OPERATIONAL EXPERIENCE WITH THE PERMANENT MAGNET RECYCLER RING AT FERMILAB

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Abstract

The Recycler [2] is a 3.3 km storage ring composed solely of permanent gradient magnets and quadrupoles. Commissioning of this accelerator was started in May 1999. In the last year a number of defects have been discovered and corrected, and a large number of beam studies have been performed, such as the exclusive use of barrier RF buckets to control the longitudinal phase space distribution. In this paper these experiences are presented.

1 RECYCLER OVERVIEW

The Recycler ring has three missions [3] in the Fermilab accelerator complex. First and foremost, it allows antiprotons left over at the end of Tevatron Collider [4] stores (typically 80% of the number injected into the Tevatron) to be re-cooled and re-used, hence the name of the ring. Second, since the antiproton production rate decreases as the beam current in the Accumulator [5] ring rises above a certain level, the Recycler acts as a post-Accumulator cooler ring, allowing the Accumulator to operate optimally. Third, permanent magnets were chosen in the construction of the Recycler in order to dramatically reduce the probability of unexpected losses of the antiprotons. In fact, the ring has been designed so that Fermilab-wide power could be lost for an hour with the antiprotons surviving.

Because of the need to build the Recycler at very low cost (approximately 15 M$ using normal U.S. accounting procedures) and because of the unique mission it serves, there are a number of other novel sub-systems in the ring. First, tune control is accomplished using a phase trombone [6]. Second, the vacuum system relies very heavily on titanium sublimation pumps, with a relatively sparse usage of sputter-ion pumps. Third, the RF system is a broad-band barrier-bucket system generating a maximum voltage of 2 kV into any waveform in the bandwidth from 90 kHz to 100 MHz.

2 COMMISSIONING PROGRESS

To date only protons have been injected into the Recycler ring (flowing in the opposite direction as the antiprotons will someday circulate).

2.1 Lattice

The lattice of the Recycler has three components: Normal arc cells generated by full-length permanent gradient magnets, straight section cells generated by 0.5 m long permanent magnet quadrupoles, and dispersion suppression cells on either side of the straight sections generated by shorter gradient magnets. The Lambertsons for injection and extraction are also permanent magnet [7]. All of the magnets were measured and tuned [8] to meet a very strict field quality specification consistent with storage ring requirements.

As described in section 3, there were two problems with the construction of the machine that caused severe distortions in both the linear lattice and higher-order field multipoles. With these problems corrected, the tunes with the phase trombone off are within 0.1 out of 26. The chromaticities are within a one or two units of design, out of a natural chromaticity of roughly 30.

There are approximately 70 closed orbit correction magnets in the ring, allowing orbit studies during commissioning. For systematic correction of closed orbit, the intent is to move permanent magnets during periodic accesses into the tunnel. At present, given the fact that the beam position monitor system is just now becoming useable, not much work has been done on the closed orbit. Typically the horizontal and vertical deviations from the closed orbit are 10 mm peak. The biggest issue at present is the closed orbit motion caused by the Main Injector [9] ramping in the same tunnel as the Recycler. One encouraging sign is that most correctors are set to zero to circulate beam. Another positive feature of the Recycler is that optimum corrector setting do not drift with time, even after months.

2.2 Barrier Bucket RF System

One of the most exciting aspects of Recycler commissioning in the last year has been working with the barrier bucket RF system. The low level portion of the system is composed of 7 arbitrary waveform generators which play out 256 points every turn at a frequency of 52.8114 MHz. Each arbitrary waveform generator has an independent table, phase, and amplitude, all of which can be changed in real time to perform operations such as synchronous transfers, stacking, and unstacking.

The protons generated by the Booster can be adiabatically reduced in momentum spread in the Main Injector before transfer into the Recycler. With the Recycler RF system loaded to play a barrier bucket generated by a pair of 2 kV square voltage pulses (where the separation of the pulses is optimized to preserve phase space area), the transfer of protons from the Main Injector takes place without feedback to damp longitudinal oscillations. By adjusting the bend field in the Main Injector to within 1 MeV/c out of 8.9 GeV/c, and the barrier bucket phase to approximately 5 nsec, there are no substantial coherent oscillations in the beam distribution.

