

# DESIGN OF THE SPEAR 3 LIGHT SOURCE<sup>†</sup>

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## Abstract

The venerable SPEAR storage ring will be replaced in 2003 with a modern, low emittance 3 GeV ring optimized for producing high flux and high brightness photon beams at the Stanford Synchrotron Radiation Laboratory. SPEAR 3 will have an emittance of 18 nm-rad, reduced from 160 nm-rad, and a 500-mA beam current, increased from 100 mA. A water-cooled copper vacuum chamber will be thermally stable and, together with mode-damped RF cavities, will assure multibunch beam stability. Beam lines will see one to two orders of magnitude increase in beam flux density and brightness after they have been upgraded for the higher beam power. A 6-month ring installation is planned to minimize the impact on the SSRL user program. SPEAR 3 accelerator design and beam properties are reviewed.

## 1 OVERVIEW

While the SPEAR storage ring at the Stanford Linear Accelerator Center was constructed in 1972 for e<sup>+</sup>/e<sup>-</sup> colliding beam research, synchrotron radiation (SR) beam lines have been included in the facility from the onset. Beam lines have been added one at a time over the last 25 years so that now there are 30 experimental stations on 11 main beam lines. The colliding beam program ended in 1989 and SPEAR became a dedicated SR source operating at 3 GeV and 100 mA with a 160 nm-rad emittance. The SSRL user program continues to grow and beam line usage is presently over-subscribed.

To better serve the expanding SSRL user community, SPEAR is scheduled for a major upgrade in 2003 [1]. With an 18 nm-rad beam emittance and 500 mA current, SPEAR 3 (following the SPEAR 2 name associated with a 1974 RF system upgrade) will provide 3<sup>rd</sup> generation light source performance, especially in the 1-4 keV photon energy range. The SR brightness and focused flux density at experimental stations will increase by an order of magnitude for insertion device (ID) beam lines and, because of a higher critical energy, by two orders of magnitude on bending magnet beam lines. With its

moderately low emittance, SPEAR 3 is optimized for applications benefiting from high focused flux density rather than brightness (e.g. macromolecular protein crystallography) and is served by several high-field wigglers. Nevertheless, new IDs are being considered, including a 4-m undulator (1.4 keV fundamental) [1], a soft X-ray elliptically polarizing undulator (EPU) and a fast-switching double EPU [2] (both EPUs operating in the 0.25-3 keV energy range). Each has a brightness approaching 10<sup>19</sup> (photons/sec/mm<sup>2</sup>/mrad<sup>2</sup>/0.1%BW).

The ~58 M\$ SPEAR 3 upgrade project is administered by the DOE, with joint funding from the National Institutes of Health. It will replace the existing storage ring magnet, vacuum chamber, RF, and power supply systems in a ~6 month shutdown period that minimizes the impact on the SSRL scientific program [3]. The new double-bend achromat (DBA) lattice fits in the existing ring tunnel and maintains the present beam line alignment (Figure 1). The lattice provides four enlarged 4.8-m straight sections flanking two 7.6-m racetrack straights, while maintaining the twelve 3.1-m straight sections in the arcs. A modified injection transport line and new septum magnet enables 3-GeV, at-energy injection. Shielding, utilities and other ancillary systems will be modified before the main shutdown period. Machine and beam parameters for SPEAR 2 and SPEAR 3 are compared in Table 1.

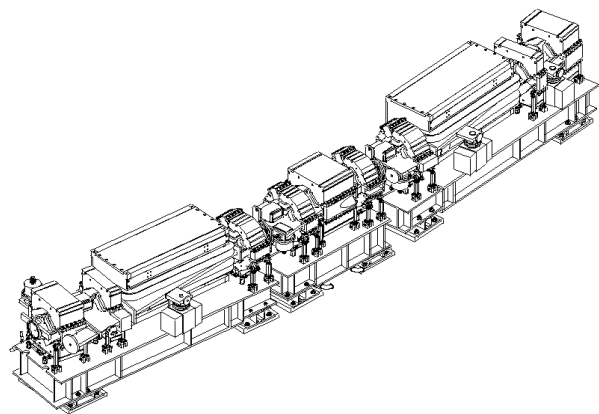


Figure 1: DBA magnet cell with 2 gradient dipoles, 5 quadrupoles, 4 sextupoles, and 4 H/V correctors.

<sup>†</sup> Work supported in part by DOE Contract DE-AC03-76SF00515 and Office of Basic Energy Sciences, Division of Chemical Sciences.

Table 1: Parameters for SPEAR 2 and SPEAR 3.

