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ELECTRON-PROTON COLLIDING BEAMS AT FERMILAB

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Abstract

This report describes a design study for an electron-proton colliding beam facility at Fermi National Accelerator Laboratory. This work has been carried out over several years, largely in summer studies in 1976 and 1977 and brought in the conceptual design stage described in this report by a more concentrated effort[1] during the end of 1977 and the beginning of 1978.

Outline of the e-p Scheme

The scheme, sketched in Fig. 1, works as follows. Protons are accelerated as usual in the Booster to 8 GeV, transferred to the Main Ring in 13 batches and accelerated to 100 GeV. At this energy, they are extracted and injected into the Energy Doubler. If desired, more 100-GeV pulses can be stacked in momentum phase space. Finally, the beam is accelerated to 1000 GeV, where the Energy Doubler is converted to the storage mode and the proton beam is kept bunched at the standard frequency of 53.1 MHz.

Table 1. 1000 GeV of Proton-Beam Parameters (Energy Doubler)

Intensity	0.15 tp 1.5 A
No. of Pulses from Main Ring	One to 10
No. of Bunches	1113
Accelerating Frequency	53.1 MHz
RF Voltage	1 MV
Emittance ($\epsilon_x = \epsilon_y$, 95% of beam)	$0.013\pi\ 10^{-6}$m
Longitudinal phase space area	3.8 eV·s(with 10 pulses)
Bunch length (σ, rms)	50 cm(with 10 pulses)
Bunch height ($\delta p/p$, rms)	1.2×10^{-4}

For the second part of our scheme, we assume that a 75-MeV electron linac is attached to the Electron Cooling Ring. This ring is ultimately to be used for the production of an intense antiproton beam and its location at the Booster is mainly governed by this requirement. The electrons are accelerated in the Cooling Ring to 750 MeV and transferred to the Booster, in which they are accelerated to 4 GeV and transferred to the Main Ring, where they are stored. This cycle is repeated several times until the Main Ring has been completely filled in box-car fashion. After the Main Ring is filled, the entire electron beam is accelerated to an energy between 11 and 12 GeV. During all these steps of the process a constant accelerating frequency of 53.1 MHz can be used. This corresponds to 24 bunches accelerated each pulse in the Cooling Ring and in the Booster; 48 such pulses are required to fill the Main Ring.

Table 2. Electron-Beam Parameters (Main Ring)

Energy	11-12 GeV
Intensity	0.38 A
No. of Pulses from Booster	46
No. of Bunches	1113
Accelerating Frequency	53.1 MHz
RF Voltage	4 MV
Emittance (95% of beam, full coupling)	$0.3\pi\ 10^{-6}$m
Energy Spread ($\delta E/E$, rms)	6×10^{-4}
Bunch Length (σ, rms)	13 cm

The Performance

The Energy Doubler superconducting magnets will be installed just underneath the Main Ring. A local vertical by-pass will be added to the Main Ring to bring the electron beam down to the level of the proton beam in the Doubler, as shown in Fig. 4. To avoid collisions of bunches next to those colliding in the middle of the interaction region, the two beams will collide at a small horizontal angle. Finally a low-β insertion will be added to both the Main Ring and the Doubler to increase the luminosity (Fig. 5). Smaller electron-beam emittances can be obtained by increasing the betatron tunes of the Main Ring to approximately 27, which is within the quadrupole capabilities at the electron-beam energy of 12 GeV.

Table 3. e-p Colliding-Beam Performance

	e	p
Energy	11.5 GeV	1000 GeV
$\beta_x^* \sim \beta_y^*$	0.35 m	5 m
$\nu_x \sim \nu_y$	26.7	20.4
Crossing angle	2 mrad	
Luminosity	$\sim 10^{32} \mathrm{cm}^{-2} \mathrm{s}^{-1}$	
$\Delta\nu$, Beam-Beam Tune Shift	0.02	0.001

The luminosity as a function of the electron beam energy is shown in Fig. 3 and as a function of the proton-beam energy in Fig. 2. The larger electron energies shown would require more rf voltage in the Main Ring. The slope of the luminosity for these energies is calculated under the assumption that more rf voltage is available, but that the power delivered to the beam is kept constant. The luminosity also increases when the electron beam energy is decreased if the beam intensity is kept constant. This increase is caused by a reduction of the beam emittance, which also allows a smaller crossing angle. The luminosity is decreased slightly by reducing the proton beam energy, mainly because of the increase of the proton beam size. Because of the available rf voltage only one colliding beam insertion is possible. In fact, each insertion gives a need for extra rf power because of the strong vertical bending.

