I = 2000A$	52.966
$I = 1700A$	52.210
$I = 1500A$	51.464
$I = 1200A$	50.336
$I = 1000A$	48.854
$I = 700A$	46.818

Booster Cavity Mode (16)

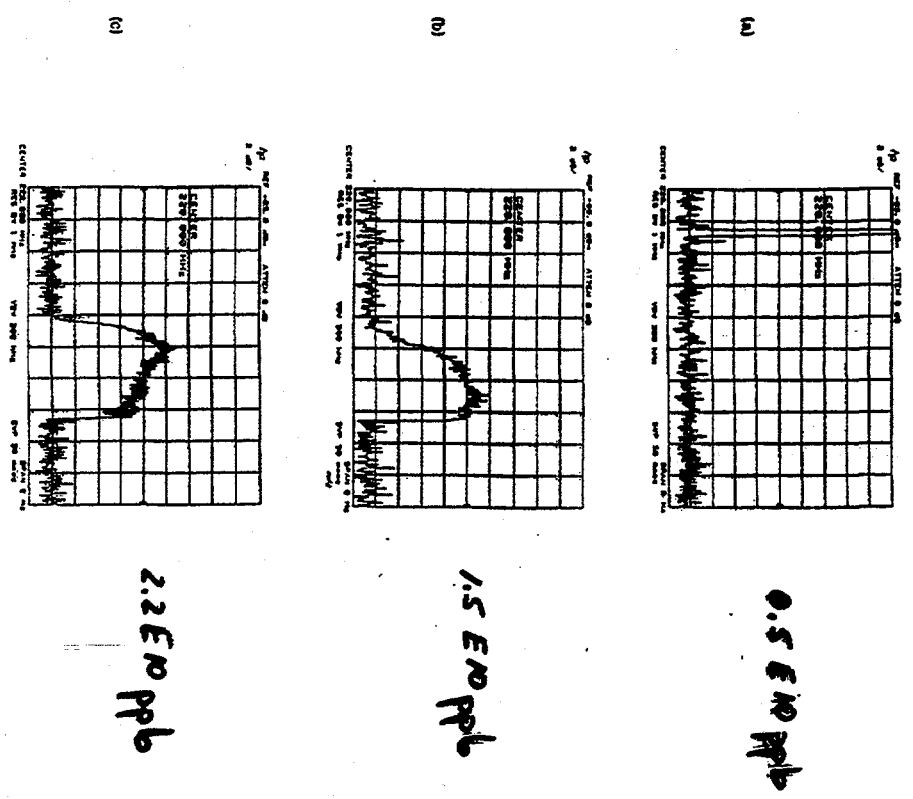


Figure 5.11 Excitation of RF Cavity Mode 16 (220.8 MHz). Shown are three beam intensities: (a) 0.5e10, (b) 1.5e10, and (c) 2.2e10 protons per bunch.

Booster

122

FFT of Resistive Wall Harmonics

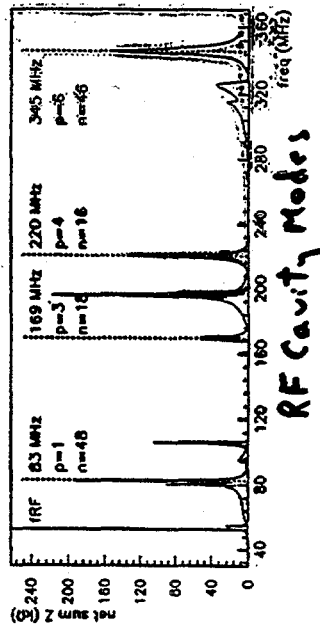
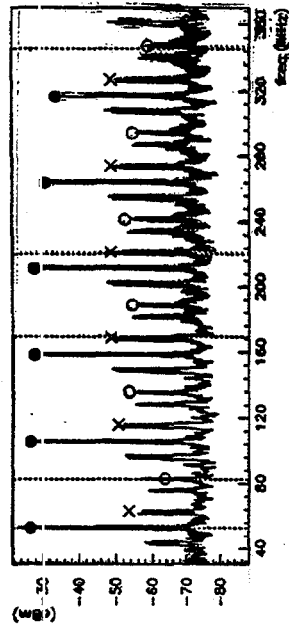
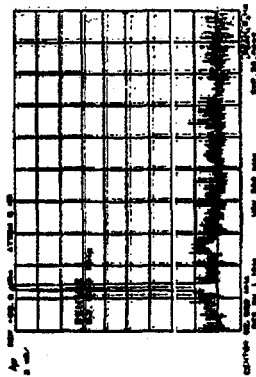


Figure 5.8 Correspondence of RF Cavity HOM Impedance and Coupled-Bunch Modp Spectrum Before HOM Dampers. The RF harmonics are marked with a filled 'O', mode 16 with an 'X', and mode 48 with an open 'O'. (R12)

Booster Cavity Mode (36)

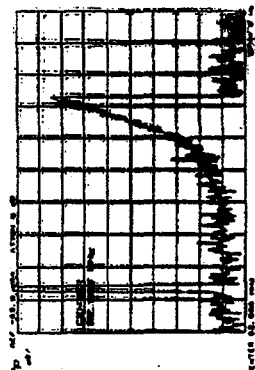
123

0.5 E10 pp/b



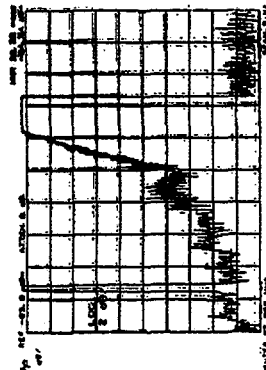
(a)

1.5 E10 pp/b



(b)

2.2 E10 pp/b



(c)

Figure 5.9 Excitation of RF Cavity Mode f2 (82.0 MHz). Shown are three beam intensities: (a) 0.52e10, (b) 1.5e10, and (c) 2.2e10 protons per bunch.

Booster Cavity

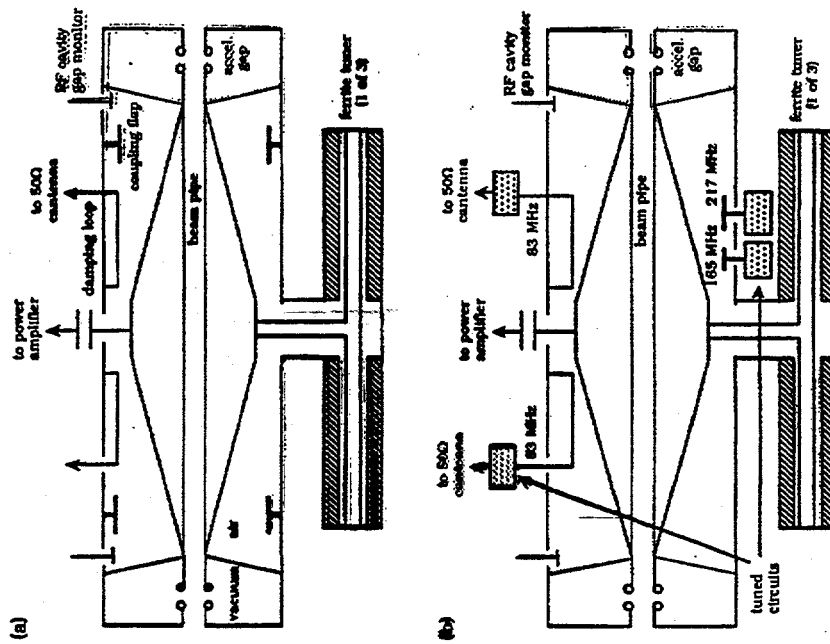


Figure 5.12. RF Cavity Showing Installation of HOM Dampers. Depicted are the (a) nominal and (b) modified cavities.

Booster RF Cavity

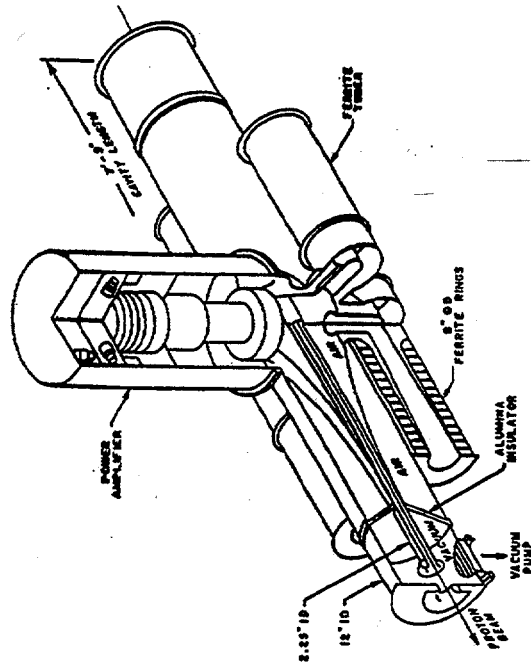


Figure 2.6 Cut-Away Drawing of RF Cavity. (Ref. 5)

Booster

190

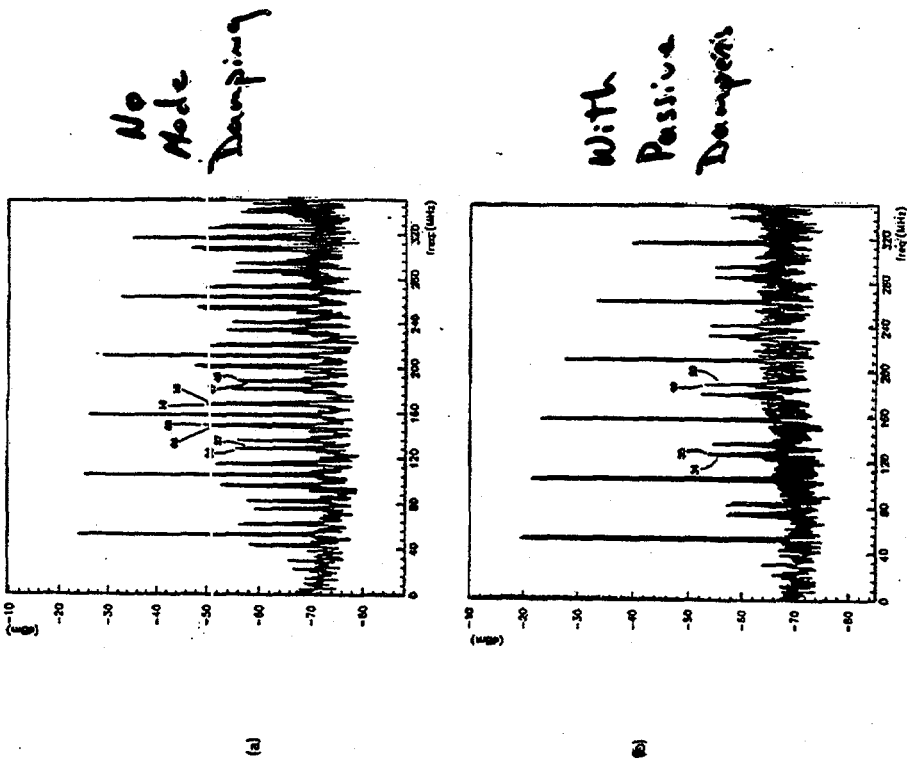


Figure 5.7 Frequency Spectra Showing the Coupled-Bunch Mode Signal Before and After RF Cavity HOM Damping. In (a), the beam intensity is 1.3e12 protons per pulse (HOM dampers off) and in (b), it is 1.3e12 protons per pulse (HOM dampers on) and the data correspond to 35 runs in the cycle. Mode 40 has been completely suppressed and mode 48 attenuated (weak, the intensity is greater in (b)).

Booster - with passive dampers

194

FFT of Resistive Wall Monitor

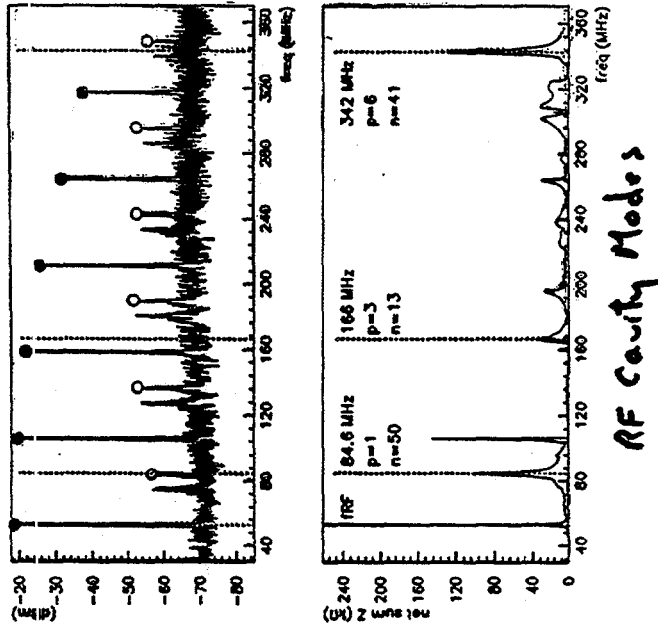
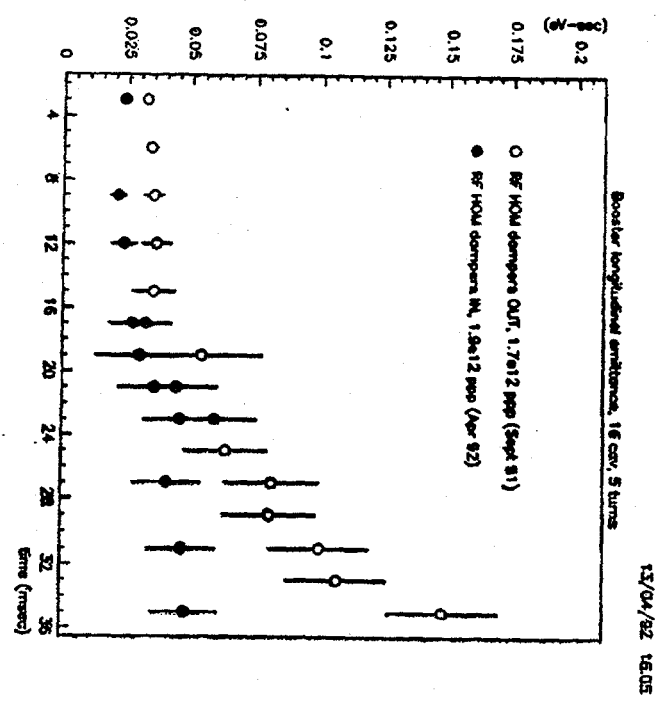


Figure 5.17 Correspondence of RF Cavity HOM Impedance and Coupled-Bunch Mode Spectrum After HOM Dampers. The RF harmonics are marked with a filled "O" and mode 50 with an open "O". (R38)

Booster

K. Hickey

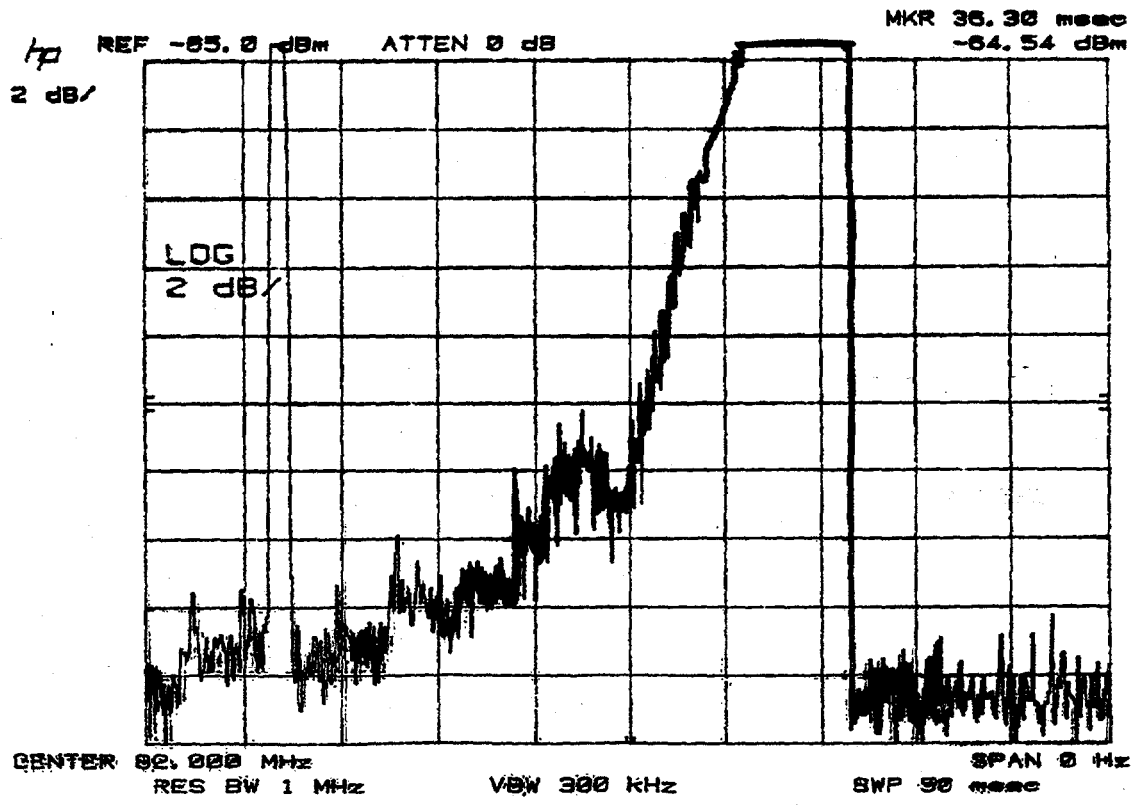


11/27/90

1990

5 Turns

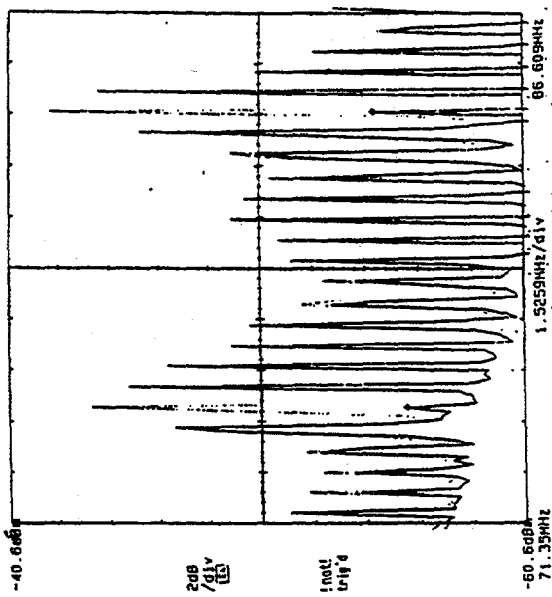
1.9E12



Damping of Booster Mode 36 with an Active Damper

DSA 802A DIGITIZING SIGNAL ANALYZER
date: 5-NOV-92 time: 19:17:37

J. Steinel & D. McGinnis, 1993 PAC



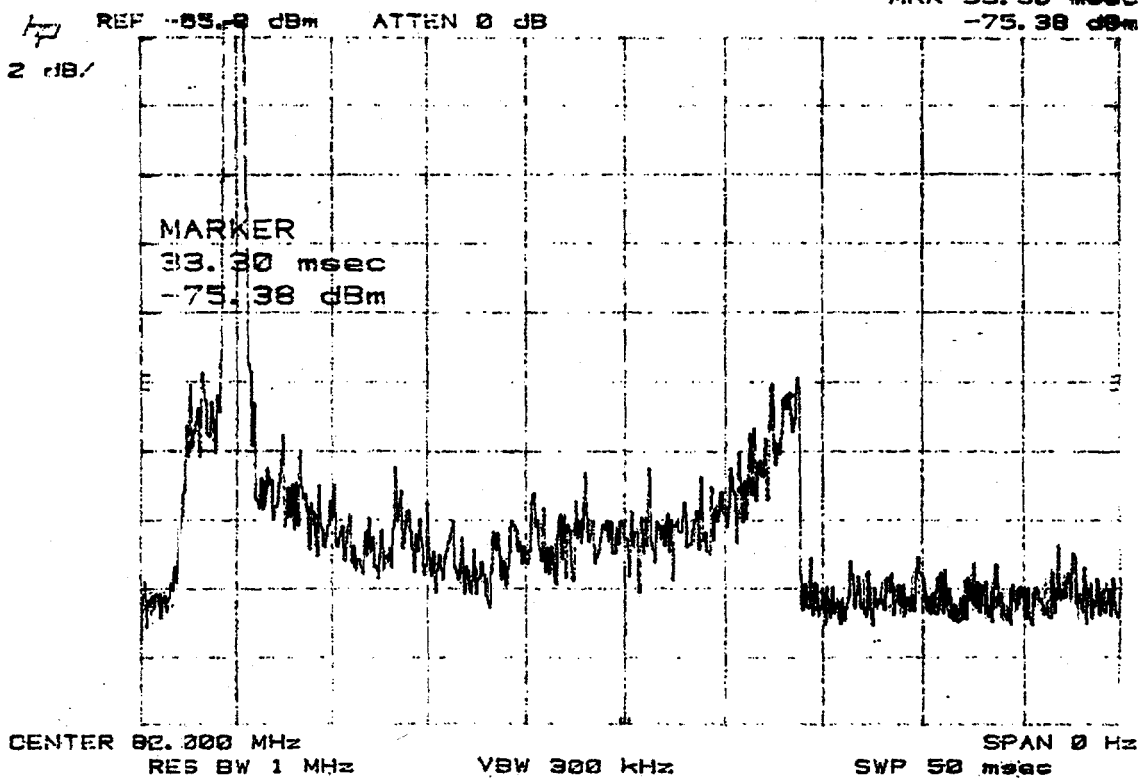
For More Information on Active Dampers:
<http://adwww.fnal.gov/proton/other/index.html>

2.3E12

1993

2.3E12

11/27/92



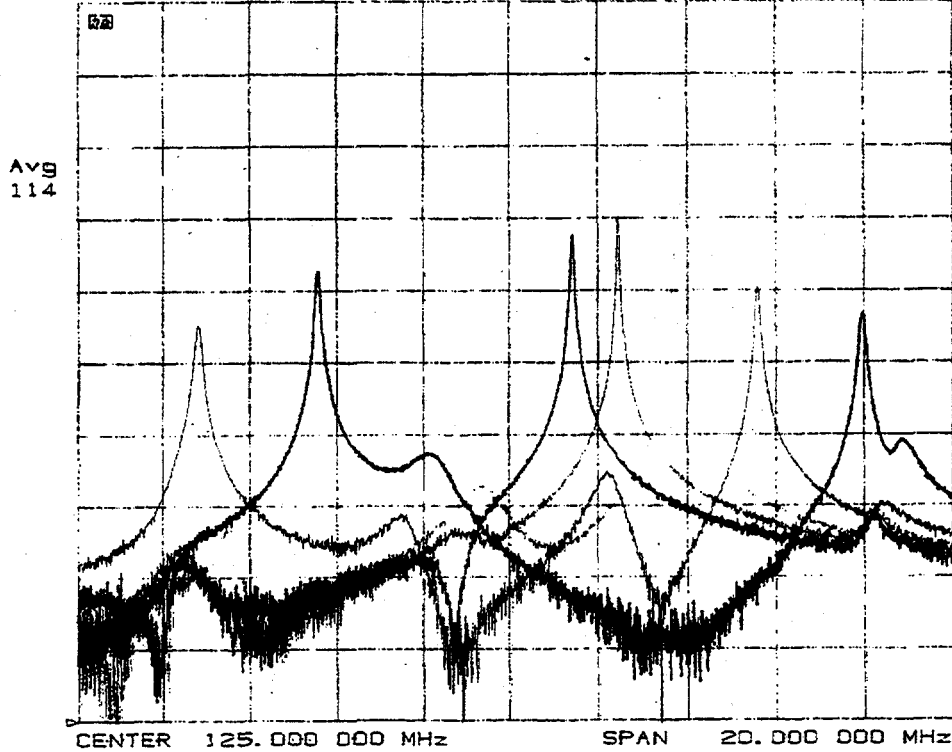
Main Ring Cavity

1021 11/24/92

11/24/92

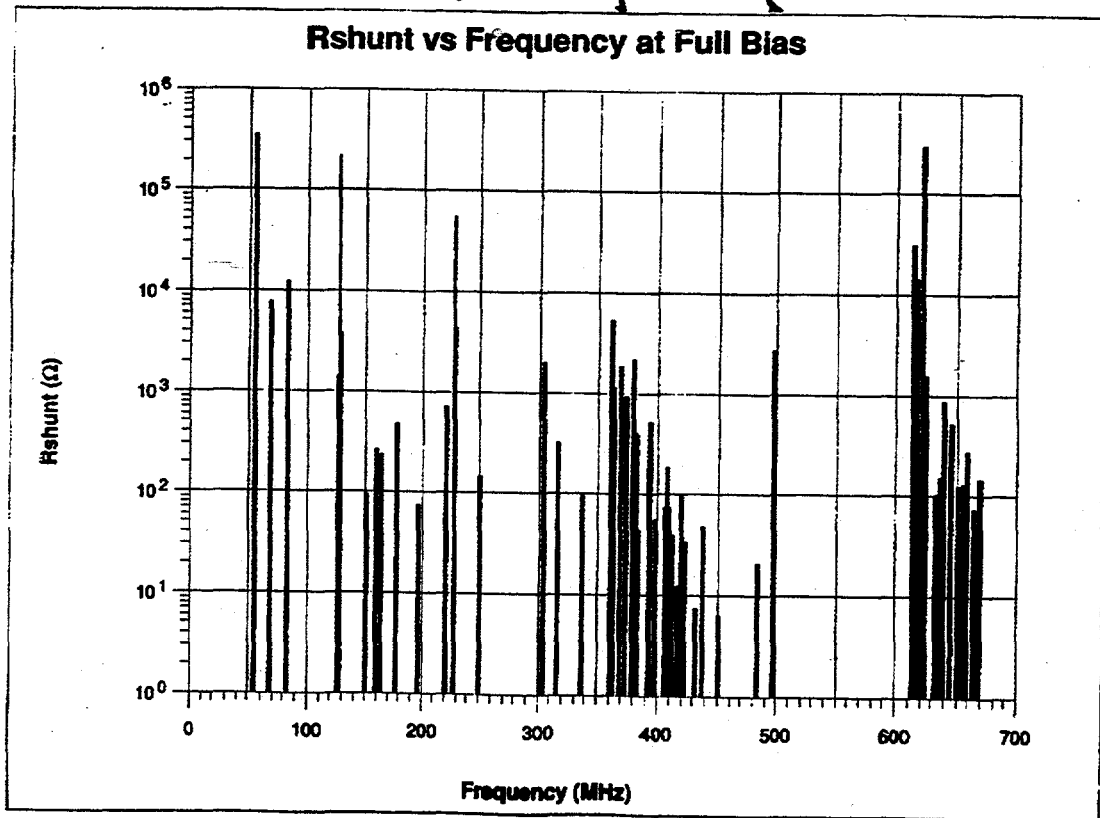
CH1 A/R log MAC 10 dB/ REF -110 dB

Blue = 0A
 Brown = 250A
 Orange = 500A
 Red = 750A
 Black = 1000A



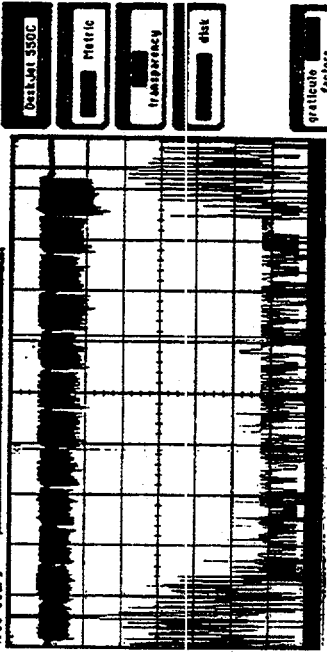
Main Ring Cavity

Rshunt vs Frequency at Full Bias



Acquired: 11 JUL 1996 20:51:31.70
4.00 GS/s

Printed: 11 JUL 1996 20:52:23
Setup print



Current
OCURS cyc(1) 35.666 mV
- width(1) 2.3086 ns
L:FT1 = 30 mV
2:FT1 = -20 mV
A = -50 mV
L:AX = 75.19 ns

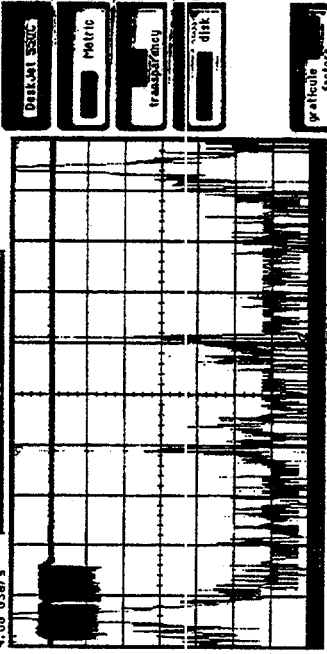
Channel 1 Scale 100 mV/div Offset -300.0 mV Input dc 50 Ohms
Time base Scale 2.10 ns/div Position 31.200000 ns Reference center
Trigger Mode edge Source trigger & Hysteresis normal Holdoff 60 ns
Level 998 mV Slope Pos
Measurement

Measurement
OCURS cyc(1) 35.666 mV
- width(1) 2.3086 ns
Marker
1(FT) = 20 mV
2(FT) = -20 mV
Delta = -50 mV
1/DX = 75.19 ns
FFT FFT magnitude channel 1
Scale 3.00 dBm/div Offset -52.6600 dBm
Scale 6.00 MHz/div Position 192.76000 MHz

75E13 @ 2.84sec on 21

Acquired: 11 JUL 1996 15:02:41.30
4.00 GS/s

Printed: 11 JUL 1996 15:03:55
Setup print



Current
OCURS cyc(1) 35.666 mV
- width(1) 2.3086 ns
L:FT1 = 30 mV
2:FT1 = -20 mV
A = -50 mV
L:AX = 75.19 ns

Channel 1 Scale 100 mV/div Offset -300.0 mV Input dc 50 Ohms
Time base Scale 2.10 ns/div Position 31.200000 ns Reference center
Trigger Mode edge Source trigger & Hysteresis normal Holdoff 60 ns
Level 998 mV Slope Pos
Measurement

Measurement
OCURS cyc(1) 37.748 mV
- width(1) 1.4550 ns
Marker
1(FT) = 20 mV
2(FT) = -20 mV
Delta = -50 mV
1/DX = 75.19 ns
FFT FFT magnitude channel 1
Scale 3.00 dBm/div Offset -52.6600 dBm
Scale 6.00 MHz/div Position 192.76000 MHz

2.84 sec on 21
Start of FlatTop

Longitudinal Coupled Bunch Instabilities

Booster $h=84$

mode #16 (3rd & 5th harmonic of RF cavities)
passive dampers

mode #36 (fixed frequency drift tube mode)
passive and active dampers

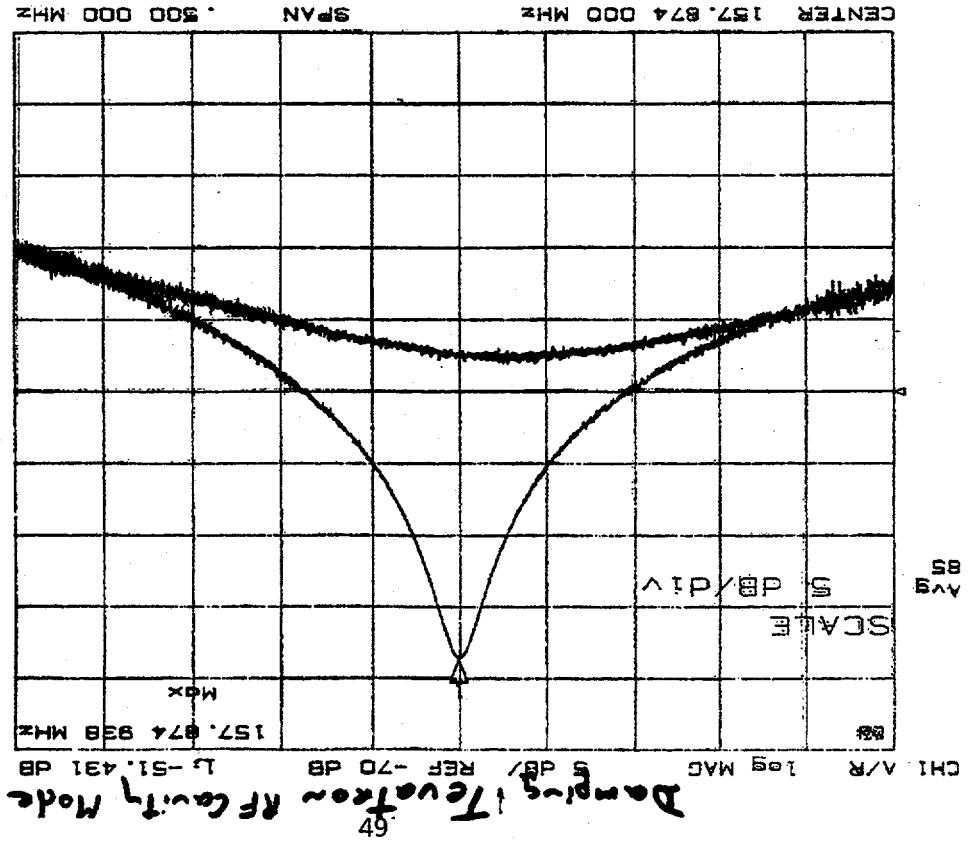
Main Ring $h=1113$

mode #457 (3rd harmonic of RF cavity)
passive dampers

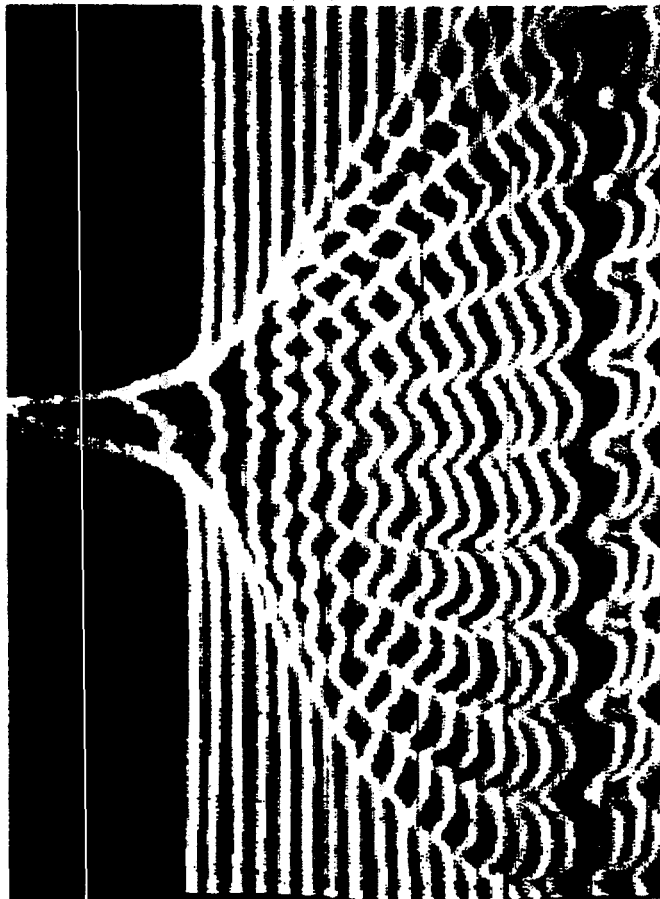
mode #327 (5th harmonic of RF cavity)
passive damper

TeVatron $h=1113$

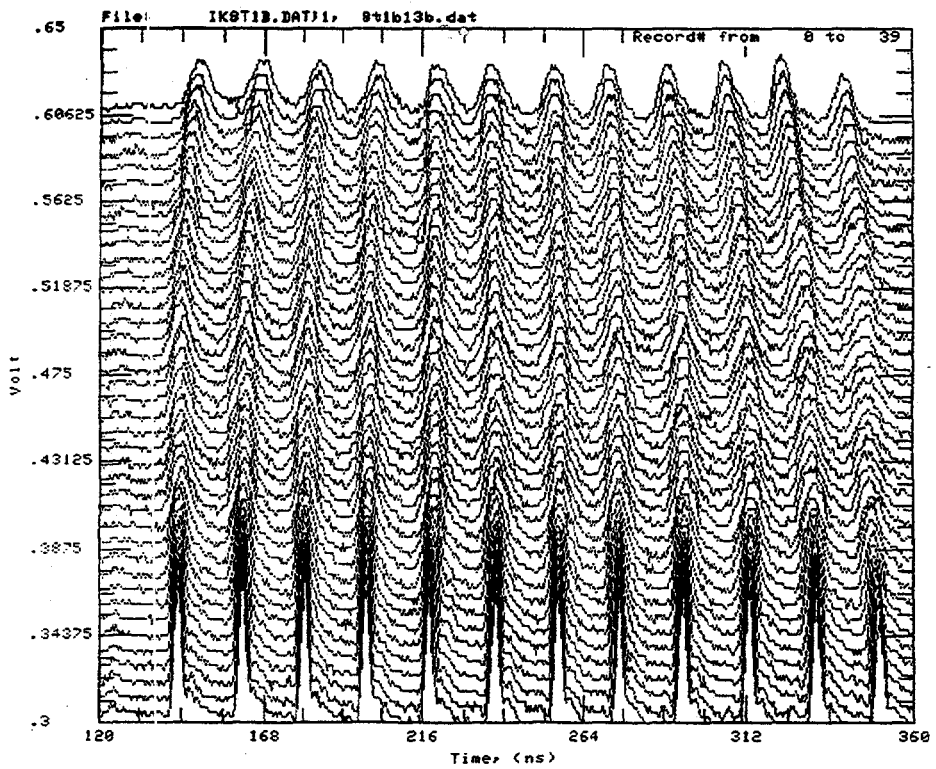
mode #40 (3rd harmonic of RF cavity/
transmission line)
passive damper



Coalescing Protons in the Main Ring (single batch)



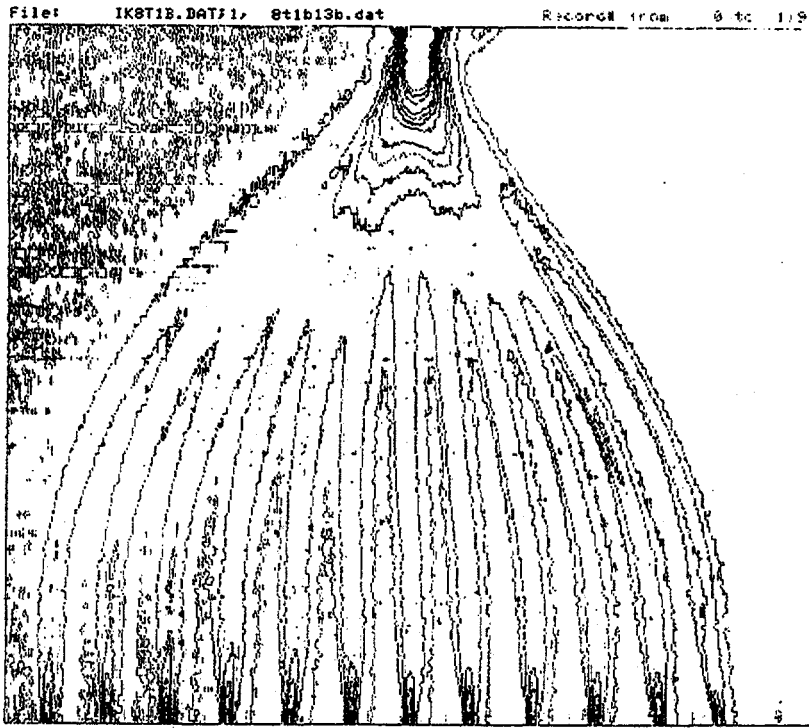
20 ns/div
4 ms/trace



CONCORDIA UNIVERSITY
Mountain Range

9-FEB-1996 13:06

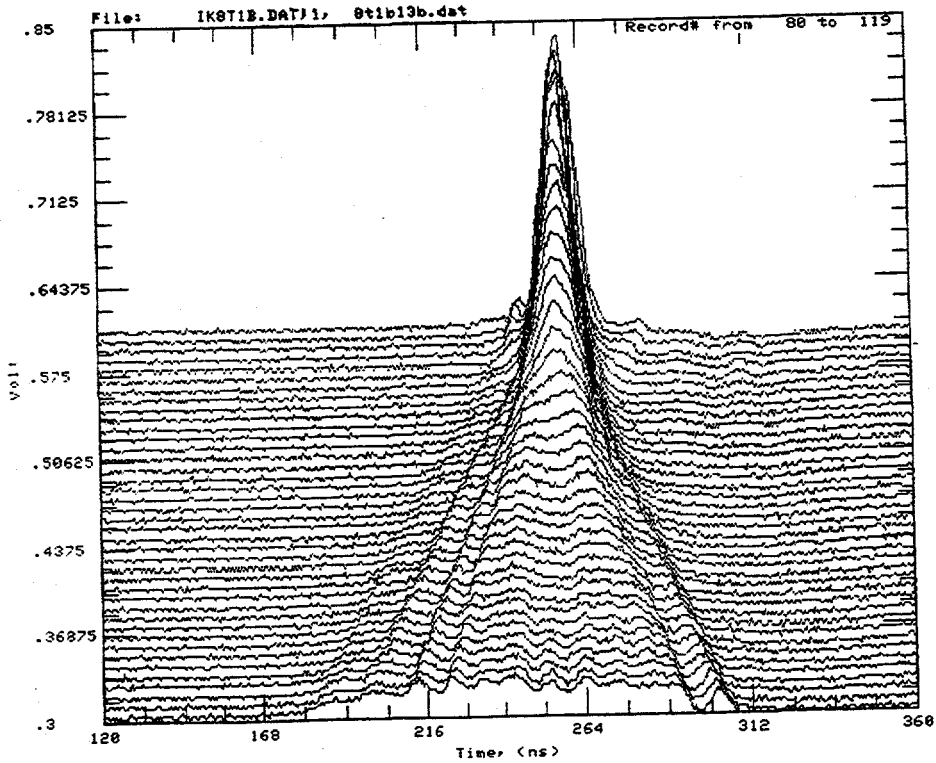
5.21



Console Location 8,
Contour plot

14-MAR-1996 11:55

41.91



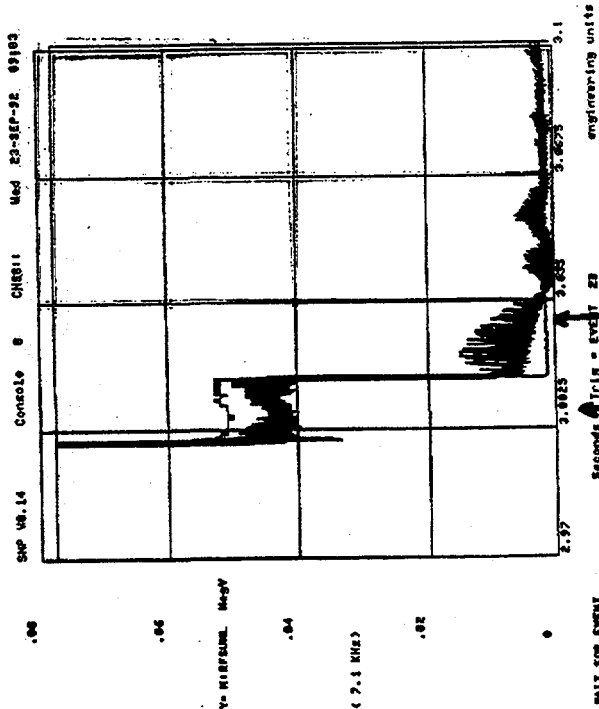
Console Location 10,
Mountain Range

9-FEB-1996 13:10

5.45

Coalescing in Main Ring

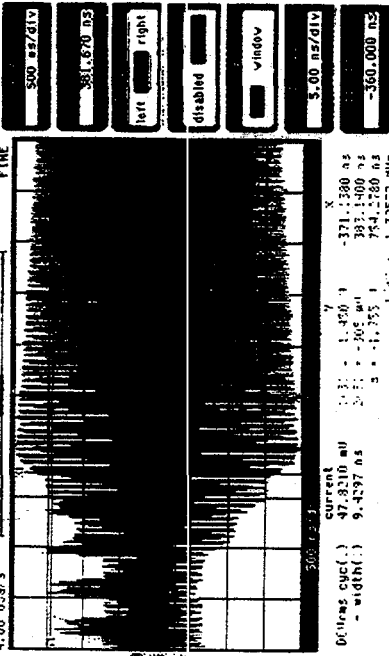
13 BUNCHES 20 ELD APPS



Rotation
2.5 + 5 MHz

Rotation
53 + 106 MHz

Acquired: 04 DEC 1995 15:07:45.00
Acquisition is stopped
4.00 0237.3



current
DCURMS cyc(1) 47.8210 ns
width(1) 9.4297 ns
current
Y 1.450 V
X -371.1380 ns
Y -305 mV
X 383.1400 ns
Y -1.755 V
X 754.2780 ns
Y 1.3257 MHz
X 1.3257 MHz

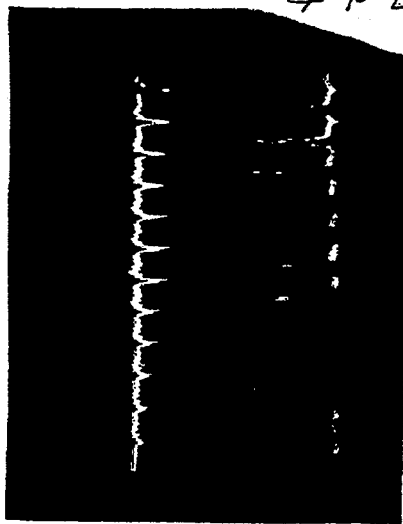
Channel 1 Scale 20 mV/div Offset 0.0 V Input ac 50 Ohms
Channel 3 Scale 500 mV/div Offset 0.0 V Input ac 50 Ohms
Time base Scale 500 ns/div Position 381.670 ns Reference center
Window scale 5.00 ns/div Window position -348.000 ns
Trigger Mode edge Source trigger 2 Hysteresis normal Holdoff 60 ns
Level 178 mV Slope Pos
Measurement

DCURMS cyc(1) 47.8210 mV
width(1) 9.4297 ns
Marker Y X
1(3) - 1.450 V -371.1380 ns
2(3) - 305 mV 383.1400 ns
Delta - 1.755 V 754.2780 ns
1/DX = 1.3257 MHz

Main Ring

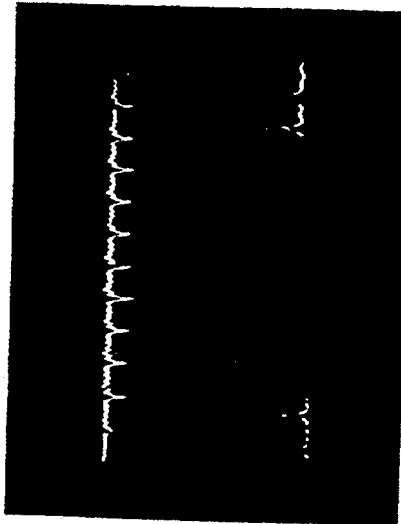
~~53 + 106 MHz~~
106 MHz off
53 + 106 MHz feedback

Multi-Batch Coalescing (Adiabatic)



5X10¹¹ 12 batches 1.2 MV at 100 GeV

Cavity shorts IN

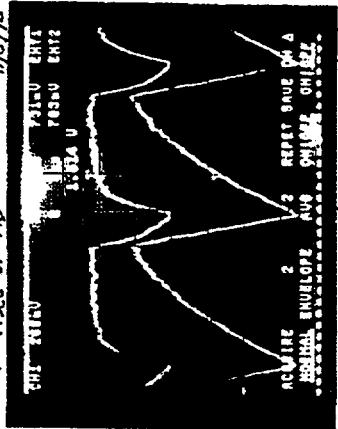


5X10¹¹ No shorts

Cavity shorts Out

Multi-batch Coalescing

Feedback On
RF Cavity
Phase
Feedback off

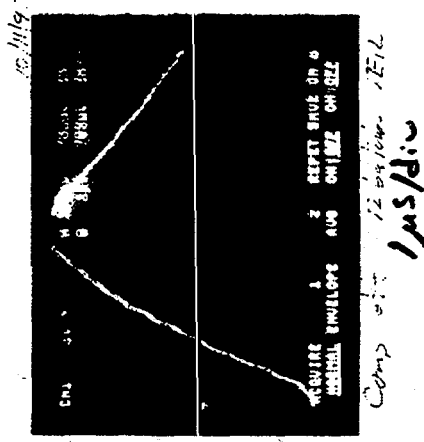


5X10¹¹ with feedback (-20dB) Feedback

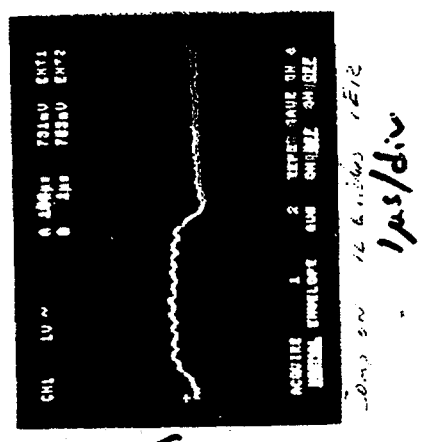
5X10¹¹ / div

Multi-Batch Coalescing

Feedforward Off
RF Cavity
Phase
9/div



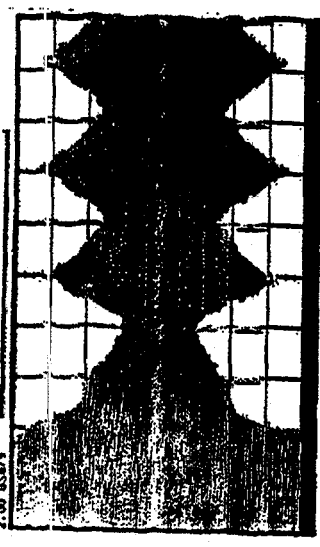
Feedforward ON
RF Cavity
Phase
9/div



Multi-Batch

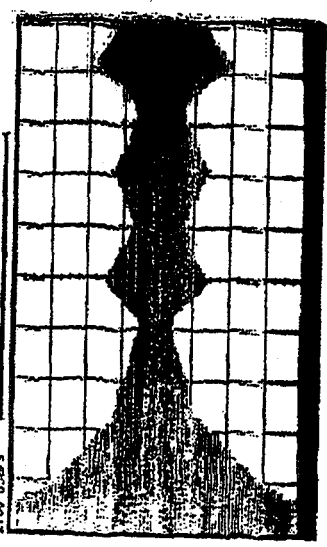
3 BT NO BLC ~ 6.2E12

Acquired: 27 NOV 1996 15:25:04.18
2.00 0.50V's
Printed: 27 NOV 1996 15:28:00



3 BTung BLC ON (+3.16) (-0.5ave)

Acquired: 27 NOV 1996 16:08:12.20
2.00 0.50V's
Printed: 27 NOV 1996 16:08:24

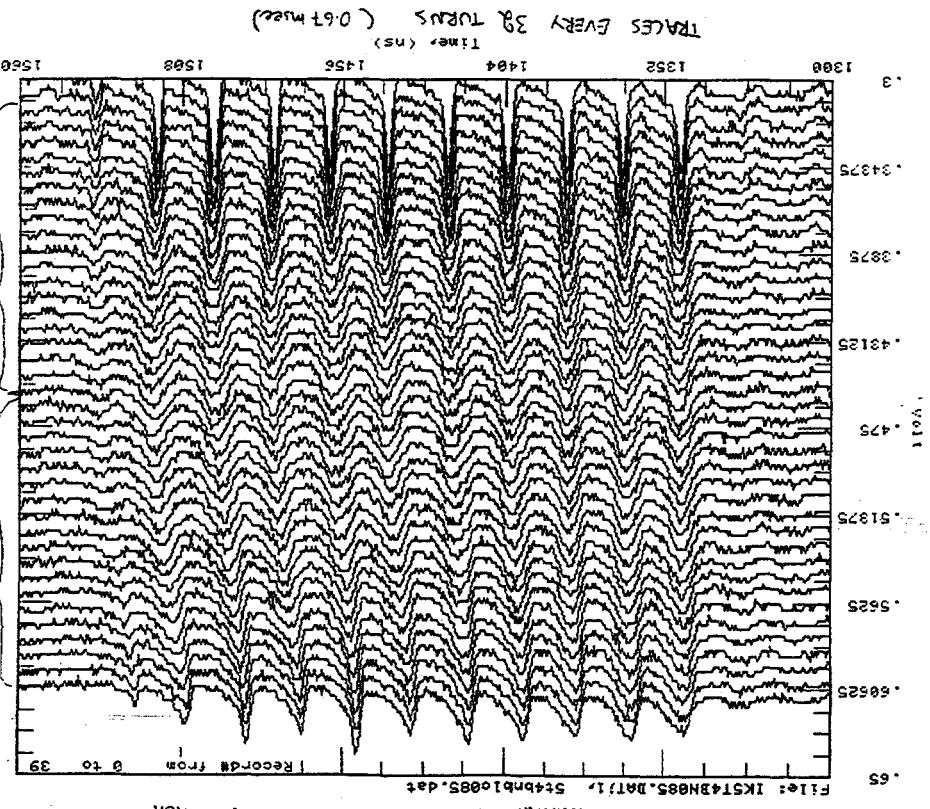


With
Feedforward
Compensation

Console Location 10,
Mountain Range
9-FEB-1996 12:42
5.46

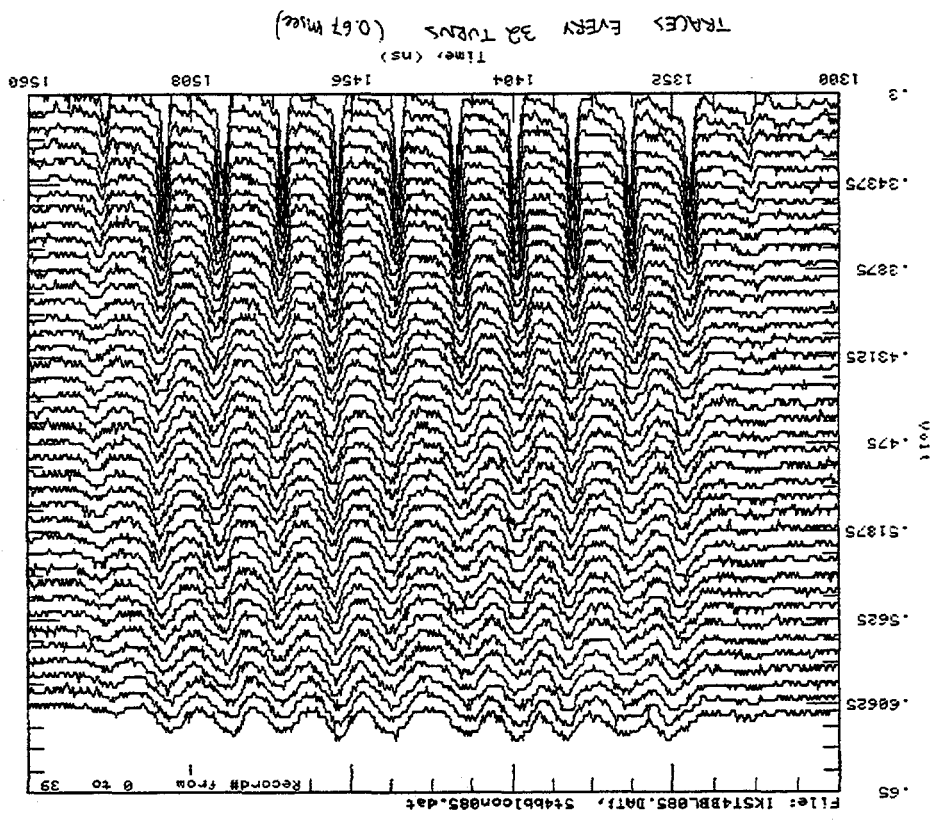
53 MHz OFF
2.5 MHz
ROTATION

DEMULTIPL
WITH
53 MHz



DESCENDING 4 BATCHES 0.85192 ND BLC
MOUNTAIN RANGE PLOT OF THE FOURTH BATCH

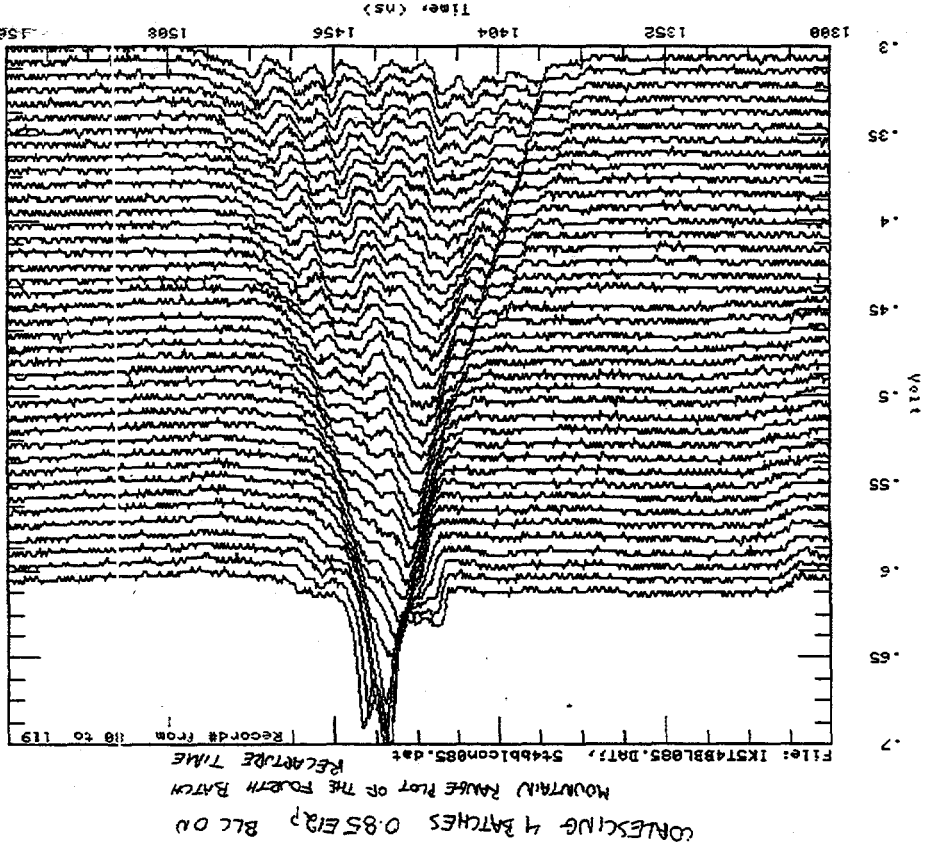
Console Location 10,
Mountain Range
9-FEB-1996 12:35
5.29



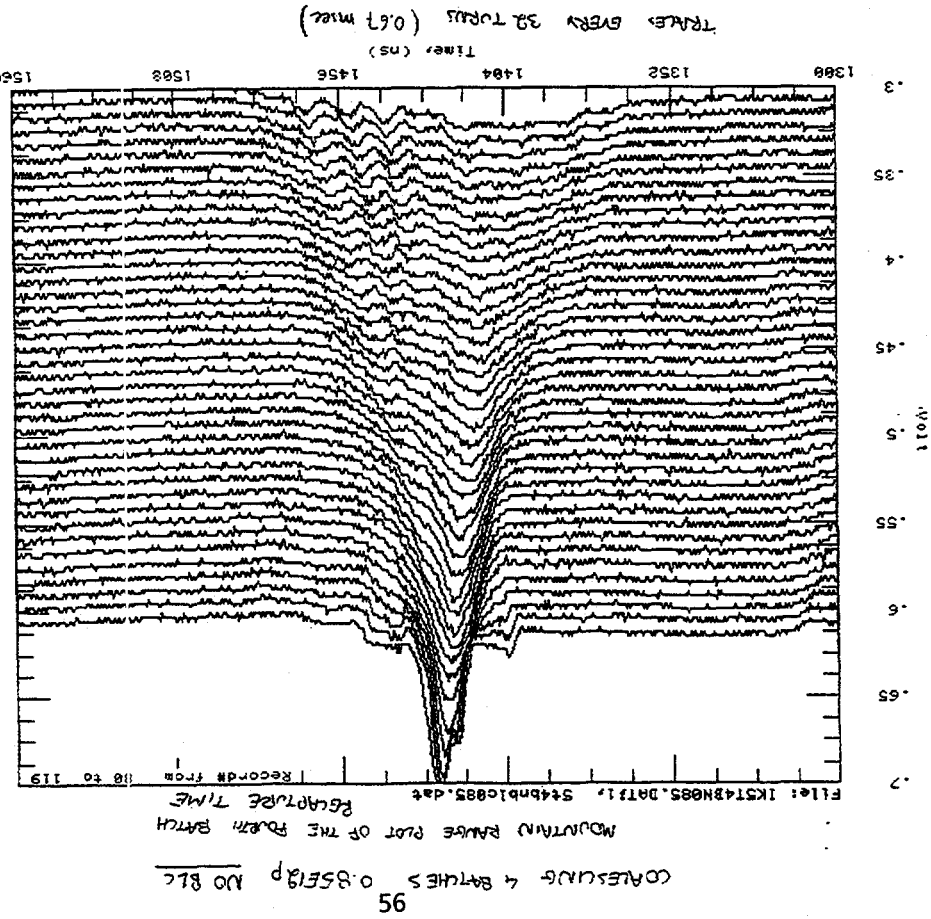
DESCENDING 4 BATCHES 0.85192 BLC ON
MOUNTAIN RANGE PLOT OF THE FOURTH BATCH

TRACES EVERY 32 TURNS (0.67 msec)

5.49
9-FEB-1996 12:37
Console Location 10,
Mountain Range



5.46
9-FEB-1996 12:43
Console Location 10,
Mountain Range



Recycler Ring

An 8 GeV permanent magnet Pbar storage ring

Located above the Main Injector Ring

Dual Purpose: Store and Cool Pbars directly from the Accumulator
Store and Cool Pbars recycled from the Tevatron Collider

Uses Wideband RF system to generate Barrier Buckets for injecting and extracting Pbars

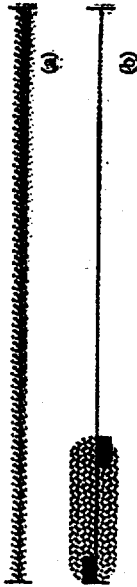


Figure 2.1.23: Full ring phase space sketches of the initial steps of antiproton recycling in the Recycler. In the top drawing (a) the cooled beam starts off basically uncooled (wide as an accumulator ring is necessary for beam clearing reasons). In the bottom drawing (b) a nonresonant barrier voltage system adiabatically squeezes the beam into a small fraction of the circumference.