During the design of both the low level RF system and the solid-state high level system, noise induced emittance growth has been a concern. To date no emittance growth has been measured which is attributable to these sub-systems. The longitudinal emittance of the beam in a barrier bucket is determined by measuring shape of the current distribution of the beam under the barrier pulses. Assuming a Gaussian momentum distribution, the expected shape of the current distribution under the square barrier pulses is exponential, with the time constant of the exponential proportional to the square of the rms momentum spread.

2.3 Vacuum and Beam Lifetime

There are 104 putter-ion pumps distributed uniformly around the ring at an approximate interval of 34 m, over 600 titanium sublimation pumps, and 26 ion gauges in the Recycler. During initial commissioning of the Recycler the titanium sublimation pumps were not fired, and the average vacuum was roughly 1E-7 Torr. Because the sputter-ion pumps are directly connected to the sublimation pump housing, leakage of titanium into some sputter-ion pumps has caused a leakage current which makes a pressure reading using the HV current unreliable. Therefore the ion gauges are used as the reference pressure monitors, and now with all sublimation pumps fired have an average reading of 3E-10 Torr, with a maximum reading of 1E-9 Torr in a single location and a minimum reading of 5E-11 Torr. At these pressures the beam lifetime due to nuclear scattering is negligible. On the other hand, because the invariant 95% admittance of the Recycler at present is 5 πmmmr (where the design aperture was 40 πmmmr), the beam lifetime due to elastic scattering is still lower than the design value of 50 hours.

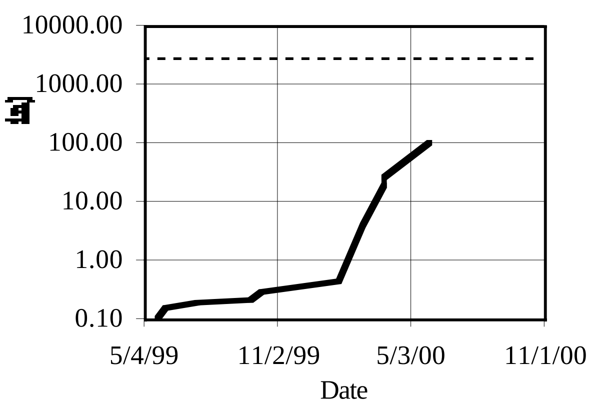

Figure 1: Evolution of beam lifetime in the Recycler over the last year. The dashed line is the commissioning goal of 50 hours beam lifetime.

As seen in fig. 1, the lifetime has been steadily improving in the Recycler. The enhanced improvement rate in January 2000 was caused by the final correction of the field quality in the magnets (see section 3). The beam position monitor system is only now becoming reliable and useful, so the improvement rate should increase soon.

2.4 Stochastic Cooling

Ultimately the design of the Recycler calls for 4 stochastic cooling systems. The momentum cooling is generated by a 1-2 GHz band supplemented by a 0.5-1 GHz band. The horizontal and vertical betatron cooling are each generated by a 2-4 GHz band. It is anticipated that the bulk of the cooling is required to overcome longitudinal emittance growth caused by intrabeam scattering. The most stringent requirement for betatron cooling is the reduction of the transverse emittance of the antiprotons which have been recycled from the end of Tevatron stores.

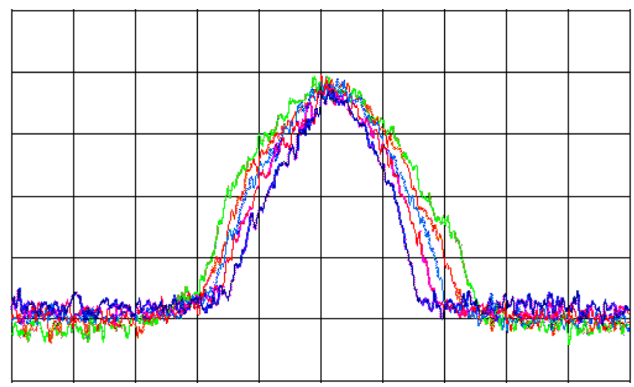

Figure 2: Measurement of longitudinal beam cooling. The center frequency was 1.1406496 GHz (harmonic 12700), frequency was 50 kHz, vertical scale was 5 dB/div, sweep time was 15 sec, video bandwidth was 10 Hz, resolution bandwidth was 1 kHz.

