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Report of the New Rings Study Group

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I. INTRODUCTION AND SCOPE

We have looked into the need for and possibility of constructing new accelerators at Fermilab in support of the proposed upgrade of the proton-antiproton collider to a luminosity of $5\text{x}10^{31}\text{cm}^{-2}\text{s}^{-1}$. The upgrade is based on running multiple batches (144 in the latest scheme) on separated orbits in the Tevatron. Beams containing on the order of $6\text{x}10^{12}$ protons and $3\text{x}10^{12}$ antiprotons with transverse emittances of 12π mm-mr are required. It is unclear what the required regeneration rate for collider beams will be, but it will probably lie in the range 12-24 hours. It is expected that luminosity degradation due to emittance dilution will be much more significant than luminosity degradation due to beam loss.

Antiproton economics represent one of the outstanding problems to be solved in the proposed upgrade. There are two shortcomings in the present antiproton source: 1) the accumulation rate is not high enough to support the upgrade; and 2) nowhere within the complex is there a place in which $3\text{x}10^{12}$ antiprotons can be stored. With two interaction regions each running with an initial luminosity of $5\text{x}10^{31}\text{cm}^{-2}\text{s}^{-1}$ antiprotons are being lost from the collider at a rate of $3.2\text{x}10^{10}$/hour (assuming a proton-antiproton cross section of 90mb). If it were necessary to replace the entire antiproton beam every 24 hours, however, the effective loss rate would be $1.3\text{x}10^{11}$/hour. Replenishing antiprotons at either of these rates is beyond the present capabilities of the antiproton source, but is probably within range of proposed upgrades, forseen to result in accumulation rates of about $1.5\text{x}10^{11}$/hour. The design value for the total number of protons which can be stacked in the existing Accumulator is $5\text{x}10^{11}$. It is believed that in actuality $1\text{x}10^{12}$ may be achievable, but that $3\text{x}10^{12}$ certainly is not.

One can contemplate means of addressing the shortcomings of the existing antiproton source which do not involve the construction of new accelerators or storage rings at Fermilab. Such means might include cooling of the antiproton beam as it circulates in the Tevatron (in order to improve the luminosity lifetime), and replacement of only a fraction (say 1/12) of the antiprotons in the collider at any one time. The consideration of such options is, by definition, outside of the scope of this report. Also outside the scope is any description of how the antiproton accumulation rate might be increased to $1.5\text{x}10^{11}$/hour. We have taken the approach here of trying to understand both the feasibility and practicality of varied options for new rings at Fermilab, rather than trying to produce a single detailed design. In other words this document is not a design report and should not be construed as such.

Our perception of the potential needs for new rings (in order of priority) is as follows:

1. **Antiproton Storage and/or Recovery**. A facility for storing up to 4×10^{12} antiprotons is needed. Recovery of antiprotons from the collider becomes a viable option if the luminosity is indeed dominated by emittance dilution rather than beam loss.

2. **New or Post-Booster**. The goal here would be to inject into the existing Main Ring above transition. Improved performance of the Main Ring would be anticipated.

3. **New Main Ring**. Advantages would include better emittance preservation, a faster cycle time for antiproton production, and the removal of interference/backgrounds at the B0 and D0 detectors.

We discuss below various scenarios based on one or more combinations of the above possibilities.

II. ASSUMPTIONS

In order to proceed without being forced to consider an infinte number of options we have taken it upon ourselves to make certain assumptions. These assumptions are based on a combination of the operating experience and common sense of the authors. We make the following assumptions before proceeding.

1. Proton and anitproton transfers should look identical. That is they should happen at the same energies, and originate in rings of the same circumference and same transition energies.

2. Any scenario involving two new rings must have the rings located in the same tunnel.

3. New rings should have harmonic numbers (@53MHz) which are divisible by seven. It is anticipated that in the collider bunches

will be located in every seventh bucket. This requirement insures compatibility with the bunch structure being formed within the new rings.

4. It is not practical to contemplate decelerating diluted antiprotons below 20 GeV in the Main Ring.

5. We would like to produce antiproton bunches with longitudinal emittances of 0.2 eV-sec in the collider. This requirement insures Main Ring transmission through transition, or in the absence of transition crossing in the Main Ring will produce short bunches which will keep experimenters happy. For 144 bunches this means we need a total emittance of 29 eV-sec for $3x10^{12}$ antiprotons. (This may be an overly restrictive requirement in that it may produce unstable beams in the Tevatron.)

6. The upgraded antiproton accumulation rate will be $1.5x10^{11}$/hour. This number is scaled from last year's estimate of $4x10^{11}$/hour by the now-known missing factor of 2.5 in the antiproton production cross section. Note that this accumulation rate puts us right at the limit for being able to replenish the collider antiproton beam from scratch every 24 hours.

7. In any antiproton accumulator capable of operating at an energy above 8.9 GeV, cooling of antiprotons from the existing Accumulator should take place at 8.9 GeV, while cooling of any recovered antiprotons should take place at the peak energy of the ring. This is not strictly an assumption since we did try looking at alternative operational modes. However such modes were deemed extremely impractical.

III. SCENARIOS

Based on the above considerations a relatively large number of scenarios can be written down. We have made a cursory examination of seven different scenarios, attempting to identify advantages and disadvantages of each, with an eye toward reducing to a manageable number those which we are willing to consider in some detail. The seven scenarios along with the pluses and minuses which we identified are given in Table I.

In the nomenclature of Table I a 'Depository' is an antiproton accumulator ring which accepts antiprotons at relatively infrequent time intervals (tens of minutes). The energy scales of the rings listed in the table

Table I. New Rings Scenarios

Scenario	Pluses	Minuses
1. 8 GeV Antiproton Depository	Cheap	
2. 20 GeV Depository 20 GeV Post-Booster	Antiproton recovery Avoid transition in MR Improved MR performance Improved B0/D0 background	Extra transfer
3. 20 GeV Depository 20 GeV New Booster	" " " "	Space-charge dilution?
4. 8 GeV Depository 150 GeV New Main Ring	Improved MR performance Higher antiproton production rate No MR at B0/D0	Antiproton recovery?
5. 150 GeV Depository	Antiproton recovery Fewer antiproton transfers	MR problems remain
6. 150 GeV Depository 150 GeV New Main Ring	" " Improved MR performance Higher antiproton production rate No MR at B0/D0	Expensive
7. 300 GeV New Main Ring	Much higher antiproton production rate No MR at B0/D0 Easier Tev injection with separated orbits Tev persistent currents reduced Makes other options look cheap	Very expensive

follow more-or-less directly from the assumptions given above. All of the comments in the table are, we believe, self-explanatory with the possible exception of the concern about space-charge dilution in a new (as opposed to a post-) booster. The concern is that we are tolerating a very large space-charge tune spread in the existing 8 GeV Booster only because the beam remains at or near the injection energy for milliseconds. It is our fear that in a more slowly cycling booster, in which the beam is required to spend tens of milliseconds near the injection energy, the performance may deteriorate substantially.

As stated above we felt that it was not feasible for us to devote real attention to more than three of these scenarios. As a result we will describe in this report our findings on scenarios 1., 2., and 6. Scenario 1 is chosen as being the cheapest thing one could contemplate doing. An accumulator/depository ring capable of containing $4x10^{12}$ antiprotons, with a stacking period of 3 hours, could be built with the same circumference and operating energy as the existing Accumulator. Scenario 2 is chosen as the least expensive solution which would solve some Main Ring problems in addition to providing the desired antiproton storage capability. And scenario 6 is chosen as something one might contemplate doing if there were a lot of money available.

IV. ANTIPROTON DEPOSITORIES: GENERAL CONSIDERATIONS

Before launching into descriptions of specific designs of antiproton depositories it is worth examining a few general principles which ultimately lead to specifications on the desired lattice characteristics. As we shall see below the longitudinal and transverse phase space densities we hope to provide, taken with the cooling system characteristics, force us to design certain types of rings.

Choice of Energy and Circumference

The range of energies which we consider is limited by the assumption that we would like each antiproton transfer to take place at the same energy as the corresponding proton transfer, and by the operating characteristics of the existing Main Ring and Tevatron. This naturally restricts us to the consideration of three energies: 1) 8.9 GeV, the injection energy of the present Main Ring and the operating energy of the existing antiproton source; 2) 20 GeV, an energy which is deemed to be sufficiently above Main Ring transition to alleviate problems associated with Main Ring transition crossing; and 3) 150 GeV, the present injection energy into the Tevatron.

The circumferences of the rings may be chosen on the basis of available magnetic fields in conventional magnets, and on the basis of numerology associated with the circumferences of the present Accumulator and the Tevatron. We have chosen rings of circumference 474.2 meters, for scenarios 1 and 2, and 2845.2 meters for scenario 6. The circumference of 474.2 meters matches the existing Accumulator and Booster. As shown below we believe that we can design an antiproton depository capable of operating at 20 GeV with this circumference. As a result the antiproton ring associated with scenarios 1 and 2 is the same ring. The circumference of 2845.2 is exactly six times the circumference of the existing Accumulator and Booster. This circumference also represents exactly half of the filled circumference of the Tevatron operating with the anticipated 144 bunches.

Choice of Lattice Parameters

In order to reach the phase space densities which we desire we will be using cooling systems operating over the band 8-16 GHz. For a ring containing $N=4\text{x}10^{12}$ antiprotons with a system bandwidth W=8 GHz the optimized cooling time is,

$$\tau = N/W = 500 \text{ sec.}$$

We will show below that this amount of cooling is necessary to provide us with a cooling rate comfortably above the heating rate due to intrabeam scattering. We will also describe how the specification of the phase space and cooling characteristics leads directly to constraints on the optics of the Depository. Finally, we will write a specification for the Depository lattice parameters based on this discussion.

Longitudinal and Transverse Emittance

As stated earlier we would like to be able to create a total longitudinal emittance of about 29 eV-sec/$4\text{x}10^{12}$ antiprotons. This will lead to an emittance of about 0.2 eV-sec/bunch in the collider. The momentum spread is then 20 MeV in the 474 meter ring, and 3.5 MeV in the 2845 meter ring. The peak densities are then $2\text{x}10^{5}$/eV in the smaller ring, and $1.2\text{x}10^{6}$/eV in the larger ring. These peak densities represent a factor of two improvement over the present Accumulator performance.

The transverse emittance requirements are given by the upgrade parameters. We need to achieve 10π mm-mr. This represents a beam density an order of magnitude greater than the design value in the existing Accumulator.

Intrabeam Scattering

The primary competition to the stochasitic cooling systems is provided by intrabeam scattering. In order to have any confidence that the desired phase space density can be achieved in any dimension it is necessary that the heating time associated with intrabeam scattering be long compared to the stochastic cooling time. The intrabeam scattering time is a function of the beam energy, the line-charge density in the beam, and the transverse beam dimensions. Figure 1 shows the calculated intrabeam scattering time as a function of momentum spread for an 8.9 GeV beam containing $4\text{x}10^{12}$ antiprotons, circulating in the existing Accumulator with an (invariant) transverse emittance of 10π mm-mr. Note that the heating effect is much more severe in the transverse than the longitudinal dimension. The figure may be scaled to larger circumferences, at the same energy and with the same lattice functions, by scaling the vertical axis proportionally to the circumference. We see from the figure that the heating time due to intrabeam scattering in the 474 meter ring specified above ($\sigma_p/p=.08\%$) is about 1600 seconds--more than three times the minimum cooling time.

Choice of Transition Energy

The choice of transition energy is dictated by the requirement that the longitudinal Schottky bands do not overlap anywhere within the bandwidth of the cooling system. The requirement is,

$$6(\sigma_p/p)h\eta < 1$$

where h is the ratio of the highest frequency in the cooling band to the revolution frequency, $\eta=(\gamma_t^{-2}-\gamma^{-2})$, and σ_p/p is the rms momentum spread in the beam. While the requirement is expressed as an inequality, we would really like to have the two sides of the equation nearly equal in order to maximize mixing and optimize cooling.

For the parameters we have described for our anitproton depositories, $f_{max}=16$ GHz and a total longitudinal emittance of 29 eV-sec. at 8.9 GeV, the requirement on η becomes

$$\eta = .009$$

independent of the circumference of the ring. For cooling at 8.9 GeV this η corresponds to a γ_t of 7.1 or 22.0. A transition gamma of 7.1 is the more convenient goal since it is a more 'natural' value for the circumferences we are considering, because it means that the anitprotons do not have to go through transition in accelerating to either 20 GeV or 150 GeV, and because it provides better cooling (better mixing) of recovered beams at 20 GeV or 150 GeV.

Accumulation and Recovery Scenarios

A cursory examination of the possible accumulation/recovery scenarios reveals that in the rings capable of acceleration the most efficient operation involves cooling of antiprotons originating in the Accumulator at 8.9 GeV, and cooling of antiprotons originating in the collider at the peak energy of

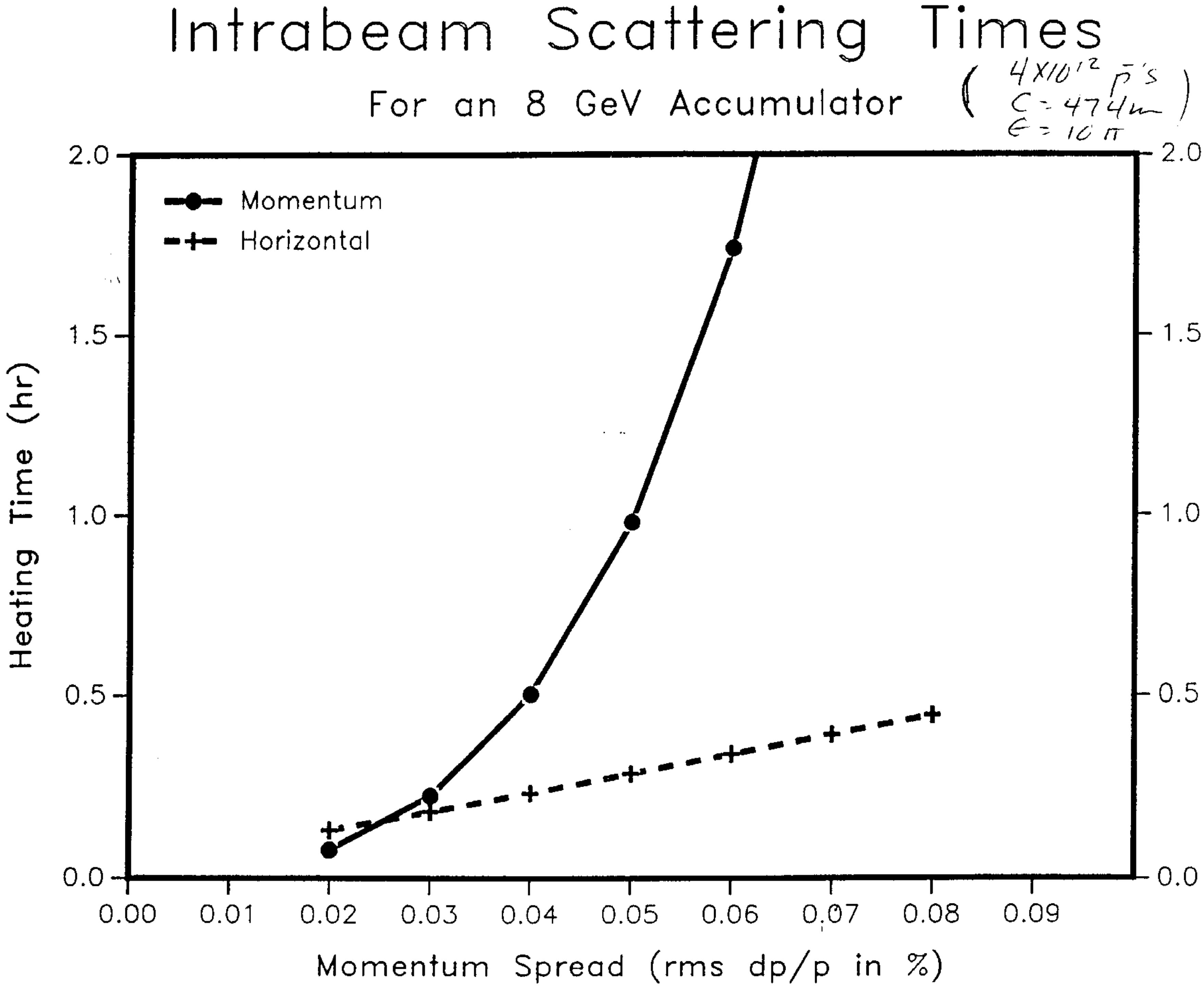

Intrabeam Scattering Times
For an 8 GeV Accumulator
(4×10^{12} $\bar{p}$'s
C = 474m
ε = 10π)
Momentum
Horizontal
Heating Time (hr)
0.0
0.5
1.0
1.5
2.0
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
Momentum Spread (rms dp/p in %)

