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CONSIDERATIONS ON MODEST COLLIDING BEAMS AT FERMILAB

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Introduction

A modest colliding beam facility can be defined as one which has a cost of at least an order of magnitude less than high performance storage and colliding beam rings such as POPAE, ISABELLE, and LSR. This lower cost must be compensated by lower performance of some sort, such as less luminosity, lower energy, fewer usable crossing regions, and so on. For such a facility to be considered at Fermilab, the use of the presently available proton beam in the main ring, or in the doubler in the future, as one of the possible colliding beams must be taken as a boundary condition. Thus, one is limited to the design of a second beam of some kind to use in collisions with the presently existing proton beam.

One important consideration in the design of a second beam is to minimize the interference with the main ring's fixed target operation. Presently, this requires the construction of a new ring, either in the main ring or booster tunnel, or one tangent to the main ring. If in the future it is found possible to inject directly from the booster into the doubler, however, then the main ring itself would become available to use as a second beam storage ring. A solution of this type is obviously premature, but nonetheless, it is a tantalizing possibility.

Hence, we look into the designs of some additional rings which could be used to collide beams with the main ring while preserving the laboratory's primary purpose as a fixed target accelerator.

There are four different kinds of modest colliding beam experiments which could be undertaken at Fermilab: (1) e^+e^-; (2) $e^{\pm}$- p; (3) p-p; (4) $\bar{p}$-p. Of these four, $e^{\pm}p$ is easily possible and we shall mainly consider it. The second type e^+e^-, is a much more formidable project, requiring very large amounts of R.F. power for high center-of-mass collisions, and shall be considered in somewhat less detail. The remaining two types shall not be considered here. The pp collisions will certainly be pursued after the doubler is in operation, and $\bar{p}p$ is already under consideration utilizing a second ring in the booster tunnel.

e^+- e^- Colliding Beams

In order for these to be of any significance at Fermilab, the beam energy has to be larger than in PEP (15x15 GeV^2) and in PETRA (19x19 GeV^2). A feasibility study has shown that a ring the size of the main ring installed in the same tunnel is capable of 40-45 GeV per beam with a total input power which does not exceed that which is presently used by the main ring itself (40-50 MW). The ring has to be strong focusing with $\nu \sim \gamma_t \sim 30$ in order to get a lifetime of at least one hour. The main ring itself, if necessary, could be used for this purpose. One would require, though, some lattice modifications in order to get the necessary focusing strength. This could be achieved mainly by overpowering the quadrupoles with respect to the bending magnets and rematching the long straight sections.

No matter which ring is used, a low-beta value of a fraction of a meter can be obtained with a combination of the Tom Collins' scheme and of addition of a few quadrupoles.

Table I is a list of the main-ring parameters for a typical operation mode. Table II shows the $e^{\pm}$-beam parameters for the main ring as specified in Table I. E is the electron energy, eV the energy loss per particle per turn, σ_e/E the equilibrium energy spread (rms), τ_E the energy oscillations damping time and $\varepsilon = \pi\sigma^2/\beta$ the equilibrium beam emittance (rms) in absence of coupling.

Table III is the list of the performance parameters. Full coupling between horizontal and vertical oscillations has been assumed, so that horizontal and vertical emittances are the same and equal to half of the value in absence of coupling. RF parameters have been extrapolated from the PEP RF system and the shunt impedance is defined as the ratio of the square of the peak voltage to the power.

The luminosity, the beam-beam tune shift, and other related parameters are shown in Table IV. Head-on collision and round, equal beams have been assumed. Finally, we summarize the RF power data in Table V.

It should be noted that in this case, both beams will share the same magnetic ring and RF system, so that only one ring would be required, as opposed to two in most other cases. Even so, this project requires a rather large amount of effort and money, particularly in the RF system, and probably should not really be considered as a very modest colliding beam facility.