Acceleration of Electrons in the Cooling Ring

The major requirement for our project is an electron linac with an output energy of 75 MeV and a pulse current of 400 mA. A linac with these specifications is in most respects a conventional one, very similar to models offered by private concerns.

In the normal $\bar{p}$-mode, the Cooling Ring operates at a constant momentum value of 644 MeV/c for cooling either protons or antiprotons. The nominal field of the bending magnets at this momentum is 4.5 kG. In addition, extremely good vacuum of the order of 10^{-10}torr is required to minimize beam-gas scattering. To obtain such low pressure, it is necessary to have a metallic vacuum chamber inside the magnet bore which will not allow ramping of the magnetic field at too rapid a rate. If the Cooling Ring is also to be operated as an electron synchrotron, the magnetic field must ramp from an injection value of 0.5 kG to the extraction level of 5 kG in a reasonably short time to match, at least partially, the Booster repetition rate of 15 cycles per second. The limitation on ramp rate

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is caused by heating of the vacuum chamber by eddy currents. We believe that it can be operated safely with no water cooling at a rate of three cycles per second. The Cooling Ring is a separated-function accelerator with a lattice which applies to either cooling antiprotons or accelerating electrons. In the first mode, however, the quadrupoles are powered with six different power supplies, which may be too many to ramp in the electron-acceleration mode. A solution was found where the quadrupoles are divided into only two groups with two different excitations, which will be much easier to cycle.

Acceleration of Electrons in the Booster

The Booster is more than adequate to capture a 750 MeV/c beam from the Electron Cooling Ring. The 24 bunches extracted from the Cooling Ring are transferred on the fly during the field rise to the Booster. They will be captured by existing rf buckets. The rf system will, of course, be operated at the constant frequency of 53.1 MHz, which corresponds to the usual harmonic number of 84. Our plan is to run the cavities at constant peak voltage and to adjust their relative phase for the required energy gain.

The Booster is a combined-function accelerator made of two kinds of bending magnets with opposite gradient and slightly different bending radii. The radiation repartition factors are anomalous. The radial betatron oscillations are anti-damped at twice the rate of other conventional electron-synchrotrons. To minimize the radial-emittance increase, it will be advantageous to ramp the magnets in the usual proton cycle to 8 GeV and extract the electron bunches on the fly when they have reached 4 GeV. At this energy, the radiation losses are already somewhat large, approximately 0.5 MV/turn, for compensation with the available rf voltage. The expected beam emittance at 4 GeV is 0.5π mm-mrad, and the total energy spread 10^{-3}. The Booster does not have a vacuum chamber to shield the laminations and the coils from radiation, but the coils are 2 in. above and below the median plane where the radiation is concentrated, so the radiation striking the coils is small. We do not expect any radiation damage to the laminations, and the heating caused by the power loss will be very small.

Acceleration and Storage in the Main Ring

Our scheme requires operation of the Main Ring at 4 GeV/c because this is the largest momentum one can expect for an electron beam accelerated in the Booster. There are obviously several concerns about operation at such low momentum. It seems relatively easy to run the magnet power supplies at half the normal injection excitation. The main concern is in the quality of the Main Ring magnets. Assuming that the remanent field $\Delta B/B$ is now twice as bad as at 9 GeV/c, that is, the nonlinear components (sextupoles, octupole,...) are twice as strong. On the other hand, because of the lower beam momentum, the correction system presently installed in the Main Ring is also twice as effective. Thus the two effects should to some extent balance off. The Main Ring is capable of accepting at least 1.5π mm-mrad at 8 GeV. Similarly, we observe that the betatron oscillation damping time is 4.3 sec., which is quite large. The question is whether the beam can survive for the time required for filling the Main Ring, 15 sec. A crude measurement of the proton-beam lifetime at 8 GeV has given about 20 sec.

