ISABELLE DIVISION

HIGH PERFORMANCE p-p COLLIDING BEAMS IN THE MAIN RING TUNNEL AT FERMILAB*

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ABSTRACT

It is pointed out that for a modest marginal investment (above the cost of a superconducting ring of the scope of the ES/D project) a high performance p-p colliding beam facility can be built essentially in parallel with the main FNAL ring and, for the most part, within the same tunnel. Six regions of 70 x 700 GeV colliding proton beams can be obtained.

At the top center-of-mass energy, $E_{cm} = 443 \text{ GeV}$, the luminosity per unit tune shift is $1.51 \times 10^{35} \text{ cm}^{-2} \text{ sec}^{-1}$. Given a tune shift, $\Delta\nu = 5 \times 10^{-3}$, a luminosity, $L = 7.6 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ results.

The marginal cost is estimated to be on the order of \$20 - 30 M.

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Introduction

Recently, there has been expressed an interest in the use of the energy saver/doubler ring (ES/D) as part of a colliding beam device. Although it may be clear to many, let me just emphasize the point that to design a ring whose magnets and tunnel location make it feasible to achieve p-p collisions at sufficiently high performance levels is not a trivial matter. In fact, in order not to preclude one or the other of potential uses for the ES/D, it is important to choose both magnet design and ring location with great care.

A proposal is made here that would provide p-p collisions at a total center-of-mass energy, $E_{\text{cm}} \approx 400 \text{ GeV}$, with a luminosity in the range $10^{32} - 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$. It is not entirely accidental that these performance figures are similar to those quoted for the ISABELLE project at BNL. Although the detailed parameters of the two systems are greatly different, the basic conceptual framework put forward here is suitable for both the BNL project and the one being proposed here.

The fundamental precept upon which the suggestions given here are based is the notion of "division of labor". This principle is ubiquitous in nature and is universally applied in man made systems, in government, industry, education as well as science. Its great potential for maximization of performance with a coupling to cost minimization should not be overlooked in the design of future accelerator systems.

An application of this principle of "division of labor", including constraints related to technology and beam stability, leads to the following general guidelines upon which a design for a p-p facility at Fermilab can be based.

(1) The main ring accelerator should not be used in the collisions.

(2) High currents can be achieved simply. However, current should be accumulated in a small storage ring about $1/8$ the circumference of the main ring and located in a separate tunnel.

(3) Related to point (2), no beam transfer should be made entirely within the main ring tunnel.

(4) The superconducting, high energy ring should be located far from the "main ring". If it is to be in the same tunnel as the main ring, the ceiling would appear to be the best position.

(5) A low field conventional ring should follow the superconducting ring in the same horizontal plane, and periodically cross providing p-p collisions.

(6) Both superconducting and low field storage rings would be filled by transfer from outside the tunnel from the small stacking ring.

(7) The requirements on the superconducting magnet design is that it is consistent with a vacuum system capable of containing many amperes of current, say 5 - 10 A. Such a magnet would run dc most of the time, but should be capable of a slow ramp (order of minutes) to accelerate the stack. The field quality at the magnet center where beam is stored should have good field quality over a wide field range, say a few kG to 40 kG, so that a wide range of beam energies are possible.

It is clear that the optimal design of a system with the above guidelines may not be compatible with a comparatively fast cycling accelerator whose aim is to produce secondary beams from targets.

However, it is not my intention here to go into this question. It is my purpose to see if from these guidelines a reasonable system can be designed to give the performance indicated above. In particular, the questions I will address are: (1) What are the lattice parameters for the storage rings consistent with having a high current beam stored? (2) What should the magnet aperture be so that the magnets will be small enough to fit into the main ring tunnel? (3) What are the attainable collision characteristics consistent with the given ring geometry, in particular, the straight section length? (4) What are the resulting performance characteristics? and (5) what is a rough marginal cost assuming that the superconducting ring is given, the cost of the latter being essentially the ES/D project cost?

