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A CONCEPTUAL DESIGN OF A 400-GeV₂₂

VERSION OF ISABELLE

ISA Division Staff

April 26, 1977

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ABSTRACT

This is a conceptual design report for 400 x 400 GeV proton-proton storage rings. It describes a facility with twice the energy capability of the recently proposed ISABELLE. The basic accelerator lattice has been modified so that the circumference of the magnet rings can be increased substantially without an increase in the transition energy. Each 400 GeV ring uses superconducting magnets of the type described in the ISABELLE Proposal, but energized to 50 kG. Other technical features are not significantly different from the 200 GeV design, and are described in this report. The beams will collide in six interaction regions where up to 60 m of space is available for the installation of experimental equipment. The research possibilities that are provided by the increased center-of-mass energy are briefly described. Finally, a cost estimate of 238 million dollars for the research facility is outlined. This is nearly 40% more than the cost of the 200 GeV ISABELLE, but this facility would provide twice the energy available for exploring new regions of high energy physics.

INTRODUCTION

Throughout the long series of design studies that have led to the present 200 GeV ISABELLE Proposal,¹ the maximum energy has consistently been a difficult parameter to establish. The choice of 200 GeV was originally made in 1971 to ensure that the intermediate vector boson could be observed. Then it was suggested during the first meeting of a HEPAP subpanel on New Facilities (Weisskopf panel) at Woods Hole in 1974 that a higher energy might be more interesting to the physics community. It was shown² shortly after this meeting that the ISABELLE design could be modified to at least 400 GeV by simply increasing the bending length of the 200 GeV design.

In spite of the interest in higher energy, the major thrust of the Brookhaven design has concentrated on the 200 GeV case because of cost and physics considerations. Recently, however, the interest in a higher energy has intensified and a new design effort has been mounted to see if this interest can be satisfied.

Technically, the problems associated with higher energy come from the circumference of the rings of magnets. This parameter clearly comes into the cost, but in a more subtle way, influences the performance. The larger circumference ordinarily increases the transition energy of the structure. If the transition energy is too close to the injection energy, then injection and stacking of protons are difficult and the longitudinal stability criteria for the bunched beam during stacking are too severe. In fact, the longitudinal instability problem is severe for all high energy storage rings and is not removed even by having a full energy injector available. There

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1. "ISABELLE, A Proton-Proton Colliding Beam Facility", BNL Formal Report BNL 50648 (1977).
 2. R.L. Gluckstern and R.W. Chasman, BNL Report BNL 19062 [CRISP 74-14 (1974)].

exists a variety of methods of circumventing the transition energy problem and its associated instabilities. The method chosen for this design consists of weakening the focusing to keep the transition energy down even in the large circumference ring. This solution requires keeping an 8 cm aperture yet appears to be economical. It is the solution developed in detail in the balance of this report. A second method consists of adding a small stacking ring to the configuration.³ In such a ring the high current would be stacked and then transferred to the main ring. A third alternative consists of changing the AGS to accelerate on the first harmonic and stacking the proton bunches end-to-end (so-called "boxcar" stacking) in the main ring.⁴ The colliding beam facility described below will be laid out on the BNL site in such a way that a stacking ring can be easily added, if later study shows that it is sufficiently desirable to justify its cost.

The philosophy of this design is slightly different than that for the 200 GeV case. In the 200 GeV study, a conservative approach on magnet performance, beam brightness, and luminosity expectation has everywhere been adopted. In this 400 GeV design, the approach is to allow parameters to be pushed to more optimistic values although still within quite reasonable limits. For example, 50 kG fields are assumed (which helps keep the circumference down), yet such performance is within the capability of our single-layer superconducting dipoles, particularly if the temperature is lowered slightly. The injected beam brightness has been assumed slightly higher although still well within the capability of the AGS. At the higher energy, a luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ can be achieved with a lower proton current than that needed in the 200 GeV case. With these assumptions, it is seen below that the aperture utilization is not much different than for the 200 GeV case.

3. M. Month, "A Low Energy Current Accumulator for High-Energy Proton Rings", Proc. 1977 Particle Accelerator Conf., Chicago, March 16-18 (in press).

4. R. Chasman, BNL Formal Report BNL 20548 [ISA 75-9 (1975)].

The extensive design work on ISABELLE at 200 GeV has made it possible to develop the concepts of this 400 GeV facility in a short time. Parameters relevant to performance are extrapolated without difficulty using analytical and computer models of the two machines. Construction cost and time schedule information can be derived directly from the 200 GeV study using unit costs or, at most, very straightforward extrapolations. The conceptual design study for ISABELLE,¹ hereinafter referred to as the 200 GeV Proposal will be extensively referenced in this report.

The overall 400 GeV design described below is very attractive and we have confidence in our ability to build this facility at the estimated price.

PHYSICS CAPABILITIES OF THE 400 GeV ISABELLE

The general objective of ISABELLE is to provide a substantial increase in available center-of-mass energy of the colliding nucleons, compared with that which can be provided by existing accelerators and the ISR. Clearly that increase would be greater for a 400 GeV beam energy than for 200. In terms of s , the increase would be to $640\,000\text{ (GeV)}^2$ instead of $160\,000\text{ (GeV)}^2$. The maximum luminosity would be maintained at the same high value, and the present design permits operation at any beam energy from 30 to 400 GeV, with a broad choice of unequal energies. There would only be a slight reduction in luminosity at the lower energies when compared with the 200 GeV design.

In the 200 GeV Proposal the most important types of high energy physics research at ISABELLE are described. They would be the same at 400 GeV as 200 GeV. The 400 GeV energy would be particularly advantageous for experiments concerned with:

1. production of W mesons,
2. production of hadrons at large transverse momentum,
3. jets,

4. energy dependence of strong interactions, and
5. new high energy phenomena.

Each of these is discussed briefly below.

For the production of W mesons a beam energy of 200 GeV should be sufficient to allow experiments with good statistics, according to current ideas of the production mechanism, provided the mass of the W is no more than twice the expected value of approximately $60 \text{ GeV}/c^2$. The justification for this statement is given in the 200 GeV Proposal. An energy of 400 GeV would give greater assurance of producing W's in greater numbers, especially possible higher-mass members of a W meson family. Exploring this possibility would be a natural step following the discovery of the W. An energy of 400 GeV for ISABELLE would about double the range of masses for W's (and other massive particles) that would be accessible for study. This should give more complete information on the nature of W mesons and their role in the weak interactions. For any W mass the production cross section is expected to rise with increasing s. The 400 GeV ISABELLE would provide greater numbers of W's to study, as shown in Fig. 1, which would be beneficial for many experiments.

For the production of hadrons at large transverse momentum the cross section has been observed to increase with increasing s for constant values of $p_{\perp}$. At the ISR the large $p_{\perp}$ spectra of the CCR collaboration have been fitted by the expression

$$E \frac{d\sigma}{d^3 p} = \frac{1.54 \times 10^{-26}}{(p_{\perp})^{8.24}} \exp(-26.1 p_{\perp}/\sqrt{s}) \text{ cm}^2 \text{ GeV}^{-2} \text{ sr}^{-1}$$

If this expression is assumed to be valid for the values of $p_{\perp}$ and s that ISABELLE provides, it can be used to estimate the increase in cross section that is obtained by going to 400 GeV. The cross

section ratio is tabulated below for values of $p_{\perp}$ that one might expect to reach.