Figure 1.

the machine. Cooling of antiprotons supplied by the exisiting Accumulator is most efficiently carried out at low energy because the physical beam sizes associated with a given emittance are greatest at low energy. In addition, a realistic scenario in which antiprotons are cooled at 20 GeV (or 150GeV), decelerated to 8.9 GeV so that more antiprotons can be accepted into the ring, and finally accelerated back to high energy for continued cooling is felt to be operationally inefficient. The preferred energy for cooling recovered antiprotons appears to be at 20 GeV (or 150 GeV) for the simple reason that attempting to decelerate the diluted antiprotons would increase the aperture requirements of the ring.

A possible accumulation scenario might look as follows:

1. The Depository ring is loaded every 3 hours with 4.5×10^{11} antiprotons from the Accumulator. These antiprotons have a total longitudinal emittance of about 16 eV-sec and a momentum spread when delivered from the Accumulator h=2 system of .25% (95% full width).

2. A shuttered kicker is used to inject the antiprotons into the depository on an orbit which is roughly 1% displaced from the core orbit.

3. The antiprotons are then moved close to the core using a low voltage, low harmonic, RF system, and are absorbed into the core over the next three hours. All of this takes place at 8.9 GeV.

The essential feature of the Depository which distinguishes it from the Accumulator is the lack of a stack tail cooling system. This is because the antiprotons in the depository can be cleared from the orbit on which they are deposited by the stacking RF system in a leisurely manner, i.e. in hours rather than in the 2 seconds required in the Accumulator.

Antiproton recovery from the collider takes place at 20 GeV or 150 GeV depending upon the ring. Without going into specifics of how the antiprotons are injected into a ring of smaller circumference than the Main Ring, we can make a general argument about what sort of momentum spread we want to be able to accomodate. The undiluted antiproton beam has a longitudinal emittance of 29 eV-sec. If we wish to accomodate a factor of four dilution in the collider this means the recovered beam may have a longitudinal emittance of 120 eV-sec. If only one of every seven buckets is filled then the best we can hope for in the 474 meter ring is a recovered beam beam with a pre-cooled momentum spread of 525 MeV. The relative momentum spread at 20 GeV is then $\Delta_p/p = 2.6 \times 10^{-2}$. This is undoubtably larger than we want to make the acceptance of the Depository. Two options exist for reducing this spread: 1) adiabatic debunching and recapture into 53 MHz buckets of the anitprotons prior to injection into the Depository; or 2) injection into the depository in discrete batches with cooling between subsequent injections. Either of these options would reduce the full momentum spread of the recovered beam in the 20 GeV Depository to about 0.5%. In the 150 GeV Depository the momentum spread of the recovered beam would be less than 0.1% even without taking extraordinary measures.

Stochastic Cooling

The cooling systems in all Depositories include horizontal and vertical betatron systems, and a momentum cooling system. These systems are analogous to the core cooling systems in the existing Accumulator. No stack-tail type system is needed because of the long time between consecutive antiproton injections and the limited dynamic range in particle densities.

For optimum cooling transverse pickups and kickers need to be located at zero dispersion points close to an odd integer times 90° of betatron phase advance apart. They should be located as close to each other as possible within the ring in order to minimize transit time jitter, yet far enough apart to allow position signals to travel a significantly shorter distance to the kickers than the beam travels. Pickups and kickers separated by one third the circumference of the Depository seems to be the optimum arrangement (and the one used in TeV I). The easiest way to achieve this arrangement is with a ring of superperiodicity three and a tune which is close to an odd integer times 0.75.

The requirements on the lattice for momentum cooling include the existence of a high dispersion region for the pickups and a zero dispersion region for the kickers. With a ring of sixfold symmetry and superperiodicity three the kickers can be halfway around the ring from the pickups. In all instances it is desirable to provide low beta functions at kicker locations.

Lattice Parameters Specification

Based on the considerations discussed above we can specify the ideal Depository lattice as follows:

1. **γ_t = 7.** This optimizes mixing while keeping longitudinal Schottky bands from overlapping at 8.9 GeV.

2. **Momentum Aperture (full width) = 1.5%.** This is needed to accomodate accumulation from the existing Accumulator

and recovery from the collider. The requirement may be somewhat reduced for the 150 GeV Depository.

3. **Transverse acceptance = 10π mm-mr.** This should be very generous since antiprotons from the Accumulator will have an emittance of 2π, and those recovered from the collider will have 1.9π at 20 GeV assuming a normalized emittance of 4x10π.

4. **High dispersion straight section with α_p > 5 meters and with at least 2 meters of free space reserved for momentum cooling pickups.**

5. **Tunes near an odd integer times 0.75, and sixfold symmetry with a superperiodicity of three.** This is to provide correct betatron phase advance between stochastic cooling pickups and kickers and to otherwise optimize cooling.

6. **Zero dispersion straight sections with 10 meters of free space reserved for betatron pickups and kickers, and momentum kickers.**

7. The usual requirements of straight sections for RF, injection, and extraction.

V. ANTIPROTON RING DESIGNS

We have designed two Antiproton Depository Rings, one with a circumference of 474 meters and a peak energy of 20 GeV, and a second with a circumference of 2845 meters and a peak energy of 150 GeV. The first ring is associated with scenarios 1 and 2 of Table I, while the second ring is associated with scenario 6. A parametric description of the rings is given in Table II.

The 20 GeV Antiproton Depository

The 20 GeV Depository is designed to have the same circumference as the existing Accumulator. The transition gamma is 6.9. Through efficient space utilization the ring is capable of operating up to 20 GeV with bending fields of only 15.4 kGauss. The ring has three zero dispersion straight sections each 10.1 meters long, and three high dispersion (α_p=7.0 m) straight sections each 6.0 meters long. In addition to stochastic cooling equipment and RF,

Table II. Antiproton Depository Designs

	Ring 1	Ring 2	
Circumference	474.2	2845.2	meters
Accumulation Energy	8.9	8.9	GeV
Peak Energy	20.0	150.0	GeV
Harmonic Number (@53 MHz)	84	504	
Horizontal Tune	6.61	9.61	
Vertical Tune	6.61	8.61	
Transition Gamma	6.9	9.0	
η @ Low Energy	.010	.0013	
η @ Peak Energy	.019	.0123	
Maximum No. of Antiprotons	$4\text{x}10^{12}$	$4\text{x}10^{12}$	
Transverse Emittance (Normalized)	10π	10π	mm-mr
Full Momentum Spread	20	7.0	MeV
Longitudinal Emittance	29	58	eV-sec
Cooling System Bandwidth	8-16	8-16	GHz
Transverse Acceptance (Unnormalized)	10π	10π	mm-mr
Momentum Acceptance	1.8	0.8	%
Number of Straight Sections	6	6	
Length of Zero Dispersion SS	10.1	46.0	meters
Length of High Dispersion SS	6.0	47.7	meters
Number of Dipoles	42	360	
Dipole Length	6.5	6.0	meters
Dipole Field (Max)	15.4	14.6	kGauss
Number of Quadrupoles	66	90	
Magnet Style	TeV I	TeV I	

there is room for two injection systems (one from the Accumulator and one from the Main Ring) and one extraction system. The 8 GeV Depository of scenario 1 is the same ring without the 20 GeV injection system and without an acceleration capability.

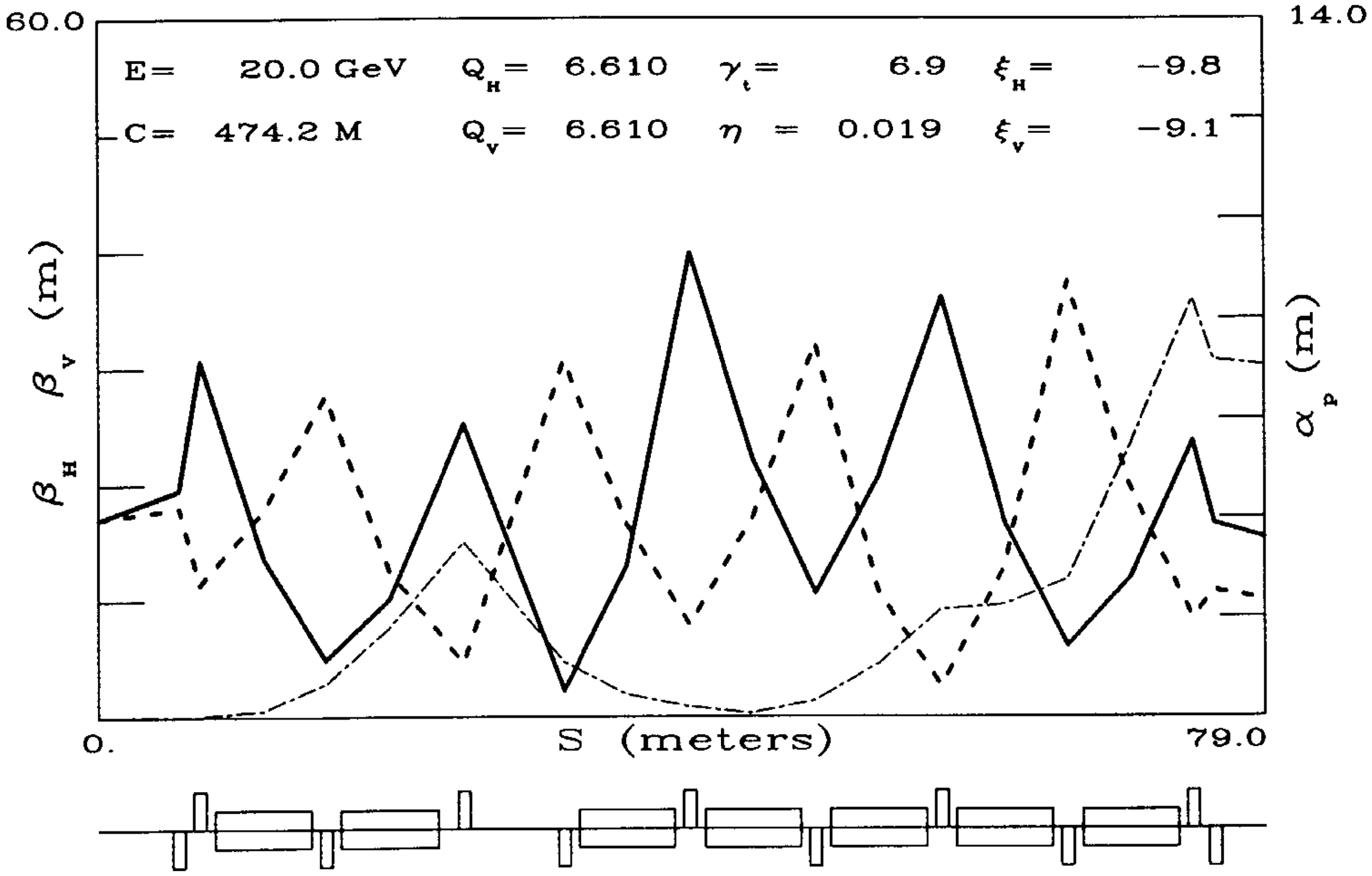
Lattice

The 20 GeV Depository lattice is shown in Figure 2. What is shown is one sixth of the ring. The ring is mirror symmetric around each of the endpoints of the figure and has a superperiodicity of three. The lattice is built up of pseudo-FODO cells with close to 90° phase advance per cell. The zero dispersion straight sections are 10.1 meters long and house the RF systems, momentum kickers, and betatron pickups and kickers. The high dispersion straight section is created by removing bending from the lattice 270° upstream of the straight section. The free space in each high dispersion straight section is 6.0 meters. These areas accomodate the momentum cooling pickups as well as injection and extraction kickers. The free space existing 270° away from the high dispersion straight sections is occupied by injection and extraction Lambertson magnets. Sixty centimeters of free space is provided between each dipole and quadrupole for installation of sextupoles and beam position monitors. The lattice shown utilizes seven different quadrupole strengths. No attempt has been made to mix and match quadrupole lengths/strengths to minimize the number of busses. It is anticipated however that four independent quadrupole busses would have to be provided in order to allow reasonable tuning of the ring.

Magnets

The aperture and strength requirements of the dipole magnets are modest and could easily be satisfied by extended length TeV I style 'small dipoles'. Outside of the last dipole adjacent to the high dispersion straight section, the aperture requirements for a $10\pi \times 10\pi \times 1.8\%$ ($H \times V \times \Delta_p/p$) acceptance are 95x40 mm^2 (HxV). In the last bending magnet the required horizontal aperture is 182 mm. The good field aperture of the TeV I 'SDB' magnet is about 100x50 mm^2 and the required operating current for 15.4 kGauss is around 1050 amps. The length of an SDB is 3.05 meters, almost half of that required, meaning one could contemplate either building longer TeV I dipoles or using two SDB's per half cell. If one were to use two SDB magnets (leaving a 0.4 meter free space between magnets) the operating current at 20 GeV would be about 1140 A. Saturation should be less of a problem in this application than in the existing Accumulator. The final magnet adjacent to the high dispersion straight section (six total @ 6.5 meters length) would have to be a TeV I 'large dipole'.

