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BEAM DIAGNOSTICS AT HIGH-INTENSITY STORAGE RINGS

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ABSTRACT

Beam diagnostics at high-intensity facilities feature their own special set of problems and characteristics. Issues peculiar to high-intensity storage rings include beam loss, beam halos, extraction efficiency, beam in the gap, clearing electrodes, and beam-profile measurement. The Los Alamos Proton Storage Ring (PSR) is a nice example of a high-intensity storage ring. I will discuss in some detail three diagnostic systems currently in use at the PSR: the beam-loss-monitor system, the electron-clearing system, and the beam-in-the-gap monitor. Much of our discussion is inspired by the problems we have encountered and the useful things we have learned while commissioning and developing the PSR. Another inspiration is our work on the next-generation neutron-spallation source, also known as the National Center for Neutron Research (NCNR).

INTRODUCTION

Beam diagnostics at high-intensity facilities present their own special set of problems and concerns. Some of the issues peculiar to high-intensity storage rings are beam loss, beam halos, extraction efficiency, beam in the gap, clearing electrodes, and beam-profile measurement. Perhaps the most important of these is beam loss. It may be perfectly acceptable to lose a percent or more of the beam in some machines, especially in the transport lines and during the injection and extraction processes. However, in high-intensity machines, losing just one percent of the beam can cause unacceptable damage to beam-line components through thermal heating and radiation damage. Beam loss can also make hands-on maintenance difficult or impossible because of high residual radioactivity levels. At the Los Alamos Meson Physics Facility (LAMPF) we have the additional complication that beam loss can cause prompt radiation in occupied areas. This is because our passive shielding is not up to the task if we consider the worst-case scenarios of losing the maximum possible beam current where the shielding is the weakest. A good real-time beam-loss system is therefore very important, especially since in practice we always end up fine-tuning the facility to minimize the beam loss.

Beam loss during extraction is similarly important, since it is not acceptable to lose even one percent of the beam during the extraction process. It is therefore important to have an efficient extraction process, and to be able to measure the extraction efficiency. For example, at the Proton Storage Ring (PSR) we limit extraction losses to about 0.2%, but even this level will be too high for the next-generation neutron-spallation sources.

It is important to maintain a beam-free gap in the circulating beam for extraction efficiency and beam instability. At the PSR, beam in the gap may lead to electron trapping, and electrons are a likely source of our instability. It is difficult to measure how much beam is in the gap because we are interested in intensity levels about four orders of magnitude below the peak beam intensity, and the time structure is on the scale of tens of nanoseconds.

Beam halo is another important ingredient in the beam-loss formula, since beam halos scrape off at aperture restrictions and cause beam loss. Halo formation is a complicated phenomenon that is not well understood.¹ Halos are also difficult to measure, since one needs profile monitors that can accurately measure beam tails four orders of magnitude below the peak beam intensity. This is why good beam-profile monitors are important at

high-intensity facilities. High-intensity machines offer the additional challenge of overcoming space-charge effects, which, for example, can make residual-gas profile monitors impractical.

To deal with the electrons and electron trapping, we need to consider clearing electrodes. High-intensity facilities lend an additional complication to clearing-electrode systems since we must bias the electrodes with potentials high enough to create electric fields that will overcome the field of the beam. For example, at the PSR we need about 20 kV on our clearing electrodes.

Much of what I plan to discuss is inspired by the problems we have encountered and the useful things we have learned while commissioning and developing the PSR. Another inspiration is our work on the next-generation neutron-spallation source, also known as the National Center for Neutron Research (NCNR). I will describe three diagnostic systems presently in use at the PSR as real-life examples that involve high-intensity issues -- the loss-monitor system, the electron-clearing system, and the beam-in-the-gap monitor. Since I'm going to talk a lot about the PSR, allow me to introduce you to the LAMPF/PSR facility. A diagram of the facility is shown in Fig. 1.

