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DESIGN OF A 400-400 GeV^2 VERSION OF ISABELLE*

ISA Division Staff
Presented by A. van Steenbergen
Brookhaven National Laboratory
Upton, New York 11973

ABSTRACT

An extrapolation of the ISABELLE 200-200 GeV^2 proton-proton storage rings to higher energy has been studied and here the conceptual design is presented for a 400-400 GeV^2 version. The basic storage ring structure has been so modified that the circumference of the rings could be substantially increased without an increase of the transition energy. Because of the now well established microwave longitudinal bunched beam instability, this is essential in maintaining a viable longitudinal impedance limit for the overall structure. The principal parameters for the 400 GeV structure are given and compared with the basic 200 GeV design. Performance limitations, where they may differ from the 200 GeV design are indicated. Each 400 GeV ring uses superconducting magnets essentially identical to those employed in the 200 GeV design, but energized to 50 kG peak field. The justification for this is given together with other technical features differing from the basic design. It is concluded that for a cost increase of 40% over the basic p-p storage ring design, twice the center-of-mass energy could be provided for the ISABELLE proton-proton colliding beam facility.

Introduction

In the course of design studies for the ISABELLE 200-200 GeV^2 proton-proton colliding beam facility, the maximum desired center-of-mass energy has consistently been a difficult parameter to establish. Although generously above the predicted energy required for possible detection of the charged or neutral intermediate vector bosons with reasonable statistics, availability of higher energy would clearly give increased assurance, especially also in the detection of higher mass members of a possible W family. Indeed, it was suggested by the High Energy Physics Advisory Panel on new facilities, Woods Hole meeting, 1974, that a higher energy ISABELLE design might be more interesting to the physics community. In spite of this, principally for reasons of total facility cost, the major thrust of the Brookhaven design has concentrated on the 200 GeV case. Recently, however, the interest of extending ISABELLE to higher energies has been revived and a new study has been made of a possible higher energy design, the essence of which is reported here.

Following the first Woods Hole meeting, a preliminary examination was made /1/ of a higher energy structure. It was shown that ISABELLE could be extrapolated to 400 GeV peak single beam energy while maintaining the basic beam-beam luminosity objective. Nevertheless, this structure had a transition energy (γ_{inj} = 25.0) rather close to injection energy (γ_{inj} = 31.4) leading to a small orbital frequency dispersion value (η = 0.58 10^{-3}) at injection. This makes beam stacking

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difficult and the longitudinal stability criteria for the beam, during various phases of the stacking process, more severe. With respect to the latter, subsequent observation and interpretation[2,3] of the so-called bunched beam microwave longitudinal instability in the CERN PS and ISR has created a greater concern of beam stacking in a structure with too low an η value. Consequently, more recent studies towards higher ISABELLE energies were aimed at circumventing the transition energy problem and its associated fast beam instability during beam stacking. A variety of methods exist. A first method consists of adding a small stacking ring, interposed between the AGS injector and ISABELLE,[4] whereby the high current would be momentum stacked into the stacking ring and transferred in a bunched fashion from this into ISABELLE. A second method consists of changing the AGS to accelerate on the first harmonic and stacking proton bunches "boxcar" fashion into ISABELLE.[5] A third alternative consists of weakening the lattice focussing to keep transition energy low even in a larger circumference ring. This latter method has been adopted as the design approach for the higher energy ISABELLE structure. Only as a result of the extensive work on the ISABELLE 200 GeV version[6] has it been possible to develop the concepts of the 400 GeV facility in a short time.

