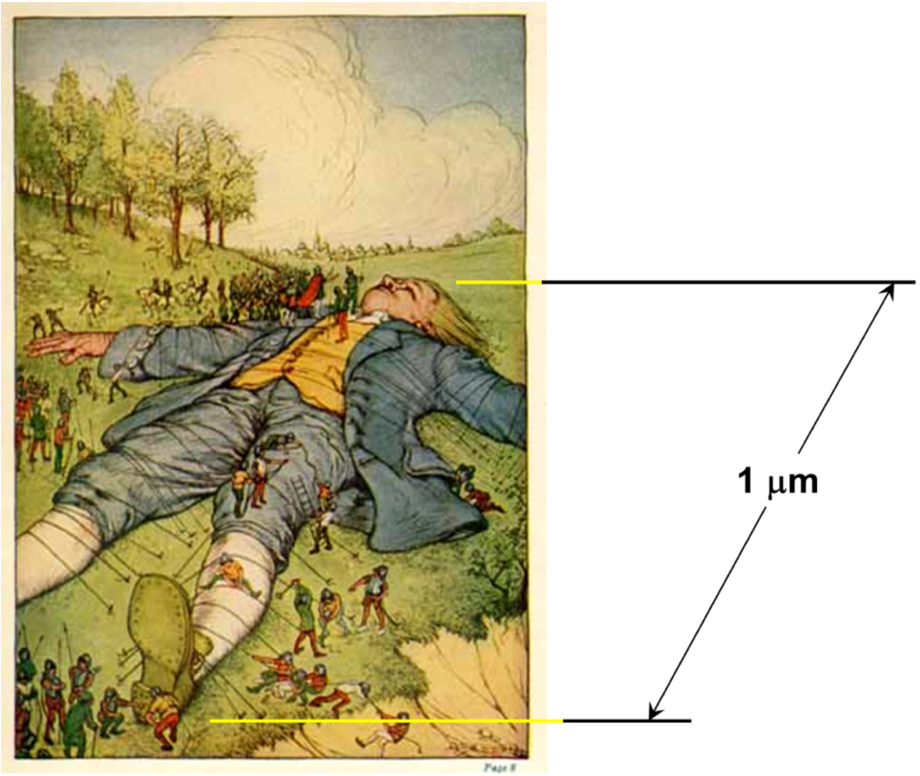
Light Source Beam Stabilization: Earlier Times



