THE U.S. E-P COLLIDER PROJECT

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Introduction

I would like to discuss briefly some of the work being done by the U.S. based group which has proposed the construction of an electron-proton collider facility in the United States. The people and institutions involved are given in Fig. 1, which is taken from the title page of Fermilab Proposal #659. A similar proposal to be submitted to Brookhaven National Laboratory is in the preparation stage.

I will start out by talking in general terms about the physics potential of an electron-proton collider because it seems to me that within the physics community there is somewhat less familiarity with this physics than with that of electron-positron or proton-proton colliders. I will then discuss the various options available for doing e-p physics in the U.S., i.e. what are the considerations involved in building a facility of say 10 x 1,000 GeV at Fermilab or of 20 x 400 GeV at Isabelle. Finally, I will describe a 10 GeV electron storage ring which would be capable of producing electron-proton collisions with high luminosity, with electrons or positrons of either helicity, at center-of-mass energies of 200 GeV when used in conjunction with the Fermilab Tevatron.

Fermilab Proposal 659/
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ELECTRON-PROTON INTERACTION EXPERIMENT

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Fig. 1

Physics

High energy electron-proton collisions provide a unique opportunity for studying details of the electro-weak interaction as well as probing nucleon structure at order-of-magnitude shorter distances than is possible at the present time (Fig. 2). For head-on collisions of 10 GeV electrons with 1,000 GeV protons, the total energy available in the center-of-mass is $\sqrt{s}$ = 200 GeV. In terms of the kinematic variables usually used to describe lepton-nucleon interactions, the accessible region in (Q^2, ν) space is:

$$Q^2 < 40{,}000 \ \mathrm{GeV}^2/c^2$$

$$\nu < 20{,}000 \ \mathrm{GeV}$$

where Q^2 is the invariant four-momentum transfer squared between the electron and proton and ν is the energy of the exchanged virtual photon (or Z^o or $W^{\pm}$) as seen in the proton rest system. Figure 3 shows the expected rates for the two inclusive leptoproduction reactions, $ep \rightarrow eX$ and $ep \rightarrow \nu X$, assuming a luminosity of $10^{32} \mathrm{cm}^{-2} \mathrm{sec}^{-1}$. Also included in the figure are the corresponding rates for the processes as they will be studied in fixed target facilities such as the Fermilab Tevatron. The electron-proton collider has the potential to explore vast regions of the Q^2 domain which are totally inaccessible to fixed target programs. If one were to assume a run consisting of a total integrated luminosity of $10^{38} \mathrm{cm}^{-2}$ (700 hours at $4 \times 10^{31} \mathrm{cm}^{-2} \mathrm{s}^{-1}$) the region of ($Q^2$, ν) space accessible with more than several tens of events is:

$$Q^2 < 15{,}000 \ \mathrm{GeV}^2/c^2$$

$$\nu < 20{,}000 \ \mathrm{GeV} \ .$$

This allows one to probe nucleon structure at distances of $< 1 \times 10^{-16}$cm.

Figures 2 and 3 also point out an additional feature of the electron-proton collider. That is that one is looking at phenomena in the spacelike domain, rather than in the timelike domain as in electron-positron or proton-proton machines. As a result center-of-mass energy is not the overriding criterion which may determine the ultimate success or failure of the machine

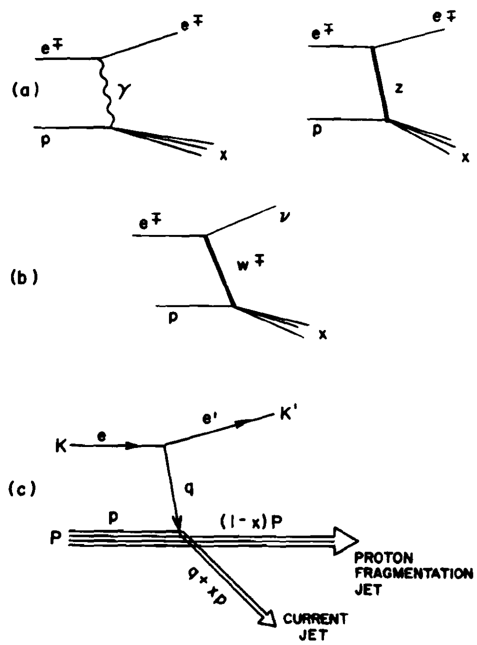

Fig. 2 The e-p interaction. a) neutral current, b) charged current, c) kinematics .