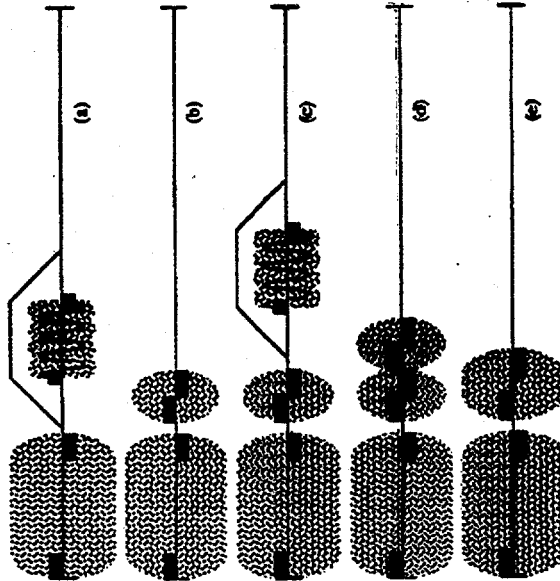


Figure 2.1.25: Recycling of antiproton bunches from the Main Injector. The leftmost charge distribution is always the cooled antiprotons. The shown Recycler injection kicker waveform has a rise-time and fall-time of 1 μ sec. The recycling process never requires more than 3 pairs of barrier voltage pulses.

Scope

4 ferrite loaded, 50 ohm RF cavities with a peak accelerating voltage of 2 kV

4 wideband amplifiers, 2500 watts CW, 10 kHz to 100 MHz

Low level RF system to generate barrier bucket pulses

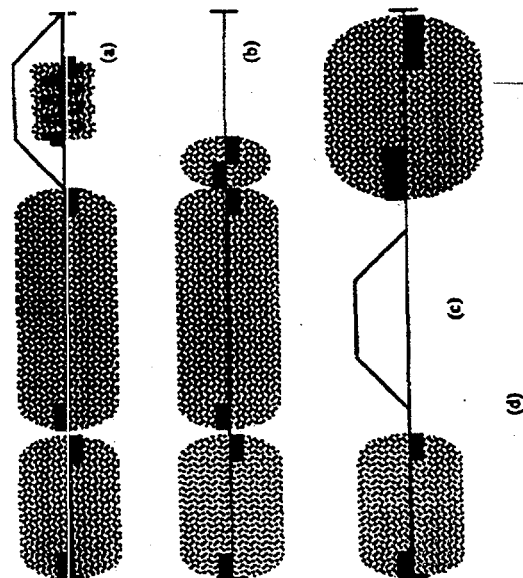
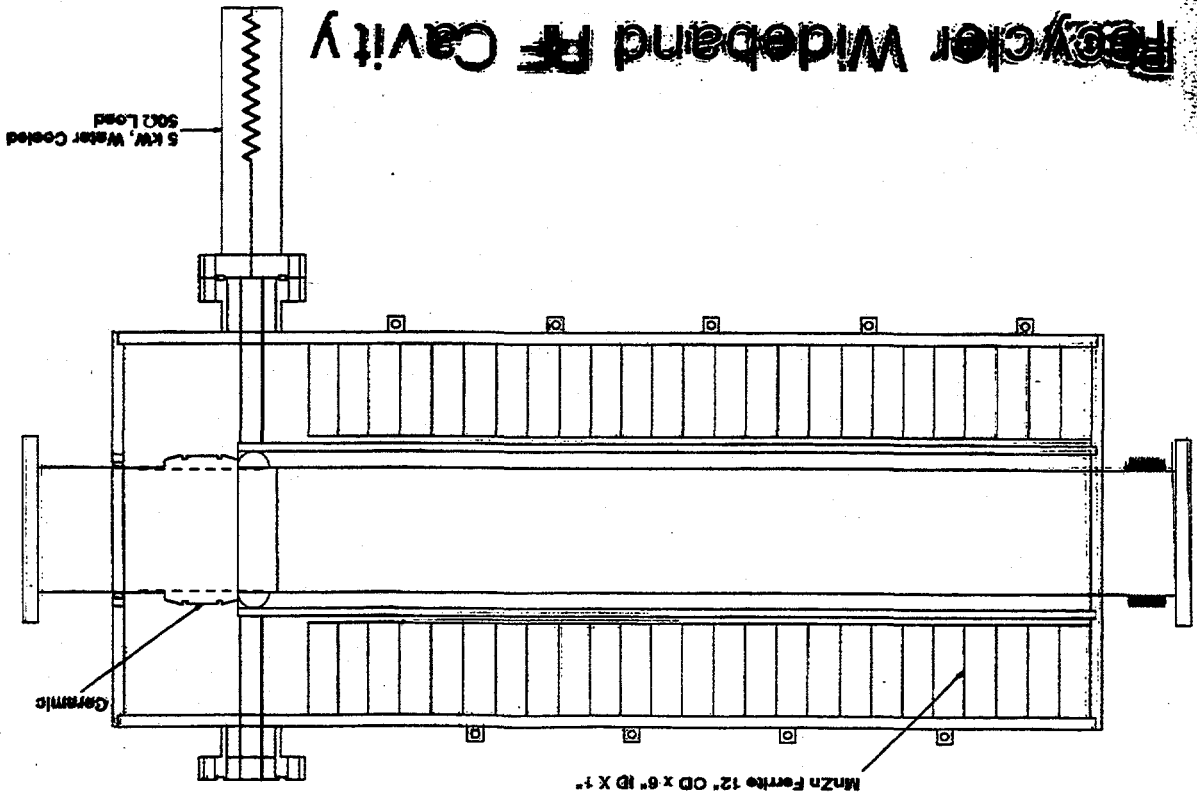
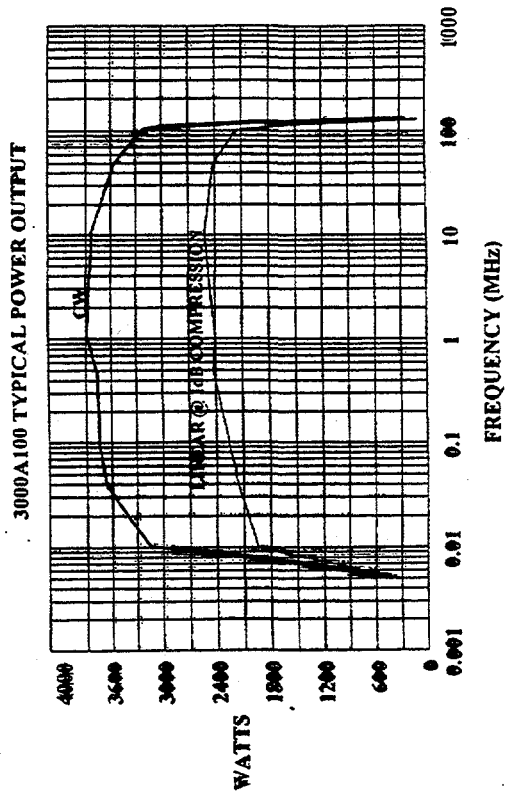
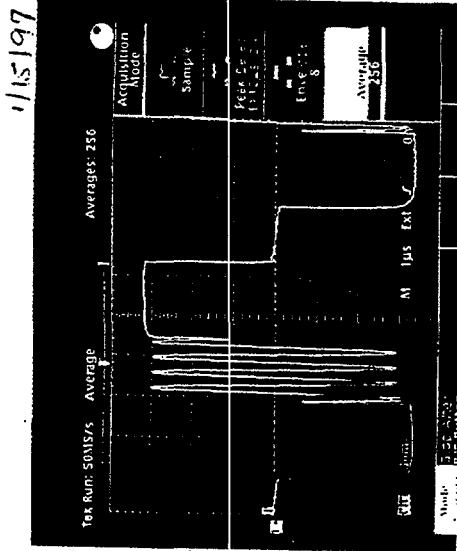


Figure 2.1.30. End of the process of antiproton recycling from the Main Injector. The leftmost charge distribution is always the cooled antiprotons. In (d) the cooled antiprotons have been injected into the Tevatron Collider and the recycled antiprotons have been debunched.

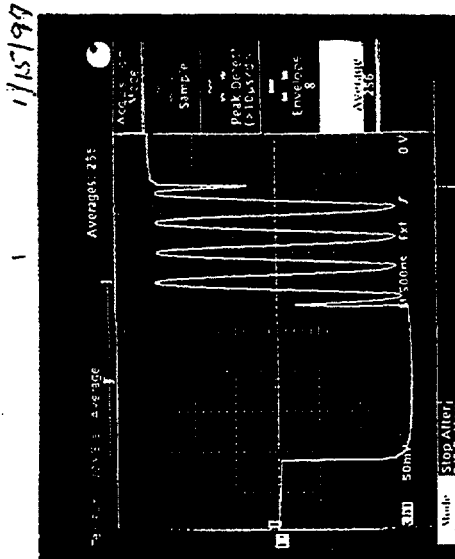
Solid-State Amp



Reception Test



1ms/div



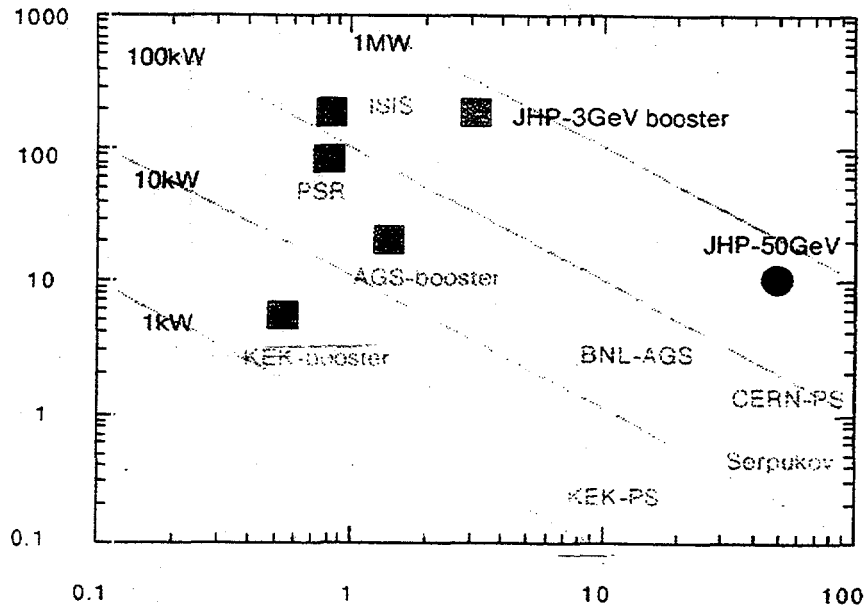
Accelerator Complex of Japan Hadron Facility

Chihiro Ohmori
KEK-Tanashi

Accelerator Complex

- **200-MeV linac** **high brightness**
 - accelerated particle H⁺ ion
 - peak beam current >30(50) mA (25Hz, 400μs)
 - structures RFQ + DTL + ACS
- **3-GeV booster** **rapid cycling**
 - intensity 5×10^{13} ppp
 - repetition rate 25Hz
 - beam power 0.6 MW
 - RF frequency 1.99-3.43MHz
 - RF voltage ~~900kV~~ ⁴²⁵ ~~900kV~~
 - circumference 339.4m (KEK-PS tunnel)
- **50-GeV main ring** **transition free(negative α)**
 - intensity 2×10^{14} ppp
 - acceleration cycle 0.3Hz
 - RF frequency 3.43-3.51MHz
 - RF voltage 270kV
 - momentum compaction $\sim -10^{-3}$
 - circumference 1442m (north site of KEK)

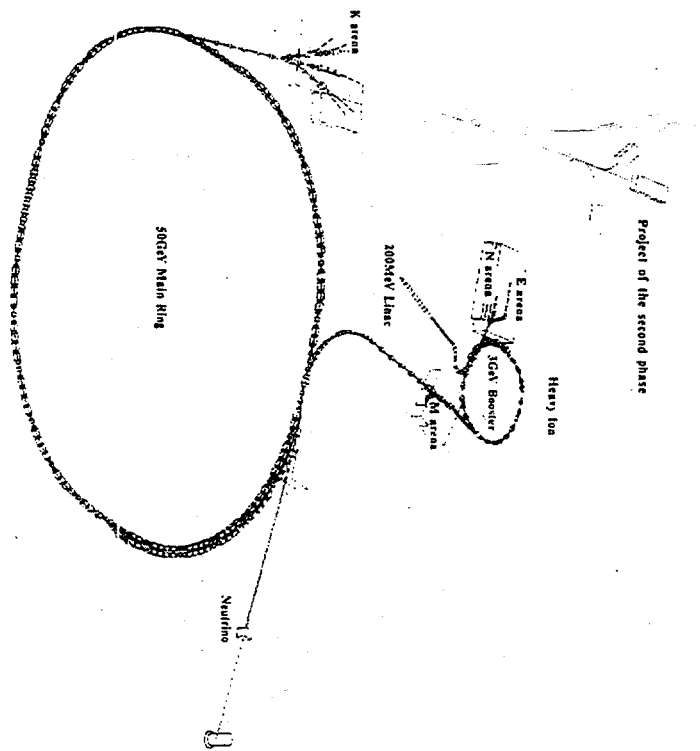
BEAM CURRENT (μA)



ACCELERATION ENERGY (GeV)

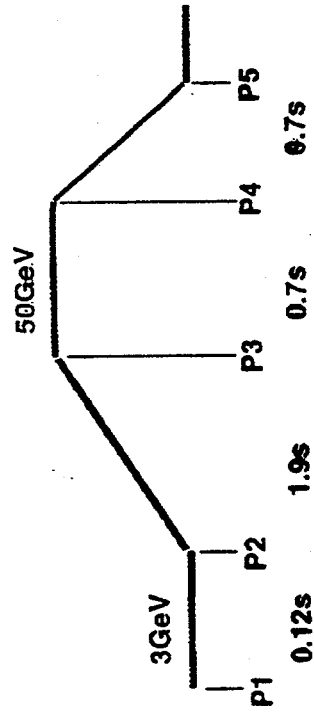
Beam intensities of high-intensity proton synchrotrons.

-1-



PROPOSED LAYOUT OF THE ACCELERATORS AND EXPERIMENTAL AREAS OF JHP

MAIN RING CYCLE



MAIN RING CYCLE: 3.42 sec

P1-P2: 0.12

P2-P3: 1.9

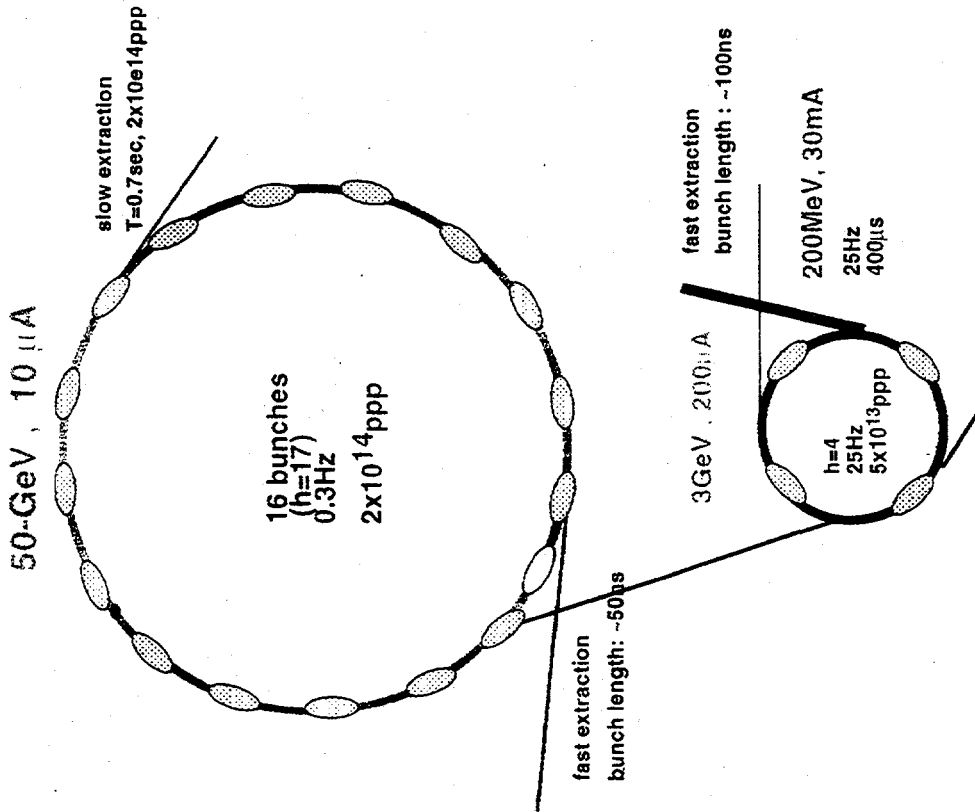
P3-P4: 0.7

P4-P5: 0.7

$h=17$, # of bunches: 16

BEAM INTENSITY: 2×10^{14} ppp

flat top duty factor: 0.21



Design Issues

50-GeV Main Ring

*Transition-free ring

Imaginary γ_r lattice: $\alpha \sim 10^{-3}$

*Free from instabilities

Low impedance ring

*Large dynamic aperture

3-GeV booster

*Tunability ($\nu_{x,y}$)

*Small emittance growth

Space charge, Coupling(x:y:z)

*Beam scraping

Imaginary γ_r lattice

"4-6-3 lattice"

(1) Stability of linear optics

*Selection of phase advance

*Beam size

* α vs dispersion and tunes

* α vs space charge (Umstatter effects)

(2) Dynamic apertures(DA)

*Chromaticity

*Synchrotron oscillation amplitudes

*Space charge

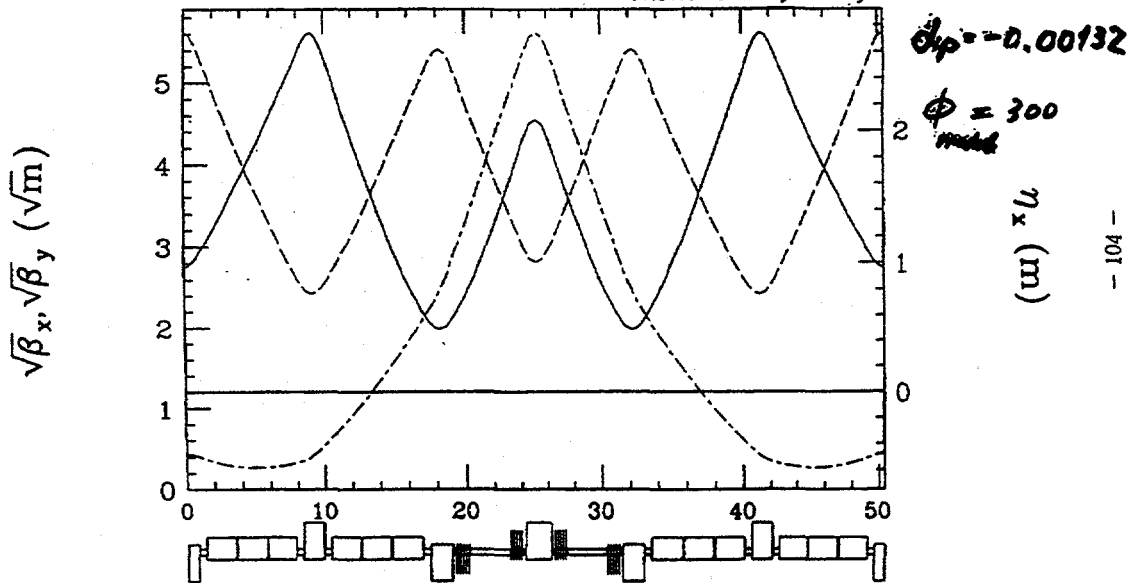
(3) COD correction

*Dry run

4-6-3

Super periodicity module Cell

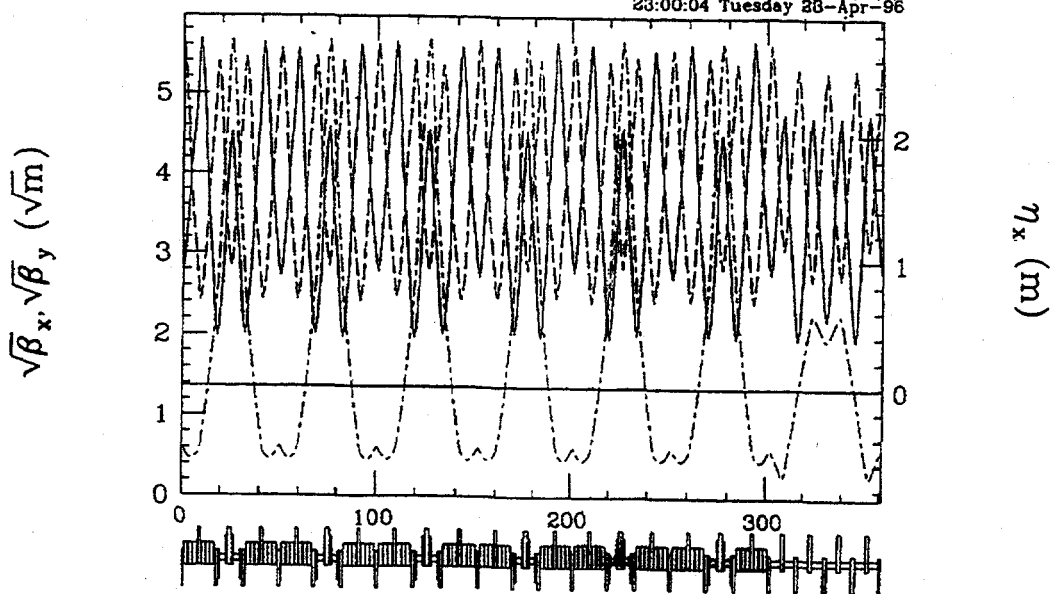
17:37:47 Tuesday 7-May-96



4-6-3 (I)

β_x : small

23:00:04 Tuesday 28-Apr-96



Maximum Apertures of the 50 GeV Main Ring

$$A_x = \sqrt{\beta_x \epsilon_x} + \eta_x \left(\frac{\Delta p}{p} \right) + COD + (\text{sagitta})$$

$$A_y = \sqrt{\beta_y \epsilon_y} + COD$$

apertures

$$\epsilon_{x,y} = 53.9 \text{ mm.mrad}$$

$$\frac{\Delta p}{p} = 0.5\%$$

$$COD = 5 \text{ mm}$$

	horizontal	vertical
B magnet	47 mm (w/o sagitta)	44 mm
Q magnet _(max)	53 mm	47 mm

summary of Lattice "4-6-3"

$$* \alpha \sim -10^{-3}$$

(1) Linear optics stability

*stable operating point O.K.

*beam size ~50mm O.K.

*tunability

$Q_{x,y}, \eta$ vs. α O.K.

*space charge O.K.

(2) Non-linear optics (Dynamic apertures)

* ξ O.K.

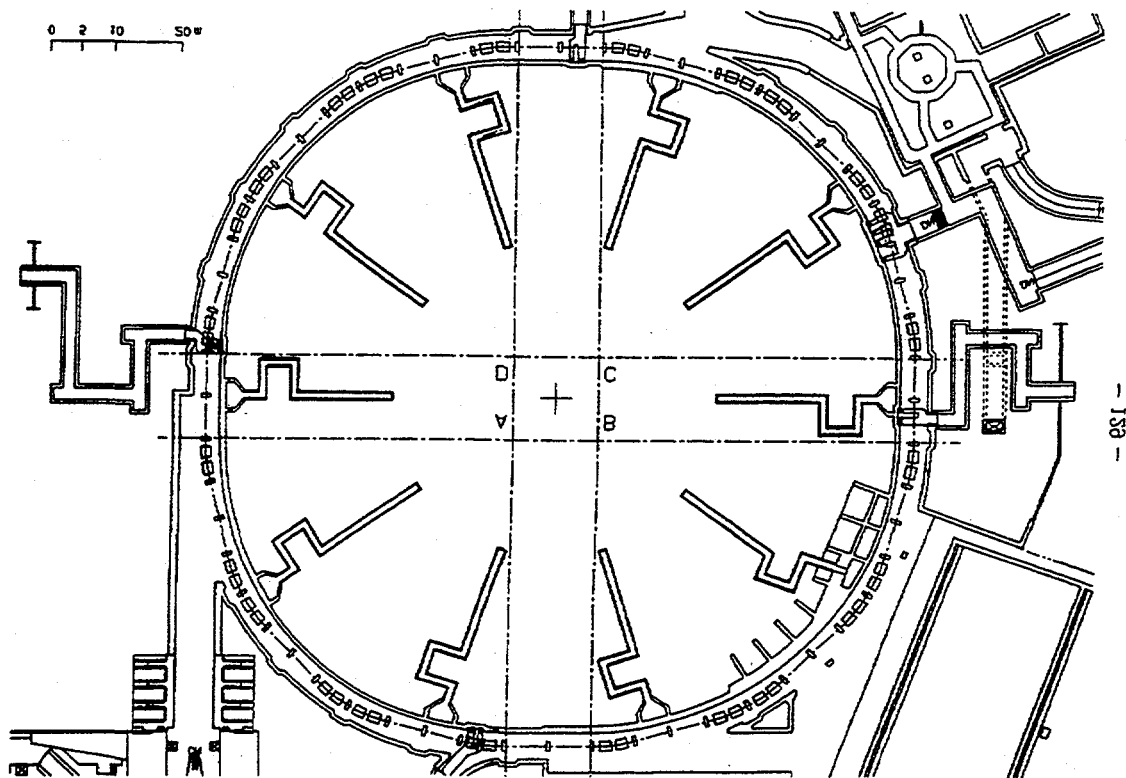
* $\Delta p/p$ O.K.

*space charge O.K.

*error fields need optimization

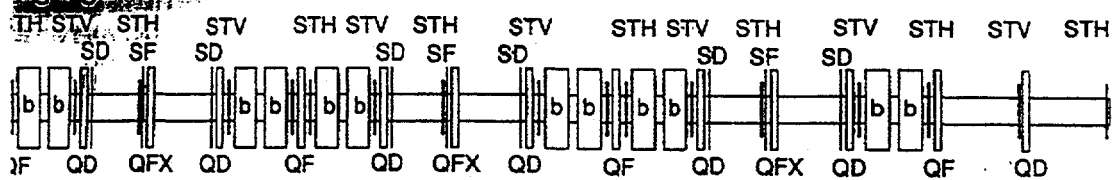
(3) Corrections COD etc. (O.K.)

**"Dry run"

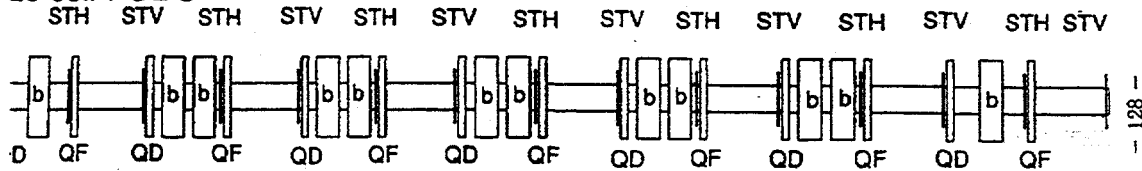


high-gamma-t

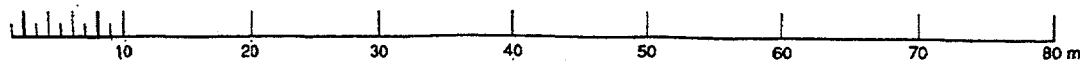
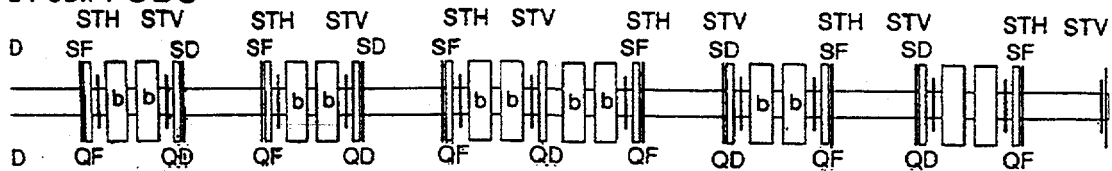
3 GeV booster lattice geometry



28 cell-FODO



24 cell-FODO



Maximum apertures of the 3 GeV booster

apertures

$$A_x = \sqrt{\beta_x \epsilon_x} + \eta_x \left(\frac{\Delta p}{p} \right) + COD + (\text{sagitta})$$

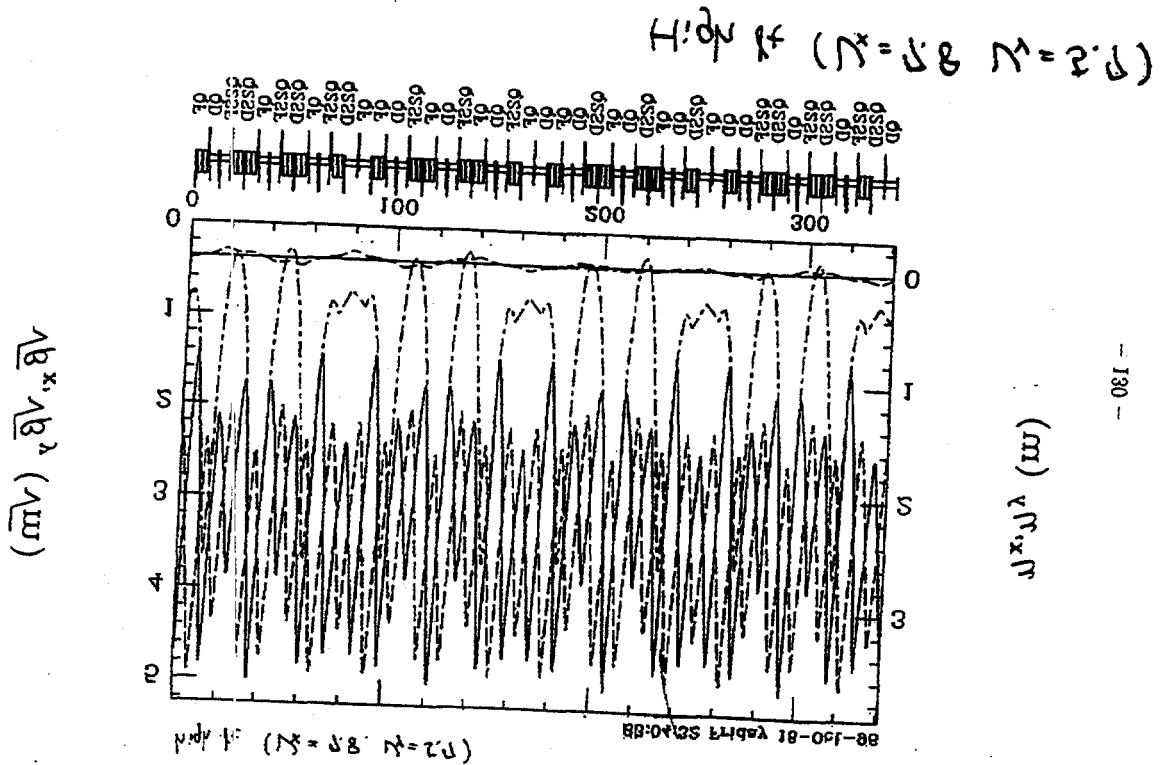
$$A_y = \sqrt{\beta_y \epsilon_y} + COD$$

$$\epsilon_{x,y} = 340 \text{ mm.mrad}$$

$$\frac{\Delta p}{p} = 0.5\%$$

$$COD = 5 \text{ mm}$$

	horizontal	vertical
B magnet	93 mm	95 mm
Q magnet _(max)	106 mm	107 mm



Space Charge Limit

$$N_{inc} = \frac{\pi \beta^2 \gamma^3 \left(1 + \sqrt{\frac{\epsilon_H}{\epsilon_V}} \right) \epsilon_V \Delta V B_f}{r F P}$$

$$N_{coh} = \frac{\pi Q_0 h^3 \beta^2 \gamma^3 B_f \Delta V}{R r F P}$$

$$\Delta V = -0.25$$

- 145 -

	Incoherent	Coherent
3 GeV Booster	5.6×10^{13} ppp	1.2×10^{14} ppp
50 GeV Main Ring	4.7×10^{14} ppp	4.2×10^{14} ppp

Summary 3-GeV lattice

	High- γ_t	FODO (20 cells)	FODO (24 cells)
$\sqrt{\beta_{max}}$	5	4.6	5.2
l_{max}	3.6m (Q_{Ax})	3.8m (Q_F)	2.6m (Q_F)
γ_t	-15	-6	-6
A (Q)	large	large	small
A (B)	large	large	small
Injection (Scrapers, ...)	○	⊙	△
Extraction (1 cell lag s.s)	○	△(?)	○
Long. matching with MR	○	△	△

- 141 -

Collective Effect

960505

b) Narrow Band

Longitudinal Coupled-Bunch

RF cavity parasitic mode: $f_p/f_{rf} \approx \frac{1}{3B_f}$ (R. Baartman)

booster(injection): $R_s < 900\Omega (Q \geq 5, f_p > \sim \text{MHz})$

main ring(injection): $R_s < 700\Omega (Q \geq 5, f_p \sim 15\text{MHz})$

"active damper" , "Q<1 cavity?"

c) Resistive Wall

Transverse Coupled-Bunch

booster: $< 0.14\text{M}\Omega/\text{m}$

main ring: $< 1.4\text{M}\Omega/\text{m}$

- 127 -

Collective Effect

960505

a) Broad Band

Space Charge, Inductive Wall

[1] Microwave Instability

main ring

3GeV(injection) $\left| \frac{Z}{n} \right| \leq 20\Omega @ \epsilon_L = 1eV \cdot \text{sec}$

space charge impedance $\equiv 55\Omega \therefore \epsilon_L \equiv 3eV \cdot \text{sec}$

booster: no problem

[2] Negative Mass Instability

Inductive wall : $-\text{Im} \frac{Z}{n} \leq 3\Omega @ \epsilon_L = 3eV \cdot \text{sec}$

space charge : no problem—capacitive, $\epsilon < 0$ (highly lattice)
 η imaginary

- 126 -

Proposed Time Profile of JHP

- 1997 New Organization
- 1996 Construction Start
- 1999 Neutrino Oscillation Experiment at 12-GeV PS
- 2000
- 2001 3-GeV Ring Installation into the 12-GeV PS Tunnel
- 2002 50-GeV Ring completion, First Beam



- 1 RF Cavity
New Material
(Fine-Crystal High- μ Metal)
Q ~ 1
- 2 Ceramic Beam Duct
*booster
200mm x 240mm x 1m
*Main Ring
100mm ϕ (i.d) x 2mm
- 3 Main Ring B magnet
106mm(gap) x 1.5m
- 4 Booster Magnet Power Supply
Resonant Network System

RF Cavity

Heavy Beam Loading

- (1) Beam Power > Cavity Power
- (2) Robinson Stability Criterion
Rs ~ small (1kΩ/m)
- (3) Coupled Bunch Instability

Q ~ small (Q<5)

Ferrite

(problems)

- *nonlinear behavior at large RF field
- *low Curie temperature

New Material

"Fine-crystal High-μ Metal"

- *high permeability
- *Rs ~ constant for larger RF field
- *Q~1

BEAM DUCT

Requirements

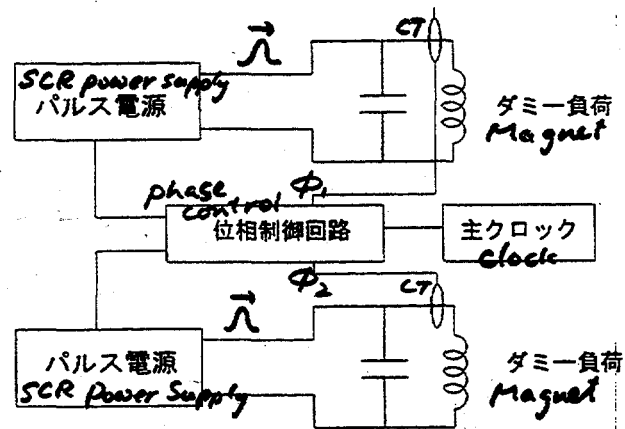
- (1) Eddy current 25Hz(3GeV)
 0.3Hz(50GeV)
- (2) Impedance RT<1.4MΩ/m@50GeV
 RT<0.14MΩ/m@3GeV
- (3) Thermal shock Beam hitting
- (4) No magnetization
- (5) Ease of fabrication
- (6) Small maintenance residual activities
- (7) Cost

3-GeV Booster >> Ceramic duct

50-GeV MR >> INCONEL duct
>> Ceramic duct

Control of Resonant Network Systems

2 ネットワーク研究のための テスト電源-ブロックダイアグラム



$$\Delta\phi = \phi_1 - \phi_2 \therefore < 8.28 \mu\text{s for } \Delta Q = 0.01 @ 25 \text{ Hz}$$

≡

Overview from Los Alamos: Current Thinking on RF Upgrade Issues

- ◆ PSR Upgrades in Progress
- ◆ Space Charge Compensating Inductor
- ◆ Barrier Bucket RF
- ◆ PSR Instability

— by Arch Thiessen
— 8 May, 1997

LANSCE

5/08/97 1

PSR Upgrades in Progress

LANSCE

5/08/97 2

PSR parameter list

◆ Beam energy	797 MeV ($\gamma = 1.85$, $\beta = 0.84$)
◆ Circumference	90.2 m
◆ Bunch length	250 ns
◆ Number of bunches	1
◆ Revolution period	357 ns
◆ Betatron tunes	$\nu_x = 3.18$, $\nu_y = 2.14$
◆ Transition gamma	3.1
◆ Maximum rf voltage	12.5 – 14 kV
◆ Chromaticity, horizontal	-1.28 ± 0.06
◆ Chromaticity, vertical	-0.8 ± 0.2
◆ Momentum spread from linac	0.05%
◆ Momentum spread in PSR	0.5%

LANSCIE

5/08/97 3

PSR parameter list (cont.)

◆ Typical injection time	600 μ s
◆ Typical storage time	10 μ s
◆ Max bunched-beam charge stored	6.4 μ C (4×10^{13} ppp)
◆ Max coasting-beam charge stored	2 μ C (1.3×10^{13} ppp)
◆ Synchrotron period	720 μ s for 10 kV buncher
◆ Coherent tune shift	0.008

LANSCIE

5/08/97 4

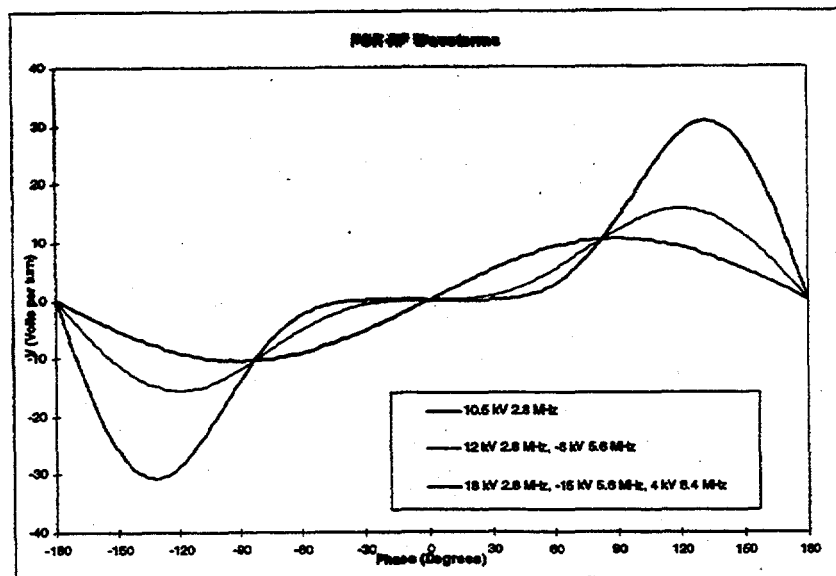
PSR Upgrade Programs In Progress

- ◆ LANSCE Reliability Improvement Program (LRIP) Phase I (complete!)
 - Improved Beam Availability from ~65% to ~85%
- ◆ LRIP Phase II
 - Goal is 100 μA @ 20 Hz
 - Direct H- Injection
 - » Construction Starts 1 Aug, '97, Complete 1 March '98
- ◆ Short Pulse Spallation Source Enhancement (SPSS)
 - Goal Is 200 μA @ 30 Hz, 4×10^{13} protons per pulse
 - » New H- Ion Source
 - ◆ 1.5-2x Existing Current at Smaller Emittance
 - Collaboration with K-C Leung, BNL
 - » New RF System
 - ◆ Phase I (1997-1998) - New Driver for Existing 2.8 MHz Cavity
 - Needed both for Beam Dynamics and Reliability Improvement
 - ◆ Phase II (1999-2000) - New Cavity and RFDriver - Sum 12 KV @ 2.8 MHz, -6 KV @ 5.6 MHz
 - » Building, Cooling Water, and Utilities

LANSCE

5/08/97 5

Voltage Waveforms Considered

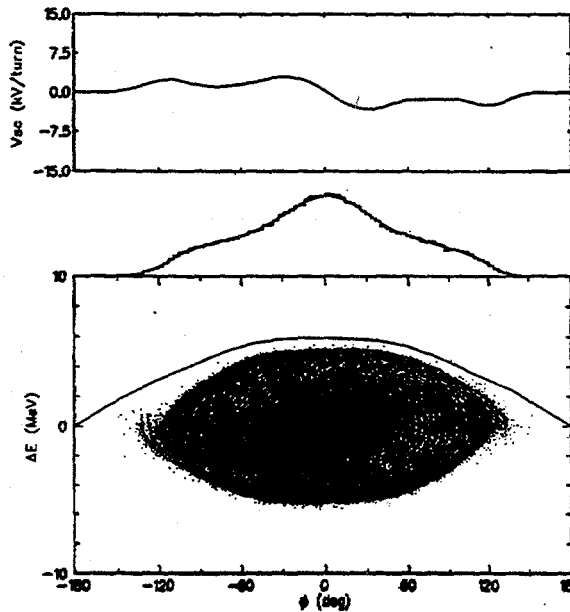


LANSCE

5/08/97 6

PSR before Upgrade

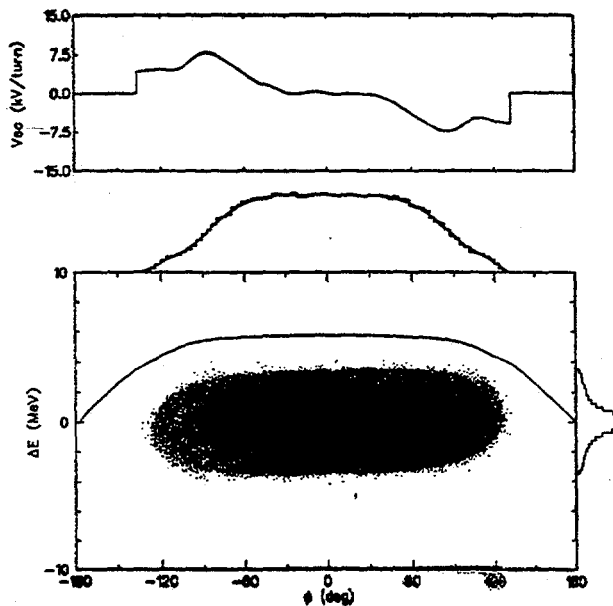
- ◆ Foil Hits 307
- ◆ Losses
- ◆ 0.15%
- ◆ 0.10%
- ◆ 0.03%



LANSCIE

5/08/97 8

PSR with 2 Harmonics



LANSCIE

5/08/97 9

Space Charge Compensation with Inductor

~~LANSCE~~

5/08/97 10

Longitudinal Space Charge Control

- ◆ Maximum Value is $\sim 1/2$ of Applied Voltage after upgrades
 - Up to Now, Propose Control by "Brute Force"
 - » Make Sure $V_r \gg V_{sc}$
 - ◆ And Test by Tracking with ACCSIM or other code
- ◆ In Any Beam
 - $V_{sc} \propto g \, di/dt$ - opposite sign from an inductance
 - » Can be compensated with an Inductor if g is a constant
- ◆ For PSR
 - For $g=3$ - inductance required in PSR is about 11 microHenries
 - Actual value of g not well known
 - » at present $g \sim 3.9$
 - » After LRIP $g \sim 3.6$
 - » After SPSS $g \sim 3.3$
 - In Process of Tracking Code (ACCSIM) Modification
 - » for any longitudinal impedance
 - » variation of g with Courant/Snyder invariant

~~LANSCE~~

5/08/97 7

A Test of Space Charge Compensator

- ◆ For Space Charge Compensator Test, ~5 microHenries Max
 - Less than 1/2 Amount Needed for Full Compensation
 - » Idea is to see effect
 - ◆ bias off vs on
 - beam in gap?
 - Stability threshold ?
 - » Look for other problems caused by inductor
 - ◆ change in instability threshold
 - » good ideas for effects to look at?
- ◆ Two Days with Access for Installation July 31, 1 Aug
- ◆ One 24 hr Day for Tests with Beam
 - Tentatively Scheduled for 2/3 August, 1997

LANSCEI

5/08/97 11

Barrier Bucket at PSR

LANSCEI

5/08/97 12

Barrier Bucket at PSR

- ◆ Study Just Getting Underway
 - Tracking Code Not Yet Adapted for Barrier Bucket
- ◆ Tradeoff between Injection Time and Voltage
 - Both Are Problems at PsR
 - » Present injection time 250 ns is too long for clean gap
 - » Voltage Available on One-Cavity, ~10kV is Low
 - ◆ $h=1.5 - 10$ kV ok, but bunching factor low
 - ◆ $h=2.5$ requires 30 kV for full height bucket
 - How Does PSR Work Now?
 - » Not many particles at high dp/p at end of bunch
 - Reasonable options are $h=1.5, h=2, h=2.5, h=3$ barriers
 - » h -integer ok if Cathode Follower Driver
- ◆ Want to Compare with a Traditional 2-Harmonic System

LANSCE

5/08/97 13

SOME QUESTIONS

R) WHAT GAP WIDTH IS NEEDED FOR $e-p$?

B) WHAT GAP WIDTH IS NEEDED (FOR 2% LOSSES) AFTER LEIP?

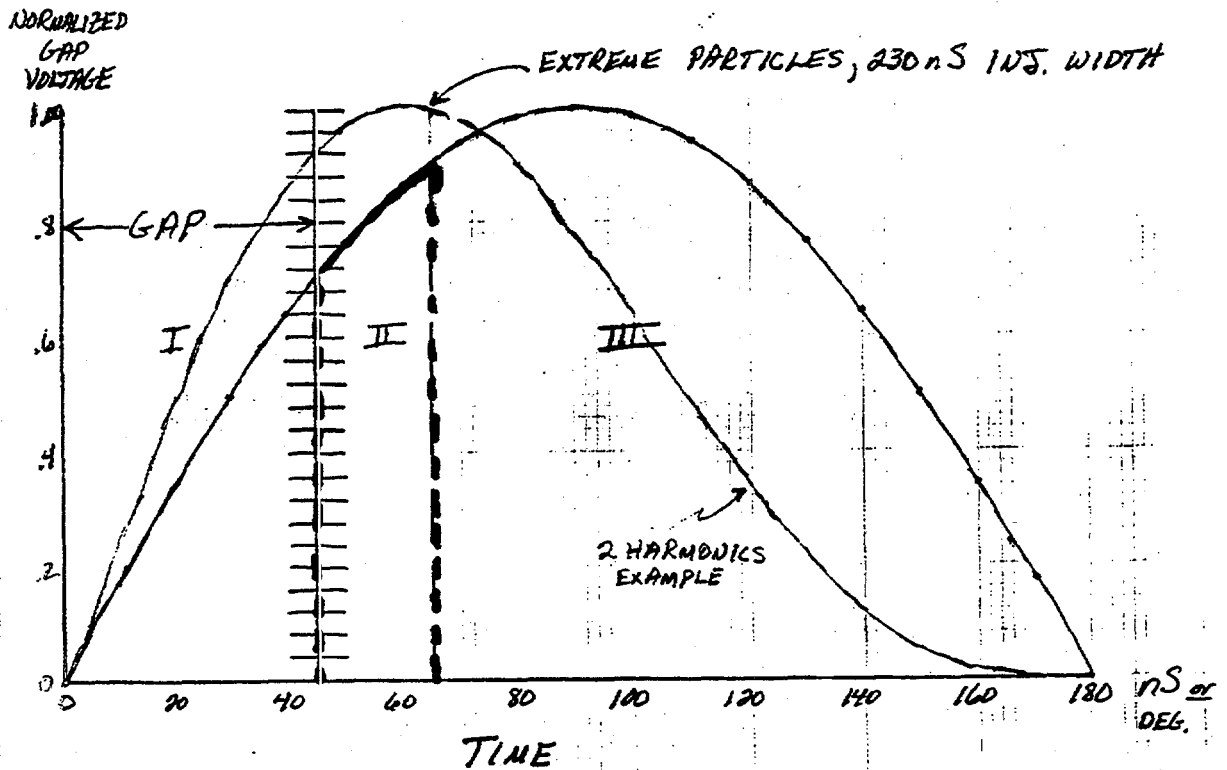
C) HOW MUCH DE IS NEEDED IN BUNCH?

D) WHAT IS THE MAXIMUM GAP IMPEDANCE ALLOWED?

E) WHAT MIN. AND MAX. BUNCHING FACTORS ARE DESIRED?

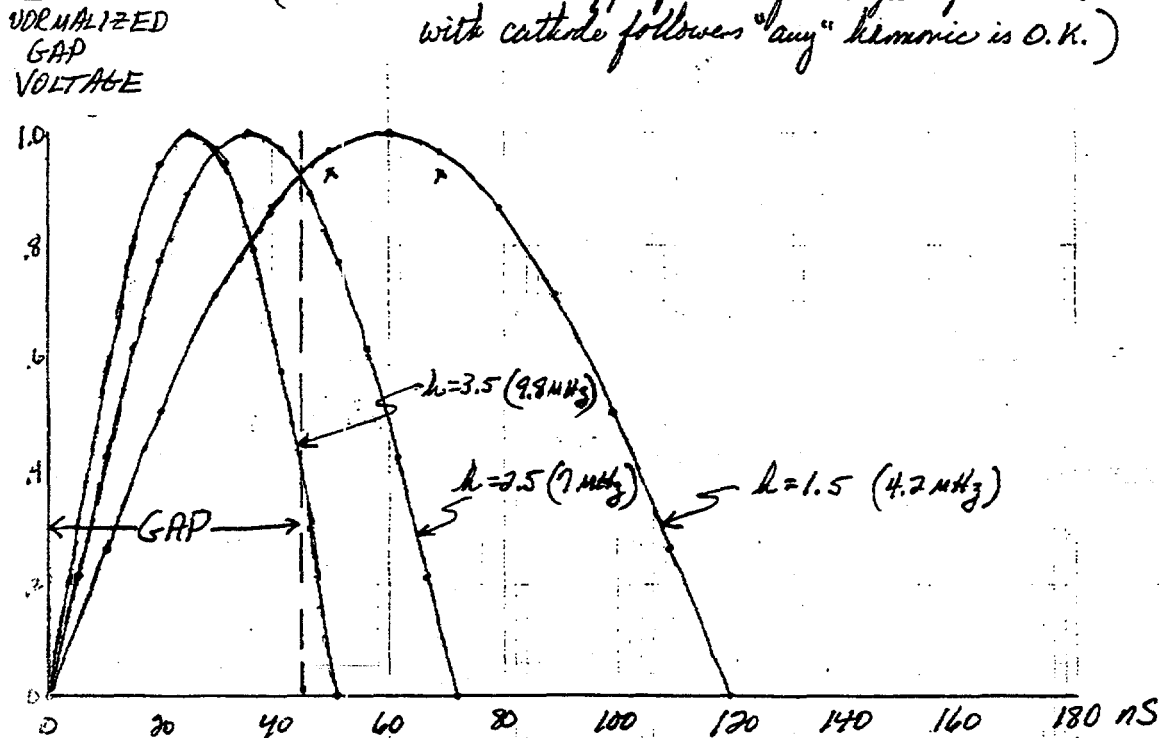
F) HOW WELL WILL PASSIVE COMPENSATION WORK? (i.e. WHAT IS "g" AFTER LEIP, HOW MUCH "EXTRA" VOLTAGE WILL BE NEEDED TO DEFLUTE?)

PRESENT OPERATION

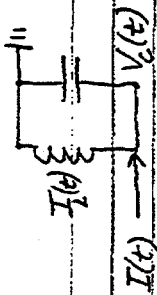


SOME HALF SINUSOIDS

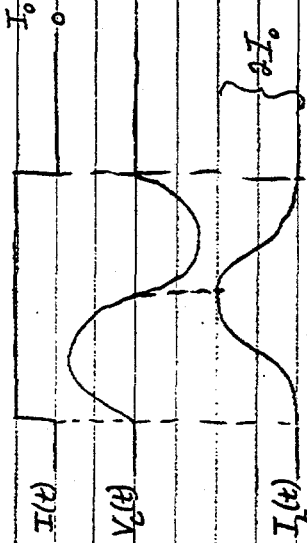
(NOTE: These are appropriate for "high impedance" drives - with cathode followers "any" harmonics is O.K.)



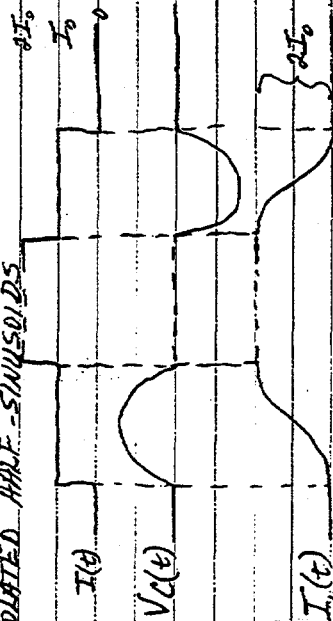
SINUSOID GENERATION IDEAS



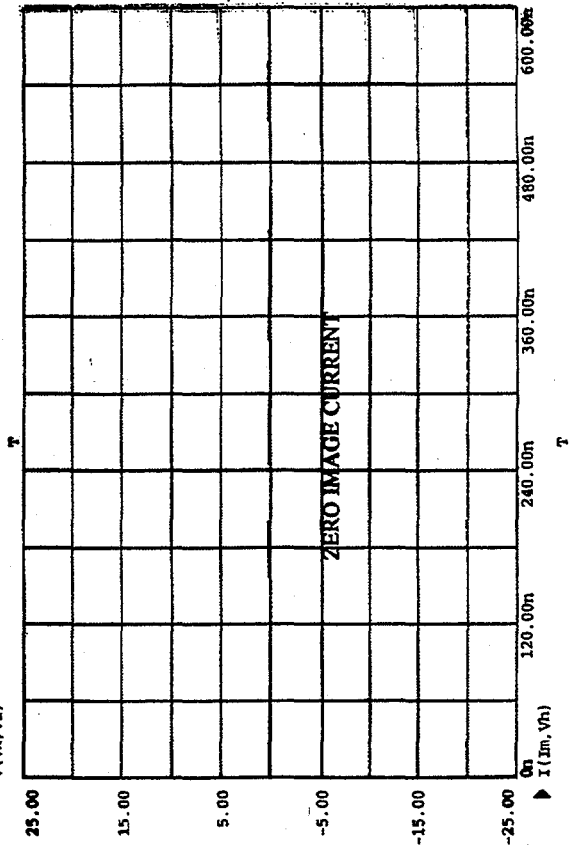
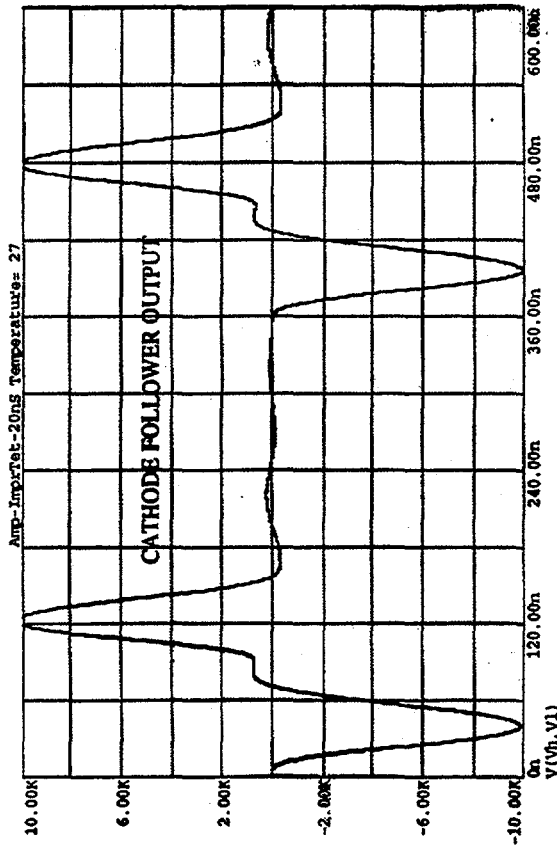
I) ISOLATED SINUSOID

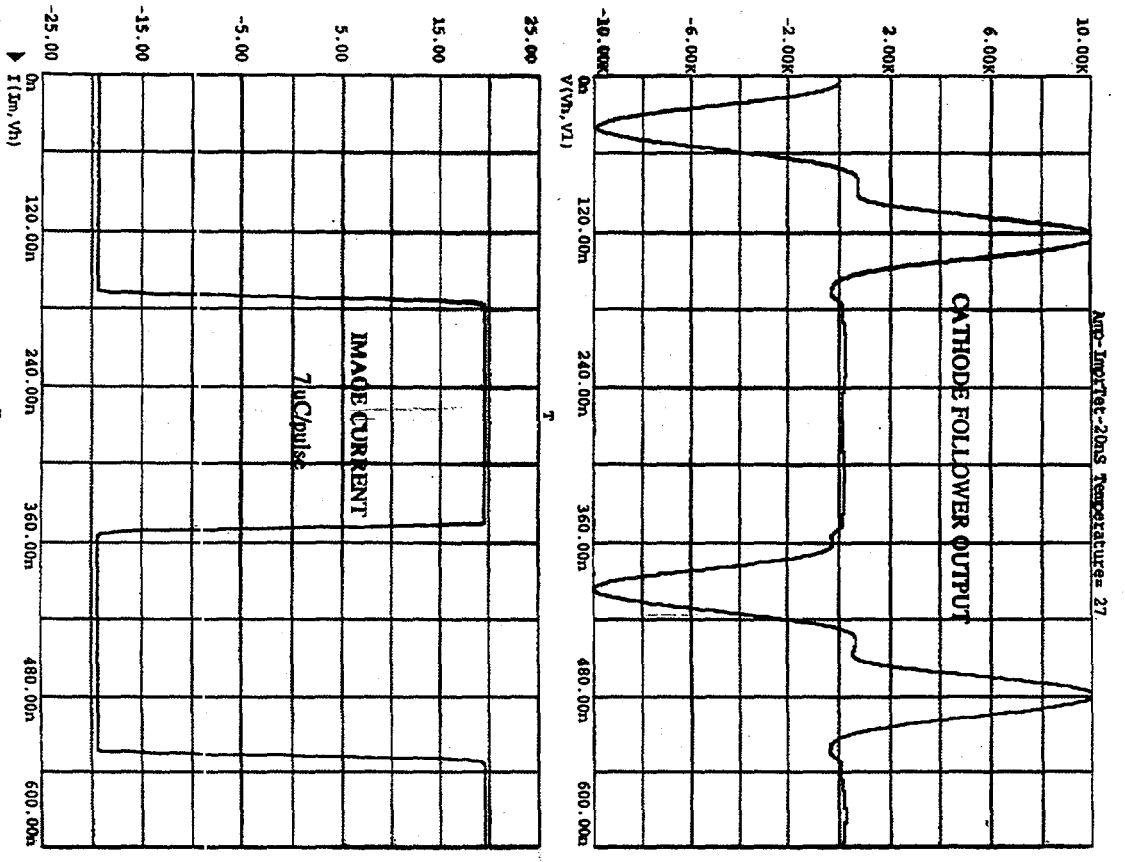


II) ISOLATED HALF-SINUSOIDS



Note: 5% D.F. MAX., EXISTING CATHODE FOLLOWER
 (ALSO: $\frac{45}{45} \frac{45}{45} \frac{45}{45}$)

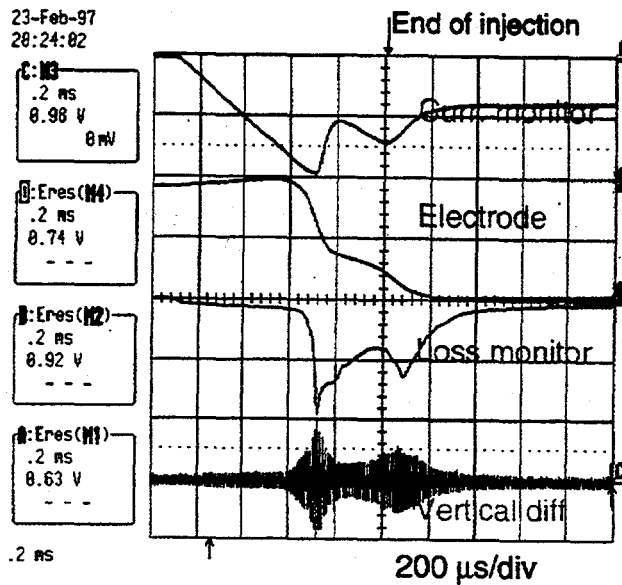




PSR Instability

- ◆ A Slide Show

Coasting beam instability signals

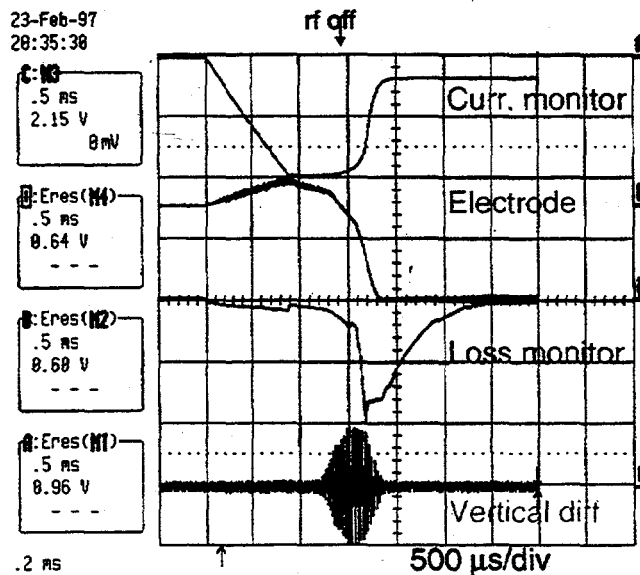


3.0 μ C injected
(2.0 μ C before instab.)
925 μ s injection
250 ns PW
rf off
-1900 V opp. elec.

