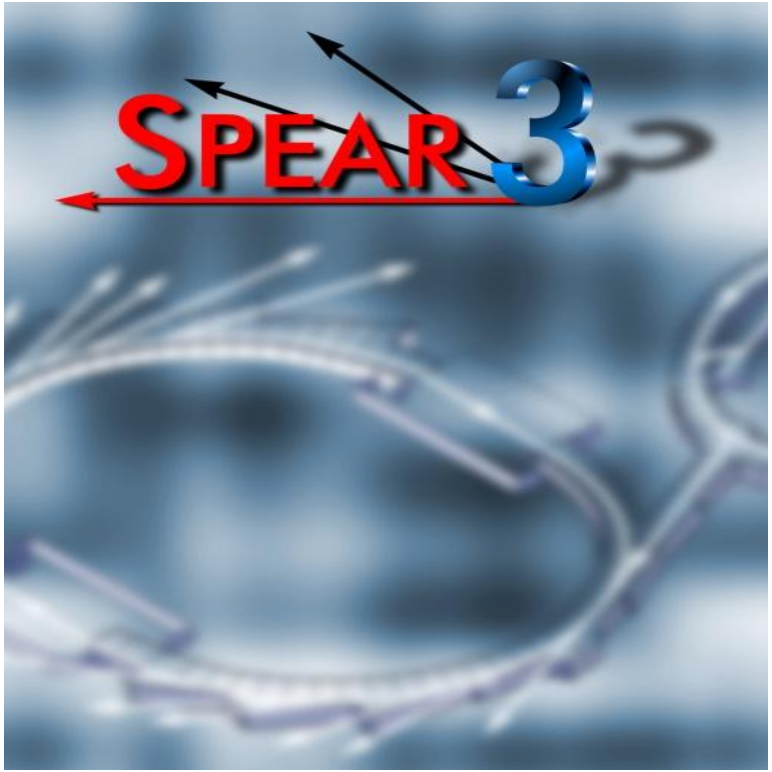
The Road to SPEAR3 and Beyond

SSRL 50th Anniversary Celebration

Robert Hettel

April 20, 2023

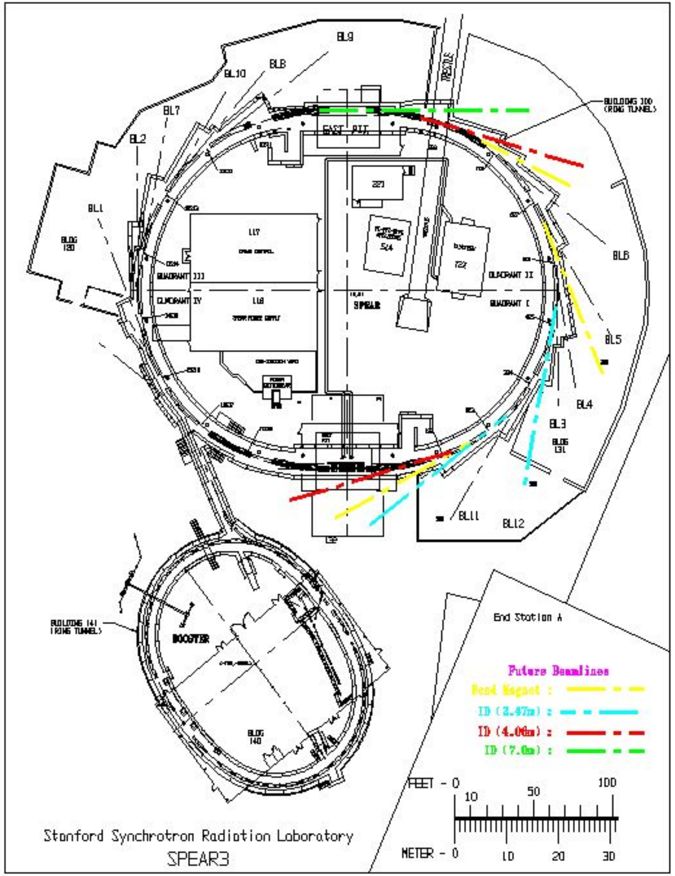


SSRL 50

U.S. DEPARTMENT OF ENERGY | Stanford University

SLAC NATIONAL ACCELERATOR LABORATORY

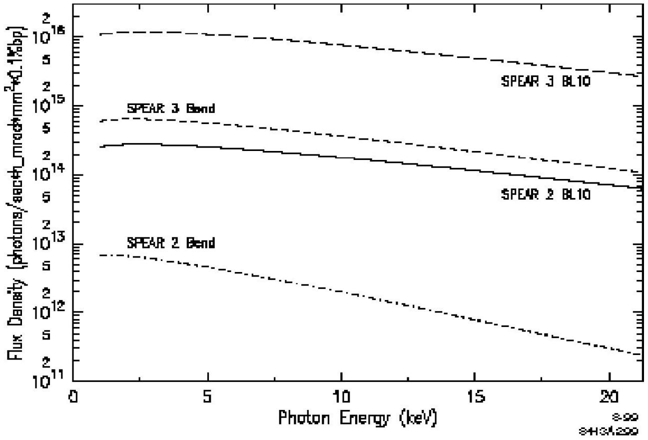
SPEAR3



SPEAR3

- 3 GeV, 500 mA
- First light March 8, 2004
- Top-off injection every 5 minutes
- 18 nm-rad emittance □ 9.8 □ 6 nm-rad
- >97% typical uptime

- SSRL operates 26 BL w/32 stations
  - Full build-out ~36 beam lines
- SSRL supports ~1,600 user annually
  - Annual growth ~5%
  - Could support 2,200+ users



