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Experiences from First Top-Off Injection At The Stanford Synchrotron Radiation Lightsource

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Abstract

As the Stanford Synchrotron Radiation Lightsource (SSRL) of the SLAC National Accelerator Laboratory (SLAC) is moving toward Top-Off injection mode, SLAC's Radiation Protection Department is working with SSRL on minimizing the radiological hazards of this mode. One such hazard is radiation that is created inside the accelerator concrete enclosure by injected beam. Since during Top-Off injection the stoppers that would otherwise isolate the storage ring from the experimental area stay open, the stoppers no longer prevent such radiation from reaching the experimental area.

The level of this stray radiation was measured in April 2008 during the first Top-Off injection tests. They revealed radiation dose rates of up to 18 microSv/h (1.8 millirem/h) outside the experimental hutches, significantly higher than our goal of 1 microSv/h (0.1 millirem/h). Non-optimal injection increased the measured dose rates by a factor two. Further tests in 2008 indicated that subsequent improvements by SSRL to the injection system have reduced the dose rates to acceptable levels.

This presentation describes the studies performed before the Top-Off tests, the tests themselves and their major results (both under initial conditions and after improvements were implemented), and presents the controls being implemented for full and routine Top-Off injection.

1. Overview

1.1. Introduction to SSRL

The "Stanford Synchrotron Radiation Lightsource" (SSRL) evolved from the high-energy physics synchrotron "SPEAR" of the early 1970s and has by now been twice upgraded. The current storage ring, SPEAR3, is fed by a 10 Hz 150 MeV Linac and a Booster, which accelerates the electrons to 3 GeV before injecting them through the BTS line (Booster-To-SPEAR) into the SPEAR3 ring. The ring carries a current of 100 mA, and is typically refilled three times a day, each time from about 85 mA back up to 100 mA. Later this year SPEAR3 will run with a current of 500 mA, and injection will also soon be upgraded from currently 1.5 to 5 W maximal injection power. SPEAR3 is currently providing synchrotron radiation to 13 photon beamlines with about 30 experiment stations.

1.2. Motivation for and Modes of Top-Off Injection

Up to now, the Injection Stoppers (IS), which isolate the storage ring from the experimental area, are being closed for the time the storage ring is being filled. While this closing ensures that neither electrons nor Bremsstrahlung can reach the beamline hutches during injection, it also causes temperature changes at optical

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components, which results in alignment changes. At 100 mA these shifts are still small enough, but at higher currents they become disruptive. Fig.1 illustrates modes of operation for future 500 mA operation. If injection would be performed three times a day (top left of Fig.1), the changes in alignment throughout the day would be large. Raising the frequency of injection keeps the alignment more stable, because the intensity of the SR beam would stay more constant. The ultimate goal is trickle injection: Injection once a minute (bottom right of Fig.1). Such high injection frequency requires Injection Stoppers to stay open and requires good injector performance. It also leads to higher beam losses over time, since the stored beam current remains high, where the beam lifetimes are shortest. Note that other facilities adopted the term "top-up" for the same mode of operation.