Storage Ring Lattice

The basic constraint on the lattice design is the geometric configuration of the main ring tunnel. A detailed design based on this constraint will not be attempted here. Only a description based on the gross main ring parameters will be given. The point is to develop the general parameters of the storage ring which will be quite different from those of the main ring. To obtain a storage ring design, we need the following characteristics of the Fermilab ring:

Bending angle per sextant	- 0.9579 radians
Bending angle per insertion	- 0.0893 radians
Length of "cell" region per sextant	- 892.9 m
Length of each of six insertions	- 154.9 m

Attempting to keep the beam size small, we suggest short cells for the storage rings. A possible set of parameters for the storage ring lattice is given in Table I.

The amount of straight section available, ~ 80 m, should be able to provide about 25 m of free straight around the collision point. Since the energies of the colliding beams are quite different

in the high center-of-mass energy mode, the luminosity is optimized by having low vertical β in the low energy beam alone. That is, the

TABLE I

STORAGE RING PARAMETERS

Energy (High Energy Ring)	700 GeV
Magnetic Field (peak)	40 kG
Number of Cells	$30 \times 6 = 180$
Number of Insertions	6
Cell Length	29.7 m
Number of Dipoles per cell	4
Dipole Length	4.66 m
Number of Dipoles per Insertion	~ 11
Packing Factor (Cell Region)	62.7 %
Packing Factor (For Dispersion Killing)	~ 70 %
Length for Dispersion Reduction (per Insertion)	75 m
Total Insertion Length	154.9 m
Straight Section	79.9 m
Tune	~ 50
Transition Energy	≤ 50
Injection Energy	70 GeV
Circumference	6.28 km

CELL PARAMETERS

Maximum Dispersion Function	0.64 m
Maximum β -function	50.7 m
Quadrupole Focal Length	10.5 m

LATTICE PARAMETERS IN COLLISION REGION

β_v^* (low energy beam)	1.0 m
β_v^* (high energy beam)	~ 5.0 m
Free Straight	$\sim \pm 12$ m
Maximum β -value	≤ 150 m

luminosity is relatively insensitive to the vertical β value in the high energy beam (assuming equal vertical emittances). With this arrangement, a staggered quadrupole system allows small crossing angles without producing high β -values in the focusing system. The latter can be kept below $\beta_{\max} \sim 150$ m. Assuming that the magnets are small enough so that the beams can be kept as close as 40 cm throughout the bending region, a natural crossing angle of about 10 mrad results. There is sufficient space in the central crossing region to provide bending magnets in at least one of the crossing regions so as to reduce this crossing angle to attain an increased luminosity. This is easily done without changing the bending geometry outside the collision region. In principle, one can imagine a crossing angle of ~ 1 mrad.

Beam Parameters

For the purposes of discussion here, the main ring intensity is not significant. The important characteristics relate to density. The longitudinal density should be maximized while keeping the transverse emittances as small as possible. If this means low intensity per pulse, then more pulses must be stacked. Remember that stacking is done in a stacking ring at relatively low energy, ~ 35 GeV. The stacked beam would subsequently be accelerated in this ring to about 70 GeV for injection into the two storage rings.

Under such operating conditions we take for the beam parameters an invariant transverse emittance for both horizontal and vertical phase planes, $E(\text{Area}/\pi) = 5 \times 10^{-6}$ rad-m, and a longitudinal density corresponding to 10^{13} protons in the 1113 bunches each of phase area, $A = 0.1$ eV-sec, or a density, $d = 9 \times 10^{10}$ protons per eV-sec.

If we want to stack an average current I given a density d , the resulting momentum spread at the injection momentum, p , is given by,

$$\frac{\Delta p}{p} = \eta_d I / e d p B, \quad (1)$$

where η_d is a dilution factor and B_b is the bunching factor at injection. Thus, taking a dilution factor 50%, a bunching factor of 0.8, an injection energy of 70 GeV, and an average stack current of 10A, we obtain for the bunched stack momentum spread, $(\Delta p/p)_{\text{stack}} = 1.86\%$.

