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**A Proposal for Construction
of a
Proton-Proton
Storage Accelerator Facility**

ISABELLE

June 1975

BROOKHAVEN NATIONAL LABORATORY

ASSOCIATED UNIVERSITIES, INC.

UPTON, NEW YORK 11973

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PREFACE

This booklet summarizes the status of the ISABELLE program. It is backed by over a year of intensive work since the appearance of the "Gray Book" in May 1974 and the summary booklet in September 1974. It represents the work of many people both from within the Laboratory and from our colleagues in the scientific community.

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I. INTRODUCTION

The advantage of using colliding beams to overcome the relativistic limitation in achieving the highest center-of-mass energies, rather than beams from conventional accelerators striking stationary targets, had been recognized early in accelerator history by Wideröe.¹ The original work at MURA on the stacking of many pulses² in each beam was fundamental for the achievement of adequate luminosity, and laid the foundation for the design of the CERN ISR³ which is, at present, the only proton-proton colliding beam device in operation.

The construction of proton storage rings at the Brookhaven AGS had been considered previously^{4,5} in response to the recommendation made by the Ramsey panel.⁶ A summer study was held at Brookhaven in 1963 to discuss the relative merits of accelerators and storage rings.⁷ It was concluded that storage rings at AGS energies would be feasible, and a first parameter list for colliding beams was worked out by Jones.⁸ At the same time he pointed out that storage rings of two or three times the circumference of the AGS could be used to accelerate the stacked protons to higher energies up to about 100 GeV. Finally, however, a decision was made not to construct storage rings, because it was thought that they lacked the versatility of a single proton accelerator of the same equivalent energy.

With the construction of the CERN ISR nearing completion the idea of building storage rings at Brookhaven was revived in 1970 by Blewett.⁹ It soon received the endorsement of the Fitch committee¹⁰ which recommended that BNL apply its pioneering development work in superconducting magnets to build two proton intersecting storage accelerating rings to operate in the neighborhood of 200 GeV. A study group was set up which issued a Preliminary Design Study¹¹ (the "Gray Book") in 1972.

At Brookhaven the Preliminary Design Study was used as a stimulus for discussion and debate at a three-week study held in June 1972. It fulfilled that role and significant new ideas both for machine design changes and future experimental apparatus and experiments came from the highly interactive sessions during the summer study. The following two years were devoted to an intensive effort to crystallize the design of the

machine, to prove the feasibility of constructing suitable superconducting magnets, and to optimize the match between the machine parameters and utilization requirements.¹²⁻¹⁷ In May 1974, the ISABELLE design advanced to a point where a revised version of the "Gray Book" was published¹⁸ and a proposal was submitted to ERDA for construction funds starting in FY 1976.

To consider various construction proposals facing the funding agencies, a special HEPAP Subpanel on New Facilities chaired by V. Weisskopf met at Wood's Hole in June of 1974. In their report¹⁹ that panel recommended "providing funds in FY 1976 of \$3 - 4 million for BNL to complete fabrication of prototypes of superconducting magnets, with the aim of making a request for early construction at BNL of a proton-proton colliding beam facility ('ISABELLE') with a design luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ and a beam energy of at least 200 GeV."

The Brookhaven staff took great encouragement from these recommendations and, using available resources, has pushed forward on many fronts to improve the design. Orbit stability calculations have shown improved flexibility and reduced sensitivity to magnetic field imperfections by changing to a configuration with the magnets of the two rings side-by-side with the beams intersecting in eight symmetric insertions. This new lattice design permits adjusting the crossing angle and beta function separately in the various insertions with minimal perturbation of the parameters of the machine and, hence, should allow a wide range of luminosity and crossing geometries for a varied experimental program without an excess of machine tune-up time.

Significant advances are also being made at Brookhaven in the technology of superconducting magnets. Research and development has continued on the one-meter long, 8-cm coil diameter, circular coil ($\cos \theta$) models. The performance of the first two of these models, ISA I and ISA II has been extensively published²⁰ and, in fact, was the basis for earlier versions of this proposal. These models showed that magnets with adequate field quality, reproducibility, and upper field limit can be built with techniques suitable for mass production and can be operated for a number of pulses and thermal cycles comparable to the life of ISABELLE. Further models in this series are being studied to reduce rate-dependent field perturbations. ISA III

was the extreme case of fully insulated wires in the braid. This model, indeed, had essentially zero rate-dependent effects, but it was not possible to push the field up to the 40 kG required for ISABELLE and this test was put aside. ISA IV uses a braid in which each wire is coated with Cu-Ni. This higher resistance layer sufficiently decreases the coupling between wires to reduce the rate-dependent effect by about a factor of 6. With the additional factor of about 10 that comes from the larger bore of the full-size ISA magnet and from improved properties of newer braids (e.g. shorter transposition length) this technique will reduce the rate-dependent effects to a value easily handled by the correction system. However, work will continue on braids with higher resistance solders, or no solder at all, to effect even further reduction in rate-dependent effects. A full-size (4½-m) ISABELLE model magnet is in an advanced stage of construction and should resolve many questions about fabrication procedures. R&D is also continuing on techniques that could lower costs by reducing the refrigeration requirements or raising the field (including the possibility of using Nb₃Sn). ISABELLE could be built with magnets like the 4½-m model that are straightforward extrapolations of ISA IV. Our R&D efforts are directed towards making it better, cheaper or both.

From the point of view of the high energy physicist, the crucial machine parameters are the maximum energy available in the center-of-mass (c.m.) and the luminosity. ISABELLE provides large increases in both key parameters, a factor of seven in c.m. energy (60 GeV to 400 GeV) and almost two orders of magnitude in luminosity ($2 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$ to $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$), as compared to the current ISR parameters.²¹ For comparison, the step in c.m. energy in going from the AGS to FNAL is at most 4. Clearly, a luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$, would not be available at turn-on. However, a luminosity of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, seems a value realistically attainable at an early period of machine operation, but which is still an order of magnitude increase with respect to the current ISR luminosity. The availability of the AGS as a high phase-space density injector provides a crucial and necessary first element to attain the desirable high luminosities. Construction of ISABELLE would be a large step, but not beyond the capability of accelerator technology. It is a fascinating facility from the point of

view of particle and accelerator physics and technology. For the extreme versatility, and the large incursion into new energy areas, the cost seems reasonable.

During the past year, new particle discoveries have renewed the excitement of high energy physics. ISABELLE represents the vehicle that can carry us to new frontiers where many questions which are beyond our horizons can be brought into clear view. Such a facility is a must if the U.S.A. is to keep its position of leadership in this most fundamental science.

II. THE PHYSICS POTENTIAL OF ISA

The ISA will be able to investigate proton-proton collisions at center-of-mass energies about an order of magnitude larger than now available; luminosity (event rate) will be higher by a factor of fifty. It is the extension of these parameters which is fundamental for the continued exploration of the strong, weak, and electromagnetic forces and to an eventual understanding of their mutual relationships. The strong belief of the physics community that new and crucial discoveries will be forthcoming from experiments at the ISA follows from a growing pool of experimental data flowing from existing lower energy accelerators coupled with strong theoretical predictions based upon this data. In the past two years we have experienced two remarkable developments in experimental particle physics: (1) Neutral currents in the weak interactions have been discovered and amply verified. This discovery emphasizes the predication of gauge models and strongly indicates the existence of charged and neutral vector bosons with masses in the 40 - 100 GeV range, a range easily accessible with the ISA. (2) The spectacular and totally unexpected discovery of the J and ψ particles points out once again that the deepest consequences from experimental investigations can be expected to come from the observation of unpredicted phenomena.

In what follows we discuss only a few of the currently most interesting topics for investigation with the ISA; these and other experiments will be studied in greater depth during the ISA Summer Study, July 14-25, 1975. Clearly, the opening up of wide, unexplored ranges of energy and cross sections to the observation of new and unpredicted phenomena is the greatest incentive for building ISA.

1. Weak Interactions at ISA

The most direct way of testing the underlying theory of weak interactions is to look for the intermediate vector bosons (positive, negative and neutral). The best hope for producing them is with proton-proton colliding beams where they can be identified by their leptonic decay modes. The expected masses in any unified theory of weak and electromagnetic interactions is of the order of $(\alpha/G)^{1/2}$ or roughly

30 - 100 GeV/c² and present facilities cannot produce such massive particles. The Q²-s plot of Fig. 1, shows the vast new terrain available at ISA energies. A very large portion of the new kinematic region is accessible to experiment as can be seen from the cross section estimates which follow. In the following the expected production rates and decay modes are estimated in terms of our present day understanding of weak interactions.

1.1 Charged W-production

The production of W[±] is related by CVC to the production of e⁺e⁻ or μ⁺μ⁻ pairs of the same mass and the same center-of-mass energy. CVC does not predict the semi-weak axial current, nor does it relate the semi-weak current to the isoscalar electromagnetic current. A relation can therefore be written only in the form of an inequality. Define

$$\tau_W = \frac{1}{2} [\tau(pp \rightarrow W^+) + \tau(pp \rightarrow W^-) + \tau(pn \rightarrow W^+) + \tau(pn \rightarrow W^-)]$$

then

$$\tau_W \geq \frac{3}{4} \frac{G^2 \cos^2 \theta_c}{2^{\frac{1}{2}} s} M_W^3 \cdot \frac{d\sigma}{dM_W} / e^+e^-$$

or

$$\tau_W \geq 0.09 M_W^3 \cdot \frac{d\sigma}{dM_W} / e^+e^- \quad (\text{Lederman-Pope})$$

where the notation of the constants is standard and dσ/dM_W is the cross section for the electromagnetic production of a lepton pair of mass M_W. This cross section is a lower bound for the production of W's. In the absence of such data at very high energies it is observed that the function s(Q²/s) = M_W³ (dσ/dM_W) should scale in the limit of s, Q² → ∞. Therefore, it is possible to use available data at lower energies in order to test the scaling law and then apply it at ISA energies to predict production rates for W-bosons. The σ(pp → W + ...) and σ(pn → W + ...) are assumed approximately equal. Figure 2 shows the available data ranging from AGS to FNAL energies. The experimental points seem to fall on a smooth curve for 5.5 < s/Q² < 100. The shape of the curve is very close to the expectations of the parton model. The solid curve indicates a parton-model calculation by Pakvasa et al.²² where the antiquark distribution is (1-x)^{7/2}. The same model gives an accurate description of the electroproduction and neutrino data. It should be noted that

Fig. 1 The Q^2 - s plot of the kinematic region available at ISA

Fig. 2 Total cross section for the production of W^+ as derived by CVC from the production of lepton pairs

even for $\tau \approx 10^{-35} \text{ cm}^2$ the counting rates should be large for ISA luminosities.

Two points should be made about the data in Fig. 2:

- (i) The data are subject to kinematic cuts in Q_L (the longitudinal momentum of the dilepton pair) and a more detailed comparison is desirable.
- (ii) Studies of the dependence of the production rates on the antiquark distributions are crucial, since not all lepton induced experiments are sensitive to small antiquark distributions.

In Fig. 3, we plot the production cross section subject to the constraint that $Y \equiv Q_L/\sqrt{s} \geq 0.4$. This constraint is satisfied in the Lederman experiment²³ with the J_{ψ} subtracted. A similar constraint with $Y \geq 0.24$ (or 0.36) is also satisfied by the FNAL-Columbia-Illinois data.²⁴ In the same figure we plot the parton scaling function for a very different antiquark distribution: $(1-x)^9$. For a large range of W masses the production cross section from the two different models are of the same order at the highest ISA energy.

The MIT-BNL experiment²⁵ on the other hand is at $Y = 0$. Figure 4 shows a double differential cross section together with the experimental point.

The main conclusions are: 1) The data from 3 different experiments seem to fall on a smooth curve, which suggests that it could be the scaling limit for the reaction. 2) The curve is very close to the scaling curve obtained from the parton model calculation with $f_{\bar{q}}(x) = (1-x)^{7/2}$.