Although we believe it would be less costly than PEP, due to the smaller RF system needed, it is not a project which should be considered to undertake at present, but rather one which should be considered for the not terribly distant future.

$e^{\pm}$- p Colliding Beams

There are three possible methods of producing $e^{\pm}p$ colliding beams. To $e^{\pm}$ beam could circulate in the main ring and collide with the doubler; the beam could be stored in an additional ring inside the main-ring tunnel and collide with either the main ring or the doubler; or it could be in a small storage ring tangent to the main ring.

Most of the considerations of the previous section apply to the first two cases for a ring the size of the main ring. Table VI shows the performance of a high-energy (40-45 GeV) electron ring colliding with the doubler. Because the proton beam is bunched at 53 MHz, the electron bunching does not really matter except for high intensity instabilities. To keep the peak current low, we have taken the electrons to also be bunched at 53 MHz.

The present proton beam performance is $2(10)^{13}$ ppp with a normalized emittance of 20π mm-mrad, and we have used these numbers to calculate luminosities and beam-beam tune shifts. The performance of this mode is rather low. The limitation imposed is the amount of electron beam current which can be stored without requiring very large amounts of RF.

The e-p performance increases considerably at low energy as one can see in Table VII. Luminosities up to $10^{32}cm^{-2}s^{-1}$

are certainly possible, all depending on how much RF power one is willing to spend. No lattice modifications are required when the main ring is used as a low-energy electron ring and the present RF system at 53 MHz can be used. At the energy of 12 GeV one merely needs an increase of the input RF power from 1 MW to 2-3 MW. At 20 GeV the present RF system has to be expanded to about five times its original length. The beta-values (β^*) shown in Table VII are for round and equal beams. It is somewhat questionable as to whether one can actually achieve beta-values much below 10 meters in either the main ring (p) or in the energy doubler.

The main-ring aperture should be adequate for a lifetime of several hours when the betatron oscillations in the two planes are coupled. A major modification would exist in that the vacuum requirement would be around 10^{-8} - 10^{-9} Torr, and that a new vacuum chamber which could be baked and water-cooled to absorb synchrotron radiation heat would be required.

In the case of an additional ring for electrons in the main-ring tunnel, one would want to modify the lattice so as to increase the tune. One possible lattice is shown in Fig. 1. This lattice increases the tune to approximately 40, which both reduces the amount of RF overvoltage required for a given electron lifetime, and reduces the beam emittance so as to more nearly match it to the proton beam. The performance parameters for this ring are shown in Table VIII.

The third possibility is the case of a separate electron ring, externally tanget to the main ring. We have done some calculations for a typical small ring and show the main parameters in Tables IX and X. The particular ring considered has a circumference of some 800 meters and a bend radius of 65 m. The maximum energy of this ring is 15 GeV. We also list the parameters for a somewhat lower energy of 12 GeV.

Again we take the spacing between electron bunches equal to that of the proton beam. The RF frequency is three times that of the main ring in order to fit in cavities with a gradient of 1 MV/m. The design limits the RF input power to 14 MW. The overvoltage and aperture requirements are modest. As one can see from the tables, the performance (luminosity) of the ring is comparable to that of the main ring used as an electron storage device and somewhat lower to a new ring inside the present main-ring tunnel. A detailed, careful design of the three possibilities would show which would be the least expensive and, exclusive of other considerations, the most suitable.

The Booster as an $e^{\pm}$ Injector

The final topic of consideration is that of an electron injector for any of these possible schemes. We look in particular at attaching an electron (positron) linac onto the booster and using the booster as a fast electrosynchrotron. This has been previously examined in some detail[1] and so we shall omit much of the possible discussion.

