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ELECTRON-PROTON INTERACTION EXPERIMENT

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Introduction

We have been considering the merits of a phased approach to a program which could culminate in the study of electron-proton collisions at 10-20 x 1000 GeV following a modest first step of installing a 5 GeV electron ring at Fermilab. Such a ring has the virtues of being capable of producing interesting physics at equivalent fixed target beam energies of 10 TeV, of being ideally suited as a booster ring for the subsequent higher energy ring which we envision and of being relatively cheap to construct (∿$11M, 1981 $).

In the enclosed document we discuss briefly an electron storage ring cabable of providing electrons for e-p collisions at 5 x 1000 GeV and the physics which can be done with such a facility. We have found that the detector described in P-659 is well suited for the physics of the 5 x 1000 GeV with the only major modification being the need to integrate the electron quadrupoles into the hadron calorimetry.

We estimate that the experiment we are proposing carries a price tag of ∿$23M, including the complete storage ring and detector. The machine and detector can be constructed by this group and brought into operation three years from the time of approval. We are looking into phasing the construction of the detector to defer ∿$4M to subsequent years.

Our present level of understanding in elementary particle physics is the result of parallel efforts in the studies of lepton-lepton, quart-quark, and lepton-quark interactions at ever-increasing energies. It is essential in the next decade to continue these parallel efforts. The removal of any one of these three may seriously hinder the advances to be made in high energy physics during the 1980's.

I. 5 GeV Electron Storage Ring

We discuss here the design of a 5 GeV electron storage ring suitable for use in a first stage e-p collider at Fermilab. The design criteria are:

1. A luminosity of 4×10^{31} $cm^{-2}sec^{-1}$ for head-on collisions with 1000 GeV protons at the Tevatron;

2. The option of colliding either electrons or positrons;

3. The construction and installation to interfere minimally with the commitments of Fermilab;

4. A minimal impact on the operation and control of the proton beam when not running in the e-p colliding mode;

5. A free space of $\pm$ 4.0 m at the interaction point for insertion of the detector.

The design philosophy of the 5 GeV ring and associated injection system is very close to that of the 10 GeV ring described in Proposal #659. Collisions occur between electrons and proton beams at 0° with both beams operating in a bunched mode at 17.7 MHz (16.936 m bunch separation). A luminosity of $4 \times 10^{31} cm^{-2}sec^{-1}$ is readily obtainable under these conditions. The primary differences in the 5 GeV ring (other than the reduced energy) are that it is slightly less than one-quarter the size of the 10 GeV ring, a bypass is incorporated into the ring to allow for debugging of the ring independent of the operation of the Tevatron, and the polarization rotators needed to produce longitudinally polarized electrons at the interaction point have not been

incorporated into the design.

As before we assume that the Tevatron beam has been rebunched by a factor of three, and that the resultant proton bunches each contain 7.8×10^{10} protons separated by 16.936 m. The proton beam has an emittance of $\epsilon/\pi(95\%) = 0.02 \times 10^{-6}$ m and if we assume a β^* of 4.5 m, the rms beam size at the interaction point is 0.122 mm (in both dimensions). The electron beam can be matched to the proton beam with a β^* of 0.25 m and an emittance of $\epsilon_x/\pi = \epsilon_y/\pi = 0.06 \times 10^{-6}$ m. The required circulating electron current for the production of $4 \times 10^{31} cm^{-2} sec^{-1}$ is then 164 mA (5.8×10^{10} electrons/bunch). The required current can probably be lowered somewhat by designing an even lower β_e^* into the electron machine although this would probably reduce the available free space at the interaction point.

The .5 GeV electron storage ring parameters for our present design are given in Table 1. The circumference of the ring is 355.6 m so that there are 21 circulating bunches assuming the bunch separation discussed earlier. Note that this design also allows one to rebunch the proton beam by seven rather than three if this were considered attractive (e.g. if the electron/proton tune shift were not limiting the luminosity and it was desireable to lower the circulating electron/proton current). The luminosity for electron-proton collisions is calculated to be $4.1 \times 10^{-31} cm^{-2} sec^{-1}$ under the assumptions shown in Table 2. This luminosity is obtained with circulating currents of 164 mA in the electron

beam and 221 mA in the proton beam. The resultant tune shifts are $\Delta\nu_e = 0.030$ and $\Delta\nu_p = 0.002$. The electron tune shift is comparable to that observed at PEP and CESR. Not included in the luminosity calculation is the effect of the finite proton bunch length. For a β_e^* of 0.25 m, it will be necessary to keep the proton bunch length under 1 m.

The injection system consists of a 40 MeV high current linac followed by a booster/accumulator ring which accelerates electrons/positrons up to the 900 MeV electron storage ring injection energy. Positrons can be accumulated and cooled (via radiation damping) in the small (50 m circumference) accumulator ring at a cycle rate of 10 Hz. Positron filling times of less than 10 minutes appear feasible for electron conversion at 40 MeV.

The free space available for the detector is $\pm$ 4.0 m. This is the distance separating the symmetrically locating focusing doublets which surround the interaction point. This space can only be increased at a cost of an increased β_e^* and an associated increase in the electron current needed for production of the desired luminosity. The entire interaction region is designed to minimize the amount of radiation entering the Tevatron and to keep the operation of the electron and proton machines as independent as possible. To this end a bypass has been incorporated into the current design which would allow operation of the electron ring independent of the proton beam.

As in Proposal #659 we bring the electrons and protons into collision at the straight section Dϕ. In our proposal we described a low beta insertion at Dϕ which would provide a β_p^* of 6.0 m with a free space of ± 20 m and required only minimal modification of the Tevatron lattice. Here we assume that a similar insertion can be designed yielding $\beta_p^* = 4.5$ m with a free space of ± 13 m between Tevatron quadrupoles. The electron optics within this space can be arranged to bring the electrons and protons into collision while at the same time limiting the radiation entering the Tevatron to less than 2 W. The perturbation to the proton orbit caused by passing through several of the electron ring magnetic elements is small and is easily corrected.

Lattice

The overall dimensions and layout of the ring are shown in Fig. 1. The ring is a racetrack design consisting of two arcs of mean radius 43.9 m, an insertion region of length 40.0 m containing the low beta interaction point and bypass (dashed line), and a 40.0 m off-side straight section containing the rf and injection systems.

The guide field in the arcs is based on the standard FODO cell shown in Fig. 2. The cell shown provides a 90° phase advance/cell. The required quadrupole gradient is 12.7 T/m for the 74 cm long quadrupole shown, and the magnetic field in the dipole is 9.4 kG. The lattice

functions through the arcs are shown in Fig. 3. Each arc contains 25 cells, some of which are modified to produce dispersion suppression at each end of the arc.

The interaction region is shown in Fig. 4. The insertion is designed to produce a minimum beam size at the interaction point, minimize the synchrotron radiation in the region, and to provide easy construction and operation of a bypass. We have shown in the figure the location of both the electron and proton beamline elements. The placement of the electron beamline elements is symmetric around the interaction point. The separation between the two beams is 19.2 cm at the entrance to the third electron quadrupole (Q3), 66.6 cm at the entrance to the first Tevatron quadrupole, and is 110 cm and the end of the insertion. The electron beam elements located upstream of Q3 are seen by the proton beam and are discussed in the following section.