Summary of the 400 GeV ISABELLE

Maintaining the basic six-fold symmetry structure, the higher energy capability is achieved by increasing the total bending length and increasing the peak magnetic field design value to 5 Tesla. Also, the experimental insertion lengths have been increased to accommodate the "physics" at the higher center of mass energy. For the larger circumference structure, the transition energy is lowered by adopting a weaker focussing structure, maintaining the original structure tune value. This is achieved by increasing the basic cell length and using three dipoles per half-cell rather than two. The added benefit is a reduction in the total number of quadrupole magnets required for the structure. A drawback is the higher lattice β and X_p, local dispersion, value, affecting potentially aperture parameters. By modifying beam injection into the AGS, the injector for ISABELLE, a somewhat higher beam brightness is possible, resulting in a stacked beam capability of 8 amperes, with an aperture filling at injection equal to that of the present 200 GeV design. With minor adjustment of the intersection region parameters the luminosity objective of 10^{33} cm^{-2} sec^{-1} at maximum energy can thus be preserved. An overview of the 400 GeV structure parameters and comparison with the 200 GeV system is given in Table I and a layout of the 400 GeV facility is shown in Fig. 1 indicating that, while preserving an adequate periphery for muon shielding, the BNL site is more than adequate for the higher energy facility.

TABLE I. General 400 GeV ISABELLE Parameters

Top energy	400 x 400 GeV^2	(200 x 200)^A
Design current	8 A	(10)
Dipole maximum field	5 T	(4)
Vacuum chamber, I.D.	8.0 cm	(8.0)
Circumference	3766.0 m	(2623.2)
Number of p-p interaction regions	6	(6)
Maximum luminosity	10^{33} cm^{-2}sec^{-1}	(10^{33})

^{A}Values for the 200 GeV design.

400 GeV Ring Structure

The lattice structure for the 400 GeV ISABELLE is qualitatively similar to the 200 GeV case. A list of principal lattice parameters is given in Table II. The lattice structure near and in the insertions given in Fig. 2. With an insertion length now of ≃ 160 m, a crossing angle of ≃ 10 mrad is obtained and a separation of the beams in the curved arcs of ≃ 97 cm. The increased insertion length permits a free space now of ± 30 m, which, with the stated crossing angle result in a separation of the two beams at the first quadrupole of the near crossing point focussing doublet of ~ 30 cm, which is adequate for the quadrupole magnets under consideration there.

TABLE II. 400 GeV ISABELLE Lattice Parameters

Circumference	$4\,2/3\,C_{AGS}$	$(3\frac{1}{4}\,C_{AGS})^A$
Insertions	6 x 160.2 m	(6 x 113.0)
Regular cell	59 x 38.9 m	(54 x 26.6)
Modified cell	18 x 38.9 m	(18 x 22.6)
Tune	22.6/22.6	(22.6/22.6)
Tune spread	0.025	(0.015)
Transition energy	19.4	(19.3)
Orbit frequency dispersion, η_{INJ}:	1.6×10^{-3}	(1.7×10^{-3})
Betatron amplitudes, $\hat{\beta}_V, \hat{\beta}_H$	67.6, 63.7 m	(43.3, 44.9)
Dispersion, X_p (max)	2.49 m	(1.75)
Phase advance/cell, $\Delta\varphi_V, \Delta\varphi_H$	0.22, 0.26 x 2π	(0.25, 0.26)
Uncorrected chromaticity	- 33	(- 33)
Chromaticity, full stack, injection	~ + 4	(~ + 2.5)

^{A}Values for the 200 GeV design.

In the standard insertion configuration ($\beta_V^* = 7.5$ m, $\beta_H^* = 30$ m), the maximum values of the structure functions are increased from the 200 GeV design, with $\hat{\beta}_H \simeq 175$ m and $\hat{\beta}_V \simeq 128$ m. Nevertheless, the effects on off momentum orbits are not significantly altered, the maximum β variation with momentum being approximately ± 10% for a ± 1% momentum aperture.

