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

ISABELLE

May 1974

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BROOKHAVEN NATIONAL LABORATORY

ASSOCIATED UNIVERSITIES, INC.

UPTON, NEW YORK 11973

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of a
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PREFACE

This proposal for the construction of a 200 x 200 GeV proton-proton Intersecting Storage Accelerator Facility is the culmination of a three-year design study, the results of which are contained here. A preliminary design study of this machine, known as the "Gray Book", was issued two years ago. Since then the machine design has undergone a number of changes, many of which are intended to increase its usefulness to the future user and others to make the design more conservative. Some of the changes made to the machine parameters include four-fold symmetry, larger magnet aperture, warm-bore vacuum system, reduced beam current, etc. Certain characteristics of the original design had to be modified to reflect the progress made in the understanding of proton storage rings. The information gained from the operation and study of the CERN ISR has had a significant impact on the ISABELLE design. Recent progress in the field of superconductivity and superconducting magnets, and the irreversibly changed attitude of this country toward energy consumption, has more than vindicated the early decision to utilize such devices in ISABELLE. Since the experimental insertions are an integral part of a storage ring it is imperative that they be incorporated into the machine design from its inception. The active participation of a large number of practicing high energy physicists in all phases of the study gives assurance that the ISA design takes full account of the experimenter's needs.

The ISABELLE design study profited enormously from the comments and suggestions made during the 1972 BNL Summer Study, attended by over a hundred experimenters and machine physicists from universities and accelerator centers in the United States, Canada and overseas. It is a privilege to acknowledge the innumerable contributions made by so many people during and subsequent to the Summer Study. The continuing enthusiastic support given to the ISABELLE project by the community of users has provided the necessary encouragement to those who had to perform the routine work

encountered in the preparation of this proposal. Indeed, the prospects for building ISABELLE at Brookhaven have created the stimulating atmosphere conducive to success. This excitement is reflected in the haiku composed by Alan Carroll:

Strong, electric, weak
Weave their patterns in and out
All together now.

The present ISABELLE design study was headed by H. Hahn and was coordinated by the ISA Parameter Committee with H. Hahn, chairman, M.Q. Barton, J.P. Blewett, R.W. Chasman, E.D. Courant, J.G. Cottingham, G.K. Green, M. Month, M. Plotkin, I. Polk, R.R. Rau, J. Sandweiss, R.P. Shutt, and J. Spiro as members. The physics input to the design study was provided by the ISA Experimental Coordinating Group under the guidance of J. Sandweiss and R.P. Shutt as co-chairman. This group had a membership of over forty active high energy physicists, the majority of whom came from the universities.

Contributions to this proposal report were made not only by members of the ISA Parameter Committee and the Experimental Coordinating Group, but also by many individuals from the Accelerator and Physics Departments, Plant Engineering Division, and by many university collaborators and visitors from other accelerator centers. It is indeed a pleasure to express thanks and gratitude to all contributors.

The task of editing this proposal report has been shared by H. Hahn and M. Plotkin.

Finally, acknowledgment is due to the unfailing support of our drafting room staff and secretaries and, in particular, to the Photography & Graphic Arts Division where this proposal was assembled and printed in final form.

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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 led directly to the design of the CERN ISR³ which is at present the only proton-proton colliding beam device.

The construction of storage rings at the Brookhaven AGS had been considered previously in response to the recommendation made by the Ramsey panel.^{4,5} A summer study was held at Brookhaven in 1963 to discuss the relative merits of accelerators and storage rings.⁶ 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.⁷ 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, from 70 to 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.

The idea of building storage rings at Brookhaven was revived in 1970 by Blewett⁸ and this time it was greeted with enthusiasm. It soon received the endorsement of the Fitch committee 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.⁹ A study group was set up under Mills which issued a Preliminary Design Study¹⁰ (the "Gray Book") in 1972. The ISABELLE design has undergone a number of metamorphoses as documented in a series of publications.¹⁰⁻¹⁶ However, the study has now advanced to a point

where this revised version of the "Gray Book" is being issued as a construction proposal to be submitted to the AEC in the near future. If funded in FY 1976 the ISA could be operational in 1981 proving an exciting facility for particle physics research.

In the Preface of the Preliminary Design Study the following quotation is found:

"... This work has been in progress for about one year and has, in our opinion, led to a viable though not yet optimum design. It was felt that an early description of all aspects of the machine would help the future user in planning his experiments and enable him to communicate his needs for changes to the machine builder."

Those objectives have been attained. In addition, this report has provided a stimulus to the accelerator physics community, worldwide. Following the publication of that report, other laboratories have initiated studies on large storage ring systems. At the present moment some seven studies are in progress in the U.S.A., Europe, and Japan. During these past two years the high energy physics community has experienced a growing excitement, an expectation that new insight into particle behavior and structure are within our technical capabilities. Perhaps the most important stimulant has been the prolific outpouring of new results from the ISR at CERN where center-of-mass energies up to 60 GeV are being explored. New results on total cross sections, particle multiplicities, extraordinary behavior at very large transverse momenta, and particle correlation studies are causing great excitement. Simultaneously, the theoretical work pointing toward a unification of the weak and electromagnetic theories has caught the imagination of everyone in the field. More recently, data have begun to flow from experiments at the National Accelerator Laboratory. Particle physicists are eager to push their experimentation to even higher center-of-mass energies, consequently colliding beam machines are looked upon as the method to attain their goal, within fiscal bounds.

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 excellently and new ideas, both for machine design changes and for future experimentation, came from the summer study. The present proposal incorporates these new ideas and consolidates progress made during these two years. Briefly, the most striking advances have occurred in superconducting magnets, theoretical understanding of accelerator problems and, finally, in making ISABELLE a versatile facility for experimentation.

Superconducting magnet technology has come of age. Brookhaven has two superb examples. Our research and development program has produced two ISABELLE model magnets. These are circular bore magnets, sometimes designated cos θ wound, 90 cm in length, with a 8 cm diameter inside the coils. Construction techniques were used which might be applied in mass production and the intention was to examine the magnetic field quality and the reproducibility of these field properties from magnet to magnet. Extensive measurements have shown the field quality to be excellent, adequate for the ISABELLE requirements, and, furthermore, the two magnets were nearly identical, well within tolerances. These magnets are now undergoing long-term pulsing life tests and further exacting measurements.

A second pair of magnets, of the window-frame design, called the 8° bend, having a length of 1.83 m each and apertures of 9.5 cm, have been put into operation to bend the full intensity primary proton beam ($\sim 6 \times 10^{12}$ p/p) in a new external beam at the AGS which services the neutrino physics area. These magnets perform as designed and experience no fundamental problems even when subjected to this rigorous application. This is probably the first significant use of superconducting beam transport magnets for high intensity beams. In addition, the field quality and reproducibility of these two magnets are again within the design requirements for ISABELLE. Confidently one may say that superconducting magnet

technology is on firm ground and will provide 40 kG bending fields as needed for ISABELLE. This does not mean that Brookhaven will be content with these achievements. R&D work on superconductivity will continue, especially to produce stable magnets with shorter time constants and to bring into use the higher critical temperature superconductors such as Nb_3Sn . Successful development of this conductor would permit a significant decrease in refrigeration cost and in complexity, as well as provide a route to magnetic fields of 60 kG and above.

From the point of view of the high energy physicist, the crucial machine parameters are the maximum energy available in the center of mass and the luminosity. ISABELLE provides large increases in both key parameters, a factor of seven in cms energy (60 GeV $\rightarrow$ 400 GeV) and approximately 200 in luminosity ($5 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ to $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$), as compared to the current ISR parameters. For comparison, the step in cms energy in going from the AGS to NAL is about 4. Clearly, a luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$, which requires 10 A flowing in each ring, would not be available at turn-on. However, only 1.5 A are required for a luminosity of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, 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. The step is very large, 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 is reasonable.

The realm of new physics in the cms energy range from 60 to 400 GeV is vast, far larger in the energy variable than that which we have been studying intensively for 30 years. Most likely, as in previous extrapolations to a new energy domain, unpredicted phenomena will provide the greatest impact on physics. However,

present theory and experiment provide predictions and extensions of such great interest that these alone warrant this large step.

There are two general domains of research which are pressingly in need of the higher center-of-mass energy available with ISABELLE. The question of structure within the proton (and neutron) has been given great emphasis by the experiments on deeply inelastic ep and en scattering at SLAC. More recently, experiments at the ISR and at NAL, which investigate particles with high transverse momenta ($p_{\perp}$) produced in pp inelastic collisions, have added a new dimension to the questions concerning constituents within the nucleus. Larger $p_{\perp}$ implies smaller impact parameters and thus the possibility to observe smaller substructure within the nucleon. Current experimental data offer a tantalizing glimpse of that structure, but much higher center-of-mass energies (> 60 GeV) are needed to probe this fascinating question further.

The second, but related, question concerns the unification of the three interactions, weak, electromagnetic, and strong, into a single description. In fact, one can just as easily argue that there is actually only one interaction (aside from gravitation), but that our investigations so far have been so limited that we have been unable to see the clear picture of a single interaction. At this moment a great theoretical onslaught is under way to try to describe the synthesis of these forces. Two general ideas arise -- namely that in the neighborhood of 100 GeV in the center-of-mass there should appear unequivocal evidence of the meshing of weak and electromagnetic interactions. Such evidence might be new particles, such as the intermediate vector bosons, or other indications. The second is at higher energies, several hundred GeV in the cms, when evidence should appear that the strong interaction also can be combined with the weak and electromagnetic interactions. These theoretical guideposts seem irrefutable -- but finally what really makes the difference is to do experiments in this tremendously exciting and compelling energy region 60 - 400 GeV. Should ISABELLE become a reality, the U.S.A. will again be in the energy forefront of particle physics research.

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II. SUMMARY OF THE PROPOSAL

1. Scope of Project

The Intersecting Storage Accelerator (ISABELLE) has as its primary function the study of the nucleon, of which all chemical elements — molecules, compounds, in fact all forms of matter — are composed. The search for the primordial or basic constituent of matter has been an aim of mankind from the time of Democritus to modern-day particle physicists. This pursuit reached a plateau of simplicity when the neutron and proton were the only nucleons known to exist. It has once again become complex with the uncovering in recent years of hundreds of resonances or excited nucleonic states. There must be something simpler, and it is precisely the aim of ISABELLE to explore the higher energy domain in search of the substructure of the nucleon. Why this approach? Beyond the obvious idea of using a nucleon to study a nucleon, there are two compelling arguments. First, historically, new and relevant phenomena have always been found as the energy of the process studied has been increased, and second, recent experimental results from both NAL and the CERN ISR indeed indicate the onset of new phenomena. In fact it is the recent new data that aids in setting the scale and assuring that ISABELLE is in the correct energy range to yield fruitful results.

The experimentation envisaged to explore these questions is of the most fundamental sort, namely measuring the effective size of a proton when it collides with another proton (the pp cross section) and the consequences of the interaction, i.e., the angles at which particles emerge after the collision, the number of particles, their energies, etc. Such measurements of the pp total cross section have many times in the past provided insight into fundamental processes. This is illustrated as follows: At low energies, proton laboratory momenta less than 500 MeV/c, one observed long ago a cross section much larger than that associated with electromagnetic (and gravitational) interactions, namely that connected with

the nuclear or strong force. It was also noted that the pp cross section decreased rapidly as the energy of the proton increased. However, with the availability of higher energy machines such as the Cosmotron, Bevatron, ZGS, and AGS having energies in the GeV region instead of the MeV region, the unexpected occurred: The frequency of pp interaction increased dramatically as the proton's energy was increased, in fact increased by a factor of two in a very limited energy domain. What was the reason? It was a new phenomenon, the production of new particles, more than a hundred of them, with different and unexpected properties. This spectroscopy of particles has been the subject of extensive investigation over the past decade which has resulted in the classification of the multitude of particles into numerous multiplets or families. The further ramification of this new data was that the basic building blocks had to be simpler, possibly a set of three, the so-called quarks. However, searches for quarks in cosmic rays and moon rocks, at accelerators, in the seas, etc., all proved negative. As had happened below 1 GeV, the proton-proton cross section now decreased again as the energy was increased in the 10-30 GeV energy range, in fact reaching a plateau at the then highest attainable accelerator energies (about 80 GeV at Serpukhov), leading to speculation that true asymptotic behavior had been reached. However, recent experiments at the CERN ISR and the accelerator at NAL have again provided a surprise. Once more the proton-proton cross section has altered its trend and started to rise. The energies of these two machines (lab energies from 200 to 2000 GeV) are sufficient to show the rising trend; however, their energy range is too limited to provide a full exploration and consequent full understanding of this new phenomenon.

The belief that new phenomena may be emerging at these higher energies is reinforced by observations of the angular distributions of particles emerging from very high energy interactions. In fact, at both the CERN ISR and at NAL, many more particles have been observed at large angles than would be expected from extrapolations

from lower energies. The observation is reminiscent of an analogous experiment in the atomic realm performed many years ago by Rutherford — the scattering of alpha particles (helium nuclei) on gold foils. In those experiments an unexpected number of scatterings at large angles was found and proved that the atom was not an amorphous blob of protons and electrons but instead consisted of a hard-core nucleus with electrons orbiting outside. The energies that will be provided by ISABELLE will allow probing for structure of dimension 10^{-15} to 10^{-16} cm, a thousand times smaller than nuclear dimensions. Are there quarks or some other elementary constituent within the nucleon? If so, what are they like: what spin, charge and other quantum number do they carry; do they have an independent existence or can they live only within the nucleon? How are they distributed within the nucleon? What is the force law of the strong nuclear interactions at very small distances? These are the basic questions facing us today and higher energies are essential to answering them.

The discussion up to this point has been mostly about strong interactions. The various types of interactions presently known are four, usually noted as strong, electromagnetic, weak and gravitational, these being ordered in terms of their decreasing strength. They are separately catalogued not because they are necessarily fundamentally independent — we are still ignorant of their origin and interrelation — but because at present energies they differ widely in strength. If one characterizes the strength of interactions of the "strong" category by unity, then the strength of the electromagnetic interaction is 10^{-2} , the strength of the weak interaction is 10^{-5} , and the strength of the gravitational interaction is 10^{-39} . However, as the energy is increased this large strength difference is expected to decrease and a clear separation in terms of strength may no longer be true. In addition, numerous recent developments, both theoretical and experimental, strongly suggest that the electromagnetic and weak interactions are not separate but are different facets of the same interaction, and there is even speculation that, at high energies, all three — strong, weak and electromagnetic —

may be unified.

The simplest observation (made recently at CERN and at NAL) is the rapid rise of the weak interaction cross section with energy. The rise is linear with respect to laboratory energy, so that the cross section is expected to become comparable to the electromagnetic cross section within the range of energies covered by ISABELLE. Taken together with the large number of similarities observed in high energy electron-nucleon scattering (electromagnetic) and neutrino-nucleon scattering (weak), it reinforces the notion that these interactions are different facets of a common interaction. Progress in the theoretical realm has gone hand-in-hand with such ideas. The Fermi theory, which has been used to describe weak interactions rather successfully in the past 40 years, has basic deficiencies, namely that infinities are encountered when more accurate calculations are attempted. This is analogous to the difficulties encountered in electromagnetic theory in the 1950's which lead to renormalization techniques and gave an enormous increase in the accuracy and predictive powers of the theory. The host of recently-produced unifying theories attempt a similar task and, in addition, place the mass of the mediator of the weak force (the W particle) in the 40-100 GeV mass range. (For reference the proton mass is 1 GeV.) ISABELLE, with a total available energy of 400 GeV and its high luminosity, is ideal for searching for W's as well as for exploring the manner in which the weak and electromagnetic interactions merge. Indeed, the discovery of such an intermediate vector boson (the W) could be one of the most fundamental results to be found with this accelerator.

With ISABELLE one is delving into the unknown; therefore, it is vitally important to provide flexibility, diversity, and expandability. Flexibility is an inherent part of the design of ISABELLE because: (1) the center-of-mass energy is continuously variable from 60 GeV to 400 GeV; (2) the intersection areas are designed to allow a large variety of experimental conditions. The use of superconducting magnets to provide 40 kG magnetic bending fields (2 to $2\frac{1}{2}$

times that from copper-iron warm magnets) also has an expandability feature arising from the fact that new superconducting materials show promise, in the future, of being able to produce larger fields, perhaps in the region of 60 kG. Various possibilities to use particles other than protons have been considered as future options to increase the diversity of the ISABELLE facility. For example, the acceleration of deuterons appears straightforward without major modifications. A more difficult but feasible option is the acceleration of antiprotons, requiring however, modifications and additions to ISABELLE. The ability to accelerate antiprotons and deuterons as well as protons would allow a comparison of proton-proton, neutron-proton, neutron-neutron, and antiproton-proton interactions, which would explore charge effects and particle-antiparticle effects that may arise at these high energies. Perhaps the option of greatest interest would be the addition of 15 GeV electrons for collisions with 200 GeV protons. This modification would allow for the exploration of electromagnetic interactions at a level five to ten times greater in the relevant parameters (momentum transfer to the hadrons and the energy loss of the electron) than NAL and 50-100 times greater than SLAC. The modification would also initiate exploration of the weak interactions at equivalent lab energies of over 1 TeV, again a factor ten times higher than now available. This would be a truly complementary program to that outlined for the primary pp machine described in this proposal.

The ISABELLE project therefore constitutes a major step in the exploration of the fundamental particles and interactions of nature. It may provide the necessary experimental information leading to a unification of the known interactions. Extrapolating from previous experience and utilizing the recently achieved theoretical and experimental advances, one feels assured that the timing of the project and the energy range proposed are well matched. In addition to the diverse issues of physics to be attacked by this accelerator, there is always the enticing prospect of unearthing new and totally unexpected phenomena. The large increase of energy envisaged in

ISABELLE, nearly two orders of magnitude in laboratory-equivalent energy, made possible by recent technological innovation is a challenge and a hope for high energy particle physics.

2. Working Principle and Expected Performance

The ISA design incorporates a series of innovations which will make it the frontier of high energy physics and accelerator technology. Its most prominent features are the high center-of-mass energy in the range from 60 to 400 GeV, the high luminosity of up to 10^{33} $\text{cm}^{-2}\text{sec}^{-1}$, the flexibility of the experimental insertions, and the use of superconducting magnets for bending and focusing of the beam.

The usefulness of the machine under consideration depends on many factors. One of these, the center-of-mass energy (usually designated by $\sqrt{s}$), is the single most important parameter in particle physics. A proton of total energy E (or $\gamma = E/m_p c^2$) striking a stationary proton provides, in the center-of-mass system, the energy $\sqrt{s} = m_p c^2 \sqrt{2\gamma + 1}$, which is available for the creation of new particles in the reaction. At the highest energies $\sqrt{s}$ varies as the square root of γ due to the relativistic limitation. Large values of $\sqrt{s}$ are obtained by substituting for the stationary target another proton beam moving against the first. For head-on collisions, with beams of equal energy, the available energy in the extreme relativistic limit becomes $\sqrt{s} \cong 2\gamma m_p c^2$. It follows that such collisions are equivalent to those from a conventional accelerator with $\gamma_{\text{equ}} \cong 2\gamma^2 - 1$. The 400-GeV center-of-mass energy of the ISA is equivalent to that of a conventional accelerator of 86 TeV. In the U.S., the NAL accelerator, at 400 GeV, provides a center-of-mass energy of only 28 GeV. The highest center-of-mass energy presently available is at the CERN ISR with an energy of 61 GeV. This is equivalent to a 2 TeV accelerator. The ISA will allow almost an order of magnitude increase in center-of-mass energy.

A design parameter for storage rings, as important as the energy, is the luminosity. The event rate, R , for a particular reaction is determined by the product of the luminosity, L , and the cross section, σ , of the reaction under consideration ($R = \sigma L$ with the

luminosity in units $\text{cm}^{-2}\text{sec}^{-1}$). The luminosity is determined by the parameters of the machine such as the circulating current, beam emittance, geometry of the beam crossing region, tolerable beam-beam tune shift, etc. The design luminosity of the ISA was fixed at $10^{33} \text{ cm}^{-2}\text{sec}^{-1}$ per interaction region. With a total cross section for reactions between high energy colliding protons of about 40 mb an extremely large total event rate of 40 MHz can be expected. The ISA luminosity will be more than two orders of magnitude above the values currently achieved at the ISR. This high value can be obtained by exploiting low-beta insertions,* head-on (or small angle) collisions of the protons and, especially, the small emittance and high phase-space density of the AGS at Brookhaven. An informative expression for the optimum luminosity of proton storage rings has been derived by Keil,¹

$$L_{\text{opt}} = \frac{4}{3} \gamma \left(\frac{I^3}{e^3 r_p} \frac{\pi}{\epsilon_{\text{inv}}} \frac{\Delta\nu_{\text{max}}}{\ell} \right)^{\frac{1}{2}}$$

which is obtained by adjusting the amplitude function at the crossing point to the value

$$\beta_{\text{opt}}^* = \left(\frac{ec}{8r_p I} \frac{\epsilon_{\text{inv}}}{\pi} \ell \Delta\nu_{\text{max}} \right)^{\frac{1}{2}}.$$

Here I is the current stacked in one ring, $\epsilon_{\text{inv}} \cong \gamma\epsilon$ is the invariant transverse emittance which is assumed equal in the horizontal and vertical planes, ℓ is the unshielded free space between magnets around the collision region, $\Delta\nu_{\text{max}}$ is the linear tune shift due to the space-charge forces of the beam-beam interaction, e is the electronic charge, c is the velocity of light and r_p is the classical proton radius. The luminosity depends strongly on the current which can be stored and, in the case of the ISA, accelerated. An estimate of the more serious current limitations due to the beam induced gas pressure rise² and the transverse resistive wall instability (CERN's brick wall effect)³ indicates

*The beta, or betatron amplitude, function determines the beam envelope. In a low beta insertion the transverse beam size is reduced to increase the local particle density and thus the frequency of collisions.

that 10 A is a realistic figure for the ISA. The beam-beam tune shift tolerable in proton storage rings is not firmly established, but there seems to be agreement that $\Delta\nu_{\max} = 5 \times 10^{-3}$ is a conservative limit. The present insertion design provides a free space between magnets of $l = 40$ m; this value could easily be halved at a later time if higher luminosities should be desired. The optimum luminosity depends directly on the emittance achievable; the AGS, with an $\epsilon_{\text{inv}} = 12.5 \pi \cdot 10^{-6}$ m.rad, is ideally suited as an injector for a proton storage ring. The optimum luminosity in the ISA is obtained with $\beta_{\text{opt}}^* = 0.7$ m and reaches the level of $L_{\text{opt}} = 3 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$, a value which is comfortably above the design requirement. Details related to the possibility of low-beta insertions, and their implications with regard to the general lattice design, are discussed in Section IV. Further questions of performance limitations due to collective effects, beam-beam interaction, or nonlinearities caused by magnet imperfections, will be treated in Section V.

In Section III the gamut of new particle physics opened up by the construction of the ISA will be discussed in some detail. Here we mention only a few typical experiments certain to be carried out with the new device. In the domain of strong-interaction physics it will be possible to study:

- the rise in total cross section with $\sqrt{s}$ which was first observed at the CERN ISR and which could be the manifestation of a novel behavior of hadronic matter;
- the unexpected copious production of pi mesons at large transverse momenta, possibly an indication of the existence of point structures inside the proton;
- the two-body correlation at wide angles, as well as clustering effects, indicating possible long range effects;
- the energy dependence of the multiplicity of produced charged and neutral particles;
- the production spectrum of secondary particles (pions, kaons, antiprotons) and their cross sections at large energies;

- small-angle and large-angle elastic scattering and the existence of a second diffraction peak.

In addition, searches for glamorous new particles such as quarks or magnetic monopoles would clearly be most exciting.

In the domain of electromagnetic and weak-interaction physics which, as a general rule, will require the highest luminosities ($L \geq 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$) it should be possible to search for:

- pair production ($\mu^+ \mu^-$ or $e^+ e^-$) which is the signature of heavy photons; rate estimates with the most pessimistic model would indicate a limit of the observable mass as $m_{\mu\mu} < 20 \text{ to } 30 \text{ GeV}/c^2$;
- production of single muons indicative of charged intermediate bosons $W^\pm$; the expected rates are very high and detection up to the mass limit, $m_W \leq 150 \text{ to } 200 \text{ GeV}$, should be possible.

The facility for studying reactions with low cross sections depends, to a large extent, on the radiation background generated by interactions of protons with residual gas in the vacuum chamber or by particles lost from the beam and striking the vacuum chamber. The vacuum requirements are set to 10^{-10} Torr in the machine section of the ISA and to 10^{-11} Torr or better in the experimental straight sections.

The anticipated experiments at the ISA differ in their specific requirements as to luminosity, tolerable momentum spread, shape and size of the crossing region, radiation background, etc. A number of experiments have been conceptually designed and the constraints on the experimental insertions have been established. It will be shown in Section III that only the small-angle scattering experiments require an unusual straight section configuration to provide the desirable angular resolution of $25 \mu\text{rad}$ or better. Most experiments studied can be performed adequately in a general-purpose, modest beta experimental insertion having adjustable optical parameters. To preserve complete four-fold symmetry during commissioning of the machine, all four experimental insertions

will be made identical. After having gained experience with the operation of the ISA, it will be possible to introduce other experimental insertions, in all likelihood no longer identical, which are better suited to experiments with special requirements. This concept provides considerable flexibility in the layout of the experiments, approaching that of a conventional accelerator.

The use of superconducting magnets has a significant impact on the expected performance of the ISA. The discussion of performance limitations due to collective effects in Section V indicates that most limitations become worse for a machine with a large radius and small vacuum chamber dimensions. Superconducting magnets are beneficial on both accounts:

- Operation at fields of 40 kG, as assumed in the ISA design, reduces the machine radius by a factor of two when compared to a conventional accelerator of equal maximum energy. Superconducting 40 kG magnets, using commercially available NbTi composite wires, have been operated at Brookhaven, reliably and economically. Work on magnets capable of higher fields, conceivably up to 60 kG, is in progress at Brookhaven. Their availability could be used to reduce further the machine size or, preferably to reach energies of up to 300 GeV.
- Operation of large gap conventional magnets is prohibitive in terms of electric power consumption. As discussed in Section XVIII, economically designed conventional magnets limit the luminosity of storage accelerators, otherwise comparable to the ISA, to values of about $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, which is an order of magnitude below the present design value.

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 need for a dewar, refrigerator and liquid helium distribution system presents an economic burden

which must be compensated for, not only by savings in the construction cost due to the smaller tunnel size, vacuum equipment, and other field-dependent items, but also by savings due to reduced operating cost from the lower electric power consumption. A comparison of the ISA with the low-luminosity conventional magnet ISA described in Section XVIII shows that the initial capital expenditures would be, at most, 10% less for the conventional magnet ISA. The annual electric power consumption, on the other hand, is clearly in favor of the superconducting machine: 35 GWh versus 90 GWh/year. Performance and economical considerations point towards the superconducting solution. In arriving at a decision the advantages must be balanced against the risk inherent in the application of a new technology. Superconducting magnet technology has advanced to the point where the performance of magnets, i.e. their peak field, field quality, and random errors due to fabrication tolerances, can be predicted with an accuracy equal to that for conventional magnets. Questions regarding the behavior of superconducting magnets in radiation environments have been proven manageable based on the experience gained from the operation of the 8° bend in the high-intensity proton beam to the North Area of the AGS. Refrigeration systems of the capacity required have demonstrated their reliability in commercial use. It is our judgment that the technical know-how for the execution of this proposal is at hand. Further advances in this field, conceivable in time for the construction of the ISA, are anticipated from the development of materials of the Al5 type such as Nb_3Sn or V_3Ga . These would be translated into an increase of the energy in each ring to about 300 GeV and a further reduction of the electric power consumption without changing essentially the financial scope of the project. The prospects for the new materials are discussed in Section VI-2.

3. General Description and Main Parameters

3.1 Ring Structure

The storage accelerator proposed consists of two intersecting magnet rings located one above the other in a common tunnel with a total circumference of 2690 m or exactly $3 \frac{1}{3}$ times the circumference of the AGS. The configuration of the ISA is essentially that of a circle expanded by four symmetrically located experimental straight sections in which the beams are brought together in horizontal small-angle or collinear collision regions. 28.5 GeV proton from the AGS will be ejected into the beam line 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. II-1. 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 complete four-fold symmetry. The regular part of the ring contains 48 normal cells. The regular cell structure is broken into octants by adding four 250 m long (200 m straight) experimental insertions and four 110 m long (50 m straight) service insertions with the latter satisfying the machine requirements of injection, fast protective ejection, rf system, etc. The vertical separation of the beams will be 46 cm, allowing a common dewar for the magnets of the upper and lower rings. On the other hand, both rings are electrically and magnetically separate to permit experiments with unequal energies and to accommodate the antiproton option. The normal cell uses a simple FODO sequence with two 4.25 m long (iron face-to-face) dipoles and one 1.3 m long (iron face-to-face) quadrupole per half cell. The total length of a normal cell is 25.40m, implying a distance between magnets of about 1 m. The maximum amplitude function, horizontally and vertically, is $\beta_{\max} = 43 \text{ m}$ and the maximum horizontal momentum dispersion is $X_p = 1.7 \text{ m}$ in the normal cell. The service insertions are fully matched to the regular lattice and exhibit zero dispersion in the center while keeping the amplitude function at low values,

Fig. II-1. ISA site plan.

$$\beta_{vmax} \leq 110 \text{ m.}$$

Conflicting design requirements prohibit the use of a unique insertion for all experiments and a number of fully-matched experimental insertions have been worked out in detail: a general purpose modest-beta insertion, a high luminosity low-beta insertion, a small-angle elastic scattering insertion, and a multipurpose spectrometer insertion where the beams interact within a bending magnet. Initially, during the commissioning of the ISA, four general purpose modest-beta insertions ($\beta_v^* = 6 \text{ m}$) will be installed to keep β_{max} to safe values, say below 300 m. Luminosities of $5 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ at each crossing point should be achievable. In these insertions the crossing angle is adjustable from 0 to 6 mrad by means of horizontal steering magnets. To achieve the design luminosities a low-beta insertion ($\beta_v^* = 2.2 \text{ m}$, $X_p = 0 \text{ m}$) will be required imposing higher β_{max} and larger chromaticity. Further improvements in luminosity resulting from an even lower beta (the theoretical optimum is $\beta_v^* = 0.7 \text{ m}$) and shorter free space between magnets, down to 20 m, are conceivable. The concept of flexibility in the design of the experimental insertions, which is highly desirable from the user's point of view, will be made possible by a corresponding flexibility on adjustment of the tune and a complete control over the working line.

3.2 Beam Transfer

A number of schemes for transferring the 28.5 GeV AGS beam to the ISA have been studied. 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 400 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, is not the limiting condition. (See Section X-6.)

The beam transport equipment from the AGS to the ISA is more economical if conventional magnets are used 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 below 100 Ω . This can be achieved by an appropriate feedback system. The AGS pulse, with its intensity reduced to 2.3×10^{12} protons in 10 bunches from the nominal 10^{13} value, is captured directly by the stacking system, decelerated, slowly debunched and deposited into the unbunched stack. The AGS pulse fills only a fraction (1/4) 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 (or 5.6×10^{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 dimensions 2.0 cm horizontally and 0.8 cm vertically. Possible limitations of the intensity of the stacked current due to coherent transverse instabilities, the beam induced pressure rise, and the methods to avoid these

limitations, will be discussed in Sections V and IX.

3.3 Acceleration System

In order to accelerate the stacked beam it will be rebunched by an rf system operating at the second harmonic, $f = 223$ kHz. Adiabatic rebunching can be done, in principle, without phase-space dilution or loss of particles. The 700Ω impedance of the acceleration rf system, however, necessitates a rebunching in the relatively short time of about 100 msec and some degradation of the beam must be expected (note that the accelerating gaps are shorted during the stacking procedure). The peak rf voltage, which is determined by the momentum spread of the stacked beam to be 40 kV, is provided by ferrite loaded cavities. The energy gain per turn of 12.5 keV during the 2 minute acceleration cycle is well within the capabilities of the rf system.

No insurmountable difficulties with accelerating the beam of 10 A are expected. The choice of the 2nd harmonic should make the beam stable, in first order, against longitudinal bunched beam instabilities.⁴ Estimates of the transverse resistive wall instability indicate that the bunched beam will remain stable if the unbunched beam was stable. Diffusion from a repeated crossing of the 5th order resonance during the acceleration cycle was numerically computed and found to be inconsequential, 3rd or 4th order resonances must, however, be avoided at all times, even when the momentum spread (and tune spread) is increased to about 2% as a result of the bunching.⁵ After the acceleration cycle, the rf is switched off, the cavities are shorted again, and the beam is allowed to debunch, retaining the 0.3% momentum spread of the bunched beam.

3.4 Superconducting Magnet and Dewar System

A program to develop superconducting magnets for use in accelerators and beam transport lines has been going on at Brookhaven for ten years. This has led to the construction of

dipole models which satisfy most of the important design criteria of the ISA magnets. The experience gained from the two identical 1 m long ISA models and the two 1.8 m long dipoles for the so-called 8° bend used in the extracted primary proton beam line to the AGS neutrino area will be described in detail in Section VI. As will be substantiated there, the results have provided conclusive information concerning the question of stability, magnetic field precision (i.e. systematic errors), reproducibility (i.e. random errors), reliability, and behavior in a radiation environment.

Stability of the magnets, with the absence of quenching (transition to the normal state) or training effects (higher fields can be reached only after repeated quenching), is essential in the application of superconducting magnets to accelerators. The Brookhaven magnets have shown a remarkable degree of stability and, in fact, operation in the resistive region above the short sample critical current, defined by a resistivity of 10^{-12} Ω -cm, has been possible.

Systematic deviations from field uniformity (actually, the dipoles will need a sextupole term for adjustment of the chromaticity) must be avoided at all field levels encountered during operation (6 kG to 40 kG). It is required that the prescribed field shape of the magnets is accurate to within a few parts in 10^5 over the entire aperture of the vacuum chamber (8 cm diameter which represents 67% of the magnet coil aperture). Systematic 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 eddy currents. Saturation and magnetization effects are field dependent and require special attention. The results from the various models indicate that a single sextupole tuning coil is sufficient to compensate all important systematic errors. Additional tuning coils are provided to adjust the machine working line; their strength and size will be discussed in Section IV-4.

Random errors, or deviations from magnet to magnet, are caused mainly by the necessary fabrication tolerances in the position of the conductors and in the concentricity of the coils in the iron shield, by a nonsymmetrical gap in the median plane of the iron shield, and possibly other causes. 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. Measurements confirmed that these tolerances can be achieved with the particular construction technique employed, but that the concentricity of coils in the iron shields needs to be improved. Multipurpose correction windings will be installed in all magnets to provide compensation of random field errors, at least up to the decapole component.

The reliability of superconducting magnets, that is, the absence of changes over long operating periods or changes due to thermal cycling, is being tested in ongoing life test; after 5000 pulses, simulating 10 years of normal ISA operation, no indication of changes has been detectable.

The effects of radiation on the materials used in the magnet construction are discussed in Section VI-2. 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.⁶ Epoxy-impregnated fiberglass, 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 the 8⁰ bending magnet has demonstrated that a properly cooled magnet is able to withstand a fair amount of beam heating without destruction of the superconducting state. An accidental beam spill of the entire stored beam may 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 5.9 kG. Here the temperature reserve of the superconductor against quenching is greatest.

The study of the recent literature on superconducting magnets proves that a number of different designs have been employed successfully. At Brookhaven two alternate styles, the window-frame and the cosine θ magnet, have been investigated. In order to be definite, the design and cost estimate of the ISA have been based on the cosine θ magnet. It is well known that a pure dipole field is provided 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, of different azimuthal widths, but equal conductor current density. Exact positioning of the blocks is determined in a way to suppress the six lowest harmonics. The current blocks are built up with a single layer of wide flat braid (about 2.1 cm $\times$ 0.05 cm). The braid is composed of roughly 100 twisted composite wires, 0.3 mm in diameter, each containing, typically, 400 superconducting NbTi filaments of 10 μ diameter. The wires in the braid have a CuNi jacket to increase the coupling resistance between wires and thus decrease eddy current effects to tolerable levels during pulsing. The iron core tightly surrounds the coil and, as an integral part of the construction, must also be at liquid helium temperature. The physical length of the dipoles is 4.25 m, that of the quadrupoles is 1.3 m. The inner diameter of the coil is 12 cm, the outer diameter of the iron is 41 cm. The stored energy per dipole is 465 kJ at 40 kG, there are 256 dipoles per ring, and the total stored energy is about 120 MJ per ring. 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 of the vacuum chamber at 200°C.

Two magnets, one from the upper and one from the lower ring, will be contained in one dewar. This configuration has the

advantage that all vacuum joints are directly accessible for leak tests at room temperature. 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 one octant of the ISA ring. In this arrangement, the current in the dipoles can be chosen almost arbitrarily. In the ISA dipole it is 3.3 kA at full field, 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 magnet, current leads which are connected to shunting diodes. Since these leads are normally not in use, they can be designed for lower current carrying capacity (here 1000 A). The quadrupoles will be designed for a current of 500 A at the highest gradient of 6.6 kG/cm and a pair of leads for each quadrupole is foreseen.

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 this country 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. The reduced current carrying capability (67%) of NbTi at 60 kG results in a larger superconductor and thus increased cost. But, since the superconductor represents only a 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 this concept for 60 kG magnets. The prospects for early development of new superconducting materials, such as Nb_3Sn or V_3Ga 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 Nb_3Sn versus 9.5 K for NbTi) makes operation at temperatures in the range from 8 - 9 K possible, resulting in a substantial savings in the capital cost and electric power consumption of the refrigeration system.

Second, the critical current of these materials is higher by an order of magnitude, considerably simplifying the design of 60 kG magnets. Filamentary Nb_3Sn or V_3Ga wires are not yet available commercially in the U.S. because these compounds are brittle and must be fabricated in ways different from the drawing process used for NbTi . A diffusion technique has been developed at Brookhaven with which conductor samples have been produced.

The ISA CP & D funds requested for FY75 would be used for the construction of two full-size dipoles (4.25 m length, 12 cm coil aperture) and two quadrupoles (1.3 m length, 12 cm aperture) which will be mounted in dewars, one above the other, as in the ISA design. This system will simulate a section of the ring and will contain all the auxiliary hardware such as correction windings (see Section VI-4) and vacuum equipment. The ongoing program at BNL projects the construction of superconducting magnets for the High Energy Unseparated Beam to the Multiparticle Spectrometer. Four 2.5 m long dipoles and four 1.5 m long quadrupoles, all with a 20 cm warm bore aperture, will be required by July 1975. In addition work on 60-kG dipoles of the window-frame type will continue. The development of Nb_3Sn conductors will be emphasized and the construction of a 1 m long dipole model using this material has been initiated. First results from Nb_3Sn magnets are expected in less than a year. A final decision on the choice of magnet can be delayed until one year after approval of the project without affecting the orderly progress of the construction.

3.5 Refrigeration System

All components of the refrigeration system required to generate the cold environment for the superconducting magnets are conventional as to their design, 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 magnets is specified at ≤ 4.5 K which can only be achieved by pool boiling of liquid helium. Some consideration has been given to the optimum choice of the operating temperature. Earlier studies⁷ 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 20 kW, of which only 15% represents excitation-dependent ohmic losses. The total refrigerator capacity of 23 kW is provided by a system consisting of a central, six-unit, four-stage compressor station and eight 2.9 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 9.5 MW with J-T valves or 7.5 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 136 000 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 1.8 MJ during the quench will result in the evaporation of 800 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 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 would evaporate, in a short time, over 8000 liters of liquid helium which could not be recovered.

3.6 Magnet Power Supply

The demands on the magnet power supply are modest as a result of the slow 2-minute acceleration cycle. The total energy stored in the bending magnets of each ring is about 120 MJ. Therefore, a 2 MVA rated power supply is adequate. With the peak dipole current of 3.3 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 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. The large total stored energy makes it important to include fault protection in case of a magnet quench. For this purpose shunting power diodes will be included across the magnets in each dewar. Their operating point is below their voltage threshold for current conduction, under normal operation, but provides a current path in case of a quench.

3.7 Vacuum System

The density of residual gas molecules in proton storage rings must be lower, by several orders of magnitude, than in conventional accelerators. This is necessary to reduce beam blow-up from multiple Coulomb scattering or inelastic nuclear scattering and the accompanying background radiation. The design, therefore, calls for a pressure of 10^{-10} Torr in the circular quadrants of the ring and 10^{-11} Torr in the experimental insertions. Electrons and negative ions trapped in the Coulomb field of the beam must be removed with suitable clearing electrodes.

Experience with the CERN ISR shows that the most serious current limitation is set by the beam induced pressure rise (pressure bump phenomenon). Qualitatively, this effect is caused by ionized residual gas molecules being propelled electrostatically against the vacuum chamber thus liberating adsorbed molecules in sufficient quantity to increase the gas pressure. At some value of the current, this pressure rise leads, avalanche-like, to 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 theory yields the limit $\eta I_{\text{crit}} \leq 30 \text{ A}$ where η is the desorption coefficient. The desorption coefficient of typical chamber materials at room temperature depends, predominantly, on the bake-out temperature and the surface condition. A

desorption coefficient of $\eta < 3$ (permitting $I > 10$ A) is expected with a bake-out temperature of 200° C and an argon discharge cleaning prior to assembly. The use of a vacuum chamber operating at liquid helium temperatures has been considered but abandoned in view of experiments indicating desorption coefficients of several thousand.⁸ Experiments to simulate the pressure bump effect are in progress and will allow an early verification of the assumptions used in the design of the ISA vacuum system.

The ISA vacuum chamber will be made of aluminum whose good thermal conductivity will prevent cold spots in the center of the cold magnets. The good electrical conductivity will alleviate resistive wall instabilities. The pumping will be provided by conventional Ti-sublimation pumps and ion-sputter pumps for non-getterable gases. The dewar construction provides direct access to all vacuum joints and pumps resulting in an almost conventional ultra high vacuum system.

3.8 Control 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 carefully designed 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. An illustrative description of the proposed control system is given in Section XII.

3.9 ISA Shielding

Many of the considerations regarding the shielding requirements of conventional accelerators are equally applicable to storage

rings. There are, however, important differences which have to be taken into account in the layout of the ISA shielding. The basic requirements are that machine components will not be damaged by radiation and that a person outside of the shield will not receive a radiation dose exceeding 100 mrem in the worst case of 10^{15} protons dumped at any point. This will be satisfied by an earth cover extending to 160 m in any tangent direction in the plane of the accelerator and by providing 6 m of earth in any transverse direction. The skyshine dose equivalent at the site boundary has been estimated to be 10^{-3} mrem per 10^{15} protons dumped. It is concluded that an off-site point would never accumulate the permissible annual dose of 1 mrem. At the end of its useful life span of, typically, one day the beam will be dumped in a controlled fashion into a beam stop consisting of a metal block shield 4 m long and 1 m wide. Special requirements in regard to shielding, which are not related to safety considerations, will exist in the experimental areas, and will be worked out after the machine has been put into operation.

3.10 List of Main Parameters of the ISA

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

Table II-1. Main ISA Parameters

FINAL ENERGY	200 x 200 GeV
- Equivalent Accelerator	86 TeV
LATTICE (four-fold symmetry)	
- Circumference ($3\frac{1}{3} \times C_{\text{AGS}}$)	2690 m
- Experimental insertion length (straight)	4 x 250 (200) m
- Multipurpose insertions (straight)	4 x 110 (50) m
- Normal cell length	48 x 25.40 m
- Vertical distance between orbits	0.46 m
- Distance between magnets D-D (iron-iron)	0.90 m
- Distance between magnets D-Q (iron-iron)	1.0 m

GENERAL PURPOSE EXPERIMENTAL INSERTIONS

(Horizontal crossing, adjustable parameters)

- β_v^*	2-6 m
- β_h^*	5-10 m
- Maximum β	1000 - 300 m
- Total Free space around crossing point	40 m
- Crossing angle	0-6 mrad
- Interaction length	<1 m

MAGNET SYSTEM

- Bending field at 200 GeV	40 kG
- at 28.5 GeV	5.9 kG
- Number of normal dipoles/ring	256
- Dipole length magnetic	4.11 m
- physical (iron-iron)	4.25 m
- Peak current in dipole	3.3 kA
- Stored energy @ 40 kG/dipole	465 kJ
- Vacuum chamber aperture (warm bore)	8 cm
- Main coil i.d.	12 cm
- Operating temperature (pool boiling)	≤ 4.5 K
- Number of normal quadrupoles/ring	88
- Quadrupole gradient	6.6 kG/cm
- Peak current in quadrupole	500 A
- Stored energy/quadrupole	30 kJ
- Quadrupole length magnetic	1.16 m
- physical (iron-iron)	1.30 m

CRYOGENIC SYSTEM

- Total heat load at 4.5 K	≈ 20 kW
- Total refrigeration capacity	8 x 2.9 (23.2) kW
- Power requirement of compressors	7.5 MW
- Total liquid helium	136 000 liter

INJECTION

- AGS energy	28.5 GeV
- Number protons/AGS pulse (10 bunches)*	2.3×10^{12}
- AGS emittance $\epsilon_h = \epsilon_v$	$0.4 \pi \times 10^{-6}$ m.rad
- Longitudinal phase space per bunch, A	0.36 eV.sec
- ISA current/ring	10 A
- Number protons/ring	5.6×10^{14}
- Number AGS pulses stacked/ring	= 250
- Stacked beam size	2.0 cm x 0.8 cm
- Momentum spread	0.7 %
- rf frequency stacking system	4.45 MHz
- rf voltage	12 kV
- Impedance (with feedback)	400 (40) Ω

ACCELERATION

- Duration	2 min
- rf frequency (h = 2)	223 kHz
- Energy gain/turn	12.5 kV
- Peak rf voltage	40 kV
- Momentum spread at 200 GeV	0.3 %

LUMINOSITY

L_{pp} (200 GeV, unbunched, $\beta_v^* = 2$ m, $\Delta v_{max} = 5 \times 10^{-3}$)	$10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$
- $\bar{p}p$ option, L_{pp}/L_{pp}	$= 10^{-4} \text{ cm}^{-2} \text{ sec}^{-1}$
- dp option, L_{dp}/L_{pp}	= 0.7
- dd option, L_{dd}/L_{pp}	= 0.7
- ep option	
Maximum e-energy	15 GeV
Number of electrons	8.2×10^{12}
Maximum luminosity @ 7 GeV-electrons	$10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$
Luminosity @ 15 GeV-electrons	$5 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$

*The AGS beam intensity is reduced, for ISA injection, from its normal value of nominally 10^{13} protons per pulse.

4. 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. Electrons would first be accelerated to 4 GeV in the AGS. They would then be accelerated to 15 GeV, providing high center-of-mass energies for ep collisions. This second acceleration would occur in an electron ring located inside the ISA tunnel or, to minimize interference with the ongoing pp work, in a separate ring to the east of the ISA. Another more economical possibility is to accelerate the electrons in one of the ISA rings. The vacuum chamber in one, or perhaps both, ISA rings would be designed to allow water cooling on one side to carry away the large amounts of energy radiated from the electron beam. However, further studies are required to ascertain the feasibility of this approach. It is estimated that the luminosity of ep collisions would be greater than $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ at electron energies up to 7 GeV and then drop to $5 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$ at the maximum electron energy of 15 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 problems and would make it possible to study proton-neutron and neutron-neutron cross sections, with luminosities of about $7 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$. Antiprotons can be produced by using one ring as a 200 GeV accelerator and the other as a storage ring, providing $p\bar{p}$ collisions with a luminosity approaching $10^{29} \text{ cm}^{-2} \text{ sec}^{-1}$.

4.1 Electron Option

The future availability of 15-GeV electrons at the 200 GeV proton facility would open up important opportunities for the study of electromagnetic interactions, including deep inelastic ep scattering, and broaden the study of weak interactions. Center-of-mass energies of up to $\sqrt{s} = 109 \text{ GeV}$ could be reached in ep

collisions. In view of the synchrotron radiation from curved electron orbits and the low magnetic fields required it is desirable to use conventional magnets in the electron ring, although it is conceivable that the ISA magnets could be modified to accommodate electrons. An additional electron ring, the circumference of which is about 2000 m, could be located in a separate tunnel to the east of the ISA, on the level of one of the proton rings. Alternatively, it could be placed inside the ISA rings or even in the ISA tunnel if the latter would be enlarged to accommodate the third ring. To minimize the downtime of the proton complex during the construction of the electron ring, and to permit easy transition from ep to pp experiments, a bypass scheme is suggested which would bring the electron beam to one (or two) experimental insertions in the ISA rings, with the possibility of two (or four) ep collision regions. With a 400 MHz rf system delivering 6 MW one can accelerate and store about 200 mA with 8×10^{12} electrons at the highest energies. The AGS could serve as an injector of 4 GeV electrons by installing a 400 MHz rf system with a peak voltage of 400 kV and by adding a typical 200 MeV electron linac as a preinjector. The luminosity for ep collisions is beam-beam limited to values of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ at electron energies below 7 GeV and declines to $5 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$ at the maximum electron energy of 15 GeV because of rf power limitations.

4.2 Deuteron Option

Preliminary tests for deuteron acceleration in the first tank of the AGS linac have been carried out successfully⁹ and give confidence that a 25 mA beam of 30 MeV deuterons can be injected into the AGS. The installation of an additional rf cavity in the AGS, to cover the expanded frequency range (0.79 to 4.8 MHz for acceleration on the 12th harmonic), would permit the acceleration of about 1.8×10^{12} deuterons per pulse. It is estimated that the longitudinal and transverse phase spaces of the deuteron pulse equal those of the protons. Thus, about 4×10^{14} deuterons, or 7 A,

can be stacked and accelerated in the ISA. Maintaining a maximum permissible tune shift of $\Delta\nu = 5 \times 10^{-3}$, by adjusting the crossing angle, luminosities of about $7 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ are obtained both for dd and dp collisions.

4.3 Antiproton Option

A straightforward method to produce antiprotons consists of bombarding an external target with 200 GeV protons. Protons are accelerated to 200 GeV in one of the rings and are extracted into a bypass during flat top. 30 GeV antiprotons from a target placed at a low- β point in this bypass are transported to the second ring, where they are injected, stacked and accelerated to 200 GeV. Protons are now stacked in the first ring in the opposite direction, accelerated to 200 GeV and made to collide with the antiprotons. The antiproton yield¹⁰ for a primary proton energy of 200 GeV has a plateau around 30 GeV with a differential cross section $d^2\sigma/d\Omega dp = 0.5 \bar{p}/\text{interacting proton/sr/eVc}^{-1}$. Assuming a permissible momentum spread of 2.5%, and a transverse acceptance of $2\pi \times 10^{-6} \text{ m.rad}$ in both planes, approximately 4×10^{10} antiprotons of 30 GeV can be stacked in one ring. The luminosity is limited by the beam-beam interaction to values approaching $10^{29} \text{ cm}^{-2} \text{ sec}^{-1}$.