Also shown in the figure are the lattice functions through the region. The values of the beta functions at the interaction point are $\beta_x^* = 0.25$ m, $\beta_y^* = 0.25$ m, corresponding to a beam size of $\sigma_x = \sigma_y = 0.127$ mm. The maximum value of beta throughout the insertion region is 205 m horizontally and 267 m vertically. The corresponding maximum beam size is 1 09 mm horizontally and 125 mm vertically ($\pm$ 15 σ). The dispersion function and its derivative are zero both at the interaction point and at the end of the insertion. Note that by bringing the dispersion function to zero at the exit of H3 a bypass can be constructed which is identical

to the insertion shown except that bends occur in the opposite direction (see dashed line in Fig. 4). The separation between the bypass and the insertion is 220 cm at the interaction point.

The off-side straight section is shown in Fig. 5. It contains 35 m of free space, which accommodates the rf system and injection from the booster/accumulator.

The tune of the electron ring is $\nu_x = 15.7$, $\nu_y = 13.4$. The high tune is necessitated by the need for a low emittance to match the beam size to the proton beam. The natural chromaticity of the ring is -66 horizontally and -42 vertically. The chromaticity will be controlled by sextupole magnets placed adjacent to the quadrupole magnets in the arcs. The fractional energy spread in the beam is 1.0×10^{-3}.

Intersection Region

The intersection is designed in much the same way as the one described in our proposal. The principal concerns are minimizing synchrotron radiation, minimizing changes to the Tevatron lattice and maximizing luminosity.

As stated earlier we assume that a proton insertion can be designed which produces $\beta_p^* = 4.5$ m with a free space of $\pm$ 13 m, and requires removal only of the proton doublet nearest the interaction point and replacing it with a triplet of the stronger three shell quadrupoles. The arrangement of dipole magnets in the electron ring is then as shown in Fig. 4.

The solution is a variation on that given in P-659. The magnets H0, H1, and H2 are used to separate the electron and proton beams. H0 is an 8 m long air core magnet with a field of 104 G. Part of its radiation strikes the superconducting Tevatron mangets. However, H0 bends sufficiently that radiation from magnets H1 and H2 can be shielded from the Tevatron mangets. H0, H1, and H2 bend the electrons by 5 mrad, 20 mrad, and 75 mrad, respectively. The radiation characteristics of these magnets are given in Table 3.

It is unavoidable that some synchrotron radiation enters the Tevatron beampipe. To reduce it as much as possible, a mask is placed just upstream of the first Tevatron quadrupole. The proton beam size at this point is 0.4 mm (rms). A 2 cm hole is adequate and subtends 1.3 mrad at the interaction point allowing 1.2 W of direct radiation to impact upon the second and third dipoles from the interaction point.

The proton beam is allowed to pass through magnets H0 and H1. By the entrance of H2 the two beams are separated by 4.3 cm, sufficient space for making H2 a septum magnet. The perturbation to the proton orbit caused by H0 and H1 is corrected by a pair of proton dipoles, HA and HB. The proton beam is also allowed to pass through the electron quadrupoles Q1 and Q2. They produce a small perturbation to the proton orbit which is corrected by HA and HB, and by adjustment of the proton triplet.

rf and Vacuum Systems

In our proposal we described an rf system based on the presently operating CESR system. We continue to advocate such an approach in the 5 GeV ring described here.

The rf system is described in Table 4. The energy loss/turn is 3.51 MeV (including an estimated 0.3 MeV to higher order modes). The system is run at a frequency of 496 MHz and a voltage of 6.0 MV. The voltage is sufficient for producing a beam lifetime due to quantum fluctuations in excess of 1000 hours, and a bunch length of 1.5 cm (rms). The total power required is 733 kW.

As described in our proposal it is necessary to maintain a vacuum of about 10^{-8} Torr throughout the machine, and 10^{-10} Torr at the interaction point. The vacuum system is based on a distributed ion pump system in the style of CESR or PEP. The total linear gas load in the 5 GeV ring is calculated to be 6.8×10^{-7} T·L/sec/m including thermal desorption. The total pump capacity required ($\sim$ 70 L/sec/m) is easily obtainable.

More details of the rf and vacuum system appear in Proposal #659.

Magnets

The total number of magnets required in the 5 GeV ring is 290, including 103 dipoles, 119 quadrupoles, and 68 sextupoles. A general description of these magnets is given in Table 5.

The arcs contain 88 full strength and 8 half strength dipole magnets. The full strength dipoles have a magnetic field of 9.36 kG and are 1.22 m long. We anticipate these magnets being C-type in order to provide ease of access to the vacuum chamber. An aperture of 50 mm x 125 mm is more than adequate for containing the beam within the arcs. The remaining seven dipoles reside in the interaction region. The magnets H1 and H3 are both completely conventional, while H0 must be an air core and H2 a septum magnet.

The 76 quadrupole magnets in the arcs all have lengths of 74 cm and gradients of 127 kG/m (3.2 kG/in.). The required apertures are quite small with a diameter of 50 mm being completely adequate. The remaining 43 quadrupoles consist of 18 in the interaction region and 25 in the dispersion suppressors and off-side straight section. The 18 quadrupoles in the interaction region require fairly large apertures and are all run with a gradient of 120 kG/in. The maximum beam size through the region is 125 mm ($\pm$ 15 σ). The pole tip field for a quadrupole with this bore is 7.5 kG.

Sextupole magnets will be located adjacent to all quadrupoles in the arcs to correct the natural chromaticity in the standard way.

Injection System

The injection system is conceptually similar to the scheme we described in our proposal. The differences are 1) the injection energy is lowered to 900 MeV; and 2) an

attempt is made to match the emittance at injection into the storage ring so that the magnet apertures are all sufficient.

The injection system consists of a 40 MeV (+ 40 MeV for e^+) linac followed by a 900 MeV rapid cycling booster/accumulator ring. The linac is capable of accelerating up to 1 A instantaneous current during a 0.85 μs pulse for positron generation. Less current (34 mA) is needed for electron filling. For positron filling the linac/booster system can be cycled at 10 Hz until the requisite 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 at this rate.

The booster/accumulator ring is a separated function machine with a circumference of 50.8 m and a maximum energy of 900 MeV. The ring contains two 6.0 m straight sections and two arcs with a mean radius of 6.2 m. Each arc contains six FODO cells with a phase advance of approximately 110° horizontally and 60° vertically. The 24 dipole magnets required are each 72.8 cm long with a 10.8 kG field. There are 36 quadrupoles with a maximum length of 26 cm and a gradient of 126 kG/m. The horizontal tune is 4.167 which allows for five turn injection as described in our Fermilab proposal. The emittance (fully damped) is 0.073 mm-mrad. The effective damping time over a cycle from 40 MeV to 900 MeV is 46.7 ms, so during one cycle at 10 Hz the beam is damped by a factor of 8.5.

The positron filling time can be calculated under the same assumptions used in our proposal. The filling for the 5 GeV ring is approximately half that of the 10 GeV ring because the reduced number of circulating particles in the storage ring more than offsets the lowered cycling rate. The calculated filling time is 37 seconds. As stated in P-659, we believe this number is certainly good to a factor of five.

Costs and Scheduling

We have estimated the cost of the 5 GeV storage ring described here using a method in which we first identify the capital expenditures and then multiply by a factor of 1.5 to account for the associated engineering and technical support (a figure consistent with the CESR and PEP experience). The costs estimated in this manner are given in Table 6.