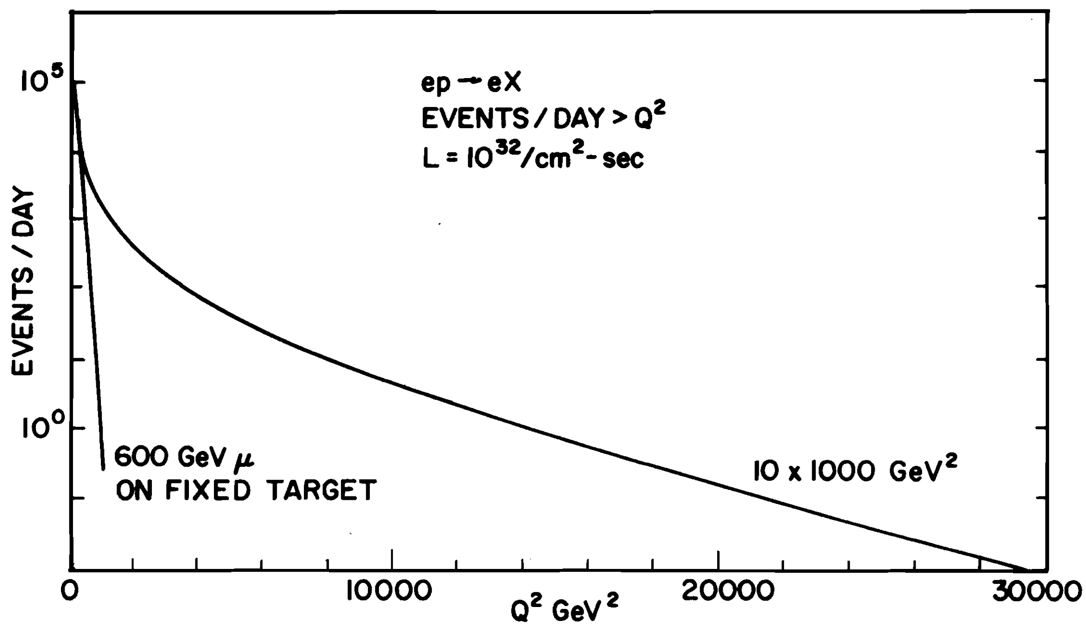
ep → eX
EVENTS / DAY > Q^2
L = 10^{32}/cm^2- sec
EVENTS / DAY
10^5
10^0
600 GeV μ
ON FIXED TARGET
10 x 1000 GeV^2
0
10000
20000
30000
Q^2 GeV^2

Fig. 3a

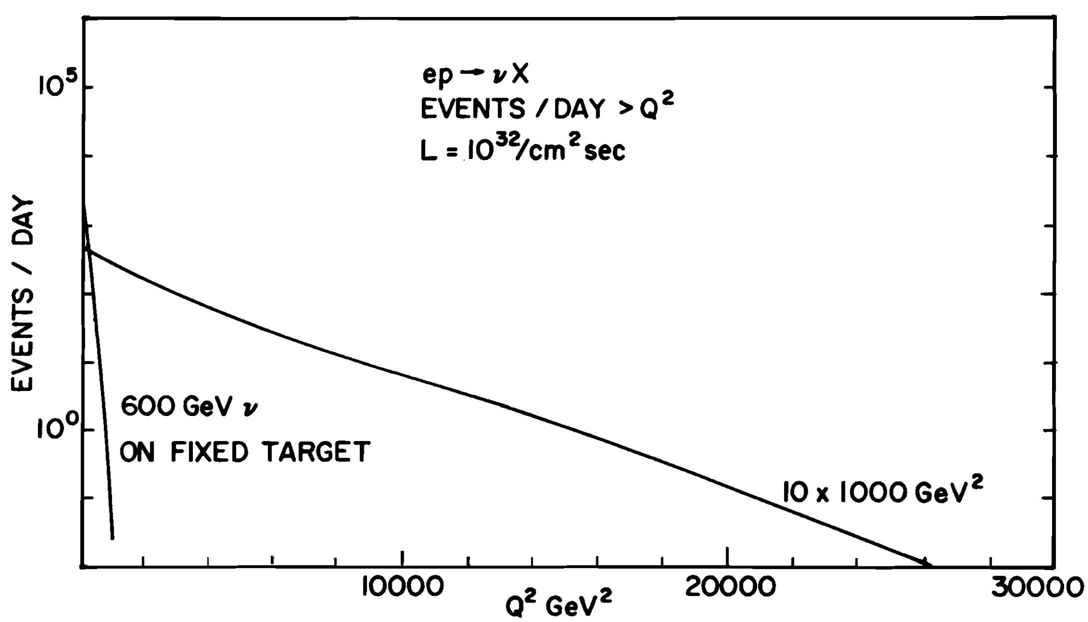
ep → νX
EVENTS / DAY > Q^2
L = 10^{32}/cm^{2}sec
EVENTS / DAY
10^5
10^0
600 GeV ν
ON FIXED TARGET
10 x 1000 GeV^2
10000
20000
30000
Q^2 GeV^2

