OPTIMIZATION OF THE BOOSTER TO SPEAR TRANSPORT LINE FOR TOP-OFF INJECTION *

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Abstract

In the past, SPEAR3 typically had 50 to 70% injection efficiency. Much of the lost injected beam hit the small gap vacuum chambers at the insertion devices. We are now implementing top-off injection with photon beamline shutters open, so these losses create bremsstrahlung down the photon beamlines, increasing radiation levels on the experimental floor. In this paper, we describe work done to better control the booster to SPEAR (BTS) transport line beam so as to reduce losses during injection. We have used new BTS BPM electronics to control the transport line trajectory. The trajectory response on these BPMs has been used to correct the BTS optics. We use single-turn BPM readings of the injected beam in SPEAR to optimize the BTS trajectory in all six transverse and longitudinal coordinates. We also use single-turn profile measurements of the injected beam to verify the BTS optics correction. The stainless steel windows have been removed from the BTS vacuum system to reduce the transverse dimensions of the injected beam.

INTRODUCTION/SUMMARY

During initial top-off measurements, injecting with SPEAR photon beamlines open, radiation levels on the beamline floor were found to be about a factor of three higher than the required limit for 500 mA operation. This note describes work done to reduce the radiation.

Radiation levels were reduced by (1) improving BTS trajectory control using the nine BTS BPMs and single-turn BPMs in SPEAR, (2) improving BTS optics control, and (3) removing windows from BTS vacuum system. With these three measures, we now routinely inject with radiation levels six times below the required limit.

The windows referred to in item 3 are thin stainless steel windows separating the vacuum system of the BTS from those of the booster and SPEAR. The injected beam passes through these windows. They were included when the BTS transport line was built in order to reduce cost. With the windows, the BTS vacuum could be run at much higher pressures (~milliTorr) rather than the nanoTorr required for SPEAR and the booster. Removing the windows required rebuilding the entire transport line vacuum system.

INJECTION EFFICIENCY SIMULATIONS

Figure 1 shows a computer model [1] of horizontal and vertical phase space at exit of the SPEAR3 injection septum, for ideal optics and trajectory control. The pink dots represent the distribution of electrons for the incoming injected beam. The stored beam (small blue circle) is bumped horizontally toward the septum magnet wall by three kicker magnets. The kicker pulses last only one turn, after which the stored beam returns to the center of the chamber (x = x' = 0) with the injected beam oscillating about it with a centroid oscillation amplitude of about 12 mm. The scattering of the BTS windows is included in this simulation.

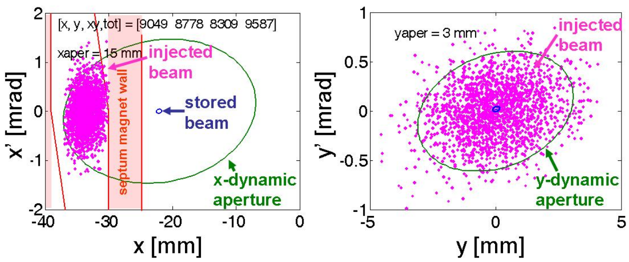

Figure 1: Simulated injected beam distribution.

Only those injected electrons with amplitudes within the SPEAR3 dynamic aperture (x ~15 mm and y ~3 mm) are captured. The injected electrons outside the dynamic aperture are lost at various locations in the SPEAR vacuum chamber, often at the small vertical apertures of the insertion devices. In Fig. 1, the pink dots outside either the x or y dynamic apertures (green ellipses) represent these lost electrons. In this simulation, 83% of the particles were captured in SPEAR.

In real injection, errors in BTS trajectory and optics result in lower injection efficiency.

The injected beam distribution (pink dots) in Fig. 1 is for a simulation including the BTS windows. It will be shown below that we achieve considerably better injection efficiency with the windows removed.

BTS TRAJECTORY CONTROL

We commissioned new BTS BPM electronics and a BTS trajectory correction program. We determined the optimum trajectory at the end of the BTS by two methods: (1) tuning for maximum injection efficiency, and (2) measuring turn-by-turn betatron oscillations of the injected beam in SPEAR. The betatron oscillations were measured using a single-turn digital-receiver BPM system designed by SSRL and built by Echotek [2]. The injected beam intensity is only ~25 pC, so single-pass BPM readings are fairly noisy. We found, however, that we could get good measurements of injected beam oscillations by averaging BPM readings over many injected beam pulses.

Figure 2 shows single-turn BPM data in SPEAR. The horizontal oscillations are the result of the injection scheme, in which the horizontal injected beam is displaced from the stored beam (Fig. 1). The vertical oscillations, however, indicated mis-steering in the BTS. We use these measurements to determine the "golden"

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trajectory in the BTS, which results in no vertical oscillations in SPEAR, among other criteria.