Before SPEAR3: SPEAR-I and SPEAR-II

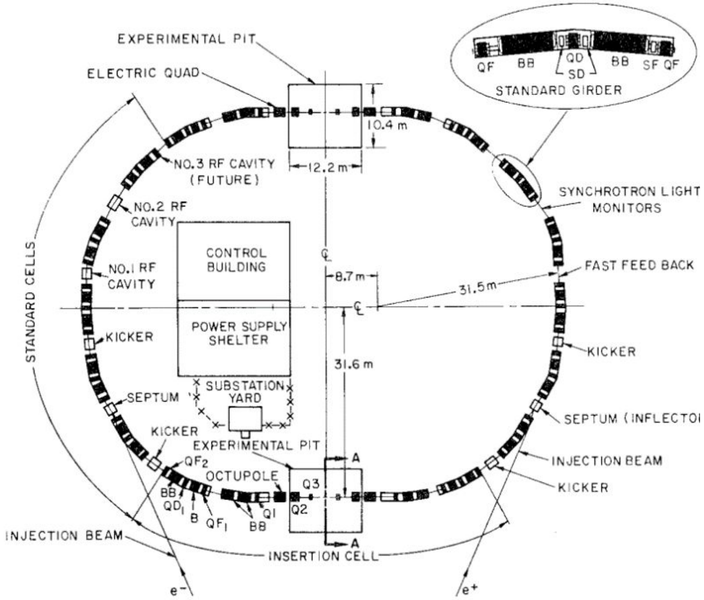
SPEAR-I:

- e-/e+ collider
- 2.5 GeV max energy per beam; 450-500 nm-rad; dispersion in straight sections; 40 MHz RF
- Inject at 1.5 GeV from SLAC linac, energy ramp
- first collisions April 28, 1972

SPEAR-II:

- Upgraded RF for 4.2 GeV max energy per beam
- 358 MHz RF
- Inject at 2.3 GeV from SLAC linac, energy ramp
- ~100 mA in a single beam for SR use
- first operation November 1974

**R. Scholl, J. Voss, H. Wiedemann (visitor from DESY, Hamburg, West Germany), M. Allen, J.-E. Augustin (visitor from University of Paris, Orsay, France), A. Boyarski, W. Davies-White, N. Dean, G. Fischer, J. L. Harris, L. Karvonen, R. R. Larsen, M. J. Lee, P. Morton, R. McConnell, J. M. Paterson, J. Rees, B. Richter, and A. Sabersky.



Origin of SPEAR at Stanford

Stanford MK III Linac – 1949-1964

- 630 MeV e- linac is fore-runner of SLAC linac

The development of linear accelerators at Stanford is due to the late W. W. Hansen's interest in x-ray problems in the mid-1930's. He wished to find an inexpensive way of obtaining high voltage electrons for use in the production of x-rays.

- H. Motz installs first undulator (1.9 mm) on MK III in 1952 and validates V. Ginzburg theory from 1947
- MKIII linac attracted Gerry O'Neill from Princeton who needed a strong source of electrons for an e-/e- collider concept

142 CHODOROW, GINZTON, HANSEN, KYHL, NEAL, AND PANOFSKY

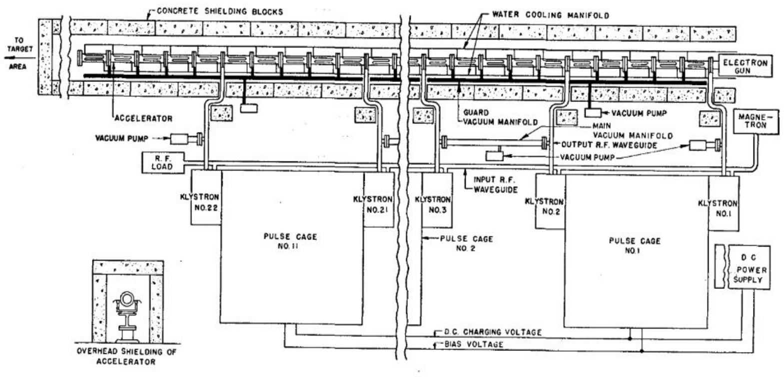


FIG. 1.4. Block diagram of Stanford Mark III Accelerator.

Princeton-Stanford e-/e- Collider- 1956-1964

- Electron injection needed fast kicker; avoided stacking problems with protons
- Vacuum technology had to improve
- ~0.5 GeV/beam; 0.6 A in single bunch
- Burt Richter joined project after MIT graduation; Norm Dean was a tech
- Panofsky a PI

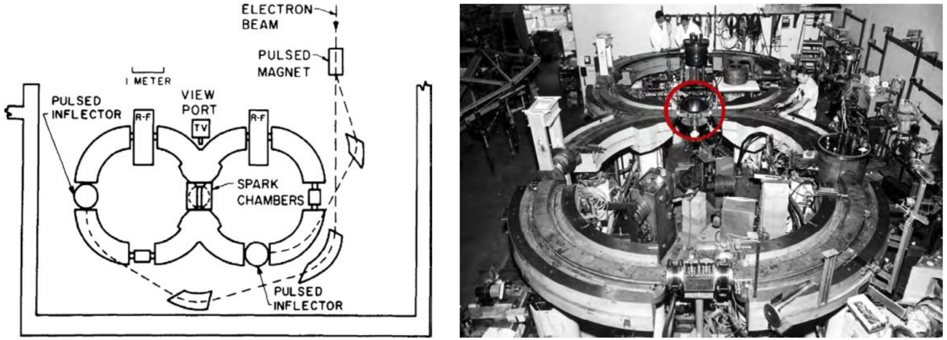
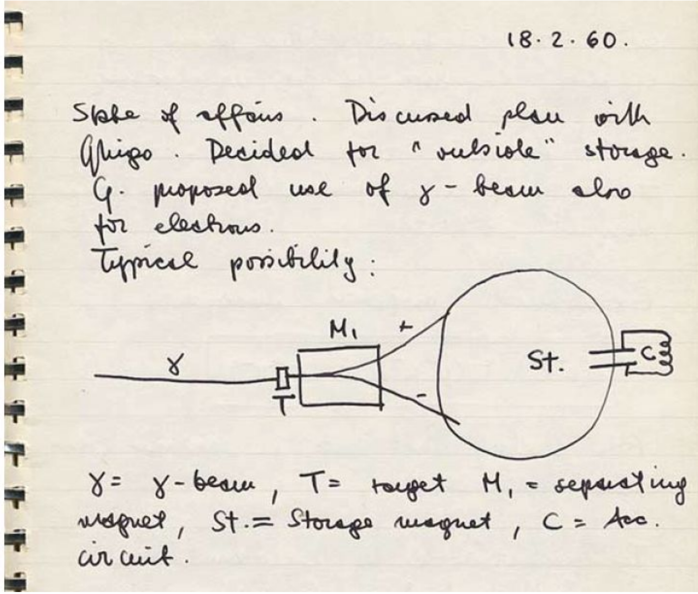