In the lattice of the Recycler there are two locations at which conduits enter the tunnel from underground electronic enclosures which are 10 m away for reasons of radiation safety. These enclosures have unlimited occupancy, and contain all of the electronics required for all of the stochastic cooling systems. They also serve as the end points of an optically straight, buried, evacuated, 2 ft. diameter steel pipe which is approximately 1800 ft. long. Four amplitude-modulated laser beams transmit the signals from the pickups across a chord to the kicker tanks. The 100-500 mTorr vacuum is needed to prevent flicker of the laser spot due to convection currents, and feedback is used to point the laser beam onto the recieving photodiode.

At present a single pickup tank and a single kicker tank generate either vertical or longitudinal cooling of the proton beam. A single laser beam is propagated in the opposite direction (also the pickup and kicker tanks are reversed) in order to generate proton cooling. In fig.2 each trace is a measure of the momentum distribution of the beam with approximately 5 watts of power in the band of 1-2 GHz, where each trace is separated by several minutes. Cooling is clearly apparent, though the peak density does not increase because the short beam lifetime is reducing the beam current simultaneously. The vertical emittance of the beam has also been measured to shrink with the vertical cooling turned on.

3 PROBLEMS AND SOLUTIONS

Since the first days of Recycler commissioning a year ago, there have been two persistent problems. The first was a proton injection efficiency of approximately 50%. The second was a beam lifetime well below the design goal of 50 hours. Related to these difficulties was the observation of horizontal and vertical tune errors in excess of 0.2 and chromaticities of approximately -30 and 10 units (instead of the design value of -2 units generated by the addition of a small amount of sextupole harmonic to all of the full length gradient magnets).

The largest culprit was found to be the heater strips attached to the beam tubes used to raise the temperature to 150 degC to improve the vacuum. Composed of stainless steel strips, which are manufactured by rolling the material around rollers and pulleys, the strips had enough permeability to devastate the magnet field quality. Since the strips were placed on the horizontal ends of the elliptical beam tubes, this permeability drew down the field strength on the horizontal edges of the pipe, introducting a very large sextupole harmonic. This problem was solved by removing all of the heater strips (and thermal insulation) from the beam tubes in the gradient magnets and quadrupoles.

The second significant problem which was discovered and corrected was the shape of the end shims used to tune the field quality of the gradient magnets [8]. Magnetic measurements on the 4 m long gradient magnets were performed with a straight rotating coil. But the beam moves on a curved trajectory with a ~10mm sagitta. The radial placement of the magnets in the tunnel was offset such that the beam saw the correct average bend field, in order to match to the design momentum. This means that the beam is to the radial inside at the magnet ends. It turns out that there was a significant systematic field error in the machined magnet poles which was corrected with these end shims. This field error was mostly in the sextupole moment. Because the beam was also systematically entering and exiting the magnets to the radial inside, this generated a systematic phase advance error, a significant betawave, and a tune error. By replacing all 200 end shims in the tunnel with a new version correcting this oversight, the tunes were corrected.

4 OUTSTANDING ISSUES

It is believed that the only outstanding issue in the Recycler limiting it's performance during Tevatron Collider operations is the restricted transverse admittance caused by aperture restrictions. These restrictions are probably the result of two factors: First, the beam position monitor system was not operational until the writing of this paper. Second, since the packing fraction of the magnets is approximately 50%, there is a large amount beam tube that is not locked into dipole magnets. This floating beam tube was never properly aligned due to the need to immediately commission the Main Injector to meet government performance milestones.

At present the beam tube is being surveyed and aligned during periodic tunnel accesses. In addition, work on the beam position monitor system is continuing.

5 ACKNOWLEDGEMENTS

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