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MASTER

PROTON STORAGE RINGS

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I. Introduction

Progress in understanding the subnuclear level of individual particles, their properties, and their mutual interactions has depende directly upon the sources of the particles.** The use of the cosmic s of particles was a natural evolution from the investigation of the re of the cosmic radiation. The discovery of the positron by Anderson 32) and subsequently the muon was the signal for using the cosmic radiation to search for new particles and to explore their properties. In the late 1930's and certainly immediately following the close of World War II, physicists' interest in the cosmic radiation increased exponentially, mainly because of the opportunity to study the interaction of high energy particles with matter. Indeed this source of particles is difficult to use because the flux is small, the particle types are mixed, and the laboratory energy of the particles is spread over a range of ten orders of magnitude or so. With such a tenuous and varied source, it seems positively miraculous that physicists could discover so many new particles and gain so much new information from and about them. The cosmic radiation had two important properties which aided enormously. It was a free and a continuous source of particles. With it π mesons and strange particles were discovered, muons were found to decay into an electron and two neutrinos, charged π mesons into a muon and a neutrino, and K mesons and hyperons were found to have several different modes of decay. This new information was extensive and impressive but lacked the detail needed to satisfy physicists seeking the answers to why and how.

The future of the field had to lie in the ingenuity and genius of the accelerator experts who promptly provided the first two very high energy accelerators capable of carrying elementary particle research forward from the cosmic radiation beginnings--the Cosmotron (3 GeV) and the Bevatron (6 GeV). These impressive machines rectified, partially, the weaknesses of the cosmic

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** For this discussion I exclude those sources which bear more directly on problems relating to nuclear physics.

particle source: a single type of particle, the proton, was available at a known energy and in unheard of abundance, $\sim 10^{10}$ protons/sec. The obvious advantages held by the new breed of machines naturally beckoned many cosmic ray physicists to come down from the mountains and queue up in front of the program committees to explain their proposals for experiments.

A qualitatively new era began in which detailed experiments could now flourish. Particle production cross sections as a function of energy and angle were measured; each strange particle was found to be produced in association with another; particle decay properties were measured; π mesons and K mesons were produced copiously so that they in turn could become source particles and their interaction properties could be studied. Physicists were soon clamoring for greater particle intensity. This desire was met as the two great machines pushed upwards to $\sim 10^{12}$ protons/sec. But the most persistent call was for more energetic particles, available only as a small fraction of cosmic ray particles. Courant, Livingston, and Snyder (1952), and Christofolis (1950) independently, provided the new idea, the alternating gradient principle, which allowed accelerator construction to reach, as of today, the 500 GeV laboratory energy level ($\sim$30 GeV center-of-mass energy). In the process of increasing energy (and particle flux) the discovery rate of new phenomena has continued to be shockingly high. In this respect most high energy physicists would agree that center-of-mass energy is the most important parameter, especially for qualitative exploratory searches. Naturally, particle type and particle flux are exquisitely important in the quantitative sense. Two examples illuminate these points. A high center-of-mass energy, $\sim$ few hundred GeV, is now thought necessary to produce the theoretically predicted and important intermediate vector boson, the proposed mediator of the weak interaction. Its existence or non-existence will constitute a major step in our understanding of the weak force. Its discovery awaits new proton accelerator facilities which could provide the required high cms energies. However, the recently discovered upsilon particle (mass $\sim$10 GeV) at FNAL can be investigated in detail most clearly by relatively low energy electron-positron colliding beams ($\sim$10 GeV cms).

About 25 years ago accelerator physicists seriously began to consider machines in which colliding beams of particles could be produced, since for a given beam energy it was the method to obtain the maximum cms energy in collisions between individual particles. The first colliding beams were obtained in 1963 with electrons and positrons. The small mass of the electron made it relatively easy to produce beams of relativistic particles. Furthermore, the synchrotron radiation from the electrons as they were deflected by the guiding dipole magnets acted as a natural damping mechanism to limit orbit oscillations. This damping provided the means for the accumulation of high currents of positrons as well as electrons and so provided the dense beams needed for adequate interaction rates. Protons on the other hand presented more difficulty. Because of their large mass, synchrotron radiation is essentially absent even at hundreds of GeV, and other natural damping mechanisms do not exist. Furthermore, in the 1950's no operating proton accelerator had the necessary dense and energetic beams which would be useful for colliding beam devices. However by 1960 the CERN group, encouraged by the very promising high performance of the new 26-GeV CERN PS, recognized its potential as a future source of protons for a storage ring facility and initiated a serious design study. This led to the ISR project which began construction in 1966 and operation for research in 1971.