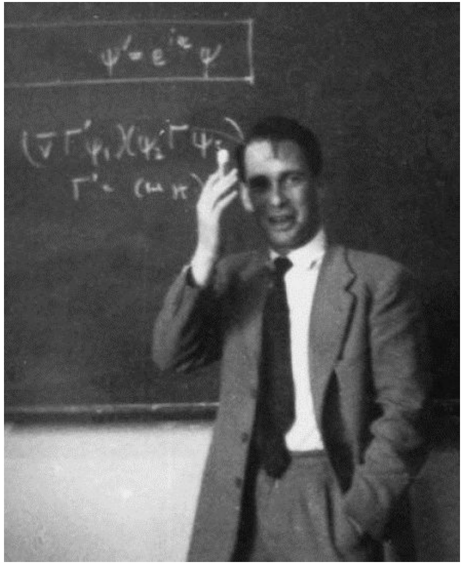
Fig. 3. Layout and photo of the Princeton–Stanford electron–electron collider.

Origin of SPEAR at Stanford – cont.

1959-1960: Frascati

- Panofsky gives symposium on e-/e+ collider
- Bruno Touschek proposes e-/e+ collider in a single ring (CPT theorem)





1961: Richter and Riston begin SPEAR design

1962: ADONE ring at Frascati encounters beam instability; Pellegrini (and Sands?) identify head-tail instability and develop theory

SPEAR Proposal

1963-69: **S**tanford **P**ositron **E**lectron **A**symmetric **R**ings proposal

No funding available in spite of favorable reviews

1964: CEA proposed. A fast cycling synchrotron that would be converted to a storage ring collider in 1970 Would become a competitor for SPEAR

1968: Bill Spicer makes a very early request that Pief Panofsky consider the possibility of using "cyclotron" radiation from the planned SLAC storage ring for solid state studies

1969: SLAC told to make SPEAR cheaper. A one-ring design is adopted. Paid with SLAC Ops budget.

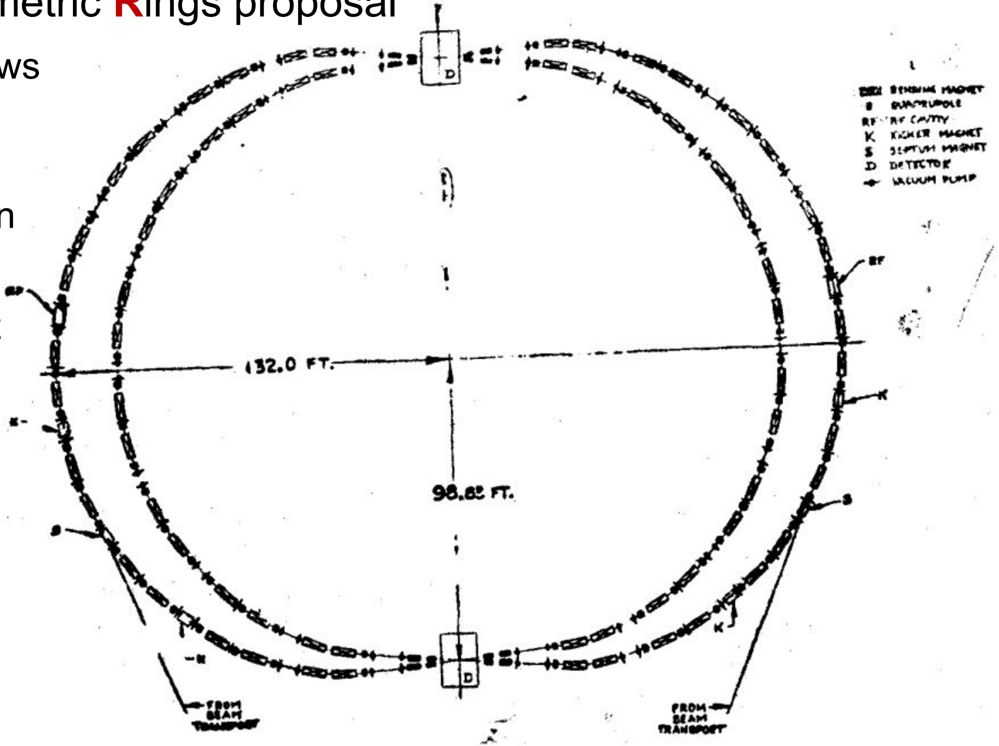
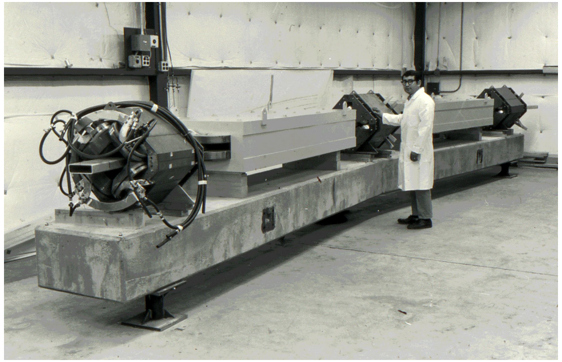
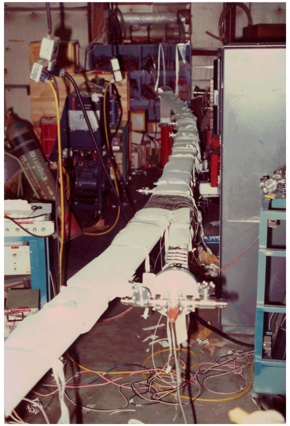


Fig. 1 Schematic of the double ring.

