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Switch Over to the High Frequency RF System Near Transition

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I. Introduction

There was a consensus among the RF group that the requirement of very short bunches can best be fulfilled by employing two separate RF systems operating at different frequencies. The first system, at 26.7 MHz, would receive the injected beam from the AGS in matched buckets. A second system, at a much higher frequency, say 200 MHz, would be used to store the beam for collisions. The bunch width in the high frequency system should be in the order of 4 ns.

The inevitable problem of this two-frequency approach is preparing the bunch width in the low frequency system so that the switch over to the high frequency system proceeds with a minimum of beam loss. Techniques for bunch compression, such as, bunch rotation in a mis-matched bucket or adiabatic narrowing, are available but incur some expense for increased capability of the low frequency RF system(s).

The purpose of this note is to point out that since bunch narrowing naturally occurs in the acceleration process in the vicinity of transition, it should be possible to switch over to the high frequency system close to transition when the bunch has narrowed enough to fit directly into the high frequency bucket. The advantage of this approach is the simplicity, no extra

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components or gymnastics are required of the low frequency system. The disadvantage, of course, is for protons which do not go through transition. But on the other hand, there is no shortage of intensity for protons and so it should be possible to keep the phase space area low for protons, and then matching to the high frequency bucket should be easily accomplished by adiabatic compression.

II. Computer Simulation

This switch over scheme has been investigated with a new longitudinal tracking code developed at BNL. The code has been used to study transition energy crossing in RHIC[1] and space charge effects during RF capture in the RHIC Booster.[2] The calculation assumes that the high frequency RF system operates at 214 MHz. An initial bi-Gaussian distribution of phase space area 0.3 eV sec/amu is generated in the longitudinal phase space at an energy well below the transition energy (Figure 1). The motion of each individual particle in the longitudinal phase space is described by the difference equations

$$\delta_{n+1} = \delta_n + \frac{Ze\hat{V}_{1,n}}{Am_0c^2\gamma_{s,n}}\cdot(\sin\phi_n - \sin\phi_{s,n}) + \frac{Ze\hat{V}_{2,n}}{Am_0c^2\gamma_{s,n}}\cdot(\sin(\phi_{2,s,n} + \frac{h_2}{h_1}\Delta\phi_n) - \sin\phi_{2,s,n}) \quad (1)$$

$$\phi_{n+1} = \phi_n + \frac{2\pi h\eta_n(\delta_{n+1})}{\beta^2_{s,n+1}}\cdot\delta_{n+1} \quad (2)$$

where

$\gamma_s = (1-\beta_s^2)^{-\frac{1}{2}}$ synchronous energy of the particle in m_0c^2 units

h_i = harmonic number of the ith R.F. system

$\delta = \frac{\Delta E}{E_s} = \frac{\Delta\gamma}{\gamma_s} = \beta_s^2\frac{\Delta p}{p_s}$, relative deviation of the particle energy

ϕ = deviation of the particle R.F. phase from ϕ_s in the first R.F. phase space

Z = charge carried by the particle

A = atomic number of the particle

n (subscript) = revolution number.

The kinematic non-linearity is included in equation (1,2) ,

$$\eta_n(\delta) = \eta_0(\gamma_{s,n}) + \eta_1(\gamma_{s,n})\delta + \ldots \tag{3}$$

where

$$\eta_0(\gamma_{s,n}) = \frac{1}{\gamma_{t0}^2} - \frac{1}{\gamma_{s,n}^2} \ , \ \eta_1(\gamma_{s,n}) = \frac{3\beta_{s,n}^2}{2\gamma_{s,n}^2} - \frac{\alpha_1}{2\gamma_{t0}^2} \ , \tag{4}$$

with α_1 as the expansion coefficient of the momentum compaction factor α, *i.e.*

$$\alpha = \alpha_0(1 + \alpha_1\delta + \ldots) \ ; \ \alpha_0 = \frac{1}{\gamma_{t0}^2} \ , \tag{5}$$

where γ_{t0} is the transition energy of the machine. The particles are tracked further on a turn-by-turn basis to higher energy (Figure 2)

$$\gamma_{s,n+1} = \gamma_{s,n} + \frac{Ze\hat{V}_{1,n}}{Am_0c^2}\sin\phi_{s,n} + \frac{Ze\hat{V}_{2,n}}{Am_0c^2}\sin\phi_{2,s,n} \ . \tag{6}$$

J. E. Griffin proposed a "best hunch" plan for the details of how the low frequency should be brought down while the high frequency system is brought up. Figure 3 shows the program used in the calculation for the voltage, V1(2), and phase, phis1(2), of the high(low) frequency system. V1 is dropped form 100 kV to 48 kV in 0.5 ms just as the center of the bunch passes transition. The phase is increased from 0.5 radians to pi/2 at the same time. V1 is then slowly decreased to zero in a linear ramp during time T. The voltage V2 is increased, starting from zero at transition, to 800 kV in the same time T. The calculation is done as a function of the parameter T. The acceleration rate is held constant at delta gamma = 2.0 x 10^{-5} per turn throughout the process.