Fig. 3b

in producing interesting physics. For example in the e-p collider, luminosity is nearly equal in importance to center-of-mass energy with a factor of three in luminosity being worth about a factor of two in S.

The physics possibilities of the electron-proton collider are quite diverse. The Q^2 dependence of the nucleon structure function F_2 can be measured over three orders of magnitude and hence provide a stringent test for possible power law contributions to scale breaking. Such contributions could be an indication of quark substructure. Additionally, quark substructure could manifest itself even more dramatically through lack of transverse momentum balance between the scattered electron and the current jet.

The electron-proton collider can also be used to test the current standard model of the electro-weak interaction. The high Q^2 data will show dramatically the effects of the W bosons in charged current interactions, and of electro-magnetic-weak interference in the neutral current events. Through the Q^2 dependence the mass of the W can be measured to an accuracy of $\pm$ 5 GeV and the mass of the Z^o to $\pm$ 15 GeV. But perhaps more interesting is the ability to test high energy modifications to the standard theory such as additional higher mass W's of W's with right-handed couplings. Additional W's with masses up to 200 GeV can be detected through propagator effects while the study of the interactions of 'wrong-handed' electrons or positrons will allow the detection of a right-handed W with a mass up to 300 GeV.

High energy e-p collisions should also provide a rich source of new heavy quark flavors. Heavy quarks can be produced either at high Q^2 from the nucleon quark sea or at low Q via photoproduction. In both cases the yield for a 700 hour run is several thousand for a top meson of mass 40 GeV and tens of thousands for a 20 GeV top. In addition somewhat more speculative particles can also be searched for. These might include heavy (charged or neutral) electrons or leptoquarks.

Finally, I would like to mention the possibility of using the electrons as a tag for doing very high energy photoproduction experiments. By tagging the scattered electron, equivalent photon energies of 20 TeV would be available for studying photon-nucleon interactions. This is almost two orders of magnitude beyond what one can do in fixed target facilities.

Options in the U.S.

Two proton rings will exist in the U.S. during the next decade and the construction of an electron-proton collider facility is possible at either. We have examined the achievable luminosities for e-p colliders at 10 x 1000 GeV (at the Tevatron), and 15 or 20 x 400 GeV (at Isabelle). The luminosities fall in the range 4-7 x $10^{31}cm^{-2}s^{-1}$ as shown in Table 1. In calculating the luminosity bunched beams at 17.7 MHz and zero angle crossing have been assumed. The assumed bunch frequency can be thought of as either one-third of the Tevatron rf frequency or as four times the Brookhaven AGS frequency. The electron linear tune shifts are comparable to those observed at CESR and PEP. The maximum proton tune shift has been assumed to be 0.003.

I show in Fig. 4 a possible layout for e-p at the Fermilab Tevatron. The ring is tangent to the Tevatron at the straight section D0. The ring as designed operates at 10 GeV but could probably be extended to 15 GeV. This ring is described in much more detail in Fermilab Proposal #659 and will be discussed later in this talk.

The various options available for constructing a 20 GeV electron ring at Isabelle are shown in Fig. 5. Basically there are three possible rings that one can imagine. Ring 1 is an electron ring built inside the Isabelle tunnel. Such a ring has the advantage that it could probably be built the most quickly and for the least amount of money since the tunnel already exists. It also has the advantage of providing the potential for multiple interaction regions. The big disadvantage is its interference with the p-p program. It is unlikely that e-p and p-p could run simultaneously or that p-p experimenters would like having an electron beam pipe running through their areas. Ring 2 lies tangent to the Isabelle ring at 5 o'clock. It has the advantage of interfering minimally with p-p but the disadvantage is that as in the Fermilab case it provides a single interaction region. Finally ring 3 is shown completely encircling the Isabelle tunnel. Such a ring has the advantages of having two interaction points while interfering minimally with the p-p program as well as being more easily extendable to higher energies than the other options.