The hardware required for the antiproton option is modest:

- i) A beam extraction system for 200-GeV protons; ii) a room temperature beam transport system to bring the antiprotons to the point where protons are ordinarily injected; iii) an injection system with a kicker that is faster (150 nsec) than the kicker needed for proton injection, but which is well within the present state of the art; iv) an rf system operating on the 10th harmonic (1.12 MHz) and capable of a peak voltage of 150 kV to accept the 2.5% momentum spread of the antiproton beam. As a consequence of the low $\bar{p}$ intensity, a high rf cavity impedance can be tolerated, resulting in low power demands. The main constraint imposed on the ISA design stems from the necessity to invert the magnetic

field in the rings used for the acceleration of the primary protons. This eliminates configurations which couple the magnetic fields of both rings. It also must be mentioned that the target will explode from the exposure to 6×10^{14} protons and will have to be replaced after each pulse.

Other, more exotic, methods to increase the antiproton intensity have been investigated. In principle, the decay in flight of Λ^- inside the ISA ring avoids the constraints of Liouville's theorem and high $\bar{p}$ densities could be achieved.¹¹ It is, however, difficult to find a practical arrangement in which this method could be used. Another approach to higher $\bar{p}$ intensities is stochastic cooling, which probably is noise limited and it is not clear if this method would turn out to be useful.¹² Budker's scheme of electron cooling has also been considered, but improvements over the simple system described are unlikely.¹³

5. An Intermediate Step Towards the ISA

A preliminary design study of a 100 GeV storage ring has been carried out in sufficient detail to provide the information required for a rough cost estimate. In a situation where available funds limit the size of a project, it may be necessary to consider a proton storage ring of lower energy and lower luminosity. The minimum energy of the next generation proton storage rings must be adequate to test the region where the strength of weak and electromagnetic interactions are about equal. From the discussion in Section III it follows that an ISA capable of 100×100 GeV, at a luminosity of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, is fully justifiable in terms of the physics as presently understood and a natural step towards a superconducting 300 GeV ISA. The particular design was done for a storage ring using the ISA tunnel. It is, therefore, natural to use conventional magnets at about 15 kG, with the exception of the 70 or so dipoles in the experimental insertions which should be superconducting to assure an optimum insertion design. Further details of the 100 GeV design are presented in the Appendix.

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III. PHYSICS JUSTIFICATION FOR THE ISA AND IMPLEMENTATION OF EXPERIMENTAL PROGRAM

1. Introduction

From the theoretical point of view the prospect of center-of-mass energies at the ISA, an order of magnitude higher than those presently available, is immensely exciting. Quite apart from the general expectation that such a significant energy increase will lead to new and (judging by experience of earlier accelerators) probably quite unexpected phenomena, our present theoretical ideas point to many crucial questions which the ISA may help to answer.

Many of these questions are associated with attempts to unify the weak, electromagnetic, and strong interactions, which have usually been considered as manifestations of separate forces and discussed as separate problems. Increasingly, over the past few years,¹ the weak and electromagnetic interactions have been brought into the same framework, starting with the conserved vector current hypothesis and developing into the extensive work on non-Abelian gauge theory models. This common behavior is masked at low energies because of the high mass of the weak boson compared with the zero mass photon, but it may be expected to emerge more clearly in experiments where the energy is high enough.

More recently, the possibility has arisen of viewing the strong interaction as arising in a closely connected manner. Part of the motivation for this comes from the rather mystifying success of the quark model at describing hadron excitations and the weak and electromagnetic interactions of hadrons, especially in the context of parton models. The absence of free quarks cannot be so easily explained and no firm dynamical basis exists. The idea of "asymptotic freedom",² in which the hadronic interactions at extremely high energies (or short distances) become more and more like those of elementary free fields, provides one possible route out of this impasse and points clearly to the importance of studying hadronic interactions at the highest available energies.

While verification and exploration of these ideas is vitally

important, the study of extremely high energies and momentum transfers is exciting on a much more directly phenomenological scale. Already, at ISR energies, we have seen the rising proton-proton total cross sections, and the qualitatively new behavior of high transverse momentum phenomena. No theory of elementary particle interactions can seriously develop without discovering how these phenomena change as the energy increases.

In discussing in more detail the prospective information to be gained from the ISA it is convenient to maintain the conventional division into strong, weak, and electromagnetic forces, while recognizing the ultimate goal of understanding their origin in a unified way.

It is only a slight oversimplification to say that the questions which we hope to answer for each of these forces are:

- (i) What are the particles which interact?
- (ii) What is their internal structure and excitation spectrum?
- (iii) What are the entities whose exchange causes the interaction?
- (iv) What is the manner in which these exchanges take place?

For the electromagnetic interactions questions (i), (iii) and (iv) are reasonably well understood, as all charged objects interact predominantly by single photon exchange. The electromagnetic structure functions, reflecting the internal charge structure of the hadrons, remain of considerable interest. In particular they have not been explored well in the large time-like region.

In the case of weak interactions, the major questions seem to be (i) and (iii), in the light of recent developments which have led to the prediction of new intermediate vector bosons and/or heavy leptons. At existing energies, however, the main features of the weak interactions are well described by low order perturbation theory and it remains the task of the theorist to understand how such simple experimental answers arise.

For the strong interactions all questions remain open, although great progress has been made at AGS energies towards classificati..

at least of the answers to question (i) in terms of multiplets and Regge trajectories and at SLAC and all the proton accelerators towards some understanding of (ii). The nature of the forces in hadronic interactions remains obscure. It is possible, in two-body processes, to associate particular phenomena with the exchange of quantum numbers corresponding to a given Regge trajectory and talk about π or ρ exchange, but that is so far only a label, not a clear dynamical prescription. Still less is understood of the nature of the vacuum exchange, or Pomeron, the dominant process at high energies. When we consider multiple production processes we do not, as yet, have even unique qualitative models.

In strong interactions, for at least some of the points mentioned above, the relevant energy scale is logarithmic. Thus an important aspect of the increase from ISR to ISA energies is the increase of two units in the natural logarithm of the center-of-mass energy.

2. Theoretical Implications

2.1 Large transverse momentum phenomena

Reactions in which particles emerge with a large amount of momentum perpendicular to the beam direction are particularly important in gaining information about the internal structure of hadrons.³ Indeed, the deep inelastic electron-scattering data from SLAC have given such information concerning internal structure. Corresponding information about the possible existence of constituents is needed from hadron collisions at higher energies where, in addition, the short range interactions between the constituents can be studied.

It is clear that, in a general way, interactions with a large transverse momentum in the final state carry information about large momentum components within the colliding particles. Exchange of longitudinal momentum can always come, in principle, from a coherent slowing down of the colliding particles, since considerable relative momentum is present before the collision, while the transverse momenta must correspond to internal momentum components.

In order to obtain large transverse momenta, $p_{\perp}$, in the first

place, high energies are needed because of energy conservation. However, since it is known empirically that cross sections fall off very rapidly with increasing $p_{\perp}$, it is not possible to reach the maximum possible $p_{\perp}$ at high energies. The motivation for seeking higher energy measurements at large $p_{\perp}$ lies, instead, in the prospect of checking scaling, as one of the ways of understanding whether the small distance structure of hadrons resembles that of an assembly of structureless points. The assertion is that the cross section dependence on the variables, s (the square of the center-of-mass energy) and $p_{\perp}$, is essentially determined by the variable $x_{\perp} = p_{\perp}/(s)^{\frac{1}{2}}$, apart from a simple power law dependence on s . To check this it is necessary to explore wide regions of $p_{\perp}$ and s at fixed x and this requires high energies. Figure III-1 shows the accessible region in $x_{\perp}$ as a function of s : accessible signifying those regions where $p_{\perp}$ is large enough to believe scaling sets in, but small enough to expect a measurable cross section.

Once scaling has been established it is then necessary to determine the shape of the scaling function. Figure III-2 shows the predictions of different phenomenological fits at lower energies⁴ which are all consistent with the current data and scaling but differ markedly at ISA energies. Estimates of the weak and electromagnetic constituents are shown for comparison.

2.2 Total and elastic cross sections

A striking result from the ISR has been the observation that total cross sections rise by something like 10% from AGS to maximum ISR energies.⁵ This has stimulated a large number of attempts to fit the rise into some dynamical model.⁶ In some pictures the rise is the beginning of an asymptotic phenomenon in which $\sigma(s)$ increases like $\log s$ or $\log^2 s$. In others what is being seen is a destructively interfering "Regge cut", giving a negative term decreasing as $(\log s)^{-1}$. Still other pictures explain the rise as due to a threshold effect for excitation of baryon-antibaryon pairs, or multipion clusters, the moderate mass of the excitation combining with a production mechanism requiring small four-momentum transfer ($\sqrt{t}$) to produce an effective threshold at very high energy.

Fig. III-1. Kinematic regions for testing large transverse momentum scaling. The upper cutoff is estimated on the basis of curve (b) of Fig. III-5a.

Fig. III-2. Transverse momentum scaling predictions for large $p_{\perp}$ cross sections. For comparison, the dotted line gives the cross section which, at $L = 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$, would result in one event per hour for a typical experimental setup. Curves (a), (b), and (c) are extrapolations from existing data. Curves (d) and (e) are estimates based on the BNK model.

To distinguish which of these or other types of behavior actually represent the extrapolation in energy will be an important clue to understanding the dynamics of the proton-proton interaction, whether or not the explicit models survive. Figure III-3 shows several different fits to the existing data extrapolated to ISA energies.

The behavior of the elastic cross section also awaits more information from higher energies. One of the fundamental quantities to be measured is the slope of the forward diffractive amplitudes, or the effective inverse radius squared of the proton. Whether or not this slope parameter ultimately becomes independent of energy or whether it attains an asymptotically linear increase can help to distinguish between models in which the diffraction peak is associated with the shape of the matter distribution in the proton which is being scattered,⁷ or with the nature of the exchanged objects responsible for the interaction. At ISR energies this forward diffractive slope is very close to the corresponding slope of the fourth power of the electromagnetic form factor at $t=0$ (Fig. III-4). If the hadronic and electromagnetic matter distribution in the proton is the same the shrinkage should stop: if the shape of the diffraction peak instead is associated with the exchange mechanism then some kind of continual shrinkage should occur.

The other striking feature of the elastic scattering is the sharp dip seen at $t = -1.5 \text{ (GeV/c)}^2$ which appears to have very little energy dependence in shape or position over the ISR range.⁸ Is this a multiple scattering or diffraction minimum or some other phenomenon? Appreciable increases in energy on a logarithmic scale will be required to test whether the dip position is really fixed or whether it moves logarithmically as would be expected from certain Regge pole cut interference interpretations.

2.3 Multiparticle phenomena

Probably the richest field in this energy region is the exploration of multiparticle phenomena. Here, again, the increases from AGS to ISR energies has revealed systematic changes which now provide a yardstick with which to calibrate projected behavior at ISA energies in different models.

Fig. III-3. Predictions for total cross section extrapolated from ISR fits.

Fig. III-4. Energy dependence of elastic diffraction peak slope parameter.

The gross features of the single particle spectra according to our current ideas are simply described in terms of the center-of-mass rapidity. (The rapidity of a particle is a dimensionless measure of longitudinal velocity equal to the inverse hyperbolic tangent of the ratio of its longitudinal momentum to its total energy.) For pions produced in pp collisions the distribution is flat for rapidities of small magnitude (the central region) and falls to zero as the rapidity approaches that of either incident particle (the fragmentation regions). At AGS energies the central region does not exist; at the ISR it occupies only one quarter of the available range while in the remaining fragmentation regions the cross sections closely resemble the corresponding ones at lower energies. Whether the central region continues to grow and whether the fragmentation regions continue to scale are important questions in understanding the dynamics of particle production. See Fig. III-5.

Many dynamical models incorporate the idea of short range "correlation" in the central region, i.e. the assertion that the production of two different particles takes place independently unless their separation in rapidity is sufficiently small. Evidence from two particle production at the ISR is quite suggestive and a typical correlation length observed is indicated in Fig. III-5(a). Evidently, with such a short central region at the ISR, it is difficult to draw any firm conclusions.

The validity of the concept of Regge poles, factorization, and the existence of triple Regge couplings are all questions which require information on single particle inclusive cross sections, at high enough energies to extract leading behavior. As remarked above, the relevant variable is the logarithm of the energy and in order to sort out the energy dependence it is essential to look over a range of several units in $\log s$.

2.4 Weak and Electromagnetic Processes

The primary weak or electromagnetic interaction processes in proton-proton collisions are the production of lepton pairs. Such experiments observe the emission of an electromagnetic or weak current carrying time-like four-momentum and decaying into a lepton

Fig. III-5a. Pion rapidity range in center-of-mass system. Shaded bars indicate central region defined by requiring deviations from the leading term less than half the measured cross section.

Fig. III-5b. Regge fit to ISR data extrapolated to higher energies. Data shown are for $\sqrt{s} = 31$, except the open circles are rescaled from $\sqrt{s} = 6.8$.

pair: (e^+e^-) or $(\mu^+\mu^-)$ in the electromagnetic case and $(e\nu)$ or $(\mu\nu)$ in the weak case. If there are neutral weak currents they would, in principle, contribute $(\mu^+\mu^-)$, (e^+e^-) , and $(\nu\bar{\nu})$ pairs, but these contributions are not of any current experimental relevance (except for some interference effects).

If heavy leptons exist, as suggested by several classes of theories,¹ then they, too, could be produced in such pairs. It would be a major discovery to observe such a phenomenon and the higher the available center-of-mass energy, the more phase space is available for production of higher masses. Except for very specific models there is no way of estimating what the expected energy range should be.

The possible observation of the intermediate charged vector boson is subject to slightly more quantitative considerations. From a number of different points of view, the idea that weak and electromagnetic processes are of the same intrinsic strength and are, in fact, closely related seems extremely attractive (even if the dynamical theories necessary to describe the consequences are only tentative at present.) As an order of magnitude estimate this suggests that the Fermi coupling constant should be related to the fine structure constant: $G_F \approx 4\pi\sqrt{2} \alpha/m_W^2$; whence it follows that $m_W^2 \approx 4\pi\sqrt{2} \alpha/G_F = 4\pi\sqrt{2} (10^5/137)m_N^2$ where m_N is the nucleon mass. We thus arrive at a figure of about $106 \text{ GeV}/c^2$ for the mass of the W. Clearly this is not an exact argument and we can expect kinematic or group theoretical factors to modify the number as is indeed the case in specific models. However, it suggests that center-of-mass energies in excess of 100 GeV are likely to be needed, and that, in fact, the failure to observe W production at center-of-mass energies much larger than 100 GeV would cause difficulty for theories of this class.

Even without the discovery of new weakly interacting particles there remains great interest in such processes. Deep inelastic electron scattering experiments have given strong indications of scaling behavior for the absorption of space-like virtual photons.

Such behavior provides information about the small scale space-time properties of matter. In particular, the scaling behavior associated with space-like electromagnetic currents has given rise to models of point-like constituents for the hadrons.⁹ Many models can fit the observed features but their extrapolations to the region of time-like currents gives rise to widely varying predictions for scaling behavior to be observed there. There are already some difficulties in reconciling the most naive picture with the observed behavior of e^+e^- annihilation into hadrons.¹⁰ To check scaling, however, total cross section measurements are not enough since only one invariant survives to describe the process. In the case of lepton pair production in hadronic collisions the total momentum of the lepton pair, relative to the incident proton, is an additional variable and allows other independent invariants to be constructed, and the discussion becomes similar to that of large $p_{\perp}$ scaling.

If the available data for lepton pairs at the AGS is used to construct a scaling function which is also consistent with the present observed upper limit at the ISR, then it is possible to make estimates for various weak and electromagnetic production processes in the ISA range, as indicated in Fig. III-6. The high energy and the high luminosity available with the ISA could provide the needed experimental conditions for major discoveries in this field.

3. Strong Interaction Studies With the ISA:

Discussion of some typical experiments.

As has been emphasized in the previous section on theoretical implications, the sharp distinction between the strong, electromagnetic, and weak interactions which characterizes elementary particle physics at the present time may well be fundamentally altered when energies up to 400 GeV in the center-of-mass are available for experimentation. Nevertheless, for convenience in organizing the discussion of the prospective physics program, we maintain these

Fig. III-6. Estimated cross sections for weak and electromagnetic processes.

distinctions in the present and the following section.

The center-of-mass energy of the proposed ISA is an order of magnitude larger than that provided by any accelerator currently operating or currently under construction. Although the most interesting discoveries may well be totally unexpected, a priori we can define the areas to which our present understanding points and we can discuss experiments which we know will be important and which also serve to illustrate the flexibility and power of the proposed design for experimental utilization. In this spirit, the strong interaction studies can be crudely divided into the following categories:

i) The high energy behavior of the predominant processes. Do elastic and inelastic cross sections have "limiting" energy dependences? As has been pointed out in the preceding theoretical section, the question of whether the total cross section, σ_T , continues to rise, and if so, how, is central to the fundamental nature of high energy dynamics. This area, which should also include the nature of the high energy behavior of the principal peripheral processes, is what has colloquially been referred to as the question of "asymptotia".

(ii) The dynamics of multiparticle inelastic events. Are there "fireballs"? Are there multiparticle correlations beyond those imposed by kinematics? Only at the ISA or higher energies is it likely that there will be a sufficient range of energy dependences to distinguish between the different dynamical models of the basic hadronic interaction.

(iii) High transverse momentum ($p_{\perp}$) physics. The recent discoveries at the ISR, showing that hadronic secondaries emerge at high transverse momentum (to the line of collision) with probabilities that far exceed earlier expectations, have created great theoretical interest and stimulated many new experimental proposals. It is widely believed that such high $p_{\perp}$ hadronic phenomena probe very deeply into the fundamental structure of hadrons. However, here, as in the case of the rising p-p total cross

sections, it is extremely important to be able to go to higher energies in order to be able to disentangle the $p_{\perp}$ and $\sqrt{s}$ ($\sqrt{s}$ = center-of-mass energy) dependence--a feature which is central to any theoretical understanding of the high $p_{\perp}$ processes.

The above, and the preceding theoretical section, argue the case for the importance of the new ISA energy range. The relevant question then is, given the geometry and intensity of the colliding beams that can be achieved, will it be possible to do experiments that meaningfully explore this high energy domain? In the remainder of this section some typical experiments in strong interactions will be discussed to show that one can indeed expect to carry out meaningful measurements at such an accelerator.

Two modifications of the basic ISA design are those which would allow the storage and acceleration of deuterons and anti-protons. Because of the great interest and importance of these possible options for strong interaction physics, this section concludes with a summary of the technical possibilities and a brief discussion of some of the most interesting physics which could be done with these beams. A more detailed account of the technical additions and modifications to the ISA which would be required to achieve the deuteron and antiproton options is given in Section XVII.

3.1 Measurement of the Proton-Proton Total Cross Section

Figure III-3 illustrates the range of behavior which is predicted by fits to the latest ISR data on total cross sections. Clearly, total cross section determinations with an error as large as 10% would be useful in eliminating extreme hypotheses. However, as there are a large range of models which fit the existing data, better precision would be highly desirable.¹¹ This is one of the most straightforward measurements at conventional accelerators where the transmission method can yield accuracies of 1% or better. This method is, of course, not accessible to colliding beam machines but two other methods discussed below offer the possibility of 1%

total cross section determinations.

i) Direct measurement of p-p interactions by detection of 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 small angle detector consisting of concentric ring counters around the proton beam is placed ~ 50 m from the interaction region. With a 5-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, which is the worst case (t is the square of the four-momentum transfer). Thus only 1 mb or less of the total cross section is expected to be lost, which can be corrected by extrapolating the observed events to 0° . A 20% accuracy in the correction would thus give an error of 1/2% 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 number of interactions/sec by the luminosity. A determination of the luminosity to 1% seems very hard but not impossible,¹¹ and will also be needed in many other experiments. 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) Extrapolation of the elastic differential cross section to 0° combined with the optical theorem. This method is a by-product of the small angle elastic scattering experiments and as such will certainly be done. However, assumptions about the spin dependence and the real part of the elastic scattering amplitude have to be made. Also required will be the determination of the luminosity which, given the validity of the assumptions, would again probably be the limiting factor in the accuracy of the measurement.

3.2 Proton-Proton Elastic Scattering

The simplicity and the well defined nature of the final state of the elastic scattering process allow a clear separation from the

inelastic background, and high precision measurements relatively free of systematic biases should be possible.

Elastic scattering provides the largest single contribution to the total hadron-hadron cross section at all energies measured to date. The forward differential cross section is related to the total cross section as noted above and the Coulomb-nuclear interference can be used to measure, or at least set limits on, the real part of the forward scattering amplitude, which in turn is related, via the dispersion relation, to the basic assumption of microscopic causality at small distances. In the proton-proton system considered here, spin dependent effects make the analysis somewhat model dependent but, nonetheless, significant checks can be made. Alternatively, by using forward dispersion relations with one subtraction, the dependence of the integrals on the high energy total cross section can be increased and thus used as a probe (assuming microcausality) of the high energy behavior of total cross sections well beyond the region available at the ISA.

One may distinguish three regions: the Coulomb interference region, $|t| \lesssim 0.002 \text{ (GeV/c)}^2$, the small angle, "diffraction scattering" region $|t| \lesssim 1 \text{ (GeV/c)}^2$ and the "large" $|t|$ region which extends beyond $|t| \gtrsim 1 \text{ (GeV/c)}^2$ to values of $|t|$ limited by luminosity and available running time. Experimentally, two setups which overlap around $|t| \gtrsim 1 \text{ (GeV/c)}^2$ can cover the accessible range of $|t|$. Figure III-7 shows the results of a fit to lower energy data calculated for two ISA energies⁽¹²⁾ (200 and 400 GeV in the center-of-mass). Aside from displaying the general shape "expected" for the cross section, the figure also shows that $|t|$ resolutions of the order of $\Delta|t| \gtrsim 0.03 \text{ (GeV/c)}^2$ are needed to resolve interesting structure in the differential cross section around the 1 (GeV/c)^2 region. In the small angle, and especially the Coulomb region, better resolution is required in order to avoid excessive averaging over the rapidly varying cross section. However, in the $|t| \gg 1 \text{ (GeV/c)}^2$ region much coarser resolution in t is accepted and the ultimate limit will be set by the available

Fig. III-7. Calculated angular distribution for elastic p-p scattering.
(Phillips and Barger model)

luminosity.

1) Small angle elastic scattering, $0.002 \lesssim |t| \lesssim 1 \text{ (GeV/c)}^2$. At 200 GeV beam energy $|t| = 0.002$ corresponds to a scattering angle of 22.4 μrad and resolutions comparable to this must be reached to measure the Coulomb-nuclear interference which is near maximum at $|t| = 0.002$, although appreciable effects extend to $|t| = 0.02 \text{ (GeV/c)}^2$. The standard low β , high luminosity intersection region has intrinsic beam angular divergences which are an order of magnitude too large, and it is necessary to use an especially designed intersection region for the small angle scattering experiment.^{13,14} The basic idea is to use a collinear intersection with a dipole at each end to separate the beams and a quadrupole triplet at each end to focus the particles scattered at small θ to regions (of radius $f\theta$) in the respective focal planes. In the design illustrated in Section III-5 of this report the effective focal length, f , is approximately 65 meters. The β in the crossing region is large ($\sim 200 \text{ m}$) leading to an intrinsic beam spread of approximately $\pm 30 \mu\text{rad}$ and a beam full width of 1.3 cm. In this design, the luminosity $L = 3 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$, which is probably too high for the small angle region¹³, and the beam emittance would be reduced to give $L \sim 10^{28} \text{ cm}^{-2} \text{ sec}^{-1}$. It is likely that this would also permit substantially smaller beam divergences. Detector rings with $\pm 1 \text{ mm}$ resolution are placed around the beam pipes at focal planes. The angular resolution of the detector system is thus $\pm 15 \mu\text{rad}$ which is smaller than the intrinsic beam spread. With modern proportional or drift chamber techniques it would be feasible to reduce the measurement error even more if the intrinsic beam spread were improved. The effective error in angular determination should be about an order of magnitude better than the angular spread and the following table has been computed for an effective angular error $\delta\theta = 2.5 \mu\text{rad}$, and full azimuthal coverage for the detector.

TABLE III-1. Counting Rates for Small Angle Elastic Scattering

t (GeV/c) ²	θ (mrad)	Fractional Error in dσ/dt	Bin Size in t	dσ/dt in t Bin cm ² (GeV/c) ⁻²	Events/Hour for L = 10 ²⁸ cm ⁻² sec ⁻¹
0.001	0.15	6.5%	0.0001	3 x 10 ⁻²⁹	1000
0.002	0.20	5.0%	0.0001	8 x 10 ⁻³⁰	300
0.01	0.50	0.1%	0.001	8 x 10 ⁻²⁹	3000
0.1	1.5	0.3%	0.005	1 x 10 ⁻²⁸	4000
1.0	5.0	1.0%	0.05	5 x 10 ⁻³⁰	200

From this table it is apparent that useful measurements can be made down to $|t| \approx 0.002$ and that a real part of the nuclear amplitude of $\sim 10^{-2}$ of the imaginary part could be detected and measured.

ii) Large angle elastic scattering, $|t| \gtrsim 1 \text{ (GeV/c)}^2$. The scattering angles in this region vary from 5 mrad upwards. In the design illustrated in Section III-5 of this report moderate values of β ($\approx 20 \text{ m}$) are used in the intersection region with resulting intrinsic beam angular divergences of $\sim \pm 0.1 \text{ mrad}$. With a detector resolution of $20 \text{ } \mu\text{rad}$ the resulting scattering angle error is essentially the beam spread which leads to a t resolution of $\Delta|t| \approx 0.04 \text{ (GeV/c)}^2$ at $|t| = 1 \text{ (GeV/c)}^2$. As can be seen from Figure III-7, this is adequate for $|t| > 1 \text{ (GeV/c)}^2$ but would be usefully improved near the region of the dip. Since cross sections are large (relatively) at the dip, the beam emittance could be reduced or the β increased to improve the resolution as required.

Because the elastic cross sections are likely to be less than 100 nb/(GeV/c)^2 for $|t| > 1$, high luminosity and good signal-to-noise rejection are required. Consequently, the apparatus must measure the outgoing protons' vector direction to good accuracy. For example, production of a low mass $p\pi^0$ state will lead to one proton having a momentum change of $\sim 0.02\%$, but an angular change of 1 mrad . Thus the angular precision discussed above should produce excellent background rejection, even for these low cross sections.

The experiment illustrated in Section III-5 employs a non-focusing two arm system which has an azimuthal acceptance, $\Delta\phi/2\pi$, of 30% at $|t| = 2$. For an angular resolution of $20 \text{ } \mu\text{rad}$, the spatial resolution of the detectors must be 0.25 mm which can be accomplished with present technologies with drift chambers or pressurized multiwire proportional chambers. The sweep magnets at each end of the collision region bend the primary beams by 4 mrad to protect the detectors from the flood of mesons produced at small x ($x = p/p_{\text{max}}$) for which $p_{\perp}/p_{\parallel}$ happens to lie between 0.004 and 0.025, the acceptance range for elastic events.

At the dip, and for $|t| \lesssim 2 \text{ (GeV/c)}^2$, Fig. III-7 indicates $\frac{d\sigma}{dt} \approx 30 \text{ nb/}(\text{GeV/c})^2$. The rate of accepted events in this region for $L \approx 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ and $|t|$ bins of 0.1 (GeV/c)^2 is ~ 1 event/sec. This will produce good statistics in the dip and secondary maximum region. If the cross section falls as $e^{-1.8|t|}$ for $|t| > 2$, as suggested by the model of Phillips and Barger, the one event per hour (for $\Delta|t| = 1 \text{ (GeV/c)}^2$) point occurs at $|t| = 6 \text{ (GeV/c)}^2$ and the one event per day point at $|t| = 8 \text{ (GeV/c)}^2$. If a power law behavior $p_{\perp}^{-10}$ prevails instead of $e^{-1.8|t|}$ there may be significantly more events at large $|t|$.

3.3 Single Particle Inclusive Spectra

The extension of single particle inclusive spectra for $\pi^{\pm}$, $K^{\pm}$, and $p^{\pm}$ into the $200 \times 200 \text{ GeV}$ region will be of great interest at the ISA. For many regions of x , $p_{\perp}$, and s , inclusive spectra will be a natural by-product of multiparticle studies with various large spectrometers such as that described in the next section. However, for extending the measurements to the maximum values of x for $\pi^{\pm}$ and $K^{\pm}$, an external spectrometer will be needed because of the particle identification problem. The Cerenkov counter technique, while not trivial, can work adequately in this energy range as demonstrated, for example, by NAL experience. An estimated 100 meters will be needed to separate π 's and K 's from protons with good efficiency. Total spectrometer lengths of ~ 250 meters appear to be necessary for reaching the maximum allowed values of $p_{\parallel}$ ($x=1$). A typical design is given in the paper by M. L. Good in reference(15). Such setups would require (a narrow) extension of the experimental area or possibly a "double-crossing" insertion so that more than half of the hall would be available for a spectrometer looking at the "first" crossing. Typically, such "single arm" spectrometers will be able to measure transverse momenta out to $\sim 2.5 \text{ (GeV/c)}^2$ before rate limitations due to the inherently small solid angle become prohibitive. Inclusive spectra for particles with larger transverse

momenta are one aspect of a range of studies of large transverse momentum phenomena and are discussed in a subsequent section.

3.4 Multiparticle Studies

It can be expected that multiparticle production will remain the dominant part of the total cross-section at the ISA energies. Thus, counting rate will not be a problem and the expected luminosity of the machine will not be a limitation on the study of these processes. Since bubble chamber detectors are not likely to be suitable for use at colliding beam machines, the main experimental problems will be similar to those of electronic detectors at the conventional accelerators: obtaining $\sim 4\pi$ solid angle and good multitrack efficiency.

A variety of multiparticle detectors have been proposed for use at the ISA¹⁵ ranging from fairly simple scintillation counter arrangements to complete magnetic spectrometers. The experimental program would undoubtedly begin with one or several of the simpler detectors and, as experience was gained, the design of a fairly full coverage 4π magnetic detector would evolve which would incorporate calorimeters for the neutral particles. As an illustration of the flexibility of the experimental insertion, and as an illustration of how such a detector might look, Section III-5 shows the layout of a magnetic detector designed for the ISA.¹⁶ In this spectrometer a large "C" magnet covers the region where the two beams collide and a set of additional magnets serve to provide magnetic analysis for the fast forward particles. Multiwire proportional chambers are used for the charged particle detectors, and lead-scintillator or iron-scintillator arrays for the neutral (γ , hadron) particle detectors. A set of threshold Cerenkov counters, with threshold γ 's up to 120, help to identify the reaction products. As mentioned earlier, the length of these counters is insufficient to identify all particle types up to $x \approx 1$ and a separate spectrometer is needed for that experiment. Nevertheless, the design shown would provide a very large amount of data, of a very complete

type, for multiparticle events. The luminosity in the insertion shown would be $2 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$ which corresponds to an event rate of $\sim 10^6$ per sec. This rate is well matched to the resolving and memory time of the detectors but not to the possible recording rate, at least with present day technology. Clearly a great variety of triggers could and would be utilized to select "interesting" events.

3.5 High Transverse Momentum Studies

The instrumentation for the study of high transverse momentum phenomena is driven by the need to handle the maximum luminosity with the largest possible solid angle detector in order to extend the measurements to the maximum $p_{\perp}$ and consequently to the smallest cross sections. This requirement is highlighted by the following table which gives the approximate (inclusive) rates for 10 steradian acceptance and uses the CCR parameterizations of the hadronic spectrum.¹⁷

TABLE III-2. Cross Sections and Rates for Inclusive Hadron Production at the ISA

$p_{\perp} \text{ min (GeV/c)}$	$\frac{d\sigma}{d\Omega} \text{ near } 90^\circ$	Rate for $d\Omega = 10\text{sr}$
		and $L = 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$
1	$2.5 \times 10^{-27} \text{ cm}^2$	$2.5 \times 10^7/\text{sec}$
2	3.9×10^{-29}	4.0×10^5
3	3.4×10^{-30}	3.4×10^4
5	1.6×10^{-31}	1.6×10^3
10	2.5×10^{-33}	2.5×10

A promising approach to these problems is provided by the "Impactometer" first suggested by Willis.¹⁵ A recent review and update of the Impactometer design for the ISA has been given by Carroll.¹⁷ The basic device, which is illustrated in Section III-5 of this report, consists of a set of large liquid argon ionization

chambers with steel walls which surround the interaction region. Such chambers have now been tested and show $\sim 5\%$ half-width at half-maximum energy determination for 5 GeV/c incident hadrons as compared with $\sim 30\%$ at 5 GeV/c for iron-scintillator sandwich calorimeters. The resolution improves as the incident energy is raised. With a 2-mm gap and an approximately equal thickness of steel the ionization chambers have an average density of 4.3 g/cm^3 so that chambers about 2-meters thick should be adequate for containing the energy of all but the most energetic particles.

As shown in the drawing in Fig. III-18, there are three components of the calorimeter in which the smaller angle components provide shielding for the large angle components. It is envisioned that at low luminosities ($\sim 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$) the entire calorimeter would be used, but as one reached the highest luminosities ($> 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$) the smaller angle components would probably become inoperative.

A short (~ 1 meter) interaction region is chosen so that the calorimeter can be made reasonably compact in order to keep the costs down. The distance from the interaction region to the calorimeter is about 1.5 m which gives reasonable angular resolution for an impact trigger and provides space for proportional wire chambers and transition radiation counters as described below, or for other detectors. As can be seen, even for $L = 10^{33}$, the rates for $p_{\perp} \geq 2.5 \text{ GeV/c}$ are reasonable. Thus, by biasing the detectors at this level, we can hope to reduce the low energy background to a 1 to 2 GeV noise fluctuation in the energy measurement. By zero crossing techniques, time resolution in the ionization chamber can be made as low as 10 nsec so that the randoms problem is manageable.

The space between the interaction region and the liquid argon ionization chambers would be filled with proportional wire chambers (PWC) and, in the case of experiments needing electron identification, transition radiation detectors. The PWC's would provide precise measurements of angles of production and help eliminate

background by eliminating tracks which did not come from the interaction region. The transition radiation detectors, in combination with the energy distribution in the liquid argon detectors, provide electron identification with a rejection against pion background of $\sim 10^4$ at 2 GeV, which improves with increasing energy.

Fast analogue computation of the maximum transverse momentum for each event, as well as other quantities describing the event, make it possible to trigger the data storage under a wide variety of interesting conditions. Of particular interest will be the summed transverse momentum of a group of particles in a predetermined band of polar and azimuthal angles. Triggers of this type will be very useful in searches for jet structure in the high $p_{\perp}$ interactions. As has been noted previously¹⁷, the ISA scale energies are necessary to be kinematically able to determine whether or not jets are produced.

3.6 Special Options for the ISA

The attractiveness of intersecting storage rings would be further enhanced if they enabled us to study the interactions of a variety of particles besides the proton-proton interaction. The ISA as presently envisioned with the AGS as an injector should be able to accelerate and store high intensity deuteron beams. The acceleration and storage of fairly intense antiproton beams seem technically feasible. The order of magnitudes of the luminosities for these options, compared to the maximum proton-proton luminosity, L_{pp} , are

$$\text{Deuterons } L_{dd} \approx 0.7 L_{pp} \quad \text{Antiprotons } L_{\bar{p}p} \approx 10^{-4} L_{pp} .$$

These options would considerably broaden the physics potential of the ISA. Deuteron beams would allow the measurements of n-p and n-n total, elastic, and partial cross sections. This would provide information about the isotopic spin, $I = 0$, nucleon-nucleon strong interactions. This is quite important, since in p-p interactions

only the $I = 1$ part of the nucleon-nucleon interaction is involved. Another exciting possibility is that, at the very large center-of-mass energies available at the ISA, the strength of the weak interactions approaches that of the strong interactions. Since the weak interactions do not conserve isotopic spin, one way to experimentally detect their increased strength would be to look for sizable violations of isotopic spin symmetry by comparing processes such as $p + p \rightarrow \pi^+ + \text{anything}$ to $n + n \rightarrow \pi + \text{anything}$ or $d + d \rightarrow \pi^+ + \text{anything}$ to $d + d \rightarrow \pi^- + \text{anything}$, especially at large transverse momenta.

Accelerating and storing antiprotons in one ring and allowing them to collide with protons in the other ring would allow a detailed comparison of the strong interactions of $\bar{p}p$ and pp . In particular, it will be very important to check the Pomeranchuk theorem, which states that particle and antiparticle cross sections will approach each other at very high energies.

3.6.1 The Deuteron Option

The acceleration of deuterons through the 200-MeV linac, the AGS, and the ISA to 200 GeV has been considered and is discussed in detail in Sec. XVII-3. There should be no serious problems with this procedure. About 10^{12} deuterons can be accelerated per pulse by the AGS and stacked into the ISA in the same way as the expected 2.3×10^{12} protons/pulse. Both of the ISA rings can be filled with deuterons, or one with deuterons and one with protons. Since the maximum pp luminosity is tune-shift limited, the dd luminosity can be higher than the square of the ratio of the deuteron current to the proton current times the pp luminosity by choosing the crossing angle appropriately. The estimates are that $L_{dd} \approx 0.7 \times L_{pp}$.

With such high luminosities pn and nn interactions can be studied with essentially the same techniques as are needed for pp interactions, i.e., similar straight-section geometries and detectors. An additional advantage in dd collisions is the presence of the nn , np , or pp spectators that come off at predictable angles

and momenta and can be used as triggers for pp, pn, and nn interactions, respectively. Figure III-8 gives a schematic illustration of a setup to use these spectators.

3.6.2 The Antiproton Option

The scheme for producing $\bar{p}$ collisions at the ISA is the following:

- i) 30-GeV protons are injected into ring 1 of the ISA and are accelerated to 200 GeV.
- ii) The 200-GeV protons are extracted from ring 1 and are allowed to hit an external target (~ 4 to 5 cm long) in which they produce 30-GeV $\bar{p}$. The reason for the external target arrangement is that the ISA can be properly shielded from the radiation produced in the target, and that the external proton beam can be focused to a very small spot (0.25 mm radius).
- iii) The phase space of the $\bar{p}$ beam produced in the external target is then tailored to match into the ISA at 30 GeV, and the 30 GeV $\bar{p}$ are then injected into ring 2 of the ISA.
- iv) Since before extraction the protons in ring 1 occupy only $\sim 1/5$ of the circumference of the ring, this procedure can be repeated five times to fill up ring 2 completely with 30 GeV $\bar{p}$.
- v) Ring 1 is now filled with 30-GeV protons, and both rings are accelerated to 200 GeV, and the $\bar{p}$ and the p beams are allowed to collide in the usual way.

Antiprotons produced in the external target in a ± 8 mrad cone, with $\Delta p/p = 2.5\%$, can be injected into ring 2. From the Hagedorn-Ranft particle production model, we expect $dn(\bar{p})/d\Omega dp = 0.5$ p/GeV/sr/interacting proton. In the 4-5 cm long target, $\sim 30\%$ of the protons should interact. With five cycles of ring 1 of the ISA, with 6×10^{14} protons each, and a 70% stacking efficiency into ring 2, we expect to collect $\sim 5 \times 10^{10}$ $\bar{p}$. The filling time should be about 20 minutes. With such $\bar{p}$ intensities, the effective luminosity for $\bar{p}p$ interactions will be of the order of $10^{-4} \times L_{pp}$.

Fig. III-8. Large angle intersection setup for measurement of ratios of p-p, n-n, and n-n total cross sections.

This procedure is discussed in more detail in Sec. XVII-4.

The above luminosity is sufficient to study the strong interactions of $\bar{p}p$ collisions. The straight section geometries and the detection apparatus would be very similar to that used for pp collisions.

4. Weak and Electromagnetic Interactions at the ISA

4.1 Introduction

In the past one has not usually thought of weak and electromagnetic interactions as part of the physics to be studied in p - p interactions. In fact, up until recently, there have been only a few experiments of this sort performed at the AGS.¹⁸ Now, however, there are many such experiments proposed or in progress at the ISR and at NAL.¹⁹ Traditionally this physics has been associated with e - p and ν - p interactions, and experiments on decays, but careful consideration has shown that, at higher energies, the study of these interactions will form a major part of the experimental program in p - p collisions. Indeed, if our present understanding is correct, this route is most likely the best approach to study the very high energy behavior of these interactions. In the following we summarize such a program of study and make reference to detailed arguments in CRISP reports and other literature.

What are the goals in our studies of these interactions?

The likelihood is that nature will provide answers to questions that we did not think to ask. Nevertheless, we believe that the critical questions have to do with the fact that our theories of weak and electromagnetic interactions appear to be the low energy limit of some richer structure.²⁰ One of the outstanding questions in high-energy physics is why the approximate theory, which Fermi applied to β decays of a few kilovolts, continues to hold up to several GeV. Perhaps the answer will lie in the unification of the weak and electromagnetic interactions, which some theories predict to occur at center-of-mass energies of some tens of GeV.²¹ The

very fundamental consideration of unitarity requires that there must be a drastic change in the present theory of weak interaction at center-of-mass energies in the one hundred to one thousand GeV regime. These new discoveries may consist in the observation of new particles which mediate the weak or electromagnetic interaction, or of a sudden change in the behavior of cross sections which have grown smoothly with energy through many orders of magnitude. In addition, theoretical insights²² into the unification of the strong, weak and electromagnetic interactions at high energies and large momentum transfers have begun to appear recently. If such insights are to confront experiment, data in the kinematic region accessible at the ISA will be required.

Specific Questions in Weak and Electromagnetic Interactions.

The experiments of interest for weak and electromagnetic interactions can be grouped together for the purpose of classifying them, although the details and techniques may be vastly different. Essentially, in p-p collisions, the interesting processes are

$$p + p \rightarrow \ell_1 + \bar{\ell}_2 + (\text{anything})$$

where ℓ_1 , $\bar{\ell}_2$ are leptons and the "anything" is nearly all hadrons. Experiments will observe the emission of an electromagnetic or weakly interacting current carrying large time-like four-momentum, decaying into a lepton pair. In the electromagnetic case this will be $(\mu^+\mu^-)$ and (e^+e^-) , for weak interactions $(\nu\bar{\nu})$ and $(\mu\nu)$ pairs. For electromagnetic interactions the lepton pair comes from a heavy virtual photon, whereas one of the major hopes for the weak case is to observe a massive charged boson leading to such a final state. The extension to $\bar{p}p$ collisions is covered in Section III-4.3 and the complementary information derived from the e-p option is discussed in Section III-4.4.

With these assumptions it is possible to list some specific forms the observations may take:

- i) First, there is the exploration of the general properties of inclusive weak and electromagnetic interactions. Will they continue to show the simple forms characteristic of bound systems

of point-like constituents? If so, will it indeed be true that at large momentum transfers the electromagnetic and weak interactions become prominent?²³ If not, will deviations show up as form factors for the partons, or in a more dramatic form?

ii) The discovery of the long sought intermediate vector boson which would explain the structure of weak interactions, as discussed above. The range of predictions for its mass is well within the range of capability for the ISA to produce such particles.

iii) The existence of such a charged vector boson does not directly allow a divergence-free theory of weak interactions. A number of ways of achieving such a theory, having observable consequences, have been suggested.^{21,24} Heavy neutral vector bosons may be needed, possibly coupled to photons as well as neutrinos, or there may be new heavy leptons. Recent experimental results from neutrino scattering suggest the existence of heavy neutral vector bosons.²⁵ As they would produce striking observable effects, the existence of such objects could be conclusively confirmed in high energy p-p collisions at ISA energies.

iv) Alternatively, there might appear new phenomena which do not take the form of particles, but of form factors appearing unexpectedly in electromagnetic interactions. Careful study of strong, electromagnetic, and weak reactions will be necessary to sort out the true meaning of the results.

v) If the weak interaction does indeed become quite strong at very high energy, we might see effects of higher order weak processes. Perhaps clues to the unification of the strong, electromagnetic and weak interactions, and the problem of electron-muon duality will be resolved.

Finally, it must be emphasized that the deepest theoretical consequences of this new energy range can be expected to come from the observation of unpredicted phenomena.

4.2 Some Weak and Electromagnetic Interaction Experiments.

The inclusive reactions involving weak and electromagnetic interactions are believed to have a relatively slow fall-off with increasing transverse momentum, when compared to the much more copious hadronic reactions. (Inclusive reactions are those in which we sum over all possible numbers of the outgoing hadrons.) Because of this slow fall-off and the high energy and luminosity of the ISA, it is possible to study experimentally regions of high transverse momentum where the weak and electromagnetic reactions are expected to be a major, and probably even dominant, portion of the inclusive spectrum.

We know that, at least up to and including the energies of the CERN ISR, the hadronic reactions fall off exponentially²⁶ with increasing transverse momentum for the first few GeV/c and then by a power law^{27,28} above 2 to 3 GeV/c. This is expressed by the invariant cross section,

$$E \frac{d^3\sigma}{dp^3} \propto p_{\perp}^{-n}, \text{ where } n = 8-10.$$

This fall-off is illustrated by Fig. III-9 in terms of the differential cross section $\frac{d\sigma}{dp_{\perp}}$ which will be useful for comparison later. Exploring whether or not this rapid fall continues is of great intrinsic interest in itself. While there may be very high precision experiments for studying these processes at small transverse momenta, we will not discuss them in this section.

Thus the quantity which seems most useful for studying these interactions is transverse momentum. The exact definition of the transverse momentum to be measured varies from reaction to reaction. It may be best to take one reaction typical of each of the interactions studied; then indicate the quantity measured, suggest an experimental arrangement, show the dependence expected, and explain the reason for our expectation.

The first reaction is governed by the electromagnetic interactions:

Fig. III-9. Cross section for single hadrons vs transverse momentum.

$$p + p \rightarrow e^+ + e^- + \dots$$

(III-1)

$$p + p \rightarrow \mu^+ + \mu^- + \dots$$

Such a reaction has actually been studied at the AGS²⁹ with muons, and an upper limit has been established at the ISR for electrons.¹⁹ In this case the quantity upon which we want to fix our attention is the transverse momentum of one of the leptons. It is a widely held conjecture that if the reaction sums over all final state hadrons, the shape of the cross section is dominated in its dependence by the kinematics of the lepton pairs which is related to the propagator of the virtual photon.²² The conjecture on which this is based is very closely related to the scaling in momentum transfer seen in deep inelastic scattering at SLAC, and in deep inelastic neutrino reactions seen at CERN and NAL.³⁰ More information on this matter will soon be coming from further experiments at NAL and the ISR. For the moment, it is generally agreed that this is the best basis for extrapolating the reactions we are dealing with up to ISA energies.²⁹ Under this assumption, the cross section will probably lie in the region between the curves in Fig. III-10 which depicts the range of such cross sections predicted by several parton models.³¹ These models range from the very optimistic to the very pessimistic in their assumptions as to the momentum distributions of the point constituents of the colliding protons. For a collision with infinite energy these models predict a cross section decreasing as the fourth power of the transverse momentum.

One proposed experimental arrangement for looking at the lepton pairs of Reaction III-1 is the muon detector of Lederman shown in Fig. III-18.³² This detector consists of a dense magnetized iron shield surrounding the interaction region to filter out hadrons, and detectors outside the shield. The entire 2π range of the azimuth and over 70% of the polar solid angle is subtended by the detector. The magnetic field serves to identify the charge of the detected particles and to determine the momentum

Fig. III-10. Differential cross section for $p + p \rightarrow \begin{pmatrix} e^+ \\ \mu^+ \end{pmatrix} + \begin{pmatrix} e^- \\ \mu^- \end{pmatrix} + \dots$

to within $\sim \pm 11\%$. The 4m thick iron shield reduces the hadron flux by $\sim 3 \times 10^6$. Effects of the multiple scattering will have to be unfolded from the measured kinematic distributions. Alternatively, electron pairs could be detected in the "Impactometer" detector described below. The background for the lepton pair experiments consists of electrons from neutral pion decay and muons from charged pion decay, which drop even faster with transverse momentum than do the pions themselves. For example, ISR experiments indicate that hadrons produce leptons at a level almost two orders of magnitude below that of the hadrons. Since there would be two lepton detectors on each side of the interaction region, the distinctive signature of this event is the presence of two coincident leptons, each with large transverse momentum. It is anticipated that this would afford a very great rejection of the ordinary sort of hadronic background. Figure III-10 shows the dependence of the cross section on the transverse momentum of the lepton, assuming that scaling holds and no new new physics is encountered. With a detector covering 4π of solid angle, the most pessimistic model in Fig. III-10 predicts a detectable rate with $p_{\perp} > 50 \text{ GeV}/c$.

If there exists a Lee-Wick heavy photon or heavy neutral boson coupled to lepton pairs, then the reaction

will produce a peak in the effective mass distribution of the two leptons and, if B^0 is the Lee-Wick particle whose properties have been well specified, the cross section is very substantial as shown in Fig. III-11. If the B^0 mass were $100 \text{ GeV}/c^2$, for example, the most pessimistic model predicts the production of over 100 B^0 's each hour if the luminosity were $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$.

Reaction (III-1) is very important in the use of the ISA to study weak interactions as well as electromagnetic interactions, since it is applied to find out whether or not one can indeed

Fig. III-11. Cross section for B^0 production vs mass.

absorb very large momentum transfers on the proton. If the cross section has the indicated shape expected on the basis of scaling, one assumes that this concept is valid in that energy region, as well as conventional quantum electrodynamics. In this case, these concepts will also be assumed valid for the weak interactions and the reactions below will be interpreted as indicative of the structure of those interactions. Some such logical chain will always be involved in studying the weak interactions, outside of purely leptonic reactions.

Turning to the weak interactions, a reaction which is a very close analogue to the foregoing electromagnetic process (Reaction III-1), and related to it by the conserved vector current hypothesis, is

In this case, the transverse momentum is again that of one of the leptons. Assuming the usual local four-fermion interactions, supplemented by the scaling hypothesis and the assumption of a conserved vector, weakly interacting, current, the cross section for Reaction III-2 can be calculated from that of Reaction III-1. Fig. III-12 depicts the range of cross sections expected at the ISA from the same set of models used in Fig. III-10. This behavior in cross section will be cut short if there is an intermediate vector boson, W . At momentum transfers well above the mass of the W the cross section falls off in the same way as the electromagnetic cross section (Fig. III-10). Whether or not a physical W particle exists, this cross section, even in the more optimistic models, is expected to decrease rapidly in the several hundred to one thousand GeV/c range when the amplitude completely saturates the lowest angular momentum state, i.e. reaches the limits of the unitarity bound.

If the W actually exists, a center of mass energy substantially greater than the W mass would result in the production of real W 's.