THE LOS ALAMOS PROTON STORAGE RING

The purpose of the Proton Storage Ring (PSR) is to compress in time the 800-MeV proton beam from the LAMPF linac. The beam is first divided into a series of 250-ns-long bunches at 360-ns intervals by the beam chopper in the low-energy transport region of the linac. These bunches are then accelerated to 800 MeV and injected into the PSR, which has a revolution period of 360 ns. The bunches are therefore stacked one atop the other, to create a single 250-ns bunch with the same charge as the injected 600- μ s bunch, for a compression factor of about 2400. The beam is then delivered to a neutron-spallation target, where a short burst of neutrons is generated for materials-science, biology, and nuclear-physics experiments. It is necessary for the neutron burst to be short so time-of-flight techniques may be used to measure the neutron energies. Some of the more important PSR parameters are shown in Table 1, and Table 2 compares our achieved performance to our design goals.

Table 1. A list of some 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 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	60 m
Repetition rate	20 Hz

Fig. 1. A schematic view of the Proton Storage Ring. This figure is not to scale. It is almost 1 km from the injector to the end of the switchyard, and the PSR diameter is about 29 m.

Table 2. A comparison of design and achieved goals.

	Design	Achieved
Peak injected current	15 mA	10 - 11 mA
Injection pulse length	750 μ s	975 μ s
Protons/pulse	5.2×10^{13}	3.8×10^{13}
Repetition rate	12 Hz	20 Hz
Average current	100 μ A	75 - 80 μ A
Losses:		
Accumulation	0.1 to 0.3%	0.6 to 0.7%
Extraction	<0.1%	0.1 to 0.3%

The PSR employs a unique two-step injection process. The incoming H^- ion beam is first stripped to H^0 by a high-field stripper magnet located just upstream of the first magnet in the ring. This neutral beam, unaffected by magnetic fields, drifts through a hole in the first dipole magnet of the ring and begins traveling along the path of the circulating protons in the ring. The H^0 particles then pass through a thin 200- μ g stripper foil where they are converted to H^+ , and they begin to circulate around the ring along with the other H^+ particles. The H^+ particles already in the ring also pass through the stripper foil, where they are unaffected except for a slight amount of emittance growth caused by Coulomb and nuclear scattering.

Let us now focus in on three systems presently in use at the PSR that involve high-intensity issues: the loss-monitor system, the electron-clearing system, and the beam-in-the-gap monitor. The latter two systems were installed earlier this year.

THE PSR LOSS-MONITOR SYSTEM

At the PSR the average beam current is about 70 μ A and the peak current is about 28 A. For such a machine one would like to keep the beam loss below 1 part in 10^4 , to allow hands-on maintenance of the machine and to prevent damage to beam-line components. However, the high level of beam loss at the PSR prevents us from reaching our design goal of 100 μ A, and so we allow an average of 0.5 μ A of beam loss, which is about 0.7% of the average beam current. Our residual activation levels routinely reach as high as 20 rad/h on contact, which is as high as we can tolerate. Beam loss is a very important issue for us, and we constantly run on the edge of tolerable losses.

To measure the PSR beam loss we use photomultiplier tubes immersed in 0.5-liter cans filled with scintillating fluid. An electronics module converts the average current to a voltage, which is read out by the controls computer. Twenty of these detectors are located on the beam-tunnel walls, equally spaced around the perimeter of the ring, at beam-line height, as shown in Fig. 2. Once each year the detectors are first gain balanced by collecting the detectors in groups of five, placing the group alongside a reference can, spilling beam to illuminate that location, and then adjusting the high voltages to equalize the gain of each can.

The detectors are then redistributed around the ring, and a known amount of beam is spilled in the ring by turning off the extraction kickers and allowing all of the injected beam to be lost (the lifetime is only about 10 ms). The pattern of the beam spill is then varied by putting bumps in the ring orbit. By measuring the summed signal from all twenty detectors as a function of the beam-spill pattern, we can show that the summed signal is mostly independent of the nature of the beam spill. The summed signal therefore gives us an absolute measurement of the amount of beam spilled in the ring. With this system we are able to accurately measure beam spill of a fraction of a percent, no matter where or how the beam is lost in the ring, and we can also determine the approximate origin of the spills. We

Radiation Monitors

Fig. 2. Loss monitor locations in the PSR. The APs are nine-stage photomultiplier tubes immersed in 0.5-liter cans of scintillating fluid, connected to averaging electronics. The LMs are the same as the APs but the analog signals are available for viewing in the control room. The LVs are the same as the LMs but the last four stages of amplification are shorted to avoid saturating on extraction losses, and the VEs are vacuum photodiodes, also for measuring extraction losses.

estimate the error in the measurement to be about 30%. An example of a recent calibration is shown in Fig. 3. Some of the more relevant specifications are shown in Table 3.