The W must be detected through its leptonic decay modes. The branching ratio into leptons is expected to be of $O(1)$. To be specific, in subsequent calculations a branching ratio of $1/3$ is used. The unique signature for charged W -production is a peak in the perpendicular momentum of the produced muon (or electron).²⁶ The parton model with $f_{\bar{q}} = (1-x)^{7/2}$ has been used to calculate the double differential cross section shown in Fig. 5. Two sharp peaks are shown at $p_{\perp} \approx 45$ and $63 \text{ GeV}/c$ corresponding to W 's of masses 90 and $126 \text{ GeV}/c^2$, respectively. The smooth curve is the envelope of the peaks of such curves for different M_W 's. The production rate at the position of the W is larger than the nonresonant muons

Fig. 3 The production cross section for W^+ subject to the constraint that Y is ≥ 0.4

Fig. 4 Double differential cross section for W production

of the electromagnetic background by a factor of roughly $1/\alpha$. It is also evident that at large momentum transfers ($p_{\perp} \approx 60$ GeV/c) the cross section holds up to give measurable counting rates and the sharp (resonant) peak survives providing a unique signature.

1.2 Neutral Z^0 -production

The expectations for the production of neutral intermediate vector bosons are similar to those for the charged bosons, but with several distinct differences. In this case, a pair of charged leptons is produced ($\mu^+ \mu^-$ or $e^+ e^-$) and a resonant peak is much easier to detect. Estimates of the production rates depend on the explicit form of the weak neutral currents and are in general smaller than the corresponding rates for $W^{\pm}$.

At energies considerably below the threshold for the production of Z^0 's, one expects to observe effects of a Z^0 virtual state by means of the neutral currents.²⁷ These effects will show up in the interference of the weak and electromagnetic amplitudes. They are expected to be of the order

$$\epsilon(Q^2) = \frac{2^{\frac{1}{2}} G Q^2}{4\pi\alpha(1 - Q^2/M_{Z^0}^2)}$$

where Q^2 is the square of the mass of the dilepton pair. To distinguish the new terms it is necessary to observe (i) charge asymmetries and (ii) polarization of the final muon. Both of the effects have been studied extensively in the Weinberg model. The charge asymmetry is defined as

$$A = \frac{\frac{d\sigma}{d\tau}(q_0 > 0) - \frac{d\sigma}{d\tau}(q_0 < 0)}{\frac{d\sigma}{d\tau}}$$

where $\tau = Q^2/s$ and q_0 the energy of the dilepton pair. Figure 6 shows the asymmetry for a range of M_Z 's and Weinberg angles. Charge asymmetries arising from higher order electromagnetic corrections are estimated to be small. Estimates for the lepton polarization are shown in Fig. 7.

Fig. 5 The double differential cross section as a function of lepton transverse momenta

Fig. 6 The lepton charge asymmetry at a c.m. energy of 400 GeV

Fig. 7 The average lepton helicity for c.m. energy of 400 GeV

1.3 Observing Weak Interactions

It is of considerable importance to understand the factors relating to the question of whether weak interactions would be observable at the ISA. For this purpose it is assumed that the quark parton model²⁸ is correct. The x distributions of the p and n quarks^{29,22} which are used are derived from deeply inelastic electron scattering (which predict the neutrino scattering so well) and an x distribution of the antipartons $[(1-x)^{7/2}]$ which are used to fit the BNL production of $\mu^\pm$ (Ref. 28, 30) and $e^\pm$ pairs,²⁵ as well as the FNAL production of $\mu^\pm$ pairs.²⁴

With these assumptions³¹ the lower limit for the cross section for intermediate boson production is calculated from pp collisions at a center-of-mass energy of 400 GeV. The result is plotted on Fig. 8 against different values of the boson mass. On the same graph is given the number of events per hour in which the muon from the decay of the boson ($W^\pm \rightarrow \mu^\pm \nu$) would pass into a 1-steradian detector. For this purpose the branching ratio ($W \rightarrow \mu \nu / W \rightarrow \text{all}$) is taken as 1/3. It is seen that the number of events is quite large for a mass of the order of 60 GeV (100 ev/h) and still substantial even at 150 GeV (10 ev/h). The events would appear as a peak in the $p_\parallel$ distribution of the muons observed in a μ -spectrometer placed at 90° to the intersection region. The apparatus could be simple and cheap (Fig. 9) and the backgrounds from the continuum of $\mu^+ \mu^-$ pairs and from known sources of single muons should be small.³²

Naturally more sophisticated measurements would follow. Other decay modes could be studied; the neutral intermediate boson could also be observed, and interference effects between the electromagnetic and weak production of the neutral boson might be studied.

If the mass of the boson were higher, then larger solid angle detectors could be constructed and the mass limit pushed to between 150 and 200 GeV. There is, of course, the possibility that the intermediate boson does not exist. Even then weak interactions of the type $pp \rightarrow e\nu$, etc., should still be observable despite their small cross section [of the order of 10^{-36} cm^2 integrated for $(e\nu)$ mass above 60 GeV]. In order to study such reactions, one requires a detector with large solid angle and with the ability to "observe" the missing neutrino. Such a device (the Impactometer) is sketched

Fig. 8 The total cross section for W production as a function of the mass of the W

ISABELLE MUON DETECTOR

Fig. 9 A muon detector for use at ISABELLE

in Fig. 10. It consists of a central detector covering angles -30° to $+30^\circ$ and two small angle detectors extending from 2° to 30° in the forward and backward directions. All detectors would consist of some form of hadron calorimeter with the central detector having in addition an electron identification capability (provided by suitable subdivisions of the calorimeter or by transition radiation). The entire calorimeter would be divided into of the order of 1000 segments, each segment being of the form of a truncated pyramid facing the intersection region. The counting rate in any given segment is only of the order of 500 K/c and easily handled. The calorimeters themselves would probably be in the form of liquid argon ionization chambers with steel or uranium plates³³ (with uranium plates the energy resolution of such devices is $\pm 0.22/\sqrt{E}$ or 5% for $E = 20$ GeV).

The trigger for the device would be the observation in the central detector of a single electron with large transverse momentum, e.g. 20 GeV/c. In a typical event the observed hadrons would have mean transverse momenta of 300 MeV/c and contribute a net transverse momentum of not more than 1 GeV/c. Thus, with the electron observed on one side, the neutrino not seen on the other and hadrons contributing only a small amount, an imbalance in $p_\perp$ of from 19 - 21 GeV would be observed. The maximum possible reduction of this imbalance due to unobserved hadrons that pass inside the 2° cones can be calculated for each event. Typically about $\frac{1}{2}$ the total energy would be observed in the calorimeter leaving only 200 GeV of energy within the 2° cones. The maximum reduction in the imbalance would then be $200 \sin 2^\circ = 6$ GeV/c, yielding a large net imbalance that can only arise from a missing neutrino.

Such a device would have many applications. Besides the above described ability to observe weak interactions, the electromagnetic interaction $pp \rightarrow e^+e^- + \text{hadrons}$ and the strong interaction production of jets would be observable. At transverse momenta of the order of 30 GeV the cross sections for these three processes are likely to be of the same order of magnitude, and their study in such a region could prove one of the most interesting achievements of the ISA.

Fig. 10 Sketch of the Impactometer

2. Higher Mass Spectroscopy

One of the major developments in the past year has been the discovery of the J and ψ particles which has led to the strong suggestion that there exists a new internal quantum number (charm) and that a new hadron spectroscopy is to be expected with masses of the order of 2 - 3 GeV and up. Clearly existing accelerators will be used to map out these new regions, should they indeed exist. Their importance for the ISA lies in the fact that they should be relatively easy to produce and will help to explore somewhat different kinematic regions than the production of lighter particles.

To estimate the production of charmed particles at ISA we can try to extrapolate from production data for $\bar{p}$ and K^- at ISR energies and below. These are also examples of particles which must be produced in pairs with their antiparticles. The evidence is, as we would expect, that they are predominately produced in the central region. The two protons act essentially as sources for the necessary four momentum. The form factors associated with all hadronic transitions require small momentum transfers ($t \approx 0.1$) which, in turn, requires the colliding protons to be moving very fast to be able to generate any appreciable energy release in the center-of-mass system.

As would be expected from this argument, but empirically observed independently of it, the $\bar{p}$ and K^- cross sections do indeed seem to show an effective threshold above which they rise rapidly to a level of about 0.1 times the π^- rates. The empirical fits³⁴ show the "threshold" to be higher for the $\bar{p}$ than for the K^- and are consistent with being roughly linear in the mass, as would be expected from the kinematic argument above. The maximum rapidity kinematically allowed is given by $y_{\max} = \text{arc cosh}[(s)^{1/2}/2m]$ for a particle of transverse mass m . The inclusive data seem to indicate that the central region begins 2.5 rapidity units inside this, and hence the effective "threshold", where the central region disappears, is given by

$$s_t = 4m^2 e^5, \quad (e = 2.7183)$$

The result³⁵ is that we would expect the "threshold" for charmed particles to be in the region $s = 2000 - 5000$, and the relative abundance in the

central region to be of the order of 0.01 - 0.05 times the pion production for each member of the fundamental representation.

There is another important aspect of the discovery of the new particles. The present theoretical picture calls for matter to be constructed out of ordinary quarks with masses of 300 MeV, strange quarks with masses of 500 MeV and now charmed quarks with masses of 1.5 GeV. There is no particular reason to suppose that this is the last such level of structure, and there may be new hadrons as yet unspecified, constructed out of still heavier quarks. Since the mass ratios seem to be increasing, the next ones might well be of order 10 GeV or more; we do not know. At 10 GeV the arguments of the last paragraph suggest a value of s of the order of 50 000 would be needed for appreciable cross sections to be observed. It is true that these states could also be produced at lower energies, but we cannot count on it, and therefore the ISA may well be a good tool to search for such heavy structures. There should be enough systematic knowledge of the production of strange pairs and charmed pairs obtained by that point that it would even be possible to set upper limits on the existence of some heavier objects of this nature, since the cross sections should be predictable in a relatively model-independent way.

3. Strong Interactions

3.1 Total Cross Sections and Elastic Scattering

The major interest in these basic phenomenological quantities remains associated with the questions of energy dependence. At present we know from measurements at the ISR^{36,37} and FNAL³⁸ that the total proton-proton cross section is rising, the forward diffraction peak is shrinking, and the real part of the forward pp amplitude is increasing through zero. (See Figs. 11 - 14.) In each of these cases the most important question is whether the observed energy dependence will persist indefinitely as an asymptotic behavior, or whether it is in some sense a local fluctuation indicating that the region above $s = 500 \text{ (GeV)}^2$ involves some new phenomena, for example, the production of new particles or new configurations of known particles.

To establish which of these is true, it is necessary to extend the energy range as far as possible. In order to give an indication of the

Fig. 11 Total cross section data and theoretical curves

- (a) Hendrick et al., Phys. Rev. 11D, 536 (1975) - asymptotic $\ln s$ dependence.
- (b) Mazur et al., Bull. Am. Phys. Soc. II 20, 82 (1975) - asymptotic $\ln^2 s$ dependence.
- (c) Sidhu and Wang, BNL 19022 - effect of a Pomeron and two Pomeron cut in the Gribov Reggeon calculus. Asymptotic value of $\sigma_T(pp) = 65.7$ mb.

Fig. 12 Data and theoretical curves on the ratio ρ of the real to the imaginary part of the nuclear scattering amplitude in pp interactions

Fig. 13 Predictions of ρ for four different parameterizations of the total cross section

Fig. 14 Energy dependence of the elastic diffraction peak slope parameter

accuracy needed, a variety of phenomenological fits to σ_{tot} (Ref. 39) and $\rho(0)$ (Ref. 40) with differing asymptotic limits are shown in Figs. 11 to 14. Measurements of accuracies in the region of 1% for σ_{tot} and a few percent for $\rho(0)$ will be needed to distinguish between, or rule out, such fits.

The specific point of interest in the measurement of the elastic slope parameter b is whether it continues to rise, as would be expected in a Regge type model, or if it stabilizes at a value consistent with a geometrical description of the proton, which would be expected in models with point-like constituents. Measurements of the slope parameter, to a few percent, will probably be needed to settle this.

3.2 Measurements of the Total Cross Section

The measurement of the total cross section is one of the most straightforward at conventional accelerators where the transmission method can yield accuracies of 1% or better. This simple method is, of course, not available to colliding beam experimenters. Two other methods may provide 1% measurements:

i) One method used at the ISR is to measure directly the final state particles. A short interaction region surrounded by detectors as completely as is physically possible is needed for this measurement. To minimize the loss of very small angle events, a detector consisting of concentric ring counters around the proton beam is placed ~ 50 m from the interaction region. With a 4-cm diameter beam pipe, the smallest angle detected is 0.5 mrad. This corresponds to a $t = -0.01 (\text{GeV}/c)^2$ at 200 GeV. Less than 1 mb of the total cross section is expected to be lost, which can be corrected by extrapolating the observed events to 0° . This correction should contribute $< 1\%$ to the error in the total cross section. The limitation of this method is likely to be the absolute knowledge of the luminosity, since the cross section is obtained by dividing the interaction rate by the luminosity. Determination of the luminosity to 1% can be attained as the method is improved and refined.⁴¹ As a check it will be possible to measure the cross section down to energies low enough to tie in with measurements made at conventional accelerators.

ii) A second method is to extrapolate the differential cross section to 0° and use the optical theorem. This method is a by-product of the small angle elastic scattering experiment and as such will certainly be done. Assumptions about the spin dependence and the real part of the elastic scattering amplitude have to be made.