LANSCE

5/08/97 15

Bunched beam instability signals

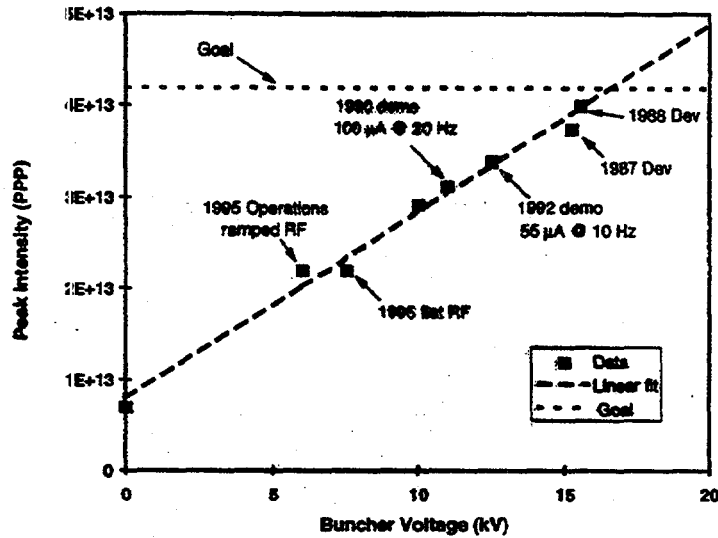


3.0 μ C
925 μ s injection
250 ns PW
6 kV rf
-1900 V opp. elec.

LANSCE

5/08/97 16

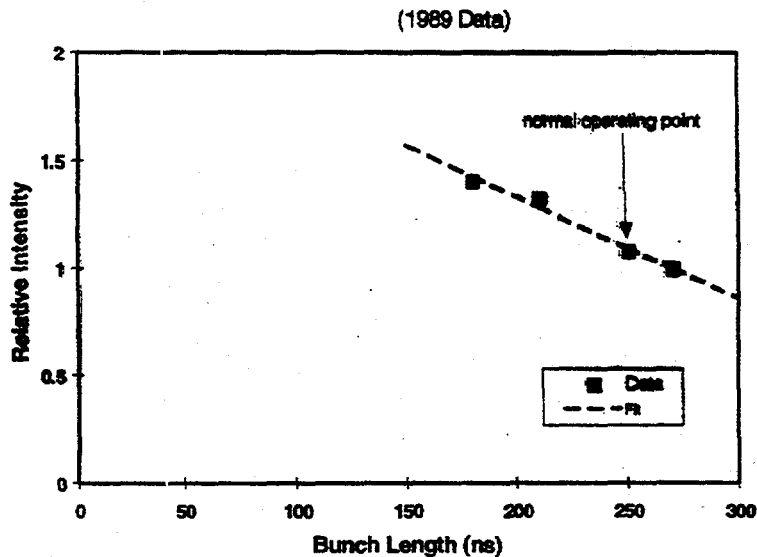
Stable Peak Intensity vs. Buncher Voltage



LANSCE

5/08/97 18

Peak Stored Charge vs. Bunch Length



LANSCE

5/08/97 19

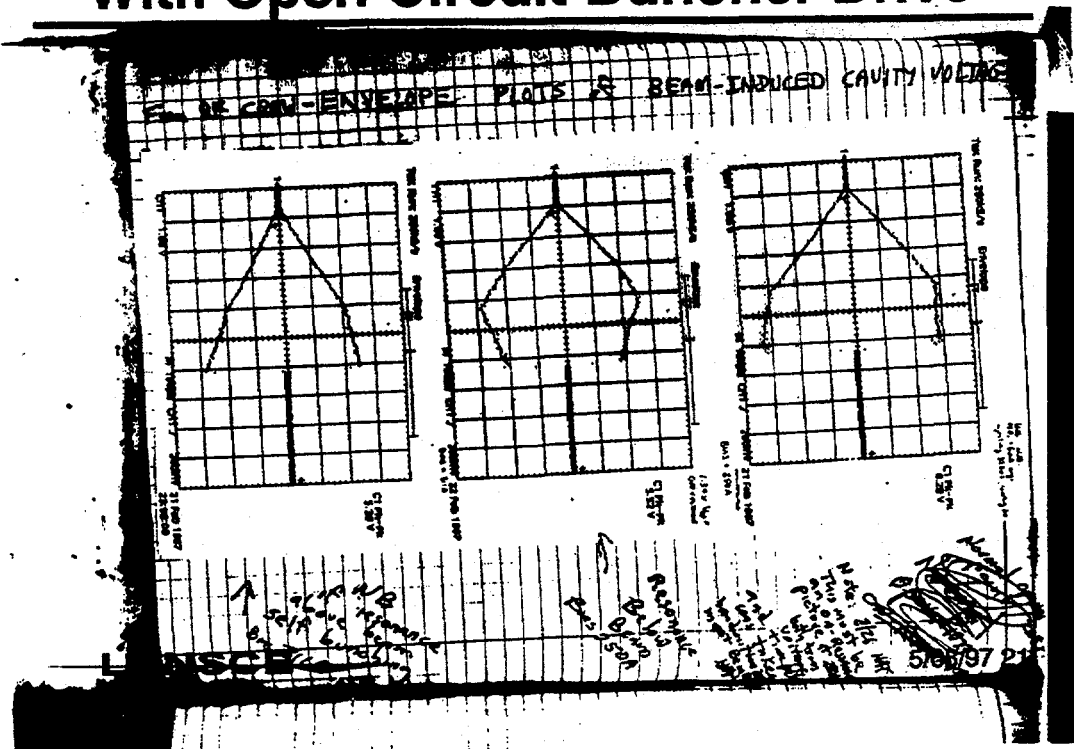
Instability from PSR RF System Problems?

- ◆ Measured Phase and Amplitude Jump at Extraction
 - Phase Change $< 5^\circ$
 - Amplitude Change $< 5\%$
 - » These Result in Tiny Changes in Beam Dynamics
- ◆ See Also Arch's Experiment
 - With Open Circuit Drive of Cavity

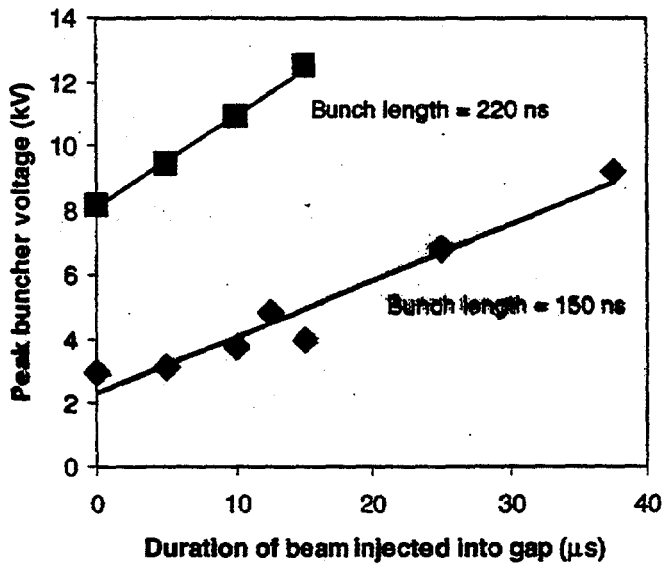
LANSCE

5/08/97 20

Logbook - Arch's Test: With Open Circuit Buncher Drive



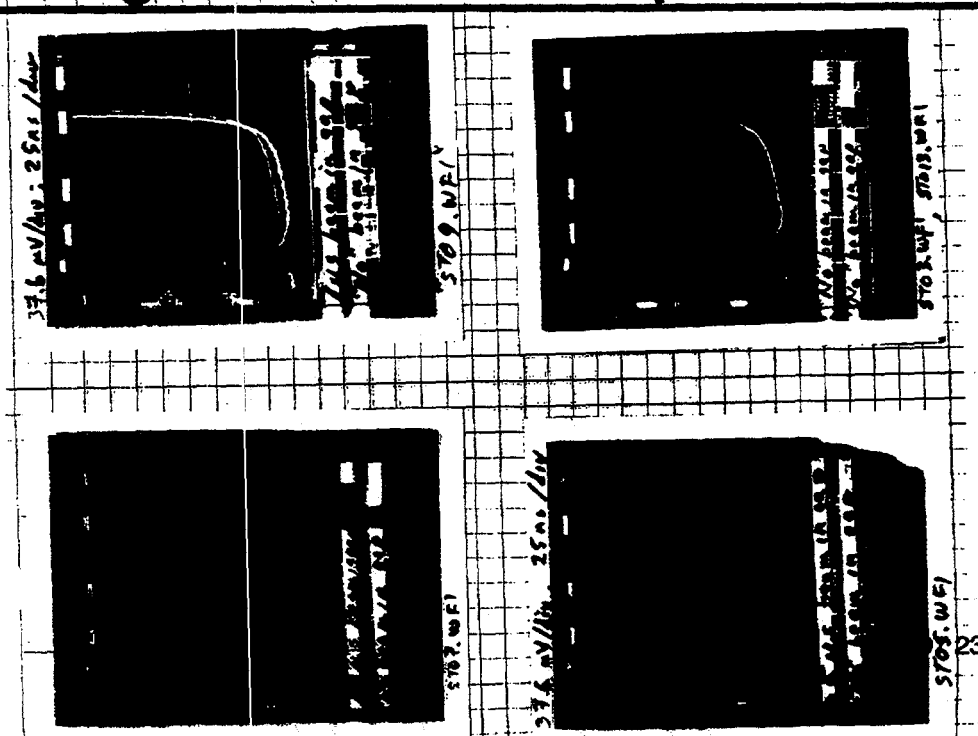
Instability from Beam in Gap?



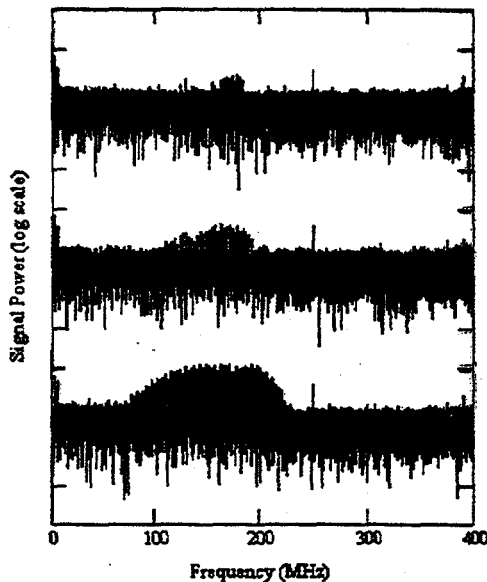
LANSCE

5/08/97 22

Logbook - Beam in Gap



Signal power vs. time



- ◆ Signal power at t , $t + 60 \mu\text{s}$, and $t + 160 \mu\text{s}$ from wide band stripline beam position monitor.
- ◆ Power begins at about 175 MHz, then spreads in width and amplitude.

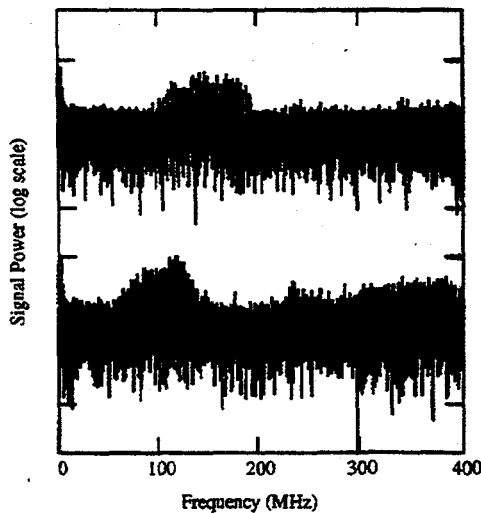
$$f = \frac{1}{2\pi} \sqrt{\frac{2Nr_c c^2 (1 - \eta_e)}{\pi b(a+b)R}}$$

Data from SRWM41 ΔV , 4/7/87.
WM41VD.ON2

LANSCE

5/08/97 24

Peak frequency vs. intensity



- ◆ The peak in the signal spectrum depends on the beam intensity.
- ◆ Top spectrum is twice the intensity of the bottom spectrum
- ◆ Beam conditions for the top and bottom spectra are the same except for the beam intensity and the buncher voltage.

$$f = \frac{1}{2\pi} \sqrt{\frac{2Nr_c c^2 (1 - \eta_e)}{\pi b(a+b)R}}$$

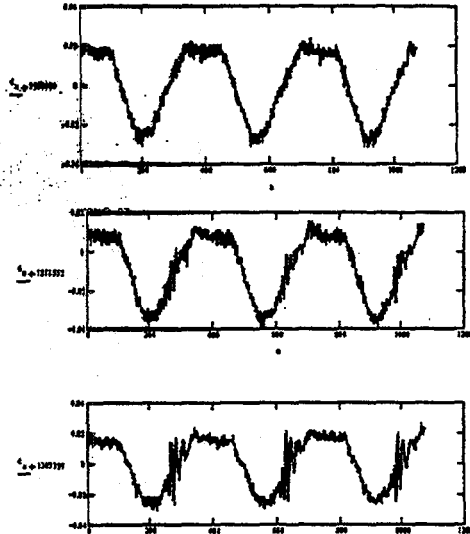
SRWM41 ΔV from 13/Apr/87 data.
WM41VD.AC, SRWM41VD.4F

LANSCE

5/08/97 25

Where Vertical Instability Grows: 2nd Half of Bunch

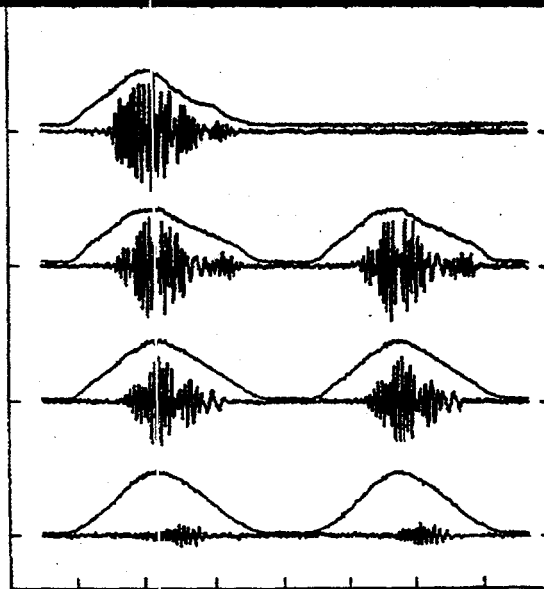
- ◆ CERN BPM Vertical Difference
- three traces at different times



LANSCIE

5/08/97 26

Vertical oscillations and beam density

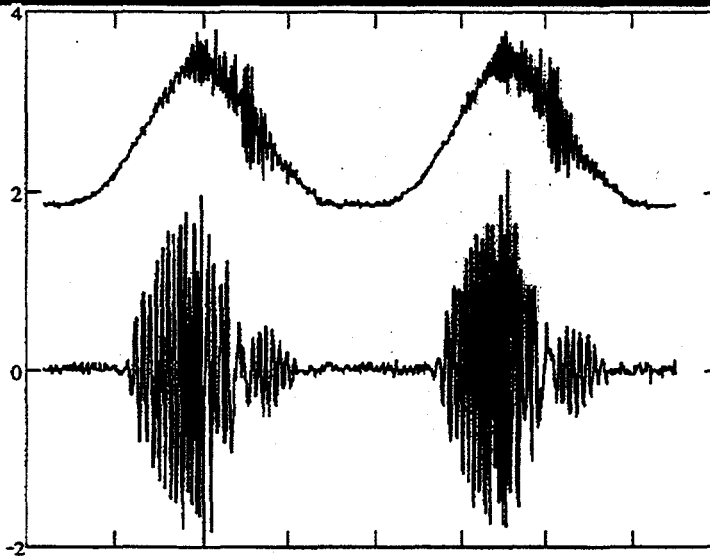


- ◆ WM41VD.4B
- ◆ WC41.4B
- ◆ Data taken Apr. 14, 1997
- ◆ Data at t , $t+115 \mu\text{s}$, $t+230 \mu\text{s}$, $t+345 \mu\text{s}$

LANSCIE

5/08/97 28

Transverse oscillation λ correlated with ρ



SRCM41 (top)
SRWM41 ΔV (Bot)
Data from 22/Feb/97

LANSCE

5/08/97 27

Sources of electrons

For each injected proton, we have:

- ◆ "Convoy" electrons 1
- ◆ SEM from stripper foil from convoy electrons 0.1 - 1
- ◆ Knock-on electrons from stripper foil 1.3
- ◆ SEM from foil from circulating protons 6
- ◆ Thermionic emission from foil <0.02

- ◆ SEM from beam loss 0.01 - 1
(2 to 200 electrons created per proton lost)
- ◆ Residual gas ionization 0.0001
- ◆ Electron multiplication from electron osc. ?

LANSCE

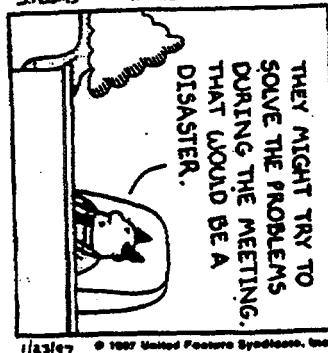
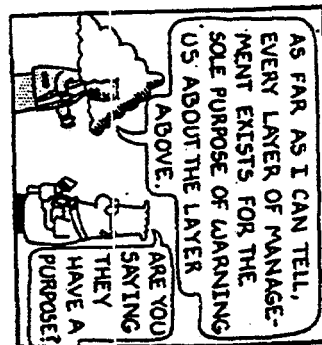
5/08/97 29

Conclusions

- ◆ Study of Inductor for Space Charge Compensation Underway
 - An Experiment Planned for August
 - » If logistics work out
- ◆ Studying Barrier Bucket for PSR Underway
 - No Results Yet
- ◆ PSR Instability is e-p
 - Frequency Dependence
 - Starts in 2nd Half of Bunch
 - » But Source of Electrons
 - » And Mechanism for Growth
 - ◆ Not Yet Understood

LANSCE

5/08/97 30



Session on Barrier Cavity Issues

M. Blaskiewicz

The working group on barrier cavity issues included two presentations. Masahito Yoshii presented plans for the AGS barrier cavity upgrade and Chihiro Ohmori presented plans for the JHF.

Plans for the AGS barrier cavity upgrade included cavity design and materials as well as drive considerations. The system will produce two single period sine wave pulses of amplitude 80 kV and period 250 ns (1/ 4 MHz) at a rep rate of 350 kHz. There will be one rf station for each pulse. Since the cavity is run in a non-resonant mode the cavity voltage V and generator current I are related via $V \approx IR/Q$ where R/Q is the ratio of shunt impedance to cavity Q for the resonant mode at 4 MHz.

Yoshii stressed the need for a high inductance and a low capacitance so that the necessary waveform could be obtained with minimum generator current. The AGS philosophy is to use a fairly low loss ferrite (Philips 4B2 or 4L2) to obtain the high inductance and to control the shape of the voltage waveform by careful adjustment of the generator. This technique minimizes the peak generator current required for a given gap voltage and cavity R/Q . The generator supplies current in one direction only, which reduces cost.

The total voltage of 80 kV is obtained using 8 gaps with 10 kV per gap. Such a design does not require high voltage feedthroughs and a prototype of a single cell using Philips 4L2 has achieved the necessary voltage.

The JHF design included an upgrade of the KEK Booster as well as a the new high energy JHF. Accelerating voltages of 10 kV/meter are required. The KEK design differs from the AGS design mainly in the choice high permeability material. Ohmori agreed that large inductance with small capacitance was needed, but is more inclined toward the very high permeability and lossy FINEMET. For a truly isolated voltage pulse the system requires a push-pull current drive, but the voltage waveform from a half sine wave current pulse was not far from ideal. The low Q leads to large power dissipation in the cavity, but FINEMET has a 600 C Curie temperature. Additionally, the low quality factor reduces the shunt impedance of parasitic modes which should reduce instability problems. A prototype cavity has been built and has achieved 11 kV/ meter. Studies of feedback and beam loading are underway.

AGS Barrier Cavity

* M. Yoshii (KEK)
M. Meth (BNL)
R. Spitz (BNL)

May 7 1987
Barkner Hall Room B
BNL, Upton NY, USA

CONTENTS

- ✓ AGS Barrier Requirements
- ✓ Design Principles
 - ✓ permeability : μ
 - ✓ μQ -product : μQ
 - ✓ capacitance : C
- ✓ Ferrites
 - ✓ $\mu(r)$ measurement
 - ✓ sample measurement
- ✓ Cavity Capacitance
- ✓ New AGS Barrier Cavity
 - ✓ design
 - ✓ 1/8 model
 - ✓ drive circuit
- ✓ Summary

MAY 7 87
M. YOSHII
Mini-Workshop

AGS Barrier Requirements

- ✓ 80 kV per each station
- ✓ Two Barrier Stations
the length of station should be
less than 102 inches (2.6m)
- ✓ 4 MHz
cf. the revolution frequency at AGS
Injection is 357 kHz

Design Principles

- ✓ to minimize the drive-tube current
- ✓ high cavity inductance
- ✓ square current waveform
- ✓ simple structure

The total current required for the barrier gap voltages is,

$$I(t) = \omega C V_o \left(1 + \frac{\sin(\omega t)}{Q} \right) + V_o \cos(\omega t) \left(\omega C - \frac{1}{\omega L} \right).$$

And, the peak current on resonance is,

$$I_p = \omega C V_o \left(1 + \frac{1}{Q} \right).$$

Therefore, following three basic parameters for the cavity ; μ , μQ -product and total C are chosen in order to minimize total tube current.

- ✓ Capacitance per gap < 200 pF
- to keep the average rf-current as low as possible

- ✓ μQ -product > 2000
- to keep the peak rf-current as low as possible

- ✓ $\mu > 500$:
- to get a high gap voltage, $\psi \propto L \frac{dI}{dt}$
- also, to make a cavity short

Radial Dependence of Ferrite μ and Magnetic Flux

G. Rakowsky (BNL) "RF Accelerating Cavity For AGS Conversion"

: $\mu(r)$, $B(r)$ distributions under biasing conditions

$I_{dc} = 0$

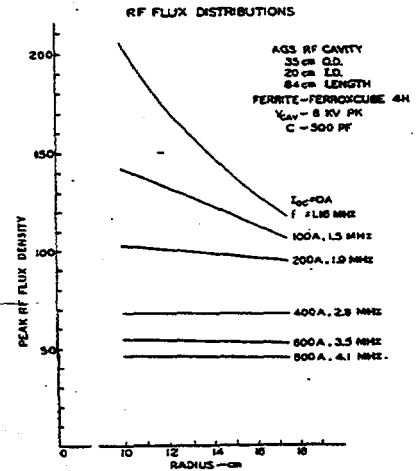
- μ has radial-dependence

For a given I_{dc} ,
 μ increases with radius
 H_{rf} decrease as radius

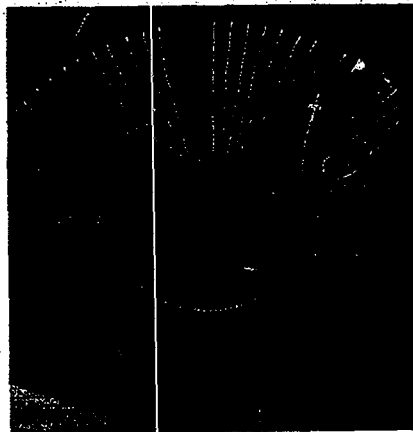
-> Magnetic Flux becomes uniform

$I_{dc} = 0$ or weekly biased

- μ is uniform in a ferrite
-> Magnetic Flux has radial dependence.



5



$$\bar{H} = \frac{\text{total current cross s in g inside a core}}{\text{average magnetic length}} = \frac{NI}{\frac{\pi d}{2}}$$

where $\bar{d} = \frac{ID+OD}{2}$

(1)

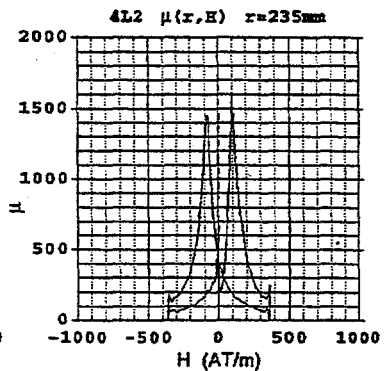
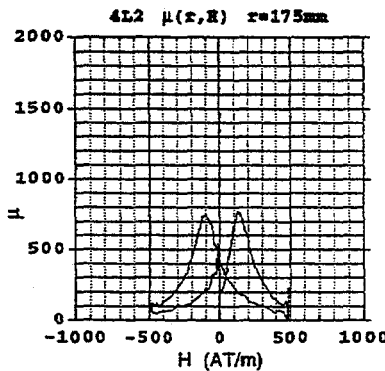
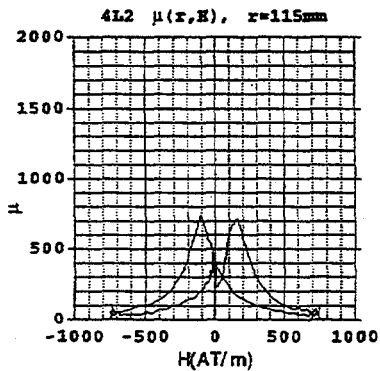
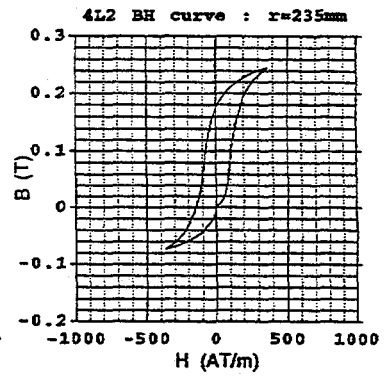
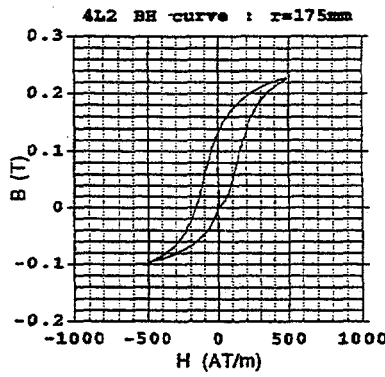
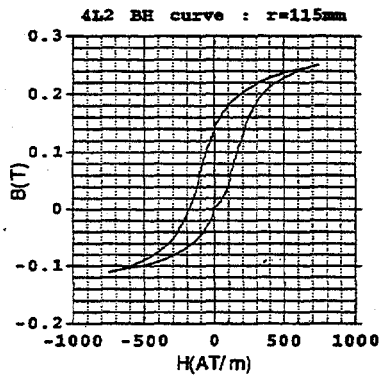
- How to calculate B and H.
- ± 15 A -> ± 1500 AT
- single cycle of magnetization with sinusoidal biasing

Measurement

- 100 turns of primary winding for biasing
- 30 turns of pick-up coil (5 positions along the radial direction)
- 4L2 $\phi 500 \times \phi 200 \times 25.4$ mm

Measurements of Permeability and Flux Distribution

6



$$\text{Differential } \mu = \frac{\Delta B}{\Delta H}$$

MAY 7-97
M.Yoshii
Mini-workshop

- An induced voltage at each pick-up is

$$\varepsilon^{(n)} = -\frac{d(N^{(n)}\phi^{(n)})}{dt} \quad (\text{volts}), \quad (2)$$

where N is the turn-number of pick-up coil, ϕ is a magnetic flux through the coil and a suffix (n) denotes the pick-up position.

$$\text{As a flux } \phi^{(n)} = \int_S \vec{B}^{(n)} \cdot d\vec{S}^{(n)}, \quad B^{(n)} = \frac{d\phi^{(n)}}{dS^{(n)}} = \frac{\text{flux } n\text{th pick-up}}{\text{crosssectional area}} \quad (3).$$

The time-integration of eq.(2) gives $\phi^{(n)}(t) = \frac{1}{N^{(n)}} \int_0^t \varepsilon^{(n)}(t) dt$ (4).

From (3) and (4), then, the average flux density B_n at n-th pick-up is given by

$$\vec{B}^{(n)}(t) = \frac{1}{N^{(n)}S^{(n)}} \int_0^t \varepsilon^{(n)}(t) dt \quad (5).$$

In the measurements all data are discretely sampled. So, integration in eq.(5) must be re-written by,

$$\vec{B}_k^{(n)} = \frac{\Delta t}{N^{(n)}S^{(n)}} \sum_{j=0}^k \varepsilon_j^{(n)} \quad (6)$$

for example, in our case,

$$N = 30 \text{ turns}, \quad S = 763 \times 10^{-6} \text{ m}^2, \quad \Delta t = 200 \mu\text{sec}$$

$$\vec{B}_k^{(n)} = 8.75 \times 10^{-3} \sum_{j=0}^k \varepsilon_j^{(n)} \quad \left(\frac{\text{volts} \cdot \text{sec}}{\text{meter}^2} \right)$$

Sample measurements

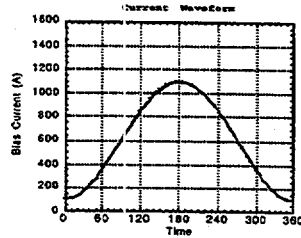
The Ferrite materials are required at 4MHz

$$\frac{\mu > 500}{\mu Q > 2000}$$

Philips:
4A11
4B3
4L2

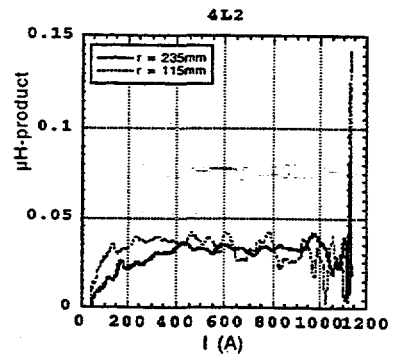
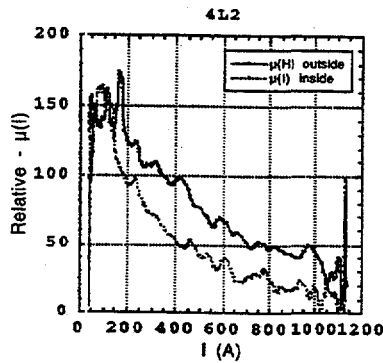
TDK:
L6H

Ceramic Magnetics :
CMD10
CMD5005



Bias Current : 100 ~ 1100 A

$$\text{Differential } \mu_s = \frac{\Delta B}{\Delta H}$$



MAY 7-67
 M.YOSHII
 Mini-Workshop

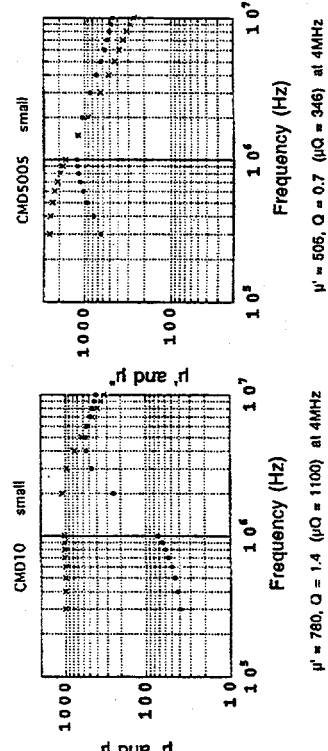
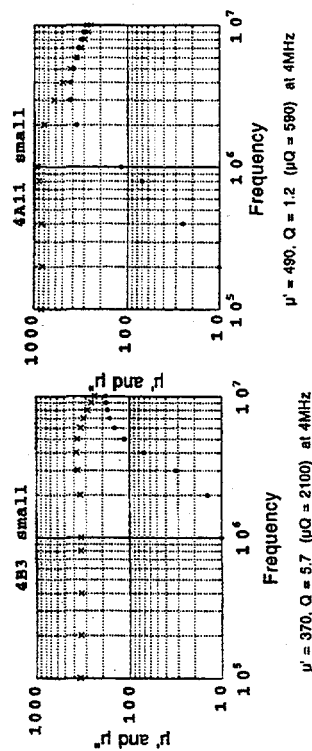
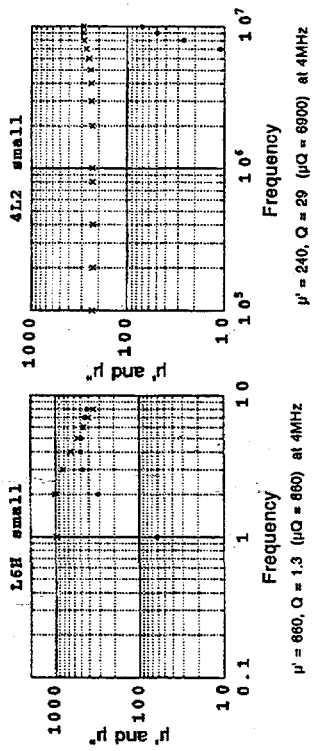
Samples

Table - 1. List of dimensional parameters of tested samples

Name	Maker	I. D. (mm)	O. D. (mm)	τ (mm)	AL/Ur (pH)
4A11	Phillips	20.	30.	8.	649.
4B3	Phillips	20.	30.	8.	649.
4L2	Phillips	20.	30.	8.	649.
L6H	TDK	19.	31.	8.	772.
CMD10	CH	32.	27.	15.	602.
CMD5005	CH	38.	25.	13.	986.

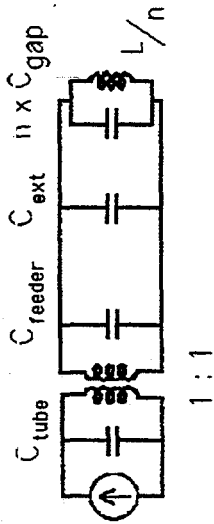
Measurements

- conditions : 4 turns winding for measuring 4A11, 4B3, 4L2, CMD10 and CMD5005
 5 turns for L6H
- instruments : HP8751A Network Analyzer
 with HP87612A Transmission/Reflection Test Set
 for 4A11, 4B3, 4L2 and L6H measurements
- HP9753A Network Analyzer
 with HP85044A Transmission/Reflection Test Set
 for CMD10 and CMD5005 measurements
- frequency range : 100kc to 10 Mc or 300 kc to 10 Mc



MAY 7-97
M. YOSHII
Mini-Workshop

Cavity Capacitance



Total Capacitance : $C_T = C_{tube} + C_{feeder} + C_{ext} + nC_{gap}$

C_{tube} : tube capacitance : 100 pF

C_{ext} : trim capacitance for tuning : as low as possible

C_{feeder} : stray capacitance etc. . . . unknown (?)

C_{gap} : gap capacitance unknown (?)

n : the number of gaps

Considering a resonant condition ,

$$(2\pi f)^{-2} = \left(\frac{C_{tube} + C_{feeder} + C_{ext}}{n} + C_{gap} \right) L.$$

Contribution of C_{tube} , C_{feeder} and C_{ext} to C_T becomes less with n .

Capacitance Measurement :

$$f^{-2} = LC_{gap} \quad : C_{gap} \text{ unknown}$$

$$f^{-2} = L(C_{gap} + C_{ext}) \quad : C_{ext} \text{ known}$$

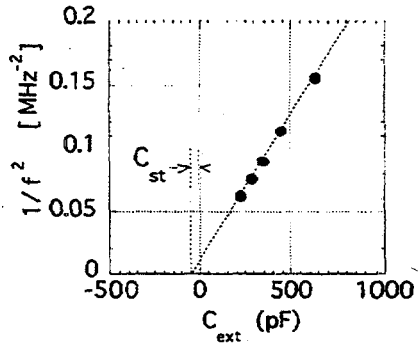
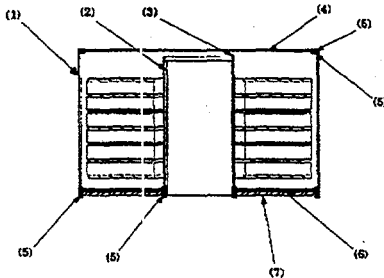
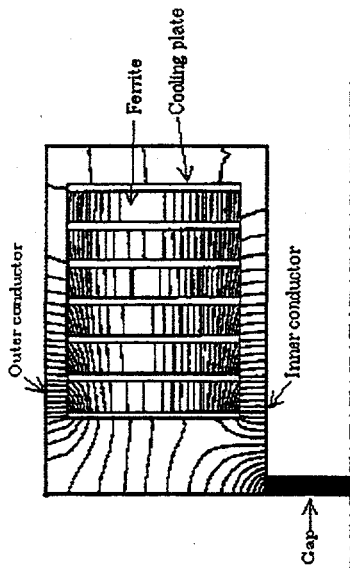
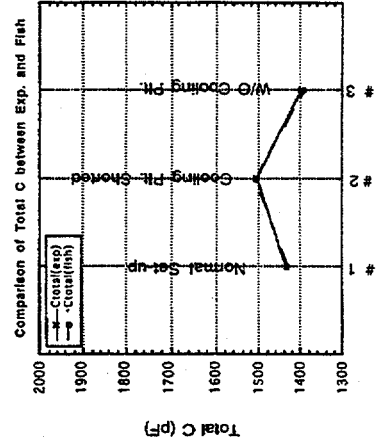
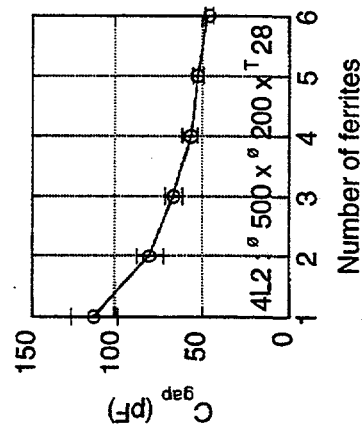
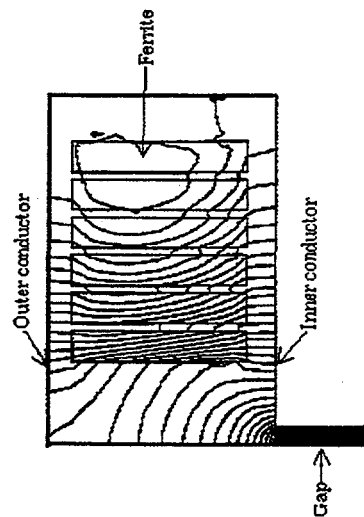


FIGURE-2: Typical plot



(a) Ferrite discs with cooling plates



(b) Ferrite discs with no cooling plate

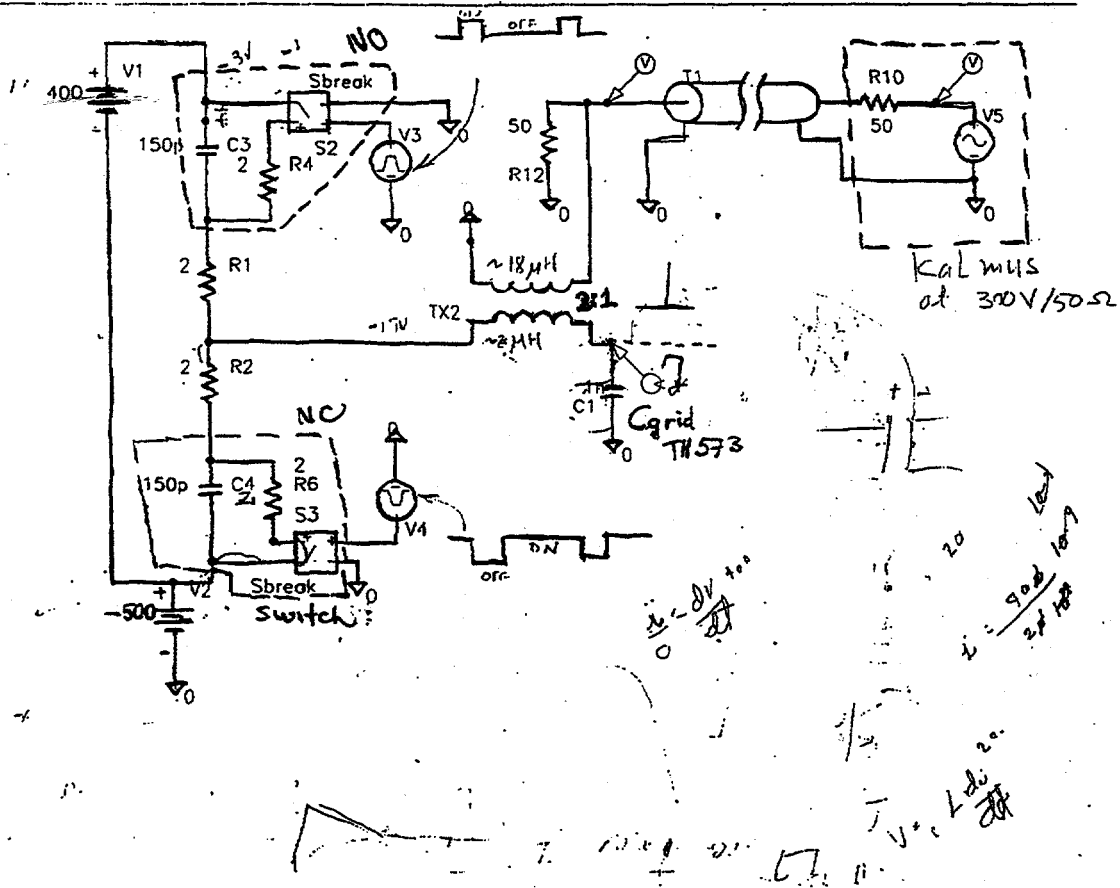
FIGURE - 5 Superfish Field Plots :
Electric field lines in the ferrite loaded cavities with the cooling plates (a), and without the plates (b) are displayed. Each cross-sectional view shows a half of the cavity

	Name	<l>	<Q>	Lp(H)/gap	CT (pF)	Cext (pF)	Total lrf	Rsh	Pw/ring (kW)	Pw density (W/cc)	P (kW)
0	8-Gap Cavity									$\tau = \tau_c$	
1											
2											
3	OD = 500 mm										
4	ID = 200 mm										
5	t = 28.1 mm										
6	Co = 50 pF										
7											
8	N = 6										
9	8 gaps										
10											
11											
12	4A11	490	1.2	25.7	61.7	-86.3	227	97	11	6.6578	517.00
13	4B3	370	5.7	11.8	134.3	484.8	318	211	5	3.0514	236.95
14	4C2	240	30.0	7.4	213.3	1126.1	443	700	1	0.92029	71.464
15	L6H	650	1.3	32.0	46.5	-183.8	178	131	8	4.9319	382.98
16	CMD10	780	1.4	36.4	43.5	-232.0	150	180	7	4.0224	312.35
17	CMD5005	505	0.7	47.4	33.4	-313.1	163	104	10	6.1710	479.20
18											
19											
20	< Brf >	157									
21	B max @ r = r1	258									
22											
23	Vgap total (kV)	10.0									
24	Frequency (MHz)	4.00									

$$N \frac{\mu}{2\pi} \ln \frac{r_2}{r_1} \left(1 + \frac{1}{Q^2}\right)$$

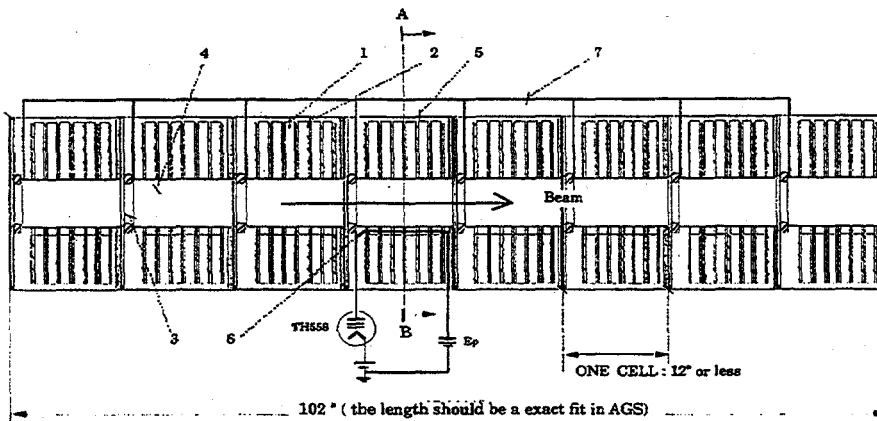
New Cavity Design

1. 8 gaps
2. 10 kV / gap
3. Ferrite
500 x 200 x 28
4B2 (?) 4L2 (?)
4. Cooling plates
electrically floated
5. $N_f = 6$

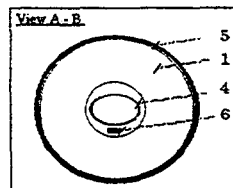


AGS BARRIER CAVITY (cross-sectional view)

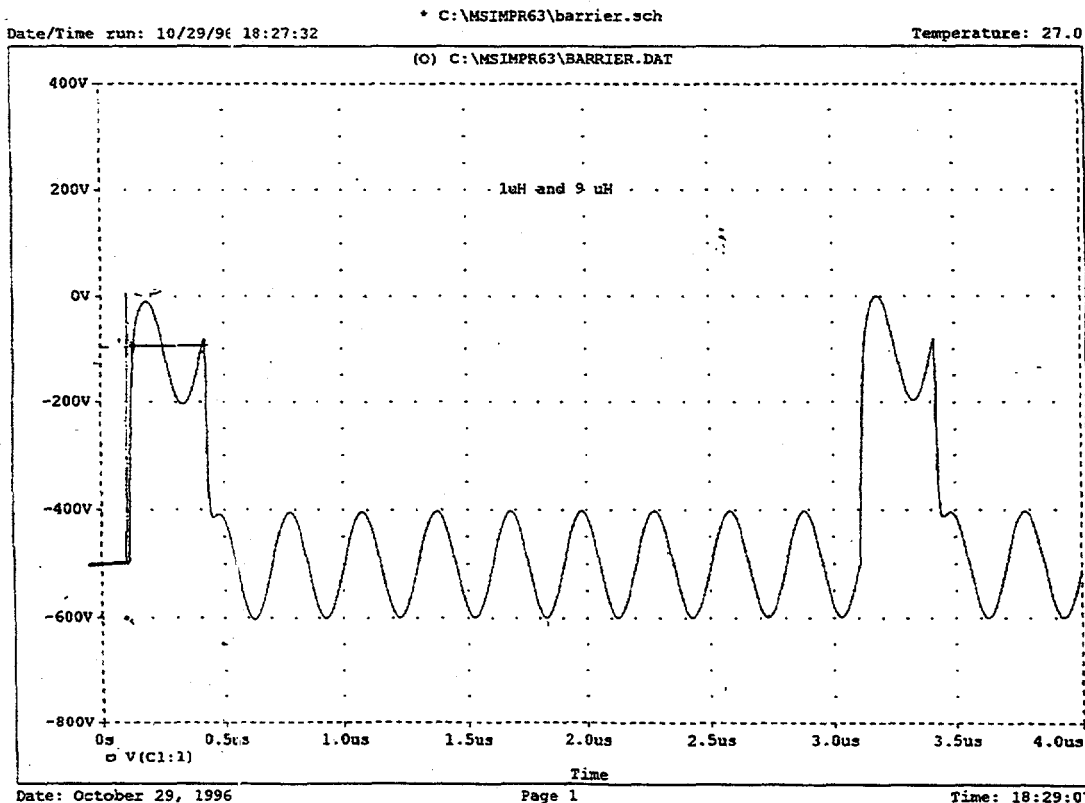
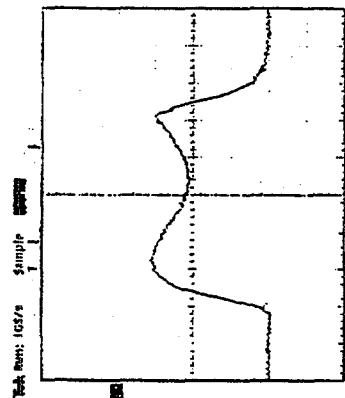
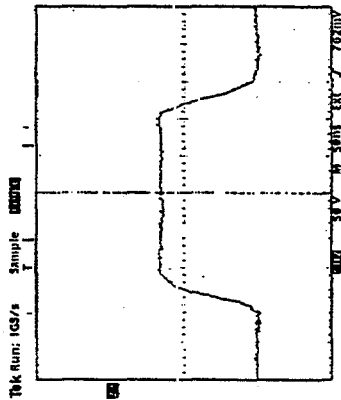
- The AGS barrier cavity consists of 8 cells of a re-entrant ferrite loaded cavity. Total gap voltage is required to be 80kV at 4MHz. And, the cavity is going to be driven by one TH 558 power tetrod (500kW).



1. Ferrite disc : $\phi 500 \times \phi 200 \times t28$ (mm), 6 per cell
2. Cooling Plate : 1/4" thick, 7 plates per cell
3. Accelerating Ceramic Gap : max. 10kV gap voltage at 4MHz
4. Beam Pipe : bore should be as same as a present pipe
5. Outer Conductor of the Cavity
6. RF Power Feed Line
7. Bus Bars Cell Connection



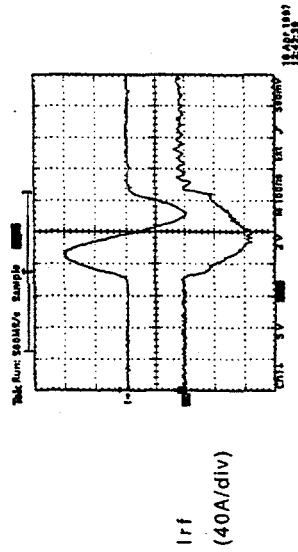
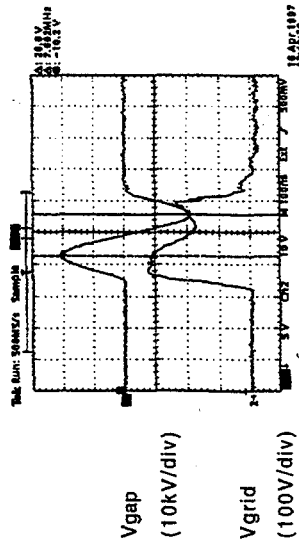
March 26 1997
M.YOSHII



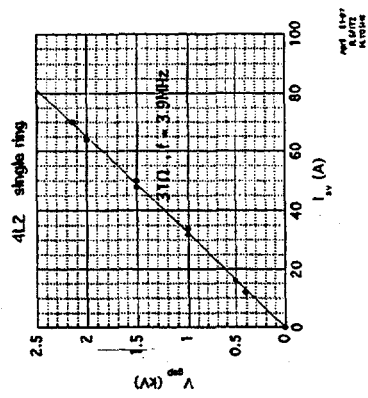
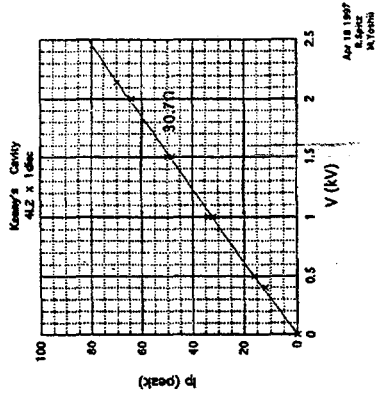
Kenny's cavity (1/8 model)

Results of High Power Test

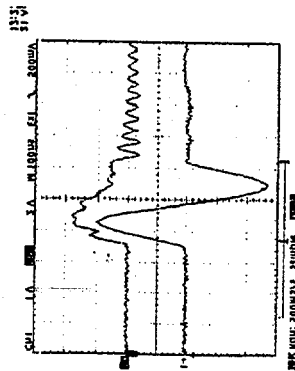
6 x 4L2 Ferrites



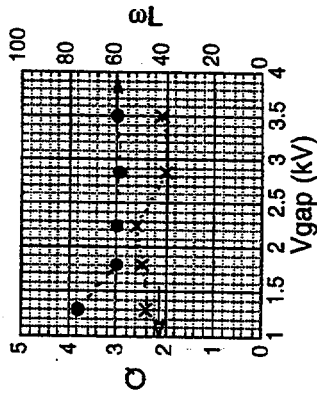
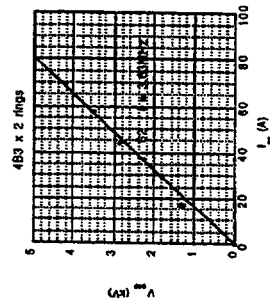
$V_g = -375 \text{ V}, f = 3.8 \text{ Mhz}$



4B3 x 2 discs



$f = 3.7 \text{ MHz}$
 $Q = 2$
 $V_{\text{peak}} = 2.8 \text{ kV}$
 $I_{\text{ave}} = 44 \text{ A}$
 $\omega L = 59$



MAY 7-87
 MYOSHI
 Mini-Workshop

SUMMARY

In order to minimize the driving current < 400A

- # N dependence of gap capacitance and the effect of cooling plates have been studied
- >> $C_{\text{gap}} \approx \text{const.} + \frac{C_1}{N}$
- >> cooling plates must be electrically isolated

Experimental results explained G. Rakousky's representations about μ and flux distribution in a ferrite

(as far as major magnetizing process)

Sample measurements

- # there were only two interesting ferrite found.

New design

- # 8 gap, 80 kV per station, six rings per gap
- # basic design has been done
- 1/8 model cavity
- # 10 kV gap voltage with 6 x 4L2 was achieved (2.2 kV II per ring with one 4L2)
- # new grid drive circuit has been test well

As a minor problem,

- # no satisfied ferrite material yet
- # fast grid circuit needs some improvements
- # to need dumping the ringing on the plate current

R&D Works for RF System of JHF

Chihiro Ohmori
KEK-Tanashi

JHP RF Group

REQUIREMENTS FOR RF SYSTEMS

	Booster	Main Ring
RF VOLTAGE	~450 kV	270 kV
RF FREQUENCY	1.99-3.43 MHz	3.43-3.51 MHz
REPETITION RATE	25Hz(50Hz)	0.3 Hz
CIRCULATING CURRENT	4 - 7 A	6.4 - 6.6 A
I _B	8 - 14 A	12.8 - 13.2 A

JSPS Meeting@Saga Univ., October 9, 1996

REQUIREMENTS FOR RF SYSTEMS

NEED HIGH VOLTAGE

SPACE IN BOOSTER IS LIMITED
(24*6m STRAIGHT SECTION).

50 Hz OPERATION NEEDS 800~900 kV

~40 kV/CAVITY/3~4M
>10 kV /m (>13 kV/m)

10 Hz OPERATION FOR MAIN RING (in future)

>10 kV /m

September 18, 1996

REQUIREMENTS FOR RF SYSTEMS

STABILITY FOR BEAM LOADING

CIRCULATING CURRENT 4 - 7 A

I_B ~14 A

$Y (=I_B/I_0)$ < 1.4

I_0 10 A

To handle Beam without direct feedback.

September 18, 1996

REQUIREMENTS FOR MAGNETIC CORE

ASSUME 20 CORES PER METER
2.5 cm thickness

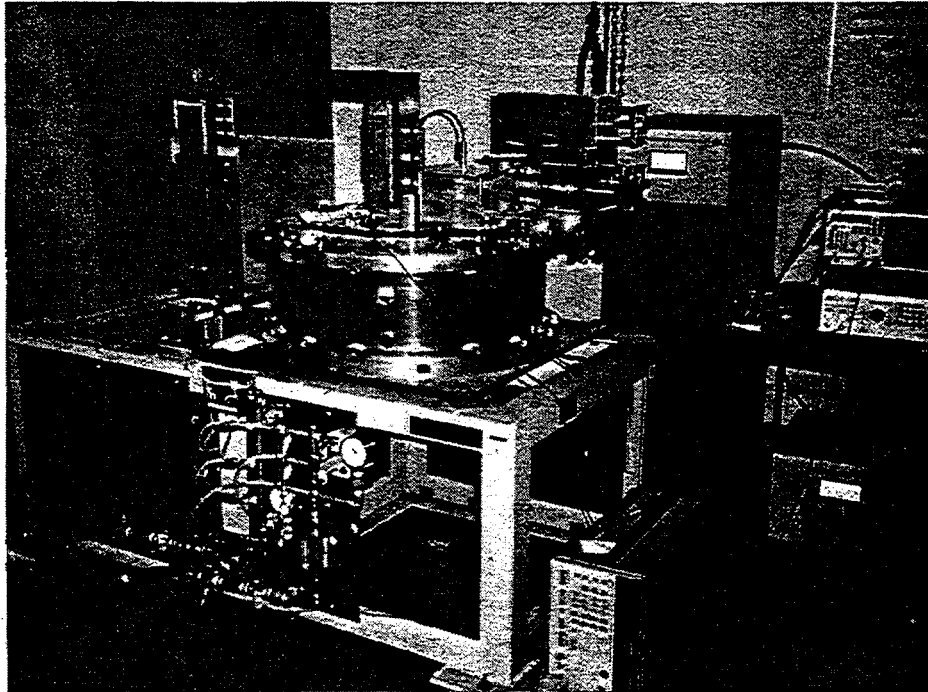
$V > 500 \text{ V}$

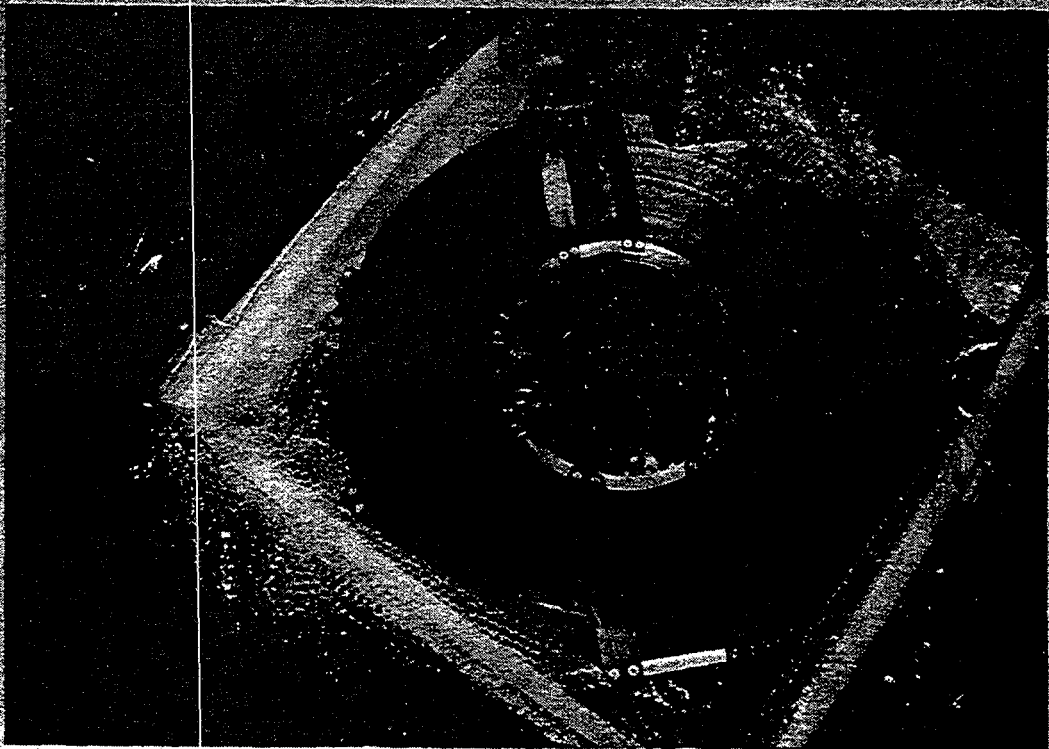
$R > 100 \Omega$

SUMMARY OF MAGNETIC CORE MEASUREMENTS

	CORE FOR BOOSTER	CORE FOR MAIN RING
HITACHI NSC	NOT GOOD	— NEED BIG CORE
PHILIPS 4M2	OK	NOT GOOD (HIGH LOSS EFFECT)
TDK SY2	NOT GOOD	NEED BIG CORE
FINEMET FT3	PROBABLY OK	OK

September 18, 1996





JHP RF Group

What is FINEMET?

Soft Magnetic Material with very fine crystallized structure.

High Permeability	1931@3.3MHz
Low Quality factor	0.63@3.3MHz
R	76 Ω @3.3MHz
R~100 Ω for new core as O.D. is large (67cm).	