$p_{\perp}$ (GeV/c)	$\sigma(400)/\sigma(200)$ from CCR expression
10	1.9
20	3.7
30	7.1

It is clear that 400 GeV provides a significant advantage. This will not, however, permit a very great increase in the maximum $p_{\perp}$ that can be reached because the power-law term, $p_{\perp}^{-8.24}$, leads to a very strong $p_{\perp}$ dependence. If the maximum $p_{\perp}$ is about 25 GeV/c for 200 GeV, it extrapolates to about 30 GeV/c for 400 GeV. Similar increases would be predicted by other models of hadron production.

Fig. 1. Cross section for the production of W mesons as a function of W meson mass, according to quark model prediction, derived from Fig. II.3 of the 200 GeV Proposal. Curves for W^- and W^0 are indistinguishable in this range. The arrow indicating one event per hour is based on the assumptions that branching ratio and detector efficiency give one recorded event per 50 W's produced and that the luminosity is $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$. Solid curves are for 400×400 GeV and dashed curves for 200×200 GeV versions of ISABELLE.

In the production of jets there is a similar advantage to 400 GeV. To the extent that jets and high $p_{\perp}$ hadrons are both thought to arise from quark-quark collisions, they represent two ways of observing the same basic phenomenon. The scattered quarks are likely to have high transverse momentum because of their point-like nature. Each quark fragments into a jet of hadrons, with each hadron inheriting a substantial fraction of the high transverse momentum of the quark. The spectrum of single hadrons is easier to measure than the behavior of correlated groups of particles in jets, but the jets are more directly related to the quark-quark collision and should provide more information about it. Since several particles may form a jet, the total $p_{\perp}$ may be considerably higher than for a single particle, as indicated by the quark model predictions shown in Figs. II.10 and II.11 of the 200 GeV Proposal. Curves for different proton energies in Fig. II.11 show that the jet production cross section at the higher values of $p_{\perp}$ would be at least 2-3 times as large for the 400 GeV ISABELLE as for 200 GeV. These high $p_{\perp}$ jets would be the easiest to recognize.

In studying the energy dependence of strong interactions the increased energy range would be valuable, especially in providing a greater energy range in which new and unexpected phenomena might appear. If, however, the behavior at these energies corresponds to models that predict variations proportional to $(\log s)$ or $(\log s)^2$, the changes in cross section are not very large. The total cross section, for example, increases by about 5 mb in going from $s = 160\,000$ to $640\,000$ $(\text{GeV})^2$, according to the extrapolations shown in Fig. II.13. Changes in elastic scattering amplitudes are expected to be fairly small, with a change of about one in the slope parameter, b , and no significant change in ρ indicated in Figs. II.15 and II.14 respectively of the 200 GeV Proposal. For inelastic interactions a larger rapidity range is available for pions of the usual $p_{\perp}$. Since it is bounded by $\pm \frac{1}{2} \log(s/m^2)$, the increase is $\log 4$, and the central region would grow from about 8 rapidity units at 200 GeV to about $9\frac{1}{2}$ at 400 GeV. In each case the greater range is beneficial, but the

benefit is moderate as long as hadronic interactions follow a smooth extrapolation from their lower energy behavior as expected. The 400 GeV energy also provides more flexibility through use of asymmetric operation. For example, use of 100×400 GeV permits operation of a $p_{\perp}$ half as great as 200×200 GeV at the same angle, for the same value of s .

These views have been based on an extrapolation from lower energies where many measurements on particles and their interactions have been performed at existing accelerators and storage rings. These extrapolations give a reasonable idea what to expect for values of s of 160 000 or 640 000 $(\text{GeV})^2$, much above those now available in our laboratories. We might take another starting point, however, utilizing cosmic rays which contain a few particles of high enough energies to provide such values of s in the center-of-mass of the colliding particles. A cosmic ray proton of 340 000 GeV colliding with a stationary nucleon provides an s of 640 000 $(\text{GeV})^2$ while a proton of only 85 000 GeV is required for s of 160 000 $(\text{GeV})^2$. What evidence is there from cosmic ray research of specially interesting phenomena at these energies?

There is not a great deal of evidence because such events are rare — most cosmic ray protons have energies that are lower by several orders of magnitude. Furthermore, the experimenter has no control over energy or direction of the incoming particle, so that such experiments are very hard to perform, and the interpretation of the results has often been controversial.

The energies of primaries that cause the events observed in cosmic ray studies extend well beyond 85 000 GeV, with energies up to $\sim 10^6$ GeV recorded in large emulsion chambers and up to $\sim 10^{10}$ GeV in extensive air shower detectors, according to recent summaries.⁵⁻⁷

5. Proc. of the Thirteenth Intern. Conf. on Cosmic Rays, Denver (1973).
6. Proc. of the Fourteenth Intern. Conf. on Cosmic Rays, Munich (1975).
7. G. Yodh, talk on Cosmic Rays at the Miniconference on Prospects of Strong Interaction Physics at ISABELLE, Brookhaven (1977).

With the emulsion chambers there is information about the angle and energy of secondary particles, whether they are charged or neutral, and about division into electromagnetic and nuclear components, at the point in the hadronic cascade development at which the observation is made. This is enough to indicate interesting properties. There are reports of high transverse momenta and high mass fireball states, $\langle p_{\perp} \rangle \approx 1.7$ GeV/c and fireball mass ≈ 250 GeV in certain "Centauro" events. There are events with dozens of charged particles and no neutrals, and vice versa. These reports suggest new phenomena to be observed at such high energies, but such suggestions are highly speculative at the present time. They provide an additional incentive to push experiments in accelerator laboratories with controlled beams and high event rates to the highest practical energies, but with no clear way to tell how much advantage 400 GeV for ISABELLE has over 200 GeV in searching for such new phenomena and providing ways to understand them.

OVERVIEW OF THE STORAGE RINGS

The 400 GeV rings can be deployed on the northwest corner of the BNL site as described for the 200 GeV Proposal. The BNL site is actually large enough to accommodate rings in the TeV range, but they would require a layout encircling the center of the Laboratory.

Figure 2 shows a map of this part of the BNL site with the 400 GeV rings in place. The facility is placed far enough from the site boundaries to permit adequate muon shielding. Other environmental problems are not significantly different from those of the 200 GeV case.

The facility has the same six-fold symmetry as developed in the 200 GeV Proposal. A few parameters giving an overview of the 400 GeV machine are listed in Table I. A more complete parameter list is given in the Appendix.

Fig. 2. Plan view of ISABELLE on BNL site.

TABLE I. General 400 GeV Parameters

Top Energy	400 GeV
Design Current	8 A
Dipole Magnetic Field (400 GeV)	50.0 kG
Vacuum Chamber i.d.	8.0 cm
Circumference ($4\frac{2}{3} C_{\text{AGS}}$)	3766.56 m
Insertions (No. $\times$ length)	6 $\times$ 160.24 m
Regular Cells (No. $\times$ length)	54 $\times$ 38.96 m
Modified Cells (No. $\times$ length)	18 $\times$ 38.96 m
Maximum Luminosity	$10^{33}/\text{cm}^2 \text{ sec}$

The higher energy is achieved by increasing the circumference of the bending arcs and by increasing the average field strength from 40 kG to 50 kG. Insertions have increased from 118 m length to 160 m and the free space from 40 m to 60 m. Appropriate modifications to all components of the facility have been examined and are described in the text which follows.