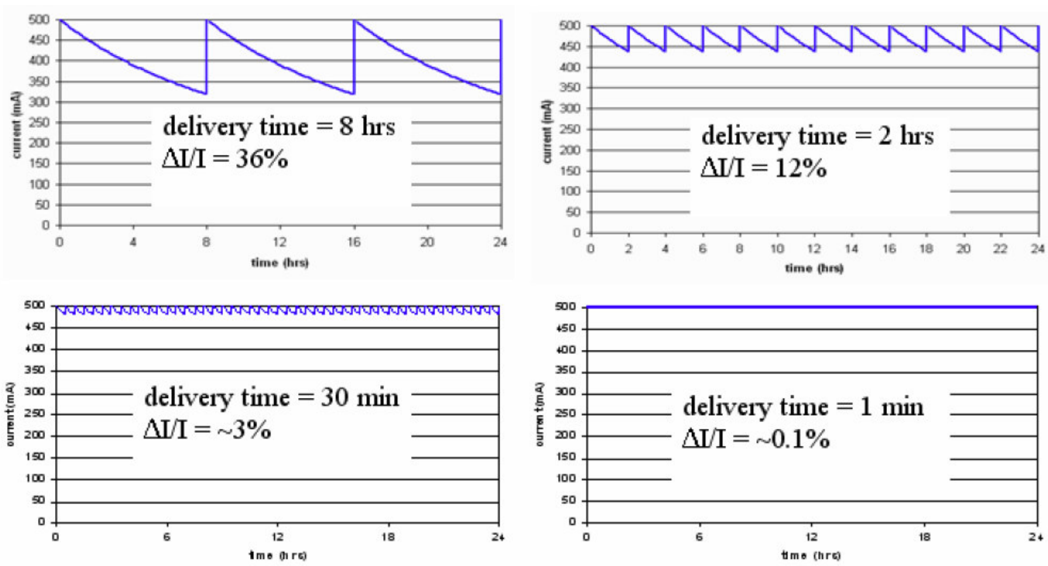

Fig.1 – Illustration of possible modes of operation throughout one day at 500 mA.

2. Preparing for Top-Off

2.1. SSRL/LBNL Ray Trace Studies

Since the beam chamber apertures and magnets constrain where beam can go and whether beam can be stored, SSRL, in collaboration with Lawrence Berkeley National Laboratory, performed a ray trace study to determine the limits on the magnet settings that ensure that injected beam will never make it past certain apertures ("safety endpoints") and hence never enter the experimental area [1]. These settings now serve as the basis for the envelope that the Top-Off Safety System is enforcing.

2.2. Radiological Considerations

During normal Top-Off operation, additional radiation can be expected from forward-angle Bremsstrahlung created when electrons from the injected beam hit apertures. This dose must be small enough that the experimental area sees not more than 1 mSv (100 mrem) in 1000 hours from all sources.

Additional radiation may be created by mis-steered beam, which is defined as beam that is not following its intended trajectory but is still within the bounds of the safety system, *i.e.*, within the safety endpoints. Simulations estimate dose rates of up to 22 mSv/h (2.2 rem/h) at 5 W injection, but such serious mis-steering is expected to happen only very rarely, and radiation monitors will be in place to terminate injection if any radiation dose rate above 0.02 mSv/h (2 mrem/h) is detected.

The worst radiological consequences would be due to beam entering a beamline hutch, but such an event is very unlikely, as it requires several serious system failures and mis-steering at the same time. According to simulations, the dose rate could reach up to 3.3 Sv/h (330 rem/h) at 5 W injection, but with radiation monitors quickly shutting off injection on such high radiation (within ~1 second), the per-event dose is limited to 0.74 mSv (74 mrem) maximum.

2.3. Dose Components

The radiation detected at the outside of the hutch can be split into a total of four components, depending on (1) whether the radiation passes through the accelerator enclosure walls or enters the hutch through the beam pipe, followed by a scatter on the first optical element, and on (2) whether the radiation is created by stored beam or by injected beam. The components are accordingly labeled in the following way:

- D_{sw} – radiation from stored beam, passing through wall
- D_{sb} – radiation from stored beam, passing through beam pipe & scattering at 1st optical element
- D_{iw} – radiation from injected beam, passing through wall
- D_{ib} – radiation from injected beam, passing through beam pipe & scattering at 1st optical element

Only the last component, D_{ib}, is added when moving to Top-Off injection. All other components are already present in current operation.

2.4. Top-Off Safety Systems

Several of the safety systems being added at SPEAR3 for Top-Off are part of the so-called "Beam Containment System" (BCS):

- The Stored Current Interlock ensures that photon beamlines can open for Top-Off injection only with stored current above 50 mA. (This is important because the lattice necessary for successfully storing beam is unlikely to result in mis-steered injected beam.)
- The ring and BTS line apertures, which were part of the above-mentioned ray trace analysis, may not be modified without prior approval.
- Magnet Power Supply Interlocks prohibit Top-Off injection if the voltage or current at specific magnets are beyond specified limits.
- Clearing Magnets along dipole photon beamlines bend away any electron that would make it into the beamline.
- Radiation monitors stop Top-Off injection if they detect a dose rate above 0.02 mSv/h (2 mrem/h) outside the photon beamline (Dose Rate Interlock).

The other Top-Off safety systems are not part of the BCS:

- A Daily Dose Interlock is implemented through the radiation monitors, restricting the dose to maximal 0.01 mSv (1 mrem) per day.
- A Charge Loss Interlock similarly blocks Top-Off injection if more than a certain number of electrons are lost each day.

Present, but not counted as safety systems, are also Machine Protection System interlocks and tight software warnings. Note that the Top-Off safety system only inhibits Top-Off injection. Non-Top-Off injection, *i.e.*, injection with Injection Stoppers closed, is not affected.