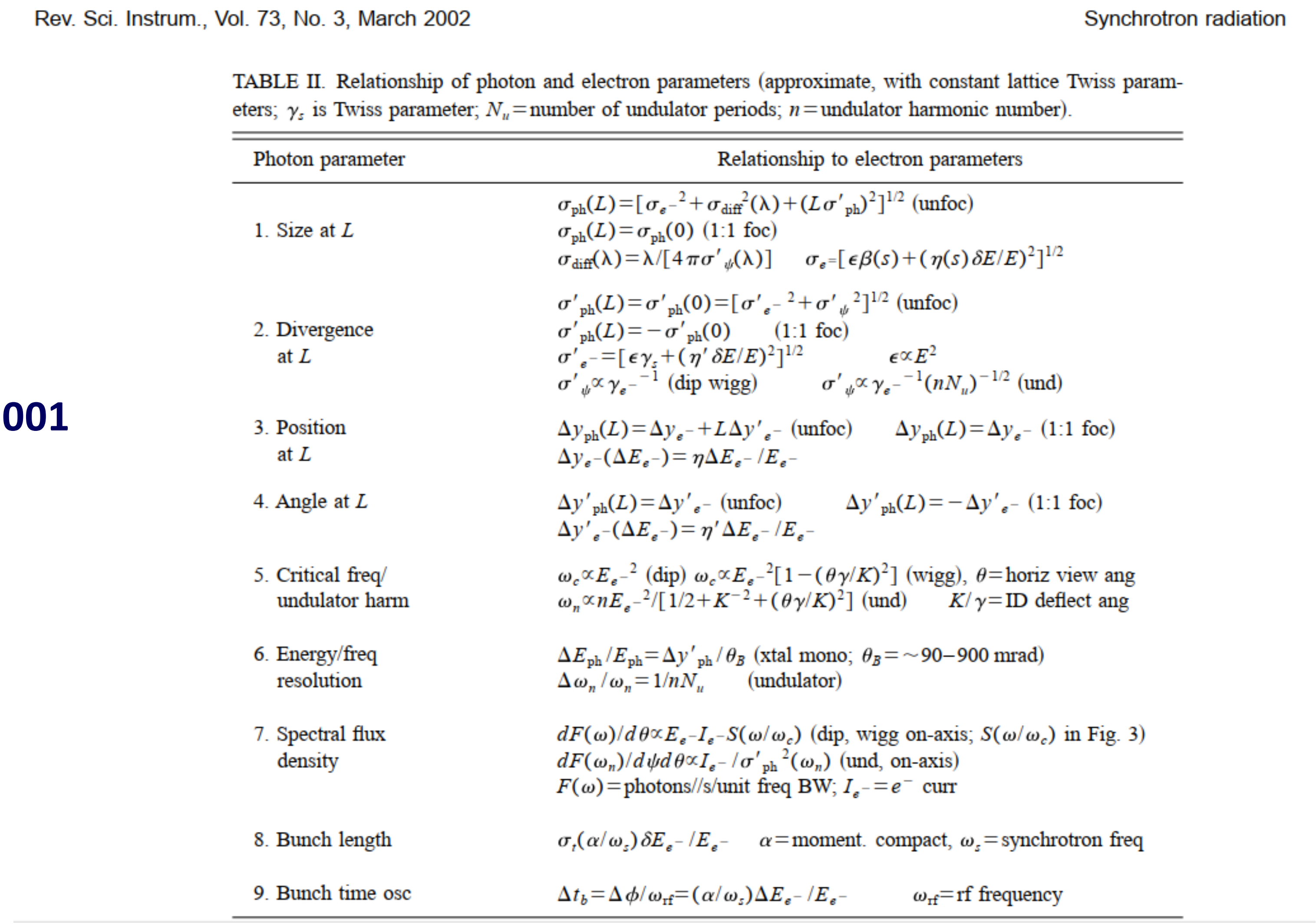
R. Hettel

2018 BES Light Sources Stability Workshop

LBNL

November 1, 2018

SRI 2001



Rev. Sci. Instrum., Vol. 73, No. 3, March 2002 Synchrotron radiation

TABLE II. Relationship of photon and electron parameters (approximate, with constant lattice Twiss parameters; γ_s is Twiss parameter; N_u=number of undulator periods; n=undulator harmonic number).