3.3 Elastic Scattering Experiments

A two-stage approach to the measurement of differential elastic scattering cross sections at the ISA seems obvious. When the machine first operates a relatively simple setup will be used to measure the shape of the forward diffraction peak in the region $0.04 \leq |t| \leq 1 \text{ (GeV/c)}^2$. It will consist of two hodoscopes to measure the angles of the two outgoing protons. Experience at the CERN ISR has shown that there is little nonelastic background in the diffraction peak region so the selection of collinear outgoing particles will select elastic events. One will use scintillation counter hodoscopes, proportional chambers or drift chambers, depending mainly on the beam-gas background levels. It is reasonable to expect to place detectors 2 cm from the beam at a position 20 m downstream of the intersection. Thus a hodoscope 8-cm wide will cover the range from $|t| \approx 0.04 \text{ (GeV/c)}^2$ to 1 (GeV/c)^2 . If elements 2-mm wide are used, then the half-width of one counter corresponds to a range of t varying from 0.005 (GeV/c)^2 at $|t| \approx 0.04$ to 0.01 (GeV/c)^2 at $|t| = 1$, which is adequate for studies of the shape of the diffraction peak.

During this early period a relatively simple double-arm magnetic spectrometer would be constructed, probably using existing AGS experimental magnets, for initial studies of the energy dependence of the dip structure near $|t| \approx 1.5 \text{ (GeV/c)}^2$.

Later, as the machine becomes well understood, a special high- β intersection (low luminosity) will be constructed for an experiment that will cover the wide range $0.001 \leq |t| \leq 1 \text{ (GeV/c)}^2$, thus including information on the real part of the nuclear scattering amplitude via Coulomb-nuclear interference and permitting a very sensitive search for new structure in the diffraction peak.

A method for the small angle p-p elastic scattering experiment was discussed in an earlier CRISP report.⁴² With recent changes in the ISA lattice structure and some of the beam parameters, the proposed arrangement for the experiment is modified. A special insertion design predicts a rms radius of the beam at a low- β point (focus) to be ≈ 0.36 mm with a long term beam position stability of ≈ 0.1 mm. These predictions, compared to earlier figures of ≈ 1 mm, will certainly reduce the focal length of the quadrupoles needed to attain a required angular resolution, i.e., shorter length for the experimental setup. A similar design is found in a preliminary study of a CERN 400-GeV storage ring facility.⁴³ The fractional effect of this Coulomb amplitude interference with the nuclear amplitude is maximal at $t \approx -0.002$ (GeV/c)². Therefore the measurement of the cross section should extend the t range down to $t \approx -0.001$ (GeV/c)² where one also observes a steep rise of the Coulomb cross section. The upper end of the t range can be ≈ -0.3 (GeV/c)², but preferably higher, where the contribution of the interference will be reduced by more than two orders of magnitude.

An important concern in this experiment is the error in the measurement. As a rough estimate, 1% error in the differential cross section will result in an error in α ($\alpha = \text{Re}f/\text{Im}f$, f = nuclear amplitude) of 0.02. Although this error is for the value of $\alpha \approx 0.2$, it is relatively independent of the value of α . Here it is assumed that a 1% measurement of the total cross section will be carried out to determine $\text{Im}f$. The major source of the error will be systematic. Due to the relatively steep t dependence of the p-p elastic scattering cross sections an accurate measurement of the t value is very important for this experiment.

In order to measure $d\sigma/dt$ to 1%, then $\Delta\theta \approx 3.5$ μrad for $|t| \approx 0.3$ (GeV/c)² and $\Delta\theta \approx 1.1$ μrad for $|t| \approx 0.002$ (GeV/c)².

A proposed layout of the experiment is shown in Fig. 15. The interaction will take place at a beam crossing angle of 11.4 mrad. The beams are blown up to $\beta_n = 107$ m and $\beta_v = 143$ m so as to obtain beams which are parallel within an rms angle of 11 μrad . The outgoing beams are focused to a point with a set of quadrupoles of focal length $f \sim 30$ m. The quadrupole lenses convert the scattering angle θ to a displacement (y) from the

SETUP FOR NUCLEAR COULOMB INTERFERENCE MEASUREMENT

Fig. 15 Experimental setup for nuclear Coulomb interference measurement

beam line at the focus according to a relationship $\gamma = f\theta$ regardless of the exact location within the intersection region at which the interaction took place. Allowing the detector to be 5 mm from the center of the beam at the focus, $t_{\min} \approx -0.0011 \text{ (GeV/c)}^2$ can be obtained for 200 GeV/c operation. A 16-cm diameter quadrupole, 15 m from the intersection allows $|t|$ values up to $|t| > 1 \text{ (GeV/c)}^2$ to be covered. This angular acceptance is particularly important for lower energy measurements. The beam spot size of $\sim 0.35 \text{ mm}$ at the focus combined with the detector resolution of $\sim 0.35 \text{ mm}$ gives 0.5 mm resolution in the measurement of the displacement, corresponding to an angular resolution of $\sim 17 \text{ } \mu\text{rad}$. This angular resolution combined with the beam angle spread is consistent with the angular measurement accuracy needed to perform the Coulomb interference experiment. In this detector a set of eight layers of proportional chambers with 1 mm wire spacing is used to obtain the required resolution. Four such sets will be needed to surround the beam tube at both downstream foci. Collinearity of the two outgoing particles in the center-of-mass system will distinguish the elastic events.

Another intersection region with low- β (high luminosity) and with a different experimental setup⁴⁴ will permit the measurement of the elastic scattering cross section to values of $|t| \approx 25$, above the range so far studied at the CERN ISR.

3.4 Hadron Production at High Transverse Momenta

One of the first questions that must be asked is what range of transverse momentum ($p_{\perp}$) can be usefully studied at the ISA. Although the kinematic limit is 200 GeV/c, it must be anticipated that the cross section will become unmeasurably small for $p_{\perp}$ far smaller than this. At the ISR in the CCR experiment,⁴⁵ the cross section and luminosity ($L \approx 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$) limited $p_{\perp}$ to about 9 GeV/c although the kinematic limit is nearly 30 GeV/c. In order to estimate the useful range of $p_{\perp}$ that will be available at the ISA it is necessary to make some assumption about the magnitude of the cross section for $200 \times 200 \text{ GeV/c}$ collisions. At present our best assumption is that the invariant cross section satisfies a scaling law:

$$E \frac{d\sigma}{d^3p} = \left(\frac{1}{p_{\perp}} \right)^n f(x_{\perp}) ,$$

where

$$x_{\perp} = \frac{2p_{\perp}}{\sqrt{s}}$$

$\sqrt{s}$ is the center-of-mass (c.m.) total energy. This is the form expected from several different models for the particle of momentum $\vec{p}$ and energy E detected at 90° in the c.m. Whether or not such a law is valid is not known and one of the most important experiments to be done at the ISA will be to test it by varying the c.m. energy $\sqrt{s}$ and $p_{\perp}$ over as wide a range as possible.

There are fits to ISR and FNAL data using these forms with n ranging from 7 to about 11. The value of n required decreases as $x_{\perp}$ decreases and since the value of $x_{\perp}$ at the ISA will be quite small, the smaller value of n will perhaps be the relevant one. Theoretical models give values as small as $n = 4$, but the theoretical situation is presently far from clear.

In order to give an unprejudiced estimate of the $p_{\perp}$ values attainable, we have assumed this scaling law for various values of n , used the measured cross section from the CCR experiment at the ISR for several values of $x_{\perp}$ that may be attainable at the ISA and calculated the cross section for 200×200 collisions at the corresponding value of $p_{\perp}$. These are tabulated in Table I.

TABLE I

a) $x_{\perp} = 0.08$ ($p_{\perp} = 16$ GeV/c)

n	$E \frac{d\sigma}{d^3p}$
4	1.68×10^{-33} ($\text{cm}^2 \text{ GeV}^{-2}/\text{sr}$)
6	4.10×10^{-35}
8	9.98×10^{-37}
10	2.42×10^{-38}
12	5.90×10^{-40}

b) $x_{\perp} = 0.11$ ($p_{\perp} = 22$ GeV/c)

n	$E \frac{d\sigma}{d^3p}$
4	3.03×10^{-34} ($\text{cm}^2 \text{ GeV}^{-2}/\text{sr}$)
6	3.80×10^{-36}
8	4.77×10^{-38}
10	5.98×10^{-40}
12	7.52×10^{-42}

c) $x_{\perp} = 0.21$ ($p_{\perp} = 42$ GeV/c)

n	$E \frac{d\sigma}{d^3p}$
4	6.8×10^{-36} ($\text{cm}^2 \text{ GeV}^{-2}/\text{sr}$)
6	2.4×10^{-38}
8	8.8×10^{-41}
10	3.1×10^{-43}
12	1.1×10^{-45}

From the ISR experience and the high ISA luminosity, it is quite reasonable to expect to measure cross sections of 10^{-38} ($\text{cm}^2 \text{ GeV}^{-2}/\text{sr}$). (This corresponds to a cross section of about $4 \times 10^{-37} \text{ cm}^2$ for an apparatus with a one steradian and 10% momentum acceptance.) $p_{\perp}$ values in the range of 20 - 30 GeV/c are reasonable. These tables are shown graphically in Fig. 16 where $E \frac{d\sigma}{d^3p}$ is plotted as a function of n for fixed $p_{\perp}$.

In order to study the structure of the proton, measurements of high $p_{\perp}$ will be essential. Using the uncertainty principle $p_{\perp}$ of 20 GeV/c corresponds to 10^{-15} cm. The major problem confronting all experiments directed at measuring these distances is the smallness of the cross section. Inclusive processes, therefore, offer the best hope of studying interactions with large transverse momenta. The problem of interpreting the data in terms of structure and force laws is naturally quite complicated and at our present level of understanding very model-dependent. There will obviously be a very great deal of theoretical work over the next few years prior to ISA experiments, and it is pointless to use the present models except as an indication of the kinds of measurements to be done.

Fig. 16 Examples of scaling laws for high transverse momenta

Fig. 17 Extrapolation of the CCR experiment to ISA energies

It is clear from the previous section that the range of x_p measured at ISA will be quite different than at ISR or FNAL. Taking $p_{\perp} = 2.5$ GeV/c as the minimum large $p_{\perp}$, FNAL measures $x_p > 0.2$, ISR measures $x_p > 0.1$, while ISA will be limited to smaller values; for a scaling law, with $n = 8$, $x_p > 0.1$. The CCR collaboration have fit their data with the form

$$\frac{d\sigma}{d^3p} = \frac{1.35 \times 10^{-26}}{(p_{\perp})^{8.32}} e^{-26.1 p_{\perp}/s}.$$

In Fig. 17, this function is plotted vs $p_{\perp}$ at $\sqrt{s} = 400$. The range of $p_{\perp}$ measured at ISR corresponds to $p_{\perp} > 16$ GeV so there is some overlap between their measured region and the potential large $p_{\perp}$ region at ISA. This is indicated in Fig. 17 along with a prediction of the electromagnetic contribution to the cross section based on Berman, et al.⁴⁶ The curve for smaller values of x_p is not based on measurements or theory and it will be very interesting to see how it actually behaves. If the CCR fit continues to hold as $x_p \rightarrow 0$, then the cross section at $p_{\perp} = 20$ GeV/c and infinity energy is up only by a factor of 3.7. Dropping the energy to $\sqrt{s} = 200$ correspondingly decreases the cross section by a factor of 0.27 and going down to the ISR ($\sqrt{s} = 62$) reduces it by more than 10^{-3} .

If we view this from the Feynman scaling or Mueller-Regge point of view appropriate to this central region, it seems likely that this small x_p region will depend more on the structure of the particle produced rather than on the proton itself, i.e., in the graph

only the central vertex depends on $p_{\perp}$. If this point of view can be implemented in detail theoretically, it will enable us to study the short distance structure of many particles.