At Brookhaven the 30-GeV AGS, closely similar to the PS in performance, was also recognized as a potential injector for storage rings. In the summer of 1963 physicists gathered from near and far to consider the next facility for Brookhaven, and proton storage rings held a prominent place in these discussions. The Board of Trustees of Associated Universities, Inc., which operates BNL, impaneled a committee to make recommendations for a new facility at Brookhaven. The committee recommended increasing the AGS intensity rather than construction of storage rings and so left the field to CERN for the ensuing decade. The CERN ISR was brilliantly executed. It remains the technological masterpiece among operating accelerators. In addition to a full experimental program, it has provided a rich testing ground for accelerator theory and the investigation of the behavior of dense high current proton beams. All future colliding beam projects will have to acknowledge their debt to the CERN ISR experience.

II. Proton-Proton Storage Ring Properties

A. Energy

Proton storage rings* can provide cosmic ray-like interaction energies, and this is precisely the reason for the great interest in them. Two protons, each at 400 GeV, colliding head on provide 800 GeV cms energy, the equivalent of a single proton of 340,000 GeV striking another proton at rest. For cost reasons alone, it is unlikely that fixed target accelerators will reach such extravagant energies in this century. Although the cosmic radiation includes particles with similar and even higher energies, the number is pitifully small and quantitative experiments on interaction channels having small cross sections are impossible to study in any detail. Thus proton storage rings provide a controlled, relatively high intensity source of interaction energies extending very far up into the cosmic ray energy spectrum. Clearly, storage rings provide a window on behavior at extraordinary interaction energies; on the other hand, fixed target accelerators provide multiple kinds of secondary particle beams, neutrino, π-meson, K-meson, antiproton, etc., as well as very large proton intensities--all however at lower interaction energies.

Proton storage rings are decidedly sophisticated and consequently technically intriguing. Some of the more obvious properties, problems, and virtues are intrinsically interesting to any physicist.

B. Luminosity

The proton storage ring energy will be decided in all probability by the costs. Once this most important parameter has been selected, one must consider the performance desired. In its simplest terms performance is usually equated with the luminosity, L, at each interaction region.** For

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* The discussion, while limited to colliding proton beams, can be construed to include collisions of protons with antiprotons, or deuterons as well. For illustration purposes I use the design parameters of ISABELLE, a 400 x 400 GeV proton-proton intersecting storage accelerator to be built at Brookhaven National Laboratory (ISABELLE, 1978). See Hahn, Month and Rau (1977) for more complete discussion of many of the technical points.

** The luminosity, L, is a machine parameter only and is basically the event rate per unit cross section, i.e., $L = R/\sigma$, R = events per second, σ = cross section in cm^2.

continuous beams, crossing in the horizontal plane at a very small angle α, the luminosity, L, can be written approximately as

$$L = \frac{I_1 I_2}{\pi^{\frac{1}{2}} e^2 c \sigma_v \alpha} \text{ cm}^{-2}\text{sec}^{-1} , \qquad (1)$$

where I_1, I_2 are the currents in each stored beam, σ_v the vertical rms beam half height at the collision point, e the electron charge, and c the velocity of light. Roughly the main effort of the design procedure is to maximize L within the many constraints which apply. In the first approximation the design maximizes the current and minimizes the crossing angle of the beams and the beam height. Beam dynamical and practical processes as well as cost limit the range over which these parameters can be optimized.

C. Limits on the Current

1. Pressure bump. One important limitation on the circulating beam current was discovered at the ISR after operations began. It is a current-dependent vacuum instability which produces local increases of pressure, now designated "pressure bumps." The mechanism responsible is the ionization of the residual gas in the vacuum chamber by the circulating proton beam and the subsequent repulsion of the positive ions by the electrostatic field of the beam. These ions are accelerated away from the beam, ultimately bombard the chamber wall and liberate surface molecules by desorption, thus increasing the pressure. Naturally the ionization process increases since it is proportional to beam current times pressure, and an avalanche process can rapidly destroy the circulating beam. The effect can be described as follows, for systems having very high pumping speeds S,

$$\eta I_{crit} = \frac{(2\pi)^{5/2}}{3} \frac{er^3}{\sigma L^2} \left(\frac{R_G T}{M}\right)^{\frac{1}{2}} \qquad (2)$$