Table I: Electron Ring Parameters

Ring	
Energy	10 GeV
Number of bunches	87
Bunch frequency	17.7 MHz
Revolution frequency	203.6 KHz
Electrons/bunch	8.8×10^{10} (0.25 A)
Circumference	1473.4 m
Emittance ϵ_x/π (rms)	0.051×10^{-6} m
ϵ_y/π (rms)	0.024×10^{-6} m
Energy spread σ_E/E	8.7×10^{-4}
Tune ν_x/ν_y	29.1/29.7
Momentum compaction	1.18×10^{-3}
Equilibrium polarization	83%
Polarization time	29 minutes
Interaction Region	
β_x/β_y max	166/400 m
β_x/β_y at IP	0.6/0.75 m
σ_x/σ_y at IP	0.17/0.13 mm
rf	
Energy loss/turn	13.4 MeV
Voltage	17.5 MV
Frequency	496 MHz
Bunch length	1.1 cm
Synchrotron tune	0.022
Power into beam	3.35 MW

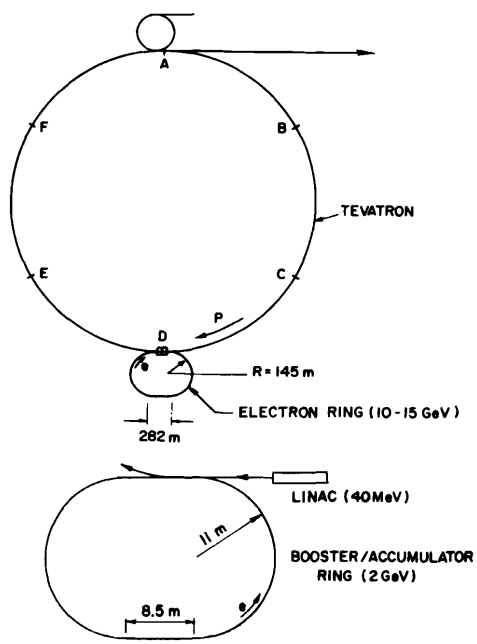

Fig. 4 Possible location of an electron ring at the Fermilab Tevatron.

