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SPEAR 3 - THE FIRST YEAR OF OPERATION*

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Abstract

The first electrons were accumulated in the newly completed 3-GeV SPEAR 3 storage ring on December 15, 2003, five days after the beginning of commissioning. By mid-January of 2004, 100 mA were stored, the maximum current allowed in the first phase of SPEAR 3 operation, and ring characterization and tuning continued until early March when the first photon beam line was opened for users. After the first year of operation the SPEAR 3 beam properties and ring performance had been extensively measured. These include micron stability using slow orbit feedback, an emittance coupling of ~0.1% and 50-h lifetimes. The performance of SPEAR 3 during its first year of commissioning and operation and the improvement plans are described.

INTRODUCTION

On March 31, 2003, the SPEAR 2 storage ring was turned off for the final time after 30 years of service for both the high energy physics and synchrotron radiation communities. Seven months later, SPEAR 2 had been completely replaced with the new SPEAR 3 storage ring (Figure 1) [1,2], a modern light source having the SPEAR 2 footprint but providing 3rd generation light source capability for SSRL (Table 1). The new ring provides 1-2 orders of magnitude higher performance than SPEAR 2 and is already benefiting the materials and molecular environmental science, structural molecular biology and macromolecular crystallography communities. The 4-year, 58 M$ SPEAR 3 upgrade project was administered by the DOE with ~50% joint funding from the NIH.

Turn-on of the accelerator systems began during the last month of installation when the ring was secured at night for magnet power supply, control system and RF

Figure 1: The rf straight section (left) and north arc (right) of the SPEAR 3 tunnel.

testing. By December 8 the ring was aligned, water cooling systems were completed, machine protection and personnel safety systems were certified, radiation shielding was installed, accelerator systems were tested and declared operational, and permission was given to begin commissioning SPEAR 3. The first beam signal

Figure 2: Some members of the commissioning team shortly after accumulating first beam on Dec. 15, 2003.

was seen on December 10, the first beam was stored on December 15, the first 100-mA fill was reached on January 22, 2004 (Fig. 2), and beam was delivered to users on March 15. The commissioning period between December 10 and March 15 was filled with a remarkable array of machine measurement and characterization

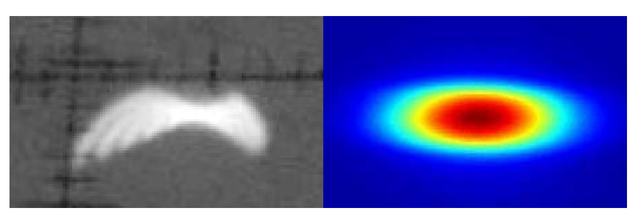

Figure 3: Radiation from individual wiggler poles (left) was seen in the first beam line (side station) opened during commissioning, first evidence of low emittance. Beam size in the x-ray pinhole image (right) is 50 x 150 μm rms, limited vertically by diffraction. Actual vertical size is expected to be ~15 μm rms.

Table 1: Parameters for SPEAR 2 and SPEAR 3.

	SPEAR 2	SPEAR 3
Energy	3 GeV	3 GeV
Current (max)	100 mA	500 mA
Emittance (w/ID)	160 nm-rad	16 nm-rad
RF frequency	358.5 MHz	476.3 MHz
RF gap voltage	1.6 MV	3.2 MV
Lifetime @ Imax	30 h	15 h†
Critical energy	4.8 keV	7.6 keV
Tunes (x,y,s)	7.18,5.28,.019	14.19, 5.23, .009
e- σ (x,y†,s) - ID	2.0,.05,23 mm	.35,.025,4.9 mm
e- σ (x,y†,s) -bend	.79,.20,23 mm	.13,.04,4.9 mm
Injection energy	2.3 GeV	3 GeV

†with 1% emittance coupling; ~10 h lifeteime with 0.1% coupling.