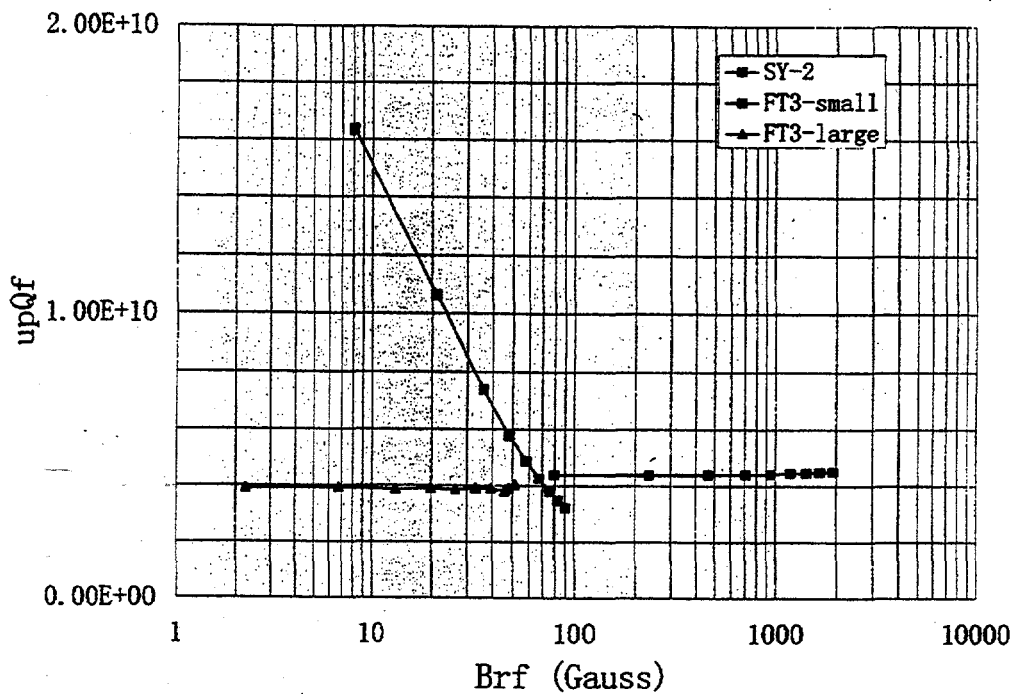
Very High Curie Temperature ~600 deg.C

Very Stable for Temperature and RF Power

Very thin tape, Easy to make a big core

Not Saturated @ 10 A

September 18, 1996



JHP RF Group

FINEMET CAVITY

Suitable for Barrier Bucket RF

Easy to make an isolated pulse

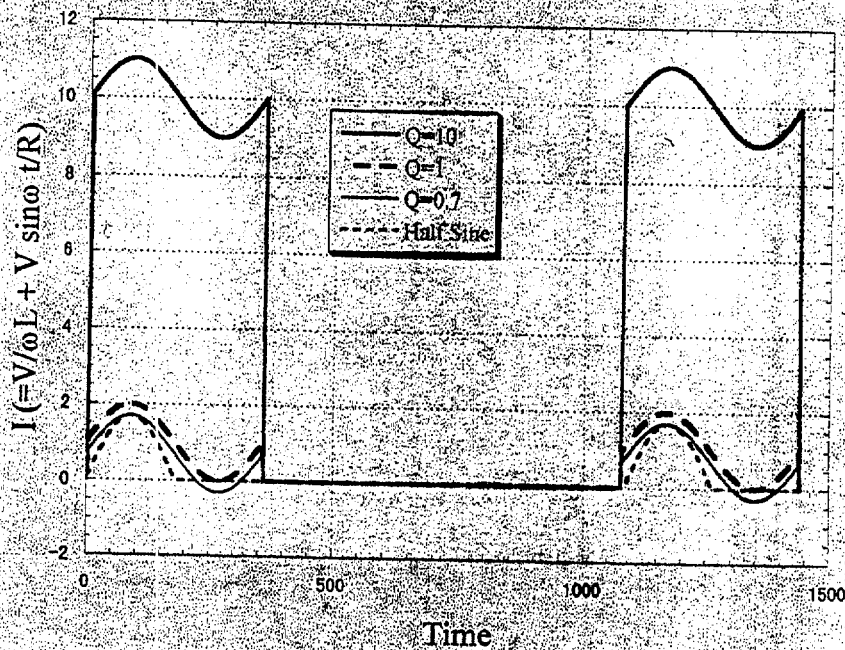
Many possibility for RF gymnastics

To store more particles
 To change RF frequency
 To make empty bucket

Decrease Peak intensity

To flatten Bunch shape

September 18, 1996



JHP RF Group

Barrier Bucket

JHP synchrotrons : very high intensity machines.

To reduce beam loss is important issue.

Stable operation @ high intensity

Reduction of S.C. tune shift.

To change Beam distribution

To store more particles in rings

Barrier Bucket is very attractive !!!

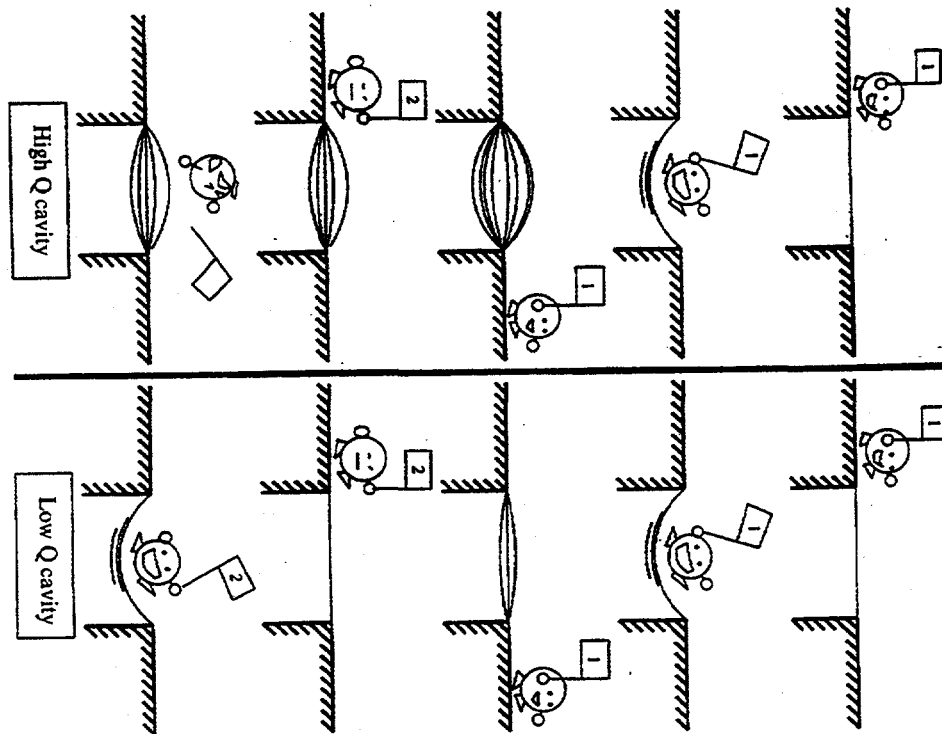
September 18, 1996

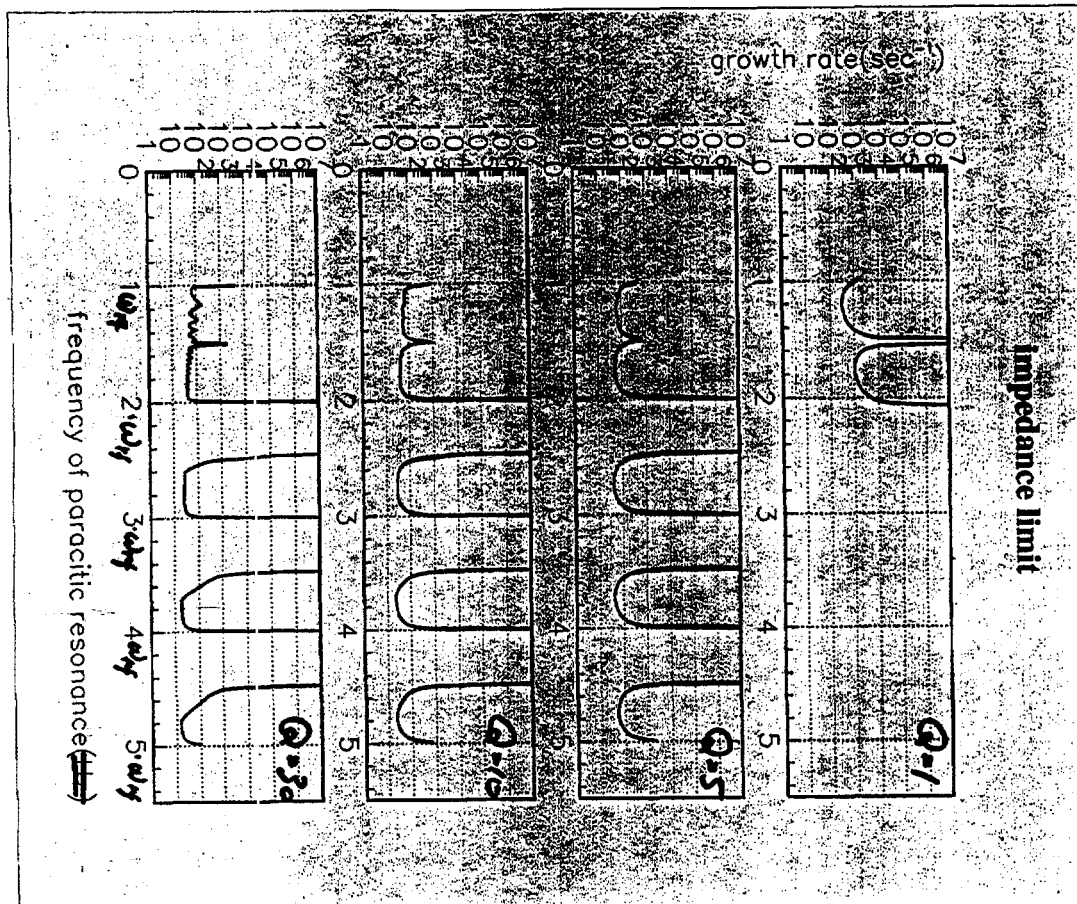
FINEMET CAVITY

Dump wake field quickly

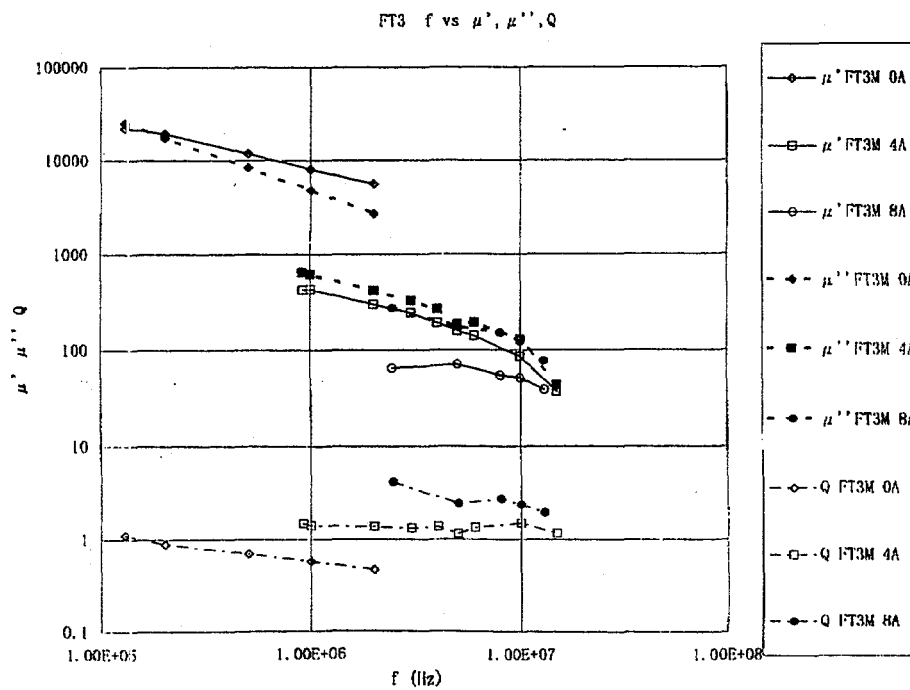
Good for instabilities,
Coupled bunch as $H=4$ for Booster
as $H=17$ for Main Ring

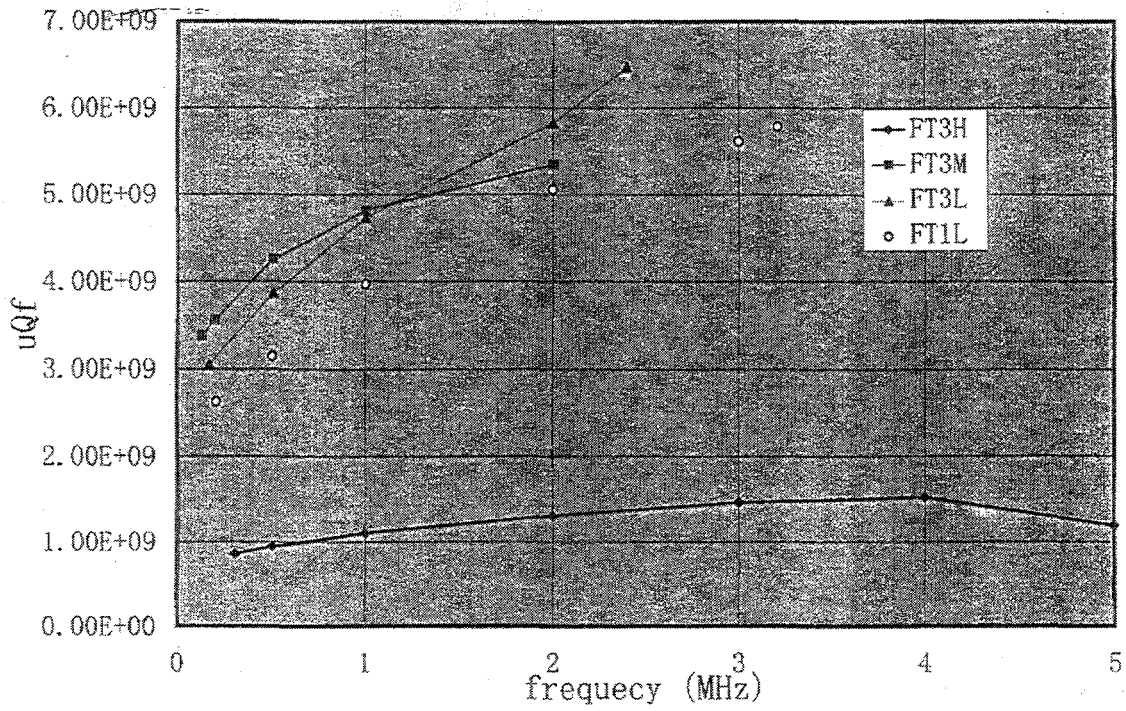
September 18, 1996





FT3 series グラフ 3



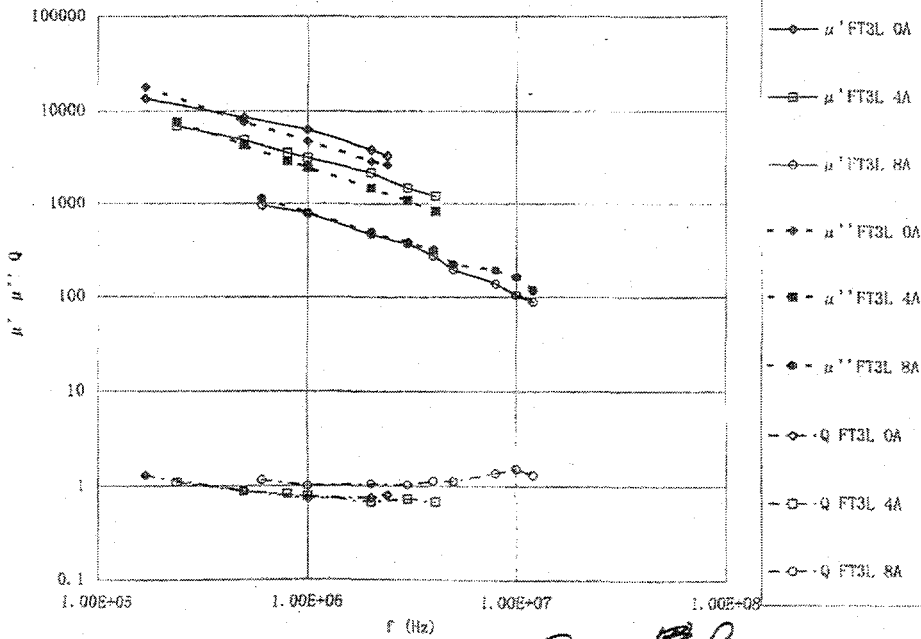


- 1 -

ft3 series グラフ 4

$$Q = \frac{R}{\omega L} = \frac{\mu'' \ln \frac{b}{a}}{\mu' \cdot \ln \frac{b}{a}}$$

FT3 f vs μ' , μ'' , Q

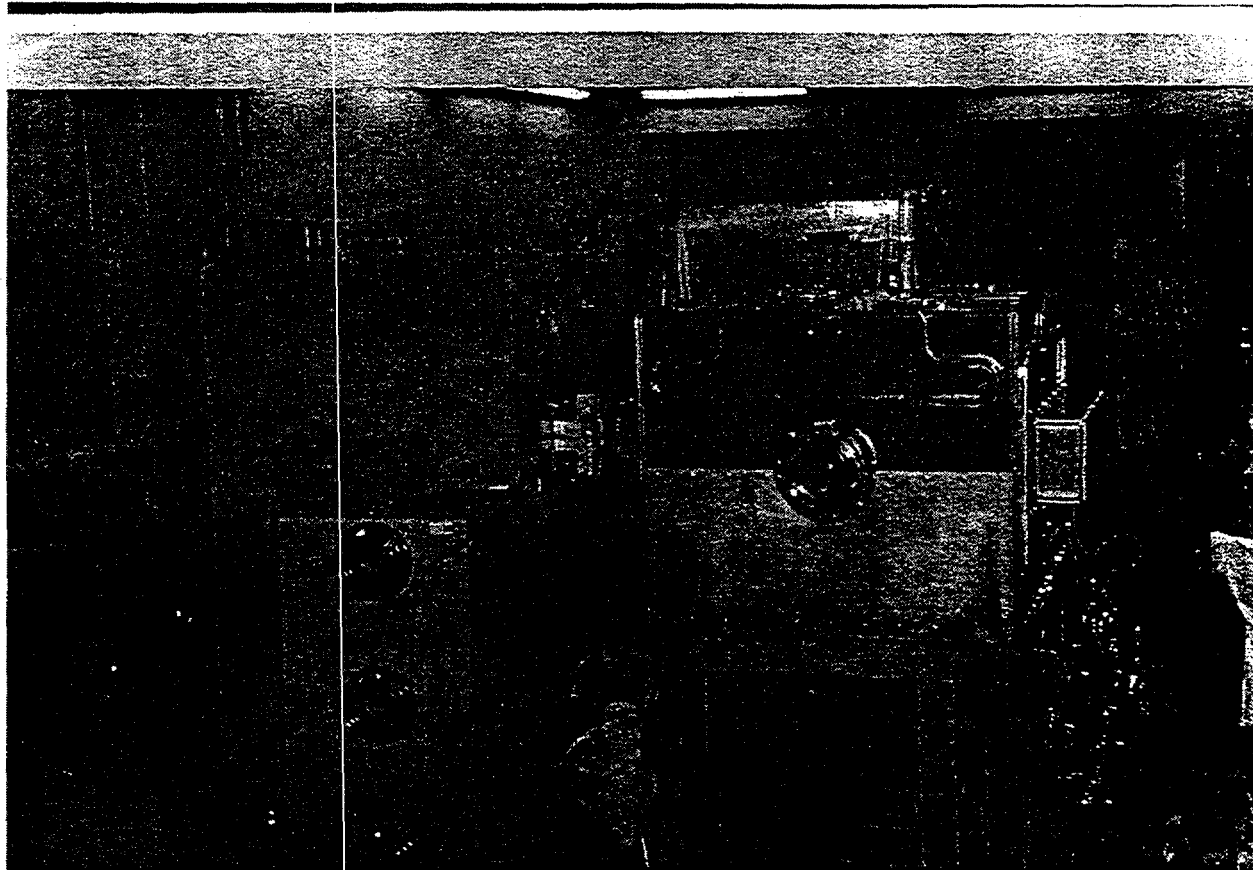


$$Q = \frac{R}{\omega L}$$

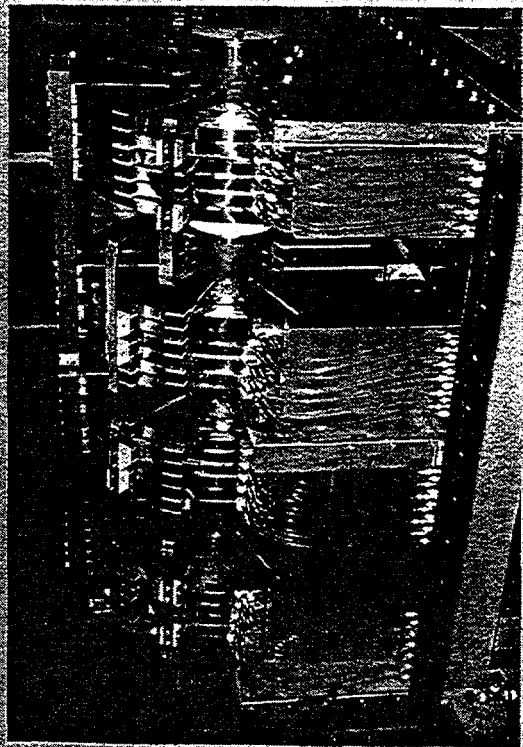
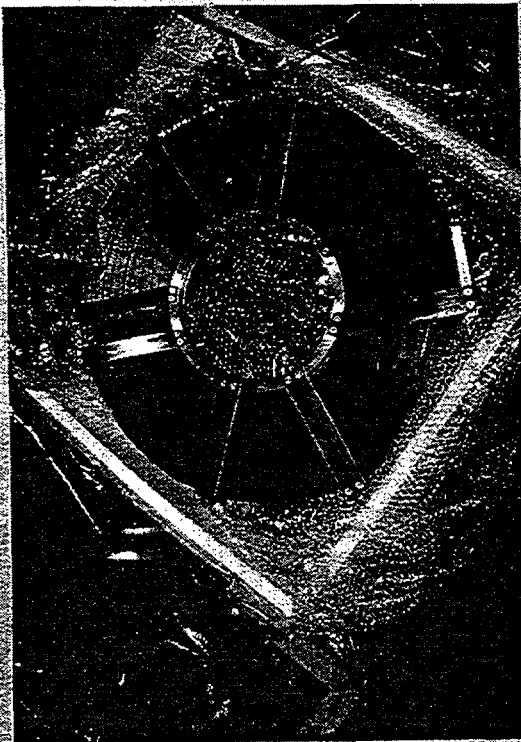
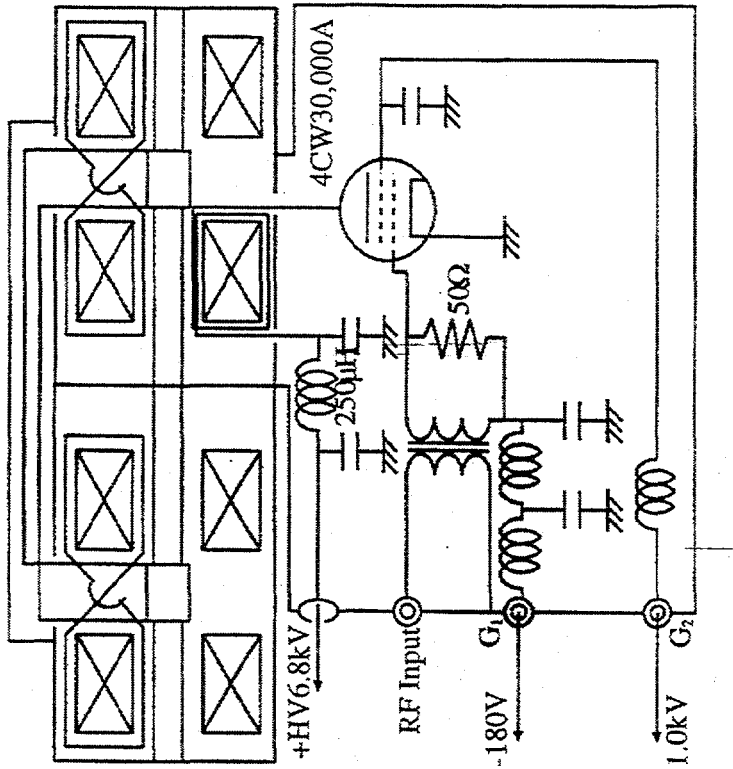
- 1 -

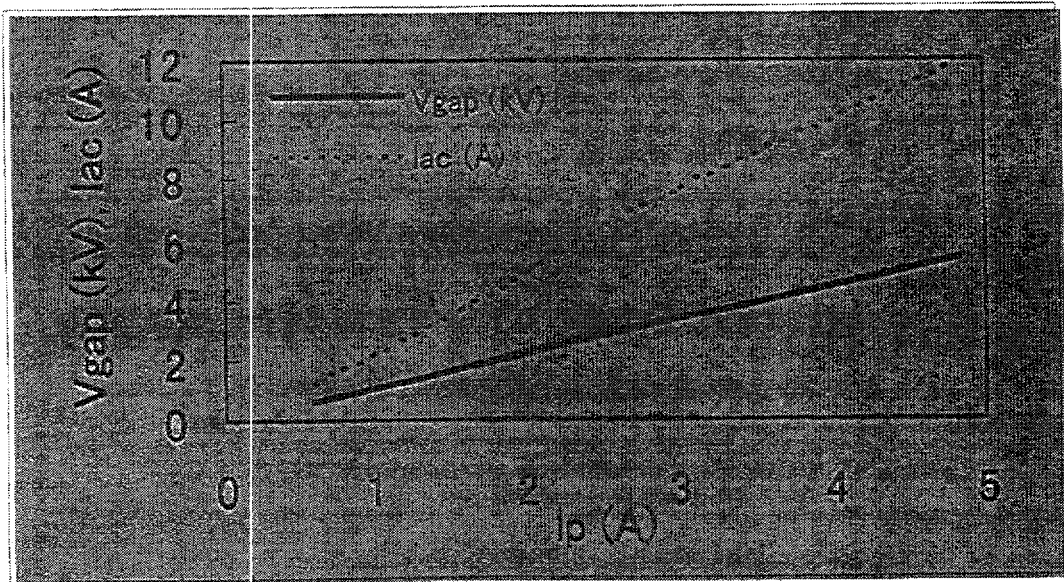
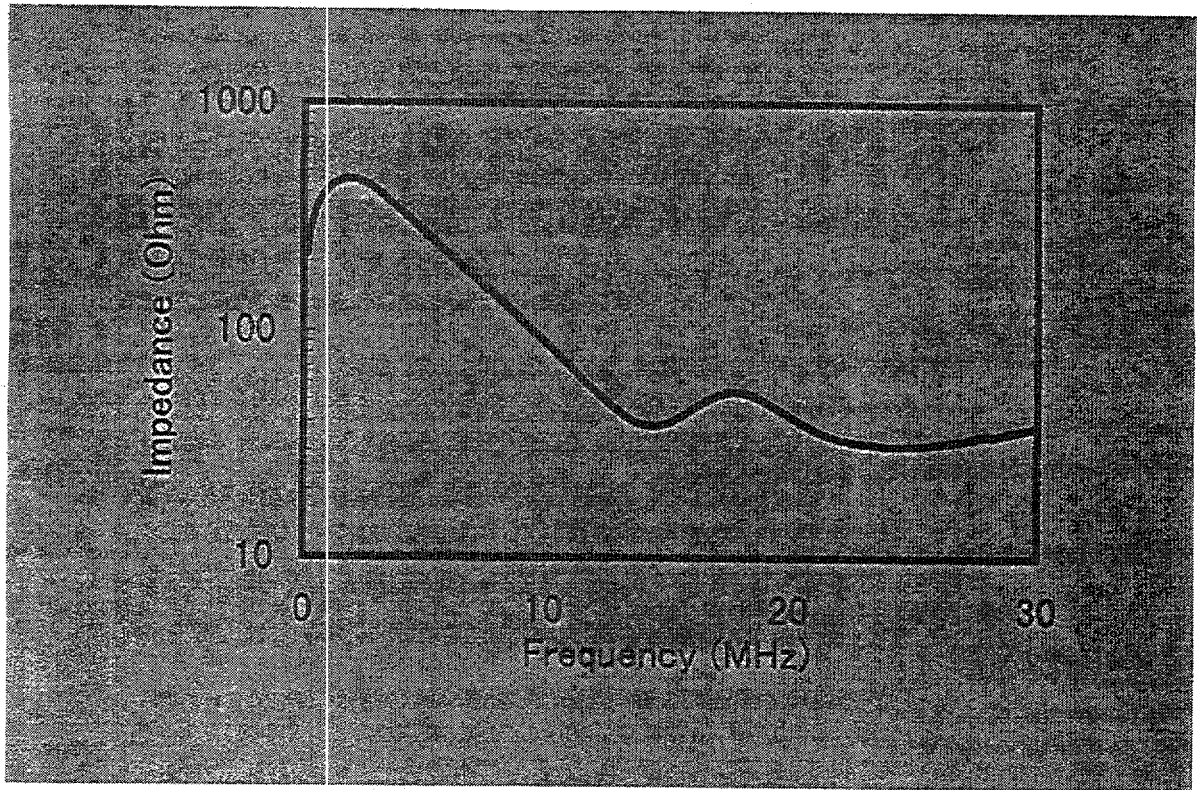
The aim of the 30 kW test cavity is to prove the following:

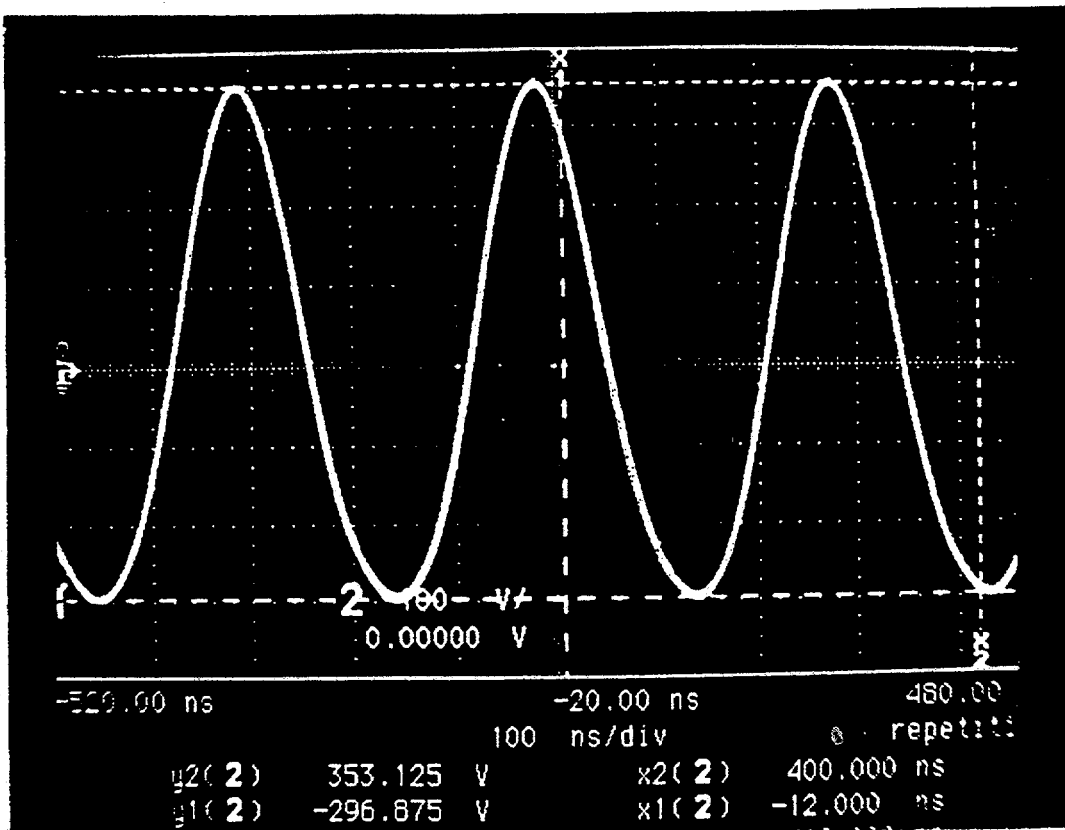
- The required accelerating voltage of 10 kV/m can be obtained.
- The isolated pulse for the barrier bucket can be generated.
- The frequency of the parasitic resonance is very high and/or the quality factor is low enough to avoid the dangerous growths of the instabilities.
- The beam loading and transient beam loading effects are controllable.



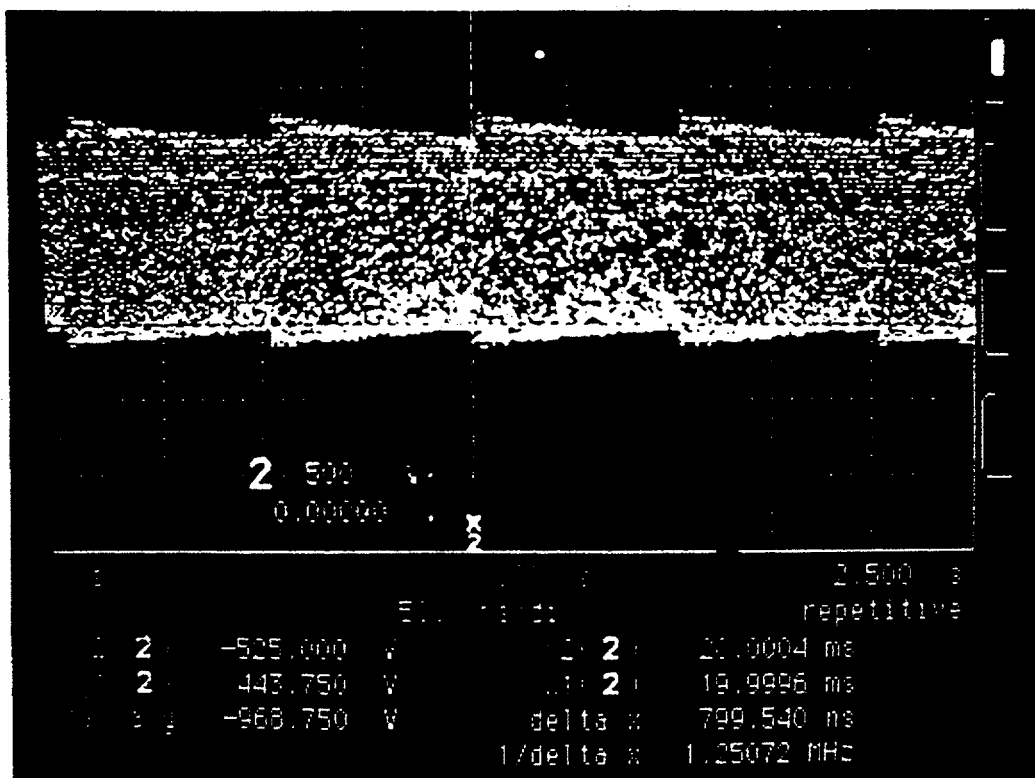
The test cavity and amplifier. Behind the cavity there are a high voltage station and a power



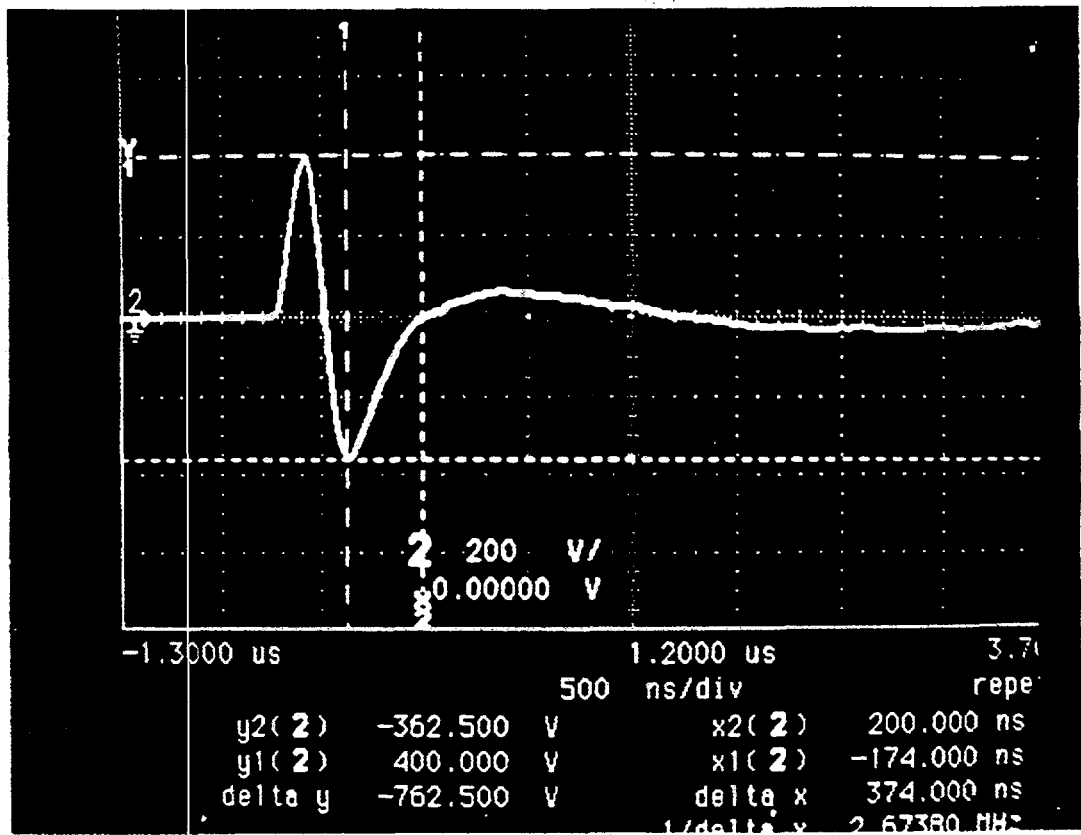




The typical RF voltage signal in the class AB operation.



The RF voltage signal for the frequency sweep of the range of 2 to 3.4 MHz. The repetition is 1 Hz.



The typical voltage signal in the class AB operation for the barrier bucket.

Beam Loading

RF system does not include the tuning loop. → Simpler

for Fundamental Frequency

$Y=1.4$ was chosen for stable operation

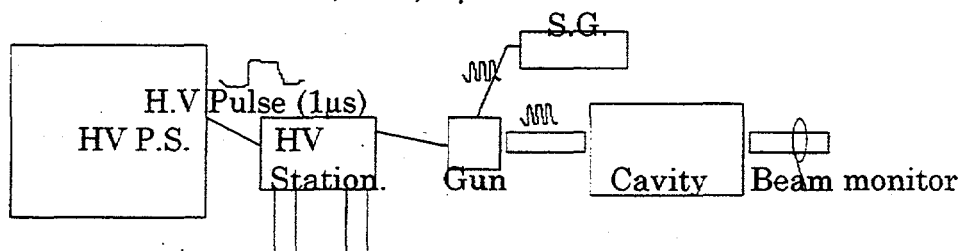
If no tuning system, compensation technique is required.

Ex.: feed-forward

Beam Loading

Electron Gun will be ready in summer.

About 200 keV, 7 A, $1\mu\text{s}$



Aims:

Beam Loading Effects

Fundamental, Higher Order (Distortion of RF Bucket)

Transient Beam Loading

Compensation Techniques.

for 2nd(3rd) harmonics

Component in the beam current is about 30% (for half-sine) of the fundamental component.

Impedance is also about 30% of that at the RF frequency.

Effects are about 10 % of those by RF frequency components.

It may be possible to compensate by feed back and/or feed-forward techniques.

Transient Beam Loading

As Q-value is low, effects excited by other bunches have been damped, automatically.

Because of fast response, compensation is applicable.

CONCLUSIONS

The test cavity using a new material has been developed.

The voltage more than the designed value has been obtained. In order to achieve the higher voltage, a new material is being developed.

The impedance measurement shows that the cavity has no dangerous parasitic resonance.

An isolated pulse for the barrier bucket was generated and the maximum voltage of 11.3 kV was obtained.

However, the distortion of RF voltage was not small because of the class B operation of the single tube. It is expected that the distortion will be improved by the planned modification of the amplifier to a push-pull amplifier.

Session on Longitudinal Emittance Control

R. Garoby

On the issue of emittance control, representatives of Brookhaven and CERN have presented their aims and worries for achieving the level of performance ultimately needed by their respective future high energy machines. One step further in the future, the issue of longitudinal space-charge effects and possible cure in the 3 GeV proton driver for the proposed muon collider was described.

1. For RHIC at Brookhaven the gymnastics taking place in the AGS are the dominant source of longitudinal emittance blow-up (J.M. Brennan). Recent results have been shown, where the final bunch emittance approaches 0.7 eVs/u, for an initial design goal of 0.2 eVs/u. Two directions are pursued for solving the problem: a) improvement of the gymnastics in the AGS. Many of the reported imperfections are attributed to the lay-out and adjustment of the low level RF hardware, and solutions are being designed (J.M. Brennan).

b) increase to 0.5 eVs/u of the nominal emittance accepted by RHIC. A larger emittance is beneficial at injection energy because it reduces intra-beam scattering. The first bottleneck used to be at transition because RHIC ramping rate is limited by the superconducting magnets, and transition is crossed slowly. But thanks to the newly agreed transition jump scheme, bunches of 0.5 eVs/u can now be accelerated with less than 10 for the second bottleneck due to the rebucketing (bunch transfer from a 28 MHz into a 196 MHz bucket), but improvement is possible doing it slightly above transition energy, where acceptance is largest (J. Kewisch).

2. For LHC at CERN most longitudinal beam characteristics are established in the PS. Specifications result from SPS characteristics (RF frequency and single bunch beam stability at injection) and LHC requirements (25 ns bunch spacing and number of protons per bunch), and the overall emittance budget is tight (E. Jensen). The undergoing LHC injectors project is implementing the most economical means to approach the nominal performance. Results will be obtained already in 1998. The hope is that the combination of these improvements with the planned SPS upgrade programme will help achieve the full beam performance needed at injection in LHC. Controlled longitudinal blow-up is a necessary ingredient and future plans include the use of a new method to generate flat-topped bunches corresponding to hollow distribution (S. Hancock). A promising technique for tomography in the longitudinal phase plane is under investigation for monitoring beam characteristics, even in the presence of non-linearities and/or time-varying potential.

3. Space-charge in the proton driver rings of the muon collider dangerously reduces the longitudinal focusing given by RF (K.Y. Ng). Compensation by an inductive impedance is a tempting challenge, which is under investigation. The design presented is based on a 2.4 m ferrite cylinder surrounding the beam with perpendicular bias by a solenoidal field to follow the variation of potential well distortion between 1 and 3 GeV. Tests are planned in the PSR ring at Los Alamos which suffers from similar effects.

Third ICFA Mini-Workshop on High Intensity, High Brightness Hadron Accelerators Brookhaven National Laboratory May 7-9, 1997

S. Hancock CERN

Controlled Longitudinal Blow-ups

As the name suggests, the purpose of a blow-up is to increase the longitudinal emittance of the beam in a reproducible fashion. This reduces the peak beam current and hence the so-called Laslett tune shift, which is important at low energy. It also increases beam stability by increasing the spread of synchrotron frequencies of particles in a bunch.

In the special case of a stationary bucket, the synchrotron frequency, f_s , may be expressed in terms of the complete elliptic integral of the first kind.

```

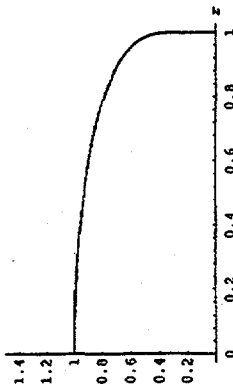
f_ratio(z) := (pi/2) / EllipticK( Sin( phihat (r/2) 1^2 ) )
phihat(z) := AccCos(1 - 2 z^2)

```

```

Plot(
  f_ratio(z),
  (z, 0, 1), PlotRange->(0, 1.5),
  AxesLabel->HapFontForm(9, ["Courier-Bold", 10])z, ["r", "fs/fs0" 11]),
  zs/fs0

```



Here, r is the synchrotron amplitude and varies from 0 at the centre of the bunch to 1 at the bucket separatrix. The addition of a phase-modulated, high-frequency RF modifies f_s depending upon the voltage and frequency ratios and upon the amplitude of the phase modulation. Normalized to the unperturbed small-amplitude synchrotron frequency, the modified value is

```

perturbedf_ratio(z) := f_ratio(z) *
(1 + VRFRatio BesselJ(0, Amod) BesselJ(1, 2 z hratio) / (2 z))

```

for $VRFRatio < 0.3$ and integer $hratio$. The SFTPRO cycle, for example, typically has $VRFRatio = 0kV/45kV$, $hratio = 479/20$, $Amod = \pi$ for BUJ and $VRFRatio = 10kV/105kV$, $hratio = 433/20$, $Amod = \pi$ for BUJ.

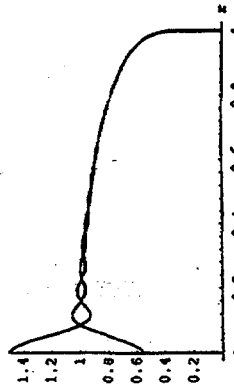
However, whenever the frequency ratio of the two RF systems, the underlying principle of blow-ups is the same: Phase space dilution occurs when particles at a certain amplitude have a synchrotron frequency which is resonant with the frequency of the phase modulation. This results in non-zero drifts for those particles.

Experiments, with both integer and non-integer $hratio$, support the theory. See CERN/PS 92-40 (RF).

```

Plot(
  Evaluate(
    perturbedf_ratio(z) / (VRFRatio->0.1, hratio->22, Amod->(1.6, 3.8))
  ),
  (z, 0, 1), PlotRange->(0, 1.5),
  AxesLabel->HapFontForm(9, ["Courier-Bold", 10])z, ["r", "fs/fs0" 11]),
  zs/fs0

```



MOTIVATION

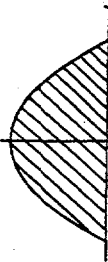
$$(Laslett) \text{ Tune shift, } \Delta Q \propto \frac{1}{B_f}$$

$$\text{Bunching factor, } B_f = \frac{\text{DC beam current}}{\text{Peak beam current}}$$

Can increase B_f

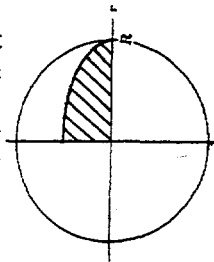
- by employing second-harmonic cavities to modify the bucket, but this
 - "wastes" RF voltage
 - introduces phasing complications
- by modifying the distribution of particles in phase space.

Projected (1-D) Density, $p(r)$



$p(r) =$ Line charge density function

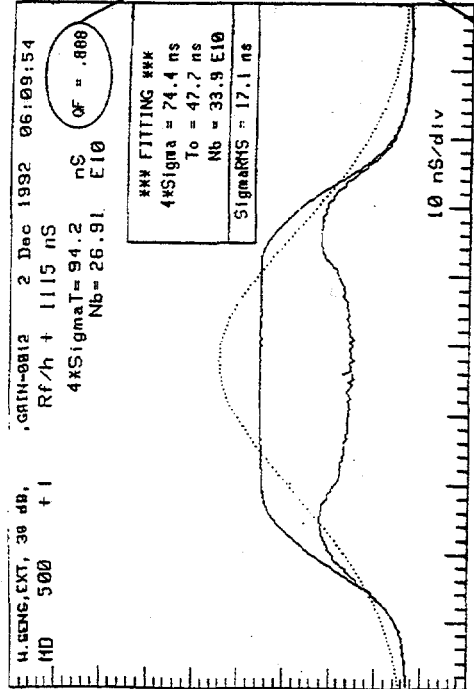
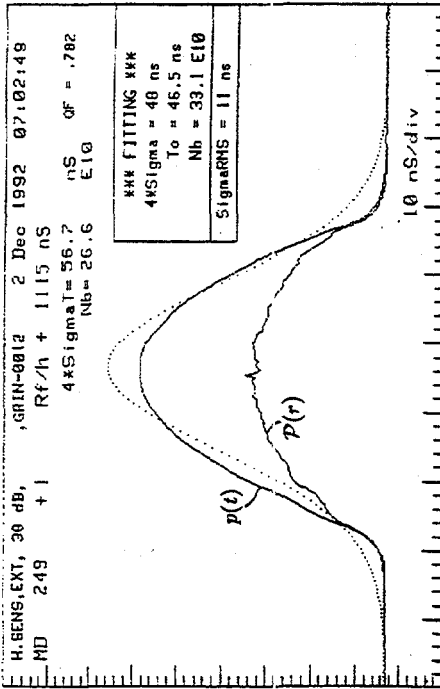
Phase Space (2-D) Density, $P(r)$



$$P(r) = -\frac{1}{\pi} \int_r^R \frac{p(t)}{\sqrt{t^2 - r^2}} dt$$

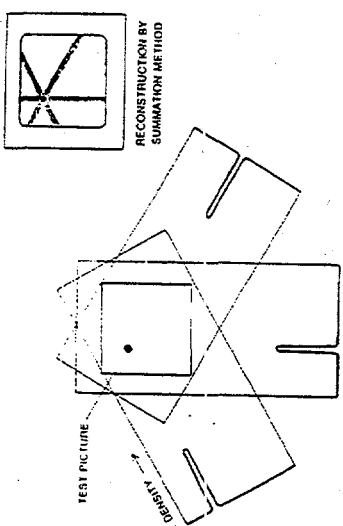
[Keempl, MPS/Int. BR./74-1]

$$p(r) = \text{Rectangular} \Rightarrow P(r) \propto \frac{1}{\sqrt{R^2 - r^2}} \text{ i.e., a "hollow bunch"}$$

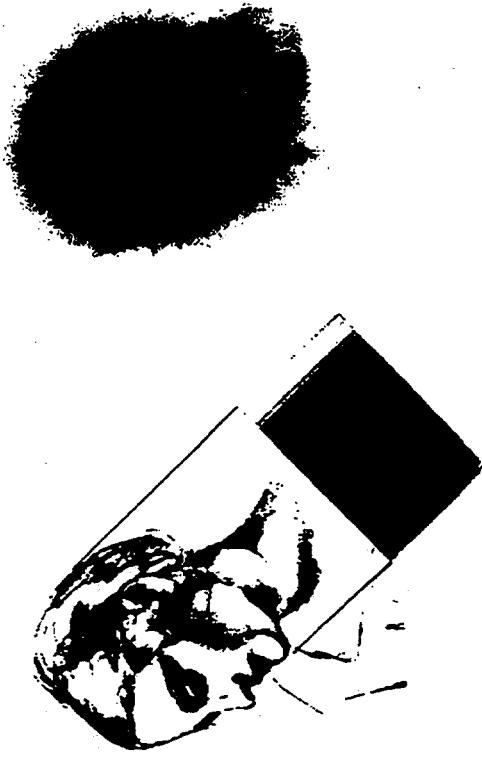


$$Q_f = \frac{\text{Mean (over } \pm \sqrt{3}\sigma_{f, rms}) \text{ line charge density}}{\text{Peak line charge density}}$$

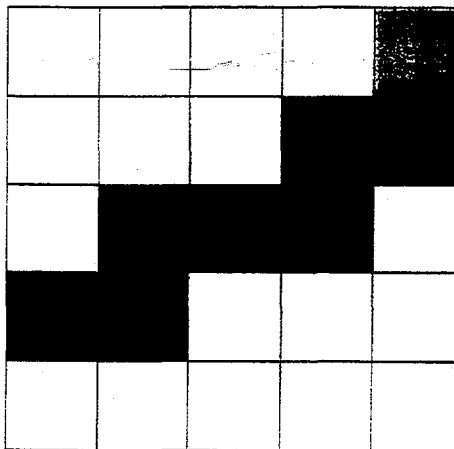
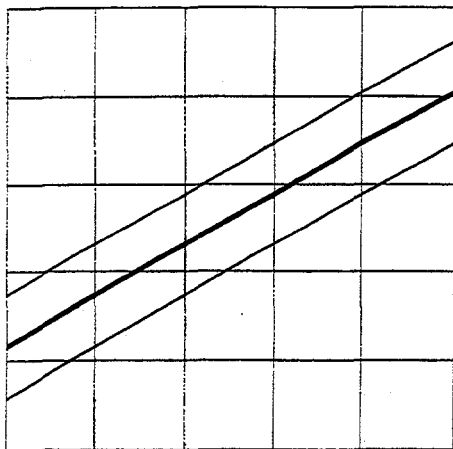
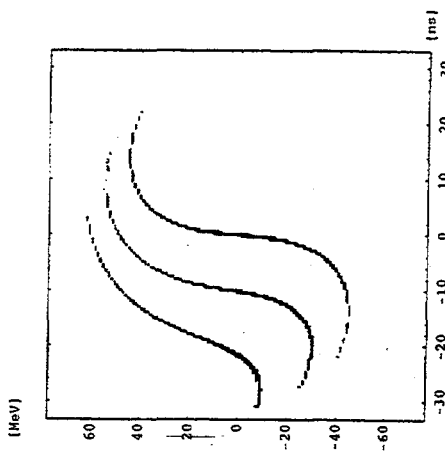
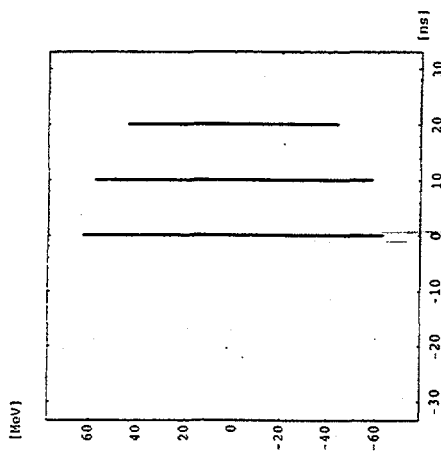
- $p(t) = \text{Rectangular} \Rightarrow Q_f = 100\%$
- $p(t) = \text{Parabolic} \Rightarrow Q_f = 80\%$
- $p(t) = \text{Gaussian} \Rightarrow Q_f = 66\%$

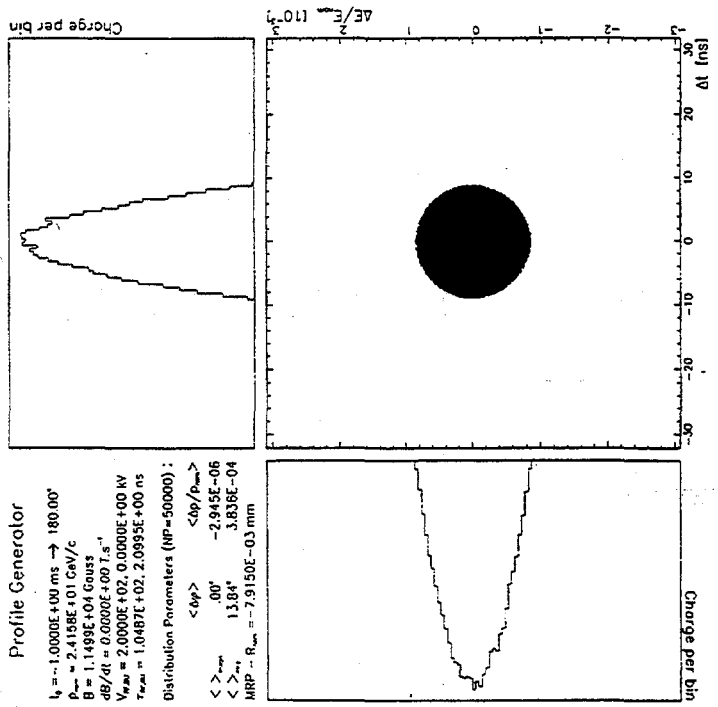
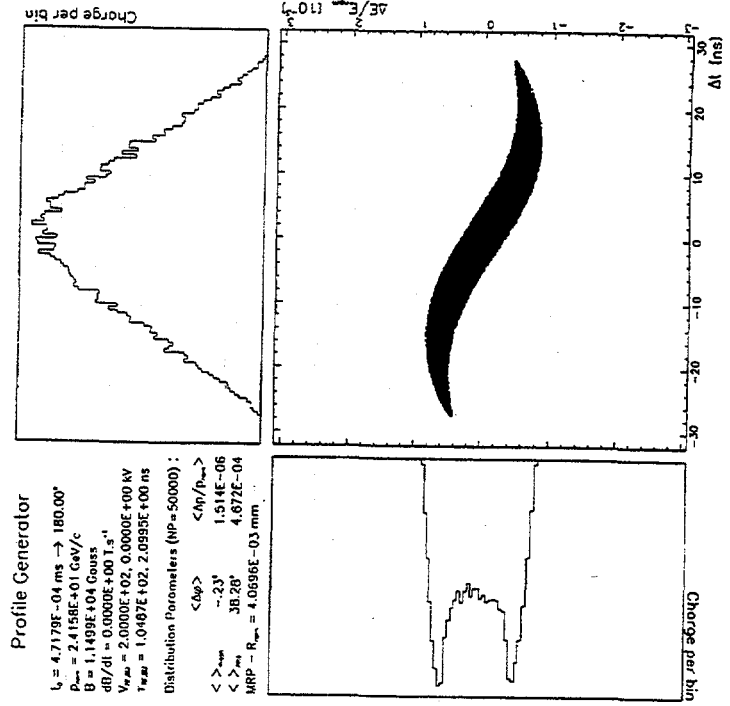


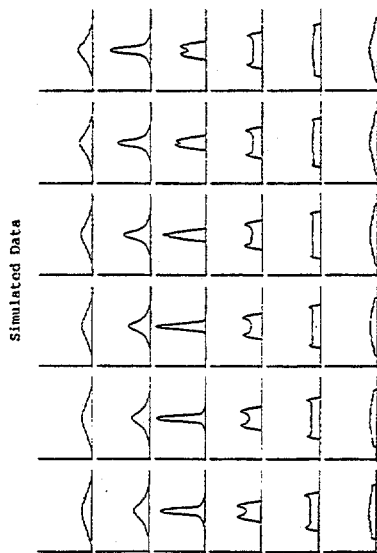
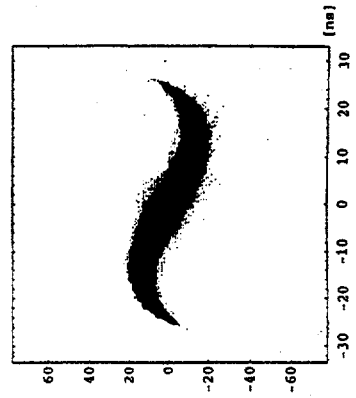
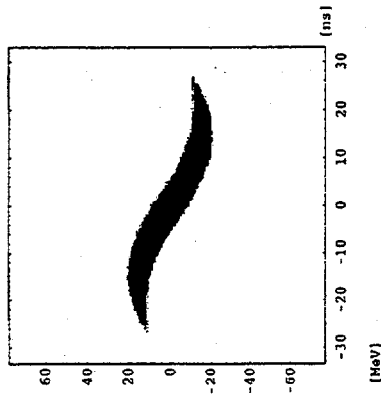
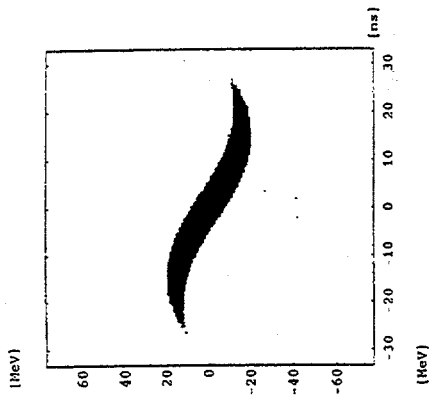
SUMMATION METHOD is a rough technique for reconstructing images from a series of projections. Here three projections are made of a simple two-dimensional test picture containing a single point. Each projection is a one-dimensional distribution of the density, or density, across the test picture as it seen from a specific angle. In the case of this test picture the projection looks the same from all directions. The picture can be reconstructed from the projections: the density of each point on the reconstructed picture is estimated by adding up the densities of all the rays going through that point. The reconstruction of the single point is a "star", or spoke-like image. The star is the "point-spread function" of the reconstruction technique. It approximately demonstrates the nature of summation method.



COMPLEX PICTURE CAN BE RECONSTRUCTED with a separable method of the summation method defined by E. E. Vanakova of the Institute of Crystallography in Moscow. The projections of the picture is made by making a series of film exposures at right angles to the film is exposed to light. The result is a "weak picture," a set of parallel lines whose darkness depends on the total density of the original picture along each line. A series of such projections can be made at various angles. The reconstruction is obtained by superposing the weak pictures photographically. Reconstruction is right away, made with 18 projections spaced at intervals of 10 degrees.







Advantages of the New Algorithm

- Large-amplitude motion is correctly treated.
- The constraint on trigger rate (re-arm deadtime) is relaxed.
- Computational investment in the maps benefits repeated use with different data - as in optimization.
- Replacement of the Runge-Kutta integration by full-blown tracking would permit the reconstruction of:
 - ◊ arbitrarily complex (even no) RF;
 - ◊ non-adiabatic processes;
 - ◊ self fields
 - ◊ particles outside the bucket (but NB normalization).

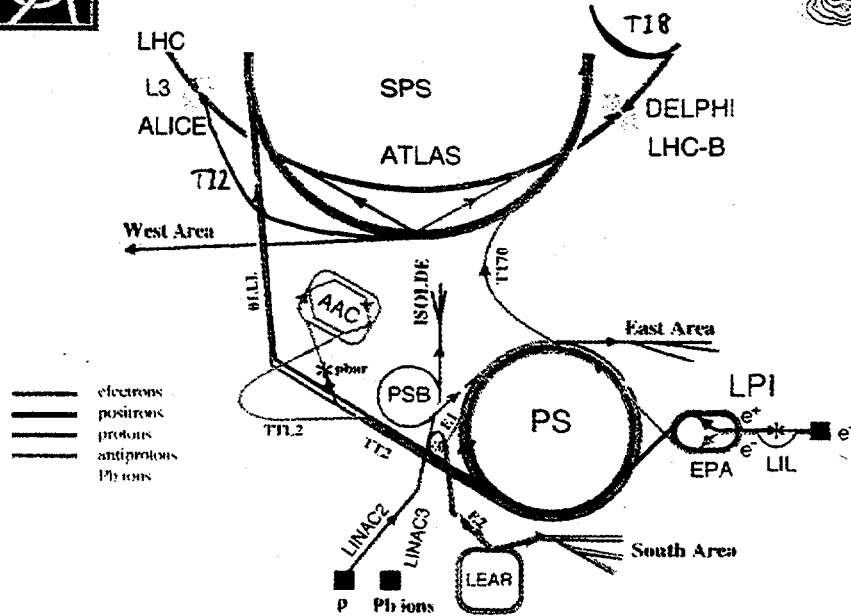
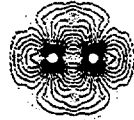
Question Marks

- How fast can it be made to run?
- Minimum number of profiles required.
- "Free" parameters: n, gain.
- Influence of the phase loop.