III. Results

The calculation was done for $^{197}Au^{+79}$ with the time parameter T varied from 5 ms (400 revolutions) to 3 sec (240,000) revolutions). The survival rate is decided by evaluating the number of particles remaining inside the single 214 MHz bucket, which the original synchronous particle occupies at an energy well beyond transition. The upper curve in Figure 4 corresponds to all the particles crossing the transition energy at the same time. $_1$ = 0. When the RF system is programmed adiabatically and the RF focusing force is strong enough, 95% of the particles can be re-captured in the new RF bucket.

If the kinimatic non-linearity is considered, say α_1 = -0.6, particles of different energy will cross the transition energy at different times. Therefore, any focusing RF force for the particles above the transition energy is a de-focusing force for the particles which are still below the transition energy. As indicated in the lower curve in Figure 4, this de-focusing force gives considerable effect if V2 is raised in a relatively short time. During passage through the transition energy, large amplitude off-momentum particles easily get far from the stable fixed point and eventually are trapped in the adjacent buckets or even lost. However, if V2 is raised gently and the programming is optimized, we expect that about 90% of the particles can be captured in a single bucket.

Figures 5,6 and 7 show longitudinal phase space diagrams for three different values of T. Parts a) correspond to no kinematic non-linearity and parts b) correspond to the

non-linearity parameter $\alpha_1 = -0.6$.

V. Discussion

Results of this préliminary study are encouraging as a first attempt. Although the capture efficiency obtained is not strictly adaquate for operation of the machine, several important parameters of the RF system design are not yet finalized. New values for the such parameters as, the total voltage available in the low frequency system, or the specific frequency of the high frequency system could have significant impact on the effectiveness of this scheme. One caveat should be pointed out. Since the switch over would take place at transition energy and not at full energy, as for bunch rotation, the relative momentum aperture is smaller and may not be adaquate for particles at the tails of the distribution.

Acknowledgement. We would like to thank J.E. Griffin for his encouragement and leadership during the workshop.

Postscript. Since the time of the workshop we have found that, when used in conjunction with a $\dot{\gamma}$ bump or a γ_{Tr} jump and with 300 keV available in the low frequency system and the high frequency system operating at 161 MHz, the transition energy switch over is equally as effective as bunch rotation or adiabatic compression.

REFERENCES

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2) J. Wei, S.Y. Lee and A.G. Ruggiero, Booster Tech. Notes (1988)

3) E. D. Courant and H. S. Snyder, *Theory of the Alternating Gradient Synchrotron*, Ann. of Phys. 3, 1 (1958).

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FIGURE CAPTIONS

Fig. 1. Bi-gaussian distribution of longitudinal phase space area $\sim 0.3ev \cdot sec/amu$ of $^{197}Au^{+79}$ at central beam energy $\gamma_s = 25.3$. The R.F. bucket corresponds to $\hat{V} = 100\ kV$, $\phi_s = 0.5\ rad.$ 27 MHz R.F. system.

Fig. 2. Distribution at $\gamma_s = 25.4$. The central transition energy $\gamma_{t0} = 25.4376$.

Fig. 3. Programming of two R.F. systems around the transition energy γ_{t0}.

Fig. 4. Beam survival rate as a function of the R.F. system programming time T (or number of revolution periods after γ_s passes γ_{t0}).

Fig. 5. Longitudinal phase space diagram at $\gamma_s = 25.9464$, $T = 4000$ turns,

a) $\eta_1 = 0$, 88% single bucket survival;

b) $\alpha_1 = -0.6$, 21% single bucket survival.

Fig. 6. Longitudinal phase space diagram at $\gamma_s = 26.4$, $T = 46000$ turns,

a) $\eta_1 = 0$, 95% single bucket survival;

b) $\alpha_1 = -0.6$, 81% single bucket survival.

Fig. 7. Longitudinal phase space diagram at $\gamma_s = 30.4$, $T = 236000$ turns,

a) $\eta_1 = 0$, 78% single bucket survival;

b) $\alpha_1 = -0.6$, 76% single bucket survival.