	<b>SPEAR 2</b>	<b>SPEAR 3</b>
Energy	3 GeV	3 GeV
Current	100 mA	500 mA
Emittance (w/ID)	160 nm-rad	18 nm-rad
RF frequency	358.5 MHz	476.3 MHz
RF gap voltage	1.6 MV	3.2 MV
Lifetime @ I <sub>max</sub>	30 h	>17h
Critical energy	4.8 keV	7.6 keV
Tunes (x,y,s)	7.18,5.28,.019	14.19,5.23,.007
e- $\sigma$ (x,y,s) - ID	2.0,.05,23 mm	.43,.03,4.9 mm
e- $\sigma$ (x,y,s)-dipole	.79,.20,23 mm	.16,.05,4.9 mm
Injection energy	2.3 GeV	3 GeV

SPEAR 3 will initially operate at ~200 mA for experimenters until all beam lines have been upgraded with liquid nitrogen-cooled monochromators or other intensively cooled elements for higher current operation. The separately funded beam line upgrades are planned for completion by 2005.

## 2 LATTICE AND BEAM PROPERTIES

The 234-m racetrack magnet lattice has 14 standard magnet cells and 4 matching cells flanking the two long straight sections. The DBA lattice maintains the existing beam line alignment and eliminates the emittance increase caused by high-field IDs. Moderately low beta functions in the straight sections ( $\beta_x=10.2$  m,  $\beta_y=4.7$  m) provide small beam size without jeopardizing injection. Betas are below 18 m globally to reduce sensitivity to field errors and minimize beam-stay-clear. Gradient dipoles are required to gain adequate vertical focusing and separation of transverse beta functions at sextupole sites. The optics can be modified for finite dispersion in the straight sections to reduce emittance by up to 30%. Vertical coupling and beam size are adjusted using 14 skew quadrupoles. The matching cells can be tuned for future applications requiring lower beta functions in the long straights. Betatron tunes were chosen to below the half integer to reduce resistive wall beam instability. Dynamic aperture with magnet errors and ID aberrations is 18 mm for 3% off-energy particles.

Electron beam dimensions at SR beam source points (assuming 1% coupling) are given in Table 1. The goal for transverse beam stability is <10% of the photon beam size and divergence. This stability level will be reached by minimizing magnet thermal motion and vibration relative to beam line optical components, and by using orbit feedback to maintain rms beam position to ~20  $\mu$ m horizontally and ~5  $\mu$ m vertically at stable BPMs. Coherent longitudinal bunch oscillations must be <~0.3° rms (dE/E <0.01%) to maintain <10% position stability at dipole source points; this energy stability is adequate for <10<sup>-4</sup> undulator harmonic energy resolution.

The total lifetime at 500 mA is calculated to be 18 h,

comprised of a 28 h gas scattering lifetime (assuming a conservative 1.8 nTorr N<sub>2</sub>-equivalent pressure) and a 53 h Touschek lifetime. The Touschek lifetime calculation assumes that 279 out of 372 bunches are filled with 3.2 MV RF gap voltage, 1% coupling, and 3% energy acceptance. A 93-bucket gap (1/4 of the ring) is left empty to avoid ion trapping. A future "top-off" injection mode will maintain a high average beam current.

## 3 ACCELERATOR SYSTEMS

The SPEAR 3 lattice has 36 C-shape gradient dipoles ( $k = -0.33$ ), 94 Collins-type quadrupoles, 72 closed-yoke sextupoles, 54 horizontal and 54 vertical combined function dipole correctors, and a vertical Lambertson septum magnet. Magnets are optimized for 3 GeV operation but can be run at 3.3 GeV. Magnets and vacuum chamber will be pre-assembled and aligned on 3 new steel girders per cell (Figure 1) prior to installation. Magnets will be mounted on the girders with 6-strut supports. The girders will be rigidly mounted on a new reinforced concrete floor and will have a lowest frequency vibration mode of ~35 Hz.

Magnet cores are made with AISI 1010 steel laminations with chamfered ends to improve integrated field quality. A straight core was chosen for the 1.45-m dipole to simplify construction at the expense of a wider pole for the 33-mm beam sagitta. The 50-mm dipole gap (at pole center), 70-mm quadrupole diameter and 90-mm sextupole diameter were chosen as a trade-off between beam chamber aperture and magnet size. Quadrupoles and dipoles have ~2% trim coils for beam-based alignment excitation; sextupoles have skew quadrupole trim coils. Lattice magnets are being built in collaboration with IHEP in Beijing, as was done for the PEP-II Low Energy Ring. Corrector cores are 16.1 cm long and provide  $\pm 1.5$  mrad horizontal and  $\pm 0.75$  mrad vertical steering. Each is enclosed with a steel field-clamping box that provides a uniform magnetic environment at various corrector sites. Magnets are powered by IGBT chopper-style supplies.