SPEAR Construction (1970-72) and First SR Beamline





SSRP

1972: Decision is made to start a pilot project to use the synchrotron radiation at SPEAR. An ultra-high vacuum valve is installed on a tangential port chamber. A beryllium window assembly and other front-end components are later added to this tangential port without venting the storage-ring vacuum system.

A proposal to build and operate the facility is submitted to the NSF by PI Sebastian Doniach.

1973: Stanford Synchrotron Radiation Project (SSRP) started by Sebastian Doniach (Director) and William Spicer (Consulting Director) with funding from the National Science Foundation; the US Navy's Michelson Lab at China Lake, California; Xerox Corporation; and Bell Telephone Laboratory. Herman Winick from the CEA, closed in 1972, joins SSRP as Associate Director.

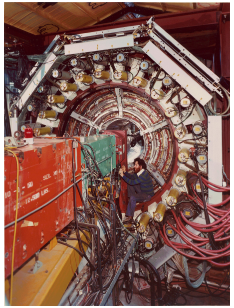
First Nobel Work at SPEAR

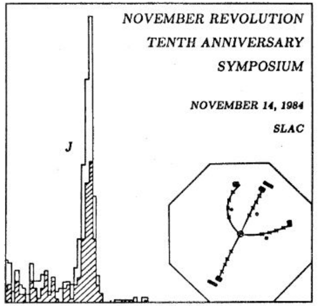
J/Psi and November Revolution – 1974

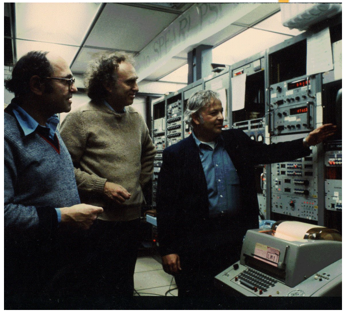
- J/ψ found at ~3.1 GeV center of mass energy (1.505 GeV per beam), a couple of weeks after SPEAR-II began operation
- ψ' found at ~3.68 GeV center of mass energy (~1.84 GeV/beam)
- ψ is composed of charm and anti-charm quark; confirms quark theory in Standard Model
- B. Richter and S. Ting (BNL) receive 1996 Nobel Prize
- (Operating SPEAR at ψ or ψ' energy not good for parasitic hard X-ray research)

Tau Lepton – 1974-77

- First evidence of a third generation of fundamental particles, necessary to complete Standard Model
- Martin Perl receives 1995 Nobel Prize



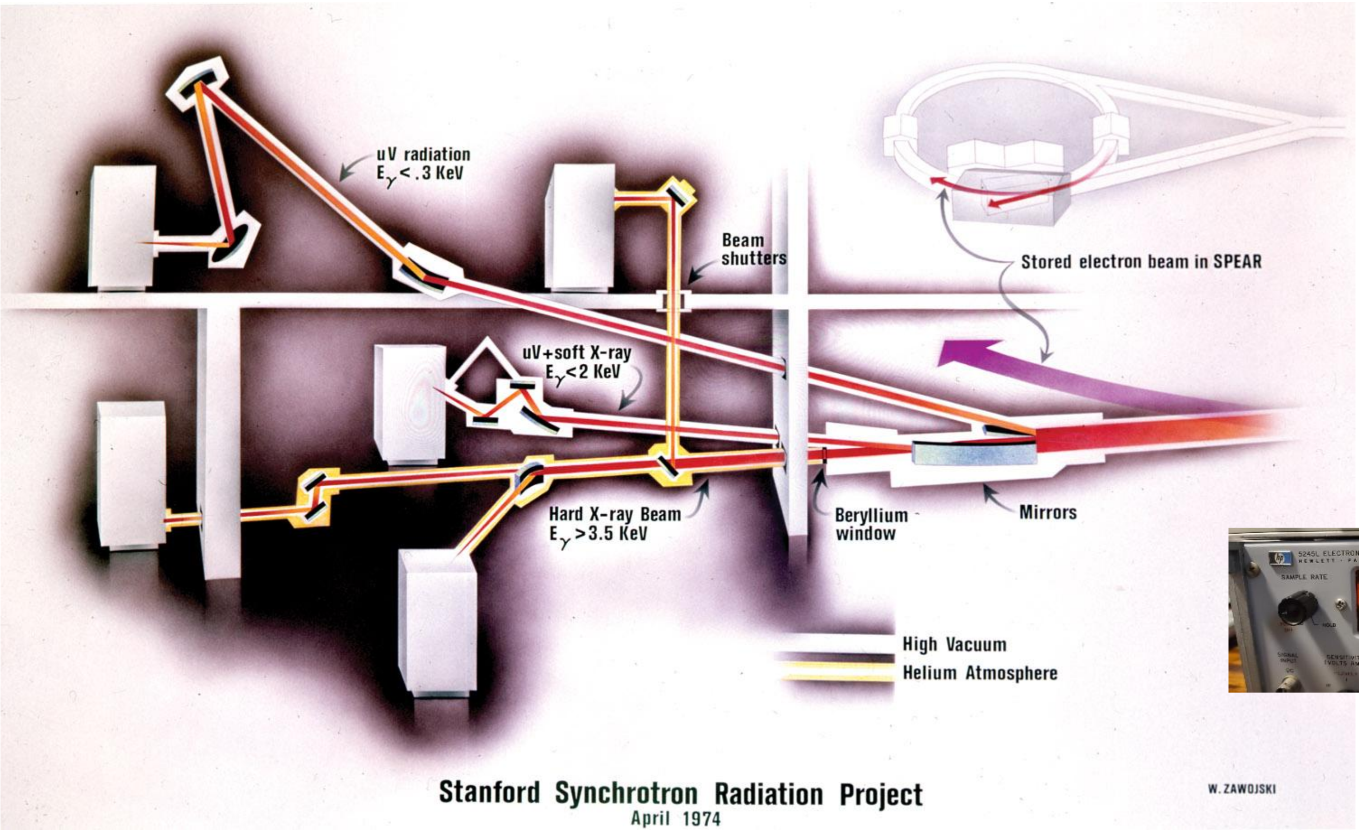




Generations of matter

Fermion categories		Elementary particle generation		
Type	*Subtype*	*First*	*Second*	*Third*
Quarks (colored)	down-type	down	strange	bottom
	up-type	up	charm	top
Leptons (color-free)	charged	electron	muon	tauon
	neutral	electron neutrino	muon neutrino	tau neutrino