The aperture requirements of the quadrupole magnets are the virtually the same as the dipoles. Once again the TeV I 'small quadrupole', with a



20GeV PBAR DEPOSITORY

Figure 2

good field aperture of 125 mm is more than sufficient everywhere except immediately adjacent to the high dispersion region. Outside of these regions the entire ring could be built out of SQD's and SQE's without having to run any magnet over 350 A at 20 GeV. The quadrupoles adjacent to the high dispersion regions could be LQE's. If so three, rather than the two shown, would be needed in each sector.

RF

The specification of the RF requirements for the 20 GeV Depository requires a rather specific scheme for beam manipulations, both for loading the Depository from the Accumulator, and for antiproton recovery (loading the Depository from the Main Ring). The following scheme is adopted and forms the basis for the RF specification. The longitudinal beam parameters for each step are given in Table III; the RF system parameters are given in Table IV. The bucket areas shown in Table IV all correspond to stationary buckets, since the assumption is made that all energy changes occur slowly.

1.Loading the Depository for the Accumulator.
Every three hours $4.5\text{x}10^{11}$ antiprotons will have been collected in 16 eV-sec in the Accumulator. The unloading sequence involves capturing the entire Accumulator core with an h=2 system, accelerating to the extraction orbit, transferring the beam to matched buckets in the Depository, and RF stacking this beam from the Depository injection orbit to the edge of the stack. The injected beam requires 0.3% of momentum aperture. Nine repetitions (over a period of 27 hours) fills the Depository with $4\text{x}10^{12}$ antiprotons.

2.Unloading the Depository to the Main Ring.
The original 144 eV-sec loaded from the Accumulator is cooled to 30 eV-sec. The entire core is then accelerated to 20 GeV with the h=84 RF system. Then, one twelfth of the stack is captured with an h=12 system and moved to the extraction orbit. The h=12 voltage is suddenly increased to rotate the bunches so that they can be captured in one out of every seven buckets of the h=84 system. The h=84 system is turned on to match to the bunches, and then the voltage is increased for transfer to the Main Ring. The beam is extracted to the Main Ring, captured in matched buckets, and accelerated from 20 to 150 GeV. The beam is then transferred to the Tevatron. This process is repeated twelve times to fill the collider.

3.Loading the Depository from the Main Ring.

~~Table 1~~

20 GeV Depository
Coasting Beam Longitudinal Parameters

ϵ_L = longitudinal emittance (ev-sec)
$N_{\bar{p}}$ = number of antiprotons
f = average density (ev^{-1})
ΔE = energy spread (MeV) (full)
$\delta p/p$ = full relative momentum spread (%)
I = beam current (ma)
Z/n = impedance limit (Ω) (Keil-Schnell)
E = Total energy (GeV)

Condition	E	ϵ_L	$N_{\bar{p}}$	f	ΔE	$\delta p/p$	I	Z/n	
1 one shot from Accumulator	8.9	16	4.5×10^{11}	4.5×10^{4}	10	.11	45	537	Loading +
2 Full depository, cooled	8.9	30	4×10^{12}	2.1×10^{5}	18.8	.21	400	220	Unloading
3 Full depository, cooled	20	30	4×10^{12}	2.1×10^{5}	18.8	.09	400	181	
4 One shot for Main Ring*	20	2.5	3.3×10^{11}	0.9×10^{5}	3.7	.019	78	42	
5 One shot, recovered beam from Main Ring	20	10	3.3×10^{11}	$.53 \times 10^{5}$	6.3	.032	33		
6 Full depository (recovered beam)	20	120	4×10^{12}	$.53 \times 10^{5}$	75.2	.36	400		Recovery
7 Full depository, cooled recovered beam	20	30	4×10^{12}	2.1×10^{5}	18.8	.09	400		
8 Full depository, cooled recovered beam; decelerated	8.9	30	4×10^{12}	2.1×10^{5}	18.8	.21	400		

* Uses bunched beam parameters

Table III

~~Table 2a~~

20 GeV Depository
RF Parameters (loading & unloading)

ϵ_L = longitudinal emittance (ev-sec)
A_b = bucket area (ev-sec)
ΔE_b = bunch height (MeV)
Δt = Bunch length (full) (μsec)
ΔE = Bunch energy spread (full) (MeV)
$\delta p/p$ = bunch relative momentum spread (full) (%)
E = Total energy (GeV)
N_b = # of bunches

V_{RF} = rf voltage (kV)
h = harmonic number
f_{RF} = RF frequency (MHz)
$N\bar{p}$/bunch = # of $\bar{p}$'s/bunch

Condition	E	ϵ_L	N_b	ϵ_L/bunch	h	V_{RF}	f_{RF}	A_b	ΔE_b	Δt	ΔE	$\delta p/p$	$N\bar{p}$/bunch
1 Accumulator, unstack	8.9	16	2	8	2	2.06	1.25	16.0	15.8	.36	22.3	.25	2.2×10^{11}
2 Depository, stack	8.9	16	2	8	2	.83	1.25	16.0	15.8	.36	22.3	.25	2.2×10^{11}
3 Depository,	8.9	30	84	.36	84	124	53	.72	29.8	.009	42.1	.47	4.8×10^{10}
accelerate	20	30	84	.36	84	106	53	.72	29.7	.009	42.0	.21	4.8×10^{10}
4 Depository, unstack	20	2.5	12	.21	12	.132	7.5	.47	2.77	.057	3.7	.019	2.8×10^{10}
5 Depository, bunch rotate	20	2.5	12	.21	12	3.67	7.5	2.5	14.6	.011	19.6	.098	2.8×10^{10}
6 Depository,	20	2.5	12	.21	84	13.6	53	.26	10.6	.011	19.2	.096	2.8×10^{10}
prebunch	20	2.5	12	.21	84	32.6	53	.39	16.2	.009	23.7	.119	2.8×10^{10}
7 Main Ring, capture	20	2.5	12	.21	1113	15.1	53	.39	16.4	.009	23.9	.120	2.8×10^{10}
& accelerate	150	2.5	12	.21	1113	8.8	53	.39	16.4	.009	23.9	.016	2.8×10^{10}

Table IV a

~~Table 2b~~

20 GeV Depository
RF Parameters (recovery)

ϵ_L = longitudinal emittance (ev-sec)
A_b = bucket area (ev-sec)
ΔE_b = bunch height (MeV)
Δt = Bunch length (full) (μsec)
ΔE = Bunch energy spread (full) (MeV)
$\delta p/p$ = bunch relative momentum spread (full) (%)
E = Total energy (GeV)
N_b = # of bunches

V_{RF} = rf voltage (kV)
h = harmonic number
f_{RF} = RF frequency (MHz)
$N_{\bar{p}}$/bunch = # of $\bar{p}$'s/bunch

Condition	E	ϵ_L	N_b	ϵ_L/bunch	h	V_{RF}	f_{RF}	A_b	ΔE_b	Δt	ΔE	$\delta p/p$	$N_{\bar{p}}$/bunch
1 Main Ring	150	10	12	.83	1113	157	53	1.67	69.5	.008	98.3	.067	2.8×10^{10}
150 GeV	150	10	12	.83	1113	3.6	53	.25	10.5				
2 Main Ring capture	150	10	1	10	13	.050	4.1	23.5	11.5	.670	14.98	.01	3.3×10^{11}
in h=13, stretch	150	10	1	10	13	.009	4.1	10	4.9	1.03	9.74	.006	3.3×10^{11}
3 Main Ring	150	10	55	.18	1113	2.76	53	.22	9.2	.011	16.6	.011	6×10^{9}
recaptured	150	10	55	.18	1113	8.3	53	.38	15.9	.008	21.9	.015	6×10^{9}
4 Main Ring	20	10	55	.18	1113	14.3	53	.38	15.9	.008	21.8	.109	6×10^{9}
decelerate, match	20	10	55	.18	1113	4.8	53	.22	9.7	.011	16.6	.083	6×10^{9}
5 Depository capture, stack	20	10	55	.18	84	9.97	53	.22	9.7	.011	16.4	.082	6×10^{9}
6 Depository	20	30	84	.36	84	106	53	.72	29.7	.009	42.1	.21	4.8×10^{10}
Decelerate recovered beam after cooling (long emittance shrinks by x4)	8.9	30	84	.36	84	124	53	.72	29.8	.009	42.0	.47	4.8×10^{10}

Table IV b

As discussed above it is assumed that the antiproton longitudinal emittance in the Tevatron will have blown up by a factor of four during colliding beam operation. During this time we have been stacking from the Accumulator, and the Depository is now filled. The Depository is ramped to 20 GeV and the following sequence of operations is carried out. The antiproton beam in the Tevatron is decelerated to 150 GeV and transferred to the Main Ring. The beam populates one out of every seven buckets, extending over a range of 1008 buckets. The momentum spread of this beam is sufficiently large that the momentum aperture of the Depository would have to be huge to contain it. To reduce the momentum spread we establish an h=13 bucket in the Main Ring and adiabatically debunch the beam into this bucket. Once the beam is stable in this bucket the h=1113 system is turned on again to capture the beam. The beam will now populate approximately 55x12=660 buckets resulting in a substantially reduced momentum spread. This beam is then decelerated to 20 GeV and transfered into the Depository in twelve shots. These shots are stacked in longitudinal phase space next to the existing Depository core. The total momentum aperture required for this procedure is about 1.2%.

After the Depository has been loaded with recovered antiprotons the Tevatron can be reloaded by pulling antiprotons out of the core through the recovered stack in the manner described in 2. The Depository will then contain only recovered antiprotons with a longitudinal emittance of 120 eV-sec and a normalized transverse emittance of perhaps 40π mm-mr. The Depository must remain at 20 GeV until the beam has been cooled to about 30 eV-sec. If this can be done in three hours or less, while the Accumulator is being filled, no antiproton production time is lost. When the beam is cool enough the Depository can be ramped down to 8.9 GeV. It is unknown what fraction of the antiprotons will be recovered in this manner. However, if even 50% are recovered the effective antiproton production rate is doubled, and if 90% could be recovered the effective rate goes up by a factor of ten.

The momentum aperture required in the Depository is 1.5%. ***The momentum aperture requirement is dominated by the antiproton recovery scheme.*** Table III includes a column estimating the Z/n requrements corresponding to coasting beam stability at each step of the above processes. There may be a problem during the Depository unloading sequence when the momentum spread of the beam at 20 GeV is roughly .02%

Injection and Extraction

Two injection systems, one for 20 GeV and one for 8.9 GeV, are required as well as one extraction system (for 20 GeV). The transverse aperture available on the injection/extraction orbits should be the same as in the remainder of the machine, i.e. 10π. The required momentum acceptance is 0.3% for the 8.9 GeV system and 0.2% for the 20 GeV systems.

We assume that all injection and extraction takes place in the horizontal plane. The various injection and extraction orbits are generically identical, except that they are placed in different sectors. The general scheme is to place a pulsed injection or extraction septum in the free space in the lattice left open by the missing dipole used for dispersion manipulation. In this gap the septum is placed as close as possible to the zero dispersion straight section to maximize the β_H at the septum. The injected/extracted beam will probably have to go through the field of the quadrupole on the side of the gap closer to the zero dispersion region. The kicker, which may be shuttered, is placed in the high dispersion straight section. Figure 3 shows the generic injection/extraction orbit relative to the machine center line including the effect of an injection/extraction momentum offset of 0.9%. For a 45 mm displacement of the beam at the septum the required kick angle is 3.2 mr. The peak deviation of the injection/extraction orbit from the machine center line is 60 mm. This is realtively large and will require careful attention to aperture at this point.

To achieve the injection/extraction channel acceptances quoted above the kicker aperture must be 46x20 mm^2 (HxV) for the 8.9 GeV system and 39x20 mm^2 for the 20 GeV systems. For a 3 meter long kicker the fields are 320 Gauss at 8.9 GeV and 720 Gauss at 20 GeV. The 8.9 GeV injection kicker must have a flattop of 1200 nsec and a fall time of less than 440 nsec. The 20 GeV injection kicker must have a flattop of 1100 nsec and a fall time of less than 600 nsec. The 20 GeV extraction kicker must have a flattop of 1450 nsec and a rise time of less than 130 nsec.

Cooling Systems

The cooling system for the 20 GeV Depository consists of a betatron cooling system which utilizes pickups and kickers separated by one third of the circumference of the ring and a momentum system pickup and kicker separated by half the ring circumference.

Betatron cooling in the Depository is straight forward. The cooling rate is given by

$$d\epsilon/dt = -(W/N)(2g-g^2(M+U))\epsilon$$

where M is the mixing factor and U is the noise coefficient. The cooling term depends only on the gain, g. The optimum gain depends on the heating term coefficients, M and U. For dense beams, such as we are considering for the Depository, it is easy to make U (noise-to-signal ratio) negligible. The mixing factor at the peak of the momentum distribution for octave cooling

INJECTION/EXTRACTION ORBIT

20 GeV Depository

~~Fig 1~~

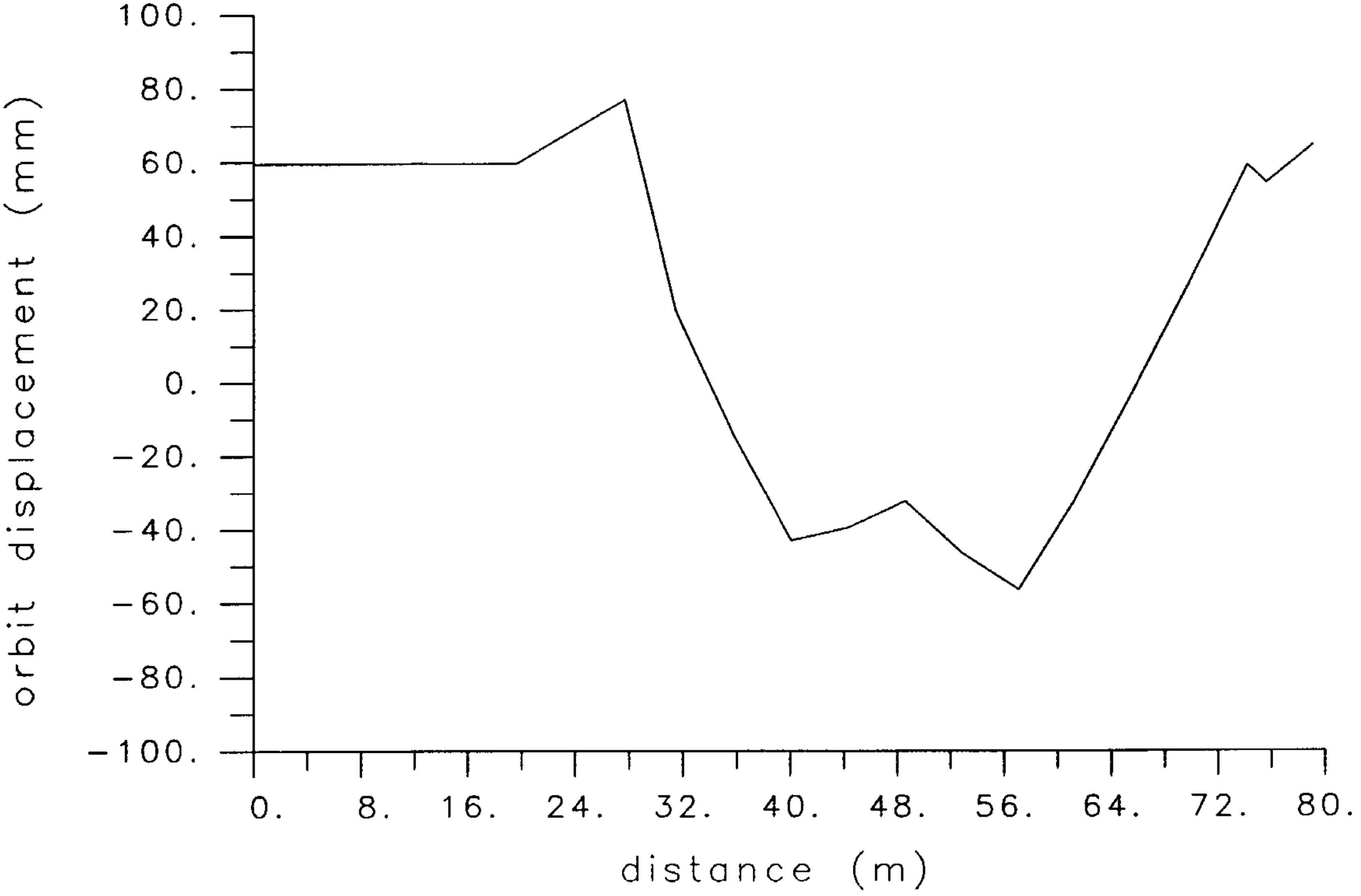


Figure 3.