RING MAGNET STRUCTURE, LATTICE CHARACTERISTICS AND 400 GeV PERFORMANCE

Increasing the top ISABELLE beam energy to 400 GeV requires an increase in the bending length of the rings. To keep this increase as small as possible, the magnetic system has been modified so as to be capable of operating at a guide field of up to 50 kG. This represents an increase of 25% from the 200 GeV design. Thus, increasing the bending length by only 60% will allow a doubling of the top ISABELLE beam energy to 400 GeV. Collisions at ISABELLE will thereby reach a center-of-mass energy of 800 GeV.

The lattice structure for the 400 GeV ISABELLE is qualitatively similar to the 200 GeV case. A list of important lattice parameters is given in Table II. The magnet layout for a half-sextant is sketched in Fig. 3. In order to achieve the required increase in the bending length, a dipole is added to each half-cell in the curved sections of the lattice. Thus, the increased bending is obtained without increasing the ring tune, or more importantly, the lattice transition energy, which remains in the range $\gamma_{\text{tr}} \sim 19$.

TABLE II. Lattice Parameters

Dipole magnetic field (400 GeV)	50 kG
Quadrupole gradient (cells, 400 GeV)	6.7 kG/cm
Circumference ($4\frac{2}{3} C_{\text{AGS}}$)	3766.56 m
Insertions (No. $\times$ length)	6 $\times$ 160.24 m
Regular cells (No. $\times$ length)	54 $\times$ 38.96 m
Modified cells (No. $\times$ length)	18 $\times$ 38.96 m
Horizontal beam separation in arcs	97.1 cm
Regular cell length - inner arc	38.91 m
Regular cell length - outer arc	39.01 m
Radius of circle through crossing points	579.7 m
Average radius of curved arc	374.3 m
Magnetic radius of curvature	266.9 m
Average machine radius	599.5 m
Distance of ring center to central outer arc cell	610.3 m
Tune ($\nu_h = \nu_v$)	22.62
Working line tune spread ($\Delta\nu_h = \Delta\nu_v$)	~ 0.02
Transition energy, γ_{tr}	19.44
Frequency slip factor, η (injection)	1.63×10^{-3}
Horizontal structure function, cell ($\beta_{\text{max}}, \beta_{\text{min}}$)	63.7, 11.0 m
Vertical structure function, cell ($\beta_{\text{max}}, \beta_{\text{min}}$)	67.7, 13.8 m
Dispersion function, cell ($X_{\text{p,max}}, X_{\text{p,min}}$)	2.49, 1.21 m
Phase advance, cell (h,v)	94.4, 79.2 deg
Natural lattice linear chromaticity (no sextupole correction)	- 33
Operating chromaticity ($\chi_h = \chi_v$, full coasting stack, 29.4 GeV)	+ 3

Fig. 3. Magnet layout in half-sextant.

The implication is that the AGS peak energy of ~ 30 GeV remains an acceptable injection energy for the ISABELLE rings. Of course, the increased cell length implies a weaker focusing cell as compared to the 200 GeV case. There is, therefore, a greater demand on the vacuum chamber aperture. However, using a different mode of AGS operation — single turn injection from the 200 MeV linac — and being able to limit the design current to ~ 8 A results in an aperture utilization similar to that in the 200 GeV ISABELLE.

The modified bending cells adjacent to the six straight insertions, as in the 200 GeV case, produce a larger deflection in the outer arc beam causing the beams to converge towards each other. The bending magnet lengths and locations within these cells are so chosen that the momentum dispersion functions are brought to zero in both inner and outer arcs. The result is a zero dispersion crossing region. Choosing an insertion length of ~ 160 m, we obtain a natural crossing angle of ~ 10 mrad. With these choices of modified bending cells and insertion length, we arrive at a horizontal separation of the beams in the curved arcs of ~ 97 cm, more than adequate to accommodate separate dewars for inner and outer arc magnets individually.

In order to attain a 400 GeV beam energy with 50 kG magnets, a small increase in the length of each dipole is required. Specifically the dipole length has been increased by 25 cm, from $4\frac{1}{2}$ m to $4\frac{3}{4}$ m. The weaker focusing cells have the effect of reducing the integrated quadrupole strength in the cells. In order to keep the dipoles and cell quadrupoles powered in series, the choice of quadrupole design is roughly the same length as in the 200 GeV case, but with a gradient increase of about 30% to accommodate the higher energy.

To perform experiments at 400 GeV, we have increased the free space around the crossing region by 50% from ± 20 m to ± 30 m. With the crossing angle of ~ 10 mrad, the separation of the two beams at the first quadrupole of the strong focusing doublet is ~ 30 cm. This separation provides sufficient space for superconducting coils and

iron thereby allowing the use of a gradient of up to ~ 4.5 kG/cm while still satisfying the tolerance we have set on the leakage field (i.e. ~ 200 G). In order to keep the gradient at this level for 400 GeV beams, the quadrupoles making up the doublet, Q1 and Q2, have been lengthened to 4.0 m and 3.5 m respectively.

In the standard insertion configuration, the maximum values of the structure functions are increased from the 200 GeV design, with $\beta_h^{\max} \approx 1/5$ m and $\beta_v^{\max} \approx 128$ m for the horizontal and vertical planes respectively. However, the effects upon off-momentum orbits are not significantly altered, the maximum β -variation with momentum being on the order of $\sim \pm 10\%$ for a $\pm 1\%$ momentum aperture.

The flexibility of the insertion designs for the 200 GeV and 400 GeV cases are equivalent, with a variety of diamond configurations possible. In particular, the low- β configuration for the 400 GeV design has β_v reduced from 7.5 m to 2 m. This reduces the rms beam height from 0.2 to 0.1 mm. With the inclusion of common dipole magnets, the crossing angle can be reduced from 9.8 mrad to 4.0 mrad, which is the setup for the high-luminosity insertion. This increases the luminosity by more than a factor of 2 by extending the 95% interaction length from ± 12 cm to ± 30 cm. The required insertion quadrupole settings for standard and low- β configurations are given in Table III.

The luminosity of two equal colliding beams of Gaussian cross section colliding at angle α in the horizontal plane is

$$L = \frac{(I/e)^2}{\pi^{\frac{1}{2}} c \sigma \alpha},$$

where σ is the rms vertical dimension of the beam at the crossing point. The estimated performance figures are shown in Table IV. As can be seen, the design luminosity at the top energy of 400 GeV is $2.3 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ for the standard setup, increasing to $1.1 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ for the high luminosity configuration. If we operate at lower energy, the beam size σ will be larger, and therefore the luminosity smaller.