Photon parameter	Relationship to electron parameters
1. Size at L	$\sigma_{\mathrm{ph}}(L)=[\sigma_{e^-}^{2}+\sigma_{\mathrm{diff}}^{2}(\lambda)+(L\sigma'_{\mathrm{ph}})^{2}]^{1/2}$ (unfoc) $\sigma_{\mathrm{ph}}(L)=\sigma_{\mathrm{ph}}(0)$ (1:1 foc) $\sigma_{\mathrm{diff}}(\lambda)=\lambda/[4\pi\sigma'_{\psi}(\lambda)]$ $\sigma_{e}=[\epsilon\beta(s)+(\eta(s)\delta E/E)^{2}]^{1/2}$
2. Divergence at L	$\sigma'_{\mathrm{ph}}(L)=\sigma'_{\mathrm{ph}}(0)=[\sigma'^{2}_{e^-}+\sigma'^{2}_{\psi}]^{1/2}$ (unfoc) $\sigma'_{\mathrm{ph}}(L)=-\sigma'_{\mathrm{ph}}(0)$ (1:1 foc) $\sigma'_{e^-}=[\epsilon\gamma_{s}+(\eta'\delta E/E)^{2}]^{1/2}$ $\epsilon\propto E^{2}$ $\sigma'_{\psi}\propto\gamma_{e^-}^{-1}$ (dip wigg) $\sigma'_{\psi}\propto\gamma_{e^-}^{-1}(nN_{u})^{-1/2}$ (und)
3. Position at L	$\Delta y_{\mathrm{ph}}(L)=\Delta y_{e^-}+L\Delta y'_{e^-}$ (unfoc) $\Delta y_{\mathrm{ph}}(L)=\Delta y_{e^-}$ (1:1 foc) $\Delta y_{e^-}(\Delta E_{e^-})=\eta\Delta E_{e^-}/E_{e^-}$
4. Angle at L	$\Delta y'_{\mathrm{ph}}(L)=\Delta y'_{e^-}$ (unfoc) $\Delta y'_{\mathrm{ph}}(L)=-\Delta y'_{e^-}$ (1:1 foc) $\Delta y'_{e^-}(\Delta E_{e^-})=\eta'\Delta E_{e^-}/E_{e^-}$
5. Critical freq/ undulator harm	$\omega_{c}\propto E_{e^-}^{2}$ (dip) $\omega_{c}\propto E_{e^-}^{2}[1-(\theta\gamma/K)^{2}]$ (wigg), θ=horiz view ang $\omega_{n}\propto nE_{e^-}^{2}/[1/2+K^{-2}+(\theta\gamma/K)^{2}]$ (und) K/γ=ID deflect ang
6. Energy/freq resolution	$\Delta E_{\mathrm{ph}}/E_{\mathrm{ph}}=\Delta y'_{\mathrm{ph}}/\theta_{B}$ (xtal mono; $\theta_{B}=\sim 90-900$ mrad) $\Delta\omega_{n}/\omega_{n}=1/nN_{u}$ (undulator)
7. Spectral flux density	$dF(\omega)/d\theta\propto E_{e^-}I_{e^-}S(\omega/\omega_{c})$ (dip, wigg on-axis; $S(\omega/\omega_{c})$ in Fig. 3) $dF(\omega_{n})/d\psi d\theta\propto I_{e^-}/\sigma'^{2}_{\mathrm{ph}}(\omega_{n})$ (und, on-axis) $F(\omega)$=photons//s/unit freq BW; $I_{e^-}=e^{-}$ curr
8. Bunch length	$\sigma_{t}(\alpha/\omega_{s})\delta E_{e^-}/E_{e^-}$ α=moment. compact, ω_{s}=synchrotron freq
9. Bunch time osc	$\Delta t_{b}=\Delta\phi/\omega_{\mathrm{rf}}=(\alpha/\omega_{s})\Delta E_{e^-}/E_{e^-}$ ω_{rf}=rf frequency

Source Stability Relationships

Can derive basic some basic relationships experimental observables and beam properties based simple (1st-order) dependencies (-- = 2nd order):

parameters	e- orbit	e- size/ rotation	e- energy/ energy spread (& RF stability)	ID field (esp EPUs)
intensity (pointing, beam size, emission)	x	x	x	x
energy and energy resolution	x	x (dispersive monos)	x	x
timing, bunch length	-- (pseudo 1-bunch?)	x	x	--
polarization	x (dipole, EPU)	--	--	x
coherent fraction	--	x	x ID high harmonics	--