We assume we have an electron linac, similar to the present CEA linac, with the following characteristics:

$E = 250$ MeV

$\varepsilon = \sigma^2/\beta = 0.25$ mm·mrad

$\Delta E/E = \pm 2\times10^{-3}$

RF frequency = ~3,000 MHz

chopper frequency = 53 MHz

Average Current = 100 mA

The present booster is capable of accelerating this type beam up to an energy of 4 GeV, this limit being imposed by the present RF system. Most of the parameters associated with this acceleration are quite acceptable. There is, however, one problem in that the booster, being a combined function machine, is anti-damped in the radial plane so that the beam grows during acceleration. Nevertheless, if the beam is accelerated at the normal 15 Hz rate to a final energy of 4 GeV, the emittance growth is only about 50%, and, by fully coupling the two transverse oscillations, the final emittances are

$$\varepsilon_H = \varepsilon_v = 1.1\pi \text{ mm}\cdot\text{mrad} .$$

Further, the final energy spread is damped to a value

$$\Delta E/E = 3.4\text{x}10^{-4}.$$

The energy loss per turn at 4 GeV in the booster is very small, and a peak voltage of some 600 kV is all that is required.

In toto, the booster does appear to be a practical electro-synchrotron which could be used to deliver a 4 GeV beam into any one of the above rings, although it certainly is not an ideal choice. It may be more desirable to try to find another source of high-energy electrons, such as a 1-2 GeV electronsynchrotron similar to the one currently in use at HEPL.

Reference

1. See, for example, T.L. Collins, et al., "Summary Report on Phase I of the POPAE Design Study, Part 2", Fermilab Internal Report, TM-600

Table I

Main Ring Parameters

Circumference ($2\pi R$)	2π x 1000 m
Bending Radius (ρ)	747.8 m
Maximum Bending Field	22 kG (500 GeV)
Minimum Bending Field	0.4 kG (8 GeV)
Maximum Quad Gradient	300 kG/m (500 GeV)
Minimum Quad Gradient	5.3 kG/m (8 GeV)
Betatron Tunes ($\nu_x \sim \nu_y$)	19.4
Transition Energy/Rest Energy (γ_T)	18.75
β_{max}	124 m
β_{min}	28 m
η_{max}	5.9 m
η_{min}	1.2 m
Repartition Factors: J_E	2-D
J_x	1+D
J_z	1
$D = R/\rho\gamma_T^2$	0.004
Revolution Frequency	47.75 kHz
Revolution Period (T)	20.94 μs

Table II

$e^{\pm}$-Beam Parameters for the Main Ring

E (GeV)	U (MV)	σ_E/E (10^{-3})	τ_E (msec)	ε (π mm·mrad)
8	0.5	0.25	336	0.018
20	18.9	0.63	22.2	0.116
25	46.2	0.78	11.4	0.177
30	95.9	0.94	6.6	0.258
35	178	1.10	4.1	0.353
40	303	1.26	2.8	0.463
45	485	1.41	1.9	0.580
50	740	1.57	1.4	0.718
55	1,083	1.73	1.1	0.872
60	1,534	1.88	0.8	1.030

Betatron Tunes ($\nu_x \sim \nu_y$)	19.4
Transition Gamma (γ_T)	18.75
Bending Radius (ρ)	747.8 m

Table III

Performance Parameters for $e^{\pm}$-Ring

Energy	40 GeV	45 GeV
Lifetime	~1 hour	
Rad. Loss	303 MeV	485 MeV
τ_E	2.8 msec	1.9 msec
Betatron Tunes (ν)	30	
Trans. Gamma (γ_T)	30	
σ_E/E	1.26×10^{-3}	1.41×10^{-3}
$\varepsilon = \sigma^2/\beta$ (full coup.)	0.06π mm·mrad	0.07π mm·mrad
Aperture Requirement	2.2π mm·mrad	2.5π mm·mrad
h	7791 (= 7x1113)	
V_{peak}	379 MV	597 MV
f_{RF}	371.735 MHz	
RF Length	350 m	
RF Average Gradient	1.1 MV/m	1.7 MV/m
Total Shunt Impedance	10^4 MΩ	1.6×10^4 MΩ
RF power (cavity loss)	14 MW	22 MW
$\sin\phi_s$	0.800	0.813
f_E	4.223 kHz	4.922 kHz
σ_τ	0.05 nsec	0.05 nsec