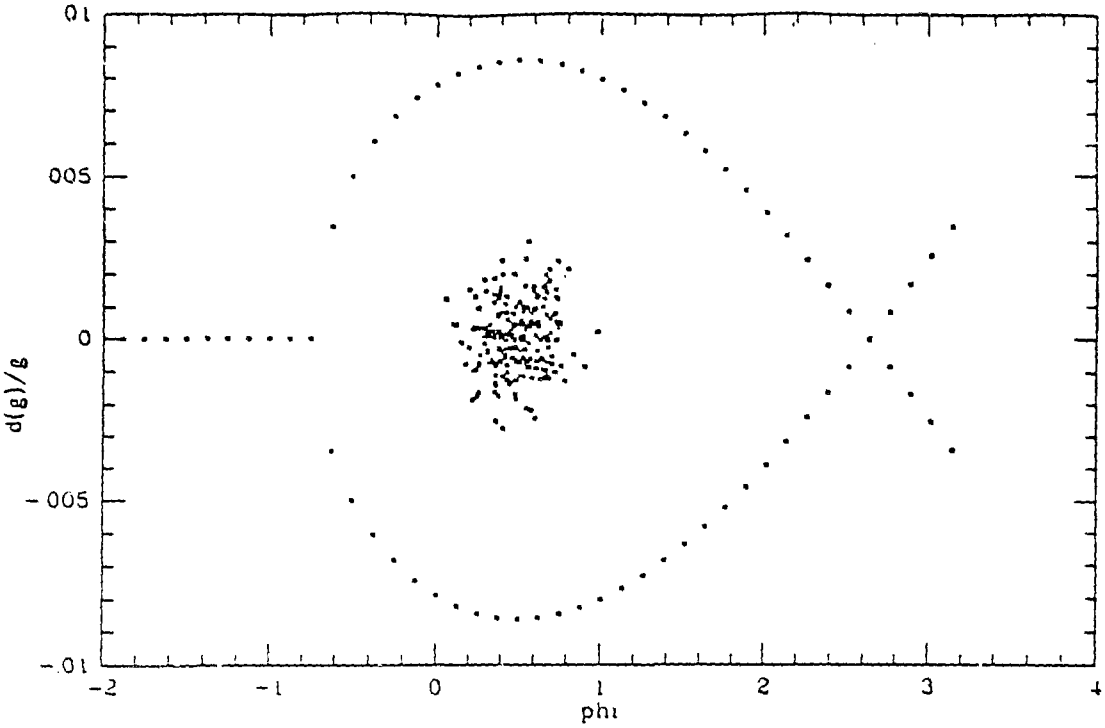


Fig. 1.