Storing electrons in the Main Ring will put an extra burden on the Main-Ring vacuum system because of desorption of gas molecules from the stainless-steel beam pipe by synchrotron radiation. At first, this desorption might be very large and the pressure could climb to a point where the accelerator cannot be run. After some running time, however, the wall will become conditioned and the desorption rate will fall. The major contribution to gas desorption is by a two-step process. The synchrotron radiation x-rays knock out an electron from the wall. That electron, if it is energetic enough (above approximately 20 eV) will desorb a gas molecule when it returns to the wall. We estimated a gas load due to radiation desorption of $2\text{x}10^{-6}$torr-ℓ/sec per pump, which is twice the load due to leaks. Eventually, an average vacuum of 10^{-7}torr with a 0.38-A, 12-GeV electron beam should be within reach.

There are several factors that can contribute to the beam-size growth and beam lifetime. The dominant one is obviously the synchrotron radiation itself. About 1,500 photons are radiated in each turn per particle, with an average energy of about 2 keV. At 12 GeV, the quantum diffusion coefficient is two orders of magnitude larger than the contribution from gas scattering and much larger than any contribution from other effects, such as intrabeam scattering and bremsstrahlung on the residual gas. Thus the synchrotron radiation is the predominant factor in beam diffusion. With a total of 4 MV rf voltage a reasonably long quantum lifetime occurs between 11 and 12 GeV. Yet, when the spectra of the various effects are compared at energy transfers so large that one kick is enough to remove the particle from the aperture, the bremsstrahlung effect is much larger than all others and the beam lifetime seems to be primarily determined by it. We estimate a lifetime of 50 min. for a pressure of 10^{-7}torr.

Another very strong limitation to the beam lifetime comes from the quantum-fluctuation effect on the betatron oscillations. In absence of coupling, the vertical beam emittance is twice as large as the horizontal one, and if one takes $1.5\pi\cdot10^{-6}$ m-rad for the Main Ring acceptance, the beam lifetime would be only a few minutes. On the other hand, if there is full coupling between the two modes of oscillation, the vertical emittance would reduce by 50% and the horizontal increase by the same amount, and the estimated lifetime becomes a few hours. Thus, full coupling in the Main Ring is crucial.

Shielding of the Interaction Region

The two upstream vertical bending magnets will produce a copious beam of photons directed toward the crossing point in the middle of the long straight section. The critical photon energy is 50 keV and the radiation loss is 175 keV per particle per magnet. Thus at every passage of an electron bunch, there will be a stream of $5x10^{11}$ energetic photons toward the central region. Synchrotron-radiation shields made of Tantalum are placed as sketched in Fig. 4. The radiation coming from the magnet to the far end is effectively shielded by the innermost magnet, which has a vertical aperture large enough so that the photons will hit the outer side of the first shield between the quadrupole and the bending magnets. This shield will also capture a large fraction of the radiation from the second bending magnets. A second shield is placed between the two low-beta quads and extends to 3 cm from the horizontal bend plane. Finally, a third shield is located between the detector and the first quad, 5 m away from the collision center. This shield extends 2 cm from the beam axis. The three shields together can then stop 95% of the total radiation. The remaining 5% originates at shallow angles and making the vacuum pipe 12 cm wide will comfortably allow it to pass the interaction region and strike the walls well beyond this point.

Reference

1. "Report of the Group Study on the Electron-Proton Colliding Beam Facility for Fermilab", April 28, 1978

