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Proposal to Construct an Antiproton Source for the Fermilab Accelerators

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Abstract

We propose to build a small storage ring for the accumulation of antiprotons produced in an external target. Stochastic and electron cooling will be used to reduce the transverse and longitudinal phase space of the antiprotons. The dynamics of stochastic and electron cooling will also be studied in this storage ring using circulating protons. The cooled antiprotons can be reinjected into the main ring or energy doubler ring; after simultaneous acceleration along with a proton bunch the accelerator will become a colliding $\bar{p}p$ machine with a center of mass energy range of 300-2600 GeV. Luminosities in the range 10^{29} - 10^{32} $cm^{-2}sec^{-1}$ are expected.

Contents

Introduction

The technological advances in the understanding of the cooling of the transverse and longitudinal phase space of R.F. bunched[1,2,3,4] beams as well as the availability of an intense source of anti-protons at Fermilab, the Fermilab main ring and Energy Doubler ring, have encouraged us to explore once again the old question of building a proton anti-proton storage ring. The physics possibilities of such storage rings operating in the 300-2600 GeV center of mass range are truly enormous. Near the top of the list of physics possibilities is certainly the production and observation of the W° intermediate vector boson through the process

$$\bar{p} + p \rightarrow W^\circ + X$$
$$\rightarrow \mu^+ + \mu^-$$

However, the collision of intense beams of matter and antimatter at extremely high center of mass energies is more than likely to involve completely undreamed of physics. We therefore think the physics frontier is justification enough for such a venture. In our feasibility study, although not entirely complete, we have uncovered no conceptual problems to building such a machine at Fermilab. The cost of the $\bar{p}$ cooling ring is modest on the scale of planned storage rings. We therefore propose that this machine be constructed at the earliest possible date at Fermilab and that one or more long straight sections be instrumented for physics experiments. The proposal submitted at this time focusses on the conceptual design of this machine. A more complete proposal for the construction of the cooling ring will be submitted in the near future.

2. Physics in Hadron - Anti-hadron Collisions

The possibilities of observing the production and decay of a very high mass ($\sim$100 GeV) intermediate vector boson are reason enough to construct such a machine. In addition for the highest energy option the average parton-antiparton collision has an energy in excess of the weak interaction unitarity limit, therefore the ultimate nature of weak interaction may be decided with this machine.

The study of purely hadronic $\bar{p}p$ interactions will be of great interest. For example the measurement of the total $\bar{p}p$ cross section at such high energies will surely be of interest. However it would be of no use to further catalouge the physics projects since the most interesting discovery to be made would almost certainly not appear on any list made at this time. This is, in fact, the main reason for building the machine.

3. General Scheme for Collecting and Cooling Anti-protons

The general scheme for obtaining a high intensity, cooled antiproton beam is as follows:

1. 3.5 GeV/c antiprotons are produced by an intense, R.F. bunched beam from the main accelerator. The beam energy should be above 50 GeV but need not be above 100 GeV.
2. The $\bar{p}$'s are transported into the accumulator ring by a special transport system that matches the phase space.
3. The antiproton bunch is initially cooled in transverse and longitudinal phase space by stochastic cooling similar to that operated at the ISR.
4. The $\bar{p}$ bunch is moved into a parking orbit and another

$\bar{p}$ bunch is injected. This operation is carried out ∿ few thousand times yielding 10^{10}-10^{12} antiprotons.

5. The antiprotons are decelerated to a momentum of 350 MeV/c. Stochastic cooling keeps the beam stable.
6. An intense electron beam is turned on with the electrons traveling with the same velocity as the $\bar{p}$ and in the same direction. Approximately 1 amp/cm^2 is used. The antiproton beam phase space is cooled further to a very small value.
7. The antiproton beam is accelerated up to 9.0 GeV/c.
8. The antiprotons are extracted into a transport system and carried back to the main ring.
9. The $\bar{p}$ are injected into the main ring and a pulse of 5×10^{10} - 5×10^{12} protons are obtained in the main ring and all accelerated up to 50 GeV/c.
10. For higher luminosity ($\sim 10^{30}$-10^{31}cm^{-2}sec^{-1}) requirements some additional R. F. bunching is required.
11. The p and $\bar{p}$ are accelerated to 200 GeV and collide at one or more long straight sections.
12. For operation of the energy doubler as a $\bar{p}p$ storage ring the $\bar{p}$ are first accelerated to 400 GeV/c and transferred to the energy doubler and coast in the "normal" direction. Protons are injected into the main ring, accelerated through transition, R. F. bunched (optional) accelerated to 400 GeV/c and injected into the energy doubler. The $\bar{p}$ and p beams are then accelerated to 1000-1300 GeV/c and collide. The main ring continues to

operate normally and continues to fill the $\bar{p}$ cooling ring for the next injection.

Before discussing in detail the scheme for cooling the transverse and longitudinal oscillations of the $\bar{p}$ beam we first briefly review the status of the theory for the cooling of massive particle beams in storage rings and accelerators.

4. Use of the Ring for Electron and Stochastic Cooling

Stochastic cooling has been successfully tried out on the ISR and electron cooling has been tested in Budker's Laboratory. We, therefore, have strong evidence that the general principles behind these cooling techniques are correct. In detail, however, there is still a great deal to be learned about stochastic cooling and electron cooling, especially as it applies to the problem of collecting and cooling a large bite in $\bar{p}$ phase space in order to construct a $\bar{p}$ injector for Fermilab. It appears that the same cooling ring that is used to store and cool the $\bar{p}$'s could be used to study these cooling processes using the copious beams of protons available from secondary targets. We would therefore propose to construct the cooling ring at the earliest possible date and carry out detailed studies of the cooling phenomena. A practical fallout from the electron cooling study might be the measurement of the e^- capture cross sections for the production of energetic H atoms. Such atoms can be useful in the heating of plasmas.

The cooling ring is therefore to be constructed in a flexible way with a varible range of parameters that would allow a detailed study of three dimensional stochastic cooling and electron cooling.

5. Cooling of Betatron Oscillations

About ten years ago, Budker[1] proposed electron cooling as a way to increase the phase space density of antiprotons stored in a small storage ring. He pointed out that the cooling process could replace the synchrotron radiation damping of e^+, e^- storage rings and permit high luminosity $p\bar{p}$ colliding beams. About five years later, Van der Meer[2] in an unpublished note, pointed out the possibility of cooling the betatron motion in a storage ring with a wide band electronic feed-back loop based on the detection of the microscopic fluctuations of the position of the beam. Experimental evidence of successful electron cooling and of stochastic cooling have been recently reported at Novosibirsk[3] and at CERN[4]. Recently, Cline, McIntyre and Rubbia[5] have pointed out that the high energy rings at CERN and at FNAL could be transformed into a $p\bar{p}$ storage ring of about 600 GeV in the center of mass. Finally the projected Energy Doubler[6] at FNAL could give access to the fantastic energy of 2000 GeV in the center of mass.[7]

The present paper concentrates on a realistic scheme of producing $\bar{p}$'s with sufficient phase space density to reach luminosities in excess of 10^{30} $sec^{-1}cm^{-2}$ at 600 GeV in the center of mass. The main step is repetitive accumulation with no increase of total phase space. The antiproton yield in a realistic collecting channel increases sharply over the energy interval 1.5-4 GeV/c and this contrasts with the increase of electronic cooling times ($\sim \beta^3\gamma^5$) and the technological difficulties of a high energy, high current electron cooling beam (about 100amps dc at 750 keV). A comparatively simpler and faster accumulation scheme is proposed. It can operate at higher antiproton momenta and is based on betatron damping with a low signal (10 V) feed-back loop.

Accumulation can be repeated until about a few times 10^{10} particles are stored. At this point, the damping time becomes increasingly long and the main stack must be separated from the newly injected beam. A two-stage accumulation scheme is proposed to reach higher numbers of antiprotons. Final operations are required in order to adjust the beam parameters to the injection in a storage ring.

6. Production of Antiprotons

Antiprotons must be produced in a high density target bombarded by the proton beam. In order to achieve a reasonable yield, the antiproton channel collects negative particles produced around the forward direction (0° production angle). The main beam is then conveyed to a beam dump. The useful duration of the proton burst is about four times the revolution of the storage ring (4 x 600 ns = 2.4 μs). Some R.F. manipulations in the main accelerator may be required in order to achieve the largest possible number of protons in this time period.

The target is an iridium rod, 4.4 cm long. Following a calculation by Ranft[8] one gets an overall target efficiency of 1.3. The total energy lost in the target can be as large as 10^5 Joules at each pulse and it leads to an instantaneous evaporation. An automatic replacement device must be provided. Care must be taken that the radioactive debris are safely handled.

The beam transport after the target must collect the largest

Table 1

Parameters of the $\bar{p}$ Focusing Front End

Nominal $\bar{p}$ momentum		3.0 GeV/c
Maximum accepted angles		
(a) Vertical plane	θ_V	30×10^{-3} rad
(b) Horizontal plane	θ_H	30×10^{-3} rad
Parameters of first doublet: (Q_1, Q_2)		
-free distance to first lens		2.5 m
-gradient of first lens (Q_1)		690 Gauss/cm
-gradient of second lens (Q_2)		560 Gauss/cm
Useful half-apertures of each lens (Q_1, Q_2)		
(a) Vertical		120 mm
(b) Horizontal		280 mm
Values of the β function at the target location		
(a) Vertical plane	β_V^*	2.5 cm
(b) Horizontal plane	β_H^*	10 cm
Emittances of the accepted beam		
(a) Vertical plane		$22.5\ \pi\ 10^{-6}$ rad m
(b) Horizontal plane		$90\ \pi\ 10^{-6}$ rad m
Maximum accepted momentum spread	$\frac{\Delta p}{p}$ =	2×10^{-2}
Target material and length	Iridium rod,	4.4 cm
Target efficiency	η_T	0.33

Table 2

List of Parameters of First Doublet

Maximum field gradient	690 Gauss/cm
Current	1130 A
Voltage	145 V
Resistance at 50 C°	0.13 Ohm
Power consumption	162 KW
Magnetic length	1100 mm
Weight of copper	1.15 t
Weight of iron	10 t

possible fraction of $\bar{p}$'s produced. We have conisdered only standard quadrupoles, i.e., we have excluded the use of pulsed lenses and/or sup and/or superconducting elements. A possible design is shown in Fig. 2. The main parameters of the critical front end of the $\bar{p}$ focusing channel are listed in Table 1. The first qudrupole doublet of lenses is taken from a realistic design (the storage ring DORIS). Parameters are given in Table 2. A drawing of the lens is shown in Fig. 3. In order to accommodate the required emittances, the aperture must be as large as 52 x 24 cm^2. Subsequent lenses are necessary to match the $\bar{p}$ beam to the betatron functions of the ring. Bending magnets move the residual proton beam to a beam dump and match momentum compactions. The whole beam transport is pulsed only for a short period during each injection cycle.

The yield of antiprotons produced in the momentum interval $3 < p < 4$ GeV/c and in the forward direction for an incident proton energy $E_p = 23.1$ GeV on a lead target has been measured by Dekkers et al.[9]:

$$\frac{d^2N}{dpd\Omega} = 2 \times 10^{-2}\ \mathrm{GeV}^{-1}\mathrm{st}^{-1}(\mathrm{int.}\ p)^{-1}.$$

Since the acceptance of the injection channel is relatively large, the variation of yield with the angle of production must be taken into account. The following parameterization has been assumed for the invariant cross section:

$$E\frac{d^3N}{dp^3} = e^{-6p_\perp} f(p_{||}).$$

Integration up to an angle of θ_M from the forward direction gives

$$\frac{dN}{dp} = 1.93 \times 10^{-4}(1 - e^{-6p\theta_M})\ \text{GeV}^{-1}(\text{int. p})^{-1}$$

The fraction of the accepted $\bar{p}$'s as a function of θ_M is displayed in Fig. 4. For $\theta_M = 30 \times 10^{-3}$ rad., about 40% of $\bar{p}$'s are collected and $\frac{dN}{dp} = 7.72 \times 10^{-5}$ GeV^{-1}(int. p)$^{-1}$. Assuming $\frac{\Delta p}{p} = 2.0 \times 10^{-2}$, i.e., $\Delta p = 60$ MeV/c, we get $N_{\bar{p}} = 4.63 \times 10^{-6}$(int. p)$^{-1}$ (at $E_p = 23.1$ GeV). Including target efficiency (1/3) and the corrections due to the finite target length (0.9), we arrive at the figure: $N_{\bar{p}} = 1.53 \times 10^{-6}$ (incident p)$^{-1}$ (at $E_p = 23.1$ GeV). For incident protons of $E_p \geq 60$ GeV, we assume a yield 2.5 times larger, i.e., $N_{\bar{p}} = 3.84 \times 10^{-6}$ (incident p)$^{-1}$.

The FNAL accelerator, at the time of the proposed experiment, probably will have reached the design intensity of 5×10^{13} ppp. One turn ejection will then give 6.36×10^{12} protons over the 4 turns of the storage ring. We can hope to accumulate about 2.44×10^{7} $\bar{p}$'s at each injection pulse. This is only 10% of the available protons from the accelerator. Schemes are possible, in which bunching at low frequency is used to increase considerably the useful number of antiprotons. We shall not consider these improvements at the present stage.

7. The Storage Ring

The main features of the lattice of the storage ring can be reasonably well defined by simple considerations. The first choice is the momentum of the antiprotons, which has been somewhat arbitrarily set to 3.8 GeV/c as a compromise between size, cost and performance. This, in turn, leads to two possible choices of the

Table 3

Main Parameters of the Cooling Ring

I. Lattice and Orbit Parameters

- Nominal momentum	p_o	3.8 GeV/c
- Guide field	B_o	12.0 K Gauss
- Curvature radius (magnetic)	ρ	10.66
- Average radius	R	34.8 m
- Number of periods	N	16
- Period structure		0/2 BBDFDBB0/2
- Period length	ℓ_p	16.54 m
- Number of bending magnets/period		4
- Quadrupole gradient for ν = 1.75	F	690 G/cm
	D	480 G/cm
- Quadrupole gradient for ν = 2.25	F	157 G/cm
	D	157 G/cm
- Nominal length of F-quadrupole		0.75 m
- Nominal length of D-quadrupole		0.5 m
- Nominal length of bending magnet		2.09 m
- Length of interelement gap		1.0 m
- Free length in empty semi-period		8.0 m
- Nominal working point	$\nu\begin{Bmatrix}\nu_x = 1.84\\ \nu_y = 1.68\end{Bmatrix}^*$	= 2.25
- Total transistion energy/rest energy	γ_t	1.9
- Phase advance/period	μ	81°
- Maximum β value in F-quadrupole	$\hat{\beta}_H$	22.97 m
- Minimum β value in F-quadrupole	$\check{\beta}_V$	9.45 m
- Maximum β value in D-quadrupole	$\hat{\beta}_V$	14.88 m
- Minimum β value in D-quadrupole	$\check{\beta}_H$	8.78 m

Table 3 (cont.)

- Maximum of momentum compaction function	$\hat{\alpha}_p$	8.78 m
- Minimum of momentum compaction function	$\check{\alpha}_p$	5.65 m

*Basic structure - long straight section at 1 integer each $2\nu_x$ and 1/2 integer each $2\ \nu_y$, thus $\nu_x = 5.84$ and $\nu_j = 3.68$ for this machine with 4 long straight sections.

II. Dipole Magnets

- Number of units	32
- Nominal length	2.09 m
- Gap height	100 mm
- Useful width	225 mm
- Lamination height	50.8 cm
- Lamination width	155 cm
- Core weight (packing fraction 0.96)	13.4 tons
- Copper weight	2.0 tons
- Number of turns	120
- Conductor dimension	43 x 14.25 mm^2
- Cooling hole	6 m dia
- Ampere turns	100,000
- Nominal current	850 A
- Current density	500 amp/sq in
- Power losses	18 KW
- Resistance	7.2 x 10^{-3} Ohm
- Voltage drop/unit	11.4 volts

Table 3 (cont.)

III. Quadrupole Lenses

- Number of units	20
- Field gradient	250 Gauss/cm
- Current	285 A
- Voltage	7.5 V
- Power consumption	2.13 KW
- Magnetic length	590 mm
- Number of turns/coil	25
- Conductor dimensions	11 x 11 mm^2
- Cooling hole (ϕ)	4 mm
- Iron weight	820 Kg
- Copper weight	140 Kg

IV. Main Power Supply

- Bending magnets	
(a) Voltage	250 V
(b) Current	1580 A
- Quadrupole lenses (2 separate supplies for D and F)	
(a) Voltage (each supply)	82 V
(b) Current	285
- Total installed power for magnets	500 KW

Table 3 (cont.)

