COMMISSIONING OF THE LOS ALAMOS PSR INJECTION UPGRADE*

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Abstract

An upgrade has been completed and commissioned to the Los Alamos Proton Storage Ring (PSR) to allow direct injection of the H^- beam into the ring and to move the circulating beam off the stripper foil using an orbit bump system. The design benefits of the upgrade are matching the transverse phase space of the injected beam to the PSR acceptance and a factor-of-ten reduction of the foil hits by the circulating beam. Foil thickness is optimized to minimize the sum of circulating-beam losses and losses caused by excited H^0 states produced at injection. Design simulations predicted an overall reduction in losses by a factor of five. We discuss results of the commissioning and PSR performance in comparison to design projections and the goals of the upgrade project.

1 BEAM LOSSES IN PSR

Beam losses in PSR and the resulting radioactivation of ring components are the dominant factors limiting average beam current, a cause of equipment failure, and a major element in repair times. Prior to the upgrade, beam losses of 0.6-0.7% limited the average beam intensity in PSR to 70 μA. The primary upgrade goal was to increase the beam intensity to 100 μA while decreasing the fraction of beam lost by a factor of five. The beam loss reduction, in turn, supports the operational goals of >85% beam availability and operation for eight months per year.

There are two main causes of beam losses in PSR. First, nuclear and large-angle Coulomb scattering of the circulating beam in the injection stripping foil [1,2] led to beam losses of 0.3-0.5% prior to the upgrade. Second, a fraction of the injected beam interacts in the stripper foil and is converted to excited states of H^0. The excited H^0s are field stripped and fall outside the ring acceptance. [3] Before the upgrade, these "first-turn" losses were 0.2-0.3% of the injected beam.

2 DIRECT H^- INJECTION

Before the upgrade, beam was injected into PSR in a two-step, charge exchange process: H^- was stripped to H^0 in a strong dipole magnet and drifted into the ring through a channel in a dipole to a stripper foil where it was converted to H^+. Losses from foil scattering were large because the average proton traversed the foil 30-35% of the time, as determined from tracking simulations. In the horizontal plane, the stripper magnet introduced a three-fold emittance growth and the injected beam was significantly mismatched. The phase space for injected and circulating beams at the stripper foil are shown in Figure 1. The neutral beam could not be manipulated to improve the match, so the beam filled the horizontal acceptance of the ring, leaving no room for a horizontal offset to reduce the number of foil traversals. In the vertical plane, the smaller emittance allowed some offset.

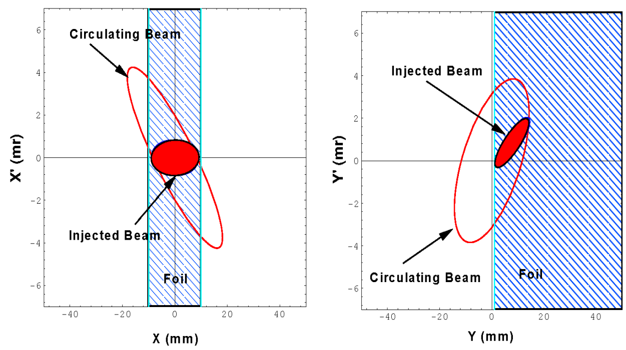

Figure 1. Injection phase space at the stripper foil for two-step H^0 injection prior to the upgrade.

In the upgrade, direct H^- injection was implemented to eliminate the horizontal emittance growth and allow optimization of the injected beam ellipses to minimize foil traversals. As can be seen in Figure 2, this substantially reduces the overlap of the circulating beam with the foil.

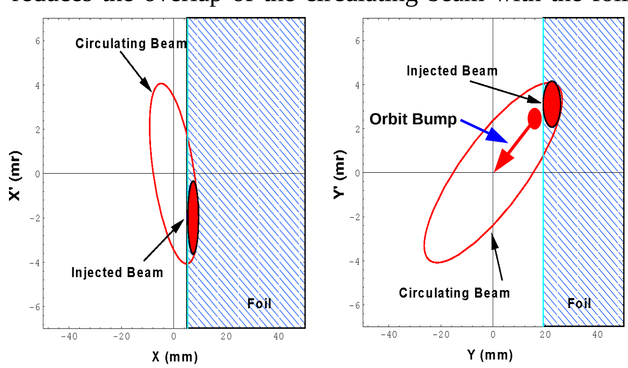

Figure 2. Injection phase space at the stripper foil for direct H^- injection.