TABLE III. Quadrupole Settings for Insertion Tuning

Element	Gradient (kG/cm)		Magnetic length (m)
	Standard	Low- β	
QF (cell quad)	+ 6.7	+ 6.7	1.48
QD (cell quad)	- 6.7	- 6.7	1.40
Q4 (insertion)	- 4.09	0	1.41
Q3 (insertion)	0	- 1.45	2.00
Q2 (insertion)	+ 4.09	- 4.24	3.34
Q1 (insertion)	- 4.09	- 4.28	3.44

TABLE IV. 400 GeV Performance

Design center-of-mass energy	800 GeV	
Single beam energy	400 GeV	
Design magnetic field	50.0 kG	
Design beam current	8 A	
Normalized emittance	$15 \pi \times 10^{-6}$ rad m	
	Standard	High Luminosity
β_h^* at crossing point	30 m	30 m
β_v^* at crossing point	7.5 m	2.0 m
Maximum β_h value	~ 175 m	~ 175 m
Maximum β_v value	~ 128 m	~ 450 m
rms horizontal size, σ_h^*	0.42 mm	0.42 mm
rms vertical size, σ_v^*	0.21 mm	0.11 mm
$\Delta p/p$ (full, ideal)	0.047 %	0.047 %
$\Delta p/p$ (full, factor 2 dilution)	~ 0.1 %	0.1 %
Crossing angle, α (total)	9.8 mrad	4.0 mrad
Interaction length, $\ell_{int} = \pm 2\sigma_\ell^*$	± 12.1 cm	± 29.7 cm
Beam-beam tune shift, $\Delta\nu_{bb}$	1.75×10^{-3}	2.18×10^{-3}
Luminosity, L	$2.3 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$	$1.1 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$

The beam size σ equals

$$\sigma = 0.4 \sqrt{\beta^* \epsilon / \pi \gamma}$$

where ϵ is the invariant emittance (enclosing 95% particles in phase space), and β^* is the amplitude function at the crossing point. Thus L would seem to scale as $\gamma^{\frac{1}{2}}$, if β^* and α are kept constant.

However, the minimum β^* attainable is probably larger at lower energies than at the top energy. If we assume that the beam size at the quadrupoles on either side of the interaction region must not be larger than at injection in the "standard" lattice, then we must have

$$\beta^* \geq \beta_{30}^* \times \frac{30 \text{ GeV}}{E}$$

and also $\beta^* \geq \beta_{400}^*$. We find, for different energies, the following minimum beam sizes and maximum luminosities:

E (GeV)	β^* (m)	$\sigma_{\min}$ (mm)	$L_{\max}$ (cm ⁻² sec ⁻¹)
29.4	7.5	0.77	1.5×10^{32}
50	4.41	0.455	2.58×10^{32}
100	2.21	0.228	5.15×10^{32}
200	2.0	0.153	7.7×10^{32}
300	2.0	0.125	9.4×10^{32}
400	2.0	0.108	1.1×10^{33}

Thus, the peak achievable luminosity at top energy is the same as in the 200 GeV design. At any given energy ≤ 200 GeV it is at most a factor $\sqrt{2}$ lower than in the 200 GeV design, and at ISR energy (30 GeV) it is still higher than at the ISR; thus exploitation of a continuous range of energies from 30 to 400 GeV will be possible.

PERFORMANCE LIMITATIONS

The current that can be injected and stored is limited by collective effects. The most important of these are the longitudinal high frequency (microwave) instability of the injected bunches, and the transverse coherent instability of the whole stacked beam just before the beginning of acceleration.

The theoretical criterion for the microwave instability of the injected bunch is roughly⁸

$$e\hat{I} |Z/n| < F\eta E(\Delta p/p)^2,$$

where $\hat{I}$ is the peak current in the bunch, $\Delta p/p$ the peak total momentum spread, Z the longitudinal coupling impedance, n the mode number, $\eta = (1/\gamma_t^2 - 1/\gamma^2)$ the frequency dispersion coefficient, and F a form factor depending on the shape of the distribution; we may take $F \sim \pi/4$.

With the rf parameters obtaining at the moment the bunch is deposited in the stack ($V \approx 445$ V, bunch area 0.6 eV·sec) one finds a peak local current in the bunch of 0.55 A, a momentum spread of 2.8×10^{-4} , and the tolerable coupling impedance Z/n is about 4 Ω , just about the same as in the 200 GeV version.

Transverse instability is induced by a transverse coupling impedance. The tune spread $\Delta\nu$ needed to suppress this instability, is approximately⁹

$$\Delta\nu \sim \frac{I|Z_\perp|R}{\pi\nu E/e}.$$

With a stainless steel vacuum chamber, the transverse impedance $Z_\perp$ scales roughly as $R^{3/2}$, where $2\pi R$ is the machine circumference. On the other hand, the current I is reduced somewhat. Thus the needed tune spread at injection is about twice that for the 200 GeV version, or about 0.02 tune units. This is still well below the spacing between resonances at our working point (between $\nu = 22.6$ and 22.667), and should be manageable.

Another limitation in performance may be the interaction between the two colliding beams at top energy. A measure of this interaction is the "tune shift" of one beam due to its passage through the other beam. If this tune shift is kept below 5×10^{-3} per interaction region, all indications are that the beam-beam effect is harmless. In the present design, this tune shift is well below that limit.

8. D. Boussard, CERN Rept. Lab II RF Int/75-2 (1975).

9. E. Keil and A. Ruggiero, Proc. 1975 ISABELLE Summer Study, Brookhaven, BNL 20550, p. 531.

To summarize: The performance limitations due to high intensity effects in the present design are no more severe than in the 200 GeV design.

BEAM TRANSFER, STACKING, ACCELERATION AND PROTECTIVE EXTRACTION

The adoption of a weaker focusing structure for the 400 GeV storage ring results in an essential reduction of its transition energy. An added consequence, however, is the potentially increased aperture demand associated with the somewhat larger betatron amplitudes and maximum dispersion value. This is circumvented by adopting a somewhat reduced maximum stacked current objective while maintaining the maximum luminosity objective of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$. Associated with this, it became of interest to examine again the desired mode of AGS operation for optimum beam stacking in the 400 GeV ISABELLE. A lower beam current from the AGS for ISABELLE injection is assumed, permitting thereby single turn lossless injection (fast turn off kicker) into the AGS from the 200 MeV Linear Accelerator. In the absence of horizontal-vertical coupling in the AGS, and with reduced space-charge effects near injection in the AGS, significantly less transverse phase dilution is expected and an improvement by a factor of two in the four-dimensional transverse density results. The present transfer parameters are summarized in Table V.

TABLE V. AGS Parameters, as Injector for the 400 GeV ISABELLE

Mode of AGS injection	1 turn, "fast"
Linac intensity ^a	114 mA
Linac emittance ^b	$< 15 \pi \mu\text{rad m}$
AGS intensity, 12 bunches	2.7×10^{12} protons
Ejection energy	29.4 GeV
Transverse emittance, horizontal	$15 \pi \mu\text{rad m}$
Transverse emittance, vertical	$15 \pi \mu\text{rad m}$
Longitudinal phase space/bunch	0.6 eV sec
Momentum spread $(\Delta p/p)_{fw}$	1.4×10^{-3}

^a (AGS capture efficiency $\eta_{rf} = 0.8$)

^b (Present performance $\approx 100 \text{ mA}$, $\approx 10 \pi \mu\text{rad m}$)

The lattice design of the 400 GeV structure has been guided by the objective of keeping $\gamma_{tr} < 20$ in order to avoid the longitudinal high frequency instability of the bunched beam during the beam stacking process. The stability threshold is proportional to the longitudinal bunch area squared divided by the bunch population, (A_b^2/N_b) . With the beam parameters as given here, this quantity is equal to that for the 200 GeV design parameters, indicating comparable magnitudes of tolerable impedances, $(Z/n)_\ell$, during injection and during acceleration in "minimum buckets" for the 400 GeV beam stacking process.