Ref: CERU 15/RF/Note 97-06



CERN injector complex



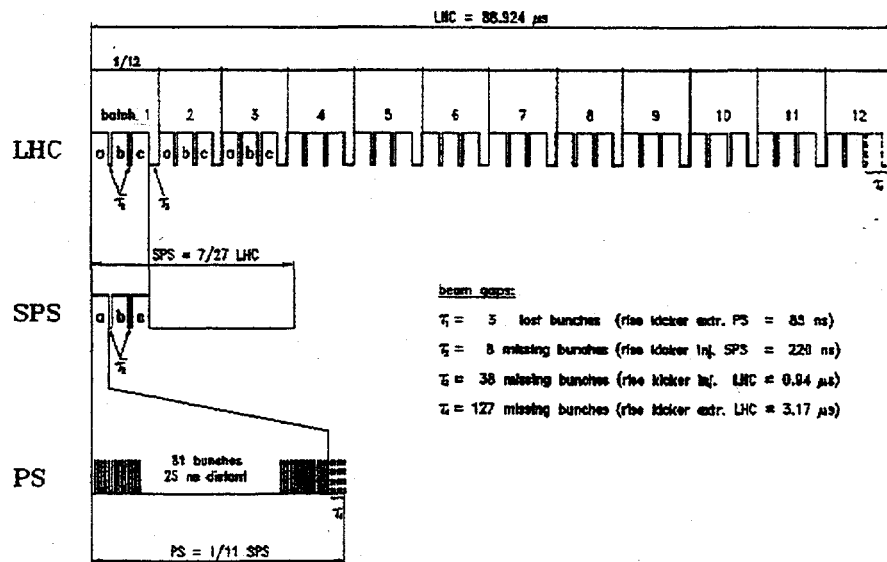
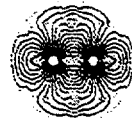
May 7-9, 1997

3rd MINI-WORKSHOP ON HIGH INTENSITY, HIGH BRIGHTNESS HADRON COLLIDERS

Erk JENSEN



LHC filling scheme



May 7-9, 1997

3rd MINI-WORKSHOP ON HIGH INTENSITY, HIGH BRIGHTNESS HADRON COLLIDERS



LHC beam ϵ_{long} "budget"



Machine & process		E_{kin}	p	$\epsilon_{longitudinal}$	h	$\epsilon_{longitudinal}$	bunch length	$\Delta p/p$	RF
		GeV	GeV/c	eVs		[LHC bunch] eVs	ns	10^{-3}	MHz
Linac		0.05	0.31	(0.65)		0.06	(1667)	2	(0.60)
PSB	capture	0.05	0.31	1.20	1	0.11	1600	4.9	0.6
	acc. (+ contr. bu?)	1.40	2.14	1.45	1	0.14	190	2.5	1.75
CPS	injection	1.40	2.14	1.45	8	0.14	190	2.5	3.5
	acceleration	2.74	3.56	1.50	8	0.14	66	4.1	3.69
	b split + contr. bu (200 MHz)	2.74	3.56	1.00	16	0.19	46	4	7.38
	acceleration	25.5	26.4	1.00	16	0.19	24	1	7.6
	adiabatic debunching	25.5	26.4	(0.25)	84	0.25	(25)	0.2	40
	adiabatic rebunching	25.5	26.4	0.36	84	0.36	12	0.7	40
	bunch rotation	25.5	26.4	0.36	84	0.36	4	2.2	40
SPS	filamentation on inj. plateau	25.5	26.4	0.52	4620	0.52	4.3	3	200
	acc. + contr. bu (800 MHz)	450	451	1	4620	1	2.5	0.6	200
	bunch compression	450	451	1	9240	1	1.7	0.8	400
LHC	injection	450	451	1	35640	1	1.7	0.9	400
	acceleration (+ contr. bu ?)	7000	7001	2.5	35640	2.5	1	0.2	400

¹: Phase space area attributed to one LHC bunch, or (total CPS longitudinal emittance)/84 or (PSB bunch emittance)/10.5.

²: Bunch half height. For upright elliptical bunch, $\epsilon_{longitudinal} = \Delta W \cdot (\text{bunch length}) \cdot \pi/2$

$\Delta p/p = \gamma / (\gamma^2 - 1) \Delta W / (m_0 c^2)$

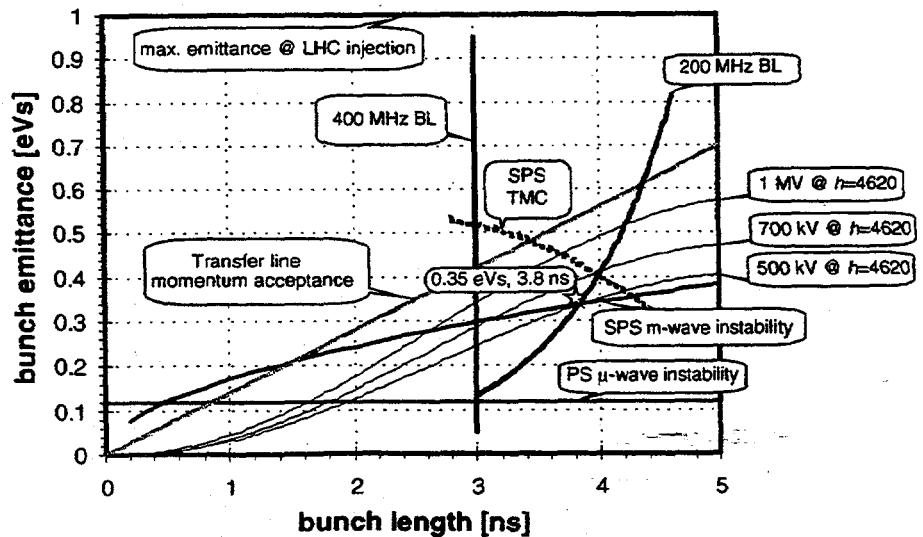
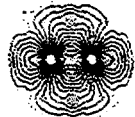
May 7-5, 1997

3rd MINI-WORKSHOP ON HIGH INTENSITY, HIGH BRIGHTNESS HADRON COLLIDERS



bunch parameter limitations

10^{11} protons/bunch

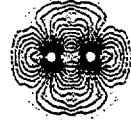


May 7-9, 1997

3rd MINI-WORKSHOP ON HIGH INTENSITY, HIGH BRIGHTNESS HADRON COLLIDERS



the most stringent bunch parameter limitations



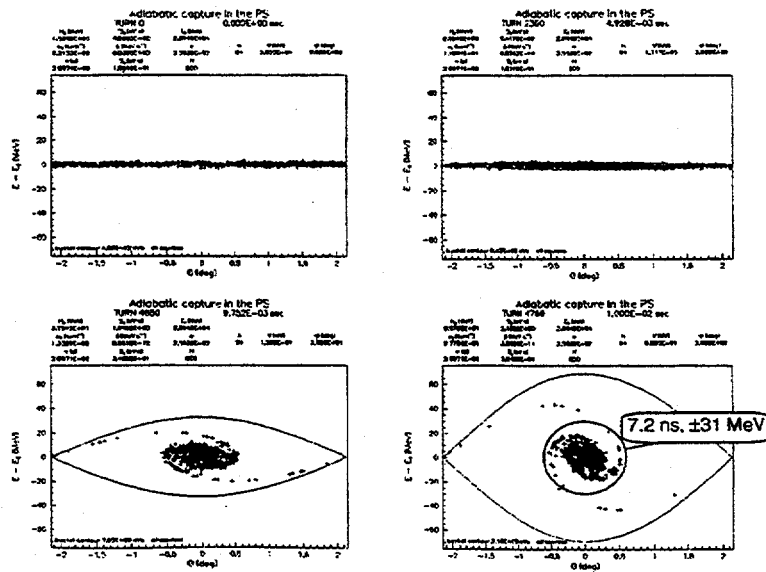
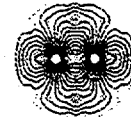
- ◆ **SPS microwave instability**
 "Keil-Schnell-Boussard", $|Z/n| = 10 \Omega$ assumed. $\epsilon_{l,max} \propto \sqrt{\frac{|Z|}{n}} \cdot N \cdot \frac{l_{bunch}}{|\eta|}$
 $\gamma: 23 \rightarrow 19$ (decreases also capture voltage)?
- ◆ **TMC (transverse mode coupling)**
 $Z_t = 23 \text{ M}\Omega/\text{m}$, $Q=1$ @ 1.3 GHz assumed
- ◆ **200 MHz periodic transient beam loading (BL)**
 $Z_{cav} = 360 \text{ k}\Omega$ assumed
- ◆ **400 MHz BL**
 300 kW installed power assumed
- ◆ **Transfer line momentum acceptance**
 $6 \cdot 10^{-3}$ total assumed

May 7-9, 1997

1st MINI-WORKSHOP ON HIGH INTENSITY, HIGH BRIGHTNESS HADRON COLLIDERS



Quasi-adiabatic compression on $h=84$ to 600 kV (!)



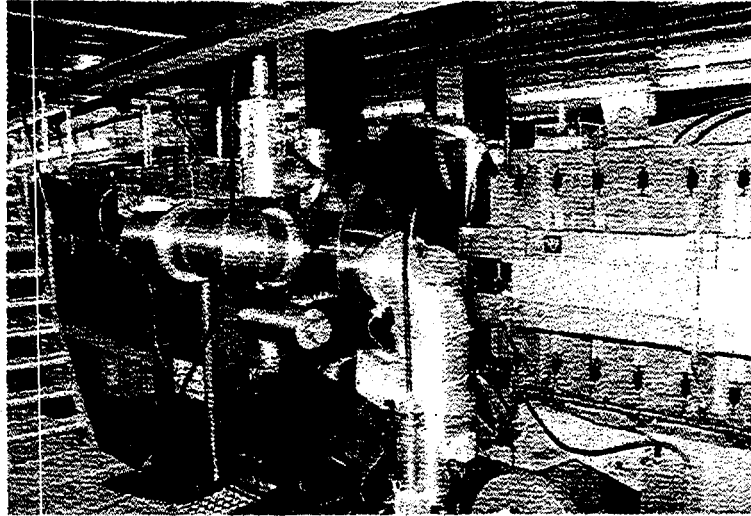
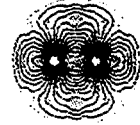
May 7-9, 1997

3rd MINI-WORKSHOP ON HIGH INTENSITY, HIGH BRIGHTNESS HADRON COLLIDERS

Animation: http://nicewww.cern.ch/~jeusene/www/htn_40/Bunching.htm



40 MHz cavity

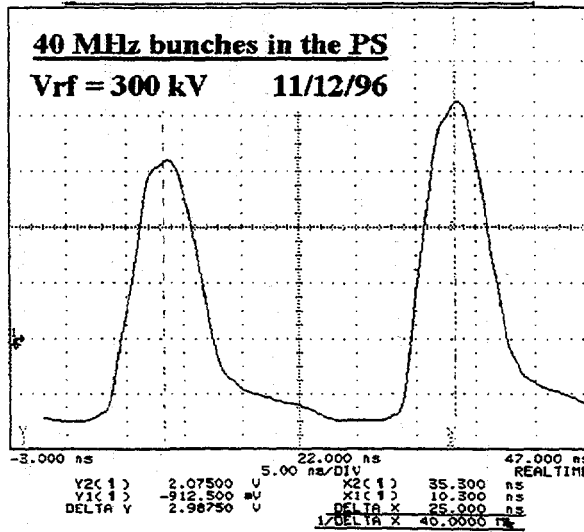
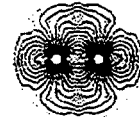


May 7-9, 1997

4d MINI-WORKSHOP ON HIGH INTENSITY, HIGH BRIGHTNESS HADRON COLLIDERS



First 40 MHz bunches

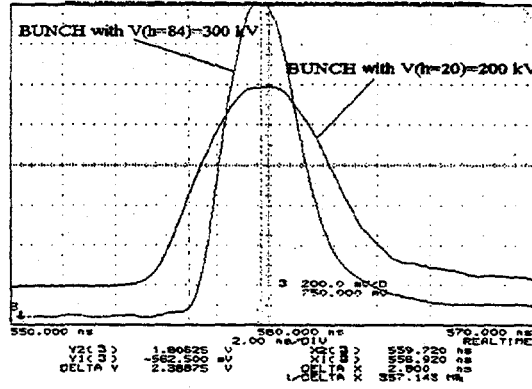
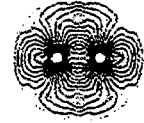


May 7-9, 1997

4d MINI-WORKSHOP ON HIGH INTENSITY, HIGH BRIGHTNESS HADRON COLLIDERS



Bunch rotation test

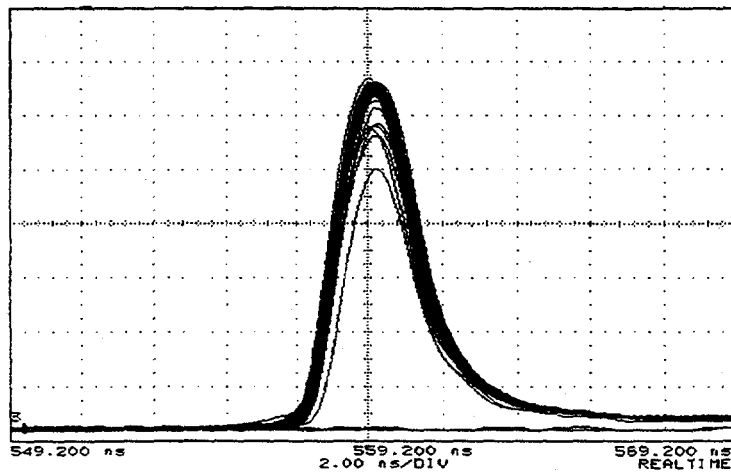
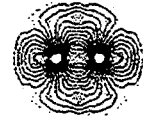


May 7-9, 1997

MINI-WORKSHOP ON HIGH INTENSITY, HIGH BRIGHTNESS HADRON COLLIDERS



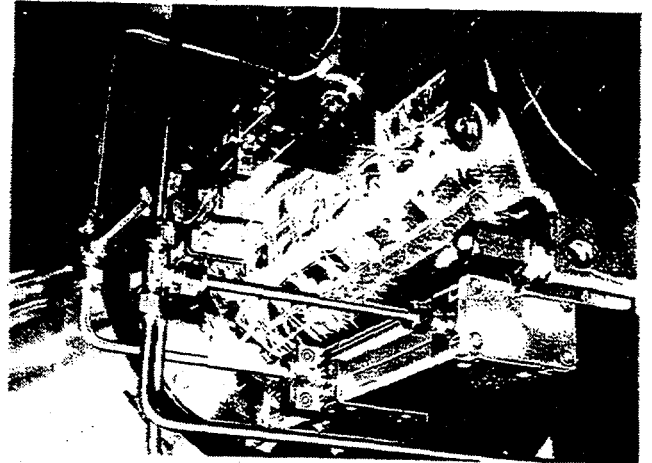
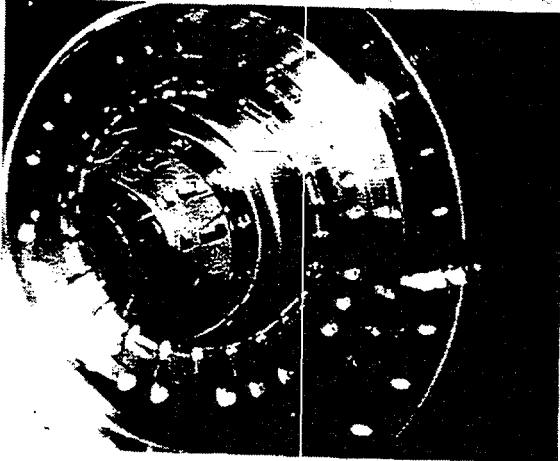
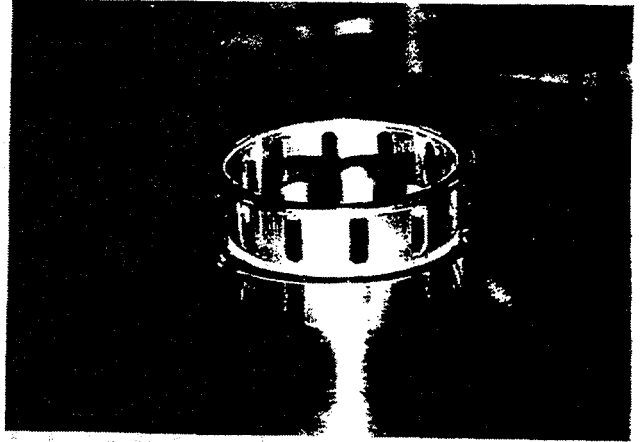
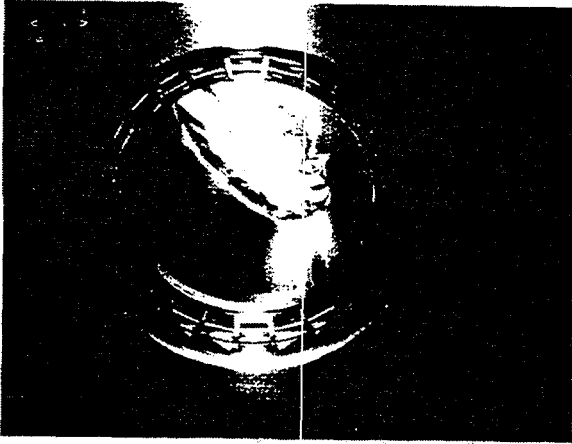
Synchronisation jitter

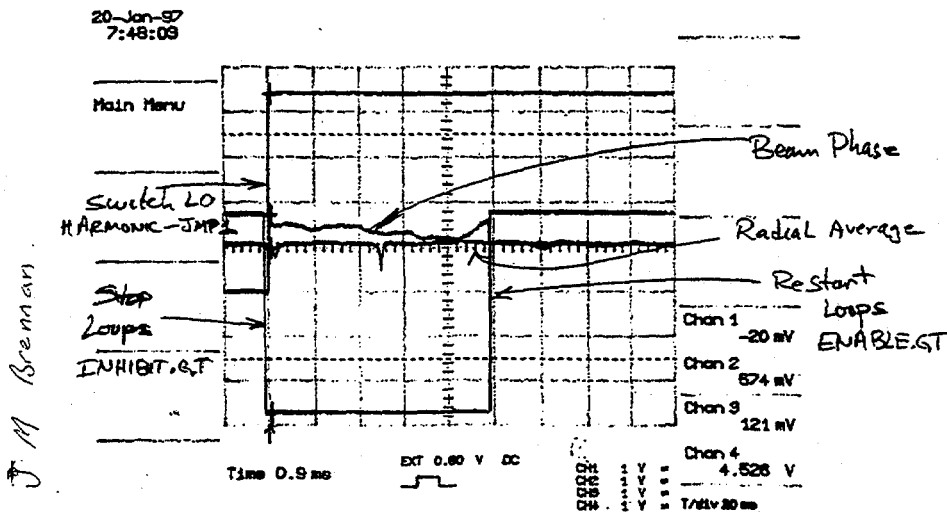
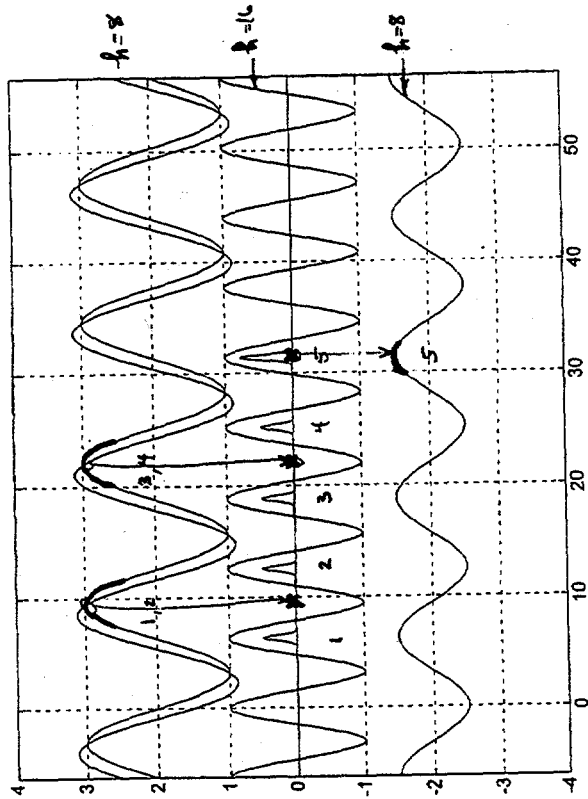


SYNCHRONISATION JITTER ON COMPRESSED BUNCH
(Ad. capture up to 60 kV & Step to 300kV . - 4/4/97)

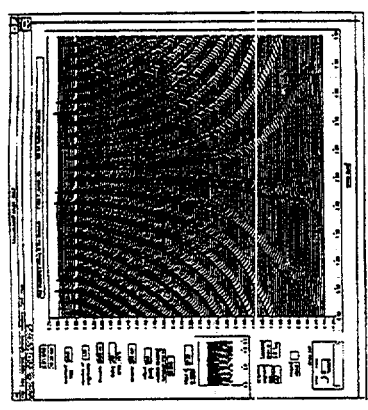
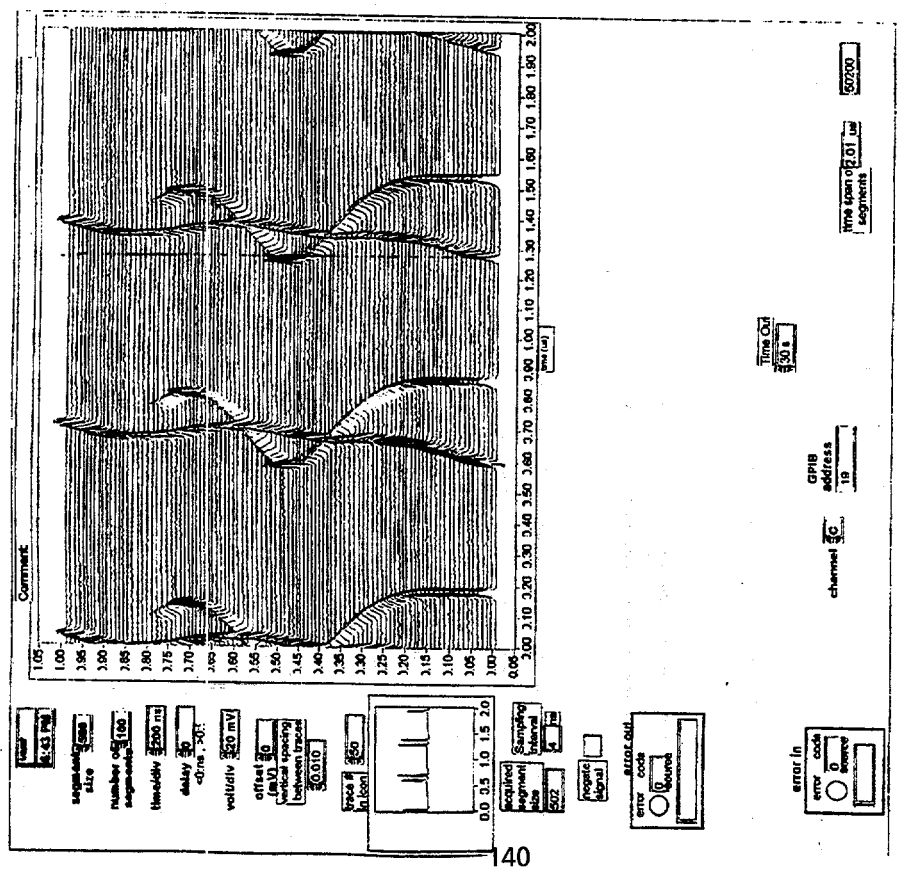
May 7-9, 1997

MINI-WORKSHOP ON HIGH INTENSITY, HIGH BRIGHTNESS HADRON COLLIDERS

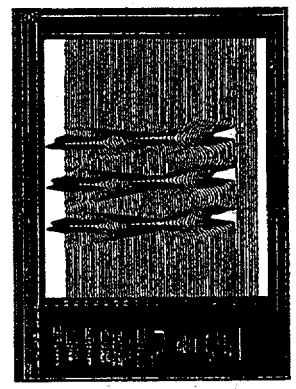




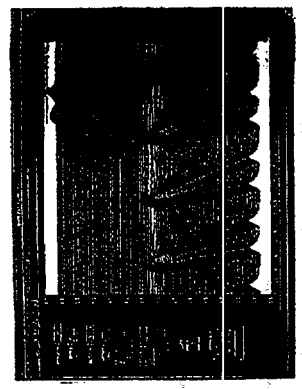
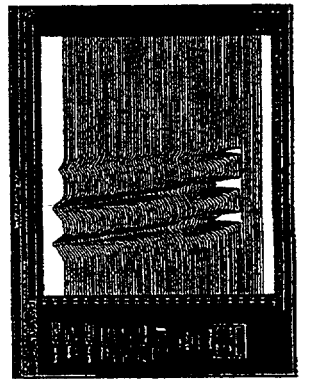
MRange_ch3
Last modified on 1/9/97 at 6:43 PM



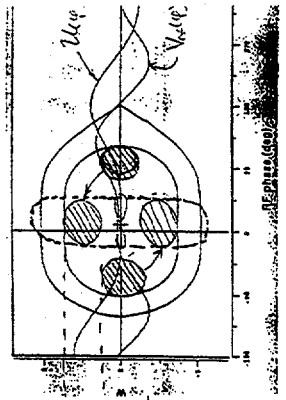
Booster Cycle



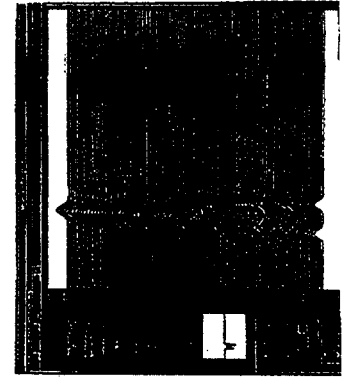
In AGS, after
+32 → +77 stripping



$h = 8 \rightarrow 4 \rightarrow \Delta T \approx 100 \mu s$

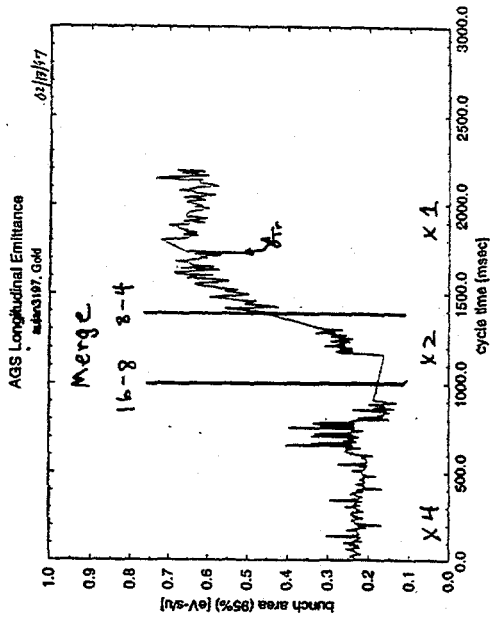
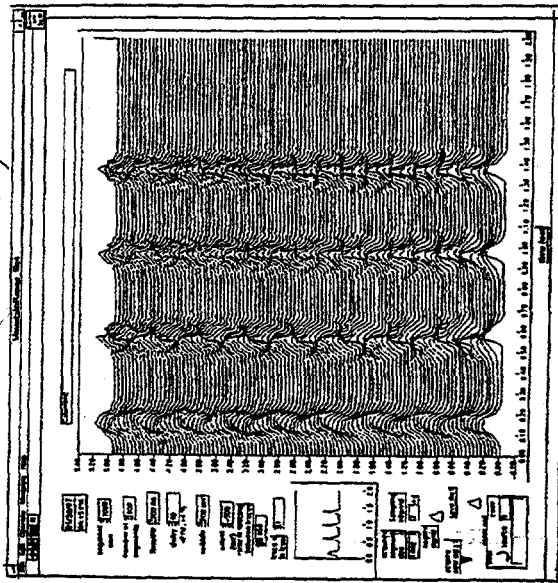


Merge in Double rf

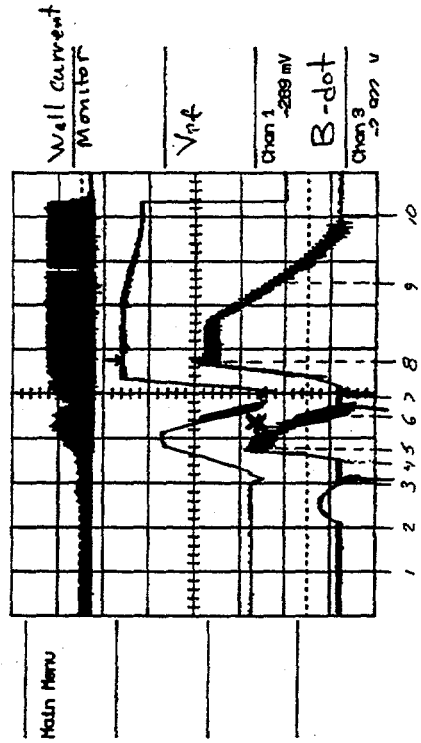


Mismatch at AGS Injection

- Momentum Error
- Bucket shape mismatch, need more V_{rf} for ΔE
- New batch perturbs old batch via phase loop
- *Batch-by-batch phase loop, bunch shape changer*



1-Feb-97
15:20:06



* $\delta \left(\frac{B}{V_{rf}} \right)$ is large + fast!

Space-Charge Effects and Ferrite Compensation

K.Y. Ng and Z. Qian

(May 7, 1997)

- I INTRODUCTION
- II TRANSVERSE TUNE SPREADS
- III MICROWAVE INSTABILITIES
- IV POTENTIAL-WELL DISTORTION
- V FERRITE COMPENSATION
- VI FERRITE-LOADED WAVEGUIDE
- VII HIGH TRANSVERSE DC BIAS
- VIII CONCLUSIONS

I INTRODUCTION

- C. Ankenbrandt suggested 2 rings for the proton driver.
- We concentrate on the first ring where space-charge is more important.

Kinetic Energy	1 GeV injection, $\gamma = 2.06579$, $\beta = 0.87503$
	3 GeV extraction
Cycle rate	15 Hz
Circumference, C	237.10 m $f_0 = 1.106$ MHz
Rf harmonic, h	2 or 4 for 2 or 4 bunches
Transition, γ_t	7
Bunching factor, B	0.25
No. per bunch, N_B	2.53×10^{13} $I_{AV} = 4.48$ amp/bunch
95% bunch area, A	1 eV-s
95% emittance, ϵ_{N95}	$200 \times 10^{-6} \pi$ m

II TRANSVERSE TUNE SPREADS

- Laslett tune shift at injection

$$\Delta\nu = -\frac{3N_{\text{total}}r_p}{2\gamma^2\beta\epsilon_{N95}B} = \begin{cases} -0.199 & \text{2 bunches, good} \\ -0.397 & \text{4 bunches, manageable} \end{cases}$$

This is an incoherent effect and cannot be compensated by ferrite.

III MICROWAVE INSTABILITIES

- For parabolic bunch,

$$B = 0.25 \implies \begin{cases} \hat{\tau} = 84.73 \text{ ns or } \hat{\ell} = 22.23 \text{ m} & \text{for } h = 2 & \overset{\hat{\delta}}{\downarrow} 5.49 \times 10^{-7} \\ \hat{\tau} = 42.37 \text{ ns or } \hat{\ell} = 11.12 \text{ m} & \text{for } h = 4 & 1.098 \times 10^{-7} \end{cases}$$

- Using Krinsky-Wang criterion and a bunch area of 1 eV-s,

$$\left| \frac{Z_{\parallel}}{n} \right| < \frac{2\pi E |\eta|}{e\beta^2 I_p} \left(\frac{\sigma_E}{E} \right)^2 = \begin{cases} 71.27 \Omega & \text{for } h = 2 \\ 142.5 \Omega & \text{for } h = 4 \end{cases}$$

Note: If the Boussard-modified Keil-Schnell criterion is used, these limits will be 1.67 times larger.

- Space-charge impedance:

With $\epsilon_{N95} = 2 \times 10^{-4} \pi$ m, bunch area 1 eV-s, and assuming a momentum dispersion of ~ 2 m, $\langle \beta \rangle = 7.28$ m

beam radius is $a = 3.35$ cm and 3.85 cm for $h = 2$ and 4 .

Using a 5 cm radius beam pipe,

$$\left. \frac{Z_{\parallel}}{n} \right|_{\text{spch}} = i \frac{Z_0}{2\gamma^2\beta} \left(1 + 2 \ln \frac{b}{a} \right) = \begin{cases} i91.1 \Omega & \text{for } h = 2 \\ i76.8 \Omega & \text{for } h = 4 \end{cases}$$

Note: Same size as the stability limit. However, we are below transition, hopefully, microwave instability will not develop.

- Assume pipe radius of 5 cm. Cutoff freq is 2.30 GHz, or harmonic

$$n_{\text{cutoff}} = 2074. \text{ Tunes: } \nu_x = \nu_y = 5.18.$$

$$|Z_{\perp}| < F \frac{4\nu\beta}{eRI_{\text{peak}}} (\Delta E)_{\text{FWHM}} |(n - \nu)\eta + \nu\xi| = 31.56 \text{ M}\Omega/\text{m}$$

- With $b = 5$ cm, $a = 3.35, 3.85$ cm for $h = 2, 4$,

$$Z_{\perp}|_{\text{spch}} = i \frac{RZ_0}{\beta^2\gamma^2} \left(\frac{1}{a^2} - \frac{1}{b^2} \right) = \begin{cases} i2.21 \text{ M}\Omega/\text{m} & h = 2 \\ i1.23 \text{ M}\Omega/\text{m} & h = 4. \end{cases}$$

Therefore transverse microwave instability will not happen.

IV POTENTIAL-WELL DISTORTION

- A particle at distance s from bunch center sees a longitudinal space-charge $E_{z\text{ sp ch}}$ field and a potential drop per turn:

$$E_{z\text{ sp ch}} = -\frac{eg_0}{4\pi\epsilon_0\gamma^2} \frac{d\lambda}{ds}, \quad g_0 = 1 + 2\ln\frac{b}{a}$$

$$V_{\text{sp ch}} = E_{z\text{ sp ch}} C = -\left(\frac{3\pi I_{av} Z_0 g_0}{4\gamma^2 \beta}\right) \left(\frac{R}{\hat{\ell}}\right)^2 \frac{s}{\hat{\ell}} = \begin{cases} 11.1 \frac{s}{\hat{\ell}} \text{ kV} & \text{for } h = 2 \\ 37.4 \frac{s}{\hat{\ell}} \text{ kV} & \text{for } h = 4 \end{cases}$$

- On the other hand, neglecting space charge, the synchrotron tune and required rf are

$$\nu_s = \frac{|\eta| \hat{\delta}}{\omega_0 \hat{\tau}} = \begin{cases} 0.000919 \\ 0.003677 \end{cases} \quad V_{\text{rf}} \cos \phi_0 = \frac{2\pi \beta^2 E}{|\eta| h} \nu_s^2 = \begin{cases} 18.41 \text{ kV} & \text{for } h = 2 \\ 147.3 \text{ kV} & \text{for } h = 4 \end{cases}$$

- For $\phi_0 = 0$, rf voltage seen by end particle of bunch is

$$V = V_{\text{rf}} \sin \frac{h\omega_0 \hat{\ell}}{\beta c} = V_{\text{rf}} \sin \frac{3\pi B}{2} = 0.924 V_{\text{rf}}$$

- The potential-well distortion is large compared with rf voltage required if there is no space-charge, especially for $h = 2$.
- We wish to compensate this distortion by ferrite. The frequency is roughly is at ~ 2.2 MHz and ~ 4.4 MHz for $h = 2$ and 4.

$$t_0 \frac{7}{2} \times 2.2 = 7.7 \text{ MHz} \quad 146 \quad t_0 \frac{14}{4} \times 4.4 \text{ MHz} = 15 \text{ MHz}$$

V FERRITE COMPENSATION

- The voltage drop per turn due to space charge can be written as

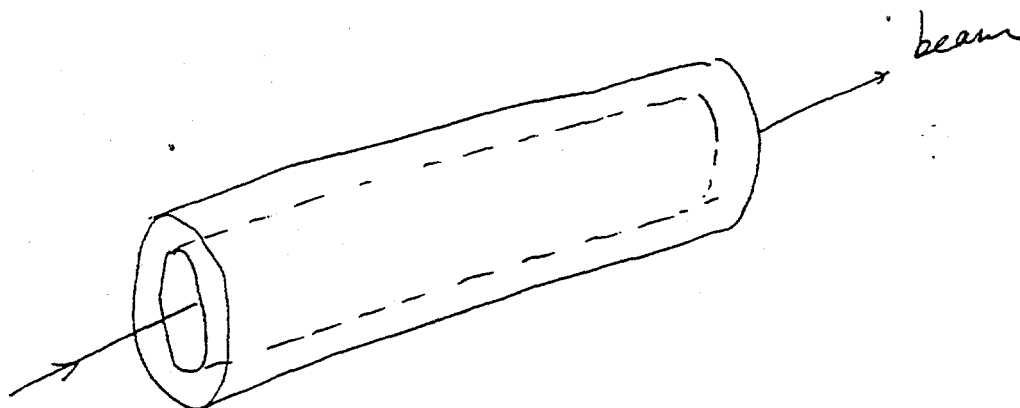
$$V_{\text{sp ch}} = \left(i \frac{3\pi I_{\text{av}}}{2} \right) \frac{Z_{\parallel}}{n} \Big|_{\text{sp ch}} \left(\frac{R}{\hat{\ell}} \right)^2 \frac{s}{\hat{\ell}}$$

Thus, it can be canceled by adding an inductance.

- Consider using a hollow cylinder of ferrite of inner and outer radii b and d and length ℓ . Impedance introduced is

$$\frac{Z_{\parallel}}{n} \Big|_{\text{ferrite}} = -i \frac{Z_0 \omega_0}{2\pi c} \mu' \ell \ln \frac{d}{b}$$

For example, with $\mu' = 1000$, $d = 5.5$ cm, $b = 5$ cm, to cancel a space-charge Z/n of $\sim 100 \Omega$, a length of $\ell = 63$ cm will be enough.



V.1 Loss

- One way to include loss is to write

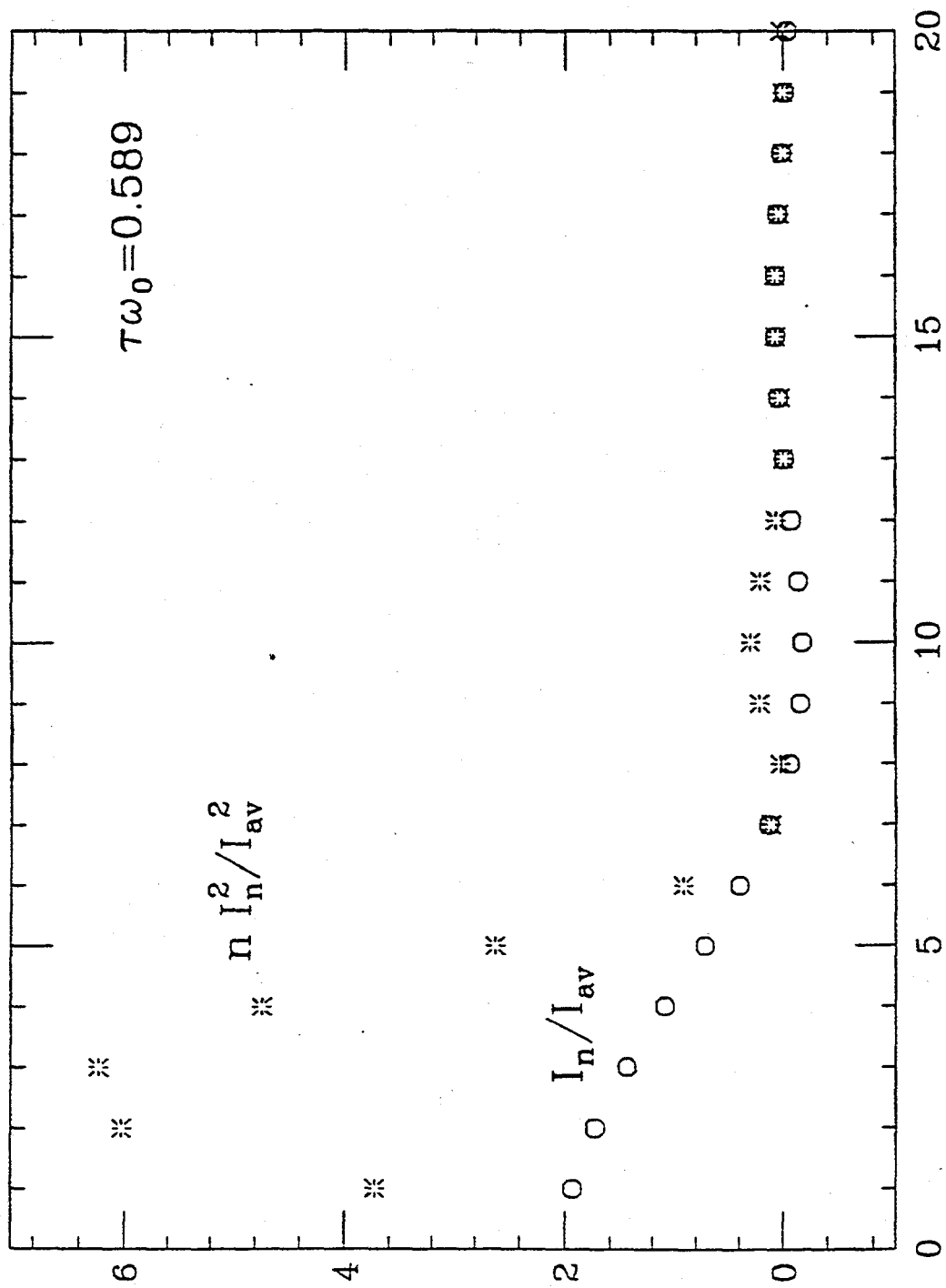
$$\mu = \mu' + i\mu'' \quad \text{and} \quad Q = \frac{\mu'}{\mu''}$$

$$Z_{\parallel} = \left(\frac{1}{Q} - i \right) |Z_{\parallel}|_{\text{spch}}$$

- We want material with large μ' . However, μ'' will be large as well. *usually*
- Since the real part is proportional to frequency, we need to sum many harmonics to compute the total loss. For *each* bunch,

$$\text{Current : } I(t) = I_{\text{av}} + \sum_{n=1}^{\infty} I_n \cos n\omega_0 t$$

$$\text{Power : } P = \frac{1}{2} \sum_{n=1}^{\infty} n I_n^2 \frac{|Z_{\parallel}/n|_{\text{spch}}}{Q}$$



Revolution Harmonics n

- If we assume Gaussian distribution, the summation can be approximated by integration to give, $\hat{\tau} = \sqrt{5}\sigma_{\tau}$,

$$P = \frac{I_{av}^2 |Z_{||}/n|_{spch}}{Q(\sigma_{\tau}\omega_0)^2}.$$

For $h = 2$, $|Z_{||}/n|_{spch} = 100 \Omega$, and $Q = 1$, the power loss is $P = 25.6 \text{ kw}$, parabolic, (29.2 kw by above formula).

Need to sum up to at least $n \sim 4/(\sigma_{\tau}\omega_0) = 7$ for $h = 2$.

For $h = 4$, need to sum to at least $n = 14$, and loss per bunch is 102.2 kw, 4 times larger.

Average

- Loss per particle per turn is 6.5 kV.

Worst of all, because of the short wake (small Q), center of bunch loses much more than the ends.

Such position-dependent loss is hard to compensate.

- There are other problems like (1) high frequency response of ferrite, (2) effect of electric permittivity ϵ , (3) transverse effects.
- If loss is small (see below), the problem can be solved analytically.

VI FERRITE-LOADED WAVEGUIDE

- Here, the assumptions are (a) a perfectly conducting medium outside ferrite and (b) the ferrite insertion is infinitely long.
- The boundary-value problem has been solved in Phys. Rev. **D42**, 1819 (1990).
- The transverse and longitudinal wakes of the m -th azimuthal is

$$W_m(z) = \frac{Z_0 c l}{2\pi m d^{2m+1}} \sum_{\lambda=1}^{\infty} \tilde{F}_{rm\lambda}(x_{m\lambda}) \sin \frac{x_{m\lambda} z}{d\sqrt{\epsilon\mu - 1}}$$

$$W'_m(z) = \frac{Z_0 c l}{2\pi(1+\delta_{0m})d^{2m+2}} \sum_{\lambda=1}^{\infty} \tilde{F}_{zm\lambda}(x_{m\lambda}) \cos \frac{x_{m\lambda} z}{d\sqrt{\epsilon\mu - 1}}$$

where $x_{m\lambda}$ is the λ -th zero of some combinations of modified Bessel functions of order m .

- The above are just summations of sharp resonances.

There are analytic expressions if the ferrite layer is thin.

$$Z_{||}(\omega) \sim \int W'_o(z) e^{-i\omega z/c} d\left(\frac{z}{c}\right)$$

$$Z_{\perp}(\omega) \sim \int W_i(z) e^{-i\omega z/c} d\left(\frac{z}{c}\right)$$

Monopole ($m = 0$)

- If $\delta = \frac{t}{b} \ll 1$, $x_{01} = \sqrt{\frac{2\epsilon}{\delta}}$, and $\tilde{F}_{z01} = 4$.

$t =$ thickness of ferrite

Resonance frequency is

$$\omega_{01} = \frac{x_{01}c}{d\sqrt{\epsilon\mu - 1}} = \frac{c}{d}\sqrt{\frac{2\epsilon}{\delta(\epsilon\mu - 1)}} \rightarrow \frac{c}{d}\sqrt{\frac{2}{\mu\delta}} \quad \text{when } \epsilon\mu \gg 1$$

$$\frac{Z_{\parallel}}{n} = -i\frac{\omega_0 Z_0}{2\pi c} \left(\mu - \frac{1}{\epsilon}\right) \ell \delta$$

- Result is ϵ independent when $\epsilon\mu \gg 1$.
- For $\mu = 1000$, $\delta = 0.1$, $d = 5.05$ cm, $\ell = 63$ cm,

$$f_{01} = 840 \text{ MHz}, \quad \frac{Z_{\parallel}}{n} = -i100 \Omega \quad (\mu \sim 1000)$$

But if loss is included as perturbation, loss is ~ 76.8 kV per turn near bunch center and almost zero at both ends.

- For the low-loss Yttrium-iron garnet, $\mu = 3$, $\epsilon = 8$, $\ell = 63$ cm,

$$f_{01} = 15.3 \text{ GHz} \quad \frac{Z_{\parallel}}{n} = -i3 \Omega$$

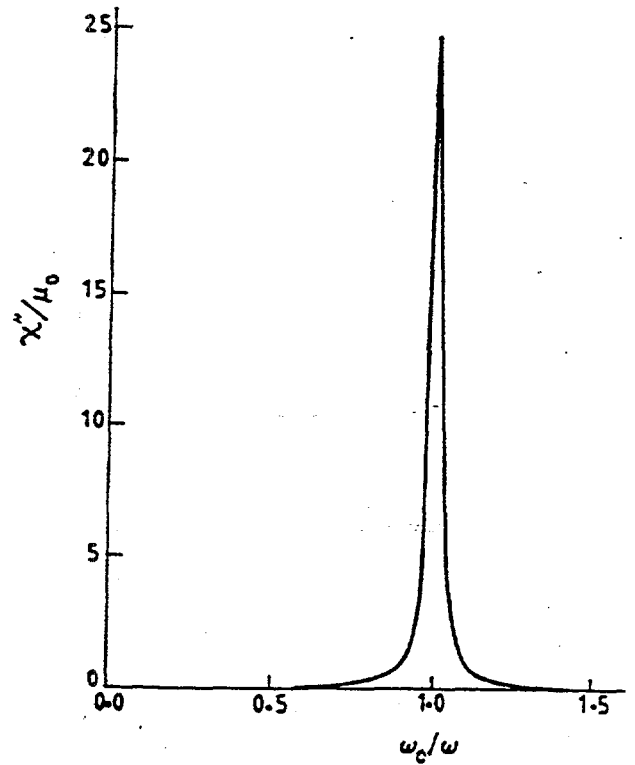
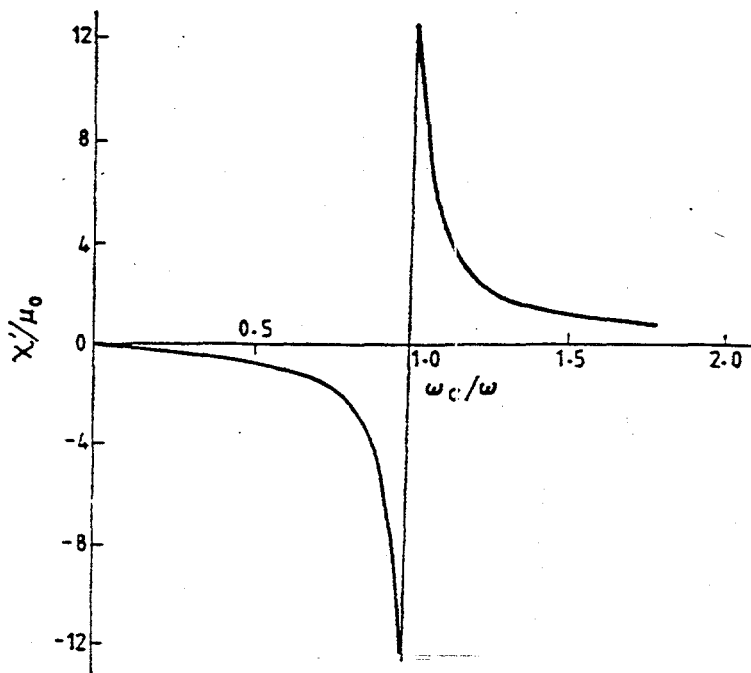
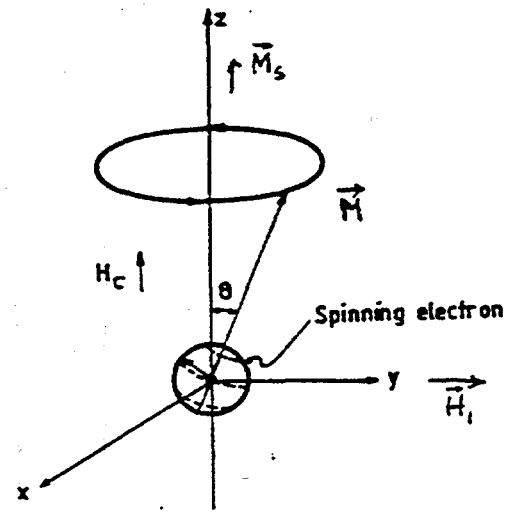
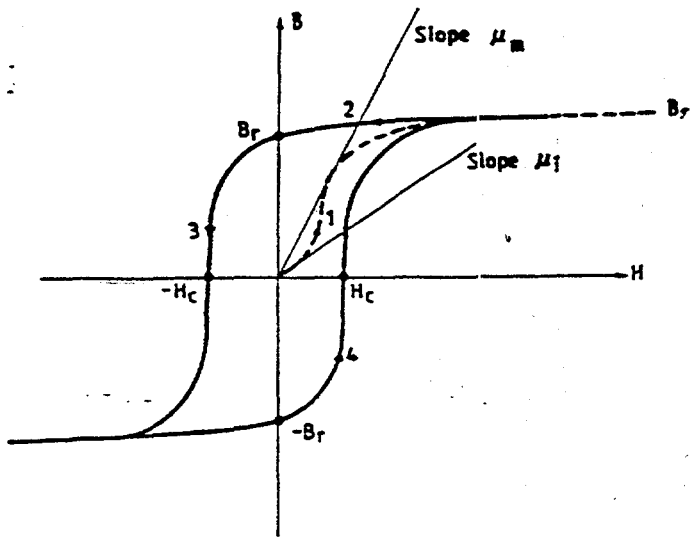
VII HIGH TRANSVERSE DC BIAS

- From KE 1 GeV injection to KE 3 GeV, the space charge impedance will be reduced by a factor of 4.58. We would like the inductance of the ferrite to decrease by the same factor.
- This can be accomplished by passing a DC bias field through the ferrite. To reduce loss, we suggest the bias field \perp field due to the bunch particles.

This can be done by putting a solenoid outside the ferrite.

- Use a dc biased field H_c in z -direction, so high that the magnetization \vec{M} inside the ferrite is saturated and becomes $\hat{z}M_s$.
- The ac field \vec{H}_1 from beam particles is in the x - y plane. This ac field causes the magnetization to precess about H_c , or creating an ac magnetization \vec{M}_1 in the x - y plane.
- Thus, we have

$$\vec{H} = \hat{z}H_c + \vec{H}_1, \quad \vec{M} = \hat{z}M_s + \vec{M}_1$$



- When $|\vec{H}_1| \ll H_c$, the equation of motion is

$$\frac{d\vec{M}}{dt} = \gamma(\hat{z}M_s \times \vec{H}_1 + \hat{z}\vec{M} \times H_c)$$

where $\gamma = 2.80 \times 2\pi$ MHz/Oersted is the gyromagnetic ratio of

the electron. Defining the magnetic susceptibility tensor $\vec{\chi}_r$ as

$\vec{M}_1 = \vec{\chi}_r \vec{H}_1$, the solution is

↑
reversible

Stationary soln.
or particular soln.

$$\vec{\chi}_r = \begin{pmatrix} \chi & -j\kappa & 0 \\ j\kappa & \chi & 0 \\ 0 & 0 & \frac{1}{\mu_0} \end{pmatrix} \quad \vec{\mu}_r = 1 + \frac{\vec{\chi}_r}{\mu_0}$$

where

$$\frac{\chi}{\mu_0} = \frac{\omega_c \omega_m}{\omega_c^2 - \omega^2}, \quad \kappa = \frac{\omega \omega_m}{\omega_c^2 - \omega^2} = \frac{\chi_v}{\mu_0} \frac{\omega}{\omega_c}$$

and

$$\omega_c = \gamma H_c, \quad \omega_m = \gamma \frac{M_s}{\mu_0}$$

- There is a resonance at the gyromagnetic resonant frequency

$\omega_c = \gamma H_c$, which is proportional to the dc H_c . This explains why

we want H_c to be large so that the resonance effect can be avoided.

- Loss can be included by letting $\omega_c \longrightarrow \omega_c - i\omega\alpha$, giving

$$\frac{\chi'}{\mu_0} = \frac{\left(\frac{\omega_m}{\omega}\right) \left(\frac{\omega_c}{\omega}\right) \left[\left(\frac{\omega_c}{\omega}\right)^2 - 1 + \alpha^2\right]}{\left[\left(\frac{\omega_c}{\omega}\right)^2 - 1 - \alpha^2\right]^2 + 4\left(\frac{\omega_c}{\omega}\right)^2 \alpha^2}$$

$$\frac{\chi''}{\mu_0} = \frac{\left(\frac{\omega_m}{\omega}\right) \alpha \left[\left(\frac{\omega_c}{\omega}\right)^2 + 1 + \alpha^2\right]}{\left[\left(\frac{\omega_c}{\omega}\right)^2 - 1 - \alpha^2\right]^2 + 4\left(\frac{\omega_c}{\omega}\right)^2 \alpha^2}$$

Note that, actually the above depend on only M_s and α .

- Usually the ac field comes from a cavity. Then, ω will not be changed by very much and can be considered fixed except very near to the resonance. Therefore, χ is plotted as a function of H_c

This explains why the formulas have been written as a function of ω_c/ω .

- In our application, the ac field comes from the beam particles. So ω has the range of the bunch spectrum. For $h = 2$, $\omega/(2\pi)$ varies up to $\sim \frac{7}{2} \times 2.2$ MHz, and for $h = 4$, up to $\sim \frac{14}{4} \times 4.4$ MHz. ~ 15 MHz
 ≈ 7.7 MHz
- The merit of this application is the low loss, because the ferrite is saturated, there will not be hysteresis loss. The only loss is due to spin wave which is small. The disadvantage is μ' is usually small.

Application

- Choose Ferramic Q-1, which has saturated flux density of 3300 Gauss at 25 Oersted.
- Thus, $M_s = 3300 - 25 = 3275$ Gauss.
- Choose $H_c = 25$ Oe.

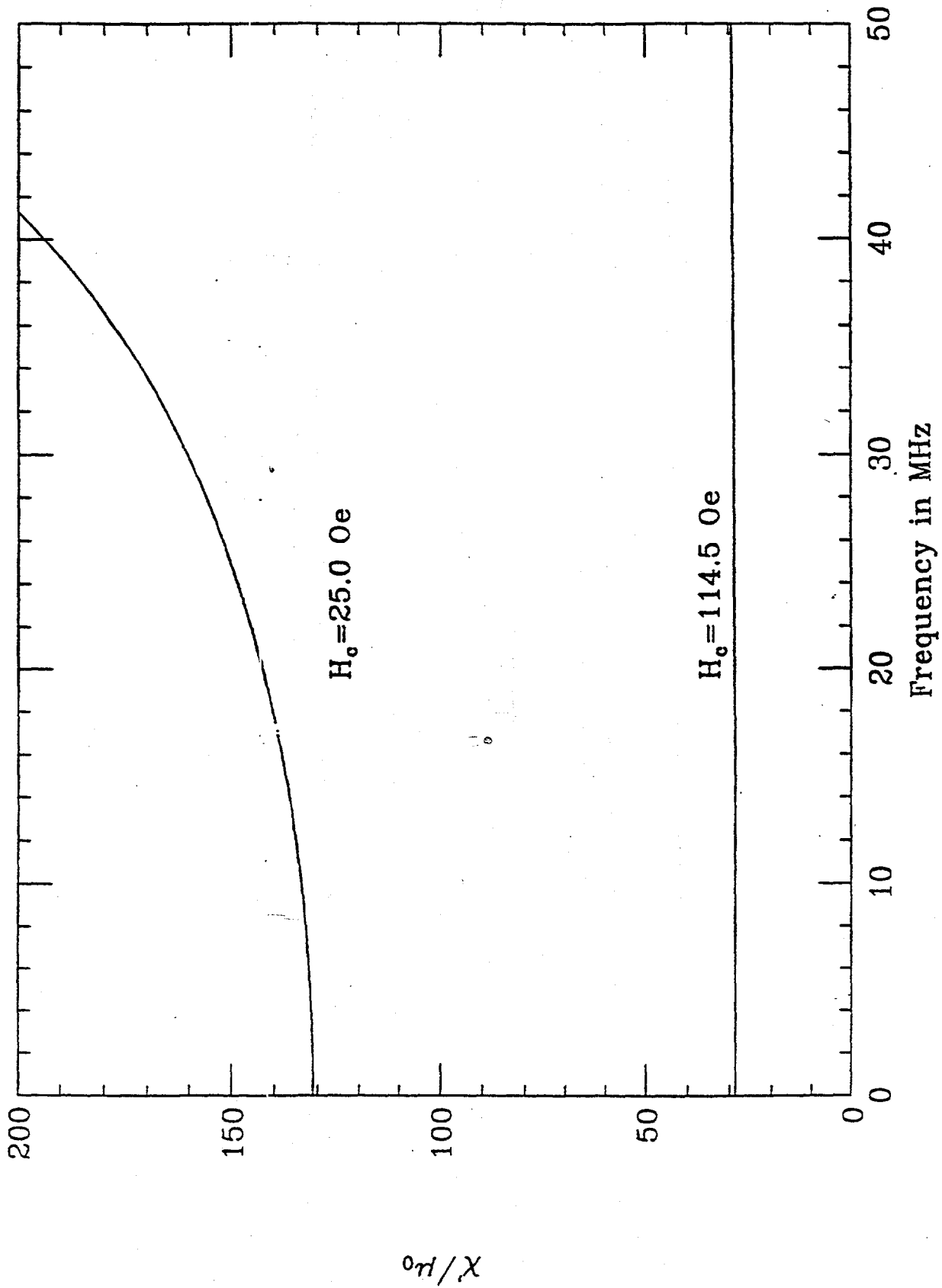
This gives resonant frequency $\omega_c/(2\pi) = \gamma H_c = 70$ MHz.

Up to 10 MHz, $\mu' \sim M_s/H_c = 131$.

- With ferrite thickness $t = 1$ cm, to cancel $|Z_{\parallel}/n|_{\text{sp ch}} = 100 \Omega$, we need a length of $\ell = 2.4$ m of ferrite is required.
- At extraction, want μ' to be reduced to $131/4.58 = 28.6$.

The biased field should be raised to $H_c = M_s/\mu' = 114.5$ Oe.

- At low frequencies, the loss is $\mu'' \longrightarrow \frac{\alpha \omega \omega_m}{\omega_c^2}$.
- Take a typical value of $\alpha = 0.05$, we find μ'' varies linearly from 0 and reaches 0.5 at 5 MHz when $H_c = 25$ Oe at injection, and is reduced by a factor of $4.58^2 = 21.0$ when $H_c = 114.5$ Oe at extraction.



VIII CONCLUSIONS

1. The most serious space-charge effect Laslett tune shift for $h = 4$.
2. Longitudinal microwave instability seems to be safe .
3. Potential-well distortion needs ferrite compensation.
4. Ordinary compensation without DC bias field gives large μ' and also large μ'' of the order of 1000. The loss is about 100 kV per turn and is position dependent along the bunch.
5. Large transverse DC bias beyond saturation eliminate hysteresis loss. Only loss is due to spin wave and is tiny.
6. However, large transverse DC bias gives small μ' , but is still good enough. Total ferrite length of 2.4 m is required if thickness is 1 cm.
7. From injection energy of 1 GeV to extraction energy of 3 GeV, the DC bias field need to be increased quadratically with energy from 25 Oe to 114.5 Oe. Hopefully, this can be accomplished by using a solenoid.

