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MASTER

STATUS REPORT ON THE LOS ALAMOS PROTON STORAGE RING

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ABSTRACT

The proton storage ring currently operates at an average current of $30\ \mu\text{A}$ corresponding to 1.25×10^{13} protons per pulse (ppp) at a repetition rate of 15 Hz. The design operating current for the machine is $100\ \mu\text{A}$. We are limited to running at the reduced yield because of beam losses during the accumulation period. These losses are understood and arise mainly from emittance growths during the injection and multiple scattering in the stripping foil during the storage. During beam studies we have succeeded in accumulating in excess of 3.7×10^{13} ppp. We have also observed a coherent transverse instability at high charge levels. The signature for the instability is rapid coherent growth of the transverse beam size followed by a loss of beam in the machine. The threshold for the instability depends most strongly upon rf voltage and beam size.

INTRODUCTION

Construction of the Proton Storage Ring (PSR) was completed in Spring, 1985. The ring provides up to a factor of 4000 time compression for production of thermal neutrons. These neutrons are useful for condensed matter physics, chemical physics, materials science, crystallography, and structural biology. The proton beam also serves to create a copious neutrino flux. A thorough review of the PSR operation through the beginning of 1987 has been presented previously.¹ In addition, we have prepared a paper on the transverse instability seen in PSR.² During 1987 we performed further experiments and developed further insight into the mechanisms responsible for beam loss during accumulation. These losses currently limit operation to an average current of $30\ \mu\text{A}$. In this work we briefly review the principles of operation, then discuss some of the measurements. Next we discuss the mechanisms responsible for the accumulation (slow) losses. Following this, we present empirical results for the coherent instability. Finally we discuss plans for a proposed upgrade which should reduce the accumulation losses to a tolerable level, which we have defined as 100 nA; with this implemented we should be able to raise the delivered current to $100\ \mu\text{A}$.

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PRINCIPLES OF OPERATION

Figure 1 shows a plan view of the PSR complete with the local injection and extraction beam transport systems. Table I lists the relevant parameters of the machine. With the exception of the chromaticities listed, all of the given values are design parameters. In fact, the design chromaticities were -0.8 and -1.3, respectively, in disagreement with the measured values.

Table I. PSR Parameters

Proton Kinetic Energy	797 MeV
Circumference	90.2 m
Focusing Structure	FODO, 10 cell
Betatron Tunes Q_x, Q_y	3.23, 2.22
Acceptance A_x, A_y	124, 167 mm-mrad
Transition Gamma	3.1
Average Beam Pipe Radius	0.05 m
Measured Chromaticities ξ_x, ξ_y	-1.3, -1.0
Buncher Harmonic, Frequency	1, 2.795 MHz
Peak RF Voltage	15 kV
Maximum Synchrotron Tune Q_s	0.0006
Bunch Length	62 m
Stored Beam	5.2×10^{13}
Repetition Rate	12 Hz

Referring to Fig. 1, H^- are transported from the LAMPF Linac and arrive at the PSR through the injection beamline. The H^- are stripped to H^0 in the fringe field of the stripper magnet; the horizontal emittance is increased by a factor of three during this process. The H^0 then drift to a $200 \mu\text{g}/\text{cm}^2$ carbon foil where 90% of them are stripped to protons. The surviving H^0 continue downstream to the H^0 beam dump. These processes continue through the injection period, meanwhile the stored protons orbit repeatedly (up to 2800 turns for a 1 msec injection). The circulating current has reached 16.5 amperes while the 1 msec LAMPF macropulse has been compressed to 250 nsec (a reduction of 4000). At the end of injection the two injection kickers are synchronously fired and the intense proton bunch is directed into the extraction beamline. This line is merged into the line D and the protons sent to the experimental targets. The circulating beam in the PSR has a gap of about 28 m in order to facilitate lossless extraction.

MEASUREMENTS

The PSR uses a host of diagnostics to perform basic measurements necessary to maintain operation. The system is sufficiently automated so that we have online representations for proton flux, accumulation losses,

Fig. 1. Plan view of PSR.

longitudinal bunch shape, and closed-orbit locations. During machine studies we have measured the synchrotron tune vs. applied rf voltage, horizontal beta functions at several locations, dispersions, space-charge tune shifts, losses vs. quadrupole settings, leading to a betatron resonance map, betatron tunes vs. relative momentum spread, and many parameters related to the coherent instabilities. We empirically found a best fit to the data for the betatron tunes vs. dp/p over the range $|dp/p| < 0.005$. We found

$$Q_x(dp/p) = Q_x(0) - 1.25 Q_x(0) dp/p + 111 (dp/p)^2$$

and

$$Q_y(dp/p) = Q_y(0) - 0.96 Q_y(0) dp/p - 84 (dp/p)^2$$

It appears that there is a zeroth-harmonic contribution of both sextupole and octupolar fields. We have also observed integral harmonic contributions indirectly through the excitation of betatron resonances. Evidence was obtained for the sum resonances $Q_x + 2Q_y = 8$, $2Q_x + Q_y = 9$, and $2Q_x + 2Q_y = 11$. The strong integer $Q_x = 3$ and $Q_y = 2$ resonances are also observed. These resonances do not affect operation at our nominal tunes.