bandwidths and non-overlapping Schottky bands is given by (for $\beta=1$ antiprotons)

$$M = E\Psi(E)\ln 2\ f_{rev}/2WN\eta.$$

For $E=8.9\text{x}10^9$ eV, $\Psi(E)=2\text{x}10^5/\text{eV}$, $f_{rev}=6.32\text{x}10^5\text{Hz}$, $W=8\text{x}10^9\text{Hz}$, $\eta=.009$, $N=4\text{x}10^{12}$, one obtains M~1. Thus, at optimum gain the cooling rate is simply,

$$\tau = N/W = 500 \text{ sec.}$$

The cooling time is small compared to the heating time due to intrabeam scattering. Assuming pickup and kicker structures similar to the TeV I design (8 pickups and kickers @ 100Ω with a sensitivity of d=1), one calculates a required amplifier gain of 116 dB and a total microwave power of 1 kW per system (horizontal and vertical are identical).

The momentum cooling is somewhat more involved. The basic system is assumed to be the same as the Accumulator core cooling system shown in Figure 4. The pickup consists of two sets of electrodes: one set near the outside edge and one set near the inside edge of the beam. The total pickup signal is derived from the subtraction of the two electrodes. Each electrode can be timed individually. Unlike the Accumulator system, it is proposed that the radial separation of the electrodes be variable.

When the pickup electrodes are both timed for particles on the central momentum the gain function is as shown in Figures 5a (outside), 5b (inside), and 5c (difference). Note that on the central momentum the phase is exactly 0° or 180°, but for off momentum particles there is a phase error due to the (undesired) mixing between pickup and kicker. Figure 6 shows the obtained beam momentum distribution for this system with a beam of $4\text{x}10^{12}$ particles at 8.9 GeV. The rms momentum spread is 4.3 MeV/c. The total beam of $4\text{x}10^{12}$ particles is close to the maximum amount of beam that can be stored with the system in this configuration. As the beam current is further increased the width of the beam will grow because of the increased heating from intrabeam scattering. This will force the edges of the beam past the point where the gain has the correct phase for cooling.

The recovery of anti-protons from the collider presents special problems for the cooling system. The recovered antiprotons have a momentum spread (full width at 20 GeV) of 1% which must be cooled by a factor of three before they can be decelerated to 8.9 GeV. It appears possible to achieve this cooling with the 8-16 GHz cooling system described above. One would begin with the pickup plates at radial positions of ±0.5% and phased for these momenta. As the edges of the distribution moved in one would decrease the separation and rephase the system for the new positions. The entire operation should not exceed an hour. The betatron cooling systems will not be able to function until the momentum spread is reduced to 0.3%, but the emittance growth over this period of time should be tolerable.

Momentum Cooling System

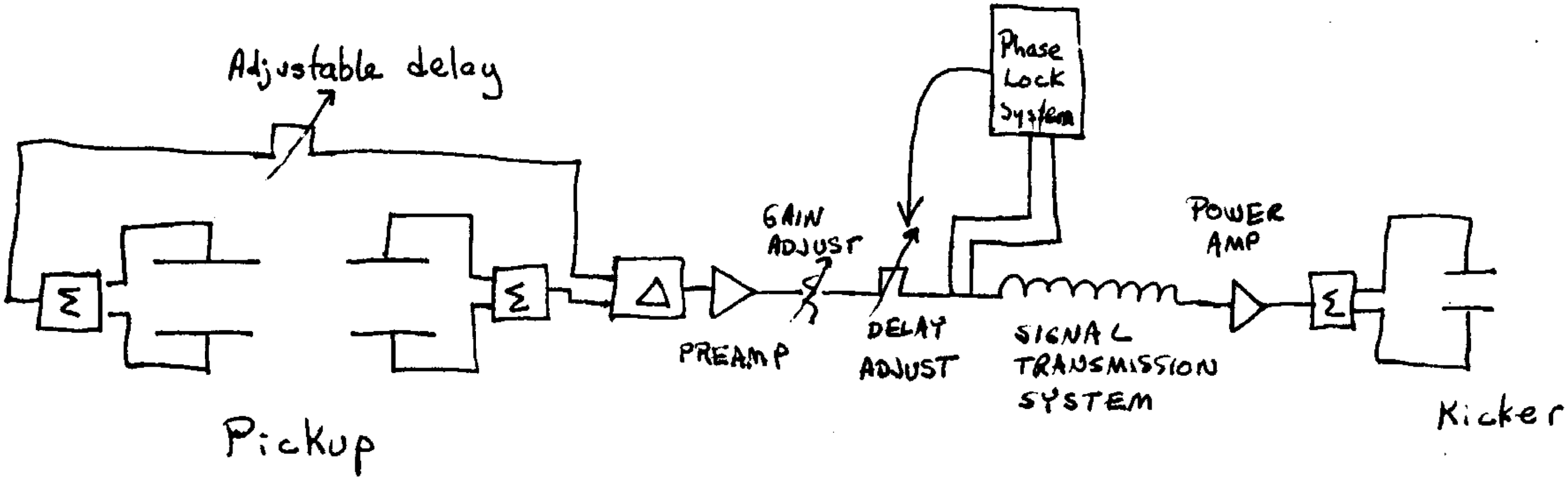


Figure 4

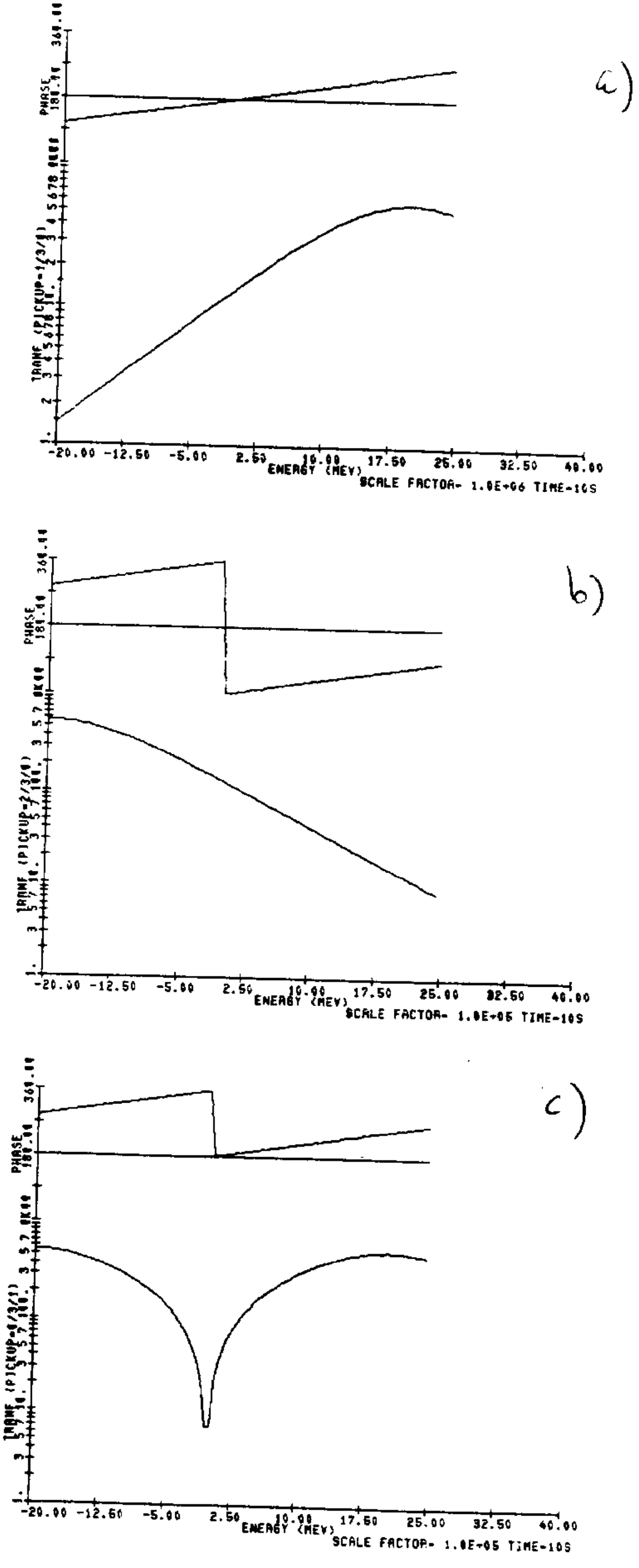
a)
PHASE
360.00
180.00
TRANF (PICKUP-1/3/1)
-20.00 -12.50 -5.00 2.50 10.00 17.50 25.00 32.50 40.00
ENERGY (MEV)
SCALE FACTOR- 1.0E+06 TIME-10S
b)
PHASE
360.00
180.00
TRANF (PICKUP-2/3/1)
-20.00 -12.50 -5.00 2.50 10.00 17.50 25.00 32.50 40.00
ENERGY (MEV)
SCALE FACTOR- 1.0E+05 TIME-10S
c)
PHASE
360.00
180.00
TRANF (PICKUP-4/3/1)
-20.00 -12.50 -5.00 2.50 10.00 17.50 25.00 32.50 40.00
ENERGY (MEV)
SCALE FACTOR- 1.0E+05 TIME-10S

Figure 5

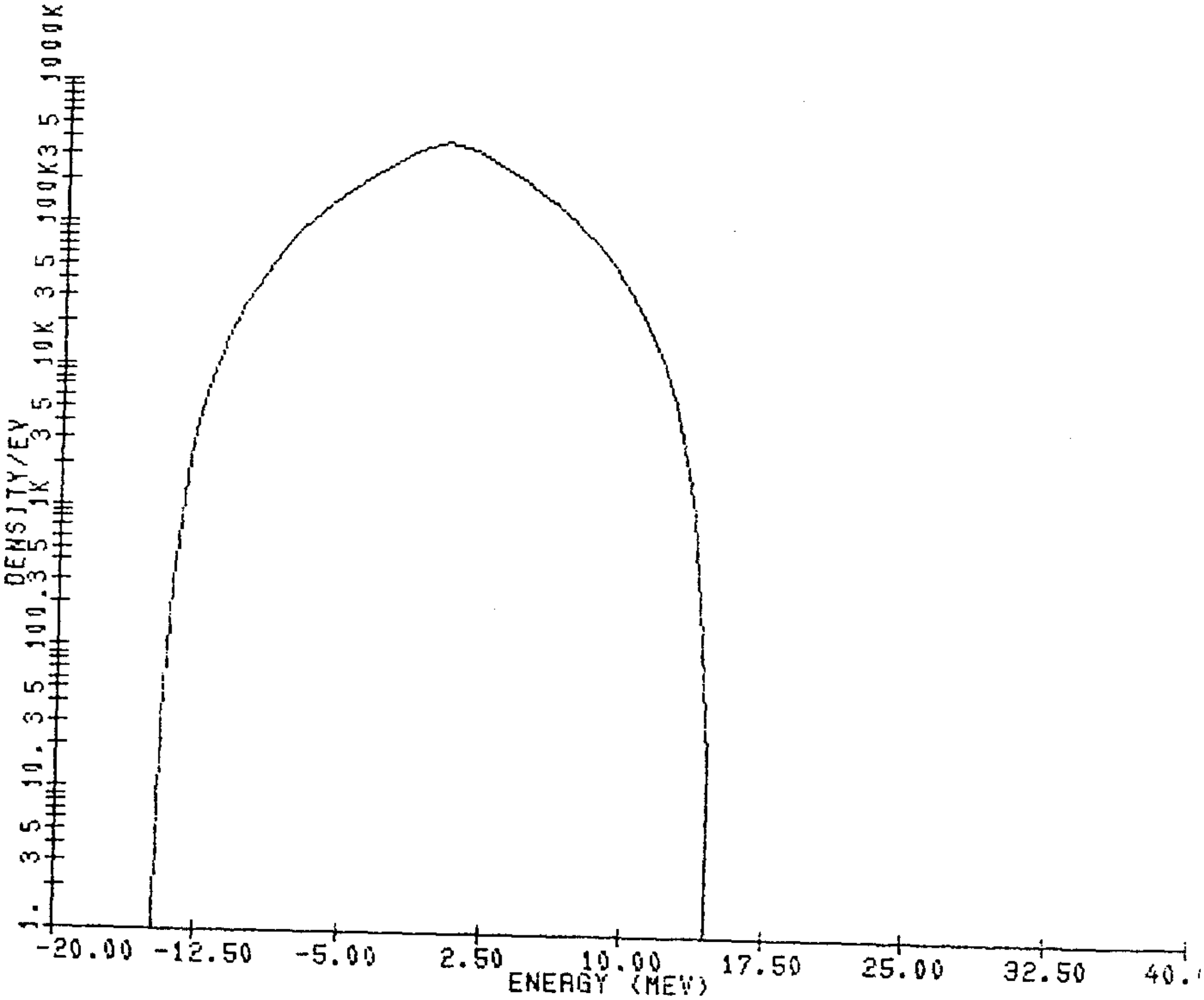

DENSITY/EV
1.
3
5
10.
3
5
100.
3
5
1K
3
5
10K
3
5
100K
3
5
1000K
-20.00
-12.50
-5.00
2.50
10.00
17.50
25.00
32.50
40.
ENERGY (MEV)

Figure 6

There are currently no 8-16 GHz cooling systems in existence, and these systems would therefore have to be developed. Most of the technology is currently available or appears to be a relatively straight forward extrapolation of existing techniques. Some critical items worth mentioning are: 1) The losses in 150 m of cable are prohibitive in single mode coaxial cable. Either a novel scheme of transmitting signal is required (lasers?) or repeaters every 25-50 m will be needed; 2) The timing cannot be assured over extended periods of time because of thermal drifts. A phase-locked loop would be required to maintain proper system timing.