To further reduce scattering losses, a vertical orbit bump was implemented to move the circulating beam off the foil during the injection cycle. These measures made possible a ten-fold reduction in the number of foil traversals. Part of this gain was traded off by increasing the foil thickness to reduce production of H^0 excited states. An optimization study using tracking simulations showed that total losses could be minimized by increasing the foil thickness from 220 to 400 $\mu g/cm^2$; the simulations predicted a reduction in total losses by a factor of five.

Table 1: Comparison of parameters for PSR before and after the upgrade

Parameter	**Before Upgrade**	**After upgrade**	
	Simulation [4]	**Simulation [4]**	**Actual**
Current (μA), protons per pulse @ 20 Hz	70, 2.2×10^{13}	100, 3.1×10^{13}	100, 3.1×10^{13}
Beam energy (MeV)	797	799	—
PSR accumulation time (μs)	625	825	825
Injected beam time spread (ns)	250	250	250
Input beam phase space: Transverse (π mm-mrad rms) Longitudinal (Δp/p rms)	1.8×1.0 0.063%	0.8 0.063%	0.65 ± 0.15 —
Injected beam offset (mm, mrad) $(x_0, x_0') =$ $(y_0, y_0') =$	0, 0 8.0, 0.9	7.21, -1.96 22.5, 3.10	5.4, -1.3 16.9, 2.8
Closed orbit bump (mm, mrad) from $(y_0, y_0') =$ to $(y_0, y_0') =$	none	16.0, 2.2 0.0, 0.0	12.0, 1.7 0.0, 0.0
Stored beam 95% emit. (π mm-mrad) $\varepsilon_x =$ $\varepsilon_y =$ $\Delta p/p =$	27 39 ±0.32%	44 57 ±0.34%	42 ± 12 76 ± 15 ±(0.27 ±0.12)%
Tune (ν_x, ν_y)	3.172, 2.142	3.172, 2.142	3.19, 2.18
RF volts per turn, linear ramp	4-8 kV	6-10.5 kV	5.25-10.5
Harmonic number, frequency (MHz), [time] (ns)	1, 2.795, [358]	1, 2.795, [358]	1, 2.795, [358]
Foil thickness (μg/cm^2)	220	400	450
Fraction of beam missing foil	7.4%	2.6%	total = 2-3%
H^- stripped to H^0	1.3%	0.6%	
Foil hits per proton	307	35	—
Total beam losses	**0.57%**	**0.12%**	**0.25-0.30%**
Stored beam loss:	0.26%	0.05%	0.11-0.17%
Excited H^0 loss:	0.26%	0.05%	0.11-0.17%
Extraction loss:	0.05%	0.01%	<0.01%

3 DESIGN AND IMPLEMENTATION

The upgrade design is described in detail elsewhere [5] so only a brief description is presented here. A comparison of parameters for the old and new injection schemes is presented in Table 1.

A skew section, rolled by approximately 27°, transports the beam from the H^- transfer line to PSR level, an elevation change of 3.35 m. Skew quadrupoles at the entrance and exit eliminate the X-Y coupling term from the transfer matrix. This coupling in the old skew section caused ~30% emittance growth. The new skew section is achromatic to prevent dispersion-related emittance growth and beam centroid motion caused by energy shifts.

Four quadrupoles downstream of the skew section are used to match the desired Courant-Snyder parameters at the injection stripper foil. Three dipoles then form a chicane to guide the beam around a ring main dipole and into a merging dipole in PSR. Quadrupoles in the chicane produce an achromat at injection. Four ferrite-based magnets in the ring produce a closed-orbit bump at the stripper foil that collapses to zero by the end of injection.

A small fraction of the beam emerges from the stripper foil as H^- and H^0. These two waste beams have large offsets at the stripper foil and are diverging; the envelope of the two beams is 350×200 π mm-mr. Therefore, the ring dipole downstream of the stripper foil was replaced by two C-magnets to provide an adequate aperture for the waste beams. A dual-plane (X-Y) bending magnet directs the waste beams to the dump, and a quadrupole doublet merges and focuses the beams at the dump.

4 COMMISSIONING

The goals of the commissioning for the upgrade were to (a) confirm the correct installation and performance of the installed hardware, (b) characterize and optimize the beam optics tunes, and (c) establish an initial beam optics tune at a beam intensity of 100 μA with low losses. The results for the commissioning, successfully accomplished in the fall of 1998, are described in the ensuing subsections.