Except for some modification in free length available, associated with the greater insertion length of the 400 GeV structure, the distribution of components and optics of the insertions is analogous to that of the 200 GeV structure. Therefore, the injection arrangement as described there is applicable to the present structure.

During beam transfer from the AGS to the ISABELLE rings, the rf bunches will be shaped to match the bucket shape of the stacking rf system. The 12 bunches are then accelerated toward the top of an already existing beam stack. During this process, the rf amplitude is gradually reduced such that before traversing the stacked beam the "buckets" are tightly fitted around the injected beam bunches. In addition, 44 of the 56 buckets will be suppressed by rf amplitude modulation when the minimum stacking voltage is reached in order to avoid unnecessary longitudinal phase-space dilution. By "stacking at the top", a low energy "tail" will be present which will provide for greater stability against longitudinal density variations in the stack and will allow a higher dynamic impedance of the accelerating system (see below).

The parameters of the stacking rf system are given in Table VI. A preliminary design of the 4.45 MHz rf cavity is given in the 200 GeV Proposal. A dynamic shunt impedance of $\approx 50 \Omega$ will be provided over a bandwidth of ≈ 50 MHz in order to ensure absence of interaction between the cavities and the stacked beam. The associated low level beam control will be similar to that employed at the CERN ISR with

the only significant differences being a smaller dynamic range in rf voltage, a smaller frequency range from injection orbit to the top of the stack, and a larger time required for stacking the individual AGS pulses.

The hardware for the stacking rf system of the 400 GeV machine will be essentially the same as in the 200 GeV ISABELLE with perhaps some minor modifications in the parameters. The hardware will consist of one stacking cavity and amplifier per ring with the associated low level control system. Since the cavities will operate at the top AGS rf frequency of 4.45 MHz, the ferrite from the old AGS cavities with proper air gaps will be used. The amplifier design will utilize a cathode follower as specified in the Continental Electronics study prepared for the 200 GeV Proposal.

TABLE VII. Stacking rf System

f	4.45 MHz
h	56
V _{max}	12 kV
V _s (suppressed bucket voltage)	677 V
Γ _{max}	0.656 ($\phi_s = 41^\circ$)
V _e (effective voltage in final bucket)	445 V
V _m (intermediate voltage for matching)	9.8 kV
N (number of AGS cycles)	275
Stacking time ^a (8 A in 0.64% Δp/p)	≈ 53 min
Stacking efficiency	80 %
Additional dilution permitted	1.2
Stacked current	8 A
Frequency range Δf/f	2.8×10^{-5}

^a Assumes stacking at the top.

In order to accelerate the stacked beam, it will be rebunched by an rf system operating on the second harmonic, $f = 159.5$ kHz. A peak rf voltage of 30 kV per ring will be provided by three ferrite loaded cavities. The total rf power requirement of this system is 1 MW per ring. The dynamic impedance seen by the beam will be kept

below a $Z/n = 25 \Omega$ per cavity. Nevertheless, it will be necessary to short the accelerating gaps during the beam stacking process in order to satisfy the impedance requirement for bunched beams. The low level rf system will be similar to that for the 200 GeV machine. The amplifiers will be similar to the Continental designs, described in the 200 GeV Proposal, modified for the lower frequency. The ferrite will be Magnetics, Inc. type F, or equivalent, which has been measured and found satisfactory for use at 160 kHz. With the use of additional ferrite in the cavities, and some cooling, the cavities could be designed to run continuously for bunched beam operation if so desired.

Adiabatic rebunching of the beam can, in principle, be accomplished without phase-space dilution or loss of beam. However, scraping will be employed during this process to remove those particles present in the low energy tail of the stacked beam and a dilution of 20% will be allowed for. The momentum spread due to rebunching and acceleration can be kept below 1.5% by programming the rate of energy gain per turn so that the maximum value of 11.9 keV per turn is not reached until the beam momentum has increased by a factor of about 1.27. The total acceleration time to 400 GeV will be $\approx 6\text{-}2/3$ minutes. Table VIII summarizes the parameters of the acceleration system.

TABLE VIII. Acceleration System

Harmonic h	2
Peak voltage, V	30 kV
Frequency	159.54 kHz
Maximum energy gain	11.9 keV/turn
Stable phase angle, ϕ_s	24 deg
Maximum momentum spread of bunched beam	1.5 %
Capture voltage (dilution factor 1.2)	5.52 kV
Maximum $\dot{B}$	117.6 G/sec
Acceleration time	$\approx 6\text{-}2/3$ min
Momentum at which maximum $\dot{B}$ is permitted	$1.27 p_{inj}$

Taking into account the beam parameters encountered during the various stages of injection, stack buildup and beam acceleration, as given above, the aperture subdivision can be evaluated. This is shown in Fig. 4, indicating that for a comparable filling as for the 200 GeV design a debunched momentum stack width of 0.64% is possible which, with the stack density of 12.4 A/\$(\Delta p/p)\$ leads to a design current of 8 A.

Fig. 4. 400 x 400 GeV ISABELLE aperture subdivision at location of focusing quadrupole (β_{max}) for 29.4 GeV.

The basic design approach for fast protective extraction from the 400 GeV structure would be analogous to that for the 200 GeV structure, since the insertion optics and component distribution are similar. The increased insertion length and longer special cell length provide for adequate space at appropriate locations for additional ejection kickers, current septa and Lambertson septa which are required because of the greater magnetic rigidity of the 400 GeV

beams. A greater reduction of beam density on external absorbers would be required because of the higher maximum beam energy and the increased caloric deposition (7×10^{14} protons, 40 MJ maximum). This would be achieved by locating the external beam dumps further downstream along their respective ejection trajectories. Graded-density, solid-absorber structures for 400 GeV protons, $\approx$ 40 MJ caloric deposition, have been studied and a conceptual design has been carried out.¹⁰

MAGNET SYSTEM

The lattice design for a beam energy of 400 GeV is based on superconducting dipole and quadrupole magnets similar to those described in the 200 GeV Proposal. The dipoles are 4-3/4 m long and operate at a magnetic field of 50 kG. The quadrupoles are 1½ m long and have a design gradient of 6.7 kG/cm. The number of each type of magnet is given in Table IX.

TABLE IX. Number of Magnets (totals for 2 rings)

Regular dipoles	648
Special dipoles	96
Cell F quadrupoles	144
Cell D quadrupoles	132
Insertion quadrupoles	96
Total dipoles	744
Total quadrupoles	372
Skew quadrupoles, conventional	48

Dipole Design

The dipole magnet coils have an inner diameter of 12 cm and are of the $\cos\theta$ type wound in a single layer from a wide braided conductor distributed in six discrete current blocks as shown in Fig. 5. The NbTi conductor is the same as that used in the dipoles for the 200 GeV design and is woven from 97 strands of superconducting wire each of which contains approximately 500 individual filaments. The coils are formed using a high pressure molding technique which

10. C. Hauviller, H. Schönbacher, and A. van Steenberg, "Beam Dump Absorber for the Superconducting LSR", CERN Rept. (in preparation).

ensures very precise location of the turns. An iron core, made from washer-like laminations of low carbon steel enclosed in a heavy walled stainless steel tube, surrounds the coils as shown in Fig. 6. This core serves several important functions:

- a) By holding the coils under compression at all temperatures, it significantly reduces training effects.
- b) The field is increased by approximately 50% for a given excitation current over that produced by the coils alone.
- c) The shielding effect reduces the external field.
- d) The stainless steel tube acts as a pressure vessel for the helium coolant and provides mechanical rigidity and straightness to the coil structure.