Beam Parameters for the 400 GeV ISABELLE

The desired mode of AGS operation for optimum beam stacking in the 400 GeV ISABELLE was reexamined. Assuming a lower beam current from the AGS for ISABELLE injection, single turn lossless injection (fast turn-off kicker) into the AGS from the 200 MeV Linear Accelerator becomes feasible. In the absence then of horizontal-vertical coupling in the AGS and with reduced space charge effects near the injection in the AGS, significantly less transverse phase space dilution is expected and an improvement by a factor of 2-3 in the four-dimensional transverse density should result.

Relevant to beam capture and acceleration in the 400 GeV structure the system parameters are essentially the same as for the 200 GeV case with the exception of stacking system harmonic number (39 → 56), acceleration rf frequency (228 kHz → 159 kHz), and number of AGS cycles required for a full beam stack (≃ 200 → ≃ 300). Also, maintaining the same energy gain per turn of 12 keV/turn, and keeping $\dot{B}$ at less than the maximum value, for $p \leq 1.3\ p_{inj}$, in order to keep the maximum momentum spread of the bunched beam below 1.5%, full width, the total acceleration time to maximum energy becomes 6.6 min (2.5 min for the 200 GeV case).

Taking into account the beam parameters encountered during the various stages of injection, stack buildup and beam acceleration, as given in Table III, the aperture requirements can be evaluated. This is shown in Fig. 3, indicating that for a comparable filling of the 8 cm warm (curved) bore, as for the 200 GeV design, a debunched stack width of 0.64% is possible, which, with the stack density of 12.4 A/%(Δp/p) leads to a design current of 8 A.

TABLE III. 400 GeV ISABELLE, Beam Parameters at Injection, 29.4 GeV

Mode of AGS injection	1 turn	(multiturn)[A]
Linac intensity[B]	114 mA	(62)
Linac emittance, 2.5σ, normalized	12π μrad.m	(< 15π)
AGS intensity, 12 bunches	2.7×10^{12} protons	(4.2×10^{12})
AGS emittance, V x H	15π x 15π $(\mu rad.m)^2$	(20π x 30π)
Longitudinal emittance/bunch	0.6 eV sec	(0.7)
Momentum spread	1.4×10^{-3} (Δp/p)	(1.6×10^{-3})
Stacked beam	7×10^{14} protons	(5.5×10^{14})
Momentum width, final stack	0.64 %, Δp/p	(0.67)
Momentum width, bunched stack	1.5 %, Δp/p	(1.6)
Momentum width, inj. beam + stack	1.7 %, Δp/p	(2.3)
Aperture demand,[C] during stacking	56 mm horiz.	(56)

[A] Values for the 200 GeV design. [B] Present performance 100 mA. [C] [illegible]

400 GeV - 400 GeV p-p Performance Parameters

The flexibility of insertion design, as developed for the 200 GeV structure, is maintained for the present 400 GeV colliding beam system. A number of insertion optics options have been worked out, of which two cases, together with ISABELLE performance parameters, are listed in Table IV. As indicated, the design luminosity at maximum energy is $2\ 10^{32}\ cm^{-2} sec^{-1}$ for a "standard" insertion setup, increasing to $10^{33}\ cm^{-2} sec^{-1}$ for a high luminosity configuration. At lower beam energy the luminosity will be lower, since L $\gamma^{1/2}$, if β_V^* and α, the crossing angle, are kept constant. However, β_V^* at low energy is limited because the maximum beam size in the insertion quadrupole doublet should not exceed that of the value for the standard insertion at 30 GeV energy. This results in lower than $\gamma^{1/2}$ proportional values below 200 GeV. Nevertheless, at any given energy ≤ 200 GeV, it is at most a factor √2 lower than in the 200 GeV design and at injection energy it is still higher than $10^{32}\ cm^{-2} sec^{-1}$.