Not included: accelerator lattice stability, lifetime stability, other

Beam Stability Requirements - Summary

SRI 2001

Parameter	Present	Future trend
intensity stability	< 0.1%	< 0.01%
steering accuracy	< 5-10% σ_{e-}, σ'_{ph}	< 2% σ_{e-}, σ'_{ph}
beam size stability	< few % σ_{ph}	~ 0.1% σ_{ph}
energy resolution	10^{-4}	10^{-5}
timing stability	< 10% bunch length	< 10% bunch length
min data avg time	order 1 ms	order 1 μs (ring) single shot (FEL)
emittance	~5-20 nm-rad	~0.05-0.2 nm-rad
e- beam size (vert)	~30-300 μm	~3-30 μm
ph beam divergence	~10-200 μrad	~0.5-10 μrad
e- bunch length	~10-100 ps	1-100 fs (FEL)
e- position stability (vert)	~1-5 μm	~0.1-1 μm
e- angle stability	~1-10 μrad	~0.05- 0.5 μrad
e- bunch length stability	~1-10 ps	~10-100 fs (FEL)
e- energy stability	$< 10^{-4}$ $(\Delta\phi < 0.1^{o})$	$< 5 \times 10^{-5}$

Some Electron Orbit- and Size-Perturbing Mechanisms

Long term (weeks-years):

- ground settlement (mm)
- seasonal ground motion (< mm, sometimes more)

Medium term (minutes-days):

- diurnal temperature (1-100 μm)
- crane motion (1-100 μm)
- fill patterns (1-100 μm)
- coupling changes
- river, dam activity (1-100 μm)
- machine fills (heating, BPM intensity dependence)
- RF drift (microns)
- gravitational earth tides (ΔC = 10-30 μm)

Short term (milliseconds-seconds):

- ground vibration, traffic, trains, etc. (< microns, <50 Hz typ)

  ground motion amplified by girder + magnet resonances (x~20 if not damped) and by lattice (x ~5+)

  ⇒ nm level ground motion can be amplified close to μm level

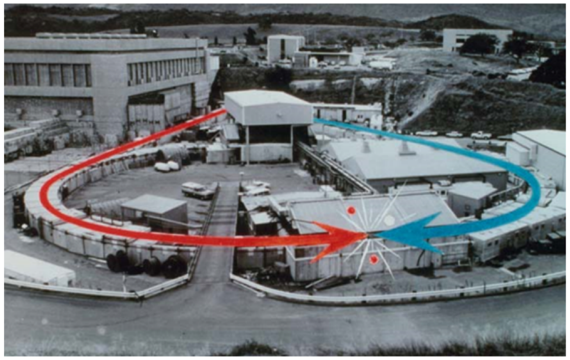
- cooling water vibration (microns)
- booster operation (microns)
- power supplies (microns)
- rotating machinery (air conditioners, pumps) (microns)
- insertion device changes (1-100 μm)
- vac chamber vibration from BL shutters, etc. (microns)

High frequency (sub-millisecond):

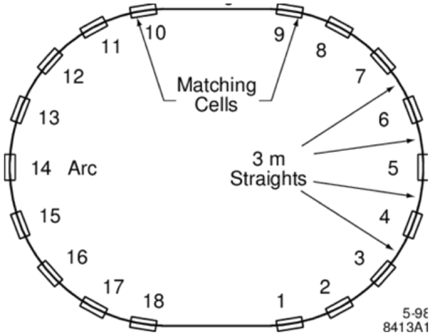
- high frequency PWM and pulsed power sources (microns)
- synchrotron oscillations (1-100 μm)
- single- and multibunch instabilities (1-100 μm)
- gas bursts, ions, dust, …..

