DESIGN AND SIMULATION OF THE ANTIPROTON RECYCLER LATTICE

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Abstract

The Recycler is a new antiproton storage ring designed to improve antiproton production and allow recovery of antiprotons at the end of stores in the Fermilab Tevatron. The ring will be situated in the Main Injector enclosure, with a circumference of 3319 meters, and will operate at 8 GeV. The design of the Recycler utilizes permanent magnets. Lattice design considerations and performance modeling will be described.

1 LATTICE DESCRIPTION

The Recycler ring [1] is composed of fifty four arc FODO cells (17.288 meter cell length) with eight zero dispersion straight sections distributed around the ring following the symmetry of the new Fermilab Main Injector(MI). [2] There are three lengths of straight sections; four 3 half-cell, two 4 half-cell, one 8 half-cell, and one high beta, for future addition of electron cooling. Each straight section is bounded on either side by a dispersion suppressor insert made up of four 12.966 meter half-cells. The phase advance of the arc and straight section cells is μ_x=85.4 and μ_y=79.2 degrees giving rise to a base tune of Q_x=24.425 and Q_y=24.415. Each focusing/defocusing location contains either two gradient magnets (F or D) or two quadrupoles. The lattice functions for the complete ring are shown in Figure 1.

The Recycler ring will be installed at an elevation of 56 inches above the centerline of the MI. The geometry of the Recycler closely resembles that of the new MI with the exception that the cell lengths of the dispersion suppressor cells on either side of the RR60 straight section were increased by two meters in order to move the closed orbit about .5 meter to the outside thus bypassing the Main Injector RF cavity power amplifiers. In order to keep the path length between the machines matched the cell lengths of this straight section were shortened. This straight section (RR60) additionally contains a phase trombone [3] that will be used for tune adjustments of up to $\pm$0.5 units.

The Recycler ring is composed of two types of permanent magnet combined function magnets, 216 long “arc” magnets which have dipole, quadrupole, and sextupole components, and 128 short “dispersion suppressor” magnets which only have dipole and quadrupole components, and 74 permanent magnet quadrupoles. The Recycler ring is designed to match the momentum of the new permanent magnet 8 Gev injection line.

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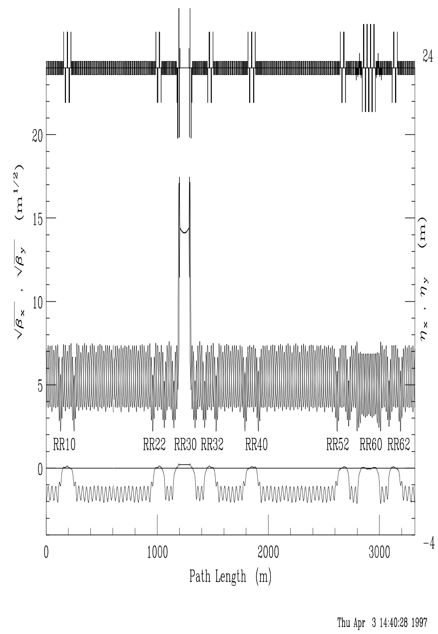

Figure 1: Lattice Functions of the full ring.

2 PERFORMANCE PROJECTIONS

The Recycler ring is unique in that it is the first storage ring to be built using permanent magnet technology for all bending and focussing elements. The exclusive use of permanent magnets dramatically reduces the cost of the magnets by avoiding the expense of coil winding and removes the necessity of power supplies and magnet cooling systems. It does however, require careful attention to the lattice and magnet design. Lattice issues related to the base operating tune, tune adjustment, closed orbit distortions[4, 5], optical function distortions [6], momentum aperture, and resonance widths[7], as well as magnet issues related to strength variations, transverse field uniformity, longitudinal field uniformity, and temperature stability[8] have been addressed through semi-analytical analysis and tracking studies to validate the base design [1]and to specify the exact properties of the magnets. We present here the results of the tracking studies used in determining the required magnet field specifications.

2.1 Tracking Calculations

Tracking studies were performed using the thin element tracking code TEAPOT [9] Although beam is expected to be stored for hours, with cooling times of tens of minutes, tracking studies were done for 10^5 and 10^6 turns representing 1 to 10 seconds beam time. We require the survivability of particles with oscillation amplitudes corresponding to at least 70π mm-mr (normalized) over the full $\pm 0.3\%$ momentum aperture of the Recycler. This oscillation amplitude corresponds to the vertical physical aperture and provides a 75% margin relative to the specified 40π mm-mr dynamic aperture.