I. Introduction

Results of 1997 Sextant Test:

- Intensity: typical 2×10^8 , up to 4×10^8 /bunch
- Bunch area: typical $S = 0.5 \pm 0.1$ eV s/u

RHIC Operation with Increased Longitudinal Bunch Area (I)

Jie Wei, Brookhaven National Laboratory

I. Introduction

II. Intra-beam Scattering at Injection

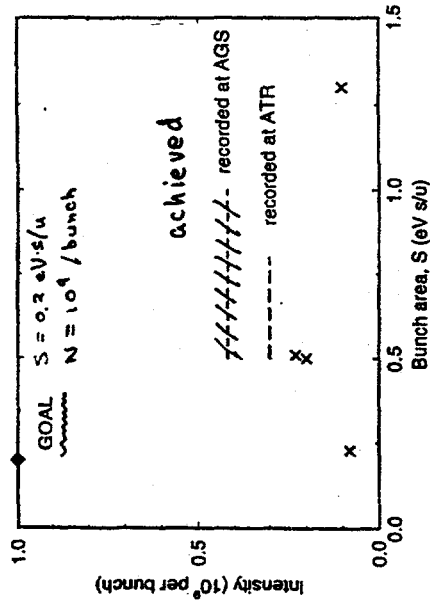
III. Transition Crossing

IV. Storage and Luminosity

V. Conclusions

part (I) by Jörg Kewisch

Au⁷⁹⁺ beam during 1997 sextant test



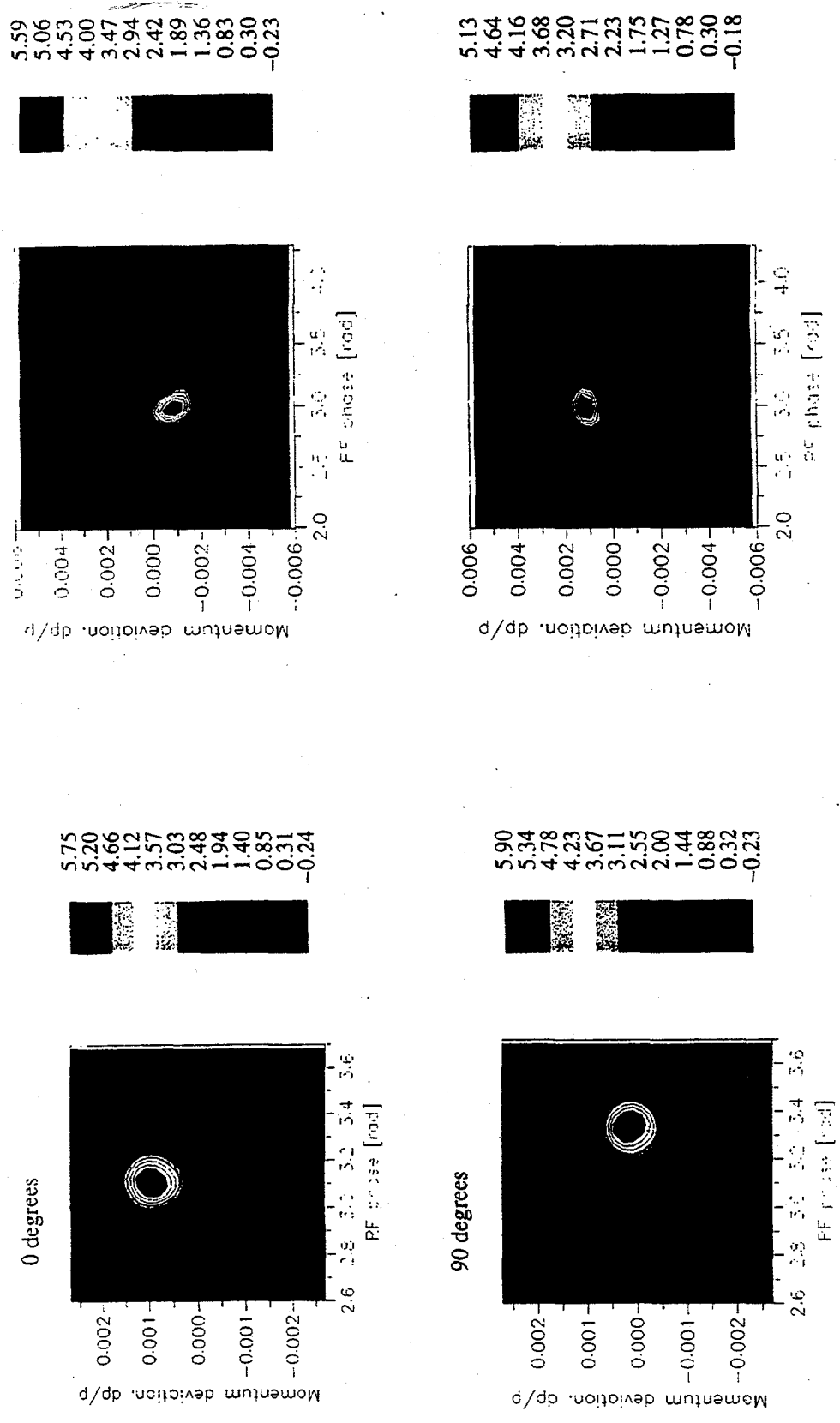


Figure 1: Au⁷⁷⁺ Beam exhibiting dipole motion in an AGS RF bucket

Figure 2: Two distinct globs of charge of Au⁷⁷⁺ due to imperfect tuning rotating in an AGS rf bucket (110 degrees)

Longitudinal phase-space reconstruction:

Radon Reconstruction, AGS Au77+
Extraction, 0 deg

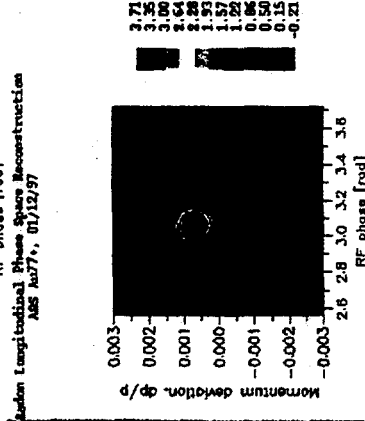
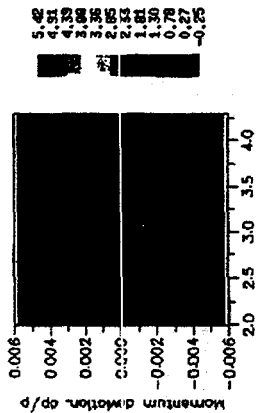


Figure 5: Longitudinal phase space of a Au⁷⁷⁺ beam in AGS reconstructed with RADON on (a) Dec. 15, 1996 and (b) Jan. 12, 1997, showing improvement of merging at bunch coalescing.

Possible problems with increased bunch area:

- *• emittance growth and particle loss at transition;
(Johnson) chromatic nonlinear effect
 - re-bucketing (28 MHz → 196 MHz);
to be discussed by Jöng
 - consequences in intrabeam scattering (injection & storage).
- IBS @ injection
Luminosity performance & IBS @ storage

II. Intrabeam Scattering at Injection

Quasi-equilibrium condition: "equal temperature
(below transition)

$$\frac{\sigma_x}{\beta_x} \approx \frac{\sigma_y}{\beta_y} \approx \frac{\sigma_p}{\gamma}, \quad \gamma \ll \gamma_T. \quad (1)$$

✓ For $\frac{\sigma_{xy}}{\beta_{xy}} \gg \frac{\sigma_p}{\gamma}$: (low longitudinal temperature)

$$\begin{bmatrix} \frac{1}{\sigma_p} \frac{d\sigma_p}{dt} \\ \frac{1}{\sigma_x} \frac{d\sigma_x}{dt} \end{bmatrix} \sim 42.4 L_c r_0^2 E_0 \frac{Z^4 N}{A^2 \gamma^2 \epsilon_{xy} S} \begin{bmatrix} \frac{\gamma \sigma_x}{\beta_x \sigma_p} \\ -\frac{\beta_x \sigma_p}{2\gamma \sigma_x} \end{bmatrix} \quad (2)$$

For $\frac{\sigma_{xy}}{\beta_{xy}} \ll \frac{\sigma_p}{\gamma}$: (high longitudinal temperature)

$$\begin{bmatrix} \frac{1}{\sigma_p} \frac{d\sigma_p}{dt} \\ \frac{1}{\sigma_x} \frac{d\sigma_x}{dt} \end{bmatrix} \sim 27 L_c \ln \chi r_0^2 E_0 \frac{Z^4 N}{A^2 \gamma^2 \epsilon_{xy} S} \begin{bmatrix} \frac{\gamma^2 \sigma_x^2}{\beta_x^2 \sigma_p^2} \\ \frac{1}{2} \end{bmatrix} \quad (3)$$

- * strong dependence on energy
- * proportional to 6-D phase space density
- * $\sim \frac{E^4}{A^2}$, problem for Au⁷⁹⁺

IBS growth at RHIC injection:

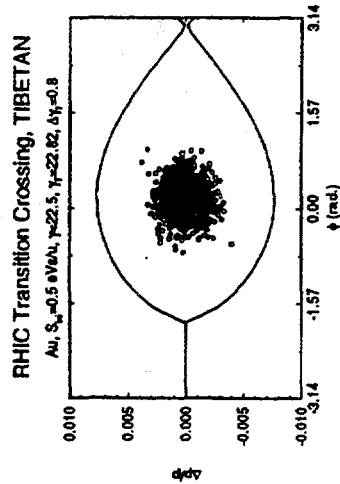
- mainly occurs in longitudinal direction;
lower longitudinal temperature
- with $S = 0.2$ eV·s/u, the growth time is about 3 minutes;
- the growth rate can be reduced by increasing σ_p (rf voltage);
- with $S = 0.5$ eV·s/u, the growth time is about 20 minutes.

III. Transition Crossing

Recent progress in transition design:

- a "first-order, matched" γ_T -jump lattice, $\alpha_1 = -0.6$ remains almost constant during the jump; $\alpha_1 = +0.6$ (old) $\rightarrow \alpha_1 = -0.6$ (new)
- two quadrupole corrector families, one for γ_T -jump, the other for optical optimization; Pegg, Tepikian, Trbojevic
- chromatic nonlinear effects greatly reduced.

$$\frac{\Delta S}{S} \sim (\alpha_1 + 1.5) \cdot \sigma_p$$



$$V_{Tf} = 300 \text{ kV}$$

- * low enough to have a smaller σ_p
- * high enough to compensate beam induced fields, especially in storage cavities.

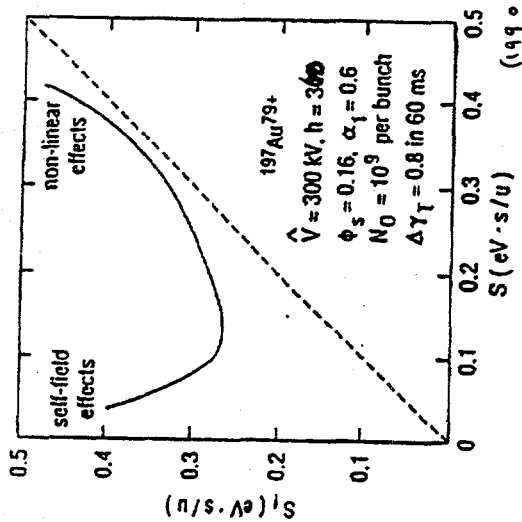


Figure 2: Effects of chromatic nonlinearities and self fields at transition.

γ_T - jump and α_1 variation :

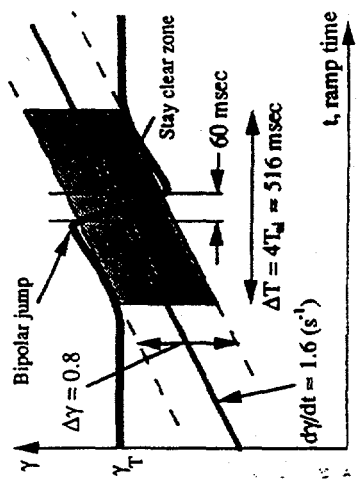
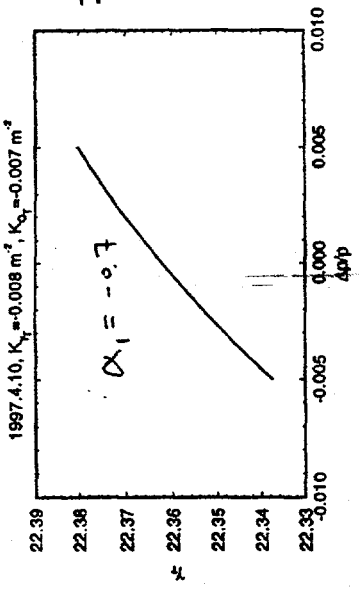
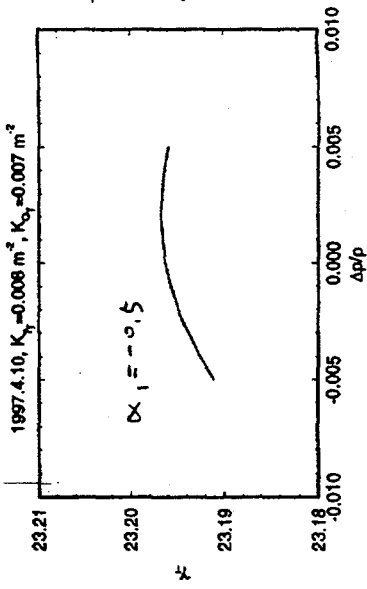


Figure 1 Transition is crossed almost 10 times faster with the principal RHIC bipolar transition jump than without. Not to scale.

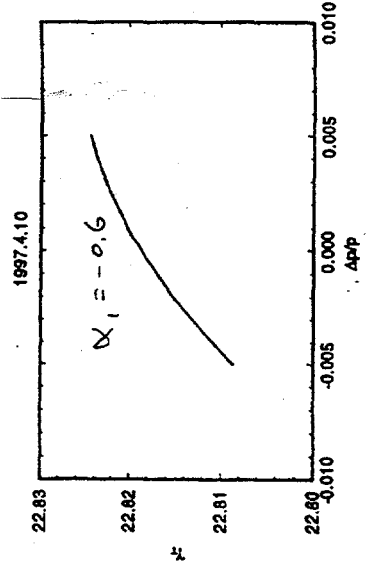
RHIC 92, rev. 06 Lattice; MAD Result



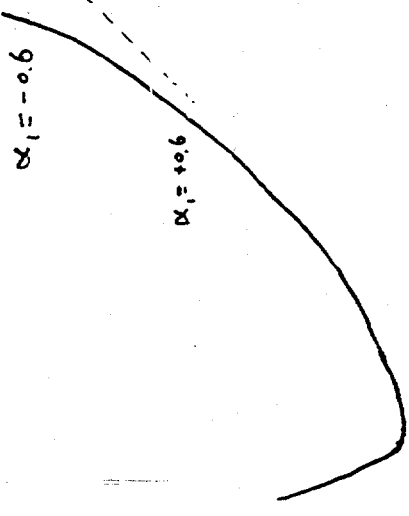
RHIC 92, rev. 06 Lattice; MAD Result



RHIC 92, rev. 06 Lattice; MAD Result



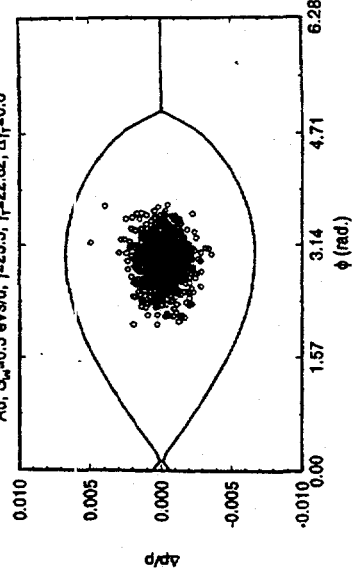
emittance growth after transition:



0.6 0.7 0.8

RHIC Transition Crossing, TIBETAN

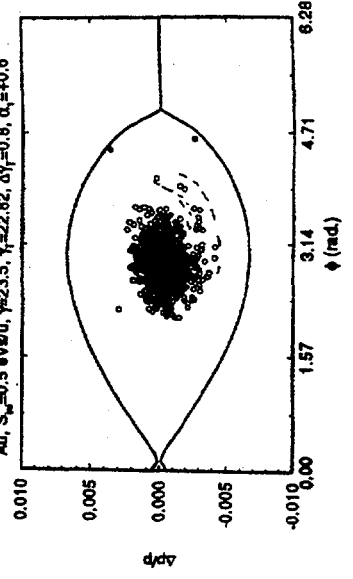
Au, $S_w=0.5$ eV/s/u, $\gamma=23.5$, $\gamma'=22.82$, $\Delta\gamma=0.8$



$\alpha_1 = -0.6$
(new)
negligible
growth

RHIC Transition Crossing, TIBETAN

Au, $S_w=0.5$ eV/s/u, $\gamma=23.5$, $\gamma'=22.82$, $\Delta\gamma=0.8$, $\alpha_1=+0.6$



$\alpha_1 = +0.6$
(old)
considerable
growth

IV. Storage and Luminosity

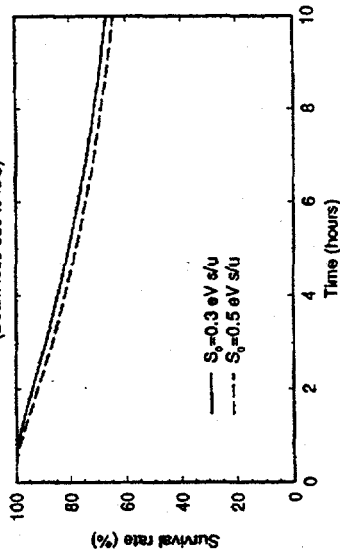
Intrabeam Scattering growth at storage:

- growth occur in both transverse and longitudinal directions with similar rates;
- there exists *no* equilibrium state (negative-mass regime)
(above transition)

$$\left[\frac{1}{\sigma_p} \frac{d\sigma_p}{dt} \right] \sim 34.6 L_c r_0^2 E_0 \frac{Z^4 N}{A^2 \gamma^3 \epsilon_x \epsilon_y S} \quad (4)$$

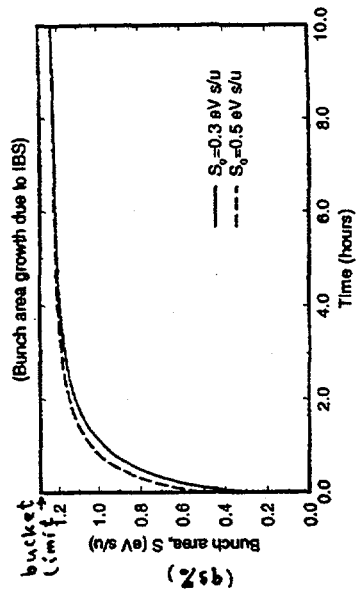
- * always grows
- * weak dependence on energy
- * proportional to 6-D phase space density
- * $\sim \frac{Z^4}{A^2}$ problem for Au³⁹⁺

BEAM LOSS (Beam loss due to IBS)



- * fills the bucket in ~ 2 hours
- * beam escapes from the bucket

BUNCH-AREA GROWTH (Bunch area growth due to IBS)

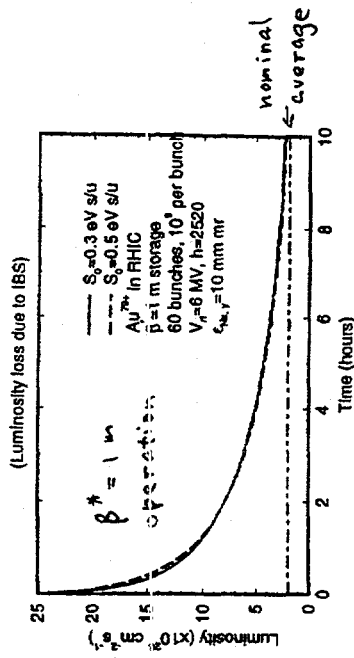


V. Conclusions

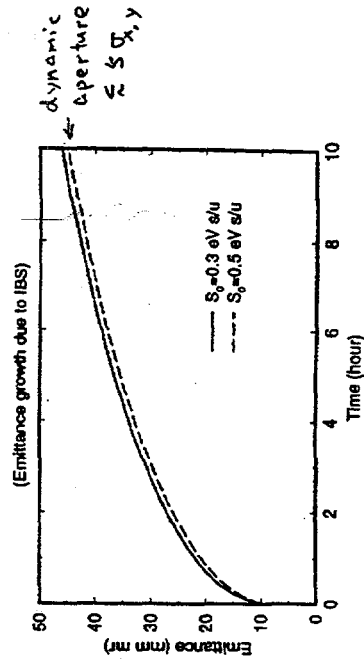
With an increased longitudinal emittance:

- intrabeam scattering growth at injection will be reduced;
- Current $\gamma\gamma$ -jump scheme is adequate for efficient transition crossing;
- No significant change is expected in luminosity performance during collision.
- Re-bucketing process will be discussed by Jorg.

INSTANTANEOUS LUMINOSITY



EMITTANCE GROWTH



Rebucketing in RHIC

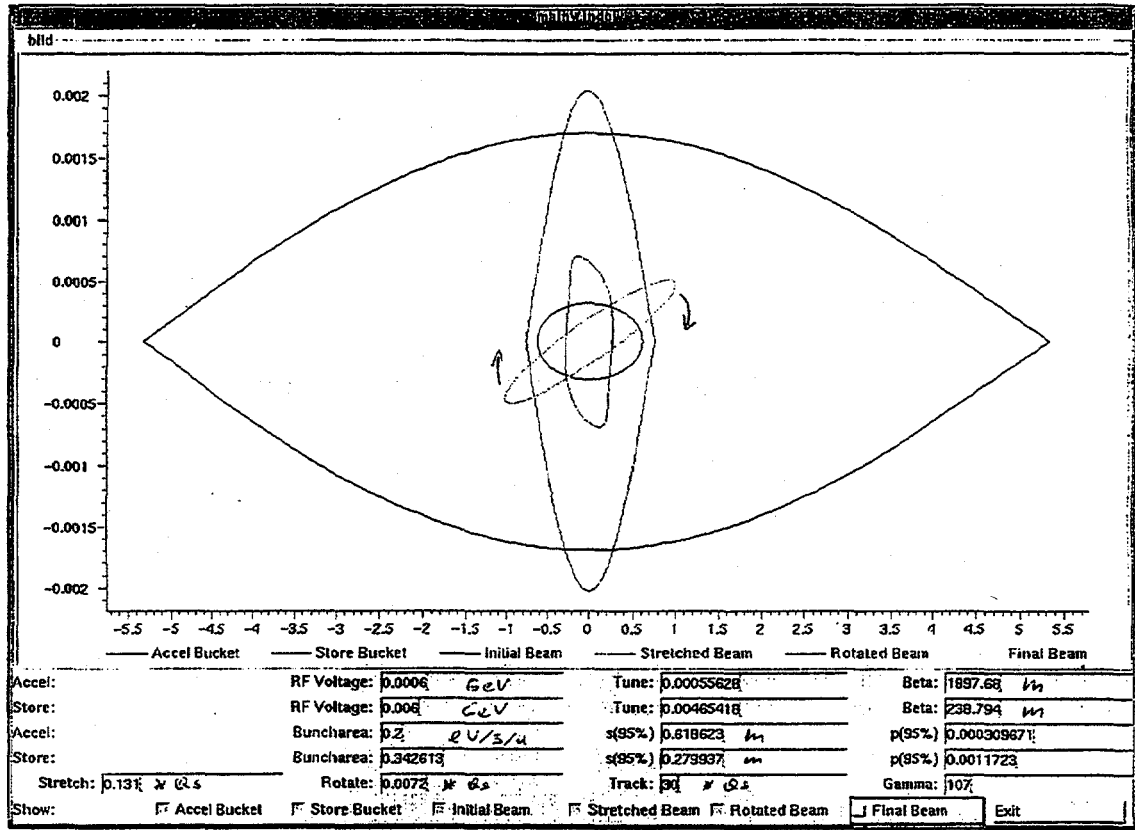
Jörg Kewisch

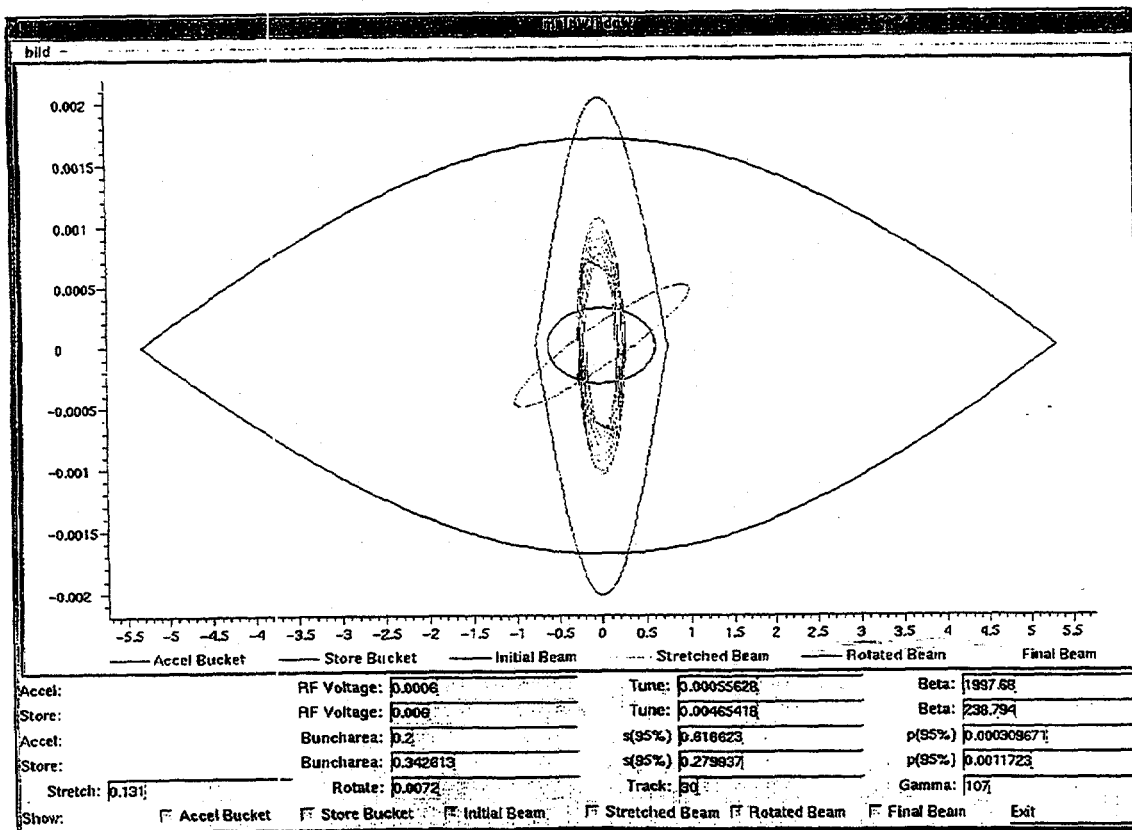
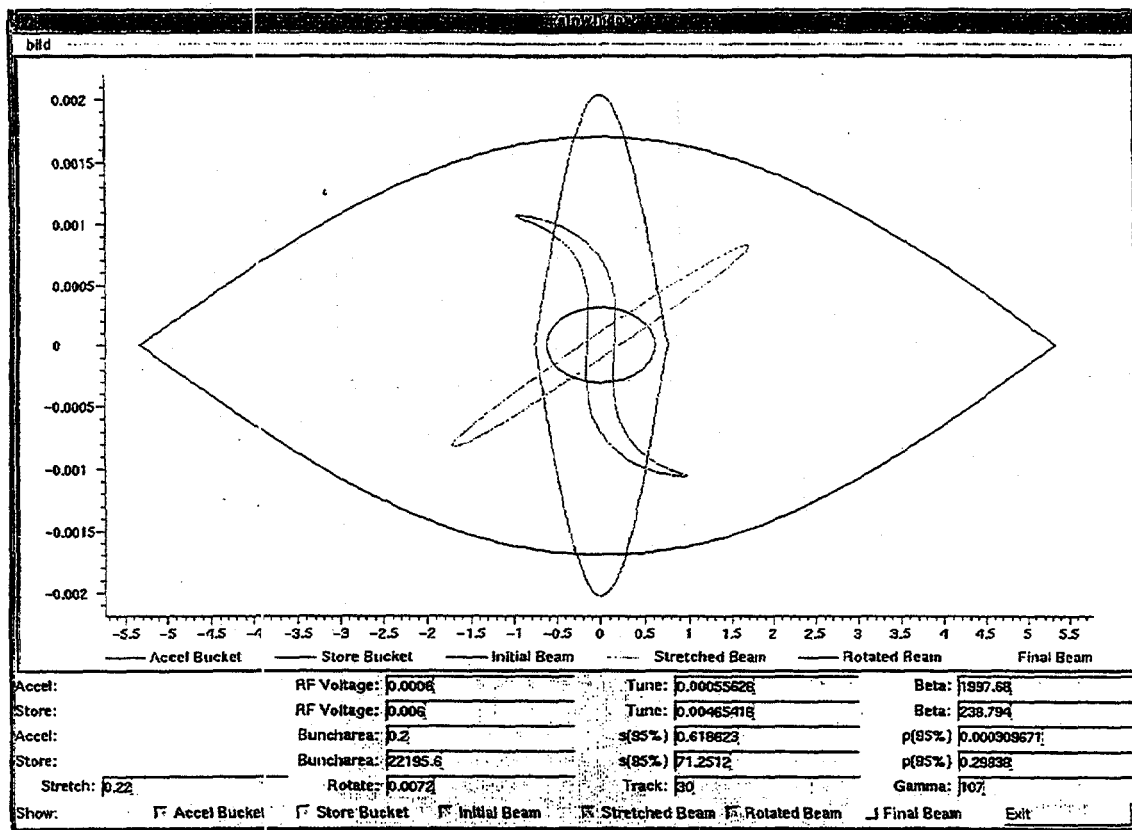
Motivation:

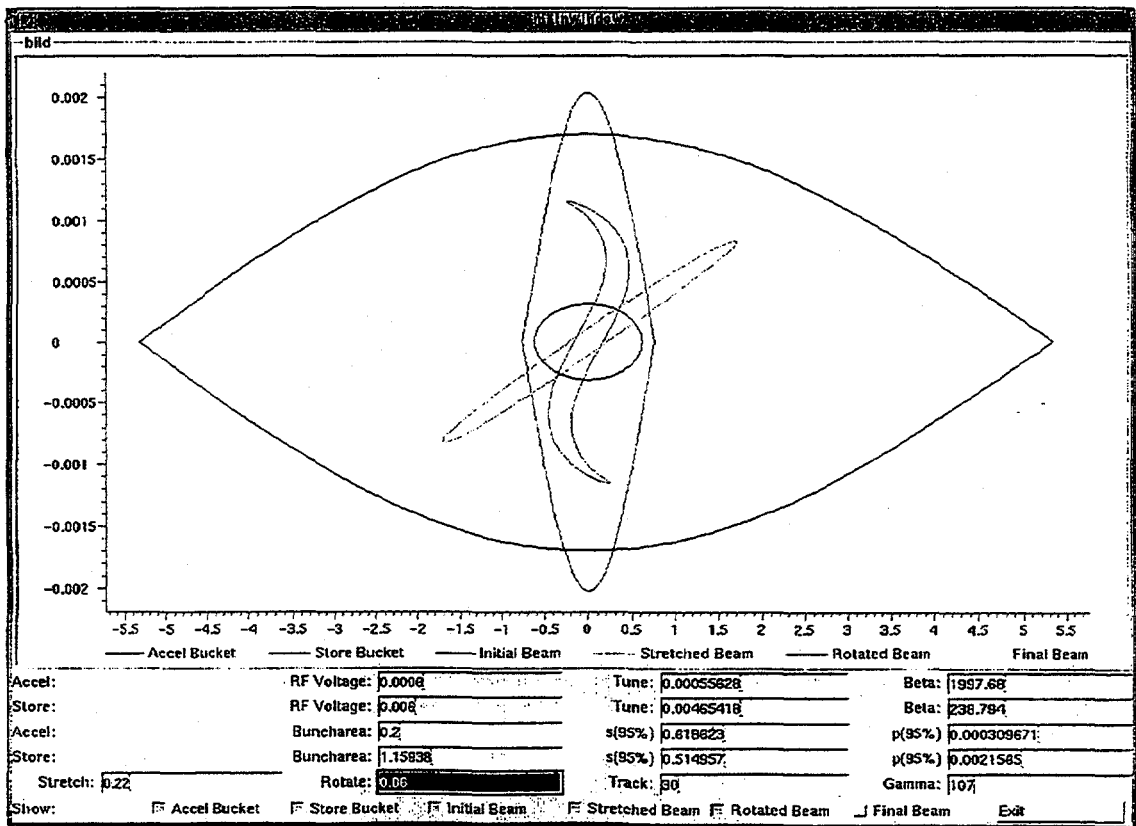
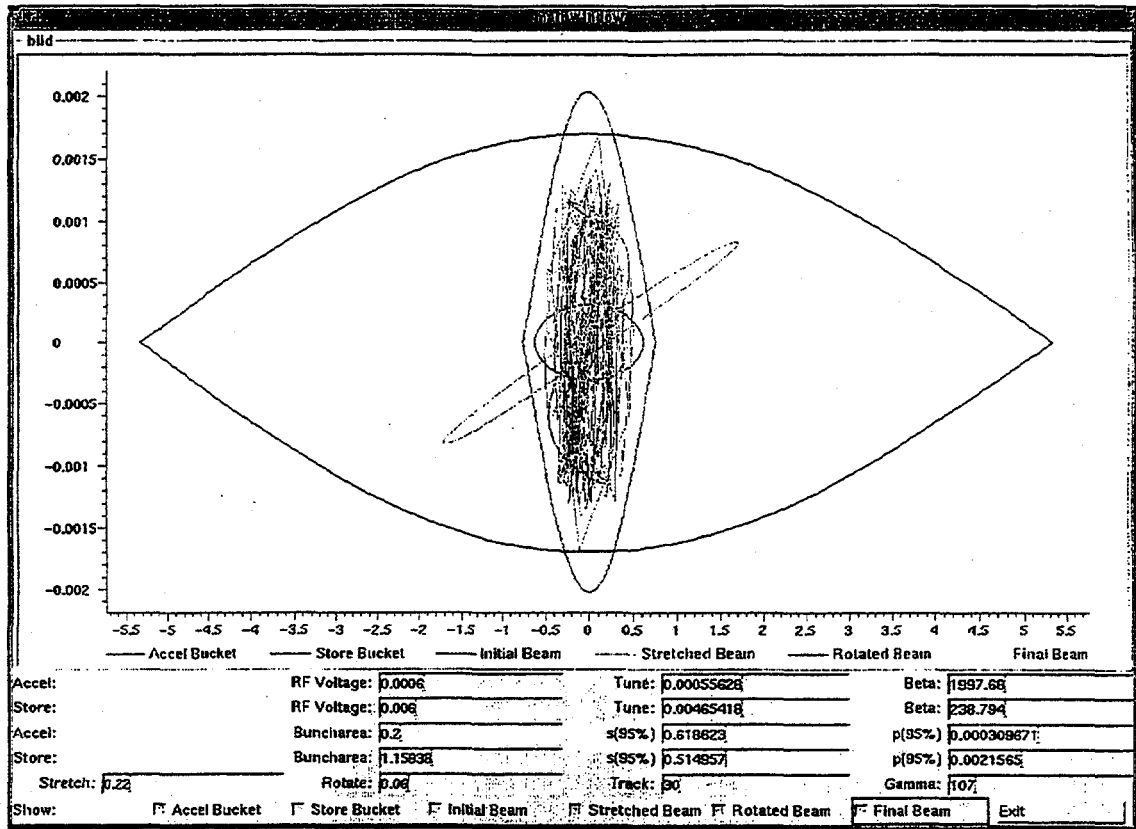
Short bunches (rms < 20 cm) are required for optimum detector design. (20 cm rms = 50 cm 95%)

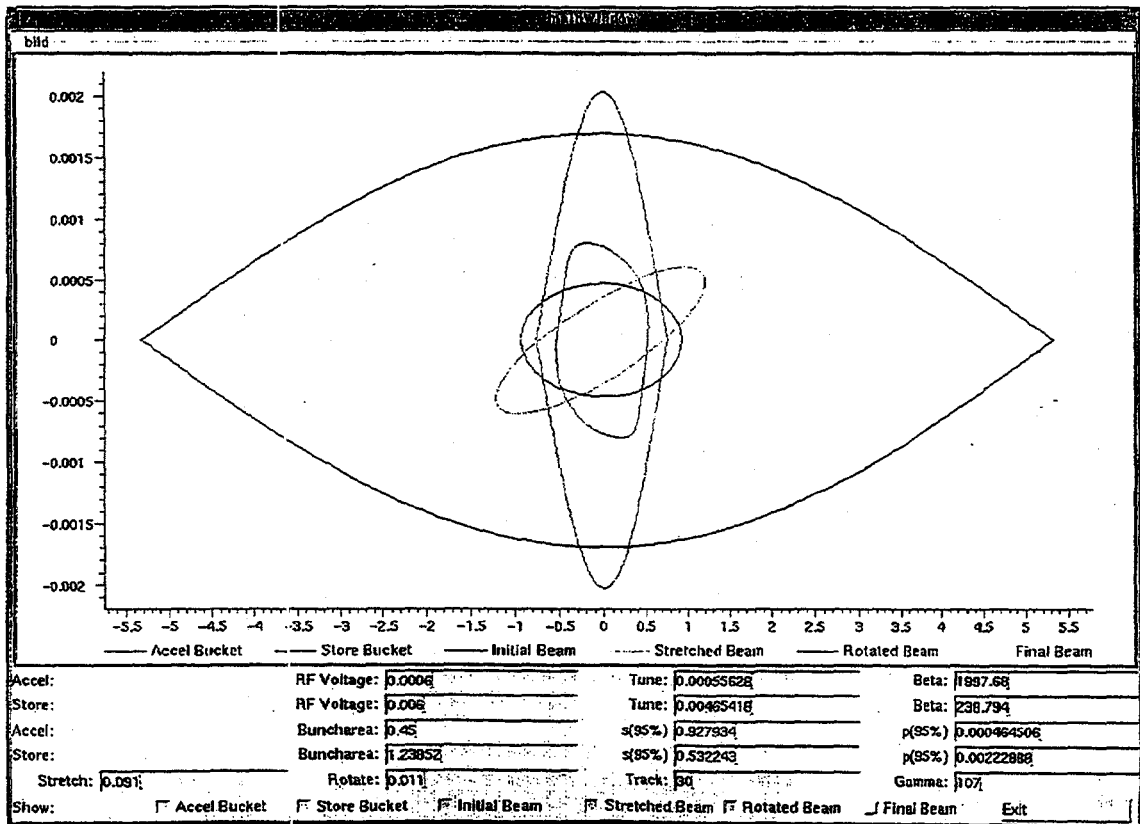
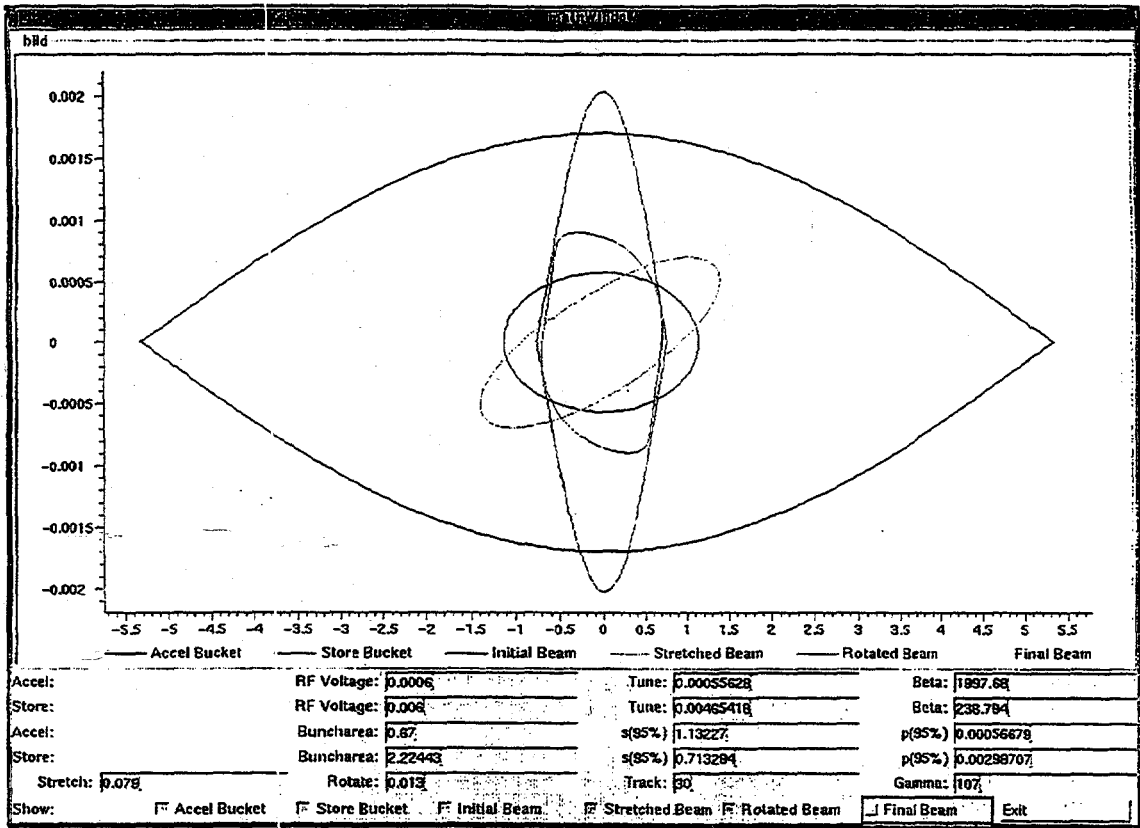
Question:

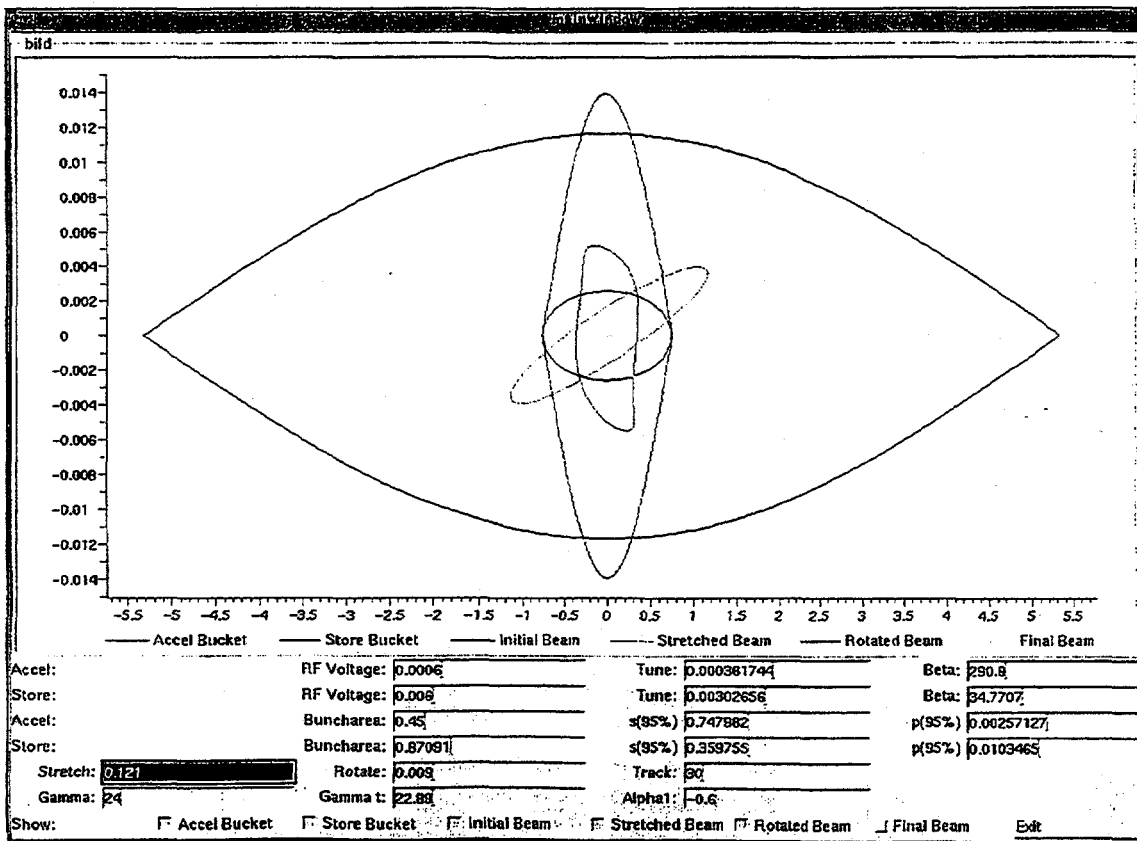
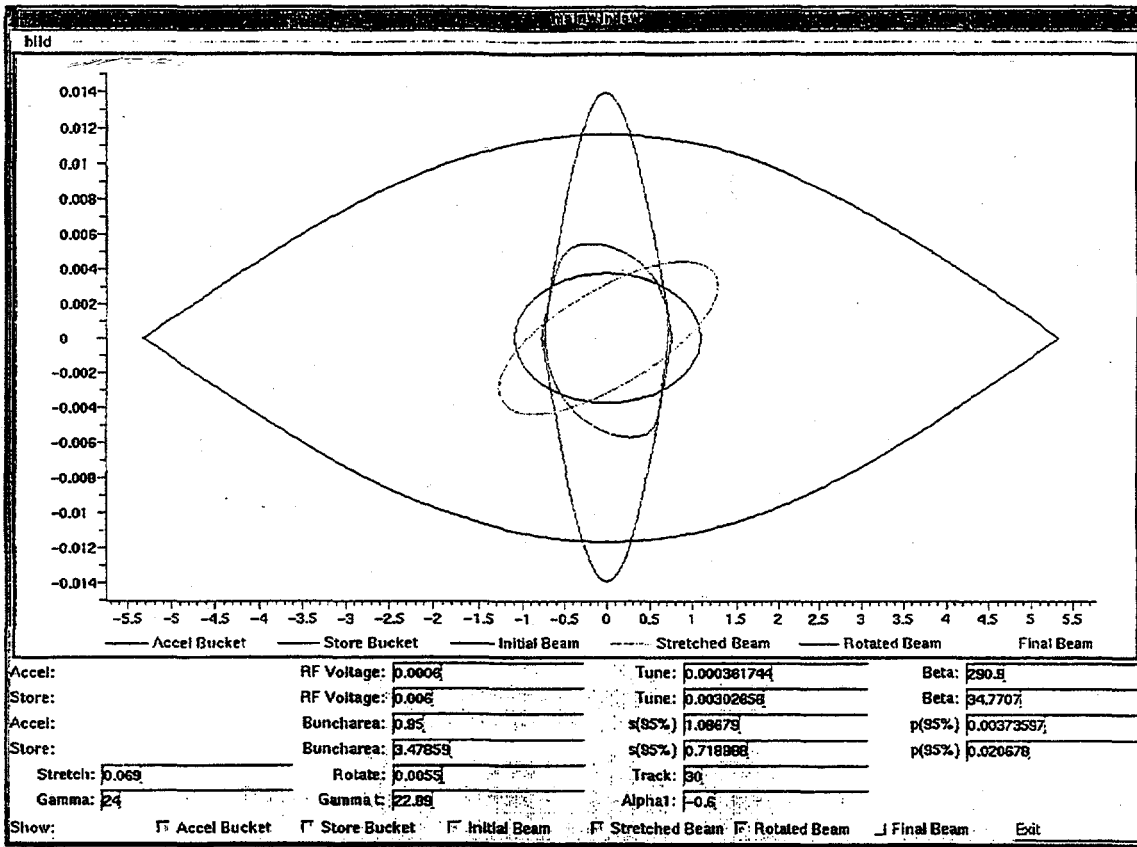
If the requirement for the longitudinal bucket area is relaxed from 0.2 eV sec/u to 0.45 eV sec/u, how does that effect the particle loss during rebucketing











Conclusion

Particles are captured up to (sigma):

Condition	Sigma
at storage 0.2 eV sec/u	8.3
at storage 0.45 eV sec/u	3.75
after transition 0.45 eV sec/u	5.4
after transition 0.45 eV sec/u, V=800kV	5.9

To do:

- Extend tracking program to simulate rebucketing while ramping

- ???

Session on Longitudinal Instabilities

K.Y. Ng

There were 3 talks in this session. The first talk was by Y.H. Chin and H. Tsutsui on "Microwave Instability in a Barrier Cavity". A bunch inside a barrier bucket behaves like a coasting beam because the bunch particles drift most of the time. However, it is also a bunch because of its finite length, and therefore we can talk about bunch modes. Chin and Tsutsui demonstrated the equivalence between mode-crossing instability and the Boussard-Keil-Schnell microwave instability. Although this equivalence had been demonstrated for a resonant impedance by many authors, they were the first to demonstrate mode-crossing instability for a pure inductive impedance below transition, which is predicted by the Boussard-Keil-Schnell theory. They expanded the bunch modes in terms of orthogonal functions and compute the eigen-modes as a function of bunch current. They also wrote a code to track the bunch particles in the longitudinal phase space, and verified that the onsets of instability agree with theory. The code is a tracking in the time domain and approximates a bunch as a series of triangular bunches.

The second talk by M. Blaskiewicz is on "Fast Particle-Particle Update Scheme" in tracking. When tracking N particles involving binary interaction, the number of steps per turn is usually $\mathcal{O}(N^2)$, which rises sharply when more particles are required. First, the time-order of the particles are sorted, which takes $\mathcal{O}(N \ln N)$ steps. Once the ordering is known, the positions of the particles can be updated using a recurrence relation, which takes $\mathcal{O}(N)$. Thus, for each turn, the number of steps is reduced from $\mathcal{O}(N^2)$ to $\mathcal{O}(N \ln N)$, and the saving in time is very significant.

The third talk by J. Rose is on "Stability in RHIC" against longitudinal coupled-bunch instability. ZAP and analytic formula computations for bunches passing through the the 28 MHz cavity shows instabilities driven by only the first few higher-harmonic modes (HOM). This is because the form factor falls off as the inverse of both the HOM frequency and the square of the bunch length. Since the bunches in RHIC will be long, the form factor is less than 0.6. Note that this is rather conservative; for a Gaussian bunch distribution, the form factor will fall off very much faster. Some passive de-Qing had been performed on these offensive modes, so that the growth rates for the unstable modes will be within the range of the injection damper rate of 10 sec^{-1} . From the MAFIA computation of the HOM dampers, it appears that there should not be any problem concerning longitudinal coupled-mode instability.

Longitudinal Bunched-Beam Instabilities in a Barrier RF System

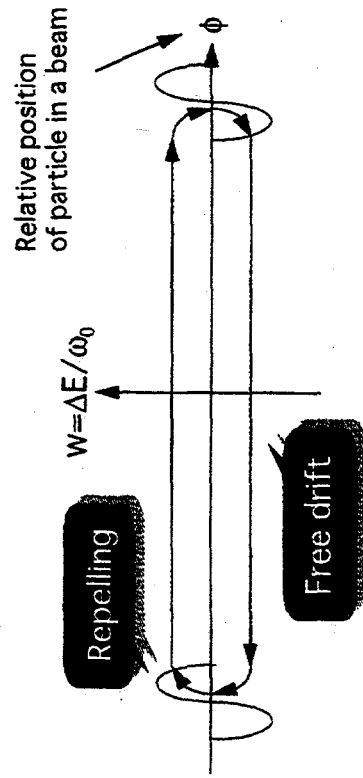
KEK

Yong Ho Chin
and
Hiroshi Tsutsui

1997 Particle Accelerator Conference
Vancouver, Canada
May 13, 1997

Introduction

- Barrier RF System



- Characteristics of a barrier RF system

- * A very flat bunch --> A smaller peak current
- * A variable bunch length
- * A small synchrotron frequency ($\nu_{rms} = 17\text{ Hz at JHF}$)
- * Synchrotron frequency proportional to the energy deviation --> A spread is comparable to the frequency itself
- * A strong Landau damping effect

- Collective stability of a bunched-beam in a barrier bucket
 - Keil-Schnell-Boussard criterion would give a reasonable estimate, IF
 - ◊ the wave length of beam density modulation is much shorter than the bunch length
 - ◊ the instability growth is much faster than the synchrotron motion.

How do we know without calculation?

If not, or no way to know if the coasting approximation is good or not, what should replace Keil-Schnell-Boussard criterion?

A need to develop a theory proper to a bunched-beam

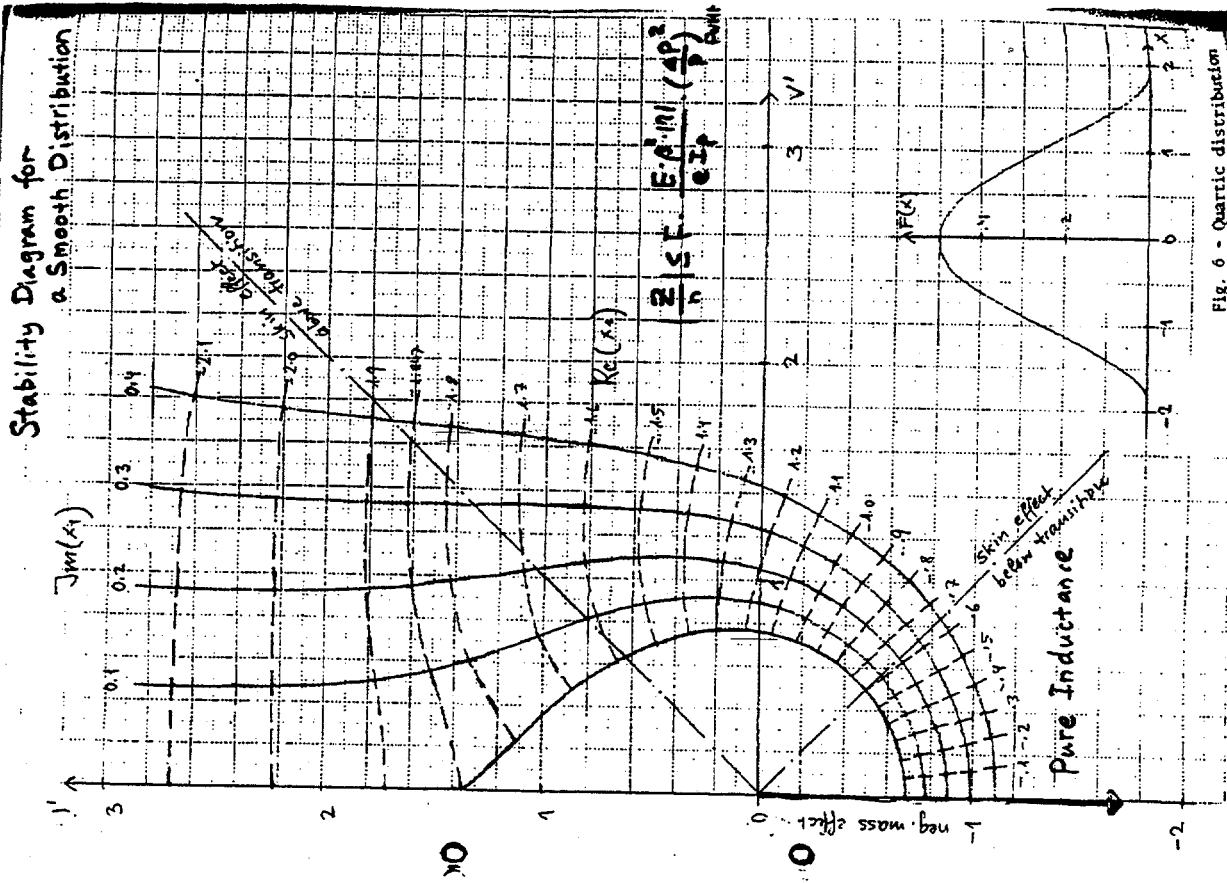
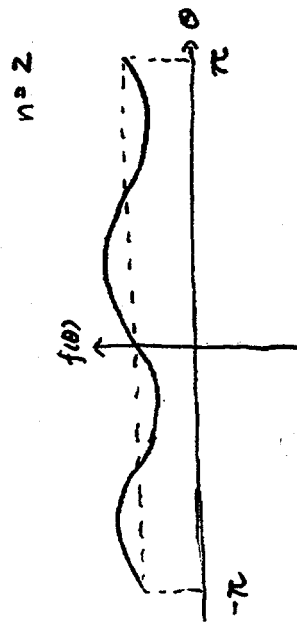
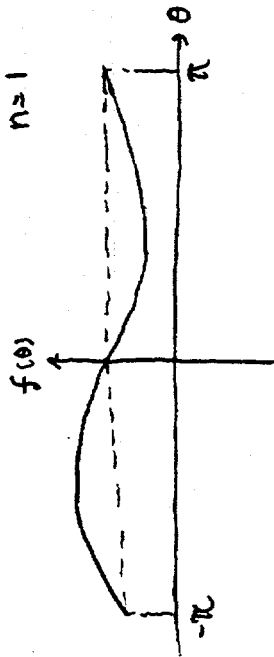


Fig. 6 - Quartic distribution

Coasting Beam Mode Number "n"



Main framework of the newly developed theory

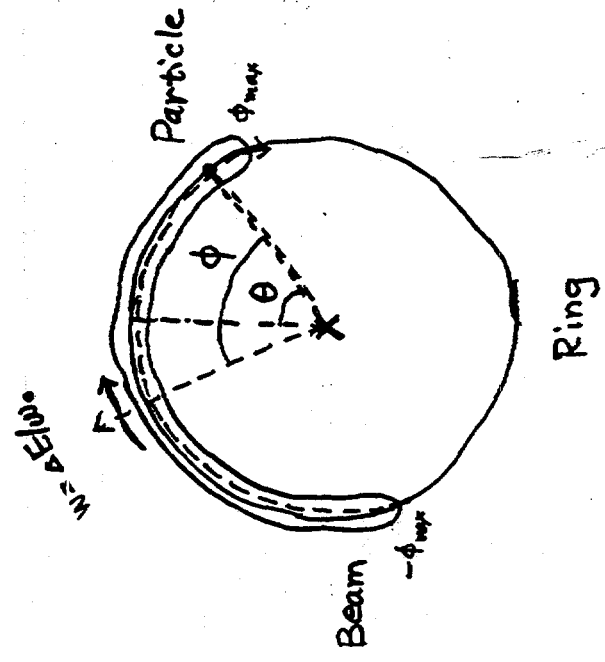
- No coasting beam approximation
- Vlasov equation for evolution of phase space distribution
- Synchrotron and energy mode expansion
- Action-angle variables to describe the squarish particle trajectory in phase space
- A Gaussian energy distribution
- A full inclusion of Landau damping effect

- A simulation code ECLIPS (Evaluation Code for Longitudinal Instabilities in a Proton Synchrotron) was also developed.
- Their application to JHF 50 GeV proton synchrotron at injection show good agreements.
- We will demonstrate (as Sacherer predicted)

Microwave and negative mass instabilities in a coasting beam

transform

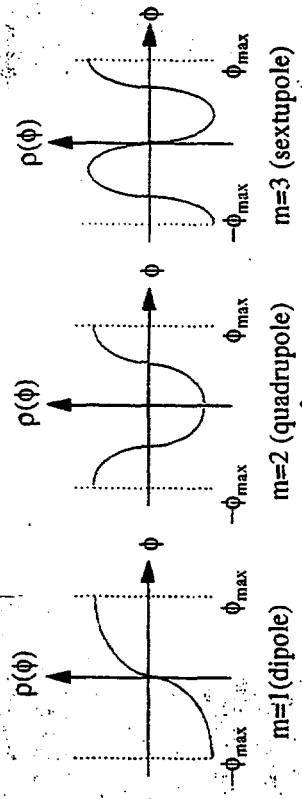
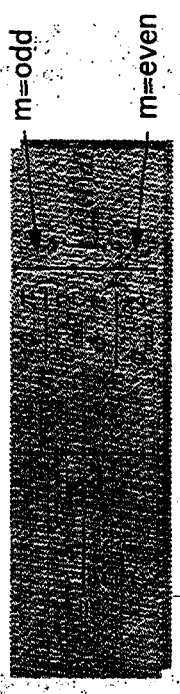
Mode-coupling instabilities in a bunched-beam



- Perturbation method + separate factorization with respect to I and ψ + Fourier expansion

$$f(I, \psi, \theta) = f_0(I) + \sum_{m=-\infty}^{\infty} f_m(I) \exp(im\psi) \exp(-i\Omega\theta)$$

Line charge density $\rho(\phi)$



corresponds to "n=1" coasting beam mode when $\phi_{max} = \pi$

- Using impedance $Z(\omega / \omega_0)$ and Fourier transform of $\rho(\phi)$, $\tilde{\rho}(v)$

$$I' = -e^2 N \frac{\phi_{\max}}{\pi^2} \text{sgn}(w) \sum_{p=-\infty}^{\infty} Z(p + \Omega) \tilde{\rho}(p + \Omega) \times \exp(-i(p + \Omega)\phi - i\Omega\theta)$$

$$\psi' = v_s(I)$$

- Vlasov eq. becomes an integral eq. for $f_m(I)$:

$$\sum_{m=0}^{\infty} \int_{-\infty}^{\infty} \dots$$

where I_b = circulating current and

$$C_m(q) = \frac{q^2}{\pi} \int_{-\phi_{\max}}^{\phi_{\max}} \left[\frac{\cos(q\phi_{\max})}{\sin(q\phi)} \right] \frac{1}{\pi} \left[\frac{2}{\pi} \phi_{\max} \right]$$

- The integral eq. for unknown $f_m(I)$ can be solved by expanding $f_m(I)$ with a set of orthogonal polynomials.

- For a Gaussian energy distribution $f_0(I)$, the best choice is the Laguerre polynomials $L_k(x)$.

