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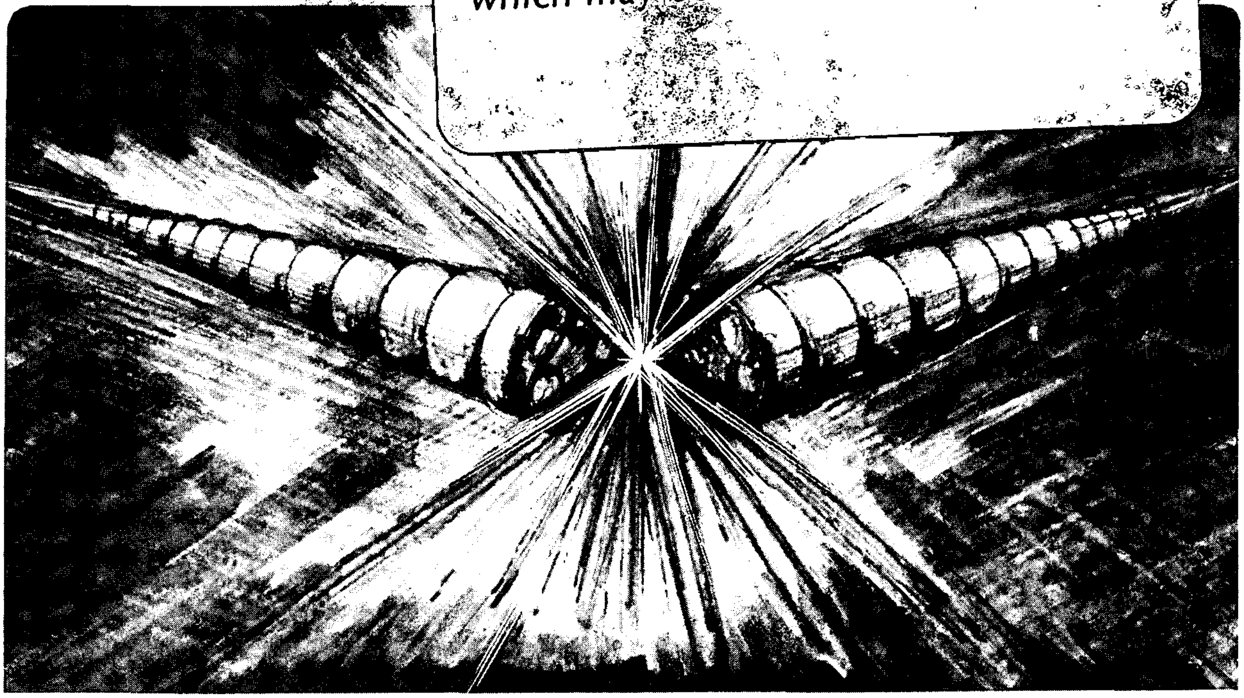

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We report on the study of a storage ring capable of sustaining an electron beam of the quality required for a High Gain Free Electron Laser in the vacuum ultraviolet and X-ray region. We describe a method for the optimization of the design of the storage ring, where several competing and often conflicting requirements come into play. We present an example design of a ring that satisfies the required conditions of beam quality and is able to produce coherent radiation at 400 Å with tens of megawatts of peak power.

1. Introduction

There has recently been remarkable progress in demonstrating the generation of coherent radiation through Free Electron Laser (FEL) interaction in the infrared and microwave region [1]. If electron beams of suitable quality were available, the technique could be extended to shorter wavelengths. The FEL would become an intense, tunable and coherent source of x-rays and vacuum ultraviolet radiation at wavelengths shorter than 1000 Å. In this paper we show how electron storage rings can be designed to meet the stringent requirements of beam quality demanded for this purpose.

With present day technology, there are two promising approaches to the production of coherent radiation via a Free Electron Laser in the XUV region.

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One is based on cavity formation by end mirrors [2] and [3], the other through the development of a high gain, single pass device. The former option, the so-called FEL Oscillator, is at present restricted to longer wavelengths because high reflectivity mirrors, although rapidly evolving through multilayer technology, are not available at the wavelengths under consideration here (< 1000 Å), [2]. In the second approach, which we call the High Gain FEL, the interaction of the beam with the undulator occurs in a single pass, and no mirrors are needed. The noise power present in the electron beam at the entrance of the undulator is sufficient to start the growth of a high power coherent signal during a single passage of the beam through the undulator, [4] and [5]. The work reported in this paper concerns the operation of a High Gain FEL.

For an efficient interaction between the beam and the radiation, the undulator must be long and must have a very narrow gap. This small gap, if placed in a normal section of a storage ring, would severely limit the acceptance of the ring and thus reduce the beam lifetime due to scattering with the residual gas. Moreover, the interaction of the beam with the FEL undulator is disruptive to the quality of the beam itself, mostly in terms of energy loss and increased momentum spread. To avoid these problems, the FEL undulator is placed in a special bypass section [5], as shown schematically in Fig. 1. The electron beam normally circulates in the storage ring without passing through the FEL undulator. Once every damping time, the beam is directed into the bypass section, where the interaction with the undulator takes place. Intense, coherent radiation is generated. As the beam leaves the undulator, it is deflected back into the storage ring, where synchrotron radiation damping reduces the energy spread. After one damping time, the beam is ready to be injected into the bypass again.

In the next sections we discuss the FEL design issues and the conditions they impose on the electron beam quality. The results of an optimization study are reported in the form of an example design of a storage ring.

A list of the symbols not explicitly explained in the text is given in the Appendix.