V. Correcting Elements	
- Sextupoles	16
- Octupoles	16
- Bending magnets for orbit correction	32
- Skew Quadrupoles (45°-tilt)	2
- Pick-up stations (for R.F. bunched beam only)	40
VI. Vacuum System	
- Ring average pressure (90% H_2, 10% N_2)	10^{-10} Torr
- Number of ion pumps	40
- Number of rotary pumps	5
- Chamber wall thickness	2 mm
- Bake-out heating elements and thermal insulation thickness	7 mm
- Temperature of bake-out	350C°
- Inner vacuum chamber apertures	
(a) Vertical	80 mm
(b) Horizontal	225 mm

transition energy γ_t (in units of the rest mass) which must be kept as far as possible from the working point: $\gamma_t >> 3$ and (b) $\gamma_t << 3$. Alternative (b) is preferred because stochastic damping requires the largest possible randomizing effect from the momentum spread.

Another relevant consideration is the radial aperture associated with the momentum spread of the beam at injection. The average radial displacement $<\Delta r>$ around the orbit and the fractional momentum error $\frac{\Delta p}{p}$ are related by the average value of the momentum compaction function $<\alpha p>$:

$$<\Delta r> = <\alpha p>\frac{\Delta p}{p}$$

The transition energy in turn is connected to $<\alpha p>$ by the relation:

$$\gamma_t = \sqrt{R/<\alpha p>}$$

where R is the average radius of the ring. A reasonable choice is $<\alpha_p> \simeq 4$ m, corresponding to a radial aperture allowance of 8 cm for $\Delta p/p = 2\%$. Since $R \simeq 2\rho = 32$ m, $\gamma_t \cong 2.00$. Furthermore, we can relate γ_t to ν the number of betatron oscillations/turn because of the relatively exact expression $\gamma_t \simeq \nu$. Taking ν values equally distant from integer and half integer resonances gives quantized values of $\nu = 1.25, 1.75, 2.25, 2.75$ and so on. The value $\nu = 2.25$ is the one suggested by the previous considerations. The number N of equal cells around the circumference of the ring is related to ν by the betatron phase advance/cell, $\mu = \nu/2\pi N$. For optimized designs, the phase advance has a value approximately around $\pi/2$, giving $5 < N < 15$. Lower values of N are preferable since (a) we can get the largest straight sections for given values of R and ρ and (b) we can exploit the characteristic shape modulation of the size due to the strong focusing in order to optimize the apertures of the components around the ring. Several possible alternatives of the initial parameters have been considered.

The main parameters of an example ring are given in Table 3. A schematic drawing of the ring is shown in Fig. 1a. A possible magnet and vacuum chamber design is shown in Fig. 1b.

8. Injection and accumulation

The injection is performed in four turns in order to collect the longest possible proton burst from the accelerator (Fig. 4b). Since the diameter of the ring is ~200m, this corresponds to an injection time of 2.4 μs. Injection of the new beam must not disturb the main stack already present in the ring. The vertical plane is preferred since in this way the stochastic damping is not affected by radial effects due to momentum spread. The injection procedure is as follows:

(i) a pair of fast (~50 ns risetime) kickers produce a vertical bump of few centimeters in order to bring the injection septum within the aperture of the ring. The bump however leaves enough aperture around the equilibrium orbit, so that the main stored beam does not hit the septum. (See Fig. 5)

(ii) The new beam is injected through the septum and four turns are stored before the first injected particle reaches the septum. At this moment the bump is quickly turned off (~50 ns decay time) and the injected beam appears in the phase space diagram as a halo around the old stack (Fig. 6).

(iii) After a few milliseconds to let π^-, K^-, etc. decay, the betatron cooling is turned on and it collapses the newly injected beam on the old stack (Fig. 7a,b,c,d,e). Note that the old stack is continuously damped, thus correcting the inevitable phase space blow-up due to the injection procedure.

The stochastic damping parameters[10] are summarized in Table 4. Figure 8 shows the expected stacking time as a function of the number of antiprotons present in the ring. Note that the large momentum spread is necessary in order to randomize the sample in a few turns.[2] If C is the circumference of the orbit,

$$\frac{\Delta C}{C} = \left(\frac{1}{\gamma^2} - \frac{1}{\gamma_t^2} \right) \cdot \frac{\Delta p}{p} \ .$$

For $C = 200\text{m}$, $\frac{\Delta p}{p} = 10^{-2}$, $\gamma_t = 2.0$, and $\gamma = 3.6$,

we get $\Delta C = 0.35$ m/revolution, which is just adequate. If, for instance, instead $\frac{\Delta p}{p} \sim 10^{-3}$, according to Monte Carlo simulations we expect an increase of about 7 times in the cooling time.

The horizontal betatron motion is almost certainly weakly coupled with the vertical one by the presence of parasitic fields. It is therefore advisable to damp both modes of oscillations. This can be done very simply by increasing the coupling of the two modes with a skew quadrupole.

9. Damping of momentum spread

After a few times 10^{10} particles are accumulated in the ring, the stacking time becomes quite long and it is advisable to remove the main beam. At this point we propose to reduce the momentum spread with stochastic momentum damping. The main parameters of the momentum damping[10] are listed in Table 5. The main feature of momentum damping is that its rate becomes progressively slower as

Table 4

Main Parameters of Betatron Stochastic Damping

Pickup aperture		30 cm
Pickup length		50 cm
Pickup bandwidth		from 100 MHz to 400 MHz
Equivalent sample length		50 cm
Noise figure of amplifier		3 db
Pickup importance		120 ohm
Number of pickup elements		16
Deflector		
Deflector length (code unit)		50 cm
Number of units		4
Deflector aperture		30 cm
Deflecting power		4.75×10^{-8} rad/volt
Cooling parameters at	2.5×10^{7} $\bar{p}$	2.5×10^{10} $\bar{p}$
Antiproton current	6.6 μA	6.6 mA
Number of $\bar{p}$'s in sample	1.4×10^{4}	1.4×10^{7}
R.M.S. rise at end cooling cycle	1.0 cm	1.0 cm
R.M.S. fluctuation in average position	84 μ	2.67 μ
R.M.S. signal from 16 pickups	59.1 mA	1.87 μA
R.M.S. noise from 16 pickups	565 nA	565 nA
Cooling time at optimum gain	11.4 sec	12.5 sec
R.M.S. deflection angle (at optimum gain)	5.74×10^{-8} rad	1.66×10^{-7} rad
Total R.M.S. voltage	11.55 V	3.49 V

Table 5

Parameters of the Momentum Cooling

Pickup aperture		30 cm
Pickup length		75 cm
Pickup bandwidth		from 100 to 200 MHz
Sample length		1.5 m
Number of pickup elements		16
R.F. cavities		10
R.F. cooling impedance		100 Ω
Cooling parameters at		2.5×10^{10} $\bar{p}$
Number of $\bar{p}$ in sample		4.2×10^{7}
R.M.S. momentum spread		
(a) at beginning	0.84×10^{-2}	
(b) at end cooling		0.84×10^{-3}
R.M.S. fluctuation of energy	3200	320 eV
R.M.S. signal from pickup	7.56	0.745 μA
R.M.S. noise from 16 pickups	565 nA	565 nA
Cooling time (inverse rate) of optimum gain	(335) 187 sec	1300 sec
R.M.S. voltage in each cooling	(184 V) 220 V	32 V
Power in each cavity	(340 V) 84 kV	84 W
Beam invariant area	36 eV sec	3.6 eV/sec

$\frac{\Delta p}{p}$ diminishes because of the corresponding increase of the de-randomizing time of the sample.[2] It is impractical to reduce the momentum spread to less than about $\frac{\Delta p}{p}$ ~2×10^{-3} full width. This corresponds to an invariant phase area of the beam of 3.6 eV sec, which is still much too large to be injected in the main ring. We propose at this point to capture adiabatically the beam with R.F. of the lowest harmonic number (h=1) and to decelerate it until it reaches approximately 350 MeV/c, corresponding to about 60 MeV kinetic energy. The relative beam sizes will increase by the factor $(\beta\gamma)^{1/2}$ which is about 3.16. The available apertures should then be sufficient. The momentum spread will also increase to about 7×10^{-3} after adiabatic debunching. Assuming some blow-up in the debunching process, it is probably appropriate to assume that the beam will have a forward relative momentum spread $\frac{\Delta p}{p} = 10^{-2}$ at p = 350 MeV/c.

The minimum R.F. voltage required to capture at p = 3.0 GeV/c a beam of area A = 4 eV-sec and h = 1 is easily calculated. It is

V_o = 7280 Volt at f_o = 1.7 MHZ.

At the value p = 350 MeV, these figures change to:

V_o = 1748 Volt at f_o = 580 KHZ.

One simple cavity of the type PPA (drift tube) is amply sufficient in order to provide the required voltage.

10. Brief Summary of the Theory of Electron Cooling

The Novosibirsk group has demonstrated that low momentum proton beams can be "cooled" to very small transverse dimensions ($<1mm^2$) and very small momentum spread ($<\delta p/p < 10^{-4}$). The basic idea is that the transverse and longitudinal oscillations of the proton beam are transferred to an electron beam that is injected in one of the straight sections of the storage ring. For maximum cooling efficiency the velocity of the $\bar{p}$ and of the e^- should be the same ($\beta_{\bar{p}} = \beta_{e^-}$) since the coulomb scattering cross section will be a maximum.

The cooling time for a parallel e^- and p (or $\bar{p}$) beam is given by ($\delta\theta_e << \delta\theta_{\bar{p}}$)

$$\tau = 0.5 \left(\frac{M_{\bar{p}}}{m_{e^-}}\right) \frac{\gamma_{\bar{p}}^5 \beta_{\bar{p}}^3 (\delta\theta_{\bar{p}})^3}{n_e r_e^2 cL\ \eta\ \ell n\ (\delta\theta_{\bar{p}}/\delta\theta_e)}$$

where r_e = classical electron radius

n_e = electron beam density

$\delta\theta_{\bar{p}}$ = $\bar{p}$ beam divergence

$\gamma = E_{\bar{p}}/m_{\bar{p}}$, $\beta_{\bar{p}} = (P_{\bar{p}}/E_{\bar{p}})$

η = cooling length/total circumference of cooling ring

L = cooling length (M)

The important features of the cooling time formula is

$$\tau \propto \frac{1}{\text{(cooling length)}} \frac{\gamma_{\bar{p}}^5\ \beta_{\bar{p}}^3\ \text{(}\bar{p}\text{ beam Divergence)}^3}{[n_e]}$$

The γ^5 factor increases the cooling times, for reasonable electron current densities, to very long times at high $\bar{p}$ moments. [i.e., ($\bar{P}_p$ = 3 GeV/c), $\gamma^5 \simeq 243$]

The dependence on the $\bar{p}$ beam divergence shows the desirability of precooling the $\bar{p}$ beam to reduce the divergence. Finally, the cooling time depends inversely on the cooling length and electron beam density. It is clear that the γ^5 and (divergence)^3 factors dominate the cooling time and since the cooling length and electron current are linear efforts, electron cooling must be carried out at low momenta.

11. Electron Cooling Times

At 350 MeV/c $\bar{p}$ momenta very short cooling times can be achieved with rather modest electron beams. A schematic of the cooling straight section is shown in Fig. 9. Electrons are obtained from a large aperature electron gun (Pierce gun) accelerated to a 33 KeV and injected into the storage ring. The electron beam divergence is kept low with a small longitudinal magnetic field in the storage ring. The electrons are deflected out of the storage ring, and deaccelerated and collected in a Faraday cup. The power dissipation is kept low by good electron beam optics. An inefficiency of $\sim$1% seems possible. The expected cooling times are given in Table 6 along with the current density and expected power dissipation. Note that the cooling times are quite short even for modest electron currents and resulting small power dissipation. The electron guns and power supply needed for the electron cooling are modest and easily obtained commercially.

We expect that the electron cooling will reduce the transverse dimension of the $\bar{p}$ beam to $\lesssim 1$ mm^2 and the beam momentum spread $< 10^{-4}$. The exact values depend on the residual gas scattering and the accuracy of satisfying the velocity conditions $\beta_{\bar{p}} = \beta_{e^-}$.

12. Luminosity Estimates

In order to estimate the luminosity we parameterize the lumi-

Table 6

Electron Cooling Times (350 MeV/c $\bar{p}$'s)

(5m Cooling Length)

Beam Size	e^- Current/cm^2	Cooling Time	Power Dissipation (1% Off)
1 cm^2	0.1 amp/cm^2	30 sec	0.16 KW
10 cm^2	1 amp/cm^2	3 sec	15 KW
10 cm^2	0.1 amp/cm^2	30 sec	1.5 KW

nosity as a function of the number of protons and antiprotons in the machine. Figure 10 shows the resulting isoluminosity curves. The assumed emittance for the proton and antiproton beam is also given on Fig. 10.

13. Costs, Early Tests and Time Table

We have estimated the cost of the cooling ring and associated devices. The estimates are listed in Table 7. These numbers are extrapolations from previous projects known to us. Harder numbers will be available by mid summer 1976 as a more complete cooling ring design is obtained.

The early tests of the cooling ring beyond simply making it work will concentrate on the study of stochastic and electron cooling of proton beams. We note that cooled proton beams might be useful to decrease the emittance of the protons in the main ring and increase the luminosity of the $\bar{p}p$ colliding beam devices. Independent of this possibility we wish to study the parameters of stochastic and electron cooling to better understand these phenomena. After the proton cooling studies we would start injecting antiprotons to study the accumulation times and characteristic cooling times as well as R. F. bunching. Finally the deacceleration of the antiprotons would be attempted and the electron cooling option.

Table 7

Estimated Cost of Cooling Ring

	$\times 10^6$ \$
Design	0.1
Electron Cooling	0.5
Stochastic Cooling	(0.5 - 1)
Dipoles	0.5
Quadrupoles	0.16
Vacuum Chamber	1.2
Power Supply	0.5
R. F. System	0.5
Injection	0.75
Extraction	0.25
	4.96 (5.46) $\times 10^6$ \$

In order to study the injection of antiprotons into the main ring we suggest that protons be used initially and accelerated the wrong direction in the main ring. We realize that the scheme of collecting, storing, cooling and reinjection protons or antiprotons into the main ring is very complex, however, we remind the reader that the scheme for obtaining 5×10^{13} protons per pulse in the present Fermilab machine seemed extremely complex only 5 years ago, but now is taken for granted.

The tentative time table for the cooling ring is as follows:

August 1976	CP and D funding starts (??)
September 1976	Full Ring design
October 1976	First prototype dipole and quadrupole magnet construction and field map
January 1977	Bids out for dipole and quadrupole magnets and coil construction

(Allow 8 months for magnet construction)

Summer 1977	Start vacuum chamber and ion pump construction - R. F. prototype
Fall 1977	Prototype stochastic and Electron cooling devices
January 1978	Start assembly of cooling ring at Fermilab
Spring 1978	Install R. F. system
Summer 1978	Install electron cooling and stochastic cooling devices
Fall 1978	Install beam injection and extraction system
Fall 1978	First injection of protons and antiproton and study of cooling phenomena

January 1979	First injection of antiprotons into Fermilab main ring
Spring 1979	Complete detector at interaction region
Summer 1979	Start of $\bar{p}p$ colliding beam experiments
Fall 1979	Observe first W production

14. Comments

It is expected that other people will join this effort including Rae Steining and perhaps others from Fermilab.

We wish to thank all the people who have patiently explained some of the details of cooling to us and have critizied our thinking on this subject.

We would like to especially acknowledge Drs. T. Collins, R. Herb, F. Halzen, S. Glashow, E. Picasso, G. Petrucci, N. Ramsey, L. Sulak, L. Thorndahl, L. Teng and S. Weinberg for helpful discussions and suggestions.

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6. Proposal for the Energy Doubler (1975).