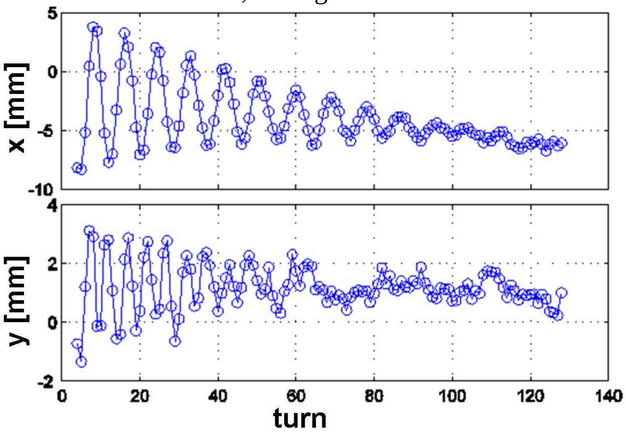

Figure 2: Measured betatron oscillations of the injected beam in SPEAR.

BTS OPTICS CONTROL

Trajectory control puts the center of the injected beam in the right place. Optics control is required to match the shape of the injected beam distribution to the SPEAR acceptance. Figure 1 shows the ideal matching. To tune the real transport line to get to this ideal optics, we used the trajectory response matrix method (LOCO [3]) that was originally developed for storage rings.

LOCO works on the following principle. The beam shape is determined by the quadrupole strengths, but the quadrupole strengths also determine how the trajectory changes when a steering magnet in the transport line is adjusted. The trajectory response to steering magnets can therefore be used to calibrate and adjust the quadrupole strengths.

In LOCO fashion, we fit the computer model of the optics to best reproduce the measured trajectory response matrix. The resulting computer model showed that the beam shape was not optimized to the SPEAR injection aperture. Using the fit computer model, we were able to adjust the BTS quadrupole currents to improve the matching into SPEAR. The BTS optics improvement was confirmed with single-turn injected beam profile measurements in the synchrotron light monitor (SLM) [4].

Figure 3 shows examples of single-turn profiles of the injected beam. The horizontal centroid oscillations are expected, because the injected beam is offset horizontally from the central orbit. The horizontal smearing of the profiles comes from decoherence of the injected beam. Ideally the vertical plane would have neither betatron (centroid) oscillations nor vertical beam size (quadrupole) oscillations. Fits to the top set of profiles indicated 1.3 mm vertical betatron oscillations, and a 50% β_y mismatch of the injected beam before BTS tuning. Fits to the bottom profiles showed 0.2 mm vertical betatron oscillations and no detectable β_y mismatch after BTS trajectory correction and LOCO correction of BTS optics.

With optics and trajectory control, we were able to reduce radiation levels by about a factor of six.

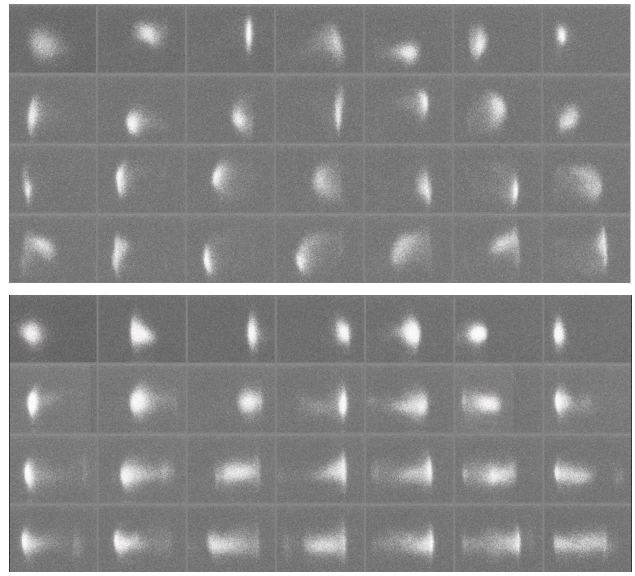
Figure 3: Synchrotron light monitor (SLM) measurements of the single-turn transverse profiles of the injected beam in SPEAR for the first 28 turns. Top: before BTS tuning. Bottom: after BTS trajectory and optics tuning.

REMOVING BTS WINDOWS

The radiation levels were further reduced by removing the BTS windows. During the 2008 summer SPEAR shutdown, the vacuum chamber of the BTS was upgraded, so the thin stainless steel windows separating the BTS vacuum from the SPEAR and booster vacuums could be removed.

Figure 4 shows the simulated injected beam distribution with the continuous vacuum from the booster to SPEAR. Comparing Fig. 4 to Fig. 1 shows that the beam size is reduced, particularly in the y dimension. This simulation predicts better than 99% injection efficiency, while the best injection efficiency we could expect with windows was 83%.

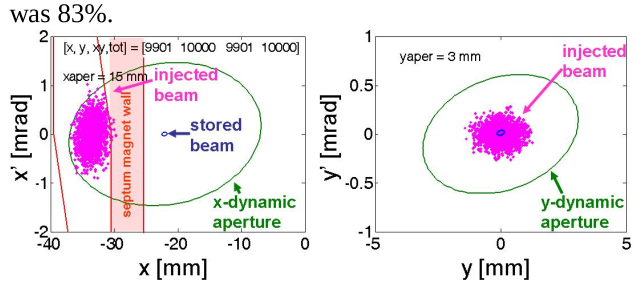

Figure 4: Simulated injected beam distribution, no BTS windows.

