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PHASE SPACE COOLING AND $\bar{P}P$ COLLIDING BEAMS OF FERMILAB

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Introduction

It has recently been suggested[1] that the present high energy synchrotrons at CERN and Fermilab could be operated as $\bar{p}p$ storage rings with a center-of-mass energy of some 800 GeV. The Fermilab Energy Doubler/Saver, in addition, would be quite suitable as a high performance storage ring, producing collisions at 2 TeV in the center-of-mass. In order to achieve useful luminosity it is necessary to: 1) collect antiprotons from ~80 GeV protons colliding on a stationary target, 2) cool the phase space of the initially diffuse $\bar{p}$'s, and 3) accumulate the cooled $\bar{p}$'s over cycles. Several methods have been devised to carry out this repetitive accumulation and cooling.[2,3,4]

One method of phase space cooling, that of electron cooling, has recently been demonstrated to work by G.I. Budker, et al.[2] They have efficiently damped both the betatron motion and momentum spread of a beam of 65 MeV protons in approximately 80 milliseconds[5].

In order to adapt this technique to antiproton cooling, one faces the problem that phase space compression with electrons works efficiently only at nonrelativistic energies, while the greatest majority of $\bar{p}$'s are produced fast in the laboratory system, i.e. $\langle\gamma_{\bar{p}}\rangle \sim \sqrt{E_p/2m} = 7$. The region between the optimum production and cooling energies for antiprotons may be covered by the introduction of a deceleration stage between the production of $\bar{p}$'s and the subsequent electron cooling.[6] A design has been developed to use the rapid cycling Fermilab booster to decelerate $\bar{p}$'s to 200 MeV where electron cooling and stacking could be performed in a modest cooling ring which could be housed in the booster tunnel.

The scheme consists of three separate phases, shown in Fig. 1:

i. Antiproton production, deceleration and accumulation.

Antiprotons at p~6.5 GeV/c (x=0) are produced on a small tungsten target by 80 GeV/c protons from the main ring. They are injected into the booster ring and decelerated to 200 MeV. The beam is transferred to the cooling ring where it is stacked and cooled. Antiprotons could be accumulated at approximately $4(10)^7\bar{p}$/pulse, leading to 10^{11} $\bar{p}$'s in some three hours.

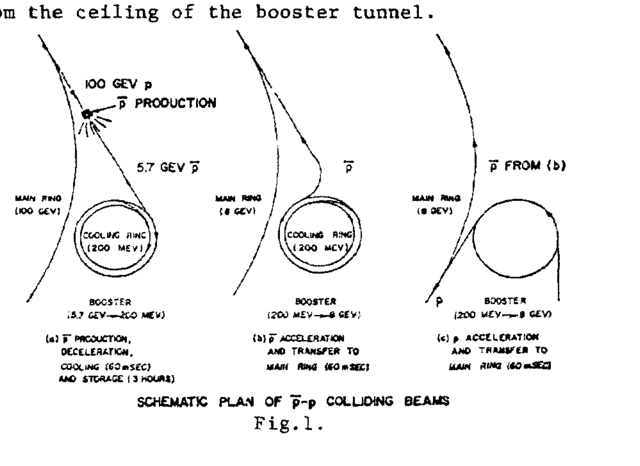
ii. Injection of p and $\bar{p}$ into the main ring, and $p\bar{p}$ collisions.

The $\bar{p}$ beam is transferred from the cooling ring to the booster, accelerated to 8 GeV, and reverse-injected into the main ring. A standard proton booster pulse is then injected into the main ring. There are then 84 protons and 84 antiproton bunches counter-rotating. The beams are accelerated synchronously to 200 GeV, and made to collide at a low-β insertion in a main-ring straight section.[7] With 10^{11} $\bar{p}$'s and 4×10^{12} p's luminosities of $\gtrsim 10^{29}$/sec/cm^2 are obtainable. Upon transfer to the ED/S and subsequent acceleration, one can achieve a luminosity of $\gtrsim 10^{30}$/sec/cm^2.

iii. Antiproton beam regeneration.