in which η is the desorption coefficient, the effective number of molecules desorbed per ion incident on the surface; I_{crit} is the threshold current at which the pressure bump occurs; σ the ionizing cross section; r the radius of a circular vacuum system; L the distance between bumps (i.e., usually the magnet length); R_G the gas constant (8.314×10^7 erg mol^{-1} K^{-1}); T the absolute temperature; and M the molar mass. (CO is considered the critical molecule.) In the example of ISABELLE, $r \approx 4.4$ cm, $L \approx 5$ meters, $\sigma \approx 1.2 \times 10^{-18}$ cm^2 for 25 GeV protons colliding with CO, so that $\eta I_{crit} \approx 40$ amps. To attain the desired luminosity requires about 8 amperes, hence $\eta \leq 5$. η depends upon the surface preparation, cleaning and baking procedures, and as well upon the mass and energy of the bombarding ions. The ISR operating experience and research and development at Brookhaven have shown that values of η near 1 are achievable. Thus the importance of this phenomenon for ISABELLE should be greatly diminished in comparison to the ISR, where currents in excess of 30A are desired.

2. Fundamental limitations. Current is limited in principle by other fundamental processes as well. Naturally the maximum current depends upon the attainable charge density of the beam as well as upon the available machine aperture. The particle density is primarily determined by the ion source and the subsequent manipulations of the beam. Interaction of the beam with the machine structure tends to dilute the density, as Liouville's Theorem dictates. Of course, the physical dimensions of the aperture are limited by cost.

a) Single beam space charge. The single beam space-charge force at high beam densities (Laslett, 1967) is an example of a fundamental limitation on the current. This force acts differently on each particle and depends upon its position in the beam as well as the beam position relative to the axis of circular symmetry of the vacuum chamber and surrounding iron shield. This time independent, beam induced force causes betatron tune* shifts. These shifts vary for the different beam positions or orbits which make up the total beam. Thus we conclude that enough tune space, i.e., space in which no harmful non-linear resonances exist, must be available or particles will be lost. Indeed this is true and this space charge detuning places some limits on the fraction of the vacuum chamber cross section aperture which is occupied by the beam. However, careful control of the working line** in the betatron –

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* Each particle has a horizontal (ν_h) and vertical (ν_v) betatron oscillation frequency. The tune of the machine is the value of ν_h, ν_v for the central (axial) orbit. Since there is a spread of orbits about the central orbit, there is a tune shift ($\Delta\nu_h$, $\Delta\nu_v$) associated with these orbits. ν is usually given in units of the revolution frequency.

** The operating ranges of ν_h and ν_v, the tune spread of the stored beam, define a linear locus of points near ($\nu_h \equiv \nu_v$) which is called the working line.

tune (ν_h,ν_v) plane by the magnetic working line control system can to some extent reduce the importance of this effect.

b) Transverse oscillations. It can be shown that limitations on circulating beam current can also arise from the time dependent electromagnetic interaction induced by coherent oscillation modes of the beam with the physical structures such as the vacuum tank walls, etc. Two examples of transverse oscillations are the "resistive wall" instability (Laslett et al., 1967) and the related "brick wall effect," seen at the CERN ISR (Zotter, 1972; Month and Jellet, 1973). Both in principle lead to a limiting current above which the beam becomes unstable. In particular, consider the electric image fields arising from resistive vacuum chamber walls. The result could be an exponentially growing transverse oscillation of the beam (Laslett et al., 1965). Fortunately, an infinitesimal transverse coherence can only be sustained if the betatron frequency (tune) spread is quite small. Therefore with a reasonable tune spread ($\Delta\nu$) the instability will be suppressed by the process known as Landau damping, roughly a washing out of coherent signals due to a mixing of frequencies. For a given tune spread, there exists a threshold beam current above which this transverse coherence can develop. The two important parameters are the vacuum tube radius and the beam density. In ISABELLE, for example, the beam density plays an important role and the tune spread needed for stability is given by

$$\Delta\nu > eI_o\, R\, |Z_T|/4\nu\, \beta\gamma\, m_p$$

$$|Z_T| \approx R\, Z_o/\beta^2\gamma^2 a^2 \qquad (2)$$

I_o, the circulating current; ν, the betatron frequency; $\beta\gamma$, the usual relativistic parameters; m_p, the proton rest mass; R, the bending radius of the machine; and a, the half beam size. For ISABELLE $\Delta\nu > 0.02$ and this is easily satisfied by choosing a working line between $\nu = 22.6$ and 22.67.