The component costs are estimated both through explicit calculation and by scaling from the known costs at CESR which is the operating ring most similar to the one described here. The cost estimated for the tunnel is $6.5 K/m (utilities installed) based on Fermilab experience. The magnets are priced at $10 K for a 1.2 m, 9.4 kG dipole, $4 K for a 74 cm long 127 kG/m quadrupole, and $800 for a sextupole correction magnet. These costs are meant to include construction and purchase of associated power supplies.

For the vacuum system, rf, and controls we scale directly from CESR. We assume vacuum costs are linear in

the circumference at $1.85 K/m. An analysis of rf costs indicates that certain components (such as cavities) scale with applied voltage, whereas others (such as klystrons) are proportional to the delivered power. We have assumed the cost is given by 0.069 V + 0.97 P where V is the voltage (in volts) and P is the power (in watts). Controls consist of certain fixed costs (such as the controlling computer) plus linear costs (such as beam monitors). We have estimated the price at $450 K + $0.74 K/m.

The linac has been priced in consultation with members of the AT Division at Los Alamos, and with the accelerator department at Argonne. Both laboratories have experience with low energy/high current electron linacs. The 900 MeV booster is priced at $1.0 M following a procedure similar to that outlined above.

Engineering and technical support staff costs are estimated at $2.6 M. Note that this is 50% of the sum of items II + III + IV + V + VII in Table 6. The personnel costs have already been incorporated into the tunnel and linac estimates listed under I and VI, Table 6.

The price of the ring is calculated to be $11.2 M (1981 $). We would expect to be able to complete construction of the ring and detector over a three year period starting in 1982. The total cost of the machine plus detector is estimated at $11.2 M + $12.0 M = $<u>23.2 M</u> (1981 $). We believe these cost estimates are accurate. The CESR ring

was built for ~ $12 M, and has twice the circumference of the ring described here and the capability of going to 8 GeV. We expect the price of the 5 GeV ring to be comparable because of the extra costs for the tunnel and injector which will be incurred at Fermilab.

Table 1: Electron Ring Parameters

Ring	
Energy	5.0 GeV
Number of bunches	21
Bunch separation	16.936 m (56.6 ns)
Electrons/bunch	5.8×10^{10} (0.164 A)
Circumference	355.66 m
Emittance ϵ_x/π (rms)	0.065×10^{-6} m
ϵ_y/π (rms ,coupled)	0.065×10^{-6} m
Energy spread	1.0×10^{-3}
Tune ν_x/ν_y	15.7/13.4
Quantum lifetime	> 1000 hours
Beam lifetime (@ 10^{-8} T)	> 10 hours
Damping time τ_x	3.7 ms
Polarization time	9.3 min
Interaction Region	
β_x/β_y at I.P.	0.25/0.25 m
β_x/β_y max.	205/267 m
σ_x/σ_y at I.P.	0.127/0.127 mm
rf	
Energy loss/turn	3.51 MeV
Voltage	6.0 MV
Frequency	496 MHz
Synchrotron tune ν_s	0.022
Bunch length	1.5 cm
Power into beam	580 kW

Table 2: Luminosity

Protons	
Energy	1000 GeV
Protons/bunch	7.8×10^{10}
Bunch frequency	17.7 MHz
Current	0.22 A
Beam size σ_x^*	0.122 mm
σ_y^*	0.122 mm
Emittance ϵ/π (95%)	0.02×10^{-6} m
β_x^*/β_y^*	4.5/4.5
Electrons	
Energy	5 GeV
Electrons/bunch	5.8×10^{10}
Bunch frequency	17.7 MHz
Current	0.164 A
Beam size σ_x^*	0.127 mm
σ_y^*	0.127 mm
Emittance ϵ_x/π (rms)	0.065×10^{-6} m
ϵ_y/π	0.065×10^{-6} m
β_x^*/β_y^*	0.25/0.25 m
Luminosity	$4.1 \times 10^{31} cm^{-2} sec^{-1}$
Tune Shifts	
$\Delta\nu_e$	0.030
$\Delta\nu_p$	0.0020

Table 3: Interaction Region Dipoles

	#	B (kG)	L (m)	Radiated Power (W)	Critical Energy (keV)	Photons/ Bunch
H0 (air core)	1	+0.104	8.00	4.60	0.2	3.0×10^{10}
H1	2	+3.33	1.00	590	5.5	1.2×10^{11}
H2 (septum)	2	+8.33	1.50	5550	13.8	4.5×10^{11}
H3	2	-9.97	1.63	8620	16.6	5.8×10^{11}

Table 4: rf System

Energy loss/turn	3.51 MeV
Voltage	6.0 MV
Frequency	496 MHz
Harmonic number	588
Synchrotron tune ν_s	0.022
Bunch length (σ)	1.5 cm
Energy acceptance	38 MeV
Quantum lifetime	30,000 hours
Power into beam	576 kW
Cavity length	8.4 m
Shunt impedance	230 MΩ
Number of modules	2
Total rf power	733 kW