In attempting to unravel the proton structure, it will also be important to look at $p_{\perp}$ near its maximum values. In many models this depends sensitively on the structure functions of the proton. Clearly, this cannot be done at 90° because the cross section is too small. But,

for example, in the popular model of Blankenbecler, Brodsky, and Gunion,⁴⁷ the relevant parameter that needs to be near to 1 is not x_L in general, but

$$x = \frac{2p_{11}}{s} = \frac{x_L^2 + x_{\bar{L}}^2}{s}$$

where $x_L = 2p_{11}/s$. In the table below we show the values of this for $p_{\perp} = 20 \text{ GeV/c}$ ($x_L = 0.1$).

θ	x_L	x
90°	0	0.1
60°	0.06	0.12
20°	0.27	0.29
10°	0.57	0.58
6°	0.95	0.96

There is little information now available on how the cross section varies with x_L . It apparently does not change much over the CCR acceptance of $\pm 30^\circ$ around 90° . It will probably drop as x_L increases, and so reduce the maximum measurable $p_{\perp}$; just how fast it decreases will be an important measurement. In the model calculations some of the elementary processes involve $(1 - x)$ to very high powers and so it may not be necessary to reach values of $x \sim 0.4$. (It is this kind of variation that is used to account for the different values of n observed at FNAL and the ISR.) For example,

$$(1 - x)^5 = 0.08 \quad \text{at} \quad x = 0.4.$$

$$(1 - x)^{11} = 4 \times 10^{-5} \quad \text{at} \quad x = 0.4.$$

The region that might reasonably be usefully studied is shown in the accompanying sketch (Fig. 18). (At AGS energies $p_T \leq 2 \text{ GeV/c}$, the cross section drops by two-three orders of magnitude in going from $x_L = 0$ to $x_L \approx 0.8$. A similar drop is seen in π^+ at the ISR for $p_{\perp} = 0.4 \text{ GeV/c}$. A drop of the same order of magnitude here would cut the maximum $p_{\perp}$ from 27 to about 12, using the CCR curve.)

It must be emphasized that the cross section at large x may fall very much faster with $p_{\perp}$ than at $x_L = 0$ and so the maximum $p_{\perp}$ shown in the figure may be an overestimate. It will be very important to study this.

Fig. 18 Sketch of the longitudinal momentum kinematic region

Considerations of high $p_{\perp}$ phenomena suggests a number of experiments to be done. They are basically the same as recent ISR experiments.

a) How do the cross sections for the production of various kinds of particles depend on $p_{\perp}$?

b) How is the momentum balanced? What is the distribution of particles on the opposite sides?

c) Are there jets? Are produced particles nearly coplanar?

One could make a good measurement of the inclusive single particle spectra near 90° with $p_{\perp} > 20$ GeV/c at the ISA with generally the same type of apparatus as is currently in use at the ISR and AGS. For charged particles a momentum analysis could be done along with Cerenkov counters to distinguish the particles produced. For neutrals, segmented Pb-glass or Pb-scintillator sandwich arrays to measure the energy and position of each photon could measure the inclusive π^0 cross sections. One could couple such detectors with a 2π multiplicity detector to look for rapidity correlations when triggering on a particle at large $p_{\perp}$. The search for jets will require a more complicated apparatus. A sophisticated detector for extending measurements to the maximum $p_{\perp}$ and consequently smallest cross section is described in "A Proposal for Construction of a Proton-Proton Storage Accelerator Facility, ISABELLE" May 1974, BNL 18891.

3.5 Multiparticle Production at Small $p_{\perp}$

3.5.1 One-Particle Inclusive Reactions. One-particle inclusive reactions provide a measure of the average behavior of multiparticle production, which accounts for roughly 80% of the proton-proton total cross section. At ISABELLE it will be interesting to study all of the inclusive reactions.

$$p + p \rightarrow c + X, \quad c = \pi^{\pm}, K^{\pm}, p^{\pm},$$

as a function of energy and of the longitudinal and transverse momenta of c . Several aspects of these reactions seem to be of particular significance.

Rapidity dependence. The main thing to look for in the cross section as a function of rapidity would be an expansion of the central plateau. At the ISR each fragmentation region covers about two units of rapidity, so that the length of the central plateau, over which the cross

section is approximately constant, is^{48,49}

$$\Delta y = \log \frac{s}{s_0} = 4$$

This gives

$$\Delta y = 4 \text{ at ISR}$$

$$\Delta y = 8 \text{ at ISABELLE}$$

The expansion of the central plateau will be interesting in its own right, and it will simplify the interpretation of correlation experiments.

Energy dependence. At the ISR inclusive cross sections have been observed to scale^{47,48}

$$k \frac{d\sigma}{d^3p} = f(y_{lab}, p_{\perp}^2) \text{ independent of } s.$$

Within the Mueller-Regge model⁴⁹ this scaling is understood by assuming that the Pomeron is a simple Regge pole. This assumption must be incorrect both on experimental^{36-38,51} and on theoretical grounds.^{52,53} The energy dependence (or lack thereof) of inclusive cross sections at ISABELLE energies should therefore be interesting.

Behavior near $x = 1$. In the triple-Regge model⁵⁴ the behavior of the $pp \rightarrow pX$ cross section near $x = 1$ is dominated by the triple-Pomeron graph. The model is certainly oversimplified, but nevertheless the cross section in this region should give information on the way in which Pomerons interact.

The main experimental difficulty in studying one-particle inclusive reactions is to detect high momentum particles at very small angles.

A preliminary design of a spectrometer suitable for studies of high momentum particles at the ISA has been made. Two aims are important: The separation of pions, kaons and protons (and their antiparticles) at a momentum up to about 150 GeV/c and the study of forward going protons up to 200 GeV/c. The main problem to face is the difficulty of measuring particles at small angles where they stay close to the outgoing beam.

The method is to use septum magnets placed very close to the beam. Particles produced at small angles are then deflected beyond the main

SCHEMATIC LAY-OUT OF THE EXPERIMENT

Fig. 19 Experimental setup to measure particles produced at small angles

downstream obstruction — probably quadrupole magnets. A second set of dipole magnets bend the selected particles into a spectrometer which identifies the particle and measures its momentum. This is shown schematically in Fig. 19. The angle of production is selected by the position of the septum magnets; the excitation of the septum magnets and the steering magnets determine the momentum transported to the spectrometer, whose magnets and Cerenkov counters are set to match. The steering magnets are dipole magnets of simple design. Figure 20 shows a septum magnet system which will accept particles at ± 3 milliradians and will deflect 200 GeV/c protons out to a spectrometer, Fig. 21. Thus one can reach $x = 1.0$ and $p_{\perp} = 0.6$ GeV/c. This system uses a similar septum magnet design to those used for injection into the ISA from the AGS. The closest point of the first septum is 2 cm from the beam line. Free space to the first quadrupole is assumed to be 30 m.

This is in no sense an optimum design, and somewhat better performance probably could be achieved with magnets specially designed for use in a small-angle spectrometer. This example shows that it is possible to do the kind of measurements of inclusive spectra that are of great physical interest.

We assume that the spectrometer (Fig. 21) starts slightly downstream of the first accelerator quadrupole magnet. As a further boundary condition all heavy equipment will be located within the "long" building ($\approx \pm 60$ m) while a very inexpensive tunnel (no real crane, no heavy foundation, basically a 6 - 7 ft steel pipe!) will house the long Cerenkov counter needed to separate high momentum pions and kaons.

At high momentum, multiple scattering is negligible so the momentum resolution of the system is determined by the spatial resolution of the detectors. For example, with ± 0.5 mm resolution we have $\Delta p/p \approx \pm 0.3\%$. This is easily achieved with proportional wire chambers; better resolution can be obtained with drift chambers, if the experiment demands it. Particle identification is excellent at 150 GeV/c, where the efficiency (for pions) of the K π counter is $\approx 99.5\%$. At 200 GeV the main intent is the study of forward going protons and perhaps pions while the kaon flux is expected to be very small. If this proves to be the case, the counter will

Fig. 20 The septum magnet system for the experimental setup to measure particles produced at small angles

Fig. 21 The spectrometer used for the small angle particle production experiment

be set just below the proton threshold and a pion efficiency of $\approx 99.9\%$ will be achieved. The accessible kinematic region for such a spectrometer would be

$$p_{||} \leq 100 \text{ GeV at } p_{\perp} = 0.3 \text{ GeV}$$

$$p_{||} \leq 200 \text{ GeV at } p_{\perp} = 0.6 \text{ GeV.}$$

3.5.2 Correlations. The very high energies available at ISABELLE are particularly useful in studying both correlations between particles in the central region and correlations between a proton near $x = 1$ and particles in the missing mass.

In the central region it is useful to distinguish long-range and short-range correlations. In the Mueller-Regge model short-range correlations are associated with secondary Regge poles,^{50,55} while long-range ones are associated with Pomeron Regge cuts⁵⁶ or, more generally, with any nonfactorizable part of the Pomeron. In models of production amplitudes short-range correlations come from clusters or similar effects.⁵⁷ Dynamical long-range correlations are not well understood, but they can arise from the production of particles off of multiple chains or from absorption.^{58,59} Additional long-range correlations are introduced by energy-momentum conservation, especially near the boundary of phase space.

The Stony Brook-Pisa experiment⁶⁰ at the ISR has shown that there is a substantial short-range correlation in the central region. Since the size of the central region is limited, it is difficult to separate any dynamical long-range correlation from the effects of energy-momentum conservation. At ISABELLE the length in rapidity of the central region is about doubled, and the study of any dynamical long-range correlations would therefore be facilitated.

For a proton near $x = 1$ Pomeron exchange should dominate. An inclusive reaction involving a proton near $x = 1$ and another particle in the missing mass can thus be viewed as a one-particle inclusive reaction for Pomeron-proton scattering.⁶¹ Such a reaction probes the nature of high-mass diffraction. In the triple-Regge model Pomeron-particle inclusive cross sections at large M^2 should be similar to particle-particle ones at large s .⁶¹

At ISABELLE energies one could reach $M^2 = 3200 \text{ GeV}^2$ for $x = 0.98$, for which the Pomeron should certainly dominate. This is comparable to the values of s reached at the ISR. If the triple-Regge model is at all correct, there should be a clear central region for particles in the missing mass. In any event it would be most interesting to explore Pomeron-particle scattering at such large values of M^2 .

At least initially correlations would probably be measured at ISABELLE using a detector which covered almost a 4π solid angle, but which measured only the angles of the produced particles. With such an apparatus rapidities can be determined approximately using

$$y \approx -\log \tan \frac{\theta}{2} ,$$

although this is valid only for $p_{\perp} \gg m$. A preliminary design of such a detector has been made.⁶² It is similar in concept to the detector used by the Stony Brook-Pisa group⁶⁰ at the ISR, and could be used for measurements of the total cross section as in the Stony Brook-Pisa case.

Among the types of correlation experiments that could be done are the following:

- i) Two particle correlations in rapidity, y ;
- ii) Two particle correlations in azimuth, ϕ .

More complicated experiments could be done in combination with other spectrometer systems which measure momentum and identify a given particle. However this 4π detector records charged particles without momentum information or particle identification. It consists of a scintillation counter hodoscope surrounding the crossing region as completely as practical (Fig. 22). In addition, a second detector level consisting of proportional wire chambers could provide two-dimensional readout, improved resolution by a factor 10, and help discriminate against γ -rays, showers, etc. First results could be obtained with only the hodoscopes.

The geometrical arrangement is a simple one with all components fitted on a vacuum system which is a pipe about 50-m long. At the intersection the vacuum pipe is 30 cm in diameter. A central detector encloses it, extending ≈ 2.5 m along the beam.

Fig. 22 4 π detector for correlation experiments

To close off the ends there are three beam-line hodoscopes that are ring-shaped. These are designated "A", "B", and "C". They cover successively smaller angles, with slight overlap. Detectors "A" and "B" fit into constrictions in the vacuum pipe; detector "C" goes at the end.

Detector	Position m	Angle	
		Minimum mrad	Maximum mrad
A	2.5	20	70
B	6.25	12	26
C	17.0	2.9	17

In most cases the radial extent of the hodoscope elements is 1.25 cm, so the resolution varies from 0.5 to 0.073 mrad. The highest resolution is at the smallest angle, keeping counting rates conservative for luminosities $\sim 10^{31}$. Operation would not be satisfactory at full luminosity.