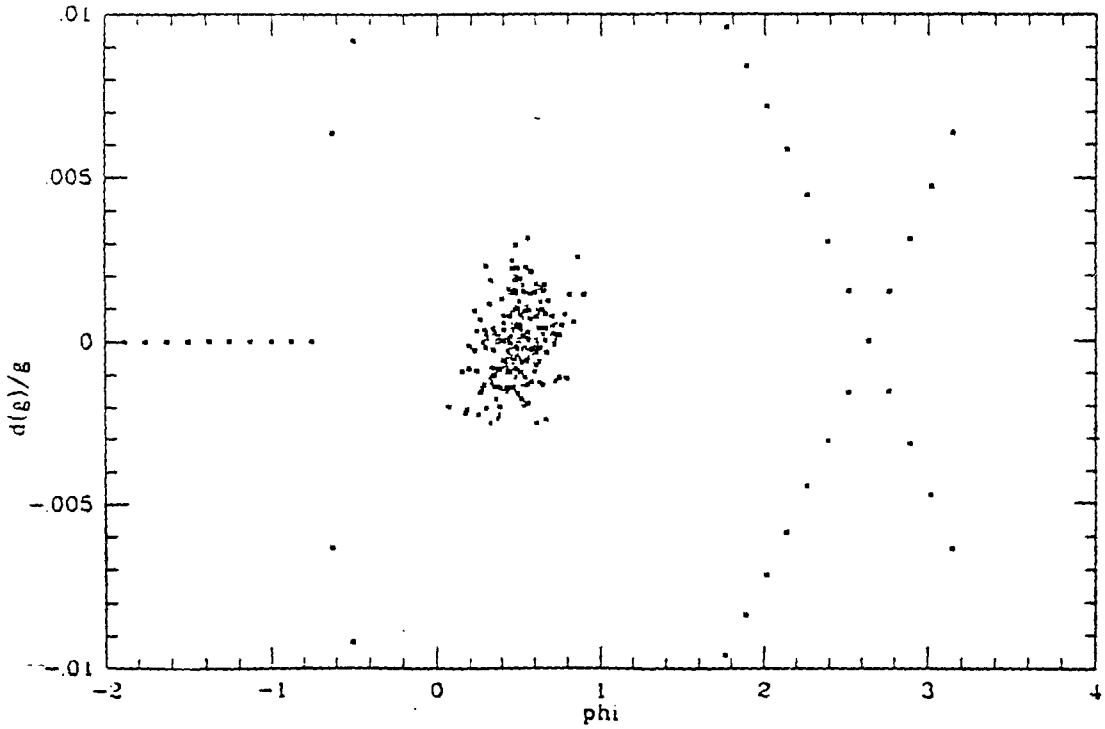
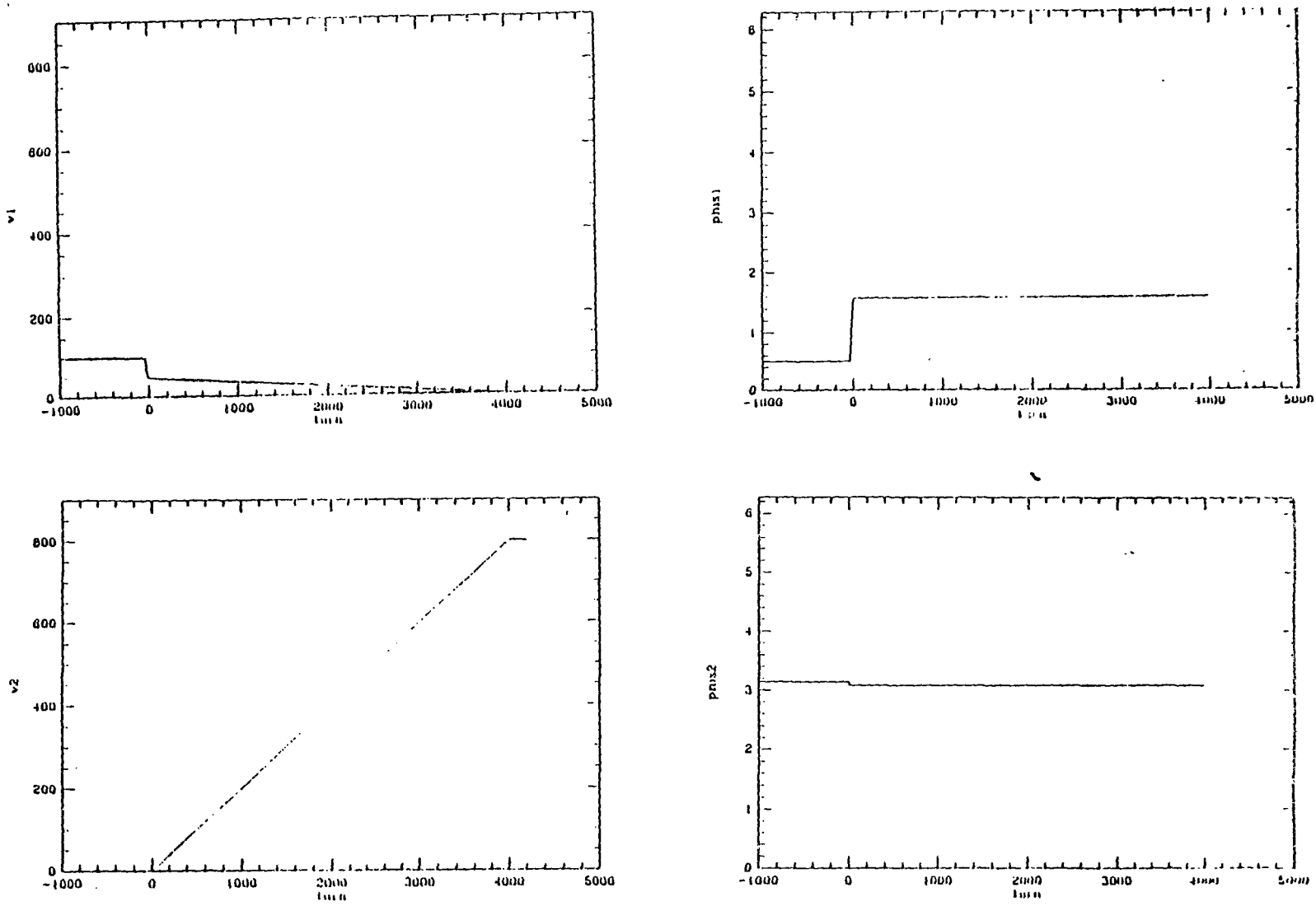


Fig. 2.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phis1
v2
phis2
turn
-1000
0
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2000
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4000
5000
200
400
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800
1
2
3
4
5
6

Fig. 3.