Fig. 5. Quadrant of dipole magnet.

Fig. 6. Isometric view of the dipole magnet, showing the configuration of the coil ends.

The higher field value (50 kG at 4250 A) is achieved by permitting a limited amount of training. Experience with the $4\frac{1}{2}$ m model magnets has shown that a field in excess of 40 kG can be achieved without training at a temperature of 4.5 K. After some training (approximately 10 quenches) fields as high as 49 kG have been reached at this temperature. If the operating temperature is reduced to 4.0 K, the expected maximum field attainable is increased to 53 kG which can be considered equivalent to an operating field of 50 kG. Figure 7 shows the temperature dependence of the field. This approach is somewhat less conservative than that adopted in earlier proposals but it is supported by the steady improvement in the performance of the test magnets. It should be pointed out that some of the reserve could be regained by increasing

the braid width slightly, but this is not considered necessary at this time. The higher operating field and increased length lead to a considerable increase in the magnetic stored energy (820 kJ vs 465 kJ) per dipole. However, the HEUB magnets,¹¹ which are of similar design, have quenched safely at a higher specific energy density (equivalent to 920 kJ), so that no changes are contemplated in the magnet protective circuitry.

Fig. 7. Temperature dependence of magnetic field in the dipole.

Quadrupole Design

Due to the weaker focusing used in the 400 GeV lattice the number and length of the main ring quadrupoles are the same as for the 200 GeV design. The increased gradient required comes about naturally due to the higher operating current (4250 A) which is equivalent to 6.7 kG/cm.

11. K.E. Robins, G. Stenby, A.D. McInturff, P.F. Dahl, A.P. Schlafke, J.H. Sondericker, J. Kaugerts, H.N. Brown, W.B. Sampson, Proc. 1977 Particle Accelerator Conf., Chicago, March 16-18 (in press).

Construction details of the coils and core are similar to those of the dipole except that the coils are, of course, an approximation to $\cos 2\theta$. A test quadrupole has operated at a gradient of 7.1 kG/cm (4500 A) at 4.2 K in liquid helium indicating that no significant problems exist for these magnets. The skew quadrupoles listed in the table are conventional iron-copper magnets of modest size and with low gradients.

Compensation Coils

For the most part, the correction coil system for the 400 GeV ISABELLE is similar to that described in the 200 GeV Proposal. The arrangement of compensating multipole coils in the main ring magnets has been revised and simplified for the 400 GeV design. The sextupole component required for chromaticity correction has now been included in the main windings of the dipole magnets by a suitable adjustment of the current block positions. Table X lists the correction coils, the maximum correction provided, the location of the correction coil, and the required accuracy of the correction. The correction field is given by $(B_0 b_n r^n)$ or $(B_0 a_n r^n)$, where B_0 is the main dipole field.

The main dipoles will have b_2 and b_4 windings to correct for iron saturation effects at high field level and also to control the shape of the working line (ν vs p). The b_2 winding needs to be considerably stronger for the 400 GeV machine because of the larger iron saturation at 50 kG, and this together with the larger dispersion, X_p , the higher β -functions, and the larger number of dipoles causes the ν -value to be more sensitive to errors in the sextupole field. The required accuracy for the b_2 coil is more severe by a factor of 2 for the 400 GeV machine. However, one can compensate for this factor of 2 by building into the dipole a negative b_2 at low fields whose magnitude is just the b_2 introduced by iron saturation at 50 kG. The size of the b_4 correction is determined by the working line control needed, rather than by the iron saturation effects, and is actually somewhat smaller for the 400 GeV machine.

The quadrupoles will have b_1 , b_3 , b_5 coils to control the working line shape, and to correct iron saturation effects. The b_1 winding needs to be stronger for the 400 GeV machine because of the larger iron saturation at 50 kG which causes the quadrupoles to fail to track with the dipoles. The trim quadrupole winding, b_1 , is increased from a 3% winding to a 4.5% winding. The b_3 and b_5 windings, which are primarily used to control the working line shape, are smaller for the 400 GeV machine, because of the larger dispersion, X_p , and β -function.

TABLE X. Correction Coil Table for 400 GeV ISABELLE

	Location	Maximum Correction Provided (cm ⁻ⁿ)	Required Accuracy
Systematic & Working Line Correction	Dipoles	$b_2 = 6 \times 10^{-4}$	10^{-3}
	Dipoles	$b_4 = 1.1 \times 10^{-5}$	10^{-2}
	QD,QF	$b_1 = 6.8 \times 10^{-3}$ (4.5% coil)	10^{-3}
	QD,QF	$b_3 = 2.7 \times 10^{-5}$	10^{-2}
	QD,QF	$b_5 = 4.5 \times 10^{-6}$	10^{-2}
	Q1,Q2 Q3,Q4	$b_1 = 8 \times 10^{-3}$ (10% coil)	10^{-3}
Equilibrium Orbit Correction	QF,Q4	$b_o = 0.028$	10^{-2}
	QD,Q3	$a_o = 0.028$	10^{-2}
	Q1,Q2	$b_o = 0.04$	10^{-3}
	Q1,Q2	$a_o = 0.04$	10^{-3}
Coupling Resonance	Q4	$a_1 = 3.5 \times 10^{-3}$ (0.18 kG/cm)	10^{-3}
Vertical Dispersion (Conventional Quads)	Between QD and QF in Matching cells	$a_1 = 0.034$ (1.7 kG/cm)	10^{-2}

The quadrupoles also contain the dipole corrections, a_o and b_o , which correct the closed orbit and provide the local beam steering near the 6 intersection points. The expected initial closed orbit

errors are about the same as for the 200 GeV machine. The larger $B\rho$, which reduces the orbit errors, is almost exactly compensated for by higher quadrupole gradients, and higher β -functions that would increase the orbit errors. The dipole correction required needs to be increased from 1000 G to 1400 G, since the field errors are larger because of the higher quadrupole gradient and the larger number of dipoles. The dipole corrections of 2000 G required in the Q1 and Q2 quadrupoles are unchanged.

The conventional skew quadrupoles required for correction of the vertical dispersion and the skew quadrupole correction windings suppressing the coupling resonance $\nu_x = \nu_z$, have been increased by the factor 1.4.

Mechanical Design

With the exception of the small increase in length of the individual dipoles, no significant changes are required in the mechanical design. The vacuum box design for the dipoles is shown in Fig. 8. The suspension and heat shield are unchanged from the design of the 200 GeV magnets.

Fig. 8. Isometric view of the dipole magnet assembled in the cryostat.

CRYOGENIC SYSTEM

The 400 GeV ISABELLE refrigeration system is similar in design to that described in the 200 GeV Proposal. The basic features remain the same, namely, a single refrigerator to supply all refrigeration and delivery of the refrigerant in the form of high pressure (15 atm) gas circulating through the magnets.