TABLE IV. 400 GeV ISABELLE Performance Parameters, at Maximum Energy

Center-of-mass energy	800 GeV	
Beam current	8A	
Normalized emittance	15π x 15π $(\mu rad.m)^2$	
Insertions	Standard	High Luminosity
β_V^*, β_H^*	7.5, 30.0 (m)	2.0, 30.0
$\beta_V(max), \beta_H(max)$	128, 175 (m)	460, 175
rms beam sizes; σ_V^*, σ_H^*	0.2, 0.4 (mm)	0.1, 0.4
$(\Delta p/p)_{FW}$ (factor 2 dilution)	0.1 %	0.1 %
Interaction length, $\ell_{INT} = \pm 2\sigma_\ell$	± 0.12 (m)	± 0.30
Crossing angle, α_{TOT}	9.8 (mrad)	4.0
Free space	± 30 (m)	19
Beam-beam tune shift, $\Delta\nu_{BB}$	1.7×10^{-3}	2.2×10^{-3}
Luminosity, L	2.3×10^{32} $(cm^{-2} sec^{-1})$	1.1×10^{33}

Performance Limitations

Since it is expected that optimum performance will be limited by collective effects, a few of these anticipated to be dominant are considered here, comparing again the 400 GeV ISABELLE version with the 200 GeV basic design.

Incoherent Tune Shift

Neglecting electrostatic and magnetic image effects, the tune shift due to the direct space charge field alone may be written as[7,8]

$$\Delta\nu_{x,y}(o) = -(R^2/2\nu_{x,y})\,(\lambda_L/e)\,(r_p/ab\gamma\beta^2)\,(\gamma^{-2}-\eta_e)\,K_{x,y}\,(a/b)$$

in the usual notation, with $K_{x,y}$ (a/b) denoting a beam shape factor. The magnitude of $\Delta\nu$ depends strongly on beam shape, however, the beam optics for the 400 GeV case is qualitatively the same as for the 200 GeV case and both insertion length and regular cell structure length have increased by about the same factor of approximately 1.4, therefore, the above equation will suffice to scale the incoherent tune shift. The largest values are encountered at injection energy and are for the 400 GeV case a factor of 1.65 larger than for the 200 GeV version, resulting in $\Delta\nu_x(o) = -0.011$, $\Delta\nu_y(o) = -0.015$ for the debunched full stack, indicating a requirement for some increased correction of the working line during the stacking process.

Longitudinal Coasting Beam Instability ("Negative Mass" Instability)

The most stringent of these is the longitudinal high-frequency (microwave) instability as applied to the bunched injected beam, especially during the debunching phase in the beam stack formation. In this case, the bunches are unstable against high frequency inside bunch oscillations for which $\lambda < \ell_{bunch}$ and $\tau_{gr} < \tau_s$ where τ_s is the synchrotron oscillation period. A convenient expression for the stability criterion is given as[9]

$$(Z_{||}/n) \leq F(E_o/e)\,(|\eta|/\gamma)\,(i^{-1})\,(\Delta p_f/m_o c)^2$$

where i is the local value of the beam current and Δp_f is the local fwhh momentum spread in the beam bunch; F is a form factor dependent on the shape of the density distribution and $Z_{||}$ is the longitudinal coupling impedance at mode number n. Since the lattice design of the 400 GeV structure has been guided towards maintaining γ_{tr} and with this η, essentially equal to that of the 200 GeV structure the relevant scaling quantity is

$$(\Delta p_f/m_o c)^2(i^{-1}) \equiv 3\, i_m^{-1}\,(\Delta p/m_o c)^2$$

where, for a parabolic line distribution, i_m is the maximum local current value and Δp is half the full momentum spread. With the beam and stacking parameters as used here, this quantity is approximately equal to that for the 200 GeV case. Explicitly, for the present case, a maximum longitudinal impedance value of $\sim 5\ \Omega$ should not be exceeded for high mode numbers (frequencies $\gtrsim$ 1 GHz), essentially the same value as for the 200 GeV ISABELLE.