Also in 1974 - SSRP



Evolution of SPEAR as a Light Source

Goals include:

- Increase spectral X-ray flux in small apertures
- Reduce focused beam size and divergence
- Extend X-ray spectrum to higher energies (> 10 keV)
- Enable specialized operation (e.g. timing mode, short bunches, etc.)
- Improve beam stability (single- and multi-bunch, orbit)

$$\text{Brightness} = \frac{\text{Flux}}{(2\pi)^2 \sigma_{Tx}\sigma_{Tx'}\sigma_{Ty}\sigma_{Ty'}}$$

$\sigma_{Tx} = \sqrt{\sigma_x^2 + \sigma_r^2}$ photon beam size

$\sigma_{Tx'} = \sqrt{\sigma_{x'}^2 + \sigma_{r'}^2}$, photon beam divergence

Emittance: $\varepsilon_x = \sigma_x \sigma_{x'}$ $\varepsilon_r = \sigma_r \sigma_{r'} = \lambda/4\pi$

Means include:

- Reduce magnet lattice emittance
- Optimize lattice functions at SR source points; ~0 dispersion in ID straight sections
- Develop improved radiation sources (e.g. wigglers and undulators)
- Low impedance vacuum chambers and components
- Tune lattice functions to reduce beam instability
- Mode-damped RF cavities
- Improve accelerator and beamline component stability
- Feedback systems for multi-bunch and orbit stability
- At-energy injection
- Develop lattice and devices for short bunches
- Etc.

SPEAR-II Light Source Development

1976: A. Garren, M. Lee and P. Morton explore ways to increase brightness by reducing SPEAR emittance from ~450 nm-rad to 103 nm-rad by increasing horizontal tune, rearranging quadrupoles for lower dispersion in dipoles, operating with high single beam current in many bunches. Increased tune disrupted 180^{O} phase advance between 2 injection kickers. Lattice not pursued.

1977: SSRP Wiggler Workshop; SSRP becomes SSRL

1978: A. Hofmann published properties of undulator radiation. Compton backscatter e+ polarimeter installed.


ELSEVIER

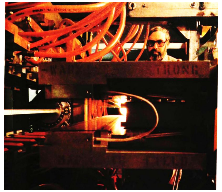
Nuclear Instruments and Methods

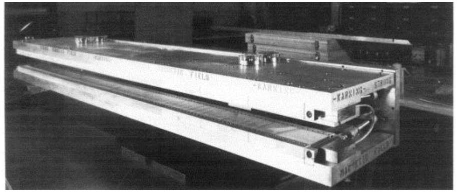
Volume 152, Issue 1, 1 June 1978, Pages 17-21

Quasi-monochromatic synchrotron radiation from undulators

A. Hofmann

1979: First 1.8 T electromagnetic wiggler installed in SPEAR.

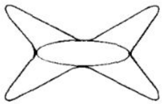




1980: First PM undulator installed in SPEAR.

1982: First fast orbit feedback for SR steering.

1983: First 1.35 T rare earth cobalt/steel wiggler (Halbach) with variable gap “omega joint” vacuum chamber installed for SPEAR BL VI; ion trapping observed when gap is moved.



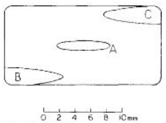


Fig. 10. Radiation patterns due to undulator and bending magnet fringe fields.

SPEAR-II Lattice Development

A LOW EMITTANCE CONFIGURATION FOR SPEAR

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SLAC, PO Box 4349
Stanford, CA 94305

J. Cerino, R. Hettel, A. Hofmann, R.Z. Liu,#
H. Wiedemann and H. Winick
SSRL*, PO Box 4349
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1984: "Low Beta Low Emittance" (LBLE) higher tune 130 nm-rad lattice that maintained 180^{O} phase advance for kickers by shunting current in quadrupoles during injection. Many difficulties with injection efficiency and other issues, some related to the very low vertical beta function at the HEP interaction regions implemented in 1984 (K. Wille. SLAC/AP-9)..

1987: A "High Beta Low Emittance" (HBLE) proposed by R. Liu in 1987. LBLE and HBLE Not practical for user operation

1988: H. Wiedemann proposes a new low-emittance lattice for SPEAR that would require replacing SPEAR-II FODO lattice with 4-bend achromat, 28.5 nm-rad lattice having 0 dispersion in straight sections, operating at 350 mA. Three electron injection kickers used to overcome phase advance problem.

J. Safranek begins thesis exploring high brightness lattices for SPEAR.

1990: SPEAR becomes 100% SR source.

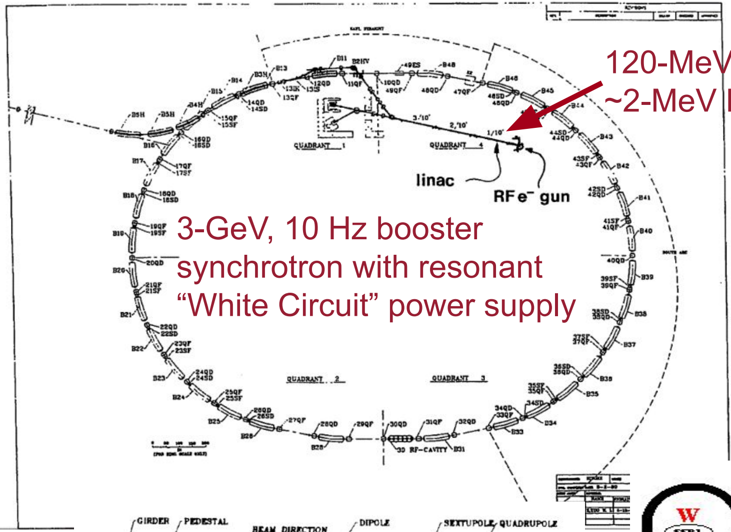
1991: Safranek publishes thesis with low emittance lattice options, including FODO, DBA, TBA. One option uses existing SPEAR-II FODO lattice and has 129 nm-rad emittance. This lattice was implemented with a 3rd injection kicker taken from the decommissioned e+ injection line and is used for user operation.