Performance in the presence of a mixture of alignment and magnetic field errors is tested by launching an array of particles at different amplitudes. Particles are tracked with betatron oscillation amplitudes relative to a corrected orbit. Following the introduction of the errors the tune is adjusted to the nominal tune for zero momentum offset using the phase trombone. The particles are launched with equal horizontal and vertical emittance, which corresponds to a horizontal displacement 'A' and a vertical displacement $\sqrt{\beta_y/\beta_x}$A. Particles are tracked with a constant momentum offset. Net chromaticities in both planes are set to -2. Simulations are performed for five different seeds with a maximum of 100,000 turns tracked.

A survival plot of the five seeds displaying how many turns a particle survived as a function of the initial launch amplitude is shown in Figure 2. The dynamic aperture of the machine is defined as the smallest amplitude particle that *did not* survive the full 100,000 turns. From figure 2 we see that the dynamic aperture of the Recycler is predicted to be 21.7±1.5 mm corresponding to a normalized emittance of 68.4±9.7 π mm-mr.

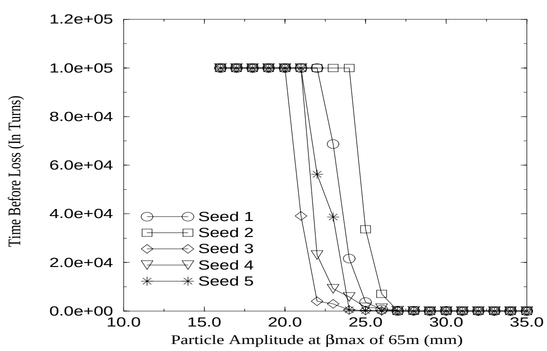

Figure 2: Dynamic Aperture of the Recycler. The number of turns survived is shown as a function of launch amplitude for five different collections of systematic and random alignment and magnetic field errors and a momentum offset of 0.3%.

The dynamic aperture as a function of momentum offset for the the largest amplitude particles that survived 100,000 turns is shown in Figure 3. This plot indicates an aperture in excess of 50 π mm-mr is maintained over the full momentum spread expected in the antiproton stack.

The detuning effect of the higher order multipoles is seen by looking at the change in fractional tune as a function of particle oscillation amplitude. Figure 4 shows amplitude dependent tune shift in the presence of only the sextupole in the long combined function magnets and in the presence

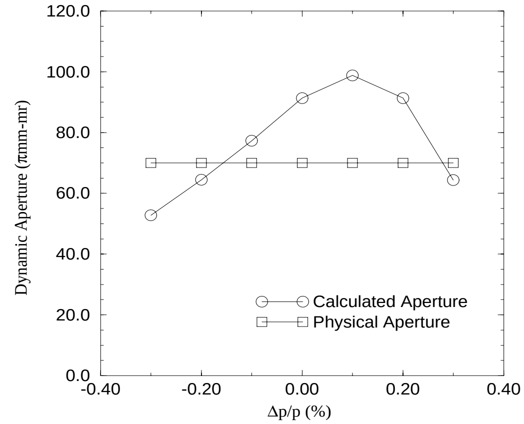

Figure 3: Dynamic Aperture as a function of momentum offset over the full range of the antiproton stack.

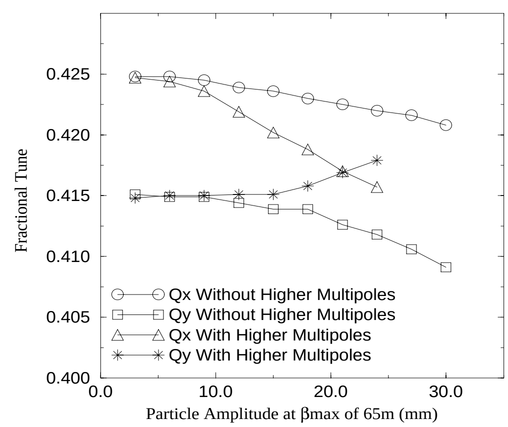

Figure 4: Fractional Tune as a function of particle amplitude for a lattice with and without higher multipoles.

of all multipole errors listed in Table 2.