A working line which is not straight results in an enhanced resistive wall instability, causing a reduced current threshold. This phenomenon is the "brick wall effect" observed at the ISR. Fortunately the working line can be shaped by using high order (octupole, decapole, and duodecapole) magnetic field multipole correction windings. Therefore in ISABELLE neither of these effects should limit the current desired for high luminosity.

c) Phase space. In proton machines limits are imposed by beam phase space arguments. For a given vacuum chamber size or momentum aperture, Δp, the phase space density of the injected beam sets an upper limit on the current which can be accumulated,

$$I \leq e\, c\, \Delta p\, (N/A)_b \quad , \tag{3}$$

$(N/A)_b$ is the number of protons divided by the longitudinal phase space per injected bunch. For the AGS parameters this puts a limit on I of about 15 amperes, when all stacking is done in momentum space.*

D. Beam Size, σ_v

Reduction of beam size (σ_v) is limited by two considerations: 1) the intrinsic nature of the beam, i.e., its emittance, ε; 2) the linear focusing properties of the storage ring, i.e., the betatron amplitude function $\beta(s)$, a function of position (s) along the central orbit. For machines constructed in the horizontal plane, i.e., with no vertical dispersion, the rms beam height at the crossing point may be written as

$$\sigma_v = 1/2 \cdot (\varepsilon_v\, \beta^*/\pi)^{1/2} \quad , \tag{4}$$

β^* is the value of $\beta(s)$ at the crossing point and ε_v is the vertical emittance. The normalized emittance,

$$E_v = \beta\, \gamma\, \varepsilon_v \tag{5}$$

(β, γ are the usual relativistic variables), is an invariant characteristic of the beam for an ideal machine in which emittance is not diluted (Courant, 1958). Thus, σ_v, by what is known as adiabatic damping, automatically decreases as the square root of the energy. Note that E_v is fundamentally determined by the ion source and can only become diluted by non-linearities in the magnet system, scattering processes, self-beam effects (discussed earlier) and beam-beam effects (see later).

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* Stacking in momentum space means the accumulation of many pulses from the injector, each of small momentum spread Δp, so as to accumulate large currents with large momentum spread.

In (4) β^* also affects the beam height. How small can it be made at the intersection of the beams? This is actually determined by how large the β-function can be at the first focusing quadrupole. This value is given by

$$\beta_{max} = \beta^* + \ell^2/\beta^* \tag{6}$$

and since $\beta_{max} >> \beta^*$

$$\beta_{max} \approx \ell^2/\beta^* \tag{7}$$

where 2ℓ is the magnet free space around the intersecting area. β_{max} is the value of $\beta(s)$ at the first quadrupoles in either direction from the intersecting point. The real limit on β_{max} is set not only by the physical aperture of these quadrupoles but also by how much momentum aperture is required for beam operation. High performance p-p rings require substantial momentum aperture since large currents are typically built up by accumulating particles in many small momentum bites. Typical values of β^* are from 2-7m in the ISABELLE design, with β_{max} = 175-450m. With $\beta^* \approx$ 2m, the beam height should be σ_v (rms) $\approx$ 0.1mm.

E. Crossing Angle, α

As the crossing angle α is reduced, the interaction region or effective target size increases in length and this may become an important factor for the acceptance of the experimental apparatus. In a practical design, the natural crossing angle is determined simply by the insertion* length and the separation of the two rings. The crossing angle at the ISR is about 15°, and in the ISABELLE design is 9.4 mrad. Smaller crossing angles can be obtained in ISABELLE by adding bending magnets common to both rings, resulting in a shortened magnet free space (~60m in the standard operating mode).

F. Beam-Beam Interaction

Naturally when two charged particle beams collide, they influence one another. The force is similar to the direct space-charge force on a

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* By insertion is meant that section around the crossing region which normally has no bending magnets (~165m in ISABELLE).

particle which is a part of an intense beam. In both cases the forces are non-linear and depend upon the transverse beam distribution. There are two major differences. First the two beams move in opposite directions. In the single beam, direct space charge is proportional to $(1-\beta^2)$ which approaches zero as $1/\gamma^2$, while the beam-beam force is proportional to $(1+\beta^2)$ which approaches a constant value, 2. Thus the beam-beam force remains important at high energies. A second distinction is that the single-beam force is uniform around the ring, while the beam-beam force occurs at only a few intersection regions, eight at the ISR and six at ISABELLE, and thus is rich in azimuthal harmonics which are responsible for the excitation of non-linear resonances.