2. FEL Issues

In the one-dimensional theory, the FEL characteristics are determined by the dimensionless parameter ρ, given by ref. [6]

$$\rho = \left(\frac{K^2[JJ]r_e n_b \lambda_u^2}{32\pi\gamma^3}\right)^{1/3} \tag{2.1}$$

where

$$[JJ] = [J_0(\xi) - J_1(\xi)]^2, \ \xi = \frac{K^2}{4(1 + \frac{K^2}{2})}. \tag{2.2}$$

The J_0 and J_1 are ordinary Bessel functions of order zero and one, respectively. For the parameters of interest to us, ρ is typically of the order of 10^{-3}. The laser saturates at a distance $z = z_{sat}$ with a characteristic saturated peak power P_{sat}. The saturation length and the peak power are given approximately, in the one-dimensional theory with zero energy spread, by ref. [6]

$$z_{sat} \approx (\lambda_u/\rho) \tag{2.3}$$

$$P_{sat} \approx \rho \, P_{beam} \tag{2.4}$$

where $P_{beam} = \hat{I}E/e$ is the peak power in the electron beam. If the momentum spread in the beam, σ_p, is non-zero, the FEL performance is significantly reduced, unless the following condition is satisfied [7]:

$$\sigma_p \lesssim 1/N \sim \rho \tag{2.5}$$

Taking the typical values of $\hat{I} = 200$ A, $E = 750$ MeV and $\rho = 1\times10^{-3}$ considered in this paper, one obtains from Eqn. (2.4) a peak laser power of

150 MW. Assuming a beam pulse length of 100 psec and a repetition time (equal to the typical longitudinal damping time of the storage ring) of 50 msec, we obtain an average power of 0.3 watts.

A coherent source of radiation of such high intensity, both in peak and average power, would certainly pioneer novel scientific applications.

3. Problems and Limitations in Achieving High Density Electron Bunches

Equations (2.1) and (2.5) show that a Free Electron Laser requires a stored beam with both significant volume density, n_b, (large peak current and small emittance) and low momentum spread. These conditions place severe demands on the storage ring design, which must address the impact of both coherent and incoherent multiparticle phenomena.

The threshold peak currents for the longitudinal and transverse single bunch instabilities are given, respectively, by the following expressions [8]:

$$\hat{I}_L = \frac{2\pi\alpha\sigma_p^2 (E/e)}{(Z_L/n)_{eff}} F_L \tag{3.1}$$

and

$$\hat{I}_T = \frac{4\sqrt{2\pi}\,(E/e)\nu_s}{Z_T\beta} F_T \tag{3.2}$$

The effective longitudinal (Z_L/n) and transverse (Z_T) impedances are averages of the full frequency dependent impedances over the bunch mode spectra. For typical FEL storage ring parameters, the longitudinal threshold is usually the more severe limit.

Coulomb scattering of strongly bunched electrons within the beam leads to excitation of betatron and energy oscillations. For large angle scatters, an electron's momentum error may exceed the acceptance of the machine aperture or the rf bucket, whichever is smaller. When this happens, the particle is lost and the beam lifetime is reduced (Touschek effect). Multiple scattering, on the other hand, causes both longitudinal and transverse diffusion. An equilibrium situation exists when the intrabeam scattering growth rates are equal to the radiation damping rates: as a result, the equilibrium emittance may be much greater than it would be if only radiation damping were considered.

For typical cases the equilibrium rms emittance is found to satisfy the relation [9]

$$\varepsilon_x \approx \frac{1}{2}\left[\varepsilon_{ox} + \sqrt{\varepsilon_{ox}^2 + C\,\frac{\hat{I}}{\sigma_p \gamma^3 g_{ox}}\left\langle \frac{H^{1/2}}{\sqrt{\beta_y}} \right\rangle}\,\right] \tag{3.4}$$

where $C = 10^{-9}\ \mathrm{m}^2/(\mathrm{A\text{-}sec})$ for $\varepsilon_y = \varepsilon_x/10$.

This discussion gives an idea of the limits imposed by the collective effects to the achievement of a high volume density and thus, ultimately, of a high value of the FEL parameter ρ [Eqn. (2.1)]. Complicated parametric relationships are involved in the optimization procedure. Parametric studies have been carried out using a comprehensive particle code, called ZAP, which is being developed at LBL. As an example, we show the results of ZAP calculations concerning some parametric dependences. A more detailed description of our optimization study may be found in ref. [9].

In terms of the peak current limitation, one of the ways of gaining (as can be seen in Eqn. (3.1)) is to increase the allowable momentum spread of the beam. For low values of σ_p, we expect the peak current to increase as σ_p^2. At larger values of σ_p this increase flattens out, because the impedance becomes rf dominated, and thus the impedance is also increasing quadratically with σ_p. (In this latter regime the longitudinal threshold is no longer dominant anyway.) This behaviour is shown in Fig. 2 for an assumed beam pipe radius of 2.5 cm. Below σ_p of about 0.005, the peak current limitation arises from the longitudinal threshold, whereas above this value the transverse threshold would dominate. Obviously the peak current performance improves with increasing momentum spread. Unfortunately, the gain of an FEL degrades rapidly if σ_p is greater than the ρ parameter. This degradation of FEL performance with increasing momentum spread is illustrated in Fig. 2, which shows the increase in e-folding length (ℓ_{eff}) and decrease in gain parameter (ρ_{eff}) compared with their zero-energy-spread values (ℓ_e,ρ). For the designs considered here, we conclude that the value of σ_p that can be achieved in the storage ring (as a compromise between storage ring and FEL performance) is about 0.002.