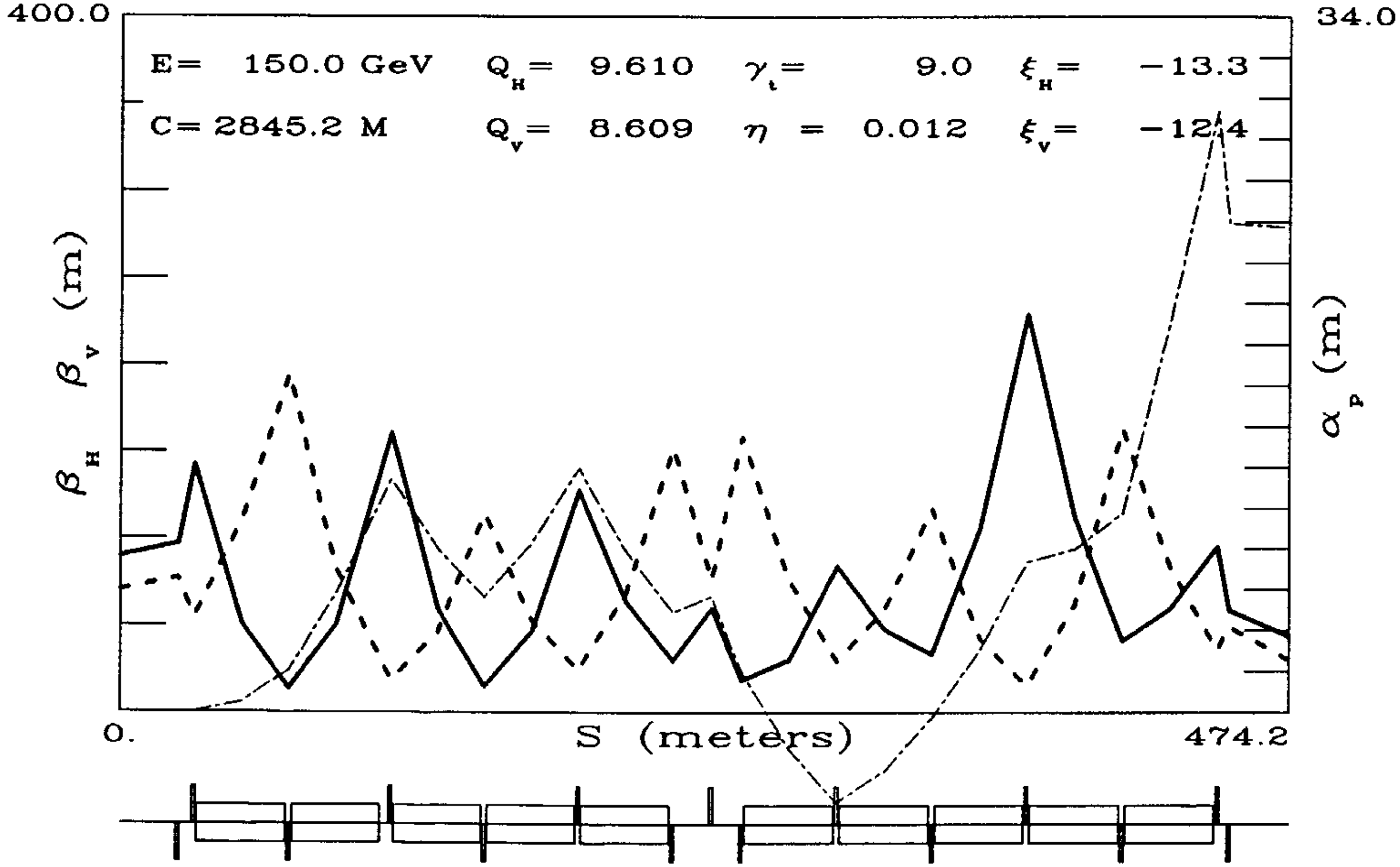
The 150 GeV Antiproton Depository

The 150 GeV Depository is designed to have a circumference exactly six times that of the exisiting Accumulator. The circumference is also such that the ring holds exactly half (72/144) of the number of antiproton bunches required for collider operation. The ring is essentially a scaled up version of the 20 GeV Depository. It has three zero dispersion straight sections, each 46 meters long, and three 48 meter long high dispersion (α_p=20.0 m) straight sections.

The 150 GeV Depository is designed with a transition gamma of 9.0 rather than the preferred 7.0. Design of a ring with this circumference and a γ_t of 7.0 results in a lattice with a dispersion of 20 meters and beta functions of 190 meters in the arcs. These values are a little higher than we felt comfortable with. The consequence of this choice of γ_t is that for the momentum spread assumed in Section IV the mixing factor, M, at 8.9 GeV becomes closer to 9 than the optimal value of 1. As a result the cooling time will be more like 4500 seconds than 500 seconds. The heating times due to intrabeam scattering also lengthen due to the larger lattice functions in the ring (see below), but only to about 3500 seconds. As a result we anticipate that this ring would operate more efficiently with a longitudinal phase space density of half that discussed in Section IV. Consequently, we have entered in Table II an expected longitudinal emittance of 58 eV-sec for this ring. Note also that because of the large value of α_p at the injection point and the high antiproton recovery energy the needed momentum aperture is reduced to 0.8%.

Lattice

The 150 GeV Depository lattice is shown in Figure 7. Once again one half of one superperiod, i.e. one sixth of the ring, is shown. The lattice is based on 90° FODO cells with slight modifications of quadrupole strengths near the straight sections to produce the desired dispersion pattern. The zero dispersion straight section is 46 meters long. This straight section accomodates RF systems, momentum kickers, and betatron pickups and kickers. The high



150GeV PBAR DEPOSITORY

Figure 7

dispersion straight section (α_p=24 m) is 48 meters long and houses momentum cooling pickups, and injection and extraction kickers. Injection and extraction septa are located in the free spaces 270° away from the high dispersion straights. Sixty centimeters of free space is provided between each dipole and quadrupole for installation of sextupoles and beam position monitors.

Magnets

The aperture requirements for the magnets in this ring are somewhat more severe than in the 20 GeV ring due to the larger lattice functions. The aperture needed outside of the last dipole and last two quadrupoles adjacent to the high dispersion straight section is 137x88 mm^2 (HxV). Unfortunately the TeV I style 'small dipole' does not have either this horizontal or vertical aperture, and the 'large dipole' does not even have this vertical aperture. So one would probably have to start from scratch building new magnets. Producing the need acceptance near the high dispersion straight requires a magnet aperture of 200x81 mm^2. Once again new style magnets would have to be produced.

The TeV I small quadrupole, SQE, is almost adequate for use away from the high dispersion straight section (if one were willing to sacrifice about 2π worth of horizontal acceptance). These magnets, with one exception per sector, would all operate at less than 400 A at 150 GeV. The last two quadrupoles before the high dispersion region cannot be 'small quadrupoles'. The TeV I 'large quadrupoles' do not, however, have the required strength to use here (by about a factor of four). A new large aperture quadrupole would have to be built.

RF

The general scheme of loading, unloading, and recovery is the same as for the 20 GeV Depository. Tables V and VI are the analogs of Tables III and IV for the 150 GeV Depository. Differences are discussed below.

1. Loading the Depository from the Accumulator.
This is essentially the same as the situation for the 20 GeV Depository.

2.Unloading the Depository to the Tevatron.
The original 144 eV-sec of antiprotons are cooled to 60 eV-sec at 8.9 GeV. The entire core is accelerated to 150 GeV with the h=504 system. Then one half of the stack is captured with an h=72 system and moved to the extraction orbit. A bunch rotation is performed to fit these buches into every seventh bucket of the h=504 system. The voltage of the h=504 system is increased to

~~Table 3~~

150 GeV Depository
Coasting Beam Longitudinal Parameters

ϵ_L = longitudinal emittance (ev-sec)
$N_{\bar{p}}$ = number of antiprotons
ρ = average density (ev^{-1})
ΔE = energy spread (MeV) (full)
$\delta p/p$ = full relative momentum spread (%)
I = beam current (ma)
Z/n = impedance limit (Ω) (Keil-Schnell)
E = Total energy (GeV)

Condition	E	ϵ_L	$N_{\bar{p}}$	ρ	ΔE	$\delta p/p$	I	Z/n	
1 One shot from Accumulator	8.9	16	4.5×10^{11}	4.5×10^{4}	1.67	.019	7.5	14	Loading
2 Full depository, cooled	8.9	60	40×10^{11}	6.4×10^{5}	6.25	.07	67.5	20.9	and Unloading
3 Full depository, cooled, accelerated	150	60	40×10^{11}	6.4×10^{5}	6.25	.004	67.5	11.5	
4 One shot for Tevatron*	150	30	20×10^{11}	2.9×10^{5}	7.0	.005	78	14.8	
5 One shot, recovered beam from Tevatron	150	60	20×10^{11}	3.2×10^{5}	6.25	.004	33		
6 Full depository (recovered beam)	150	120	4×10^{12}	3.2×10^{5}	12.5	.008	67.5		Recovery
7 Full depository, decelerated	8.9	120	4×10^{12}	3.2×10^{5}	12.5	.14	67.5		

* Uses bunched beam parameters

Table V

~~Table 4~~

150 GeV Depository
RF Parameters (loading & unloading)

ϵ_L = longitudinal emittance (ev-sec)
A_b = bucket area (ev-sec)
ΔE_b = bunch height (MeV)
Δt = Bunch length (full) (μsec)
ΔE = Bunch energy spread (full) (MeV)
$\delta p/p$ = bunch relative momentum spread (full) (%)
E = Total energy (GeV)
N_b = # of bunches

V_{RF} = rf voltage (kV)
h = harmonic number
f_{RF} = RF frequency (MHz)
$N_{\bar p}$/bunch = # of $\bar p$'s/bunch

Condition	E	ϵ_L	N_b	ϵ_L/bunch	h	V_{RF}	f_{RF}	A_b	ΔE_b	Δt	ΔE	$\delta p/p$	$N_{\bar p}$/bunch
1 Accumulator, unstack	8.9	16	2	8	2	2.06	1.25	16	15.8	.36	22.3	.25	2.2×10^{11}
2 Depository, stack	8.9	16	2	8	12	.66	1.25	16	15.8	.36	22.3	.25	2.2×10^{11}
3 Depository, accelerate	8.9 150	60 60	504 504	.12 .12	504 504	10.97 6.36	53 53	.24 .24	9.95 9.89	.009 .009	14.0 13.99	.158 .009	8×10^9 8×10^9
4 Depository, unstack	150	30	72	.42	72	.227	7.5	.84	4.95	.060	6.99	.005	2.8×10^{10}
5 Depository, bunch rotate	150	30	72	.42	72	6.36	7.5	4.5	26.1	.011	37.0	.025	2.8×10^{10}
6 Depository, prebunch	150 150	30 30	72 72	.42 .42	504 504	29.2 77.9	53 53	.52 .84	21.1 34.6	.011 .009	38.3 48.9	.026 .033	2.8×10^{10} 2.8×10^{10}
7 Tev capture	150	30	72	.42	1113	40.1	53	.84	35.0	.009	49.5	.033	2.8×10^{10}
							Recovery						
8 Tev 150 GeV	150	120	144	.83	1113	158	53	1.67	69.5	.008	98.3	.066	2.8×10^{10}
9 Depository, 150 GeV capture and stack	150	60	72	.83	504	307	53	1.67	8.7	.009	97.2	.065	2.8×10^{10}
10 Depository, decelerate recovered beam	150 8.9	120 120	504 504	.24 .24	504 504	25.4 43.8	53 53	.48 .48	19.8 19.8	.009 .009	28.0 28.0	.019 .315	8×10^9 8×10^9

Table VI

match the Tevatron. The beam is then extracted from the Depository into the Tevatron. After one repetition of this procedure the collider is filled.

3.Loading the Depository from the Tevatron.
We assume again that during colliding beam operation the antiproton longitudinal emittance has blown up to 120 eV-sec. Meanwhile we have been stacking from the Accumulator and the Depository is full. The Depository is ramped to 150 GeV and the antiproton beam in the Tevatron is decelerated to 150 GeV. One half of the Tevatron beam is extracted directly into the Depository and captured into matched h=504 buckets. This beam is stacked next to the existing core. The remainder of the beam is extracted from the Tevatron and deposited next to the first shot. The total momentum aperture used is about 0.25%.

After the Tevatron is unloaded the antiproton core in the Depository is extracted from the Depository and transferred to the Tevatron as outlined in 2. The Depository is still at 150 GeV and contains the recovered beam. The beam can either be cooled for several hours at 150 GeV or decelerated immediately to 8.9 GeV for further accumulation.

The total momentum acceptance required is 0.6%. The small momentum spread in the 150 GeV Depository may not be tolerable as shown in the Z/n entries in Table V. Emittances even larger than 60 eV-sec might emanate from this ring.

Injection and Extraction

Two injection system, one for 150 GeV and one for 8.9 GeV, and one extraction system (150 GeV) are required. The transverse aperture requirements should be the same as that of the rest of the machine, i.e. 10π. The required momentum acceptance is 0.3% for the 8.9 GeV system and 0.1% for the 150 GeV systems.

We assume that all injection and extraction takes place in the horizontal plane. The various injection and extracton orbits are generically identical. The general scheme is the same as in the 20 GeV Depository. Figure 8 show the injection/extraction orbit for a 45 mm displacement of the beam at the septum with a momentum offset of 0.4%. The required kick is 0.9 mr.