3. Beam Test Phase

3.1. Beam Conditions

Two major types of injection were studied during the tests: (1) High-Efficiency Injection, consisting of normal 1 W injection with about 60 to 80% injection efficiency. (2) Low-Efficiency Injection, during which the 1 W injection beam was intentionally mis-steered inside the BTS by modifying specific parameters. This created losses inside the SPEAR3 ring at apertures and lowered the injection efficiency to about 30 to 50%.

3.2. First Tests

The first set of Top-Off tests took place April to July 2008. Two types of detectors with remote readouts monitored radiation close to the hutches: The interlocked, SLAC-built Beam Shut-Off Ion Chambers (BSOIC); and the Beamline Radiation Monitors, HPI 6030 ion chambers with HPI 6012 readout modules. Since the Top-

Off BCS did not yet exist at that time, access to the experimental area was restricted. Surveys were taken with handheld dose meters to determine the location of the highest radiation at the hutches.

Fig.2 illustrates a typical period of such tests for two photon beamlines, BL 5 (top) and BL 11 (bottom). The left half of each plot shows three high injection efficiency fillings to 100 mA (light blue lines with triangle shape). The measured radiation outside BL 5 (red) rose whenever the Injection Stoppers of that beamline were opened (indicated by green box-lines). Such behavior was not seen at BL 11 (pink line indicating the measured radiation, orange the stopper open/closed state). The data from low-efficiency injection are displayed in the right part of the plot. As expected, the time to reach 100 mA increased. The radiation reached higher levels at BL 5, and BL 11 also showed measureable radiation.

At other times during the tests, even higher radiation was seen than displayed in Fig.2: Up to 18 microSv/h (1.8 mrem/h) during high-efficiency injection, and up to 30 microSv/h (3 mrem/h) during low-efficiency injection, both at BL 5. The levels of radiation measured by the remotely read instruments were confirmed in field surveys.

The results fall into three major categories: Beamlines like BL5 with significant radiation during both high- and low-efficiency injection; beamlines like BL11 at which excess radiation was only measured during low-efficiency injection; and beamlines that did not display excess radiation in either situation.