The implications of the beam-beam interaction are not well understood, but overall it is considered to be a fundamental limitation on the luminosity. The linear betatron tune shift is a measure of the strength of the beam-beam interaction (Keil, 1974a)

$$\Delta\nu_{bb} \approx \sqrt{2}\, r_p\, I\, \beta^* / \pi^{\frac{1}{2}}\, e\, c\, \gamma\, \sigma_v\, \alpha \tag{8}$$

r_p is the classical proton radius. $\sigma_v \propto \beta^{*\frac{1}{2}}$, thus we see that

$$\Delta\nu_{bb} \propto \frac{I\, \beta^{*\frac{1}{2}}}{\gamma\, \alpha} \quad . \tag{9}$$

Thus to limit $\Delta\nu_{bb}$, with a given beam current, I, note that small β^*, high energy (γ) and not too small crossing angle α are indicated. In ISABELLE the beams will be kept apart until the desired energy is reached (maximum γ). It is believed that the tolerable maximum value of $\Delta\nu_{bb}$ for proton-proton beam is very small. The ISR operates with $\Delta\nu_{bb} \sim 10^{-4}$ with only minor indications of a beam-beam effect. For the present the canonical upper limit used by designers is that $\Delta\nu_{bb} \leq 5 \times 10^{-3}$. ISABELLE is designed with $(\Delta\nu_{bb})_{max} \sim 2 \times 10^{-3}$.

G. Longitudinal Instability

In ISABELLE there are two quite different beam configurations: 1) bunched and 2) unbunched. Condition (1) occurs twice, first when the bunched AGS beam is accepted on the injection orbit, and second during acceleration of the high current beam from 30 GeV to the selected operating energy. Condition (2) also occurs twice, first during the beam filling stage when particles are parked in the so-called "stack" and left to unbunch, and then following acceleration the coasting beam is unbunched for use by experiments. Longitudinal instabilities can in principle be important for all phases, but the most dangerous case, the one not obviously amenable to applied correcting techniques, is the "fast" longitudinal instability induced by high frequency beam induced fields and manifested in the low current injected bunches as they are being stacked. In practice the first injected beam pulse from the AGS should be the most critical. The high (microwave) frequency with wave length shorter than a bunch length suggests that the interaction between bunches can be neglected and so we are dealing with instabilities within single bunches (Hereward, 1975a; Messerschmid and Month, 1976a; Hübner and Zotter, 1978). This coherent longitudinal instability in the microwave frequency range and with a very large frequency band width is not controllable by means of external feedback systems. The stability criterion is written as a limit on the longitudinal coupling impedance,

$$\left|\frac{Z_n}{n}\right| \lesssim \frac{E\,\eta\,B}{2\,I_o\,e}\left(\frac{\Delta E}{E}\right)^2_{total} \tag{10}$$

n is the mode (harmonic) number; E, the injection energy; I_o, the current from a single injection cycle; η, the energy slipping factor,

$$\eta = \frac{1}{\gamma_{t_r}^2} - \frac{1}{\gamma^2} \quad ; \tag{11}$$

γ_{t_r}, the transition energy for the storage ring, in proton mass unita; γ, the particle energy; B, the bunching factor (bunch length/bunch separation); ΔE, the full energy spread at half-maximum at the bunch center. This impedance limit for the injected bunches in ISABELLE is

$$\left|\frac{Z_n}{n}\right| \lesssim 10\ \Omega \tag{12}$$

a severe, but manageable, design constraint on the hardware. This small impedance limit results from the small energy slipping factor, η, which is characteristic of large rings. This factor is an order of magnitude larger in the ISR than in ISABELLE.

H. Effects of Scattering Processes

It is amusing to estimate the effects of some of the more obvious scattering processes.

1. Beam-gas nuclear scattering. The beam proton loss rate from single nuclear scattering events (we assume that a scattered proton leaves the aperture) can be written

$$(\dot{I}/I)_{bg} = - c\, k\, \sigma\, P \ , \tag{13}$$

$k = 3.3 \times 10^{16}$ molecules/cm^3 Torr; P, the average pressure in Torr; σ, the interaction cross section. For $P = 10^{-11}$ Torr, $\sigma_{H_2} \approx 80$ mb, the loss rate is $\approx 3 \times 10^{-6}$/hour, not important in terms of decrease in luminosity.

2. Beam loss from proton-proton collisions. For N_{int} interaction regions, the beam-beam loss rate is

$$(\dot{I}/I)_{bb} = - e\, f_{rev}\, N_{int}\, \sigma_{pp}\, L/I \ , \tag{14}$$

f_{rev}, the proton revolution frequency; I, the average beam current; L, the luminosity. For ISABELLE, with six intersection regions, I = 8 A, $L = 10^{33}$ cm^{-2} sec^{-1}, $(\dot{I}/I)_{bb} \approx 2 \times 10^{-3}$/hour, or about 5% for a 24-hour period. Thus for reasonable parameters beam-beam loss rate exceeds beam-gas loss rate by several orders of magnitude.