- Finally, we get a matrix eigenvalue eq. for Ω :

$$\Omega \mathbf{a} - \mathbf{N} \mathbf{a} = \mathbf{M} \mathbf{a}$$

where

$$N_{nl}^{mk} = -m \frac{\pi \eta}{\sqrt{2\phi_{\max}} \beta^2} \left(\frac{\Delta E}{E_0} \right)_{\text{rms}} \delta_{mn} L_{kl}$$

$$L_k = \int_0^{\phi_{\max}} \sqrt{x} e^{-x} L_k(x) L_m(x) dx$$

$$\dots$$

Resonator impedance

Analytical result

GAUSSIAN, $\sigma_E = 0.212\%$, $R = 10k\Omega$, $Q = 1$, $f_r = 3.4MHz$, $Imax = 29$, $nmax = 10$
 Barrier Buckets at $\pm 150^\circ$, $\Omega_0 = 1.065640e+02$ /sec

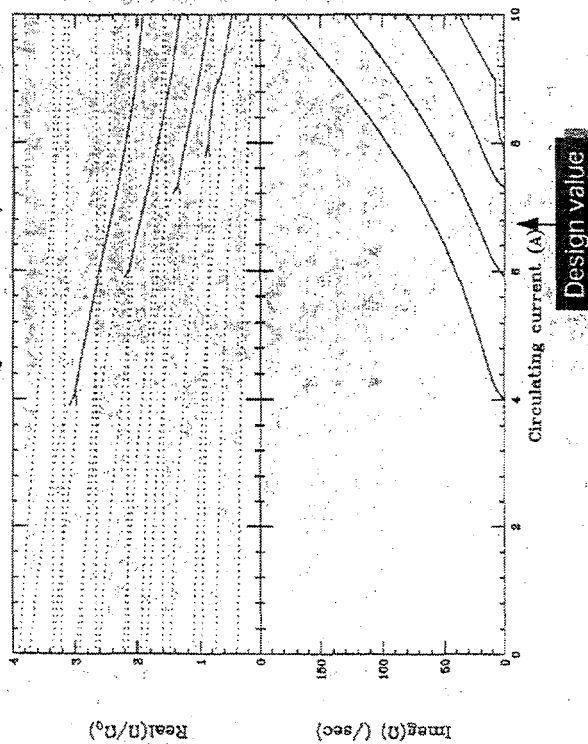


Fig. 1: Coherent synchrotron mode frequencies (Ω_0) and the growth rate as a function of circulating current.

Numerical examples

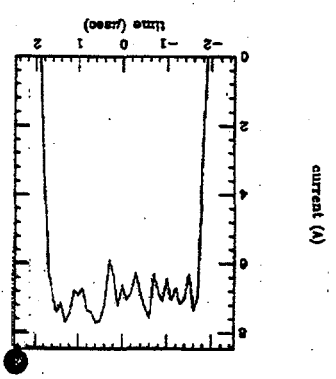
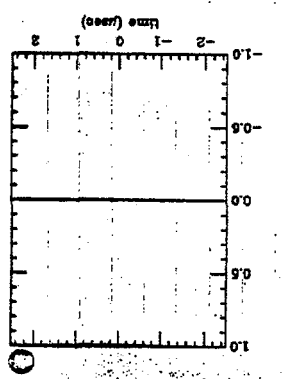
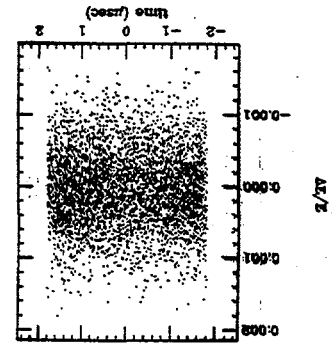
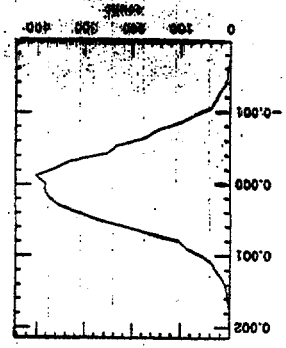
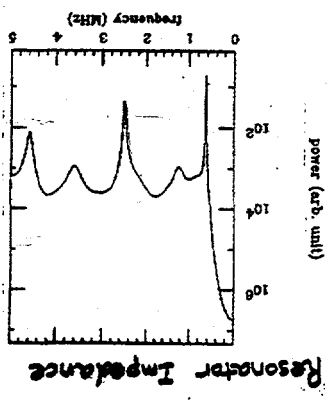
Main parameters of JHF 50 GeV proton synchrotron at injection

Injection energy, E_i	3 GeV
Circumference, C	1442 m
Design circulating current, I_b	6.65 A
Slippage factor, η	-0.05
Half bunch length in angle, ϕ_{max}	150 degree
RMS energy spread, $(\Delta E/E_0)_{rms}$	0.212%
RMS synchrotron frequency, $\Omega_0/2\pi$	16.97 Hz
Impedance of the ring, R_s	10 k Ω
Resonant frequency, f_r	3.4 MHz
Q-value	1

- Two impedance cases to be studied by the theory and simulations:
 - # Resonator impedance
 - # Pure inductive impedance
- the strength chosen to be equal to that of the resonator impedance at low frequency

Before wakes on
 $\left(\frac{\Delta E}{E}\right)_{rms} = 0.05\%$

TURN = -20000
 Energy = 5 GeV
 Idrac = 5 A
 TD = 5 mas
 NSUPERM = 5000
 dspace = 0.01 mas
 dpart = 0.1 mas
 calgmsid = 1.8 mas
 opestrmsid = 0.0005
 thar = 0.0121161 mas
 talgms = 1.03712 mas
 ephbar = 1.08877e-05
 opestrms = 0.00051133



Simulation result

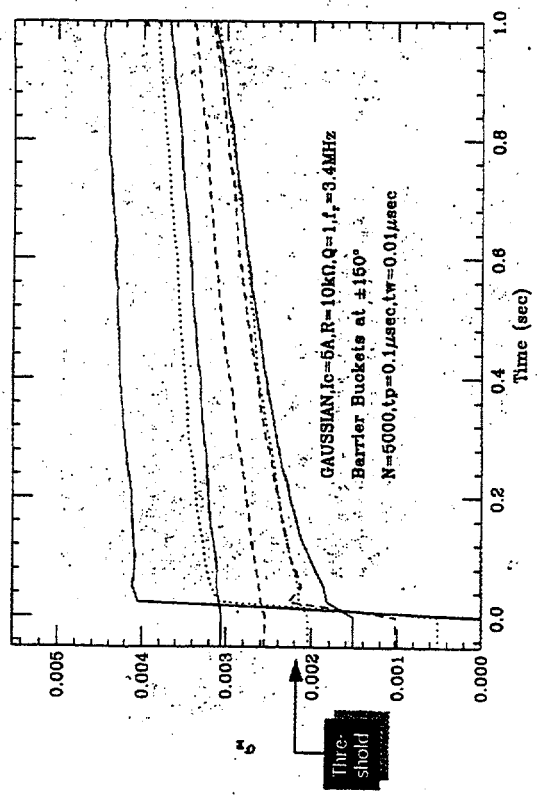
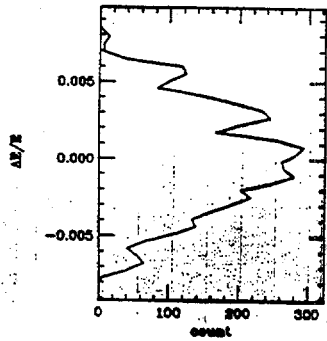
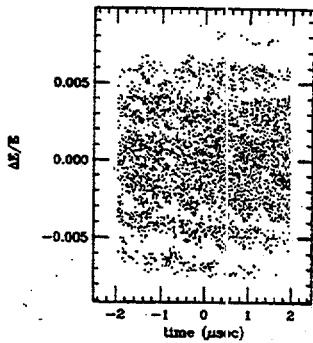
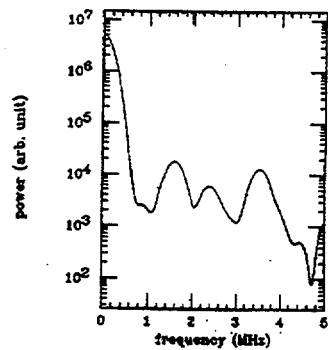
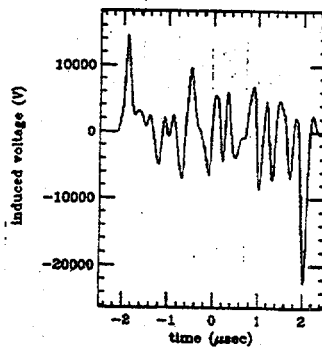
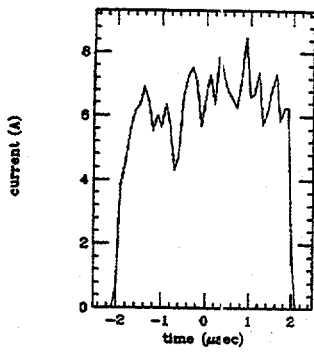


Fig. 2: Time evolution of the rms energy spread at 5A for various initial energy spreads.

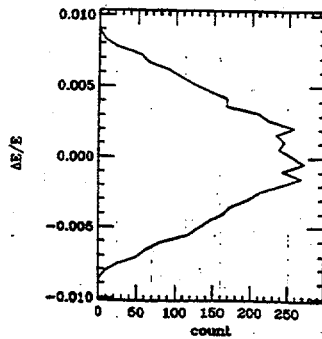
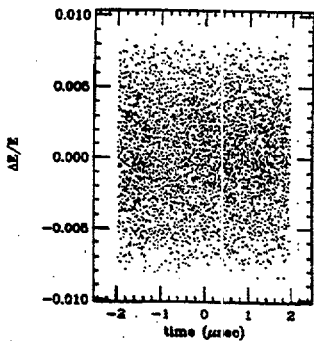
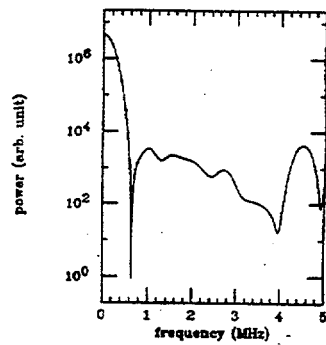
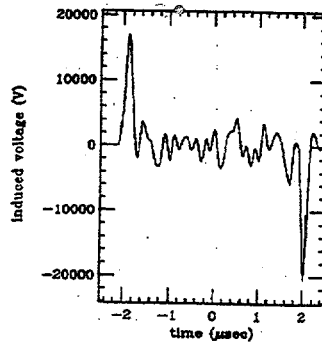
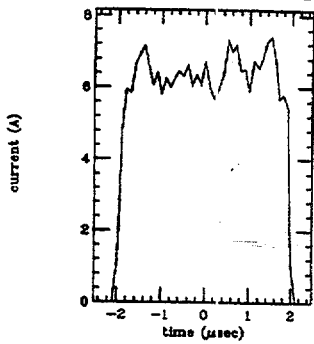
Resonator Impedance



75 nsec ($\frac{5}{4}$)

TURN = 15000
 Energy = 3 GeV After Wakes On
 Icir = 5 A
 T0 = 5 μs
 NSUPER = 5000
 dtwake = 0.01 μs
 dtpart = 0.1 μs
 tsigmaint = 1.8 μs
 epsigmaint = 0.0005
 tbar = 0.0789089 μs
 tsigma = 1.10414 μs
 epibar = 0.00019916
 epsigma = 0.00321979

Resonator Impedance



500 nsec ($2.3 \frac{1}{2}$)
 After Wakes On

TURN = 100000
 Energy = 3 GeV
 Icir = 5 A
 T0 = 5 μs
 NSUPER = 5000
 dtwake = 0.01 μs
 dtpart = 0.1 μs
 tsigmaint = 1.8 μs
 epsigmaint = 0.0005
 tbar = 0.019706 μs
 tsigma = 1.12515 μs
 epibar = 9.40349e-05
 epsigma = 0.00351361

Inductive Impedance

- The coasting beam theory predicts the excitation of the negative mass instability.

Analytical result

- The simulation for 5A shows that the energy distribution stops to blow up at the initial spread of about 0.20%, in good agreement with the analytical result.
- The phase space plots show a uniform particle density after the blow-up the energy spread.

A signature of the microwave instability

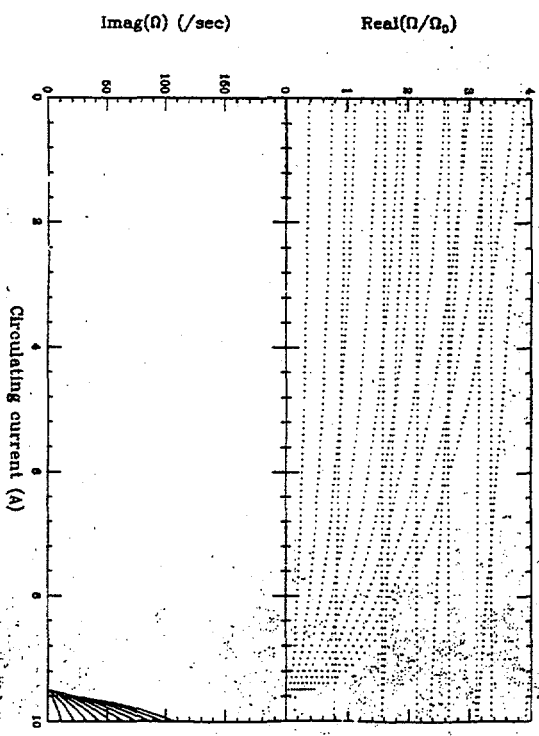
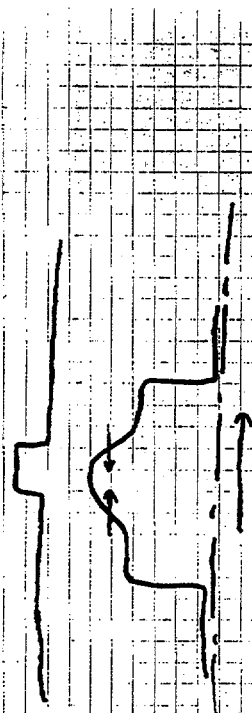


Fig. 4: Coherent synchrotron mode frequencies (Ω / Ω_0) and the growth rate as a function of circulating current.



Negative Mass Instability

Simulation result

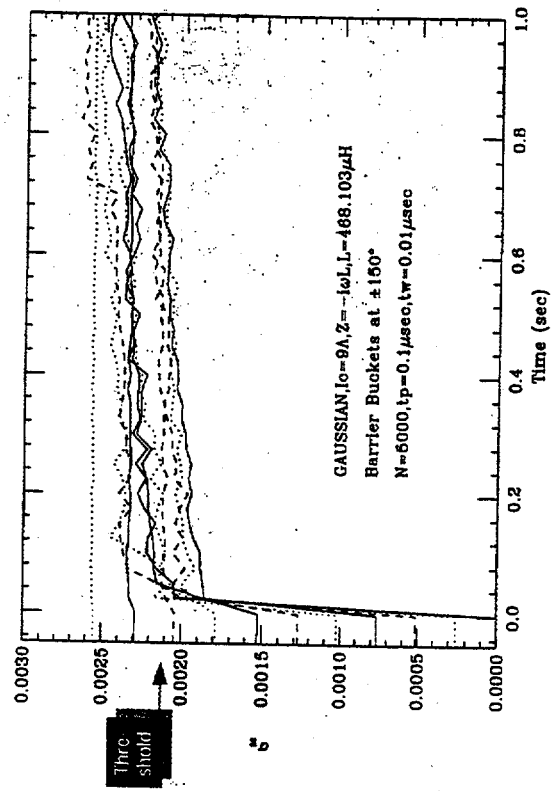


Fig. 5: Time evolution of the rms energy spread at 9A for various initial energy spreads.

Simulation result

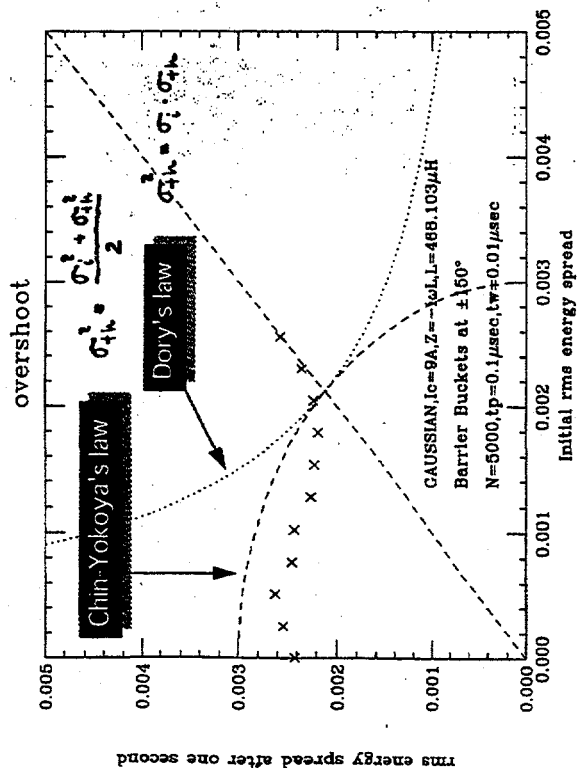


Fig.7: Overshooting of the energy spread. The final spread versus the initial spread.

Simulation result

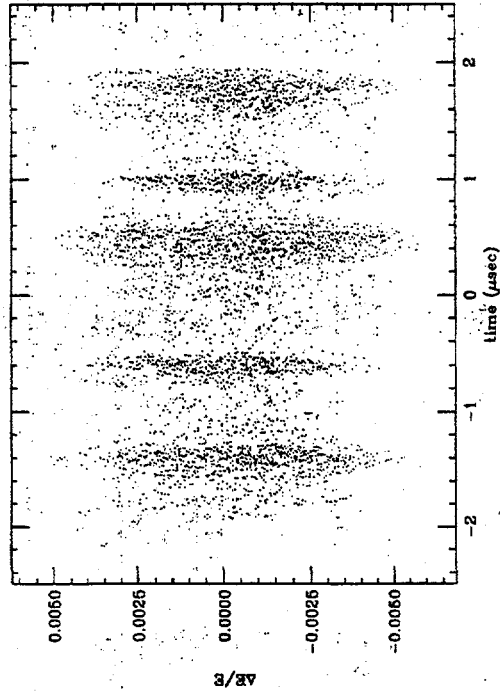
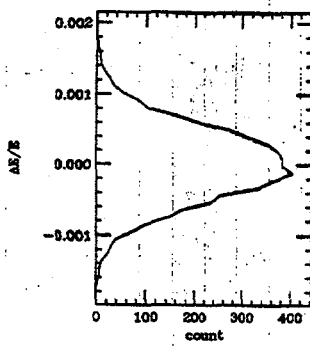
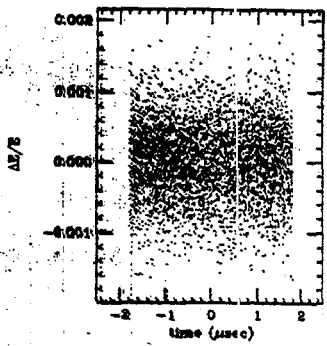
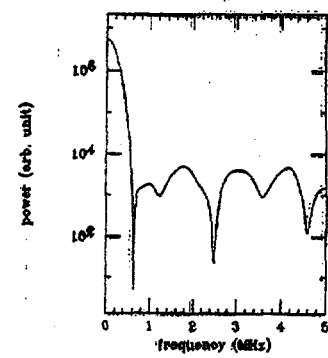
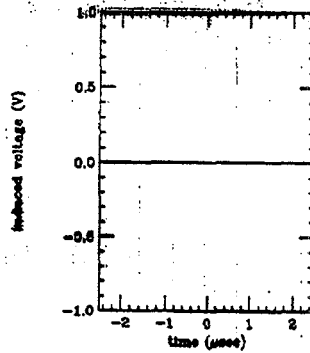
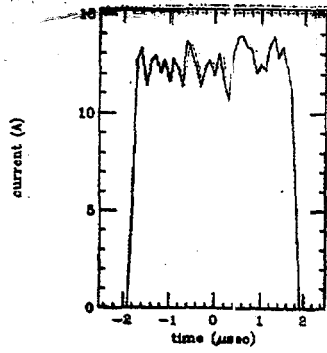


Fig.6: Phase space distribution after the instability ceased for the initial energy spread of 0.05%.

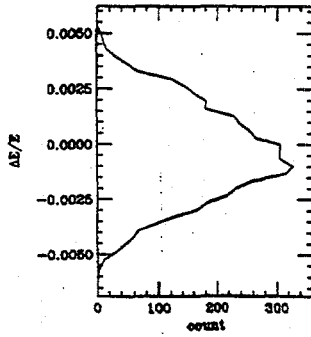
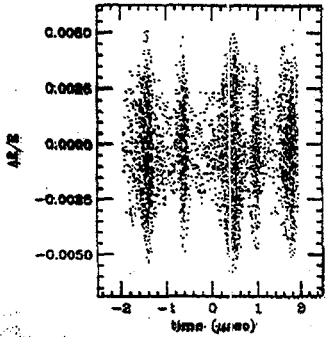
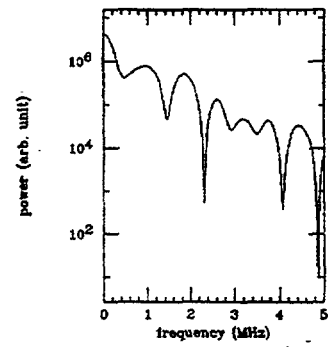
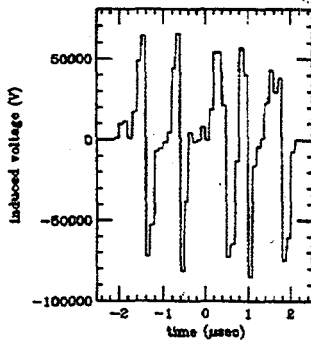
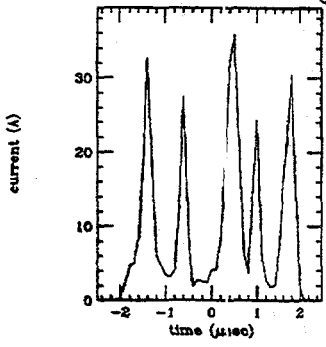
Inductive Impedance



Before Wakes On

TURN = -20000
 Energy = 3 GeV
 icirc = 9 A
 TU = 5 mus
 NSUPER = 5000
 dtwake = 0.01 mus
 dtpart = 0.1 mus
 tsigmam1 = 1.8 mus
 epsigmam1 = 0.0005
 tbar = 0.0121161 mus
 tsigma = 1.03712 mus
 epabar = 1.08877e-05
 epsigma = 0.00051133

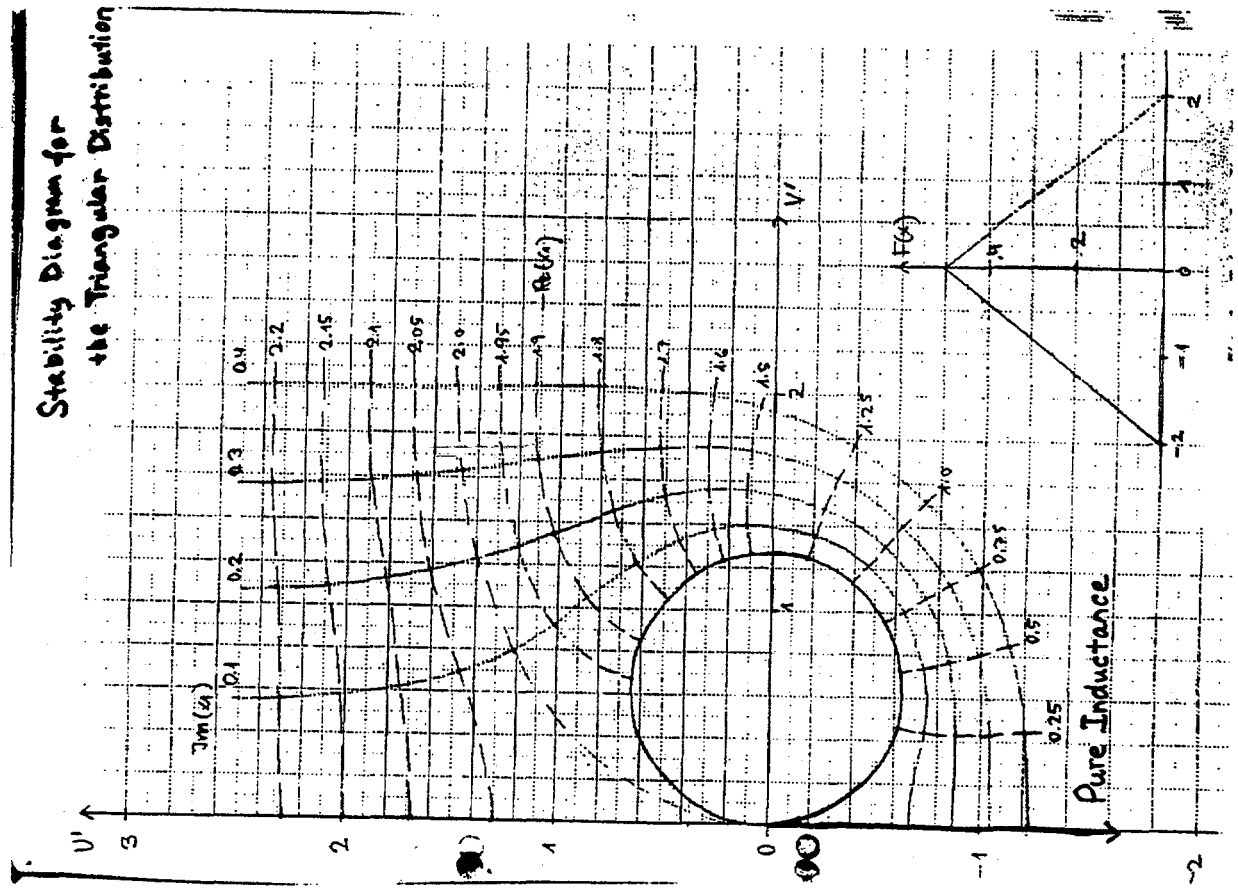
Inductive Impedance



25msec (0.4%)
 After Wakes On

TURN = 6000
 Energy = 3 GeV
 icirc = 9 A
 TU = 5 mus
 NSUPER = 5000
 dtwake = 0.01 mus
 dtpart = 0.1 mus
 tsigmam1 = 1.8 mus
 epsigmam1 = 0.0005
 tbar = 0.16608 mus
 tsigma = 1.14167 mus
 epabar = -0.000372246
 epsigma = 0.0019937

Stability Diagram for the Triangular Distribution



- The simulation at 9A shows that the energy distribution stops to blow up at the initial spread of about 0.21%, in good agreement with the analytical result again.

- Strong concentration of particles can be observed in the phase space after the instability ceased.

An evidence of the
negative mass instability

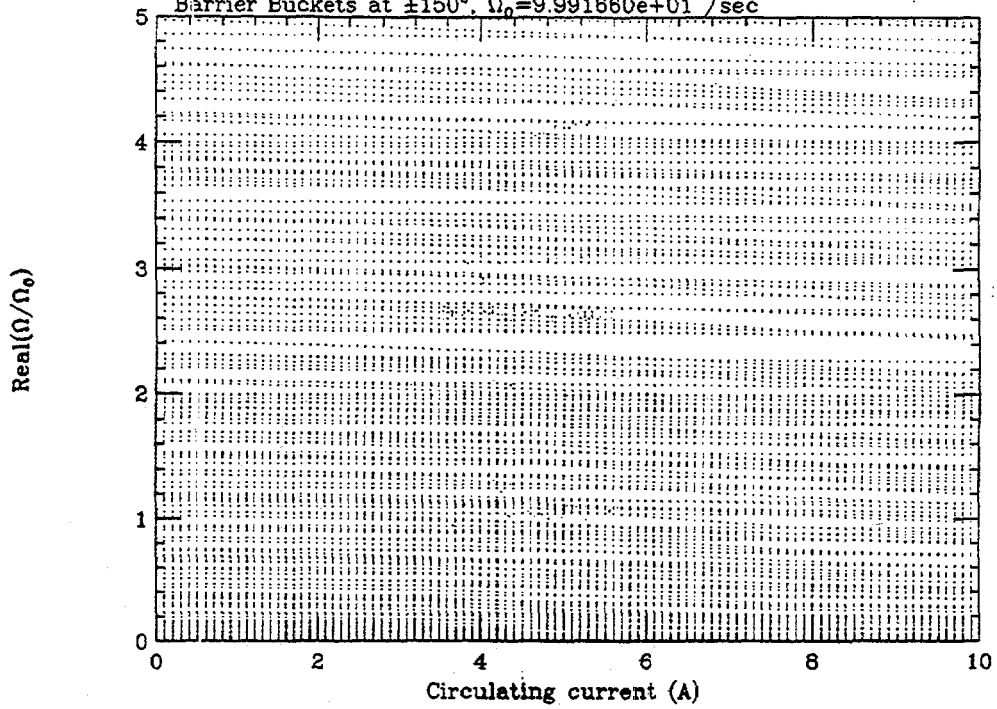
- The negative mass instability has the same threshold for all coasting beam mode "n" for an inductive impedance:

$$\left| \frac{Z_L}{n} \right| \leq \frac{E\beta^2 |n|}{eI_p} \left(\frac{\Delta p}{p} \right)_{FWHM}^2$$

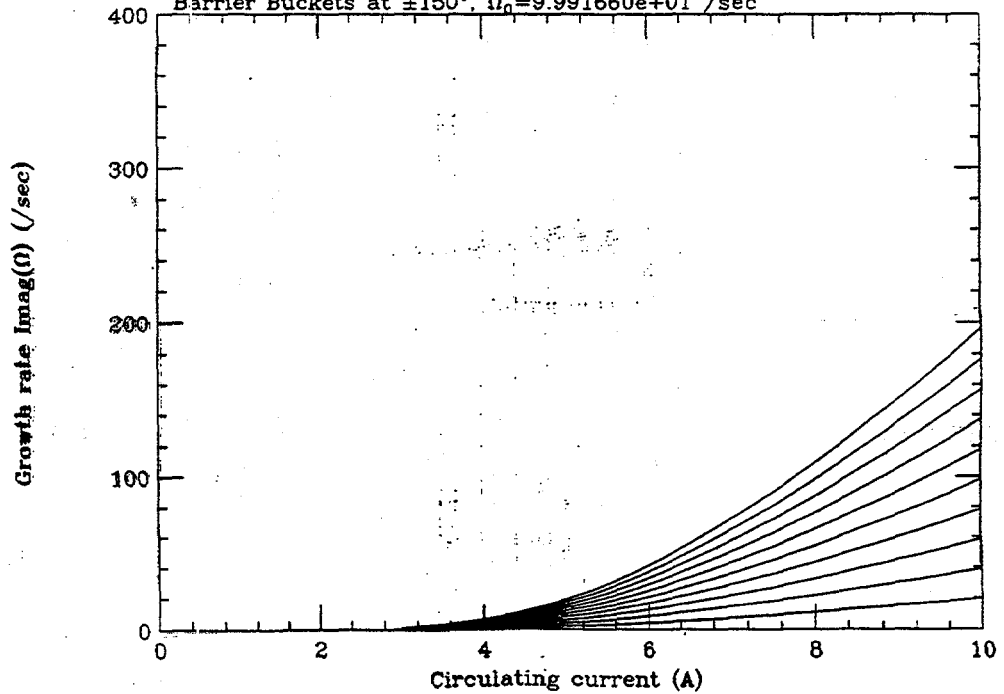
(Keil-Schnell-Boussard
criterion)

This behavior agrees with the simultaneous onset of mode-coupling instabilities of all synchrotron modes.

TRIANGULAR, $\sigma_p=0.204\%$, $L=468.103\mu\text{H}$, $l_{\text{max}}=29$, $m_{\text{max}}=10$
Barrier Buckets at $\pm 150^\circ$, $\Omega_0=9.991660\text{e}+01$ /sec



TRIANGULAR, $\sigma_p=0.204\%$, $L=468.103\mu\text{H}$, $l_{\text{max}}=29$, $m_{\text{max}}=10$
Barrier Buckets at $\pm 150^\circ$, $\Omega_0=9.991660\text{e}+01$ /sec



Fast P-P Update Schemes M. Blaschke

Motivation: Allows for smooth symplectic modeling of the space charge force in reasonable time
 γ_k = arrival time of particle k
 $k = 1, 2, \dots, N$

δ_k = momentum deviation

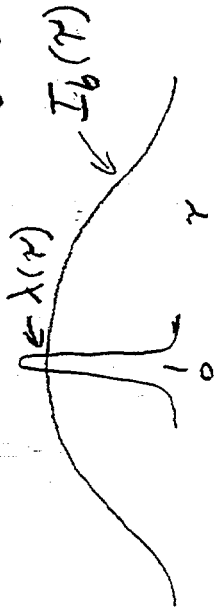
$$\hat{V}(\vec{\delta}, \vec{\gamma}) = \frac{k}{2} \sum_{j,k} \lambda(\gamma_j - \gamma_k)$$

$$F = - \sum_k \tilde{\gamma}_k \delta_k + \hat{V}(\vec{\delta}, \vec{\gamma})$$

$$\gamma_i = - \frac{\partial F}{\partial \delta_i} = \tilde{\gamma}_i$$

} Canonical Transformation Goldstein #3

$$\delta_i = - \frac{\partial F}{\partial \tilde{\gamma}_i} = \delta_i - \frac{\partial \hat{V}}{\partial \tilde{\gamma}_i}$$



SO

$$\bar{\delta}_k = \delta_k - k \sum_{j=1}^N \lambda'(\gamma_k - \gamma_j)$$

The pairwise sum for all N particles can be done in $O(N \log N)$ operations for appropriate $\lambda(\gamma)$.

$$\lambda(\gamma) = (1 + \alpha|\gamma|) e^{-\alpha|\gamma|}$$

continuous with continuous 1st and 2nd derivatives

$$\lambda'(\gamma) = -\alpha^2 \gamma e^{-\alpha|\gamma|}$$

$$\bar{\delta}_k = \delta_k + k \alpha^2 \sum_j \gamma_j e^{-\alpha|\gamma_k - \gamma_j|}$$

$$= \delta_k + \alpha^2 K F_k$$

[$\delta \rightarrow P_x$
 $(\gamma_k - \gamma_j) \rightarrow (X_k - X_j)$]

$$F_k = \sum_{j=1}^k (\gamma_k - \gamma_j) e^{-\alpha(\gamma_k - \gamma_j)}$$

The Trick:

Sort $\gamma_j \leq \gamma_{j+1}$ which is $O(N \log N)$ with Heapsort or Quicksort

$$F_k = \sum_{j=1}^k (\gamma_k - \gamma_j) e^{-\alpha(\gamma_k - \gamma_j)} + \sum_{j=k+1}^N (\gamma_k - \gamma_j) e^{\alpha(\gamma_k - \gamma_j)}$$

$$= \gamma_k (S1_k^- + S1_k^+)$$

$$- (S2_k^- + S2_k^+)$$

$$S2_k^- = \sum_{j=1}^k \gamma_j e^{\alpha(\gamma_j - \gamma_k)}$$

$$= \gamma_k + \sum_{j=1}^{k-1} \gamma_j e^{\alpha(\gamma_j - \gamma_k + \gamma_{k-1} - \gamma_{k-1})}$$

$$= \gamma_k + e^{\alpha(\gamma_{k-1} - \gamma_k)} S1_{k-1}^-$$

$$\text{Since } \gamma_k \geq \gamma_{k-1}, e^{\alpha(\gamma_{k-1} - \gamma_k)} \leq 1$$

and the recurrence relation

is stable

$$S2_k^+ = \sum_{j=k+1}^N \gamma_j e^{-\alpha(\gamma_k - \gamma_j)} = (S2_{k+1}^+ + \gamma_{k+1}) e^{\alpha(\gamma_j - \gamma_{j+1})}$$

again stable

So, start with

$$S0^- = 0, S_N^+ = 0$$

and use

$$S1_{n+1}^- = 1 + e^{\alpha(\gamma_n - \gamma_{n+1})} S1_n^-$$

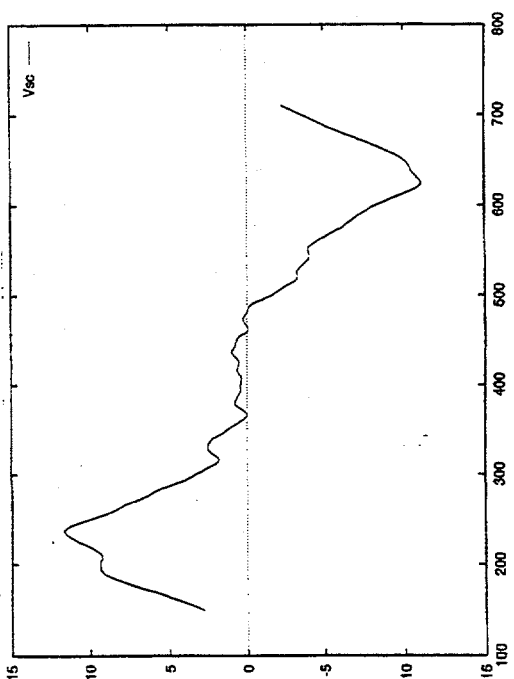
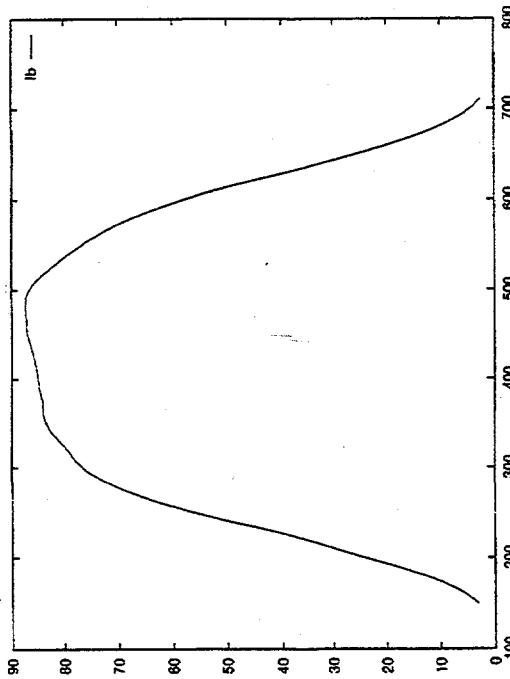
$$S2_{n+1}^- = \gamma_n + e^{\alpha(\gamma_n - \gamma_{n+1})} S2_n^-$$

$$S1_{n-1}^+ = (1 + S1_n^+) e^{\alpha(\gamma_{n-1} - \gamma_n)}$$

$$S2_{n-1}^+ = (\gamma_n + S2_n^+) e^{\alpha(\gamma_{n-1} - \gamma_n)}$$

Recurrence is $O(N)$ so $O(N \log N)$ total

2



2 MW
NSNS

HOM Dampers for RHIC 28.1 MHz
Accelerating Cavity:

Stability in RHIC?

RF Workshop @BNL
May 8, 1997

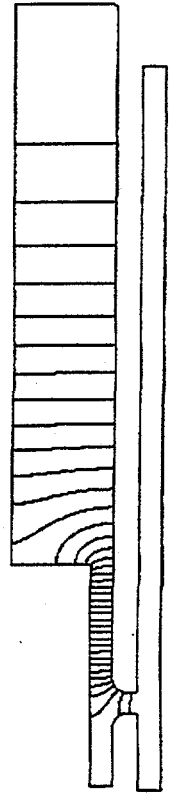
Jim Rose, RHIC rf

SUPERFISH Output for 28 MHz
Cavity (150 kHz low to allow final
tuning after manufacture)

1SUPERFISH DTL summary 11/19/95 11:27:39
Problem name =FINAL 28.15 Mhz Cavity- 14 Sep 1
Mesh problem length [L] = 200.0000 cm
Stored energy [U] for mesh problem only = 7179.22754 mJ
Power dissipation [P] for mesh problem only = 77675.50 W
Q (2.0*pi*f(Hz)*U(J)/P(W)) = 16200
Transit time factor [T] = 0.92430
Shunt impedance [Z] mesh problem only, ((Eo*L)**2/P) = 1.030 Mohm
Shunt impedance per unit length [Z/L] = 1.030 Mohm/m
Magnetic field on outer wall = 2748 A/m
Hmax for wall and stem segments at z=214.43, r=13.49 cm = 8534 A/m
Emax for wall and stem segments at z= 29.69, r=13.07 cm = 10.776 MV/m

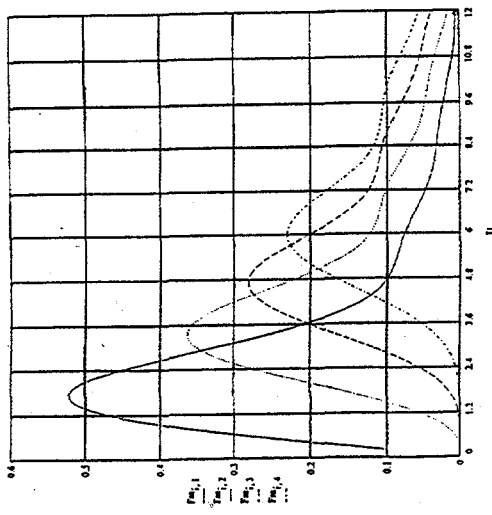
Beta T Tp S So G/L Z/L
0.37221783 0.92430 0.02374 0.37410 0.05623 0.007191 1.029926

ISEC	zbeg (cm)	rbeg (cm)	zend (cm)	rend (cm)	Emax*eparel (MV/m)	Power (W)	df/dz (MHz/mm)	df/dr	
Wall	0.0000	6.1900	20.9500	6.1900	4.4639	0.0395	0.0000	0.0006	
2	20.9500	6.1900	21.4500	6.6900	7.9438	0.0542	0.0011	0.0011	
3	21.4500	6.6900	21.4500	9.4800	8.5137	1.0077	0.0061	0.0000	
4	21.4500	9.4800	17.4500	13.4800	6.7360	9.0926	0.0056	0.0023	
5	17.4500	13.4800	1.5600	11.4900	0.4071	31.2894	0.0000	0.0000	
6	1.5600	13.4900	1.5600	20.0000	0.0185	10.5454	0.0000	0.0000	
7	1.5600	20.0000	62.7000	20.0000	8.2558	1329.1914	0.0000	0.0958	
8	62.7000	20.0000	63.3350	20.6350	8.4820	87.3094	0.0049	0.0000	
9	63.3350	20.6350	63.3350	41.9989	6.2291	1738.2368	0.0044	0.0000	
10	63.3350	41.9989	216.9305	41.9989	0.6321	16276.6230	0.0000	-0.0229	
11	216.9305	41.9989	216.9305	15.3988	0.1076	5750.1382	-0.0103	0.0000	
12	216.9305	15.3988	215.0255	13.4938	0.1962	1206.7163	-0.0013	-0.0014	
13	215.0255	13.4938	31.4597	13.4938	8.9394	51211.0625	0.0000	0.0777	
14	31.4597	13.4938	27.4465	9.4806	10.7765	22.9688	0.0253	0.0291	
15	27.4465	9.4806	27.4465	6.6980	9.1360	1.1670	0.0079	0.0000	
16	27.4465	6.6980	27.9585	6.1900	8.2337	0.0596	0.0012	0.0012	
17	27.9585	6.1900	27.9585	6.1900	8.2337	0.0596	0.0012	0.0012	
Wall	Total =					77675.5078			

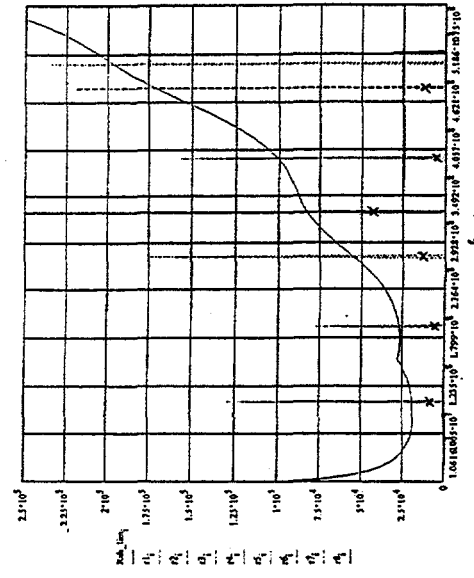


FINAL 28.15 Mhz Cavity- 14 Sep 1995= 27.897

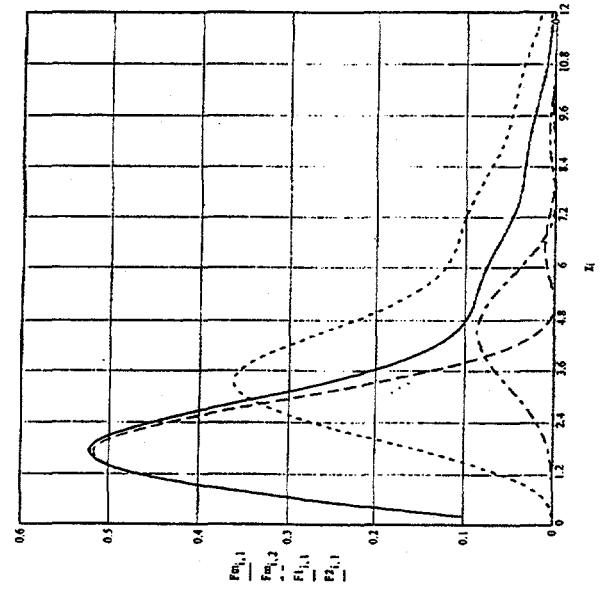
Form Factors for Degenerate case (Σ azimuthal modes)



Impedance limit for growth rates of 2 sec⁻¹ with undamped (lines) and damped (x's) HOM impedances superimposed



Form Factors for the degenerate case of the radial modes summed over $k=1,4$; $m=1$ (dipole) $m=2$ (quadrupole)



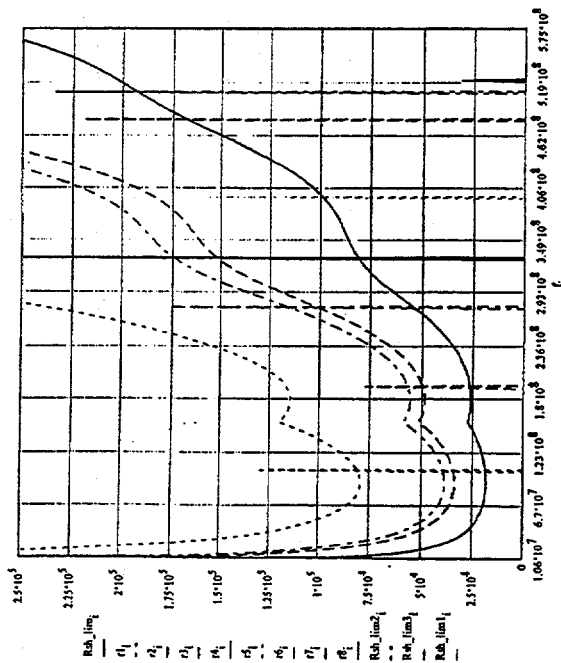
$$F_{1,1,1} = \frac{m_1 \mu (\mu + 2k) \frac{J_1^{(2k+1)}(k)}{k}}{(m_1 + 2k + \mu) \Gamma(k + \mu) \Gamma(m_1 + k + \mu) \ln(n_1 \gamma_1)^2}$$

Distribution $\varphi(\epsilon) = K \left[1 - \left(\frac{\epsilon}{\epsilon_0} \right)^2 \right]^\mu \quad \mu = 1$

Impedance limit for $\frac{1}{\tau} = 2 s^{-1}$
and various bunch lengths and gap volts

$$\chi = \frac{\omega_{res}}{\omega_{rf}} \hat{r}_\phi ; \hat{r}_\phi = \text{bunch half length in radians } r_f$$

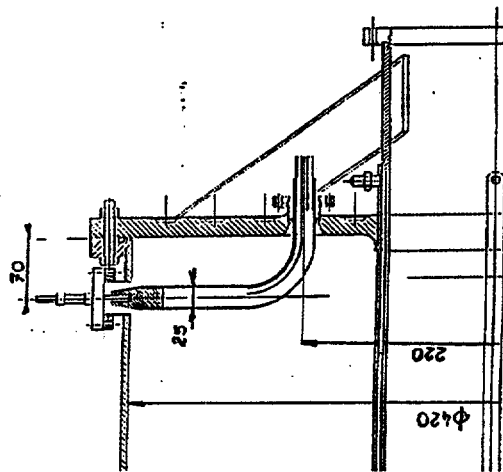
$$\frac{1}{\tau} = \frac{\omega \phi}{\hat{r}_\phi} = \frac{I_0 R_{sh}}{V_r \cos \phi_r} F$$



$$R_{sh_lim} = \frac{\tau \hat{r}_\phi V_r \cos \phi_r}{\omega_r I_0} F$$

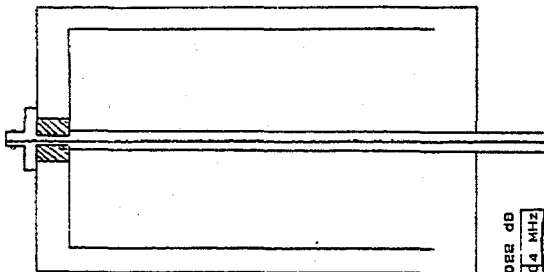
HOM dampers performances (two damping loop-longitudinal modes only). MAFLA results.

Nr.	NO HOM INSTALLED						DAMPERS INSTALLED		ENERGY FACTOR
	F [MHz]	R _{sh} [kΩ]	Q [-]	R/Q [Ω]	R _{sh} [kΩ]	R _{sh} /R _{sh'}			
1	27.7	1120	17900	62.6	1120	1			
2	104.7	166	29250	5.7	1.3	128			
3	197.9	5.4	22800	2.4	1.4	38.6			
4	269.2	86.3	21400	4.0	7.0	12.3			
5	279.0	105.0	20400	5.2	10.1	10.4			
6	324.3	342.5	31400	10.3	14.5	23.6			



HOM DAMPER (COUPLING LOOP)

Prototype HOM Damper Notch Filter

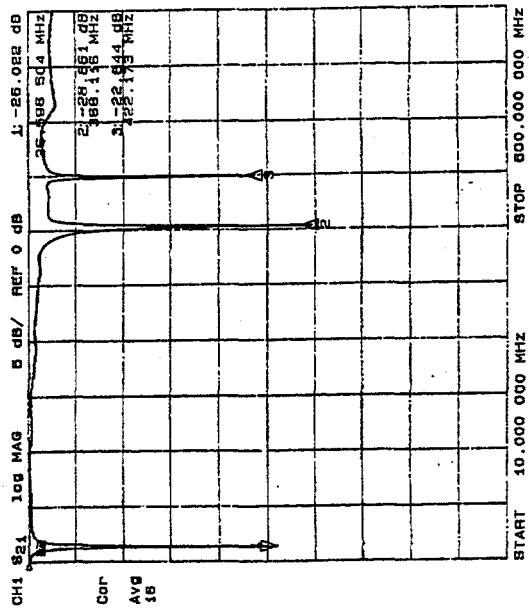


"Folded" Quarter wave resonator creates open circuit at fundamental rf frequency; similar to parallel L-C notch filter

Dimensions of 370 mm long by 150mm diameter

Bench test:

Notch depth of -49 dB, 2nd notch at 368 MHz, 3rd at 422 MHz



```

SHOndamp.dat HOM notch Jan 03, 15
$reg dx=0.1, xmax=32.48, ymax=15.24,
freq=27, xdir=30.48, ydir=15.24,
$po x=0.0, y=0.0 $
$po x=30.48, y=15.24 $
$po x=30.48, y=2.064 $
$po x=1.635, y=2.064 $
$po x=1.635, y=13.9225 $
$po x=28.48, y=14.24 $
$po x=1.0, y=14.24 $
$po x=1.0, y=1.939 $
$po x=32.48, y=1.939 $
$po x=32.48, y=0.0 $
$po x=0.0, y=0.0 $

```

SHOndamp.dat HOM notch Jan 03, 1995 Freq = 27.000

$V_{in} = 10.7 \text{ kV}$ at 400kV gap volts

$R_{shunt} = 81 \text{ k}\Omega$, Power dissipated = 700 Watts

~325 mm long x 300 mm diameter

W. 1.3 eV's
26.1 mHz, 600KV

2 DAMPERS
WITH 1/2 UNIT
90-1004

MAFIA RESULTS (NO HOM INSTALLED)					2 Dampers installed		Damping factor		Loop resonances		Loop voltage	
Nr	F _{res} (Hz)	Re ₀ (kΩ)	Q ₀ (-)	R/Q ₀ (Ω)	Re ₀ /R _{sh}	R _{sh} /R _{sh}	X ₀ (Ω)	-R _{sh} /R _{sh}	X ₀ (Ω)	-R _{sh} /R _{sh}	X ₀ (Ω)	-R _{sh} /R _{sh}
1	26.3	1060	17900	59.4	1060	1	+j16.8	10.4	+j16.8	10.4	+j16.8	10.4
2	103.2	133	29500	4.5	4.7 (1.3)	28.3	+j92	123	+j92	123	+j92	123
3	192.2	88	37000	2.4	1.4 (1.4)	63	+j950	1250	+j950	1250	+j950	1250
4	275.1	236	28100	8.4	8.6 (1.6)	27.4	-j134	64	-j134	64	-j134	64
5	313.3	58	16700	3.5	52.5	1.1	-j95	5.9	-j95	5.9	-j95	5.9
6	322.7	270	22400	12.1	23 (4.4)	26.2	-j92	26.2	-j92	26.2	-j92	26.2
7	377.5	20	46300	0.4	4	11.7	-j70	50.1	-j70	50.1	-j70	50.1
8	390.6	165	46700	3.5	6.6 (3.5)	25	-j61	40.3	-j61	40.3	-j61	40.3
9	453.6	223	20800	10.7	112 (2.36)	2	-j42	5.9	-j42	5.9	-j42	5.9
10	492.7	24	35500	0.7	12.4 (4.2)	1.9	-j33	15	-j33	15	-j33	15

Table 2

POP CAVITY - MAFIA RESULTS

MOD E-NR	TEST RESULTS										
	F _{res} (Hz)	Re ₀ (kΩ)	Q ₀ (+1000)	R _{sh} /Q ₀	R _{sh} /R ₀	R ₀ /R ₀	F _{DRH}	Q ₀ (+1000)	Q ₀ (-1000)	Q ₀ (+1000)	Q ₀ (-1000)
1	26.7	1110	16.4	67.7	76	14.6	26.88	17.3	1.1	15.7	15.7
2	99.1	72.1	25.5	2.8	0.8	90	98.8	19.8	0.19	102	102
3	157.9	5.8	30.8	0.19	0.03	193	157.7	22.3	0.11	203	203
4	215.7	4.4	38.2	0.12	0.07	63	216.3	29.0	0.46	63	63
5	286.4	98	27.6	3.6	9.0	10.9	287.4	8.0	1.5	5.3	5.3
6	343.4	180	19.2	9.4	32.0	5.6	342.2	8.7	2.1	4.2	4.2
7	406.0	112	40.5	2.8	4.7	23.8	402.2	2.3	1.1	2.1	2.1

TABLE 3.

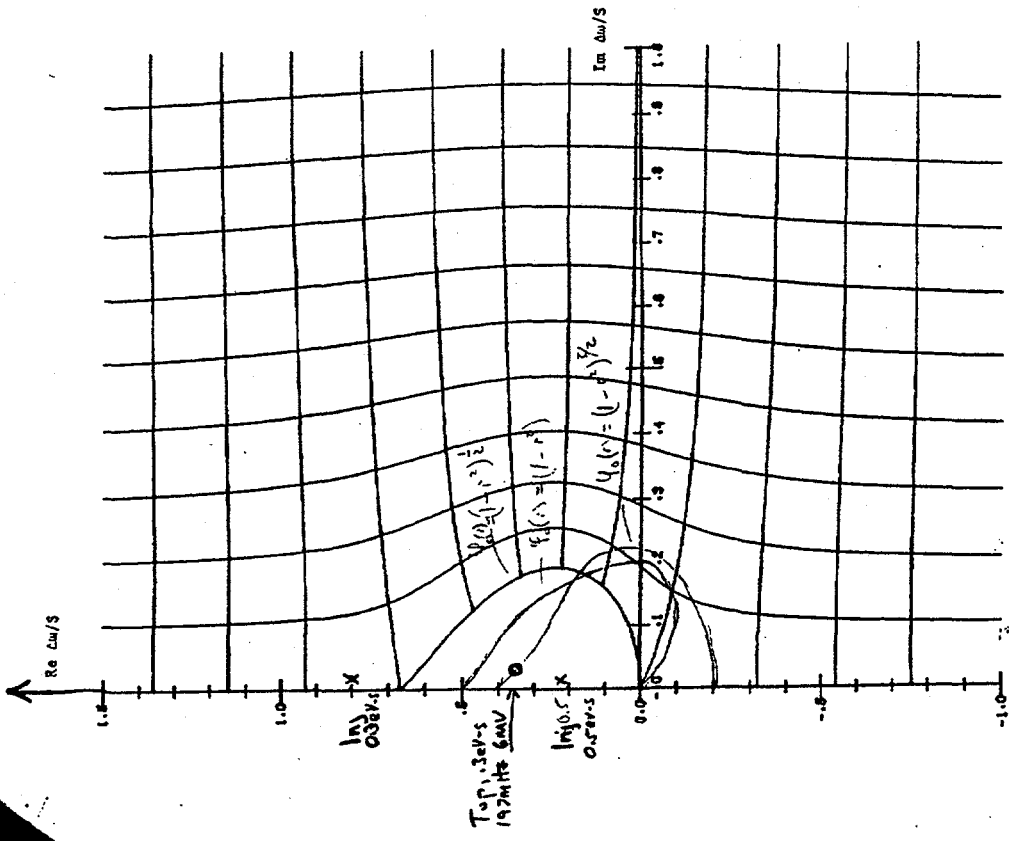


Fig. 1 Stability diagram for beams with parabolic line density.

Session on Beam Loading and rf System Stability

J.M. Brennan

Emmanuel Onillon of Brookhaven gave a lecture on state variable techniques for feedback system analysis and design. He presented a pedagogical summary of the state variable formulation of the analysis of dynamical systems, with frequent references to the classical transfer function technique. For feedback systems used in accelerator applications the state variable technique is attractive because it provides a means for optimizing the performance of complex systems where many loops operate simultaneously. Two techniques were described which allow the designer to find the best set of settings of loop parameters in multi-loop feedback systems such as frequently occur in rf systems.

The two techniques, pole placement and LQR (linear quadratic regulator) were developed in some detail and shown to be complementary. Pole placement is a convenient technique when one wants to obtain analytic formulae for feedback gains in the presence of a changing system parameter, such as, synchrotron frequency or beam energy. LQR is a technique that obtains the optimum set of gains that maximize some performance criterion. Typically the criterion is a weighted sum of output accuracy plus a measure of the control effort.

Onillon showed that in the design of the RHIC beam control system the two techniques were used together. First LQR was used to produce a set of feedback gains and the system poles were obtained. Then analytic relations were found for the gains as functions of beam and rf parameters by pole placement. These analytic relations will be imbedded in the digital signal processing (DSP) algorithms for the RHIC rf beam control system. The benefit is that the system dynamics, bandwidth and tracking error, for example, will be independent of beam energy or rf voltage.

M. Blaskiewicz of Brookhaven presented a description of the rf system for the US National Spallation Neutron Source (SNS) project. Although the rf system does not accelerate the beam because the ring is only an accumulator it is a high power system because of very high beam loading. At 2×10^{14} protons in the ring the rf beam current will approach 80 A. Making the assumption that the cavity will be essentially uncompensated because the injection period (1ms) is shorter than ferrite response time requires full reactive beam current from the power amplifier. The system employs high power tetrodes (600 kW) which are capable of 300 A peak current. Results of a detailed analysis of the tetrodes capabilities based on the constant-current characteristics published by the manufacturer were presented.

Results from particle tracking calculations which included space charge were presented that showed the benefit of tailoring the rf waveform to increase the bunching factor. Addition of a second harmonic voltage improved the bunching factor by 25%, while using a isolated sinewave for a barrier bucket could give an even greater improvement of 35% intensity will ultimately be limited by space charge driven tune spread any improvement in bunching factor will likely translate into increased intensity.

System stability was analyzed according to the conventional considerations used for synchrotrons even though the NSNS ring will not accelerate. Blaskiewicz pointed out that although these consideration are sufficient they may not be necessary and that further work is called for in analyzing the accumulator problem.

Roland Garoby of CERN/PS presented a brief description of a newly commissioned diagnostic system at the PS that measures the phase turn-by-turn of each bunch in the PS. The system is based on a commercial DSP board and commercial constant-fraction timing discriminators. Some typical results were shown that showed how the system can reveal coherent dipole oscillations from injection phase errors from one ring of the PS Booster. The main role of the new system will be in detecting and analyzing longitudinal coherent instabilities in the PS.

STATE VARIABLE ANALYSIS

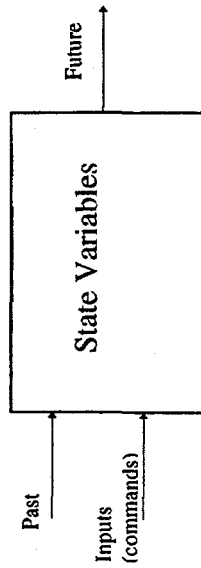
E. Onillon

Concept introduced in control science in the 50's.

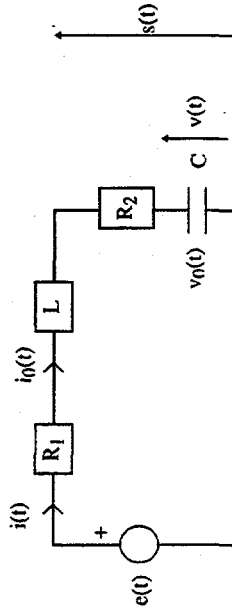
Powerful method, can be used for the study of numerous systems, linear or not, stationary or not, continuous or discrete.

Naturally leads to the idea of optimum control.

Associated with the idea of a prescribed trajectory the system has to follow with a minimum error and at a minimum cost (power for instance).



