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INITIAL OPERATION OF THE FERMILAB ANTIPROTON COOLING RING

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Introduction and Summary

The "cooling" of protons by electrons has been studied by the accelerator group at the Institute of Nuclear Physics at Novosibirsk, U.S.S.R.[1]. They have achieved damping of proton-betatron oscillations by Coulomb interactions with "cold" electrons as described by simple theory. They also observe fast damping when the longitudinal velocities of all the protons and electrons are very nearly the same and the electrons are trapped in a longitudinal magnetic field. This effect results from the extended interaction between the same electrons and protons.

A 200-MeV storage ring has been constructed at Fermilab to extend the results of the Novosibirsk group to higher energy and to study the accumulation of protons in combination with cooling. It is also planned to use the ring for doing stochastic cooling experiments[2]. The location of the ring, in close proximity to the Fermilab linear accelerator and booster accelerator (see fig. 1), will make it possible in the future to use the storage ring as an accumulator of antiprotons where cooling will be essential if a reasonably intense, high quality beam is to be obtained. Such an anitproton beam would allow very high center-to-mass energies to be achieved for proton-antiproton collisions in either the Fermilab 400 GeV main ring or superconducting energy doubler ring.

A 200 MeV proton beam from the linac was injected into the storage ring in August, 1978 and observed to circulate for many seconds. Tune-up studies on the ring are in progress while improvements are being made in the vacuum, beam diagnostics, power supplies, controls, correction magnets, injection kickers, beam abort system, and shielding. An RF system is being installed. The electron system is being tuned-up off-line of one of the storage ring's long straight sections. At the appropriate time, the electron system assembly will be moved a few feet onto the beam line of the storage ring so that electron cooling experiments can start.

Description of Storage Ring

The lattice functions for one-half of the storage ring are shown in Fig. 2. The entire lattice consists of 24 dipoles and 32 quadrupoles arranged in a configuration with two long straight sections in which the beam properties are adjusted to the desired values by means of matching quadrupoles connected to regular curved sections made of FODO cells. A short straight section, made by the omission of one bending magnet from a normal cell, has been put into the middle of each curved section to facilitate such devices as an internal dump and beam monitors at one end, and for injection at the other end. The beam size and momentum dispersion of the long and short straight sections have been chosen to be nearly optimal for electron cooling and multiple-turn injection (momentum stacking), respectively.

To compensate for the large tune shifts due to the focussing effect of a totally unneutralized 26 A electron beam used in the electron cooling experiments, the three quadrupoles on either side of the electron beam will be retuned. The natural chromaticity can be nearly cancelled over the desired momentum stacking variation of ± 1% by the use of two families of sextupoles, having a maximum integrated field of about 10 kG/m.

For reasons of economy and ease of construction, the dipole magnets were chosen to be straight in spite of their large bending angle. The vertical aperture is sufficient to accommodate 20π mm-mrad acceptance and 1¼ in. of vacuum chamber, heaters, and insulation for the in-situ vacuum baking. The radial aperture is sufficient to contain two 40π mm-mrad beams separated by $\Delta P/P = 2\%$ at all points in the lattice, the 1.6-in. sagitta, 1.5-in. wide vacuum ion pump elements on both sides, chamber walls and insulation. The pumping elements are located in fringe fields unacceptable for particle motion. The construction of the magnets is discussed elsewhere[3].

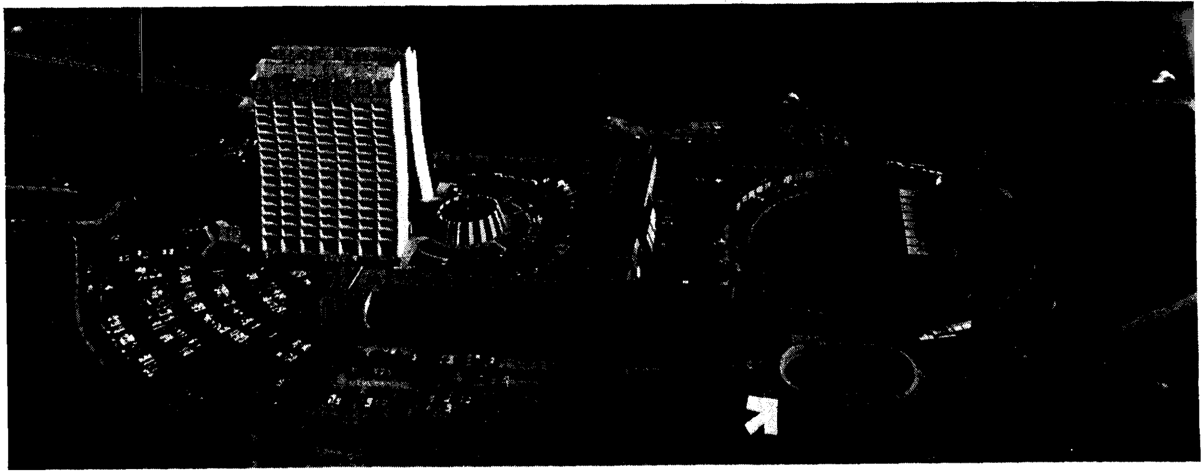

Fig.1 Aerial view shows newly commissioned cooling ring in lower right foreground.