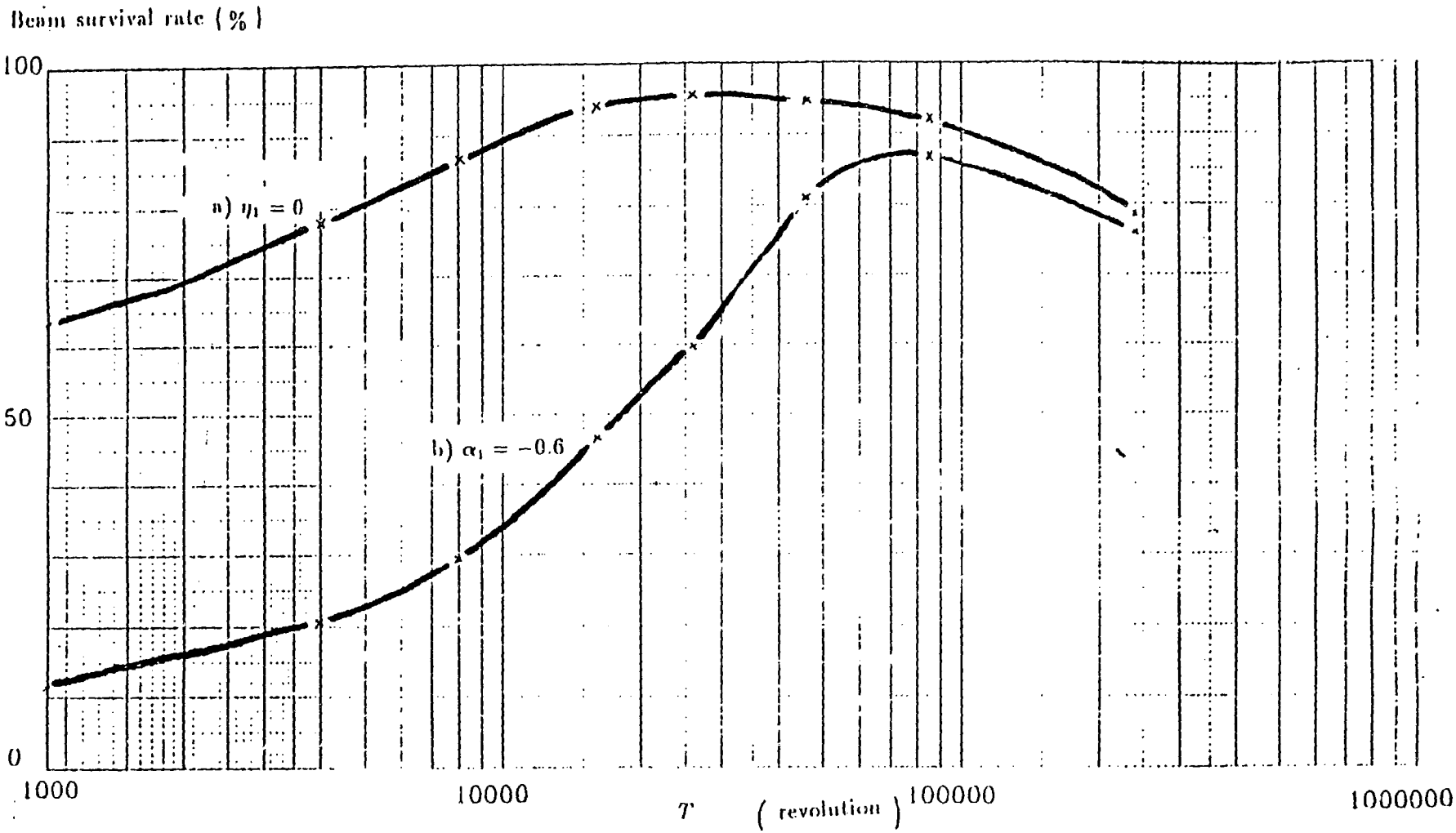
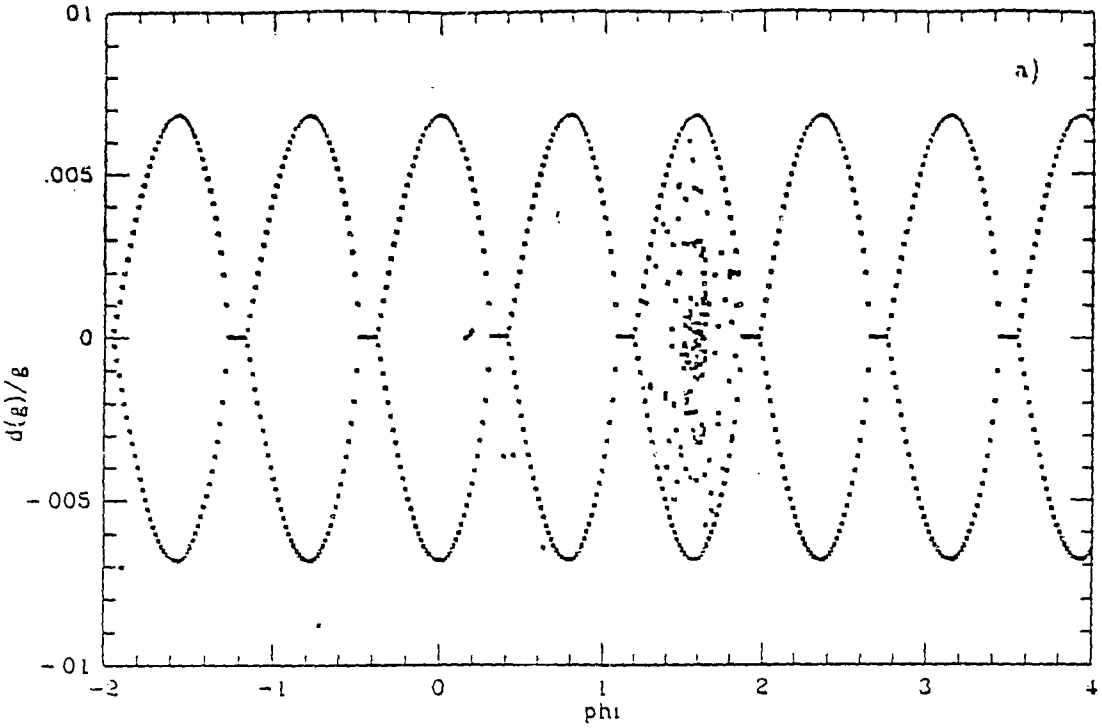