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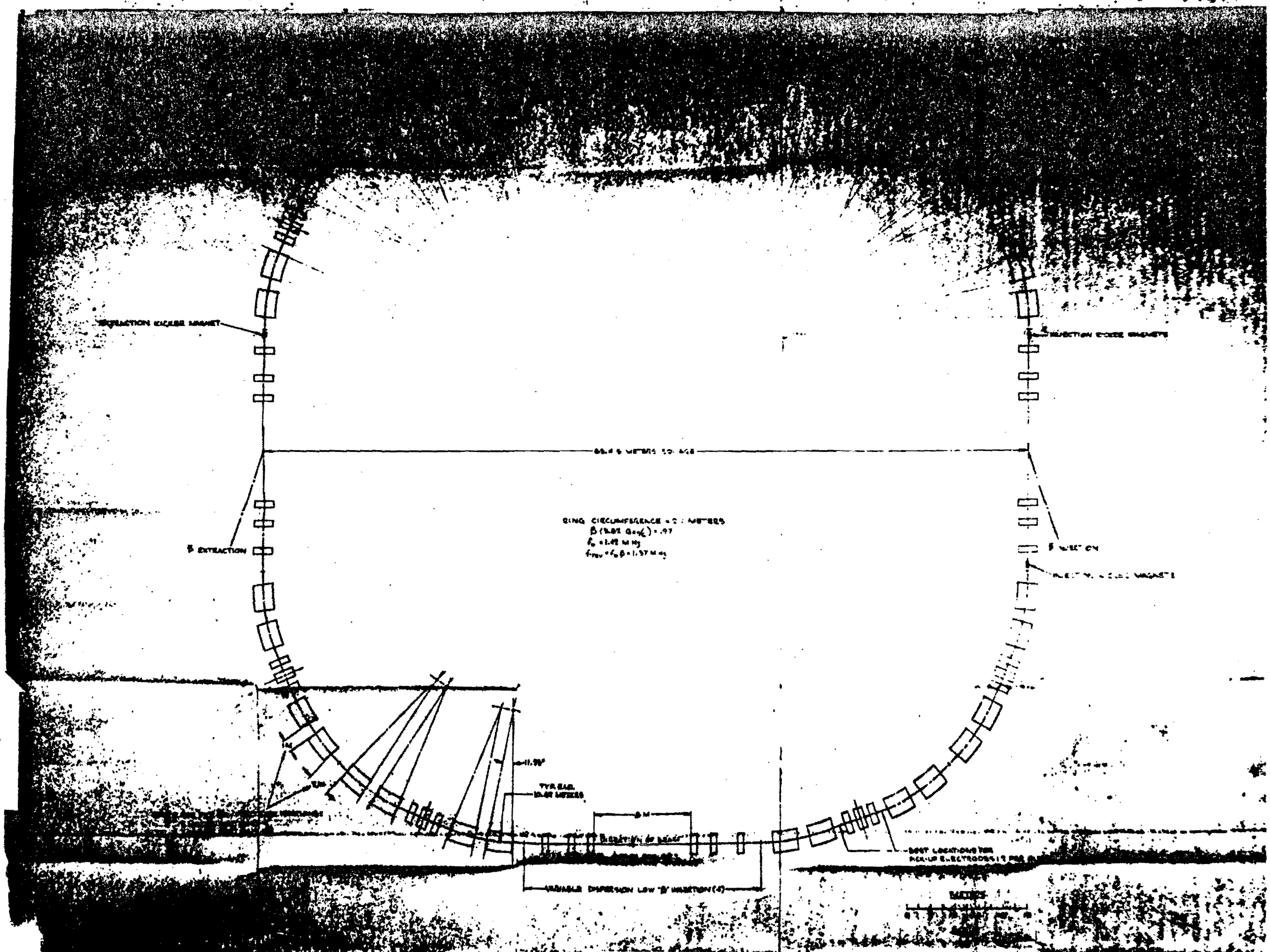


Fig. 1a

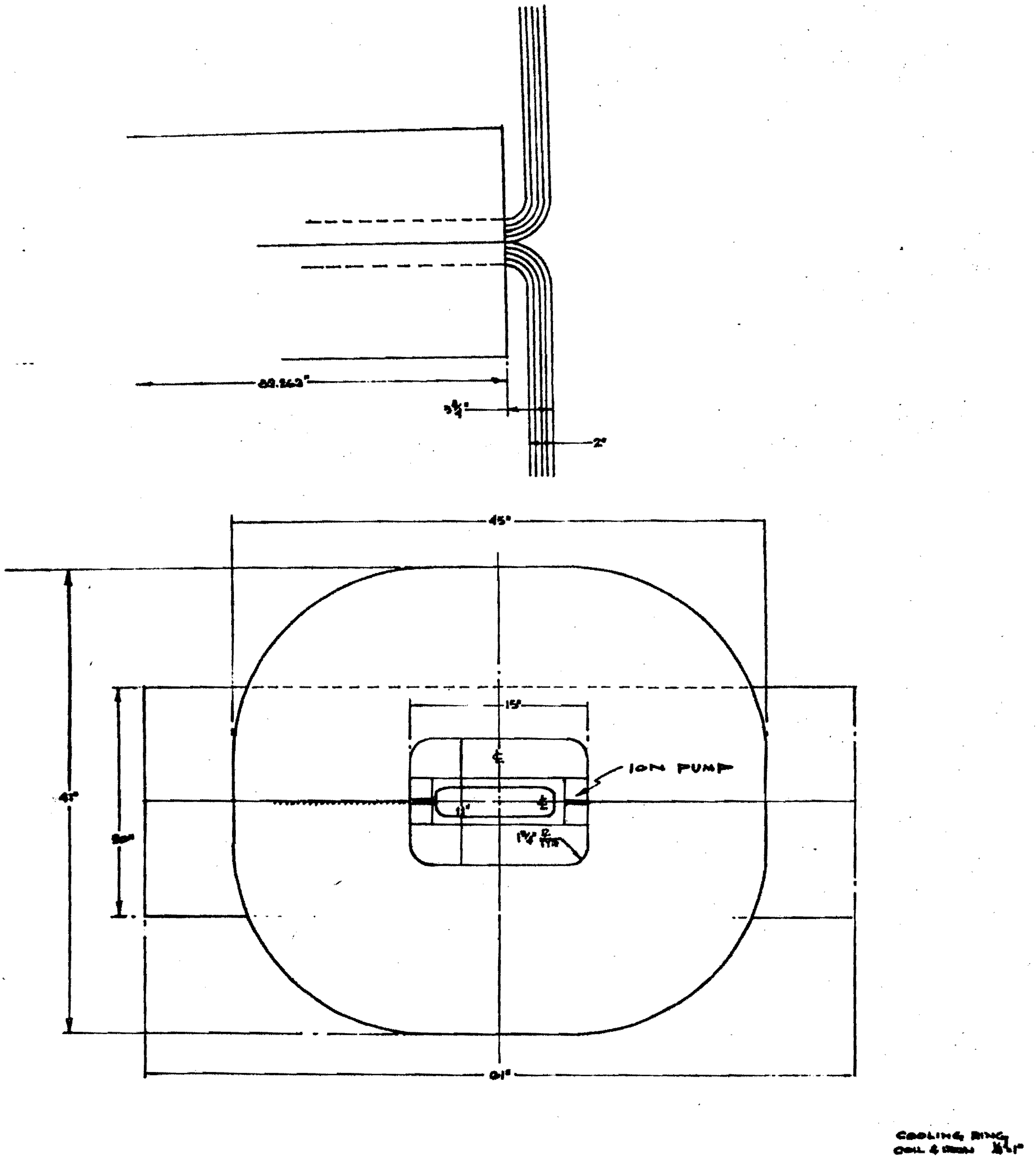
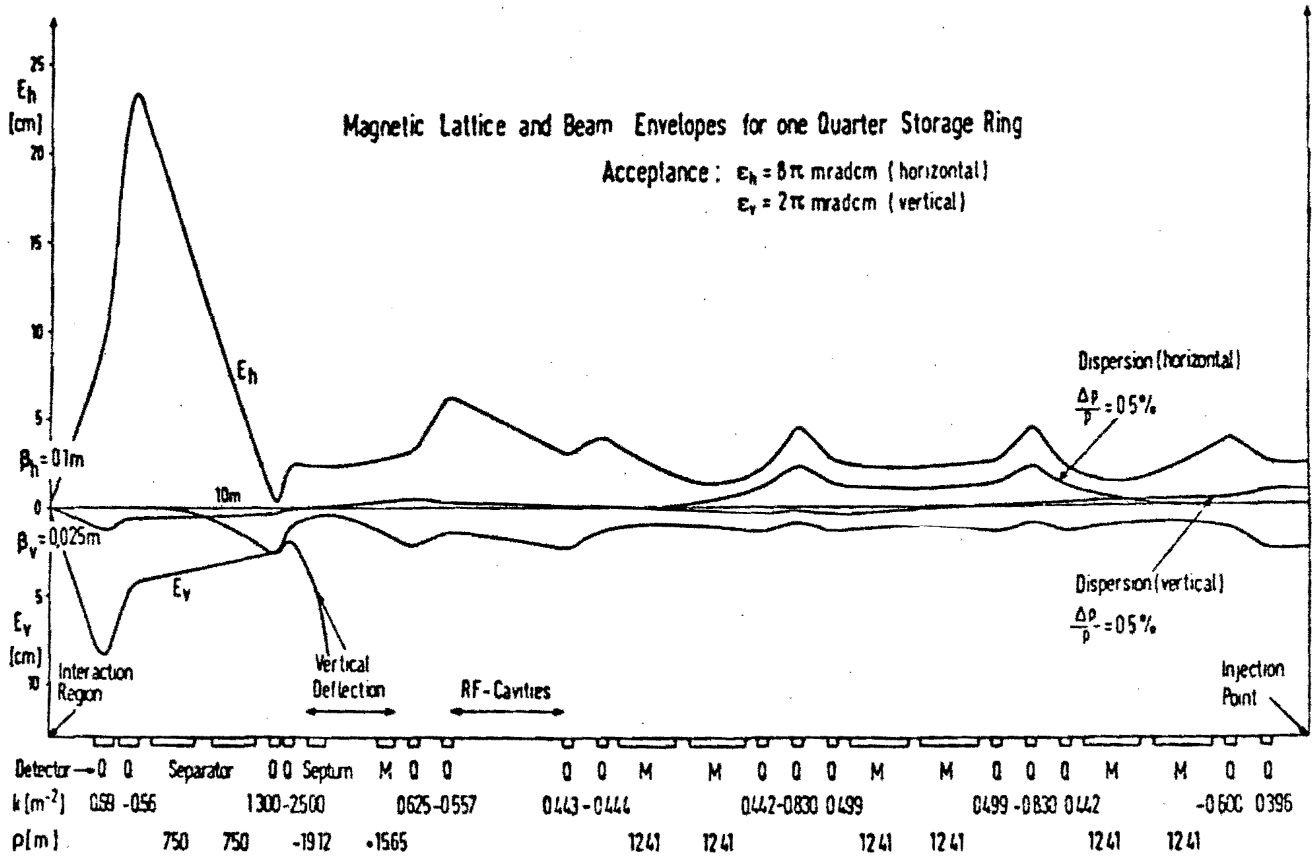


Fig. 1b



Magnet lattice, beam envelopes and dispersions for one quarter storage ring (ϵ_h = 8mrad·cm, ϵ_v = 2mrad·cm, $\frac{\Delta p}{p_o}$ = 0,5%)

Fig. 2a

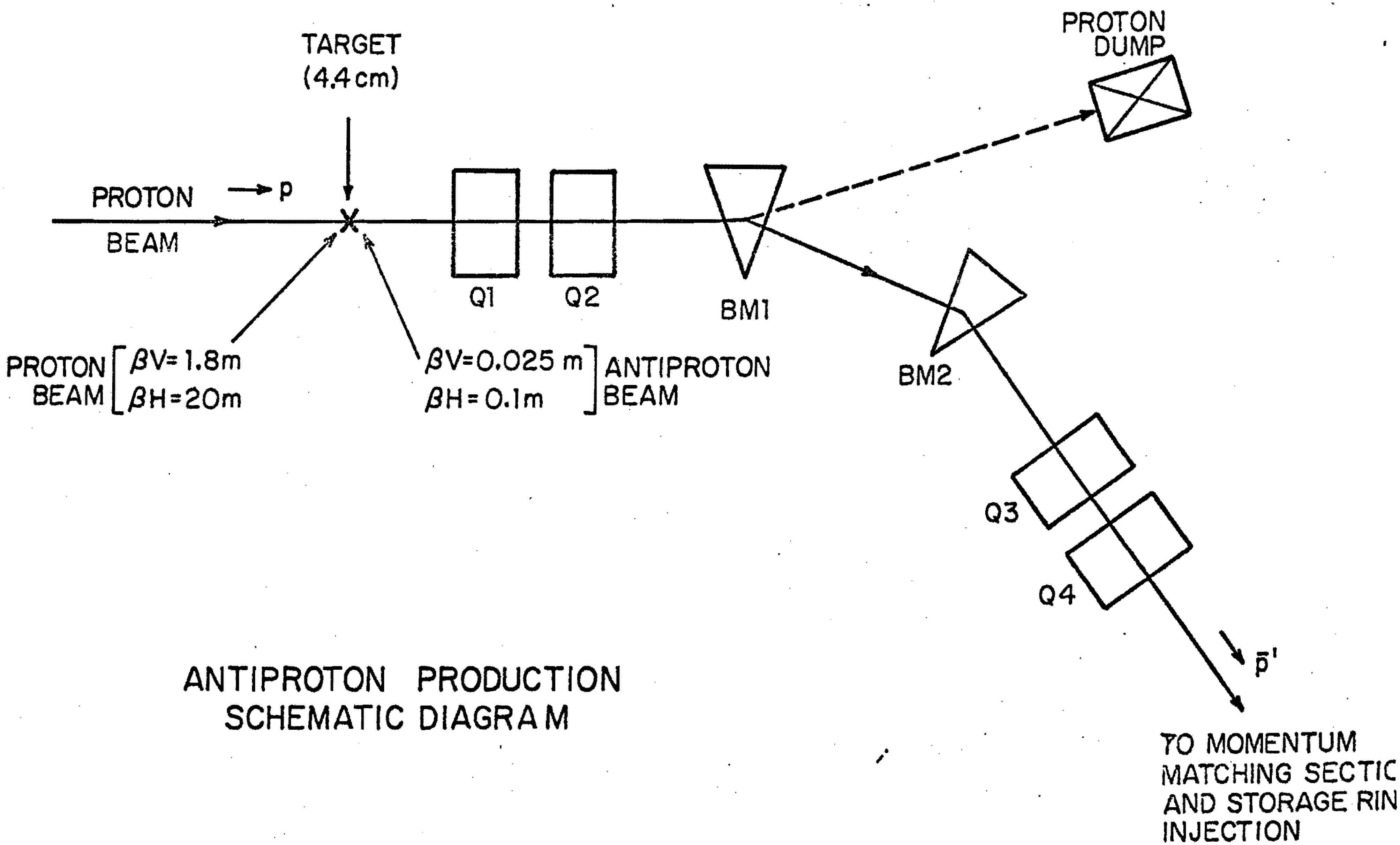

TARGET
(4.4 cm)
PROTON DUMP
PROTON BEAM
p
Q1
Q2
BM1
BM2
Q3
Q4
PROTON BEAM [βV= 1.8m βH=20m
βV=0.025 m βH=0.1m] ANTIPROTON BEAM
p̄'
TO MOMENTUM MATCHING SECTIC AND STORAGE RIN INJECTION
ANTIPROTON PRODUCTION SCHEMATIC DIAGRAM

Fig. 2b.