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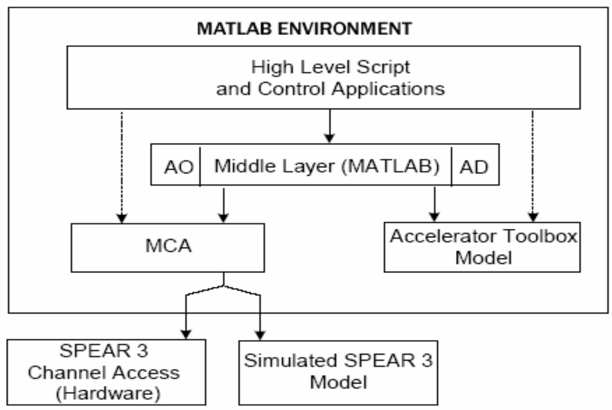

Figure 4: Many application programs are written in MATLAB®, communicating with the SPEAR control system through a Channel Access interface and facilitated with a software middle layer. The AT Simulator [5] was used extensively to develop the applications prior to commissioning.

programs [3], facilitated by MATLAB-based control application programs, many of which were ported from the ALS [4], and communicating with the SPEAR control system via a Channel Access interface (Fig. 4). The commissioning team was augmented by visitors from international light sources [3].

SPEAR 3 is presently operating at 100 mA, but with the completion of beam line upgrades, operation at currents up to 500 mA is scheduled for the 2006 user run. High current test runs with beam lines closed are scheduled in June and July of 2005 after completion of the DOE-mandated "Phase 2 Accelerator Readiness Review" for 500 mA operation in early June.

MACHINE CHARACTERIZATION

SPEAR 3 diagnostic instrumentation includes a Bergoz DCCT having microamp resolution, a tune measurement system, a beam position monitoring system having 54 BPMs instrumented with Bergoz processing electronics and 2 BPMs with digital turn-turn parallel-button processors built by Echotek, horizontal and vertical scrapers and an x-ray pinhole camera. The EPICS-based control system provides process variable control and read-back of diagnostics and other accelerator systems, including power supplies, rf, injection kickers, etc. Read-

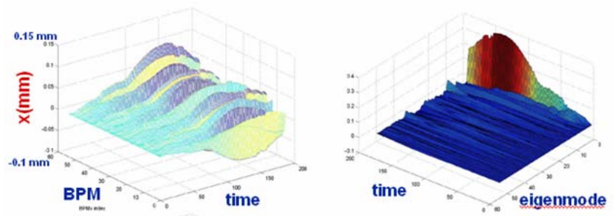

Figure 5: Horizontal orbit drift over 10 hours (left) is on the order of 100 μm. Orbit distortion is decomposed analyzed into eigenmodes of the response matrix (right) and used for orbit feedback.

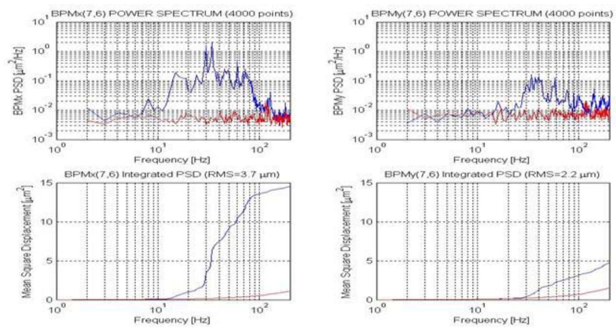

Figure 6: Horizontal (left) and vertical orbit noise spectra, with beam (blue) and without (red), up to 200 Hz detected with electron BPMs. Integrated noise as shown is ~2% of the horizontal beam size and ~10% of the vertical beam size. Peaks <100 Hz are associated with known magnet vibration modes.

back data is stored every 2 seconds in short-term history buffers which are later decimated to 1-minute long-term history records. Much faster read-back data can be acquired in the EPICS IOCs, including orbit BPM and corrector power supply read-backs at 4-kHz.

Closed Orbit Measurement and Control

Orbits are acquired from the BPM processors at a 4-kHz rate. The data is averaged for 0.5 or 1 seconds for display and archiving (Fig. 5), although the 4 kHz data or that having fewer averages can be used for higher frequency orbit analysis (Fig. 6). The typical rms noise in this bandwidth is ~100 nm, while that for the 4 kHz is data is a few microns. BPM electrical centers are measured using a quadrupole modulation system (Fig. 7).