III. GENERAL DESCRIPTION OF FACILITY

1. Ring Structure

The proton-proton storage accelerator facility proposed consists of two intersecting magnet rings located side by side in a common tunnel. The circumference of each ring is 2960 m or exactly $3\frac{2}{3}$ times the circumference of the AGS. The configuration is essentially a circle broken by eight symmetrically placed insertions in which the beams, travelling in a straight line, are made to cross in their common median plane. Protons from the AGS with kinetic energy of 28.5 GeV will be ejected into the beam line which is now feeding the North Area and the 7 ft bubble chamber and which would be extended to the proposed location of the ISA, shown in Fig. 23. The area north of the AGS is reasonably level and the Brookhaven site provides ample space for future expansion.

The separated function lattice structure initially will have quasi-eight-fold symmetry. The main portion of the bending is done in 56 regular FODO cells, 7 per octant. A small part of the bending is performed in the 3 modified cells adjacent to the insertion, $1\frac{1}{2}$ on each side. These cells are the same as the regular bending cells in terms of their focusing structure. The bending magnets, however, are arranged so that the beams begin to converge towards each other heading for the proper collision point. Furthermore, the bending is designed such that the dispersion function is brought to zero in both inner and outer arc configurations. The geometry of the insertions, including the 3 adjacent modified bending cells, is depicted in Fig. 24. The collisions take place at the insertion center where there is ± 20 m of free space provided for experimental apparatus. There is another large free space of almost 30 m on each side of the center which will to some extent be available for experimental apparatus. These straight sections will also be used for equipment needed for various machine functions, in particular, injection, ejection, rf systems, and special beam diagnostics. In addition, this space can be used for magnets, allowing the entrance into one of the beam channels of an electron beam for the electron-proton option (Section VII).

The horizontal separation of the beams before being brought together is 75 cm, providing sufficient space to accommodate separate dewars for

Fig. 23. ISA Site Plan.

Fig. 24. Beam trajectories in the crossing region. The transfer limit of each magnet includes dewar enclosure.

each individual magnet. On the other hand, both rings are electrically and magnetically separate, which permits experiments to be performed with unequal energies and accommodates the antiproton option (Section VII).

A list of lattice parameters is given in Table II. The β -function and the horizontal dispersion function are plotted in Fig. 25. Two quadrupole doublets on each side of the collision point are required to match the β -functions to the FODO cells and provide for the necessary range of β -values at the collision point. The betatron matching can only be achieved at one central momentum. For off-momentum particles, a mismatch results.⁶³ The primary effect on off-momentum particles is the tune shift. However, by applying high order multipoles, primarily sextupoles, the tune variation with momentum can be removed. Since for transverse beam stability there must be a residual tune variation with momentum, i.e. a working line, these multipoles provide the necessary control of its shape. On the other hand, the β -function mismatch cannot be eliminated. For the case of the standard insertion configuration, i.e. $\beta_v^{\max} \approx 100$ m, we plot in Fig. 26 the variation of β with momentum at the crossing point. This variation is typical of the variation around the ring.

TABLE II. Lattice Parameters

Circumference (3-2/3 C_{AGS})	2960 m
Insertion length	8 × 116 m
Regular cell length	56 × 25.4 m
Modified cell length	24 × 25.4 m
Horizontal separation of orbits	75 cm
Tune ($\nu_h = \nu_v$)	25.63
Transition energy (ν_{tr})	21.6
Dipole field at 200 GeV	39.3 kG
Regular cell dipole length	4.11 m effective
Max. Quadrupole gradient at 200 GeV	6.64 kG/cm
Regular cell quadrupole length	1.16 m effective
Amplitude function regular cell, $\beta_{\max}$	42.7 m
$\beta_{\min}$	7.7 m
Max. dispersion, X_p	1.64 m

Fig. 25. ISA amplitude and dispersion functions, β_h , β_v and X_p . The β -functions for inner and outer arc configurations are indistinguishable on the given scale.

Fig. 26. β variation across the momentum aperture at the crossing point for the standard ISA lattice configuration. The maximum stack occupation is $\pm 0.8\%$ for the bunched beam at 28.5 GeV. During stacking a maximum of 2% momentum aperture is required, more than half of which is required for the separation of the stack from the injected orbit.

The ISA is designed to allow operation with a symmetry in the focusing structure of "almost" 8. The symmetry breaking which results from the difference in inner and outer arc configurations is insignificant. With our choice of tunes, $\nu_h = \nu_v = 25.63$, "structure" or "strong" resonances up to order 5 can be avoided. In particular, the operating region is far removed from structure resonances of order 3 and 4 excited by the chromaticity correcting sextupoles. The 5th order structure resonance ($\nu = 25.6$) has been tested by particle tracking and shows an effect only at an amplitude corresponding to about 4 times the beam size when situated directly on the resonance. Since the beam-beam interaction in the standard lattice configuration has a symmetry of 8, the low order structure resonances (i.e. the even-ordered resonances) are far removed, the closest being the 10th order at $\nu = 25.6$.

As the beams approach the collision point they are converging towards each other. To obtain the low β -values required at the collision point, a focusing doublet is required. In order that the two beams reach separate quadrupole apertures at the same distance from the collision point, an optimum condition, quadrupole designs with beam separations of about 23 cm are required. This has been accomplished by using long quadrupoles with low gradient for which a minimum of both superconducting coil and iron shielding is needed and by placing the corresponding quadrupoles of the two rings in a combined dewar. With this concept, the standard ISA insertion has a peak vertical β -function of about 100 m in the focusing quadrupole doublet.

2. Performance

The basic ISA design is conceived as an extrapolation of the only existing set of p-p storage rings, the CERN ISR. Drawing upon the ISR experience, the ISA has been designed so as to have a superior performance potential. (1) By accelerating the stack, the ISA provides pp collisions over a large range of center-of-mass energies, 60 GeV to 400 GeV, as well as allowing independent energy setting in each beam from 30 GeV to 200 GeV. (2) With its small crossing angle and low- β characteristics the ISA can reach luminosities two orders of

magnitude higher than the ISR, about $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$. (3) The use of matched insertions allows the design of a stable lattice (stable over a sufficient momentum aperture) which has a long magnet-free straight section around the central collision point. In the standard ISA insertion design, $\pm 20 \text{ m}$ can be used for experimental detection and measurement apparatus.

The operation of the ISA will proceed in phases. The initial performance characteristics are given in Table III. Starting from the standard quadrupole configuration, a small change in the strength of the vertically defocusing doublet at the entrance to the insertion leads straightforwardly to the low- β configuration, giving a luminosity of $5 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ at 400 GeV c.m. To reach the design luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$, large aperture bending magnets as sketched in Fig.27 are required to reduce the crossing angle from its standard value of 11.4 mrad to half this value, 5.7 mrad.

TABLE III. ISABELLE Performance

	Standard	Standard Low Energy	Low- β	Low- β Low Energy	Hi-Luminosity
Luminosity ($\text{cm}^{-2} \text{ sec}^{-1}$)	2.6×10^{32}	1.0×10^{32}	5.3×10^{32}	1.4×10^{32}	1.0×10^{33}
Tune shift	1.7×10^{-3}	4.5×10^{-3}	0.9×10^{-3}	3.2×10^{-3}	1.7×10^{-3}
Crossing angle (mrad)	11.4	11.4	11.4	11.4	5.7
Free space (m)	± 20	± 20	± 20	± 20	± 13
$l_{\text{interaction}}$ (m)	± 0.19	± 0.50	± 0.19	± 0.50	± 0.38
β_V^* (m)	4.0	4.0	1.0	2.0	1.0
β_{max} (m)	≈ 100	≈ 100	≈ 400	≈ 200	≈ 400
Energy (GeV)	200	28.5	200	28.5	200
Current (A)	10	10	10	10	10

The initial performance is predicated on the choice of crossing angle and stack current of 10 A. The significance of these parameters is reflected in the beam-beam tune shift which they produce under various

conditions. Since the beam-beam tune shift is a measure of the beam-beam interaction and is positively correlated with radiation background in the experimental areas, it was deliberately chosen to have a small value. For example, the low- β configuration has $\Delta\nu \approx 8 \times 10^{-4}$, only about a factor of 2 larger than at the ISR. However, the nonlinear resonances which can be expected to produce beam loss, and so background, in a design with high periodicity, such as the ISA, are odd-ordered ones, and they are excited by random errors in the closed orbit positioning at the collision points. It is estimated that, at the tune shift levels proposed for the ISA, acceptable beam loss rates will result with orbit control at the collision points of a few tenths of a mm. With the present design, however, greater orbit precision could allow a larger tune shift and thus a luminosity larger than the design value.

Future ISA operation calls for a reduction of ring orbit symmetry. This phase would be characterized by the alteration of the insertions (1) to allow the introduction of a large spectrometer arrangement to study scattering events at small angles and (2) to allow the study of small angle elastic p-p scattering in the Coulomb interference region up to t values on the order of 1. Options such as electron-proton colliding beams and the possibility for the study of deuteron and anti-proton physics are outlined in Section VII.

3. Beam Transfer

A number of schemes for transferring the 28.5 GeV AGS beam to the ISA have been studied.⁶⁴ The method of energy stacking now used at the CERN ISR has been adopted in view of its numerous advantages:

- Operation of the AGS can be optimized for highest transverse phase space density (instead of highest intensity) which is a prerequisite to achieving the highest luminosities. The intensity in the ISA is then simply built up by a large number of AGS pulses.
- No modifications or additions to the AGS are required. Prior to ejection the total rf peak voltage in the AGS will be reduced from 386 kV to approximately 36 kV in order to match the AGS bunch shape to the bucket of the ISA stacking system. Existing equipment

for fast ejection of the beam to the North Area would be retained for the beam transfer to the ISA.

- Aperture requirements are not excessive in spite of additional needs for injection purposes. In fact, the minimum aperture of 8 cm has been established by the vacuum requirements and the required aperture, for beam purposes, does match this reasonably well.

The beam transport equipment from the AGS to the ISA will have conventional magnets since it only needs to be energized during the stacking process. The ISA stacking rf system operates on the same frequency as the AGS (4.45 MHz) and is designed for a peak voltage of 12 kV. To prevent self-bunching and dilution of the stacked protons the impedance seen by the beam must be kept low, $Z/n < 80 \Omega$. This can be achieved by an appropriate feedback system for the rf system and careful design of the vacuum chamber, avoiding discontinuities. The AGS pulse, with its intensity reduced to 2.5×10^{12} protons in 11 bunches from the nominal 10^{13} value, is captured directly by the stacking system, accelerated, slowly debunched and deposited into the unbunched stack. The AGS pulse fills only a fraction ($\frac{1}{2}$) of the ISA circumference; dilution of the stack is prevented by designing a stacking rf system with suppressed buckets. The design current of 10 A (for 6.2×10^{14} protons) will be reached in about one hour by repeating this cycle 250 times or more. Assuming a total longitudinal phase space dilution of 2 (which according to the CERN ISR experience is not unrealistic) the momentum spread of the stacked beam will be $\Delta p/p = 0.7\%$, and its maximum dimensions in the regular structure 2.0 cm horizontally and 0.9 cm vertically. The ISA aperture subdivision at 28.5 GeV is shown in Fig. 28 where a transverse emittance $\epsilon_h = \epsilon_v = 0.4 \pi \text{ rad}\cdot\text{m}$ is taken. Possible limitations of the intensity of the stacked current due to the pressure bump phenomenon⁶⁵ or coherent transverse instabilities (CERN's brickwall effect⁶⁶), and the methods to overcome these constraints, have been studied and found to be manageable. In particular, Landau damping from a tune spread of about 0.02 will overcome the transverse resistive wall instability at injection.

Fig. 27. Beam trajectories for high luminosity configurations. The crossing angle is reduced by a factor of two.

Fig. 28. ISA aperture subdivision at 28.5 GeV.

4. Acceleration System

In order to accelerate the stacked beam it will be rebunched by the acceleration rf system operating at the second harmonic, $f = 202$ kHz. A peak rf voltage of 40 kV per ring will be provided by four ferrite-loaded cavities. The total rf power requirement of this system is 1.24 MW in both rings. The dynamic impedance seen by the beam will be kept below $Z/n = 30 \Omega$ per cavity. Nevertheless it will be necessary to short the accelerating gaps during the beam stacking procedure in order to satisfy the impedance criterion for unbunched beams.

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. The momentum spread due to bunching can be kept below 1.6% by programming the rate of energy gain per turn so that the maximum value of 12.5 keV is not reached until the momentum has increased by a factor of 1.4. This will increase the acceleration time to 165 sec from the 120 sec, required for acceleration at maximum rate.