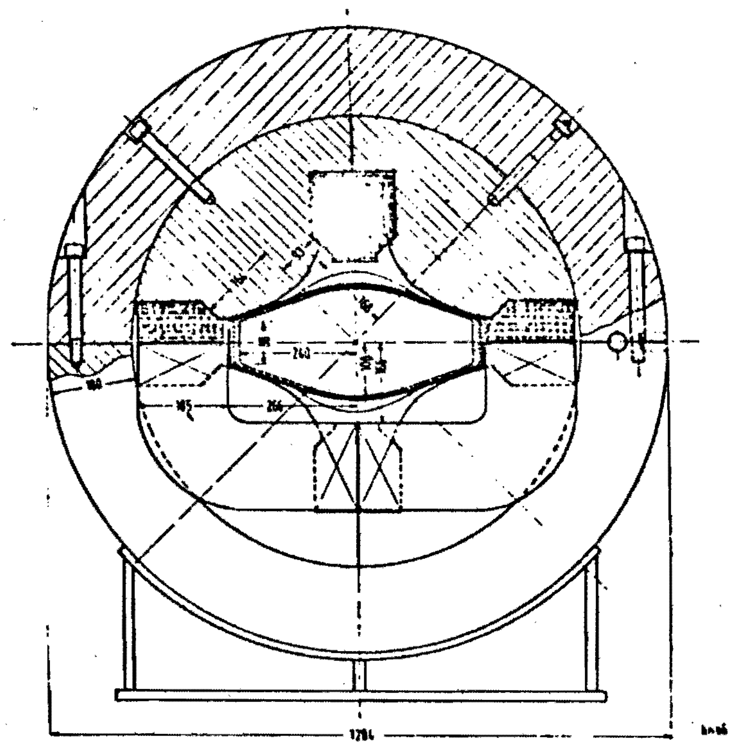


Fig. 3

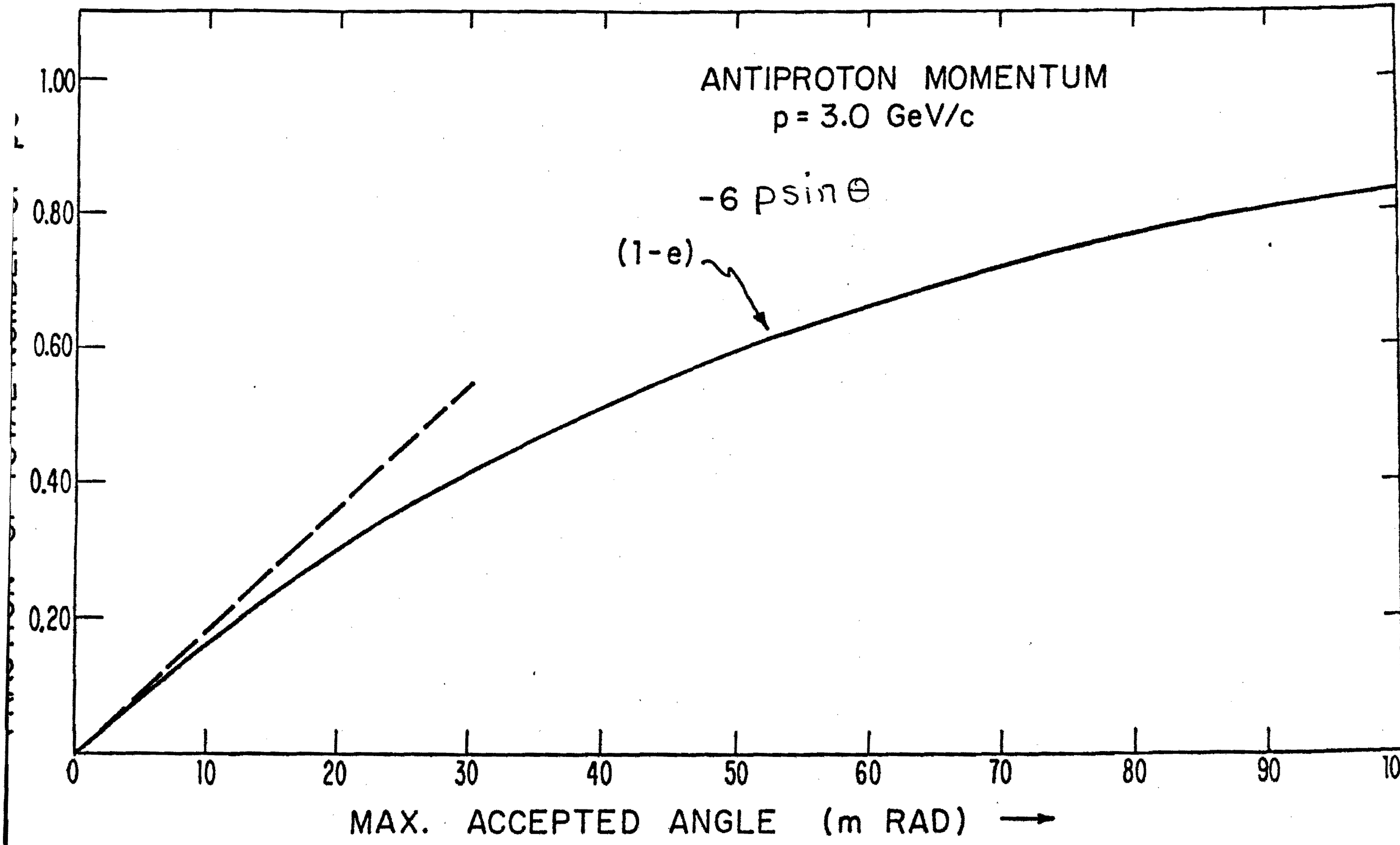

ANTIPROTON MOMENTUM
p = 3.0 GeV/c
-6 psin θ
(1-e)
1.00
0.80
0.60
0.40
0.20
0
10
20
30
40
50
60
70
80
90
100
MAX. ACCEPTED ANGLE (m RAD)

Fig. 4

FOUR TURN INJECTION SCHEME IN VERTICAL PLANE

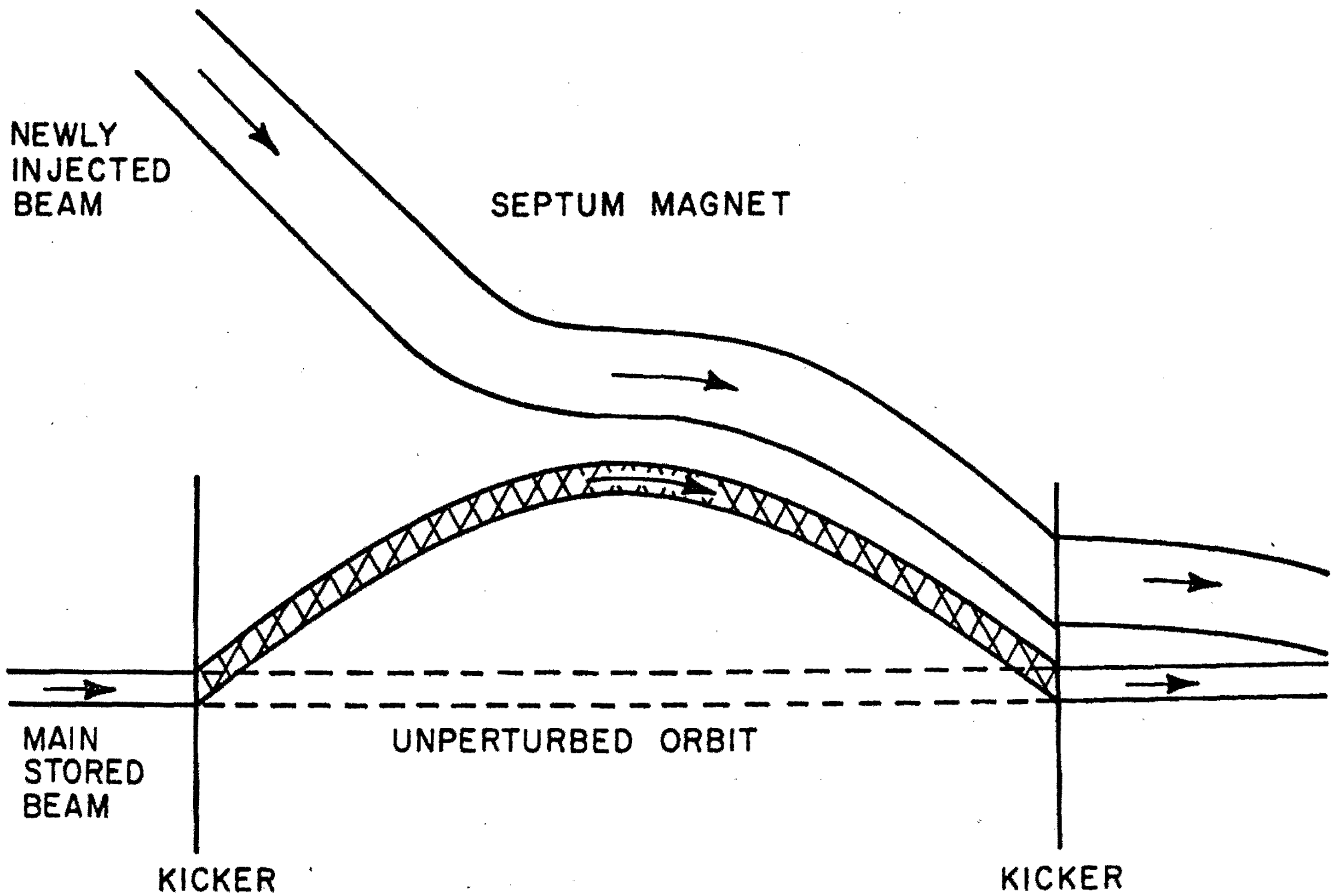
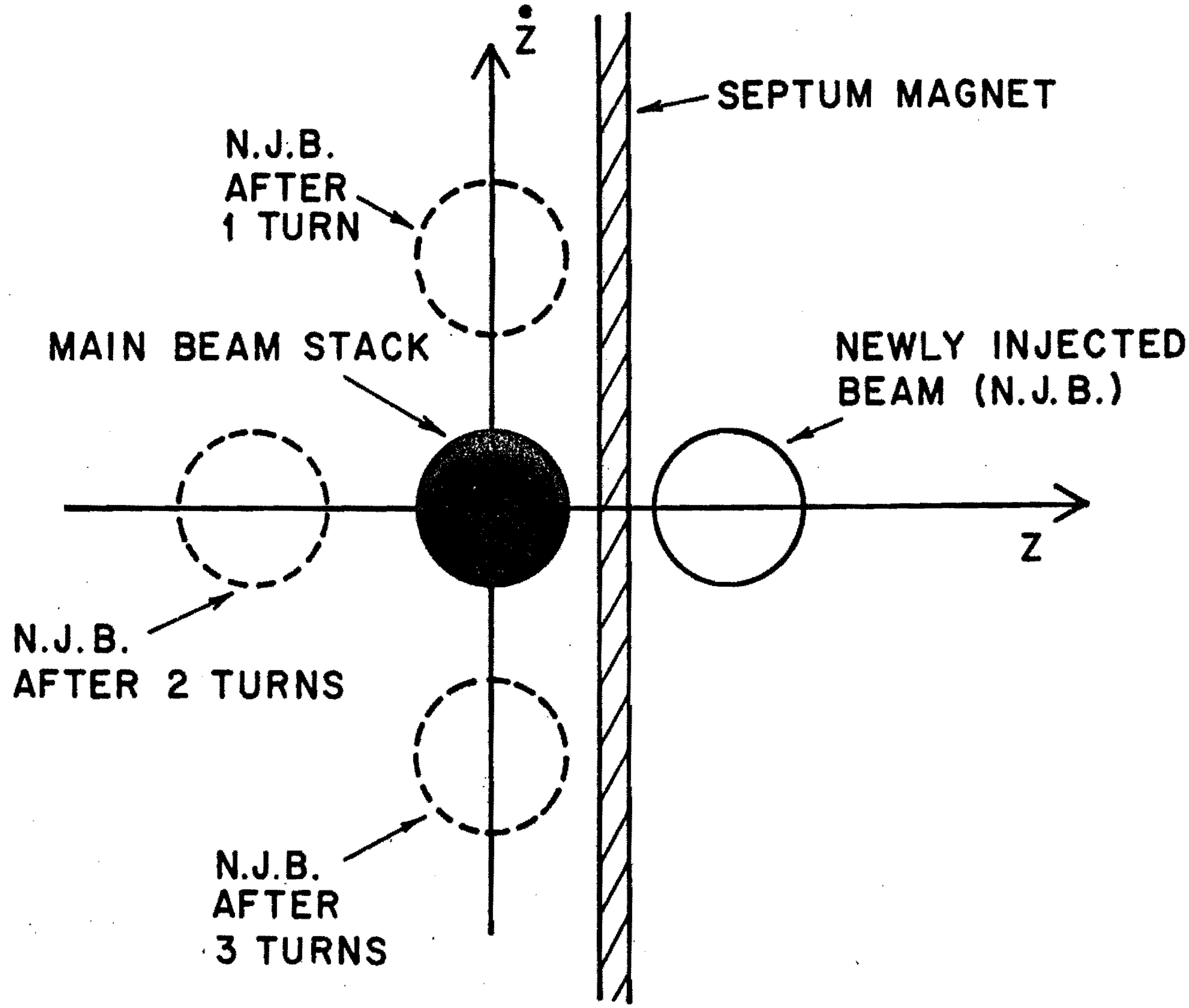


Fig 5



Ż
SEPTUM MAGNET
N.J.B.
AFTER
1 TURN
MAIN BEAM STACK
NEWLY INJECTED
BEAM (N.J.B.)
Z
N.J.B.
AFTER 2 TURNS
N.J.B.
AFTER
3 TURNS