3. Beam-gas multiple scattering. Multiple Coulomb scattering of protons by the residual gas molecules causes the proton beam emittance to grow linearly with time. The growth rate for a fractional change in rms beam height decreases linearly as the energy increases. For ISABELLE parameters the multiple scattering growth rate at 30 GeV is 0.3×10^{-4}/hour and an order of magnitude smaller at 400 GeV. Thus beam-gas multiple scattering should not significantly affect performance.

4. Experimental background from beam-gas interactions. A major problem with which experiments at the ISR have had to cope is background (non-beam) particles. Naturally there are many sources of such particles. The most obvious source is from beam-gas interactions, especially from those interactions which occur in the long straight sections where no bending magnets exist which could deflect the lower energy secondary particles from the general beam direction.

From the beam-gas nuclear loss rate given in equation (13), we can write the interaction rate over a length ℓ,

$$\dot{N} = \frac{I}{ec} \ell \left(\frac{\dot{I}}{I}\right)_{bg} \quad . \tag{15}$$

For ISABELLE with a current of 8 amps, $P = 10^{-11}$ Torr,

$$\dot{N} \cong 140 \ \ell \ \mathrm{sec}^{-1} \tag{16}$$

where ℓ is in meters. For a length $\ell \approx 80$ meters, taking into account both beams and an average particle production multiplicity per interaction, $m \approx 20$, we obtain the total particle background

$$2\dot{N}m \approx 2.25 \times 10^4 \ m \approx 4 \times 10^5 \ \text{particles/sec} \quad , \tag{17}$$

produced in beam-gas interactions. At the ISR the residual gas pressure in the straight sections has been reduced to $\sim 10^{-12}$ Torr and thus this source of background particles is relatively unimportant. For comparison, note the total particle production rate in beam-beam collisions at ISABELLE. For $\sigma_{pp} \approx 40$ mb, $L = 10^{33}$ cm^{-2} sec^{-1} the interaction rate at one interaction region is 40×10^6 sec^{-1}. The estimated multiplicity is about 30 or a total particle production rate of $\sim 10^9$ sec^{-1}. This rate is clearly an important problem for detector design.

As a practical fact, particle backgrounds at the ISR have arisen from very subtle sources and great effort has been needed to understand and reduce or eliminate them. This background reduction is especially important for experiments seeking channels with very small cross sections, e.g., lepton pair production at high effective masses (Chen, 1977). Suppressing background will clearly constitute a major effort at ISABELLE, especially at the maximum luminosity of 10^{33} cm^{-2} sec^{-1}.

III. The Future

In the previous paragraphs are outlined some of the more important aspects of the design of proton-proton colliding beam machines. The ISR at CERN has solved the major technical problems and serves as the successful prototype for future machines. The next generation machines can confidently use the ISR experience to stretch the machine parameters and add new capabilities (see Table I).

A. Higher Center-of-Mass Energy

Higher center-of-mass energy is clearly the primary goal in the extension of parameters. In the ISABELLE design the energy per beam will cover the range from 30 to 400 GeV, a factor of 13 more than the ISR in the maximum center-of-mass energy.

B. Acceleration of Beams

Although the injectors for the ISR and ISABELLE are essentially identical, it is now possible to add a new dimension, namely full-scale acceleration of large beam currents by standard techniques. Actually this idea was put forth by Jones (1963) in considering the proposal to add storage rings to the AGS. He argued that the storage rings should be three times the diameter of the AGS so that collisions between 100-GeV beams could be possible by accelerating the beams in the storage rings, following injection from the AGS. Although acceleration in the ISR has been accomplished up to 31 GeV using the phase displacement technique,* it was not an integral part of the original design. Its success is an example of the ingenuity of the ISR group. Injection at a relatively low energy followed by acceleration to the desired higher energy turns out to have significant advantages for eventual research capabilities. In addition to the obvious ease of providing continuously variable and precise energy, it automatically provides the optimum luminosity at each intermediate energy, given the design luminosity at maximum energy. For ISABELLE, at 400 GeV, $L \approx 10^{33}$ cm^{-2} sec^{-1} and at 30 GeV $L = 10^{32}$ cm^{-2} sec^{-1}, which is somewhat more luminosity than currently available at the ISR.

A simple numerical example is useful in understanding in a crude way the relative sensitivity which the proton-proton storage ring has compared to a fixed target accelerator. For example, a beam of 2×10^{12} protons/sec colliding with a meter-long hydrogen target has an equivalent luminosity of $\sim 10^{37}$ cm^{-2} sec^{-1}, some 10^4 times larger than the design maximum for ISABELLE. Equivalently, a secondary π beam of 2×10^8 π's/sec would have the same luminosity as ISABELLE. Asymmetric energies will clearly be a capability should

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* Phase displacement acceleration is accomplished by sweeping empty rf buckets through the stacked beam (Henrichsen and deJonge, 1974).

