SSRL Performance Enhancements

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Abstract. SSRL plans an ambitious program of beam line upgrades including replacing some existing wiggler beam lines with in vacuum undulators as well as developing up to five new in vacuum undulator beam lines resulting in as many as 10 undulator beam lines in a fully built out SPEAR3. SSRL also plans accelerator upgrades in the near future to further reduce the effective beam emittance to $\approx 6$ nm and minimize vertical motion of the tunnel floor. By upgrading the injector rf system to a frequency commensurate with SPEAR3 and operating the electron gun in photo-cathode mode, top-off injection can be implemented in a multi-bunch pulse train mode. Short pulse operation for ultrafast pump/probe science is accomplished with a few-ps low-alpha configuration in either a few discrete buckets or in a hybrid mode with discrete buckets and hundreds of other buckets filled to higher charge and longer pulse length. All of these improvements are part of a coordinated plan to provide the User community with reliable operations and increased experimental capability.

1. Introduction
The SPEAR3 accelerator at the Stanford Synchrotron Radiation Lightsource was commissioned in 2004. Since that time a number of improvements have been implemented including the beam emittance reduced from 18 to 10 nm, the lattice modified to operate in a `double waist' configuration, user operations current increased from 100 mA to 450 mA, three new beamlines added, low-alpha mode developed to deliver 1-10 ps long bunches and top-off operation implemented with automated injections every 5 minutes. The injector was commissioned in 1990 and is now over 20 years old but the injector RF system is over 30 years old. Recent upgrades including new injection and extraction kicker pulsers, removal of multiple vacuum windows in the Booster-to-SPEAR (BTS) transport line and commissioning of new transport line BPMs to optimize optics and trajectory were implemented to enable top-off operation. Now that the accelerator has reached the design performance parameters, we are beginning to implement an ambitious beam line and accelerator upgrade program to provide the User community with reliable operations and increased experimental capability.

2. Performance Improvements
SSRL plans to add up to five new in-vacuum undulator (IVUN) beam lines and to replace some existing wiggler beam lines with IVUNs, resulting in as many as 10 undulator beam lines in a fully built out SPEAR3. We are investigating options to decrease the emittance to the 5 nm level over the next few years. We have recently begun dedicated low-alpha user operation with bunches as short as 1 ps with

* Work supported by the U.S. Department of Energy under contract number DE-AC02-76SF00515.
low charge and are exploring ways to simultaneously deliver high charge bunches to other users. We are also working to decrease beam motion at the beamlines and to reduce the duration of injection transients with injector upgrades.

### 2.1. Reduced Emittance

We are investigating options that reduce the emittance of the ring from 10 nm to 5 nm in a two-phased approach [1-2]. In phase I we consider new lattices using existing magnets to fully exploit the potential of the ring. The integer part of the horizontal tune for these lattice options is increased by one unit. The fractional part was determined by tune scans in various regions of the tune diagram. In general a larger increase of horizontal tune leads to a smaller emittance, but with a reduced dynamic aperture due to large tune shifts with amplitude. We have focused on two lattices. The first has 6.8 nm emittance and a measured injection efficiency of 60% and the second has a 6.1 nm emittance and a measured injection efficiency of 15% both with IDs closed. This compares to injection efficiencies greater than 90% for the standard 10 nm lattice. Both reduced emittance lattices currently require perturbation to the stored beam but that can be eliminated by increasing the injection kicker strength, reducing the separation between the injected beam and the stored beam in an upgraded septum magnet, and increasing the number of sextupole power supply families from four to ten.

In phase II super-conducting damping wigglers could be added to two of the matching straight sections or one of the long straight sections (currently occupied by rf cavities) to reduce the emittance from 6.8 nm to 5 nm. The peak magnetic field may be 5 T. These devices can be excellent hard X-ray sources, although it may be challenging for photon optics to handle the high power and power density.

### 2.2. Insertion Devices

With 5-10 nm emittance, SPEAR3 is well suited to instrumentation with IVUN beam lines for high brightness applications. Present plans include development of a 19mm period, 154 pole IVUN beam line for micro-crystal macromolecular crystallography. This IVUN would share the 10 mrad east pit chicane straight with the 22 mm period, 134 pole IVUN currently serving as the source for macromolecular crystallography beam line 12-2. Further, two 22 mm period, 174 pole IVUNs are slated for installation in standard 2.3m SPEAR3 straights. The first of these IVUNs, which is scheduled for installation in the summer of 2013, will be utilized for a high brightness advanced spectroscopy beam line with tandem experimental stations featuring an ambient pressure photo-emission system upstream and an X-ray Raman Scattering and X-ray Emission Spectroscopy station downstream. A small and wide angle X-ray scattering beam line will be implemented on the other U22 IVUN. The performance characteristics of these sources with the 5 nm phase II SPEAR3 emittance is depicted in Figure 1. Installation of these three IVUNs leaves two 3.5m long IVUN-capable matching straights available for future development.

**Figure 1:** Brightness (left) and central cone flux (right) tuning curves of the U19 and U22 IVUN for 5 nm SPEAR3 emittance with 0.1% coupling at 500 mA. Only odd harmonics are depicted and the central cone flux is calculated at peak axial brightness.