The choice of the second harmonic should make the beam stable, in first order, against longitudinal bunched beam instabilities.⁶⁷ Since only one of the four accelerating cavities will be needed during the capture process the remaining three can be kept shorted. The resulting impedance seen by the stacked beam along with the stabilization contribution of the low energy tail should remove the possibility of self-bunching before adiabatic capture can take place. Once the beam is bunched, the remaining cavities can be brought on in a controlled manner. After the acceleration cycle is completed, the rf is switched off, the cavities are again shorted, and the resulting debunched beam will retain its final momentum spread ($\leq 0.46\%$ at 200 GeV).

Even if Landau damping by octupole fields is ignored, the nominal machine chromaticity will insure stability of the bunched beam against transverse resistive wall effects up to modes of a very high order.⁶⁸ An estimate of the growth rate of the first unstable mode gives about

0.5/sec; this modest value can easily be controlled by electronic feedback. Diffusion from a repeated crossing of the 5th or higher order resonance during the acceleration cycle was numerically computed and found to be inconsequential. Third or 4th order resonances must, however, be avoided at all times; this is readily achieved by proper choice and control of the working line.

5. Beam Dump

Because of the high stored energy in the ISA beams (about 20 MJ) and the high specific density of the beams at 200 GeV (typically 10 A within a beam cross section of a few square millimeters) major damage could be incurred if the beam would exit from the ring vacuum chamber in an uncontrolled fashion either due to orbit perturbations or due to beam growth as a result of beam instabilities. For this reason, a fast protective extraction system will be incorporated capable of extracting the beam in the time of one orbit, about 10 μ sec, and directing this beam to an external beam absorber system which will consist of a sequence of materials with increasing specific density. The latter part is essential to prevent "explosive" damage to the dump absorber. In order to improve the degree of protection of the low-temperature ISA envelope a simple internal dump system will be added for redundancy. This will make use of a shorter, medium-density, absorber which in case of failure of the primary system (and for a worst-case set of parameters) will localize the damage caused by the beam to an interchangeable absorber section of the machine. The absorber of the redundant internal dump will also be used as the absorber element for the beam scraper systems, which are essential in reducing radiation background in the experimental areas and will be used extensively during the injection and stacking process to achieve the desired high beam density.

The extraction systems will incorporate fast extraction beam kickers, special magnetic septum units, and small aperture beam bending elements. Most of the external beam will be in air, but beam detection instrumentation will be required along the exit trajectory. Additional in-ring beam detectors will be incorporated to trigger the protective extraction sequence.

Multiple adjustable target units are required, with associated controls and computer interface for the beam scraper systems.

6. Magnet System

The ISA magnet system will be superconducting because of the enhanced performance and reduced electric power consumption possible with this approach. The use of superconducting magnets obviously necessitates the generation and maintenance of a low-temperature environment, 4.5 K in the case of NbTi conductors. The cost increment due to the refrigeration and liquid helium distribution system is compensated for by reductions in the construction cost of the shorter tunnel which contains less vacuum equipment and other field-dependent items. In addition there is a significant saving in the annual operating costs. A program to develop superconducting magnets for use in accelerators and beam transport lines has been going on at Brookhaven for over ten years. Superconducting magnet technology has advanced to the point where the performance of magnets, i.e. their peak field, field quality, random errors, etc. can be predicted with an accuracy equal to that for conventional magnets. The experience gained from the operation of superconducting magnets in the high-intensity proton beam to the North Area of the AGS indicates that the effects of radiation heating are manageable. Refrigeration systems of the capacity required have demonstrated their reliability in commercial use.

The superconducting magnet development program directly related to the ISABELLE project has involved the construction and testing of several dipole magnets of the 1-m long 8-cm coil aperture type. Work is in progress on a full-size ISA dipole magnet, 4½-m long with 12-cm coil and 8-cm vacuum chamber aperture (Fig. 29); completion of this model is imminent.⁶⁹

The lattice design requires dipoles capable of operating at 40 kG for an energy of 200 GeV. Stability of the magnets, with the absence of premature quenching (transition to the normal state) or training effects (higher fields can be reached only after repeated quenching), is essential

Fig. 29. Cross section of full-size ISA model.

in the practical application of superconducting magnets. The first two magnets in the one-meter series, ISA I and II, were built to establish the reproducibility of the construction technique. In these magnets, the first quench occurred at 41 and 37.5 kG respectively with subsequent training to 45 and 43 kG. Short-sample critical current was reached in both magnets, the difference in peak field reflecting slight differences in the conductor used. The best operating characteristics were achieved with the ISA IV dipole. This magnet was intended to be a test vehicle of improvements to be incorporated in the full-size ISA model. The braided conductor uses filamentary superconducting wires with a high-resistance cupro-nickel jacket to reduce rate-dependent effects and indium-lead filler for mechanical and thermal stability. Short sample critical current of the conductor was higher than that of previous models and construction was improved by honing the bore of the iron core. This magnet quenched the first time at 44 kG and reached a peak field of 45 kG at 4.6 K. The ISA magnets are operationally safe, having a high capacity to sustain quenches without self-destruction. This desirable feature is a result of the single-layer design which provides tight thermal coupling between turns.

Deviations from the required field configuration must be avoided at all field levels encountered during operation (6 kG to 40 kG). Errors, which are the same from magnet to magnet, may be introduced by the conductor arrangement, by the construction of the coil ends, by iron saturation effects, by diamagnetic effects in the superconductor itself, and by rate dependent induced currents. To achieve complete control over the beam it is necessary that the magnetic field shape be accurate to within a few parts in 10^5 over the aperture of the vacuum chamber (8-cm diameter which represents 2/3 of the magnet coil aperture). The magnetic field is completely described by a median plane polynomial expansion, $B_y = B_0(1 + \sum b_n x^n)$, where the coefficients b_1, b_2 , etc. are referred to as quadrupole, sextupole, etc. terms. The multipole terms caused by iron saturation and magnetization are field-dependent; the variation of the sextupole term with field is shown in Fig. 30 for illustration. The

results from the various models indicate that an added sextupole tuning coil effectively compensates the important systematic magnet errors. Additional tuning coils are provided to adjust the machine working line in the presence of space charge and other systematic effects. Field deviations caused by induced currents in the wide conductor during acceleration have been studied extensively on ISA II and IV as well as in a special apparatus to measure the conductor magnetization.⁷⁰ The observations are in good agreement with theory which predicts a sextupole term change $\Delta b_2 \approx 4 \times 10^{-4} / \text{cm}^2$ at $\dot{B} = 300 \text{ G/sec}$ for the $4\frac{1}{2}$ -m ISA model. This should be correctable without particular difficulty. In fact, a system for controlling systematic nonlinear effects, including rate dependence, of the magnitude expected in the ISA is presently in operation at FNAL.⁷¹ Further models in the one-meter series are being constructed to test conductor improvements which should reduce the induced sextupole term by two orders of magnitude.

Random errors, or deviations from magnet to magnet, are caused by the fabrication tolerances in the positioning of the individual conductors and in the concentricity of the coils in the iron shield. Closed orbit deviations, gradient errors, and imperfection stopbands are caused by random errors. The required reproducibility in the dipole fields is $\Delta B/B \leq 5 \times 10^{-4}$ rms and in the quadrupole gradients is $\Delta G/G \leq 10^{-3}$ rms. Estimates of the permissible random field errors indicate that tolerances on the conductor position $\leq 50 \mu\text{m}$ rms are required. Measurement results are conveniently expressed in terms of the out-of-phase multipole terms, a_n , which are defined by way of the radial field on the median plane. Random fabrication errors result in equal $|a_n|$ and $|b_n|$ values. In the magnets under discussion all a_n 's and odd numbered b_n 's should vanish because of symmetry. The magnitude of the out-of-phase terms therefore provides a direct indication of how well position tolerances have been achieved. Table IV lists the results for ISA I, II and IV which are compared with predictions based on $50 \mu\text{m}$ rms position tolerances. The full-size ISA magnet will have smaller random errors because of its larger aperture. It is seen that the measured random errors are consistent with expectations, except for the quadrupole term which is due to the nonconcentricity of the entire coil in the iron shield. The assembly technique for the $4\frac{1}{2}$ model will be improved to give more accurate centering. Although imperfection

resonances are not expected to play a role in the standard ISA configuration it is considered prudent in view of possible future needs to install multipurpose correction windings. These will be capable of compensating random field errors up to the decapole component.

TABLE IV. Magnet Random Errors

cos		ISA I			ISA II			ISA IV			Theory 50 μ m rms	Units
		6	24	40	6	24	40	6	24	40		
26	$ a_1 $	3.5	3.7	5.4	0.9	2.0	0.2	1.6	1.4	1.3	1.1	$\times 10^{-4}/\text{cm}$
	$ \Delta b_1 $	0.9	1.1	0.7	2.7	2.2	2.5	2.0	1.8	1.7		
39	$ a_2 $	0.2	0.1	0.1	0.1	0.1	0.0	0.21	0.20	0.23	0.3	$\times 10^{-4}/\text{cm}^2$
59	$ a_4 $	0.5	0.5	1.4	0.4	0.4	0.8	2.1	1.9	1.2	2.6	$\times 10^{-6}/\text{cm}^4$
76	$ a_6 $	7	7	4	11	4	4	8	8	8	19	$\times 10^{-8}/\text{cm}^6$

The reliability of superconducting magnets, that is, the absence of changes over long operating periods or changes due to thermal cycling, has been examined for the one meter models ISA I and II after 5000 pulses, simulating 10 years of normal ISA operation; no detectable changes were observed in the harmonic coefficients.

The effects of radiation on the materials used in the magnet construction have been considered. The critical current density of NbTi is essentially unaffected by particle fluxes up to $10^{17}/\text{cm}^2$ so that it is unlikely that the superconductor will be degraded in normal operation.⁷² Epoxy-impregnated fiberglass which is relatively insensitive to radiation damage is used almost exclusively in the windings. The resistance ratio of the copper matrix in the superconducting wire may be reduced by radiation, but only by levels well above those to be expected around the ISA. Quenches may be initiated by localized heating from beam spills, but experience with the 8° bending magnet has demonstrated that a properly cooled magnet is able to operate in a controlled radiation environment. An accidental beam spill of the entire stored beam would present a serious problem for superconducting and normal magnets alike. It can be pointed out here that beam spills are most likely to occur during beam transfer which, in the ISA, is done at the relatively low field of 5.6 kG. Here the temperature reserve of the superconductor against quenching is greatest, resulting in a tolerable proton flux about 200 times higher than at full field.

The recent literature on superconducting accelerator magnets shows that a number of different magnet designs can be made to operate with some success. At Brookhaven two alternate styles, the window-frame and the cosine θ magnets, have been investigated.^{20,73} It is anticipated that the ISA magnet will be of the cosine configuration and closely resemble the $4\frac{1}{2}$ -m model, the details of which are described below. It is well known that a pure dipole field is produced by coils located about a circle with a cosine θ current density distribution. In the actual construction, the ideal current distribution is approximated by six current blocks per quadrant, containing 19, 18, 16, 13, 9 and 5 turns respectively (Fig. 31). The conductors are spread over their respective block areas by inserting inert stainless steel braids in order to minimize the peak field (the two-dimensional peak is 4.5%, the peak at the ends is 6% higher than the central field). Exact positioning of the blocks is determined in such a way as to suppress the six lowest harmonics. The current blocks are built up with a single layer of wide flat braid (bare dimensions about 1.66 cm x 0.064 cm). The braid is composed of 97 twisted composite wires, 0.3 mm in diameter, each containing 517 superconducting NbTi filaments of 8- μ m diameter. The braid is fully locked and has a transposition length of about 11 cm and a packing density of 72%. The $4\frac{1}{2}$ -m model requires 90 kg of superconducting wire or a total of 1400 m of braid. The braid is filled with indium- 7 wt% lead filler to give mechanical rigidity and electrical stability. The wires in the braid have a 0.01 mm thick Cu- 10 wt% Ni jacket to increase the coupling resistance between wires and decrease eddy current effects. The iron core tightly surrounds the coil and, as an integral part of the construction, must also be at liquid helium temperature (Fig. 29). The physical length of the dipole is 4.30 m, its weight about 5000 kg. The inner diameter of the coil is 12 cm, the outer diameter of the iron is 43 cm and the stored energy per dipole is 465 kJ at 40 kG. Since the vacuum chamber is warm, adequate thermal insulation must be installed between the vacuum chamber and the magnet coil. Special requirements on this insulation are established by the need for outgassing the vacuum chamber at 200°C.