Considering the longitudinal stability of the debunched coasting beam, a low impedance requirement would only be encountered during the very early stage of stack formation where I and $(\Delta p/p)$ may be lower by one or two orders of magnitude. Consequently, it is expected that some beam shake-up might occur during this stage. The threshold for this is the same for either the 200 GeV or the 400 GeV version of ISABELLE. The growth time is nevertheless a factor of 1.4 larger for the 400 GeV case, since it scales with the orbital frequency.

At the start of beam acceleration the dominant impedance is that of the "just" unshorted rf accelerating cavities, i.e. assuming the use of feedback, $(Z_{||}/n) \simeq 75\ \Omega$ for the three accelerating cavities for the 200 GeV ISABELLE. Since, also in the 400 GeV case, the peak rf voltage is kept at 30 kV by increasing the total acceleration time, the same impedance value can be maintained and the stability criterion for the debunched full stack can be met generously.

Longitudinal Bunched Beam Instability

The stability criteria and growth rates of the longitudinal bunched beam instability has been developed by Sacherer.[10] No concern exists during beam acceleration, since also for the 400 GeV case a low harmonic number has been adopted. During injection up to 56 high (longitudinal) density bunches may be circulating. Stability can be provided with adequate Landau damping. The stability criterion has been given as

$$|\sqrt{m}\ \Delta\omega_{sc}| + |\Delta\omega_m| \leq (\sqrt{m}/4)\ S$$

where $\Delta\omega_{sc}$ is the shift in synchrotron frequency due to space charge, $\Delta\omega_m$ the same due to, say, the injection rf cavity impedance, and S the spread in frequency between center and edge of the bunch due to the nonlinear longitudinal focussing force. Since in the 200 GeV design $\Delta\omega_{sc} > (S/4)$ the bunches are expected to be unstable. This will be similarly true for the 400 GeV design. Fortunately, the growth time is large $(1/\tau \simeq 1\ \text{sec}^{-1})$. In the absence of frequency spread its inverse is given by $(1/\tau) = \text{Im}\ \Delta\omega_m$ giving an inverse proportionality of the growth time with $I.\omega_s$, where both I and ω_s are smaller for the 400 GeV structure, i.e. the relevant growth time is estimated a factor of 1.5 larger for the 400 GeV ISABELLE. Also here, in case of need, a feedback system can readily be built for suppression of the dipole and quadrupole mode.

Transverse Resistive Wall Instability

The stability criterion may be written as[11,12]

$$|Z_T| \leq \pi\ (E_o/e)\ (\nu/IR)\ \beta\gamma\ (\Delta p/p)_{fw}\ |(n - \nu)\ \eta - \xi|$$

in the usual notation with $n > \nu$ and $\xi = \Delta\nu/(\Delta p/p)$, the chromaticity. The required tune spread, in case of Landau damping only, for all modes $n > \nu$, is obtained from this as

$$\Delta\nu \geq IR\ |Z_T|\ /\ [\pi(E_o/e)\ \nu\ (\beta\gamma)]$$

Since presently a stainless steel chamber will be used, the required tune spread has been recalculated for the 200 GeV case. Its value (and chromaticity) to suppress the instability at injection energy by Landau damping alone is $\Delta\nu = 0.015$ ($\xi = 2.2$) and the corresponding value for the 400 GeV case is $\Delta\nu = 0.026$ ($\xi = 4.1$). The latter value is still well below the spacing between resonances at the working poing (22.6 - 22.667) and, consequently should be manageable.

Similarly, as for the 200 GeV design, the use of octupoles and electronic feedback should reduce the required tune spread for the bunched beam to a value of approximately 0.02.

Further, for the so called "head-tail" instability, a transverse resistive wall, bunched beam instability, theory[14] predicts stability for the lower modes for:

$$2\ T_B\ \omega_o\ \xi/(\eta\nu) \simeq 30$$

with T_B the bunch length in seconds and $\xi = \Delta\nu/(\Delta p/p)$ as before. For the 200 GeV design a ξ value of 1.5 would be adequate. For the 400 GeV case, with identical bunch length, η and ν values, a lower value ($\xi = 1$) would suffice because of scaling with ω_o, indicating that, with the larger ξ value required for the ordinary transverse resistive wall instability, the head-tail instability should not occur.