State vector $\bar{X}(t)$ = minimum set of variables (information on the past) sufficient to calculate the future evolution of the system when we know for $t \geq t_0$ the inputs and its internal physical laws



$$\frac{d}{dt} \begin{bmatrix} i \\ v \end{bmatrix} = \begin{bmatrix} -(R_1 + R_2) & 1 \\ \frac{1}{L} & -\frac{1}{C} \end{bmatrix} \begin{bmatrix} i \\ v \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} e$$

$$s = \begin{bmatrix} 1 \\ 0 \end{bmatrix} v$$

$$F = M\ddot{x} \\ x(0), v(0) \\ x(t), v(t)$$

State vector $\bar{X}(t) = [x_i(t)]^T$ $1 \leq i \leq n$ in order of the system

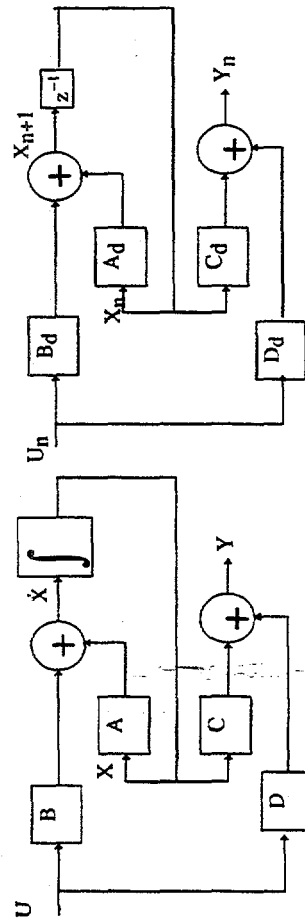
Input vector $\bar{U}(t) = [u_j(t)]^T$ $1 \leq j \leq m$

Output vector $\bar{Y}(t) = [y_k(t)]^T$ $1 \leq k \leq l$

STATE AND OBSERVATION EQUATIONS

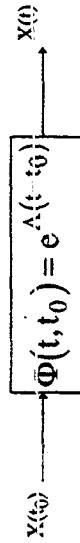
Linear and stationary system: $\begin{cases} \dot{X}(t) = AX(t) + BU(t) & \text{state} \\ Y(t) = CX(t) + DU(t) & \text{observation} \end{cases}$

For a discrete system: $\begin{cases} X_{n+1} = A_d X_n + B_d U_n \\ Y_n = C_d X_n + D_d U_n \end{cases}$



Resolution of the state space equation:

Look for a linear solution



State space representation / Transfer function:

$$\begin{cases} \dot{X}(t) = AX(t) + BU(t) \\ Y(t) = CX(t) + DU(t) \end{cases} \Rightarrow \begin{cases} sX(s) - X(0) = AX(s) + BU(s) \\ Y(s) = CX(s) + DU(s) \end{cases} \Rightarrow$$

$$Y(s) = C(sI - A)^{-1}X(0) + (D + C(sI - A)^{-1}B)U(s)$$

$$H(s) = \frac{Y(s)}{U(s)} = D + C(sI - A)^{-1}B$$

Poles = eigenvalues of A

Example

$$A = \begin{bmatrix} -7 & -12 \\ 1 & 0 \end{bmatrix}, B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, C = [1 \ 2], D=0$$

$$(sI - A) = \begin{bmatrix} s+7 & 12 \\ 1 & s \end{bmatrix}, (sI - A)^{-1} = \frac{\begin{bmatrix} s & -12 \\ 1 & s+7 \end{bmatrix}}{s(s+7)+12}, H(s) = \frac{s+2}{s^2+7s+12}$$

Passage transfer function / state: introduce a new variable

$$\frac{Y(s)}{U(s)} = \frac{Y}{X_1} \cdot \frac{X_1}{U} = \frac{s+2}{s^2+7s+12} \Rightarrow$$

$$Y = sX_1 + 2X_1 + 2X_1 + 7sX_1 + 12X_1 = U$$

or with $X_2 = \dot{X}_1$, (successive derivative)

$$Y = X_2 + 2X_1 \text{ and } \dot{X}_2 = -7X_2 - 12X_1 + U$$

$$\dot{X} = \begin{pmatrix} \dot{X}_1 \\ \dot{X}_2 \end{pmatrix} = \begin{bmatrix} 0 & 1 \\ -12 & -7 \end{bmatrix} \begin{pmatrix} X_1 \\ X_2 \end{pmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} U \text{ and } Y = [2 \ 1] \begin{pmatrix} X_1 \\ X_2 \end{pmatrix}$$

Discrete state space representation

$$\begin{cases} \dot{X}(t) = AX(t) + BU(t) \\ Y(t) = CX(t) + DU(t) \end{cases} \Rightarrow X_{k+1} = e^{A\Delta t} X_k + \int_{t_k}^{t_{k+1}} e^{A(t_{k+1}-\tau)} BU(\tau) d\tau$$

$$\begin{cases} X_{k+1} = e^{A\Delta t} X_k + \int_{t_k}^{t_{k+1}} e^{A(t_{k+1}-\tau)} B d\theta U_k \\ Y_k = CX_k + DU_k \end{cases}$$

POLE PLACEMENT, LQR

$$\text{System: } \begin{cases} \dot{X} = AX + BU \\ Y = CX + DU \end{cases}$$

Commandability

$$X(t_0) \xrightarrow{U(\tau) \tau \geq t_0} X_f \quad ?$$

$$\text{rank} \begin{bmatrix} B & AB & \dots & A^{n-1}B \end{bmatrix} = \text{number of commandable states}$$

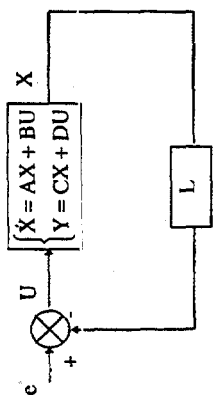
Observability

$$Y(t) \xrightarrow{t \geq t_0} X(t_0) \quad ?$$

$$\text{rank} \begin{bmatrix} C^T & A^T C^T & \dots & A^{n-1} C^T \end{bmatrix} = \text{how many states we can reconstruct}$$

POLE PLACEMENT

Specify the poles you want the system to have



$$U = -LX + e \Rightarrow \dot{X} = \underbrace{(A - BL)}_{\substack{\text{eigenvalues } \lambda_i \\ \text{eigenvectors } v_i}} X + Be$$

(A,B) has to be commandable

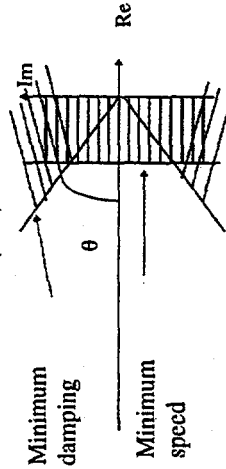
Choice of the eigenvalues (poles of the system)

$\text{Re}(\lambda_i) < 0$ and if $\lambda_i, \bar{\lambda}_i$

The further the λ_i are from the eigenvalues of A, the bigger the command effort is.

If $\lambda_i = a_i + jb_i \rightarrow e^{a_i t} \sin b_i t, e^{a_i t} \cos b_i t$. The bigger $|a_i|$, the faster the system is.

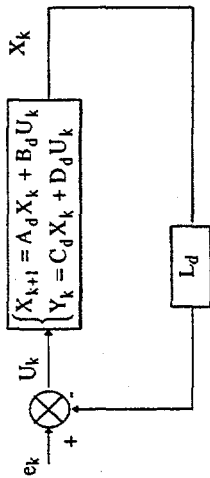
With $|\lambda_i| = \omega_0$ and $\lambda_i + \bar{\lambda}_i = \xi \omega_0 = |\sin \theta| \omega_0$



Determination of L

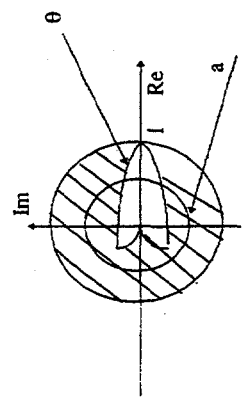
$$\det(\lambda I - (A - BL)) = (\lambda - \lambda_1) \dots (\lambda - \lambda_n)$$

Discrete Systems

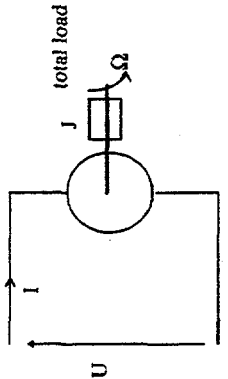


$$U_k = -L_d X_k + e_k \Rightarrow X_{k+1} = (A_d - B_d L_d) X_k + B_d e_k$$

$$\det(\lambda I - (A_d - B_d L_d)) = (\lambda - \lambda_1) \dots (\lambda - \lambda_n)$$



discrete pole = $e^{\text{continuous pole} \cdot \tau_d}$



$$\begin{cases} U(t) = RI(t) + L \frac{dI}{dt} + \Phi_0 I(t) \Rightarrow \frac{d(\Omega I(t))}{dt} = \begin{bmatrix} 0 \\ \frac{\Phi_0}{L} \end{bmatrix} - \begin{bmatrix} \frac{\Phi_0}{L} \\ R \end{bmatrix} I(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} U(t) \\ \Gamma(t) = J \frac{d\Omega}{dt} = \Phi_0 I(t) \end{cases}$$

$$\frac{d\Omega}{dt} = \begin{bmatrix} \Phi_0^2 \\ -RJ \end{bmatrix} \Omega(t) + \begin{bmatrix} \Phi_0 \\ RJ \end{bmatrix} U(t)$$

Numerically, $R=10\Omega$, $J=5 \cdot 10^{-5} \text{ kg m}^2$, $\Phi_0 = 0.1 \text{ USI}$, $T=5\text{ms}$

$$\frac{d\Omega}{dt} = -20\Omega(t) + 2000U(t)$$

$$\Omega(k+1) = -0.905\Omega(k) + 0.952U(k)$$

Continuous system: eigenvalue -20 (50ms)

Divide it by 2

$$e^{-40T} = 0.819 \quad \Omega(k+1) = (-0.905 - 0.952L)\Omega(k) \quad L=0.090$$

LINEAR QUADRATIC REGULATOR (L.Q.R.)

Linear system

$$\begin{cases} \dot{X}(t) = AX(t) + BU(t) \\ X(0) = X_0 \end{cases}$$

Goal: bring the state back to zero (regulator) while minimizing

$$J = \frac{1}{2} \int_0^{\infty} \left(\underbrace{X^T(t) Q X(t)}_{\text{GOAL}} + \underbrace{U^T(t) R U(t)}_{\text{COST}} \right) dt$$

$U_{\text{opt}}(t) = -LX(t) = -R^{-1}B^T P X(t)$ where P satisfies the algebraic Riccati equation: $PA + A^T P - PBR^{-1}B^T P + Q = 0$

Optimal cost $J_{\text{opt}} = X_0^T P X_0$

To find an optimal command

- choose Q and R
- solve the Riccati equation to find L
- command=linear combination of the state variables, the new poles being the eigenvalues of $A-B*L$

(A, B) has to be commandable

Choice of Q and R :

Choose diagonal matrices:

$$J = \frac{1}{2} \int_0^{\infty} (Y^T Q_y Y + U^T R U) dt \text{ with } Y = CX$$

$$Q_y = \begin{bmatrix} q_1 & 0 & 0 \\ 0 & \dots & 0 \\ 0 & 0 & q_p \end{bmatrix}, R = \begin{bmatrix} r_1 & 0 & 0 \\ 0 & \dots & 0 \\ 0 & 0 & r_1 \end{bmatrix}$$

In that case: $J = \frac{1}{2} \int_0^{\infty} (\sum (q_i y_i^2) + \sum (r_j u_j^2)) dt$

q_i and r_j represent the relative importance of the variables toward each other

$$Q_y = \begin{bmatrix} 1 & 0 & 0 \\ 0 & a^2 & 0 \\ 0 & 0 & 0 \dots \end{bmatrix}$$

y_1 .

the bigger a^2 , the bigger the priority of y_2 is compare to

If $R \rightarrow kR$ with $k > 1$, the command will be less strong, the closed system will be slower.

If $Q_y \rightarrow kQ_y$ with $k > 1$, closed loop faster, stonger command

RHIC CASE

Choice of Q and R

done at injection

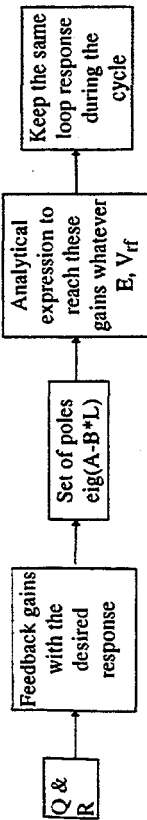
requirement: loop response time

modify Q and R to reach that target

limit the phase excursion by having a stronger coefficient on the phase Command frequency error sent to a DDS: limit the input by minimizing R

Compromise between speed/amplitude of the command and phase excursion

Several iterations before finding Q and R



Just a set of gains could not do it (compromise loop response/stability)

$$\begin{cases} X_{k+1} = A_d X_k + B_d U_k \\ X_{k=0} = X_0 \end{cases}$$

$$J = \frac{1}{2} \sum_{k=0}^J (X_{k+1}^T Q X_{k+1} + U_k^T R U_k)$$

Solution:

$U_k = -L X_k$ with $L = B_d^T P^{-1} B_d + R^{-1}$ where P satisfies the discrete Ricatti equation:

$$P = A_d^T P A_d - A_d^T P B_d (B_d^T P B_d + R)^{-1} B_d^T P A_d + Q A_d$$

Example:

$$\ddot{x}(t) + 2\xi\omega_n \dot{x}(t) + \omega_n^2 x(t) = K u(t)$$

$$\omega_n = (2\pi), \xi = 0.1, K = \frac{1}{(2\pi)^2}$$

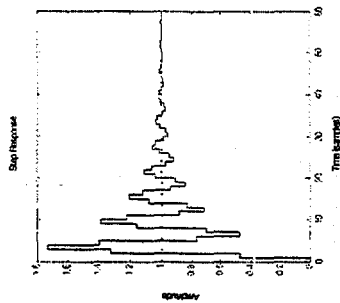
$$x_1 = \dot{x} \text{ and } x_2 = x$$

$$\gamma = 2\xi\omega_n$$

$$T_s = \frac{T_n}{6}$$

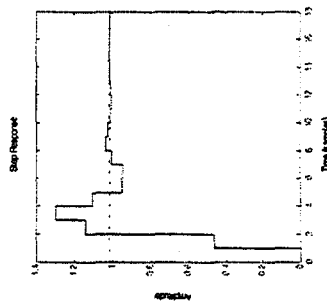
$$A = \begin{bmatrix} 0 & 1 \\ -\omega_n^2 & -\gamma \end{bmatrix}, B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, C = K[1 \ 0], D = 0$$

$$A_d = \begin{bmatrix} 0.5325 & 0.7815 \\ -0.7815 & 0.3762 \end{bmatrix}, B_d = \begin{bmatrix} 0.4675 \\ 0.7815 \end{bmatrix}, C_d = C, D_d = D$$



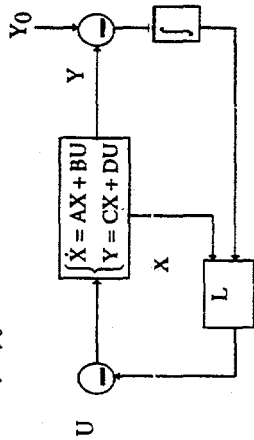
$$Q_d = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, R_d = 1 \Rightarrow L_d = \begin{bmatrix} -0.020 & 0.5246 \end{bmatrix}$$

$$A_d - B_d * L_d = \begin{bmatrix} 0.5381 & 0.5362 \\ -0.7721 & -0.0337 \end{bmatrix}$$



Integral action

If one wants $y = y_0$



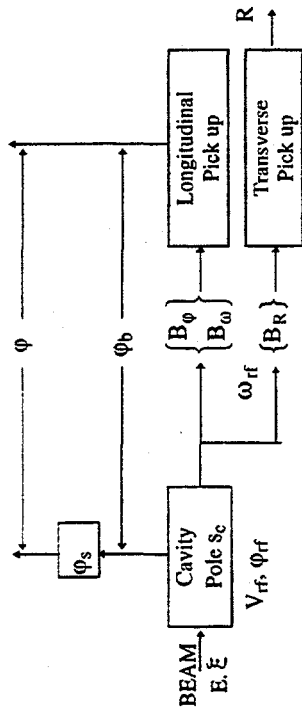
New state variable $z = \int_0^t (y(\tau) - y_0) d\tau$

$$\frac{d}{dt} \begin{pmatrix} X \\ z \end{pmatrix} = \begin{bmatrix} A & 0 \\ C & 0 \end{bmatrix} \begin{pmatrix} X \\ z \end{pmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} U + \begin{pmatrix} 0 \\ -y_0 \end{pmatrix}$$

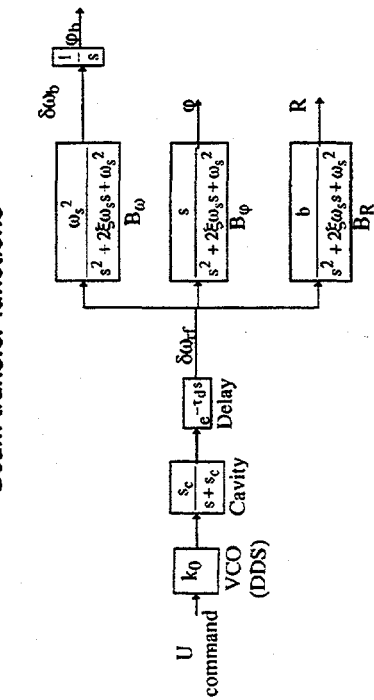
Discrete case

$$z_{k+1} = z_k + (y_k - y_0)$$

Variables

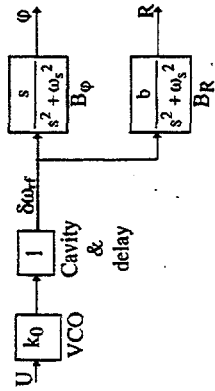


Beam transfer functions



$$b = \frac{ceV_{rf} \cos\varphi_s |\eta|}{2\pi\beta\gamma_{rf} E} \text{ and } \omega_s = f_{co} \sqrt{\frac{2\pi eV_{rf} \cos\varphi_s |\eta|}{E}}$$

THE PHASE AND RADIAL LOOP



Two state variables:

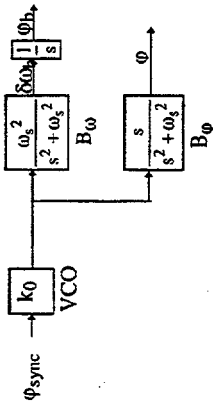
$$\begin{cases} \dot{x}_1 = \frac{R}{b} - \frac{k_0}{s^2 + \omega_s^2} U \\ \dot{x}_2 = \dot{x}_1 = \varphi \end{cases}$$

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -\omega_s^2 & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} 0 \\ k_0 \end{pmatrix} U$$

$$\begin{pmatrix} \dot{\varphi} \\ \dot{R} \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ b & 0 \end{pmatrix} \begin{pmatrix} \varphi \\ R \end{pmatrix}$$

Third state variable: $x_3 = z = \int (R - R_0) dt. \Rightarrow \dot{x}_3 = R - R_0 = \frac{1}{b} x_1 - R_0.$

THE SYNCHRONIZATION LOOP



$$X_s = \begin{bmatrix} x_4 = \varphi_b \\ x_5 = \omega_b \\ x_6 = \varphi \end{bmatrix}, Y_s = \begin{bmatrix} x_4 = \varphi_b \\ x_5 = \omega_b \\ x_6 = \varphi \end{bmatrix}$$

$$\text{Evolution: } \begin{cases} \dot{x}_4 = x_5 \\ \dot{x}_5 = \omega_s^2 x_6 \\ \dot{x}_6 = -\omega_s^2 x_6 + k_0 \varphi_{sync} \end{cases}$$

$$\begin{bmatrix} \dot{X}_s \\ Y_s \end{bmatrix} = \begin{bmatrix} A_s & B_s \\ C_s & D_s \end{bmatrix} \begin{bmatrix} X_s \\ \varphi_{sync} \end{bmatrix}$$

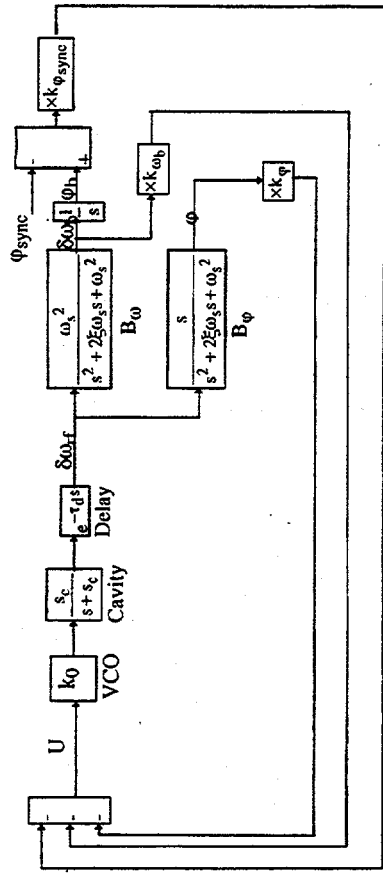
$$A_s = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & \omega_s^2 \\ 0 & -1 & 0 \end{bmatrix}, B_s = \begin{bmatrix} 0 \\ 0 \\ k_0 \end{bmatrix}$$

$$C_s = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, D_s = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

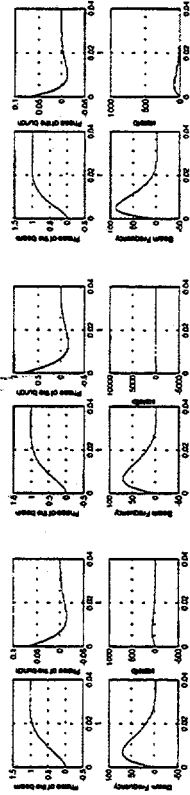
State space representation:

$$\text{rank}[B_s \ A_s B_s \ A_s^2 B_s] = 3 \Rightarrow \text{Pole placement}$$

$$\begin{cases} k_{\varphi_b} = -\frac{l_1 l_2 l_3}{k_0 \omega_s^2} \\ k_{\omega_b} = \frac{l_1 l_2 + l_1 l_3 + l_2 l_3}{k_0 \omega_s^2} \\ k_{\varphi} = \frac{l_1 + l_2 + l_3}{k_0} \end{cases}$$

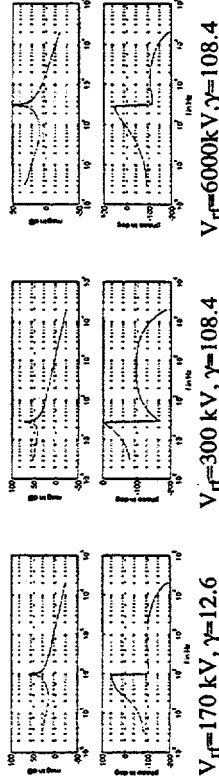


Desired poles: $-1202 + j*1047$, $-1202 - j*1047$ during acceleration and -220.3 , -1469 , -9442 during storage.



$V_{rf}=170 \text{ kV}, \gamma=12.6$ $V_{rf}=300 \text{ kV}, \gamma=108.4$ $V_{rf}=6000 \text{ V}, \gamma=108.4$
Step response of the synchronization loop

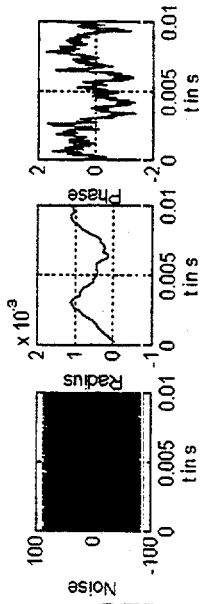
Rise time roughly 20ms. Phase margin 80° , amplitude margin 20 dB and the cut off frequency 1.5 kHz.



$V_{rf}=170 \text{ kV}, \gamma=12.6$ $V_{rf}=300 \text{ kV}, \gamma=108.4$ $V_{rf}=6000 \text{ V}, \gamma=108.4$
Open loop Bode plots

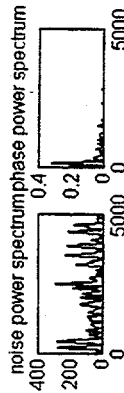
PHASE ERROR FOR A GIVEN FREQUENCY ERROR

Phase measurements errors



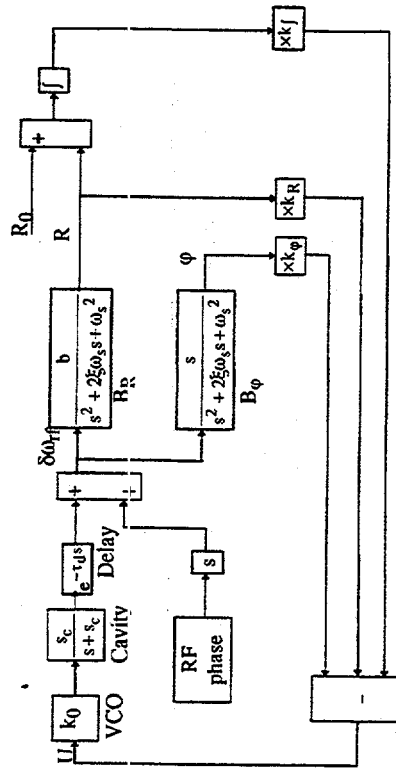
System excited by a white noise (90° amplitude, bandwidth 5000 Hz)

Noise attenuated by a factor of 40.

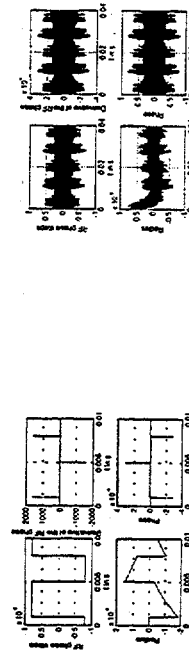


Effects of the tuner on the phase and radial loop.

Tuner effect = rf phase steps.



The same simulation has been performed by using real RF phase measurements



Step on the rf phase \Rightarrow the feedback tries to bring the phase to zero.
The radius integrates the step \Rightarrow the phase deviates.

$$(\varphi_{rf} \rightarrow R) = b \int (\varphi_{rf} \rightarrow \varphi) \Rightarrow a(t) = \int_0^t \varphi(u) du = k * R$$

Perturbations due to the tuner can be seen as radius steps.

DISCRETE REALIZATION OF THE LOOPS

Previous analog representation is sampled at the revolution frequency to get a discrete representation which includes the delay.

The phase and radial loop

Original state space-representation with no integral:

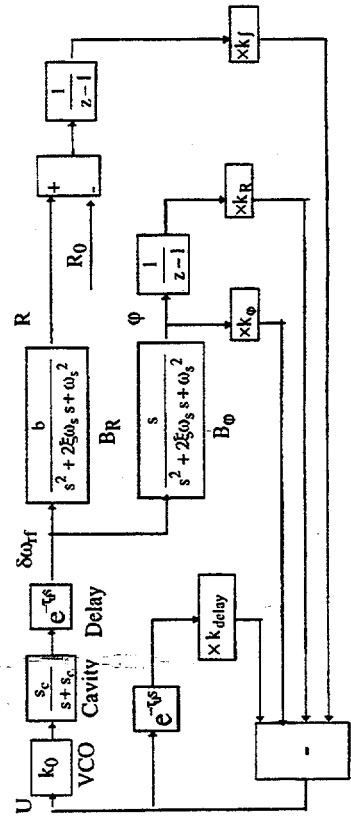
$$\begin{cases} \dot{x}(n+1) = a_d x(n) + b_d U(n) \\ \dot{Y}(n+1) = c_d x(n) + d_d U(n) \end{cases} \text{ where } R(n+1) = C_{d2} x(n)$$

$$x(n) = \begin{bmatrix} \frac{R(n)}{b} \\ \varphi(n) \\ U(n-1) \end{bmatrix}$$

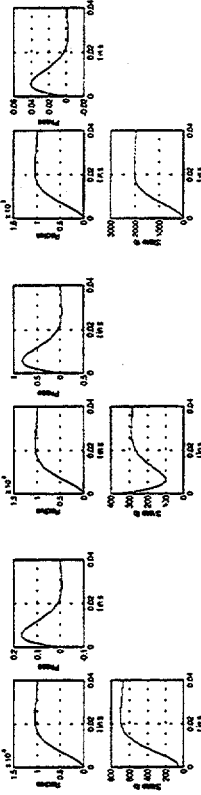
complete state space representation

$$\begin{bmatrix} x(n+1) \\ z(n+1) \\ X(n+1) \\ Y(n+1) \end{bmatrix} = \begin{bmatrix} a_d & 0 \\ c_{d2} & 1 \\ 0 & 0 \\ c_d & 0 \end{bmatrix} \begin{bmatrix} x(n) \\ z(n) \\ X(n) \\ Y(n) \end{bmatrix} + \begin{bmatrix} b_d \\ 0 \\ 0 \\ 0 \end{bmatrix} U(n) + \begin{bmatrix} 0 \\ -R_0 \\ 0 \\ 0 \end{bmatrix}$$

discrete pole = $e^{-\text{continuous pole} \cdot \tau_d}$



Radius reference: 1mm step.

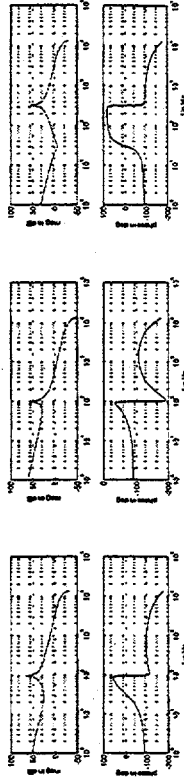


$V_r=170 \text{ kV}, \gamma=12.6$

$V_r=300 \text{ kV}, \gamma=108.4$

$V_r=6000 \text{ kV}, \gamma=108.4$

Radius response



$V_r=170 \text{ kV}, \gamma=12.6$

$V_r=300 \text{ kV}, \gamma=108.4$

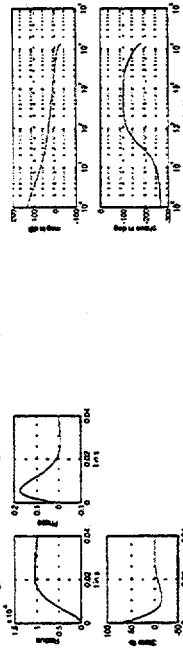
$V_r=6000 \text{ kV}, \gamma=108.4$

Open loop Bode plots

Phase margin is 70° , amplitude margin 15 dB, cut off frequency 3.2kHz.

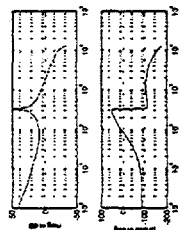
Same response at transition (rise time $\approx 20 \text{ ms}$)

phase margin 80° , amplitude margin 10 dB, cut off frequency 3 kHz

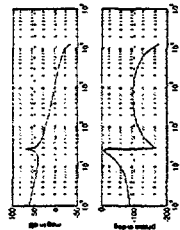


Loop behavior at transition (step response and Bode plot)

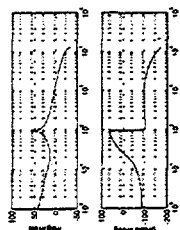
Phase comes back to zero in less than 100ms.



$V_{rf}=6000 \text{ kV}$,
 $\gamma=108.4$



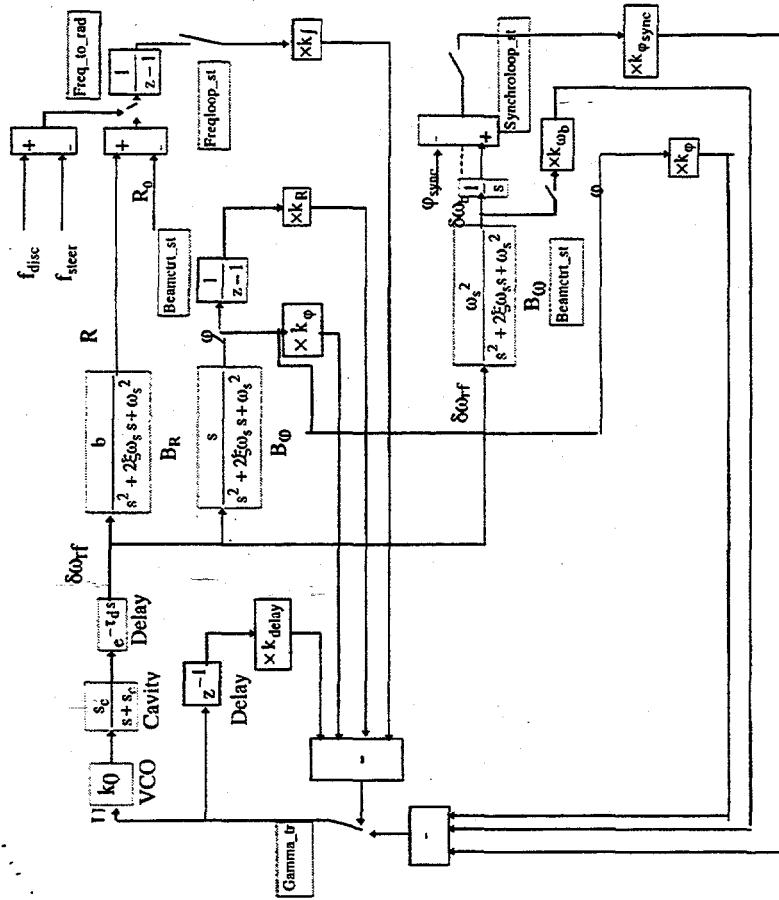
$V_{rf}=300 \text{ kV}$, $\gamma=108.4$



$V_{rf}=170 \text{ kV}$, $\gamma=12.6$

Open loop Bode plots

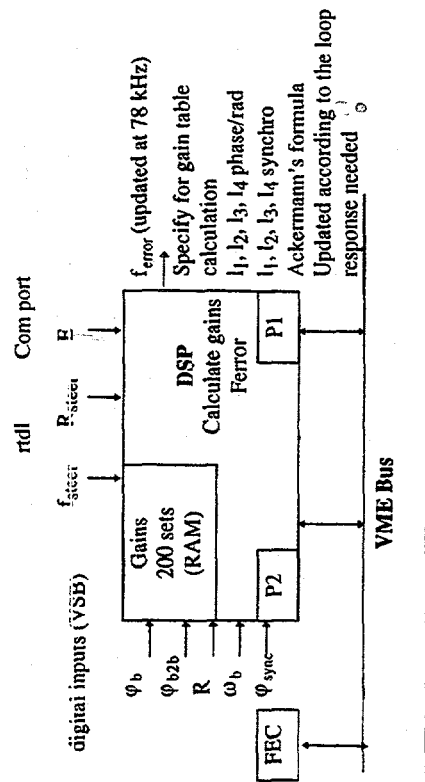
Phase margin 80° , amplitude margin 20 dB, cut off frequency 1.5 kHz.



Practical realization

Use of a VME DSP board

Store the feedback gains in a table (RAM), as a function of energy
 Access the gain table as a function of the energy



Triggers: VSB interrupts, corresponding to a different part of the DSP code

Gain table

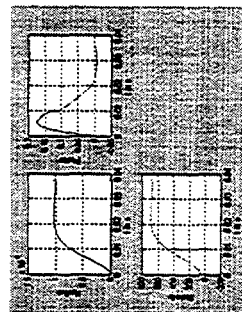
Phase and radial loop

	k_{phase}	k_{phase}	k_{radius}	k_{delay}	k_{radius}
$V_{\text{rf}}=170 \text{ kV}, \gamma=12.6$	0.0242 10^6	6.249 10^6	0.0208 10^6	0.291	0.0208 10^6
$V_{\text{rf}}=300 \text{ kV}, \gamma=108.4$	0.0243 10^6	6.671 10^6	0.0017 10^6	0.291	0.1014 10^6
$V_{\text{rf}}=6000 \text{ kV}, \gamma=108.4$	0.0242 10^6	1.13 10^6	0.1014 10^6	0.290	0.005 10^6

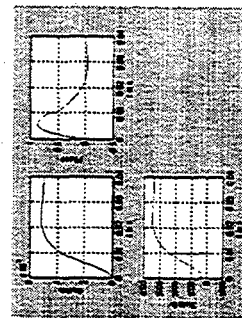
Only k_{radius} changes during acceleration

	k_{radius}
$V_{\text{rf}}=170 \text{ kV}, \gamma=12.6$	0.0208 10^6
$V_{\text{rf}}=170 \text{ kV}, \gamma=108.4$	0.1796 10^6
$V_{\text{rf}}=300 \text{ kV}, \gamma=12.6$	0.0017 10^6
$V_{\text{rf}}=300 \text{ kV}, \gamma=108.4$	0.1014 10^6

Range: 0.0017 10^6 to 0.1796 10^6
 200 points: $\Delta\text{gain}=1000$



1 mm step: 1° phase jump



5 mm step: 7° phase jump

Synchronization loop

	$k_{\phi hb}$	$k_{\phi b}$	k_{delay}	k_{ob}
$V_{rf}=170$ kV, $\gamma=12.6$	$9.6386 \cdot 10^3$	$0.6653 \cdot 10^3$	$0.0001 \cdot 10^3$	$0.0053 \cdot 10^3$
$V_{rf}=300$ kV, $\gamma=108.4$	$9.6447 \cdot 10^3$	$7.7186 \cdot 10^3$	$0.0001 \cdot 10^3$	$0.0728 \cdot 10^3$
$V_{rf}=6000$ kV, $\gamma=108.4$	$10.614 \cdot 10^3$	$0.6617 \cdot 10^3$	$0.0001 \cdot 10^3$	$0.0024 \cdot 10^3$

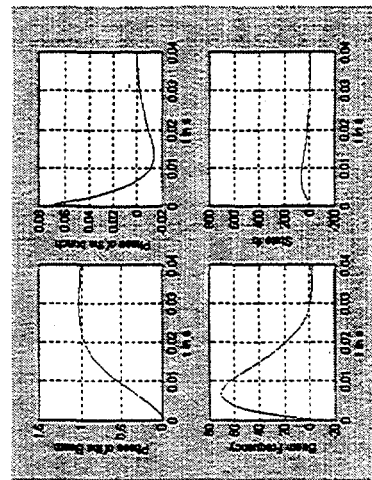
	$k_{\phi hb}$	$k_{\phi b}$	k_{ob}
$V_{rf}=170$ kV, $\gamma=12.6$	$9.6386 \cdot 10^3$	$0.6653 \cdot 10^3$	$0.0053 \cdot 10^3$
$V_{rf}=170$ kV, $\gamma=108.4$	$9.6446 \cdot 10^3$	$7.7186 \cdot 10^3$	$0.0728 \cdot 10^3$
$V_{rf}=300$ kV, $\gamma=12.6$	$9.6386 \cdot 10^3$	$0.6653 \cdot 10^3$	$0.0052 \cdot 10^3$
$V_{rf}=300$ kV, $\gamma=108.4$	$9.6447 \cdot 10^3$	$7.7186 \cdot 10^3$	$0.0728 \cdot 10^3$

Only $k_{\phi b}$ and k_{ob} change during acceleration

Range:

$k_{\phi b}$ from $0.6653 \cdot 10^3$ to $7.7186 \cdot 10^3$ 20 points $\Delta gain=35$

k_{ob} from $0.0052 \cdot 10^3$ to $0.0728 \cdot 10^3$ 20 points $\Delta gain=0.33$



No noticeable effect

The NSNS rf System

M. Blaskiewicz, J.M. Brennan, A. Zaltsman

charge exchange injection for 1ms then extract in one turn

60 Hz repetition rate

2×10^{14} 1 GeV kinetic energy protons at extraction

less than 10^{-4} uncontrolled losses

keep peak current small

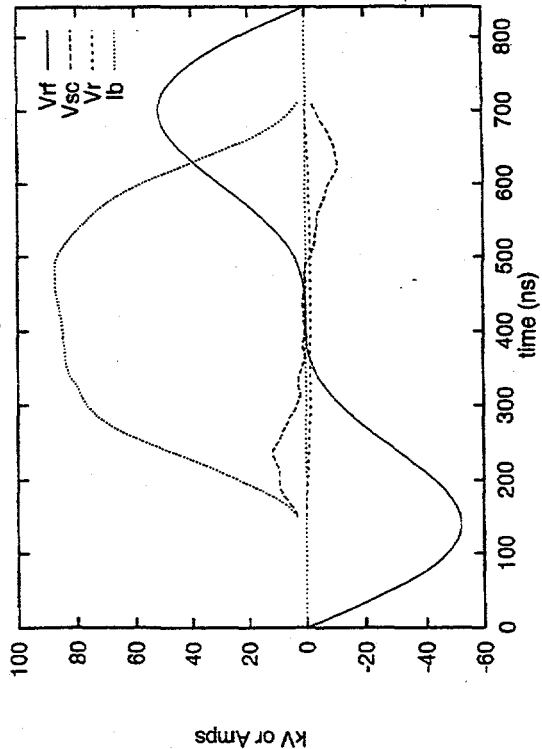
Dual Harmonic system:

$$V_r(t) = 40kV \sin(\omega_0 t) + 20kV \sin(2\omega_0 t)$$

$$\frac{Z_{ac}}{\eta} = 120\Omega, \quad R_{wall} = 20\Omega$$

$$|E - E_0| \leq 5.6MeV \text{ in Linac, } 9.4MeV \text{ in Ring}$$

$$T_{rev} = 841ns, \quad T_{chop} = 480ns$$



Cavity and Amplifier Design

$$h = 1, \quad f = 1.26 \text{ MHz}$$

$$h = 2, \quad f = 2.52 \text{ MHz}$$

$\pm 5\%$ variability built in.

Need 40kV at $h = 1$ and 20kV at $h = 2$

Want to retain the option of zero detuning angle $\omega_r = \omega_0$ so full beam current must be compensated.

$\leq 10kV$ per gap. Direct coupling to \sim AGS cavity.

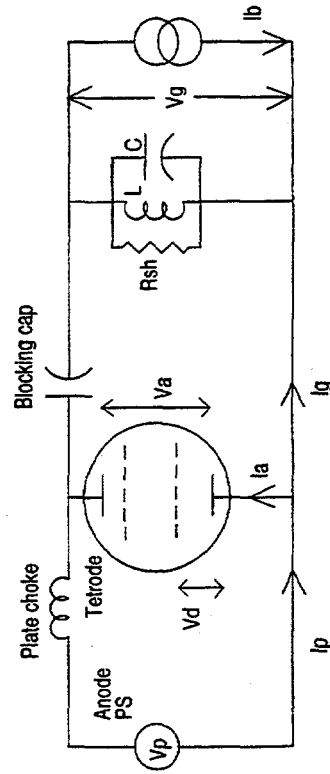
Beam current

$$I_b(t) \approx \bar{I}_b(t) [1 + a_1 \cos(\omega_0 t) + a_2 \cos(2\omega_0 t)]$$

$$a_1 = 1.3, \quad a_2 = .1, \quad \text{and } \bar{I}_b(t) = 40t \text{ Amp rms}^{-1}.$$

$$a_1 \bar{I}_{max} = 52 \text{ Amps} \gg a_2 \bar{I}_{max} = 4 \text{ Amps}$$

Equivalent Circuit



assume blocking capacitor and plate choke are very large
gap voltage

$$V_g(t) = V_a(t) - V_p$$

generator current across gap

$$I_a(t) = -I_a(t) + I_p$$

anode current

$$I_a = I_a(V_a, V_d)$$

$$I_g(t) = -I_a(V_g(t) + V_p, V_d(t)) + I_p$$

power amplifier supplying n_g accelerating gaps in parallel

$$V_g(t) = \int_0^{\infty} W(\tau)(I_a(t-\tau) + I_g(t-\tau)/n_g)d\tau$$

$W(\tau)$ is the wake potential of the unloaded cavity

$$W(\tau) = \frac{1}{2\pi} \int d\omega Z(\omega) e^{-i\omega\tau}$$

$$Z(\omega) = \frac{R_{sh}}{1 + iQ(\omega_r/\omega - \omega/\omega_r)}$$

R_{sh} is the shunt impedance per gap of the unloaded
cavity

ω_r is its resonant frequency

Q is the unloaded quality factor.

Grid drive voltage

$$V_d(t) = \bar{V}_d + \Delta V_d \sin(\omega t + \phi_d)$$

Anode Voltage

$$V_a(t) = \bar{V}_a + \Delta V_a \sin(\omega t)$$

$\Delta V_a = V_g$ for direct coupling Current through tetrode

$$I_a(t) = \bar{I}_a - a\bar{I} \cos(\omega t) + I_0 \sin(\omega t) + \text{higher harmonics}$$

$-a\bar{I}$ compensates the beam current

I_0 drives the cavity

For the $\omega = \omega_r$ case $I_0 = \Delta V_a / R_{sh}$

$$R_{sh} \approx 10k\Omega \rightarrow I_0 = 1 \text{ Amp}$$

irrelevant compared

$$a_1 I = 52 \text{ Amp}$$

Take

$$n_g = 2 \rightarrow I_g = 104 \text{ Amp}$$

Anode Voltage, 6 gaps at $h = 1$

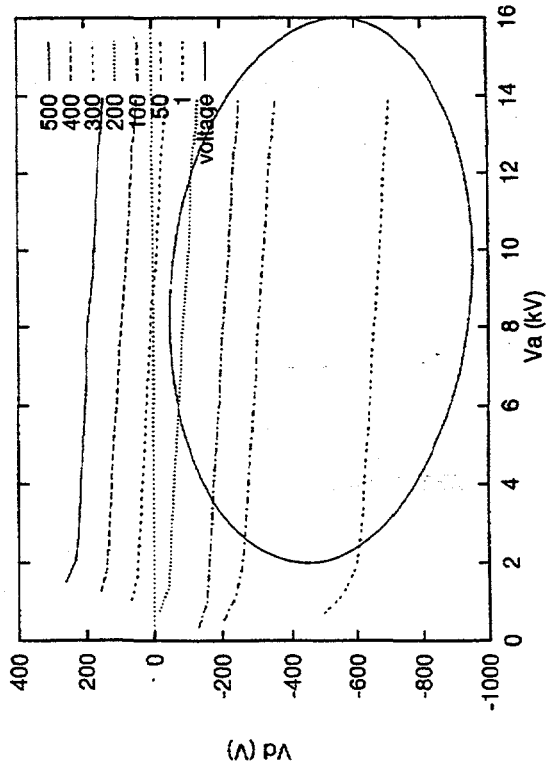
$$V_a(\omega t) = 9kV + 7kV \sin(\omega t)$$

Grid drive voltage

$$V_2(\omega t) = -500V + 450V \cos(\omega t) - 53V \sin(\omega t)$$

Screen grid voltage = 2kV.

Load Line for $h = 1$, TH558 tetrode



For $V_a > 2kV$

$$V_a/1000 + (0.132 \pm 0.002)V_d = \text{constant}$$

$$\text{So } I_a = I_a(V_a + 132V_d)$$

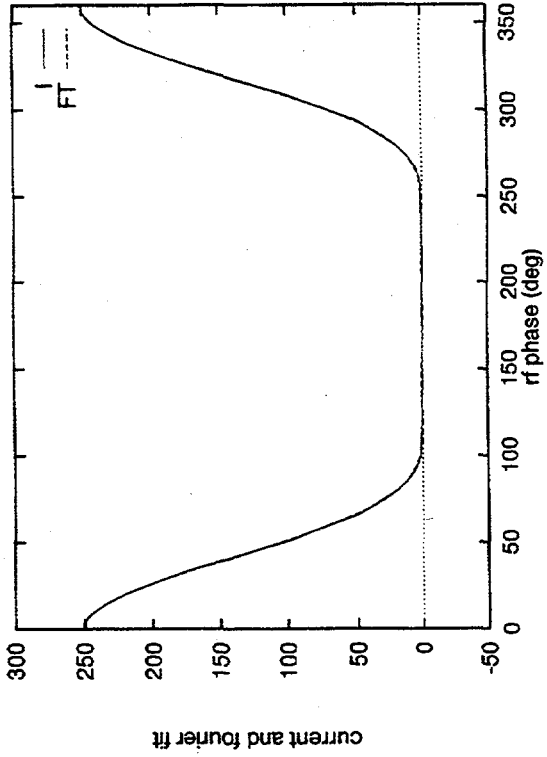
in region of interest \rightarrow 1 dimensional interpolation

$$< I_a V_a > = 585 \text{ kW} \leq 600 \text{ kW manufacturers spec}$$

How far can we push it?

For $h = 2$ two gaps, one tetrode, 20kV/gap, $\approx 100 \text{ kW}$

Anode Current and its Fourier Reconstruction, $h = 1$



Dynamic tuning of the cavity resonant frequency
steady state first

$$\text{gap volts} \quad V_g(t) = \hat{V}_g \exp(ih\omega_0 t)$$

$$\text{beam current} \quad I_b(t) = \hat{I}_b \exp(ih\omega_0 t)$$

$$\text{generator current} \quad I_g(t) = \hat{I}_g \exp(ih\omega_0 t)$$

$$\hat{V}_g = Z_c(\hat{I}_b + \hat{I}_g)$$

relative phase of \hat{V}_g and \hat{I}_b is $\approx 90^\circ$, (R_{out})

tune the cavity resonant frequency by biasing the ferrite,
for minimum current

$$I_g = V_g / R_{sh}$$

Where $R_{sh} \sim 10k\Omega$ is the unloaded cavity impedance
Problem is now beam stability (Pederson 1975)
Have Robinson's criteria for single harmonic
Dual harmonic rule of thumb?
took $Y = I_b R_t / V_g \lesssim 3$
 R_t = effective resistance of cavity and tetrode in parallel.

Calculating R_t

$$I_g = I_p - I_a(V_d, V_a)$$

$$\delta I_g = -\delta V_a \left. \frac{\partial I_a}{\partial V_a} \right|_{V_d}$$

$$\delta I_g + \delta I_b = \frac{\delta V_g}{R_{sh}} + \frac{1}{L} \int \delta V_g(t') dt' + C \frac{d\delta V_g}{dt}$$

$$\delta V_g = \delta V_a$$

$$\delta I_b = \delta V_g \left[\frac{1}{R_{sh}} + Y_a \right] + \frac{1}{L} \int \delta V_g(t') dt' + C \frac{d\delta V_g}{dt}$$

where

$$Y_a = \left. \frac{\partial I_a}{\partial V_a} \right|_{V_d} \geq 0$$

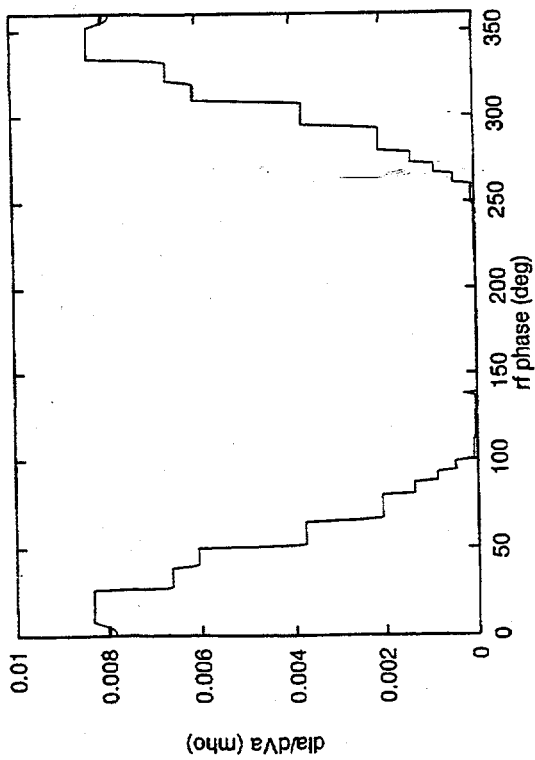
So

$$\frac{1}{R_t} = \frac{1}{R_{sh}} + \left\langle \left. \frac{\partial I_a}{\partial V_a} \right|_{V_d} \right\rangle$$

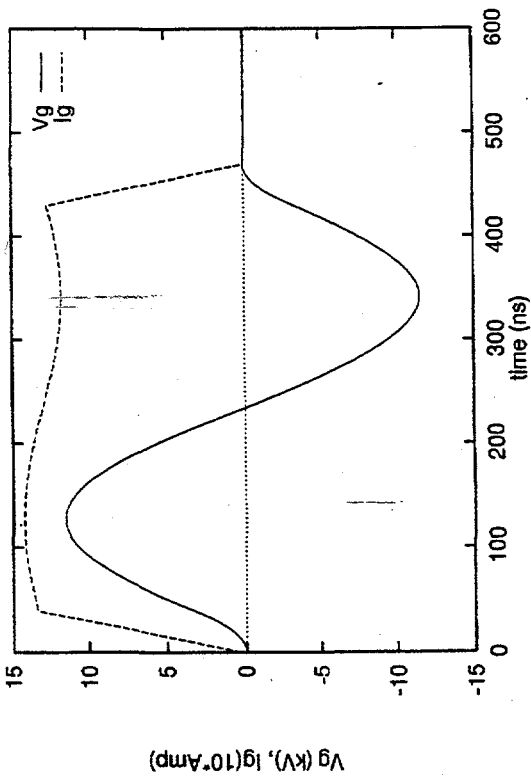
Using $\langle Y_a \rangle_t = 1/375\Omega$ and 2 gaps per tetrode $R_L \approx 750\Omega$

$Y = 5.6$ without rf feedback

Use one turn feedback to reduce R_L by a factor of 3.



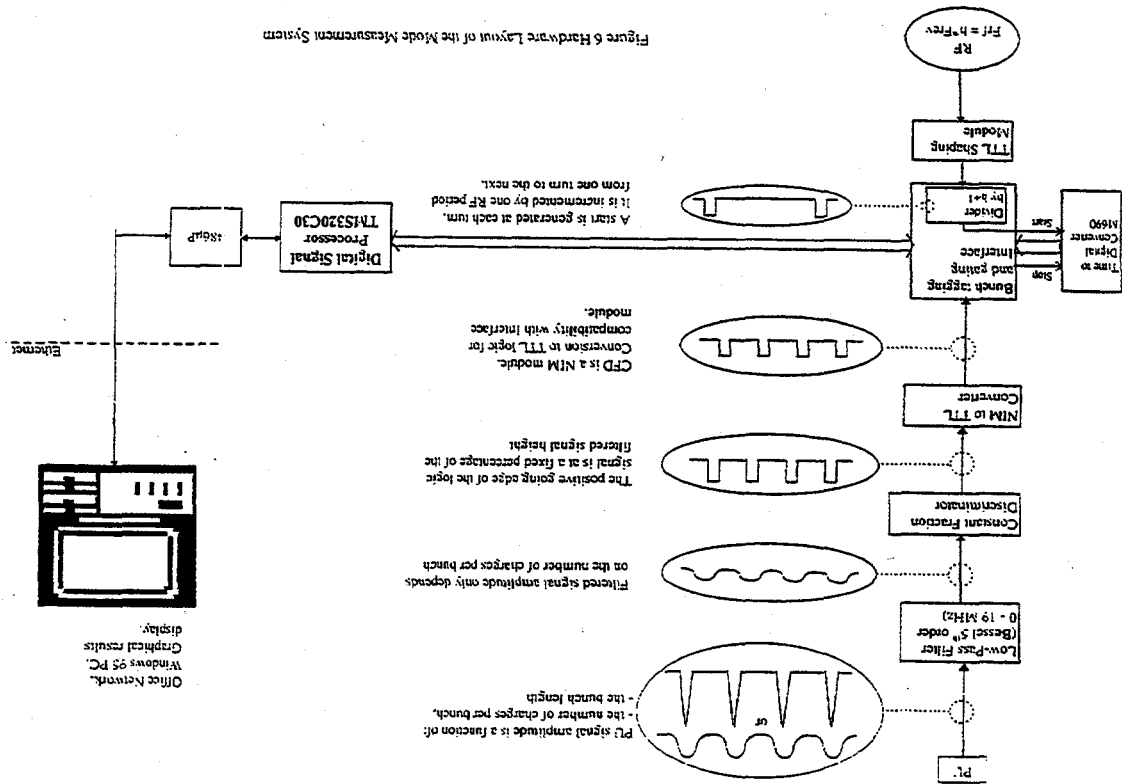
Barrier cavity upgrade
 Use same tetrodes, but drive with a pulse
 reduce gap capacitance
 $f_r = 2.33\text{MHz} > 2f_0$ for no debunching
 $\langle I_a V_a \rangle >= 1.8\text{MW}$ over one fill
 $\langle I_a V_a \rangle >= 220\text{kW}$ over many cycles



References

- [1] M. Blaskiewicz, J.M. Brennan, Y.Y. Lee NSNS tech note # 9, (1996).
- [2] Y.Y. Lee NSNS tech note # 26 (1997).
- [3] J.M. Brennan, PAC95, pg 1489, (1995).
- [4] F. Pederson, IEEE, TNS, Vol. NS-22, No. 3, pg 1906, (1975).
- [5] M. Blaskiewicz, J.M. Brennan 5th European Particle Accelerator Conference, pg 2373, 1996.
- [6] S. Koscielniak, 5th European Particle Accelerator Conference, pg 1129, 1996.
- [7] D. Boussard, CERN 91-04 (1991).
- [8] R. Garoby, Frontiers of Particle Beams: Intensity Limitations, US-CERN School on Particle Accelerators, Springer-Verlag, pg 509, (1990).

R. Garoby



5.1 Sensitivity

The Mode Measurement System must be a highly sensitive tool in order to pinpoint the birth and duration of beam instabilities. Proof of the sensitivity can be seen in Figure 33.

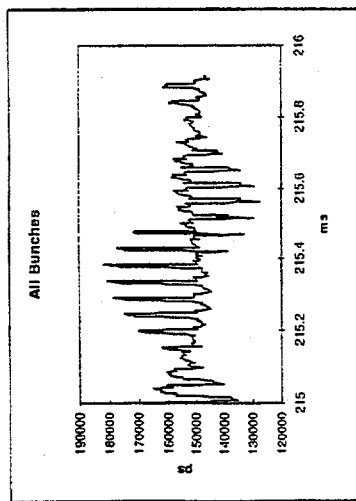


Figure 33 Evidence that bunches are oscillating at f_{ω} proves high sensitivity

This plot was taken at C215 just before injection. Given that the small amplitude synchrotron frequency f_{ω} is approximately 1.6 kHz on this beam at injection energy, the graph should be able to confirm this statement.

Closer inspection reveals that the period of the signal in Figure 33 is approximately 600 μ s, the frequency is thus given by

$$f = 1/T = 1/600E-06 = 1.67 \text{ kHz} \approx f_{\omega}$$

With the knowledge that synchrotron oscillations can successfully be observed, it is true to say that the system sensitivity is of a high quality.

5.2 Analysis of Beam Instabilities

The results of beam instability analysis were the key to completion of the project specification. If coherent longitudinal dipolar instabilities could be identified then RF specialists would be able to better isolate the source(s) of impedance driving the instability.

The first stage in this process - identification of the birth and nature of an instability - was successfully completed during the MD session.

³ The small amplitude synchrotron frequency describes the motion of particles which are extremely close to the synchronous point whilst still performing synchrotron oscillations.

The user then selected a new session following the progress of two chosen bunches, and zooming on the region of instability by selection of new Start, Stop and Step settings (see Figure 36).

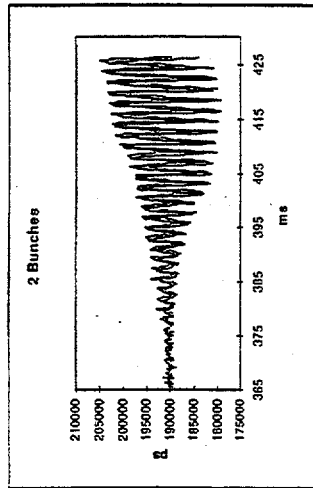


Figure 36 The effect on two bunches due to a growing instability

And inspecting the difference in phase between the two bunches (see Figure 37)

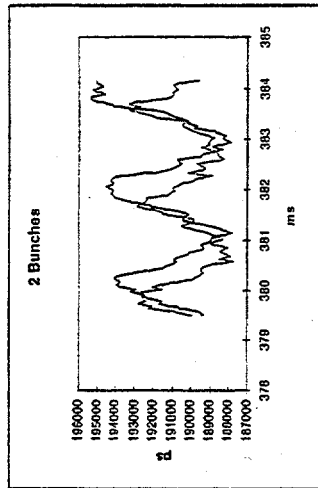


Figure 37 Difference in phase of the two bunches during instability growth

Figures 35 to 37 clearly identify a growing instability. The peak-to-peak magnitude is between 180 and 205 ns which, with an RF period of 110 ns, corresponds to nearly 25 % of one RF turn. The longitudinal movement of the bunches is therefore quite large. The phase difference between two chosen bunches is also quite large. In the ideal case where no instabilities are present, all bunches should remain fixed at the synchronous point with a single phase, φ_s , the synchronous phase.

Increasing the blow-up and hence the longitudinal emittance the situation was restored to that of Figure 34, stable beam.

Participants

Michael Blaskiewicz	BNL
J. Michael Brennan	BNL
Yong Ho Chin	KEK
Weiren Chou	FNAL
Roland Garoby	CERN
Steven B. Hancock	FNAL
Thomas Hayes	BNL
Erk Jensen	CERN
Ioanis Kourbanis	FNAL
Yong Y. Lee	BNL
Trevor Linnecar	CERN
John T.M. Lyles	LANL
King Y. Ng	FNAL
Chihiro Ohmori	KEK
Emmanuel Onillon	BNL
Zubao Qian	FNAL
Jim Rose	FNAL
Thomas Roser	BNL
Shinya Sawada	KEK
Michael J. Syphers	BNL
Arch Thiessen	FNAL
Hiroshi Tsutsui	KEK
Tomonori Uesuigi	KEK
Peter L. Walstron	FNAL
Tai-Sen F. Wang	FNAL
David W. Wildman	FNAL
Masahito Yoshii	KEK
Alex Zaltsman	BNL