The higher field performance of the magnets requires that they operate at a temperature lowered by 0.5 K and the steady state design temperature for the 400 GeV machine is thus 3.8 K. More magnets are required to fill the longer lattice. This, of course, results in an increased heat load. The estimated heat load for the 400 GeV machine is shown in Table XI. The heat load is estimated at 19.7 kW. The refrigerator would be designed to produce approximately 30 kW.

TABLE XI. 400 GeV ISABELLE Steady-State Heat Load Estimate Summary

<u>Magnets</u>		14,000 W
Support Losses	5,300	
Radiation from Vacuum Tank	4,800	
Radiation from Beam Pipe	2,200	
Connecting Piping	1,700	
<u>Transfer Lines</u>		1,100
<u>Magnet Power Leads</u>		
(Total equivalent refrigerator load)		4,600
Main Current	259 W + 12.96 g/sec	
Correction Coils (100 A)	92 + 4.61	
Correction Coils (50 A)	2185	
Low- β Insertion Quads	43 + 2.16	
ISABELLE Total Heat Load		<u>19,700 W</u>

The refrigerator itself will be designed similarly to the 200 GeV machine refrigerator, but the subcooler will require an additional heat exchanger in order to achieve proper thermodynamic balance. This heat exchanger is shown as HX 6 in Fig. 9. As in the 200 GeV Proposal, dry screw compressors would be utilized in the system. About 16 MW input power would be required to drive the compressors.

Fig. 9. Subcooler flow diagram.

The increased heat load and the lowered temperature requirement make it necessary to increase the mass flow rate of helium coolant (3200 g/s) to the magnets as compared to the 200 GeV design (1800 g/s). In order to hold the pressure drop in the system to a reasonable value, only one-half of the magnets in a sextant will be cooled in series and a lower (2.6 K vs 2.8 K) magnet inlet temperature will be used. The helium will be introduced at the center of a sextant and flow through the cooling channels of 46 magnets until it reaches the end of a sextant where it will return to the center of the sextant in a tube which cools the heat shield. There the flow passes through a flow control valve into the return header.

Other design features of the 200 GeV Proposal would be retained in the 400 GeV design. This includes a system which uses no liquid nitrogen precooling and redundancy of refrigerator components to achieve high reliability.

VACUUM SYSTEM

The vacuum system calls for a circular, stainless steel, chamber of 8 cm diameter with a residual hydrogen pressure of 3×10^{-11} Torr in the magnets and 10^{-11} Torr in the insertion regions. Pumping stations will be placed at the ends of each magnet and at 5 m intervals in the straight sections. With this arrangement, the ηI_{crit} product, which determines the initiation of the beam induced pressure rise, is 27 A. For the desired beam current of 8 A, it is therefore required that the ion desorption coefficient η be less than 3.3. This requirement, which is not significantly different from that of less than 3 in the 200 GeV Proposal, should be readily met.

Corresponding to the operating pressures, the production rate of free electrons per circulating proton due to beam-gas collisions will be about 12×10^{-3} /sec, again essentially the same as the 200 GeV design. However, because of the increased magnetic field in the dipole magnets (50 kG compared to 40 kG) and the decrease in beam current (8 A compared to 10 A), the longitudinal drift motion of the electrons toward the clearing electrodes will be reduced, and the equilibrium neutralization of the beam is calculated to be $\sim 3 \times 10^{-4}$. Though the associated clearing efficiency in the dipoles is less than that in the 200 GeV design, the neutralization is still sufficiently low. Thus, the net betatron tune changes are small (less than 0.01) and the onset of the "e-p instability" will be inhibited.

POWER SUPPLIES, INSTRUMENTATION, AND CONTROLS

The power supply system for the 400 GeV storage accelerator requires 360 individually controlled power supplies. (See Table XII.) The demands on the main dipole and quadrupole power supply are modest due to the slow accelerator cycle, 6-2/3 minutes.

The large stored energy in the main dipoles and quadrupoles makes it important to include protective devices in the event of a magnet quench. Pairs of back-to-back solid state diodes, at liquid He temperature, are connected across each magnet. The function of these

diodes is two-fold: 1) to provide a path through which the quenched magnet can discharge its energy, 2) to provide a current conduction path for the remaining magnets and thus prevent other magnets from quenching.

TABLE XII. Magnet Power Supply System (2 rings)

Description	Number Required	Specifications
Main Dipole & Quads	2	600 V, 4500 A, $\pm 0.01\%$
Low- β insertion quads	4	10 V, 4500 A, $\pm 0.005\%$
Systematic and	44	± 15 V, ± 100 A, $\pm 0.005\%$
Working Line	12	± 35 V, ± 100 A, $\pm 0.05\%$
Controls	8	± 60 V, ± 100 A, $\pm 0.005\%$
Equilibrium Orbit	144	± 10 V, ± 50 A, $\pm 0.05\%$
Correction	96	± 10 V, ± 50 A, $\pm 0.005\%$
Skew Quads (vertical dispersion)	48	± 15 V, ± 400 A, $\pm 0.05\%$
Skew Quads (coupling)	2	± 60 V, ± 100 A, $\pm 0.005\%$

The beam monitoring systems and instrumentation are discussed in detail in the 200 GeV Proposal. In the 400 GeV case the increase in the number of dipole magnets requires that the number of clearing electrodes be increased from 1000 to about 1500.

The control system for the 400 GeV machine represents a slightly expanded, conceptually identical version of the 200 GeV solution.

PHYSICAL PLANT

The physical location of the 400 GeV ring is in the northwest corner of the Brookhaven site, similar to the machine described in the 200 GeV Proposal. The same considerations apply regarding its siting, impact on the ecosystems, and the close proximity to existing utilities and roadways.

1. Injection Tunnel:

Modifications to the existing H-10 transport tunnel from the AGS will be more extensive under this proposal compared to the 200 GeV case. Specifically, the existing switch-out tunnel of the transport enclosure will be reworked to accommodate the new injection beam line. This enclosure is approximately 2.4 m wide by 2.4 m high. A separate support building will be constructed at the junction point where the tunnel branches into two separate enclosures, thence to the ISABELLE. This building will be approximately 465 m² and will house injection power supplies and ancillary equipment.

2. Main Magnet Tunnel:

The siting of the main 400 GeV ISABELLE ring recognizes the need for radiation protection by requiring adequate distances from the west and north boundaries. The circumference of the main ring is 3767 m and it is constructed identical to the 200 GeV configuration, i.e. 4.6 m wide by 3.1 m high. However, an enlarged tunnel (6.0 m wide) is provided at the experimental areas and is described below. The ring structure is designed for an ultimate shielding thickness of about 6 m. The muon shield is considerably wider radially in this proposal because muon energies are higher. Its width varies from approximately 100 m at the northwest quadrant of the site to about 70 m at the southeast sector. The height of the muon shield is about 2.65 m above beam elevation.

3. Experimental Halls:

The experimental halls are similar in construction to those planned in the 200 GeV Proposal, but with greater length along the beam line, and minor increases in some other dimensions. The halls with locations and dimensions are shown in Table XIII. In each case an enlarged tunnel of 6.0 m in width by 3.65 m in height extends from either side of the halls to the ends of the straight section. The total length of enlarged tunnel is 160 m less the length of the

experimental hall within the straight section. In the case of the injection areas, the enlarged tunnel continues beyond the end of the straight section to the point of conjunction of the main ring enclosure and the beam injection tunnel.