With regard to the energy optimization, we can only say that the behaviour of the various effects of concern (emittance growth, intrabeam scattering, Touschek scattering) is rather complicated because each effect scales differently. For this reason we have used ZAP to determine the expected behaviour. The results are displayed in Fig. 3, which shows the predicted IBS and Touschek lifetimes along with the equilibrium emittance values, the bunched beam volume density, and the FEL figure of merit parameter ρ. It is qualitatively clear from Fig. 3 that basically everything follows the overall pattern dictated by the emittance values. For the 400 Å wavelength specified here for the FEL output, it is apparent that the chosen energy of 750 MeV is close to optimum. We also note that the energy dependence of ρ is not terribly strong, so that any energy between about 700 and 1100 MeV should be acceptable for the particular lattice shown.

4. Design Example of a Storage Ring

The lattice we have adopted for the design example (and denoted CF144) was suggested by a comparative study of various lattice options [9]. Its main parameters are listed in Table I.

The design utilizes a hybrid FODO structure first proposed by Vignola [10] for a 6 GeV synchrotron light source. The Vignola lattice design makes use of combined function dipole-and-gradient magnets.

A full period of the structure is given in Fig. 4 . The pattern is repeated six times around the ring. The lattice functions and other parameters are shown in Fig. 4 and Table I, respectively.

This lattice may be considered as a hybrid of a Chasman-Green [11] and a FODO lattice. The use of a combined dipole-gradient magnet makes it possible to achieve the low emittance typical of a Chasman-Green type using the same number of achromats but with weaker focussing. The partition damping number J_x, which is usually ~1 in a storage ring with separated functions, is ~1.5 in the Vignola lattice. As a consequence, the chromaticity, for the same emittance, is lower than in a Chasman-Green lattice. The use of three dipoles in the arcs increases the momentum compaction (a favorable feature, since it increases the peak current threshold for the microwave instability) and makes the lattice layout similar to a double FODO structure, but with the advantage of more free space, since the D-quadrupole of a normal FODO cell is distributed in the dipoles. This layout makes it possible to distribute the chromaticity correction in four sextupoles per period, divided into two families. The two families are well decoupled in the two planes, with a resultant improvement in chromatic behaviour and dynamic aperture. The main parameters predicted by the code ZAP for this lattice are given in Table II. A schematic layout of the main ring bypass and booster is shown in Fig. 5. In our study of the ring design, we have assumed that a full energy injector is required at an energy that is interesting to users of conventional undulators. Thus, in spite of the fact that the FEL is intended to operate at 750 MeV, we set the injection energy at 1.3 GeV.

The rf system requirements for an FEL storage ring are similar to those of other electron storage rings, with the exception of two novel features. Firstly, the peak current demand is higher than anything achieved or designed in existing storage rings in this energy range. For this reason, special emphasis must be placed on damping the higher-order modes of the cavity. This is important in all electron storage rings, but even more so in an FEL ring because of the high peak current. Secondly, transient coherent longitudinal oscillations are executed by the beam as it reenters the storage ring after a passage through the FEL undulator. These oscillations are excited because the beam loses energy to the FEL undulator. The maximum amplitude of the momentum oscillations is expected to be of the order of $\sigma_p = 0.002$, the expected relative energy loss by the beam to the undulator. This momentum deviation falls comfortably within the momentum acceptance of the accelerator. The coherent oscillations will be damped by radiation and, even more rapidly, by Robinson damping. A list of the rf parameters is given in Table III.

The purpose of the <u>bypass</u> is to extract the electron bunch from the storage ring, to channel it to the FEL undulator, and to reinject it into the storage ring with high transfer efficiency. The beam is extracted vertically from the downstream end. This scheme has a total bend of 180°, and requires only one kicker each for extraction and injection. Its layout is shown schematically in Fig. 6.

The layout of the achromat is a compromise between the geometric conditions imposed by the FEL beam extracted from a straight section of the ring, and the need for sufficient space to match the lattice functions. The layout we propose, shown in Fig. 6, is a system with two 45° dipoles separated by a 4 m straight. The straight section incorporates a geometrically symmetric DFD quadrupole triplet to complete the achromat. Besides completing the achromatic section, the triplet can be used to control the amplitude of the beta functions at the exit of the bending section. Some data on the <u>FEL undulator</u> are given in Table IV.

5. Summary and Conclusions

We have reported on a feasibility study of a storage ring for a single-pass, high gain Free Electron Laser operation. Important aspects of collective instabilities, lattice design, bypass considerations and operational requirements have been covered by the study. The general conclusions are that the high beam quality demanded by this particular mode of operation can be achieved with presently available accelerator technology. We have presented an example design of a storage ring able to produce coherent radiation at a wavelength of 400 Å with a power of the order of 150 MW peak and 0.3 W average.

Such a ring can also be used as a source of conventional undulator radiation because of its small natural emittance and lattice flexibility in the choice of the length of the straight sections.