A MATLAB-based slow orbit feedback system employing 54 BPMs and 54 correctors per plane and having a 6-second update period is used to maintain low-frequency orbit stability to the sub-micron level. The system is not fast enough to suppress orbit noise caused, for example, by traffic on the trestle that passes over the

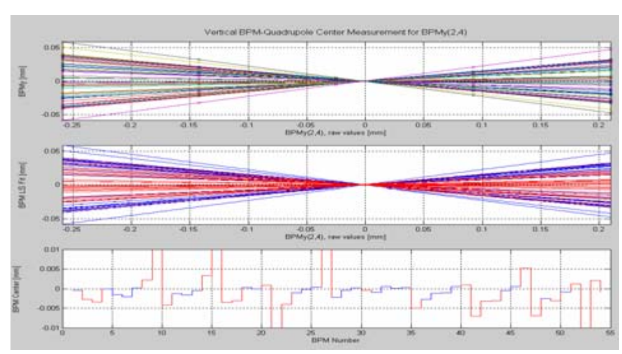

Figure 7: BPM electrical centers are measured with a quadrupole modulation system having a resolution of order 10μm. Beam is moved horizontally and vertically in a quad adjacent to the BPM while the quad strength is varied by ~1% until BPMs elsewhere in the ring show no orbit variation as indicated by "bow-tie" plots (top two graphs). The resulting BPM readings give offsets (lower) that are subtracted from orbit measurements.

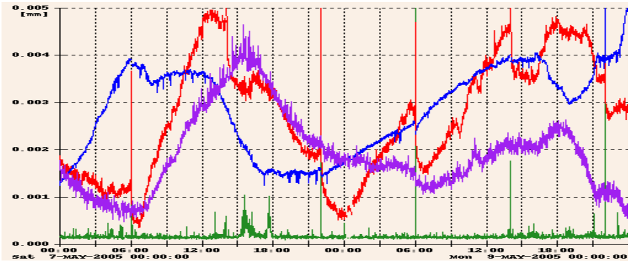

Figure 8: Vertical rms orbit over 48 h is held to <1 µm by feedback (green) while beam line photon monitors (red for bend magnet line, blue for undulator line) indicate diurnal orbit motion correlated with the temperature of BPM processors (violet, 6°C pk-pk). Glitches in rms orbit are caused by traffic on the trestle over the ring and during injection.

ring (Fig. 8). A faster feedback system (50-100 Hz), now being commissioned, will remedy this and improve orbit stability during insertion device gap changes

Data from BPMs upstream and downstream of insertion devices are used in an interlock to maintain tight control of the beam trajectory in to protect against damage to the vacuum chamber from mis-steered synchrotron radiation beams. The orbit interlock is active above 20 mA and will abort the beam within 3 ms if the orbit at any one of the insertion device sites exceeds limits defined by

$$\frac{|y|}{1.15\,\mathrm{mm}}+\frac{|y'|}{0.36\,\mathrm{mrad}}<1 \qquad \frac{|x|}{4.8\,\mathrm{mm}}+\frac{|x'|}{1.1\,\mathrm{mrad}}<1$$

While sub-micron stability with feedback is indicated by the electron BPMs, vertical photon position monitors in the synchrotron radiation beam lines show beam motion which can reach a few tens of microns depending on the distance between monitor and beam source point. This motion is correlated with the diurnal temperature variation of the electron BPM processors (Fig. 8) which are located in remote housings having no temperature control. A plan is now in place to implement a temperature regulating system that will reduce variations from the order of 10°C (on warm days) to <1°C.

The orbit feedback system also adjusts the rf frequency to track changes in ring circumference. While tunnel temperature is typically stable to <1°C over days, the site as a whole appears to expand and contract daily, causing frequency changes of order 50 Hz, while large excursions are seen over longer periods as the site environment and

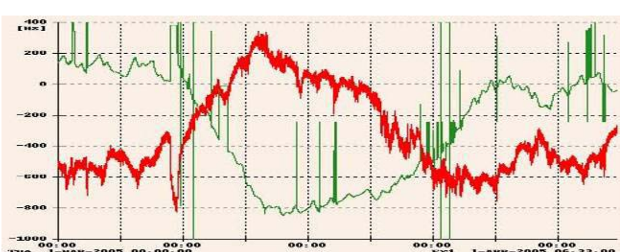

Figure 9: RF frequency changed by 1 kHz during April 2005 (green) by action of the orbit feedback system, correlated with a 2°C tunnel temperature change (red).