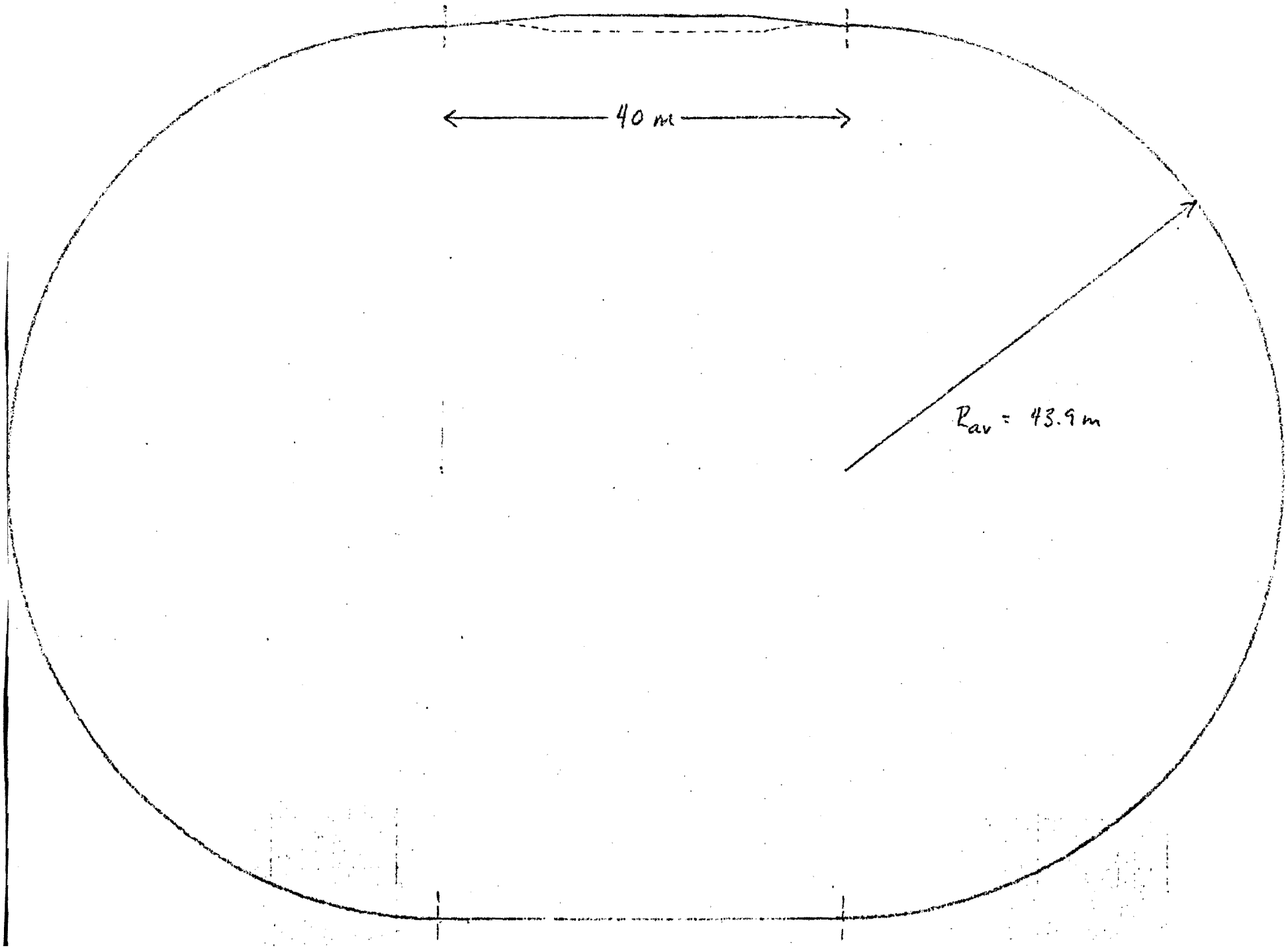
Table 5: Storage Ring Magnets

Magnet	Length (m)	Strength (kG or kG/m)	#	Comments
Dipoles				
H	1.22	9.36	88	Standard Dipole
H/2	1.22	4.68	8	Dispersion Supp.
H0	8.00	0.10	1	Interaction Region
H1	1.00	3.33	2	"
H2	1.50	8.33	2	"
H3	1.63	9.97	2	"
Quadrupoles				
QF	0.74	127.5	38	Standard Quad.
QD	0.74	126.7	38	"
Q	0.1-1.48	48.0-140.	43	Interaction Region Dispersion Supp. Straight Section
Sextupoles			68	

Table 6: Costs

I.	Tunnel (6.5 K/m)	$2.3 M
II.	Magnets	
	Dipoles	1.0 M
	Quadrupoles	0.5 M
	Sextupoles	0.1 M
III.	Vacuum (1.85 K/m)	0.7 M
IV.	rf (0.069 V + 0.97 P)	1.1 M
V.	Controls (450 K + 0.74 K/m)	0.7 M
VI.	Linac	1.2 M
VII.	Booster	1.0 M
VIII.	Engineering/Technical	2.6 M
	Total (1981 $)	11.2 M