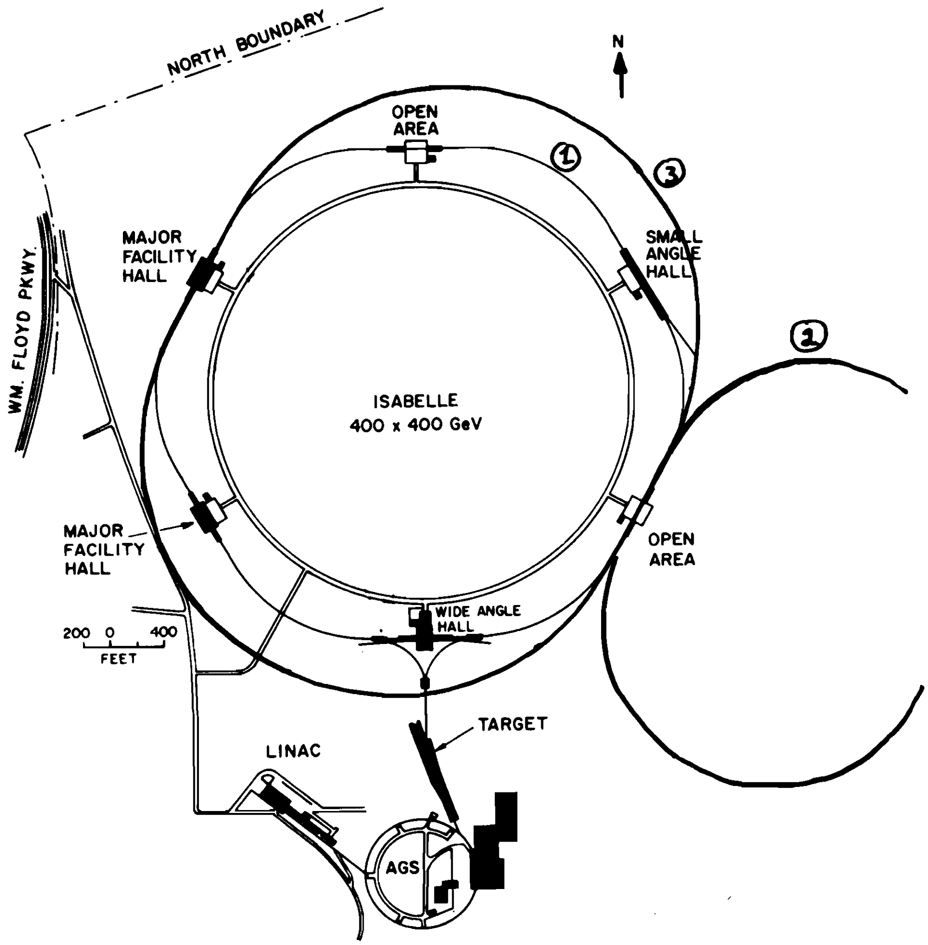

Fig. 5 Possible locations of electron rings at Isabelle.

The disadvantage is that it is large and so would cost somewhat more than the others although its larger bending radius results in 20% savings in installed rf power.

The Electron Storage Ring

I would like to spend the remainder of this talk describing a 10 GeV electron storage ring which could be used to produce high energy/high luminosity electron-proton collisions at the Fermilab Tevatron. A much more complete description exists in Fermilab Proposal #659 and I would refer those interested in more of the details to that document.

The electron storage ring has been designed satisfying the following criteria:

1. A luminosity of $4 \times 10^{31} cm^{-2}s^{-1}$ for head-on collisions between 10 GeV electrons and 1000 GeV protons.
2. The option of colliding either e^+ or e^- of either helicity.
3. A positron filling time of less than 10 minutes.
4. A free space of +6.5 meters at the interaction point.
5. The construction and installation to interfere minimally with commitments of Fermilab.
6. A minimal impact on the operation and control of the proton beam when not running in the e-p colliding mode.

The electron ring design parameters are given in Table 2. The total circumference of the ring is 1473 meters with 87 circulating bunches. The luminosity has been maximized by producing a round beam at the interaction point which is matched to the proton beam size. The appropriate vertical emittance is produced by the vertical bending magnets present in the polarization rotator to be described later. Notice also that the polarization level obtainable as calculated using the computer code 'SLIM'[1] is 83% with a polarization time of 18 minutes.

The ring itself is of a racetrack design with two 282-meter long straight sections. The long straight section around the interaction region is needed for rotating the electron spin from transverse to longitudinal, and for bringing the electrons into collision with the protons while minimizing the synchrotron radiation into the Tevatron vacuum chamber. One half of the interaction straight section is shown in Fig. 6. The magnets labeled Q are Tevatron quadrupoles arranged to produce a $\beta_{x,y}^*$ of 6 meters at the interaction point (labeled IP). The helium turnaround box on the first quadrupole is located 20 meters from the interaction point. The electrons are brought into collision with the protons through the series of soft bends labeled H0, H1, and H2. H0 is a 6.5 meter long, 51 Gauss air core dipole which deflects the electron beam by 1 mrad. H1 and H2 are 4.5 and 5.0 meter long magnets with fields of 963 and 2000 Gauss respectively. The proton beam passes through both H0 and H1 as well as the first two electron quadrupoles. H2 is a septum magnet used to compensate for the effects of H0 and H1 on the proton beam. The geometry is such that only radiation from the magnet H0 can enter the Tevatron. The 11.2 watts radiated in this magnet represents an acceptable load on the Tevatron quadrupoles. The magnets labeled VR and HR are the polarization rotator magnets and will be described later. Also shown in the figure are the lattice functions in the horizontal plane. The maximum β through the region is 166 m and $\beta_{x,y}^* = 0.75$ m. The lattice has the special feature that the betatron phase advance from the interaction point to the $\alpha = 0$ point in the rotator region is exactly 2π. This is also true in the vertical plane and is required if the beam is to retain its natural polarization.