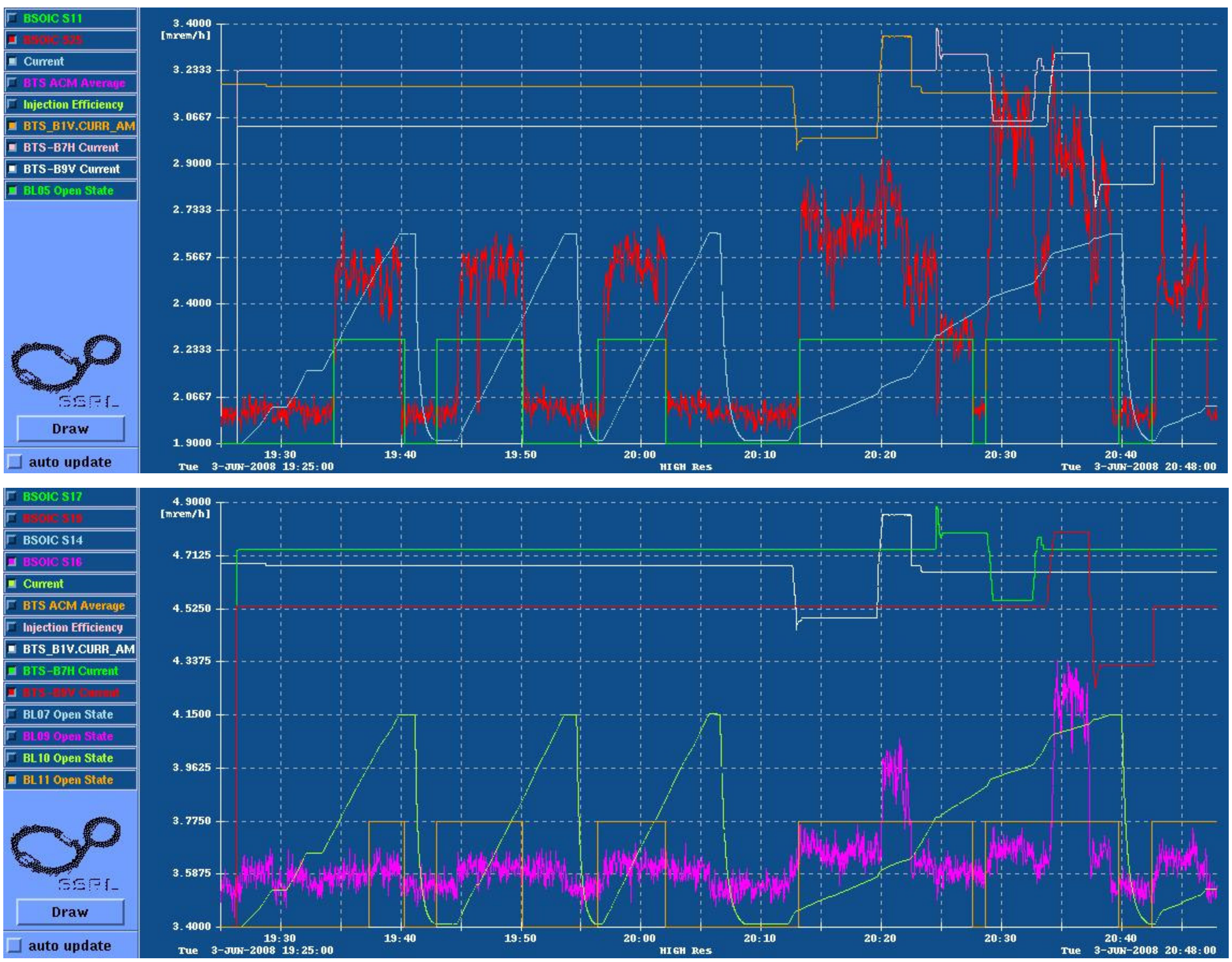

Fig.2 – Typical results from first Top-Off tests for BL 5 (top) and BL 11 (bottom). Three high-efficiency injections (left) were followed by one low-efficiency injection. The units on the vertical axis correspond to the radiation measurements of the BSOIC (red on top, pink on bottom).

Extrapolating the measured radiation to long-term operation at 100 mA, 200 mA and 500 mA trickle injection reveals that even for the worst beamline, BL 5, the total dose during 100 mA operation would lead to a dose on the order of only 190 microSv (19 mrem) in 1000 hours. At 500 mA trickle injection, however, the additional dose from component D_{ib} (the component special to Top-Off) can be up to 2.34 mSv (234 mrem) in 1000 hours. This clearly indicated a need to improve injection.
Of the other dose components, only D_{sb}, the dose from the stored beam's Gas Bremsstrahlung traveling through the beam pipe into the beamline hutch, was high with a maximum of 1.66 mSv (166 mrem) in 1000 hours of future 500 mA trickle injection operation. This dose is solely due to stored beam and does not increase during Top-Off injection. Additional shielding will be required for the beamlines with the highest values of D_{sb}.

3.3. SSRL Improvements to Injection

While the injection system was adequate up to now, Top-Off injection raised the bar, and SSRL responded. The effect of changes to the horizontal and vertical position and angle of the injected beam, to its energy and to its timing were studied. With new diagnostic devices, SSRL gained better control of the beam optics and lattice. During the Summer 2008 down-time, the last vacuum windows were removed from the BTS line, creating one single vacuum volume from the Linac all the way to SPEAR3. The simulations promised sufficient improvements (Fig.3).