Figure 5 shows SLM measurements of the injected beam in SPEAR, after the BTS windows were removed. The measurements confirm the expected injected beam size reduction.

With BTS trajectory and optics control, and the BTS windows removed, we have reduced the measured radiation level on the beamline floor when injecting with photon beamlines open by about a factor of 20, well below the limit required for top-off injection.

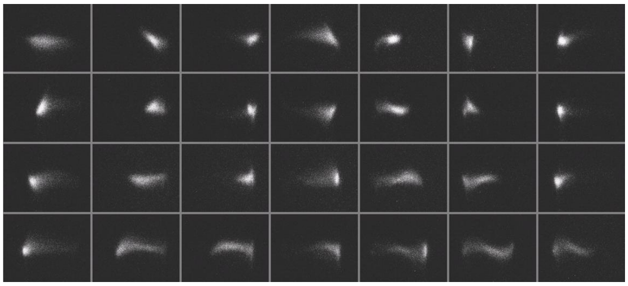

Figure 5: Single-turn injected beam profiles after removing the BTS vacuum windows.

TIME AND ENERGY MATCHING

Thus far we have discussed the control of the injected beam in the four dimensions x, x', y and y'. The energy and time of arrival of the injected beam also must be controlled. The single-turn BPMs in SPEAR can measure the longitudinal (synchrotron) oscillations of the injected beam. Figure 6 shows synchrotron oscillations with amplitude of about 1 radian in RF phase. The initial phase of these particular oscillations indicates that they arise from an error in arrival time of the injected beam. We can adjust the arrival time of the injected beam to eliminate the synchrotron oscillations.

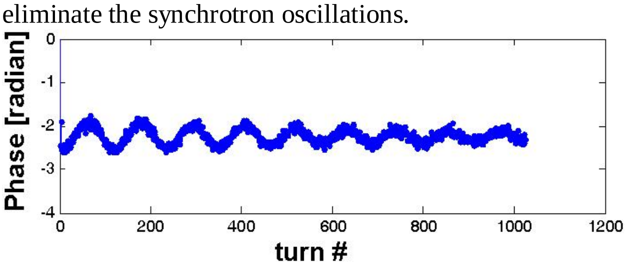

Figure 6: Measured synchrotron oscillations of injected beam in SPEAR.

Unfortunately, to make these measurements, we had to dump the stored beam, because the stored beam signal swamps the injected beam signal. For these measurements, we mis-timed two of the injection kickers to kick one injected beam pulse out before the arrival of the next, so no stored beam was accumulated. The injection kicker downstream of the injection septum is timed correctly to capture an injected pulse, but the two upstream kickers are fired a few tens of milliseconds later, kicking the pulse out. A new pulse arrives 100 msec (10 Hz injection) later. This wouldn't work during top-off operations, so we can not use this technique to maintain the injected beam match in time and energy.

The energy of the BTS electrons is determined according to the time they are extracted from the ramping booster. The trigger for extraction is generated by the ETG (extraction trigger generator), which fires when the booster dipole current reaches the appropriate level. We have used measured synchrotron oscillations in SPEAR to optimize the ETG several times over the course of a few months. Every time we ended up with the same optimum ETG value. The energy of the BTS beam is therefore quite stable, so we do not need a feedback to maintain it. Checking the energy every two weeks during accelerator physics will be sufficient.

The time of the injected beam, however, does vary significantly. Presently, timing adjustments are generally required at the start of each of the three daily fills. This is not surprising, because the booster RF is locked to the SPEAR RF. A long cable runs from the SPEAR master oscillator to the booster master oscillator. The cable length changes with temperature, altering the phase between the booster and SPEAR. We are presently investigating various ways to measure and correct this timing error.

These timing errors are not an immediate problem. A timing error can degrade injection efficiency, but radiation measurements indicate that this loss in injection efficiency does not lead to higher radiation levels on the beamline floor. The synchrotron oscillations most likely lead to injected beam loss at the SPEAR energy collimator rather than at the small gap insertion devices.

MAINTAINING OPTIMIZED INJECTION

In addition to our work to control the BTS trajectory with BTS BPMs, we have been working to eliminate sources of drift. We found that the pulsed booster extraction septum was the largest source of trajectory drift, so we have added a feedback to better stabilize the strength of this magnet.

The SPEAR optics also must be accurately controlled in order to maintain good injection efficiency. We have found that β-beating with peaks of 6% increases radiation levels by a factor of 2 to 3 during injection. In order to ensure that the SPEAR optics are well corrected, the SPEAR operator analyzes and (if necessary) corrects optics with LOCO every accelerator physics period. Nominally, β-beats are maintained below 1%.

ACKNOWLEDGEMENTS

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