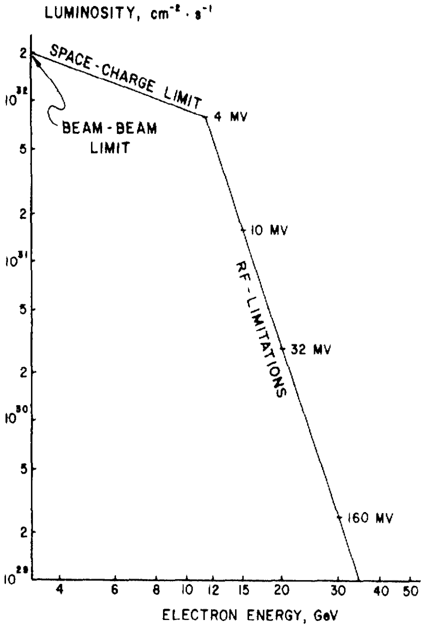

Fig. 3. Luminosity vs. Electron Energy

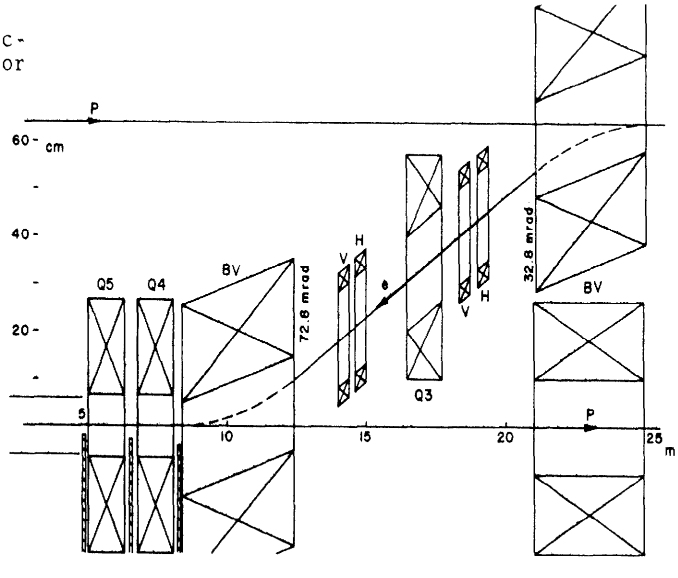

Fig. 4. Half of the e-p Colliding Region

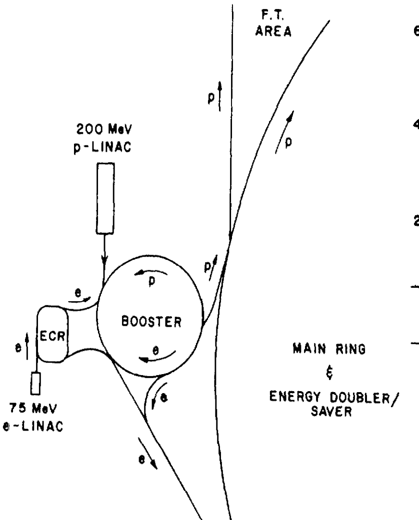

Fig. 1. The e-p Scheme Layout

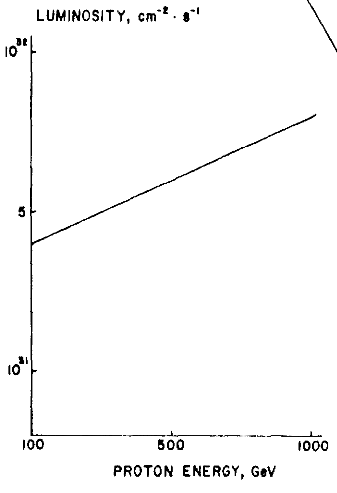

Fig. 2. Luminosity vs. Proton Energy

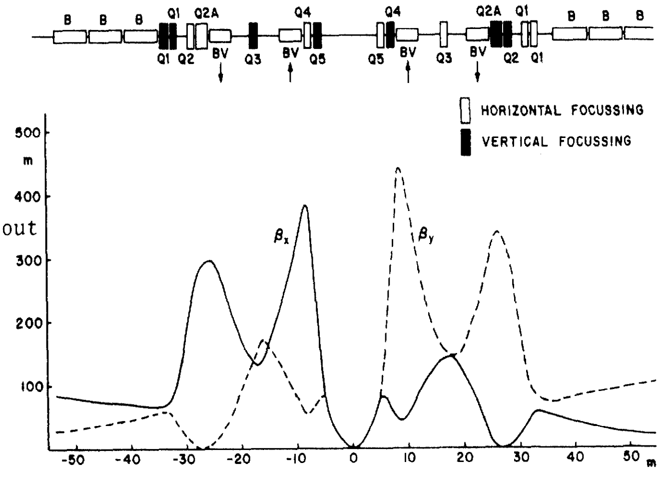

Fig. 5. Low-Beta Insertion for the Main Ring