Fig. III-12. Cross section for $p+p \rightarrow \left(\begin{smallmatrix} e \\ \mu \end{smallmatrix} \right) + \nu + \dots$

The W presumably has a substantial branching ratio for decay into a lepton and a neutrino, leading to the reaction

This production process is a semi-weak interaction, and its expected dependence on the mass of the W is shown in Fig. III-13 for the same set of models³¹ used previously. The W decay is isotropic in its rest frame, so if W's were produced with zero transverse momentum, and one observed the transverse momentum of one of the leptons, the result would be that shown in Fig. III-14. The dotted curve shows qualitatively the effect to be expected from production of W's with a finite transverse momentum of about 300 MeV/c. Since most of the events are peaked at a specific characteristic transverse momentum, Fig. III-13 may be understood as the range of the peak cross sections predicted by the models at the peak in transverse momentum, the different W masses each associated with a characteristic transverse momentum of $m_W/2$.

The physics of weak interactions can perhaps be studied best with an array of calorimeters covering the complete solid angle, known as the Impactometer (see Fig. III-18). This device can be used to provide rough but adequate information on all the hadrons, electrons and photons produced, and can indicate the existence of neutrinos and muons by requiring energy and momentum conservation.³³ Electron identification using transition radiation detectors, as well as the shower development in the calorimeters, would give hadron rejection of 10^4 . The transverse momentum of most of the particles in a jet of hadrons would be summed electronically and be available as a trigger. Such a detector is now being developed and tested for use with the ISR.³⁴ More of the details of the device are discussed in the previous sections on strong interactions.

Using the Impactometer we see from Fig. III-12 that, assuming a luminosity of about $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$, we can readily explore an extremely wide range of transverse momenta for the weak interactions.

Fig. III-13. Cross section for W production vs mass.

Fig. III-14. Differential cross section for electrons from W production and decay, showing effect of about 300 MeV/c of $p_\perp$ in the production process.

Let us consider again the Reaction (III-2). Under conditions such that the electrons or muons from weak interactions dominate those from other sources, it may be advantageous to concentrate on detecting the electrons or muons, even at the cost of losing the possibility of establishing the presence of the neutrino. Thus, one approach is to use the electron or muon detectors in this reaction as in Reaction (III-1).^{28,31} In this case, the leptons due to Reaction (III-1) must be subtracted from the total number observed. This can be done if the lepton pairs due to Reaction (III-1) have been studied and understood. Additional information is afforded by the possible charge symmetry in the weak reactions, which is not anticipated to be present in the electromagnetic case. Clearly, this kind of study is profitable only in the region where Reaction (III-2) is comparable to or larger than Reaction (III-1). If scaling is valid, and there is no new structure in the weak or electromagnetic interactions, these cross sections might vary with transverse momentum as shown in Figs. III-10 and 12. With a detector covering 4π of solid angle the most pessimistic model considered predicts a rate of ≥ 1 event/hr for $p_{\perp} > 40$ GeV/c. If scaling is valid there is a momentum transfer region accessible at the ISA in which the weak Reaction (III-2) is larger than the electromagnetic Reaction (III-1).

The case where this approach is most profitable is that where the intermediate boson is observed, Reaction (III-3). In that case, the transverse momentum of the electrons or muons associated with the W's will be given by Fig. III-14, and, with the large cross sections anticipated on the basis of scaling and the conserved vector current, these leptons will stand out very clearly above the background due to the electromagnetic process. If the W mass were $100 \text{ GeV}/c^2$, for example, the most pessimistic model predicts the production of over 100 W's each hour if the luminosity were $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$. (Of course, if both the W and B^0 exist with comparable masses, the situation can be more complicated but most interesting!)

Admittedly, in studying these reactions, it would be much more satisfying to have an indication of the presence of a neutrino. This can be achieved by using the Impactometer calorimeter array covering the full solid angle to infer the existence of the missing neutrino with high transverse momentum. Essentially, all the other particles are observed and their transverse momenta are summed up, electronically, leaving a signal representing a transverse momentum imbalance which triggers a system allowing one to examine the reaction in more detail. In this case, the momentum components of the neutrino are known to reasonable accuracy, and the electron can also probably be picked out. This allows one to know the effective mass of the two leptons, as well as distinguishing the weak interaction from the electromagnetic one. This would be a particularly attractive way of searching for a structure in this effective mass distribution, either that due to the W, or possibly some more complex feature.

In reaction

$$p + p \rightarrow \dots \text{hadrons} \quad (\text{III-4})$$

we refer to a reaction which does not contain any leptons. On the face of it, then, this reaction would appear to be a normal hadronic reaction mediated by the strong interactions. However, if the nucleon does indeed contain point-like constituents, or some current-like structure which can simulate these, it might make sense to expect that these would suffer electromagnetic or weak reactions with large transverse momenta.

The Impactometer is very well suited to the study of these reactions, since it can be set to trigger on any event where large multiplicities or transverse momenta are present, even if the large transverse momentum is distributed over a number of particles. In this way, one can trace out a curve, a possible example of which is given in Fig. III-15, and learn what kinds of hadron configurations actually occur; for example, very large multiplicities at high transverse momenta. A comparison of the $s = \infty$ and ISA curves in Fig. III-15 shows how important it is to have a high center-of-mass

Fig. III-15. A possible inclusive (non-leptonic) cross section differential in $p_{\perp}$. Hadronic, electromagnetic and weak interactions dominate successively.

energy for these studies.

If the observed distribution happens to follow exactly the form predicted in Fig. III-15, it will immediately be asked how we know the breaks in the curve are due to the take-over by the electromagnetic or weak interactions, and not a peculiar structure in the strong interactions. The answer must be that the electromagnetic interactions do not conserve isospin, and the weak interactions violate parity, in general. A possible approach, then, is to store deuterons in the rings, and test the relationship that twice the number of neutral pions equals the number of charged pions, for all configurations. The calorimeter array should allow this to be done to reasonable accuracy. Then one will see if isospin violation is associated with the region of putative electromagnetic dominance. Just the comparison of the general features of p-p and p-n reactions in this region will probably be very suggestive.

If it is suspected that the weak interactions are dominant in some momentum transfer region, one possible verification is to observe the hyperons associated with these events, and determine if they have a parity-violating longitudinal polarization. This can be done by removing a sector of the 4π calorimeter covering a reasonable solid angle, and providing an adequately long decay region and a magnetic spectrometer for identification of the hyperons and accurate measurement of their polar decay angles. The rest of the calorimeter allows the correlation of other particles with the observed hyperons.

A similar approach can be taken with a Cerenkov spectrometer inserted in a relatively small solid angular interval for mass identification of single particles, which may then be correlated with the remaining particles measured in the calorimeter.

If one wants to say that the strong interactions develop these features of the weak and electromagnetic interactions as well as their characteristic momentum transfer structure, it becomes a more subtle discussion. T.D. Lee, among others, has suggested that,

at the large momentum transfers encountered at the ISA, the normal component of strong interactions will become negligible, and that another component, characterized by a small coupling constant and point-like behavior, will take over²². This renormalizable component of the strong interactions would have a deep and intimate relation with the weak and electromagnetic interactions. Furthermore, at the energies available in the ISA, we might expect a breakdown of the present-day scaling and a new basic energy scale would emerge. Clearly, the anticipation of these results is even more speculative than for the leptonic ones, but it will be fascinating to see how the real world behaves.

4.3 The $\bar{p}p$ Option

The luminosities of $\bar{p}p$ interactions at the ISA are likely to be 3×10^4 less than pp interactions unless cooling of the antiprotons is used to damp their transverse phase space. Even in such a case the $\bar{p}p$ luminosity would only reach approximately 1% of the pp luminosity. It may therefore seem unrealistic to consider a study of weak and electromagnetic interactions in $\bar{p}p$ collisions. However, the cross sections for the reactions

$$\begin{aligned}\bar{p} + p &\rightarrow \begin{pmatrix} \mu^+ \\ e^+ \end{pmatrix} + \begin{pmatrix} \mu^- \\ e^- \end{pmatrix} + \text{anything} \\ \bar{p} + p &\rightarrow \begin{pmatrix} \mu \\ e \end{pmatrix} + \begin{pmatrix} \mu \\ e \end{pmatrix} + \nu + \text{anything} \\ \bar{p} + p &\rightarrow B^0 + \text{anything} \\ \bar{p} + p &\rightarrow W + \text{anything}\end{aligned}\tag{III-5}$$

may be much larger with $\bar{p}p$ and the interpretation of the data more straightforward than for pp .

Of the three models used to describe electromagnetic and weak interactions for pp collisions, the model of Drell and Yan (D-Y in Figs. III-10, 11, 12 and 13) was considered very optimistic since it assumes equal parton and anti-parton distributions within the

colliding protons. This model, however, is essentially the correct model to describe $\bar{p}p$ interactions since the parton distribution in a proton and the anti-parton distribution in an antiproton should be equal. Thus the D-Y curve in Figs. III-10, 11, 12, and 13 can be considered reasonable estimates for the cross sections for Reactions (III-5). It is thus evident that the relatively large $\bar{p}p$ cross sections allow one to begin to approach the event rates for electromagnetic and weak interactions predicted for pp collisions. In addition, the problem of detection of leptonic final states is simplified in that the equality of parton and antiparton momentum distributions in the $\bar{p}p$ collisions tends to produce final states with little longitudinal momentum as compared to the corresponding pp case. Detectors at 90° to the intersection region will thus have a higher average detection efficiency for $\bar{p}p$ than for pp weak and electromagnetic reactions.

Other advantages are gained from the assumption that only one parton (antiparton) momentum distribution dominates Reactions (III-5). It is easier to relate the $\bar{p}p$ lepton pair-production data to the scaling structure functions observed in deep inelastic lepton scattering than for lepton pair production in pp interactions. Also, the combination of data from pp , pn and $\bar{p}p$ would be a very powerful tool to disentangle the contributions from individual quark-like parton types.

One concludes that, while the rates for weak and electromagnetic processes in $\bar{p}p$ interactions are likely to be somewhat low, such observations could add a great deal to the understanding of the interactions responsible for such processes. The apparatus required for such experiments is essentially the same as that for the pp case.

4.4 The e-p Option

It has been realized that an attractive future option for the ISA is to provide for electron-proton collisions. Since the purpose is to investigate electromagnetic and weak interactions, it

is useful to compare the possibilities in e-p colliding beams with those for p-p collisions we have just been discussing.

The complementary nature of the physics with the two beams should be recognized. This may be illustrated by comparing the crucial reactions in each machine, Figs. III-16a and 16b in the case of electromagnetic interactions and Figs. III-16c and 16d in the case of weak interactions. In (a) and (c), the p-p case, the momentum transfer between the two leptons is time-like, allowing a study of the two-lepton effective mass distribution. This may bring to light new particles, such as the W or the B^0 , or even some more unusual kind of structure. In (b) and (d), the momentum transfer is space-like. If there are no physical particles, or similar structures, observed in (a)-(c), the momentum transfer dependence in (b)-(d) is probably the key to the problem, elucidating the kind of non-locality we believe must set in. In any case, we know that in the past history of particle physics the study of scattering distributions and the study of mass distribution have meshed together to lead to advances in our understanding, with the new particle observation perhaps a bit more important. In the case of the weak and electromagnetic interactions in colliding beams, it happens that these studies require, by and large, different beams. We can expect, on this basis, that both p-p and e-p collisions offer complementary information of comparable value.

This is too general a view of the matter, though, since the conditions of the observation and the parameters of the beams are not the same. The most important difference which has emerged is that the luminosity is likely to be about one to two orders of magnitude higher in the p-p case. That factor is large enough to be crucial in many cases, where event rates are just feasible in the p-p collisions. Also, the energy available in the p-p center-of-mass is larger by a factor of perhaps three to five, which might be completely decisive in the end.

On the other side, it is possible that the scaling phenomenon, on which all our present speculations are based, behaves differently

Fig. III-16. Representation of most interesting weak and electromagnetic processes in p-p option (a and c) and e-p option (b and d).

in the two cases. Certainly, at this time, it is much better verified for e-p collisions. It might possibly hold there and fail in the p-p case, and then it may be that only e-p collisions are useful for the weak and electromagnetic interaction. It is also sometimes argued that the e-p collisions can be interpreted more clearly in studying the weak reactions. In fact, the opposite might be true. For, whether we are studying the cases in Figs. III-16a or 16b, we are always comparing the electromagnetic and weak reactions. But at the largest momentum transfers, the electromagnetic cross sections may be considerably smaller than the weak, as shown in Fig. III-15. In that case, the higher luminosity of the p-p collisions may be essential in allowing the electromagnetic reactions to be studied in the same regime as the weak.

It is not worthwhile to try to add up the plus and minus factors in these two cases since they are based on such speculative grounds. We may conclude that it is very likely that both colliding beam reactions will need to be studied, and that it is entirely reasonable to proceed with the p-p collision as the first stage, even considering only the physics of the weak and electromagnetic interaction. The experimental apparatus to implement such a program is similar to that described for the pp case.

5. Implementation of the Experimental Program at the Intersecting Storage Accelerators

A model experimental program has been designed for the initial ISA operation. The interaction regions, facilities, and buildings have been designed to accommodate this program, but with the view toward future expansion.

Studies have concentrated on experiments with p-p collisions. Many of the experiments with e-p collisions can be carried out with apparatus which is used for the p-p program. Implementation of experiments with other beams, such as anti-protons for $\bar{p}$ -p collisions, is only in the formative stages; attempts are made to avoid precluding their addition at a later time.

Although many experiments involving p-p collisions are possible, they fall into two classes. Each imposes different conditions on the experimental areas. There are the experiments at small t , expected to be dominated by strong interactions, and those at large t which may involve three interactions: weak, electromagnetic, and strong. In general, the small t experiments require a luminosity less than the maximum and spectrometer systems designed to analyze 200-GeV particles with high resolution. The large t experiments, with small cross sections, require high luminosities but cruder momentum and position measurements. The apparatus for experiments at high t is, therefore, small and compact. Calorimeters, of adequate precision, scale logarithmically with s , so the size of experiments is only slightly larger than those familiar at the AGS.

The properties of the interaction regions for experiments at small t can be understood by considering the experiments discussed in Section III-3. Angular distributions from elastic and inelastic interactions, momentum spectra, and particle multiplicities are measurements which will be made early in the life of the machine. Requirements for these experiments are indicated in Table III-3. The length of the spectrometer always is less than 100 m on each side of the interaction region. Luminosities vary from 10^{28} , for scattering in the Coulomb region, to the full luminosity available for the large-angle elastic scattering experiments. Multi-particle correlation studies require a large spectrometer system such as the multipurpose spectrometer listed in Table III-3.

The only experiment which involves an unusual straight section configuration is the small angle elastic scattering experiment designed to measure the interference between the Coulomb and nuclear scattering amplitudes. The experiment requires an angular resolution of less than 25 μ rad which is achieved by enlarging the beam in the interacting region so the angular divergence of the beam is small. With a system of quadrupoles analogous to an optical telescope, the particle scattering angle is transformed

Table III-3. Summary of Experiments in p-p Collisions (200-GeV x 200 GeV)

	Typical Luminosity ($\text{cm}^{-2} \text{sec}^{-1}$)	Accessible Space (m)	Total Spectrometer Length (m)
<u>Elastic p-p scattering</u>			
Coulomb interference $t \approx 0.002 (\text{GeV}/c)^2$	10^{28}	140	140
large angle $1 < t < 25$ $(\text{GeV}/c)^2$	10^{32}	70	70
<u>Particle production</u>			
multiplicity		25	
multipurpose magnet spectrometer	10^{31}	110	110
<u>Total cross section</u>			
detection of all interactions	10^{30}	100	
n-p, n-n (deuteron option) (Sec. XVII-3)	10^{30}		
<u>Interactions with large momentum transfer</u>			
muon spectrometer	10^{33}	80	25
calorimeter (Impactometer)	10^{33}	25	
p + p $\rightarrow e^+ + e^- + \dots$			
$\mu^+ + \mu^- \dots\dots$			
W + $\dots\dots\dots$			
L $\rightarrow e + \nu$			
μ^+_{O}			
B + $\dots\dots\dots$			

into a distance from the beam axis. The telescope arrangement requires close access to the proton beam 70 m from the interaction region, which therefore requires a special design. Although the telescope arrangement is not the only way to do the experiment, there seems to be no simple way to avoid the requirement for an accessible total length of 140 m of the straight section.

A technical difficulty with many of the strong interaction experiments is that, in order to reach small t , the apparatus must be placed very close to the beam. This means that detectors which measure particle positions, and septum magnets to deflect the secondary reaction products away from the circulating beam, must be moved into place after the protons are accelerated. Beam halo and beam gas scattering appear to be major background sources for these experiments.

The proposed weak and electromagnetic interaction experiments are all high t experiments. The range of predictions of the rate of large momentum transfer reactions caused by the strong interactions is very large.

For the reactions at large t there is speculation that the strengths of the weak and electromagnetic interactions are equal to, or greater than, the strength of the strong interaction. Experimentally, this unknown area of physics is explored by using events with components having large transverse momentum as a trigger. For this type of experiment the interacting regions are small and the apparatus is contained in a relatively small volume, but the trigger rates are low. The highest achievable luminosity is required.

5.1 Experimental Arrangements at Model Intersection Regions

Several layouts of experiments and straight sections are sketched in Figs. III-17 and III-18. One area, designed specifically for the needs of the small t experiments, has 140 m of accessible space for the experiments beyond what is needed to achromatize ($X_p = 0$) the stored proton beam. For the most part,

SMALL ANGLE ELASTIC SCATTERING

LARGE ANGLE ELASTIC SCATTERING

Fig. III-17. Strong interaction experimental layouts in long north, south & west buildings.

IMPACTOMETER

- MUON SPECTROMETER

Fig. III-18. Weak interaction experimental layouts.

the equipment is similar to standard AGS experimental apparatus.

The large t experiments need high luminosity and calorimeters which, because of their massiveness, will remain in one place for a long time. Therefore, one of the four experimental areas is designed especially for high luminosity. It does not require a long building.

Some large t experiments can be done with a lead-glass spectrometer similar to the apparatus for the CERN two-lepton production experiment. An alternate apparatus in the same straight section is the Impactometer, a 4π total absorption calorimeter triggered by a high t event. This device is somewhat longer than the lead-glass spectrometer, but has comparable transverse dimensions.

The experimental magnets needed to carry out this program are listed in Table III-4.

Table III-4 Table of Experimental Magnets

Magnet	Aperture	Strength	# Required
Superconducting Septum	4m L x 1m W x 1/2m H	40kG	2
Superconducting C-Magnet	6m dia. x 2m gap	10kG	1
Superconducting H-Magnet	3m dia. x 2m gap	12kG	2
Superconducting H-Magnet	2m x 2m x 2m gap	18kG	2

The development of multi-purpose, multi-particle, electronic detector systems is proceeding at a rapid pace, and before the ISA is instrumented, versatile equipment of long life utility, high efficiency, and high precision will have been used in many instances. The ISA will therefore be able to service many user groups per year.

5.2 Electron-Proton Colliding Beams Experimental Program

This section reviews the experimental program suggested for the optional electron-proton colliding beam facility. All of the experiments so far proposed can be carried out using the 4π solid angle calorimeter (Impactometer). Although a detailed design for

the e-p facility has not been completed, it is attractive to have the e-p collisions take place in at least the same straight section which was designed for the large t, p-p interactions. Furthermore, it appears feasible to achieve the change-over from p-p to e-p experiments with no substantial change to the detector. A partial list of the experiments proposed is given in Table III-5. An interesting experimental program can be mounted, with luminosities between 10^{30} and 10^{32} cm⁻² sec⁻¹.

Table III-5. Proposed Experiments. 15-GeV Electrons-200 GeV Protons

-
1. e-p elastic scattering (CRISP 71-43)	
2. e-p deep inelastic scattering (CRISP 71-43 and 72-9,15)	
3. e-p $\rightarrow \nu + \dots$ (CRISP 72-9,15)	See also Section III.4
4. neutral currents, e-p $\rightarrow \mu + \dots$ (CRISP 72-9,15)	
5. e-p $\rightarrow$ heavy lepton + hadrons (CRISP 72-9,15)	
-

The Impactometer is also adequate for separating e-p elastic and inelastic scattering over a large kinematic region. Magnetic spectrometers have been discussed for e-p scattering, both elastic and deep inelastic. Because the new domain (of q^2 and γ) opened by the availability of 5 to 15 GeV electrons upon 200-GeV protons is so large, a device with large spatial and energy acceptance is advantageous.

A comparison of positron and electron interactions is needed to untangle multiple from single-photon exchange processes in the deep inelastic region. It would be desirable therefore to be able to charge the electron ring with positrons as well as electrons.

5.3 Experimental Building Services

The experimental areas will consist of four enlarged sections of tunnel enclosing the experimental long straight sections of the machine. The East straight section (East Area) will be short, mostly for weak interaction experiments at large t. The three others, mostly for strong interaction experiments at smaller t, will be long.

Three of the buildings will be 200 m long and 10 m wide, except for a 25 m long "bubble" at the intersection area where the hall will expand to 14 m wide and 10 m high at the center, providing 5 m between the floor and the beam collision region. These buildings were designed primarily to accommodate strong interaction experiments involving moderately small transverse momentum. An important class of large t experiments could be done in the bubble at the intersection region which would be used for magnetic spectrometers analyzing relatively low momentum (say to 30 GeV/c) particles emitted at large angles from the interaction region.

The East Area building will be approximately 50 m long, 18 m wide, and 12 m high at the center with a 30 m long pit at the center providing 7 m between the floor and the collision region. Its size was selected to accommodate the weak interaction experiments with large transverse momentum. Figure III-18 shows typical beam layouts in the East experimental building. These buildings are designed to allow expansion with moderate cost should there be a need for the beams to extend outside the confines of the buildings. This, and additional design details of the buildings, are covered in Section XV.

Access for personnel and equipment into the interaction areas will be by tunnels connecting a service building to the interaction areas. The tunnels will be designed to prevent radiation leakage. The method for transporting large components such as magnets, shielding, and detection apparatus into the interaction areas has not been considered in sufficient detail for final selection. Also, since some regions of the interaction areas will not be provided with permanent overhead cranes, methods will be developed to handle heavy equipment in these areas. It is assumed that experiments will contain equipment similar to present-day standards, and that the frequency of experimental changes will remain about the same. Therefore, methods will be developed to handle 100-ton devices in each area several times each year. Techniques under consideration are: air pads, rail cars, electrically driven vehicles, and gantry cranes.

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IV. ISA RING STRUCTURE AND ORBIT DYNAMICS

1. Introduction

The guide and focusing fields of a storage ring are similar to those of a synchrotron, but the storage ring fields must be more precisely controlled. The two major problems are instability and diffusion. Beam instability can be induced in many different ways by the high charge density. Even instabilities with long (seconds or minutes) growth time must be avoided or suppressed. Slow diffusion of some of the protons into the vacuum chamber wall can result from various processes and must be minimized in order to permit experiments to be done with reasonable background. In general, one wants the highest feasible ratio of luminosity to background. This preliminary ring design has been done with the objectives of high luminosity, high instability thresholds and minimum diffusion. The theory of orbit dynamics permits calculation or estimation of most effects, and the theory has been refined by observations on the CERN ISR. However, some phenomena are not well enough understood and may need theoretical refinements to achieve highest luminosities and minimum background.

2. Lattice

A straightforward FODO lattice is chosen for the normal cells. Separated function elements are advantageous with superconductors because the magnetic forces are symmetrical in symmetrical elements. Four medium length insertions are provided for machine functions and four long insertions for experimental use. The overall geometry is shown in Fig. IV-1.

2.1 Normal Cells

The normal cells consist of four bending magnets and two quadrupoles per cell. The phase shift of the betatron oscillations is near $\pi/2$ per cell, resulting in the amplitude functions shown in Fig. IV-2. Maximum to minimum β ratio is about 5.7.

Fig. IV-1. General four-fold symmetry arrangement of the ISA.

Fig. IV-2. Normal cell and service insertion.

Although this rather large ratio increases the aperture requirement, it also reduces the interaction between the horizontal and vertical tuning coils (see below). Forty-eight cells are proposed, divided into eight pseudoarcs of 6 cells each. General properties of a normal cell are listed in Table IV-1.

Table IV-1. Orbital Characteristics of Normal Cells

Cell length	25.70 m
Bending magnet length	4.11 m
Field at 200 GeV	40 kG
Quadrupole length	1.16 m
Gradient at 200 GeV (nominal)	6.5 kG/cm
Straight section B-B	1.09 m
Straight section B-Q	1.19 m
Phase shift (nominal)	$\pi/2$
Maximum β	43 m
Maximum dispersion, X_p	1.7 m
Chromaticity* of 48 cells (nominal)	- 15.2

*Chromaticity is here defined as $\Delta v/(\Delta p/p)$. The normal cells contribute a total bending angle somewhat less than 2π because bending is needed in the insertions for control of the momentum function X_p . Items indicated as "nominal" will vary slightly with adjustment of tune.

2.2 Service Insertions

The major machine functions requiring space in the ring are injection, beam dump or extraction, radiofrequency acceleration and beam observation. Four service insertions provide space for the machine functions. A design of a service insertion is also shown in Fig. IV-2. The central straight section is 37.95 m long, in addition to two 5 m straight sections, one at each end. All three amplitude functions are matched and X_p is made zero in the central region. Manipulation of X_p requires bending magnets in the insertion. It is important that the amplitude functions be matched in order to avoid disturbing the rest of the ring.

However, it is not as important that X_p be exactly zero, or that β_h and β_v be nearly equal. The insertion can then be "tuned" to less extreme values. Some important orbital characteristics are given in Table IV-2.

Table IV-2. Orbital Characteristics of Service Insertions

	Horizontal	Vertical
Phase shift per insertion (nominal)	2.02π	1.29π
Chromaticity of 4 insertions (nominal)	-6.19	-5.30
Phase shift center of 5 m to center of 38 m	0.99π	0.55π
Phase shift in 38 m straight section	0.43π	0.41π
Total length	110 m	

2.3 Experimental Insertions

Four insertion locations, each 250 m long, are provided for colliding beam experiments. These are regarded as variables to be adjusted to suit the experimental program. The following general classes of insertions will clearly be required for different experimental applications. One, for large-angle, low-event rate experiments will want maximum luminosity, reasonable length of unobstructed central region, low β , small or vanishing X_p and Y_p and adjustable crossing angle. Another insertion for small-angle pp experiments will want small angular divergence at the crossing region and as long as possible unobstructed regions. Two other experimental insertions have been worked out; an insertion with a magnet arrangement identical to the low-beta insertion, but with different magnet excitations leading to a modest-beta at the crossing point and reduced chromaticity. Another example of an insertion is the "Multipurpose Spectrometer" (MPS) insertion which is designed around a spectrometer magnet at the crossing point. In principle, the crossing can be either horizontal or vertical. Since the beams must be deflected vertically to intersect, there will be a vertical momentum compaction function, Y_p . It is important to match the four amplitude functions, β_h, β_v, X_p and Y_p for any

usable insertion.

An example of a low- β insertion is shown in Figs. IV-3a and IV-3b. Such an insertion should achieve a luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$. This insertion has a horizontal crossing at angles variable from 0 to 6 mrad, matched amplitude functions at its ends and momentum functions X_p and Y_p zero at the center. The unobstructed central region is 40 m long. In order to reduce beam-beam interaction the two beams are separated horizontally up to the central region. The orbital characteristics are given in Table IV-3.

Table IV-3. Low- β Experimental Insertion

	Horizontal	Vertical
Phase shift per insertion (nominal)	4.29 π	3.35 π
Chromaticity per insertion (nominal)	-11.4	-12.2
β_{max}	630 m	950
β^* at center	5.4 m	2.2 m
Total length	250 m	

An insertion with a magnet configuration identical to the low- β insertion, but different magnet excitations resulting in a smaller chromaticity than the low- β insertion, will be useful for machine start-up and for exploratory experiments. The characteristics are shown in Table IV-4.

Table IV-4. Reduced Chromaticity Insertion

	Horizontal	Vertical
Phase Shift per insertion (nominal)	4.13 π	3.10 π
Chromaticity per insertion (nominal)	-7.5	-5.2
β_{max}	213	340
β^* at center	18.4	6.4
Total length	250 m

Fig. IV-3a. Low β insertion - amplitude functions.

Fig. IV-3b. Low β insertions - central orbit design.

An example of a quite different insertion, of a type suitable for small angle observations, is shown in Fig. IV-4. The crossing is brought to approximately zero angle in the central region of about 3 m. Two unobstructed straight sections, each 56 m long, are arranged for placement of detection equipment. This insertion has characteristics given in Table IV-5.

Table IV-5.

Orbital Characteristics of Small-Angle Scattering Insertion

	Horizontal	Vertical
Phase shift per insertion (nominal)	2.74 π	2.64 π
Chromaticity per insertion (nominal)	-3.10	-2.86
$\beta_{\max}$	245 m	205 m
β^N at center	190 m	205 m
Total length	250 m	

The MPS insertion is shown in Figs. IV-5a and IV-5b. This example will require special magnets in order to accommodate the specialized crossing region and the spaces required for the detection and analyzing equipment.

The insertions have a strong influence on the properties of the ring. Contributions of two of the examples given above are summarized in Table IV-6. These represent the largest and smallest probable values of phase shift and chromaticity.

Rings of this type will not operate with a single ν value; rather they will be set to ν 's in the range of 17 to 25 depending on the specific insertion and insertion tuning being used. Note, however, that structure resonances in a four-fold periodicity, with deceleration into the stack, suggest operation between $\nu = 19$ and $19 \frac{1}{2}$ or $\nu = 23$ and $23 \frac{1}{2}$. Insertions are needed for proper employment of the rings. Their large phase shift is not troublesome, but their large negative chromaticity creates problems. It is clear that the machine would be started with four-fold symmetry and simple insertions, perhaps tuned to even lower chromaticity than the example of Table IV-4. Following achievement

Table IV-6. Total Ring Characteristics-
Without Sextupole Corrections

	Phase Shift		Chromaticity	
	Horiz.	Vert.	Horiz.	Vert.
48 Normal cells	24 π	24 π	-15.2	-15.2
4 Service insertions	8.1 π	5.1 π	- 6.2	- 5.3
4 Reduced chromaticity ins.	16.5 π	12.4 π	-30	-20.8
2 Low- β ins.	8.6 π	6.7 π	-22.8	-24.4
2 Small-angle ins.	5.5 π	5.3 π	- 6.1	- 5.7

Total ring with				
4 Reduced chromaticity ins.	48.6 π	41.5 π	-51.4	-41.3
2 Low- β and 2 small-angle ins.	46.2 π	41.1 π	-50.4	-50.5

Fig. IV-4. Small angle scattering insertion.

Fig. IV-5a. MPS insertion-amplitude functions.

Fig. IV-5b. MPS insertion-central orbit diagram.

of stable operation, two low- β insertions could be activated and compensated. Once the rings have been corrected, this reduction of periodicity to two should not be a serious problem. The presence of two classes of long insertions would be advantageous for operation of a varied experimental program. Whether the periodicity could be reduced to one is unclear. The results depend on the details of the ring imperfections. However, the successful operation of the ISR with the split-field magnet, a somewhat less radical single periodicity, has been encouraging. The consequences of the large negative chromaticity are treated more fully in the next section.

3. Working Line

The particles will have a frequency of oscillation about their closed orbit which is a function of momentum (or radius) and amplitude. Small amplitude frequency vs momentum can be plotted on a $v_h - v_v$ chart, Fig. IV-6, to show the working line of either ring. The "bare machine" working line computed for this ring, with insertions per Table IV-6, is shown as A in Fig. IV-6. Nonlinear resonances can be excited if $k v_h + l v_v = m$, where k , l and m are positive integers. These "sum" resonances are troublesome, whereas the "difference" resonances, for which k and l have opposite signs, do not result in large growth of amplitude. The order of the resonance is $k + l$, and it is excited by the m^{th} azimuthal harmonic of the order $k + l$ driving term. Excitation is provided by magnet imperfections, stray fields and beam-beam interactions, and in general decreases as the order of the resonance increases. Particles on high order resonances are subject to slow amplitude growth in a complex fashion which resembles diffusion. Those on low order resonances (4th and lower) undergo rapid amplitude buildup, rapid on the time scale of a storage ring, and are lost on the chamber wall.

The working line, A, is not usable because it passes across a whole spectrum of resonances. In addition, the slope, dv/dp , is

Fig. IV-6. Resonance diagram.

negative. Avoidance of instabilities due to collective effects (Section V) requires a positive slope. The positive derivative dv/dp should be as large as possible for Landau damping of instabilities, yet must not be so large as to cause a beam of given momentum spread to cross damaging resonances. Two of the many possible working lines are shown as B and C in Fig. IV-6. Of these, B allows the greatest v spread, but crosses the fan of 5th and, perhaps, also 7th order resonances. It has been the experience on the ISR that beams crossing the 5th order resonances are subject to a slow diffusion-like amplitude growth of some protons, producing high background for the experiments. Working line C is usable for most ISA purposes and it is probable that line B can be made usable by application of 5th order azimuthal corrections or fine adjustment of the intersections.

During acceleration the v -value of individual particles will vary periodically with time as a result of synchrotron oscillations. This leads to repeated crossings of those nonlinear resonances included in the particle's v -swing. Because the two beams will be separated during acceleration, excitation of nonlinear resonances is due primarily to magnet imperfections and not to the otherwise dominating beam-beam interaction.

Examination of the random magnetic field errors quoted in Sec. VI-3.5 shows that, with the ISA beam and machine parameters, even the low order nonlinear resonances ($n = 4$) are relatively weak. The change in a particle's betatron amplitude caused by a single resonance crossing is then small and the amplitude will have grown significantly only after many synchrotron periods. One can calculate the time it takes for the betatron emittance to double using a statistical model based on the assumption that the betatron phase gets randomized between consecutive crossings.

Resonance widths, Δv , and doubling times, t_d , for a betatron amplitude corresponding to the beam emittance at 30 GeV and a v -swing of ± 0.03 , have been calculated for the different order resonances and are shown in Table IV-7. The calculation of t_d

is done for the most pessimistic case of an off-momentum particle, when higher order terms contribute to the n th resonance. The results show that, as long as the working line keeps clear of third and fourth order resonances, the effects of magnet imperfections should be negligible during an acceleration time of a few minutes, even without compensation.

Table IV-7.

Nonlinear Resonance Width and Emittance Doubling Times

n	Δv	t_d (sec)
3	1.8×10^{-4}	0.58
4	5.0×10^{-6}	680
5	1.2×10^{-7}	7.6×10^5
6	3.2×10^{-9}	10^9
7	7.4×10^{-11}	2.8×10^{12}

3.1 Compensation

The ring system requires an extensive set of compensating windings. These will be referred to as "tuning windings" and "correcting windings", and it will be noted that the same physical coils can, in most instances, serve both purposes. The tuning windings establish the working line and are excited uniformly in azimuth while the correcting windings compensate for imperfections and are variable with respect to azimuth.

Setting of the central tune, v_h and v_v at $\Delta p = 0$, is done by the lattice quadrupoles. It is presumed that, in each ring, the dipoles and each of the two classes of quadrupoles will be connected in series. The central tune should be maintained to about a milli- v unit (10^{-3} in v) which requires that the quadrupoles be tracked to the dipoles to about 50 parts per million. It will be necessary to store the history of the diamagnetic currents and to use standard cycles to maintain the correspondence of dipoles and quadrupoles.

3.2 Tuning Coils

The lattice needs sextupoles for setting the chromaticity of the working line. The chromaticity of line A, Fig. IV-6, requires positive ($\beta_h > \beta_v$) and negative ($\beta_v > \beta_h$) sextupoles in all normal cell quadrupoles and dipoles. A sextupole having a pole tip field, B_T , at 6 cm, of about 1 kG is required to reduce this chromaticity to zero. This represents a $b_2 = 6.9 \times 10^{-4} \text{ cm}^{-2}$.^{*} The working line must be stretched in the positive dv/dp sense. In addition, sextupole compensation is required for the magnets at high induction (VI-3.3) to keep the working line fixed. These factors add about 50% to the field, leading to a needed sextupole in all elements of about $B_T = 1.5 \text{ kG}$. The sextupole windings would be programmed to compensate for magnetization and dynamic effects (VI-3.4).

The working line of a real ring will not be straight, as sketched in Fig. IV-6. It will be curved by higher order field components and space charge effects. Adequate adjustment of curvature can be obtained by octupoles, in the quadrupoles, having a B_T about 0.5 kG. Similarly, a small amount of ten-pole and twelve-pole field component is needed to correct the ends of the working line. One of these would be put in the dipoles, the other in the quadrupoles. It is doubtful that higher order tuning coils would be needed, or that the measurements necessary for their systematic adjustment could be made. The tuning winding requirements are summarized in Table IV-8.

^{*}The vertical magnetic field in the median plane is defined by $B_y = B_0 (1 + b_2 x^2 + b_4 x^4 + \dots)$.

Table IV-8 Required Tuning Windings

Order*	Function	Location	B_T (kG)	b_n	Ampere-turns/pole
2	Operating point	Main quads	---	---	
3	Chromaticity	All normal magnets	1.5	$1 \times 10^{-3} \text{ cm}^{-2}$	9500
4	Curvature	Quads	0.5	$6 \times 10^{-7} \text{ cm}^{-3}$	2380
5	High-order	Dipoles	0.05	$1 \times 10^{-6} \text{ cm}^{-4}$	200
6		Quads	0.05	$1.6 \times 10^{-7} \text{ cm}^{-5}$	150

*Order is number of poles/2, and the order of the nonlinear resonance excited by the corresponding field term. n of b_n is order -1.

3.3 Correction Windings

Correcting windings are required for application of azimuthal harmonics to compensate for imperfections. Imperfections arise from the inevitable small variations in magnet construction, small errors in alignment, stray fields and beam-beam forces. Perturbation of the horizontal equilibrium orbit is caused mostly by variations of bending strength of the dipoles and errors of alignment of the quadrupoles. The former can be held to $\Delta B/B = 5 \times 10^{-4}$ and the latter needs a tolerance of 0.5 mm rms. For the corresponding vertical equilibrium orbit effects the deviation of the dipole field from the vertical needs a tolerance of 0.5 mrad. Correcting dipoles, horizontal and vertical, of field strength 200 G in each normal cell dipole, will correct any likely orbit perturbation. Quadrupole trim windings are needed in the lattice quadrupoles to compensate for quadrupole strength variation, and possibly for off-momentum orbit distortions caused by misalignment of the sextupoles. Skew quadrupoles will align the normal modes of the rings using the observing and correcting apparatus. Higher order corrections may be required due to magnetic field errors and beam-beam forces.

There are indications, in observations made at the ISR, that small nonlinear multipole imperfections have an appreciable effect on the loss rate and associated background in storage rings at high beam intensity and long beam lifetime. The nonlinearities induced by the beam-beam interaction depend on the differences between the beam-beam interaction regions. Experiments and calculations indicate that this source of nonlinear excitation is at least as large as that due to errors in the magnetic fields¹. A multiple turn correcting winding in the dipoles will produce high order nonlinearities large enough to correct expected random errors (VI-3). During storage, azimuthal harmonics can be applied to reduce the diffusion apparently caused by these high order resonances.

Sextupole and octopole excitation will be provided by

azimuthal variation of the current in the corresponding tuning windings.

4. Compensating System

The foregoing lists of tuning and correcting windings are lengthy. Currents must be adjusted to set the working line, orbit corrections and azimuthal corrections for injection. Then, during acceleration, the working line must be kept fixed with a precision of a few thousandths of a v -unit. In addition, the orbit must be kept central, and bothersome azimuthal harmonics must be corrected. Finally, when the guide field is stabilized for storage, the tuning and correcting windings must be adjusted for best beam-beam collisions and minimum experimental background. Such a process, involving large numbers of adjustments and systematic observation of results, has been demonstrated successfully on the ISR and on SPEAR.

Each magnet will have compensating windings wound and molded on a production fixture. Currents, not more than 25 A, can then be supplied by local control electronics, which is instructed from the control computer. The amount of data which must be stored and processed is very large but within the capability of presently available computer and solid state technology. Data will be accumulated stepwise beginning with magnetic measurements and continuing with successive incremental accelerations of protons. As observations are refined the stored tables of data will be modified accordingly.

A useful proton storage ring must have an elaborate compensating system. Present solid state technology can perform the control at the eight and ten bit precision level required and at relatively modest cost. It should be noted that a storage ring, operated over a wide range of energies, needs the same compensation, and the same tables of values, as are needed by an accelerating storage ring. Superconductors are particularly useful for compensation because their current density is high. By comparison,

small copper windings are difficult to cool and can operate at rather limited current density. Combining superconducting and solid-state technology makes compensation of an accelerating storage ring feasible.

5. Luminosity Estimates in the ISA

We have presented three types of experimental insertions. The beam crossing arrangements are described in Section III-5 and the amplitude function and orbit characteristics of the insertions are given in Section (IV-2). Here we will give the luminosity estimates for the three cases. The first is a setup designed to give both a high luminosity and a significant free space for experimental equipment. We have designated this type of insertion, "Low- β Insertion". The long free space and high available luminosity make this insertion applicable to a wide variety of experiments. The other two types of insertions are of a rather specialized nature. The one denoted "Small Angle Scattering Insertion" is designed for small angle p-p scattering and involves the collinear interaction of the two beams, which are rapidly separated by bending magnets after a few meters of interaction. Finally, we have the insertion denoted, "Multipurpose Spectrometer Insertion", which requires a total space for the experimental apparatus of over 100 m. In this specialized insertion, the beams interact within a bending magnet, which serves as the means of separating the beams.

To compute luminosities and beam-beam tune shifts, we assume uniform density distributions in both transverse directions. This allows us to obtain closed expressions for the luminosity and tune shift densities per unit length of interaction region, even for the case when the emittances, ϵ , and β -functions are different, horizontally and vertically. To make the model realistic we choose the distribution widths in such a way that for round beams ($\epsilon_h = \epsilon_v$, $\beta_h = \beta_v$) we obtain, in the limits of zero and large crossing angles, luminosities and tune shifts equivalent to those

obtained with a Gaussian distribution. The equivalent rms emittance is found to be

$$\epsilon_{\text{rms}} = \epsilon/\pi \quad . \quad (\text{IV-1})$$

We assume horizontal crossing and, therefore, only the vertical beam-beam tune shift need be considered. Introducing the beam separation parameter,

$$\eta = \frac{\alpha \sqrt{\beta_h^*}}{\sqrt{\epsilon_h}/\pi} \quad , \quad (\text{IV-2})$$

the beam interaction length parameter,

$$\xi = \frac{\ell}{2\beta_h^*} \quad , \quad (\text{IV-3})$$

the β -function ratio,

$$u = \frac{\beta_h^*}{\beta_v^*} \quad , \quad (\text{IV-4})$$

and the emittance ratio,

$$\epsilon_{\text{hv}} = \frac{\epsilon_h}{\epsilon_v} \quad , \quad (\text{IV-5})$$

with ϵ_h, ϵ_v the horizontal and vertical emittances, β_h^*, β_v^* the horizontal and vertical β -values at the crossing point, ℓ the total interaction length, and α the total crossing angle, we write the luminosity and vertical tune shift as

$$L = L_0 K(\eta, \xi, u) \quad (\text{IV-6})$$

$$\Delta v_v = \Delta v_0 I_v(\eta, \xi, u, \epsilon_{\text{hv}}) \quad , \quad (\text{IV-7})$$

where

$$\Delta v_0 = \frac{I}{e} \frac{r_p \ell \pi}{c \gamma \sqrt{\epsilon_h \epsilon_v}} \quad , \quad (\text{IV-8})$$

and

$$L_0 = \left(\frac{I}{e}\right)^2 \frac{\pi}{c \sqrt{\epsilon_h \epsilon_v}} \quad . \quad (\text{IV-9})$$

The K and I_v integrals over the interaction length are given by

$$K = u^{1/2} \int_0^{\xi_m} \frac{dt}{(1+t^2)\sqrt{1+u^2t^2}} \left[\sqrt{1+t^2} - 1/2 \eta t \right], \quad (IV-10)$$

$$I_v = \frac{u^{-1/2}}{\pi \xi} \int_0^{\xi} dt \frac{\sqrt{1+u^2t^2}}{\sqrt{1+t^2}} [\operatorname{arctg} v_+ + \operatorname{arctg} v_-], \quad (IV-11)$$

where

$$\xi_m = \operatorname{MIN} [\xi, (\eta^2/4 - 1)^{-1/2}] \quad (IV-12)$$

and

$$v_{\pm} = e^{1/2}_{hv} u^{1/2} \frac{\sqrt{1+t^2} \pm \sqrt{2} \eta t}{\sqrt{1+u^2t^2}}. \quad (IV-13)$$

Low- β Insertion. In this insertion, Figs. III-17 and IV-3a, IV-3b, the beams are arranged for horizontal crossing. For the ISA parameters, the luminosity can be estimated from the asymptotic (i.e. large crossing angle) expression,

$$L = \frac{I}{e} \frac{\gamma}{2 r_p \beta_v^*} \Delta v_v, \quad (IV-14)$$

where γ is the energy in mass units, I is the circulating current, e is the charge of the proton, r_p is the classical proton radius, and the crossing angle, α , enters implicitly in Δv_v . The crossing angle can be estimated from

$$\alpha = \left(\frac{I}{e} \right) \frac{\sqrt{2} r_p \beta_v^*}{c b \gamma (\Delta v_v)} \quad (IV-15)$$

where b is the vertical half size of the beam, and c is the velocity of light. The asymptotic expressions (IV-14 and IV-15) can be obtained from the general expressions for L and Δv_v by taking the limit $\eta \rightarrow \infty$.

Using the design values, $b = 0.32$ mm, $\gamma = 214$, $I = 10$ A, $\beta_v^* = 2.2$ m, and assuming a beam-beam limit $\Delta v_v = 5 \times 10^{-3}$, we obtain

$$L = 1.4 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1} ,$$

and

$$\alpha = 2.9 \text{ mrad}.$$

Although we have assumed a beam-beam limit of 5×10^{-3} , it should be pointed out that this may be somewhat low. It is conceivable that, in reality, the limit is 2 to 4 times higher, which could mean a significantly higher luminosity.

The asymptotic expressions above neglect the long-range beam interaction.² Note also that they are independent of β_h^* . Because of the long free space for experimental use, it is advantageous to gain luminosity by decreasing β_v^* , but leaving β_h^* at some higher value. Thus, after the long free space, the first quadrupole of the focusing triplet can be vertically focusing. This has the effect of keeping the maximum β value in the triplet significantly below what it would be if both β -functions were taken to "low" values. Now, at first glance, there would be no barrier to doing this. The expressions for L and α are independent of β_h^* while the parameters determining the effect of the long-range interaction are independent of β_v^* . These latter are just the beam separation parameter

$$\xi = \frac{\sigma_{\beta_h^*}}{a} = 31.9 ,$$

where the horizontal β value, $\beta_h^* = 5.5$ m, and the horizontal half size, $a = 0.5$ mm; and the beam interaction length parameter,

$$\zeta = \frac{\ell}{2\beta_h^*} = 3.6 ,$$

where ℓ is the beam interaction length, which is related to the distance from the collision center to the focusing triplet:

$l = 40$ m. However, there is a flaw in this argument. When the horizontal and vertical β^* values are not equal their ratio, $u = \beta_h^*/\beta_v^*$, must now be considered. As u increases, a saturation arises, even though η and ξ are remaining constant. Thus, it can be shown that the luminosity is limited by the increasing u as β_v^* is made smaller. However, for the values chosen here, the saturation effect is small. A numerical computation gives the result, $L = 1.3 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ and $\alpha = 2.4$ mrad. The total overlap length is roughly $l_{\text{INT}} = 4a/\alpha = 0.8$ m.

In order to avoid, in the initial stages of storage ring operation, the problems related to "high" β values (for example, the high chromaticity) we have modified the low- β insertion to provide only a moderate β_v^* . (The modified low- β insertion is shown in Table IV-4.) Thus, we have found that by increasing β_v from 2.2 m to 6.0 m, the maximum β values are reduced to about 300 m and the chromaticities are reduced by almost a factor of 2. The cost of doing this, however, is a reduction in luminosity of a factor of 2.7. But, even at this reduced level of operation, the attainable beam-beam limited luminosity is $L = 5 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$.

Small Angle Scattering Insertion. For the small angle p-p scattering experiment, Figs. III-17 and IV-4, it is expedient to use collinear crossing. The beams are then separated by bending magnets placed nearby. However, nuclear interactions taking place within the bending magnets, and in fact within 30 cm of each bending magnet, cannot be used. Nevertheless the electromagnetic interaction of the two beams in these regions cannot be neglected. Thus, we write the effective luminosity,

$$L = \frac{I}{e} \frac{Y}{r_p \xi^*} \Delta v_{\text{eff}} \quad . \quad (\text{IV-16})$$

But there are two terms contributing to the tune shift,

$$\Delta v = (\Delta v)_{\text{eff}} + (\Delta v)_{\text{lost}}, \quad (\text{IV-17})$$

where $(\Delta\nu)_{\text{lost}}$ corresponds to the beam-beam interaction in the bending magnets and in a given region near the bending magnets, where the nuclear interactions are deemed unusable. It can be shown that, to maximize luminosity, we should choose conditions such that

$$(\Delta\nu)_{\text{eff}} = (\Delta\nu)_{\text{lost}} \quad . \quad (\text{IV-18})$$

For a beam-beam tune shift limit $\Delta\nu = 5 \times 10^{-3}$, we have $(\Delta\nu)_{\text{eff}} = 2.5 \times 10^{-3}$. Thus, with $\beta^* = 200$ m, $\gamma = 214$ and $I = 2.78$ A, we find $L = 3.0 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$. This can be achieved with bending magnets 1.8 m in length providing kicks of 10.7 mrad to separate the beams. The effective interaction length is $l_{\text{eff}} = 2.4$ m. The beam-beam tune shift is proportional to the current density. To attain the current $I = 2.78$ A, we must therefore have sufficient transverse emittance in order not to exceed the beam-beam limit. In fact, the current, $I = 2.78$ A, was chosen, so that, at the beam-beam limit, it corresponds to a required emittance, $\epsilon = 0.2 \times 10^{-6} \pi$ m.rad at $p = 200$ GeV/c, which, from aperture considerations, is deemed the largest which is reasonably attainable.