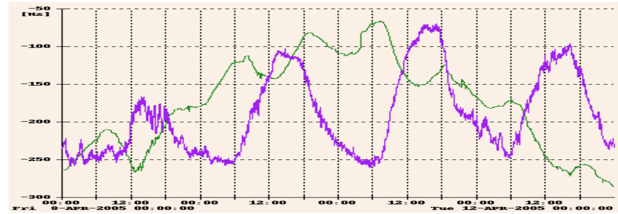

Figure 10: RF frequency varies 30-Hz twice daily from moon-induced earth tides (green, 50 Hz/div) and reacts to outside temperature (9°C pk-pk) over 4 days (violet).

tunnel temperature gradually change (Fig. 9). Circumference and rf also change with a half-day cycle in response to lunar tides (Fig. 10).

Optics Measurement and Correction

The LOCO code [6] is used to measure and correct lattice functions, including tunes, beta functions and dispersion, based on analysis of the orbit response matrix data. LOCO is used to correct emittance coupling (<0.1%), vertical dispersion, and focusing errors caused by insertion devices (Fig. 11). The skew quadrupole error introduced by the BL 5 elliptically polarizing undulator was recently corrected as well [7]. BPM gains, corrector strengths, local chromaticity and transverse impedance distribution have all been measured using the code [3].

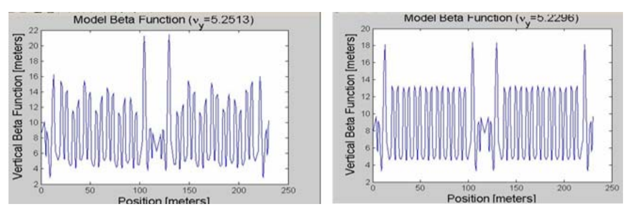

Figure 11: Vertical tune shift for each high-field ID are corrected with local quadrupoles according LOCO.

Beam Dynamics and Apertures

The tune working point has been optimized by measuring dynamic aperture and lifetime as a function of tunes (Fig. 12). A ~20-mm horizontal dynamic aperture and 4.7-mm vertical physical aperture, both predicted in tracking studies, have been measured using a horizontal injection kicker. The measured horizontal and vertical lattice acceptances are 40 mm-mrad and 4.5 mm-mrad, respectively. A kicker was used as well to measure the reduction of dynamic aperture caused by a high-field wiggler (Fig. 13). A momentum aperture of ~ ±3% has been measured using the kicker and varying the rf frequency, and also be varying rf gap voltage.

Broadband transverse impedance has been calculated to be ~0.15 MΩ/m based on measurements of vertical tune shift with beam current. Longitudinal broadband impedance (Z/n) is estimated to be 0.5 to 1Ω, derived from the transverse value. Measurements of bunch length and longitudinal dynamics have not yet been made but are scheduled for the 2006 run when the visible/UV synchrotron light monitor is commissioned.

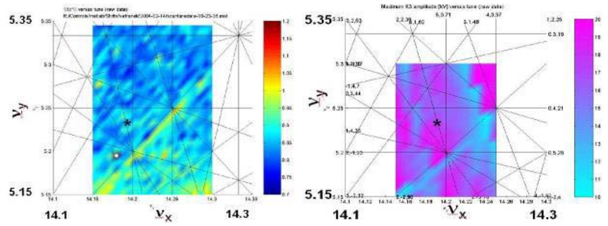

Figure 12: The working point (ν_x=14.19, ν_y=5.23) was optimized by measuring dynamic aperture (left, by increasing horizontal kicker amplitude until was beam lost) and lifetime (right) as a function of tunes. The main resonance line is $\nu_x - \nu_y = 9$.

Lifetime and Vacuum Quality

The evolution of ring lifetime over the course of the 2004 and 2005 user runs is shown in Figure 14. Lifetime is slowly improving as the ring pressure decreases. Ion gauges located near vacuum pumps (which are at a lower pressure than in the beam duct) now indicate pressure of order 0.1 nTorr at 100 mA, down by an order of magnitude from a year ago. With the present >50-h lifetime at 100 mA, the beam decays to ~87 mA over the 8-h period between fills (Fig. 15)

The breakdown of total lifetime into its various components was determined using a vertical beam scraper (Fig. 16). Scaling the 100-mA measurements to the future 500-mA operating current indicates the total lifetime will be ~10 h given the present vacuum quality and low vertical coupling.