At 10 GeV the synchrotron radiation loss per turn is 11.4 MeV. In addition there are significant losses due to interaction of the beam with the vacuum chamber and cavity walls. We have estimated these higher-order-mode losses to be about 2 MeV for a total energy loss per turn of about 13.4 MeV. This energy is supplied by the rf system described in Table 3. The system is a copy of the CESR system and runs at a voltage of 17.5 MV, and a frequency of 496 MHz. The total cavity length is 29.4 m and the total power requirement is 3.75 MW.

Electrons/positrons are injected into the electron storage ring at 2.0 GeV. The injection system consists of a 40 MeV (+40 MeV for e^+) linac followed by a 2.0 GeV, rapid cycling (30 Hz) booster/accumulator ring. The linac is capable of accelerating up to 1 A instantaneous current during a

Table II: Luminosity

	Tevatron	Isabelle 15	Isabelle 20
Protons			
Energy	1000	400	400 GeV
Protons/bunch	6.9×10^{10}	1.4×10^{11}	2×10^{11}
Bunch frequency	17.7	17.7	17.7 MHz
Current	0.20	0.40	0.54 A
Emittance (95%)			
$\epsilon_x/\pi = \epsilon_y/\pi$	0.02	0.04	0.04 mm-mrad
$\beta_x^* = \beta_y^*$	6.0	4.5	4.5 m
$\sigma_x^* = \sigma_y^*$	0.14	0.16	0.16 mm
Electrons			
Energy	10	15	20 GeV
Electrons/bunch	8.8×10^{10}	3.5×10^{10}	6.2×10^{10}
Bunch frequency	17.7	17.7	17.7 MHz
Current	0.25	0.10	0.18 A
Emittance (rms)			
ϵ_x/π	0.051	0.02	0.036 mm-mrad
ϵ_y/π	0.024	0.02	0.036 mm-mrad
β_x^*/β_y^*	0.6/0.75	0.75/0.75	0.75/0.75 m
σ_x^*/σ_y^*	0.17/0.13	0.12/0.12	0.16/0.16 mm
Luminosity	4×10^{31}	4×10^{31}	$7 \times 10^{31} cm^{-2}s^{-1}$
Tune Shifts			
$\Delta\nu_e$	0.03	0.03	0.03
$\Delta\nu_p$	0.003	0.003	0.003

Table III: rf System

Energy loss/turn	13.4 MeV
Voltage	17.5 MV
Frequency	496 MHz
Harmonic number	2436
Synchrotron tune (2 GeV, 10 GeV)	0.062, 0.022
Bunch length (rms)	1.1 cm
Energy acceptance	65 MeV
Quantum lifetime	> 1000 hours
Power into beam	3.35 MW
Cavity shunt impedance	800 MΩ
Total cavity length	29.4 m
Total rf power	3.75 MW

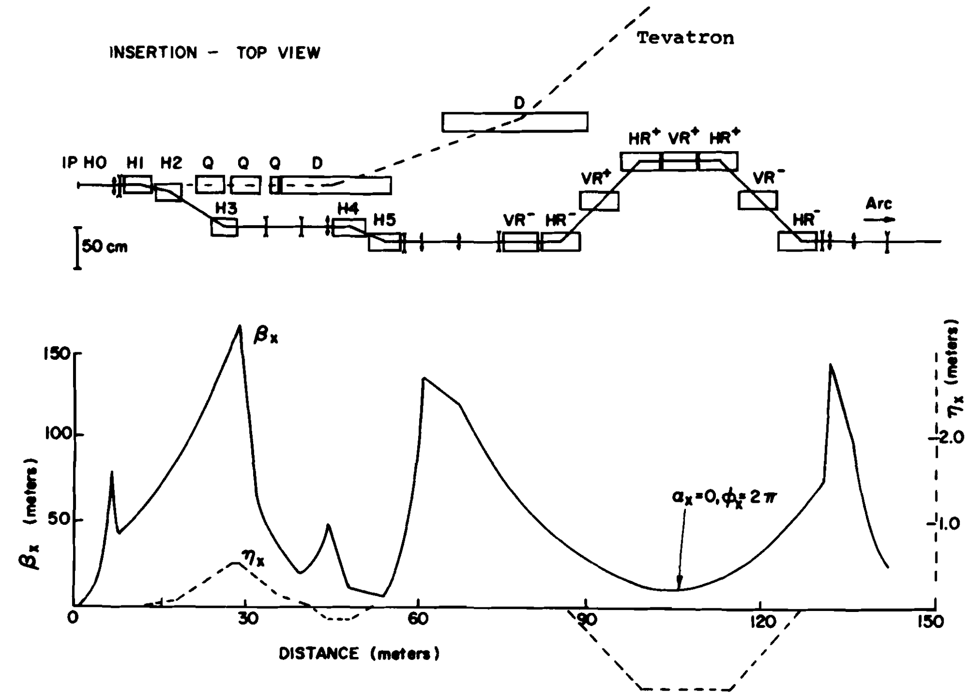

Fig. 6a The interaction straight section at the Tevatron. The dashed line is the proton orbit.