TABLE I

	ISR	ISABELLE
Maximum cms energy	31 + 31 = 62 GeV	400 + 400 = 800 GeV
Equivalent fixed target accelerator energy	2,000 GeV	340,000 GeV
Luminosity	$\sim 2 \times 10^{31}$ cm^{-2} sec^{-1}	10^{33} cm^{-2} sec^{-1}
Circumference	945 m	3,834 m
Magnet free length around intersection region	17 m	60 m
Maximum dipole field	12 kG	50 kG
Circulating beam current	∿35 A	8 A
Stored energy per beam	∿2.5 MJ	∿32 MJ
Aperture of vacuum chamber	160×52 mm^2	88 mm (diameter)
Magnet system	Cu-Fe	NbTi-Fe (Superconducting)
Lattice	Combined function magnets	Separated function magnets
β-function at intersection points	Fixed	Variable
Acceleration of beam	Not in design. Phase displacement successfully used. (26-31 GeV)	Integral part of design. Normal RF system. (30-400 GeV)
Injection	PS ≤ 26 GeV	AGS ≤ 30 GeV

special kinematic properties be needed (Cutts and Rosenberg, 1977). Most probably early experiments will stress the maximum energy so as to explore the highest energy domain, but eventually the entire available energy region should be explored as well.

In addition, the acceleration process in ISABELLE will be done on the third harmonic (3 bunches), thus in principle bunched beam collisions can also be attempted (Marx 1977). This mode of operation has some advantages. For example, following acceleration to the desired energy, collisions between the bunches of the two beams can be controlled by slow r.f. phasing and not by rapid beam deflection. Bringing the beams into collision slowly minimizes harmful effects of the beam-beam interaction. The colliding energy can be changed during a given physics run without restarting the accumulation process. The beams can be de-accelerated down to about 30 GeV for ejection (under normal operating procedures) resulting in less particle loss to the accelerator structure. Several other interesting possibilities can be suggested by the reader, including the possibility that bunched operation will not be as stable as D.C. operation! Nonetheless, bunch-bunch collisions are an integral part of plans to provide $\bar{p}p$ storage ring collisions at FNAL and at the CERN SPS.

C. High Magnetic Fields

Superconducting magnets have reached a state where one can confidently design a storage ring using this new technology. The maximum dipole field at the ISR is 12 kG, at ISABELLE 50 kG. Three obvious advantages are obtained by using superconducting magnets: 1) the circumference is much smaller for a given energy; 2) the electric energy consumption with the superconducting magnet system will be 1/4 to 1/3 of a copper-iron system with the same design energy and luminosity; and 3) the smaller circumference for a given energy becomes very important for very high energies since above about 200 GeV the actual machine construction cost will be less using superconducting magnets. The earlier discussion of the current limitations indicated that most limitations due to collective effects become more stringent for a machine with larger circumference and smaller vacuum chamber aperture. Superconducting magnets clearly reduce the circumference for a given energy. It is also true that superconductors allow very much higher current densities, resulting in magnet designs where coils are smaller and close to the magnet region. This implies that the vacuum chamber diameter can be increased with a resulting linear increase in cost (at most), whereas for conventional magnets, the cost rises more rapidly with increasing magnet gap.

Superconducting magnets bring with them a new set of conditions and limitations, some of which we now consider.

i) Naturally all superconducting materials require exceedingly low temperature. The current material of choice is NbTi which, under usual operating conditions of 40-50 kG, must be kept below $5^{o}K$. For example, in ISABELLE the design field is 50 kG and the operating temperature will be $3.8^{o}K$, although the input gas temperature will be $2.6^{o}K$. The cryogenic system needed to provide this temperature is large, sophisticated, and is an added operational burden to the facility. Clearly the major user of electric power at ISABELLE will be the refrigerator system, about 16 MW for the compressors.

ii) The magnetic field quality is determined by the placement of the superconducting wires and not by the iron, as in a standard magnet. Tolerances in conductor placement are typically 50μm in order that random field errors are small enough not to cause beam loss by non-linear effects (ISABELLE, 1978). In addition the tolerance on relative conductor motion under pulsing is severe. The conductors carry large currents, 4000 amperes, and are in a 50 kG field, thus forces on them are large. Mechanical stability is fundamental to the successful use of superconducting magnets for storage rings.