Table 3. Some specifications of the PSR loss-monitor system.

Absolute accuracy of total ring loss	~30%
Phototube	RCA 4552
Scintillator fluid	1 pt. NE235H
Time to shut off beam	~30 μ s
Dynamic range	10^5

Some disadvantages of a photomultiplier-tube-based system are that each tube needs a separate high-voltage supply, gains can change with age, and if a defective tube must be replaced, the new tube must first be calibrated. Scintillator fluid is also a hazardous substance, and when irradiated it becomes a mixed waste. The nice thing about photomultipliers is they are fast. If speed is not critical then ion chambers can be a good choice. We are presently in the process of upgrading our photomultiplier-tube-based system to an ion-chamber-based system.

Earlier I mentioned that the passive shielding at LAMPF is not adequate to protect against the worst-case beam-spill scenarios. We therefore embarked on an extensive effort to build a system of loss monitors and radiation detectors qualified for use in a personal safety system. We settled on a three-prong approach: a fail-safe ion-chamber-based system located in the beam tunnels to detect beam spill,² current limiting toroids located in the beam lines to detect excess beam current,³ and neutron detectors located in the occupied areas to detect unsafe levels of prompt radiation due to beam spill.⁴ These systems shut off the beam if they detect unsafe operating conditions. LAMPF is the only facility that I know of, probably the only one in the world, that relies so extensively on electronic systems for this purpose. I would like to discuss the fail-safe ion-chamber system as an example of how a loss-monitor system can be used for personal protection.

For the fail-safe ion-chamber system we use ion chambers filled with nitrogen gas at 1 std. atm., so if the ion chamber springs a leak, and the ion chamber becomes filled with air at local pressure (0.80 std. atm.), the ion-chamber response will change by just 20%.⁵ A 20% change is big enough to detect with a radioactive source, but small enough that it will not compromise personnel safety. We also use a 40-G Ω resistor between the high-voltage and signal electrodes to generate a background current to check that the high voltage is set to its proper value, all the cables are connected, and to check the internal connections within the ion chamber. We have spent several man-years developing the electronics to be fail-safe against loss of power, any failure of any single component, and any two points in the circuit becoming connected by any resistance. The latest generation of the system has been performing nicely since it was first installed in 1991. Some of the more relevant specifications are shown in Table 4, and Fig. 4 shows a schematic view of the ion chamber.

Table 4. Some specifications for the fail-safe ion-chamber system.

Response time	~50 ms
Ion chamber active volume	180 cm ³
Ion chamber gas	Nitrogen at 1 std. atm.
Threshold range	8 to 8000 rads/h
Dynamic range of detectable signals	~5 x 10 ⁴

I chose to discuss the fail-safe ion-chamber system as an example of how one can use active electronics for personnel protection, and because the need for such a system will be greatest at high-intensity facilities. However, I should point out that it is far better to use

Fig. 3. An example of how the perimeter loss-monitor system responds to a constant beam spill for various beam spill scenarios, created by putting closed-orbit bumps in different locations in the ring.

Fig. 4. The ion chamber used in the fail-safe ion-chamber system.

sufficient passive shielding instead. It is safer, and one can install it and forget it. Electronic systems require constant maintenance and checking, and in the long run they do not pay off.