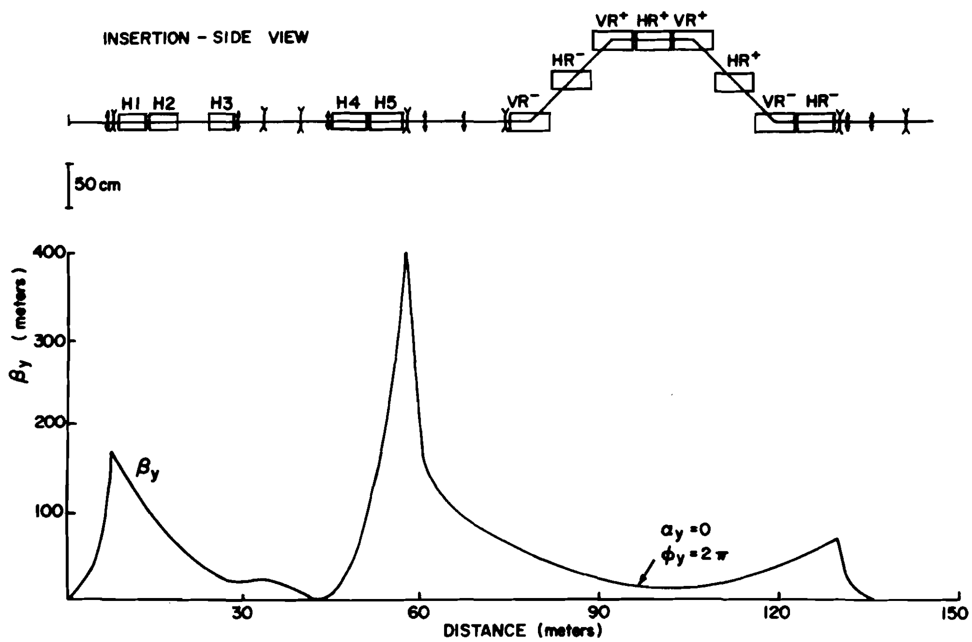

Fig. 6b The interaction straight section side view.

1.41 μs pulse for positron generation. Less current (50 MA) is needed for electron filling. The booster ring is shown in Fig. 7 and circulates five bunches containing 8.8×10^{10} e^-/e^+, each of which are filled via five turn injection from the linac at 40 MeV and accelerated up to 2 GeV. For positron filling the linac/booster system is cycled at 30 Hz until the required number of e^+/bunch is obtained. Radiation damping in the booster provides adequate cooling of the positrons during a single booster cycle to allow injection of positrons into the booster at this rate. The calculated positron filling time for the main ring is 1-2 minutes.

As mentioned earlier physics considerations make the ability to produce longitudinally polarized electrons at the interaction point an important goal in the design of the electron storage ring. In high energy electron storage rings transverse polarization occurs naturally at a level of 92.4% via the Sokolov-Ternov mechanism. Rotation of the spin through 90° to produce longitudinally polarized electrons is easily accomplished through a combination of horizontal and vertical bends near the interaction point. One such scheme is shown in Fig. 8 (see also Fig. 6) where each rotator magnet produces a 90° rotation of the helicity angle as shown. For a 10 GeV electron the required field integral is 23.1 kG-m.