Complete exploitation of the reduced SPEAR3 emittance necessitates conversion of some of the legacy wiggler beam lines presently installed on SPEAR3 into undulator beam lines. Conversion is complicated by the presence of well-established user communities on the existing wiggler stations. A
carefully orchestrated beam line upgrade program relocates several experimental programs to new beam lines thus affording the opportunity to upgrade two wiggler sources to IVUNs without displacing users. When brought to fruition this program of new beam line development and conversion of legacy wiggler beam lines will transform SPEAR3 insertion device sources from the six wigglers and three undulators circa 2012 to four wigglers and as many as 10 undulators.

2.3. Short Pulses
SPEAR3 is well suited to operate in the short-pulse, low-alpha optics mode with electron bunch lengths less than 10 ps fwhm [3-4]. Applications include high rep-rate X-ray pump-probe science and (with installation of a new beamline) short-pulse high-field THz research. The short pulse low-alpha mode is complementary to the low repetition rate, high temporal resolution LCLS facility. However, short pulse operation generates high-frequency spectral components which interact with the storage ring to increase the bunch length and limit the total current to approximately 30 mA or less.

In order to accommodate more users in the low-alpha mode, SPEAR3 now offers periodic beam operation in ‘hybrid’ mode whereby 1-4 low-alpha bunches circulate with low beam current for short-pulse production and the remaining bunch pattern is filled with higher current but longer pulses to deliver an average beam current of 100 mA or more. The short bunches are isolated by >50 ns to allow time for detector gating and, in some cases, sample relaxation. The remaining buckets are filled to just below the ‘bursting threshold’ (about 400 µA each in the 10 ps mode) to deliver stable photon beam on sample. To date SPEAR3 has operated in ‘hybrid’ mode in three separate 48 hour intervals. Despite reduced beam quality (35 nm emittance and 100 mA), standard users representing a range of measurement disciplines on remaining beam lines at SSRL have reported successful data acquisition. Nonetheless we are investigating alternative means of delivering higher current and shorter bunches as well as the impact of increasing the impedance on pulse length in hybrid mode due to installing multiple IVUNs in the future.

2.4. Beam Stability
The SPEAR3 accelerator shielding has been upgraded for seismic stability one small section at a time over the last 20 years. Beam stability was not part of the design considerations, and thus the SSRL floor exhibits differential mode vertical motion on the order of 10 microns per day due to thermal gradients. Various experiments were undertaken to determine the source of the floor motion. Painting the shielding white to reflect as much solar radiation as possible reduced the motion by 15%. Temporarily installing mylar to reduce solar heating of the asphalt region inside the ring inner diameter that could be pushing on the ring walls had no measureable effect. Ultimately an order of magnitude reduction in motion was realized by adding insulation on the roof and inner wall of the concrete tunnel shielding. Figure 2 shows the 24 hour motion around the ring before (blue) and after (red) R20 insulation was added around beamlines 7 and 10 (sensors 1 to 4 in figure). This corresponded to a reduction in photon beam pointing error from ~0.7 µradian/outdoor ° C to ~0.4 µradian/outdoor ° C after the insulation was added. We are in the process of adding identical insulation around the majority of the ring. Additional efforts to reduce photon beam motion include adding insulation to the mirror cooling water supply lines and adding roughly 20 gallon water mixing tanks to reduce temperature fluctuations to better than 0.05°C.

2.5. Injector Enhancements
The Booster RF system has been in service for more than 30 years. In the last few years the klystron and klystron high voltage power supply have both failed, resulting in multiple day repair times. Only two functioning klystrons remain out of the original four, leaving only one spare. Due to the frequency difference between the booster (358 MHz) and SPEAR (476 MHz), it is only possible to inject into a single bucket at a time. In order to operate the machine reliably for another 20 years the booster RF system needs to be upgraded.
The new system will operate at 475 MHz which is close to the SPEAR frequency and allow injecting 10-20 long pulse trains while still maintaining the current injection timing configuration. The baseline design is a copy of the PEP-II (a decommissioned SLAC high energy physics facility) RF station consisting of two single-cell cavities and a 1.2 MW klystron powered by a 2.75 MW high voltage power supply [5]. While these components are available at no cost, the cost for installation and commissioning is substantial. Once in service, the system will operate at a small fraction of the design values, leading to expected high reliability but low energy efficiency.

The SPEAR injector derives its electron beam from a thermionic cathode inside a 1.5 cell RF gun. Current from the gun is naturally bunched at the radio frequency (2856 MHz). Three to six successive bunches are subsequently selected by an electromagnetic chopper magnet commissioned in 1990. Injection into multiple 475 MHz booster buckets will require the thermionic cathode to be operated as a laser-driven photo-emitter [6]. To this end we have measured the quantum efficiency of a dispenser cathode and have demonstrated injection rates > 80 mA/minute with only a single booster RF bucket. The booster RF and photo-cathode upgrades will enable multi-bunch injection into SPEAR3. This will reduce the injection interval and thereby reduce the impact of injection transients on sensitive users as well as improve reliability by eliminating the obsolete chopper.

![Figure 2: 24 hr Fourier component of vertical beam motion at various sensors located around the SPEAR3 ring before and after insulation was added around areas marked 7U, 7D, 10U and 10D.](image)

3. Conclusion
SSRL is beginning to implement a long term strategic plan to increase the number of insertion devices, reduce the emittance, provide ps pulses, improve beam stability and improve the injector reliability.

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