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INJECTION, MAGNET, AND VACUUM SYSTEMS FOR THE FERMILAB ANTIPROTON COOLING RING

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Summary

This paper gives construction details of the dipole and quadrupole magnets, a brief description of the proton injection line, and a short report of the vacuum system design for the existing Fermilab Cooling Ring.

I. MAGNET CONSTRUCTION

Dipole Magnets

The dipole magnet was chosen to be a modified picture frame magnet with a small pole. This gives a smaller current density and locks the coil in place. There is no other coil restraint. A Rose shim was employed to extend the good field region to within one half gap from the coil.

The magnet was fabricated of two laminated half-cores clamped together by 26-3/8 in. bolts. The laminations were stacked in a fixture together with the end plates and recompressed after each additional 6 in. of laminations. Laminations were alternated in direction each 2 in. in order to remove any asymmetry caused by the die or by remanence due to rolling direction. The core was welded while clamped to a let-in key and to let-in angle irons which are used to clamp the two cores together. Length variations were kept less than one lamination.

The 1 in. end plates were fabricated of normal laminations glued together with epoxy. A bevel was machined at 30° to the pole surface to terminate the magnetic field without saturation. The bevel was machined in steps to achieve uniformity of magnetic field length across the radial aperture. Delamination of the glued end plate occurred in several cases, causing a field integral variation of $\sim 7 \times 10^{-5}$, and was repaired by regluing and adding stainless steel screws. Longitudinal grooves on the mating surfaces accepted a 3/16 in. drill rod to register the two half cores in the horizontal direction. It was found that the corner of the lamination was drawn up by the welding and produced an apparently large back leg gap in this region, but no obvious deterioration of magnet performance resulted.

During early production measurements, it was found that the fields were not reproducible after magnet disassembly and reassembly. This was solved by tightening the clamp bolts near their tensile limit with additional C-clamps between them at the same stress level. After this treatment, all magnets tested reproduced fields to about one part in 10^4. The local stress placed on the lamination surfaces was equivalent to $\sim$500 tons total on the mating surface. This is approximately ten times the magnetic force at normal fields. The final clamping stress was 40% of the maximum.

The coils ends are bent at 45° to clear the vacuum chamber. The coils were wound on a rocking fixture on a carousel. It was found that the work hardening of the copper due to this bend gave enough strength to support the coil end. An automatic tension mechanism was employed to assure straightness. Each half coil is composed of two double pancakes of five turns giving 20 turns per half coil. The coils were insulated after winding with polyester tape and each pancake was wrapped. Pancakes were separated with 1/16 in. G-10 insulation; the half coil was surrounded with G-10 and wrapped again. Each pancake has a separate water circuit with $\sim$65 psi pressure drop.

The magnets fields were corrected empirically by machining the end plates 1/16 in. deeper over the central 6 in. and adding a 1 in. shim 1/16 in. thick at each pole edge. The effective magnetic length of the dipole is 51.52 in. The magnets have a slightly concave field distribution at a level of 1-2 parts in 10^4 over an 8 in. aperture. Figure 1 shows the field in the central region of the magnet and field integral of a typical magnet as a function of horizontal position. The rms deviation of the central field integral for all magnets fabricated was 7×10^{-4}. This is consistent with length control during stacking.

Quadrupole Magnets

The general construction features of the quadrupoles are similar to those of the dipoles. Extra steel width was stamped into the back legs of the laminations to avoid oil-canning. The laminated end plates were made 1-1/2 in. thick to resist bowing of the salient poles. The problem of reproducibility after disassembly and reassembly was not as serious as in the dipoles.

The coils are double layer solenoid-wound. They were insulated with polyester tape before winding, insulated with G-10 and ground wrapped. It was determined that the tape retain its rated insulation value after bending through a minimum 1 in. radius of curvature.

Correction was achieved empirically, and resulted in a flat beveled surface at 30° to the pole penetrating 5/8 in. into the end. The measured gradient integral and calculated central gradient are shown in Figure 2. The remaining error is predominantly 20-pole in form ($B' \sim x^8$).

The central gradient integral variation for all 38 quadrupoles produced was 7×10^{-4}, for those chosen for the ring, 5×10^{-4}. The effective gradient length of the quadrupoles is 26.64 in.