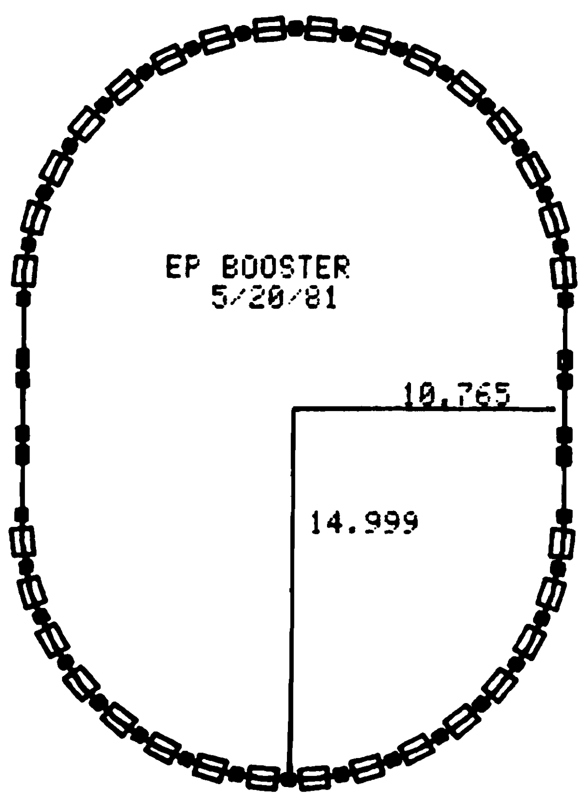

Fig. 7 The 2 GeV booster ring layout .

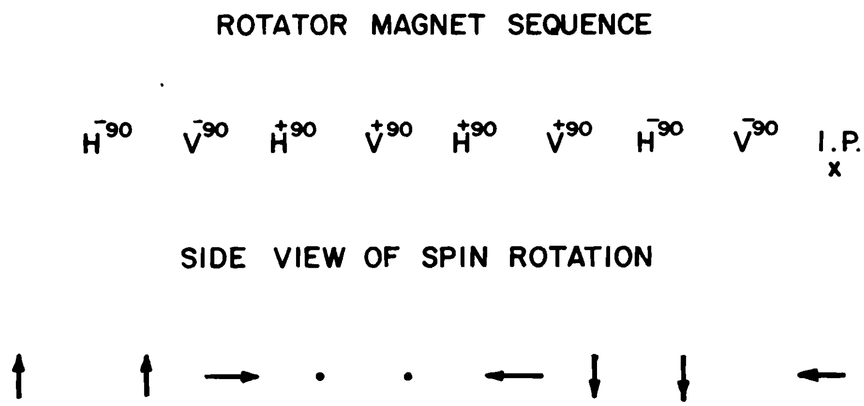

Fig. 8 The polarization rotator.

Unfortunately the presence of these rotator magnets leads to several effects which tend to reduce the equilibrium value of the polarization in the ring and which if not dealt with carefully can destroy it completely. The first effect is due to the fact that some of the rotator magnets have their field lines oriented in directions which are not preferred by the Sokolov-Ternov mechanism. Such 'reverse bending' effects can only be cured by making the rotator magnets as long as possible. The second effect is called stochastic depolarization. Stochastic depolarization is driven by fluctuations in the synchrotron radiation process and is exacerbated by the presence of the rotator magnets themselves and by machine imperfections. Certain constraints can be applied to the lattice design which serve to minimize the effects of stochastic depolarization. These are described in detail in Fermilab Proposal #659 and have been incorporated into the ring I have described here. A calculation using the computer code 'SLIM' shows that the ring attains a polarization level of 83% with this level being entirely reverse-bend limited. Machine imperfections and beam-beam effects have not been incorporated into this calculation yet.

Time Scale

We believe that an electron storage ring and detector could be built, and e-p physics could commence approximately three years after approval of the project. At the present time a full proposal has been presented to Fermilab, and a preliminary proposal has gone to Brookhaven while a more complete document is being prepared. The prospects for an electron-proton collider project in the United States should become much better defined by the end of this year.

To summarize, let me just say that the physics opportunities presented by electron-proton colliders are in many ways unique. They include studies of nucleon structure, the electro-weak interaction, high energy photoproduction, and searches for new leptonic states in ways which are not accessible to other colliding beam or fixed target facilities. It would be a shame if this potential were never realized.

Reference

[1] 'SLIM' program provided to us by A.W. Chao, SLAC.

Discussion

V. Soergel, DESY: Which fraction of time do you expect to run up at the Tevatron?

S. D. Holmes: That depends on which proton ring you are at. At Fermilab you presumably will not get more than a third of the time because you have to compete with the $\bar{p}p$ and fixed target program, whereas at Isabelle, especially in the two schemes, where the ring is not inside the Isabelle tunnel, it is likely that you would run up at the same time as pp.