Multipurpose Spectrometer Insertion. The "large-spectrometer" experimental setup, Figs. III-17 and IV-5a and IV-5b, has been designed so that the beams interact within a bending magnet.³ In this case, the luminosity and beam-beam tune shift can be expressed approximately as

$$L = \frac{8}{3\pi} \frac{I}{e} \frac{\gamma \Delta\nu}{r_p \beta^*} \quad , \quad (\text{IV-19})$$

$$\Delta\nu = \frac{I}{e} \frac{\pi \sqrt{2} r_p \sqrt{\rho} (\beta^*)^{\frac{1}{4}}}{4c\gamma (\epsilon/\pi)^{3/4}} \quad , \quad (\text{IV-20})$$

where ρ is the magnet radius of curvature. The experiment utilizes a 10 kG magnet, giving $\rho = 670.3$ m (at $p = 200$ GeV/c). The value of β^* is related to the amount of experimental space required until the first focusing element. We have chosen $\beta^* = 100$ m.

Then, assuming a beam-beam limit, $\Delta v = 5 \times 10^{-3}$, and an emittance, $\epsilon/\pi = 0.2 \times 10^{-6}$ m.rad (the largest reasonable value), we find for the maximum current, $I = 3.47$ A. Thus, we obtain for the luminosity $L = 1.28 \times 10^{31}$ cm⁻²sec⁻¹. The total overlap length is estimated from

$$l_{\text{INT}} = 2\sqrt{2} (\beta^*)^{1/4} (\epsilon/\pi)^{1/4} \rho^{1/2}; \quad (\text{IV-21})$$

or $l_{\text{INT}} \approx 4.9$ m.

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V. COLLECTIVE EFFECTS IN ISA

1. Introduction

The stability of particle orbits in an accelerator or storage ring is affected by the electromagnetic fields produced, directly or indirectly, by the beams. When these become comparable to the externally imposed guiding, focusing and accelerating fields (in many cases even when the self fields are still an order of magnitude or so below the external fields), the amplitudes of oscillation in the beam can become large, leading to degradation of the beam and loss of particles. These effects, therefore, impose maximum limits on the attainable beam intensity.

The effects that have to be considered include:

1.1 Transverse space charge effects

The effective transverse oscillation frequencies are shifted by the field gradient due to the charge and current of the beam, and image charges and currents induced in the surrounding chamber walls.

1.2 Transverse resistive wall instabilities

These arise from the phase difference between the oscillations of the beam and the induced currents in the walls; these phase differences are due to the finite resistivity of the wall material.

1.3 Longitudinal instabilities

These arise because the beam induces longitudinal electric fields which accelerate or decelerate particles. Such fields are particularly apt to be induced in the rf accelerating cavities. They compete with the accelerating field in the stacking and acceleration process and can also degrade the energy spread and uniformity of a coasting beam.

1.4 Interactions between the two beams

The field of one beam affects the particles of the other beam in the vicinity of the crossing region. Unlike the other collective effects mentioned above, this one is sharply localized. This is unfavorable because the perturbation is rich in azimuthal harmonics

up to very high orders, exciting nonlinear resonances.

All these effects have to be considered, if applicable, for the beam in four stages of its career: first during the injection and stacking process; second, for the coasting unbunched beam at injection energy at the end of the stacking process; third for the bunched beam during acceleration from injection to 200 GeV; finally for the coasting intersecting beams at 200 GeV.

2. Detailed Discussion of the Effects

2.1 Space charge detuning

This effect has been treated by Laslett.¹ The most important terms here are those due to image charges and currents in the walls (the direct effect contains a near cancellation between electric and magnetic forces). The result may be simplified to

$$\nu - \nu_0 = - \frac{2}{\gamma} \frac{r_p R^2}{\gamma a^2} \frac{I}{ec} g \quad (V.1)$$

where ν is the betatron tune, r_p is the classical proton radius, a the vacuum chamber radius, R is the average ring radius, I the current in amperes, e the proton charge, c the velocity of light, γ the energy in mass units, and g is a geometrical factor. The value of g is, in fact, zero for a circular vacuum chamber with the beam at its center. During the stacking process, however, the beam will not be centered exactly. It may be estimated that for the ribbon beam in the expected locations, $g \leq 0.1$. Thus, with $I = 10A$,

$$\nu - \nu_0 \leq - 0.01$$

The tolerable tune shift is usually taken as whatever it takes to push to the nearest linear (half-integral) resonance, e.g. a shift of about 0.1 unit in our case. But it is, in fact, necessary to control the tune of all parts of the beam to within about 0.01; thus the space charge effect will probably have to be

compensated dynamically during the stacking process. (This is the procedure called "prestressing of the working line" at the CERN ISR.) Provisions for such "prestressing" have to be incorporated in the ISA magnet control system. This is discussed further in Section IV.

The detuning effect becomes much smaller during acceleration and full energy operation, both because of the increase of γ and due to the fact that during and after acceleration the beam will be centered in the chamber, making the coefficient g in Eq. V.1 small.

2.2 Limitations due to wall resistivity

The transverse motion of intense particle beams can be unstable as a result of the resistivity in the chamber walls. The formation of unstable collective modes can, however, be prevented by having sufficient spread in betatron tunes in the beam. The basic limitation can be stated as follows: for a given current, there is a minimum tune spread which is proportional to the current. That is,² when the required tune spread is accomplished by sextupoles the necessary condition is

$$\left| (k-v)\eta + \frac{\partial v}{\partial \rho} \Delta \rho \right| > \frac{4r_P R^{5/2} I}{e v \gamma a^3} \sqrt{\frac{2 \epsilon_0 \rho}{c |k-v|}} \quad (V.2)$$

where $\Delta v = \frac{\partial v}{\partial \rho}$ is the full tune spread, ρ is the chamber resistivity, k is the mode number for the unstable mode ($k > v$), ϵ_0 is the free space dielectric constant, η is $1/\gamma_t^2 - 1/\gamma^2$ and we have assumed the proton velocity, $\beta = 1$.

For the ISA, $R = 428$ m, $v = 19.4$ (vertical), $\gamma = 31.4$ (Injection), $a = 4$ cm, $\rho = 1.6 \times 10^{-8}$ ohm-m (aluminum), thus the stability criterion for the lowest mode, $k = 21$, is $\Delta v > 1.4 \times 10^{-4}$. This criterion is sufficient to stabilize all higher modes as well, provided that $\partial v_z / \partial \rho > 0$.

For the 10 A design current, the tune spread required is 1.4×10^{-3} , which is well below the design estimate of $4-6 \times 10^{-2}$. In fact, the use of stainless steel for the chamber is not precluded. In this case, $\rho = 0.7 \times 10^{-6} \Omega.m$, and the current limit is $I < 1000\Delta v$. With $\Delta v = 0.04$, $I < 40$ A, well above the design current.

Thus, the design satisfies the basic constraint imposed by the transverse resistive wall instability. There are, however, two aspects to this problem, which are overlooked in writing the condition, (V.2), and which must be considered. First, there is the possibility of the "brick wall effect", which is a phenomenon observed at the CERN ISR and which has been satisfactorily explained by combining the resistive wall effect with a non-uniform (across the beam) incoherent tune shift.^{3,4} It can be shown⁵ that with the circular geometry, our stacking mode, and for a properly positioned beam, the parabolic term in v versus radius (across the chamber), that is, the term responsible for the brick wall effect,^{3,4} can be neglected. Thus, the brick wall effect is not expected to impose any serious constraint. Secondly, we must consider the fact that in writing Eq. (V.2), we have neglected the beam dependent term. Although such a term causes only a real frequency shift in any collective oscillation mode and therefore, by itself, cannot induce an instability, it can combine with the resistive component to lower the threshold. In the ISR, this term is rather small and is usually neglected. However, our design uses a very small beam size and the ISA has a radius almost three times that of ISR. Because the real frequency shift is proportional to R^2 and inversely proportional to the transverse beam area, it becomes an important factor in our design. In fact, the threshold criterion in the ISA design is dominated by the real part of the frequency shift and can be written,³

$$\Delta v > \frac{16\pi R^2 I}{\epsilon v c \gamma^3 A B} \quad , \quad (V.3)$$

where A is the beam transverse area, and B is the bunching factor ($B < 1$). With $A = 1 \text{ cm}^2$, and $B = 1$ (no bunching), $\Delta v > 1.8 \times 10^{-3} I$. This required spread is an order of magnitude more than arises from the resistive term. For $I = 10 \text{ A}$, the required spread, $\Delta v \approx 0.02$, is uncomfortably large. With a bunching factor, $B = 1/3$, the required spread increases to $\Delta v \approx 0.06$. This would mean that the working line of the bunched beam would at least have to cross the 5th order resonances. In order to avoid these difficulties, we suggest that a system of programmed working line prestressing would relax the constraint (V.3). By including an azimuthally uniform octupole in the ring, a parabolic term in the v versus p variation results. This shifts the stability threshold.³ Then, by choosing the proper octupole sign, the real frequency shift can be partially cancelled. If the octupoles are properly programmed during bunching, the required tune spread can be reduced³ by at least a factor of 2. Furthermore, with the use of electronic feedback, we can reduce the required spread by another factor of 2. Thus, finally, we arrive at a required bunched beam tune spread of $\Delta v \approx 0.015$ for the design current of 10 A.

In summary: By employing the techniques of working line prestressing and electronic feedback, we can effectively remove the resistive wall instability as a current limitation for the ISA design.

During stacking, when tight bunches from the AGS are circulating in the ISA, a transverse instability, known as the head-tail effect, can occur. Here, particles at the head of one bunch exert forces on the particles at its tail, through the wake fields due to finite resistivity of the vacuum chamber. Theory predicts that as long as the chromaticity, defined as $\Delta v / (\Delta p/p)$, is positive and greater than a given value, all lower modes are stable, even in the absence of Landau damping by octupoles. In particular, with $[2T_B \omega_0 / \eta] (\Delta v/v) / (\Delta p/p) \approx 30$, stability is achieved up to 11th mode.⁶ Here T_B is the full bunch length in time units and ω_0 the angular betatron oscillation frequency. With the ISA parameters

$T_B = 2.3 \times 10^{-8}$ sec, $\omega_0 = 1.4 \times 10^7$ sec⁻¹ and $\eta = 0.0014$ one gets $(\Delta v/v)/(\Delta p/p) = 0.065$, consistent with the requirement for Δv found earlier in this section for the ordinary transverse resistive wall instability.

2.3 Longitudinal effects

Coasting beams. The well-known "negative mass instability" amplifies small nonuniformities in a supposedly uniform coasting beam by a mechanism where a nonuniformity induces longitudinal electric fields of such a sign that the nonuniformity is further enhanced. The instability is suppressed by Landau damping, which arises from a spread in the revolution frequencies of the particles in the beam, counteracting the tendency of the lumpiness to amplify coherently.

The original theory of this effect⁷ concerned itself only with a beam in a vacuum chamber pipe of uniform cross section. But similar, and generally much stronger, fields will be induced in rf cavities (or other devices) that are present at various places around the circumference.

The modern theory⁸ of the coasting beam instability shows that the crucial quantity is the coupling impedance, Z , at a given frequency, i.e. the voltage induced in the sum total of all components along the circumference by a unit current. The stability criterion is

$$IZ_n < n\eta \frac{E}{e} \left(\frac{\Delta p}{p}\right)^2 F, \quad (V.4)$$

where η is the coefficient of dependence of angular velocity on momentum, Δp is the momentum spread of the beam, F is a form factor depending on the shape of the momentum distribution ($F \approx 1$ for a Gaussian distribution if Δp is taken as the full width at half maximum), and Z_n is the coupling impedance for the n^{th} harmonic of the revolution frequency.

It is of interest to note that, with the factor F replaced by $\pi/8$, Eq. (V.4) is precisely the voltage for a zero-acceleration

"bucket" at harmonic number n containing a beam with total maximum momentum spread Δp .

For our nominal parameters ($E = 28.5$ GeV at injection, $\Delta p/p = 0.007$, $\eta = 0.0015$, $I = 10$ A), we find

$$Z_n/n < 216 \Omega$$

The impedance presented to the beam is due to contributions from the vacuum chamber and passive insertions, and from the two rf systems, the stacking system (operating on the 40th harmonic of the revolution frequency) and the accelerating system operating on the second harmonic.

The coupling impedance of a smooth cylindrical vacuum chamber is known to be

$$Z_n/n = \frac{Z_0}{2\gamma^2} \left(\frac{1}{2} + 2 \log a/b \right)$$

where a is the chamber radius, b the beam radius, and $Z_0 = 377 \Omega$ is the impedance of free space. With $a = 4$ cm, $b = 0.7$ cm, $\gamma = 31.4$, we have $Z_n/n = 0.75 \Omega$, which is negligible. Pickup electrodes, pumping ports, vacuum chamber junctions, etc. will surely add something to this, but careful design should keep these contributions tolerable.

The rf systems have impedances primarily at their resonant frequencies. It is necessary to ensure that their impedances at higher harmonics are not greater by more than the harmonic ratios. The stacking system operates at the 40th harmonic, $n = 40$, and has an impedance of 400Ω , reducible by feedback to 40Ω . This is well below the limit found above; thus, the system is unlikely to disturb the full stacked beam. But, at the initial stages of the stacking process, the beam's momentum spread and intensity are both down by the same factor of about 50 to 100. Thus the criterion (V.4) becomes more stringent by this same factor. Some stirring up of the phase space during the initial phases of stacking may therefore take place, even though the time constant is fairly long, namely

$$\tau = \frac{1}{\omega_0} \left(\frac{2nE}{eIZ_0n} \right)^{1/2} \quad (V.5)$$

For one tenth of the full beam (1 A) and $Z = 40 \Omega$, $\tau = 0.4$ sec.

The accelerating system, with $n = 2$, is expected to have an impedance of 700 Ω , and feedback is believed to be impractical. This is almost twice the allowable $2 \times 216 = 432 \Omega$; thus some instability may again be expected. But here again the time constant (V.5) is long, about 0.15 sec. Therefore, if the accelerating cavities are shorted out during the stacking process, and acceleration commences within a few tenths of a second of the time when the short circuit is removed, the instability will grow by only about two or three factors of e starting from very small initial inhomogeneities. This should be acceptable. During the acceleration process itself, the bunched beam criterion (see below), which is much less stringent in this case, will apply. The instability returns at the end of the acceleration stage; at that time, it will again be necessary, and sufficient, to short the cavities out.

Bunched beams. Longitudinal instabilities of bunched beams occur both in "dipole" modes, where the bunches maintain their shapes but move relative to one another due to coupling between them, and in higher multipole modes where the shape of the bunches changes. These modes are excited by coupling impedances at frequencies corresponding to twice the bunch length for the dipole mode, and fractions of the bunch length for higher modes.

Sacherer⁹ has derived stability criteria and expressions for the growth rates of these modes. He gives the stability criterion

$$D F(\omega) Z(\omega) < \frac{V B \cos \phi_s}{0.16 I} - \frac{S}{4\omega_s} \quad (V.6)$$

where ω is the frequency of the oscillating mode, S is the spread of synchrotron oscillation frequencies, ω_s , in the bunch, B is

the bunching factor, B is a factor depending on the number of bunches and on the Q of the cavities, and $F(\omega)$ is a form factor depending on the frequency, having a maximum for $\omega = \omega_c = m\pi\lambda/c$, λ being the bunch length and m the multipole order (1 for dipole, 2 for quadrupole, etc.).

For two equal bunches, the coupling modes are not excited at all, e.g. B is effectively zero.⁹ Therefore, to this approximation, the bunched beam coupling instability does not arise in the acceleration process when the harmonic order $h=2$ is chosen. But for higher modes, where the wavelength is short compared to the bunch length, the instability mechanism is essentially the same as for coasting beams with I and Δp replaced by the local current intensity and momentum spread. Since the bunching process increases both of these quantities by the same factor of $1/B$, the criterion given in Eq. (V.4) for the tolerable impedance becomes less stringent by this same factor. Therefore, it appears that the bunched beam instability will not occur during the acceleration process in the ISA.

In the stacking process, on the other hand, we have 40 rather tight bunches, containing a total current of about 0.2 A in each stacking pulse. If the bunching factor is $B = 0.1$, we have $S/4\omega_s \cong 0.004$, and the form factor F peaks (with a value about unity) at 22 MHz for the dipole mode. The critical impedance at that frequency is then (with $V = 12$ kV) about 200 Ω . Higher multipole modes are excited at higher frequencies; their critical impedances increase approximately with $\sqrt{m}$.

Since the stacking rf system resonates at 4.45 MHz, and has an impedance there of about 400 Ω , it is likely that its impedance at its own fifth harmonic and above will be small enough. If this is not the case, for example, if the impedance at 22 MHz is about 1000 Ω , the growth rate is of the order of 1 sec^{-1} , slow enough for a feedback system to inhibit the instability.

Higher multipole modes are even less likely to be unstable, but also more difficult to detect and compensate with feedback systems.

2.4 Beam-Beam Interactions.

The instabilities detailed above occur in ordinary accelerators as well as in storage rings. But perhaps the most fundamental limitation to the performance of a colliding beam system is the instability of one beam induced by the other, where the two intersect. One cannot eliminate the electromagnetic interaction between the two beams without separating them, and then they do not undergo the collisions which are the very *raison d'être* of the colliding beam system.

Amman and Ritson first pointed out this dilemma at the 1961 Brookhaven conference¹⁰. They showed that one beam acts as the equivalent of a focusing lens on the other, thus shifting the tune of betatron oscillations. They believed that the maximum allowable tune shift would be whatever it takes to shift to the nearest linear resonance, on the average a tune shift of $1/4$ unit.

The first electron-electron and electron-positron colliding beams (Stanford, Novosibirsk, Orsay) showed that, in fact, intensities corresponding to much smaller tune shifts were sufficient to cause blowup of the beams. At present, many electron-positron colliding beam rings are in operation, and in all of them the beam-beam interaction limits the luminosity below what could be achieved if the best attainable single beams could be made to collide. On the other hand, beam-beam effects are, at worst, a minor nuisance, so far, in the only existing proton-proton storage ring system, the CERN ISR.

In the ISR the tune shift of one beam due to the other in the ISR is only of the order of 5×10^{-4} units, while in the e^+e^- systems the maximum allowable tune shift, $\Delta\nu$, ranges between 0.02 and 0.1, apparently increasing with energy.

The explanation of the fact that the effect is serious well below the "naive" limit, $\Delta\nu = 0.25$, lies in the nonlinear character of the field of one beam as seen by the other, coupled with the sharp azimuthal localization of the disturbance. Nonlinear resonances of all orders can be excited by such a perturbation.

Mathematically, the fact that a system with azimuthally varying focusing forces is stable at all may be considered as something of a freak phenomenon, being strictly valid only for linear fields. No proof of complete stability exists for nonlinear systems with azimuthal variations (energy of transverse motion is, however, conserved in the case of azimuthal uniformity).

It would be going too far afield here to give even a brief outline of the general theory. But Chirikov¹¹ and Keil¹² have analyzed it, at least semiquantitatively, as far as application to storage rings is concerned. A summary of their results is as follows:

If the perturbation affecting one beam is sharply concentrated in azimuth (as is the case in ISA) and has the content of nonlinear components to be expected from a concentrated beam, say a two-dimensional Gaussian distribution, then there is a strength of the perturbation beyond which particle oscillations become essentially random in amplitude and phase with a short time constant. This is known as the stochastic limit. It occurs when, at the amplitude corresponding to beam dimensions, the widths of nonlinear resonances are comparable with their spacing. This limit corresponds to a tune shift, calculated from linear theory for infinitesimal amplitudes, of 0.05 to 0.1 per interaction region. (This tune shift should be regarded as a convenient measure of the strength of the perturbation, rather than as the root cause of the instability.) Below this limit the oscillations are essentially stable if the system is one-dimensional; however, in the case of two (or more) degrees of freedom with coupling, the nonlinear resonances cross even below the stochastic limit, and a slow diffusive growth of amplitudes, known as "Arnold diffusion", is likely to take place.

In electron-positron storage rings there is another effect: synchrotron radiation causes damping of oscillations. This damping competes with the growth due to Arnold diffusion mentioned above. Since the damping becomes stronger with increasing energy,

it is not surprising that the effective limit of the strength of the perturbation approaches the stochastic limit for high energy e^+e^- storage rings (such as SPEAR) but is well below it (at $\Delta\nu = 0.2$ or so) at lower energies, for example, in the original Princeton-Stanford $e-e$ rings.

Since synchrotron radiation is effectively absent in proton systems (time constants of years or more) it is to be expected that Arnold diffusion will cause a slow growth of oscillations, no matter how weak the perturbation is. But Keil's estimates based on Chirikov's theory indicate that the time constant for this growth increases about exponentially with the ratio of the actual $\Delta\nu$ to the stochastic limit.

For the ISA it is required that the beam survive with, at most, a modest growth of amplitude for times of the order of hours, e.g. 10^{10} revolutions. Keil's calculation shows that this necessitates a tune shift of the order of one tenth of the stochastic limit (depending, of course, on the particular form of the beam density distribution). Computations carried out at Brookhaven by Courant (unpublished) tend to confirm this. For a simplified model, in which the assumed shape was sharper, and therefore richer in the harmful high harmonics than a realistic beam would be, the amplitude grows by less than 0.1 per cent in 10^8 revolutions with $\Delta\nu = 0.005$, but appreciably faster with $\Delta\nu = 0.01$. It therefore seems reasonable, probably even pessimistic, to assume that this slow growth of amplitude will be slow enough when the tune shift is limited to 0.005. Accordingly, this number is adopted as the criterion for designing the intersection region geometry and estimating achievable luminosities.

If the actual limit is different, and it is not unlikely that it is higher, the performance limit of ISA will be altered accordingly; this can easily be done, for example, by changing the crossing angle in the intersection regions.

In connection with the choice of a $\Delta\nu$ limit for design purposes, it should be pointed out that recent experience at the ISR

indicates that there is a definite relationship between the beam lifetime and the presence of single nonlinear resonances, excited by beam-beam interaction, within the working line.¹³ Better understanding of this phenomena is required in order to relate it to an upper limit for Δv and to judge the feasibility of resonance compensation by nonlinear magnetic fields.

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VI. MAGNET AND DEWAR SYSTEM

1. Choice of Magnet

1.1 General Considerations

The ISA design is based on the use of superconducting magnets, which has a significant impact on the expected performance. In addition to the important advantage of the reduction in electric power consumption is the equally significant advantage of constructing magnets of large vertical aperture and high magnetic field. It will be shown in Section XVIII that an economical solution with conventional warm magnets is limited to magnets with small gap. The small gap and large bending radius impose a limitation on the current which can be stored in one ring, due to the incoherent v -shift resulting from the transverse space-charge effects. It is estimated that a luminosity of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ is a practical limit for the ISA with conventional magnets. On the other hand, the circular geometry of the vacuum chamber and the iron shield in a superconducting magnet eliminates the transverse space-charge effects almost completely and an order of magnitude larger current and luminosities, up to $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$, are achievable.

Superconducting magnets using NbTi must be operated at liquid helium temperatures. Although superconductors have zero dissipation at constant magnetic field, the typical situation at a storage ring, the generation and maintenance of the cold environment consumes energy. The ISA magnet is designed for superconducting NbTi, which, at present, is the only material commercially available in the necessary filamentary form. The optimum operating temperature of NbTi depends, to some extent, on the details of the magnet design, the expected heating by the protons lost from the beams and the requirements of the refrigeration system. We have specified magnet cooling by pool boiling at temperatures $\leq 4.5 \text{ K}$. Details of the refrigeration system will be given in Section VII, but it should be mentioned here that the total heat load at 4.5 K has been estimated as 20 kW under normal operating conditions. The

removal of the heat load requires an electric power of about 7.5 MW. The annual power consumption depends on the projected running time of the machine: at 4000 h per year one obtains a 30 GWh energy usage. For comparison, in FY 73, the Accelerator Department used a total of 130 GWh. The power requirements of a conventional machine have been estimated in Section XVIII at $50 \text{ MW} \times 0.6 \times 3000 \text{ h} = 90 \text{ GWh}$. (The running time of a superconducting machine is probably higher because it cannot be warmed up for short down times.) This comparison, which would indicate an energy savings of a factor of three from the use of superconducting magnets, needs some explanation. First, as already mentioned, the two machines differ by an order of magnitude in luminosity. Second, the average operating time of the conventional machine depends strongly on the assumed demand for proton energies: equal demand for all energies gives a factor $1/3$. (The factor of 0.6 used above is based on the experience at the CERN ISR.) It is, however, reasonable to predict an increase of the effective running time by some factor. Finally, and most important, the availability of filamentary Nb_3Sn conductors in production quantities is imminent in this country and there is a good chance that the ISA magnets will actually be built with a high- T_c superconductor. The operating temperature could then be raised to about 8 to 9 K and the power requirement would drop by a factor of about 2. In conclusion, one can optimally hope to keep the energy consumption in the ISA at a level which is about six times below that of a storage ring with conventional magnets.

A further important consideration in choosing superconducting magnets is the possibility of operating at high magnetic fields. The peak bending field in the AGS, which is a combined function machine, is 13 kG. Separated function machines are designed for higher fields; the NAL 400-GeV accelerator and the CERN SPS are using 18 kG dipoles. The optimization of a 200-GeV storage ring with conventional magnets, given in Section XVIII, indicates that 15 kG would be the best choice. Initially, the magnets in the

ISA will be operated at a conservative 40 kG. Experience with ISA models and the 8° bend shows that this field value can be reached, essentially without training, which is probably the most important question in the application of superconducting magnets to storage rings. The interest in operating at high fields stems from consideration of beam dynamics and economy. Most collective effects depend strongly on the machine radius, providing a compelling argument for high fields. Superconducting magnets require a cryogenic system, representing a sizable fraction of the total capital cost, which must be offset by savings due to the reduction in length of the ring tunnel and other radius dependent costs. The field in the magnets should be as high as possible to effect the greatest savings. However, since the ISA would be the first large-scale application of superconductivity, it was thought prudent to limit the field to a value already achieved. It must be pointed out that development on 60-kG magnets with NbTi conductor is in progress at this laboratory and also that the availability of Nb₃Sn filamentary conductors will make 60-kG magnets realizable with relative ease.

The ISA is to be a separated function machine in which the functions of bending and focusing are performed separately by dipoles and quadrupoles. Some thought has been given to the question of using normal conducting quadrupoles. The power consumption of normal quadrupoles represents only a small fraction of that of the bending magnets whereas, in the case of superconducting quadrupoles, they contribute a comparatively large fraction to the heat load because of the large number of current leads. The quadrupole alignment, which is more critical than that of dipoles, is considerably simpler with normal magnets. In spite of these arguments the present ISA design uses superconducting quadrupoles. Their higher gradient allows a shorter length for each quadrupole, but, equally important, is the fact that the required magnetic correction and tuning elements can be incorporated in the dipoles or quadrupoles. Otherwise it would be necessary to increase the

circumference to $4 \times C_{\text{AGS}}$ or more instead of the present $3\text{-}1/3 C_{\text{AGS}}$.

The possibility was considered of operating the magnets in the persistent mode or with flux pumps in order to reduce the heat load from current leads. The first approach would require lossless switches and the second would require well regulated, high-current, flux pumps. It was felt that either approach is not within the state-of-the-art and the present design relies on conventional, easily regulated, current sources. Future developments could result in a change of our concepts.

1.2 Description of ISA Dipoles

The art of building superconducting magnets has been developed only recently and it is fair to say that no canonical design has evolved so far. At Brookhaven we have pursued and tested two alternate solutions, the so-called cosine θ and the window-frame configuration. Successful magnets have been constructed with each design and the experience gained with them will be discussed in detail in Section VI-9. The results indicate that either magnet can be made to meet all requirements established by the ISA design. Operational experience with the 8° bend, which uses the window-frame design, has been exceptionally good. The ongoing long-term pulsing test of the cosine magnet has shown excellent behavior. It appears that the window-frame magnet would have smaller random errors, but that the cosine magnet exhibits smaller systematic variations of the field harmonics with changes in the dipole field. Without prejudging the decision on the final design, we are basing the present study and cost estimate on the cosine configuration. A few open questions related to the speed of the magnet, behavior under irradiation, design of the ends, etc. will have to be answered in the course of the future work on ISA models, but it is expected that the magnet described below (Table VI-1) will satisfy all design requirements set forth in this study.

Table VI-1. Major Design Parameters of ISA Dipole

Vacuum chamber aperture	8 cm
Inner diameter of coil	12 cm
Outer diameter of coil	16.2 cm
Outer diameter of iron core	41 cm
Dipole length (iron-to-iron)	425 cm
Dipole length magnetic	411 cm
Operating field	40 kG
Operating current	3300 A
Current density in SC @ 40 kG	120 kA/cm ²
Overall current density in windings	25 kA/cm ²
Conductor (braid with about 100 wires)	
- Dimension of braid	about 2.1 cm x 0.05 cm
- Diameter of multifilamentary wire	0.3 mm
- Twist pitch	2/ cm
- Diameter of filament	about 10 μ
- Matrix to superconductor ratio	1.5:1
Stored energy per dipole	465 kJ
Weight of superconductor	80 kg
Weight of iron core	4280 kg

A cross section of the next generation of ISA models, that is with 12 cm coil aperture, showing the windings in one quadrant of a dipole magnet is presented in Fig. VI-1. In the cosine θ magnet the current distribution varies azimuthally approximately as the cosine of the angle from the median plane. The current is divided into six discrete groups of turns. This number of "current blocks" is sufficient, in principle, to give a very good field of $\Delta B/B \leq 3 \times 10^{-5}$ in the aperture of 8 cm. In principle, the greater the number of separate blocks the more uniform the field, but in practice six blocks are about optimum since the tolerance of mechanical placement does not permit realization of the potential

MAIN COIL I.D. 12cm
 MAIN COIL O.D. 16.2cm
 IRON I.D. 16.85cm
 IRON O.D. 41cm
 40 KG REQUIRES APPROX. 3300 A PER TURN
 WEIGHT (4.25m LONG) 4280 kg

Fig. VI-1. Magnet cross section, 12 cm coil aperture.

of more elaborate distributions. The exact positioning of the turns is determined by the computer program MAGFLD¹ which specifies the locations so that the first six allowed harmonics are eliminated. In contrast to earlier designs, no inert ribbon spacers are incorporated in the current blocks. Spacers are an added complication, their coefficient of expansion must be matched to the superconductor, and shaping of the end configuration is complicated. In fact, computations show that they can be eliminated without any degradation of the field uniformity.²

The conductor used will be a wide flat braid (2.1 cm x 0.05 cm) composed of approximately 100 fine wires (0.3 mm diameter) each containing about 400 superconducting NbTi filaments. The wires in the braid have a CuNi jacket to increase the coupling resistance between wires and thus decrease eddy current effects during pulsing (the field uniformity depends on the rate of change of the magnetic field) to tolerable levels. The braids used in the earlier ISA models have been filled with an indium-thallium alloy to assure the highest degree of stability.³ However, these metal filled braids exhibit an undesirable degree of interwire coupling, resulting in excessive eddy current effects, and are also substantially more expensive in fabrication.

The coils are wound in a single layer from a continuous piece of braid using a pressure molding technique (see Section VI-5). The end configuration can be seen in Fig. VI-2. The ends will be corrected for harmonic content using the same technique axially as used azimuthally in the central region. Tuning and correction coils are incorporated in the beam tube as outlined in Section VI-4 and these are shown schematically in Fig. VI-2.

With the air-core coil geometry of the cosine magnet, there are still advantages to including iron in the magnet circuit. Iron directly surrounding the cylindrical coil will add about 15 kG to the useful field at maximum coil current, it can be used as a powerful mechanical restraint against the magnetic forces, and it introduces only small correctable distortions into the field pattern.

Fig. VI-2. Dipole magnet end configuration.

In Section VI-3 it will be shown that these field errors can be minimized by a proper choice of the iron dimensions. The iron surrounding the coils is an integral part of the magnet design, and thus must be cooled to liquid helium temperatures. Details of the core construction to match different expansion coefficients in axial and radial direction will be discussed in Section VI-5. The presence of the large iron mass (4280 kg per 4.25 m long dipole) increases the time for cooldown and the radiation losses of the dewar, but it is felt that the advantages mentioned outweigh the few disadvantages.

Magnets of the cosine design are perfectly suited for mass production with a high degree of accuracy. Estimates of the tolerances in the location of the coil indicate a requirement of about 50 μ m rms. Tolerances in this range have been achieved with the existing ISA models.

1.3 Superconducting Magnet Development Program

The development of superconducting magnets for accelerator magnet⁴ or beam transport⁵⁻⁷ applications has been in progress at BNL for several years.

The initial emphasis was on relatively fast rise time magnets for very high energy proton synchrotrons. A large number of pulsed magnets have been built and tested to verify ac loss and stability theory. These include a number of 5 cm bore, 35 cm long dipoles capable of reaching 40 kG in a few seconds. During the last two years the emphasis has shifted away from pulsed synchrotron magnets and is now concerned with the development of slow pulsed magnets of very high field quality for use in storage rings. Two magnets which have been completed recently are the first model dipoles whose design is based on storage ring considerations. These magnets, designated ISA I and II, have an 8 cm bore and are 93 cm long. Their design uses the cosine configuration and is closely related to the earlier smaller magnets. At

the time of writing, these two magnets are being subjected to continuous pulsing as part of a long-term testing program. Experience with these magnets is described in some detail in Section VI-9.1. Two more magnets of this size are planned, to evaluate modified conductor configurations. The first of these coils, ISA III, will use fully insulated braid and will be tested early in 1974. The other magnet, ISA IV, employs the cupro-nickel insulated braid proposed for the ISA prototype and is scheduled for completion in June of 1974. The purpose of these dipoles is to demonstrate that the undesirable dynamic effects present in ISA I and II can be eliminated without sacrificing the excellent stability exhibited by their design.

The development of superconducting magnets for beam transport applications has led to the construction of the 8° dipole. This has been installed in the primary beam line to the 7-ft. bubble chamber and has been operated since October 1973. The design specification of 37 kG for the dipole field has been exceeded after a few training quenches. The performance of the magnet seems to have answered several outstanding questions concerning reproducibility of superconducting magnets and their ability to withstand heavy doses of radiation. The major parameters and details of the performance of the 8° dipoles is given in Section VI-9.2.

As a next step, it was decided to construct the "A" beam line to the multiparticle spectrometer with superconducting magnets. Four 2.5 m dipoles and four 1.5 m quadrupoles, each of 20 cm aperture, will be required.

The ISA CP & D funds, requested for FY76 would be used for the construction of two full-size dipoles (4.25 m long; 12 cm aperture), and two quadrupoles (1.3 m long; 12 cm aperture), which will be mounted one over the other as in the design in the dewars described in Section VI-6. This system will simulate a section of the ring and will contain all the auxiliary hardware such as compensating windings (see Section VI-4) and vacuum equipment.

In addition, it is planned to test the feasibility of slowly

pulsable, 60 kG, magnets which use the window-frame design (see Section VI-10). The development of Nb_3Sn conductors will receive stronger emphasis than in the past. A technique has been developed at BNL to overcome the brittleness of Nb_3Sn by forming the compound after braiding.⁸ The construction of a 1 m long magnet has been initiated and completion is expected by mid 1975.

2. Magnet Materials

2.1 Superconductor

High field, high current density superconducting materials were first discovered⁹ in 1961 and were promptly used to make magnets. These early magnets (mostly small solenoids) were very unstable and exhibited "degradation" and "training". Degradation is a term used to describe the inability of a magnet to perform at as high a current and field as a test sample indicates it should. Training describes the phenomenon whereby magnets can be energized to successively higher fields after each transition to the normal state. Large magnets, or coils of unusual shape, were found to be even more susceptible to those undesirable traits. In the past few years two important improvements in magnet technology have essentially eliminated these early difficulties and made the construction of large and sophisticated magnets possible.

The first of these improvements involves combining large amounts of copper with the superconductor to form a "cryogenically stable" conductor. When the magnet is being energized the current can be carried in the copper during periods of superconductor instability, thus preventing premature quenches. While this technique is extremely valuable for the construction of very large coils, such as those used in bubble chambers, the overall current density is too low for accelerator or storage ring applications.

The second, and more important, technological advance was the development of "intrinsically" stable conductors.¹⁰ These conductors are composites consisting of many fine superconducting strands imbedded in a normal metal matrix. The principle of

intrinsic stability is illustrated by the following "adiabatic" stability criterion:

$$d \leq \frac{\pi}{2J_c} (C_v T_o / \mu_o)^{1/2}$$

where $T_o = - J_c / dJ_c / dT$. In this expression, d is the diameter of the superconducting filaments, C_v is the specific heat per unit volume and J_c is the critical current density (the highest current at which it remains superconducting at the operating magnetic field and temperature). The quantity, T_o , can be shown to be approximately equal to the difference between the critical temperature of the superconductor and the operating temperature. This stability criterion simply states that if the superconductor is small enough the energy dissipated in it during the charging of the magnet can be absorbed by the superconductor itself without reaching an unstable condition. This is true because the energy released per unit volume decreases with size more rapidly than the heat capacity. The intrinsic stability criterion refers only to filaments which act independently of one another. It can be shown that for a composite wire consisting of many filaments the filaments can be effectively decoupled by axially twisting the wire according to the following equation:

$$l_c^2 = \lambda \frac{wd}{w+d} J_c \rho / \dot{B}$$

where l_c is the "critical length" which is equal to one-quarter of the twist pitch, J_c is the critical current density, ρ the resistivity of the matrix material, d is the filament diameter and w the separation between filaments. The constant λ depends on the spatial distribution of the filaments and is usually about 0.5.

Only one superconducting material, an alloy of niobium and titanium, is currently available in the fine filamentary form. This material has been developed to a level of sophistication already sufficient for the construction of the ISA. Because of the small diameter of the filaments required for storage ring magnets the high-current conductor used in the windings must be made up of many small composite wires cabled together to form a

fully transposed conductor. The cosine θ type of magnet described in Section VI-1.2 can be most easily constructed from a wide flat braid such as that used in the model magnets ISA I and II.

The current density obtainable in the windings is determined by the basic properties of the superconducting material and the efficiency of its use. In practice, the current density in the superconductor can be 120 kA/cm^2 at 40 kG and 4.5 K and the maximum overall current density in the windings is about 25 kA/cm^2 due to the space requirements of insulation and cooling passages.

2.2 Low Temperature Properties of Materials

Magnetic properties of iron: The iron core is an important part of the magnet design and performs three functions:

- i) It restrains the magnetic forces and plays an important role in preventing conductor motion, the major source of "training" effects.
- ii) It reduces the stored energy and significantly increases the magnetic field.
- iii) It reduces the external field, preventing magnetic interaction between the two rings.

In general, the magnetic properties of iron are unchanged at low temperatures although the medium field permeability and the hysteretic loss are somewhat greater than at room temperature.¹¹

Mechanical properties¹²: The mechanical properties of most materials improve as the temperature is reduced. In some cases, materials become brittle at very low temperatures e.g. iron. Plastics and unfilled epoxies also become brittle and may crack if stressed by differential thermal expansion. The most difficult design problem, from a materials point of view, is matching the thermal expansion of the various magnet components to ensure that the magnet is not distorted on cooldown. Magnetic iron, in particular, has a rather low expansion coefficient but this can be adjusted axially by making the magnet core a laminated composite structure. Table VI-2 gives the integrated expansion coefficient

of the materials used in magnet construction, from room temperature down to 77 K and 4.2 K. The rate of thermal expansion decreases rapidly with temperature so that almost all contraction has occurred by liquid nitrogen temperature.

Table VI-2. Expansion Coefficients of Magnet Materials

Material	$\Delta L/L$ (4.2 K)	$\Delta L/L$ (77 K)
Copper	3.4×10^{-3}	3.2×10^{-3}
304 Stainless	3.04	3.0
Aluminum	4.3	4.2
NbTi	2.8	2.7
Magnet Coils (ISA I & II)	2.7	2.7
Iron	2.0	1.9
Laminated Core (ISA I & II)	2.7	2.6
G-10 (epoxy fiberglass)	2 to 5 [†]	2-5

[†]The coefficient is different in different directions due to the laminated nature (i.e. stacked glass cloth) of this material.

2.3 Radiation Effects

The working lifetime of most accelerators is approximately 20 years. The magnets in a device such as the ISA will receive a significant radiation dose in this time, even if there are relatively few accidental beam spills. The effect of radiation on superconducting materials has been the subject of considerable investigation but a great deal of additional research will be required before definitive results are available. It is, however, possible to make several general statements based on experiments performed at BNL and elsewhere:

i) The critical current density of NbTi is essentially unaffected by an absorbed dose of 10^{10} to 10^{11} rad^{* 13,14}. Conductors which have the highest possible current density may be

^{*} 1 rad = 10^{-5} J/g.

degraded somewhat by radiation. Material of less than the maximum current density may in fact be improved by radiation.

ii) The critical temperature of alloy superconductors (i.e. NbTi) is unaffected by radiation.

iii) The critical temperature of compound superconductors (i.e. A-15, see Section VI-2.4) is not changed by doses up to 10^{11} rad but may be drastically lowered for higher doses.

iv) The critical current density of A-15 does not change appreciably until the critical temperature begins to drop.

The annual dose absorbed in the ISA magnets is expected to be less than 10^8 rad so that it is very unlikely that the superconductor will be affected.[†] The insulation used in the windings is the component most sensitive to radiation damage; plastics as a group tend to show signs of deterioration at approximately 10^8 rad. Glass loaded epoxy is used almost exclusively in the windings because of its relatively high radiation resistance. The copper matrix of the composite conductor may become more resistive due to the production of lattice defects and thereby affect the stability of the magnets. This is not expected to be a problem since the resistivity ratio is relatively modest (~ 100) and not easily changed. Even in the first few magnets downstream of the beam dump a life of > 10 yrs. can be expected.

2.4 New Superconductors

While at the present time the only commercially available composite superconductor is NbTi, the prospects for perfecting A-15 conductors in this form are very good. Several laboratories

[†]The estimate is obtained by scaling the annual dose observed at the CERN ISR (see A. Perrot and B. Bourist, Report CERN ISR-MA/74-7) to ISA energies.

(including BNL) have active programs of conductor development and the recent interest of the Controlled Fusion Program has improved considerably the prospects for their early development. The most promising compounds are Nb_3Sn and V_3Ga . Their critical parameters are contrasted with those of NbTi in Table VI-3.

Table VI-3. Critical Properties of Superconductors

Material	T_c (K)	H_c (kG)	I_c (A/cm ²) @ 40 kG and 4.2 K
NbTi	9.5	110	2×10^5
Nb_3Sn	18	230	$> 10^6$
V_3Ga	15	230	$\sim 10^6$

Unlike NbTi, which is a ductile alloy and can be formed by more or less standard metallurgical processes, the A-15 compounds are extremely brittle and must be fabricated in a somewhat different way. The technique which appears to be the most promising involves co-reducing pure niobium rods in a matrix of tin bronze and then forming the niobium-tin filaments by heat treatment, after twisting and braiding or cabling. An improvement on this process uses pure copper as the matrix and diffuses tin into the niobium to form the compound as a final step.⁸ This latter technique, invented at BNL, has significant advantages for large volume production. The procedure outlined above can also be used for V_3Ga with vanadium rods substituted for the niobium and gallium bronze used as the matrix.¹⁵ As mentioned previously, the significance of these new conductors is that they would make it possible to operate at higher temperatures and fields, resulting in a significant reduction in refrigeration and operating cost. The conductor development program has, as its ultimate objective, the direct replacement of the NbTi braid with the new conductor so that magnet development will be minimal. Results on short samples indicate that such a substitution would make it possible to

operate at a temperature of 8 - 9 K at fields up to 60 kG.

3. ISA Magnet Properties

3.1 Magnetic Fields Requirements

The magnet dipoles are designed to have a field which is very closely uniform. There are, however, two effects, which vary with the field level, and which introduce nonuniformities or nonlinear multipoles into the magnetic field. These are the iron saturation which introduces nonlinear multipoles primarily at the high fields, and the diamagnetic behavior of the superconducting filament which introduces nonlinear multipoles primarily at low fields.

In addition to the systematic field changes, that is, field changes which are the same in similar magnets around the ring, there are also field errors which vary randomly from magnet to magnet. These are due primarily to errors in construction of the magnets. The tolerance set on the variation of the dipole field from magnet to magnet is $\Delta B/B = 5 \times 10^{-4}$. This will cause a probable average displacement of the equilibrium orbit of 3 mm at positions where β has its maximum in the normal lattice. The tolerance set on errors in the positioning of the current blocks in the main coil of the dipole is 50 μ m rms, which will introduce random linear and nonlinear multipoles in the median plane field (see section VI 3.5).

3.2 Conductor Arrangement

An exact cosine current distribution is known to produce an exactly uniform magnetic field in the entire region inside the current distribution, if the iron shield has infinite permeability. There are limitations in approximating the cosine distribution using a finite number of current carrying conductors. One way of approximating the cosine current distribution is the method used for the ISA magnet of Fig. VI-1, in which current blocks of different width are wound from braided ribbon conductors.

The percentage of the aperture which has an acceptable field

is determined by the choice of the number of blocks. The choice of six blocks in a quadrant of a dipole will give about a 66% good field aperture. Using these six blocks one can cancel out the lower six undesired multipoles by displacing each current block azimuthally.

The conductor arrangement in a circular quadrupole could be based on similar considerations as are used for the dipole. One approximates the desired $\cos 2\theta$ current distribution using a braided ribbon wound in blocks, and the blocks are displaced to cancel out the lowest undesired multipoles.

3.3 Iron Saturation Effects

Computer studies have been done, using the GRACY magnet program, of the effects due to iron saturation.¹⁶ Cylindrical dipoles, with circular iron cores, have been found to be exceptionally uniform and have much less iron saturation effects than conventional shaped-iron magnets. Nevertheless, appreciable nonlinear multipoles are introduced at field levels above 20 kG.

The results of the numerical computations have indicated that the multipoles due to iron saturation can be minimized by a proper choice of the distance between the main coil and the iron shield, and the thickness of the circular iron shield. The computed properties of the ISA magnet shown in Fig. VI-1 at 40 kG are as follows: Stored energy per unit length is 114 kJ/m, ampere-turns required are 554 kA, the leakage field just outside the iron on the median plane is 390 G, and the multipole coefficients are

$$\begin{aligned} b_2 &= 2.9 \times 10^{-4}/\text{cm}^2 \\ b_4 &= -2 \times 10^{-6}/\text{cm}^4 \\ b_6 &= -3 \times 10^{-8}/\text{cm}^6 \\ b_8 &\leq 1 \times 10^{-10}/\text{cm}^8 \end{aligned}$$

The multipoles generated by iron saturation effects at 40 kG are large enough to require correction since they would cause a considerable v -variation with the particle momentum. Multipoles of about the same order are also introduced at the low field end

by superconductor magnetization effects as will be discussed below.

3.4 Magnetization Effects

(i) Persistent magnetization effects. At low field levels, nonlinear field multipoles are introduced by the induced currents that flow in the superconducting filaments of the conductor. These field multipoles, due to the superconductor diamagnetism, can be estimated in the following manner. Each superconducting filament has an induced circulating current flowing in it, so that each filament behaves like a magnetic dipole whose direction is opposite to that of the field and whose strength is proportional to the diamagnetic current and the diameter of the superconducting filament, d . The circulating magnetization current corresponds to a current density which is the critical current density for the superconductor, J_c , less the transport current density which is required to produce the main magnetic field. The persistent magnetization is therefore strongest at low fields where one finds the approximate expression¹⁰ $M_0 \cong \frac{2}{3\pi} J_c d$.

The magnetization effect on the field can then be found by summing the fields due to all these induced magnetic dipoles in all the superconducting filaments. The summation can be done using the GRACY magnetic program.¹⁷ The multipoles, b_n , introduced by the magnetization effect at 6 kG for a 12 cm aperture cosine dipole magnet, wound from a conductor with 7 μ filaments are.

$$\begin{aligned} b_2 &= -1.3 \times 10^{-4} / \text{cm}^2 \\ b_4 &= -0.4 \times 10^{-6} / \text{cm}^4 \\ b_6 &= -3.2 \times 10^{-8} / \text{cm}^6 \\ b_8 &\leq 1 \times 10^{-10} / \text{cm}^8 \end{aligned}$$

At high field levels, the multipole coefficients drop roughly inversely with the square of the field level.

(ii) Dynamic magnetization effects. Dynamic magnetization is a temporary diamagnetic moment induced in composites of a superconductor and normal metal by a changing field, $\dot{B}$, similar to that due to eddy currents in normal metals, but greater in magnitude and

having a longer time constant. The theoretical expression for the magnetization in twisted composite wires has been derived as^{10,18}

$$M = \frac{2}{\pi} \frac{w + d}{d} \frac{\ell^2}{\rho} \dot{B}$$

with ℓ being 1/4 of the twist pitch, d the filament diameter, w the separation between filaments, and ρ the interfilament matrix resistivity.

The magnetization of a braided conductor made up from composite strands (wires), not completely insulated from one another is, in general, the dominant rate dependent effect. The expression for the magnetization can be derived as¹⁸⁻²⁰

$$M = \frac{\kappa n}{15\pi} \frac{h^2 L}{R D^2} \dot{B}_L$$

with κ being the compaction density (0.68), n the number of strands in the braid, h the conductor width, R the resistance at each crossover of two strands, D the strand diameter, and L equal to 1/4 of the conductor transposition pitch. In fast-pulsed accelerator magnets, dynamic effects in the conductor can be an important source of heat generation; in slow-pulsed storage ring magnets, the effect on the field shape is more important. Complete insulation of the strands eliminates this source of rate-dependent magnetization, leaving only that due to the individual strands. Such fully insulated cables, however, are less stable in a magnet. The present metal-filled braid does not meet the design requirements, with regard to rate dependence, which demand that dynamic effects are smaller than 1/10 of the static effects (for example, the tolerance on the sextupole term, generated by a $\dot{B} = 300$ G/sec, is $\Delta b_2 \lesssim 0.03 \times 10^{-4} / \text{cm}^2$ at all field levels). The ISA design described in Section VI-1.2 is, therefore, based on Cu-Ni insulated strands. The only ways to achieve a sufficiently low magnetization are to increase the effective matrix resistivity and to decrease the cable width (transposition length is assumed proportional to width). Since the amount by which the crossover resistance can be

increased is limited, it may be necessary to reduce the cable width, which could necessitate a double layer magnet design.

3.5 Random Magnetic Field Errors

We will now discuss errors in the magnetic field which vary randomly from magnet to magnet. They are caused by errors in the location of the current blocks in the main coil of the dipole. Superconducting magnets are more sensitive than warm conventional magnets with regard to errors in the positions of the current blocks because the current blocks are closer to the median plane, and the magnetic field variation across the aperture is determined more by the current distribution than by the shape of the iron pole surface.

Random errors in the current block position will generate random error multipoles in the median plane field which can be defined by expanding the median plane magnetic field as

$$\Delta B_y = B_0 \sum_{m=0}^{\infty} \Delta b_m r^m ,$$

$$\Delta B_x = B_0 \sum_{m=0}^{\infty} \Delta a_m r^m ,$$

where ΔB_y is the error in the median plane vertical field, ΔB_x is the error in the median plane radial field, and B_0 is the unperturbed field in the dipole magnets.