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APPENDIX

LIST OF SYMBOLS USED IN THE TEXT

(in approximately the order they appear in the text)

r_e = classical electron radius

e = electron charge

λ_u = undulator wavelength

K = undulator deflection parameter

γ = ratio electron energy/rest energy

n_b = electron volume density = $\frac{\hat{I}}{ec2\pi\sigma_x\sigma_y}$

E = electron energy

$\hat{I}$ = peak electron current

N = number of undulator periods

$\epsilon_{xo}(\epsilon_{yo})$ = horizontal (vertical) rms natural beam emittance (i.e., as determined by radiation effects only)

$\beta_x(\beta_y)$ = horizontal (vertical) beta function

σ_ℓ = rms bunch length

F_L = form factor of the longitudinal microwave instability (≈ 1)

F_T = form factor of the transverse microwave instability (≈ 1)

α = momentum compaction factor

ν_s = synchrotron oscillation tune

β = ratio electron velocity/velocity of light

H = function related to the intrabeam scattering calculation

g_{ox} = horizontal emittance damping rate from synchrotron radiation

τ_T = Touschek scattering lifetime

g_{IBS} = growth rate of the horizontal intrabeam scattering process

τ_{IBS} = $1/g_{IBS}$

Table I. Short List of Lattice Parameters

Bending radius:	3.495 m
Beam Energy:	750 MeV
Field index in bending magnets:	5.0
Momentum compaction:	0.00492
Natural emittance:	4.6×10^{-9} m-rad
Betatron tunes:	$\nu_x = 7.85$, $\nu_y = 4.35$
Natural chromaticity:	$\xi_x = -16.6$, $\xi_y = -15.3$
Correction sextupole strengths:	$K'_F\ell = 4.94\ \mathrm{m}^{-2}$, $K'_D\ell = -4.6\ \mathrm{m}^{-2}$
Natural momentum spread:	$\sigma_{po} = 0.37 \times 10^{-3}$
Transverse damping times:	$\tau_x = 69.4$ ms, $\tau_y = 89.4$ ms
Longitudinal damping time:	$\tau_\varepsilon = 52.3$ ms

Table II. Some Parameters Predicted by ZAP

Parameters	$\varepsilon_x/\varepsilon_y$ a)		
$\varepsilon_x \times 10^9$	10:1	10.1	m-rad
$\hat{I}$		199	A
σ_ℓ		0.0125	m
τ_T	10:1	1.4	h
$\frac{\hat{I}}{\sqrt{\varepsilon_x \varepsilon_y}} \times 10^{-10}$	1:1	5.0	$\begin{pmatrix} A \\ m^{-1} \end{pmatrix}$
	10:1	6.2	
	100:1	10.5	
$\rho \times 10^3$	10:1	1.3	

a) horizontal/vertical emittance ratio

Table III. Some Acceleration and RF System Parameters

Peak effective rf voltage, V_o (including transit time)	1.3 MV
Radiation energy loss/turn, U_o	8 keV
Energy loss/turn in machine impedance, U_m	84 keV
RF frequency	500 MHz
Harmonic number	240
Synchrotron oscillation tune (ν_s)	0.018
Number of bunches for FEL operation	1
Average beam current	44 mA
Peak beam current	200 A
Shunt impedance	13.2 MΩ
Power dissipated in rf cavities	137 kW
Power dissipated in machine impedance	3.8 kW
Power delivered to beam	350 W
Robinson damping time	0.5 msec

Table IV

Undulator Parameters*

Photon wavelength (Å)	400		1000	
Electron energy (MeV)	500	750	500	750
Magnet period (cm)	1.85	2.29	2.36	2.91
K	2.50	3.61	3.77	5.26
Peak Magnetic Field (T)	1.45	1.67	1.71	1.93
$\beta_x = \beta_y$ (m)	2.31	2.97	1.95	2.59

*Undulator gap : 0.3 cm

FIGURE CAPTIONS

Figure 1	Schematic drawing of a storage ring with a bypass containing a high gain FEL.
Figure 2	Dependence of the peak current, $\hat{I}$, equilibrium emittance, $\hat{\varepsilon}_x$, and some FEL parameters (ρ, ℓ_e) on the momentum spread, σ_p. Degradation of performance (ρ_{eff}, ℓ_{eff}) with increasing momentum spread is apparent. A Lorentzian momentum distribution was assumed in the calculation of the degradation.
Figure 3	Energy dependence of the following parameters: Touschek lifetime for 3% rf bucket height, $\tau_T^{3\%}$; Intrabeam scattering lifetime, $\tau_{x,IBS}$; Equilibrium emittance, $\hat{\varepsilon}_x$; Bunch volume density, $\hat{I}/\gamma^2 \sqrt{\varepsilon_x \varepsilon_y}$; FEL parameter, ρ.
Figure 4	Lattice structure and functions in one period. The pattern repeats six times around the ring.
Figure 5	Layout of the transfer line to the FEL undulator.
Figure 6	Schematic layout of the storage ring and bypass.