Electron Storage Ring Dimensions



FODO Cell

Curved Section

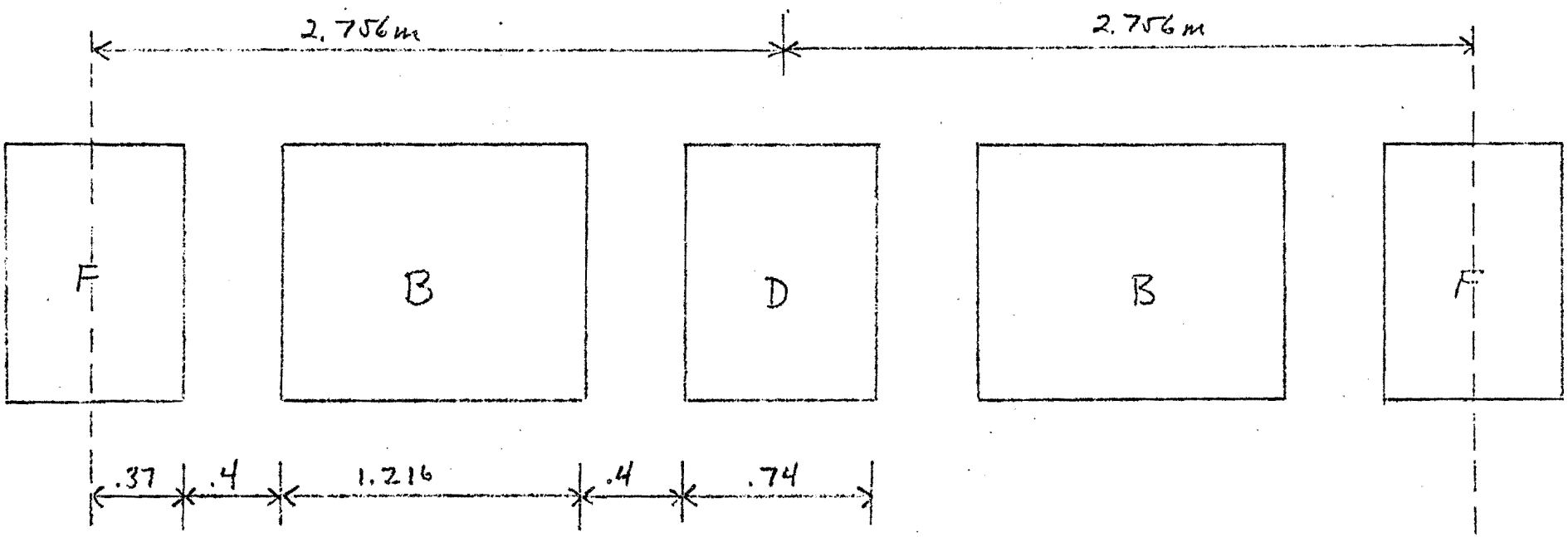


Figure 2

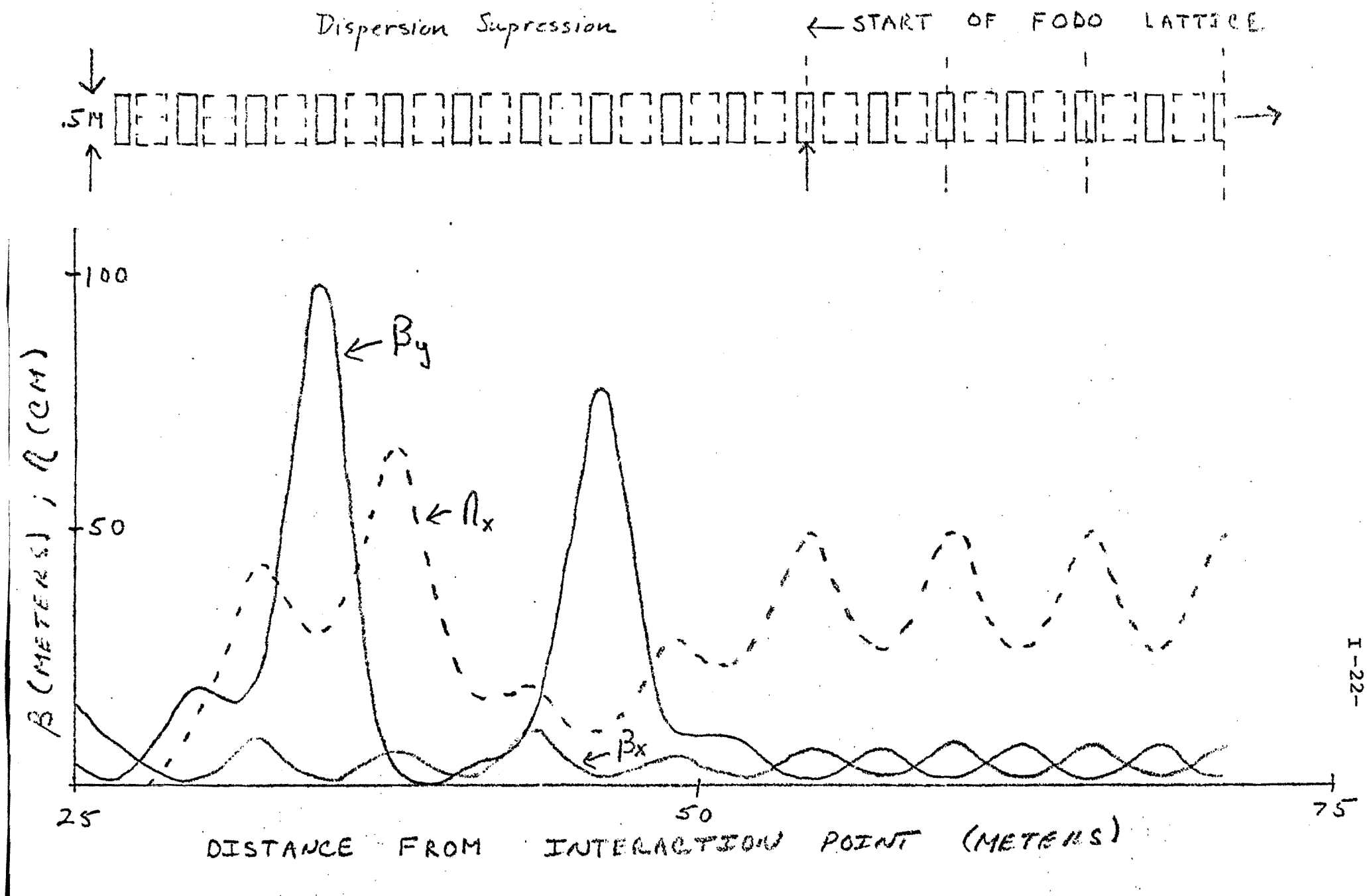

Dispersion Supression
START OF FODO LATTICE
.5M
100
50
β_y
η_x
β_x
β (METERS) ; η (CM)
25
50
75
DISTANCE FROM INTERACTION POINT (METERS)

Figure 3

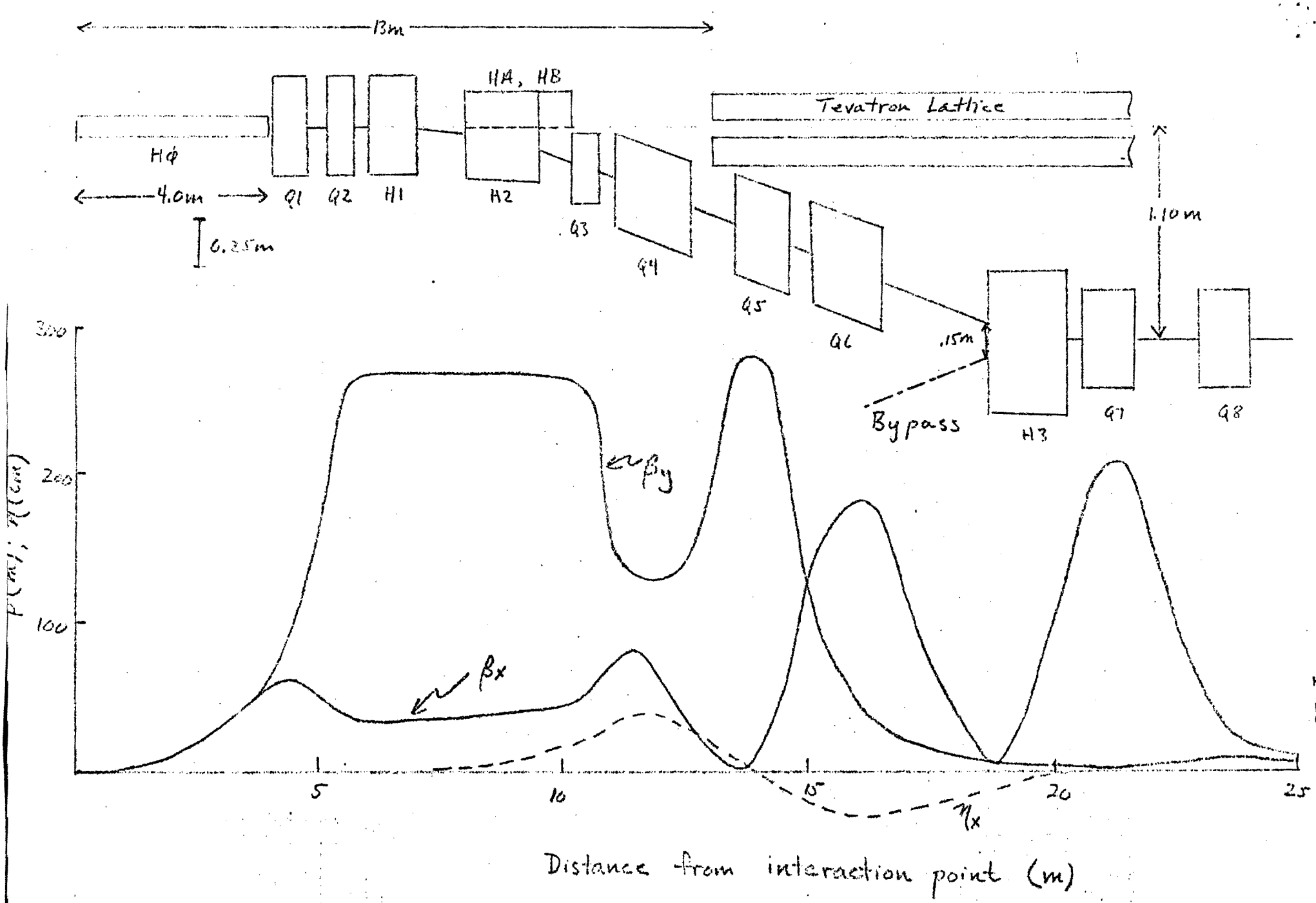

13m
HA, HB
Tevatron Lattice
Hφ
4.0m
Q1
Q2
H1
H2
Q3
Q4
Q5
Q6
H3
Q7
Q8
0.25m
1.10m
.15m
Bypass
βy
βx
ηx
300
200
100
5
10
15
20
25
β (m), η (cm)
Distance from interaction point (m)