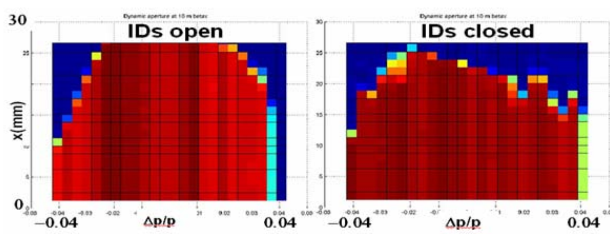

Figure 13: Reduction of energy-dependent dynamic aperture from the BL 11 wiggler was measured by increasing horizontal kicker amplitude until beam was lost as function of rf frequency.

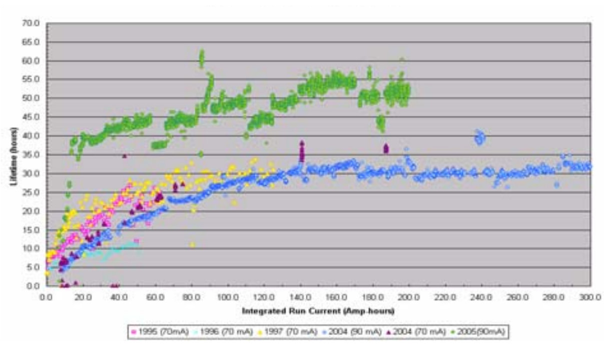

Figure 14: Lifetime leveled out to 30 h @ 100 mA in 2004 (blue) due to running with reduced rf gap voltage (2.5 MV). Gap voltage was restored to 3.2 MV in 2005 and lifetime is >50 h @ 100 mA after 160 A-h of integrated run current. Vacuum improved much more quickly at the beginning of the '05 run than it did in prior years for SPEAR 2.

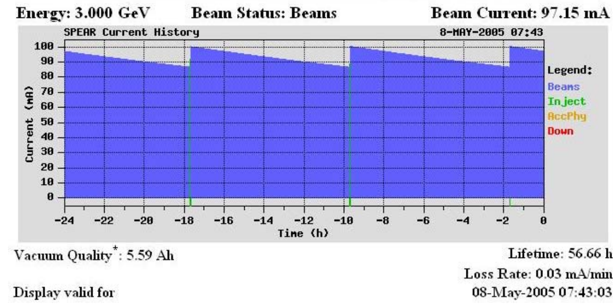

Figure 15: Beam is topped up to 100 mA every 8 hours. Lifetime is >50 h @ 100 mA as of May 2005.

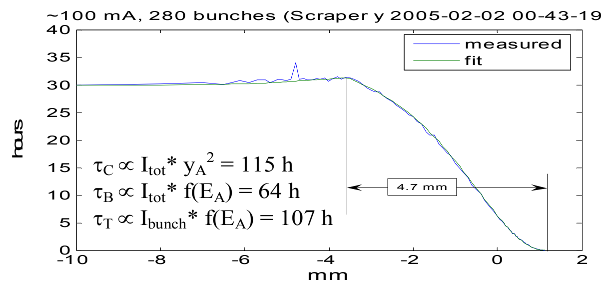

Figure 16: Coulomb, bremsstrahlung and Touschek lifetimes (τ_C, τ_B, τ_T) are derived from total lifetime measurements at as a function of vertical scraper position for two fill patterns: 100 mA in 280 bunches and 20 bunches. Knee in curve indicates vertical aperture y_A is 4.7 mm elsewhere in ring. E_A designates energy aperture.

User Beam Time and Equipment Performance

SSRL allocates 79% of the 8-10 month user run as beam time for users. Another 11% is assigned to machine studies, 5% to scheduled maintenance, and 2% to injection. Users have received an average of 97% of their scheduled beam time since SPEAR 3 began user operation in March 2004.

Equipment problems contributing to missing user beam time include the failures of the booster rf high voltage power supply and arcing in the IGBT injection kickers, and various power supply and water leak and flow mishaps. The rf window for one of the cavities developed a sudden heating problem, accompanied by a pressure burst that necessitated reducing the total gap voltage for the 4 cavities from 3.2 MV to 2.5 MV until the window could be replaced in the summer shutdown.

In general the new SPEAR 3 systems, including the in-house designed digitally controlled fast corrector power supplies and the injection timing system, have performed remarkably well, although improvement work is ongoing to make those systems more robust. The SLAC-designed power supply controllers are delivering 10-20 ppm regulation for the main power supplies, and the EPICS control system network has proven to be very reliable.