Magnet System

Magnets

The higher dipole field value (50 kG at 4250 A) is achieved by permitting a limited amount of training. Experience with the 4.25 m long magnets has shown that a field in excess of 40 kG can be achieved without training at a temperature of 4.5^oK. After approximately 10 quenches, fields as high as 49 kG have been reached at this temperature. If the operating temperature is reduced to $\leq 4.0^oK$ the expected maximum field attainable is increased to 53 kG which would permit an operating field value of 50 kG. The temperature dependence of the field is shown in Fig. 3.

The present approach is somewhat less conservative then that adopted for the 200 GeV design, but it is supported by a steady improvement in the performance of ISABELLE prototype magnets. It should also be pointed out that a slight increase of conductor width would regain extra reserve, without changing the basic magnet design.

The higher operating field and increased magnet length lead to a considerable increase in magnetic stored energy, i.e. presently 0.82 MJ/dipole compared with 0.46 MJ/dipole for the 200 GeV design. However, the "HEUB" magnets,[15] which are of similar design, have quenched safely at a higher specific energy density (equiv ~ 0.92 MJ), therefore, no changes are contemplated in the magnet protective circuitry for the 400 GeV design.

For the most part, the correction coil system for the 400 GeV ISABELLE is similar to that described in the 200 GeV proposal, however, the sextupole correction has been increased here because of the larger iron saturation at 50 kG which, together with the larger X_p and β function values, causes the ν value to be more sensitive to errors in the sextupole field (by approximately a factor of 2). Further details of the 400 GeV ISABELLE field correction system are presented in Ref. 16.

Refrigeration

The 400 GeV ISABELLE refrigeration system is similar in design to that described in the 200 GeV proposal, i.e. a single refrigerator supplies all refrigeration in the form of high pressure (15 atm) He gas circulating through the magnets. For the 400 GeV design, the higher dipole field value requires a steady-state temperature maximum of 3.8°K (2.6°K in/3.8°K out) compared with 4.3°K for the 200 GeV design, necessitating a larger mass flow rate of helium coolant. The heat load and cryogenic system parameters are given in Table V.

TABLE V. 400 GeV ISABELLE, Cryogenic System Parameters

Magnets	14000	W	(9500)^A
Transfer lines	1100	W	(600)
Magnet power leads, equiv. load	4600	W	(5500)
Refrigeration capacity, design	30	kW	(25)
Power requirement, compressors	16	MW	(10)
Total liquid helium, equiv.	45	kℓ	(30)
Cooldown weight	5400	Mg	(3600)

^A Values for the 200 GeV design.

Conclusion and Summary

A study of a higher energy version of the ISABELLE colliding beam system has been carried out, which indicates that increasing the single beam energy to 400 GeV does not result in any particular problem. Performance limitations due to high intensity effects are no more severe than in the 200 GeV design and the luminosity objective of 10^{33} $cm^{-2}sec^{-1}$ with a diamond length of < 1 m can be maintained. At energies ≤ 200 GeV the luminosity value is at worst a factor of $\sqrt{2}$ lower than that of the 200 GeV design.

Since the only inhibiting factor against adoption of the higher energy design would be construction cost, the ISABELLE design team has evaluated the cost of the 400 GeV version. The results indicate that for a cost increase of approximately 40% over that of the basic 200 GeV design (173 M$) twice the center-of-mass energy could be provided for the ISABELLE p-p colliding beam facility.