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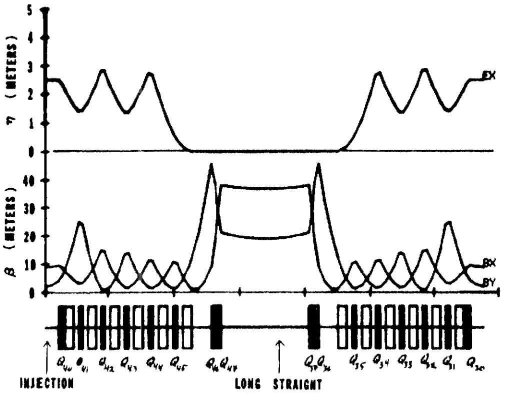

Fig. 2 Cooling ring superperiod

The quadrupole magnets are rather weak; ∿0.5 kG/in. nominal and 24-in. long. The 6-½ in. bore is sufficient to contain a 6-in. beam pipe and allow insulation for bake-out. A beam position detector is installed in the vacuum chamber in each quadrupole gap. The quadrupole construction details are given elsewhere.

The vacuum required for a 24-hour beam lifetime due to nuclear interaction is $\sim 10^{-10}$ torr. To achieve this requirement, the vacuum system is an all-welded stainless-steel chamber which is bakeable to 400° C. The main pumping is achieved by distributed ion pumps located inside each dipole magnet. The vacuum system is described in reference 3.

TABLE I

STORAGE RING PARAMETERS[5]

Momentum	645 MeV/c
Bend Field	4.29 kG
Magnetic bend radius	5.01 m
Radius	21.56 m
Revolution time	∿800 n secs.
Superperiodicity	2
Focussing structure	separated function FODO normal cell
Nominal tune (stacked orbit)	$\nu_H = 3.68$ $\nu_V = 5.42$
Number of dipoles	24
Length of dipoles	48.00 in.
Effective dipole length	51.52 in.
Number of quadrupoles	32
Length of quadrupoles	24.00
Number of sextupoles	16
Length of straight sections (half)	
short straight (2 each)	6 ft. 5.91 in.
long straight (2 each)	22 ft. 2.44 in.
Total length of orbit	135.48 m
Vacuum chamber aperture	$a_H = \pm 76$ mm $a_V = \pm 25$ mm
Sagitta	42.9 mm
Available aperture	$a_{H_{tot}} = \pm 54.6$ mm
Acceptances:	$\varepsilon_H = 40\pi$ mm-mrad $\varepsilon_V = 20\pi$ mm-mrad $\Delta P/P = \pm 1.5\ 10^{-3}$

The RF requirements for the cooling ring are established by the energy and momentum spread of the incident beam together with the required harmonic number and the stacking acceleration rate (to match the Fermilab booster accelerator frequency and cycle). An RF voltage of 16 kV is sufficient to create bucket area large enough to contain the injected longitudinal emittance and provide some accelerating voltage. The RF rest frequency will be near 7.52 MHz and frequency tuning of a few percent about this frequency is necessary. The accelerating resonator vacuum chamber must also be bakeable and of a quality consistent with the high-vacuum requirements of the cooling ring. These requirements are met nicely with a slightly modified accelerating resonator from the Princeton-Pennsylvania Accelerator (PPA)[4].

The PPA cavity has two accelerating gaps and is heavily ferrite-loaded. The operating frequency of 7.5 MHz can be reached with a ferrite bias current of 1000 A at a few volts. The cavity is driven by two kW RF tetrodes which are mounted directly on the cavity. Because the cavity has two gaps, each capable of generating a gradient which is almost two times the anode voltage, the system can easily meet the RF voltage requirements. At 200 MeV, protons drifting between gaps move about 13 degrees in RF phase. This phase shift causes about 2 percent decrease in accelerating voltage.

The center drift tube of the cavity consists of stainless-steel tubing brazed to cylindrical ceramic insulators. Because the ferrite biasing current flows longitudinally through the cavity shell, it is necessary to isolate the accelerating structure from the remainder of the cooling ring vacuum chamber to prevent a fraction of the biasing current from flowing away from the cavity and into various ground loop paths. Therefore, at least one insulator in addition to the accelerating gap insualtors has been installed. Heating devices have been installed in the structure so that it will be possible to bake the beam tube in place. Because the RF field at the longitudinal mid-plane of the cavity is zero, it is possible to heat the mid-section of the vacuum chamber with heating leads entering at the mid-plane.

Cooling and accumulation of many pulses of protons is a major goal of this phase of the cooling ring program. The accumulation scheme must be compatible with the 15-Hz rate of the booster. At the same time, it should avoid difficult mechanical devices such as moving septa or magnets, and employ equipment which is within the present state of technology. Accordingly, the scheme is based on electron cooling RF stacking, and single-turn injection.