TABLE I
COOLING RING MAGNETS

	Dipoles	Quadrupoles
Field	4.3kG	0.5 kg/in
magnet length	48in	24in
magnet gap/aperture	3.25in	6.5in
coil aperture	12in	--
field aperture	±4.0	±3.0
field quality	$\pm 10^{-4}$(3in)	.5%
coil turns	40 total	10/pole
copper conductor	0.46in sq	0.46in sq
cooling hole dia.	0.25in	0.25in
conductor corner rad	0.063in	0.063in
conductor current	771A	535A
magnet inductance	0.01h	1.75mh
coil resistance	0.025	0.0132
voltage drop	17.8V	7V
power	12.6kW	3.8kW
water pressure	65psi	65psi
water paths	4	2
water flow	4.4gpm	2gpm
temperature rise	13.1°C	7°C
outside dimensions	10x22in	21x21in
iron weight	2100 lb	1590 lb
copper weight	288 lb	140 lb

II. INJECTION AND ACCUMULATION

Protons are extracted from the switchyard area of the linac for the cooling experiments. The protons are directed up a 1 in. diameter vacuum pipe centered in an existing 16 in. casing to ground level and transported to the south end of the cooling ring as indicated in Figure 3. The beam extracted from the linac must meet several requirements listed in Table II.

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TABLE II
INJECTION BEAM PARAMETERS

Momentum	644 MeV/c
Intensity	$\sim 10^7$/2 sec
Filling time	800 nsec
Beam size (horizontal)	$\sim$18 mm
(vertical)	$\sim$8 mm
Beam divergence (horizontal)	$\sim$2.1 mrad
(vertical)	$\sim$2.6 mrad

The time duration of the beam pulse for the cooling ring is restricted to 800 nsec by a chopper in the 750keV transport line at the low energy end of the linac. This beam pulse is extracted from the 200 meV transport line after the spectrometer magnet in the mementum dump line. Emittance measurements at the beginning of the spectrometer magnet have been used to estimate the shape of the beam downstream of the spectrometer magnet. This estimate of beam size was then used to determine the necessary aperture size of three magnets that are used to pitch the beam 8° vertically and 7° horizontally. The 8° magnet is located close to the spectrometer magnet and is ramped on when beam is desired to the cooling ring. This magnet is followed by two horizontal magnets to give a 7° bend onto the centerline of the existing 16 in. casing, which carries the beam to ground level. The first of these horizontal magnets is a fast pulsed magnet (approximately 1/2° bend) which is designed as part of the safty system. This pulsed magnet is followed by a 6.5° magnet to complete the horizontal bend.

Currents of approximately 20mA are anticipated during H^- operation of the linac. Coupled with the 800 nsec duration of the pulse, this leads to intensities of 10^{11}/pulse. In order to reduce the intensity, collimators have been installed in the existing 16 in. casing. The first collimator is made of aluminum. The pipe following this collimator is filled with water which serves as a heat sink for the collimator and as a shield against neutrons that would steam up the pipe. There are temperature sensors in the dump to monitor the heat rise. A vacuum window upstream of the first collimator strips the H^- ions and produces protons.

The beam is bent vertically immediately after the second collimator on to a horizontal plane below the cooling ring elevation. After bending 32° horizontally the beam then passes under the cooling ring vacuum pipe and is brought up to the cooling ring elevation via a vertical dogleg by using two small (1/3°) trim magnets.

There are a total of 6 horizontal bending magnets arranged to give an S-shaped curve which has a final angle of approximately 7° coming into the septum located in the south straight section. The bend magnets all bend at approximately 16° except for the last bend which is at 19-1/2°. Retractable Fermilab type-D multiwire chambers for measuring beam position and profile are placed before the last two quadrupole magnets and after the septum.

Because of the physical length of the line, four quadrupoles are used to match into the ring. A doublet has been assigned to each set of bending magnets.