THE PSR ELECTRON-CLEARING SYSTEM

Let us now move on to the electron-clearing system. Electrons are an important issue for the PSR because we suspect our instability is an e-p instability. In this instability, background low-energy electrons are trapped in the space-charge potential of the proton beam. Above a certain threshold the electrons and protons develop coupled oscillations that grow in time, leading eventually to beam loss.⁶ The biggest source of electrons at the PSR is in the injection section, also known as section 0. In this section we have secondary emission (SEM) and thermionic emission of electrons from the stripper foil, residual-gas ionization, beam scraping on the beam-pipe walls causing further SEM of electrons, and electrons stripped from the injected H^0 particles, also known as convoy electrons. We also have delta-ray electrons, with energies up to 2.4 MeV,⁷ caused by knock-on collisions of the protons with electrons in the foil.

We built three subsystems to clear out these electrons: 1) clearing electrodes for the ions and electrons from residual gas ionization, and the electrons from SEM off the beam-pipe walls caused by beam-halo scraping; 2) a bending magnet and Faraday cup for the convoy electrons; and 3) a stripper-foil-biasing system to prevent the thermionic and SEM electrons from leaving the foil. The system is illustrated in Fig. 5.

The clearing electrodes work by creating an electric field (E-field) strong enough to overcome the E-field due to the beam. In high-intensity machines, these space-charge fields can be considerable. For example, from a case taken from the PSR, for a Gaussian beam with $\sigma_x = 3.4$ mm, $\sigma_y = 8.9$ mm, and a beam current of 43 A, the maximum space-charge electric field is about 250,000 V/m. This translates to about ± 20 kV on the clearing electrodes. Note that the space-charge fields will be even greater for the next-generation neutron-spallation source. In general it may be necessary to put clearing electrodes in every cell of the machine, and if this is the case one must also consider the effects of coupling impedance. We installed two pairs of clearing electrodes, one upstream and one downstream of the stripper foil. Our electrodes are curved to match the cross section of the beam pipe, and each one covers 90 degrees of the circumference. Each electrode can be biased up to 30 kV.

The purpose of the Faraday cup is to clear out the 430-keV convoy electrons. The energy of these electrons is too high to clear with electrodes, so we chose to bend them into a Faraday cup with a low-field bending magnet. To install the device we inserted a 6-inch tee into the beam line as close as possible to the stripper foil. The first of two C-magnets bends the convoy electrons 90 degrees into the Faraday cup, which fills as much of the 6-inch pipe as possible. The second magnet is identical to but opposite in polarity from the first. It is located just downstream of the first to cancel the closed-orbit distortion and the nonlinear magnetic fields. We also installed a screen at the entrance to the Faraday cup, flush with the inside of the beam pipe, to avoid any wake-field effects. We can bias this screen to reduce the SEM effects when the convoy electrons hit the Faraday cup, and also to attract any low-energy electrons and negative ions from within the beam-pipe volume. Biasing the Faraday cup to 200 V and the foil to 100 V is more than sufficient to clear the convoy electrons.

To deal with the SEM and thermionic electrons from the foil we cannot simply use clearing electrodes or clearing rings. The E-field would be strong between the foil frame and the electrodes but weak at the center of the foil where we need it the most. So we chose to bias the stripper foil. With our high beam intensities the electric field at the center of the surface of the foil is about 1 MV/m, assuming a perfectly conducting foil. Because of the very high surface E-field created by the beam we cannot bias the foil enough to prevent the SEM and thermionic electrons from being ripped off. However, we can create a potential well a centimeter or so away from the foil if we bias it below the depth of the beam's potential

well. The electrons will then be trapped until the beam intensity drops at the end of the bunch, when the bias E-field will be strong enough to attract the electrons so they can be absorbed on the foil surface. The electrons are therefore cleared after each revolution of the beam around the ring, or about every 360 ns. The potential well created by the beam is about 8 kV deep, and we can bias the foil up to about 10 kV, limited by the existing construction of the foil-mounting system.

These three subsystems deal efficiently with all the electron sources but one — the delta-ray electrons. These electron energies span the range from a few eV to 2.4 MeV. Most of the delta rays have low kinetic energy, and they will be trapped between the foil and the Faraday-cup magnets, and should eventually be cleared by the biased foil. The medium-energy delta rays will be deflected into the Faraday cup, and the few (about 3×10^{-5} per proton) high-energy delta rays that pass through the Faraday-cup magnets will be lost on the beam-pipe walls.