The tolerance set on the rms error in the current block positions is $\epsilon = 50 \mu\text{m}$. With this value of ϵ , random error multipoles will be present whose rms values, for a cosine magnet having a 12 cm coil inner diameter, are

$$\begin{aligned}
\Delta b_0 &= 1.84 \times 10^{-4} \\
\Delta b_1 &= 0.39 \times 10^{-4}/\text{cm} \\
\Delta b_2 &= 0.08 \times 10^{-4}/\text{cm}^2 \\
\Delta b_3 &= 0.15 \times 10^{-5}/\text{cm}^3 \\
\Delta b_4 &= 0.26 \times 10^{-6}/\text{cm}^4 \\
\Delta b_5 &= 0.47 \times 10^{-7}/\text{cm}^5 \\
\Delta b_6 &= 0.7 \times 10^{-8}/\text{cm}^6 \\
\Delta b_7 &= 1 \times 10^{-9}/\text{cm}^7 \\
\Delta b_8 &< 1 \times 10^{-10}/\text{cm}^8
\end{aligned}$$

For a cosine θ magnet, the Δb_m and Δa_m are about equal. The central orbit displacement caused by the above Δb_0 and Δa_0 is about 0.1 cm at positions where β has its maximum in the normal lattice.

3.6 Configuration of Magnet Ends

The ISA model dipole magnets have ends with a harmonic content per unit length substantially greater than the central part of the magnet. These ends were designed for ease of fabrication, mechanical simplicity, and structural integrity. Integrated over the entire magnet length, the increase in undesirable harmonics is modest, but still too large. It could be compensated by designing into the central part an appropriate amount of harmonic of opposite sign to that of the ends, but a better solution is to modify the spacing of the blocks at the ends. Using this procedure it has been estimated²¹ that in a 12-cm aperture, six-block cos θ magnet, the sextupole coefficient can be eliminated and the remaining terms, with the possible exception of the decapole term, kept within acceptable values when averaged over a 4.25 m length. The decapole term is expected to be $b_4 = 0.53 \times 10^{-6} \text{ cm}^{-4}$. The decapole term could, in principle, be reduced by reshaping the ends, but a modeling program would be required.

4. Compensating Coils

The coils for tuning and correction of the rings will be incorporated into the insulating sleeve between the cold bore pipe and the main coils. In order to employ inexpensive solid state regulators, the current will be limited to 25A in a 0.2 mm diameter, superconducting, composite wire. One or two layers of the correcting winding will be utilized for the sextupole coils. Two additional layers will be required for the dipole, quadrupole, octupole and higher order coils. These could be discrete windings or could be a universal winding consisting of 24 conductors equally spaced around a circle, of which 12 are independently excited. This universal winding probably makes more efficient use of the current carrying capacity of the winding. The total radial extent of these correcting windings, in their insulating sleeve, will be about 1.5 mm in both dipoles and quadrupoles.

5. Mechanical Design and Construction of the ISA Magnet System

Two counterrotating beams of protons are guided through vacuum chambers in magnets arranged vertically one over the other. At the four intersection regions, where experiments will be done, the beams are brought together for horizontal crossings. Each of the curved sections connecting the intersecting regions subtends an arc of 90° , and, located at the 45° points, are four short straight sections for injection, ejection and acceleration. The ISA, then, has four-fold symmetry with the bending and focusing magnets arranged in octants.

In the lattice structure of the ISA ring with low- β insertions there are 48 normal cells, each containing two identical half cells, consisting of two 4.25 m long dipole magnets and one 1.3 m long quadrupole magnet. This arrangement is repeated vertically in the over-under magnet configuration. Thus, the magnet system consists of 384 normal dipoles and 176 normal quadrupoles. In

addition to the above number of normal magnets, there are 128 normal dipoles in the momentum matching sections, 192 quadrupoles of regular aperture but different length in the service and experimental insertions, and 72 special bending magnets in the experimental insertions.

One of the major problems in storage rings is attaining and maintaining an ultrahigh vacuum in the beam tubes for the circulating proton beams. In this design, each superconducting pair of one magnet over the other will be mounted in a separate dewar container. The warm-bore beam tubes for both the upper and lower magnets will be an unbroken length of aluminum tubing extending through the dewar vacuum space with thermal insulation between the tube and the inner diameter of the magnet bore tube. These beam tubes will be connected outside the dewar vessel to the ring vacuum system and accelerator components. A typical half cell is shown in Fig. VI-3.

In each ring octant, the upper set of dipole magnets is connected electrically in series, as is the lower set. At the ends of each octant are gas-cooled leads from outside the dewar connecting to the end magnet coils to provide the main magnet current. The interconnection between adjacent magnets is made with heavily stabilized superconducting material which passes through the liquid helium feed lines from dewar to dewar.

Each half cell is connected to the cryogenic transfer lines as a unit, with cryogenic valves available so that a half cell can be disconnected for servicing.

In case a magnet unit in a half cell quenches, it is expected that all magnets in the half cell will quench due to electrical and cryogenic coupling. To protect the magnets from excessive voltage peaks during a quench, at the end of each half cell there is a gas-cooled electrical lead connected to the main magnet coil lead in the dewar. A solid state diode is connected between each set of protective leads so that quench current will be shunted through this bypass, but normal current will not. (See Section VIII.)

Fig. VI-3. Typical half cell.

The protective leads will be sized at 1 kA and the main current leads will be sized at 3.3 kA.

The cosine θ magnet. The cosine θ magnet consists of a tubular coil section 12 cm i.d. and 16.2 cm o.d. split along the horizontal median plane. Each half section consists of six coils, wound of superconducting wire, made into a transposed braid. The braided superconductor is wrapped with spaced glass tape impregnated with B-staged epoxy resin. After each of the six coils is wound, the epoxy resin will be activated while retaining the coil accurately in place in an assembly fixture. Then the next coil will be wound and the resin activated; this process is continued until the half coil has the proper diameter and an accurate relationship exists between each coil.

The iron shield for the magnet will be made of 1 mm thick (very low carbon) Vitrenamel steel laminations. The lamination cross section will be a half annulus with slots in its outer periphery. The outer diameter will be 40.6 cm and the inner diameter will be 16.9 cm. The inner diameter will be about 0.1 mm smaller than the outside diameter of the coil assembly to maintain the coils under compression when cooled to 4.5 K, and also to prevent the coils from moving due to the large magnetic forces when the coils are energized.

The shield will be split along its median plane for installation of the coil system. Small slots will be provided at intervals along the shield length, in the vertical plane, to align the coils in azimuthal direction; chimneys through the top and bottom of the shield will permit flow of liquid helium.

There will be 1 cm thick stainless steel end plates at each end of the magnet shield. The laminations will be compressed axially in an accurate jig under a force of 14 kgf/cm^2 and held by four stainless steel bars 2 cm by 7.5 cm in cross section welded to the end plates and interval welded to the laminations.

The 4.25 m long (iron-to-iron without stainless steel end plates) magnet, under compressed conditions as described in the

previous paragraph, will contract axially 11.7 mm when cooled to 4.5 K. This is about 90% of the thermal contraction of stainless steel. Tests of the polymerized coil system have shown a longitudinal contraction to 4.5 K approximately that of stainless steel. Therefore, the differential thermal contraction between the coil and shield should be minimal.

The magnet will be supported at points one-quarter of the length from each end. At these locations, stacks of laminations will be inserted which have ears extending from the outer diameter of the shield in the vertical plane. These ears will have accurately punched holes through which fastenings will pass to engage the fittings on the support legs. A cross section of the magnet is shown in Fig. VI-4.

Another part of the magnet assembly is the helium vessel inner tube. This will be made of 1 mm thick stainless steel wound with B-staged glass tape which will be activated by heating. Longitudinal grooves will be machined into this electrically insulating layer for the magnet compensating windings, which will be inserted and sealed with epoxy resin. Bands of resin impregnated glass tape, 1 cm wide and spaced 1 cm apart, are wound on the tube. These bands of tape are activated and machined to an accurate outside diameter, matching the inner diameter of the two coil halves. The spaces between the bands form channels for the flow of liquid helium inside the coils.

The two coil halves are clamped around the completed helium vessel inner tube with the compensating windings installed and banded. This is done while maintaining the proper angular relationship between the compensating windings and the main coil. Glass tape, impregnated with epoxy resin, is wound around the coils in bands similar to the inner bands. The epoxy resin is heated, activated, and then machined to fit accurately the inside diameter of the magnet shield. The spaces between the bands form the outer cooling channels for liquid helium flow.

A special jig will be made to assemble the magnet coil and

shield. This jig will fit the outside diameter of the magnetic shield. It will accept stainless steel bands bent to fit around the magnet shield and it will be split at the median plane. After the various components are assembled in the jig and clamped together, the upper and lower stainless steel bands are welded to each other and to the stainless steel longitudinal bars. The shrinkage of the weld beads will tightly clamp the assembly together, thus causing the magnet to be held axially and radially by stainless steel strapping. This strapping will retain its strength at liquid helium temperature.

6. Cryostat and Magnet Support

The dipole dewar system, Figs. VI-4 and 5, is designed to provide a stable base for the superconducting magnets, as well as a reliable, easily maintained, cryogenic unit. To simplify the cryogenic system, two magnets in the over-under configuration are installed in the same helium vessel. The helium vessel consists of two cylindrical sections of 4 mm thickness joined by a stiffener midplane of 6 mm stainless steel. This is tightly fitted to the outside dimensions of the magnet so that a minimum quantity of liquid helium will be needed. The centerlines of the magnet axes are spaced 46 cm apart and the midplane of the two magnets is 1.17 m above the tunnel floor. Wherever possible the inner vessel and its attachments will have welded joints to insure leak tightness.

The base plate will be steel, 7.5 cm thick, and will have fastened to it the cryogenic support legs which will be attached to the lower magnet through the wall of the helium vessel. One of the cryogenic support legs will be a G-10 epoxy tube 25 cm diameter, of 1 cm wall thickness, which will fix one end of the magnet, while the other will be made of 1 cm thick G-10 epoxy flat sheet which will be flexible in an axial direction to allow for contraction of the helium vessel and magnets.

The center section of the vacuum vessel has cylindrical legs which fit over the cryogenic support legs and are welded to the

Fig. VI-4. Dipole transverse cross section.

Fig. VI-5. Dipole longitudinal cross section.

base plate. The center section of the helium vessel fits inside the vacuum vessel and is welded to metal fittings at the upper end of the support legs. Special fixtures are then used to install first the lower magnet, and then the upper magnet.

With the two magnets installed on the base, measurements can be made between the alignment points on the upper magnet and the bores of the magnets, as well as to the magnet base. Then the magnet leads and interconnections can be dressed to engage the openings in the ends of the helium vessel and the ends welded to the center section. Electrical leads for the correcting windings and cryogenic control will also have to be installed and brought out of the helium vessel. The vacuum containment is completed by bolting the ends to the vacuum vessel center section. Of course, many fabrication tests and electrical tests will have to be made as the assembly and installation of the superinsulation material proceeds, but the above description outlines the assembly process.

The quadrupole dewar system is similar in concept to the dipole dewar, but, since the quadrupole length is only 1.3 m, it has one support leg. The quadrupoles each have two 500 A gas-cooled leads, and the horizontally focusing quadrupoles are connected electrically in series as are the vertically focusing quadrupoles.

Magnet alignment and transport. Each magnet dewar is designed to be transported by a wheeled transporter which will be attached to the magnet base and which is able to raise the magnet off the ground. However, before this is done, locking screws are inserted through the vacuum vessel legs to lock the top of the support legs to prevent motion of the magnet when it is transported. After the magnet is positioned approximately, and the transporter detached, the locking screws are removed and vacuum sealing plugs are inserted in the tapped holes.

Near the ends of each upper magnet there is an alignment fixture which has an accurate counterbore whose position has been previously related to the magnet centers. The alignment fixtures

are reached by removing cover plates on the top of the vacuum vessel, and plugs of superinsulation. Targets can then be installed in the counterbores of the alignment fixtures, and the magnet position determined using the magnet tunnel survey system.

The magnet can be adjusted to the proper vertical position and level by means of jacks in the magnet base. Horizontal adjusting screws which act on the magnet base are also available for horizontal positioning.

7. Quadrupoles and Special Magnets

7.1 Quadrupoles

The ISA lattice design calls for 1.3 m long quadrupoles in the regular sections with a peak field gradient of 6.6 kG/cm over the vacuum chamber aperture of 8 cm. Cryogenic considerations require that the operating current at the peak field gradient be not larger than about 500A. As yet, the design of the ISA quadrupoles has not been worked out in detail. It seems natural to construct the quadrupole with single composite wires similar to that used in the window-frame design for dipoles. Alternatively, constructions derived from the cosine θ dipole concept are also conceivable. Fig. VI-6 depicts a possible quadrupole cross section.

7.2 Special Magnets

The experimental insertions contain a number of special magnets, some of which differ considerably from the ring magnets. The insertion quadrupoles are essentially the same as ring quadrupoles except for a difference in length. The special dipoles required are listed in Table VI-4.

Fig. VI-6. Quadrupole cross section.

Table VI-4. Special Dipoles in Experimental Insertions

Magnet	No. Required	Length(m)	Aperture(cm)
H ₁	16	1.5	12
H ₂	16	1.5	12
V ₁	16	5	16
V ₂	8	5	27
H ₃	8	2	14
H ₄	8	2.5	19

All the dipoles are constructed in the same fashion used for the ring magnets. The large aperture magnets V₂, H₃ and H₄ are single magnets since both beams pass through them and thus their cryostats are only slightly larger than standard ring cryostats.

8. Magnetic Measurement Techniques

8.1 Requirements for Dipoles and Quadrupoles

Measurements of the magnetic field quality are necessary to ensure that individual magnets are within tolerances. In addition, measurements must be made to relate magnetic field position and orientation to magnet fiducial marks, to permit proper installation.

Since all magnets have a circular aperture, and axial dimensions are all much less than the bending radius, the quality of the s-independent field of a magnet is best expressed in terms of the Taylor expansion coefficients a_n and b_n at the magnet center. These can be measured directly, using harmonic coils. Ends can be similarly analyzed.

Although the lower terms ($n = 1$ through 5) in a dipole may be individually controlled by compensating windings, it is still necessary to measure them in each magnet to ensure that excessive constructional errors are not present. The data may also be used in the individual control units. The allowable variations in the b_n are assumed to be equal to the error introduced by random displacements of 50 μ m rms of the magnet current blocks. These

requirements are similar to Parzen's criterion that $B^{-1} d^2 B / dx^2 < 1.6 \times 10^{-4} \text{ cm}^{-2}$ at all points of the useful aperture.

All the installation parameters, and the harmonic terms b_n , must be measured in all of the magnets (a three position survey of $\Delta\theta$ will probably suffice for $\Delta\theta_{\text{twist}}$). In general, the installation parameters are not expected to be strongly dependent on excitation; however, this hypothesis must be verified in a representative number of the magnets. Since the number of magnets is large, it would be highly desirable to be able to make the installation parameter measurements at room temperature, probably with 60 Hz excitation. However, since the harmonic content of all magnets, and possibly the magnetic center of the quadrupoles, can be expected to be different during superconduction, cooldown of all magnets for magnetic measurements would appear unavoidable. In any case, training characteristics, if any, will require cooldown for study. A complete measurement of a single magnet, including two quenches, will probably require one eight hour shift after cooldown. Hence, to complete measurements on 584 dipoles and 368 quadrupoles in less than two years with shift work, would require parallel measurement facilities.

8.2 Recommended Techniques

Methods of measuring the desired parameters to the necessary accuracy, under dc excitation, are available and some are currently in use. Measurements under pulsed conditions can be made in a single pulse but with reduced accuracy. All the suggested coils can be used with repeated pulses if the pulse shape is sufficiently reproducible and a sufficiently precise field marker is used; in this case the coil is flipped or rotated stepwise between pulses.

A brief description of the recommended devices is as follows: x , y and s are the horizontal, vertical and axial coordinates:

(i) x -flipped coil. A circular coil of many turns, parallel to the y - s plane.^{22,23} Rotation about the x or y -axis gives a

measure of coil tilt with respect to this plane.

(ii) Long stretched coil. Thin tungsten wires stretched between precisely machined bobbins. These coils may be constructed with an accuracy in effective width of a dipole coil of 1 part in 3000 and relative measurements to a few parts in 10^5 are possible. Calibration using a short NMR surveyed magnet is possible.

(iii) Colloid cell. This is an optical cell containing a ferromagnetic colloid²⁴ through which polarized light is transmitted. It is comparable in sensitivity to conventional coil techniques and is probably easier to use but cannot be used in a cold bore.

(iv) Morgan coil.²⁵ A coil with a winding having only a few turns which is sensitive primarily to a particular multipole. The coil is insensitive to angular and radial positioning errors but suffers from low electrical sensitivity. Stretched wire versions have not yet been attempted. Existing versions are used with a stepping motor and integrating voltmeter output. A high speed rotating version is being constructed which will have a factor of $n\omega$ increase in output signal level; the signal may be read with a wave analyzer. The coils may be used without rotation in a pulsed field.

Table VI-5 lists the quantities to be measured, the magnet type (dipole - D, quadrupole - Q), the required accuracy, the preferred measuring device and its accuracy and its developmental status on a relative scale.

Other methods which have been used to measure the harmonic content of beam transport magnets are long, narrow dipole coils, displaced in steps transversely on the median plane, and point dipole coils displaced axially and transversely in both planes. In either case, the data are fitted to a Taylor expansion. Rotating coils sensitive to B_r or B_θ , with auxiliary windings to reduce sensitivity to the dipole fundamental, are also used; this technique is superior to the point-by-point method. Radial and angular tolerances are more severe than in the Morgan coil, but

Table VI-5. List of Magnet Field Measurements

Quantity	Magnet Type	Required Accuracy	Preferred Device	Device Accuracy	Status*
$\Delta\theta_{\text{rotat}}$	D, Q	3.5×10^{-4} rad rms	x-flipped coil	5×10^{-5}	a
$\Delta\theta_{\text{twist}}$	D, Q	3.5×10^{-4} rad rms	x-flipped coil	5×10^{-5}	a
$\Delta BL/BL$	D	5×10^{-4}	long stretched coil	3×10^{-5}	a
$\Delta x, \Delta y, \Delta z$	D	1 mm rms	mechanical measurement†	0.3 mm	
$\Delta x, \Delta y$	Q	0.5 mm rms	colloid cell	0.02 mm	c
$\Delta GL/GL$, lattice	Q	1×10^{-3} rms	stretched Morgan coil		c
$\Delta GL/GL$, l.s.s	Q	1×10^{-4} rms	stretched Morgan coil		
b_1	D	0.4×10^{-4} cm^{-1}	Morgan coil	0.2×10^{-4} cm^{-1}	a
b_2	Q	na	Morgan coil	0.05×10^{-4} cm^{-2}	b

*a - currently in use or previously used here; b - not previously used here, but minor modification of current device; c - not previously used here, or major modification.

†The tube on which the magnet coils are wound can be taken to be coaxial with the coils to within the stated accuracy.

#The ratio of random error of the n^{th} multipole to coil sensitivity decreases as $(n + 1) (R_m/R_c)^n$ where R_m is the measuring coil radius and R_c is the magnet coil mean radius; $R_m/R_c = 0.76$ in the present coils, which are adequate up to b_8 with this ratio.

the induced voltage is greater and all harmonics are obtained using a single coil pair.

With either coil type, the coils may be full length or short; the Morgan coils would be difficult to construct full length for a 4-m dipole, but coils of modest length (5 to 10 magnet coil diameters) can be moved axially to analyze end effects in the magnet.

8.3 Special Techniques

A 22 MHz fixed frequency, nuclear magnetic resonance (NMR), apparatus has been obtained. Two resonances are observed: Aluminum at about 20 kG and hydrogen at 5.2 kG. With care, the resonance peak may be observed to 1 part in 10^5 . The intended use for this device is the determination of absolute point field magnitude. Small gradients are measurable, in principle, by transverse displacement, and axial variation can be used to determine the effective length; high accuracy is, in principle, obtainable with a precision traverse mechanism, but the technique is cumbersome.

A superconducting quantum interference device (SQUID) has been obtained but is as yet untried. The device may be used, either directly as an ultrasensitive fluxmeter, connected to a superconducting measuring coil, or as an ultralow noise voltmeter. The first anticipated use is as a fluxmeter, connected to a miniature superconducting coil pair for gradient measurement. A good discussion of the dc and ac SQUID with applications to magnetometry and voltage measurement is given by Clarke.²⁶ The device purchased is an ac SQUID, operating at a frequency of 30 MHz. Its disadvantage is an unspecified thin film Dayem bridge, which must be operated at 4.2 K or below, a handicap. The bridge is said to have limited shelf-life, is sensitive to thermal shock, and the operating temperature must be carefully controlled.

Single-turn versions of the Morgan coils, which suffer from low output voltage, can also be made from superconducting wire.

Since

$$b_n = \frac{1}{n!} \left. \frac{\partial^n B_y}{\partial x^n} \right|_{x=0}$$

Morgan coils measure the local value of the n^{th} derivative of the vertical field; higher order terms are made negligible by reducing coil dimensions. A combination of a SQUID fluxmeter and a miniature Morgan sextupole coil would thus enable one to measure directly the extent of the magnet aperture satisfying Parzen's second derivative criterion.

9. Recent BNL Experience with Superconducting Magnets

9.1 ISA Models

As mentioned previously, two dipoles, ISA I and II, have been built and tested as part of the ISA magnet development program. These magnets have an 8 cm aperture and are 93 cm long. Figure VI-7 is a picture of one of the magnets with the top half of the iron core removed to show the windings. The objective of the modeling program was to demonstrate that reliable, reproducible, magnets, with the required field quality, could be built at reasonable cost. A secondary objective was the extended operation of the magnets in an accelerator-like situation to gain experience with cryogenic systems. The tests were an unqualified success and the highlights of the results are presented below.

Training - Both magnets reached design current (i.e. equivalent short sample resistivity of 10^{-12} Ω -cm at 4.2K) without training. After about 5 quenches the current reached a maximum value about 10% higher than that achieved on the first quench. After warm-up and recooling, the magnets could be operated at the highest current previously achieved, without transitions to the normal state. Because of differences in the current capabilities of the conductors used, ISA I reached a somewhat higher central field (44 kG) than ISA II (42 kG) at 4.2K. This corresponds to an overall current density of approximately 30 kA/cm^2 in the coil which is equivalent to 60 kA/cm^2 in the individual wires in the braid or 130 kA/cm^2 in

Fig. VI-7. ISA dipole model (upper iron core removed).

the superconductor. This performance is significantly better in this respect than that obtained with magnets of this type at other laboratories. It is notable that this kind of training-free performance can be obtained from magnets whose current density is considerably higher than that achieved in most superconducting devices.

Field Quality - Magnetic measurements for the two models are given in Table VI-6 for 6 kG (injection), 24 kG and at a high field, 40 kG, where the effect of iron saturation is evident. Calculated values for the harmonic coefficients are also given in Table VI-6. The calculated values take into account the actual dimensions of the wedges used and the differential contraction of the coils on cooldown. These affect only the in-phase (b_n) terms. The calculated values for the out-of-phase (a_n) terms are based on a random error in current block placement of 50 μ m rms. The b_n terms are, of course, also subject to these random errors. Since the calculated values do not include the effect of superconductor magnetization or iron saturation they are only valid at medium fields where the magnetization is small and iron saturation is not taking place. In general, the measured values fall within the range allowed by the assumed error of 50 μ m in block placement for both magnets. The quadrupole component (2θ) is sensitive to coil centering in the iron shield and does not fall within the range allowed. Improvements in the centering technique will be required to control this component.

The variation in field with distance along the median plane is shown in Fig. VI-8 for ISA I and ISA II with and without sextupole correction. These curves have been reconstructed from the harmonics in Table VI-6 without the quadrupole component. The corrected curve is for a correction coil current which minimizes the sextupole in both magnets so that the curve would apply to both magnets operating in series with a common correction coil current, as in actual accelerator operation.

Reproducibility - Despite the small differences in the two

Table VI-6. Harmonic Coefficients for ISA I and II

ISA I

Harmonics	Measured 6 kG		Measured 24 kG		Measured 40 kG		Calculated 24 kG		Units
	b_n	a_n	b_n	a_n	b_n	a_n	b_n	a_n	
30	- 3.1	- 0.2	- 2.7	- 0.1	+ 2.8	- 0.1	- 2.6	± 0.3	$10^{-4}/\text{cm}^2$
50	- 3.1	- 0.5	- 3.4	- 0.5	- 8.7	- 1.4	- 1.4	± 2.6	$10^{-6}/\text{cm}^4$
70	11	7	7	7	4	4	11	± 19	$10^{-8}/\text{cm}^6$
90	- 230	< 1	- 170	< 1	- 120	< 1	- 300	± 170	$10^{-10}/\text{cm}^8$
20	0.9	3.5	1.1	3.7	0.7	5.4	± 1.1*	± 1.1	$10^{-4}/\text{cm}$

ISA II

Harmonics	Measured 6 kG		Measured 24 kG		Measured 40 kG		Calculated 24 kG		Units
	b_n	a_n	b_n	a_n	b_n	a_n	b_n	a_n	
30	- 3.6	- 0.1	- 3.3	- 0.1	+ 2.2	0.0	- 2.8	± 0.3	$10^{-4}/\text{cm}^2$
50	- 5.1	- 0.4	- 4.6	- 0.4	- 9.4	- 0.8	- 1.9	± 2.6	$10^{-6}/\text{cm}^4$
70	7	11	7	4	- 4	- 4	8	± 19	$10^{-8}/\text{cm}^6$
90	- 400	< 1	- 350	< 1	- 290	< 1	- 350	± 170	$10^{-10}/\text{cm}^8$
20	2.7	0.9	2.2	2.0	2.5	0.2	± 1.1*	± 1.1	$10^{-4}/\text{cm}$

* No allowance made in the calculation for noncentering of coil in iron core.

Fig. VI-8. Field deviation across aperture.

models (i.e different conductor and wedge batches) their magnetic field patterns were very close to being identical. This is illustrated in Fig. VI-9 where the uncorrected sextupole signal is plotted against central dipole field. At 40 kG the difference between the sextupole signals is only $\Delta b_2 = 0.6 \times 10^{-4}/\text{cm}^2$. Mass production of magnets would also tend to make them more uniform.

Reliability - The long-term effects of magnetic and thermal cycling on superconducting magnets have never been thoroughly examined. Since such information is vital to the ISA design, a program of extended testing has been instituted on the two model magnets. The coils were mounted in a horizontal cryostat, one behind the other, much as they might be if part of an accelerator ring. The cryostat was provided with a room temperature aperture containing two sets of harmonic measuring coils, one for each magnet. In this configuration the magnets were subjected to continuous pulsing for a period of three months. The cycle parameters were 100 sec rise, 10 sec flat top, 100 sec down and 10 sec wait before repetition. After each thousand pulses the harmonic coefficients were remeasured to determine if any changes had taken place. During the run several thermal cycles from 4.8 K up to ~ 150 K were required for refrigerator maintenance. Because of the somewhat higher operating temperature in the closed-cycle refrigeration mode (4.8 K), the magnets have a maximum current of 3100 A (37 kG) rather than the peak current of 3650 A (42 kG) which can be achieved at 4.2 K. To date, no significant changes have been detected in the dc harmonic content as a result of magnetic or thermal cycling. The resolution of the magnetic measuring apparatus is $1 \times 10^{-5}/\text{cm}^2$ for the sextupole component, and somewhat better for higher harmonics.

Dynamic Effects - The harmonic coefficients measured during pulsing differ from those measured under dc conditions in these magnets. This is due to currents between the wires in the braid induced by the changing field. The tolerance for effects of this sort has been set at a change between dynamic and static coefficients

Fig. VI-9. Sextupole component vs dipole field of ISA models.

of less than 10% (Section VI-3.4). The present ISA models do not meet this criterion due to the metal filled braid used in their construction. New conductor designs will be used in forthcoming models to determine if the dynamic tolerance can be met while maintaining the other excellent properties of the magnet design.

9.2 The 8° Bending Magnet

The 8° bend was designed and constructed for use in a primary proton beam line leading to the 7 ft. bubble chamber in the North Area. The magnet is constructed as two modules with a total length of about 4 m. It has a rectangular aperture (window-frame type) with the iron core surrounding coils also of rectangular cross section. The overall transverse dimensions are 37.8 cm high and 43.5 cm wide. The magnet has a semi-warm bore aperture of 7.3 cm diameter. The operating current, at the design field of 37 kG, is 1200 A in the main coil and 300 A in the auxiliary sextupole coil.

Below saturation the iron core, wrapped closely around the coil, reduces the ampere turns required for the magnetic field by a factor greater than two. Below 20 kG the magnetic images of the coil in the iron simulate extended dipole sheets, producing very uniform fields. Above this field, saturation requires an auxiliary correcting coil which is approximately an air-core sextupole. The correcting coil needs to be powered at field levels of about 20 kG, increasing linearly to several percent of the dipole coil ampere turns by 40 kG. The combination of the two coils permits precise fields to be obtained at all levels, as well as providing available sextupole turning where desired.

The dipole coil is wound with 340 turns of superconductor composite with a rectangular cross section of about 1.4 mm by 2.9 mm. In this conductor, 361 filaments of niobium titanium, 75 μ m diameter, are embedded in copper and the whole matrix is twisted one turn per inch. Sheets of anodized, high purity aluminum are placed between each of the vertical layers of conductor and are grooved to provide vertical liquid helium coolant channels

over 50% of the surface area. The aluminum gives good thermal and dynamic stability.

The magnet has been in operation since October 1973 and its performance seems to have answered several outstanding questions concerning achievable field quality, reproducibility and resistance to heavy doses of radiation. The performance and results of detailed magnetic measurements will be published elsewhere. Although designed for beam transport applications, a number of results are relevant to storage ring magnets. Magnetic field measurements were carried out with bucked rotating dipole coils sensitive to the radial field component. Both long integrating and point coils were used to determine, separately, the central field quality and end effects. The raw data are analyzed in terms of the harmonic coefficients a_n and b_n which completely describe the field quality.

The calculated field coefficients at 24 kG are compared to the corresponding values measured on magnet unit #1 for a rising field cycle in Table VI-7. Column 1 lists the computed coefficients for the perfectly constructed magnet. Column 2 gives the corresponding values measured in the central two-dimensional part of the magnet. Column 3 gives the results integrated over the entire magnet length, including the end effects. The difference between column 2 and 3 is, therefore, a measure for the quality of the ends. The presence of coefficients not allowed by symmetry results not only from random errors due to the magnet construction but also from magnetic measurement errors. A detailed analysis indicates that only the quadrupole (20) term is caused predominantly by construction errors whereas the higher order non-allowed terms are consistent with measurement errors. The magnitude of in-phase (b_n), and out-of-phase (a_n), coefficients due to random construction errors is statistically about equal and essentially independent of field level. The magnitude of the quadrupole coefficient is estimated at $\Delta b_1 < 0.6 \times 10^{-4}/\text{cm rms}$.

Table VI-7. Harmonic Coefficients of 8° Bend Module #1 at 24 kG
with Theoretical Current in Sextupole Coil

Harmonic	Calculated		Measured Point Coil		Measured Long Coil		Units
	b_n	a_n	b_n	a_n	b_n	a_n	
30	0.83	0	0.17	0.08	0.09	0.02	$10^{-4}/\text{cm}^2$
50	4.30	0	5.33	0.05	3.18	0.0	$10^{-6}/\text{cm}^4$
70	-19.8	0	- 23.6	0.32	-15.3	0.32	$10^{-8}/\text{cm}^6$
90	-74.2	0	-113.5	2.2	-96.0	0.0	$10^{-10}/\text{cm}^8$
110	150	0	- 15	0.0	30	15	$10^{-12}/\text{cm}^{10}$
20	0	0	0.86	0.44	0.89	0.73	$10^{-4}/\text{cm}$
40	0	0	- 0.14	0.16	- 0.07	0.25	$10^{-5}/\text{cm}^3$
60	0	0	0.24	1.58	0.12	1.1	$10^{-7}/\text{cm}^5$
80	0	0	2.5	6.7	1.7	5.0	$10^{-9}/\text{cm}^7$
100	0	0	- 5.7	17.1	- 5.7	11	$10^{-11}/\text{cm}^9$

The discussion of differences between computed predictions and measurement, for terms allowed by symmetry, must involve results from both magnet units. Table VI-8 lists the two-dimensional coefficients b_n allowed by symmetry, plus their out-of-phase equivalents a_n , as a rough indicator of random errors. These are shown for the two units at three field levels on a rising cycle. The values quoted assume a current setting in the sextupole coils which is equal in both units and adjusted to make the average $b_2 = 0$. The sextupole term computed for this current setting is shown in Fig. VI-10 together with the measured values for rising and falling excitation current. The large difference between predicted and measured results is caused by hysteresis. A more detailed analysis of all measurements seems to indicate that the random error of the sextupole term is $\Delta b_2 < 0.1 \times 10^{-4}/\text{cm rms}$.

The two-dimensional decapole measurements show very small hysteretic effects. The magnitude of this coefficient varies considerably with field level, but it should be noted that it follows computations exactly and is therefore correctable in the next generation design. The 50 term has the only significant diamagnetism in this magnet design; a $\Delta b_4 = 2 \times 10^{-6}/\text{cm}^4$ in the central region is caused by this effect. This diamagnetism is due to the correcting coil used. In a first approximation diamagnetism in the main coil returns through the iron. For higher order terms no hysteretic or diamagnetic effects are evident.

The field uniformity on the median plane, $\Delta B/B_0$, of the 8° magnets, at three field levels (6, 24 and 38 kG), is shown in Fig. VI-11. The curves are obtained by using the harmonic coefficients of Table VI-8, that is with the sextupole current adjusted to make the average $b_2 = 0$ and without the random quadrupole term. The absolute field nonuniformity is $\leq 10 \times 10^{-4}$ which is reasonably good. More important is the fact that the field shape is predictable and the difference between units is smaller than 1 part in 10^{-4} .

The detailed results of extensive magnetic field measurements on the two 8° modules can be summarized as follows. Predicted fields

Table VI-8. Harmonic Coefficients of 8° Bend Module #1 and #2
(Current in Sextupole Adjusted to Make Average $b_2 = 0$)

Harmonic	Module #	6 kG		24 kG		38 kG		Units
		b_n	a_n	b_n	a_n	b_n	a_n	
30	1	- 0.01	0.18	- 0.02	0.17	-0.15	0.0	$10^{-4}/\text{cm}^2$
	2	+ 0.01	0.01	+ 0.02	0.02	+0.15	0.01	$10^{-4}/\text{cm}^2$
50	1	8.2	0.05	5.3	0.05	-7.3	0.19	$10^{-6}/\text{cm}^4$
	2	8.4	0.19	5.8	0.14	-6.6	0.05	$10^{-6}/\text{cm}^4$
70	1	-32.3	0.3	-23.6	0.3	-6.4	4.5	$10^{-8}/\text{cm}^6$
	2	-35.1	0.6	-27.1	0.6	-6.7	2.9	$10^{-8}/\text{cm}^6$
90	1	-31.3	10.9	-113	2.2	-715	2.2	$10^{-10}/\text{cm}^8$
	2	-34.9	4.4	-107	4.4	-709	0	$10^{-10}/\text{cm}^8$
110	1	149	15	- 15	0	582	75	$10^{-12}/\text{cm}^{10}$
	2	179	30	+ 15	0	432	60	$10^{-12}/\text{cm}^{10}$

Fig. VI-10. Sextupole identity in 8° bending magnets.

Fig. VI-11. Field deviation across aperture in 80 bending magnet (sextupole term compensated).

and the smoothed experimental results agree to the order of 1×10^{-4} , which indicates that the magnets are correctly constructed within measurement accuracy. The quadrupole terms are $< 1 \times 10^{-4}/\text{cm}$ in both planes. Other terms not allowed by ideal construction are small by comparison and within measurement accuracy. Field errors due to construction in these two magnets appear comparable to those in high performance conventional magnets. There are small differences between computer predictions and experimental results, involving incomplete knowledge of μ and hysteretic effects in iron. These differences are also found in conventional magnets, etc. and could be reiterated into later designs. Such effects will drop out of the difference between both magnets, as computed and as measured, which should include only errors in construction and in measurement.

The 8° magnets show extreme stability. Very little training was experienced, and this only when first cooled and operated, and the magnets can be charged to 40 kG in seconds without quenching, in spite of very large heating due to the solid iron cores. Small models with laminated iron showed rate dependent ($\dot{B}$) losses and field distortions to be negligible for rise times of ≤ 4 kG/sec.

During operation, the magnets also absorbed several hundred joules of radiative energy in a period of 3 μsec without quenching while small pulses were observed in the magnet dewar helium pressure from the momentary beam heating. The capacity of the magnets to absorb relatively large beam heating is of great significance since the magnets of superconducting accelerators planned for the future will have to have a reasonable capacity to operate when subjected to heating from sudden beam loss. These observations are the first experimental evidence anywhere bearing on this fundamental question.

10. A 60 kG Window-Frame Dipole Design

Magnets similar to the 8° superconducting dipole could also be applied to the ISA design. The first magnets of this type were nominally 40 kG designs with essentially square apertures. These parallel current sheets are effectively extended in the vertical

direction by images in the iron which surrounds the coil and aperture. The iron yoke is of sufficient thickness that no saturation occurs except in the vicinity of the pole surfaces. Even at 40 kG, saturation only increases the current required by 1.2 over that for $\mu = \infty$. Above 20 kG a correction coil is necessary to compensate for the aberration produced by pole surface saturation, which is almost pure sextupole. The need for correction introduces some operational complexity. However, for precise applications, high field superconducting magnets of any type will require some sextupole correction. Available controlled sextupole, distributed throughout the lattice, is essential in the ISA.

Two separate elements have been combined in this design. First, the window-frame geometry itself, and second, the fact that the field in the coil region is vertical to first order has made it feasible to use vertically oriented pure aluminum sheets, between layers of conductor, for ultrastabilization. The anodized pure aluminum sheets, with residual resistance ratios of 4500, are placed between each layer and grooved to provide intimate contact between the superconductor, liquid helium and aluminum over a large wetted surface area. The coil has generally been fabricated from vertical layers of rectangular conductor which is capable of carrying several hundred to several thousand amperes in a single composite wire. In coil fabrication, the rectangular coil is wound to fill tightly the surrounding structure on all sides. In the magnet assembly, it is prestressed horizontally towards the magnet center. The auxiliary coil, approximately an air core sextupole, is a single series circuit comprising a horizontal midplane coil (centered at 0° and 180°) plus two flat pancake coils respectively at the top (60° and 120°) and the bottom (240° and 330°). Maximum field in the 8° bend is arbitrarily set at 40 to 45 kG for two reasons. The correction required at maximum field becomes quite large; i.e., $b_2 = 30 \times 10^{-4}/\text{cm}^2$ for a magnet of 10 cm diameter to the superconductor. This requires $\sim 5\%$ of the primary ampere-turns in the auxiliary coil. Second, the simple correction coil used

becomes, itself, a source of aberrations which become quite significant. The correction, approximating a six-wire air core sextupole, can generate strongly the first odd harmonic of 30, that is $r^8 \sin 9\theta$. This results in some shrinking of aperture at the highest fields.

Although the 8° magnets used solid iron, the construction technique can be applied to laminated cores. Small laminated models showed rate dependent losses and field distortions negligible for rise times ≤ 4 kG/sec. This rate dependence is determined by eddy currents induced in the aluminum sheets by horizontal field components. For slow cycling ISA magnets such a coil construction technique should be satisfactory. Where faster rise times are desired, a simple "lamination" of the aluminum might be employed while retaining its stabilizing effect almost intact. For example, the single sheet between layers might be divided into several sheets stacked and joined vertically. For completeness, this window-frame circuit can be used for very fast magnets by replacing the aluminum with plastic or a low conductivity metal cooling channel material. However, this seems unnecessary for high-energy applications, and must be weighed against the loss of the ultrastabilization.

One systematic effect present in superconducting magnets is field aberration at low fields due to diamagnetism in the superconductor. In the window frame circuit such induced fields in the dipole coil return through the iron yoke, giving essentially no effect in the aperture (except at the ends). Diamagnetism in the auxiliary coil produces high multipoles, predominantly a decapole term in the center of the magnet, most of which is, however, cancelled by the ends. All other diamagnetic effects appear negligible, in spite of the fact that very coarse superconducting filament sizes were used.

The field uniformity of the 8° magnet is quite excellent for its purpose. However, a second generation design would produce a much more uniform field. In fact, a 60 kG version, which is inherently very accurate and uniform in field, has been conceptually designed. The windowframe magnet circuit, with its extended dipole

sheet approximation, rapidly improves in performance as the vertical gap is increased. The level of dipole saturation, and of aberrations on the horizontal midplane at any field above 20 kG, drops off as a steep function of increase in vertical gap. It has been estimated that the extra cost and labor for the increased coil height would be a minor perturbation, resulting in only a small increase in magnet cost. Fig. VI-12 shows field uniformity, $\Delta B/B$, on the horizontal midplane as a function of B_0 for a model calculation.

Figure VI-13 shows, conceptually, one quadrant of a 10 cm x 10 cm aperture 60 kG design. The correction auxiliary coil consists of two Helmholtz pairs connected in series. At 60 kG this magnet has an uncorrected sextupole of $15 \times 10^{-4}/\text{cm}^2$ and 10% more current than for $\mu = \infty$, in contrast to $b_2 = 30 \times 10^{-4}/\text{cm}^2$ and 21% more current in the 8° magnets at 40 kG.

Another feature of this design is that the field is nowhere higher in the dipole coil than in the aperture. The 1/2 m model of the 8° magnet has been tested to 50 kG. Because the iron yoke was designed for 40 kG, saturation is large, resulting in 57 kG peak in the coil and considerably higher current densities than contemplated for a 60 kG design. Computations show that a 60 kG design, uncorrected, has extremely small aberrations at all fields, except for sextupole. The corrected magnet meets the design specifications for the uniformity of the ISA magnet fields at all levels.

At first sight it appears unusual to make the aperture higher than wide. However, in Fig. VI-13, visualize wrapping the coil around the dotted outer round aperture tube in the familiar $\cos \theta$ arrangement. The net result, for equal current densities in the coil and effective use of the iron, will be a slight decrease in the distance from the center to iron on the vertical midplane, and some slight increase on the horizontal midplane. Thus, for 60 kG designs, where iron contributes less to round or cosine type magnet designs, the stored energy and total ampere turns of the high vertical aperture are roughly the same as for a comparable round

Fig. VI-12. Field uniformity of 60 kG window frame dipole shown in Fig. VI-13.

Fig. VI-13. 60 kG magnet design.

tube design, and the overall magnet size can be slightly less. Thus, there is no real penalty for the higher aperture and, in practice, this space might be put to good use for pumps, reduced pumping impedance, etc.

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VII. REFRIGERATION AND LIQUID HELIUM DISTRIBUTION SYSTEM

1. Introduction

The refrigeration system for the ISA is similar in principle to those described earlier.^{1,2,3} The distribution of refrigerant is performed in a somewhat different manner and the total system capacity is greater than previously described, to reflect the increased size of the ISA. Other changes are that the beam vacuum chambers are at ambient temperature when the accelerator is in use and the heat load to the refrigerator due to chamber bake-out is markedly less.

The refrigerator requires a process control system equivalent in size, response and complexity to a small petro-chemical plant, the gas compression and refrigeration effect of a medium sized air separation or liquefied natural gas plant and the techniques employed in the realization of the large helium liquefiers of the Kansas Gas Fields. Such a refrigerator could now be designed and fabricated at a reasonable cost.

Additional work is required, however, particularly in the area of coupling the refrigerator to the load and the control of the system. This must be accomplished in simple ways. Since the refrigeration effect is distributed over large distances, labor costs for operation and maintenance are high. The purpose of this refrigerator is to provide, at minimum annual cost, continuous refrigeration for the accelerator with a minimum risk of interruption of operations due to component malfunction.

2. System Requirements

The refrigeration system of the ISA must operate under a variety of conditions:

- i) Accelerator in normal operation, i.e., magnets energized and beam circulating; remove all heat generated.
- ii) Accelerator at ambient temperature; the refrigerator must

cool down the total mass to operating temperature, about 4.5 K.

iii. Accelerator at operating temperature; maintain accelerator at temperature and charge magnet dewars with liquid helium.

iv. A section of the accelerator requires maintenance or replacement; continue refrigeration effect on remainder of accelerator, with reserve refrigeration available, to compensate for additional heat load to dewars resulting from a bake-out of the beam vacuum chamber and, further, to cool and fill these sections with liquid upon completion of repairs.

v. During warm-up of entire accelerator; return liquid helium to storage dewars and reliquefy helium as it is vaporized. The refrigerator capacity in terms of mass flow and refrigeration effect is determined, to the first approximation, by requirements to satisfy condition i) above.

Table VII-1 details the steady state load values. For conditions ii through iv, the refrigeration required is less by 14%, since the magnet lead cooling flow drops to 26 g/sec. The connected capacity is greater by 17% over steady state conditions and by 36% over that required to allow for cool down and malfunction of compression or refrigeration equipment.

The heat load due to bake-out is less than the refrigeration required for the 26 g/sec of helium used for lead cooling when the magnets are energized. The bake-out temperature is 475 K. A temperature difference of 470 K across 1.5 cm of multilayer insulation, in a vacuum $\sim 5 \times 10^{-5}$ Torr, using an apparent thermal conductivity, k_e (corrected for elevated temperatures) from values measured between the temperature of 4.5 to 300 K yields a heat load of 1.2 W/m. If both beam vacuum chambers are baking simultaneously, this represents an increase in total load on the refrigerator of 10% of the operating accelerator, and this will not inhibit the retention of liquid helium within the dewars. The heat load to the dewars was established using an apparent thermal conductivity of 0.5×10^{-6} W/cm $^{\circ}$ K. This value is conservative in that several manufacturers have stated that they fabricate industrial style dewars with an average insulating value equal to or better than this.

TABLE VII-1. Normal Operation Heat Loads, Total System

Magnet Dewars

a) Radiation and conduction via supports, connections and instrumentation	7150 W
b) Conduction via magnet power leads	1530 W

Low Temperature Distribution

Radiation and conduction via supports, valves, connections and instrumentation	5520 W
Helium gas entering leads at 4.5 K and exiting at 295 K	52 g/sec ~ 5300 W
Total heat load	19,500 W
Compressor power required	7500 kW
	10,100 HP
Mass flow - Total	3120 g/sec
	41,200 SCFM

The gas bleed required represents a high performance value obtained by precision regulation of helium flow to maintain a gas discharge temperature not in excess of 295 K. Ohmic heating of the ambient electrical circuitry must be removed in conventional ways, such that the lead junction temperature is not greater than 300 K. A conduction heat leak of 1 W, together with a bleed gas mass of 0.05 g/sec per 1000 A lead, was used.

3. General Description

The refrigeration system is illustrated in Fig. VII-1 and consists of: 1) a central compression facility with auxiliary mechanical services, 2) eight refrigeration stations, 3) an accelerator liquid and gaseous helium distribution system and 4) a process control system with a central control station.

3.1 General Compression Facility

A single centrally located station supplies all eight refrigerator stations. A number of compressors of a conservative, heavy

Fig. VII-1. Refrigeration system.

duty design have been selected. One of the compressors used during steady state operations is smaller in capacity than the other and is sized to recompress, into high pressure storage, all gas evolved from liquid remaining in the accelerator when an electrical power loss is incurred. This compressor, which requires 420 HP to compress 1600 SCFM to 15 ATM, can receive drive power from 500 kW of standby diesel power generation which also supplies storage dewar auxiliary refrigerators and is an energy source for process control.

The number of larger compressors includes one more additional unit than necessary for steady state operation. This allows for maintenance and repair while operating the refrigerator and provides extra capacity during chill down. For cost estimating purposes, six installed nominal 2000 HP compressors were assumed, each capable of 7920 SCFM at 15.7 ATM discharge pressure at 300 K, with a suction pressure of 1.65 ATM at 300 K. Five of these compressors, plus the smaller one described earlier, will provide a total of 41,200 SCFM with a power requirement of 10,100 HP - (7500 kW).

The cost estimate is based on a four-stage reciprocating, non-lubricated, compressor of the horizontally opposed design with teflon reinforced piston rings, rider shoes and shaft packing. No oil lubrication is in contact with the process gas. Helium leakage past piston rods is recovered, purified, and returned to the process. Another alternative using rotary screw compressors and gas turbine motive power has to be examined for possible application here, and must be investigated as to initial cost, efficiency, long term reliability and ease of maintenance. The rotary screw compressor is also non-lubricated but, unlike the reciprocating variety, operates without any slipping contact between moving parts. The power consumption is, however, higher.

The compressor facility is equipped with vacuum pumps for evacuation and purging the air from the process piping, which enters when any portion of the system is opened for reasons of service. The refrigerator stations are similarly equipped to service the

magnet dewars, distribution piping and cold box.

A low pressure buffer volume and a high pressure (15 ATM) volume for helium gas are part of the compressor facility and are continuously associated, by means of the control system, to refrigerator operation. The low pressure side is a volume of 40,000 cubic feet to damp surges in the suction pressure. The refrigerator overpressure reliefs to atmosphere are located at this point in the system. The discharges of all other relief valves are returned to this point by the return line. The high pressure gas storage is sized to contain as much as 650,000 SCF at 15 ATM. This is the amount of gas that cannot initially be recovered as liquid when power is lost. The control system will cause helium to fill and empty from this storage, as necessary, during operation.

Impurity removal is accomplished in several ways. Particulate matter is filtered from the gas, upstream of the compressors, to reduce the risk of scoring cylinder and piston surfaces. The same kind of filtration is performed downstream of the compressors to remove matter formed as a result of piston ring and packing wear. Low temperature adsorption purification, to remove air and water vapor, is located at each of the refrigerator sections.

The purifiers are cooled by gas extracted from, and returned to, the refrigerator at about 61 K. The purifiers will limit the total impurity circulating in the helium stream to not more than ten parts per million.

One of the reasons for the selection of a central compressor facility, over one for each refrigerator station, is the labor cost of manning a station continuously. From a safety standpoint it is unwise for one person to stand watch alone in a machinery room of this type. Therefore, with two people on watch continuously, ten employees are required for the compressor station. Most rotating watch schedules, however, arrange for one of these groups to supply maintenance labor on the day shift.

The cost estimate of this report considers a single compressor facility continuously manned by two employees together with a day

maintenance and repair force. Later design studies would aim for a compressor facility that is instrumented and controlled in such a way that, as soon as the accelerator is out of the initial test and operations phase, the facility can operate unattended during the second and third shift. Experience can be drawn from the long distance gas transmission industry which uses totally unattended compressor stations along the pipe lines.