After some time, beam-gas scattering, rf noise and higher order resonances could lead to an appreciable blow-up of the beams with consequent loss of luminosity. In order to restore beam quality, the proton beam would be dumped and the antiprotons would be decelerated, first in the main ring to 8 GeV and then in the booster to 200 MeV, and cooled again in the cooling ring. The whole sequence should take only seconds. After this $\bar{p}$'s are accelerated again by the booster, injected into the MR with a new companion proton beam and accelerated to high energies.

In order to test the speed and efficiency of electron cooling at these energies, a modest dc storage ring is presently being constructed at Fermilab. Table I lists the important parameters for the storage ring design. It is specifically designed to allow relocation in the booster tunnel after having gained sufficient understanding of the cooling and accumulation techniques. The same magnets, rf, vacuum, and injection can be mounted in a 12-sided cooling ring suspended from the ceiling of the booster tunnel.



SCHEMATIC PLAN OF $\bar{p}$-p COLLIDING BEAMS

Fig.1.

*Operated by the Universities Research Association, Inc. under contract with the Energy Research and Development Administration.

†Operated by Stanford University, under contract with the Energy Research and Development Adminstration.

Electron Cooling

In order to achieve efficient cooling the initial electron and proton random velocities must be approximately equal in the system moving at the average velocity of the particles. The equilibrium proton random velocity is $\sqrt{\frac{m_p}{m_e}} \sim 40$ times smaller than the electron random velocity, except for intrabeam scattering, gas scattering, and other effects such as space charge and instabilities. To cool booster size beams at 200 MeV, (ε_H, $\varepsilon_V \sim 40\pi$, $20\pi \times 10^{-6}$ rad m, $\frac{\Delta p}{p} \sim 1.5\times10^{-3}$) it is advantageous to have β functions of about 20 m for the protons and the electron temperature $T_e \lesssim 1$ eV.

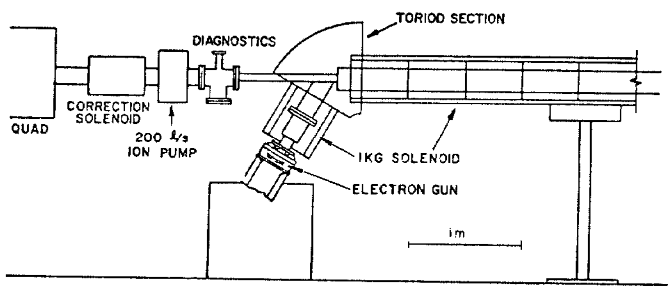


Fig. 2. Electron Cooling Straight Section

In the cooling region, the effective temperature of the electron beam is determined by (1) magnetic field errors, in which $\delta B/B \sim 10^{-3}$ yields $\Delta T_\perp \sim 0.4$ eV in the transverse direction and (2) space charge potential variation and voltage regulation in the electron beam, which determines the effective longitudinal temperature of the beam. In order to achieve the rapid transverse cooling observed in NAP-M. it is necessary that these energy variations in the lab system be kept below 5 eV, leading to $T_\parallel$ in the particle frame of 10^{-4} eV. Then the electron velocity distribution in the particle frame is disc shaped, contours having a shape like a phonograph record. To achieve this 5 eV it is necessary to space charge neutralize the electron beam in the cooling region with ions whose temperature is no higher that 5 eV.

The cooling rates for the anisotropic electron velocity distribution, ignoring the presence of the magnetic field, are predicted to be roughly the same as those of an isotropic distribution with $T_e = T_{e\perp}$ viz.

$$\lambda_{Lab} = \frac{4\sqrt{2\pi}\, r_e r_p n_e \log\Lambda}{\gamma^2 (T_e/mc^2)^{3/2}}\, \eta. \qquad (1)$$

Here n_e is the electron density and η is the fractional cooling length. $\Lambda = \lambda\text{Debye}/r\,\text{min}$, where $\lambda_D \sim 0.05$ cm and $r\,\text{min} \sim 5\times10^{-7}$cm is the distance of closest approach. The magnetic field splits this impact parameter (b) range into two parts, that above the electron gyroradius $\rho_e \sim 10^{-3}$ cm and that below. For the lower range where the collision time is short compared to an electron gyroperiod the momentum transfer is essentially the same as the no-field case. For the upper range, the electron transverse motion is adiabatic and $T_{e\perp}$ disappears from the calculation. In addition there may be resonant effects in the range $b \sim \rho e$. It is felt that these magnetic effects, together with the anisotropic electron velocity distribution, are the source of the unexpected rapid transverse cooling rates measured with proton beams in NAP-M, where cooling rates are observed which are ten times those predicted by formula 1.[5]