Figure 4

DISPERSION SUPPRESSOR AND OFFSIDE STRAIGHT SECTION

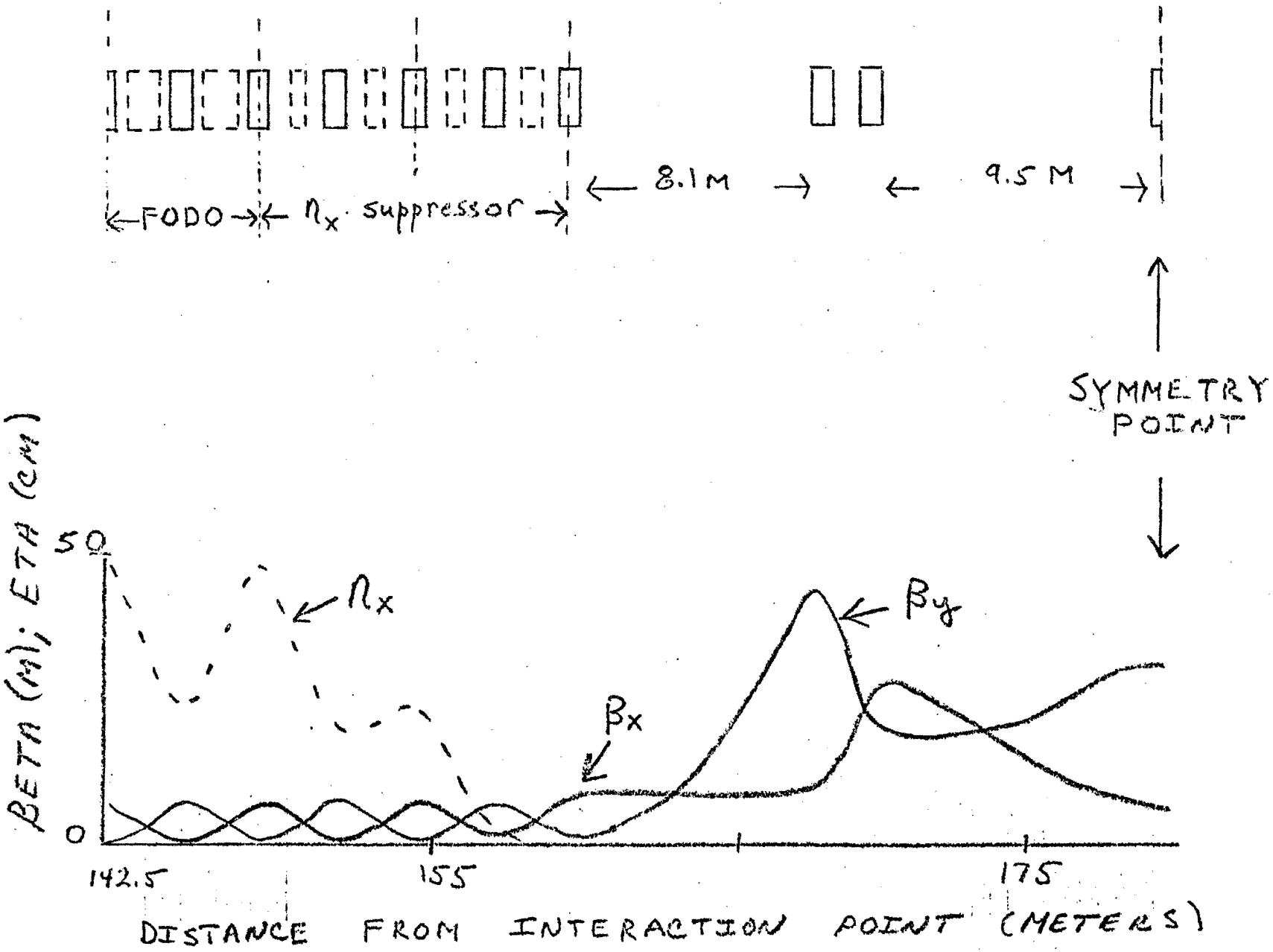


FIG 5

II. 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. For head-on collisions of 5 GeV electrons with 1000 GeV protons, the total energy available in the center of mass is $\sqrt{s} = 140$ GeV. In terms of the kinematic variables usually used to describe lepton-nucleon interactions, the accessible region in (Q^2, ν) space is:

$$Q^2 \leq 20{,}000 \text{ GeV}^2/c^2$$

$$\nu \leq 10{,}000 \text{ GeV} .$$

The electron-proton collider has the potential to explore vast regions of the Q^2 domain which are totally inaccessible to fixed target programs. The expected rates for $ep \rightarrow eX$ and $ep \rightarrow \nu X$ are shown in Figs. 1 and 2 for 5 x 1000 GeV collisions. The figures give the rate/day for a luminosity of $4 \times 10^{31} \text{cm}^{-2}\text{sec}^{-1}$. Also included in the figures are the corresponding rates for the processes as they will be studied at fixed target facilities such as the Fermilab Tevatron.

The point is further emphasized in Table 1 where we have examined the rates for a range of electron energies in collision with 1 TeV protons. The first line lists the center-of-mass energy squared, the second line gives the equivalent fixed target beam energy, and finally the

accessible Q^2 regions are shown. The significance of the energies entered in the table is as follows:

1. 300 MeV x 1000 GeV is equivalent to the $\sqrt{s}$ obtainable in the fixed target μ, ν, or γ beams at the Tevatron.

2. 5 GeV is the energy of the electron ring described in this report.

3. 10 GeV is the ring described in our Fermilab proposal.

4. 20 GeV represents perhaps the ultimate e-p experiment at Fermilab. A 20 GeV ring has already been designed and is described in our Brookhaven proposal.

It is clear from the table that even with collisions at 5 x 1000, one can gain more than an order of magnitude in the Q^2 region covered relative to the projected Tevatron fixed target programs.

Figures 1 and 2 point out an additional feature of the electron-proton collider. In e-p collisions one is looking at phenomena in the spacelike domain, rather than in the timelike domain as in electron-positron or proton-proton collisions. As a result center-of-mass energy is not the overriding criterion which may determine the ultimate success or failure of the machine 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 5 x 1000 GeV electron-proton collider are quite diverse and in many ways complementary to the other projected HEP facilities. The Q^2 dependence of the 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. This structure could be detected if it were greater in extent than $\sim 10^{-16}$ cm. Additionally, quark substructure could manifest itself even more dramatically through lack of transverse momentum balance between the scattered electron and 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-weak interference in the neutral current events. Through the Q^2 dependence, the mass of the W can be measured to $\pm$ 9 GeV and the mass of the Z^o to $\pm$ 25 GeV during a run with an integrated luminosity of $10^{38} cm^{-2}$ (700 hours at 4×10^{31} $cm^{-2} sec^{-1}$). But perhaps more interesting is the ability to test high energy modifications to the standard theory such as additional higher mass W's or W's with right-handed couplings. Additional W's with masses up to 140 GeV can be detected through propagator effects.

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^2 via photoproduction (with equivalent photon energies of up to 10 TeV). At 5 x 1000 GeV, the photoproduction rates for a 50 GeV top meson remain in the 500-1000 range for a run with an integrated luminosity of $10^{38}cm^{-2}$, as shown in Table 2. Such observations are completely outside the scope of fixed target photoproduction and leptoproduction programs, and are probably difficult at the next generation of e^+e^- colliders. In addition, the e-p collider is the ideal place to look for heavy (charged or neutral) electrons with masses up to 70 GeV. Somewhat more speculative particles, such as leptoquarks can also be searched for.