Each magnet of the inner and outer ring will be contained in its own dewar (Fig. 32). The arrangement of dipole and quadrupole dewars in a

Fig. 30. Variation of sextupole term with magnetic field. Use of low carbon steel in ISA IV is the reason for the smaller saturation effects.

Fig. 31. Conductor arrangement in full-size ISA model.

Fig. 32. Dipole dewar cross section.

regular half cell is shown in Fig. 33. This configuration has the advantage that all vacuum joints are directly accessible for leak tests at room temperature and that the position of each magnet is separately adjustable. It may, however, lead to higher heat loads unless special precautions are taken. Heat loads from current leads will be minimized by having cold connections between all dipoles of each octant. In this arrangement, the current in the dipoles can be chosen to meet other conditions. In the ISA dipole 3.5 kA at full field was selected so as to keep voltages induced during a quench within tolerable bounds. However, for the purpose of magnet protection during a quench, it is necessary to provide, from every other dipole, current leads which are connected to shunting diodes. Since these leads are not required to operate continuously, they can be designed for lower current carrying capacity (here 1000 A). The quadrupoles will be designed for a current of 1 kA at the highest gradient of 6.6 kG/cm. Simplifications of the dewar system are under study which would integrate core and dewar design and eliminate the helium vessel.

The ISA design calls for 40 kG superconducting magnets. This choice is based on the present-day availability of NbTi filamentary superconducting wires from commercial sources in the United States and the experience with magnet models at Brookhaven and at other laboratories. It is conceivable that improvements of magnet design and construction techniques will result in magnets which can be operated reliably at 60 kG and which would permit operation at energies up to 300 GeV. The reduced current carrying capability (67%) of NbTi at 60 kG results in a larger superconductor requirement and thus increased cost. But, since the superconducting material represents a small fraction of the total magnet cost, the price increase for 60 kG is not significant when compared to the total cost of the project. Work is in progress to test concepts for 60 kG magnets. The prospects for early development of new superconducting materials, such as Nb₃Sn or V₃Ga are encouraging. These materials would have an impact on the ISA design in two ways. First, their high critical temperature (18 K in the case of Nb₃Sn versus 9.5 for NbTi) makes operation at temperatures in the range from 8 - 9 K possible, resulting in a substantial reduction in electric power consumption of the refrigeration system.

Fig. 33. Regular half cell.

Second, the critical current of these materials is higher by an order of magnitude, considerably simplifying the design of 60 kG magnets. Filamentary Nb₃Sn wires are just becoming available commercially in the U.S. but are not yet in a form suitable for accelerator magnet fabrication. A diffusion technique has been developed at Brookhaven with which conductor samples have been produced. The results have been sufficiently encouraging to start construction of a one-meter long dipole model, (ISA VII) using this material. This unit will be tested in the fall of 1975.

7. Refrigeration System

All components of the refrigeration system required to generate the cold environment for the superconducting magnets are conventional as to their design, which is similar to that used in large helium liquefiers in gas fields. Their sizes are comparable to the industrial liquid nitrogen or natural gas liquefiers which have an established record of reliability. The operating temperature of the superconducting NbTi magnets is specified at ~ 4.5 K which can only be achieved by use of fluid helium. Some consideration has been given to the optimum choice of the operating temperature. Earlier studies⁷⁴ of the GESSS (General European Superconducting Synchrotron Study) group seemed to favor lower temperatures, down to 3.5 K. Our analysis showed, however, that the greater cost and complexity of a refrigeration system designed for subatmospheric pressure does not seem to be commensurate with the gains made possible in the magnetic design. Furthermore, operation at lower temperatures increases the electric power consumption thus providing a compelling argument for temperatures at or above 4.2 K.

The refrigeration system of the ISA must function in a variety of situations: normal operation, cooldown, bake-out of vacuum chamber, etc. The system's requirements are set by the normal operating condition with all magnets excited to full field. The total accelerator heat load is, in this case, about 26 kW, of which only 15% represents excitation-dependent ohmic losses. The total refrigerator capacity of 30 kW is provided by a system consisting of a central, eight-unit, four-stage compressor station and eight 3.7 kW refrigerator cold boxes which are installed close

to each octant. The refrigerator units are designed with four expansion engines, with the final expansion employing either a wet engine or a Joule-Thompson (J-T) valve. The electric power requirements at the compressor motor are 12.4 MW with J-T valves or 9.8 MW if wet engines are used. Since available information about the reliability of wet engines is insufficient, it is planned to install a parallel J-T valve which could be put into operation if the wet engine fails. For greatest operational simplicity the refrigeration system is designed entirely without liquid nitrogen usage. A total of 100 000 liters of liquid helium is contained in the filled dewars of the ISA. It will be possible to cool and fill the entire ISA in less than 1 week.

The response of the refrigeration system to a number of faults has been analyzed in detail and precautions to prevent possible loss of refrigerant have been incorporated into the design:

- The quench of a single magnet may lead to a quenching of all cryogenically coupled magnets in one half-cell. The release of the 0.9 MJ during the quench will result in the evaporation of 400 liters of liquid helium which will be vented into a low-pressure buffer device. The dewars will be refilled and ready for operation after about $\frac{1}{2}$ hour.
- Shutdown of one of the 8 refrigerator units can be tolerated during normal operation of the ISA, since the system was sized so that 7 units are adequate to carry the full load. The helium distribution system is interconnected around the entire ring, and the computer control system will assure equal loads in the refrigerator units.
- Unscheduled loss of electric power would cause transfer of the liquid helium to liquid storage vessels by pressure build-up in the dewars. A loss of 15% of the helium must be expected if the electric power remains off for longer than 10 hours. By providing an emergency, diesel-powered, compressor this loss of refrigerant can be prevented.
- The worst fault would occur if the protective beam dump fails and the beam, with its 20 MJ energy, is spilled into the magnets.

This might evaporate, in a short time, as much as 10% of the liquid helium which could not be recovered.

8. Vacuum System

The density of residual gas molecules in proton storage rings must be lower, by several orders of magnitude, than that in conventional accelerators. This is necessary in order to reduce beam loss and the accompanying radiation background in the experimental areas caused by nuclear scattering. The design, therefore, calls for a pressure of 10^{-11} Torr in the lattice sections of the ring and, if possible, lower than this in the experimental insertions. At these pressures the beam loss from gas scattering is smaller than 1 ppm/min and the total background in the experimental straight sections is estimated to be about 2×10^5 particles per second for a circulating current of 10 A. Beam growth due to multiple Coulomb scattering is expected to be negligible at the operating pressures. At 10^{-11} Torr it is still necessary to prevent the beam from becoming neutralized, that is, to prevent the trapping of the electrons and negative ions produced by the beam-gas collisions. This beam clearing will be achieved in the ISA by a system of clearing electrodes placed at regular intervals around the ring. The average ratio of trapped electrons to circulating protons is calculated to be about 3×10^{-4} at full beam current. With such a degree of neutralization the changes in betatron tune are small, about 1 to 2×10^{-3} .

Experience with the CERN ISR has shown that the most serious limitation on current is set by the beam induced pressure rise, or "pressure bump phenomenon".⁶⁵ Qualitatively, this effect is caused by ionized residual gas molecules being propelled by the electric field of the beam against the vacuum chamber wall and liberating adsorbed molecules in sufficient quantity to increase the gas pressure. At a certain value of current, I_{crit} , the pressure rise leads, avalanche-like, to a local pressure peak and the destruction of the beam. For the geometry of the ISA vacuum system (8-cm i.d. circular vacuum chamber, 5-m distance between pumps, each with 500 l/sec pumping speed), the theory⁷⁵ predicts the product $\eta I_{crit} \leq 30$ A. The desorption coefficient η (defined as the number of released molecules per incident ion), characteristic of the chamber wall, depends on the material surface preparation, and bake-out temperature, as well

as the mass and energy of the bombarding ions. Recent measurements of this coefficient for aluminum samples, initially vapor-degreased and then baked out to 300°C, have yielded values of $\eta < 3$ when these samples were bombarded by 2 keV N_2 ions.⁷⁶ In the ISA where the residual gas will be predominantly H_2 and the beam to wall potential is 1 kV, a desorption coefficient of less than 3 is, therefore, to be expected. The current limit will then be greater than 10 A. It should be mentioned here that the use of a vacuum chamber operating at liquid helium temperature had been considered¹¹ but abandoned in view of experiments indicating desorption coefficients of several thousand⁷⁷ and other practical engineering considerations. Experiments to simulate the pressure bump effect are in progress. These should not only verify the criteria used in the vacuum system design, but also provide a more fundamental understanding of the desorption process.

The vacuum chamber material will be aluminum alloy Al 6061. Extensive surface treatment and outgassing tests have been made on pipes of this alloy. It has been found that a surface treatment consisting of chemical polishing and a glow-discharge cleaning in argon and oxygen followed by 200°C bake-out results in a surface with an outgassing rate (99% H_2) of 1×10^{-14} Torr liter $cm^{-2} sec^{-1}$, which is below the design requirement to obtain the operating pressure of 10^{-11} Torr. The good electrical conductivity of aluminum is an asset, reducing the resistive wall instabilities. The good thermal conductivity also simplifies the necessary bake-out equipment. In addition, Al 6061 is easily machinable and relatively inexpensive as compared with stainless steel.

The pumping is provided by conventional Ti-sublimation pumps and ion-sputter pumps for nongetterable gases. The dewar construction provides direct access to all vacuum joints and pumps. The result is essentially a "conventional" ultrahigh vacuum system.

9. Magnet Power Supply

The demands on the magnet power supply are modest as a result of the slow acceleration cycle. The total energy stored in the bending magnets of each ring is about 125 MJ. Therefore, a 2 MVA rated power supply is adequate. With the peak dipole current of 3.5 kA, the required power

supply voltage is about 600 V. These are ideal parameters for solid state rectifiers-inverters. The power supply will be a six-phase SCR system including a passive inductance-capacitance filter to reduce the ripple to the required $\Delta I/I \leq 10^{-6}$.

The large total stored energy in the bending magnets makes it important to include fault protection in case of a magnet quench. For this purpose shunting power diodes will be included across pairs of dipoles in a half cell. Under normal magnet operating conditions the voltage operating points of the diodes are below their current conduction threshold, but if a quench occurs, the diodes will provide a conduction path to discharge the stored energy in the magnet.

The quadrupoles, sextupoles and correction element windings, and the magnets in the experimental insertions, will be supplied by similar power supplies at much lower power levels.

10. Control and Monitoring System

It is planned to operate the whole ISA-AGS accelerator complex from a central control center. This maximizes the information interchange between the two accelerator systems and minimizes the operating crew required. The various functions encountered in the operation of the machines, such as data collection, analysis and display, beam monitoring, or execution of operator instructions, will be carried out by a computer-based control system. If computers are considered as integral parts of the control system from the inception, a powerful system of great flexibility at relatively moderate cost will result.

Basically the ISA will be controlled and monitored by a network of computer subsystems, each containing at least one programmable processor. At least three types of subsystems will exist:

- Control subsystems, which will execute control procedures. They will be physically distributed throughout the ring and connected to the machine electronics such as power supplies.

- Manipulation subsystems, such as the subsystems supporting the numerous monitor displays, will be used to organize data, procedures and commands given to the system by operators and experimenters as well as data submitted from the system to the operator and experimenter.
- Database subsystems will manage records containing the complete status of the ISA in real time. The subsystem will be connected via a long distance communication subsystem.

It is presently estimated that the system will include approximately 30 control subsystems, 2 database subsystems and 2 manipulation subsystems.

11. ISA Shielding

Many of the considerations regarding the shielding requirements of conventional accelerators are equally applicable to storage rings. The basic requirements are that points beyond the laboratory boundary never accumulate an annual dose in excess of 1 mrem and that persons working in the ISABELLE area not receive a dose exceeding 100 mrem per week of normal operation or in one uncontrolled loss of beam of up to 10^{15} protons. Furthermore, machine components must not be damaged in such a case. During normal operation the beam will be dumped in a controlled fashion into a beam stop. Approximately 6 m of earth above the tunnel meets radiation requirements with a conservative margin, provided some additional shielding is provided in the beam stop area and in the tangent direction in the plane of the rings, where muons tend to emerge. Special provisions may be necessary around experimental halls as dictated by the needs of individual experiments.