Table IV

Luminosity of $e^{\pm}$-Colliding Beams

Energy	40 GeV	45 GeV
$\Delta\nu$	0.06	
N_e/bunch	6.4×10^{11}	8.4×10^{11}
No. of bunches	3	
Revolution Frequency	47.71 kHz	
β^*	0.5 m	
Luminosity	$1.6\times10^{31}cm^{-2}s^{-1}$	$2.3\times10^{31}cm^{-2}s^{-1}$
Average Current	15 mA	19 mA
Power Loss (Rad)/Beam	4.5 MW	9.2 MW

Table V

Total RF power for $e^{\pm}$-Colliding Beam

E	40 GeV	45 GeV
Lifetime	~1 hour	
Rad. Loss	303 MeV	485 MeV
f_{RF}	371.735 MHz	
V_{peak}	379 MV	597 MV
RF Length	350 m	
RF Average Gradient	1.1 MV/m	1.7 MV/m
Total Shunt Impedance	10^4 MΩ	1.6×10^4 MΩ
RF Power (cavity loss)	14 MW	22 MW
Average Current	17 mA	19 mA
Power Loss (Rad)/Beam	5 MW	9 MW
Power Transmission	70 %	
Input RF power (ep)	27 MW	44 MW
($e\bar{e}$)	34 MW	57 MW

Table VI

High-Energy e-p Colliding Beams

Electron Ring Colliding with Energy Doubler

E_p		1000 GeV	
E_e	40 GeV		45 GeV
N_p/bunch		2×10^{10}	
N_e/bunch		2×10^{9}	
Frequency of Encounter		53 MHz	
β_e^*		0.5 m	
β_p^*	9 m		10.5 m
Luminosity	$0.56\times10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$		$0.48\times10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
$\Delta\nu_p$		7.4×10^{-4}	
$\Delta\nu_e$	9×10^{-4}		7×10^{-4}
Average Current (e)	17 mA		17 mA
Power Loss (Rad.)	5.2 MW		8.2 MW

Table VII

e-p Low-Energy Mode (MR)

Energy	12 GeV	20 GeV
Rad. Loss	2.454 MeV	18.9 MeV
σ_E/E	$0.375\text{x}10^{-3}$	$0.63\text{x}10^{-3}$
τ_E	0.10 sec	0.02 sec
$\varepsilon = \sigma^2/\beta$ (f.c.)	0.021 mm·mrad	0.058 mm·mrad
Peak Voltage	4.0 MV	23.0 MV
h	1113	1113
f_{RF}	53 MHz	53 MHz
$\sin\phi_s$	0.6135	0.8217
f_E	0.55 kHz	0.867 kHz
σ_τ	0.30 nsec	0.33 nsec
τ_{life} (E-oscill.)	∞	94 hours
Aperture Requirement	0.8π mm·mrad	2.1π mm·mrad
Proton Energy	1000 GeV	
N_e/bunch	$2\text{x}10^{10}$	
N_p/bunch	$2\text{x}10^{10}$	
β_e^*	0.5 m	
β_p^*	3.1 m	8.7 m
Luminosity	$1.6\text{x}10^{31}\text{cm}^{-2}\text{s}^{-1}$	$0.6\text{x}10^{31}\text{cm}^{-2}\text{x}^{-s}$
Rad. Power	0.4 MW	3.2 MW
$\Delta\nu_e$	0.009	0.002
$\Delta\nu_p$	$6.9\text{x}10^{-4}$	
λ_c	3 A° (4 keV)	0.65 A° (19 keV)
ν	19.4	
γ_T	18.75	

Table VIII

e-p Low-Energy Mode (new ring)