2.2 Correction Schemes

Since the Recycler will not have active orbit correctors other than those required around the injection and extraction areas, the correction strategy will be based upon measuring the orbit and adjusting the transverse positions of the 15 most effective gradient magnets. Random alignment errors with a sigma of 0.25 mm in each plane and a roll with a sigma of 0.50 mr were assigned to all gradient magnets, quadrupoles, and beam position monitors. In addition, a field error,σ_{BL}/BL, of 5E-4 for all gradient magnets was included. With these errors the uncorrected orbit is expected to show peaks of up to 15 mm. A model in which 15 gradient magnets were chosen to be moved was analyzed and shown to produce a corrected orbit with a rms of less than 1 mm and peak distortion under 3 mm. Th maximum transverse motion of any gradient magnet was on the order of 2 mm, well within the tolerable mechanical motion allowed.

Global tune adjustment is accomplished by adjusting the local phase advance through the phase trombone located at RR60. The phase trombone utilizes five families, each with two adjustable quadrupoles, to adjust the local phase over a range of ± 0.5 with no perturbation to the optical functions outside the trombone region.

The natural chromaticity of the ring is compensated to -2 in both planes by the addition of a sextupole component in the long "arc" gradient magnets. Additional control of the chromaticity, with ± 5 units of adjustment, will be provided by two families of sextupoles.

Compensation of coupling due to systematic and random skew quadrupole errors and alignment errors (roll) will be controlled via two skew quadrupole circuits. Although, the location of the circuits provides acceptable global decoupling, all tracking simulations performed to date have have utilized a coupled lattice.

2.3 Magnetic Field Quality Specifications

The specification on the tolerances for the strength of the dipole, quadrupole, and sextupole components of the combined function magnets are derived from studies related to: the sensitivity of the lattice to systematic and random strength variations of both the long and short gradient magnets and their effect on the closed orbit,[4] the sensitivity of the lattice on the systematic and random strength variations of the gradient in the gradient magnets and their effect on the optical function distortion, [6]and the required sextupole strength for the compensation of the natural chromaticity. These strength tolerances are summarized in Table 1.

Table 1: Magnet strength tolerances for Recycler combined function (CF) magnets.

Performance Measure	Tolerance (Sys.)	Tolerance (Random)
Abs. bending strength of long CF magnet	5E-4	5E-4
Ratio of short/long bend strength in CF magnets	5E-4	5E-4
Ratio of quad. to nominal dipole in CF magnets	2E-4/in.	1E-4/in.
Ratio of sext. to nominal dipole in CF magnets	1E-4/in.^{2}	1E-4/in.^{2}
Field flatness over ± 25 mm	± 1.5E-4	± 1.5E-4

Based upon the tracking studies and dynamic aperture analysis, the magnet field quality specifications are given for both the systematic and random strength variations in the dipole, quadrupole, and sextupole components and well as the harmonic content and field uniformity of the combined function magnets and quadrupoles. These are summarized in Table 2.

Table 2: Modeled Multipole Components in the Combined Function Magnets, in Fermilab units.

Multipole Component	Normal (Sys.)	Normal (Ran.)	Skew (Sys.)	Skew (Ran.)
Quadrupole	1	1	.5	1
Sextupole	0.5	1	–	0.5
Octupole	0.5	0.5	–	0.5
10-pole	0.2	0.5	–	0.5
12 to 18-pole	0.1	0.5	–	0.5

3 SUMMARY

The design of the Recycler ring has been established. Semi-analytical and tracking studies were used to specify the required field uniformity necessary for beam storage. Four prototype gradient magnets with dipole, quadrupole, and sextupole have been built and measured which meet the specifications for field strength and field uniformity.[10] The detailed design and specification of harmonic correction systems, and specialty magnets to be used for injection/extraction systems continues.

4 REFERENCES

[1] "The Fermilab Recycler Ring Technical Design Report", Fermilab TM-1991, November 1996.

[2] The Fermilab Main Injector Technical Design Handbook, August 1994.

[3] Al Garren and Dave Robin, "A Phase Trombone for the Recycler", internal MI note MI-0181, July, 1995.

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[8] J.-F. Ostiguy, "Permanent Magnet Stability:Addendum", internal MI note MI-0177, July, 1996.

[9] l. Schachinger and R. Talman, Particle Accelerators 22, 1987.

[10] W. G. Foster, "The Fermilab Permanent Magnet Antiproton Recycler Ring", session 3C.01, these proceedings.