MACHINE UPGRADE PLANS

SSRL is planning several machine and system upgrades, some of which are already in progress.

Work is ongoing to commission 24 turn-turn BPMs using Echotek digital receivers and integrate them into the orbit feedback system when they are operating in averaging mode. Two turn-turn BPMs are already operating (Fig. 17). The 50-100 Hz orbit feedback system is also being commissioned and should be ready for the 2006 user run. The visible/UV synchrotron light monitor [8] will also be ready in that run.

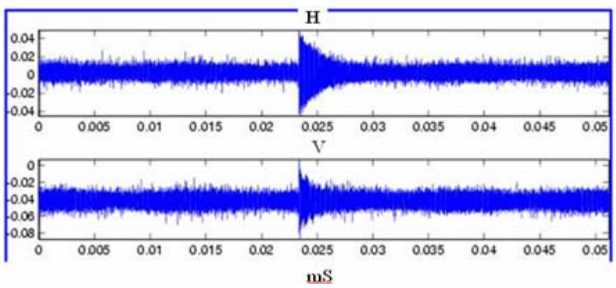

Figure 17: Injection kicker transient recorded with turn-turn BPMs. The BPMs are also used to study non-linear beam dynamics.

Preparation for 500-mA operation is underway, with test runs planned before the end of the 2005 user run. Tests up to 225 mA were made in 2004 with no detected problems. The main issues for high current operation include absorber, chamber transition and bellows heating and the possible onset of vertical multibunch instability (the calculated threshold is close to 500 mA when the vertical chromaticity is set to ~+1 (un-normalized). Transverse stripline kickers are presently in design that can be used for feedback should it be required, but will be used for beam dynamics studies in any case. The PEP-II style mode-damped rf cavities eliminate the need for longitudinal feedback. The injection current will be raised from the present 0.5 nA to 1.5 nA in support of 500 mA operation for the 2006 user run after a system of long ion chamber beam loss monitors (LIONs) in the tunnel are connected to the Beam Containment System.

A new double-waist chicane optics has been designed that will accommodate two small-gap insertion devices (Fig. 18) [9]. A quadrupole triplet will be installed in the east long straight section during the 2005 shutdown in order to commission the optics in advance of the 2006 installation of the BL 12 in-vacuum undulator. The new

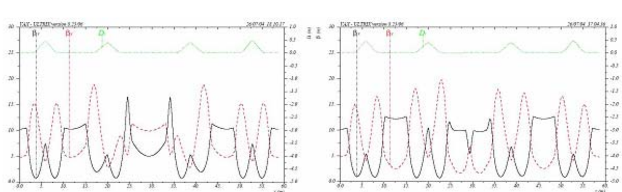

Figure 18: A new quadrupole triplet in the east long straight section creates a double-waist chicane optics that reduces the vertical beta function from 10 m (red, left) to 1.6 m (right) and accommodates two small-gap IDs.

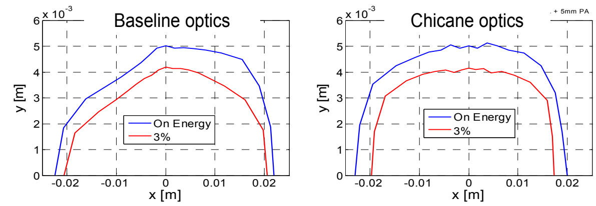

Figure 19: Dynamic aperture for the standard "baseline" and double-waist chicane optics.

optics, which also reduces the vertical betas in the four matching straight sections, has been extensively studied with tracking and frequency map analysis and reduces dynamic aperture by only a few percent (Fig. 19).

Top-off injection is in the early stages of planning and is expected to be implemented over the next two years. Besides the usual radiation safety issues associated with injecting with beam lines open, several system upgrades will be required, including improving the performance of the injector linac and 10 Hz booster, and rebuilding the Booster-to-SPEAR transport line to eliminate several thin stainless steel windows that spoil the emittance of the injected beam. A regulating system for the booster White Circuit is already being developed to enable fast turn-on and off of the system for top-off injection so that it is not continuously running. Improvements of linac and transport line diagnostics are underway, and the replacement of the thermionic cathode in the rf cavity gun with a photocathode is being considered as a way to eliminate back-bombardment problems and improve gun stability. A user workshop is planned for October 2005 to discuss optimal top-off modes.

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