During the design of the injection line, the computer programs TRANSPORT and TURTLE were used to determine the necessary apertures, collimator sizes, and quadrupole location and strength. At present the quadrupole doublets are connected in series and hence we do not have proper matching into the ring, however, at settings which maximize coasting beam the predicted beam size at injection using the program TURTLE agrees quite well with a polaroid of the beam and also with the SWIC output traces. The intensity at injection has been measured by activations techniques to be 1.6×10^7 p/pulse. The absolute intensity predicted by TURTLE is larger than this. One hypothesis for this descrepancy is the alignment of the two collimators which are respectively .2cm and .6 cm in radius and separated by 1300 cm of 2 cm radius vacuum pipe where it is inaccessible for realignment. The phase space acceptance of the slit system is approximately 1 πmm mrad. However, we also have slit scattering and multiple scattering from the windows and air gaps in the line as indicated by a halo on beam polaroids. The slit system in fact reduces the momentum spread from the Linac ($\Delta p/p = \pm.15\%$) to our final momentum spread at injection of $\Delta p/p = \pm.11\%$.

III. COOLING RING VACUUM SYSTEM

Vacuum requirements for storage of antiprotons are at a level of 10^{-10} torr. Basic design choices of the vacuum system were: a) 304 stainless steel, b) all welded, c) in-situ 400°C bake, d) distributed ion pumps, and e) preassembly 900°C vacuum bake for one hour below 10^{-5} torr of all stainless steel parts.

Baking System

A 1/2 in. thick high temperature ceramic fiber insulation surrounds the chambers in the dipole and quadrupole magnets. Inconel sheath heater cables are strapped to the chamber. A less expensive heater tape is used in normally accessible places. Total Cooling Ring heater power is about 180kW.

Vacuum Chambers

The basic chamber is 6 in. O.D. 1/16 in. wall type-304 stainless steel tubing. The two quadrupoles next to the injection short straight have rectangular chambers 7 in. wide. A bellows is positioned every six feet of straight section and on each side of every dipole to take the 1/2 in. per 6 foot thermal expansion.

The dipole chamber is a 2-1/4 x 10-1/4 in. rectangle made from 1/8 in. stainless sheets bent into a flat "U" and welded along the sides. Vertical supports provide a 1-1/2 in. wide ion pump chamber on each side. The ring center side support was shortened and the other one bent toward the ring center to provide a full 6 in. curved aperture. Stress calculations, assuming the supports are only vertical support, indicate a maximum stress for 1/8 in. walls of 20,000 psi. The yield point for type 304 stainless drops 40% from 20°C to 400°C putting it close to 20,000 psi. A prototype chamber flexed about 50 mils in the center in close agreement with calculations. The first dipole chamber was tested at 525°C. Each end of a dipole chamber has a flat plate transition to 6 in. round welded to the chamber at half of the magnet bend angle.

Roughing System

Three all metal (400°C open) sector valves divide the ring into two pieces plus the cooling straight. A roughing chamber with a magnetic bearing totally oil free turbomolecular pump and trapped mechanical pump are connected by a valve to each half of the ring. The turbo will allow the in-situ bake to occur in the 10^{-5} to 10^{-6} torr range.

Distributed Ion Pumps

Assuming a surface area of 7.8×10^3 cm^2, a pressure of 10^{-10} torr, and an outgassing rate of 10^{-12} torr l/cm^{2}s, the required pumping speed at 10^{-10} torr is about 325 l/s per dipole. The pump design is basically a variation of a Physical Sciences Laboratory (University of Wisconsin) design adapted to fill all available space. A module unit is 2 cells by 27 cells long. Two units are on the interior ring side and three on the outside. The pumping speed per dipole was estimated to be approximately 200 l/s at 10^{-10} torr from higher pressure measurements. This value is 1/3 less than estimated from early model tests. The base pressure observed was consistant with earlier outgassing measurements of a factor of 2 or 3 below the design value of 10^{-12} torr l/cm^{2}s for high temperature degassed stainless steel; so that a base pressure near 1 x 10^{-10} torr should be possible without additional pumping.

Twenty Main Ring style triode pumps are in the ring to provide some inert gas pumping and hold the pressure in the upper 10^{-9} torr range when the magnets are off.

Miscellaneous

A position detector design of the capactive cross-cut tube design has been made using five inch tubing supported by ceramic bars. Because of space limitations in the ring, these detectors are placed inside all the quadrupole magnets except the two in the injection short straight.

An injection kicker design of the strip line type has also been made using ceramic bars for support. The only materials in the vacuum are ceramic, stainless steel, and OFHC copper.