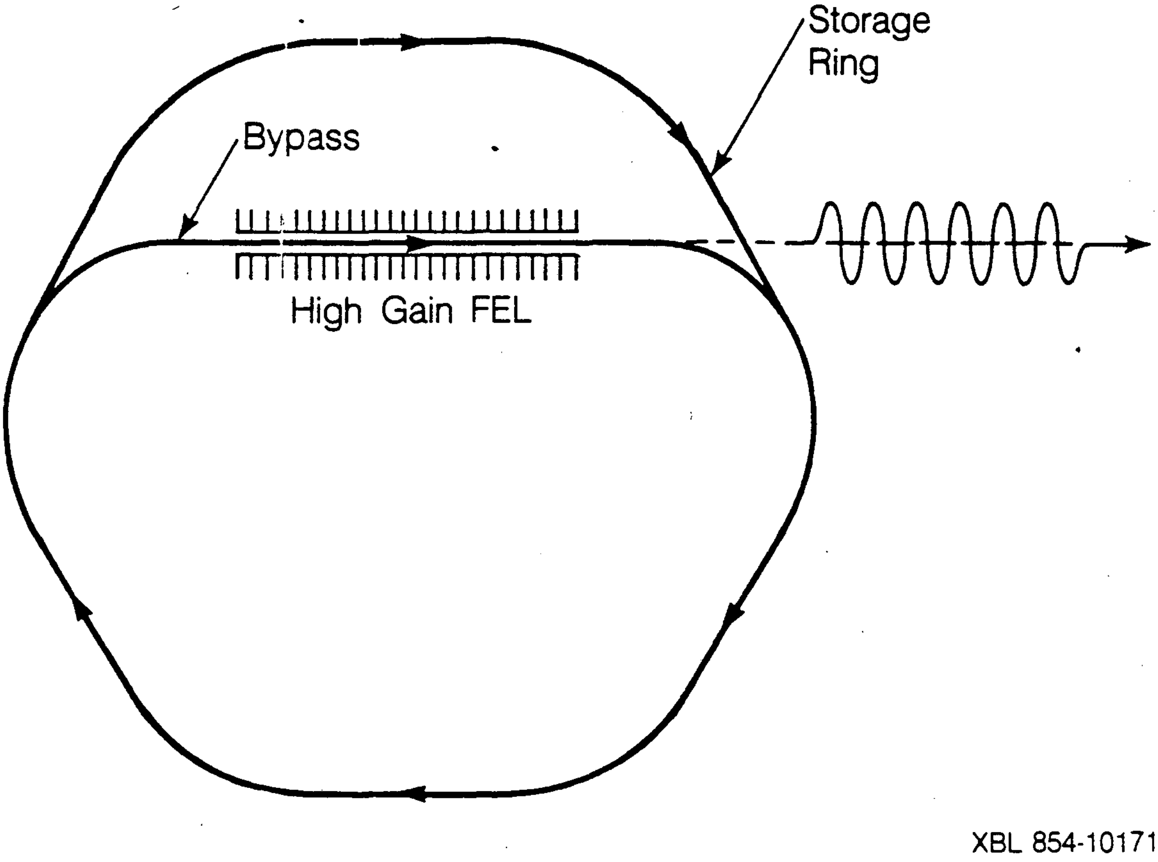
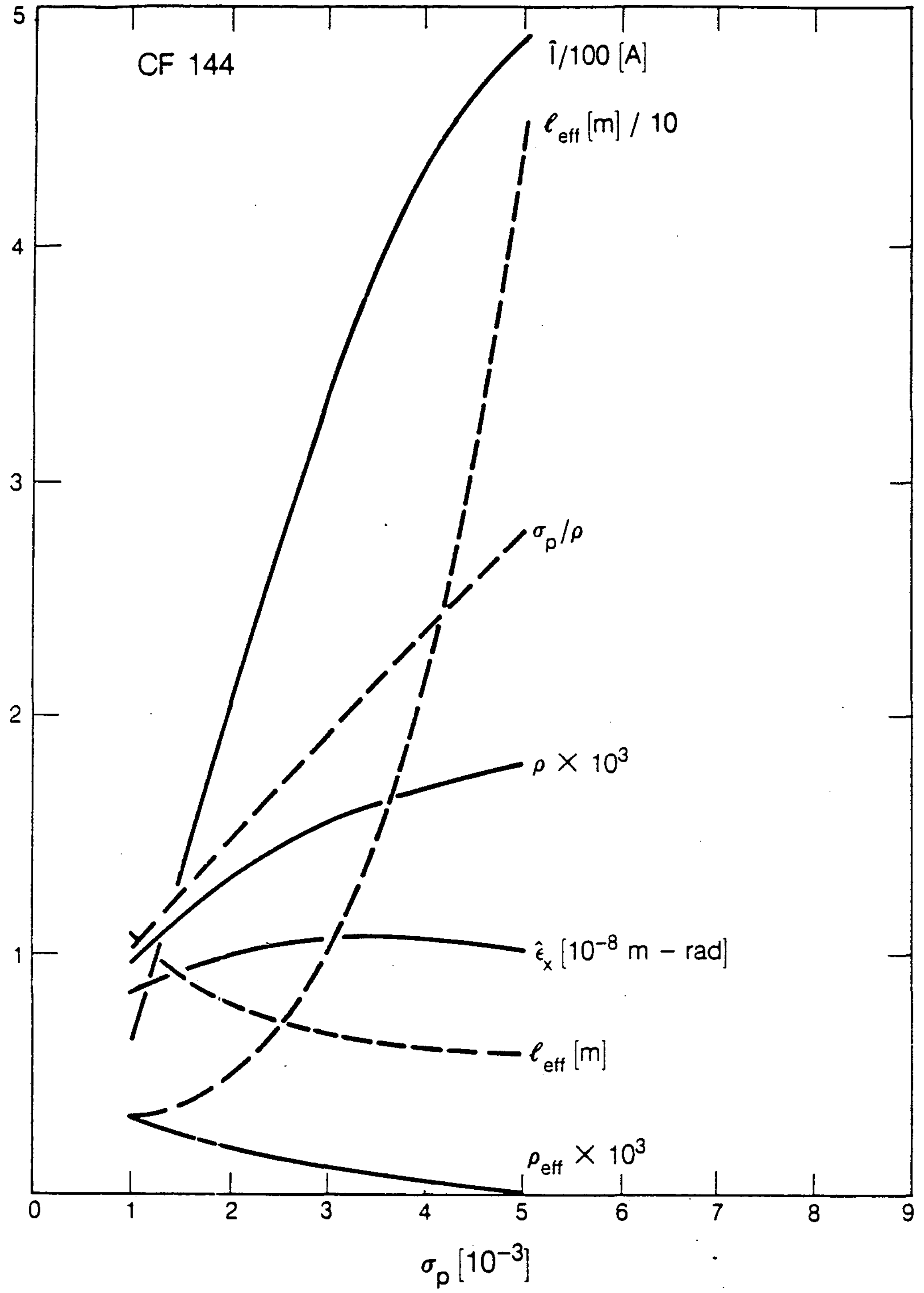