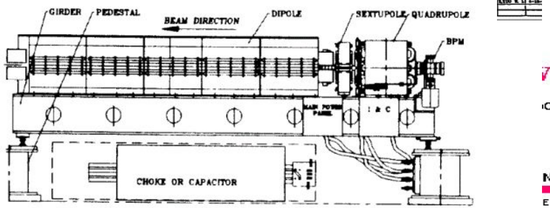
The 18 nm-rad DBA looks most promising for a future lattice.

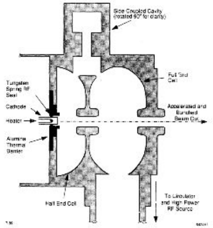
The stage is set for SPEAR3

Meanwhile……3 GeV Injector

1987: H. Wiedemann proposal to DOE to build 3-GeV injector for SPEAR to mitigate SLC-related SLAC linac injection interruptions. Project approved and construction began in 1988. J. Voss project manager.







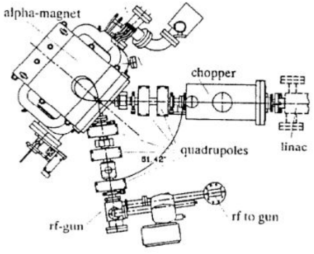


Figure 3
Rf gun, compressor and chopper unit

M. Borland thesis

1990: ~16-M$ Injector operational. No longer necessary to ramp SPEAR from 2.3 GeV injection energy to 3 GeV

Meanwhile……PEP

1986-87: X-ray BL PEP5B installed, and later BL PEP1B, with 2-m undulators on 2.2-km PEP. The 16-GeV PEP energy reduced to 7.1 GeV (4-6 nm-rad, 15 mA). Physicists from many institutions gathered to study and remedy accelerator and X-ray beamline issues.

1987: SPEAR Injector booster magnets designed for potential 5-GeV injection to PEP for future SR use.

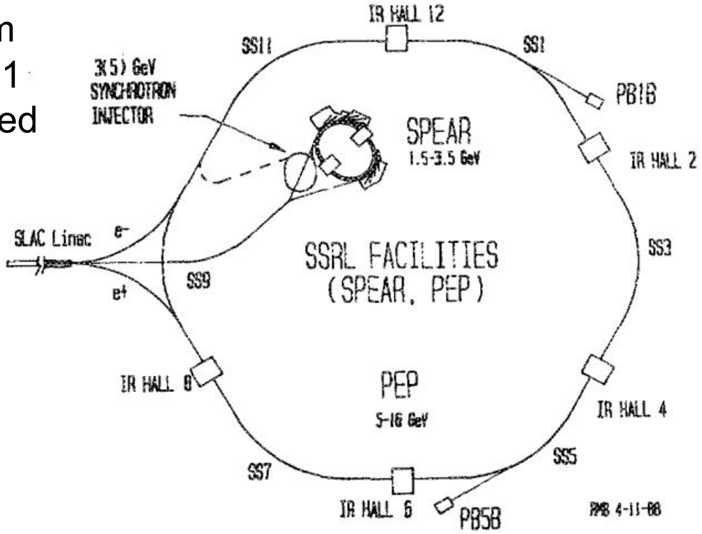
1988: H. Wiedemann explores using damping wigglers to reduce PEP emittance. 0.6 nm-rad, 6 GeV, 194 m of 1.26-T wigglers.

1989: L. Emery explores low emittance damping ring lattices. Finds 25 pm-rad @ 4 GeV with 360 m of wigglers and optimized lattice functions.

1991-92: Pellegrini, Nuhn, Tatchyn, Winick, Fisher, Gallardo explore 40-Å FEL on 4-GeV, 0.27 nm-rad PEP, 100-m undulator.

1991: PEP funding and operation end.

(but PEP as a light source will be back!)



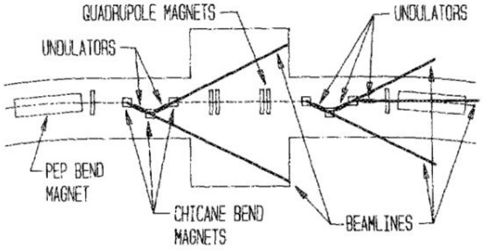


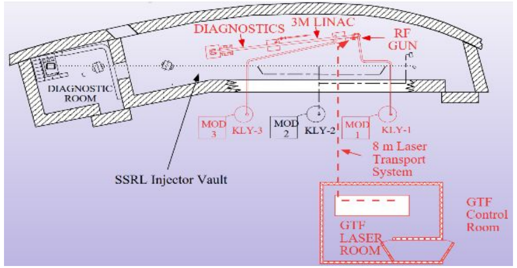
FIG. 5. Schematic layout of five insertion device beamlines in a PEP interaction region straight section.

Meanwhile……LCLS with SSRL Support

Feb 1992: H. Winick and M. Cornacchia organize the "Workshop on 4th Generation Light Sources". Many future concepts presented, including "A 4 to 0.1-nm FEL based on the SLAC Linac" by C. Pellegrini. This idea had been floating around for a while, but this presentation brought focus.

Feb 1993: SLAC Director B. Richter agrees this FEL idea is worth pursuing and the LCLS design study was launched, led by H. Winick with collaboration between SLAC, UCLA, LLNL and LBL and funded from SSRL budget.

Mid-90s – SLAC/UCLA/BNL photocathode gun collaboration for LCLS. J. Schmerge joined SSRL in 1996 and built Gun Test Facility in SSRL Linac enclosure. GTF work extended through 2005, and gun design went to LCLS. UED demonstrated in 2006.