3.2 Refrigerator Stations

Eight refrigerator stations are located along the arc of the accelerator, approximately at the center of each octant. Each of the stations is identical in design and is independent in operation. Each has a capacity of 2900 W at 4.5 K so that any seven stations can carry the full accelerator operating load. The cold box is a large enclosure about 4 m in diameter and 10 m tall. At a minimum, the lower temperature sections will be both vacuum and multilayer insulated. The heat exchanger's valving and interconnecting piping, as well as the four expanders for extraction of work, are part of this assembly.

Since the expanders are the only parts moving continuously at load, they have the highest wear and the highest risk of malfunction. For this reason they are designed to allow for rapid replacement without breaching the piping or insulating casing. Also, each level of work extraction in the cycle contains two expansion engines connected in parallel, either of which is capable of producing full capacity. This increases the initial cost by 5%, but the reliability, to a first approximation, doubles. A second benefit is realized during cool down. The amount of refrigeration effect available for cooling the accelerator at each temperature level is approximately doubled as both engines of a pair are operated, cooling twice as much gas. As the temperature of the gas returning from the magnet system approaches the outlet temperature of the expansion engines in use, the next lower set of engines are brought into play. The lower end of the refrigerator section is circuited

so that it can be operated independently of the accelerator, using an electrically heated calorimeter. The refrigerator piping is also arranged to provide gas for cooling the absorber purifiers and the liquid helium storage inner dewar. The latter circuit is arranged to provide 4.5, 100 or 300 K inner dewar temperatures. The storage dewar is piped so that it can receive liquid helium from the refrigerator, and receive or discharge liquid helium to and from the accelerator magnet dewars.

The liquid helium storage dewars each have a 6000 gallon capacity. They are sized to store all of the helium required within an octant of magnet dewars and distribution piping. During steady state operations of the accelerator, the dewar is empty and evacuated of helium and is maintained at a 100 K temperature level. In this state, the storage dewar is ready to receive 4.5 K gas to the cooling loop from the accelerator return piping and liquid from the magnet dewars. Helium recovery is described in Section VII-5.

Coupled to the liquid storage dewars are completely independent 35 W helium refrigerators which can maintain the storage of helium, continuously, without loss. They, in fact, can recharge the dewar to 100% liquid capacity at a slow rate from the ambient storage. These refrigerators are driven from power circuits with standby diesel electric generating capacity.

Heat removed as work from the helium during the refrigeration process amounts to 19.7 kW per refrigerator section, or a total of 158 kW for steady state operation of the ISA. The expansion engine capacity requirements are in the range where oil lubricated turbines or gas bearing turbines can be applied with good efficiency. Methods to dissipate the work extracted as useful energy have not been evaluated as part of this study. Techniques to utilize this energy, and the heat rejected at the compressors, are to be examined in the future and the gains compared against the complexity of the installation as well as capital, operating and maintenance costs.

4. Analysis of Refrigeration

Cycle and Distribution System

The refrigeration cycle shown in Fig. VII-2 is the familiar Claude cycle with two exceptions. The first of these is a work-producing expansion engine in place of a nitrogen precooling bath, and the second is the addition of another engine, E1, to increase the cold end efficiency over that of a cycle using the normal Joule-Thompson (J-T) valve. The E1 engine has a J-T valve in parallel with it. The J-T valve can be utilized whenever the E1 engine requires maintenance or repair. Use of the valve requires a 24% increase in compressor power to maintain the same refrigeration effect. This utilizes the total connected capacity of the compressor facility.

4.1 Refrigerator Cycle

The proposed cycle, shown in Fig. VII-2, is an idealized thermodynamic representation of the temperature vs entropy. The temperatures shown are approximate for the normal operating condition. Computer programs are now available to refine the estimates of a refrigeration cycle performance. By reiteration of energy balances at each level of the refrigerator, using subroutines of the thermodynamic and transport properties of helium and heat exchanger performance, an accurate indication can be obtained of cycle state points, power and mass requirements.

The use of the E1 engine increases the available refrigeration, at the lowest temperature level, about 24% over that available with the same mass flow using a J-T system. The normal mode of operation would employ the E1 engine with the J-T valve as standby. Total connected compressor power was determined on the basis of cool-down time and redundancy of equipment. Operation of the accelerator using J-T expansion at all refrigerator stations continuously is marginal.

Three Claude cycle engines, E-2, E-3 and E-4, are utilized to maintain a high overall efficiency by minimizing the pinch effect

Fig. VII-2. Refrigerator cycle.

common in helium heat exchange, reducing the temperature at the end of the exchangers and thereby minimizing the total mass flow.

There are a number of possible cycles or combinations of cycles that can be applied to this refrigerator. Further study is required to establish the best balance between simplicity and operating cost, with particular emphasis on power consumption.

4.2 Distribution System

This system comprises all of the components involved in the regulated delivery of helium refrigerant to the magnet dewars of the accelerator. The basic unit, sixteen to the octant, with mass flow regulation to load demand, is the half cell. The half cell consists of two dipole magnet dewars and one quadrupole dewar. In addition, each octant contains several special quadrupole and dipole magnet dewars that are clustered or individually controlled as regards their coupling to the refrigerator. The typical half cell load loop is delineated in Fig. VII-1.

The refrigerant helium leaves as liquid, at 4.65 K and 20 psia, and is distributed to supply the octants and the insertions, a distance of about 150 m on either side of the refrigerator section. A flash tank and control are at each end of the line to separate, vent, and return to the refrigerator, vapor which represents about 3% of the mass flow transmitted.

The transfer lines are insulated with 5 cm of multi-layer insulation, in vacuum of about 5×10^{-5} Torr, and without an intermediate temperature shield. Fluid flow to the half cell is controlled by liquid level in the dewars. The vapor pressure within the dewar is a function of the pressure drop of the entire return system back to compressor suction. The pressure gradient along the magnet dewar return line, from the octant end to the refrigerator, which is approximately at the central point, results in a dewar boiling temperature difference of about 0.005 K. The cold lines are continuous around the accelerator. Dewars in the half cell are interconnected at the bottom and top for gas and liquid flow and

level equalization.

A portion of the cold gas within the magnet dewars is not returned to the refrigerator but is, instead, used to cool the magnet power leads. The leads have been optimized^{4,5} such that the heat leak to the 4.5 K liquid vaporizes the exact amount of gas required to cool the lead when operating at rated current. To insure no more gas flow through a lead than is necessary, a flow control valve is placed on the outlet of each lead. The flow is modulated to maintain a fixed gas bleed discharge temperature of 500 K under variations of 0 to 100% of rated magnet excitation current.

5. Transient Operations

5.1 Cool Down Time Estimate

Estimating the time to cool and immerse in liquid helium a mass such as is involved in the magnet and dewar system of this accelerator, approximately 2500 tons, goes beyond all previous experience. This is because of the size, the impedance offered by 3000 meters of lower temperature supply line, an equal amount of return line, and the degree of coupling the refrigerant has with the mass to be cooled.

The total heat to be removed involves the cooling of 2.11×10^9 g of accelerator and 2.15×10^7 g of helium of which 1.8×10^7 g is liquefied.

Charging the refrigerator with helium is best accomplished using purchased two phase fluid at ~ 4.3 K. The liquid is delivered directly into the storage dewars, with the gas entering the refrigerator piping. Without the accelerator as a load, the liquefaction rate available for converting excess gas into liquid is about 7500 liters/hour. This capacity diminishes to 1700 liters/hour when the accelerator is filled with liquid helium, but not operating.

The heat to be removed from the accelerator is shown below for several temperature levels, as determined by the outlet temperature of each refrigerator stage. An average heat capacity for each

range was used, along with the total mass of the accelerator of 2.11×10^9 g and 2.15×10^7 g of helium:

300 → 61 K	1.95×10^{11} J
61 → 30 K	3.57×10^9 J
30 - 12 K	5.41×10^9 J
12 - 4.5 K	1.57×10^7 J

Using expanders in parallel, plus spare compression and wet engines, at the final temperature level the refrigerator capacity for each level is:

300 - 61 K	1000 g/sec	1.24×10^6 J/sec
61 - 30 K	750 g/sec	1.21×10^5 J/sec
30 - 12 K	750 g/sec	0.71×10^5 J/sec
12 - 4.5 K	625 g/sec	0.27×10^5 J/sec

The temperature difference between the magnet surface and the refrigerant varies as the distance along the exchange path and with elapsed time. The approximations listed below employ an average temperature difference which reduces the refrigeration effect to half of the available capacity. Recent tests⁶ with a prototype magnet and dewar coupled to a refrigerator indicate that the bulk heat transport rate from the magnet surface will not limit this. The tests indicate a transport rate from the iron of 1.1×10^6 J/s in the 300 to 80 K range and a rate of 6.5×10^5 J/s in the 140 to 4.5 K range. Using these refrigeration effects, and dividing them into the loads for each temperature level, gives the following elapsed times to transit the range:

300 - 61 K	87 h
61 - 30 K	16 h
30 - 12 K	4 h
12 - 4.5 K	1 h

The accelerator is then charged with liquid from the storage dewars and the system is stabilized preparatory to energizing the magnets.

5.2 Unscheduled Loss of Electrical Power

Interruption of electrical drive power requires that immediate steps be taken to minimize the loss of helium refrigerant gas since 3.8×10^6 standard cubic feet are at 4.5 K in liquid and gas phase when the accelerator is operational.

The liquid within the magnet dewars will be driven into the 6000 gallon storage dewar associated with each refrigerator via the liquid supply line. The dewar volume has been isolated from the refrigerator, and at sub-atmospheric pressure at 100 K, by means of a cooling coil on the inner dewar exterior surface. The dewar is kept in this condition to minimize the cold helium involved, without allowing it to fill with liquid air should the atmospheric vent system leak.

When loss of power occurs the dewar is first back filled with process gas, from the vapor side of the refrigerator, at atmospheric pressure. The dewar cooling coil is now coupled to the vapor side process gas returning to the refrigerator to facilitate its cooling to 4.5 K. The vapor return lines of all dewar half cells are closed off and the liquid is driven back by dewar liquid vaporized from heat inleak.

This step in the recovery requires about two hours for the magnet dewars to empty. About 85% of the liquid helium, previously within the accelerator, is now within the storage dewars. The storage dewars are of the zero loss type since they are equipped with small, about 35 W, refrigerators supplied by electric circuits which have diesel auxiliary power available. Vapor at 4.5 K, formed in the dewars, and existing within the process lines, will heat at a rate such that relief valves, set at 3 atm absolute, will vent to the 1 atm vent lines at 15% of the contents each succeeding hour, until all pressure is equalized. Recovery of this vapor into ambient high pressure storage requires 600 HP, also supplied with auxiliary diesel power. A total of 650,000 SCF of helium will be stored in this manner. Ambient temperature gas, at 15 atm, will be trapped in the discharge lines and gas within the compressors will

be vented to the 1 atm storage. The accelerator volume requires only 1500 cubic feet of helium at 300 K and 1 atm.

5.3 Scheduled Shutdown of the Refrigerator

A slower, more controlled, method will be employed to relocate the refrigerant charge within the storage dewars for scheduled shutdowns. When using all compression equipment to maximize the liquefaction rate the liquid produced by the refrigerator is proportioned between the storage dewars and the accelerator. This proportion will allow a net input into the storage dewars of 2800 liters per hour and this will continue for 48 hours until the refrigerator performance is inhibited by a lack of feed gas. This liquefaction rate is available when providing the necessary bleed to de-energized electrical leads. By modulating this flow to match the refrigeration effect the heat input to the accelerator is enhanced, which will further shorten the time of transfer. The accelerator is then warmed by circulating gas from the compressors. The return from the accelerator is shunted through ambient air heat exchangers to keep the compressor suction temperature normal. This heating rate is controlled to allow gas recompression into high pressure storage as described earlier.

5.4 Magnet Quench

The magnet protection circuitry, and the arrangement of the magnets within the dewars, is such that a quench will normally couple 4 of the 4.25 m dipole magnets, i.e., two magnets in the upper and two in the lower accelerator within two adjacent dewars. Approximately 1860 kJ will be released as heat. This release of energy to the helium is smeared in time by heat storage and transfer effects such that the vapor products of 800 liters will have vented in 10 to 15 seconds, via relief valving, to the 1 atm uninsulated return to compressor suction. It is important that the refrigerator be protected against surges of return vapor of sufficient mass to disturb temperature and pressure equilibriums.

Similarly, the compressor facility controls must sense the 8 psi or so increase in suction side pressure and 1) modulate the compressor through-put to prevent compressor overloading and 2) deliver the excess system gas to the 15 atm storage until it can be reabsorbed as liquid within the accelerator. The time required to reliquefy the 800 liters is estimated to be about 0.5 hours, considering that all cold boxes are contributing their reserve capacity.

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VIII. MAGNET POWER SUPPLY

1. Introduction

The main dipole magnet system requires a relatively low voltage (< 1000 V) and a current of 3300 A. This is an ideal range for the application of solid state components. In many industrial applications, as well as in accelerator installations, wholly solid state systems are in use and are demonstrating excellent performance, life and reliability.

2. Main Magnet Supply

From the stored energy and current, the inductance of the magnet system can be computed from $J = 1/2 LI^2$. The maximum magnet voltage can be determined from $E = L di/dt$, once the acceleration time is specified. Table VIII-1 tabulates these results. The required magnet voltage is 600 V, which is an ideal voltage range for solid state rectifier-inverters.

Table VIII-1. Basic Parameters of Magnet Power Supply

Stored energy per dipole magnet	465 kJ
Stored energy per protection group	930 kJ
Total stored energy, bending magnets, each ring	120 MJ
Magnet current	3.3 kA
Inductance per bending magnet	85.4 mH
Total inductance, bending magnets (256 magnets)	21.9 H
di/dt , 120 sec rise time	27.5 A/sec
Magnet voltage	600 V
Peak instantaneous power ($E_{\max} I_{\max}$)	2.0 MW

Figure VIII-1 shows a possible schematic of the magnet power supply system. Ripple filtering is accomplished by a combination of the effects of the passive filter, consisting of the R, L, and C's shown, and the feed-back system controlling the firing of the SCR rectifiers.

Table VIII-2 tabulates, versus frequency, the raw ripple, the

Fig. VIII-1. Magnet power supply system.

attenuation that results from the two filtering systems, the resulting ripple voltage and finally the ratio ($\Delta I/I$) for the ripple current in the bending magnet system. For the purpose of these calculations, the rectifier system was assumed to have a 5% reactance. The total fractional ripple current, and therefore total magnet field ripple, will be of the order of two parts in 10^9 . This small value is due to the large inductance of the cryogenic magnet.

3. Auxiliary Supplies

The focusing quadrupoles and other auxiliary magnets can be powered from a system similar to the main magnet supply but reduced in size in proportion to the reduction in energy stored. Current tracking, as required, can be accomplished by electronic control with computer inputs.

4. Fault Protection

Each main magnet ring contains 120 MJ of stored energy. Some mechanism must be found to prevent this large amount of energy from dissipating in a magnet fault. Such faults, called "quenches", occur when the superconducting material jumps to its "normal" state.

The simplest protection mechanism is a shunting power diode connected across a two-magnet group. These power diodes have a voltage threshold for current conduction. Below this voltage only a few milliamperes will flow in the forward direction. By connecting diodes in series, this threshold voltage can be engineered to exceed the maximum expected operating voltage of the magnet group during acceleration (approximately 3.5 V).

During a fault the terminal voltage of the diode system will exceed this threshold voltage and the current will commutate to the diodes, from the faulting magnet system. This condition will be electronically detected and the main rectifier triggered into its invert mode. This will remove the majority of the stored energy

Table VIII-2. Ripple Analysis

Harmonic Number	Frequency (Hz)	Raw Ripple Peak to Peak (V)	Attenuation From Feedback	Attenuation From Filter	Final Ripple (mV)	$\Delta I/I \times 10^{-9}$
1	60	0.75	0.03	0.25	3.5	0.29
2	120	6	0.01	0.065	4.0	0.1
3	180	1.5	0.03	0.03	1.4	0.025
6	360	4.5	0.05	0.007	1.5	0.013
12	720	210	1.0	1.7×10^{-3}	360	1.56
24	1440	84	1.0	0.43×10^{-3}	36	0.08
36	2160	35	1.0	0.2×10^{-3}	6.9	0.01
48	2880	4.5	1.0	0.1×10^{-3}	4.5	0.0005

and return it to the power mains.

The current shunting diodes can be attached to an air-cooled heat sink and can deliver the heat generated in the diode to convecting air. Since the failure mode for a power diode is always to produce a short circuit, never an open circuit, this creates a fail-safe system.

The energy stored inside the two-magnet protection groups must be dissipated inside the magnet. The magnet, dewar and cryogenic system must be engineered to withstand this event.

The enthalpy, mass and thermal conduction properties of the material of the magnet are reasonably well known. It is possible, therefore, to construct a computer code to represent the physics of a quench event. However, considerable programming effort is required to generate a fully adequate code. To date, several simplified codes have been generated¹ and the results of these codes have been compared with experimental results. The agreement is very good.

The computer codes were used to extrapolate from the latest voltage-current measurements made on a 1 meter model pair, to the proposed magnet configuration. In all of the experimentally observed magnet quenches, a quench in one magnet would induce a quench in the other magnet a short time later ($10 < \text{time} < 50$ milliseconds). Thus the magnetic energy stored in the magnet pair would dissipate, some in one magnet, the remainder in the other. In some cases, a sizable fraction of the energy would be concentrated in one magnet. The design limit must consider the case where all the energy is deposited in a single magnet. Computer extrapolation to this case is shown in Fig. VIII-2.

The terminal-to-terminal voltage on the magnet coil, during the fault, reaches a maximum of 1200V. Dielectric insulation must be provided to withstand this potential. The voltage gradient in the coil reaches a turn-to-turn potential of just under 11 volts. This is a modest potential and production quality controls are easily devised to test and insure the ability to withstand this

Fig. VIII-2. Magnet characteristics during quench.

potential.

The terminal-to-terminal magnet voltage may be reduced by increasing the copper to NbTi ratio which increases the thermal mass and decreases the normal resistance. This slows the rate of magnetic energy release and thus reduces the magnet terminal voltage. Another possible method for reducing this voltage is to employ internally connected shunt resistors across the magnet with or without series diodes.

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IX. VACUUM SYSTEM

1. General Considerations

The vacuum requirements of the ISA are determined mainly by the desire to avoid the beam induced pressure rise observed at the CERN ISR,¹ considerations of radiation background, and the need to clear trapped electrons and negative ions from the beam. Further design constraints are imposed by the necessity to remove the heat generated in the vacuum chamber due to beam induced rf currents and eddy currents caused by the rising magnetic field during acceleration.

The vacuum system to be described will maintain an 8 cm i.d. tube at an average pressure lower than 1×10^{-10} Torr inside the lattice and $\leq 1 \times 10^{-11}$ Torr in the interaction regions. The chamber will be fabricated of aluminum and operated at room temperature.² It will be insulated from the 4.2 K superconducting magnets by a 1 cm thick layer of superinsulation, so that it can be baked out to a minimum of 200°C while the magnets are maintained at 4.2 K.

1.1 Radiation Background

The facility for studying reactions with low cross sections depends, to a large extent, on reducing the radiation background generated by interactions of protons with residual gas in the vacuum chamber or by particles lost from the beam and striking the vacuum chamber. In order to achieve acceptable operating conditions, the density of residual gas molecules in storage rings must be several orders of magnitude lower than in conventional accelerators.

The vacuum requirements are set at 10^{-10} Torr in the machine section of the ISA and at 10^{-11} Torr or better in the experimental straight section. At 10^{-11} Torr, there are about 3.3×10^5 molecules (predominantly hydrogen) per cm^3 . For a 100 m long straight section, the number of beam-gas interactions with the 10 A circulating proton beam (line density $\lambda = 2.0 \times 10^9/\text{cm}$) would be approximately 1.5×10^4 per sec. At an average multiplicity of 50 in

each interaction one obtains the number of background particles from each straight section as 7.5×10^5 per sec which is only a factor of 50 below the total event rate from beam-beam interactions. Evidently, a vacuum of less than 10^{-11} Torr must be a goal and careful shielding is essential.

1.2 Beam-Induced Pressure Rise

At these design pressures, the most important limit on the maximum current will be the pressure rise produced by beam-induced desorption from the walls of the vacuum chamber when it is bombarded by the beam ionized residual gas molecules.¹ Using Fisher's equation,³ we can calculate the maximum circulating current, I_{crit} , at which value the onset of an instability, called the pressure bump, destroys the circulating beam. Figure IX-1 shows the dependence of the product ηI_{crit} on the distance between pumps, L , for various pumping speeds, S . The gas desorption coefficient, η , represents the number of gas molecules released per incident ion. The sticking factor is assumed negligible at room temperature. η is, of course, strongly dependent on the beam intensity, which determines the number of bombarding ions and their energy, and on the surface condition of the chamber. In the unbunched beam condition an ion will receive an energy of about 200 eV per ampere of 200 GeV circulating current. In bunched beams, where the current density is dependent on the bunch shape, the ion energy will vary with its position relative to the bunch.² Even though the ion energy is increased during the bunched condition, the empty space between the bunches is expected to decrease the probability of pressure bumps.

Consulting Fig. IX-1 one finds that $\eta I_{crit} = 30$ A can be realized in our system with a 500 liter/sec pump. Increasing the pumping speed above this value results only in a negligible improvement in ηI_{crit} due to the conductance limited condition. A higher maximum accelerated current can be realized by decreasing either the magnet length or the desorption coefficient η . Taking into account

Fig. IX-1. Critical current limits.

a bake-out temperature of about 200°C, a surface treatment can be developed which will yield $\eta < 3$, thus permitting a 10 A circulating current. At present the ISR can store more than 20 A in a stainless steel vacuum chamber baked out at $\sim 300^\circ\text{C}$ which implies a value of $\eta < 2$.

The beam blow-up due to multiple Coulomb scattering, and beam loss due to inelastic nuclear scattering, are expected to be negligible at the operating pressure of $< 1 \times 10^{-10}$ Torr which corresponds to a gas density of 3×10^6 molecules per cm^3 . Using the CERN expression⁴ for beam loss due to inelastic nuclear scattering, one finds the expected decay rate to be about 4 ppm/min, which would be acceptable.

1.3 Beam Neutralization

The Coulomb field of the proton beam creates a potential well within the beam pipe which traps electrons and negative ions produced by ionization of the residual gas. The resulting neutralization of this field has the undesirable effect of shifting the betatron tune of the circulating protons. Pairs of clearing electrodes, semi-cylindrical in shape (to increase the field strength near the axis), approximately the same diameter as the beam pipe, and about 10 to 20 cm long, will be installed at the ends of the magnets and will operate at voltages up to ± 10 kV. Similar electrodes will be installed in the long straight section at intervals of about 30 m. At the gas densities mentioned above, the clearing rate should be sufficient to maintain an adequate degree of neutralization.

1.4 Beam Heating and Eddy Currents

Since the ISA beam is bunched during stacking and acceleration, it will induce a current, J , in the vacuum chamber walls, and dissipate power according to $P = \frac{1}{2} R_s |J|^2$, where the surface impedance $R_s = \sqrt{\pi f \mu_0 \rho}$. Taking the average circulating current of 10 A, a bunch length of 120 rf degrees and a cosine squared charge distri-

bution, a maximum power dissipation of 0.25 W/m occurs in the beam tube during acceleration. The heat will flow towards the end of the magnet where it will be dissipated into the ambient atmosphere.

During acceleration, the rising magnetic field will induce eddy currents in the chamber walls which in turn will cause an additional magnetic field in the magnet aperture and additional heating of the walls.⁵ Assuming a maximum dipole field of 40 kG, a maximum quadrupole field of 6.7 kG/cm and an acceleration time of 120 sec, the dissipation is significant only in the tube inside the dipole where it is ~ 0.18 W/m.

It can be shown that these eddy currents in the circular chamber will give rise only to dipole fields in the dipole magnets and only quadrupole fields in the quadrupole magnets of about 0.7G and 0.08 G/cm respectively. If required, corrections for these fields can be incorporated into the control systems of the power supplies for the dipole magnets and the quadrupole magnets.

1.5 Surface Treatment and Bake-out

As previously mentioned, a careful surface preparation is of utmost importance in achieving a low desorption coefficient η , especially since the in situ bake-out temperature of the aluminum chamber will be limited to 200°C. A somewhat higher temperature, up to 250°C, would probably be safe since most of the tube will be inside the dewar vacuum. This margin can also be used to obtain higher circulating currents.

Prior to installation, the vacuum chamber will be subjected to the following treatments:

- i. Chemical polishing or electropolishing to reduce the effective surface area.
- ii. Firing at 350°C in a 10^{-6} Torr vacuum furnace.
- iii. Argon and oxygen discharge cleaning.

After assembly the chamber will be baked out at 200°C after every exposure to the atmosphere, using heaters installed between magnets.

2. Mechanical Design

2.1 Vacuum Chamber

The vacuum chamber will be constructed entirely of aluminum to achieve economical and operational advantages which are as follows:

- i. The high electrical conductivity lowers the power dissipation due to induced rf currents during bunched beam operation, and improves the situation for the resistive wall instability.
- ii. The high thermal conductivity eliminates heating and cooling devices inside the superconducting magnet dewars. The bake-out is simply accomplished by heaters installed between magnets.
- iii. Aluminum is an excellent high vacuum material and has been baked successfully up to 200°C resulting in outgassing rates below 1×10^{-13} Torr liter/sec-cm².
- iv. Aluminum is cheap and easy to machine.

Inside the magnets there will be an 8 cm i.d. tube, with a 2 mm wall thickness, supported in the middle of each dipole. It will be insulated by a 1 cm layer of superinsulation to withstand a 250°C bake-out. It will be welded to a larger diameter tube between the magnets where clearing electrodes, pick-up electrodes, sector valves and other beam diagnostic equipment will be located. It is planned to install one pair of clearing electrodes per magnet, one set of vertical and horizontal pick-up electrodes per cell and one sector valve per 2 cells. Straight sections will contain similar equipment.

The inter-magnet vacuum chambers of both rings will be connected to a common pumping unit (Fig. IX-2) through an aluminum to stainless steel transition having a N₂ conductance of ~ 500 liter/sec. The transitions will be made from explosively bonded material made by DuPont, or by friction welding. Both types have been tested at temperatures above 250°C. Explosively bonded transitions were used at SPEAR and found to be leak-free. The entire inter-magnet section, including the pump, will be provided with heaters and heat shields. Assuming superinsulation with a thermal conductivity of

Fig. IX-2. ISA pumping unit.

5×10^{-7} W/cm $^{\circ}\text{C}$, the heat leak into the 4.2 K magnet system will be 0.37 W/m during operation and 1.8 W/m during the 200 $^{\circ}\text{C}$ bake-out.

2.2 Pumping System

The pumping unit, which services both chambers, is shown in Fig. IX-2. It is constructed from stainless steel and contains a Ti ball, modulated Bayard-Alpert gauge, sputter ion pump, bakable valve and a spare "Conflat" flange, to be used either for a mass spectrometer or another vacuum instrument. This unit is connected to the vacuum chamber via a "Conflat" flange and a copper gasket. The entire unit is bakable to 350 $^{\circ}\text{C}$. Most of the pumping speed (in excess of 10,000 liter/sec for H_2) is provided by titanium sublimation, which pumps all getterable gases very effectively at low pressures. Nongetterable gases (such as He, A_2 and CH_4) are pumped by a 400 liter/sec sputter ion pump. The system is roughed out via a bakable valve connected to the manifold of a turbomolecular pumping station, one per cell. One mass spectrometer head is also provided at a rate of 1 per 2 cells for leak checking and other diagnostic purposes.

2.3 Pump-Out Procedure

The vacuum system is first pumped out by turbomolecular pumps to below 1×10^{-5} Torr whereupon the bake-out is switched on. After initial outgassing, lasting a few hours, the sputter ion pump is turned on and the bakable valve closed; the 200 $^{\circ}\text{C}$ bake-out continues for an additional 20 to 30 hours with only sputter ion pumping. After the system cools down, the Ti balls are energized and a layer of titanium deposited on the walls. Assuming an outgassing rate* of 5×10^{-13} Torr liter/sec-cm² the pumping unit will hold the pressure to 1×10^{-10} Torr in the middle of a dipole and

* In recent tests, an outgassing rate of 4×10^{-14} Torr liter/sec-cm² has been measured in a 2.5 m long aluminum tube after discharge cleaning with argon and oxygen and a 24 hr bake-out at 200 $^{\circ}\text{C}$.

2×10^{-11} Torr in the intermagnet section. It is sufficient to turn on titanium sublimation for a few minutes every 2 to 3 weeks or whenever the pressure in the intermagnet chamber reaches 4×10^{-11} Torr. At the above outgassing rate the Ti ball unit will last indefinitely.

3. Experiments

In order to be in a position to select the most economical and efficient vacuum system, studies are being carried on in several areas.

3.1 Surface Preparation

Spectrometer studies on a 2.5 m long, commercially available, aluminum AL 6061-T6 beam tube are presently being conducted to determine the outgassing properties of aluminum as a function of the following treatments:

- i. electropolishing
- ii. chemical polishing
- iii. firing in a vacuum furnace up to 400°C in the 10^{-6} Torr range
- iv. glow discharge cleaning
- v. bake-out temperature.

After the completion of the aluminum 6061 test, other types of aluminum, as well as other suitable materials for vacuum chambers, will be tested. In parallel, mechanical and structural properties of metals at desirable bake-out temperatures will also be investigated.

3.2 Ion Bombardment

The most important property of the beam tubes for storage rings is low gas release under ion bombardment. Ionized molecules, in an energy range of 0.5 to 5 keV, of gases commonly found in high vacuum will be used to bombard aluminum, copper and stainless steel samples with various surface treatments. In addition, a long

"Bayard-Alpert gauge type ion source" will be tried inside a beam pipe to ionize the residual gas and simulate actual beam desorption. A fast spectrometer will determine desorption coefficients in both cases.

3.3 Superinsulation

The increase in thermal conductivity at high temperature, and deterioration of insulating properties after repeated bake-outs in our application, will be investigated.

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X. BEAM TRANSFER AND INJECTION

1. Introduction

A number of schemes have been proposed for injecting the AGS beam into the ISA. They fall into two categories, azimuthal stacking and energy stacking.

The simplest scheme uses azimuthal stacking by merely injecting four AGS pulses with 10 bunches each to fill most of the circumference of the ISA. After the 36 bunch stack is accelerated to 200 GeV, keeping the beams bunched, a luminosity of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ can be achieved. Another method of azimuthal stacking involves combining the AGS bunches into a single bunch which is stacked azimuthally in the ISA as close as possible to previously injected bunches. A further possibility is to transfer single AGS bunches and, using rf gymnastics in the ISA, to move the bunches azimuthally until they are separated by about one-tenth of their original spacing in the AGS. Both of the latter schemes should result in sufficient current and density to give luminosities of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ or more with unbunched beams.

Although all of these schemes seem to be feasible, the preferred method for the ISA is that of energy stacking used at CERN in the ISR. This is a method having great flexibility, requiring little or no modification of the AGS, and, most important of all, known to work because of the very successful operation of the ISR. The successive steps, with implications on hardware, are outlined below.

2. Beam Preparation and Extraction in the AGS

To minimize aperture requirements in the ISA, AGS operation during injection will differ slightly from present practice. The emittance at 30 GeV will be kept low by using only two turn injection from the linac into the AGS. This will result in lower than usual AGS final intensity (2.3×10^{12} protons per pulse). Intensity in the ISA will be built up to the design level by

injection of a large number (about 250) of AGS pulses.

To prepare the beam for transfer, the total peak rf amplitude in the AGS will be reduced gradually from 400 kV to approximately 36 kV to reshape the proton bunches, increasing phase spread and reducing energy spread, to match the rf stacking system in the ISA.

The beam would then be ejected from the AGS using the fast extraction mode developed for bubble chamber use. The only new equipment in the AGS tunnel would be a full aperture fast kicker of the type developed at BNL.¹ This unit will deflect the beam sufficiently to clear a thin septum magnet which deflects the beam into an extraction channel. It is possible that the shaving mode of extraction currently used in the AGS would give adequate performance; in this case no physical change would be required in the AGS.

3. Beam Transport from AGS to ISA

After leaving the AGS, the beam is transported, using conventional techniques, to the two ISA rings. The transport system has, first, a switching magnet permitting selection of which ring is to be filled. Each beam line then has an achromatic 45° bend to steer the beam toward the ISA inflector. Quadrupoles along the beam lines will keep the beam size in reasonable bounds and will match the beam optics requirements to the injection requirements for the ISA rings.

Since the transport equipment only needs to be energized during the filling operation, conventional iron-copper magnets should be used. The 45° bend for each beam could be achieved with 20 magnets, each 2 m long and operating at just under 20 kG. The first magnet of the bend could be shared with the two beams and with a reversing switch becomes the switching element. A total of 20 quadrupoles should be sufficient for focusing, matching, and momentum recombination. An 8 cm aperture would be used throughout, allowing ample margin for small errors in alignment. Beam profile monitors would be provided at the entrance to the switching element,

the center of each bending section, and just before the inflectors.

4. Injection

The ISA lattice provides a 40 m straight section in each ring for injection. Injection hardware includes a septum magnet which brings the beam into a fast kicker. The fast kicker deflects the beam onto a closed orbit separated by 1.5 cm from the high momentum limit of the stack. The aperture of the kicker will be shielded by a shutter (as at the CERN ISR) to prevent perturbations of the stack by stray fields of the kicker. Two basic modes of injection are possible. In the simplest mode, a single AGS pulse is injected. The fast kicker turn-off time can then be as long as two-thirds of an ISA revolution, or nearly 6 μ sec. Alternatively, a fast kicker could be designed to turn on and off in a shorter time than the spacing between AGS bunches (200 nsec) so that four AGS pulses could be stacked azimuthally at the kicker radius. Kicker design to this specification is well within existing practice.

5. Stacking in the ISA

During injection, and any azimuthal stacking, the beam is held in an rf system whose frequency is exactly matched to that of the AGS (4.45 MHz) and with the correct amplitude to match the beam shape. Then the shutter is removed and the frequency is modulated to decelerate the injected beam into the edge of the stack. The holding and stacking rf system must have a very low, though not impractical, impedance to prevent possible longitudinal instabilities (See sections V and XI). This calls for use of class A amplifiers which can be turned on and off in a single rf cycle. This, in turn, permits suppression of rf buckets so that, if only a fraction of the azimuth is filled with injected beam, it can be stacked without phase dilution. A description of the rf stacking hardware will be found in Section XI.

6. ISA Aperture

Since the aperture required in the ISA is fixed primarily by the injection parameters of the machine it will be discussed briefly in this section. In passing, we note the fact that a minimum 8 cm aperture is determined by pumping speed requirements (see Section IX). It will be found that the aperture dimensions determined by the considerations listed below match the pumping speed specifications of the vacuum system.

Five items contribute to the total aperture required as follows:

i. Emittance of the beam from the AGS. With two turn injection to the AGS the emittance at 30 GeV will be $0.4\pi \times 10^{-6}$ m.rad. This places an aperture requirement of $4 \sqrt{\beta_{\max} \epsilon / \pi}$ where ϵ is the emittance and β is the amplitude function describing orbits in AG machines. In the normal lattice the maximum β will be 40 m. Consequently, the emittance aperture requirement is 1.6 cm.

ii. Momentum spread of the stacked beam. This will be 0.7%. The aperture required to include this momentum spread is given by multiplying the momentum spread by a factor, $X_{p \max}$. This factor for the ISA is 1.7 m and the aperture required for momentum spread is 1.2 cm.

iii. Shutter on injection kicker. For this item an aperture contribution of 1.5 cm is included.

iv. Sagitta. In a 4 m magnet the sagitta requirement is 1.3 cm.

v. Clear space. This is needed to keep the beam as far as possible from its images in the vacuum chamber wall, thus reducing any possible tendency to instability. Magnet misalignments will cause beam displacements of a few millimeters. A total of 2.4 cm of clear space has been included.

The total of the five items listed above is 8 cm. This has been chosen as the aperture to be included inside the vacuum chamber of the ISA.

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XI. RF ACCELERATING AND STACKING SYSTEM

1. Introduction

There are two distinct requirements for rf systems in the ISA. The first must take the beam from the AGS, over many pulses, and stack it to build up the required current in the ISA. After the required beam is stacked in the ISA, at an energy of 28.5 GeV, it must be accelerated to 200 GeV by the second system. The parameters of these two systems are completely different as to frequency, power, impedance level, voltage, etc., and, thus, two separate rf systems are provided.

2. Stacking RF System

The system will operate on a harmonic of 40 and will have the power capability of developing 12 kV across a 400 Ω resonant load. The rf amplifier will operate in the class AB region at top voltage, but below 8 kV the system becomes fully class A. With class A operation, the system can employ strong feedback which can reduce the effective impedance and make wave shape corrections. Dynamic cavity impedances down to 40 Ω should be obtainable for frequencies approaching 30 MHz. A missing rf bucket can be accommodated in any arrangement, as well as a wide variety of other electronic gymnastics.

3. Accelerating RF System

The rf voltage necessary to rebunch the stacked circulating beam and accelerate it to full energy is given by the following expression

$$V = \frac{E_o^2 h \pi \eta (2\pi \Delta E/E_o)^2}{128 E [\alpha_N(\phi_s)]^2}$$

in which

$$\eta = 0.00136$$

$$\Delta E = \text{energy spread of the circulating beam} = 200 \text{ MeV}$$

$$E_o = \text{proton rest energy} = 0.9382 \text{ GeV}$$

h = harmonic number = 2

E = total energy = 29.4 GeV

$\alpha_N(\phi_s)$ = ratio of area of accelerating bucket to area of bucket for $\phi_s = 0$ (see Ref. XI-1)

ϕ_s = stable phase angle.

Inserting the above numerical values the voltage becomes

$$V = \frac{1.3347 \times 10^3 h}{[\alpha_N(\phi_s)]^2}$$

For harmonic numbers of 1 or 2, the longitudinal bunched beam instabilities do not exist in the current understanding of the theory.² A harmonic number of 2 will therefore be chosen. During the beam stacking time, and during the long beam circulating time interval, the main rf accelerating cavities will be shorted so as to present a very low rf impedance to the circulating beam. During the switching intervals between these operating states, unbunched beams will experience the effect of the impedance of the rf accelerating cavities. This will cause instabilities in the beam, but the growth rates can be controlled by keeping the impedance small. An impedance (R_s) of 700 Ω will keep the beam growth small during switching times as long as 100 milliseconds.

4. Beam Stability Considerations

As mentioned in the section on instabilities, Section V, the bunched beam can be unstable against coherent longitudinal oscillations during the injection and stacking process. This condition is little affected by the choice of the stacking system parameters. The low impedance requirement arises from the necessity of eliminating interaction between the first few stacked pulses and this system. Class A operation is necessary so that feedback systems for damping bunched beam, or unbunched beam, instabilities can be employed.

The choice of $h = 2$ for the accelerating rf system assures that the rebunched, 10 A, stacked beam will be stable against oscillations driven by resonant impedances. In addition the

bunching factor will be quite large (≈ 0.5) as well as the spread in synchrotron frequency. Hence the space charge effect will be small and it, along with the resistive wall contribution, are not expected to cause instability.

Interaction between this rf system and the high current stacked beam, before the capture process is completed, is also covered in Section V. As pointed out there, the choice of 700 Ω as the shunt impedance should provide sufficient time for the accelerating gaps to be unshorted (< 100 msec) before significant current modulations can occur in the beam at frequencies that could produce damaging voltages.

5. Cavity Design

When the stable phase angle (ϕ_s) is small the current presented by the beam will look reactive to the cavity and will act to detune it. The amount of detuning is given by

$$\Delta g = \frac{I_b f_o}{2I_{cir}}$$

where I_{cir} is the reactive circulating current in the tank circuit of the cavity, I_b is the beam current and f_o the center frequency.

The bandwidth of the cavity is given by $\Delta f = f_o/Q$ and r , defined as the ratio of detune to bandwidth, is $r = \Delta g/\Delta f = I_b Q/2I_{cir}$.

The tank circuit capacitance C is

$$C = \frac{1}{2\pi f_o X_c} \quad \text{where} \quad X_c = \frac{V}{I_{cir}}$$

Combining these expressions we get

$$C = \frac{I_{cir}}{2\pi f_o V} = \frac{1}{2\pi f_o} \times \frac{I_b Q}{2r V} .$$

The rf cavity excitation power becomes

$$P = \frac{\frac{1}{2} C V^2 2\pi f_o}{Q} = \frac{I_b V}{4r} = \frac{V^2}{2R_s} ;$$

therefore

$$r = \frac{R_s I_b}{2V} .$$

When the beam is bunched, a peak instantaneous current near 50 A is expected. The circulating current in the tank circuit must be larger than this value so that wave shape distortions can be reasonably small. A circulating current, in the resonant circuit, of 275 A will be chosen.

All the electrical parameters of the resonant cavity structure can now be determined. Table IX-1 summarizes the results.

TABLE XI-1. Acceleration rf System Parameters

Frequency, f	0.222 MHz
Harmonic Number, h	2
Shunt impedance, R_s	0.7 k Ω
Peak voltage, V	40 kV
Beam Detuning Ratio, r	0.0875
Quality Factor, Q	4.9
Number of Gaps	4
Circulating Current, I	275 A peak
Capacitance per Gap, C	20 000 pf
Voltage/gap	10 kV
Peak Flux*	460 G
Ferrite Material	3B7
Ferrite Core Area, A	1560 cm ²
Ferrite Air Gap	0.75 cm
Weight Ferrite (both rings)	7.9 tons
Cavity Excitation Power (each ring)	1.14 MW
Beam Power (each ring)	120 kW
Total Power (both rings)	2.52 MW

* The peak rf flux level was limited to keep the power dissipation in the ferrite to 0.25 W/cm³.

Since the transfer from a stacked beam to a bunched beam will take place at $\dot{B} = 0$, there will be a very large rf voltage available during this time.[†] This will allow a large stable rf bucket to be used, resulting in low proton losses during the bunching process.

6. RF System Noise

In a storage ring, the interaction between the rf system and the beam is an important factor. Phenomena with slow growth times can affect the beam because of the long times involved, compared to those in a conventional accelerator. For this reason, the rf system must be designed to keep all sources of phase and amplitude noise to an absolute minimum. The selection of all components and circuits in the system will have to be made with minimum noise characteristics a prime consideration.

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[†] The minimum required voltage during bunching is 3.9 kV with a system capability of 40 kV.

XII. CONTROL AND MONITORING SYSTEM

1. Introduction

It is desirable that the whole ISA-AGS accelerator complex be operated from a central control center. This maximizes the information interchange between the two accelerator systems and minimizes the operating crew required. The amount of data that must be received, organized and displayed for easy assimilation by the operator, is large and complex. Operator instructions must similarly be translated into numerous hardware commands. Routine testing and monitoring must be carried out with minimum operator attention.

These requirements can only be met by a carefully designed, computer based, control system.

2. System Layout

If computers are considered as integral parts of the control system from the start, many additional benefits can be obtained. The additional benefits come mainly from the flexibility of such a system, and the ability to process the data and present it in a convenient form, or to initiate routine control functions without the intervention of the operator.

Figure XII-1 is an illustrative block diagram of the control system envisioned. It consists of a main computer, which processes control data to and from satellite subsystems. These subsystems vary in type and complexity dictated by the requirements of the accelerator component being controlled. The prime function of the central computer is to process data and command instructions on a time shared basis. It would not handle routines requiring real-time computation synchronized to the accelerator. Such real-time computational requirements would be handled by the local subsystem, which would be engineered and dedicated to this purpose. In this way the complexity and overall cost of the total control system is greatly reduced.

Fig. XII-1. Control system block diagram.

Some of the types and forms that subsystems may take are shown on Fig. XII-1. Other combinations however, are possible and may be required.

The quality of analogue processing elements has increased greatly in recent years. Using these to solve many of the real-time delicate subsystem control functions relieves the digital system of the requirement. This will result in large cost savings. Some of the subsystem block assemblies shown are mixed analogue and digital systems, thus preserving the advantages of both.

Data transmission will be accomplished in serial, digital, multiplexed data links using large signal levels to minimize noise errors. A small number of interconnecting cables are required. Only in very special cases, such as viewing of critical wave shapes, will analogue information be transmitted to the control center.

Electrical interlocking necessary to prevent equipment damage will be "hard wired" locally with detailed status information made available to the control complex. Subsystem and higher level interlocking control will be handled through the appropriate computer in a fail-safe manner.

Interlocking necessary for personnel protection will all be "hard wired", and redundant where necessary.

The ISA itself will have a number of instrumentation bays to serve as collection points for subsystem parameters. These equipment bays will, in turn, channel data and control signals to a normally unmanned ISA control center. All controls and instrumentation, routinely used in operation of the ISA and its experimental program, will then be forwarded to the Main Control Room. The intrinsic hierarchy of controls will permit emergency accelerator operation at various control levels in the event of computer or data distribution system failure. This system also lends itself to easier subsystem checkout.

All ISA subsystem controls and instrumentation will be packaged into a standard format; this will permit orderly system modification and growth. As proposed, the ISA control system

combines the elements necessary for low-cost, long-term operation with the flexibility necessary for a major research tool.

3. Beam Instrumentation and Monitoring

It is essential, in a storage ring, to be able to extract detailed information from the beam. The tune, oscillation frequencies, position, shape, density, losses, etc., of the beam must be readily and accurately determined.

At the ISR, at CERN, the following types of beam information and control systems have been found to be essential:

- i. v-meter,
- ii. v measurement in stacks,
- iii. Schottky scans for beam density variation measurements, both longitudinal and transverse.
- iv. rf scans;
- v. general pick-up electrodes for central orbit measurements and for wide-band information,
- vi. beam position detectors for stacks,
- vii. beam profile monitor,
- viii. scrapers,
- ix. beam probes,
- x. secondary emission monitors,
- xi. ionization chambers,
- xii. microwave pick-up system,
- xiii. various feedback controls for stabilization,
- xiv. various computer controls.

The ISA will incorporate systems of these types, plus additional systems as required to answer the special needs encountered during the acceleration process.

XIII. FAST PROTECTIVE EJECTION

The high intensity ISA beam, having a stored energy of ~ 20 MJ at 200 GeV, has to be dumped before it hits the vacuum chamber, in the case of magnet or vacuum system failure. The dumping system designed for this purpose will also be used for scheduled beam dumping in order to localize the beam loss and to reduce the induced radioactivity in other places around the rings.

The beam could be dumped outside the machine. However, this requires an elaborate ejection system of large kicker and septum magnets which may not necessarily meet the very stringent requirements of extremely high reliability. A simple alternative is to divert the beam slightly onto a large, transversely movable, cylindrical metal block built into the vacuum chamber, the way it is done at the ISR. Under normal operating conditions, the beam passes through a hole in the block. The position of the block is adjusted so that it constitutes the limiting aperture of the ring. One can then deflect the beam with a single kicker magnet having a very moderate rise time of ~ 10 μ sec, corresponding roughly to the ISA revolution time. If a particle misses the dump block after having gone through the activated kicker magnet it will be transmitted through the entire ring and get dumped during the next turn. The time to effect a protective dump is of the order of 20 μ sec while the time required for a build-up of orbit distortions, after failure, takes milliseconds.

A suitable place for such a beam dump is the upstream end of the central 40 m long free straight section in one of the service insertions described in Section IV. The X_p function in this region is zero and both horizontal and vertical β -functions are about 25 m. This results in a beam radius of ~ 3.4 mm and 1.3 mm at 30 and 200 GeV respectively. A horizontal kicker in the 5 m free space at the upstream end of the service insertion has to deflect the beam by 0.42 mrad in order to displace it by 1 cm at the front of the dump block. The corresponding angle in the case of a vertical kicker

is 0.67 mrad. For a maximum vertical displacement of 3 cm, a 4 m long kicker magnet with 3.5 kG field strength is required. The amplitude of the kick may have to be roughly programmed to match the beam energy.

The dimensions of the beam dump block should be such that nearly all protons and cascade particles will be absorbed in it. These requirements are fulfilled in the beam dump designed for the 300 GeV SPS beam. It consists of a cylindrical metal block, about 4 m long and 1 m in diameter, with a copper-beryllium core surrounded by iron. In order to reduce the thermal problems involved in dumping the much more intense ISA beam, it might be necessary to sweep the beam both horizontally and vertically over the front face and bore of the dump block. The block will be water cooled to facilitate removing the heat released during the dumping process.

The muon flux emerging from the downstream end of the dump block has been estimated at $3 \times 10^9 \mu/\text{cm}^2$ per 10^{15} protons. The absorbed dose in the machine components downstream from the beam dump is thus about 100 rad per 10^{15} protons, which corresponds roughly to an annual absorbed dose of 10^5 rad. No harmful radiation effects on machine components, including the superconducting magnets, are expected. On the other hand, the dose equivalent would be about 200 rem per 10^{15} protons implying that the ring is not accessible during operation.

The beam dump block also constitutes the only location within the machine where there will be regular periodic beam loss and, therefore, it is the primary area where build-up of induced radioactivity may be a problem. If we assume that 10^{15} protons are dumped into the stop on a daily basis, the residual radiation level will reach up to several R/hr at a distance of one foot from the upstream face. Equipment in the immediate vicinity will need to be minimized in order to reduce maintenance exposure to radiation, and health physics administrative controls will be utilized.

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XIV. ISA SHIELDING

1. Introduction

Many of the considerations regarding the shielding requirements of conventional accelerators are applicable to storage rings or intersecting storage ring accelerators. There are, however, important differences which must be taken into account.

In the past, proton accelerator shielding has been calculated to limit the dose rate under steady-state operation at or below the maximum permissible exposure to a person in an accessible area outside of the shield wall. The intensities of proton accelerator beams were 10^{12} to 10^{13} p/sec. Except for possible beam losses from scraping in the injection regions of the storage rings, the shielding criteria to be applied to the ISA under steady-state conditions or intermittent faults are quite different due to the 6×10^{14} circulating protons. Shielding is required for radiation protection against beam spills whose location and occurrence in case of accident are unpredictable; hence average dose rate cannot be defined, and is not too useful as a shielding criterion.

The worst fault is assumed to be 10^{15} protons dumped at a point during a time that is short compared to that which would be required for a person to be warned to move to a safer location. Arbitrarily, the shielding should be sufficient so that a person outside the shield wall will not receive a radiation dose greater than 100 mrem from a fault anywhere.

When 10^{15} protons, with energy between 28 and 200 GeV, interact wholly or partially with solid matter, phenomena arise which require control, namely:

- i. Secondary particle radiation fields which necessitate shielding for:
 - a) personnel in the vicinity of the storage rings.
 - b) radiation background in the experimental areas.
 - c) skyshine control of radiation backgrounds in other experimental areas at the Laboratory.