The invariant beam and injection parameters are given in Table II. As can be seen the required aperture is on the order of 4 cm. This appears consistent with a magnet size of about 40 cm for both the superconducting magnet as well as the low field conventional magnet.

TABLE II. BEAM AND INJECTION PARAMETERS

Invariant Transverse Emittance (95%)	5×10^{-6} rad-m
$(\Delta p/p)_{\text{stack}}$ (Bunching Factor, $B = 0.8$) (Full)	1.86 %
Maximum Dispersion	0.64 m
Maximum β (Cell)	50.7 m
Vertical Beam Size (Max., Cell)	3.8 mm
Horizontal Beam Size (Max., Cell)	1.6 cm
Aperture Required	≥ 4 cm

Luminosity

It is conceived in the proposal made here that collisions can take place in the center-of-mass energy range $E_{\text{cm}} = 140$ to 443 GeV although, with decreased performance, center-of-mass energies extending down to 60 GeV are possible. Therefore, a link to ISR energies can be obtained. We will consider here the case of the highest center-of-mass energy, corresponding to 70 x 700 GeV collisions.

For Gaussian beams, the luminosity, L and tune shifts (which measure the strength of the electromagnetic beam-beam force and when small are a reflection of how well one is able to detect the effects of the nuclear collisions) can be expressed by

$$L = \left(\frac{I}{e}\right)^2 \frac{2\sqrt{\gamma_L}}{\alpha \sqrt{\pi} \alpha \sqrt{E} \sqrt{\beta_L^*}} , \quad (2)$$

$$\Delta\nu_L = \left(\frac{8}{\pi}\right)^{\frac{1}{2}} \frac{r_p I}{e \alpha \sqrt{E}} \frac{\beta_L^* \sqrt{\gamma_H}}{\gamma_L \sqrt{\beta_H^*}} , \quad (3)$$

and

$$\Delta\nu_H = \left(\frac{8}{\pi}\right)^{\frac{1}{2}} \frac{r_p I}{e \alpha \sqrt{E}} \frac{\beta_H^* \sqrt{\gamma_L}}{\gamma_H \sqrt{\beta_L^*}} , \quad (4)$$

where

$\Delta\nu_L$, $\Delta\nu_H$ are the tune shifts for the low and high energy beams respectively,

β_L^* , β_H^* are the corresponding vertical β functions at the collision point,

γ_L , γ_H are the energies in proton mass units,

I is the current,

α is the crossing angle,

E is the invariant emittance, and

r_p is the classical proton radius.

In writing the formula for the luminosity, it is assumed that the high energy beam is smaller than the low energy beam, which means that

$$\beta_H^* < \frac{\gamma_H}{\gamma_L} \beta_L^* , \quad (5)$$

or $\beta_H^* < 10$ m in the case considered here. Under these conditions, we can ignore the tune shift for the high energy beam since

$$\Delta\nu_H < \Delta\nu_L . \quad (6)$$

Taking $I = 10A$, $\alpha = 10$ mrad, $E = 5 \times 10^{-6}$, $\beta_L^* = 1$ m, $\beta_H^* = 5$ m, $\gamma_H = 746.3$, and $\gamma_L = 74.6$, we obtain a luminosity, $L = 5.66 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, with a tune shift, $\Delta\nu_L = 3.75 \times 10^{-3}$. A luminosity 10 times larger can be achieved by decreasing the crossing angle to 1 mrad, but then of course the tune shift becomes very large: that is, for $L = 5.66 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$, the tune shift becomes $\Delta\nu_L = 3.75 \times 10^{-2}$, which is a strength of beam-beam interaction observed in electron colliding beams.