Fig 6

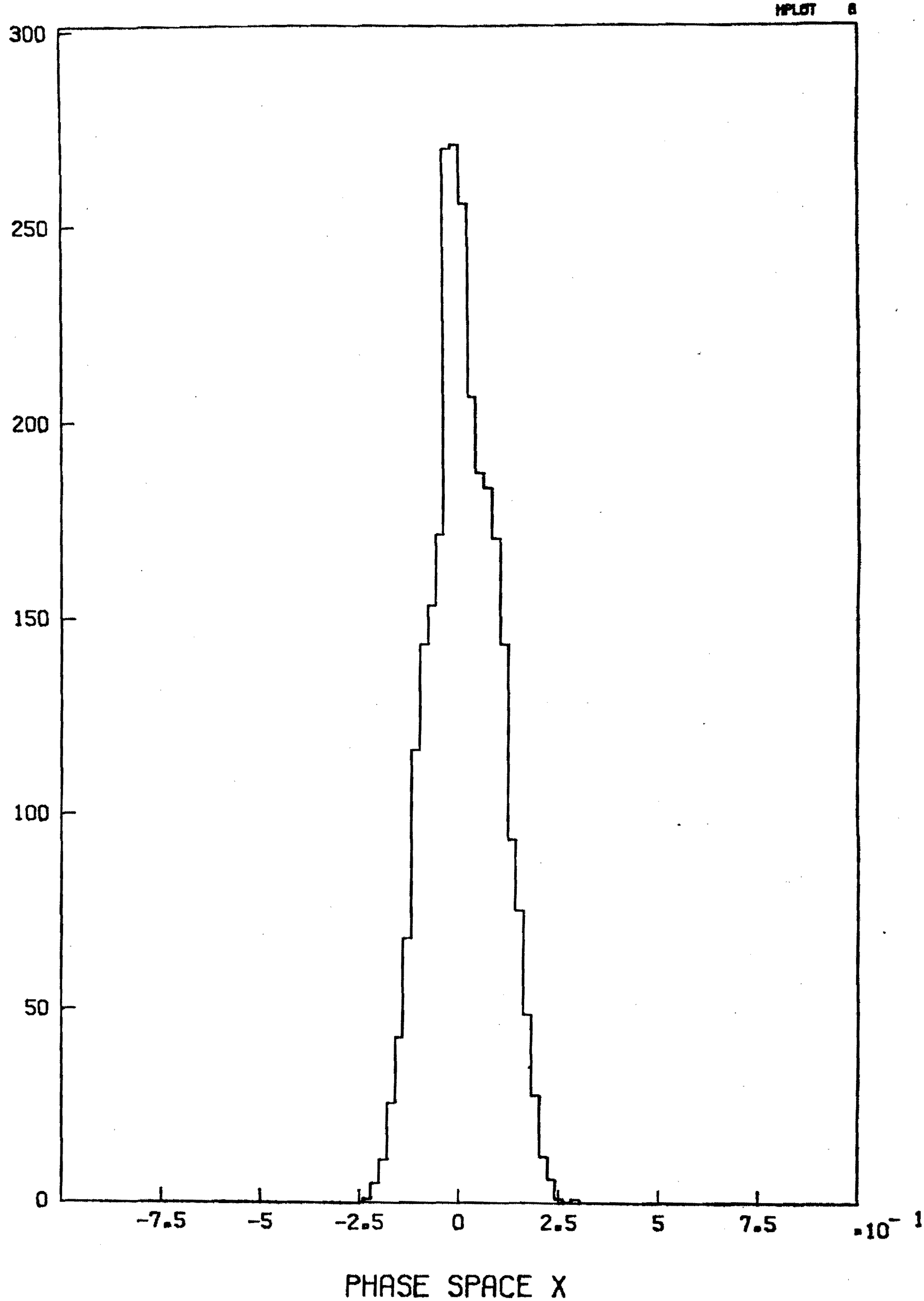
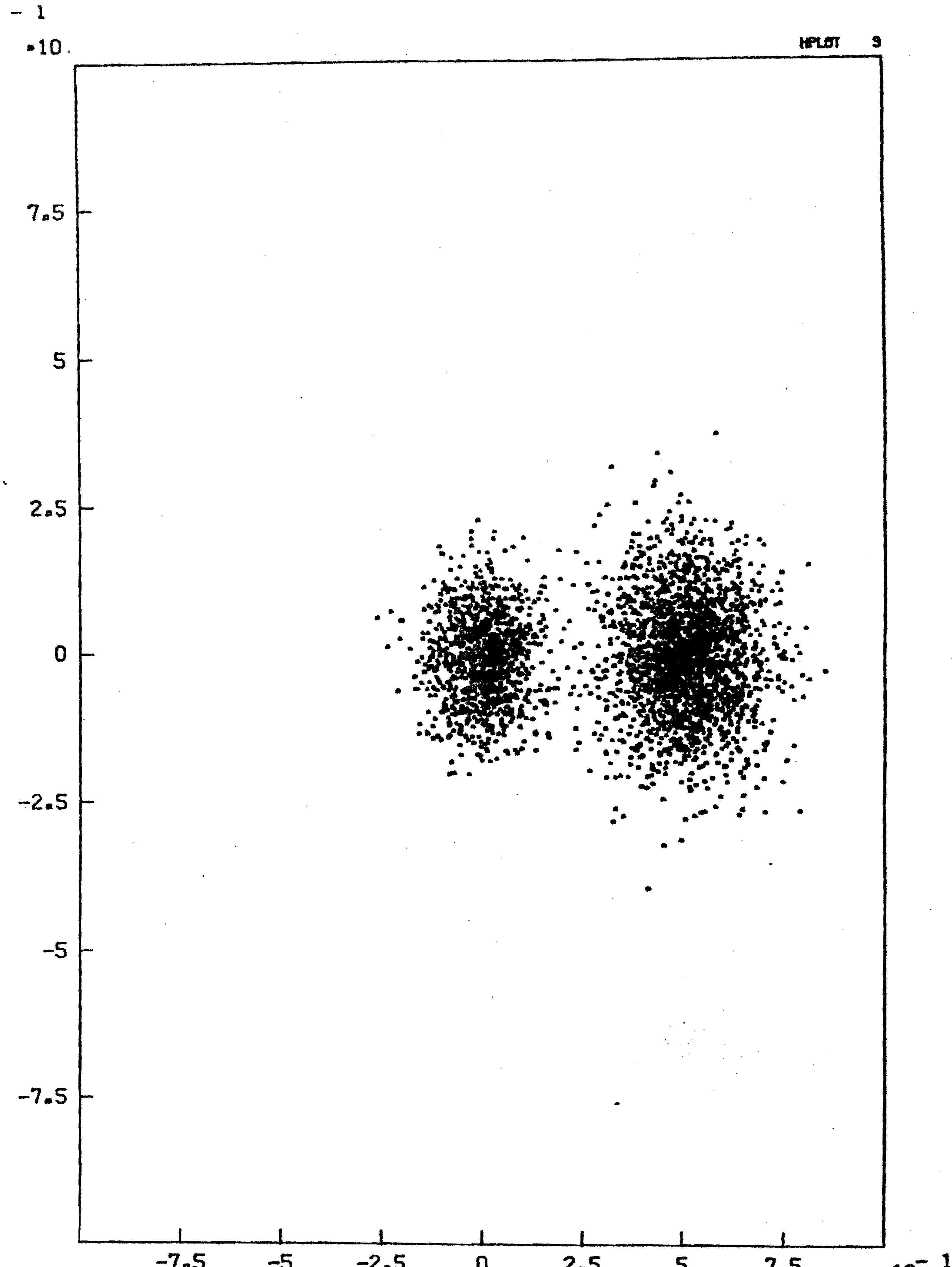


Fig. 7a



INITIAL PHASESP. Y
Fig. 7b

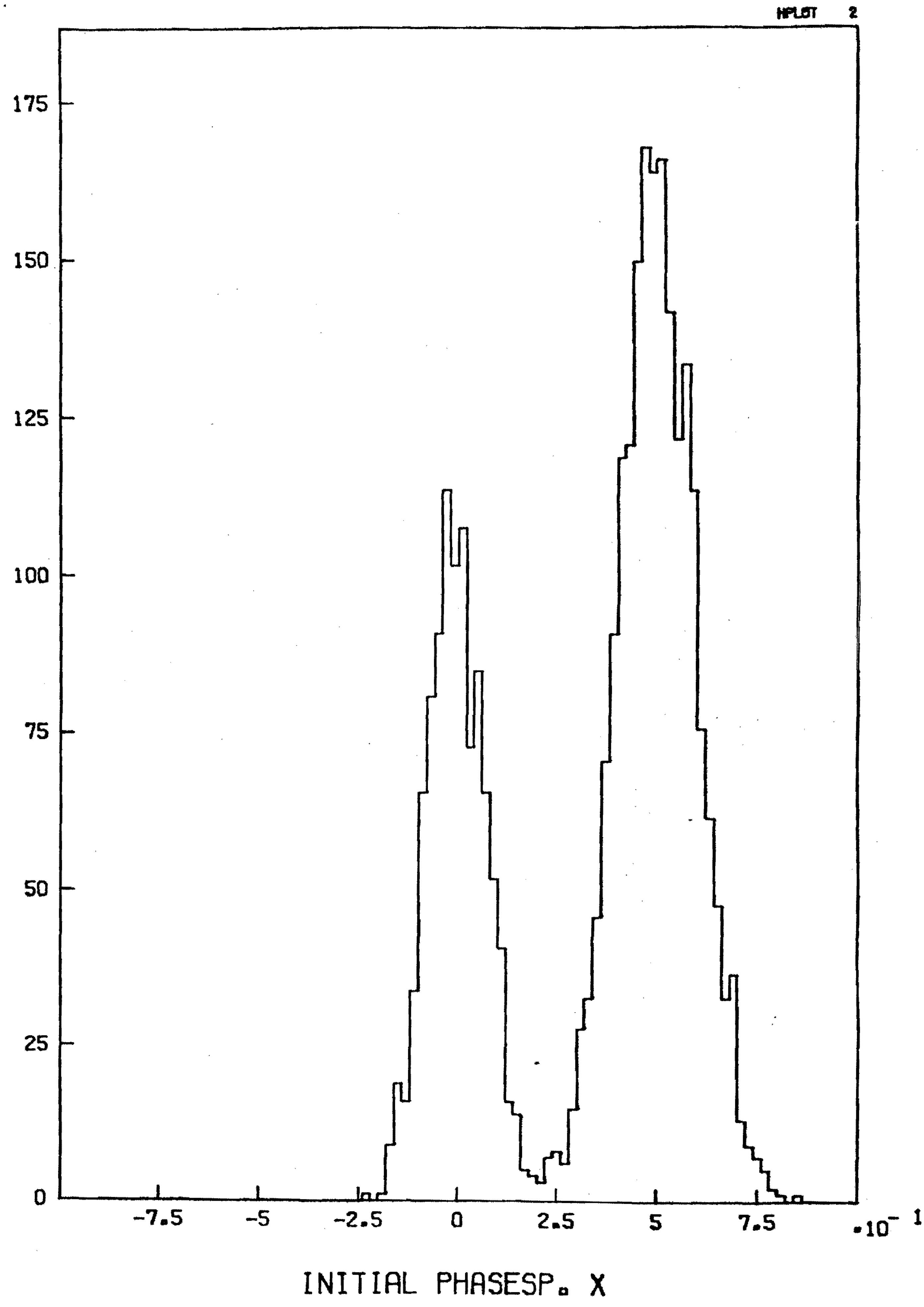

HPLOT 2
175
150
125
100
75
50
25
0
-7.5
-5
-2.5
0
2.5
5
7.5
*10⁻ 1
INITIAL PHASESP. X

Fig. 7b

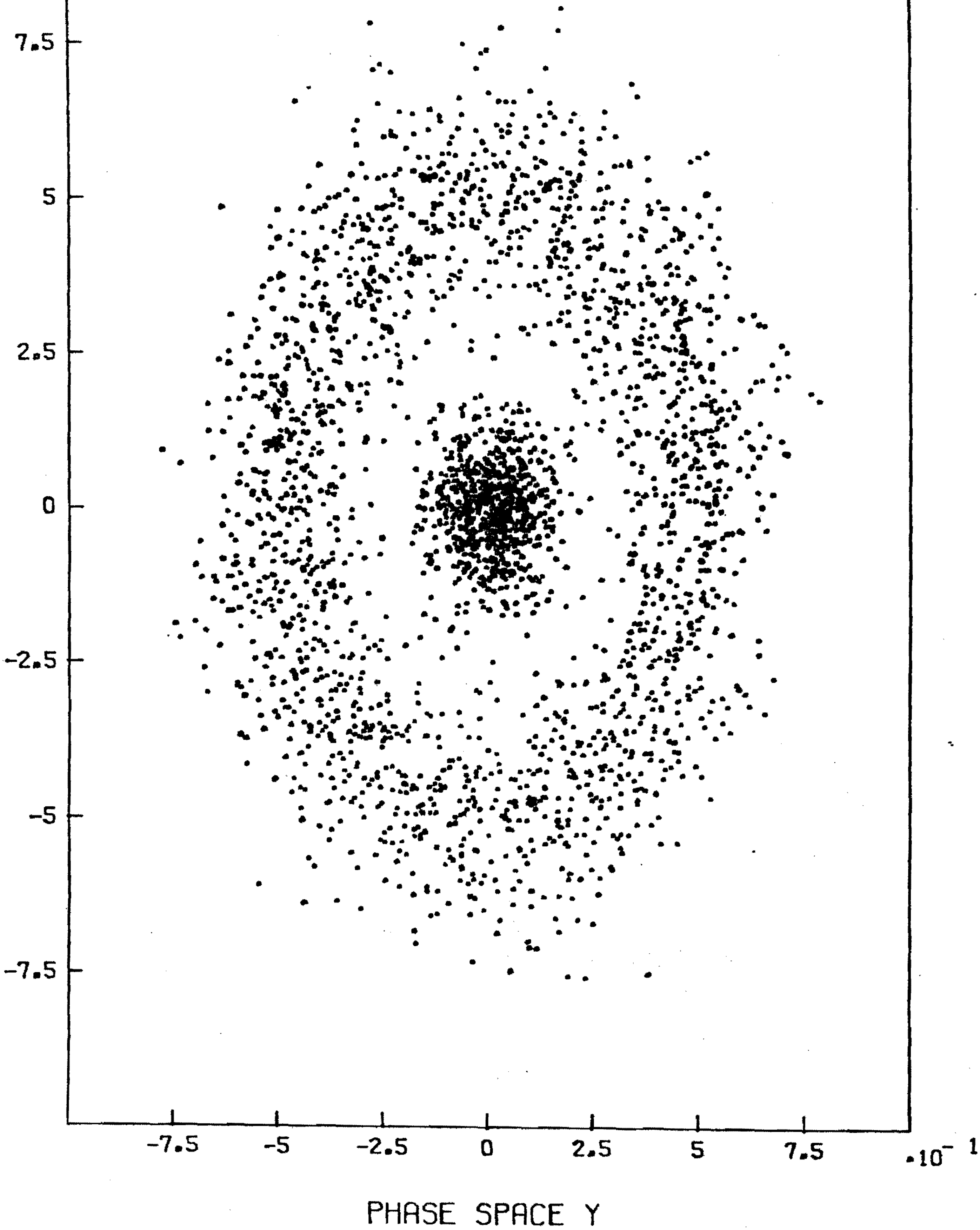
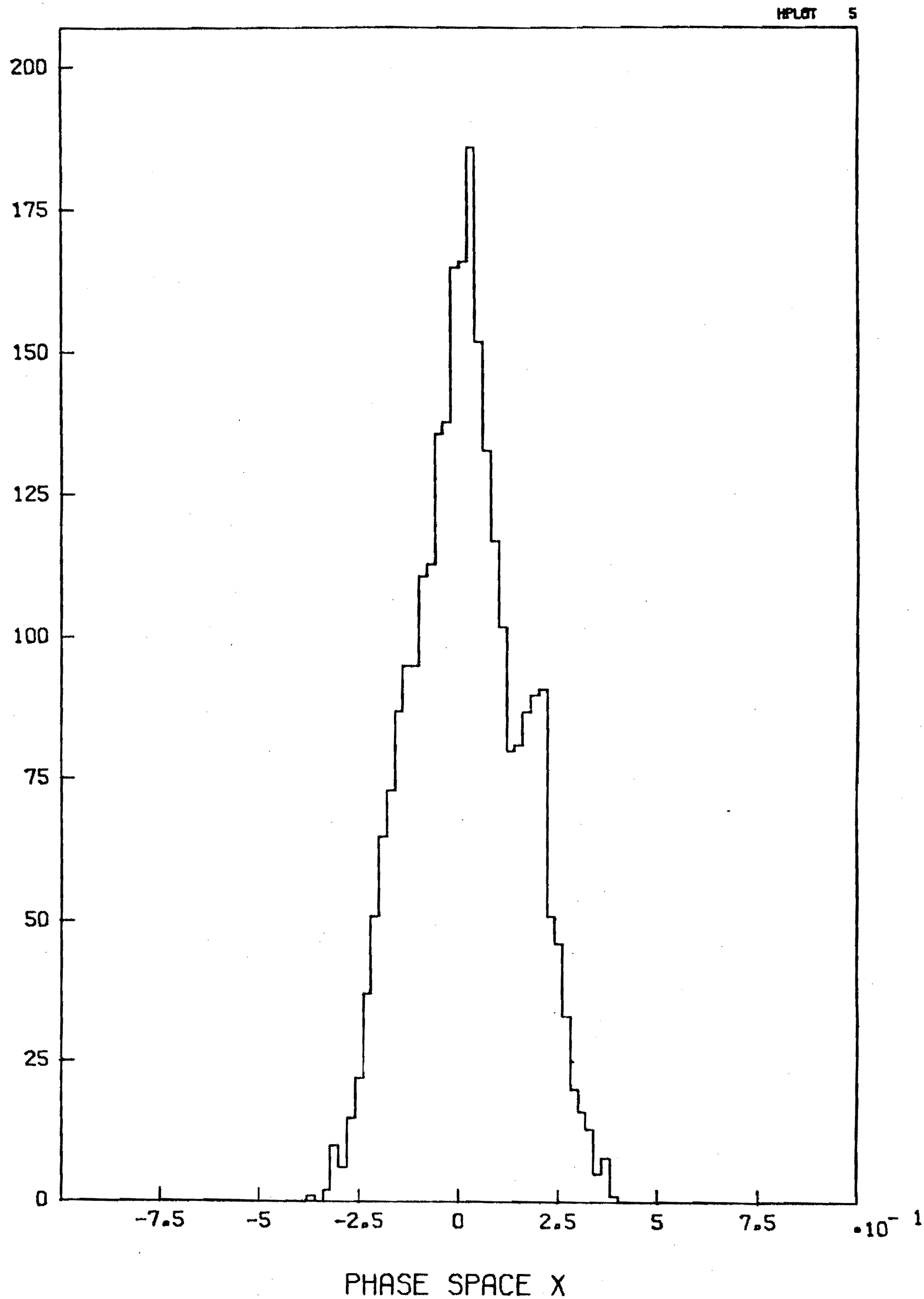
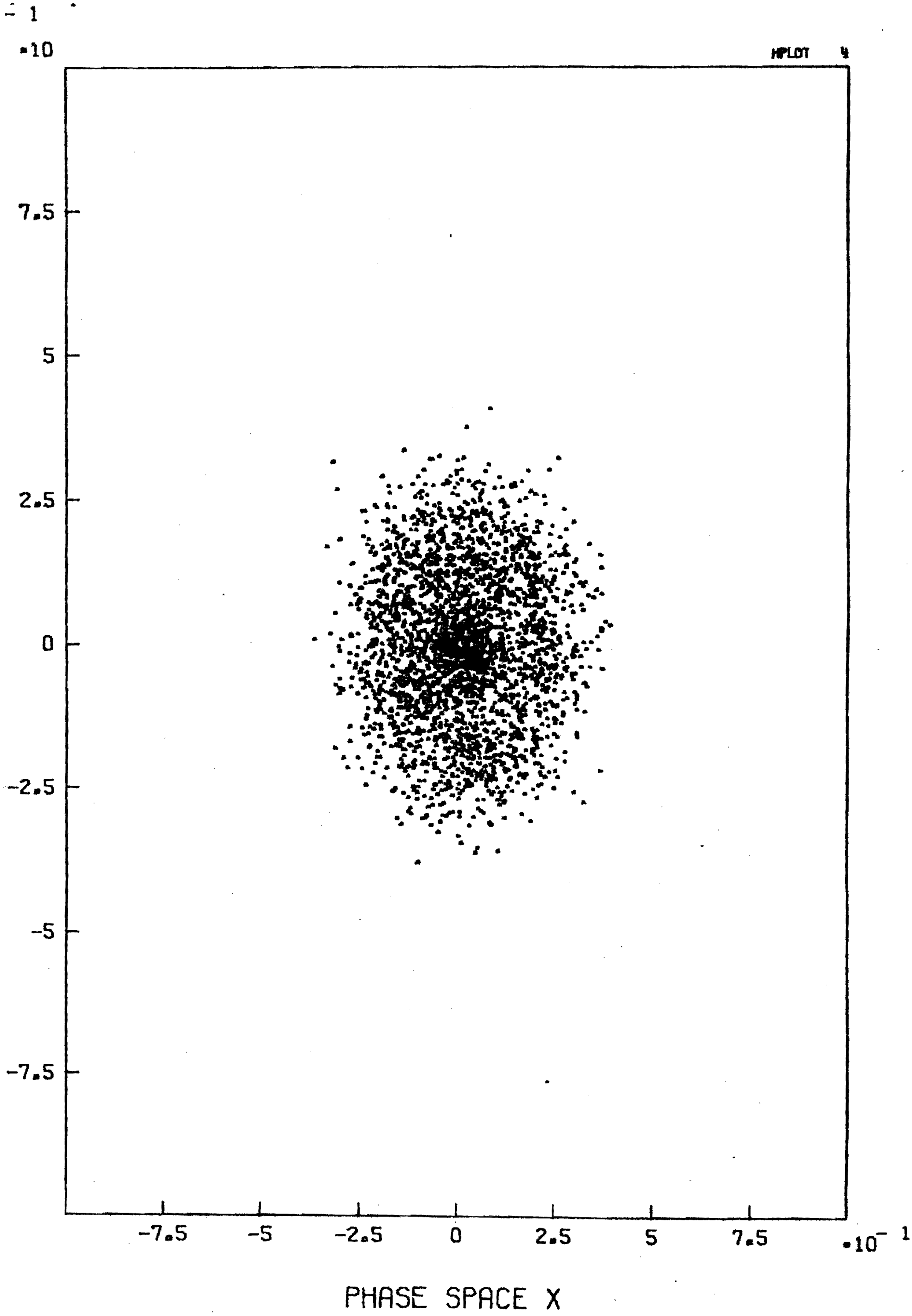