- d) stringent reduction of skyshine dose to unmonitored persons residing near the site boundary.
- ii. Instantaneous temperature rise which, under certain conditions, can melt or vaporize any solid matter.
- iii. Residual radioactivity after repeated beam dumps in the same region which build up a gamma-ray background, substantially reducing the maximum permissible working time in the area.

Beam stops are needed to absorb the heat released from the beam dump and to localize the residual radioactivity in a region remote from personnel. (See Section XIII)

2. Shielding Criteria

The minimum time of two minutes between pulses in the storage rings, and an expected operational condition of much longer periods, allows one to design the radiation shield with the primary criterion of safety if an accidental beam dump should occur. It is assumed that a multitude of radiation detectors will locate the dump area and terminate operations in ample time so that personnel can be evacuated from the hazardous area before acceleration is again attempted. A recipient of radiation from a fault is exposed to one pulse only and the usual concept of steady state dose rate is not applicable.

The worst situation is assumed to be 10^{15} protons dumped at a point in zero time. When this occurs, we accept as a reasonable criterion that a person anywhere outside the shield must not receive a dose greater than 100 mrem.

3. Shielding

The shielding problem divides naturally into three parts:

- 1) the hadron shielding required for the strongly interacting particles generated from the collisions in the nuclear cascade;
- 2) the muon shielding required for protection against muons arising from the decay of charged pions in flight and 3) the skyshine.

3.1 Hadron Shielding

The determination of the side shielding is based on a permissible radiation dose of 100 mrem corresponding to a total neutron flux of 1.9×10^6 n/cm² anywhere outside the cover over buildings, tunnels, and beam ducts. In all cases sand or earth is considered to be the shielding material for side shielding.

The shield thickness depends upon: 1) the angular distribution of the hadronic secondaries $S(\theta)$, 2) the particle multiplicities at 200 GeV, 3) the distance of the shield face from the beam line D , 4) the absorption length in the sand, and 5) the fault condition which is taken as 10^{15} protons dumped at a point in zero time.

The angular distribution, shown in Fig. XIV-1, has been measured at various laboratories¹ with the general result that $S(\theta)$ is insensitive to incident proton energy (7 to 28 GeV) and to target material. It has been assumed that the shape of the curve on Fig. XIV-1 is also invariant with energy between 28 to 200 GeV. Particle multiplicities¹ have been scaled by a factor proportional to the energy, which is quite conservative since it is expected that particle multiplicities will vary proportionally to somewhere between the square root of the energy and linearly with the energy. Hence the normalization factor to be used on Fig. XIV-1 should be 700 at 200 GeV.

Combining the source function, $S(\theta)$, with the inverse-square of the distance from the fault to the face of the side shield shows that the maximum flux density on the shield is 45° downstream from the fault. Upon entering the shield (sand), the secondary particle intensity attenuates exponentially with a mean free path of about 60 cm after the first two interaction lengths. From the decay law, it is a simple matter to compute the diagonal length (45° to the beam direction) in the shield required to attenuate the neutron intensity to 1.9×10^6 n/cm². The required perpendicular thickness of the sand cover is shown in Fig. XIV-2 as a function of the perpendicular from the beam to the inside of the shield. It is concluded that a general sand cover over the

Fig. XIV-1. Normalized (at $\theta = 0$) angular distribution of secondary hadrons with energy ≥ 20 MeV.

Fig. XIV-2. Side shield thickness requirements.

tunnel of about 6 m should be adequate shielding for a sudden, full beam dump.

Since shielding over regions of small D requires more shield thickness than over larger D , and since the maximum of the hadron intensity is along a line at 45° to the beam, the thicker shield should be continued until the outside surface reaches an intersection of the 45° line from a fault occurring at the downstream end of the region with the smaller D or radius. Beyond this point the thicker cover can be blended into the thinner one using the hadron intensity variation with angle as a guide.

The assumption that 10^{15} 200 GeV protons are dumped at a point is the most severe condition and requires more shield cover than a beam dump in an extended region. For this reason any neutrons diffusing from sources in the pits in the straight sections will be amply shielded.

3.2 Muon Shielding

The same maximum permissible dose of 100 mrem is used for muons as for hadrons. About $10 \text{ muons/cm}^2/\text{sec}$ is equivalent² to a dose rate of 2.5 mrem/hr or $100 \text{ mrem} = 1.4 \times 10^6 \text{ muons/cm}^2$.

When the high energy protons strike a target (as in the case of a fault), charged pions are made from the nuclear interactions. While in flight (mostly in air) between the production point in the target and the shield wall, some of these pions will decay and those which do decay will practically always produce a charged muon. This is the muon source for which shielding must be considered in the ISA. The remaining charged pions which enter the shield are quickly absorbed by nuclear interactions so that any muons arising within the shielding material can be neglected in comparison with the former source.

We consider first the tunnel shielding for muons along the straight sections. When protons of incident energies between 28 and 200 GeV strike matter, the production angles of the pions which decay into muons are, on the average, less than those for the neutrons and protons. The maximum decay angle between the

pion and the muon is $0.04/p\pi$ ($p\pi$ in GeV/c), hence, for shielding purposes, the direction of the muon is the same as the parent pion. It is concluded that the lateral shielding thickness along the straight sections, which is sufficient for hadrons, will be ample for muons. The multiple Coulomb scattering of the muons in the shield will increase their lateral extent somewhat, but not sufficiently to alter this conclusion as shown³ from Fig. XIV-3.

Multiplying the 10^{-10} contour of Fig. XIV-3 by 10^{15} protons, we arrive at a muon flux density of 10^5 muons/cm²/ 10^{15} protons which is lower by over a factor of 10 from the 1.4×10^6 cm⁻² arrived at from a dose of 100 mrem. This lower value is used because of the theoretical uncertainty in the pion production, hence the reason for the two families of contours shown on Fig. XIV-3, one set according to Trilling⁴ and the other due to Coconni, Koester, and Perkins(CKP)⁵. Distances in the sand may be scaled from the graphs for heavy concrete simply by increasing them by a factor of two, since sand has half the density of heavy concrete¹. The sand cover needed from the figure is about 4 m whereas the graph of Fig. XIV-2 shows about 7 m required for hadrons over a tunnel 2 m in radius, thus clearly illustrating that the lateral shielding requirements are determined by hadrons.

On the other hand, the longitudinal extent of the shielding required is determined by muons, due to their long range. Consider shielding for muons entering the sand in the curved sections of the storage rings. Crudely, the muon trajectories in the sand lie in the median plane and are tangents in contact with the proton beam near the point where the muon was created. It is the locus of the points on these tangents where the muon intensity falls to 10^5 muons/cm²/ 10^{15} protons which determines the contour and therefore the lateral extent of the shielding around the curved sections. These tangents are long compared to the transverse dimensions of the hadron shielding. The reason for this is that muons interact mostly electromagnetically and are slowed down chiefly by the stopping power of the sand, although pair produc-

Fig. XIV-3. Isoflux contours for muon flux/ cm^2 for one incident 200 GeV proton. (From Ref. XIV-4.)

tion, some nuclear interactions, and bremsstrahlung compete to some degree. An average value for muon energy loss rate in flight⁶ is about $2.82 \text{ MeV g}^{-1} \text{cm}^2$ which amounts to a range in sand of almost 400 m for a muon decaying from the high energy end of the pion spectrum. Therefore, a shield which would have sufficient range to stop all the muons would be very massive and expensive. However, a shield which will reduce the dose per burst to 100 mrem reduces the lateral extent of the shield to a reasonable value.

Referring to Fig. XIV-4, which shows the muon isocontours for 200 GeV protons in a heavy concrete beam stop³, it is seen that the 10^{-10} contour intersects the median plane about 80 m downstream or 160 m in the case of sand.

Tangents 160 m long can be drawn from assumed fault locations at various points along the curved orbits in both directions and an envelope drawn through the terminations of these tangents. The result is close to a circle 313 m in radius.

In summary, the shielding for the curved sections should be about 6 m of sand cover for the hadrons with a muon shield added in an outward radial direction. The top of the muon shield should be 3.6 m above the median plane. Its outer limit is an arc of a circle 313 m in radius whose center coincides with the center for the radius of the bending magnet sections.

3.3 Experimental Halls

The exact amount of shielding required over the experimental halls will be dependent on their exact configuration.

However, the presently planned configurations should be adequately shielded with about the same earth cover (i.e. about 6 m of sand) as used for the ring area.

In view of possible future, higher beam currents, uncertainties in the radiation calculations, and future radiation standards which may eventually prevail, provision for up to 9 m of sand cover should be made.

In some part of the experimental hall shielding one may wish to use concrete to provide easy accessibility to doors, entrances,

Fig. XIV-4. Isoflux contours for muon flux/cm² for one incident proton.
(From Ref. XIV-6 and XIV-7.)

etc. It seems best in those cases to consider using retaining walls to support the sand around such sandless areas and to use light concrete of the same thickness (i.e. about 6 m) to avoid exposing the radioactive interior of the sand shield.

3.4 Skyshine

Distenfeld and Colvett⁷ have measured the skyshine radiation pattern at ground level out to 1000 m from the skyshine source employing a 30-cm Bonner sphere. Correcting their data for a factor of two increase in the sand cover over the source yields the expected skyshine doses shown below in Table XIV-1.

TABLE XIV-1. Skyshine Dose for 10^{15} Protons as Function of Distance from Source.

Distance (m)	mrem/ 10^{15} p
50	1.2×10^{-1}
100	3.6×10^{-2}
500	8.7×10^{-4}
1000	9.4×10^{-5}
1500	1.8×10^{-5}
2000	4.7×10^{-6}

From site drawings, the closest fault to the Laboratory boundary is about 300 m. From Table XIV-1, the skyshine dose for a single pulse is approximately 10^{-3} mrem. It is concluded that an off-site point would never accumulate the permissible annual dose of 1 mrem.

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XV. STRUCTURES, UTILITIES, SITE WORK AND GEODETIC SURVEY

1. Site Planning

1.1 Site Selection

The proposed site for the ISA, shown on Fig. XV.-1 was selected after balancing the effects of a large number of parameters. Among them, the more important items were:

30-GeV Beam Availability. Presently authorized programs provide for a full intensity 30-GeV beam through the North Experimental Facility. For economic reasons, and to prevent a major shut-down of the AGS research program, this beam will be utilized. This locates the machine to the north of the AGS.

Machine Lattice Structure. In order to keep the four long straight sections free for research use, the beam will be injected into the ISA at the SE and SW short straight sections. This gives the machine approximately a north-south orientation.

Radiation Considerations. The machine has been located so that the closest site boundary is about 366m to the northwest.

Site Considerations. The existing ground level at the ISA site varies from elevation 55.0 ft. (15.4m) to elevation 90.0 ft. (27.5m). Preliminary analysis of shielding requirements, topography, water table elevation and construction costs indicate that the ISA beam should be placed at elevation 65.0 ft. (19.8m).

Cost Considerations. The cost of extending existing utilities and road networks to the ISA, and providing adequate drainage, has been considered.

1.2 Access and Road Work

The road network will be placed inside the ring and connected to Upton Road on the west and Railroad Ave. on the east.

1.3 Site Storm Drainage

The site selected straddles the existing natural drainage swale which now drains the northeast portion of the site. This

Fig. XV-1. Brookhaven site plan.

drainage channel will be redirected under the 30-GeV beam transport enclosures and carried under Railroad Ave. on the east to a recharge basin. Storm drainage within the ring will be carried off to four or five recharge basins.

2. Magnet Enclosure and Auxiliary Structures

2.1 Main Magnet Enclosure

Figure XV.-2 shows a cross section of the main magnet enclosure. Cost studies have been made of both corrugated steel multiplate enclosures, as shown, and precast reinforced concrete. Enclosure costs are about equal, and, as either type will suffice, alternate construction quotations will be taken. The enclosure, which has a total length of about 2690m, will be covered initially with 6m of sand for radiation shielding but its design will be such that this shield may be increased to 9m if necessary. Major equipment entrances will be provided at the midpoints of the experimental halls. This will place all points of the machine within 366m of a major equipment access. At the south and west halls a 3m x 6m elevator will be installed for equipment handling. At the north and east halls a ramp from outside service areas will provide direct access to the magnet enclosure via the experimental hall. Four intermediate emergency exits will be provided so that the maximum distance to an exit will not exceed 366m.

An underfloor drainage system will be provided which will drain to sumps located at the research halls. Emergency ventilation will be provided, as well as dehumidified air for normal ventilation and to keep the enclosure dry. The normal air supply will be conditioned for winter and summer although no heating system for the enclosure is contemplated. A compressed air distribution system will be installed around the enclosure.

Electrical services will consist of normal and emergency lighting, a 120/208-V four-wire distribution system for general and machine power, and a 480-V distribution system for machine power. Three trays will circle the enclosure, two for power wiring and the other for control, timing and communication services. The enclosure will be protected by automatic fire alarm systems in

Fig. XV-2. Tunnel cross section.

those areas where equipment and content are nonflammable and by automatic sprinkler systems in all other areas.

2.2 Service Building

A 2-story 1850 m² service building will be constructed near the center of the ring. It will house a mechanical assembly area with an overhead traveling crane of 10 ton capacity, a technicians shop, stockroom, equipment area, and lavatories on the first floor. Office space, Main Control Room, computer room and an electronics laboratory will be located on the second floor. The building will be steel frame with a reinforced concrete foundation; siding will be of either masonry block or aluminum insulated panel wall and interior partitioning of lightweight masonry units. Conventional lighting, telephone and fire alarms, heating and air conditioning will be provided as required.

2.3 Compressor Facility

An 1100 m² compressor building will be constructed adjacent to the 69 kV switchyard in the center of the ring. It will house six large helium compressors, vacuum pumps, switchgear, and gas system control apparatus and have a small operations office and maintenance area and a ten ton overhead crane to service the compressor units. The building will be of industrial construction having a steel frame on a special reinforced concrete foundation. Siding will be either masonry block or aluminum sandwich wall with special steel grating type flooring around the compressors, for access of underfloor piping.

2.4 Refrigeration Buildings

Eight small 40 m² buildings will be located around the inside perimeter of the ring (two per quadrant). These will serve as control and equipment buildings adjacent to cold boxes and liquid dewars. They will be of conventional construction, slab-on-grade masonry block or aluminum siding exterior walls. Lighting, heating, fire alarm and telephone are included.

2.5 Exit Structures

Seven exit buildings will be constructed, one in each quadrant of the main magnet enclosure at the short straight sections, and 3 in the beam transport tunnel. These buildings will house exit

stairways and passageways from the tunnel floor to outdoor grade.

2.6 Assembly Buildings

At each of the experimental halls, a 1000 m² assembly building will be constructed adjacent to the access points to each hall. The buildings will be masonry block with insulated aluminum panels over a steel frame. They will be equipped with a 20 ton overhead crane for equipment assembly and material handling. Conventional services, light, heat, power, etc., will also be provided. A small equipment service room and toilet facilities will be included. A paved yard area will connect with the access ports to the experimental halls.

3. Magnet Foundation

The AGS was supported on steel pile sections to average the effects of differing soil responses for a depth of 8 m. Data have shown that, as major changes in foundation loadings result in minute deflections for at least several hundred feet vertically, the piles are unnecessary. This is due to the fact that, although the well-graded sand and gravel has minor lenses, over any sizable area and depth the soil is remarkably homogeneous and can easily support loadings up to 16 000 lb/sq. ft. Studies of annual soil temperature changes at various depths show that the foundation slab will be subjected to less than a 2° C yearly temperature swing. This variation will be further reduced by the presence of the water table a few feet below the foundation, which maintains a year-round temperature of 8° C. Some differential settlements between the high fill areas and high ground areas will occur, but as final alignment will take place about two years after the completion of the magnet enclosure, over 90% of the maximum expected settlements will have already occurred and the differential settlements will be very small. For these reasons it has been concluded that a simple slab foundation utilizing the floor of the tunnel will be entirely satisfactory.

4. Experimental Halls

4.1 Large Interaction Halls (north, south and west).

As shown on Fig. XV.-3 the large interaction halls will be about 200m long by about 10m wide and 6m high. A section about 14m wide with a height of 10m (floor elevation of this section is 3m below the floor level of the main magnet enclosure) will be placed at the center of the hall. The construction of the halls will be largely the same except for access to outdoor grade. Slab, walls and arch (roof) will be of reinforced concrete capable of supporting the ultimate 9m depth of earth fill. Each hall will be equipped with overhead traveling bridge cranes (3 per hall) of 10 ton capacity. Access to the north hall will be via a ramped incline through a steel barrel arch tunnel. Access to south and west halls will be via a 3m x 6m equipment elevator to the lower level of the experimental area. Small service and equipment buildings will be provided at access points to halls for switchgear, air compressors, ventilation equipment, etc. A system of under-floor covered trenches for cooling water, cabling and instrumentation to the experimental areas is included. Drainage is provided to a sump, thence ejected to the site system. Electrical power and distribution systems, including experimental power, emergency power, building power, lighting, fire alarm, telephones are provided. A system of cable tray will be installed for "co-ax" systems including machine communication, instrumentation, data handling, monitoring systems, etc.

All environmental systems are provided i.e. air handling, heating, ventilating and filtering.

4.2 Small Interaction Hall (east)

As shown in Fig. XV.-3, the small Interaction Hall will be 50m long by 18m wide. A center section about 30m long will be lowered about 5m from the main magnet enclosure floor level, forming a pit. Access to this hall is a ramped incline. All other construction features and services are identical to the large experimental hall

previously described in section XV.-4.1.

5. Beam Transport Enclosure

The beam transport enclosure will consist of corrugated steel multiplate or precast concrete approximately 2.5m wide by 2.5m high, covered by 3m of sand radiation shielding. Approximately 900m length will be required for the two branches. One exit structure will be constructed near the first bend, and one in each spur. Services will be similar to the main magnet enclosure.

6. Utilities

6.1 Electric Supply and Distribution

It is estimated that a minimum of 20 MVA will be required for the ISA refrigeration plant, machine power and general lighting and power. It is proposed to provide an extension to the 69-kV transfer bus at the Fifth Avenue substation, install a line protection, outdoor oil circuit breaker and take-off structure, and run an overhead 69-kV wood pole transmission line to the center of the ISA ring. Here a 30-MVA, 69 kV-to-13.8 kV, transformer and switchgear would be installed adjacent to the compressor building. Distribution to 15 secondary 13.8-kV to 480-V transformers would be in cable trays run over the surface of the ground. Secondary transformers would be placed at the eight refrigerators, rf building, one at each of the research halls, and one at the service building and compressor facility.

6.2 Domestic Water

A 25cm dia. domestic water line will take off from the existing 25cm dia. main at the corner of Upton and Fifth Avenue, run north and east to the center of the ISA, loop around the inside service road, and connect to the existing Railroad Avenue 25cm dia. main at the intersection of Fifth Avenue.

6.3 Sanitary Sewer

A pumped (force main) sanitary system is planned from the center of the ring to an existing sanitary manhole just east of the H-10 beam tunnel. A gravity system will be utilized from main magnet ring and experimental halls to an ejector station at the service building, thence pumped to the site system.

6.4 Telephone, Fire Alarm, Control and Signal

A tray system will connect the five exit and equipment structures, the refrigeration buildings and the four research halls to the service building, and then go overland to the North Experimental Facility through existing tray to the AGS Main Control Room. An underground duct bank will be provided between all of the ISA structures and the Laboratory system for telephone and fire alarm service.

7. Geodetic Survey

Since the construction of the proposed ISA ring will follow a cut and fill technique no particular problems will be imposed upon the survey program during the tunnel construction phase. The construction will be controlled from a standard benchmark system which will simply be an extension of the existing geodetic grid already in existence at Brookhaven. In extending this grid, special attention will be given to control of the beam transfer lines from the AGS to the proposed ISA rings.

Survey techniques will, on the other hand, be sorely taxed during the radial alignment of the machine in the tunnel. As in almost all accelerators built to date the final machine component alignment will be made with reference to a system of previously aligned survey control points. To a high accuracy, the deviation of the proton orbit in the machine from its prescribed orbit can be expressed as a linear function of the radial errors in the control monument survey.¹ The limited aperture allowance for closed orbit errors of ± 12 mm limits the rms radial placement errors to about 0.5 mm for the quadrupoles. If a goal of 0.25 mm is assumed

for the primary survey control stations a first order survey of one part in 10^6 uniformity in the placement of the primary monuments is required.

The general approach to this problem is shown in Fig. XV.-4. As part of the general construction program a set of 31 control stations, 3° equal spacing, will be erected in each circular quadrant portion of the ring. Each control station will be provided with a replaceable brass plate with a bushing insert sized to accept the standard spherical base with which all AGS theodolites are equipped. A radius of 270 m for the control stations, consistent with the average machine radius and tunnel cross section, is assumed for purposes of this proposal. After allowing for the initial settlement following the soil loading of the tunnel, a first order survey of the control stations will be made.

A first order theodolite will be set up at each control station and the angles φ_n , φ_n^+ and θ_n^- will be measured. The lengths between adjacent monuments and their next nearest neighbor on either side will also be measured. As in the AGS primary survey a rejection limit of one second of arc on the closure of the individual small triangles will be imposed. That is

$$| \theta_n + \theta_{n-1}^+ + \theta_{n+1}^- - 180^\circ | \leq 1 \text{ sec of arc.}$$

This will serve as the control on the consistency and accuracy of the angular measurements. As of this moment it is anticipated that the length measurements will be made using constant tension, constant temperature, calibrated Invar tapes. Using a low-power field microscope, offsets between the tape graduations and the control station bench marks can be measured to 0.05 mm or better. At least two matched tapes will be used for each measurement as a control. The possibility of using the Mekometer¹ for the length measurements is not ruled out. This instrument uses a light beam, modulated at microwave frequencies, and reflected from a mirror at the ranging distance back to the instrument. The absolute distance can be measured by phase comparison of the transmitted and reflected beams at two modulation frequencies. Readings can be made quickly,

Fig. XV-4. Basic survey parameters.

but to date the instrument is not yet capable of the resolution obtainable with the more cumbersome Invar tape system. Typical resolution reported for the Mekometer is 0.25 mm over a distance of 50 m.

As shown in Fig. XV.-4, three angle measurements and several length measurements can be obtained at each of the N points (not including the first and last) in each 90° sector of the machine. One can then compare the measured values with the computed values for each element of the survey. In general, differences will exist. If one now assigns two arbitrary displacements, a_n and b_n , to each of the control stations one can write equations for the differences between the observed values and the true values. A simple computer program will produce the required a_n and b_n .

The above system was used for establishing the 24 primary control stations for the AGS and yielded short chords (approximately 15 m between adjacent monuments) with an rms variation of 0.017 mm and interior angles of a 24-sided inscribed polygon (165° each) which totaled less than one sec of arc from the theoretical value of $(N - 2) \pi = 22 \pi$. The distributed error in angle amounted to 0.04 to 0.08 sec of arc per interior angle for the two checks that were made.²

Until the fiducial system is established for the magnet and dewar module little detailed thought can go into the method of establishing the requisite radial offsets. Here, however, the large radius of curvature helps since, in general, the offsets will be short and therefore capable of being made to a high order of accuracy. The faithfulness with which the fiducial marks define the significant magnetic parameters of the magnets will control, to a large extent, the correct placement of magnets once the control stations are properly established.

For some time it was felt that the placement accuracy for the quadrupoles in the long straight sections would be beyond the limits of even a first order survey. A more careful study now indicates that a placement accuracy of 0.25 mm could be acceptable

although it will use some aperture reserve. An initial placement of 0.12 mm vertically can be realized while an accuracy of 0.25 mm horizontally appears just within reach. It is therefore proposed that these quadrupoles be mounted on remotely adjustable bases so that their position can be trimmed using the beam itself as the surveying instrument.

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XVI. COST ESTIMATE AND SCHEDULE

The cost estimates summarized in this chapter have been prepared in detail by our experts in the component field. Wherever possible there have been discussions with others, both within and outside of the Laboratory. In addition, industry sources have been consulted, and in many cases have provided vital cost figures used in assembling the estimates.

In addition to developing the costs of components we have also provided the projected personnel requirements for the entire program. From the figures submitted, we separated the assembly and test forces and costed them with the component. All others were consolidated and costed in the EDIA category. It is interesting to note that our costing of the EDIA developed in this way turns out to be remarkably close to the so-called "standard" 25% of the accelerator systems cost generally used in generating estimates. In summary, it is estimated that construction of the ISA will require about 1200 man years of effort. For comparison, we note that the AGS Conversion required about 740 man years of which about 400 were devoted to construction of the new linear accelerator. The original construction of the AGS required 695 man years.

The AEM cost has been 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 January 1974 dollars. We are including our best estimate of escalation costs during the construction period. In arriving at the approximate percentage increases, we have used projections from sources such as the "Engineering News Record", as well as our own experience. These percentages are FY 1974 - 9%, FY 1975 - 8%, subsequent years - 5%. The downtrend in escalation cost assumes the strengthening of the economy.

It is estimated that the cost to operate the ISA and four experimental halls and perform the initial experiments will be \$15,500,000 the first year (in FY 74 \$). This includes: 374 man years of direct scientific and technical personnel, \$180,000 for one charge of liquid helium, \$1,850,000 for electrical power, and supporting services amounting to \$1,200,000. These costs also include approximately \$2,000,000 for personnel involved in the development of experimental set-ups and accelerator refinements.

A preliminary estimate of \$7,000,000 for FY 80 has been made to provide funds for the large experimental apparatus planned to be used for the initial experimental program at the ISA. In addition, it is expected that much of the ancillary equipment will be made available from the ongoing AGS experimental program. An estimate of \$10,000,000 is projected for experimental equipment in FY 81.

Each of the component groups charged with preparing this estimate was provided with a "framing schedule" so that jurisdictional interaction could be discussed and accommodated. This approach seems to help individual programs. It also confirmed the overall time schedule as being reasonable and achievable.

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

May 1974	Proposal submitted.
July 1974	CP & D funds requested.
Late 1974 - Early 1975	A/E selection for review of design.
October 1975	Authorization and first year appropriation - start of design.
January 1976	Start of building construction and start of machine fabrication.
January 1978	Beneficial occupancy of buildings and start of machine installation.
October 1980	Completion of installation and start of system testing.
July 1981	Start of high energy physics.

Table XVI-1. Summary of Preliminary ISA Cost Estimate (in \$1000)

System		Totals
A. Accelerator Systems		62,764
I. Injection System	2,281	
II. Main Magnet System	35,041	
III. Magnet Power Supply	709	
IV. Vacuum System	5,863	
V. RF System	3,727	
VI. Correction Coil System	507	
VII. Refrigeration System	12,911	
VIII. Central Control System	1,725	
B. Special Equipment	120	120
C. Facilities		20,582
I. Land Improvements	836	
II. Magnet Enclosure	4,427	
III. Beam Injection Tunnel	786	
IV. Research Halls - large (3)	4,554	
V. Research Hall - small (1)	692	
VI. Compressor House	975	
VII. Refrigerator Houses (8)	1,144	
VIII. Assembly Buildings (4) at each Hall	3,400	
IX. Central Control and Service Building	1,600	
X. Yard Tray, Piping & Gas Storage Yard	300	
XI. Utilities	1,868	
D. A/E (@ 20%)		4,116
E. Engineering, Design, Inspection, Administrative		<u>15,447</u>
		103,029
F. Contingency - Facilities @ 15%		
Accelerator Systems & EDIA @ 25%		
A/E @ 20%		<u>23,493</u>
		126,552
G. Escalation - FY 74, FY 75 - 17½%, Thereafter 5%/yr.		<u>25,478</u>
TOTAL ESTIMATE		<u>152,000</u>

Table XVI-2. Component Cost Breakdown (in \$1000)

System	Item	Totals
	\$	\$
A. Accelerator Systems		
I. Injection System		2,281
1. Modifications to AGS	0	
2. Magnets	1,740	
a. 20 Quads - 1 meter long	240	
b. 39 Bending Magnets		
3" x 2 meters long	800	
c. Switches and Inflectors	500	
d. Power Supplies	200	
3. Vacuum System	148	
a. Pipe	33	
b. Pumps and Power Supplies	24	
c. Roughing System	84	
d. Monitoring and Controls	7	
4. Support and Alignment System	4	
5. Services	35	
a. Electrical	5	
b. Cooling Water	30	
6. Controls and Instrumentation	45	
a. Beam Monitors	30	
b. Computer Interface	10	
c. Cabling	5	
7. Labor - Installation and Test		
(BNL) & Misc.	309	
II. Main Magnet System		35,041
1. Dipoles (512)*	9,920	
2. Quadrupoles (368)*	3,461	
3. Special Aperture Dipoles (72)*	575	
4. Dewars	14,559	
5. Controls & Quench Fault System	150	
6. Beam Dump	300	
7. Labor - Installation and Test		
(BNL) & Misc.	6,076	
III. Magnet Power Supply		709
1. Power Supply	400	
2. Cable and Installation	100	
3. Controls	75	
4. Labor - Installation and Test		
(BNL) & Misc.	134	

*Includes Insertion Magnets

	<u>Item</u> \$	<u>Totals</u> \$
IV. Vacuum System		5,863
1. Chamber Valves	260	
2. Pumps and Power Supplies	2,280	
3. Roughing System	455	
4. Bake Out System - 200°C	250	
5. Monitoring and Controls	515	
6. Pick Up Electrodes	60	
7. Clearing Electrodes	160	
8. Labor - Installation and Test (BNL) & Misc.	1,883	
V. RF System		3,727
1. Accelerating Cavities 4 each-2 rings-total 8	398	
2. Power Amplifiers	2,520	
3. Stacking System	500	
4. Control System	100	
5. Labor - Installation and Test (BNL) & Misc.	209	
VI. Correction Coil Control System		507
1. Corrections Coils and Power Supply	240	
2. Beam Monitoring	200	
3. Labor - Installation and Test (BNL) & Misc.	67	
VII. Refrigeration System		12,911
1. Compressor Station		
2. Refrigerator Station } (Cold Box) 8 each	5,320	
3. Liquid Helium Storage Dewars	1,120	
4. Gas Storage and LP & HP Gas Buffer Tanks	400	
5. Gas Purification	320	
6. Ambient Temperature Gas Distribution (Compressor House to Refrigeration House)	400	
7. Low Temperature Gas Distribution (Refrigeration House and in Ring)	2,579	
8. Initial Gas Charge	183	
9. Liquid Cryogenic Controls	250	
10. Control Interface	300	
11. Labor - Installation and Test (BNL) & Misc.	2,039	

	<u>Item</u>	<u>Totals</u>
	\$	\$
VIII. Central Control System		1,725
1. Control Console/Display	50	
2. Computer	250	
3. Cabling	140	
4. Interlock/Personnel/Safety/Security	250	
5. Labor - Installation and Test (BNL) & Misc.	1,035	
B. Special Equipment		120
I. Laboratory Test Instruments	100	
II. Vehicles	20	
C. Facilities		
I. Land Improvements		836
1. Site Preparation	72	
2. Storm Drainage	327	
3. Roads and Paved Areas	361	
4. Fencing	76	
II. Magnet Enclosure		4,427
1. Structural	3,419	
2. Mechanical	230	
3. Electrical	296	
4. Exit Buildings	40	
5. Service Sleeves	90	
6. Air Tempering	352	
II. Beam Injection Tunnel		786
1. Structural	531	
2. Mechanical	96	
3. Electrical	129	
4. Exit Buildings	30	
IV. Research Halls - Large (3)		4,554
1. Structural	910	
2. Mechanical	133	
3. Electrical	146	
4. Cranes	120	
5. Air Tempering	209	
	3 @	1,518
V. Research Hall - Small		692
1. Structural	328	
2. Mechanical	70	
3. Electrical	51	
4. Cranes	120	
5. Air Tempering	123	
VI. Compressor House		975
VII. Refrigerator Houses (8)		1,144

	<u>Item</u>	<u>Totals</u>
	\$	\$
VIII. Assembly Buildings at Each Experimental Hall (4)		3,400
IX. Central Control and Service Building		1,600
X. Gas Storage Area, He Piping		300
XI. Utilities		1,868
1. Domestic Water	174	
2. Sanitary Sewer	91	
3. Steam Condensate	320	
4. Electrical - Primary 69 kV	802	
5. Electrical - 13.8 kV	411	
6. Telephone and Fire Alarm	70	
D. Architect/Engineer @ 20% of Buildings Costs (\$20,582)		4,116
1. Preliminary Design @ 2.7%	556	
2. Detailed Design @ 7.0%	1,441	
3. Construction Supervision @ 3.7%	761	
4. Procurement @ .3%	62	
5. Construction Management @ 6.3%	1,296	
E. Engineering, Design, Inspection, Administrative		15,447
1. Preliminary Design 146.5 MY's	3,256	
2. Detailed Design 242.0 MY's	5,443	
3. Construction Inspection & Supervision 213.5 MY's	6,748	
F. Contingency		23,493
1. Facilities @ 15%	3,087	
2. Accelerator Systems @ 25%	15,721	
3. EDIA @ 25%	3,862	
4. Architect Engineer @ 20%	823	
G. Escalation		25,478
1974 - 9%		
1975 - 8%		
1976 thru 1980 - 5% per year		
 TOTAL ESTIMATE (\$1000)		 \$152,000

XVII. FUTURE OPTIONS

1. Introduction

Several options for expanding the capabilities of the ISA have been investigated. The most attractive, from the standpoint of physics research, has been the addition of an ep option. Electrons would first be accelerated to 4 GeV in the AGS. They would then be accelerated to 15 GeV, providing high center-of-mass energies for ep collisions. This second acceleration could take place in a separate electron ring located either to the east of the ISA, or inside the ISA tunnel.

Another more attractive possibility is to accelerate the electrons in one of the ISA rings. The vacuum chamber in one, or perhaps both, ISA rings would be designed to allow water cooling of one side to carry away the large amounts of radiated energy from the electron beam. This idea is under investigation.

Deuterons have been accelerated in the 200-MeV linac and could be injected into the AGS. Subsequent acceleration and storage in the ISA would allow pd and dd interactions to be studied.

Another option, involving the use of a bypass on the ISA would allow generation of antiprotons from a target in the bypass and, after further acceleration and stacking of p and $\bar{p}$, 200 GeV x 200 GeV $p\bar{p}$ collisions.

2. The e-p Option

During the ISA preliminary design study, it became clear, from the response of the high energy physics community, that the addition of an electron ring as a future option to the proposed 200-GeV colliding proton beam facility would be very attractive. In view of the complementary nature of p-p and e-p reactions, a combined p-p and e-p facility seems to guarantee further important discoveries in particle physics.

An electron ring with the capability to reach 15 GeV is felt

to be a fair compromise between high energy and practical considerations. Maximum c.m. energies of 109 GeV in e-p collisions will then be achieved.

2.1 General Design Features

One possibility is for the electron ring to be situated 25 m to the east of, and on the same horizontal plane, as one of the proton rings. A bypass will take the electrons to the east long straight section of the proton ring, which the electrons will intersect twice at an angle of 8.6 mrad at points separated by 80 m. The general layout is shown in Fig. XVII-1. With minor modifications the electron ring can also fit inside the proton ring and intersect the east and west long straight sections of that ring. Altogether, four e-p interaction areas will then become available. The preferred location of the electron ring can be decided on later, on the basis of the relative importance of more interaction areas versus minimum interference with the operation of the proton rings.

Another possibility is the modification of one or both ISA rings to permit their use for electron acceleration. The most serious problem with electrons is the large amounts of radiative energy which will be absorbed by the vacuum chamber on the outside median plane. About one centimeter of chamber thickness would be required to contain water cooling channels for carrying away the generated heat. The magnet aperture may have to be expanded slightly to allow for this extra space. In order to keep all magnets uniform, both magnet rings would be modified similarly. This arrangement, for electron acceleration, is being studied.

The AGS, which is the proton injector, will also serve as an electron booster. Injection into the electron ring will occur at 4 GeV and the energy at which the electrons are stored in the ring can vary between 4 GeV and 15 GeV.

The electron ring will be operated in a many bunch mode. Since the proton beam is unbunched, it is desirable to fill as many of

Fig. XVII-1. Layout of ISA e-p rings.

the rf buckets as possible in the electron ring in order to minimize the proton tune shift.

2.2 Lattice

2.2.1 General Description

The electron ring is designed with some resemblance to the proton rings. It consists of four 90° arcs separated by four matched straight sections. The two long straight sections are experimental insertions for future $e^- - e^+$ collisions, while the two short ones are designed to accommodate the rf system. All straight sections have zero dispersion, which is accomplished in adjacent momentum matching sections. Each arc consists of 10 regular cells, one matched insertion and two momentum matching sections. The 60 m long matched insertion is removed by one cell from the momentum matching section of the adjacent experimental insertion. It has a 10 m free space in its center to be used for injection or fast protective extraction, depending on its location in the ring. The electron bypass will connect to two of these insertions. The bypass consists of a similar, but slightly longer, matched insertion and one regular cell followed by the momentum matching section of the e-p experimental insertion. If the electron ring is situated inside the proton ring, a second bypass will be added on the other side of that ring. Further theoretical studies on the seriousness of a slight perturbation in two-fold periodicity of the electron ring will show if it is necessary to add a second bypass, even in case the two rings lie side by side.

2.2.2 e-p Experimental Insertion

The design of the e-p experimental insertion was aimed at obtaining maximum luminosity together with a reasonable amount of free space around the interaction points. Furthermore, it seemed desirable to avoid the use of common quadrupoles and the electron and proton rings are kept completely decoupled from each other.

The basic electron ring lattice parameters are shown in Table XVII-1.

Table XVII-1. Lattice Parameters of e^- Ring

Type of Lattice	Separated Function	
Average Radius	310 m	
Average Radius of Circular Area	212 m	
Magnetic Radius	180 m	
Number of Regular Cells	40	
Type of Cell	FBDB	
Betatron Phase Advance Per Cell		
Horizontal	1.63 rad	
Vertical	1.57 rad	
Magnetic Field in Cells	2.77 kG	
Quadrupole Gradient in Cells	~ 1 kG/cm	
Cell Length	25 m	
Number of Insertions	8	
Number of Momentum Matching Sections	8	
Number of Superperiods	2	
Length of Experimental Insertion*	200 m	
Length of rf Insertion*	58 m	
Length of Injection, Extraction Insertion	59.4 m	
Transition γ	19	
Cell β -Function		
Maximum	42 m	
Minimum	6.6 m	
Cell Off-Momentum Function		
Maximum	1.65 m	
Minimum	0.8 m	
Effective Beam Sizes (at 15 GeV)		
	<u>H</u>	<u>V</u>
Cell F	2.51 $\times$ 0.20 cm $\times$ cm	
Cell D	1.10 $\times$ 0.51 cm $\times$ cm	

*Excludes momentum matching section.

A schematic of the e-p interaction regions is shown in Fig. XVII-2, together with the horizontal beam profiles. At the end of the momentum matching section, the electron beam emerges at the desired crossing angle with respect to the proton beam. Both beams are brought to a narrow focus (low β region) at the crossing point by two sets of doublets, QDE1, QDE2, and QDP1, QDP2 for electrons and protons respectively. QDE2 and QDP2 are 14 and 20 m away from the crossing point. At QDE2, the proton beam is sufficiently far removed from the electron beam that it can pass, unaffected, through a hole in the iron cores of the electron quadrupole magnets. The electron beam just clears the proton doublet QDP2. The beams are again brought to focus at the center of the insertion by the doublets QDE3 and QDP3. QDE3 and QDE2 are symmetric with respect to the crossing point and the same holds for QDP2 and QDP3. Two bending magnets, placed symmetrically about the electron insertion center, accomplish the necessary bend for the second intersection. The additional electron triplet, QTE1, keeps the dispersion function zero in the intersection region and in most of the electron insertion. Both electron and proton insertions are symmetric about their centers. The β and X_p functions are shown in Fig. XVII-3.

2.3 RF System

The electron ring rf system is designed to store a 200 mA current at 15 GeV. At this energy, the radiation loss per turn is 25 MeV. A frequency of 400 MHz is chosen as an optimal value considering minimum zero current excitation power and favorable geometries of the rf cavities. The peak voltage required at this frequency, to contain greater fluctuations, is 38 MV. Chains of π -mode coupled cavities, with a shunt impedance of 25 M Ω /m, are suggested. They would be a scaled down version of the 800 MHz cavities used in the electron linac at Los Alamos. It will be necessary to distribute 270 cavities over 50 m. In each of the two rf straight sections there are three 18 m long free spaces to accommodate the six groups of rf cavities. The X_p -function is zero in these spaces and the maximum value of the β -function is 70 m.

Fig. XVII-2. e-p interaction regions.

Fig. XVII-3. Electron and proton β and X_p functions in the interaction region.

There will be 5.0 MW of power going into the beam and 1.2 MW into the cavities. When the electron ring is operated at energies below 15 GeV, the current will be increased to a limit set by the available rf power or by the proton tune shift to obtain higher luminosity. This will be done by lowering the shunt impedance of the rf system. The rf parameters are shown in Table XVII-2.

Table XVII-2. ISABELLE e-Ring RF System

Frequency	400 MHz
Harmonic Number	2596
Power Dissipated in Cavities	1.2 MW
Power Radiated by Beam	5.0 MW
Peak RF Voltage	38 MV
Total Shunt Impedance	1250 M Ω
Total Accelerating Cavity Length	50 m

2.4 Injection Scheme

The AGS will serve as an electron booster so that maximum advantage can be taken of radiation damping during the electron ring filling process.

A 400 MHz rf system with a peak voltage of 400 kV would be added to the AGS, allowing electron acceleration to 4 GeV. At this energy, the damping times are of the order of 0.5 sec. The AGS can be cycled at 10 pulses/sec for acceleration up to 4 GeV. It takes 3 AGS pulses to fill the electron ring and hence radiation damping will cause considerable reduction in the betatron and synchrotron oscillation amplitudes between consecutive injected turns.

The AGS, being a combined function and not a separated function machine, will be radially antidamping for electrons. However, an estimate shows that this increases the radial width of the beam by about 25% only and no special damping system is required. Using a typical 200-MeV electron linac, the AGS can trap and accelerate 10 mA. Taking into account the transfer to, and rebunching

inside, the storage ring an electron injection rate of 25 ma/sec can be obtained.

2.5 Performance of e-p Option

Table XVII-3 gives the performance parameters for 15 GeV electron - 200 GeV proton collisions and Fig. XVII-4 shows luminosity and vertical tune shifts as a function of electron energy. The luminosity is power-limited for electron energy above 7 GeV, while it is limited by the proton tune shift for $4 \text{ GeV} \leq E_e \leq 7 \text{ GeV}$. In calculating the luminosity, it has been assumed that the highest permissible value for the electron and proton tune shifts are 0.05 and 0.005 respectively. As can be easily ascertained from Fig. XVII-4, a maximum luminosity of $1.1 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ is obtained for an electron energy of 7 GeV (c.m. energy = 75 GeV) and the luminosity is $0.5 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ at the maximum electron energy of 15 GeV (c.m. energy = 109 GeV).

2.6 Electron Acceleration in the ISA

If the electron acceleration, from 4 GeV to 15 GeV, takes place in the ISA the equipment and facility requirements are significantly reduced. In addition to the hardware necessary to achieve 4 GeV acceleration in the AGS, the only other major requirement is an rf accelerating system for electrons as described in Section XVII-2.3.

3. The Deuteron Option

3.1 Introduction

The physics community has shown considerable interest in colliding deuterons on deuterons and protons on deuterons in the ISA. In particular d-d collisions would make it possible to measure the ratios of proton-proton, proton-neutron and neutron-neutron total cross sections.

Preacceleration of deuterons in the 200-MeV injector linac, acceleration to 30 GeV in the AGS, and stacking in the ISA will be

Fig. XVII-4. e-p luminosity and tune shift.

Table XVII-3. Performance Parameters for e-p Collisions at Top Energy

	Proton 200 GeV	Electron 15 GeV
Energy		
Total Number of particles	5.6×10^{14}	8.1×10^{12}
Number of Bunches	nonbunched	≈ 2500
Transverse rms Emittances		
Horizontal	$0.015 \times 10^{-6} \pi \text{ m} \cdot \text{rad}$	$0.159 \times 10^{-6} \pi \text{ m} \cdot \text{rad}$
Vertical	$0.015 \times 10^{-6} \pi \text{ m} \cdot \text{rad}$	$0.018 \times 10^{-6} \pi \text{ m} \cdot \text{rad}$
Crossing Angle (horizontal)	8.6 mrad	
Free Drift Space	$\pm 14 \text{ m}$	
Dispersion Function	0.0 m	0.0 m
Beta Function at Crossing Point		
Horizontal	2.10 m	1.28 m
Vertical	0.48 m	0.24 m
rms Momentum Spread	1.5×10^{-3}	1.0×10^{-3}
rms Beam Sizes at Crossing Point		
Horizontal	0.017 cm	0.045 cm
Vertical	0.008 cm	0.007 cm
Longitudinal		3.75 cm
Luminosity at 200 GeV $\times$ 15 GeV	$0.50 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$	
Δv_v	5×10^{-5}	0.012

*If it is indicated that the use of 2500 bunches is excessively troublesome for controlling collective instabilities, it will be necessary to greatly reduce the number of bunches. This will allow for damping by feedback systems. The luminosity will remain unchanged near $E_e = 15 \text{ GeV}$ but the luminosity peak will be reduced and shifted towards higher electron energies.

briefly discussed and an estimate for d-d and d-p luminosities will be given.

3.2 Deuteron Preacceleration

In most Alvarez-structured proton linacs, including the BNL 200-MeV injector, acceleration of protons takes place in the 2π -mode. This means that the protons progress one cell during one rf period. They are electrically shielded by the drift tube when the electric field is in the decelerating direction (Fig. XVII-5a). For deuteron acceleration in this mode, the deuterons have to traverse each cell with the same speed as the protons. However, the available rf power and quadrupole fields do not allow this type of operation. Another possibility is to accelerate deuterons at half the proton velocity, in the 4π -mode across each gap (Fig. XVII-5b). Maintaining the electric fields used for proton acceleration, the energy gain for deuterons is about one-half (at the low energy end) and lower (at the high energy end).

The energy gain for the synchronous particle in each cell of a linac is given by

$$\Delta W = eVT \cos \varphi_s, \quad (\text{XVII-1})$$

where V = voltage across the gap,

φ_s = synchronous phase, and

T = transit time factor.

The transit time factor, on the axis, for operation in the 2π mode, can be calculated accurately if the axial electric field, $E_z(z)$, is known along the cell. The transit time factor is given by

$$T_m = \frac{\int_{-L/2}^{L/2} E_z(z) \cos\left(\frac{2\pi m z}{L}\right) dz}{\int_{-L/2}^{L/2} E_z(z) dz}. \quad (\text{XVII-2})$$

The transit time factor can be approximated by

$$T_m = \frac{\sin(m\pi g/L)}{(m\pi g/L) I_0(2\pi m\pi a/L)} \quad (\text{XVII-3})$$

where $m = 1$ for the 2π -mode,

$m = 2$ for the 4π -mode,

Fig. XVII-5. Axial electric field component for proton and deuteron acceleration.

g = gap length,
 L = cell length, and
 a = bore hole radius of drift tube.
 I_0 = zero'th order modified Bessel function.

The effect of the bore is included in $E_z(z)$ in Eq. (XVII-2). For the BNL 200-MeV linac, $E_z(z)$ has been calculated numerically for each cell using the computer program MESSYMESH. The electric field required for deuteron acceleration in the 4π -mode (E_2), relative to that for proton acceleration in the 2π -mode (E_1), is given by:

$$E_2/E_1 = V_2/V_1 = (T_1 \Delta W_2)/(T_2 \Delta W_1) \quad (\text{XVII-4})$$

for the same synchronous phase.

Tables are available giving the velocity, kinetic energy and momentum of protons and deuterons in the BNL 200-MeV linac and the fields required for deuteron acceleration for $\phi_s = -32^\circ$.¹ These tables indicate that it should be possible to accelerate deuterons through tank 3, or up to 30 MeV, without excessive increase in electric field gradients.

A preliminary test for deuteron acceleration through the first 10 MeV tank was performed in 1970 and yielded the following results without attempts for optimization²:

Preinjector voltage:	390 $\pm$ 10 kV
Preinjector current ($D^+ + D_2^+$):	125 mA
Injected current (D^+) to Linac:	70 mA
Accelerated current:	
without buncher	12 mA
with buncher	18 mA
Final energy:	5 MeV

On the basis of these results, it can be expected that, with some optimization of preinjector voltage, buncher parameters and electric fields in the linac, it will be possible to accelerate a 25 mA deuteron beam to 30 MeV in the first three tanks and, with

proper adjustment of the quadrupoles, drift it through the remaining 6 tanks at this energy.

It seems reasonable to assume that 125 mA of deuterons have an emittance of 10π cm.mrad at the output of the preinjector. Allowing for an emittance growth of a factor of 2 in the linac, the 25 mA deuteron beam will have a transverse emittance of 2π cm.mrad at 30 MeV.

An estimate of the expected energy spread at 30 MeV can be made in the following way: The present proton beam has a measured energy spread of about 2 MeV for constant synchronous phase. The height of the rf bucket at injection is proportional to $(v^3 ET/M)^{1/2}$ (v is the velocity, and M the mass, of the accelerated particle and E the electric field) and hence is reduced by $\sqrt{1/32}$ for deuterons accelerated in the 4π -mode relative to that for protons in the 2π -mode. Furthermore, the energy spread varies as $(\beta\gamma)^{3/4}$. This leads to an estimate of energy spread of ~ 150 keV for 30 MeV deuterons.

3.3 Linac-AGS Transport Channel

The acceptance of this transport channel is determined by the aperture of the inflector and is 2.5π cm.mrad. It should, therefore, be possible to transport the deuteron beam without losses between the AGS and the ISA.

3.4 Acceleration in the AGS

At 30 MeV, $\beta = 0.178$ for deuterons and the orbital frequency in the AGS is 66 kHz. The present AGS rf system, operating on the twelfth harmonic, has a frequency range of 2.3 - 4.8 MHz and consequently cannot be used for low energy acceleration of the deuterons.

A new cavity, also operating on the twelfth harmonic, with the frequency range 0.79 - 2.3 MHz, would have to be installed in one of the free straight sections. It would accelerate the deuterons from 30 to 900 MeV. A total voltage of 50 kV is required

in order to reach 900 MeV in ~ 0.5 sec. The existing high voltage rf system would be used for continuing the acceleration to 30 GeV.

One turn injection into the AGS, at 30 MeV, of a 25 mA deuteron beam yields 2.3×10^{12} particles. (The space-charge limit at injection is 2×10^{12} deuterons.) Assuming a capture efficiency of 70%, approximately 1.8×10^{12} deuterons can be accelerated. Allowing for doubling of both transverse and longitudinal phase-space areas in this machine, the 30 GeV emittances are $\sim 0.4\pi \times 10^{-6}$ m-rad and ~ 0.36 eV-sec per bunch. These are the AGS-ISA transfer emittances that are assumed for 2.3×10^{12} protons per AGS pulse.