Figures 6 through 8 show some data from the various components of this system. In Fig. 6 we see some signals from the stripper foil with and without the bias turned on. Part (a) shows a strong signal that ramps up during the 500 μ s of beam injection. This is due to more and more circulating beam passing through the foil. During the 300 μ s of beam storage, the rate of electron emission decreases, and after extraction we see the signal drop off due to the RC time constant of the biasing circuit. In part (b), where the foil is biased to 3 kV, the electron-emission rate continues to grow until extraction, but the overall signal amplitude is four times lower, indicating a reduced emission of electrons because they are now collected by the positively charged foil. The signal amplitude continues to drop as we raise the foil bias, but we have never observed the amplitude to drop completely to zero because of restrictions on the bias voltage due to breakdown effects. The highest we ever biased the foil was about 9 kV. In Fig. 7 we see some signals from the Faraday cup and screen. Part (a) shows the signals with the biases turned on but the bending magnets SRHM01 and SRHM02 turned off. These signals are due to low-energy electrons sucked out of the beam pipe, caused by SEM off the stripper foil and beam-pipe walls, and possibly a few delta rays and electrons from residual-gas ionization. In part (b) the bending magnets are turned on, thus steering the 430 keV convoy electrons into the Faraday cup. The signal now has a rectangular shape to match the time structure of the injected beam, as expected. In Fig. 8 we show some clearing-electrode signals. Parts (a) and (b) show the positive electrode at 0- and 10-kV bias. As expected, turning up the bias voltage results in more electron collection. Parts (c) and (d) are the same thing but for the negative electrode. As expected, there is very little charge collected on this electrode since the collected particles are dominated by electrons. Part (e) shows an interesting phenomenon during the onset of beam instability. Huge amounts of electrons are collected when the beam goes unstable. We see similar signals from the stripper foil, the Faraday cup and screen, and a pair of pinger electrodes located in section 3 of the ring. Three traces are shown to illustrate the pulse-to-pulse variations in the beam instability.

After commissioning the electron-clearing system this summer we found we can collect almost all the electrons created in section 0. However, this raises the instability threshold of the coasting-beam instability by only about 20%, and it increases the growth time of the bunched-beam instability by almost an order of magnitude but does not alter its threshold. This is a disappointing result for us but also an educational one. We now suspect there are other strong sources of electrons in the PSR, and we have initiated a new set of experiments to identify and characterize them.

BEAM-IN-THE-GAP MONITOR

By beam in the gap I mean beam that leaks into the gap between the front of the head and behind the tail of the single beam bunch in the PSR. The primary contribution to beam in the gap is space charge, which pushes protons out of the rf bucket into the inter-bunch gap. We need to maintain this gap, nominally about 110 ns long, to allow time for the

Fig. 6. Signals from the stripper foil, using capacitive coupling to the HV cable. There is a dc offset caused by the capacitive coupling circuit, so the baselines of the waveforms should be considered meaningless. Part (a) is for 0-V bias, and part (b) is for 3-kV bias. Note that biasing the foil reduces the signal caused by electron emission from the foil. Beam parameters: Injection time = 500 μ s, storage time = 300 μ s.

Fig. 7. Signals from the Faraday cup (bottom trace) and screen (top trace), using a low-pass filter on an oscilloscope, with the power supply between the oscilloscope and the Faraday cup. The waveform baselines are arbitrary. In part (a) the SRHM01 and SRHM02 magnets are off, and in part (b) they are set to steer the convoy electrons into the Faraday cup. Faraday cup voltage = 200 V, screen voltage = 100 V. Beam parameters: injection time = 500 μ s, storage time = 300 μ s.