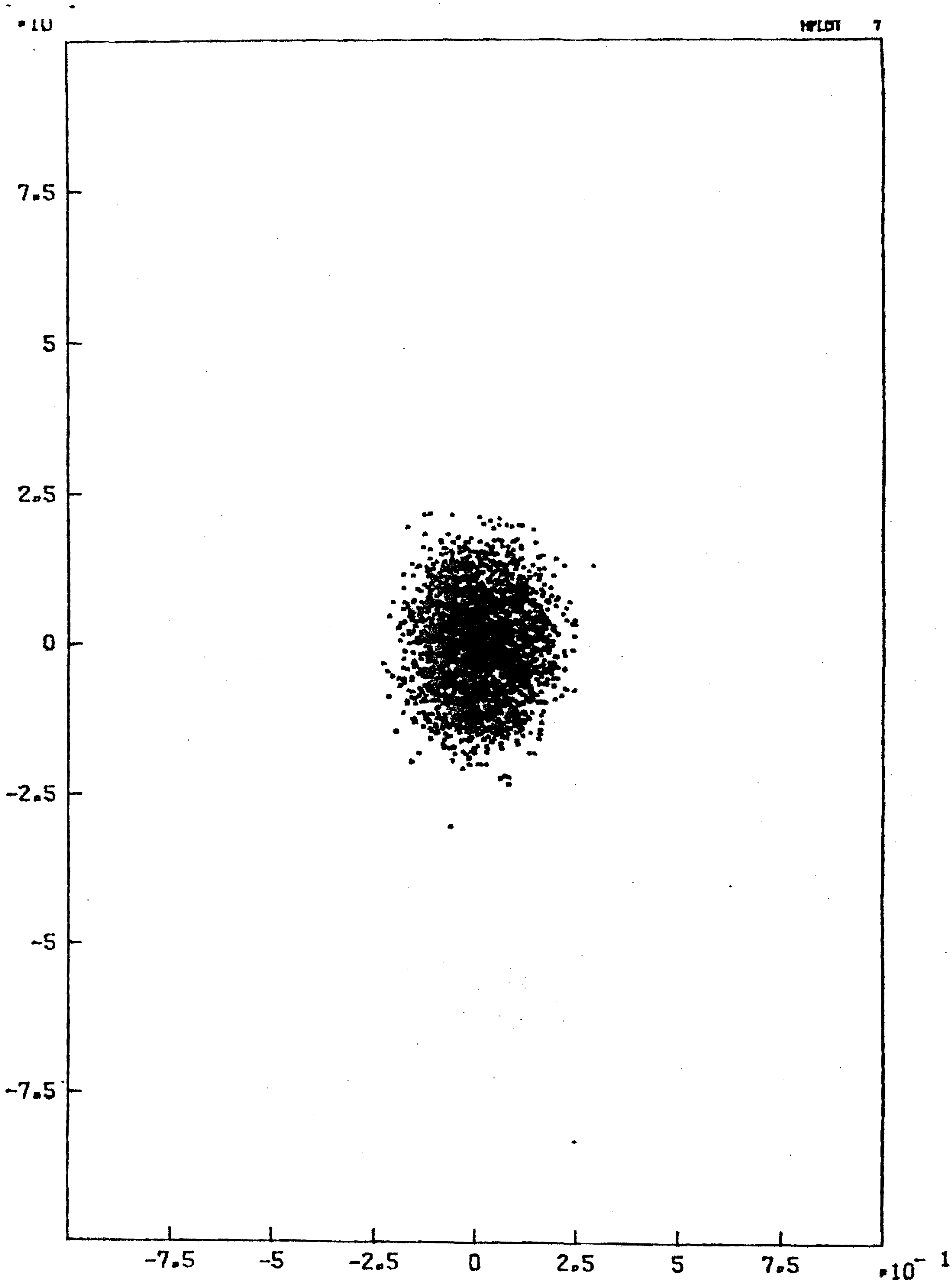
Fig. 7c


HPLOT 5
200
175
150
125
100
75
50
25
0
-7.5
-5
-2.5
0
2.5
5
7.5
$\cdot 10^{-1}$
PHASE SPACE X



HPLOT 4
$\cdot 10^{-1}$
7.5
5
2.5
0
-2.5
-5
-7.5
-7.5
-5
-2.5
0
2.5
5
7.5
$\cdot 10^{-1}$
PHASE SPACE X