Fig. 1



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$\hat{I}/100\ [A]$
ℓ_{eff} [m] / 10
σ_p/ρ
$\rho \times 10^3$
$\hat{\epsilon}_x\ [10^{-8}$ m − rad]
ℓ_{eff} [m]
$\rho_{eff} \times 10^3$
0
1
2
3
4
5
6
7
8
9
$\sigma_p\ [10^{-3}]$
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Fig. 2

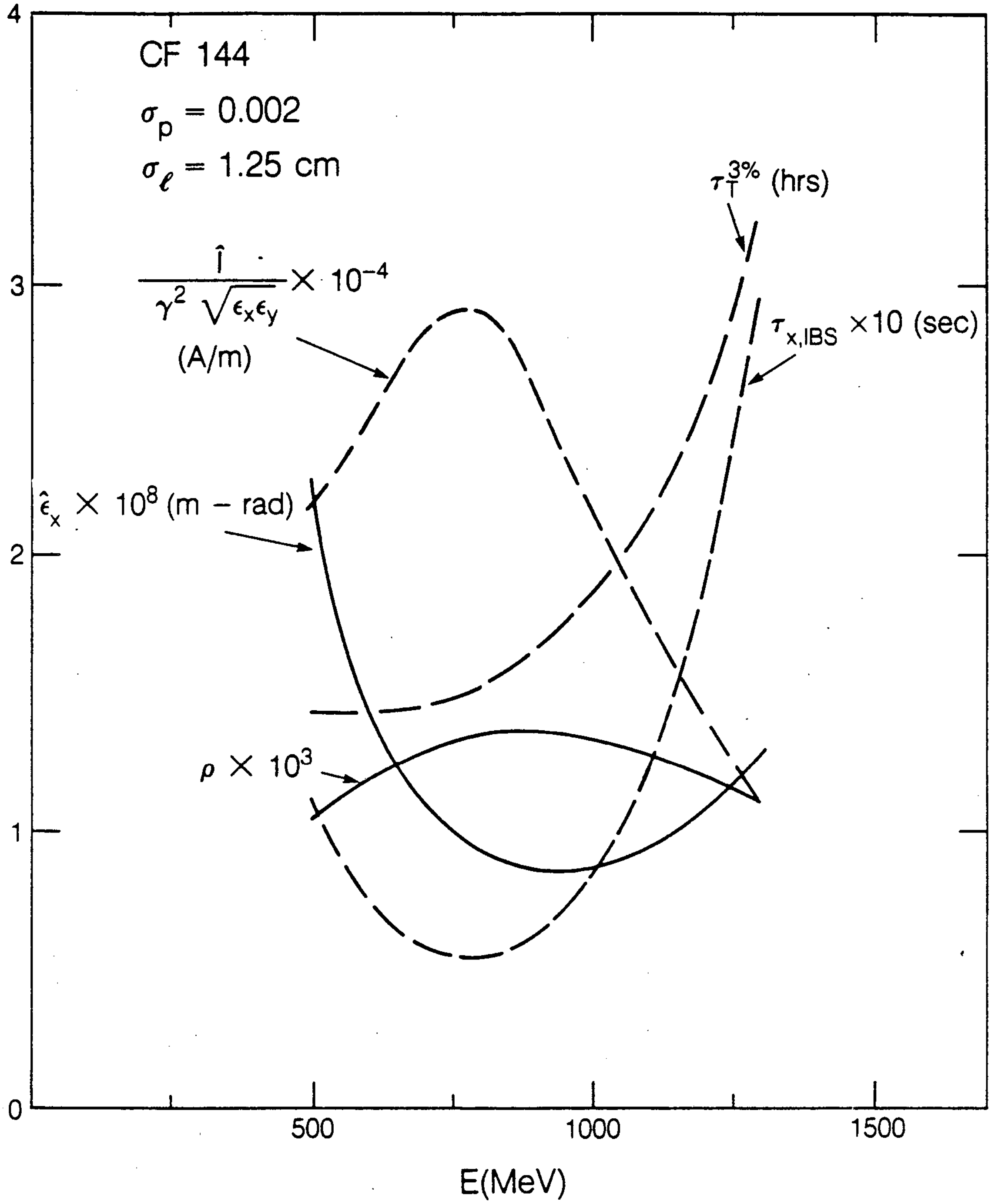

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Fig. 3

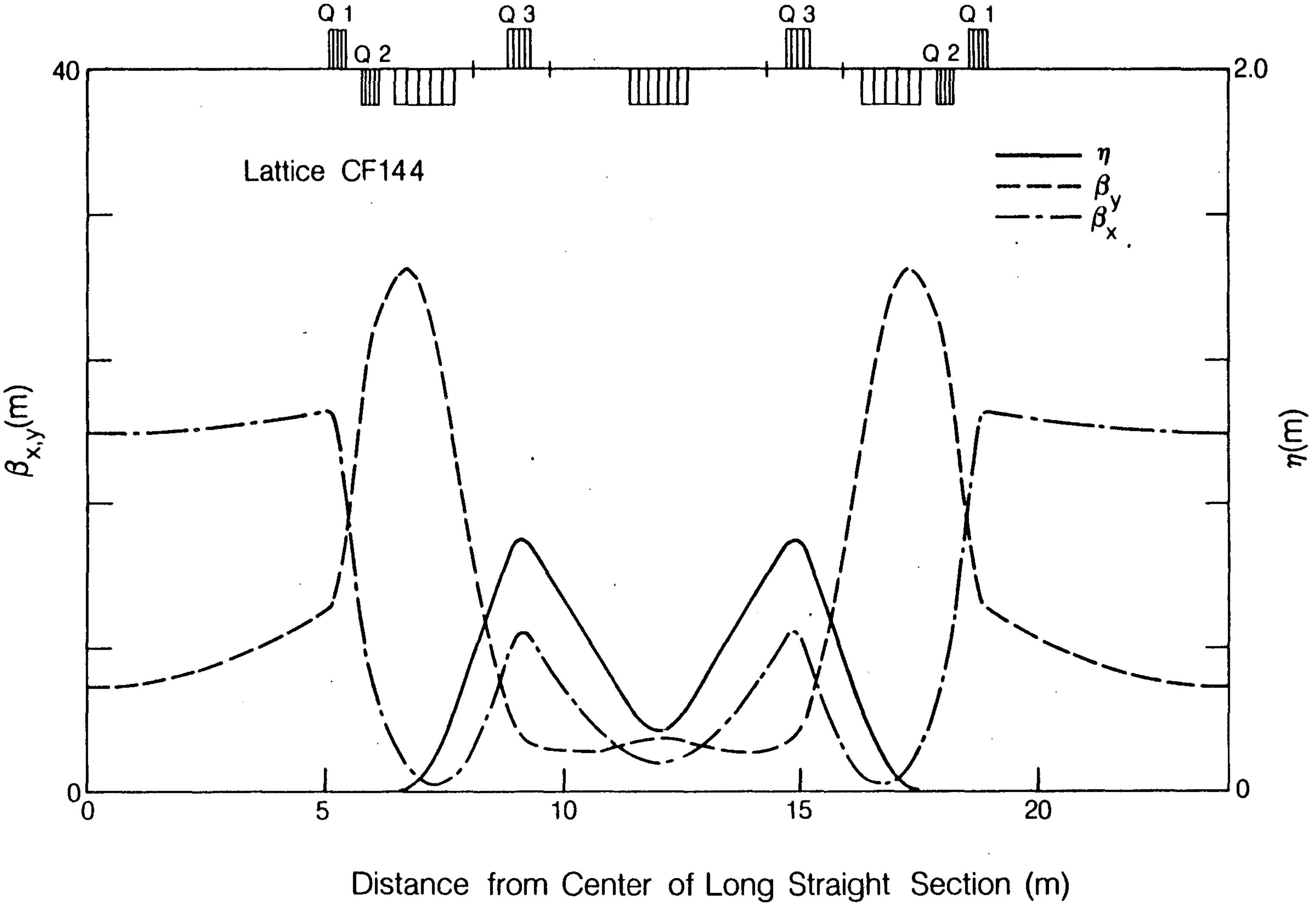

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Fig. 4