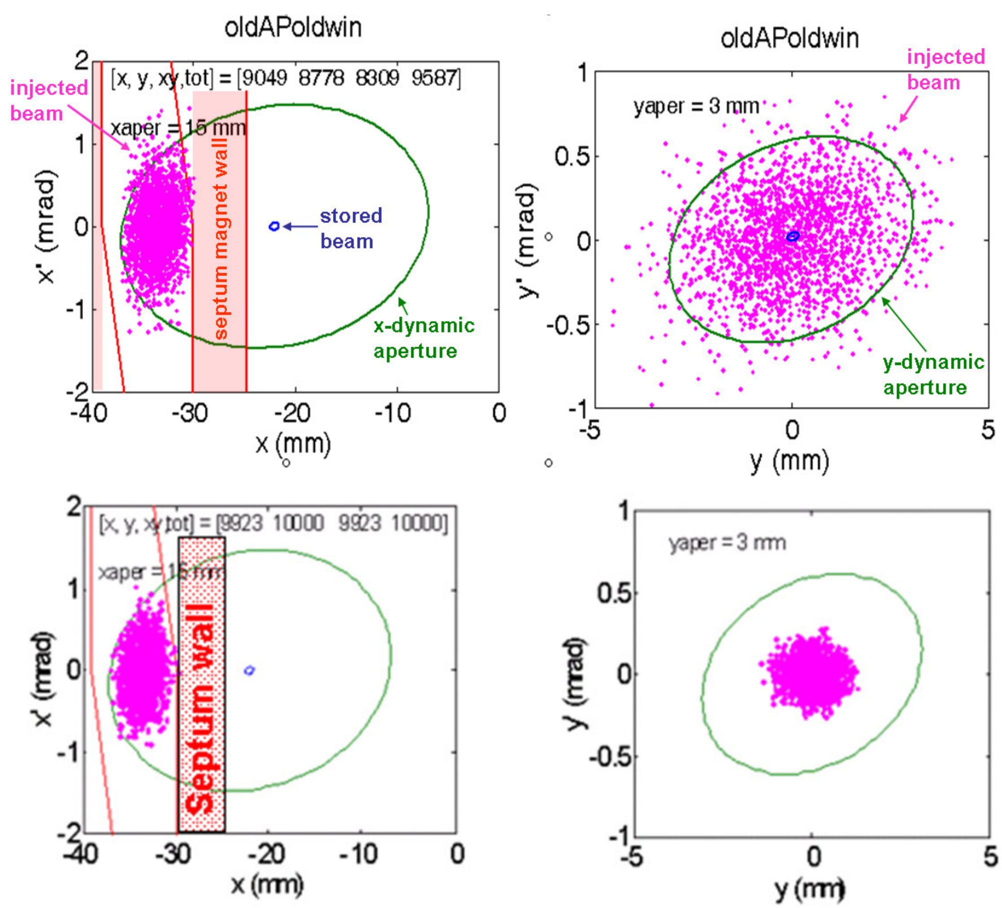

Fig.3 – Results of SSRL simulations studying the effect of the vacuum windows (top with windows, bottom without windows) on the x and x' (left) and the y and y' distributions of the injected beam. The plots indicated that removal of the windows leads to tighter focused beam.

3.4. Measurements with New Injection

In Fall 2008, the measurements of radiation during Top-Off were repeated with the improved injection beam. The dose rates were indeed found to be lower, about 10 times lower than before, with 1.6 microSv/h (0.16 mrem/h) now being the worst reading measured during high-efficiency injection. Extrapolating this worst dose rate to 1000 hours leads to an estimation of just 92 microSv (9.2 mrem) during 500 mA trickle injection operation.

Low-efficiency injection also showed much lower dose rates than before, only up to a maximum of 4.8 microSv/h (0.48 mrem/h). The 1000 hour dose comes still to 2.8 mSv (280 mrem), but prolonged operation in this mode would be untenable, since it would take 50 minutes to just add 100 mA to the stored current. The measurements with the new injection therefore cleared the way to Top-Off injection operation.

4. Summary of Test and Path Forward

The initial tests revealed that the long-term dose rate was of no concern for 100 mA Top-Off operation, but that improvements to the injection system were needed for higher currents. Once these improvements were in place, the system performed with radiation levels low enough that radiation can be expected to be within the limits even for 500 mA trickle injection.

Top-Off is scheduled to start in July 2009, first only for a few photon beamlines, others to be added in the coming months. Warning systems for injection beam lattice and optics, as well as Daily Dose Interlock and Charge Loss Interlock are expected to be in place for operation at higher currents. 500 mA operation is scheduled to start in Fall 2009. Additional shielding will be needed for some beamlines, not for Top-Off operation, but for radiation from Gas Bremsstrahlung created in stored beam operation, and a new safety system will lower the risk from thermal damage caused by the beam. And on the horizon, beyond 2009, are upgrades to trickle charge injection and to injection above 1.5 W in power.

5. Conclusion

After the first Top-Off tests measured higher dose rates than expected, SSRL improved the injection system such that the radiation during Top-Off injection is now projected to be low enough even for 500 mA trickle injection. Still, stored-current dose issues will need to be addressed for operation at more than 200 mA. Normal user runs will soon include Top-Off injection, and operation at higher currents will follow shortly thereafter, leading to a major improvement in the performance of SSRL.

References

[1] J. Safranek *et al.,* “SPEAR3 Accelerator physics update,” PAC07-TUPMS055, SLAC-PUB-12949, Proceedings of Particle Accelerator Conference (PAC 07), Albuquerque, New Mexico, U.S.A., June 2007.