Beam survival rate (%)
100
50
0
a) $\eta_1 = 0$
b) $\alpha_1 = -0.6$
1000
10000
100000
1000000
T (revolution)

Fig. 4.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-.005
-.01
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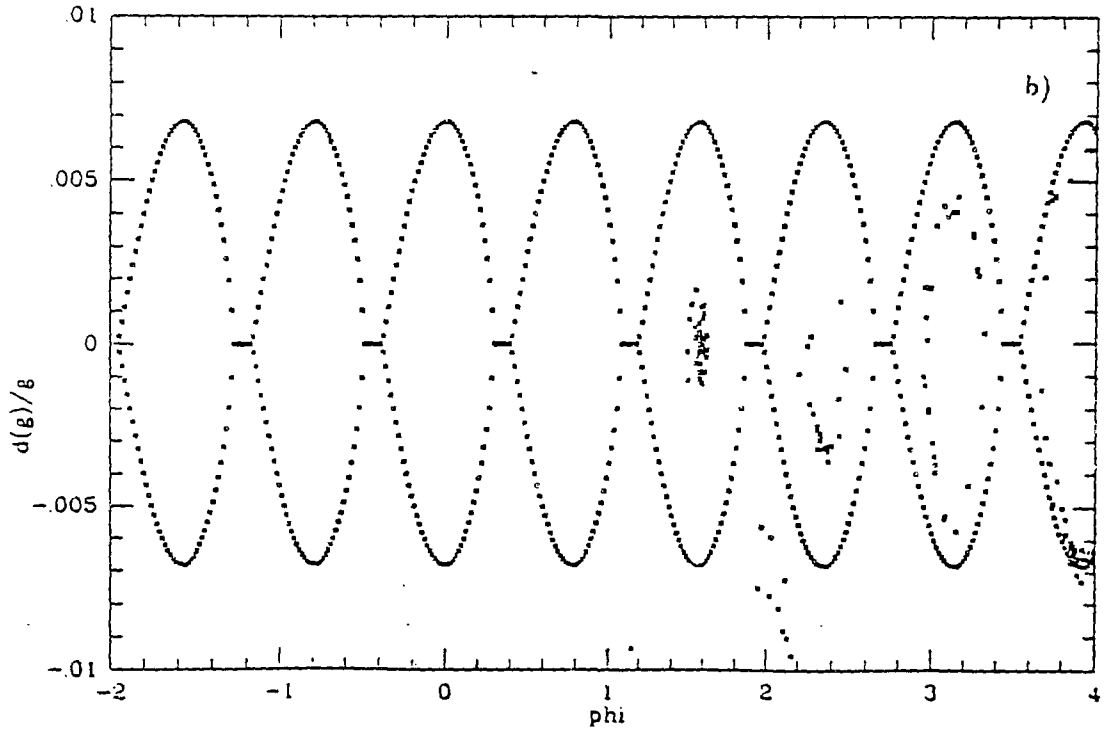
0
1
2
3
4
phi