A particular virtue of the electron-proton collider is its complementarity with respect to the nucleon-nucleon and lepton-lepton colliders which are projected in the 80's. One only has to look back over the last twenty years (see Fig. 3) to appreciate the impact that the lepton-nucleon experiments completed at SLAC, Fermilab, and CERN have had on our view of physics. These experiments provided information which was not accessible to the nucleon-nucleon or e^+-e^- programs (and vice versa). We have the opportunity to insure that this continues to be true in the future. The e-p collider described here allows us to gain at least an order of magnitude in the distances over which we can probe nucleon structure, and to increase our knowledge in a corresponding manner.

Table 1. The accessible Q^2 domains at the 10 event/day and 1 event/day levels for four different center-of-mass energies. We list the total energy squared in the center-of-mass and the equivalent fixed target beam energies for electron collisions with 1 TeV protons. At s = 1200 the rates are calculated for the projected fixed target μ and ν programs at the Tevatron. For the others, a luminosity of $4 \times 10^{31} cm^{-2} sec^{-1}$ for e-p collisions is assumed.

Electron Energy	0.3	5	10	20	GeV
S	1200	20,000	40,000	80,000	GeV^2
$E_{\mu,\nu}$	0.6	10	20	40	TeV
Circumference		356	1473	3834	m
Neutral Current					
Q^2 (10 ev/day)	150 400*	3000	4500	7000	
Q^2 (1 ev/day)	400 600*	6000	10000	17000	
Charged Current					
Q^2 (10 ev/day)	100 380*	2500	5000	8500	
Q^2 (1 ev/day)	300 600*	6500	11500	17000	

* Iron detector - no final state hadron identification.

Table 2. Virtual photoproduction of heavy quark states.

	Assumed Cross Section	Expected Yield
1) $\gamma^* \to D\bar{D}$	$500\ \text{nb}\ (1-\frac{12\ \text{GeV}}{\nu})$	14 M
2) $\gamma^* \to B\bar{B}$	$27\ \text{nb}\ (1-\frac{68\ \text{GeV}}{\nu})$	500 K
3) $\gamma^* \to t\bar{t}$ (20 GeV top)	$7\ \text{nb}\ (1-\frac{893\ \text{GeV}}{\nu})$	45 K
4) $\gamma^* \to t\bar{t}$ (50 GeV top)	$1.2\ \text{nb}\ (1-\frac{5447\ \text{GeV}}{\nu})$	0.9 K
5) $\gamma^* \to t\bar{t}$ (60 GeV top)	$0.78\ \text{nb}\ (1-\frac{7796\ \text{GeV}}{\nu})$	0.2 K

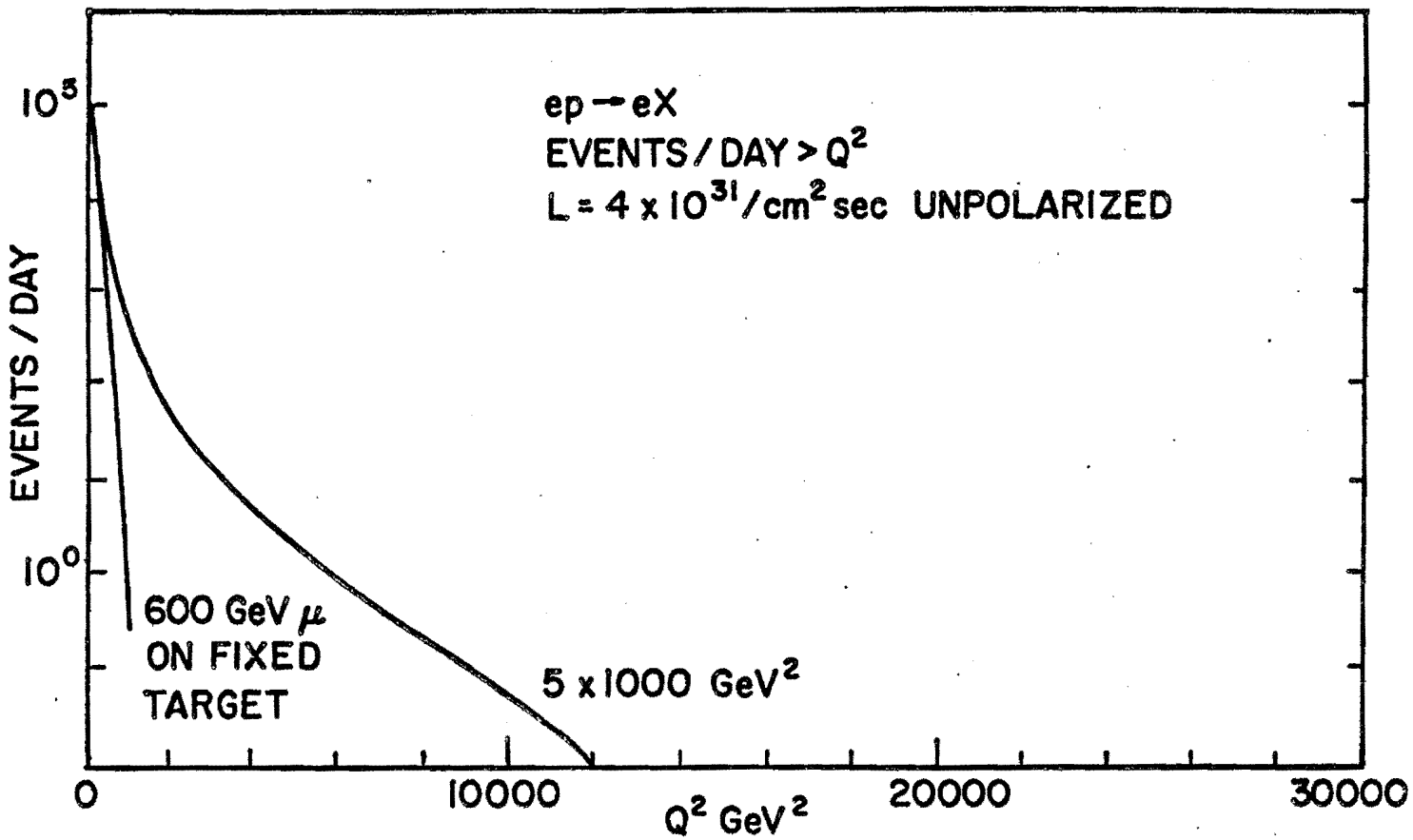

ep → eX
EVENTS / DAY > Q²
L = 4 x 10³¹/cm² sec UNPOLARIZED
EVENTS / DAY
10⁵
10⁰
600 GeV μ
ON FIXED
TARGET
5 x 1000 GeV²
0
10000
20000
30000
Q² GeV²