Fig. 8. Signals from the SRCQ02 (downstream) electrodes in the Electron-Clearing System, using capacitive coupling to the HV cable. There is a dc offset caused by the capacitive coupling circuit, so the baselines of the waveforms should be considered meaningless. Parts (a) and (b) show the positive electrode at 0- and 10-kV bias, and parts (c) and (d) show the same thing but for the negative electrode. Beam parameters for parts (a) through (d): Injection time = 500 μ s, storage time = 300 μ s. Part (e) shows signals from the positive electrode of SRCQ02 during the coasting-beam instability. The electrodes are at 20 kV, the foil is at 6 kV, the SRHM01 and SRHM02 magnets are at 150 A, the Faraday cup is at 200 V, and the screen is at 100 V. Three traces are shown to illustrate the pulse-to-pulse variations. Beam parameters: Injection time = 420 μ s, storage time = 500 μ s, coasting beam (no bunching, injected beam fills the ring circumference).

extraction kickers to turn on. Beam in the gap therefore has important implications to extraction beam loss. If there is beam in the gap, that beam will be sprayed onto the beam pipe when the extraction kickers turn on. Beam in the gap can also trap electrons that lead to an e-p instability, as opposed to a beam-free gap that will clear out the electrons as the gap sweeps around the ring by allowing the mutual repulsion of the electrons to cause them to fly away to the beam-pipe walls.

A good beam-in-the-gap monitor will accurately measure beam current more than four orders of magnitude below the peak beam current and have a response time of a couple of tens of nanoseconds. If the monitor is in the ring we would like a droop of less than 0.01%/ms, and if it is in the extraction line we would like a droop of less than 1%/μs. We thought of four ways to accomplish this measurement: with an electron beam probe, with a wide-band current monitor with very good low-frequency droop, by measuring secondary emission off the stripper foil, and with a current transformer in the extraction beam line. We ended up choosing the last option, but let me tell you why.

The idea behind the electron beam probe is to shoot an electron beam across the proton beam.⁸ The degree of vertical deflection is a measure of the proton current, and a pair of electrodes sweeps the electron beam horizontally to resolve the time structure. It's like running the proton beam line through the middle of an oscilloscope. After some investigation we decided this concept is not a good idea for several reasons: 1) an electron gun that would do the job (50 micron spot size at 1 meter, 2- to 20-keV energy, and 30 mA/cm² current density) is a very specialized device. The only one we found was a field-emission gun. It has to be handled very carefully and it must be serviced at the factory, which is not equipped to deal with radioactive items. 2) A 2-keV electron beam is very sensitive to stray electromagnetic fields. For example, in a test at the factory, just putting a pair of pliers or scissors next to the beam pipe caused severe distortions for a 5-keV beam, even with a mu-metal shield inside the beam pipe. 3) The data would be difficult to interpret. We suspect there are a lot of electrons in the beam pipe, and these electrons would also deflect the electron beam. Additionally, a bunched proton beam will deflect the electron beam both vertically and horizontally, thus confusing the time-resolving axis.

We rejected the idea of a wide-band current monitor in the ring due to high cost and long development time. We rejected the idea of SEM off the stripper foil because of the high radiation fields, the low signal levels in a noisy environment, and because we expect the high-frequency response to be marginal due to the foil construction.

We settled on using a fast current transformer (FCT) in the extraction line. The idea here is to turn on the extraction kickers before the beam in the gap reaches the kicker electrodes, thus sending any beam in the gap down the extraction line and through the FCT (and also spraying full-intensity beam on the PSR beam-pipe walls). We purchased a custom-made FCT from Bergoz and installed it earlier this year, about 47 meters downstream of the extraction kickers. Some of the specifications are shown in Table 3.

Table 5. Some specifications for the FCT.

	Goal	Achieved
Post-pulse settling time	30 ns to 0.1%	50 ns to 1%
Rise time (10% - 90%)	<5 ns	17 ns
Droop	<1%/μs	0.6%/μs over 4 μs
Transfer impedance	>1.25 Ω	1.0 Ω
Inside diameter	180 mm	180 mm

We devoted a lot of effort to carefully shielding the FCT for noise. We stacked two tons of iron blocks for gamma-ray shielding, and we used 1.625-inch Helix cabling inside a solid steel conduit to transmit the signal about 30 meters.

Although we missed our most important specification (the post-pulse settling time) by more than an order of magnitude, it turns out there is enough beam in the gap to measure it

FCT output for
 -20, -15, -10, -5, 0, 5, 10, 15, and 20-ns changes in kicker timing

Fig. 9. Beam-in-the-gap monitor signals taken during production conditions. The extraction kicker timing was changed by -20, -15, -10, -5, 0, 5, 10, 15, and 20 ns. Beam parameters: Injection time = 525 μ s, storage time = 10 μ s. The oscilloscope was triggered on the extraction-kicker waveform.