Fig. 7d



PHASE SPACE X

Fig. 7e

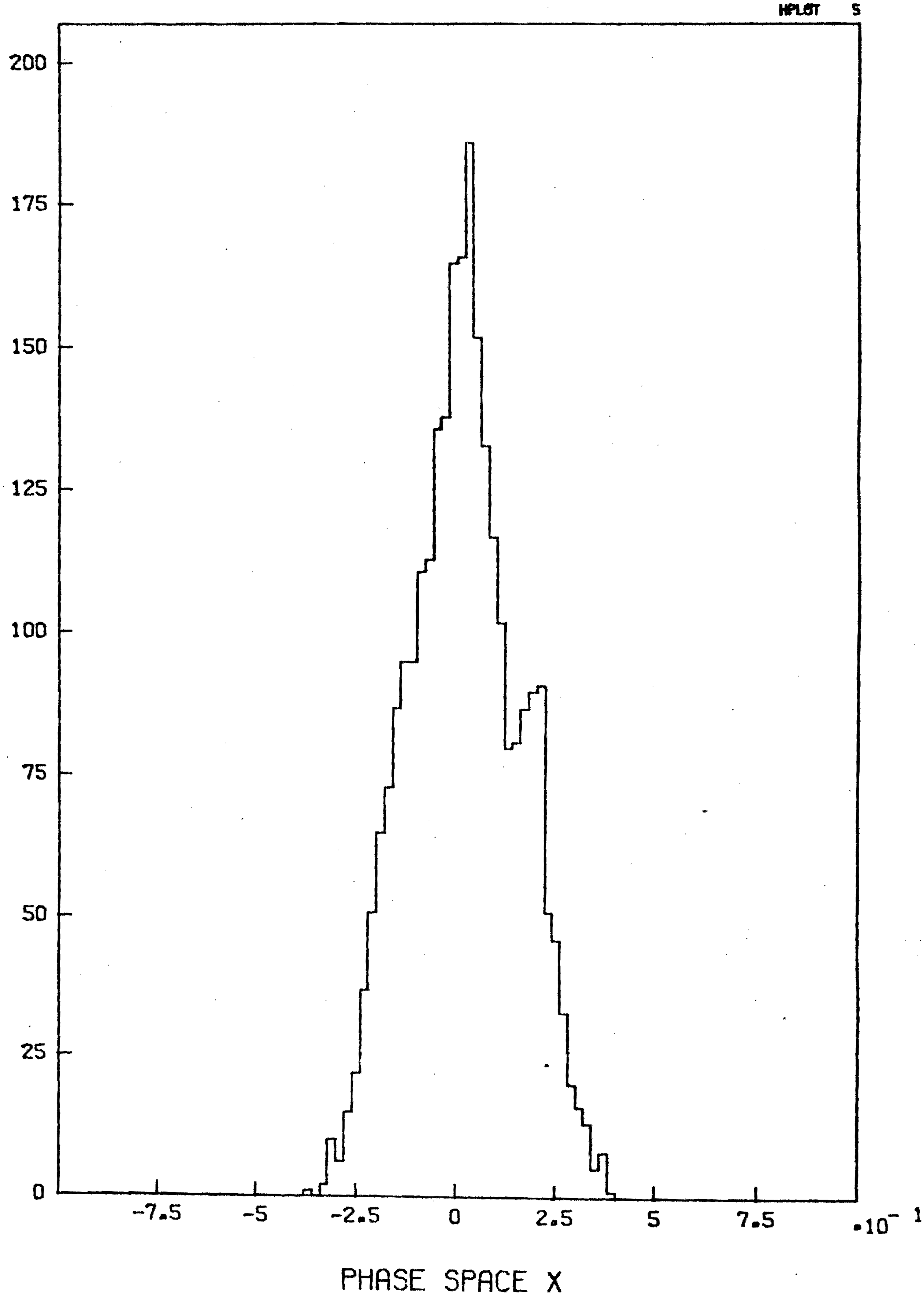

HPLOT 5
200
175
150
125
100
75
50
25
0
-7.5
-5
-2.5
0
2.5
5
7.5
*10^-1
PHASE SPACE X

Fig. 7e

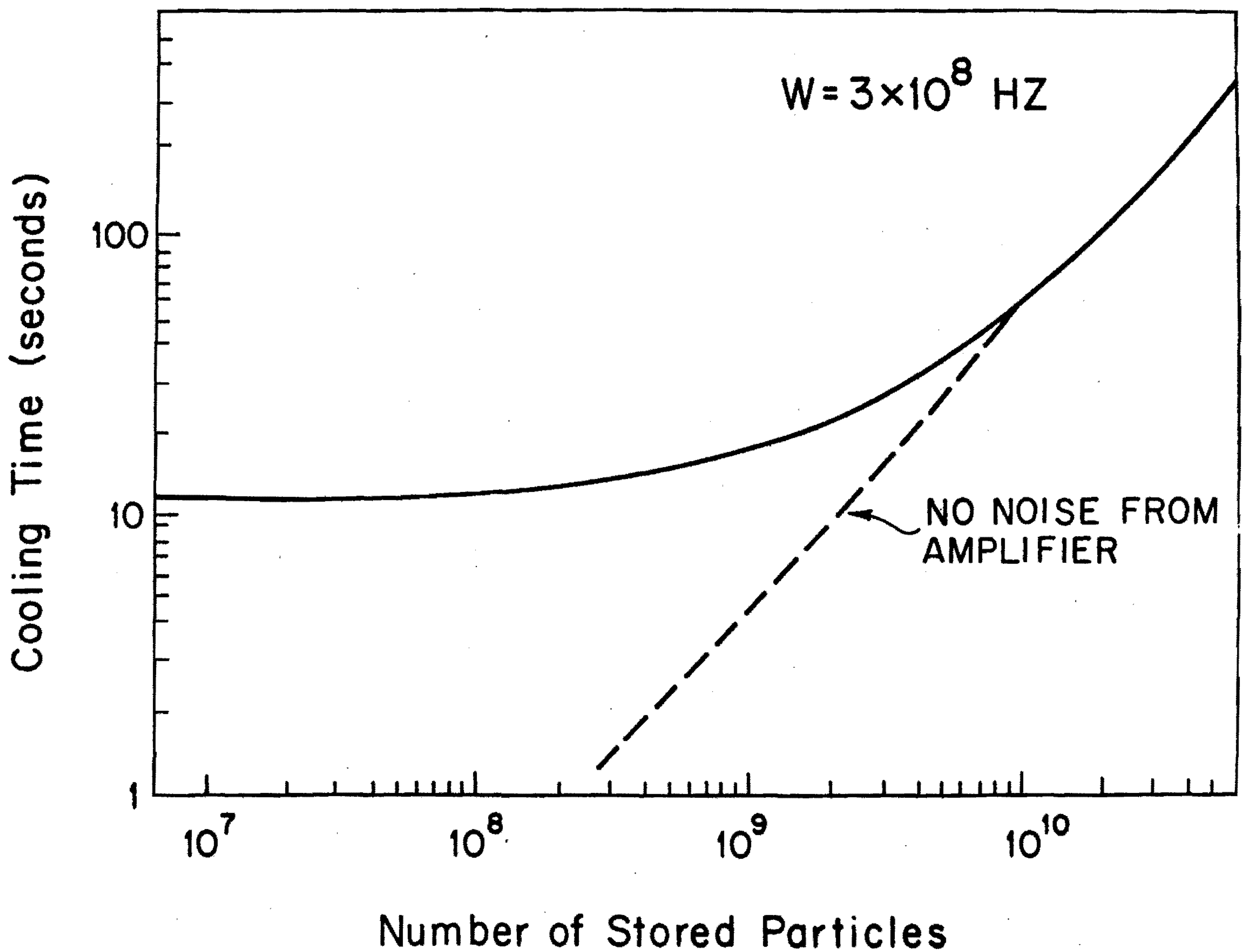
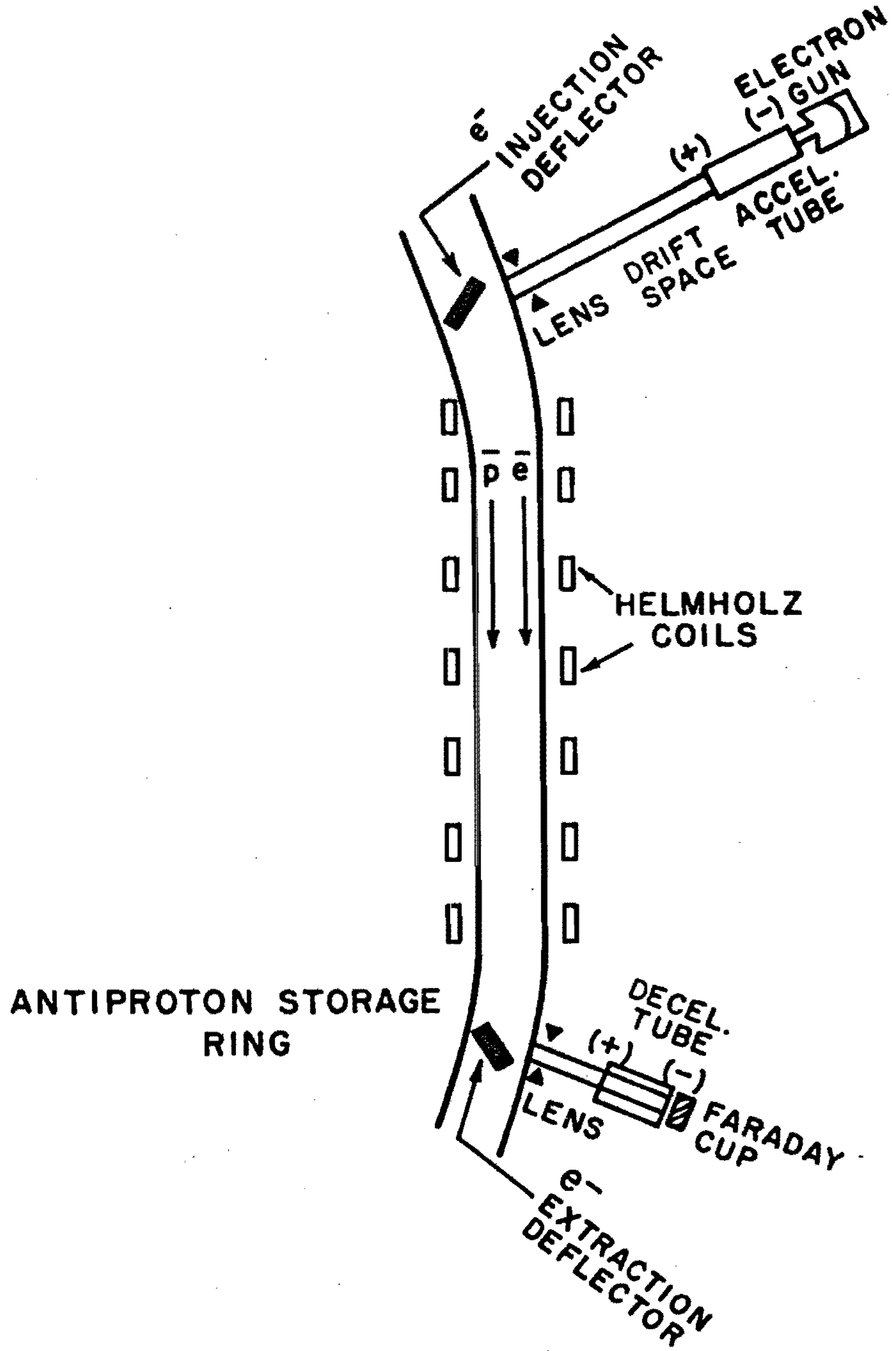
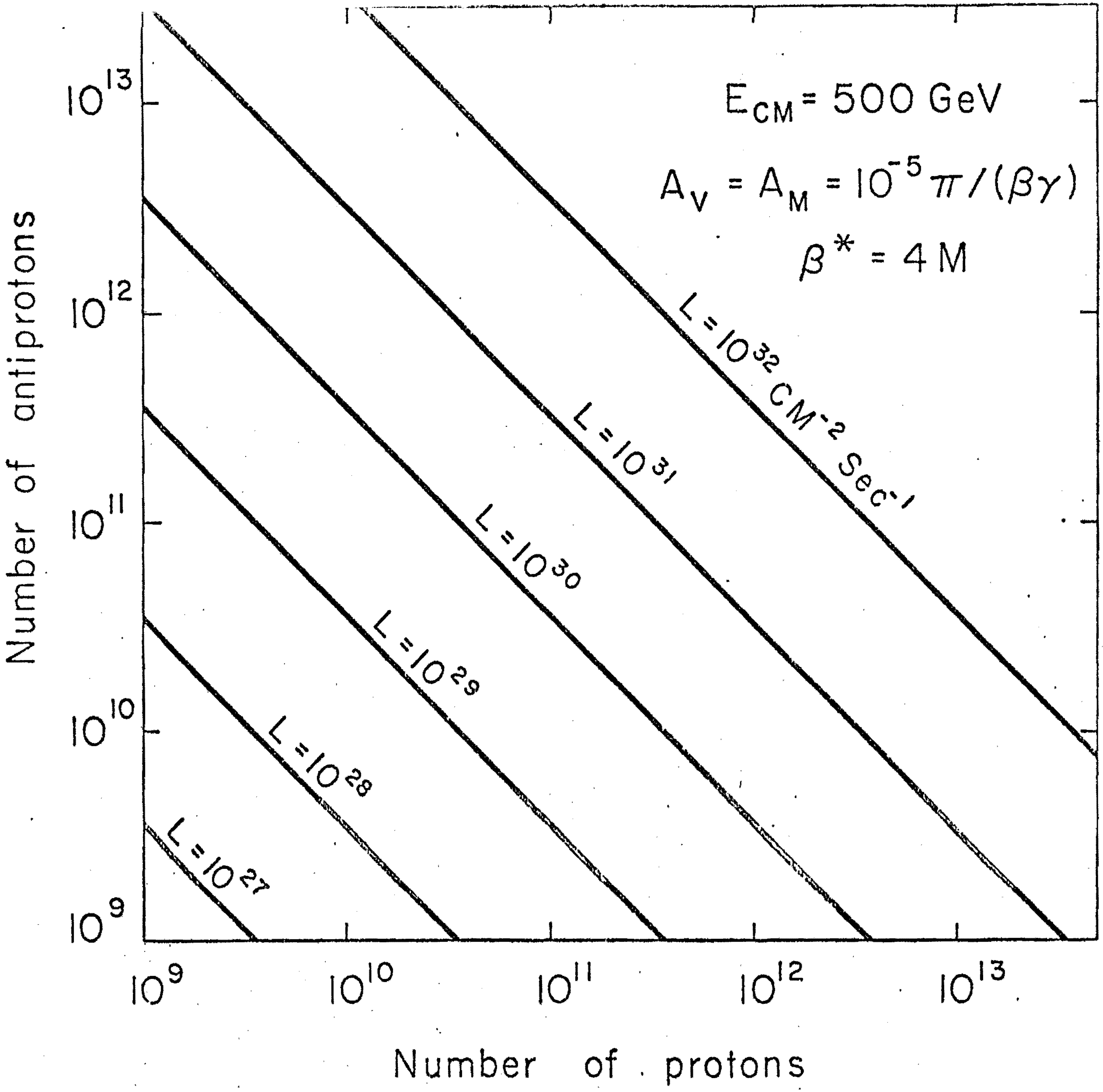

W = 3×10^8 HZ
Cooling Time (seconds)
100
10
1
NO NOISE FROM
AMPLIFIER
10^7
10^8
10^9
10^10
Number of Stored Particles

Fig 8



ELECTRON COOLING
STRAIGHT SECTION

Fig 9



E_CM = 500 GeV
A_V = A_M = 10^-5 π/(βγ)
β* = 4 M
L = 10^32 CM^-2 Sec^-1
L = 10^31
L = 10^30
L = 10^29
L = 10^28
L = 10^27
Number of antiprotons
Number of protons
10^9
10^10
10^11
10^12
10^13

E. L. Goldwasser

Research Proposal Submitted to the NSF

Research and Development of Particle Beam Cooling Techniques and a Feasibility Study of Proton-Antiproton Colliding Beam Facility

Proposed Amount:	$ 490,000
Starting Date:	January 1, 1977
Duration:	1 year

Submitted by the U. S. Energy Research and Development Administration for Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, IL 60510

Principal Investigator:

F. R. Huson
Head, Accelerator Division
Fermilab

(312)840-3245
FTS# 370-3245

Soc. Sec. #520-36-9124

Administrative Approval:

R. R. Wilson
Director
Fermilab

ERDA

Abstract

The fundamental discoveries[1,2,3] in high-energy physics during the past few years surpasses the discovery of the antiproton 25 years ago. These discoveries, which include hardonic structure indicative of quarks[2,3] and the existance of weak neutral currents[1], have greatly increased theoretical understanding via unified gauge theories.[4] These theories predict a new level of fundamental physics in the 50 to 100 GeV region. One of the most promising predictions is the existance of intermediate vector bosons of mass about $M_{\pm} = 64$ GeV and $M_o = 79$ GeV.

To experimentally achieve this new level of physics requires an accelerator facility that can produce at least a few hundred GeV in the center of mass. To realize such an energy by bombarding a stationary target with protons would require an energy of at least 5,000 GeV (5 TeV). This would mean a completely new accelerator facility. An alternative step for the immediate future is to use existing Fermilab facilities for colliding beams. With the addition of a small .2 GeV "cooling" and storage ring for antiprotons, the present Fermilab accelerator can be used to simultaneously accelerate protons and antiprotons providing 500 GeV of energy in the center of mass.

Recently research at Novosibirsk[5] has achieved success in reducing the phase space of protons in a storage ring by "cooling" them with electrons. It is proposed to construct a small 0.2 GeV ring to study and develop electron cooling of protons.

If initial results of this study are encouraging, a proposal would then be submitted for enlarging the cooling ring and inserting it in the present booster tunnel with the necessary injection and ejection equipment to accept and store antiprotons. The completion of that phase would provide 250 GeV protons on 250 GeV antiprotons in the main accelerator.

Fermilab already has planned a new experimental area that would be ready for use by this facility. Sometime within the first year Fermilab would hold a workshop for experimenters to discuss the first experiments to be done in this new facility.

RESEARCH GRANT PROPOSAL BUDGET

Budget Category		Proposed Amount 1977
A.	Salaries	90K
B.	Staff Benefits at 18.5%	17K
C.	Permanent Equipment	270K
D.	Expendable Supplies	-
E.	Plant Construction	-
F.	Travel	-
G.	Other Costs	-
H.	Total Direct Costs (A-G)	377K
I.	Total Indirect Costs (30% G&A)	113K
J.	Total Costs	490K
K.	Total Contributions from Other Sources	741K
L.	Total Estimated Project Cost	1,231K

PHASE I - CALENDAR YEAR 1977

R&D Summary (1976 dollars)

	Requested Division Fermilab	Requested Division NSF
Salaries		
1. Design		
Physicists(2)	60K	
Engineer(1)	30K	
Drafting(2)	20K	20K
2. Construction & Testing		
Physicists(3)	60K	30K
Engineers(2)	50K	
Techs(6)	80K	40K
	300K	90K
Staff Benefits 18.5%	55K	17K
	355K	107K
Permanent Equipment		
1. Magnets for Ring		75K
2. Power Supplies for Ring		50K
3. Controls	25K	
4. Electron Source		75K
5. Vacuum System		50K
6. Utilities	75K	
7. Miscellaneous		20K
	100K	270K
Expendable Supplies	50K	
Temporary Pad and Building	65K	
Total Direct Cost	570K	377K
Indirect Cost G&A @ 30%	171K	113K
TOTAL	741K	490K

I. Introduction

II. Physics Justification

III. Construction Proposal

IV. Luminosity

V. Manpower

VI. Conclusion

I. Introduction

There are two effects that have stimulated enthusiastic discussions about colliding beams at Fermilab. First, the recent discoveries[1,2,3] implying a new level of physics at 50-100 GeV and second the realization that Fermilab facilities can be modified relatively easily to provide colliding beams. One of the most promising ideas[5] is to produce, collect and accelerate antiprotons to collide with protons. This proposal describes the first phase for such a facility.

During the summer study at Aspen for the energy saver/doubler, many ideas were presented relative to collecting and storing antiprotons (see Appendix I). After the summer study, biweekly meetings on colliding beams were continued at Fermilab. This proposal represents the combination of the best ideas of Fermilab and interested users (see Appendix II).

The general scheme for providing proton-antiproton collisions is as follows (see Figure 1). Protons (5×10^{13}) are accelerated to 100 GeV in the main ring, then extracted at F17 and transported to a small target where 5.2 GeV antiprotons (4.6×10^{7}) are produced and collected into a transport channel which leads to injection into the booster in a clockwise direction. The antiprotons are decelerated in the booster to 600 MeV and injected into a cooling ring which is also located in the booster tunnel. The antiprotons are decelerated to 200 MeV and cooled by electrons and stored in this ring. This cycle is repeated every 3 seconds for 3 hours yielding a stored antiproton beam of 1.6×10^{11} particles. This beam is injected clockwise into the booster and accelerated to 8 GeV and injected counterclockwise at F17 into the main ring, then one booster batch of protons (4×10^{12}) is accelerated to 8 GeV and injected clockwise into the main ring. Then both beams are accelerated simultaneously to 250 GeV. A low beta (2.5m) section at B_0 is used to enhance proton-antiproton collisions at that point. The expected luminosity is 2×10^{29} cm^{-2} sec^{-1}.

This proposal is to construct and test the idea of electron cooling of protons presented and developed by Novosibirsk.[5] A small 200 MeV ring would be built west of the present booster (see Figure 2). Protons would be injected from the present linac and cooling and storing studies would be done in this ring. The ring would be constructed so that it could be expanded and placed in the booster tunnel for antiproton cooling and storage.

II. Physics Justification

The discovery 3 years ago of neutral currents in the Gargamelle Bubble Chamber at CERN[1] was the beginning of the recent important new discoveries. Neutral currents were soon verified by experiments at Fermilab.[6,7] Subsequent measurements of the ratio[8,9,10] of neutral currents to charged currents in neutrinos and antineutrinos started to give credibility to the unified gauge theory of Weinberg-Salam.[4] Then simultaneous discovery of a high mass - narrow resonance (ψ/J)[2,3] at SLAC and BNL gave strong support to the idea of an additional quark with a new quantum number "charm" suggested by Glasshow and Bjorken.[11] Finally, the apparent discovery of a charm meson at SLAC[12] followed by a charm baryon at Fermilab[13] strongly supported the existance of the charm quantum number.

The success of the above mentioned theories to understand the new discoveries lends credibility to other predictions of those theories. The most spectacular prediction is the existence of an intermediate vector boson that mediates the weak interaction and couples the weak and strong interaction particles. The masses of these bosons are a function of the Weinberg angle,[4] the only parameter in the Weinberg-Salam theory.[4] Recent measurements[8,9,10] of this angle give

$$\mathrm{Sin}^2\theta_\omega = .34 \pm$$

The charged vector bosons are predicted to have a mass of about 64 GeV and the neutral about 79 GeV.

$$M_\pm = 37/|\sin\theta_\omega| = 64 \pm \quad \text{GeV}$$
$$M_o = 74/|\sin 2\theta_\omega| = 79 \pm \quad \text{GeV.}$$

Therefore, it takes an interaction with at least a few hundred GeV of energy in the center of mass to produce vector bosons with a reasonable probability. Except for $e^+ + e^-$ which can produce M_o directly with 40 GeV on 40 GeV.

If the predicted masses are correct the PEP e^+e^- machine cannot produce vector bosons since it is only 15 GeV on 15 GeV (30 GeV in the center of mass). Therefore, there is not an existing or approved accelerator with sufficient energy to produce a vector boson. To build a new facility to study this new level of high energy physics would probably take 5 years at a cost comparable to that of the 243 million-dollar Fermilab facility. We present in the next section a proposal that could lead to 250 GeV protons on 250 GeV antiprotons (500 GeV in the center of mass), by exploiting the major facilities already in operation or planned at Fermilab. The required new components could be built in 3 years at a cost of less than 4 million dollars.

The reactions that we believe produce vector bosons are

quark + antiquark → vector boson + hadrons[14,15,16,17]
electron + positron → neutral vector boson[18]
electron + coulomb field → vector boson + electron + hadrons[1]
quark + coulomb field → vector boson + quark + hadrons.[20]

The energy needed to produce vector bosons and the corresponding cross section is given in Table I. A very rough cost estimate is given for the construction of a minimal machine at Fermilab using as much of the existing facilities as possible.

Table I. Various facilities for production of vector bosons.

	Particles	Energy	σ_ω	Luminosity	Cost
(1)	e^+e^- [18]	40 x 40	$\sim 10^{-30}$	10^{32}	$50M
(2)	e^-p [19]	20 x 500	10^{-36} (ref.21)	10^{32}	10M
(3)	pp[14,15,16]	250 x 500	10^{-33}	10^{31}	10M
(4)	$\bar{p}p$[17]	250 x 250	10^{-32}	2×10^{29}	4M

This gives the motivation for using protons on antiprotons. The 3rd machine will be obtained automatically when the energy saver/doubler is completed (i.e., 250 GeV protons on 1000 GeV protons).