Each quadrant and long straight of the ring has an ion guage with an X-ray limit of less than 1 x 10^{-10} torr. If the peak pressure in the long straight is too high, additional lumped pumps will have to be installed.

Injection of protons from the linac is on the inside of the south short straight through a 2 mil stainless steel window.

Vacuum Results

Initial unbaked operation produced base quadrant pressures of 1 x 10^{-9} torr with 6-8 x 10^{-9} torr in the long straights. The first in-situ bake ended abruptly when six of the 277V heater tapes failed by a sustained arc that punctured the chamber walls; a problem never encountered with 110V heater tapes. New 110V tapes will be used in the future. A partial bake of only dipole and quadrupole chambers, as expected, moved the gas around producing quadrant reading of 2-4 x 10^{-10} torr at the expense of increased pressure in the long straights. A complete bake of the entire ring is expected to give the desired 1 x 10^{-10} torr pressure.

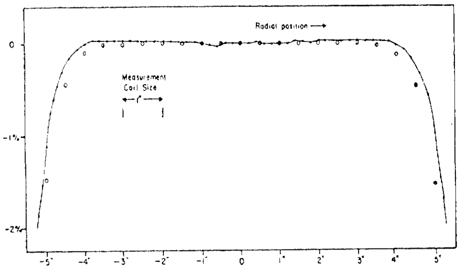

Fig. 1. Variation of $\int B\, dl$ in Dipole

• • • • Measured Field in Magnet Center(Magnet 1002)
o o o Measured Integral (Magnet 1005)

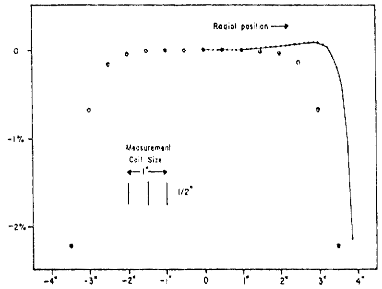

Fig. 2. Variation of $\int B' dl$ in Quadrupole

• • • • Computed for center of Quadrupole
o o o Measured Integral (Magnet 1037)

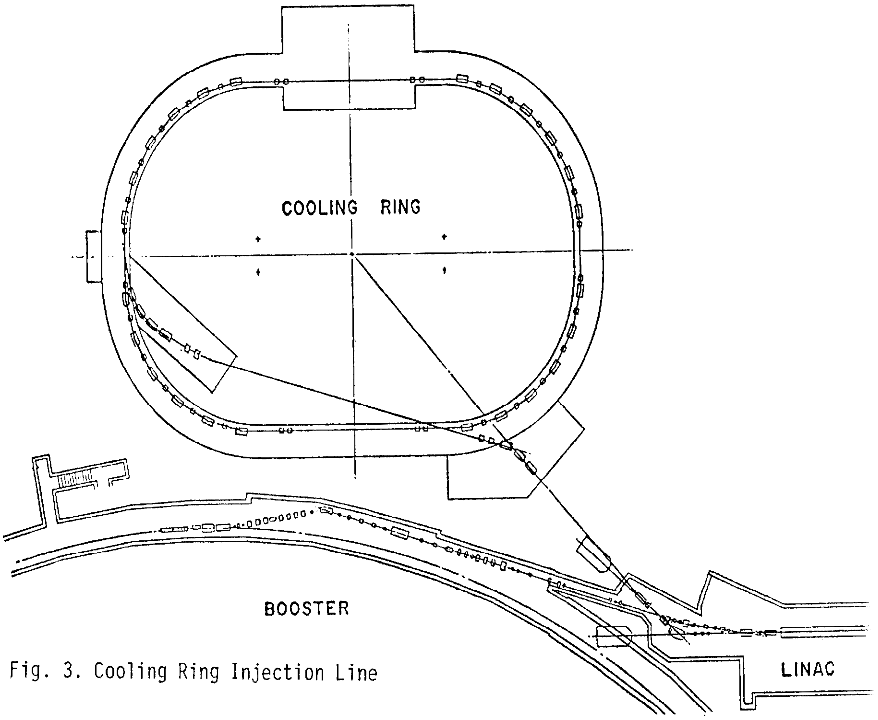

Fig. 3. Cooling Ring Injection Line