Conceptually, the momentum aperture is split into two regions, centered at P_1 and P_2, respectively. Each region will accept the full emittance, full momentum spread uncooled beam. Injection is accomplished at momentum P_1. The uncooled beam is RF captured and moved to the neighborhood of momentum P_2, the cooling momentum, where it is stored and cooled.

Injection is presently accomplished by a single kicker located 90° in radial betatron phase downstream of the septum magnet. The septum magnet bends the beam parallel to the equilibrium orbit in the center of the short straight section where x_p is maximum and β_x is small. The single kicker deflects the beam parallel to the central orbit. The position of the septum and the entering beam are chosen to accommodate the emittance and momentum width of the beam, plus the thickness of the septum. This determines the strength of the kicker necessary to deflect the beam parallel to the equilibrium orbit. The kicker is shut off after one revolution time. For beam stacking,a second kicker is placed

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90° in betatron phase upstream of the septum magnet and dc dipole trims are placed over both kickers. The dc trims center the three beams in the injection straight quadrupole. The net effect on the stacked beam is only to cause it to follow a different path during the time new beam is being injected. Errors in betatron phases, beta functions, kicker strengths and kicker timing away from ideal values will cause a small betatron oscillation to be induced in the stacked beam. Experience with cooling has shown that for this condition, i.e., small momentum spread, the cooling of betatron oscillations is fast. The strength required for each kicker is .011 Tm. The air-core strip line kickers are 20-in. long with a 4.5-in. radial aperture and have an inductance of 0.4 μH They are driven by a 3Ω line and have a rise time of about 200 ns. With a 3500A pulse, the proton deflection is about 5 mrad.

Accumulation will be accomplished by RF capturing the beam, accelerating the beam to the cooling momentum and stacking it there, as indicated pictorially in Figure 3. This method allows some margin in the cooling rate as compared to the anticipated 15-Hz accumulation rate. The harmonic number of the RF system is 6, (f = 7.5 MHz) corresponding to the number of bunches desired when the cooled beam is recaptured. The voltage required to capture the ± .15% momentum spread is 12 kV. The beam can be moved (2% in momentum) to the stacking region in 2 msec with 3-kV accelerating voltage. The phase oscillation frequency is 6 kHz; thus capture and stacking can be accommodated in several milliseconds with a 15-20 kV RF system with a 1.2% frequency range.

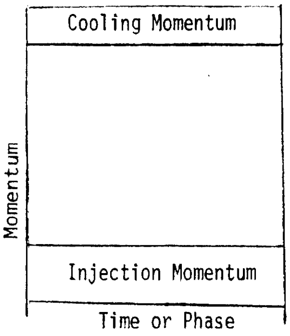

Fig. 3 Momentum Stacking

Cooling Ring Status

The construction and installation of components for the storage ring and electron cooling system in its most primitive state is nearing completion. The building was completed in September, 1977; the fabrication of the magnets in June 1978; the injection system for bringing 200 MeV protons from the linac in May, 1978; and the vacuum system in August, 1978. Minor construction remains to be completed for the electron gun and collector, the RF cavity, controls, beam-abort system, and the second injection kicker power supply.

The ring magnets have been installed and aligned. Operation of the magnet system has shown the power-supply ripple to be about 0.2%, which is too large for stable operation and beam measurements. A shunt regulator to reduce the ripple has been designed and is being tested.

The vacuum chamber achieved a pressure of about 1 x 10^{-9} torr in the quadrants and 6 - 8 x 10^{-9} torr in the long straight sections before a bake. A partial bake of only the dipole and quadrupole chambers produced pressures of 2 - 4 x 10^{-10} torr in the quadrants but resulted in an increase in pressure in the unbaked long straights. A complete bake of the ring is expected to give the desired pressure of 1 x 10^{-10} torr.

A 200-MeV proton beam from the linac was injected into the storage ring in August, 1978, and coasting beam in the ring was observed to circulate for many seconds. Tune-up of the ring and coasting beam studies have not been actively pursued while construction continues and power supply, control-diagnostics problems have priority. However, the beam intensity has been measured to be about 10^7 protons after the injection septum. The intensity of the captured coasting beam has not been measured. The beam lifetime is about 10 secs and is strongly dependent upon the voltage fluctuations on the electrical power mains resulting from the Fermilab main accelerator load when the magnets are ramping. Power supply regulation improvements will be helpful. The radial and vertical tunes have been measured and the working point has been verified. The momentum aperture of the ring is in rough agreement with the expected value for the ring without corrections.[5] Current studies are aimed at improving injection steering and matching conditions to increase coasting-beam intensity. The beam-diagnostic system [6] is being developed to facilitate beam measurements and tune-up of the ring.

The magnetic confinement system [7,8] for the electron cooling system has been assembled, measured, and the fields corrected. The field lines have been mapped with a low-velocity electron beam. Tests will soon begin with the high-power electron gun and beam collector. When these tests and the tune-up of the electron system is complete, the assembly will be installed in the storage ring so that the first electron cooling experiments can start.

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