Comments on Cost

To get an estimate of the marginal cost (i.e. above that for the superconducting high field ring), we will roughly extrapolate from projects requiring similar magnets. A recent proposal to collide 25 GeV protons with the main Fermilab beam uses 18 kG magnets. For the small storage ring proposed here, we need magnets capable of 10 kG dc operation with "slow" pulsing to 20 kG. However the peak energy of 70 GeV implies about 2.5 times more magnet length. If we take the cost estimated in the above-mentioned proposal, subtract out equipment designated for experimental detection and multiply by 2.5, we arrive at an estimate for our small storage ring of \$8.5M. To obtain a crude cost figure for the conventional ring running along with the superconducting ring, we note that the magnets are to be of the low field dc variety, with a field, $B_0 \leq 4$ kG. Although the magnetic length in our case is over three times that for the PEP proposal at SLAC, the aperture we need is substantially less. Doubling their magnet cost, we get an estimate for the low field ring here of $\sim \$10$ M. Adding $\sim 50\%$ for contingency and escalation, we arrive at an estimate of the marginal cost, \$20 - 30 M.

Conclusions

It has been pointed out that for a modest marginal investment (relative to the cost of a superconducting ring of the scope of the ES/D project) a high performance p-p colliding beam facility can be built essentially in parallel with the main FNAL ring and for the most part within the same tunnel. One can envisage six collision regions each with 70 GeV protons in a low energy ring colliding with protons in a high field superconducting ring capable of energies ranging from 70 to 700 GeV. The beam parameters are such that a luminosity per unit beam-beam tune shift of $L/\Delta\nu = 1.51 \times 10^{35} \text{ cm}^{-2} \text{ sec}^{-1}$ can be achieved. With a crossing angle of 7.5 mrad, a beam-beam tune shift of $\Delta\nu = 5 \times 10^{-3}$ leads to a luminosity, $L = 7.6 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ for 70 x 700 GeV collisions. For such collisions the center-of-mass energy is $E_{\text{cm}} = 443 \text{ GeV}$, meaning that this project is capable of attaining such high performance as that characterizing ISABELLE, the project proposed at BNL. Center-of-mass energies lower than 140 GeV can also be obtained, but with significantly reduced luminosity.

The specific details of the collision geometry have still to be worked out and will be guided to a large extent by the presence of the main ring vacuum chamber running through the straight sections. The required separation is a function of the specific experimental detection apparatus to be used for each insertion.

The use of a small storage ring to stack high current means that the "energy" stability of the beams is not strongly sensitive to wall impedances. This eases greatly the constraints on the vacuum chamber design in the circular part of the rings as well as in the insertions. Compared to other high performance p-p colliding beam designs, such as ISABELLE, POPAE and the LSR at CERN, designs which do not utilize a stacking ring, this is a significant advantage. In these latter cases, a strong sensitivity to wall impedances does exist,

especially in the microwave frequency region, and very special precautions must be taken in the design of all chamber discontinuities. The chamber design is, in fact, a major and difficult part of these projects. A second advantage of this small storage ring is that in the large superconducting ring the beam is always centered in the vacuum chamber. The fact that the full vacuum chamber aperture is not used reduces the beam sensitivity to magnetic field errors arising from errors in coil placement. For a given current, stacking directly in the superconducting ring means more aperture is used and results in a beam with a greater tendency to instability. Thirdly, avoiding the "lossy" momentum stacking process in the superconducting ring reduces the potentially harmful effects of radiation heating of the superconducting coils.

A final advantage to an "outside the tunnel" ring is related to the "division of labor" concept. All beam transfer is essentially performed outside, that is, beam does not have to cross the tunnel directly. This makes possible the attainment of optimal beam transport.

The use of a low field ring alongside the superconducting one is based primarily on cost considerations. The idea is to minimize the marginal cost. Removing this constraint would allow the use of two superconducting rings, with the possibility of colliding two 700 GeV proton beams, thus giving a top center-of-mass energy, $E_{cm} = 1.4$ TeV. The result of course is a substantial cost increase. Also, the short insertion space makes the insertion design more complex and leads to a comparatively lower performance potential.

There is no essential interference of the colliding beam facility with main ring operation. After the construction phase, stacking is accomplished by periodically taking a fraction of a main ring pulse, $\sim 1/8$, for feeding the stacking ring. The use of a pulsed fast kicker is all that is needed.