To achieve the injection/extraction channel acceptances quoted above, the kicker aperture has to be 104x28 mm^2 (HxV) for the 8.9 GeV system and 56x28 mm^2 for the 150 GeV system. For a 6 meter long kicker we need a 45 Gauss field at 8.9 GeV and 750 Gauss at 150 GeV. The 8.9 GeV kicker must have a flattop of 1200 nsec, but can have a fall time of up to 8400 nsec. The 150 GeV injection kicker must have a 9330 nsec flattop and a fall

INJECTION/EXTRACTION ORBIT

150 GeV Depository

~~Fig 2~~

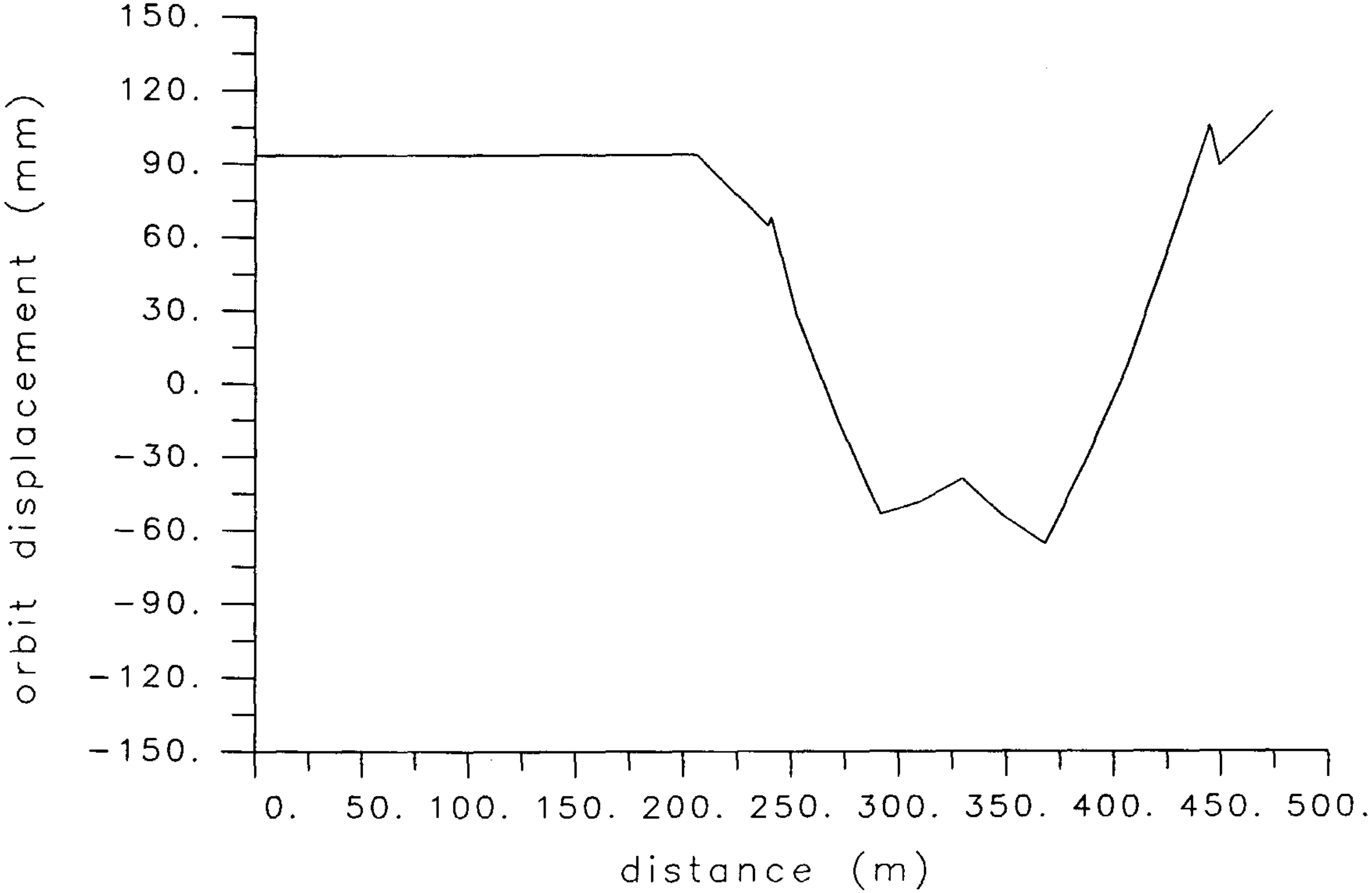


Figure 8

time of less than 133 nsec. The 150 GeV extraction kicker must have a rise time of less than 133 nsec and a flattop of 9330 nsec. Shuttered kickers with long flattops may be a problem because of field penetration through the shutter.

Cooling Systems

One would like to use cooling systems in the 150 GeV Depository which are essentially the same as those described for use in the 20 GeV Depository. Unfortunately, several problems arise. The first, related to the higher than desired γ_t, has already been alluded to. It is felt that one would not be able to produce a total longitudinal phase space out of this ring of less than 58 eV-sec, with the possibility that it might actually be substantially larger. The second problem has to due with the physical dimensions required of the pickups and kickers required to provide a 10π mm-mr aperture. The β functions in the straight sections are about 80 meters. The physical aperture corresponding to 10π mm-mr in the straight sections is then 56.5 mm. Since this is larger than the wavelength at 12 GHz it is not at all obvious that one could construct pickups with this physical aperture operating at 8-16 GHz. These problems remain unsolved by us at the present.

VI. THE 20 GEV POST-BOOSTER

The primary purpose of the 20 GeV Post-Booster is to provide a proton beam which can be injected into the Main Ring above transition. However, in designing the ring we tried to keep in mind the three distinct roles that this ring will be expected to play during the upgraded collider era: first, as the source of protons for fixed target operation; second, as the source of protons for antiproton production; and third, as the source of protons for the collider. The real impact of these varied responsibilities is to force us to design a ring which is moderately rapid cycling. We were also constrained in the design of this ring by the self-imposed assumptions described in Section II which required matching of the Post-Booster to the previously described companion 20 GeV Antiproton Depository.

Operating Scenarios and Expected Performance

Discussions of the collider upgrade have not defined the preferred method of producing the desired 132 nsec bunch spacing in the collider. For the sake of consistency with what we said about antiproton depositories we will assume that the proton bunches need to come out of the Post-Booster with the correct bunch spacing. Probably the easiest way to achieve this is by bunch coalescing in the Post-Booster just prior to transfer into the Main Ring.

Protons are injected into the Post-Booster from the existing Booster in a bunch-to-bucket transfer. Since we ultimately require $6\text{x}10^{10}$ protons/bunch in the collider (after coalescing of seven to one) we require only $9\text{x}10^{9}$ protons/bunch, or $7.2\text{x}10^{11}$ total protons in the ring. It is expected that the Post-Booster should be able to preserve the beam emittances delivered from the existing Booster at these intensities. At the moment the 8 GeV Booster is capable of delivering this intensity of beam with a normalized transverse emittance of about 9π mm-mr, and a longitudinal emittance of about .09 eV-sec. Following the 400 MeV linac upgrade it is expected that the transverse emittances of beams delivered from the 8 GeV Booster will be even smaller. This anticipated transverse phase space density is 25% higher than what is specified for the collider and so leaves some room for dilution during beam transfers. Following coalescing of proton bunches the projected longitudinal emittance for a proton bunch containing $6\text{x}10^{10}$ protons becomes 7x.09=.63 eV-sec. This longitudinal emittance is about three times what we projected for the antiproton bunches emanating from the 20 GeV depository. Twelve cycles (6 seconds) of the Post-Booster are required to load the collider.

No coalescing is necessary (or even desireable) for either antiproton production or fixed target operation. It is thought that following the linac upgrade the 8 GeV Booster will be capable of delivering about $4\text{x}10^{12}$ protons/batch ($5\text{x}10^{10}$/bunch) with a transverse emittance of about 15π and with a longitudinal emittance of perhaps 0.2 eV-sec. The Post-Booster should be able to accelerate this beam without dilution. Open questions include the Main Ring lifetime at 20 GeV, and transmission properties of the Main Ring at this sort of intensity.

Post-Booster Ring Design

The 20 GeV Post-Booster design is based on a design for a New Booster which one of us (SDH) prepared last summer at the request of Helen Edwards. The only changes are a slight increase in the circumference to make the harmonic number (@ 53 MHz) divisible by seven, and the raising of the injection energy to 8.9 GeV accompanied by an increase in the cycle rate from 1 to 2 Hz. The machine parameters are given in Table VII. The ring is designed to reside in the same tunnel as the 20 GeV Antiproton Depository (scenario 2). The circumference is 7x5.645=39.517 meters greater than, and the mean radius 6.3 meters greater than, the Depository. The transition gamma is nearly identical to that of the Depository and probably could be made so with a little more work. As in the Depository the beam is not required to cross transition in the Post-Booster.

The design aperture of the Post-Booster as listed in the Table VII is significantly larger than the beam emittance given in the table. This is because the emittances in the table are meant to reflect the performance of

Table VII. Post-Booster Machine Parameters

Circumference	513.7	meters
Injection Energy	8.9	GeV
Peak Energy	20.0	GeV
Cycle Time	0.5	sec
Harmonic Number (@53 MHz)	91	
Horizontal Tune	7.41	
Vertical Tune	7.41	
Transition Gamma	7.1	
Number of Bunches	84	
Protons/Bunch	8.6x10^{9}	
Transverse Emittance (Normalized)	8π	mm-mr
Longitudinal Emittance/Bunch	0.09	eV-sec
Momentum Spread (Max, full width)	0.3	%
Transverse Acceptance (Unnormalized)	5π	mm-mr
Momentum Acceptance	0.6	%
β_{max} (Arcs)	21	meters
β_{max} (Straights)	29	meters
Maximum Dispersion	2.3	meters
Number of Straight Sections	12	
Total Length in Straight Sections	60	meters
RF Frequency (Injection)	52.8	MHz
RF Frequency (Extraction)	53.0	MHz
RF Voltage	250	KV
Synchronous Phase (Max)	23	degrees
Number of Dipoles	76	
Dipole Length	4.1	meters
Dipole Field (Max)	13.5	kGauss
Number of Quadrupoles	88	

the Post-Booster during collider filling, while the acceptances are made compatible with fixed-target and antiproton production operation.

Lattice

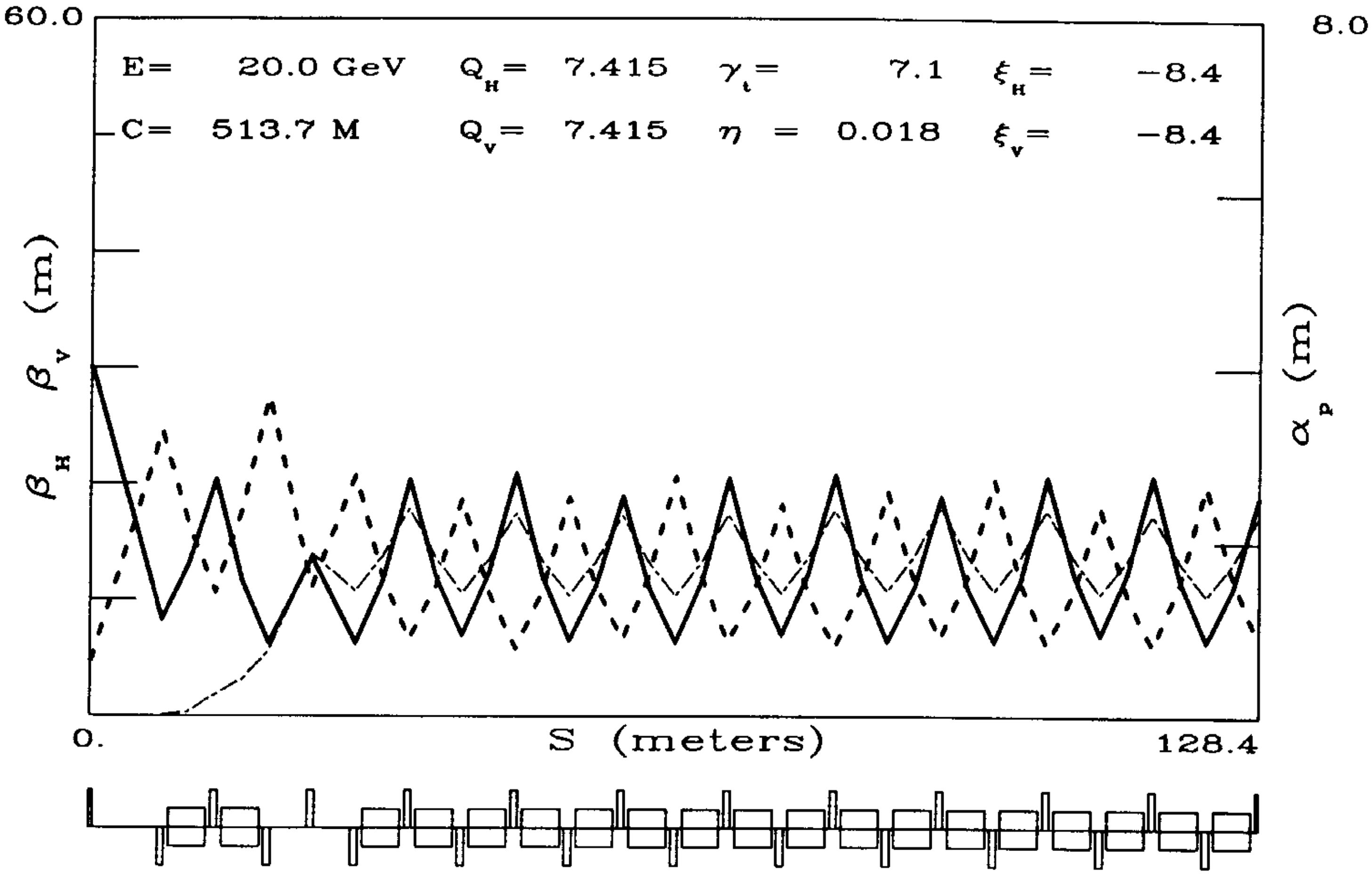
The lattice of the Post-Booster is shown in Figure 9. What is shown is one half of one superperiod, i.e. one quarter of the ring. The lattice is symmetric around the endpoints of the figure. The lattice is basically the Antiproton Source Debuncher lattice with the long straight sections eliminated and with a lower superperiodicity. The lattice is built from 60° cells with missing magnets used to supress the dispersion. The ring contains four dispersionless straight sections each 7.2 meters long. These straights contain the h=91 and h=13 RF cavities and the injection/extraction kickers. In addition there are eight 4.0 meter long straight sections in which the dispersion is about 2 meters. These straight section accomodate the injection/extraction septa, damper pickups and kickers, and assorted diagnostics. Fifty centimeters of free space is provided between each dipole and quadrupole for installation of sextupoles and beam position monitors. The functional allocation of straight sections is shown in Figure 10.

Acceleration and RF Systems

An example acceleration half-cycle using the h=91 system is shown in Figure 11. The figure shows the beam energy, the RF voltage, the bucket area, and the momentum spread (for ϵ_L=0.2 eV-sec) as a function of time for a 2 Hz cycle rate. The RF voltage at injection is 126 KV to match to the 8 GeV Booster buckets. The maximum voltage required is 250 KV and the synchronous phase is 23° through most of the cycle. With this voltage it is possible to maintain an acceleration rate of 57 GeV/sec accompanied by a bucket area in excess of 0.4 eV-sec. The required voltage can be supplied by two Main Ring style RF cavities which can both be situated in one of the four dispersion-free straight sections. An h=13 RF system is required for performing bunch coalescing. We have not examined the required performance characteristics of this system.

Magnets and Power Supplies Requirements

In order to provide the desired Post-Booster aperture (5πx5πx0.6%) the physical aperture through the ring needs to be at least 25x25 mm^2. The rapid cycling time of the ring requires low inductance magnets. The dipole and quadrupole magnets to be used could be the same as those described in the SSC Conceptual Design Report for use in the Medium Energy Booster with the dipole magnet shortened by about 20%. The operating characteristics for these magnets in the Post-Booster are given in Table VIII.