3.5 Stacking in the ISA

Assuming the same stacking efficiency for 1.8×10^{12} deuterons as for 2.3×10^{12} protons, it is possible to accommodate and accelerate 4×10^{14} deuterons, or 7 amperes, in each ISA ring. Maintaining a maximum permissible tune shift of $\Delta\nu = 0.005$ by adjusting the crossing angle, the luminosities are $L_{dd} \cong 0.7 L_{pp}$ and $L_{dp} \cong 0.7 L_{pp}$.

4. The Antiproton Option

The possibility of storing 200 GeV antiprotons in one of the ISA rings has been investigated. A straightforward method to produce antiprotons by bombarding an external target with 200 GeV protons was assumed. Protons are accelerated to 200 GeV in one of the rings and are extracted into a bypass during flat top. 30 GeV antiprotons from a target placed at a low β point in this bypass are transported to the second ring, where they are injected, stacked and accelerated to 200 GeV. Protons are now stacked in the first ring in the opposite direction, accelerated to 200 GeV and made to collide with the antiprotons (Fig. XVII-6).

4.1 ISA Antiproton Intensity

The antiproton yield^{3,4} for a proton energy of 200 GeV has a plateau around 30 GeV with $d^2\sigma/d\Omega dp \sim 0.5 \bar{p}$ per interaction/sr-(GeV/c).

(a) $-p$ INJECTION AND ACCELERATION
IN LOWER RING FOR PRODUCTION

(b) $\bar{p}$ PRODUCTION IN BYPASS AND
ACCELERATION IN UPPER RING

(c) $-p$ INJECTION AND ACCELERATION
IN LOWER RING

Fig. XVII-6. Antiproton bypass. Schematic representation.

For small forward angles (< 10 mrad), the number of 30 GeV antiprotons that can be stacked in the ISA ring is given by:

$$N_{\bar{p}} = \frac{d^2\sigma}{d\Omega dp} N_p \frac{C_{ISA}}{M_p \ell_B} \Delta\Omega \Delta p \eta_s \eta_t \quad . \quad (XVII-5)$$

Here N_p is the number of protons in the ISA

M_p is the number of proton bunches

C_{ISA} is the ISA circumference

ℓ_B is the proton bunch length at 200 GeV ($\bar{p}$ bunch length at 30 GeV)

$\Delta\Omega$ (in steradians) is the solid angle at the target, inside of which antiprotons will be accepted by the ISA ring

Δp (in GeV/c) is the momentum spread which will be accepted in the ring at 30 GeV

η_t is the target efficiency including the effect of $\bar{p}$ interactions within the target

η_s is the stacking efficiency.

$\Delta\Omega$ is related to the horizontal and vertical betatron acceptances of the ring, A_h and A_v , by $\Delta\Omega = A_h A_v / \pi a b$. a and b are the horizontal and vertical beam sizes at the target. There is an effective increase in the beam spot size at the target due to the finite target length, ℓ_t . For maximum $\Delta\Omega$, it is required that $a \leq 0.7 \ell_t A_h / a\pi$, and $b \leq 0.7 \ell_t A_v / b\pi$. With

$$a = \left(\frac{0.7 \ell_t A_h}{\pi} \right)^{\frac{1}{2}} \quad \text{and} \quad b = \left(\frac{0.7 \ell_t A_v}{\pi} \right)^{\frac{1}{2}}$$

it follows that

$$\Delta\Omega = \frac{(A_h A_v)^{\frac{1}{2}}}{0.7 \ell_t}$$

and the number of stacked antiprotons

$$N_{\bar{p}} = \frac{d^2\sigma}{d\Omega dp} N_p \frac{C_{ISA}}{M_p \ell_B} \frac{(A_h A_v)^{\frac{1}{2}}}{0.7 \ell_t} \Delta p \eta_s \eta_t \quad . \quad (XVII-6)$$

Betatron and momentum acceptances are closely related to the available aperture, which should be as large as possible for maximum $N_{\bar{p}}$. For antiprotons the available aperture can be made larger

than that assumed for protons, considering the low $\bar{p}$ intensity (~ 1 mA). Space-charge effects will be negligible in this case and one can virtually let the beam fill the vacuum chamber horizontally. Furthermore, beam loading problems do not exist. One can use a different, low cost, rf accelerating system of higher frequency and voltage. This in turn will make it possible to stack the antiprotons azimuthally rather than in momentum space, gaining both in available aperture and stacking efficiency. At the same time, with sufficient voltage, the rf system will be able to accommodate as large a momentum spread as can be contained in the vacuum chamber.

Protons in the ISA are accelerated on the second harmonic frequency, resulting in two circulating bunches. On flat top, during which the protons are extracted, 70% of the particles in one bunch lie within $1/10$ of the circumference. The antiprotons, produced by the protons, will have the same bunch structure and can be injected, in the second ring, into the buckets of a 10th harmonic rf system with an efficiency of 70%. Ten ISA proton pulses (the second $\bar{p}$ pulse from each ISA pulse will be dumped) are required to fill the ten buckets with antiprotons.

Assuming a momentum spread of 2.5% and a horizontal acceptance $A_h = 2\pi \times 10^{-6}$ m-rad (which is matched to the production cone), the horizontal aperture of 8 cm is subdivided in the following way at 30 GeV:

Betatron amplitude:	1.86 cm
Phase oscillation amplitude $X_p \Delta p/p$:	4.25 cm
Sagitta:	1.30 cm
Reserve:	<u>0.59 cm</u>
Total:	8.00 cm

A 4.4 cm long iridium target has an optimum target efficiency of $\eta_t = 1/3$. With these numbers and taking $A_v = A_h$ and $C_{ISA}/M_p \ell_B = 5$, one gets $N_{\bar{p}}/N_p = 7.7 \times 10^{-5}$.

4.2 Extraction and Targetting of Primary Proton Beam

The 200 GeV proton beam will be extracted in the south experimental insertion (Figs. XVII-6 and XVII-7). The quadrupole magnets in this insertion will be rearranged to give slowly varying β -functions in the central part ($\beta_h \sim 12$ m, $\beta_v \sim 25$ m at the center) and to leave a free space of 100 m there. In the beginning of this 100 m drift space, a 1 mrad horizontal kicker magnet will be installed. The time between proton bunches is about 4 μ sec so that only very moderate demands are put on the kicker rise time. After a 10 m drift space following this kicker, the beam will be sufficiently displaced to enter the array of 3 septum magnets listed in Table XVII-4. They are followed by a 24 m drift space at the end of which the beam will enter a 60 mrad achromatic bend, followed by a triplet that will focus the beam at the target 5 m away. The target is located at a distance of ~ 3.5 m from the ISA ring, which leaves adequate space for shielding.

The beam spot size at the target is only ~ 0.5 mm $\times$ 0.5 mm corresponding to $\beta = 0.60$ m. The target will most likely explode from the exposure to 6×10^{14} protons and will have to be replaced for each proton pulse.

Table XVII-4. Septum Magnets

Septum	Unit	1	2	3
Length	(m)	1	1.5	1.5
Deflection	(mrad)	1.79	4.03	4.03
Peak field	(kG)	12	18	18
Gap height	(cm)	1.5	1.5	1.5
Septum thickness	(mm)	2.5	5	5
Peak current	(kA)	15	22.5	22.5
Current density	(kA/cm ²)	40	30	30

4.3 Antiproton Beam Transport

Antiprotons emerging from the target will be focussed by a strong, large aperture, room temperature triplet located 3 m

Fig. XVII-7. Antiproton bypass.

downstream from the target. Thereafter, they will enter a 21 mrad bending magnet, which will separate them from the protons that were transmitted by the target. The protons will continue into a beam dump while the antiprotons will go into an achromatic bend from which they will emerge parallel to the ISA ring. Two quadrupole doublets will now match the antiproton beam into a transport channel, with room temperature magnets, that runs in parallel with the ISA ring and which simulates an ISA octant.

4.4 Antiproton Injection and Acceleration

The antiprotons will be injected into the ISA by a fast kicker at the injection insertion ordinarily used for protons. (The rise time of this kicker has to be ~ 150 nsec which is well within the present state of art.) They will be captured and matched into buckets of a 10th harmonic (1.12 MHz) rf system. The peak voltage per turn required for matching is ~ 150 kV, which is also suitable for 2 min acceleration to 200 GeV, using a synchronous phase of 5° . Because of the low antiproton intensity, the rf system can have high impedance resulting in low power demands.

4.5 p-p Luminosity

The expected luminosity for p-p collisions has been calculated. It is limited by beam-beam interaction and it has been assumed that the maximum permissible tune shift for the antiprotons is $\Delta\nu = 0.005$. For a 1.71 mrad horizontal crossing geometry, with $\beta_v = 2.5$ m and $\beta_h = 5$ m at the intersection point, one gets $L_{pp} = 7.7 \times 10^{28} \text{ cm}^{-2} \text{ sec}^{-1}$.

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XVIII. 200-GeV ISA WITH CONVENTIONAL MAGNETS

1. Assumptions and Basic Design

In this section a conceptual design study¹ of 200-GeV proton intersecting storage accelerators with conventional magnets is presented. This study was intended to give an answer to the obvious question of how storage accelerators, with superconducting magnets, compare in regard to luminosity, cost and electric power consumption with a more conventional solution.

In the Gray Book,² a comparative cost estimate for a warm ISA was based on NAL-type magnets operating at 15 or 20 kG. It was assumed that the injection system, experimental insertions, tunnel cross-section, cost of vacuum system per unit length, construction schedule, and manpower be identical for the ISA with superconducting or room temperature magnets. Under these assumptions, it was concluded that a saving in capital cost of about 20% and an order of magnitude smaller operating costs would result from using superconducting magnets.

The motivation for a new comparative study was given by our intuition that magnets designed for the NAL accelerator may not be economical in the operation of storage rings. Most of our efforts were therefore directed at the study of optimization of those items which dominate the cost of storage rings, that is the magnet system with its power supply, and the vacuum system. Since, otherwise, the performance and cost estimates are based on the same general assumptions entering the superconducting ISA study, the conclusions presented here should be fairly reliable in a general comparison of room temperature vs superconducting machines. With more effort, the cost of the conventional solution could have been determined quite accurately; as it stands, however, the cost estimates quoted are less accurate than those for the superconducting solution.

The key to our study was the desire to keep the electrical power consumption to an acceptable level. Because of the present

attitudes toward energy usage, and the uncertainty of its future cost, we have chosen an arbitrary limit of 40 MW in the dipoles (about 50 MW total), probably a smaller power consumption than would result from the conventional optimization of operating and capital costs. It should be emphasized that this is the power at full energy. Many colliding beam experiments like to obtain excitation functions of the reactions being studied, so that the average power is less than the maximum by a duty factor proportional to the root mean square energy, which we take as 0.6. Furthermore, we believe that a moderately intensive program of exploitation, allowing time for experimental access, machine studies, and beam stacking and acceleration, would provide 3000 hours per year of colliding beam time. This power limitation then implies an annual energy consumption of about 90 GWh.

The magnet has been designed using aluminum conductors, which seem to offer substantial savings for this type of magnet. As shown in a subsequent section, the total capital costs are optimized by selecting a magnetic field of about 15 kG. Keeping the experimental insertions unchanged, this choice leads to a total circumference of $6 \times C_{\text{AGS}} = 4843 \text{ m}$.

As expected, we found that economical operation requires magnets with a small gap; here, $2g = 4 \text{ cm}$ was chosen. It turns out that the small magnet gap, and the concomitant small vacuum chamber aperture, together with the large circumference imposes severe performance limitations viz. space charge and transverse resistive wall effects. To obtain luminosities comparable to the superconducting machine, it is considered necessary to rely on a 200-GeV injector.

Associated with the magnet design is a novel type of vacuum system which results in a major saving compared to the conventional approach, without compromise in performance. The essential point of this vacuum system is the use of a continuously distributed titanium-sublimation pump as an integral part of the aluminum

vacuum chamber.

The principal parameters of 200-GeV ISA with conventional magnets are listed in Table XVIII-1. The circumference of the machine is fixed at $6 \times C_{\text{AGS}}$. The design assumes four-fold symmetry with four experimental insertions, each 250 m long; the momentum matching sections are part of the insertions. Four injection and ejection insertions, each 100 m long, have been assumed. The lattice cell structure adopted here uses separated function magnets with a FODO sequence.

In both options, the regular lattice structure is subdivided into $4 \times 17 = 68$ unit cells, each $L = 50.6$ m long and containing six 6.15 m dipoles and two 3 m quadrupoles. With this, a reasonable ν -value of about 20 can be obtained allowing injection above the transition energy. The resultant betatron phase shift per cell is about $\pi/2$ and the maximum β -value is, in the thin lens approximation, $\beta_{\text{max}} \approx 86$ m.

At first we consider Option I with beam transfer from the AGS to the ISA based on stacking in the longitudinal phase space of the ISA (energy stacking scheme³). The emittance of the AGS at transfer is* $\epsilon_v = 0.3\pi$ m· μ rad, resulting in a maximum rms beam height in the ISA of $\sigma_v = 2.5$ mm rms in Option I. The vacuum chamber, with its clear aperture of $2h = 30$ mm, is adequate, but shaving to reduce the vertical beam size may be indicated.

The total horizontal beam width corresponding to a momentum spread of $\Delta p/p = 0.3\%$, which is required to obtain the nominal operating current of 1 A, is, at injection, $2a \approx 1.6$ cm in Option I. Consequently, it is not practical to achieve wide ribbon beams as would be desirable for space-charge reasons.⁴

*The AGS emittance is dependent on the number N_{AGS} (in units of 10^{12}) of protons accelerated in the AGS according to $\epsilon \approx N_{\text{AGS}} \times 0.25\pi 10^{-6}$ m·rad.

Table XVIII-1. Parameters of 200 GeV ISA
With Conventional Magnets

	Option I	Option IB [*]
Final energy, GeV	200	
Injection energy, GeV	28.5	
Circumference ($6 \times C_{\text{AGS}}$), m	4843	
Current, A	1	0.36
Luminosity (200 GeV), $\text{cm}^{-2} \text{sec}^{-1}$	1×10^{32}	8×10^{31}
Number of dipoles/ring		
- regular lattice, m	408 x 6.15	
- insertions, m	48 x 6.15	
Magnet half gap, cm	2	
Vacuum chamber half aperture, cm	1.5	
Lattice parameters:		
v-value	≈ 20	
Number of regular cells	4 x 17	
Length unit cell, m	50.6	
Length exp. insertions, m	4 x 250	
Maximum β , m	86	
Crossing point β^* , m	2	
Beam height at injection, cm	1.0	2.4
Beam width at injection, cm	1.6	2.5

We have assumed in the above discussion that the beams are unbunched for physics experiments. A bunched mode operation is conceivable in which each ring is filled with six AGS pulses, retaining the original bunch structure through acceleration and experiments. In this mode of operation (Option IB) no advantage is gained from injection at 200 GeV. The conceptual simplicity of this

* Option IB assumes bunched beams during operation. Values not printed are identical in both options.

approach, although it entails some difficulties in regard to counting rates in a certain class of experiments, makes it an attractive mode of operation. However, the questions of bunch lengthening due to phase noise and of beam losses due to diffusion remain to be investigated in detail. The limit on the injected current is here set by the vertical aperture. We estimate that 0.36 A can be achieved, corresponding to an AGS pulse with 6×10^{12} protons.

2. Current Limitations and Estimated Luminosities

The "ultimate" current limit in a single ring is imposed by the incoherent ν -shift resulting from the transverse space-charge effects which, at higher energies, are predominantly due to image forces caused by the surrounding vacuum chamber and magnet poles. Neglecting a possible neutralization of the beam, one can write the expressions for the vertical ν -shift of a circulating beam with a total of N particles per ring and with dimensions small compared to the vertical semiapertures of the vacuum chamber, h , and magnet gap, g , in the form⁵

$$\Delta\nu_{inc} \approx - \frac{NRr_p}{\pi\gamma v} \left\{ \left(1 + \frac{1}{B\gamma^2} \right) \frac{\epsilon_1}{h^2} + \frac{\rho}{R} \frac{\epsilon_2}{g^2} \right\}$$

with the classical proton radius $r_p = \mu_0 e^2 / 4\pi m_p = 1.535 \times 10^{-18}$ m, the bunching factor B equal to the ratio of average to maximum current, the storage ring radius $R = C/2\pi$, the bending radius ρ , and the geometrical constants ϵ_1 and ϵ_2 . For the parallel plate geometry assumed here, the geometrical constants are known to be⁵ $\epsilon_1 = \pi^2/48$ and $\epsilon_2 = \pi^2/24$. For $N = 3.6 \times 10^{13}$ (that is six AGS pulses with 6×10^{12} protons or 0.36 A circulating current) one obtains a $\Delta\nu \approx 19/\gamma v$. At injection, this leads to a tune shift of 0.03 in Option IB.

Using dynamic corrections to the working line a ν -shift on the order of 0.1 should be tolerable (the CERN ISR operates with⁶ $\Delta\nu_v \approx 0.05$ at 20 A), which leads to an upper limit of $I \approx 1.2$ A

in Option I. We must conclude that due to the small magnet gap and large circumference the maximum current of 10 A of the superconducting counterpart cannot be achieved in a storage accelerator with conventional magnets.

An estimate for the threshold current in Option I, imposed by the transverse resistive wall instability, is obtained by scaling the CERN ISR current according to⁷

$$\frac{I}{I_{ISR}} = \left(\frac{h}{h_{ISR}} \right)^3 \frac{\gamma \gamma}{\gamma_{ISR} \gamma_{ISR}} \left(\frac{R_{ISR}}{R} \right)^{5/2} \left(\frac{\rho_{ISR}}{\rho} \right)^{1/2} \frac{f(a/h)_{ISR}}{f(a/h)}$$

with the ratios of

- chamber height, $h/h_{ISR} = 1.5/2.5$ cm
- machine radius, $R_{ISR}/R = 150/770$ m
- chamber resistivity (stainless steel vs Al)
 $\rho_{ISR}/\rho = 10^{-4}/2.5 \times 10^{-6} \Omega \cdot \text{cm}$
- form factor⁸ $f(a/h)_{ISR}/f(a/h) \sim 0.7/0.9$
- energy $\gamma/\gamma_{ISR} = 31/29$
- betatron number $\nu/\nu_{ISR} = 20/9$.

Taking $I_{ISR} \approx 20$ A, we find the limit $I = 0.85$ A. We note that the resistive wall instability, too, presents a severe limit on the current achievable in the ISA. But it has been demonstrated on many accelerators that coherent oscillations of the beam can be damped out by the use of electronic feedback.⁹ In conclusion, we assume a current of $I = 1$ A in Option I.

To avoid the brickwall effect¹⁰ it will be necessary to pre-stress the working line as done at the CERN ISR⁶ and to provide sextupole and octupole correction magnets.

The expected luminosities are calculated by scaling the results for the superconducting ISA without changing the geometry and optical properties of the experimental insertions. The scaling laws for estimating the luminosity are based on the simple model²

of a collinear collision region of adjustable length l and uniform charge density in the beam. In this model, the luminosity is given by

$$L = \frac{\pi}{\langle \epsilon \rangle} \frac{I^2}{ce^2} \operatorname{arctg} \frac{l}{2\beta^*}$$

with the average emittance $\langle \epsilon \rangle = \sqrt{\epsilon_h \epsilon_v}$, the amplitude function at the center of the collision region β^* , and the other quantities as previously defined. The beam-beam interaction will limit the maximum luminosity obtainable. A measure for this basically non-linear effect is the linear tune shift

$$\Delta\nu = \frac{r_p}{ec} \frac{\pi I}{\langle \epsilon \rangle \gamma} l$$

which in the case of proton-proton storage rings is thought to be limited to $\Delta\nu_{\max} \approx 5 \times 10^{-3}$. Taking into account the beam-beam limit, the luminosity may be expressed as

$$L = \frac{\pi I}{\langle \epsilon \rangle \gamma} \frac{I\gamma}{ce^2} \operatorname{arctg} \left(\frac{1}{2} \frac{\langle \epsilon \rangle \gamma}{\pi I} \frac{ec}{r_p \beta^*} \Delta\nu_{\max} \right).$$

For a given injector the phase-space density, and thus the ratio $\pi I / \langle \epsilon \rangle \gamma$, can be kept constant by an optimum beam transfer or beam shaving. Consequently, the luminosity scales with the current rather than with the square of the current. In practice arctg may be substituted by its argument, leading to¹¹

$$L_{\max} \approx \frac{1}{2} \frac{I\gamma}{er_p \beta^*} \Delta\nu_{\max}.$$

We find the numerical relation at 200 GeV of

$$L/I \approx 1 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}/\text{A}$$

with the current I in amperes, resulting in $L \approx 10^{32}$ for the Option I.

The luminosity in the bunched beam mode (Option IB) is estimated from¹²

$$L_0 = f_{n_B} \frac{N_B^2}{\langle \epsilon \rangle \beta^*}$$

with f the revolution frequency, n_B the number of bunches, and N_B the number of protons per bunch. To be valid it is required that the total bunch length $l < 2\beta^*$. The beam-beam interaction imposes a limit on the number of protons per bunch

$$N_{Bmax} = \frac{\gamma \langle \epsilon \rangle}{r_p} \Delta v_{max} .$$

In our case, where the maximum $\gamma \langle \epsilon \rangle = 46\pi \mu\text{m}\cdot\text{rad}$ is imposed by the vacuum chamber aperture, one has $N_{Bmax} \approx 5 \times 10^{11}$ which, incidentally, is independent of γ since $\gamma \langle \epsilon \rangle$ is invariant.

$N_{Bmax} \approx 5 \times 10^{11}$ corresponds to an AGS pulse with 6×10^{12} particles. The maximum luminosity follows to be

$$L_o = \gamma \frac{f n_B N_B}{r_p \beta^*} \Delta v_{max}$$

which gives, at 200 GeV, the value $L = 8 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$. In principle, the luminosity could be increased by a larger number of bunches. This, however, would reduce the distance between bunches C/n_B (67 m for $n_B = 72$ as taken here) and seriously complicate the geometry of the experimental insertion.

The luminosity estimates show that the operation with bunched beams would be a conceivable operating mode.

Finally, it should be mentioned that it is impractical to increase the gap sufficiently to raise the current limit imposed by the incoherent tune shift to values comparable to the superconducting ISA. From the above formulas it follows that a circular cross section of the beam tube ($\epsilon_1 = 0$) and a gap of about 10 cm would be required. A magnet design which keeps the power consumption at the 40 MW level is prohibitively expensive. Minimizing capital equipment cost plus operating expenses over 10 years can, in principle, be done but it is not obvious that this would lead to an economical solution.

3. Magnet System

The cost of the magnet system depends strongly on the choice of the magnetic field in the dipoles. However, the total cost of magnet system, tunnel, and vacuum system is only weakly dependent on the magnetic field. We costed two different solutions with circumference of $C = 7 C_{\text{AGS}}$ ($B \approx 13$ kG) and $C = 6 C_{\text{AGS}}$ ($B \approx 15$ kG), and found a cost ratio of 1.06:1.0, indicating that the cost considerations provide no decisive arguments. Collective effects clearly favor the machine with smallest circumference whereas the field quality of the magnet indicates lower magnetic fields. The choice of a machine with $6 \times C_{\text{AGS}}$ and $B = 15$ kG appears to be a reasonable compromise.

The magnet design is based on the use of aluminum instead of the more usual copper coils. At an assumed fabricated cost of \$5.50/lb for copper and \$4.00/lb for aluminum the total costs for camel-back type copper and aluminum coils stand in a ratio of 3:1 whereas the cost of iron cores (\$0.35/lb) is essentially the same. As an overall result we find that the use of aluminum allows for a substantial savings. A further cost reduction is achieved by the use of flat coils (\$3.00/lb) instead of camel-back-type coils. In summary, we find a unit cost (6 m length) of

- 19.1 k\$ with Al flat coil,
- 20.0 k\$ with Al camel-back coil,
- 34.4 k\$ with Cu camel-back coil.

The schematic cross section of the magnet chosen is shown in Fig. XVIII-1. The magnetic properties of this design have been computed indicating that its field quality is adequate up to 15 kG (Fig. XVIII-2). The stored energy per magnet is about 60 kJ at 15 kG and thus 27 MJ per ring.

4. Vacuum System

In this section, a summary of the vacuum system for the warm ISA will be given. A more detailed discussion may be found in

Fig. XVIII-1. Cross section of warm magnet (dimensions in centimeters).

Fig. XVIII-2. Computer results for warm magnet shown in Fig. XVIII-1. The coefficients are defined by writing the magnetic field in the median plane as $B(X) = B_0(1 + b_2x^2 + b_4x^4)$.

Ref. 13. The magnet gap severely limits the vacuum chamber height (3 cm). Adequate pumping speed must be obtained by an increased chamber width which is only limited by the width of the magnet pole (≈ 20 cm).

The conductance of an elliptical duct with 3 cm x 20 cm internal dimensions is about 30 liter/sec which may be compared to the 60 liter/sec of the CERN ISR beam tube. Using the results of Refs. 13 and 14, we conclude that the pressure bump instability limits the current to $\eta I_{\text{crit}} \approx 6$ A since the H-type magnet considered prevents the distance between pumps to be shorter than the magnet length (≈ 6 m). From the CERN experience on the typical desorption coefficients, $\eta < 2$, we conclude that such a vacuum system would permit currents of about 3 A, which is adequate for both options.

Another approach, using distributed pumping, appears to circumvent this problem and is suggested to be used in the present design. SPEAR¹⁵ employs distributed sputter-ion pumps for vacuum in the 10^{-8} to 10^{-9} Torr range. The magnetic field is provided by the ring magnets. Besides the rather complicated structure and the requirement of high voltage, the pumping speed of these pumps decreases by a factor of 2 to 3 in the 10^{-11} Torr range, making them less suitable for our design. Distributed titanium sublimation pumps, on the other hand, present a possibility of an inexpensive vacuum system with ample pumping to the 10^{-11} Torr range all along the chamber and permits large circulating currents. The possible cross section of the proposed aluminum chamber shown in Fig. XVIII-3 uses a Ti-Mo rod located in the larger of the side ducts. The smaller channel is used for heating during bake-out and can also provide cooling in a future conversion into an electron storage ring.

During the bake-out, the chamber will be pumped by 150 liter/sec sputter-ion pumps between the magnets (6 m apart). After the bake-out, a maximum pressure of 2×10^{-9} Torr occurs in the middle of the magnet if an outgassing rate of 10^{-12} Torr liter/sec cm²,

Fig. XVIII-3. Cross section of vacuum chamber (dimensions in centimeters).

and the gas conductance for N_2 , are assumed. In fact, the pressure will be lower, since most of the residual gas will be H_2 . When the Ti rod is heated, and Ti deposited on the walls, the pressure will drop to the 10^{-11} Torr range. The resulting pumping speed, S_o , per 1 cm length of the chamber shown in Fig. XVIII-3, is given in Table XVIII-2.

Table XVIII-2. Pumping Speed Per Centimeter of Chamber Length
Due to the Ti-Mo Rod

Gas	H_2	N_2	O_2	CO	CO_2	H_2O	CH_4	A	He
S_o (liter/sec)	30	45	90	90	90	30	0	0	0
S_{eff} (liter/sec)	12	4	4	4	3	5	0	0	0

Since we want to prevent the deposition of Ti on the areas to be bombarded by ionized residual gas molecules, we limit the aperture to 4 mm (Fig. XVIII-3) which decreases the pumping speed to S_{eff} in Table XVIII-2. Ti-Mo rods similar to those commonly used in sublimation cartridges yield a total of over 0.1 g of Ti per centimeter of length which provides 1.8 Torr-liter of pumping. A monolayer of Ti can be deposited either at preset intervals or whenever the pressure increases above the 10^{-11} Torr range. This represents at least two weeks if an outgassing rate of 10^{-12} Torr liter/sec cm^2 is assumed. Nongetterable gases will be pumped by sputter-ion pumps between the magnets. Under normal conditions, the rods should last indefinitely, but even if a new Ti film of a few monolayers had to be deposited every day, the rods would last about 10 years.

It is clear, from the above discussion, that the proposed chamber, combined with Ti pumping, can provide a very economical and effective vacuum system. Thus, our cost estimate of 7.2 M\$ is about equal to the 7.8 M\$ spent on a smaller vacuum system at CERN.¹⁶ The main features resulting in the cost savings are:

- the UHV pumping is obtained through the use of Ti sublimation

directly inside the vacuum chamber.

- An aluminum chamber is much cheaper, easier to machine, and requires lower bake-out temperature than stainless steel.
- The sections of the vacuum chamber are welded together wherever feasible rather than being flanged.

In the final design of the vacuum system a number of other problems will have to be considered, among which are:

- Induced eddy currents in the vacuum chamber during acceleration.
- Heat generation in the vacuum chamber in the case of bunched beams.
- Effect of a bunched beam on the pressure bump phenomenon.

However, to first order, no significant changes in the general conclusions reached here are expected.

5. Comparative Cost Estimate

We have carried out a rough estimate for a 200-GeV ISA with conventional magnets, the results of which are summarized in Table XVIII-3. Since there exists no detailed technical design we resorted frequently to a simple scaling from other machines, in particular the cost estimates given in the design reports for the CERN ISR,¹⁶ the NAL 200/400-GeV accelerator (NAL),¹⁷ and the NAL 100-GeV pp colliding beam storage rings (NALSR).¹⁸

The cost estimate for the superconducting 200-GeV ISA has been redone since the last edition of the "Gray Book".² In fact, the ISA estimates are probably more accurate than those given here for the ISA with conventional magnets in spite of the uncertainties of a new technology. Nevertheless, we consider the comparisons to be qualitatively significant.

Our cost figures for technical components quoted in Table XVIII-3 include fabrication and installation. EDIA (engineering, design, inspection and administration costs on technical components are taken to be 25% of component costs. AEM (architectural engineering and management) costs on facilities have been estimated at

20% of facilities costs.

Contingencies on technical components have been estimated at 25% of total component cost whereas contingencies on conventional facilities have been estimated at 15% of total facility costs.

The superconducting ISA cost estimate has been obtained by a different procedure, but an attempt was made in Table XVIII-3 to allow for a direct comparison of subtotals.

To arrive at our cost estimate the following additional assumptions were made:

Magnet system. The fabrication cost of the dipole magnets has been estimated directly, $2 \times 456 \times 19.1 \times 10^3 = 17.4$ M\$. The total cost (including quadrupoles, other magnets, installation and magnet alignment) is obtained by using the multiplier of 1.56 taken from NALSR.

Ring magnet power supply and cooling. The assumed power handling capabilities for bending magnets alone is about 40 MVA, the total requirement is taken to be 50 MVA, which is estimated at 5 M\$. Using a typical multiplier, 1.3, we obtain the total cost of 6.5 M\$. Low conductivity water cooling is estimated directly from NAL to be 2.8 M\$. The total for power supplies and cooling is thus 9.3 M\$.

Vacuum system. The cost of the vacuum system was estimated directly at 7.2 M\$. The use of distributed Ti-sublimation pumps represents a major cost saving factor.

RF system. The cost of the rf system has been obtained by scaling the superconducting ISA system. The stacking system is identical in both cases whereas the rf power of the acceleration system is reduced by the cube of the ratio of the momentum spreads (0.3/0.7). The cost, including controls and installation, is thus 1 M\$.

Beam transfer. The cost for beam transfer, injection, and protective ejection equipment does not differ substantially from the ISA. The transfer tunnel is somewhat longer, which has been

taken into account in the conventional facilities cost.

Computer and controls. We take the cost of the computer and control system to be equal to the ISA.

Conventional facilities. It is assumed that ring tunnel costs are twice those of the ISA, with the costs for four experimental halls unchanged. Adjustments are made for the absence of refrigerator and compressor housing and increase of electric power handling capabilities.

Table XVIII-3. 200-GeV ISA Cost Estimates in M\$
(without escalation)

	Superconducting ISA*	Warm ISA
<u>TECHNICAL COMPONENTS</u>		
Magnet system	35.0	27.2
- Dipoles		
Magnet power supply	0.7	9.3
- LCW cooling		
Refrigeration	12.9	0
Vacuum system	5.9	7.2
RF system	3.7	1.0
Injection system	2.3	2.3
Modification to AGS	0	0
Correction coil system	0.1	
Computer and controls	1.7	1.7
Special equipment	0.5	0
Component cost	62.8	48.7
EDIA (25%)	15.4	12.2
<u>CONVENTIONAL FACILITIES</u>		
Ring tunnel	4.4	8.8
Experimental Halls, etc.	16.2	16.0
Subtotal	20.6	24.8
AEM (20%)	4.1	5.0
Subtotals	103.0	90.7
<u>CONTINGENCIES</u>		
Technical components (25%)	}	15.2
Conventional facilities (15%)		4.5
Total	126.5	110.4

*From Section XVI.

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APPENDIX

A Two-Stage Approach to ISABELLE

1. Basic Design

This design study represents an intermediate step towards ISABELLE.¹ It is conceived as a first stage toward the ultimate goal of a high energy (200 - 300 GeV) superconducting ISA. This guiding principle has led us to choose tunnel, magnet arrangement, injection system, dump system, and vacuum system in the first stage to be compatible with the transition to the superconducting machine. This means a somewhat higher cost in the 100 GeV phase than would be the case if a design optimization had been performed without thought of a future superconducting modification. The savings in the transition to the final stage certainly justifies this procedure. The performance goals are to achieve an average luminosity of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ at a top energy of 100 GeV.

The primary constraints on the design effort have been to keep down the cost and the electric power consumption. These constraints lead to the choice of small gap (4 cm) aluminum coil dipoles operating at 15.4 kG, identical to those in the 200 GeV room temperature option described in Section XVIII. However, the beams will be brought together for collision using superconducting magnets in the intersection regions. For this purpose we can use the experimental insertion dipoles designed for the superconducting ISA. The resultant design cost estimate is \$69.2 M, while the dipole magnet power consumption is estimated to be 20 MW. Operating at 13 kG, i.e. at an energy of 85.4 GeV, the power consumption is reduced to 12 MW.

To satisfy the guiding principle of minimizing cost in the transition to higher energy, the beam transfer, injection (including injection rf system), vacuum and dump systems have been chosen to be identical to those in the superconducting ISA design except for the fact that fewer vacuum pumps will be needed in view of the

lower current. This is reflected in the cost estimate which is detailed later. The accelerating rf system, however, can be operated at a significantly lower voltage, meaning a substantial decrease in rf power consumed. Since the cost of the rf system is directly related to the rf power dissipated, a large saving relative to the full cost is made in stage I.

In part 2, the influence of using room temperature magnets on the lattice structure is considered. The performance of the 100 GeV design, and concomitant limitations, are discussed in part 3. Specifically, the luminosity is limited by how much current can be stacked in each ring and how low the value of β at the crossing point, β^* , can be made. It is assumed that the luminosity is beam-beam limited and, for the weak-strong beam-beam tune shift limit, the currently accepted value of 5×10^{-3} for protons is used. Vacuum considerations and transverse space-charge effects limit the attainable beam current. The maximum beam current is 3.5 A. To achieve a luminosity of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, β^* will have to be reduced to 5.0 m. The question of how the low β relates to the chromaticity, together with the question of how the low current implies low momentum spread, which in turn influences the rf cost and power consumption, will be treated in more detail in the part on performance. In part 4, some details on the potential use of these rings for electron storage are presented and, thereby, e^-p collisions. Finally, part 5 presents a detailed cost estimate.

A list of the main parameters, in particular those significantly different from the stage II superconducting design, is provided in Table I.

2. Lattice

Our fundamental presumption in this 100 GeV design study is the fact that it is the first stage of a two-stage process to achieve an energy of 200-300 GeV with superconducting magnets. To allow a simple transition, the 100 GeV machine is designed to fit into the tunnel for the superconducting ISA. Therefore the identical octant

TABLE I: Main Parameters for Interim 100 GeV ISA

Final Energy, GeV	100
Injection Energy (kinetic), GeV	28.5
Circumference ($3 \frac{1}{3} \times C_{\text{AGS}}$) m	2690
Average beam current, A	3.5
Dipole Magnet half-gap, cm	2.0
Vacuum chamber half-height, cm	1.5
Tune (β)	19.4
Length, normal cell, m (no. = 40)	30.2
Length, [‡] multipurpose insertion, m (no. = 4)	50
Length, [‡] experimental insertion, m (no. = 4)	200
Magnet filling factor in curved portions of rings	0.815
Beam Height [†] (total) at inj., cm	0.9
Beam Width [†] (total) at inj., cm	1.7
Horizontal aperture for stacking at inj., cm	4.1
Emittance (h and v) at inj., rad.m	$0.4\pi \times 10^{-6}$
Momentum spread (total) at inj.	3.5×10^{-3}
Peak Voltage, Accelerating System, kV	10
rf Power (both rings), MW	0.2
Dipole Power consumption, both rings, MW	20.0
Total Electric power consumption, both rings, MW	25

β^* (m)	Total free space (m)	Luminosity ($\text{cm}^{-2} \text{sec}^{-1}$)
5	20.8	1.1×10^{32}
10	50.0	0.55×10^{32}

[‡] Only straight portion.

[†] At maximum β in normal cell. ($\beta = 52.0$ m, $X_p = 2.3$ m for horizontal case.)

has a length 1/8 of the ISA circumference. If the "straight" lengths for experimentation, injection and ejection are subtracted, the "curved" or bending portion of the octant is left, amounting to 211.3 m. Thus, with a 62% dipole filling, an energy of 200 GeV can be obtained with 40 kG magnets. If L_c is the length available for bending, B is the dipole field, and p the energy in units of magnetic rigidity (kG-m), then the filling factor required is

$$f = \frac{2\pi p}{BL_c}.$$

With $p = 3370$ kG-m (100 GeV), $L_c = 8 \times 211.3$ m and $B = 15.4$ kG, the required filling factor is 81.5%. Assuming a minimum separation of 30 cm between magnets, this filling can be achieved with dipoles of length 6.15 m, leaving 1 m at each cell quadrupole for correcting magnets, which consist, primarily, of sextupole component for chromaticity correction.

The lattice structure is, in essence, identical to the superconducting ISA design. For the purposes of a cost estimate, superconducting magnets have been chosen in the intersection regions for the purpose of bringing the beams into collision. If these magnets are the same as in the superconducting design, they serve the purpose for a 100 GeV machine and entail no incremental cost in the transition to stage II.

3. Performance

The beam-beam limited luminosity for each collision region can be estimated from

$$L = \left(\frac{I}{e} \right) \frac{\gamma \Delta v_v}{\sqrt{2} r_p \beta_v^*},$$

where L is the average luminosity,

I is the average current in each ring,

γ is the energy in proton mass units,

Δv_v is the vertical beam-beam tune shift,

β_v^* is the vertical β -value at the crossing point,

and we have assumed horizontal crossing. Since the energy is chosen, there are 3 parameters which determine the luminosity, Δv_v , I , and β_v^* .

Beam-Beam Limit and Crossing Angle

The beam-beam tune shift is taken to be, at the limit, $\Delta v_v = 5 \times 10^{-3}$. To attain this, we must choose a horizontal crossing angle, α , given by

$$\alpha = \left(\frac{I}{e} \right) \frac{\sqrt{2} r_p \beta_v^*}{cb\gamma(\Delta v_v)},$$

where α is the full crossing angle, and b is the vertical beam half-size at the crossing point. Anticipating a little, the maximum current, $I = 3.5$ A, and $\beta_v^* = 5.0$ m are known. Taking $\gamma = 108$ (100 GeV) and $b = 0.72$ mm (corresponding to an emittance, $\epsilon = 0.12\pi \times 10^{-6}$ rad.m at 100 GeV), the crossing angle becomes $\alpha = 1.9$ mrad, and the luminosity is $L = 1.1 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$.

Current Limit

The beam current is vacuum limited. The critical current is determined by the conductance of the vacuum chamber, the pumping speed and the distance between pumps, the latter following essentially from the dipole length. Assuming, as in the superconducting ISA design, a desorption coefficient, $\eta \approx 2$, and with a 14 cm $\times$ 3 cm vacuum chamber, the vacuum limited current is 3.5 A.

The small magnet gap (4 cm) means the vacuum chamber will have a vertical half-height, $h = 1.5$ cm, in the curved (bending) portions of the lattice. This is small compared to the chamber radius of 4 cm in the cold ISA design. The space charge limitations must therefore be examined. The beam is essentially unchanged from the latter design; thus, beam dominated effects need not be considered. In fact, the reduction in current introduces a safety factor of about 3 as compared to the superconducting design. However, image effects, which are strongly dependent on h , must be looked into. Actually, it is important to point out that, in the superconducting design, the current limitations from the resistive wall instability arise from the beam dependent term and not the image dependent term.

It is thus not too surprising that stability from the resistive wall effect, even with its strong dependence on h , can be achieved in the 100 GeV design with the reduced chamber height.

Two effects must be considered; the standard resistive wall effect, which has an h^3 dependence, and the "brick-wall" effect which arises as a consequence of the combined influence of the resistive wall effect and the incoherent image tune shift. The constraints due to these effects can be written as a lower limit on the tune spread, a sufficient amount of which is required to provide stabilization through Landau damping. The conditions are, respectively,

$$\delta\nu > \frac{4 r_p R^{5/2} I}{e\nu\gamma h_{\text{eff}}^3} \sqrt{\frac{2\epsilon_0 \rho}{c|k-\nu|}}$$

and

$$\delta\nu > \frac{0.7\pi^2 r_p R^2 I}{12e\nu\gamma h_{\text{eff}}^2},$$

where $\delta\nu$ is the full tune spread,

R is the average ring radius,

ν is the betatron tune,

h_{eff} is the effective (or average) vertical chamber half-height,

ρ is the chamber resistivity, in units of ohm-m,

ϵ_0 is the free space dielectric constant

k is the azimuthal mode number for the unstable mode ($k > \nu$).

Clearly, the constraint is most stringent at injection. Thus, taking $R = 428.2$ m, $\nu = 19.4$, $\gamma = 31.4$ (28.5 GeV), $\rho = 1.6 \times 10^{-8}$ Ω -m (aluminum), $k = 20$ (lowest mode), $I = 3.5$ A, and $h_{\text{eff}} = 2.4$ cm (assuming 64% of the circumference requires the small chamber height of 3 cm, while 36% of the circumference, in the experimental and multipurpose straight sections, can have a chamber with radius 4 cm), we obtain

$$\delta\nu > 2.4 \times 10^{-3} \text{ (classical resistive wall),}$$

and

$$\delta\nu > 0.033 \text{ (brick-wall).}$$

It therefore appears that 3.5 A could be achieved without either

working line prestressing or electronic feedback. Some of either, or both, could however be added in practice if necessary.

The lower current of 3.5 A permits stacking with a total momentum spread smaller by a factor of 2 from the superconducting ISA design or $\Delta p/p = 3.5 \times 10^{-3}$. The voltage required for rebunching and acceleration is related to $\Delta p/p$ by

$$V \propto (\Delta p/p)^2 ,$$

while the limiting coupling impedance to the beam is

$$|Z_s| \propto \frac{1}{I} (\Delta p/p)^2 .$$

and for the rf power,

$$P_{rf} \propto V^2 / |Z_s| = I (\Delta p/p)^2 .$$

Thus, the required voltage is reduced fourfold to $V_{rf} \text{ (peak)} = 10 \text{ kV}$ (for a harmonic number, $h = 2$). The coupling impedance also must be reduced, but by a factor of only 1.4 to 0.5 k Ω . And finally, and most importantly, the rf power is reduced by a factor of 11.4. This means a relatively insignificant rf power requirement of 100 kW for each ring.

Low β Limitation

The limitation to the reduction of β^* arises from the large β -values at the nearest focusing elements. Since horizontal crossing implies that only the vertical β^* be low, the maximum β is related to β^* by

$$\beta_{\max} \beta^* \approx \ell^2 ,$$

where ℓ is the distance from the crossing point to the first vertically focusing quadrupole. The crossing arrangement requires a space of 25 m for bending magnets on both sides of the crossing point. This large length is self-imposed in the sense that magnets designed for the 200 GeV stage II have been chosen in order to save the cost of replacing them in the transition. To obtain $\beta^* = 5 \text{ m}$, and setting a limit $\beta_{\max} = 250 \text{ m}$, and $\ell = 35.4 \text{ m}$, means a free space for experiments of $2\ell_{\text{exp}} = 20.8 \text{ m}$ around the crossing point. A much larger free space for experiments can be obtained if we

increase β^* to 10 m. With the same limit on $\beta_{\max}$, $l_{\exp} = 50$ m. The choice $\beta_{\max} = 250$ m is rather conservative compared to the cold ISA design. It also relaxes the tolerance on quadrupole placement. More significantly, it means the chromaticity is kept to manageable size. It should be recognized that chromaticity correction and control is to be done with separate sextupole magnets and not with coils in the dipoles as in the cold ISA design. Thus, large chromaticity means "more" length for sextupoles, and, in turn, less length for bending, which ultimately translates to more magnet power consumption (higher dipole field) or less energy, i.e. a reduction in performance. The choice $\beta_{\max} = 250$ m gives a chromaticity, or rate of tune change with momentum, of $\Delta\nu/(\Delta p/p) \approx -40$. To correct this chromaticity in both vertical and horizontal planes requires sextupoles at all cell quadrupoles. For sextupoles of 0.5 m length, an estimated peak sextupole strength of 0.035 kg/cm^2 is required.

Luminosity

As already computed, $\beta^* = 5 \text{ m}$ gives a luminosity $L = 1.1 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$. Because of the chromaticity limitation, this means that the total experimental free space available is 20.8 m. Allowing the value of β^* to increase to 10 m has the effect of reducing the luminosity to $L = 0.55 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, while increasing the available experimental free space to 50.0 m.

4. Electron Experiments

To include the possibility of accelerating electrons up to 15 GeV in one of the proton rings and colliding them with 100 GeV protons stored in the other ring requires the addition of an rf system for the electrons, with a power capability of about 6 MW. The vacuum chamber of the ring used for storing electrons would have to be cooled to avoid excessive temperature rise from absorption of synchrotron radiation. Preacceleration in an electron linac, followed by acceleration to 4 GeV in the AGS, would be done as outlined in Section XVII. Assuming the same interaction horizontal crossing geometry as for p-p collisions at 100 GeV ($\alpha_H = 1.9 \text{ mrad}$, $\beta = 5 \text{ m}$)

and an electron beam current of 200 mA, the luminosity and tune shifts for 15 GeV e^- -100 GeV p collisions are:

$$L_{e-p} = 0.8 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$$

$$\Delta v_v^p = 1.1 \times 10^{-4}$$

$$\Delta v_v^e = 0.06$$

For lower electron energies, higher electron currents can be stored for a given rf power, resulting in higher luminosities. The electron current can be increased as E_e^{-4} until $E_e = 7.9$ GeV, at which point $L_{e-p} = 1.0 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, $\Delta v_v^p = 0.005$ and $\Delta v_v^e = 0.106$. Although the electron tune shift is on the high side through the electron energy range $7.9 \text{ GeV} \leq E_e \leq 15 \text{ GeV}$, it can be reduced, if necessary, by going to lower β -values at the intersection point in the electron ring. Also, increased vacuum requirements, arising as a result of the synchrotron radiation impinging on the vacuum chamber, could necessitate a change from discrete to distributed pumping. If discrete pumping is to be used in Stage II, for economic reasons pertaining to magnet size, this means a total cost increase by the cost of the distributed pump system, about \$3 M. However, because distributed pumping is comparatively lower in cost, a Stage I saving of the order of \$1 M would actually result.

5. Cost Estimate

The details of a cost estimate for the interim 100-GeV storage accelerators are presented in Table II. Technical components include fabrication and installation. EDIA (engineering, design, inspection and administration) costs on technical components are taken to be 25% of component costs. AEM (architectural engineering and management) costs on facilities have been estimated at 20% of facility costs. Contingencies on technical components have been estimated at 25% of total component cost whereas contingencies on conventional facilities have been estimated at 15% of total facility costs.

With regard to technical components, the injection system, the vacuum system and the central control system have been assumed to be identical to the ISA superconducting design. The ring room temperature magnets are individually costed. This includes dipoles, quadrupoles and sextupoles. The power supply cost for these magnets is listed. A separate listing is given for the superconducting magnets to be used in the collision areas and include, as well, the associated refrigerator cost. As has already been pointed out, the rf accelerating system cost represents a substantial saving as compared to the cold ISA design. This is reflected in the cost summary in Table II. In the area of facilities, some cost savings have been attempted. Here again, the constraint of minimizing cost in the transition to Phase II has been self-imposed. The main Stage I saving is in the assembly buildings. Only one of the four assembly buildings is constructed in Stage I, deferring the remaining three to Stage II. The Stage I cost estimate is \$69.2 M, as shown in Table II. The incremental cost to Stage II is estimated at \$79.6 M, leading to a final cost of \$148.8 M. This is an increase in total cost over the ISABELLE cost, due to the use of the 2-phase approach, of \$22.5 M. Of this, about \$15 M represents the cost of the room temperature magnet system with associated power supply and cooling, which is a "salvageable" commodity. For example, these magnets could be used in the future construction of a separate electron ring, such an addition markedly enhancing the facilities available for physics in the ISA complex.

The time for changing over from Stage I to Stage II, during which the machine will be shut down, is estimated at approximately one year.

TABLE II: Cost Estimate for Two- tage ISA (M\$)

	Stage I	Increment Stage II	Total Stage II
<u>Technical Components</u>			
Injection System	2.28	0	
Main Magnet System	10.35	33.03	
Magnet Power Supply & Cooling	4.50	0	
Special Superconducting Magnets With Dewars	2.01	0	
Refrigeration System	3.00	9.91	
Vacuum System	3.91	1.95	
RF System	1.11	2.62	
Central Control System	1.73	0	
Correction Coil System	0	0.51	
Subtotal - Components	28.89	48.02	76.91
EDIA @ 25%	7.22	12.00	19.22
<u>Conventional Facilities</u>			
Land Improvements	0.84	0	
Magnet Enclosure	4.43	0	
Beam Injection Tunnel	0.79	0	
Research Halls - Large (3)	4.55	0	
Research Halls - Small (1)	0.69	0	
Compressor House	0.97	0	
Refrigerator Houses (2 - 2)	0.57	0.57	
Assembly Buildings (1 - 3)	0.70	2.70	
Central Control & Service Bldg.	1.60	0	
Yard Tray, Piping & Gas Storage Yard	0.30	0	
Utilities	1.87	0	
Subtotal - Facilities	17.31	3.27	20.58
AEM (@ 20%)	3.46	0.65	4.11
Subtotals	56.88	63.94	120.82
Contingency -			
Acc. Systems & EDIA @ 25%			
Conventional Facilities @ 15%			
A/E @ 20%	12.31	15.63	27.94
Totals	69.19	79.57	148.76

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