At the time of this writing, the High Energy Advisory Committee subpanel on new facilities (Woods Hole III meeting) released its recommendations. Not only did it indicate as a first priority the authorization of ISABELLE for FY 79, but in a most positive response to the higher energy ISABELLE version, stated ....." to operate with a maximum energy of about 400 GeV per beam" and emphasized that "while the physics interest of the lower energy is great, the incremental physics benefits at the higher energy are impressive relative to the incremental cost".

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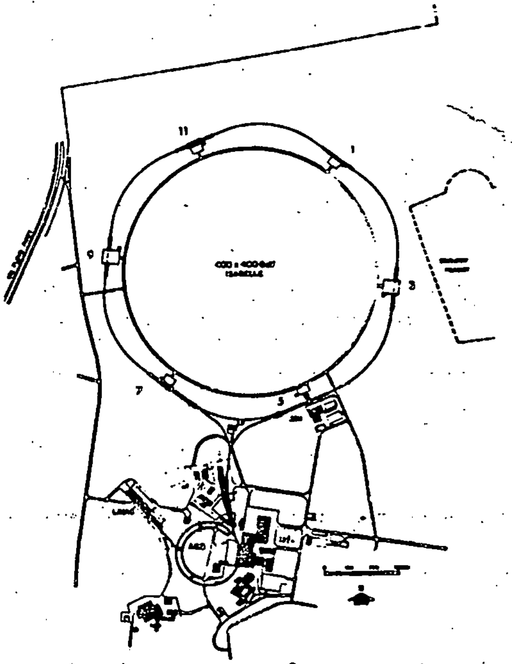


PLAN VIEW OF THE 400 X 400 GeV² ISABELLE ON THE BNL SITE

Fig. 1.

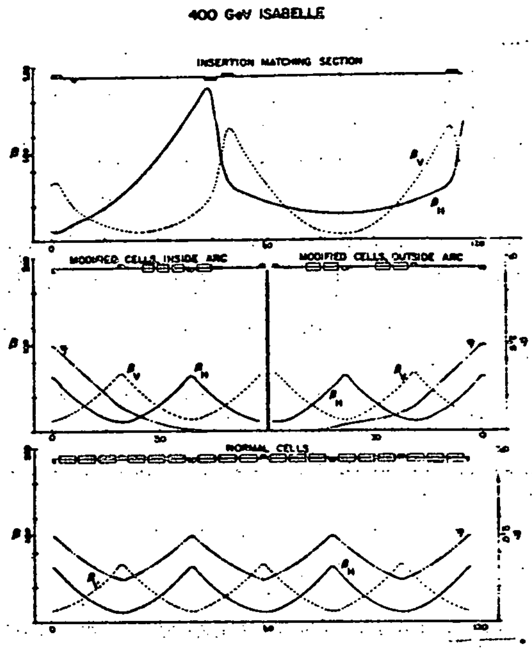
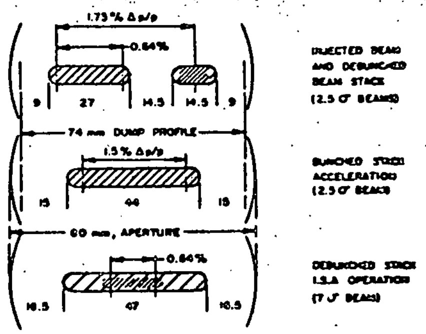
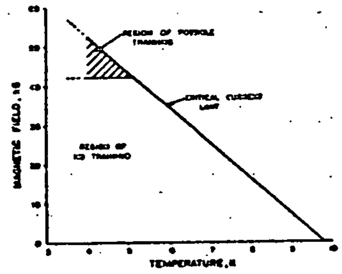


Fig. 2.



400 X 400 GeV² ISABELLE APERTURE SUBDIVISION AT THE LOCATION OF A FOCUSSING QUADRUPOLE (β_H) FOR 29.4 GeV PROTON ENERGY

Fig. 3.



TEMPERATURE DEPENDENCE OF THE DIPOLE MAGNETIC FIELD

Fig. 4.