Energy	20 GeV
Rad. Loss	18.9 MeV (due to normal lattice)
σ_E/E	$0.63\text{x}10^{-3}$
τ_E	0.02 sec
$\varepsilon = \sigma^2/\beta$ (f.c.)	0.0091 mm·mrad
Peak Voltage	21.0 MW
h	1113
f_{RF}	53 MHz
$\sin\phi_s$	0.8217
f_E	0.867 kHz
σ_τ	0.08 nsec
τ_{life} (E-oscill.)	∞
Proton Energy	1000 GeV
N_e/bunch	$2\text{x}10^{10}$
N_p/bunch	$2\text{x}10^{10}$
β_e^*	0.5 m
β_p^*	8.7 m
Luminosity	$1.04\text{x}10^{31}\text{cm}^{-2}\text{s}^{-1}$
Rad. Power	3.2 MW
$\Delta\nu_e$	0.002
$\Delta\nu_p$	$4.4\text{x}10^{-3}$
λ_c	0.65 A° (19 keV)
ν	~35
γ_τ	~35

Table IX

Small e-Ring Structure

E	12 GeV	15 GeV
ρ	65 m	
$\nu = \gamma_\tau$	14	
Rad. Loss	28 MeV/turn	69 MeV/turn
τ_E	1.1 msec	0.6 msec
lifetime	few hours	
σ_E/E	1.30×10^{-3}	1.63×10^{-3}
$\varepsilon = \sigma^2/\beta$ (full coupling)	0.86×10^{-2} mm·mrad	1.35×10^{-2} mm·mrad
$2\pi R$	801.628 m	
f_{RF}	159.315 MHz	
h	426	
No. of buckets	142	
Aperture Requirement	1.2π mm·mrad	2.0π mm·mrad
Peak Voltage	40 MV	90 MV
Gradient	1 MV/m	
RF Length	40 m	90 m
Shunt Impedance	20 MΩ/m	
RF Power to Cavities	2.0 MW	4.5 MW
Rad. Power	8.0 MW	5.5 MW
Transmission Efficiency	70 %	
Input Power	14 MW	
Average Current	286 mA	80 mA
N_e/bunch	3.4×10^{10}	9.4×10^{9}

Table X

Small e-Ring : Performance

Energy	12 GeV	15 GeV
E_p	1000 GeV	
N_p/bunch	$2x10^{10}$	
No. of p-bunches	1113	
$\varepsilon_p = 6\pi\sigma^2/\beta$ (1000 GeV)	0.02π mm·mrad	
β_e^*	1.0 m	
β_p^*	2.6 m	4.0 m
$\Delta\nu_p$	$1.2x10^{-3}$	$0.3x10^{-3}$
$\Delta\nu_e$	0.022	0.011
Luminosity	$1.4x10^{31}cm^{-2}s^{-1}$	$3.4x10^{30}cm^{-2}s^{-1}$
(head-on)	(max 1.8)	(max 4.8)
λ_c	0.4 A° (31 keV)	0.2 A° (62 keV)
f_E	10.7 kHz	13.7 kHz
σ_τ	0.10 nsec	0.10 nsec