The machined copper vacuum chamber will be electron beam-welded at SLAC, as was done for the PEP-II High Energy Ring chamber. A water-cooled design with antechamber, discrete photon stops and titanium sublimation pumps (TSPs) has been chosen to achieve low pressure, high thermal stability and resistance to damage from the high powered SR beams (Figure 2). The 8.9-m girder chamber has 3 bellows-connected sections to fit on the 3 support girders. The wall thickness is 4 mm in the electron beam channel and machined to 3 mm at quadrupole and sextupole sites to accommodate magnet poles. Sloped masks and crenulated crotch-type absorbers intercept powers of 0.5-8 kW with power densities as high as 20 W/mm<sup>2</sup> and fan heights as small as 0.5 mm. They employ GlidCop™ to handle the thermal stresses. New chambers are passively

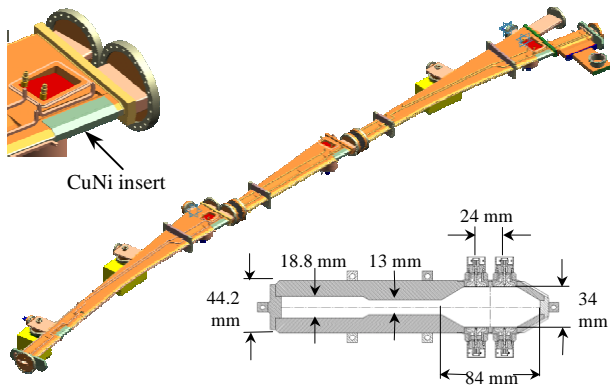


Figure 2: Water-cooled copper vacuum chamber with CuNi inserts at corrector sites for higher AC field penetration. BPM button diameter is 12 mm.

safe to 50 mA for ID radiation and to >500 mA for dipole radiation. An orbit interlock system using 20 BPMs will be activated for currents >20 mA to prevent chamber damage from mis-steered ID beams and damage to un-cooled bellows in dipole beam lines.

Resistive CuproNickel™ inserts in the copper chamber at corrector sites (Figure 2) reduce eddy currents and increase AC field penetration from orbit correctors to the order of 100 Hz (3 dB attenuation). BPM thermal motion is reduced to  $3 \mu\text{m}/^\circ\text{C}$  vertically using Invar supports mounted to the bottom of the girder. Chamber RF impedance is reduced by minimizing step discontinuities, providing 5:1 transitions between different cross sections, using RF-shielded bellows, and slotted pipe injection kickers [4]. Solid-state induction pulsers (using IGBTs) will power the 3 kickers [5].

Four PEP-II mode-damped 476.3 MHz RF cavities [6] (Figure 3) located in the West long straight section, together with the digital control system, will replace the present 358.5 MHz 5-cell cavity system to provide stable high current operation. The 1080 kW needed to produce a 3.2 MV gap voltage for 500 mA will be supplied by a PEP-II-style 1.2 MW klystron with HV power supply (90 kV, 27 A, SCR voltage control).

The existing VMS computer control system is being enhanced with a Channel Access server to enable the use of high level EPICS tools and applications. Many control and machine modelling applications will be configured using MATLAB™, which has a Channel Access interface [7]. Some existing CAMAC systems will be kept, but new processing and interface systems will be configured in VME using Motorola G4 PowerPC controllers that serve both as EPICS IOCs and DSP engines. This technology will be used for the distributed orbit feedback system, which will have a 1-4 kHz cycle rate to achieve a bandwidth of >100 Hz. It will acquire orbit information from 90 BPMs over reflective memory links from 4 remote processing stations and update 18-bit set-points in digital power supply controllers for 108 correctors over a dedicated Fast Ethernet network.

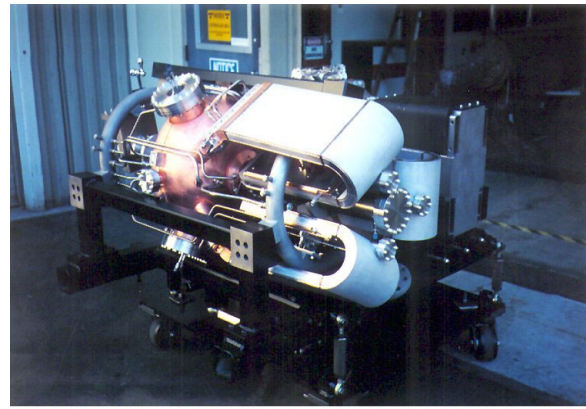


Figure 3: One of four 476 MHz PEP-II style RF cavities with mode-damping loads.

The BPM processing system, capable of turn-turn and first-turn measurements, employs a 4:1 switched-button analog RF-IF down-converter and a commercially built VME digital IF processing channel for each BPM [8]. A quadrupole modulation system will be used for beam-based alignment and BPM calibration. Other beam diagnostics include tune and current monitors, scrapers, UV SR monitor, and transverse and longitudinal bunch motion monitors. Since the booster RF frequency will remain at 358.5 MHz, it must be phase-locked to the SPEAR 3 RF frequency to enable single-bucket injection. Machine and personnel protection systems will be expanded, and a new cable plant will be installed.

## ACKNOWLEDGMENTS

The authors are grateful for the support of J. Dorfan, K. Hodgson, E. Paterson, R. Larsen, T. Donaldson and R. Humphrey; and for contributions from T. Rabedeau, I. Evans, M. Cornacchia, members of SPEAR 3, SSRL and SLAC technical and administrative groups, and from the IHEP magnet production team. We are indebted to H. Wiedemann for the original SPEAR 3 concept.

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