1995: R. Bonifacio, H-D. Nuhn and S-K Nam propose FEL Amplifier Test Experiment (FATE), a 1-10 mm FEL using SSRL linac to generate short, high current bunches. Linac never reached desired performance.

2002: SLAC Final Focus Test Beam (FFTB) line modified for Sub-Picosecond Photon Source (SPPS) to test short photon pulse production in a 2.5-m undulator in preparation for LCLS. 12 μm rms (40 fs rms) bunches produced with compressed 28.5-GeV electron beam.

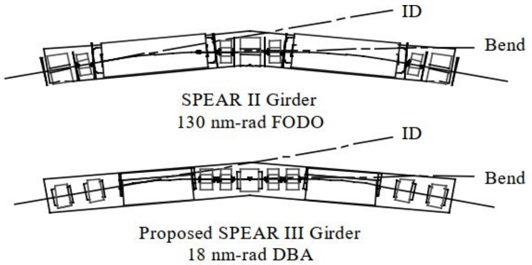
M. Cornacchia leads LCLS CDR. LCLS is on its way!

Back to SPEAR3

1997: Continued operation of SSRL is endorsed by BESAC (Birgeneau/Shen Committee). Motivation for SPEAR 3 grows with input and consultation with users, staff, SSRL faculty, advisory committees. A workshop concluded that SPEAR3 should proceed in the most rapid way. A design group was formed to embellish the initial design plan developed by H. Wiedemann and W. Davies-White.

Original plan:

- 18 nm-radian (or lower) beam emittance, a decrease from 160 nm-rad, using DBA lattice
- 200 mA stored beam current, up from 100 mA, using existing RF
- Long beam lifetimes (>15 h)
- Insertion device locations unchanged; bending magnet beamlines slightly realigned
- Improved machine reliability and beam stability
- ~29 M$



1998: T. Elioff joins as Project Director/Manager in January

Additional funding from NIH enables RF replacement and 500 mA operation. ~58 M$ total funding

Design Report completed 1999:.

Authors:

P. Bellomo, R. Boyce, J. Corbett (Deputy Editor), P. Corredoura, E. Daly, D. Dell'Orco, T. Elioff, I. Evans, A. Fisher, R. Hettel (Editor), N. Kurita, J Langton, G. Leblanc, C. Limborg, D. Martin, Y. Nosochkov, T. Rabedeau, S. Park, J. Safranek, H. Schwarz, J. Sebek, J. Tanabe, C. Wermelskirchen, K. Wille, R. Yotam, F. Zimmermann

SPEAR3 Project

Accelerator physics for the SPEAR 3 light source

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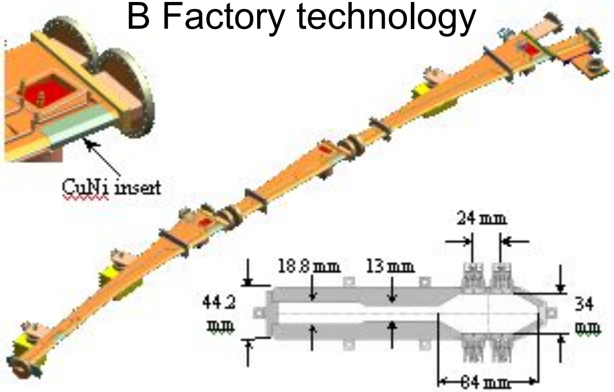
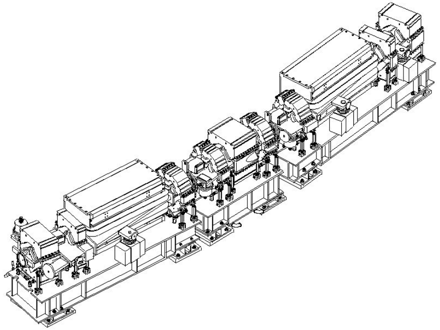
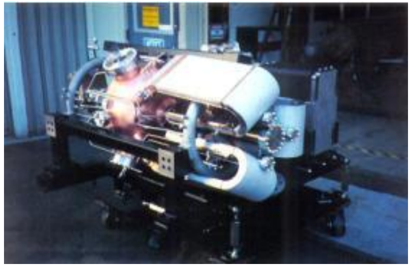
B Factory technology





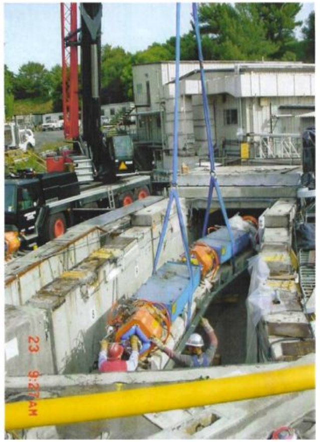


- East and West pits filled in
- New tunnel floor
- New East and West pit shielding and labrynth access
- Fast global orbit feedback system
- ….

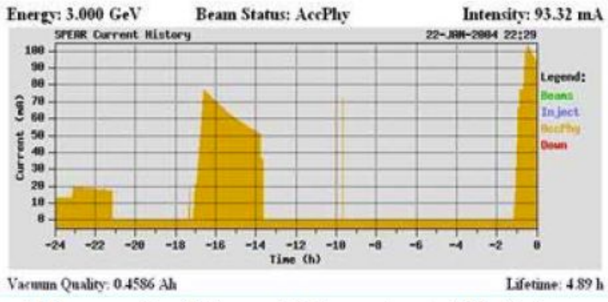
SPEAR3 Project – cont.

2003: SPEAR-II removal began in April. SPEAR3 commissioning began end of November

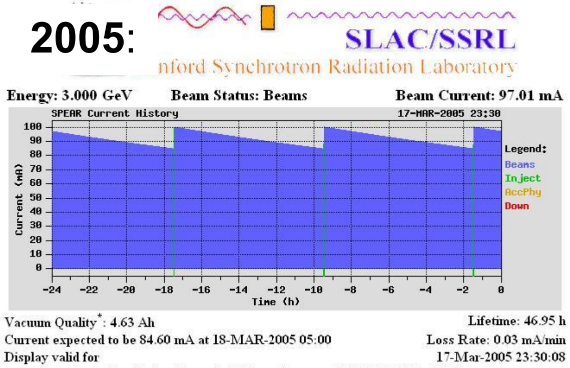
Nov. 24, 2003: CD-4 approval by DOE



2004: First 100 mA on Jan 22.