iii) A small source of local heating in the superconducting coil from any source will induce a local change from the superconducting state to the "normal," non-superconducting state. The finite resistance of the normal state in turn produces more heat and the local "quench" propagates through the coil until the entire coil is normal. This is a vitally important fact of life and a serious limitation. Recall that the specific heat is extremely small at such temperatures and furthermore the local temperature rise needed to produce a quench is only about $1/2^{o}-1^{o}$ at the peak 50 kG field. (At the low injection field a temperature rise $\geq 5^{o}$ can be tolerated.) There are two important sources of heat; first, a small mechanical motion of the conductor will generate eddy current heating and, second, charged particles traversing the coil deposit heat (Hahn, 1977). Mechanical motion plagued early magnets and was a major cause of poor performance. The phenomenon of "training" was observed, a form of learning process where successively higher fields are attained as the number of quenches increases. At least a part of this behavior results from conductors moving to a new, more stable position. Naturally, there are other effects as well. Training is not yet fully understood, but rigid clamping of the superconductor is the best remedy currently available. Even most "good" magnets exhibit some training at the highest magnetic fields where the conductor is operating near its critical current value.

Heating by charged particles must also be essentially eliminated, i.e., the number of particles lost from the beam and which traverse the coil must be very small. It is interesting that the requirements on low background for experiments require even fewer lost particles, so great care must go into the entire machine design to keep particle background small. However, there is a period at the ISR in which a very large fraction of the eventual circulating beam is lost, namely during the beam stacking period. It is quite common that one-half of the injected beam is removed from the beam stack, either by direct loss or by beam scraping, all in the attempt to create a dense beam stack. Clearly such particle losses depend upon how the beam is stacked in the machine. Both at the ISR and in the ISABELLE design, momentum stacking is used. Under such conditions it would be very difficult to stack beam in a ring at full energy (∿50 kG) and keep the magnets from quenching due to particle heating. In ISABELLE, however, the beam will be stacked at 30 GeV (∿3.7 kG) where the tolerance of the magnets to heating will be at least an order of magnitude larger than at full field and therefore no problem is expected from particle-produced heating.

Tolerances on the magnetic field properties for a proton storage ring are stringent in order that the beam remains dense, produces and maintains high luminosity, has low particle loss, and thus has low background necessary for sensitive experimental apparatus. At Brookhaven superconducting magnets meeting these demands have been designed, constructed, and tested. Nevertheless, it remains a challenging venture to assure that some thousand magnets using a very new technology will indeed meet all of the known and perhaps some unknown specifications.

D. Luminosity

By varying current, vertical β-function at the collision points, and crossing angles, ISABELLE can operate over a large range of luminosities; a large part of the range is attainable without physical modification of the standard structure. In addition a large variety of diamond shapes (interaction regions) are also possible with changes in crossing angle, α, and β^* values.

Quite naturally the second generation p-p storage rings build upon the knowledge gained at the ISR so that higher luminosity at the same cms energy should be available. Furthermore, since beam size shrinks as the square root of the momentum, luminosity increases as the square root of the momentum. Higher energy p-p machines can therefore provide much higher interaction rates at the same cross section.

E. Physics

Suppose one asks, "What new physics can be investigated with p-p colliding beams which cannot be done otherwise?" Two general arguments apply:

i) No other known accelerator system can provide such an enormous energy region. For example, fixed target accelerators are hardly likely ever to get above ∿4000 GeV or ∿90 GeV in the cms. Even this "low" energy would cost a few billion dollars. e^+-e^- colliding rings at 100 x 100 GeV or 200 GeV in the cms have been estimated (CERN, 1977) to cost several times as much as a 400 x 400 GeV p-p facility. Going to even higher e^+-e^- energy seems more or less excluded because of the enormous problem with energy loss from synchrotron radiation coupled with the severe orbit control problems for extremely large rings. Thus only p-p rings are available at superhigh energies to investigate the smallest regions of space, and to search for massive, ∿100 GeV, particles such as intermediate vector bosons.

ii) It is only in p-p collisions that the internal structure of the hadron finally may be completely understood. For example, consider the postulated Higgs boson with spin 0. No direct evidence is available which guarantees that they exist, but the popular theories require at least one such particle (Georgi, 1978). Theory suggests that Higgs bosons are produced primarily by virtual gluon-gluon collisions, thus should they be discovered in p-p collisions, some new and perhaps vital information would be available on the gluon behavior in hadrons. We should also note that only in p-p interactions can direct quark-quark collisions be studied--providing of course that our current theoretical concepts concerning quarks and gluons are reasonably near the truth.

Finally, if we use our experiences from the past as a guide, we should expect that the most profound discoveries which will come from the future proton storage rings will be unexpected and unpredicted.

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