Let us discuss the peculiarities of each of the machines listed in Table I:

(1) The electron-positron colliding beams[18] with 40 GeV on 40 GeV would require a new low-magnetic field set of magnets in the main-ring tunnel, with an ultrahigh vacuum (10^{-9} Torr). The cost would be about 2.5 million dollars. The expensive parts of the machine would be the rf (25-50 megawatts) for acceleration and compensation for radiation loss. This would require hundreds of meters of rf cavities. It would be the dominating cost for the machine. The physics may be easier to understand since the interaction involves one pointlike particle

interacting with another. When the total energy of the beams equals the mass of the neutral vector boson the cross section is expected to be large (10^{-36}).[21]

(2) The electron-proton colliding beams[19] would require about the same low magnetic field set of magnets in the main-ring tunnel as the e^+e^- ring, however, only 1/16th the rf since rf~E^4. The physics is very interesting since the weak interaction cross section is expected to be larger than the electromagnetic cross section. The vector boson production in Table I (10^{-36} cm^2)[21] is calculated assuming production via a virtual photon.

(3) A proton-proton machine of 250 GeV on 500 GeV[14,15,16] would require an additional ring of magnets in the main-ring tunnel of one-half the field of the present magnets plus an ultrahigh vacuum of 10^{-9} Torr. As mentioned above, this facility will occur automatically when the energy saver/doubler is completed (250 GeV in the main ring on 1000 GeV in the doubler).

(4) The proton-antiproton machine[17] may be as simple as just adding a small "cooling" and storage ring in the booster tunnel of our present facility to provide 250-GeV protons on 250-GeV antiprotons. There are three technical problems to be studied before such a machine can be built with guaranteed success of operation. To obtain a sufficient number of antiprotons ($>10^{11}$) to give enough interactions with protons to observe interesting physics requires collecting about 2200 pulses (3 hours) of antiprotons produced from 100-GeV protons on a stationary metal target. Each pulse of antiprotons fills a large phase space equal to the maximum phase space of the accelerator. Therefore, to accept another pulse the phase space of the anitprotons must be reduced. One method of reducing the antiproton phase space is to mix the "hot" anitproton "gas" with a "cold" electron "gas," let the mixture come to an equilibrium temperature and then separate the two gases leaving the antiproton phase space reduced. Hereafter this will be referred to as <u>electron cooling</u>. This method was proposed and tested by Budker at Novosibirsk USSR.[5] The technology of this process must be reproduced at Fermilab as a first step in achieving an antiproton beam. The second technical problem involves the collecting and storing of 2200 pulses. The beam can perhaps be stored at low energy (200 MeV)

in the same ring that is being used for electron cooling. This appears to only be feasible if electron cooling is also used on the stored beam. The difficulties involved with storing beam are inversely proportional to the momentum. It would be much easier to store the beam at 8 GeV in an accumulator in the main-ring tunnel. The third problem is to improve the vacuum in the main ring by at least an order of magnitude. The present vacuum is 5×10^{-7} Torr and limits stored beam lifetime to less than an hour at 250 GeV. A vacuum of 10^{-8} Torr should give a beam lifetime of more than 3 hours, assuming multiple scattering is the limit. This would give a duty factor of at least 50%.

The expected cross section (see Appendix II) for intermediate vector boson production by protons on antiprotons is

$$\sigma(p + \bar{p} \rightarrow W + \text{hadrons}) = 10^{-32}\text{cm}^2$$
$$\hookrightarrow e^+ + e^-$$

Putting in an efficiency of 50% for $e^+ + e^-$ detection and a luminosity of $2 \times 10^{-29}\text{cm}^{-2}\text{sec}^{-1}$ gives 4 vector bosons per hour.

There are many other interesting physics "secrets" that may occur with 500 GeV energy available, for example production of Higgs bosons[22], heavy leptons[23], or perhaps even production of free quarks!

III. Construction Proposal

The results of the electron cooling experiment at Novosibirsk[5] must be reproduced. Therefore, this proposal is for the construction of the 200-MeV cooling ring and the testing of electron cooling. The small ring will be first assembled above ground on a pad west of the present booster (see Figure 2). A 200 MeV proton beam already exists at that point. This has two principal advantages. First, a small machine will be simpler to build and less expensive. Secondly, being separate from the other machines will permit instant access to work on it.

Electron Cooling

The Novosibirsk group has achieved electron cooling of 65 MeV protons in 20 milliseconds.[24] An approximate formula for electron cooling[5] is given by

$$\tau \cong 1.2 \times 10^{7} \frac{\gamma_p^5 \beta_p^4 \theta_{max}^3}{j_e \eta \ln\left(\frac{\theta_{max}}{\theta_{min}}\right)} \quad \text{for } \theta_{max} \gg \theta_{min}$$

where

$$\gamma_p = \frac{E_p}{m_p} \quad \beta_p = \frac{p_p}{E_p}$$

j_e = electron current density (Amps/cm^2)

η = cooling length/circumference of ring

θ_{max} = larger divergence of electrons or protons

θ_{min} = smaller divergence of electrons or protons.

A comparison between the Novosibirsk and Fermilab situations is summarized in the following table. The Novosibirsk numbers are based upon second-hand information.[24]

Table II. Comparison of Novosibirsk and Fermilab

		Novosibirsk	Fermilab
Proton energy	T_p	65	200 MeV
γ_p, β_p	γ_p, β_p	1.07, .35	1.21, .566
Electron energy	T_e	35	110 keV
Electron current density	j_e	.25	1.0 amp/cm^2
Proton current	I_p	100	1.7μamps
Fraction of circumference cooled	η	.016	.064
Angular divergence	θ_e	1 ?	.5 mrad
	θ_p	.1?	1.1 mrad
Cooling time measured predicted	τ	.018 [illegible]	.060 sec

The question marks on the angular divergence for Novosibirsk indicate that we do not know for sure their values. The values put in the table are best guesses and make the simple formula consistent with the measured data. The clear point to be made from the formula is the strong (cubic) dependence of the cooling time on the divergence. The difficult properties to achieve for our electron beam will be the 1 amp/cm^2 with a divergence less than 0.5 milliradian. It maybe that we will have to reduce the energy of the protons to less than 200 MeV to achieve cooling in less than 60 milliseconds. For example, if the energy is reduced to 100 MeV the predicted cooling time is 20 milliseconds. This will be kept as a possibility in the design of the machine.

The space charge of the electron beam leads to a tune shift of about .25 in both transverse dimensions. Although this may seem large, it should be noted that the electron density must, in any case, be very uniform so the tune spread will be small and correction, if necessary, can be straightforward. The electron beam must be maintained parallel over 5m length. Space charge effects will blow up the electron beam unless a solenoidal magnetic field is maintained over the entire length of cooling. Furthermore, as discussed in Appendix II, the magnetic field lines must be shaped and carried all the way back into the electron gun cathode. The electrons, after exiting the cooling section, are to be decelelerated to regain the large energy in the beam. The system is shown schematically in Fig. 3.

The accelerating voltage must be 110 kV, equivalent to a beam power of 2.5 MW. Assuming a 98% efficiency of recovery, we have a dissipation of 50 kW/beam or a total of 200 kW, which is acceptable.

The electron current requirement is about 1 A/cm^2 over at least 20 cm^2 at 110 keV energy. The beam is ~70 cm^2, however, on subsequent passes the particles are not in the same position and thus the electron beam can be smaller than the antiproton beam. The cooling time will be longer. CW electron guns have been constructed that give this performance. For example, one such gun is shown in Fig. 4, that is to be used in PEP. This gun gives ~23A of current for a voltage of 110 keV over an area of approximately 18 cm^2.

Lattice

The lattice of the machine is primarily fixed by the requirements on the beam in the straight sections and the criteria that the lattice can be expanded to fit into the booster tunnel at a later time. The most important criteria is to have a small angular divergence and momentum compaction factor in the cooling section. This requires

$$\beta_h \gtrsim 40\text{m}$$
$$\beta_v \gtrsim 30\text{m}$$
$$\eta \lesssim 1\text{m}$$

Table III, and Fig. 5 give the characteristics of a lattice that satisfies the above criteria. This lattice can be expanded to have 12 straight sections by the addition of 26 quadrupoles and to have maximum energy of 600 MeV by the addition of 24 dipoles and fit in the booster tunnel.

Table III. Lattice of Cooling Ring

Energy	200 MeV
Momentum	645 MeV/c
Dipoles 4.6 kG 4' (see Fig. 6)	24
Quads 20 kG/m 2' (see Fig. 7)	34
Magnetic Radius	4.6 meters
Oval	25m x 45m
Long Straight Section (2-1 for cooling)	25m
Short Straight Section (2-1 for inject.)	5m
Superperiod	2
β (cooling horiz.)	40m
(cooling vert.)	30m
β_{hmax} (magnets)	10m
β_{vmax} (magnets)	20m
η_{max} (cooling straight)	2.9m
Accep. at 200 MeV ε_h	60πmm mr
ε_v	30πmm mr
Momentum Spread	$\frac{\Delta p}{p} \pm .35\%$
Transition Energy $E_{tr.}$	5.78 GeV
Tunes ν_h	7.86
ν_v	5.86

The acceptance has been chosen to match the present booster acceptance at 600 MeV. The Phase II of this program would be to accept antiprotons from the booster at 600 MeV and decelerate to 200 MeV (or 100 MeV if necessary) for electron cooling.

The good field clear aperture required for the possibility of operating at 100 MeV is

In magnets
$$2x_{max} = 2\left(\sqrt{\frac{\varepsilon_h\beta_h}{\pi}} + \eta\frac{dp}{p}\right) = 8.0 \text{ cm}$$
$$2y_{max} = 2\sqrt{\frac{\varepsilon_v\beta_v}{\pi}} = 5.7 \text{ cm.}$$

In long straight section
$$2x_{max} = 12 \text{ cm}$$
$$2y_{max} = 7 \text{ cm.}$$

The requirements for injection into the ring are opposite that for cooling, that is, a low β and a large momentum compaction factor. Therefore, injection will be done one quarter of the way around the ring from cooling (see Fig. 5). The stored cool beam will have a momentum 2% less than the central orbit and thus be $\eta\frac{\Delta p}{p} = 6$ cm inside at the injection point allowing almost full aperture for the injected beam. The electron cooling will bring the two beams together. A set of orbit bump magnets and a septum magnet similar to that used in the booster will be required. A small amount of rf is also needed for this manipulation.

Vacuum

Beam growth occurs by Coulomb scattering from gas molecules, and beam loss occurs each time an antiproton collides with a gas nucleus. The rate of increase in the mean square of the projected angle of Coulomb scattering is:[25]

$$\frac{d\langle\phi^2\rangle}{dt} = \frac{4\pi\ r_p^2 c}{\beta^3\gamma^2}\sum_i n_i Z_i \ \ln 38360/\sqrt{A_i Z_i}$$

where $r_p = 1.54 \times 10^{-16}$ cm the proton radius, n_i is the density and Z_i and A_i are the atomic number and atomic weight of atoms of type i. Snowdon[26] has analyzed the residual gas composition in the MR at a pressure of 0.21μ Torr. We will assume the same composition in the Freezer, and follow here his calculation of beam growth. The angular growth is

$$\frac{d\langle\phi^2\rangle}{dt} = \frac{p}{\beta^3\gamma^2}\, 2.8 \times 10^4 \ \frac{\text{rad}^2}{\text{sec Torr}}.$$

The diffusion rate of the quantity $W = (dy/d\phi)^2+\nu^2y^2$ is $D = R^2d<\phi^2>/dt$ where y is the amplitude of betatron motion, $\nu\sim4$ is the tune, and R = 19m is the average radius. The beam lifetime is[27]

$$\tau = \frac{1}{D}\left(\frac{2\nu a}{2.4}\right)^2$$

where a = 1 cm is the tolerable aperture growth. The lifetime against Coulomb scattering is then $\tau\,[\mathrm{sec}] = 3.2 \times 10^{-6}/P[\mathrm{Torr}]$. A lifetime of three hours requires a mean pressure of 3×10^{-9} Torr.

The fraction f of beam removed by nuclear collisions with gas is

$$df/dt = \beta c\sigma_{p\bar{p}} \sum_i n_i A_i^{2/3}$$

where $\sigma_{p\bar{p}}$ = 170 mb is the $p\bar{p}$ total cross-section at 650 MeV/c.

$$\frac{1}{p}\,\Sigma n_i A_i^{2/3} = 1.5 \times 10^{17}\mathrm{cm}^{-3}\mathrm{Torr}^{-1},$$

$$\tau\,[\mathrm{sec}] = 2.3 \times 20^{-3}/P[\mathrm{Torr}].$$

A lifetime of one day requires a mean pressure of 2.5×10^{-8} Torr.

The vacuum in the Freezer should thus be $\lesssim 3 \times 10^{-9}$ Torr. One appealing approach to achieving this in the bending lattice is to locate a distributed ion pump system in the fringe field of the dipoles.[28] Rowe and Winter[29] estimate a pumping speed of 1600 ℓ/sec from each 1m dipole so equipped. The cost is about 1/2 that of a standard ion pump of capacity 500 ℓ/sec. Standard ion pumps would still be required in the straight sections. The conductance of a 5m section of the Freezer vacuum pipe is approximately 22 ℓ/sec.

IV. Luminosity

Even though this proposal does not achieve the final machine, the luminosity effects the design of the test machine. Therefore, the luminosity is discussed here.

The production of 5.2 GeV antiprotons from 100 GeV protons is taken from Appendix II. The acceptance is determined by the booster at 600 MeV. From Table III, these acceptances at 200 MeV are

$$A_h = 60\pi \text{ mm mrad}$$

$$A_v = 30\pi \text{ mm mrad}$$

$$\frac{\Delta p}{p} = \pm .0035.$$

Assuming adiabatic damping during deceleration the emittances scaled to 5.2 GeV injection energy are

$$\varepsilon_h = 6.4\pi \text{ mm mrad}$$

$$\varepsilon_v = 3.2\pi \text{ mm mrad}$$

$$\frac{\Delta p}{p} = \pm .0015.$$

From Appendix II the antiproton yield for this acceptance is 4.6×10^7 antiprotons per 12 booster bunches.

The luminosity is given by the following expression

$$\mathcal{L} = \frac{N_p N_{\bar{p}} f}{2\pi \sqrt{\sigma^2_{x_p} + \sigma^2_{x_{\bar{p}}}} \sqrt{\sigma^2_{y_p} + \sigma^2_{y_{\bar{p}}}} N_B} .$$

where N_p and $N_{\bar{p}}$ are the number of protons (4×10^{12}) and antiprotons (1.6×10^{11}), $f = 47$ kHz is the main ring revolution frequency, $N_B = 84$ is the number of bunches in each beam and σ is the beam size. The emittance of a main ring proton beam is $\varepsilon = 6\pi\sigma^2/\beta^* = \varepsilon_o/\gamma$ where $\varepsilon_o \cong 20\pi 10^{-6}$m is the invariant emittance of the present main ring beam, and $\beta^* = 2.5$m is the local β at the intersection point.

$$\mathcal{L} = \frac{3N_1 N_2 f\gamma}{\varepsilon_o \beta N_B} \simeq 2 \times 10^{29} \text{ cm}^{-2}\text{sec}^{-1}.$$

V. Manpower

The manpower necessary is given in Table IV.

Table IV. Manpower for Phase I

2 - physicists 1 - engineer 2 - designers	design of machine
1 - physicist 1 - engineer 2 - technicians	construct ring of magnets
1 - physicist 2 - technicians	vacuum system
1 - physicist 1 - engineer 2 - technicians	electron beam

VI. Conclusion

The feasibility of obtaining a proton-antiproton colliding beam facility appears to be very promising. The principal research and development necessary is the cooling of protons (antiprotons) by electrons. This proposal presents a research and development project that should prove the feasibility of electron cooling.

The possibility of achieving an energy of 500 GeV in the center of mass, almost an order of magnitude larger than existing machines, is very exciting. The probability of a new level of physics being uncovered is very high. This is a unique opportunity made possible by the Fermilab facilities and we believe this facility must be brought to fruition.