20 GeV POST−BOOSTER

Figure 9

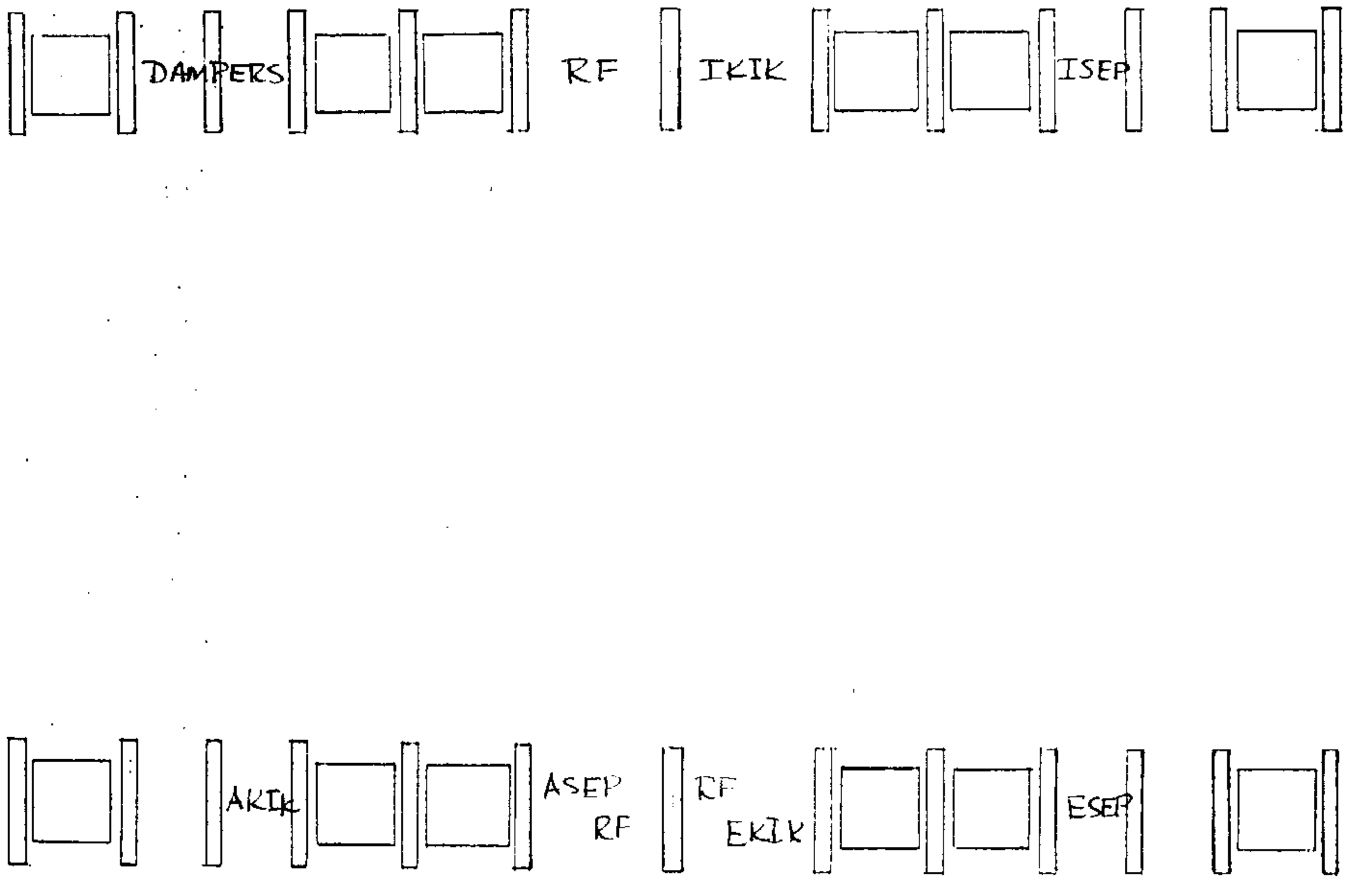
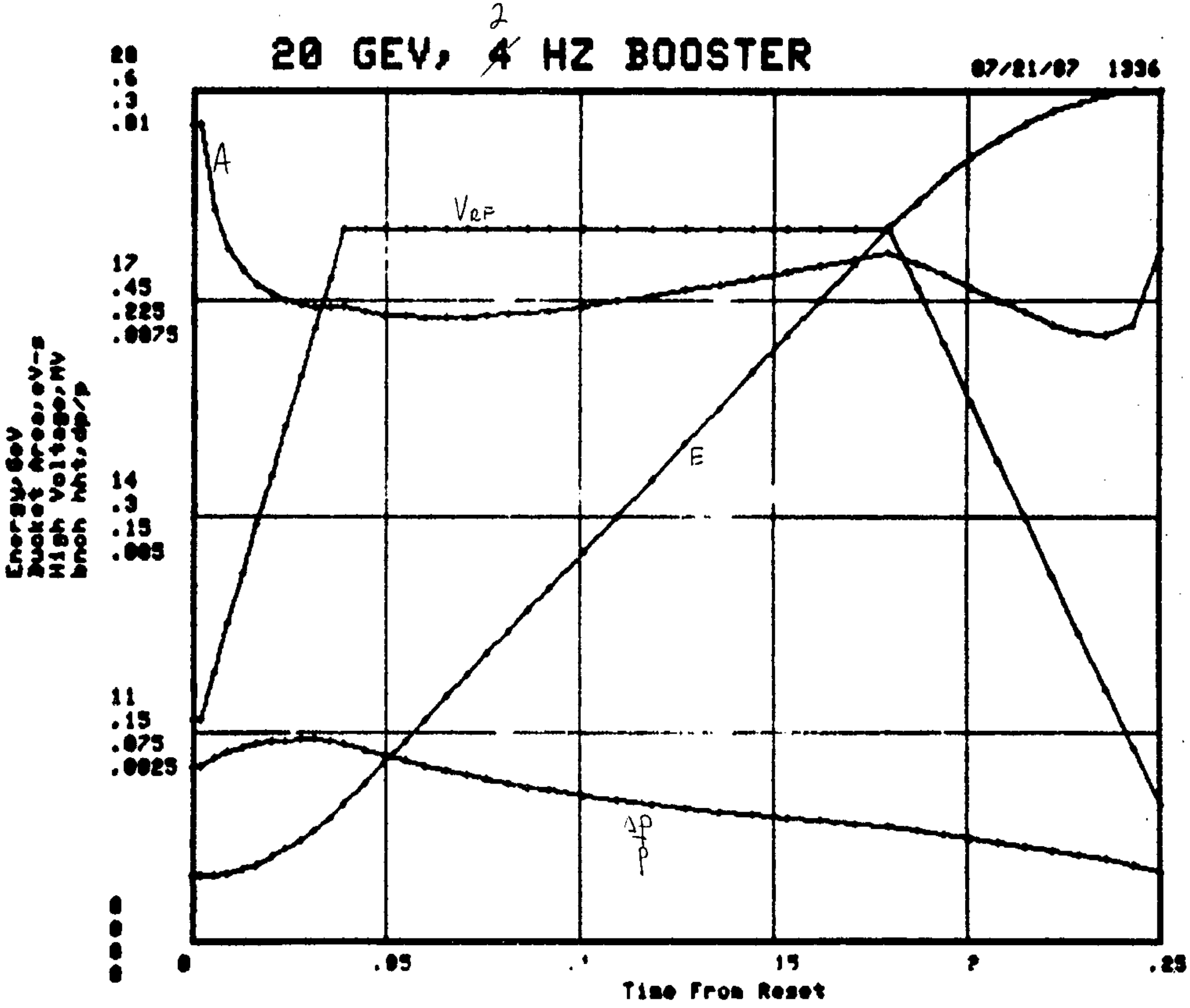


Figure 10


20 GEV, ~~4~~ 2 HZ BOOSTER
07/21/87 1336
20
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17
.45
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.0075
14
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11
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0
0
0
Energy,Gev
Bucket Area,eV-s
High Voltage,MV
bnch hht,dp/p
0
.05
.1
.15
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.25
Time From Reset
A
V_{RF}
E
$\frac{\Delta p}{p}$

Figure 11

Table VIII. Post-Booster Magnet Parameters

	Dipole	Quadrupole
Strength	13.5 kGauss	165 kGauss/m
Length	4.1 meters	.75 meters
Full Aperture	10x5 cm^2	8.4 cm
Turns/Pole	8	10
Maximum Current	3400 A	1270 A
Maximum dI/dt	9700 A/sec	3620 A/sec
Coil Resistance	4.5 mΩ	6.8 mΩ
Coil Inductance	2.7 mH	0.6 mH
L/R	0.6 sec	0.1 sec
Voltage Drop (Resistive, Peak)	15.3 V	8.6 V
Voltage Drop (Inductive, Peak)	26.2 V	2.2 V
Peak Power (Dissipative)	52 kW	11 kW
Average Power	17 kW	4 kW
Magnets Required	76	88

Injection and Extraction

Space is allocated for an injection system and two extraction systems (one for sending beam to the Main Ring and one for an abort) in the Post-Booster. The allocation has already been shown in Figure 10. Injection from the Booster and extraction to the Main Ring are both done using septum magnets in zero dispersion straight sections in conjunction with kicker magnets in straight sections located 90° away. The kicker and septum strengths are modest and a 132 nsec gap is present in the beam to accomodate kicker rise/fall times.

VII. THE 150 GEV NEW MAIN RING

The primary reasons for contemplating the construction of a new Main Ring are the expectation of improved performance over the existing Main Ring in terms of beam quality and cycle time, and the elimination of the existing interference between the Main Ring and the experimental detectors at B0 and D0. As in the case of the Post-Booster this ring has to be designed to deliver protons for three distinct purposes: for fixed target operations, for collider operations, and for antiproton production. If built in tandem with the 150 GeV Antiproton Depository, this ring would never be required to accelerate or transport antiprotons. The design given below is constrained by the assumptions described in Section II to look similar to the 150 GeV Depository.

Operating Scenarios and Expected Performance

As in the case of the Post-Booster we assume that bunch coalescing would be performed here to create the correct proton bunch spacing prior to injection into the collider. Protons are injected into the New Main Ring from the existing Booster in a bunch-to-bucket transfer. Six Booster batches are needed to fill the ring. Before coalescing we require 9×10^9 protons/bunch or 4.3×10^{12} total protons in the ring. The existing Booster is capable of delivering a normalized transverse emittance of 9π mm-mr and a longitudinal emittance of .09 eV-sec at this intensity. Two cycles of the New Main Ring are required to load the collider. It is expected that the New Main Ring would be able to accelerate beam from the Booster without dilution.

New Main Ring Design

The New Main Ring is designed to reside within the same tunnel as the 150 GeV Antiproton Depository. The machine parameters are given in Table IX. The circumference is 7x5.645=39.517 meters greater than the Depository. The transition gamma is identical to that of the Depository, and as in the Depository the beam is not required to pass through transition during acceleration to 150 GeV. The acceptance of the New Main Ring as given in Table IX. reflects the expected performance of the existing Booster during fixed target operations following the 400 MeV linac upgrade. The emittances listed in the table reflect collider operation.

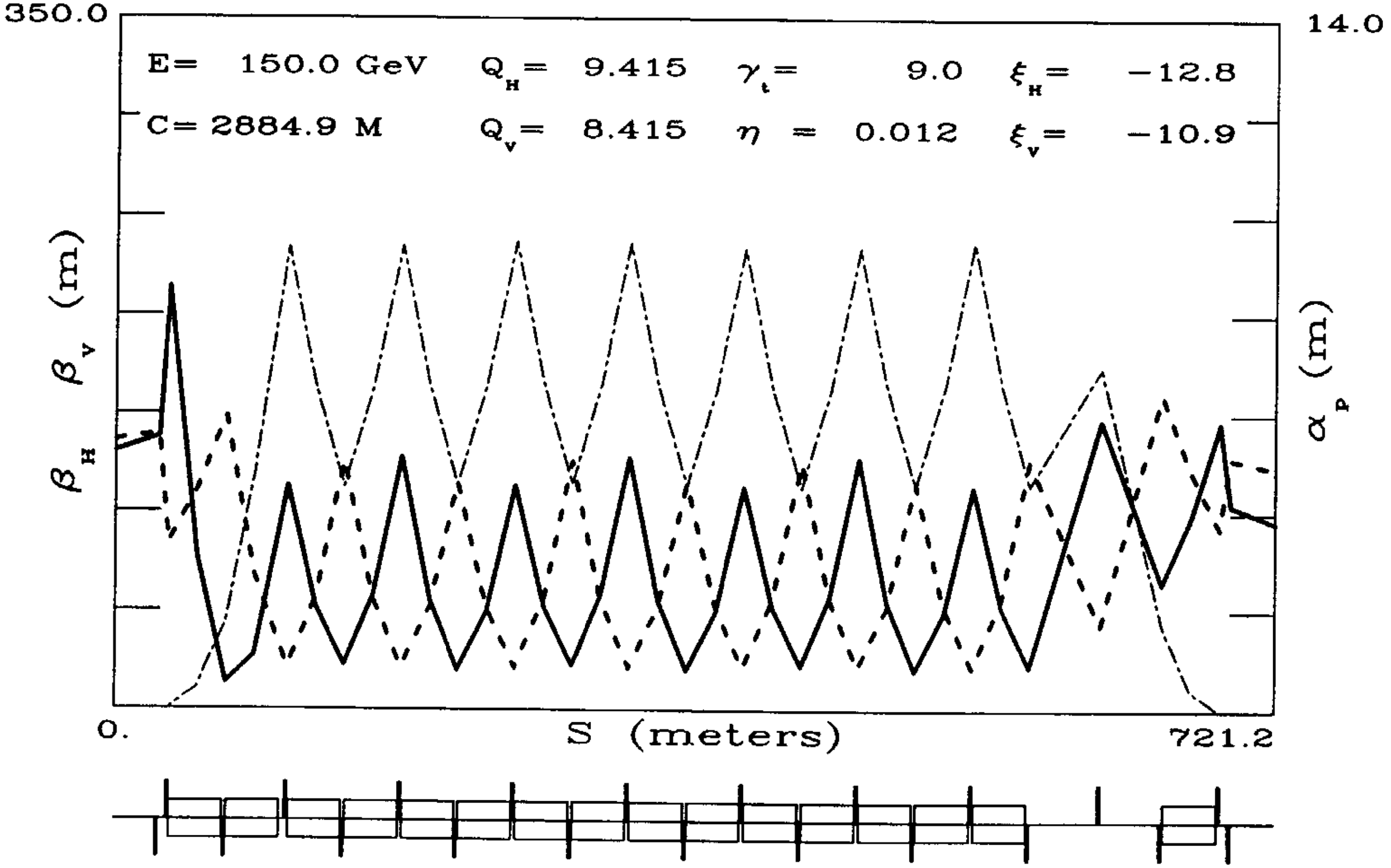
Lattice

The lattice of the New Main Ring is shown in Figure 12. The figure displays one half of one superperiod, i.e. on quarter of the ring. The lattice is symmetric around the endpoints of the figure. The lattice is built out of 90° FODO cells with adjustments made to quadrupoles at the end of the arcs to eliminate dispersion in the straight sections. The ring contains four dispersion free straight sections each about 53 meters in length, and eight non-dispersionless straight sections each about 40 meters long. The latter are ~90° away from dispersionless straight sections. There is plenty of room in the straight sections for injection/extraction devices, RF systems, dampers, and assorted diagnostics. Sixty cetimeters of free space is provided between each dipole and quadrupole for installation of sextupoles and beam position monitors.