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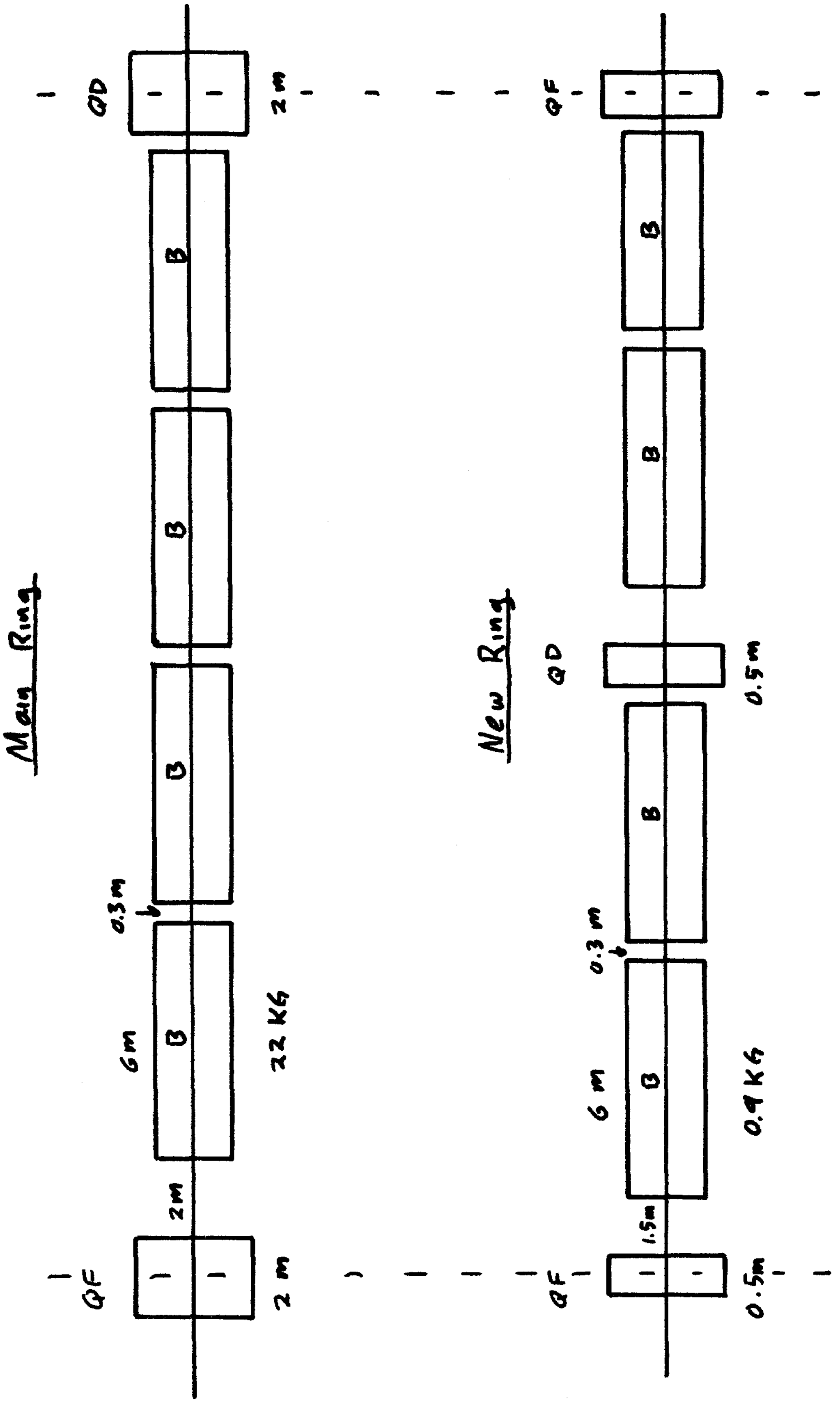