b)
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d(g)/g
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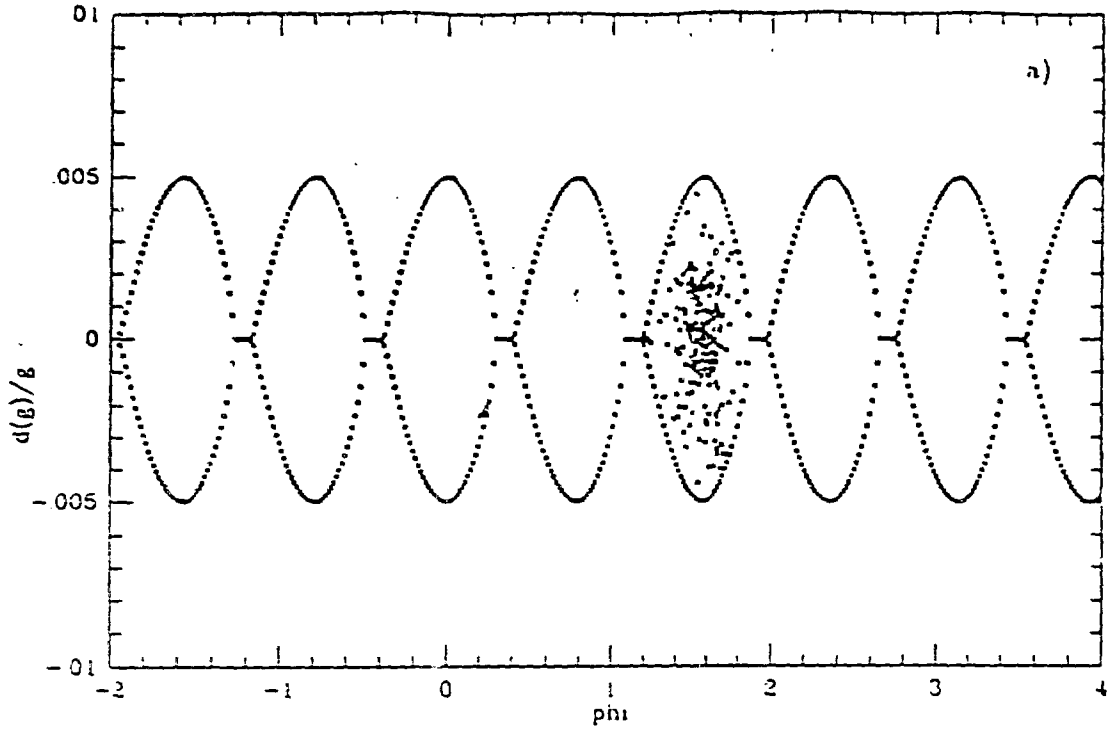
3
4
phi

Fig. 5.


a)
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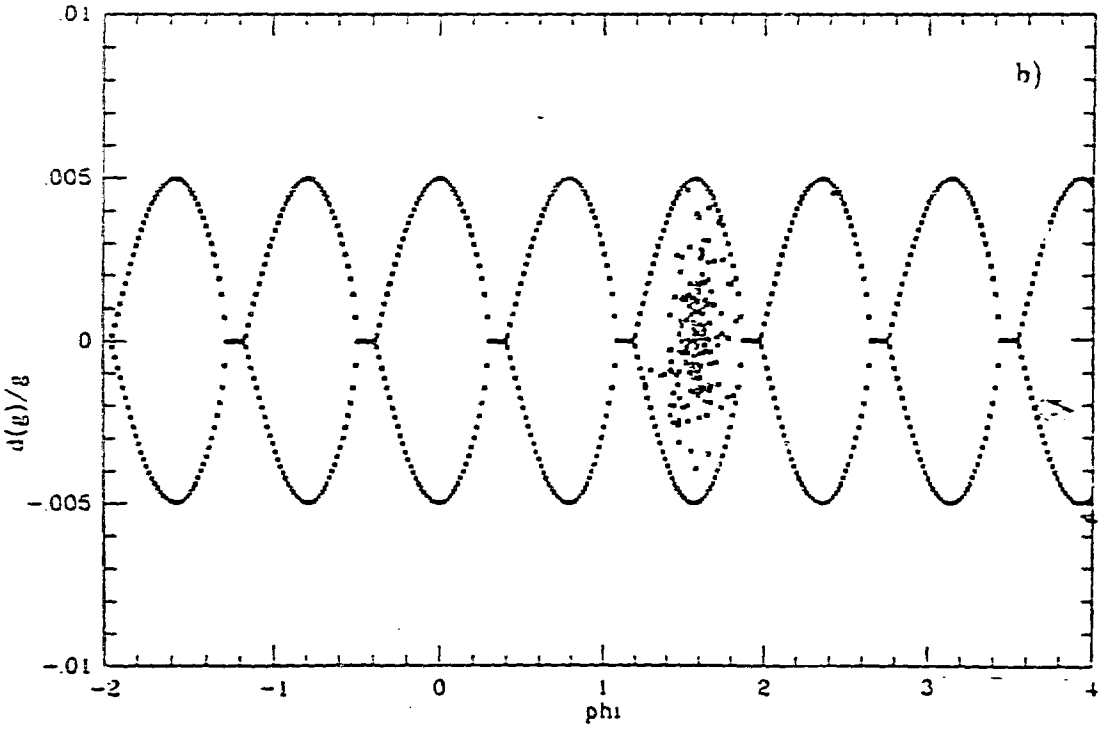
phi