Acceleration and RF Systems

Table IX. New Main Ring Machine Parameters

Circumference	2884.7	meters
Injection Energy	8.9	GeV
Peak Energy	150.0	GeV
Cycle Time	1.3	sec
Harmonic Number	511	
Horizontal Tune	9.41	
Vertical Tune	9.41	
Transition Gamma	9.0	
Number of Bunches (Uncoalesced)	504	
Protons/Bunch (Uncoalesced)	8.6×10^9	
Transverse Emittance (Normalized)	8π	mm-mr
Longitudinal Emittance/Bunch	0.09	eV-sec
Momentum Spread (Max, full width)	0.2	%
Transverse Acceptance (Unnormalized)	5π	mm-mmr
Momentum Acceptance	0.5	%
β_{max} (Arcs)	120.	meters
β_{max} (Straights)	220.	meters
Maximum Dispersion	9.4	meters
Number of Straight Sections	12	
Total Length in Straight Sections	530	meters
RF Frequency (Injection)	52.8	MHz
Rf Frequency (Extraction)	53.1	MHz
RF Voltage	4.0	MV
Synchronous Phase (Max)	46	degrees
Number of Dipoles	384	
Dipole Length	5.2	meters
Dipole Field (Max)	15.7	kGauss
Number of Quadrupoles	84	



150GeV NEW MAIN RING

Figure 12

An example of an acceleration cycle using the h=511 RF system is shown in Figure 13. The figure shows the beam energy, the RF voltage, the bucket area, and the momentum spread (for ϵ_L=0.2 eV-sec) as a function of time for a 1.3 second acceleration cycle. The RF voltage at injection needs to be 42 KV to match to the 8 GeV Booster buckets. The maximum voltage required is 4 MV. With this voltage it is possible to maintain a bucket area of 0.5 eV-sec with an acceleration rate of 300 GeV/sec. Approximately 36 Main Ring style RF cavities would are required to supply the necessary voltage. These could be situated in two of the dispersion free straight sections. An h=73 system would be required for bunch coalescing at 150 GeV. We have not worked out the parameters of this system.

Magnets Requirements

The physical aperture required to provide the desired acceptance (5πx5πx0.5%) is 68x51 mm^2. As in the Post-Booster low inductance magnets are required. The magnets described in Table VIII. are close to meeting the needs of this ring once an appropriate length adjustment is made. The operating characteristics of these magnets are given in Table X.

Table X. New Main Ring Magnet Parameters

	Dipole	Quadrupole
Strength	15.7 kGauss	190 kGauss/m
Length	5.2 meters	1.3 meters
Full Aperture	10x5 cm^2	8.4 cm
Turns/Pole	8	10
Maximum Current	3950 A	1460 A
Maximum dI/dt	7910 A/sec	2920 A/sec
Coil Resistance	5.7 mΩ	11.8 mΩ
Coil Inductance	3.4 mH	1.0 mH
L/R	0.6 sec	0.1 sec
Voltage Drop (Resistive, Peak)	22.5 V	17.2 V
Voltage Drop (Inductive, Peak)	26.9 V	2.9 V
Peak Power (Dissipative)	89 kW	25 kW
Average Power	29 kW	8 kW
Magnets Required	384	84

Injection and Extraction

Space is allocated for an injection system, an extraction system, and an abort system. All systems use kickers located in the zero-dispersion straight

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NEW 150GEV MAIN RING

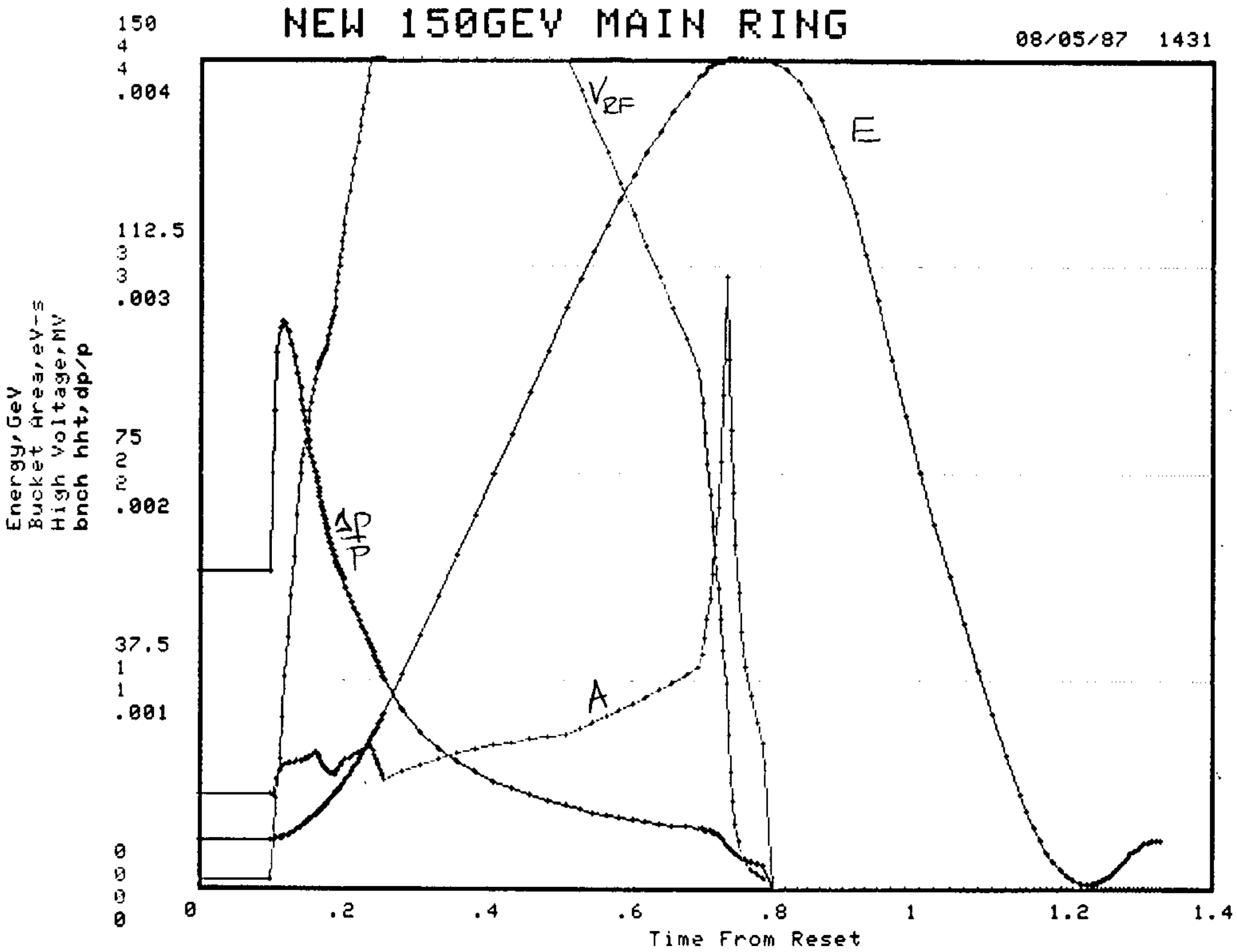

Figure 13

sections with associated septum magnets located in the straight sections 90° away. A 132 nsec gap is present in the beam to accomodate kicker rise and fall times.

VIII. SITING OF THE NEW RINGS

We have invested little time in studying the optimum manner of siting the rings associated with the scenarios studied. We do, however, still make a few observations. For scenario 1, a new 8 GeV Antiproton Depository, we suspect the best location would be southwest of F0, tangent to the existing AP1 beamline. In this location the ring would become nearly transparant from an operational point of view. For scenario 2, the 20 GeV Antiproton Depository and Post-Booster, a possible siting is due west and between the Booster and Antiproton Source as shown in Figure 14. The choice of site is somewhat harder in this case than in scenario 1 because of the need to have both protons and antiprotons being fed into and extracted from a common tunnel in the appropriate direction. An extensive set of new beamlines would have to be built to support this scenario. Possible sites for scenario 6, the 150 GeV Antiproton Depository and New Main Ring, might include southwest of F0 as in scenario 1, or east of and tangent to the Tevatron at A0. Once again extensive new beamlines are required to support this scenario.

IX. SUMMARY

We have looked at a range of options for new rings needed to support proposed luminosity upgrade of the Fermilab collider. The primary needs, as we perceive them, are related to production and storage of 4×10^{12} antiprotons, and to improving Main Ring performance. We anticipate an antiproton production rate of 1.5×10^{11}/hour during the era of the upgrade, and regard this as extremely marginal given the luminosity lifetimes currently being measured in the collider. Given that the antiproton beam lifetime in the collider is much longer than the luminosity lifetime, recovery and recooling of spent antiprotons becomes an attractive (but not the only) option for enhancing the effective antiproton production rate.

We have looked in modest detail at three possible scenarios for new rings at Fermilab. The most simplest option involves the construction of a new 8 GeV antiproton Depository capable of accumulating up to 4×10^{12} antiprotons fed to it infrequently from the existing Antiproton Accumulator. This ring is described in the body of this report as the '20 GeV Antiproton Depository' even though in this application it would not be used to accelerate antiprotons to 20 GeV. This ring has the same circumference as the existing Accumulator

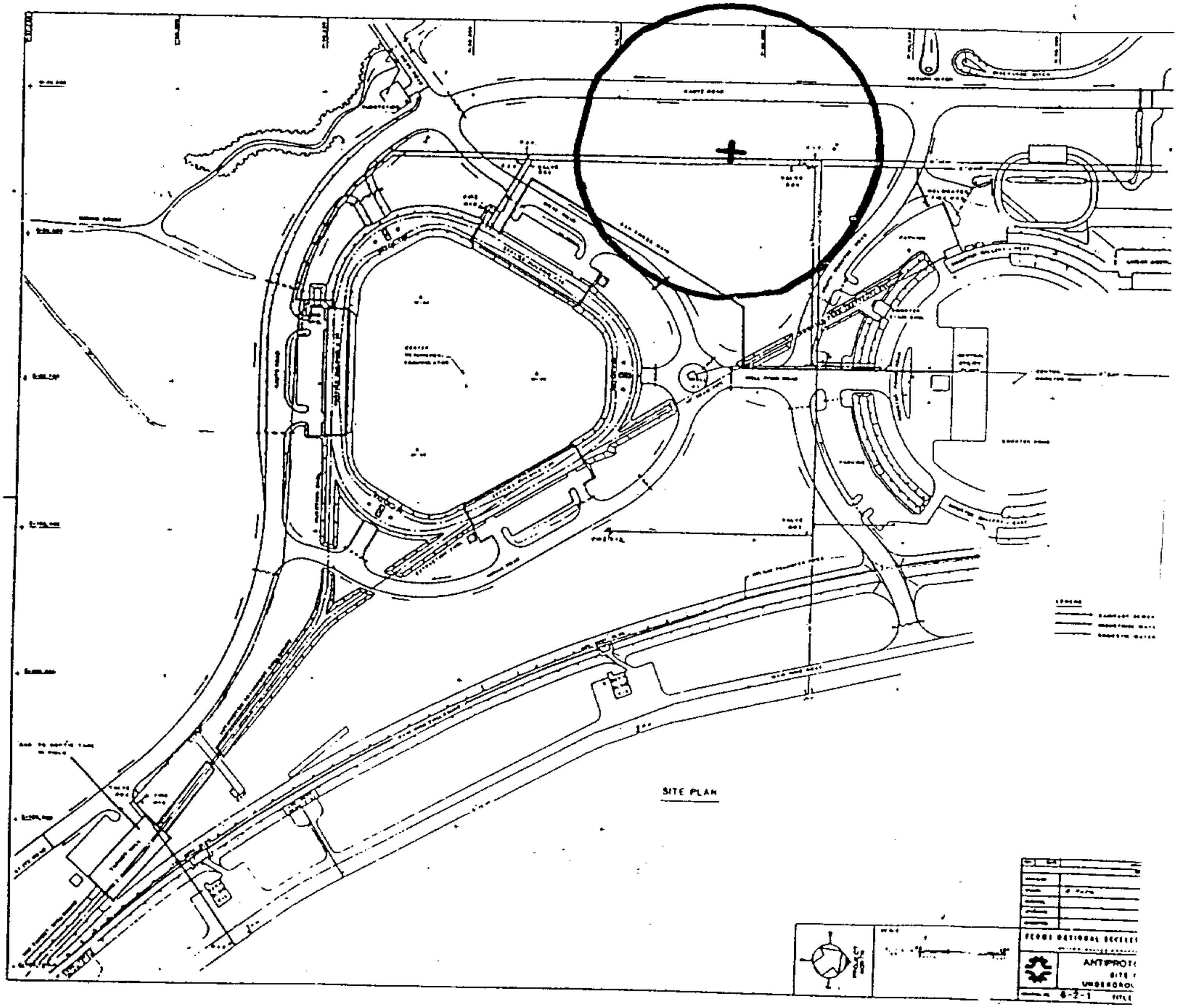

Figure 14

and represents the easiest means of providing one of the most pressing needs of the upgrade--the ability to have 4×10^{12} antiprotons collected in one place ready for injection into the collider. This ring on its own would not be able to collect antiprotons at a high enough rate to support the upgrade and is incapable of being used in a recovery scheme. It might however prove to be an attractive option if bunched beam cooling in the Tevatron were deemed to be feasible.

The second scenario we examined consists of a 20 GeV Antiproton Depository and 20 GeV Post-Booster situated in a common tunnel. This option address the needs for total number of antiprotons, antiproton accumulation rate (since we believe antiproton recovery is possible with this ring), and improved Main Ring performance. The two rings are designed to have similar optical properties so that beams emanating from either ring look the same to the Main Ring. Both rings have what one would call 'reasonable optics', that is the optics are not distorted from what an accelerator designer would do naturally in rings of this size by the requirements imposed by antiproton accumulation. The Antiproton Depository in particular is very well matched to the antiproton accumulation and cooling requirements both at 8.9 GeV and at 20 GeV.

The third scenario involves a 150 GeV Antiproton Depository and a 150 GeV New Main Ring sharing a common tunnel. This scenario again addresses the needs for total number of antiprotons and antiproton accumulation rate (again through recovery), and goes even further than the second scenario in alleviating problems associated with the existing Main Ring. Unfortunately, the design of the rings is not altogether satisfactory. In particular we found that we were not able to provide a lattice very well matched to the stochastic colling requirements without creating lattices which do not look very attractive to the accelerator physicist. The rings presented in the body of this report represent a compromise between cooling requirements and what we believe is reasonable optics for accelerators of this scale. As such the designs do not really do very well in either sense, and we do not regard these designs as satisfactory. A more satisfactory solution might be obtained by changing the ground rules given in Section II to allow cooling at an alternative energy (say 20 GeV) or by considering cooling systems with lower bandwidths.

In conclusion, we have found that either the construction of an 8 GeV Antiproton Depository, or the construction of a 20 GeV Depository and a 20 GeV Post-Booster in a common tunnel with the circumference of the existing Accumulator appear to be technically feasible. Construction of a 150 GeV Depository and 150 GeV New Main Ring within a common tunnel and satisfying the needs of the collider upgrade is more difficult.