Figure 1

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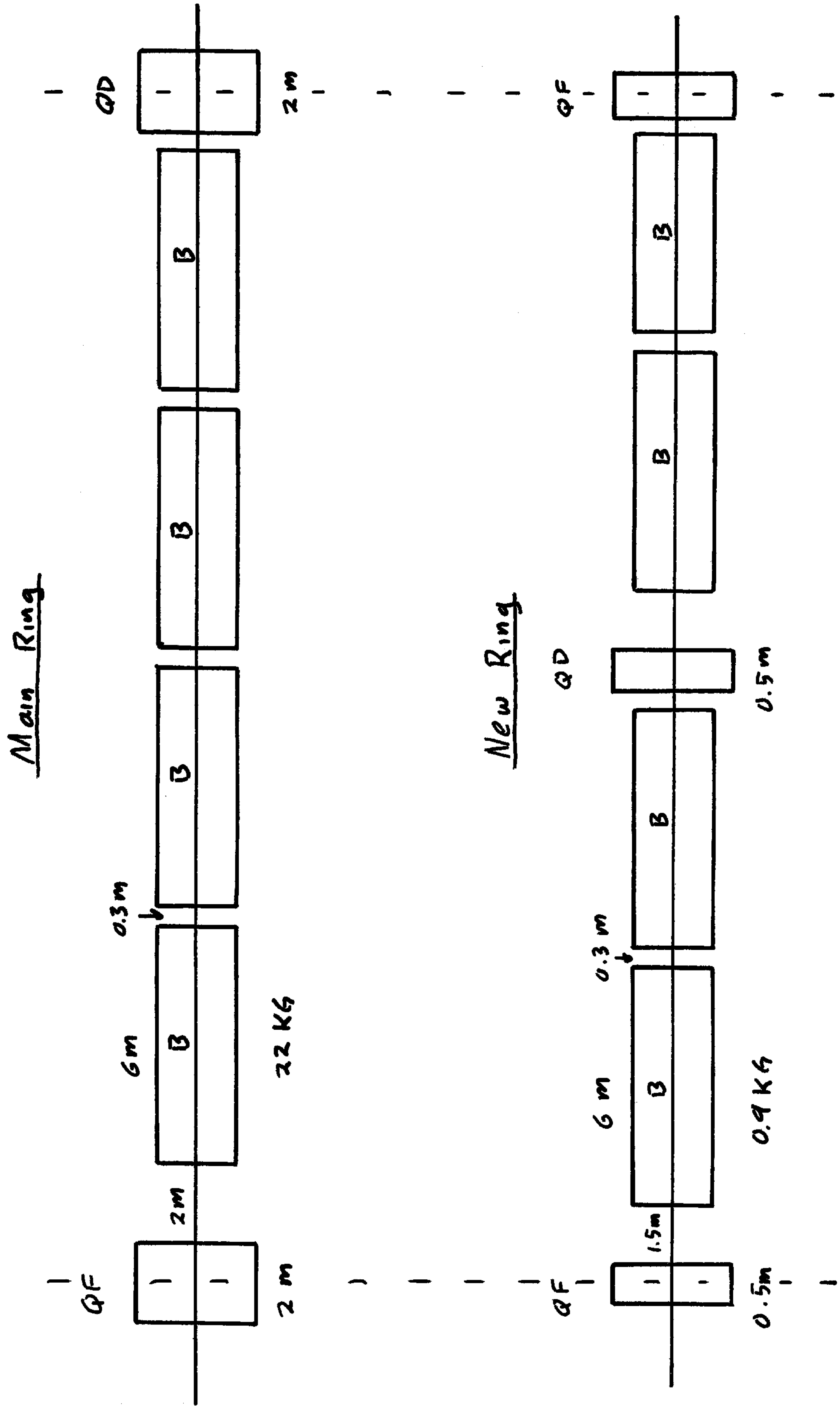

Figure 1

Table X

Small e-Ring : Performance

Energy	12 GeV	15 GeV
E_p	1000 GeV	
N_p/bunch	2×10^{10}	
No. of p-bunches	1113	
$\varepsilon_p = 6\pi\sigma^2/\beta$ (1000 GeV)	0.02π mm·mrad	
β_e^*	1.0 m	
β_p^*	2.6 m	4.0 m
$\Delta\nu_p$	1.2×10^{-3}	0.3×10^{-3}
$\Delta\nu_e$	0.022	0.011
Luminosity	$1.4\times10^{31}cm^{-2}s^{-1}$	$3.4\times10^{30}cm^{-2}s^{-1}$
(head-on)	(max 1.8)	(max 4.8)
λ_c	0.4 A° (31 keV)	0.2 A° (62 keV)
f_E	10.7 kHz	13.7 kHz
σ_τ	0.10 nsec	0.10 nsec