SLOW LOSSES

During production we inject beam for 375 microsec which is about 1050 turns. During this period we lose about 1.6%. These losses are quantified as being 0.2% first turn, 0.15% from nuclear and large angle coulomb scattering in the foil, 0.5% from action of the rf cavity, and 0.85% from emittance growth from foil scattering in the absence of rf. The losses take place at several horizontal aperture restrictions, namely the foil holder and extraction septa. The two stage injection into PSR involves a horizontal emittance growth at the stripper magnet as well as a horizontal plane mismatch of the beam to PSR in both dispersion and phase space at the injection stripper foil. The net result of all this is a first-turn loss, and a beam that is too wide and has non-Gaussian tails. The rf cavity just makes the beam wider, and narrower, as time proceeds due to synchrotron motion, i.e., it is just a dp/p effect. When the beam is widened losses occur at the horizontal restrictions. The rms emittance growth in the foil is simply given by the expression

$$\epsilon = \epsilon_0 + \beta_f \langle \theta^2 \rangle f N_t / 2$$

where ϵ_0 is the initial rms emittance, β_f is the beta function at the foil, $\langle \theta^2 \rangle$ is the mean squared scattering angle for a single foil traversal, f is the probability of a foil traversal on a turn, and N_t is the number of turns. The emittance grows linearly with time, with the result that $\langle x^2 \rangle$ the mean square value of the beam width increases linearly with time. We have, in fact, observed such a growth in beam width. Presently, the foil traversal probability is high, greater than 50% even when we steer the injected beam so as to reduce the foil traversal. We have observed that the losses increase quadratically with time - a doubling of the injection period results in 4 times the losses. Even with a time averaged current of 30 μA , we are seeing losses of about 0.5 μA which are 5 times the desired maximum.

COHERENT INSTABILITY

A sudden loss of beam current is observed when we exceed a certain current threshold with typically half of the beam vanishing in about 50 microsec. A rapid coherent transverse beam growth is observed just before the loss. Figure 2 are oscilloscope traces showing the time dependences of the beam current for injected fluxes below and above the threshold. These pictures were taken for a coasting beam, i.e. with the rf cavity off; the threshold varies from $0.4 - 1.1 \times 10^{13}$ protons depending upon the injected vertical beam size. The instability threshold can be pushed up by energizing the rf cavity - the higher the voltage, the higher the threshold. In fact, additional measures, such as inclusion of a second-harmonic component to the cavity voltage, and the use of sextupole and octupole magnets, allowed us to reach 3.7×10^{13} ppp; we are source limited at this value because we dispense with 30% of the beam

during injection in order to maintain the beam gap for the kicker rise time.

The instability threshold can be represented by the standard coasting beam formula³ which is expressed as an inequality

$$|Z_{\perp}| I_{\text{thresh}} > 4 m_0 c^2 \beta \gamma \frac{Q}{R} [(n-Q) \eta + \xi Q] \frac{\delta p}{p}$$

where $Z_{\perp}$ is the transverse coupling impedance, Q is the betatron tune, R is the machine radius, n is an integer $> Q$, $\eta = \gamma_t^{-2} - \gamma^{-2}$, and $\delta p/p$ is the relative momentum spread (fwhm) of the beam. The major impedance of the ring is the space charge impedance, given by

$$Z_{\perp} = \frac{i R Z_0}{\beta^2 \gamma^2} \left(\frac{1}{a^2} - \frac{1}{b^2} \right)$$

where Z_0 is the impedance of free space (approximately 377 ohms), and a and b are the beam radius and beam pipe radius, respectively. The magnitude of $Z_{\perp}$ is in the neighborhood of 5-10 Mohms/meter. Increasing a reduces $Z_{\perp}$ and tends to stabilize the beam. Increasing the rf voltage raises the relative momentum spread of the beam, thus also stabilizing the beam; an increase in betatron Q also helps too. The instability growth rate is quite large, of the order of $2 \times 10^4 \text{ sec}^{-1}$; it is directly proportional to the real part of the transverse coupling impedance which has to be of the order of 0.5-1.0 Mohm/meter for such a large growth rate. We have searched for potential contributors to $\text{Re}(Z_{\perp})$ with little success. We have eliminated the orbit bumper magnets, rf cavity, and the housing containing the stripper foil as active agents. Furthermore, it does not appear that there is a single resonator which is responsible for the short growth time.

A PROPOSED UPGRADE

We are currently planning a staged modification to the PSR. The first is a direct H^- injection system to replace the present two-stage injection system. The use of direct H^- injection has some distinct advantages over the present scheme. The obvious gains are: We can totally match the linac beam to the PSR at the injection point; the emittance growth during the injection will be reduced. The smaller injected emittances can be used to reduce the foil traversals in a number of ways which include linear coupling, collapsing orbit bumps, etc. There is more flexibility in filling of phase space so we can, e.g., balance between space charge effects and accumulation losses. Figure 3 shows a possible rework of section 0, the injection straight, so as to permit direct H^- injection. The lattice bends are each reduced by 3 degrees at the opposite ends of the straight section and a weak combining dipole with 6 degree bend merges the circulating protons and injected H^- at the

midpoint; a H⁻ to proton stripping foil follows thereafter. The detailed design is under study-so far it looks promising. Another important change will be an increased horizontal aperture in the machine - this requires a new extraction system. The increased aperture in the machine can be obtained by a redesign of the fast extraction area; we are planning to replace the stripline extraction kickers with a fast ferrite kicker supplying 18 mrad of kick. After this, the extraction septa can be moved so that the aperture of the machine will be 50 mm radius throughout.

CONCLUSIONS

For the immediate future, we hope to increase the average current via techniques involving reduction of the foil traversals as well as through optimization of the betatron tunes. We will continue to research the coherent instability. We hope to have completed the above improvements by FY 90. After this we look forward to reaching the design current of 100 μ A.

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