Using the parameters of the cooling system given in Table 1 and described more fully below, one finds from formula 1 cooling rates of $\lambda \sim 3$ Hz. The magnetic effects would be expected to increase the transverse cooling rate by a factor comparable to that measured on NAP-M. An added bonus in cooling comes from the drag force exerted by the already cooled and accumulated beam on the newly injected beam. Because the density of the cooled beam is so high, and cooling length so long (η=1), this drag force can be orders of magnitude higher than the electron drag force. On the other hand, the large emittance of the new beam causes it to spend a small fraction of its time in the cooled beam, so the cooling rate is nonlinear. This effect will be studied in the cooling ring described below.

Electron Cooling Region

The electron cooling of the stored proton beam occurs in the straight section shown in Fig. 2. The design must provide a cold, intense electron beam and bring it into nearly perfect alignment with the proton beam. The electrons are confined in the drift region by a 1 kG solenoidal magnetic field to avoid divergence produced by space charge forces.

Electron Gun

The electron beam must have a rest frame temperature of $\lesssim$1 eV. To produce such a low temperature, the electron gun has been designed with a classic Pierce geometry, and is itself immersed in the magnetic field. The electron gun design developed for the SPEAR kylstron will be used. It produces a 28 A, 27 cm^2 beam at 110 kV. The dispenser cathode can be reactivated repeatedly after exposure to air. Figure 3a shows the field design of the gun and the calculated electron trajectories. The defocusing lens action of the anode causes the electrons to spiral, resulting in the undulation clearly visible in Fig. 3 a. This undulation can be cancelled by a "resonant" focusing system, as shown in Fig. 3 b. Electrode potentials are adjusted to match the spiral motion so that the electrons emerge parallel.[8]

Drift Region

After leaving the gun, the beam is bent 60° to superpose it with the proton beam. The bending is accomplished with a crossed toroidal and dipole magnetic field. The resulting trajectory bends on a circular arc without exciting gyrations. The toroid has a gradient 6.7 kG/m, and a dipole field 80 G.

The cooling takes place in a 5-m long drift region, where the electron beam is confined by a uniform-field solenoid. The solenoid is an assembly of 0.5-m long coils of anodized aluminum strip conductor. The field produced by a long sequence of the coils with minimum spacing has a uniformity $(\delta B/B)_{rms} \lesssim 5\times10^{-4}$, sufficient for optimum electron cooling.

The ground potential surface throughout the cooling region is a drift tube 6" in diameter which is split into four 90° segments, each connected to an independent voltage source. Thus the "ground" in the cooling section may be floated relative to the drift sections in each 60° bend and hence, it is possible to trap the ions formed by beam-gas scattering in the cooling region, and neutralize the space charge in the electron beam. The pressure equivalent to the needed ion density is $p_i = \frac{1.6\times10^{-8}}{Z}$ Torr. Since beam growth $(d\langle\phi^2\rangle dt) \propto P_i Z_i^2$, it is desirable to use hydrogen for neutralization.

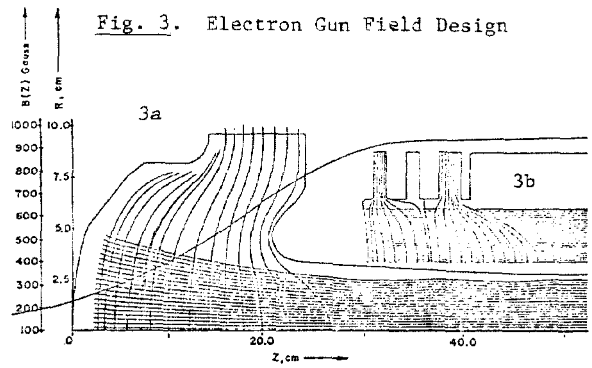


Fig. 3. Electron Gun Field Design

Depressed Collector

After a second 60° bend, the beam is decelerated and absorbed in a collector assembly. In order to minimize the power dissipation the collector is operated at a potential only slightly lower than that of the electron gun cathode. The collection is then efficient only if no electrons have lost more than $e\delta V$ since their birth at the gun cathode. Any energy coupled to gyration in the deceleration process is difficult to recover into longitudinal motion. For this reason the collector geometry closely approximates that of the gun itself, including the carefully tapered magnetic field.