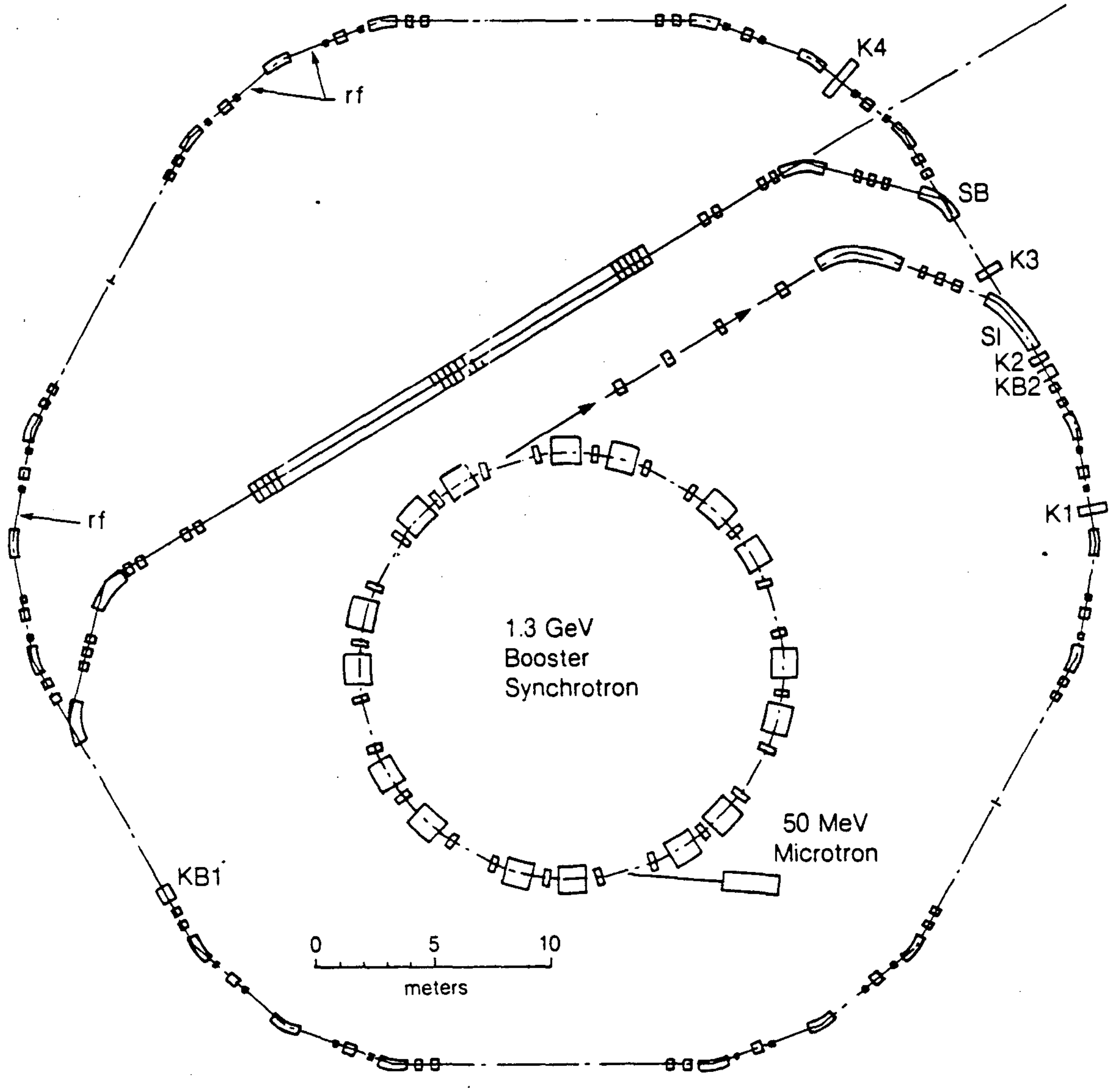

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Fig. 5

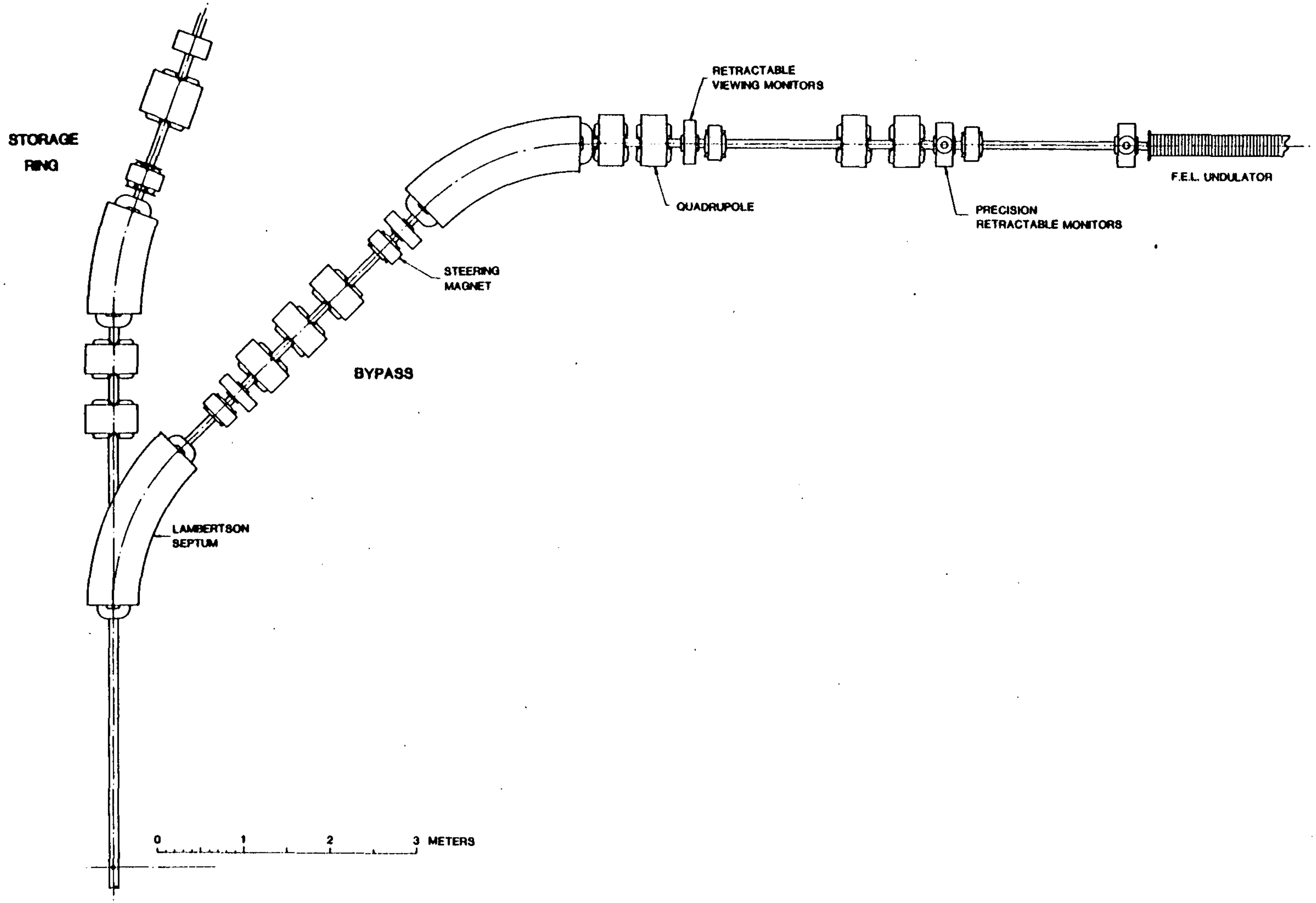

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Fig. 6

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