b)
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.005
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-.005
-.01
d(g)/g
-2
-1
0
1
2
3
4
phi

Fig. 6.

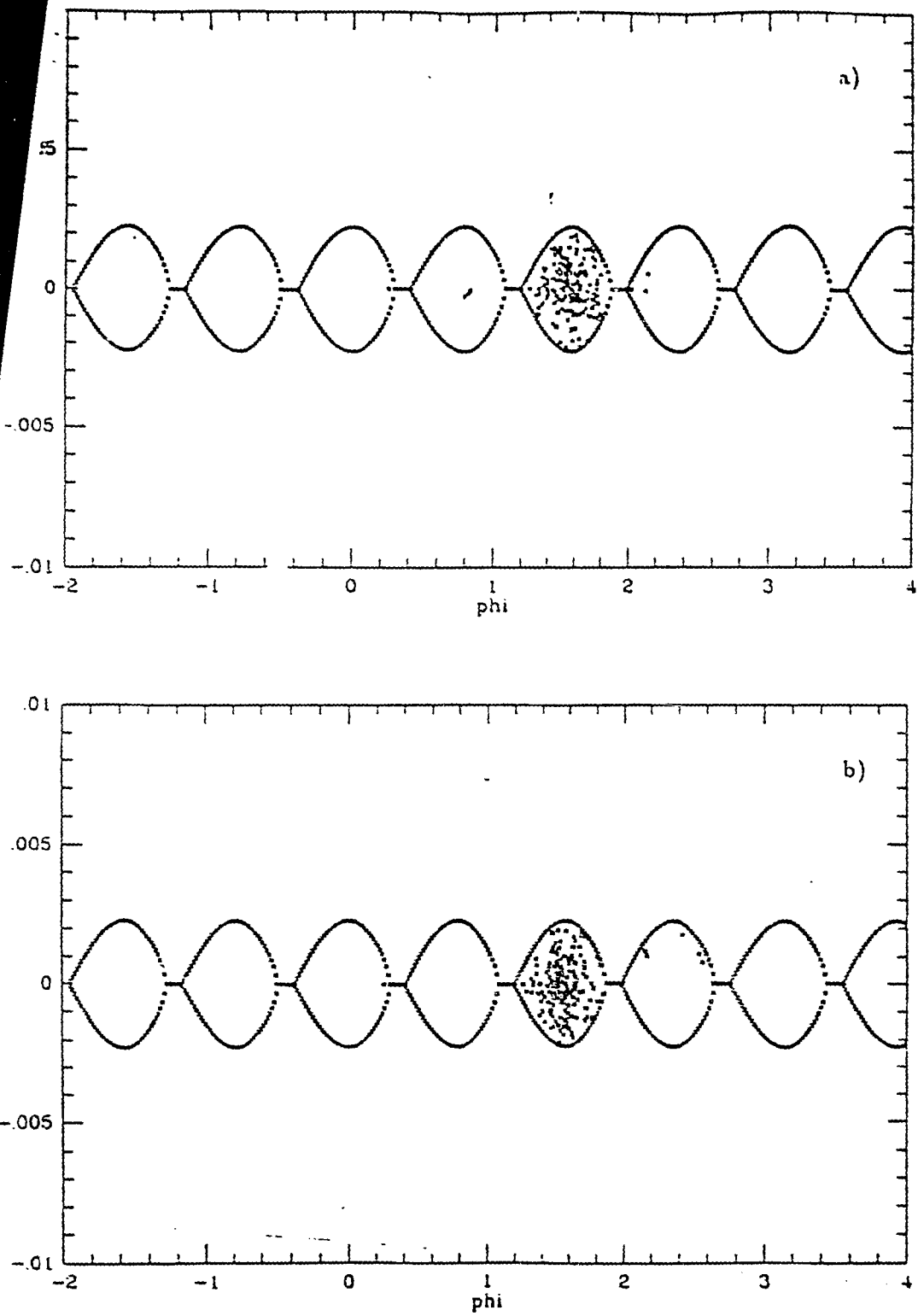

Fig. 7.