4.1 Hardware Performance

The installed hardware comprised 38 dc magnets, 4 time-varying bump magnets, 36 beam diagnostics instruments, a foil stripper system, 70 support and alignment stands, vacuum and water cooling systems, a cable installation, and controls hardware and software. Following extensive pre-beam checks, all hardware systems performed within design requirements. The only exception was the carbon foils produced with the mCADAD method, [6] which initially failed after rather short exposures to modest beam intensities. This was surprising because the maximum foil temperature was estimated to be approximately the same

(1700-1800 °K) at 100 µA after the upgrade as at 70 µA before the upgrade. Following these observations, the foil facility and production technique were modified, and the excellent dimensional stability and long life observed in the past for these foils appears to have been regained.

4.2 Beam Optics

The initial objective was to confirm that the design optics tune was established. The achromat at the downstream end of the skew section (upstream end of the matching section) was verified with an uncertainty of <0.1 cm/% by varying the beam momentum and observing beam motion at all BPMs in the beam line from the linear accelerator to the PSR stripper foil. The absence of X-Y coupling in the skew section was verified at approximately the 5% level by varying the upstream horizontal steering and observing beam motion in the horizontal and vertical planes downstream of the skew section.

We reconstruct rms beam ellipse parameters at injection from beam profiles measured at four locations upstream and downstream of the stripper foil. Uncertainties are typically ±10-15% for the emittance area and ±15-20% for α and β. Achieving a match to the desired beam ellipses at injection proved difficult using the design tune. The desire to separate control of transverse beam parameters and dispersion, coupled with the requirements for an achromatic beam and a small spot size (1.0 × 1.6 mm rms) at the foil, led to large beam spot sizes in the matching section (up to 18 mm rms). The magnifications inherent in this tune led to large uncertainties in projecting the ellipse parameters back to the entrance of the matching section, so the matching process did not converge. To remedy these problems, a compromise tune was adopted that reduced the maximum beam spot size in the matching section to 7 mm. As a consequence, 0.5 cm/% dispersion was introduced at injection, not an important consideration because this dispersion is an order of magnitude smaller than that of the circulating beam. More significantly, the match at injection was compromised, particularly in the vertical plane. Shown in Fig. 3 are the injected and circulating beam ellipses at the stripper foil for the design (Fig. 3a) and achieved (Fig. 3b) injection parameters. For the injected beam, the value achieved for β_y was 2.0 m *vs.* the design value of 3.2 m. With this injected beam, only 75% of the design beam offset at injection could be achieved; as the offset was increased, the emittance area of the circulating beam exceeded design, and losses from beam scraping were observed. Similarly, in the horizontal plane, the value achieved for β_x was 1.8 m *vs.* the design value of 1.3 m, and the maximum offset without scraping was also about 75% of the design value.

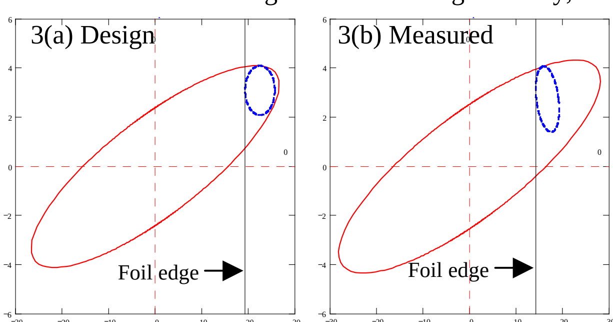

Figure 3. Design (a) and measured (b) beam ellipses at the stripper foil in the vertical plane for the (2σ) injected beam (dashed ellipse) and circulating beam (solid ellipse).

4.3 Optimization of Beam Losses at 100 µA

To reduce beam losses at high intensities, we conducted a multi-parameter search about design values for beam ellipses and offset at injection, stripper foil thickness, fraction of injected beam missing the foil, bump magnet amplitudes, PSR fractional tune, and the voltage, phase and ramp of the PSR buncher during injection. As can be seen in Table 1, the adopted operating parameters are all essentially equal to the design (simulation) values, with the exception of the injected beam ellipses and offsets.

During post-commissioning operations, early problems with stripper foils caused losses to be relatively high, and problems with cooling the moderator for the spallation neutron production target limited the beam current at times. However, during January operations, these initial problems were resolved, and 100 µA was delivered to the target with average losses of 0.25%, a reduction by a factor of 2.5-3.0 from pre-upgrade values for operation at 70 µA. This is approximately twice the value predicted for losses by tracking simulations. [4] However, the simulations do not include a complete treatment of space charge effects, and, therefore, somewhat underestimate the losses. Nevertheless, improving the match at injection may further reduce losses. As can be seen in Fig. 3, the overlap of the circulating beam with the stripper foil for the injection parameters achieved in the vertical plane is about twice that for the design case. Improving the match will require a higher-current power supply for the final quadrupole in the injection line; we anticipate this can be accomplished in a relatively short time.

5 REFERENCES

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