Fig. 1

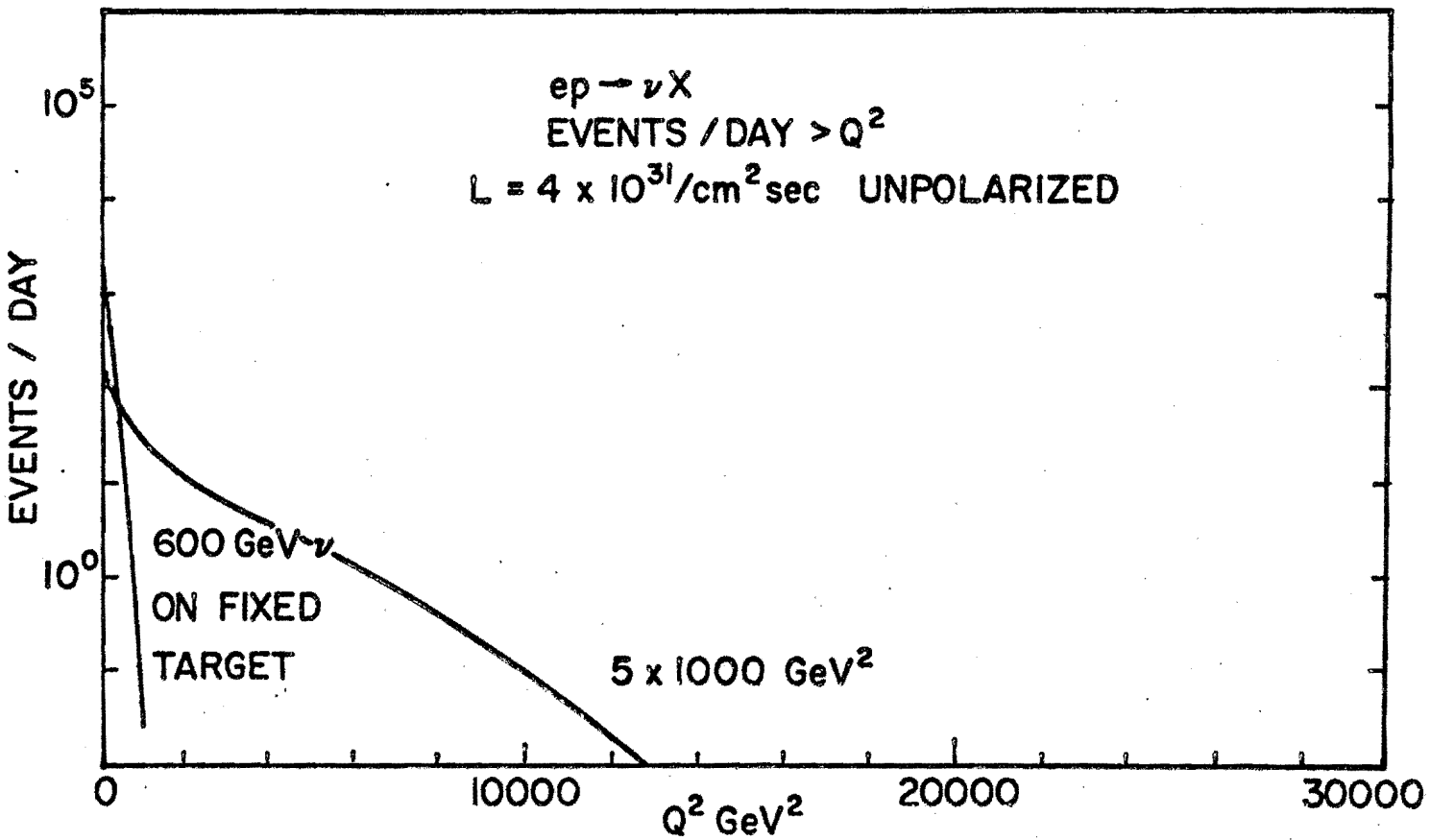

ep → νX
EVENTS / DAY > Q²
L = 4 x 10³¹/cm²sec UNPOLARIZED
EVENTS / DAY
10⁵
10⁰
600 GeV ν
ON FIXED
TARGET
5 x 1000 GeV²
0
10000
20000
30000
Q² GeV²

Fig. 2

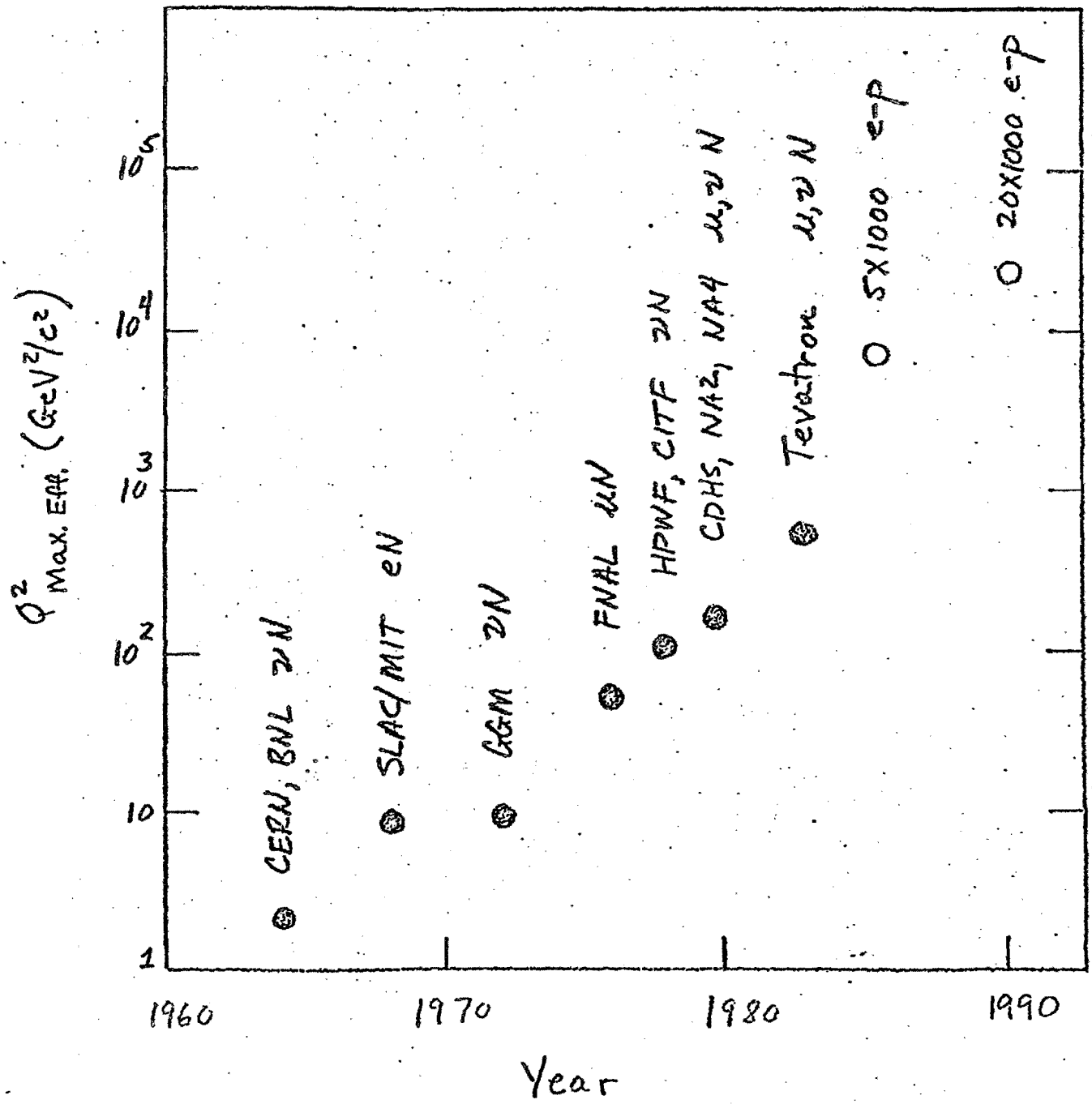


Fig. 3. The maximum Q^2 effectively obtainable in lepton-nucleon interaction over the last 20 years.