2005:



2006: SPEAR approved for 500 mA in June. Some beamlines must wait till 2007 to be ready for 500 mA

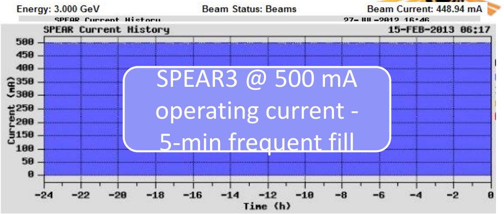
2007: Steve Jobs introduces the iPhone on Jan 9

Post SPEAR3 Project

With Secretary of Energy S. Abraham

SPEAR-II: RIP

Some SPEAR3 Developments

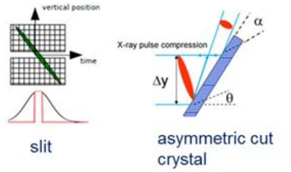


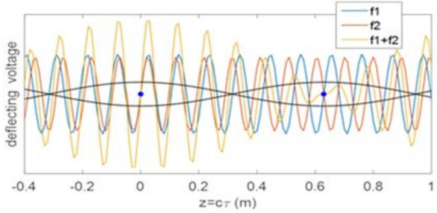
Top-Up Injection: Injection with beamline stoppers open. Began safety analysis in 2007; full user operation in 2009.

Lower Emittance: Emittance reduced to 10 nm-rad, then to 6 nm-rad by increasing number of independent sextupole families and installing a new septum magnet that reduced injected beam oscillation amplitude.

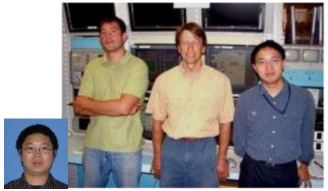
Temperature Stability: Temperature-related accelerator motion of 10s of microns reduced by a factor of 10 with tunnel wall insulation. An experiment with aluminized mylar on infield ground showed that it was the walls, not the parking lot, causing motion.

Short Bunches: Picosecond bunches obtained with low momentum compaction lattice, but very low current. Zholents proposed using 2 transverse deflecting cavities operating at 2 different frequencies that kick every other bunch, leaving intervening bunches unkicked – allows simultaneous normal and short bunch operation. Program stopped because of mediocre projected performance for users.





Accelerator Physics: Developments in beam-based non-linear lattice optimization. Robust conjugate direction search (Powell's method) and particle swarm methods are robust to noise and much faster than beam-based MOGA.



Beyond SPEAR3 – 4th Generation Storage Ring Light Source?

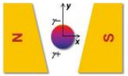
MBA Lattices: Many light sources now adopting multi-bend achromat lattices to reach diffraction-limited emittance for keV photons (e.g. λ/4π = 8 pm-rad for 1Å X-rays)

$$\varepsilon \propto \frac{E^2}{N_d^3}$$

N_d = number of dipoles

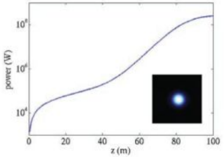
PEP-X: A "low-key" design study for 2.2-km PEP-X began in 2009, supported by SSRL Director J. Stohr. By 2015 a lattice with <10 pm-rad emittance. Lattice studies led by Y. Cai from SLAC ARD with much collaboration with APS, MAX-IV, ESRF, etc. Very expensive!

SRN 2013: 1.5-nm FEL with 100-m transverse gradient undulator in PEP-X



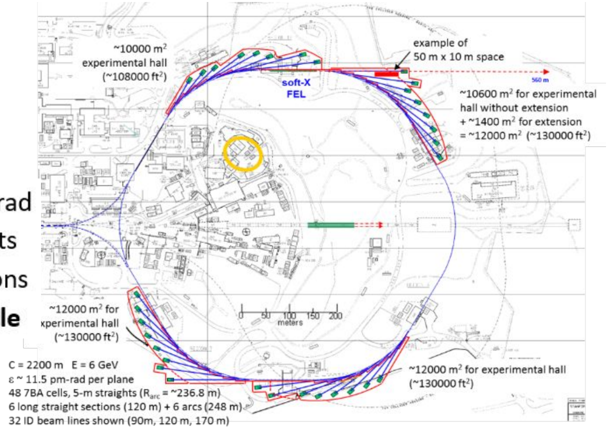
An X-ray Free Electron Laser Driven by an Ultimate Storage Ring

YUNHAI CAI, YUANTAO DING, ROBERT HETTEL, ZHIRONG HUANG
LANFA WANG, AND LILING XIAO
SLAC National Accelerator Laboratory, Menlo Park, California, USA

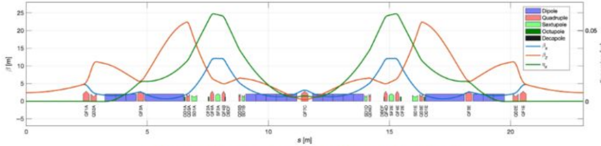


E = 6 GeV I= 200 mA $\varepsilon_{x,y}$ = 11.5 pm-rad

- Hexagonal geometry, six 120-m straights
- 7BA lattice, 48 cells, 5-m straight sections
- **$\varepsilon_{x,y}$ = 5 pm-rad if ring converted to circle**



SSRL-X: J. Safranek, X. Huang, P. Raimondi, J. Kim, T. Rabedeau exploring other MBA rings for SSRL, focusing on hybrid 6BA (H6BA) cell



The H6BA cell for a 6-GeV, 72-cell storage ring

Raimondi H6BA

Options	SSRL-UP	SSRL-X	SDLS
Beam energy (GeV)	3	4	5
Circumference (m)	234	587	2190
Emittance (pm) - bare	364	86	28
Emittance (pm) –w/ DW	310	60	15

The Road to SPEAR3 and Beyond – some colleagues