IV. PHYSICAL PLANT

1. Location of ISA

The location of the ISA on the Brookhaven site, shown in Fig. 23 was selected by considering the AGS beam availability, the topography and water table elevation of the terrain, and the cost of extending existing utilities and road networks to the ISA.

2. Magnet and Beam Transfer Enclosures

A cross section of the magnet enclosure is shown in Fig. 34. The enclosure, which has a total length of 2960 m, will be made of multiplate steel arch 4.2-m wide and 3-m high. This will be covered with 6 m of sand for radiation shielding, but will be designed to permit an increase to 9 m if necessary. Access to the enclosure will be from the experimental halls.

Based on experience with the AGS, which showed that the soil of the proposed ISA site can easily support loading to $80\,000\text{ kg/m}^2$, a simple slab foundation for the ring magnets will be entirely satisfactory.

The beam transfer enclosure will consist of steel multiplate or pre-cast concrete arches 2.5-m wide by 2.5-m high, covered by 3 m of sand for radiation shielding. There will be 900-m length required for the two branches.

3. Experimental Halls

At each of the eight intersection regions there will be a hall providing space for experimental activities. The halls will be different in size and shape to accommodate different experimental requirements and are shown in Fig. 35.

The two lepton halls will each have 684 m^2 of space, and are 38-m long, 18-m wide, and 15-m high. Each hall will have an overhead crane of 40 tons capacity.

The two small angle halls will each have 784 m^2 of floor space, 98-m long, 8-m wide, and 8-m high. They will have overhead cranes of 10 tons capacity.

Fig. 34. ISABELLE tunnel cross section.

SMALL ANGLE HALL

LEPTON HALL

HADRON HALL

Fig. 35. Experimental halls.

The two hadron halls will each have 926 m^2 of floor space. The central section will be 25-m long, 14-m wide, and 15-m high serviced by a 40 ton crane. There will be an extension on either side, 38-m long, 8-m wide, and 8-m high with 10 ton crane coverage.

The hadron spectrometer hall has the same dimensions and crane coverage as the hadron halls.

The ejection hall of 375 m^2 area will be 61-m long, 6-m wide, and 3-m high.

The construction of the halls will be largely the same except for access from the outdoor grade. Slabs, wall, and roof will be of reinforced concrete capable of supporting 9 m of earth fill for radiation shielding. Entry to the halls will be through shielding doors from a ramp or crane covered pit depending on the adjacent grade. The ejection hall will be entered from the magnet enclosure on either end. Each hall, except the ejection hall will have a 100 m^2 building for utilities and support of the experimental area with an adjacent deck area of about 2000 m^2 .

It is intended that the experimental halls be completed as soon as possible after construction starts to be used for working space to assemble and test machine components for the ISA.

4. Auxiliary Buildings

A 2-story 1850 m^2 service building will be constructed near the center of the magnet enclosure. It will house a mechanical assembly area with an overhead traveling crane of 10 tons capacity, a technician's shop, stockroom, equipment area and laboratories on the first floor. Office space, main control room, computer room and an electronics laboratory will be located on the second floor.

An 1100 m^2 compressor building will be constructed adjacent to the 69 kV switchyard in the center of the ring. It will house eight large helium compressors, vacuum pumps, switchgear, and gas system control apparatus, and have a small operations office and maintenance area. There will be a 10 ton overhead crane to service the compressor units.

Eight 40 m² buildings will be located around the inside perimeter of the ring. These will serve as control and equipment buildings adjacent to cold boxes and liquid helium dewars.

V. LIST OF MAIN PARAMETERS OF THE ISA

The main parameters of the ISA as described above have been summarized in the following table.

TABLE V. Main ISA Parameters

ENERGY	
Maximum energy	200 x 200 GeV
Equivalent accelerator	86 TeV
LATTICE	
Circumference ($3\frac{2}{3} \times C_{\text{AGS}}$)	2960 m
Insertion length	8 x 116 m
Regular cell length	56 x 25.40 m
Modified cell length	24 x 25.40 m
Horizontal separation of orbits	0.75 m
Distance between magnets D-D	0.90 m
Distance between magnets D-Q	1.0 m
Tune ($\nu_h = \nu_v$)	25.63
Transition energy (ν_{tr})	21.6
Amplitude function regular cell, β	42.7 m
	β_{max} 7.7 m
	β_{min} 1.64 m
Maximum dispersion, X_p	
STANDARD EXPERIMENTAL INSERTIONS	
(Horizontal crossing, adjustable parameters)	
β_v^*	4 (1) m
β_h^*	20 m
Maximum β	100 (400) m
Total free space around crossing point	40 m
Crossing angle	11.4 mrad
Interaction length	< 1 m
MAGNET SYSTEM	
Bending field at 200 GeV	39.3 kG
at 28.5 GeV	5.8 kG
Number of dipoles/ring	264
Regular dipole length magnetic	4.11 m
physical	4.30 m
Peak current in dipole	3.5 kA
Stored energy @ 40 kG/dipole	465 kJ
Vacuum chamber aperture (warm bore)	8 cm
Main coil i.d.	12 cm
Operating temperature	< 4.5 K
Number of quadrupoles/ring	160

Regular quadrupole gradient	6.64 kG/cm
Peak current in quadrupole	1 kA
Stored energy/quadrupole	30 kJ
Quadrupole length magnetic	1.16 m
physical	1.30 m
CRYOGENIC SYSTEM	
Total heat load at 4.5 K	26 kW
Total refrigeration capacity	8 x 3.7 (30) kW
Power requirement of compressors	12.4 MW
Total liquid helium	100 000 liter
INJECTION	
AGS energy	28.5 GeV
Number protons/AGS pulse (11 bunches)	2.5×10^{12}
AGS emittance $\epsilon_h = \epsilon_v$	$0.4\pi \cdot 10^{-6}$ m-rad
Longitudinal phase space per bunch, A	0.36 eV·sec
ISA current/ring	10 A
Number protons/ring	6.2×10^{14}
Number AGS pulses stacked/ring	≈ 250
Stacked beam size	2.0 cm x 0.9 cm
Momentum spread (with tail)	0.7 (1.0) %
rf frequency, stacking system	4.45 MHz
rf voltage	12 kV
Impedance tolerance Z/n	< 80 Ω
Tune spread	≤ 0.02
ACCELERATION	
Duration	3 min
rf frequency (h = 2)	202 kHz
Energy gain/turn	12.5 kV
Peak rf voltage	40 kV
Total rf power	1.24 MW
Momentum spread at 200 GeV	< 0.45 %
Maximum momentum spread, bunched	1.6 %
LUMINOSITY	
Standard insertion, 200 GeV	2.6×10^{32} cm ⁻² sec ⁻¹
Low- β insertion, 200 GeV	5.3×10^{32} cm ⁻² sec ⁻¹
High luminosity insertion, 200 GeV	10^{33} cm ⁻² sec ⁻¹

VI. COST ESTIMATE AND SCHEDULE

The cost estimate presented in this section was prepared following the pattern used in assembling the May 1974 estimate. In each major area our experts reviewed and updated the design, drawing on advice from the broadest possible base. Wherever feasible industry sources were used to provide cost figures to insure as current-as-possible estimates.

Each component group provided equipment costs, personnel requirements and a time estimate. From the personnel figures submitted, we separated assembly and test forces and costed them with the component. All other personnel were costed in the Engineering Design Inspection and Administration (EDIA) category. Thus, it is estimated that ISABELLE will require about 1350 man years of effort through completion.

The Architect-Engineer-Management (AEM) cost was estimated at 20% of the facilities cost.

We have included contingency against the estimate as follows:

Accelerator Systems	25%
Facilities	15%
EDIA	25%
AEM	20%

This estimate is in 1975 dollars. Escalation in these times is weighted, guesses based on our own experience and as well as commercial sources. The percentages are FY 1975 to FY 1977 - 17½%; subsequent years - 5%.

It is estimated that the cost to operate the ISA, experimental halls and perform the initial experiments will be \$17,000,000 the first year. This includes 347 man years of direct scientific and technical personnel, \$180,000 for one charge of liquid helium, \$2,800,000 for electrical power, and supporting services amounting to \$1,600,000. This cost also includes approximately \$1,200,000 for personnel involved in the development of experimental set-ups.

A preliminary estimate has been made for capital equipment funds amounting to \$7,000,000 in FY 1981 for equipment required for the first

experiments at the ISA. In addition, much of the auxiliary equipment would be supplied from the ongoing AGS program. An estimate of \$10,000,000 is projected for experimental equipment in FY 1982.

Target dates for the ISA Project have been set as follows:

October 1976	Start Preliminary Design (Project Authorized)
October 1976	Start Detailed Design of Buildings
January 1977	Start Detailed Design
January 1977	Start Procurement of Critical Building Components
April 1977	Start Procurement of Critical Accelerator Components
January 1977	Start Clearing of Site and Magnet Tunnel
January 1979	Beneficial Use of First Buildings and Start Installation of Accelerator System
October 1981	Assembly of Accelerator Completed Ready to Start Beam Injection and Test
June 1982	Complete Construction - Accelerator ready for HEP

The schedule assumes that funds for Construction Planning and Design will be allocated in advance of project authorization.

TABLE VI. Summary of Preliminary Cost Estimate (in \$1000)

System		Totals
A. Accelerator Systems		84,102
I. Injection System	3,605	
II. Main Magnet System	46,244	
III. Magnet Power Supply	1,902	
IV. Vacuum System	6,692	
V. RF System	4,374	
VI. Correction Coil System	851	
VII. Refrigeration System	16,894	
VIII. Central Control System	3,540	
B. Special Equipment	120	120
C. Facilities		23,972
I. Land Improvements	846	
II. Magnet Enclosure	5,247	
III. Beam Injection Tunnel	890	
IV. Research Halls - (8)	7,957	
V. Compressor House	1,057	
VI. Refrigerator Houses - (8)	1,201	
VII. Support Buildings - (19)	1,503	
VIII. Central Control and Service Building	1,851	
IX. Yard Tray, Piping & Gas Storage Yard	486	
X. Utilities	2,934	
D. AEM (@ 20%)		4,794
E. Engineering, Design, Inspection, Administrative		<u>17,412</u>
Subtotal		130,400
F. Contingency - Facilities @ 15%; Accelerator Systems & EDIA @ 25%; AEM @ 20%		<u>29,700</u>
Subtotal		160,100
G. Escalation - FY 1975 to FY 1977 - 17½%, thereafter 5% per year		<u>31,900</u>
TOTAL ESTIMATE		<u>192,000</u>

VII. FUTURE OPTIONS

A number of options have been investigated which could be added to the basic ISA at a later stage. The most attractive, from the standpoint of physics research, would be the addition of a facility for ep collisions.^{78,79} Electrons would first be accelerated to 4 GeV in the AGS. They would then be accelerated to 15 GeV in an additional ring, providing high center-of-mass energies for ep collisions ($\sqrt{s} \approx 109$ GeV). The electron ring, with room temperature magnets, would fit in the ISA tunnel and be placed on top of one of the proton rings. It could be run independently as an electron storage ring (for testing, etc.) or in combination with one of the proton rings. At the location of the proton interaction regions the electron ring would bend in and out in order to minimize the interference with the experimental equipment in these areas. For e-p collisions the electron beam would be brought down to the plane of the proton rings. The e-p interaction region would be very similar to that described for p-p collisions, employing small angle horizontal crossing. With an available power of 6 MW in the electron ring rf system, a luminosity of $2 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$ seems feasible at 15 GeV electron energy. Taking advantage of the available rf power and going to larger electron currents at lower electron energies, higher luminosities can be reached. Luminosities in the $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ region seem quite possible for electron energies up to 8 GeV.

Special care was taken in the design of the basic ISA so as not to preclude the deuteron and antiproton options. Acceleration and storage of deuterons should not present any particular problems⁸⁰ and would make it possible to study proton-neutron and neutron-neutron interactions with luminosities above $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$. The antiproton option involves a comparatively simple modification of the basic ISA.⁸¹ A promising scheme involves the fast ejection from one ring of the bunched 200 GeV proton beam which would be focused onto an external target where antiproton bunches of 30 GeV would be produced. These bunches would be injected into the second ring and fill directly the buckets of an added 10th harmonic low power acceleration rf system. Due to the large acceptance of the ISA ring and the strongly forward peaking of the $\bar{p}$ production, it would

be possible to collect almost all antiprotons produced within a 2.5% momentum bite, leading to calculated luminosities of about $10^{29} \text{ cm}^{-2} \text{ sec}^{-1}$.

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