4. Support Buildings

At each of the six experimental areas, a support building is provided to house services for the respective areas. These buildings are approximately 107 m^2 in area and contain equipment space, rest rooms and an experimenters work space.

TABLE XIII. Dimensions of Experimental Halls

Location	Type	Length (m)	Width (m)	Height (m)	Depth Below Beam (m)	Crane Capacity (tons)
One o'clock	enclosed	100	8	6	1.75	10
Three o'clock	free	54	54^a	--	3	--
Five o'clock	enclosed	16	48	11	3	10
Seven o'clock	enclosed	58	18	15	5	40
Nine o'clock	free	54	54^a	--	3	--
Eleven o'clock	enclosed	58	18	15	5	40

^a For free areas the width is the total for the open hardstand on which shielding blocks would be placed.

5. ISABELLE Service Building:

At the 5 o'clock region of the main ring a large multipurpose service building will be constructed. This building remains much the way it was previously proposed. Some alteration in siting is necessary in the 400 GeV scheme. Refrigerator/compressor area will be somewhat larger, however, total gross area should be under 4647 m^2 .

6. Roads:

The road network proposed for the 400 GeV machine parallels the layout of the 200 GeV Proposal. There are increases in the lengths of some roads, mainly the inner ring road. Most other access roads are approximately the same or in some cases shorter in length.

7. Utilities:

In the case of the underground utilities the runs of water, telephone and fire alarm and the 13.8 kV primary service will be somewhat longer. However, no new services will be required over the 200 GeV Proposal. In the case of sanitary, steam and condensate, and heavy electrical power feeders to the helium compressors, runs will be somewhat shorter, since the main service building is located appreciably closer to the existing site services.

COST ESTIMATE

The 400 GeV cost estimate, given in Table XIV was prepared by the same group responsible for the 200 GeV estimate and system costs are based on the design and prices so carefully established for the 200 GeV machine. A comparison of manpower for the 2 machines shows a 29% increase in assembly man years and a 14% increase in EDIA man years for the 400 GeV Proposal. Escalation and the overall construction schedule follow the same pattern developed for the 200 GeV machine. Because of the somewhat higher risk involved, the contingency was increased to an overall average of 16.7%.

TABLE XIV. Summary of Preliminary Cost Estimate for 400 x 400 GeV Six-Fold ISABELLE
(in \$1000)

		<u>Totals</u>
A. Accelerator Systems		\$111,770
I. Injection System	\$ 5,410	
II. Main Magnet System	63,590	
III. Main Magnet Power Supply	1,750	
IV. Vacuum System	8,360	
V. RF System	5,200	
VI. Correction Coil and Beam Monitoring System	4,690	
VII. Refrigeration System	15,780	
VIII. Central Control System	6,990	
B. Special Equipment	120	120
C. Facilities		30,570
I. Land Improvements	1,030	
II. Magnet Enclosure	11,380	
III. Beam Injection Tunnel	1,110	
IV. Research Areas (6)	8,300	
V. Support Buildings (7)	590	
VI. ISA Service Building	5,330	
VII. Gas Storage Yard	150	
VIII. Utilities	2,680	
D. Architect/Engineer (@ 16%)		4,890
E. Engineering, Design, Inspection, Administrative (~17.2%)		19,250
Sub Total		166,600
F. Contingency-Facilities @ 15%; Accelerator Systems @ 15-20%; EDIA @ 20%; A//E @ 15%	} (~ 16.7%)	27,830
Sub Total		194,430
G. Escalation		
1977-1979 Sal. & Wages @ 14.5%; All other @ 6% per year; 1979 thru 1984 - 6% per year	} (~ 22.4%)	43,570
Total Estimate		\$238,000

APPENDIX. ISABELLE Parameters

ENERGY

Maximum energy	400 x 400 GeV
Equivalent accelerator	340 000 GeV
Energy range, center-of-mass	60 - 800 GeV

LUMINOSITY

Standard insertion, 400 GeV	$2.3 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$
Standard insertion, 30 GeV	$0.6 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$
Low- β insertion, 400 GeV	$4.5 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$
High-luminosity insertion, 400 GeV	$1 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$

LATTICE

Circumference (4-2/3 C_{AGS})	3766.56 m
Insertion length	6 x 160.24 m
Regular cell-length	54 x 38.96 m
Modified cell length	18 x 38.96 m
Horizontal separation of orbits	97.1 cm
Distance between magnets D-D	0.90 m
Distance between magnets D-Q	1.00 m
Tune ($\nu_h = \nu_v$)	22.6
Transition energy (γ_{tr})	19.44
Structure function regular cell, β_{hmax}	64 m
Maximum dispersion, X_p	2.5 m
Phase advance per cell (h,v)	94, 79 deg
Uncorrected chromaticity, standard ring	- 33

STANDARD EXPERIMENTAL INSERTIONS

β_v^* (low- β insertion)	7.5 (2) m
β_h^*	30 m
Maximum β_v (low- β insertion)	128 (450) m
Total free space around crossing point	60 m
Crossing angle	9.8 mrad

Appendix. ISABELLE Parameters - continued

MAGNET SYSTEM

Bending field at 400 GeV	50 kG
at 30 GeV	3.75 kG
Number of dipoles/ring	372
Regular dipole length effective	4.63 m
laminations	4.73 m
Dipole current @ 50 kG	~ 4.3 kA
Stored energy @ 50 kG/dipole	~ 800 kJ
Vacuum chamber aperture (warm bore)	8 cm
Main coil i.d.	12 cm
Operating temperature	< 4.0 K
Number of quadrupoles/ring	186
Regular quadrupole gradient	6.7 kG/cm
Stored energy/quadrupole	~ 80 kJ
Quadrupole length effective	1.44 m
laminations	1.49 m

CRYOGENIC SYSTEM

Total refrigeration capacity	30 kW
Power requirement of compressors	16 MW
Total liquid helium (equivalent)	45 000 liter
Cooldown weight	5.4×10^6 kg

INJECTION

AGS energy	29.4 GeV
Number protons/AGS pulse	2.7×10^{12}
AGS normalized emittance, $\epsilon_v = \epsilon_h$	$15\pi \cdot 10^{-6}$ m·rad
Longitudinal phase-space per bunch	0.6 eV·sec
ISABELLE current/ring	8 A
Number protons/ring	6.3×10^{14}
Number AGS pulses stacked/ring	~ 275
Momentum spread of stack	0.64 %
Maximum stacked beam size at 30 GeV	2.7 cm × 0.7 cm
rf Frequency, stacking system	4.45 MHz
rf Voltage	12 kV
Impedance tolerance, Z/n	~ 4 Ω
Tune spread	≤ 0.02

Appendix. ISABELLE Parameters - continued

ACCELERATION

Duration	~ 7 min
rf Frequency (h = 2)	160 kHz
Maximum energy gain/turn	11.9 kV
Peak rf voltage/ring	3×10 kV
Total rf power/ring	1 MW
Maximum momentum spread at 30 GeV, bunched	1.5 %
Momentum spread at 200 GeV	0.1 %