FCT output for 100, 200, 300, 500, 600, 700, 725- μ s accumulation times

Fig. 10. Beam-in-the-gap monitor signals for seven different injection times, and therefore seven different space-charge fields. Note the gap fills in as more and more beam is injected into the ring.

with this instrument. One can see from Fig. 9 that as one advances the kicker timing, one cuts into the tail of the beam more and more. In this figure, the trace with the lowest-amplitude prepulse is from the kicker timing delayed 20 ns. As we advance the kicker timing the prepulse amplitude increases, indicating that we are cutting into the tail of the beam pulse. The figure shows that if the amplitude of the prepulse is small enough, the FCT settles down enough to make the measurement. In this series of measurements, taken during production conditions, the beam in the gap dips down to about 2 mA, or to about 0.007% of the peak beam intensity.

This instrument has also proven itself to be a useful diagnostic for setting the extraction-kicker timing, since it is more sensitive to the timing than our usual method of minimizing the extraction beam loss. From the above set of measurements we concluded that the initial kicker timing (0 ns on the figure) had been set too early, since the prepulse amplitude was not minimized. After we finished the measurements we left the timing delayed by 20 ns, which resulted in a small improvement in the operating conditions.

We can also vary the duration of the PSR injection cycle and thus vary peak beam intensity and the space charge forces. Figures 10 and 11 show some preliminary data on how the beam-in-the-gap current changes as a function of the injection time. In Fig. 10 we see the FCT output plotted for seven different accumulation times, and therefore seven different peak currents in the ring. During these measurements we used three different extraction-kicker timings to keep the prepulse amplitude below acceptable limits. The figure shows that the gap current increases as we inject more and more beam into the ring. In Fig. 11 we plot the beam in the gap as a function of the accumulation time, expressed as a percentage of the peak beam current. In this figure there are three groups of data points because of the three different sets of extraction-kicker timings and therefore three different manifestations of the droop. We see from this figure that as we increase the beam current, and therefore the space-charge fields in the ring, the beam in the gap increases correspondingly.

SUMMARY AND CONCLUSIONS

We have discussed some of the constraints that high intensity accelerators and storage rings place on beam-diagnostic instruments. Most of these are related to beam halos and beam space charge. We also discussed in some detail three diagnostic systems in use at the PSR that are related to high-intensity issues — the loss-monitor system, the electron-clearing system, and a fast-current transformer for measuring beam in the gap.

We have a wide variety of beam-loss-monitoring systems at LAMPF because beam loss is so important to us — for example, it prevents the PSR from reaching its design goal of 100 μ A average current. We discussed two of our loss-monitor systems — the PSR perimeter system with twenty detectors that can measure absolute beam loss that is a fraction of a percent of the total beam current, and the fail-safe ion-chamber system that is a necessary ingredient in our personnel-protection system.

Next we moved on to the electron-clearing system, which we built to remove the electrons from section 0 of the PSR. Although we succeeded in clearing out these electrons we did not substantially improve the instability threshold. However, new experiments suggest other sources of electrons, and we are now working to identify and characterize them.

The final subject was the beam-in-the-gap monitor. We installed a custom-made fast-current transformer in the PSR extraction line. By firing the extraction kickers early beam in the gap is directed into the extraction line to the FCT. Preliminary results show that for production conditions the beam-in-the-gap current is 0.007% of the peak beam current.

I hope these three examples of beam-diagnostic systems at PSR have highlighted some of the interesting challenges available at high-intensity facilities.

Fig. 11. Minimum beam-in-the-gap current as a function of injection time.

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- ⁵ M.A. Plum and D. Brown, "Response of Air-Filled Ion Chambers to High-Intensity Radiation Pulses," Proceedings of the 1993 Particle Accelerator Conference, Washington, D.C., May 17-20, 1993. Also Los Alamos National Laboratory report LA-UR-92-4066.
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