Vacuum

The extreme tolerance on magnetic field uniformity precludes any gaps in the solenoid wide enough to accommodate pumping ports in the electron cooling region. To ensure an adequate vacuum ($<10^{-10}$Torr), Ti sublimation pumps are located in the 1" gap between the drift tube and vacuum pipe wall at intervals along the cooling region. The sublimation units can also be used as electrodes for ion discharge cleaning of the entire cooling region.

Storage Rings

The lattice of the cooling ring is shown in Fig. 4. It consists of two long straight sections in which the beam properties are adjustable to the desired values by means of matching quadrupoles connected to curved sections made of FODO normal cells. A short straight section in each curved section accommodates RF cavities, beam profile monitors, etc., and also allows space for secondary extraction and injection. The lattice can be easily modified to produce more nearly optimal betatron and momentum functions for injection and cooling. The natural chromaticity will be cancelled with two families of air core sextupoles, so that the tunes in the two planes may be changed without significantly affecting the ring's performance.

Vacuum

The vacuum required for a ~1 day beam lifetime due to nuclear interaction, is $\sim10^{-10}$ Torr. To achieve this, the entire vacuum tank is bakeable to 400°C. Distributed ion pumps are located inside each dipole magnet, each having 300ℓ/sec pumping speed.

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Table I

Storage Ring and Electron Cooling Parameters

Lattice Properties

Momentum		644 MeV/c	
Bend field		4.6 kG	
Radius		21.5 m	
Revolution time		800 nsec	
Superperiodicity		2	
Focussing structure		FODO	
Length of straight sections		10 m	
Nominal working point:			
Tune: $\nu_H = 3.70$		Natural chromaticity:	$\xi_x = -8.10$
$\nu_v = 3.69$			$\xi_y = -5.49$
Transition gamma $\gamma_T = 3.62$			
Dipoles	24 @ 1.2 m		
Quadrupoles	30 @ 0.6 m		
Nominal aperture:		$a_H = \pm76$ mm	
		$a_v = \pm25$ mm	
Sagitta		40 mm	
Lattice functions:	Maxima		In center of s.s.
β_H	29 m		20 m
β_v	36 m		20 m
η_H	5 m		5 m
Injected beam		$\varepsilon_H = 40\pi$ mm-mrad	
		$\varepsilon_v = 20\pi$ mm-mrad	
		$\Delta p/p = \pm1.5\,(10)^{-3}$	

Electron Cooling Properties

Electron temperature	$Te_\parallel$	≤.5 eV
	$Te_\perp$	≤.5 eV
Initial proton temperature	$Tp_\parallel$	1300 eV
	$Tp_\perp$	540 eV
Electron current density	j_e	1.5 A/cm^2
Electron beam radius	r	2.5 cm
Electron density (rest frame)	n_e^*	4.5 (10)^8/cm^3
Debye length	λ_D	0.02 cm
Plasma parameter	$N_D \equiv n_e^* \lambda_D^3$	10^4
Solenoid field	B_o	1 kG
Cyclotron frequency	Ω_e	2.8 GHz
Collision frequency	ν_e	27 kHz
Gyroradius	ρ_e	0.0012 cm

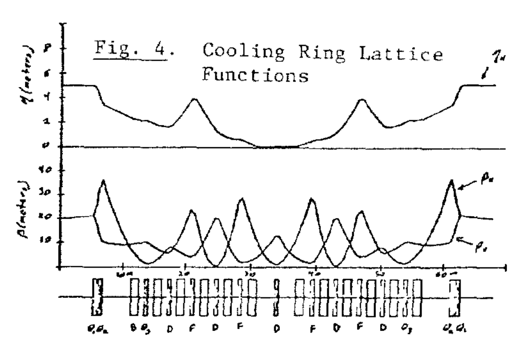

Fig. 4. Cooling Ring Lattice Functions