SPEAR I and II

1970

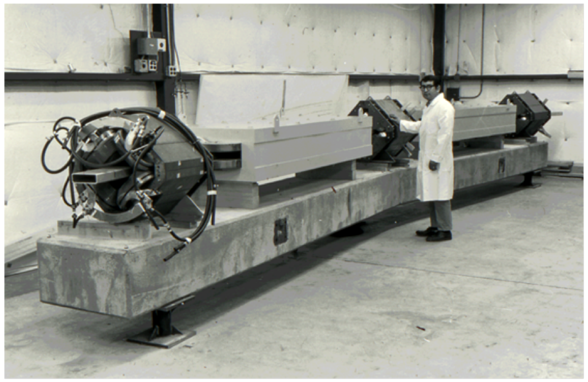


1971



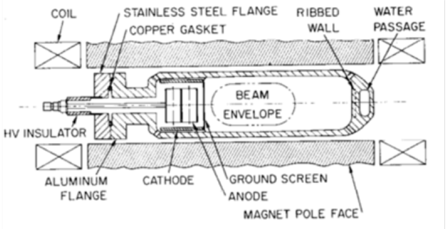
SPEAR II FODO, dispersion in straights

Herman Winick and his wiggler

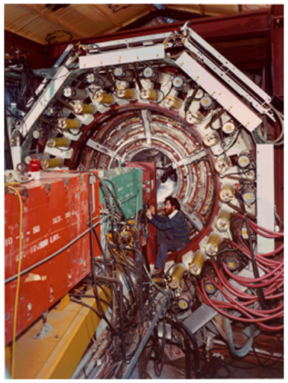


Vcorr: trim windings on solid core quads

Hcorrs: trim windings on solid core dipoles



15.6 cm x 4.4 cm Al chamber, 0.39 cm wall thickness



MK I (II?) detector in pit, 1978

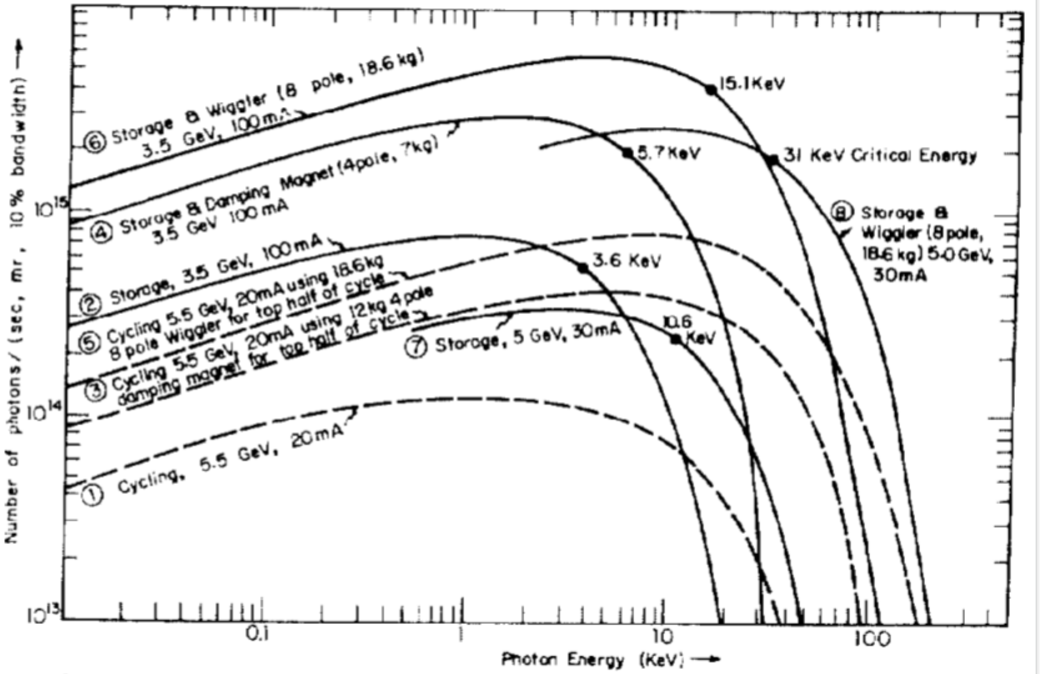
Burt Richter giving SPEAR to Artie Bienenstock and SSRL

SYNCHROTRON RADIATION AT THE CAMBRIDGE ELECTRON ACCELERATOR*

Herman Winick

Cambridge Electron Accelerator
Harvard University and Massachusetts Institute of Technology
Cambridge, Mass.

1972

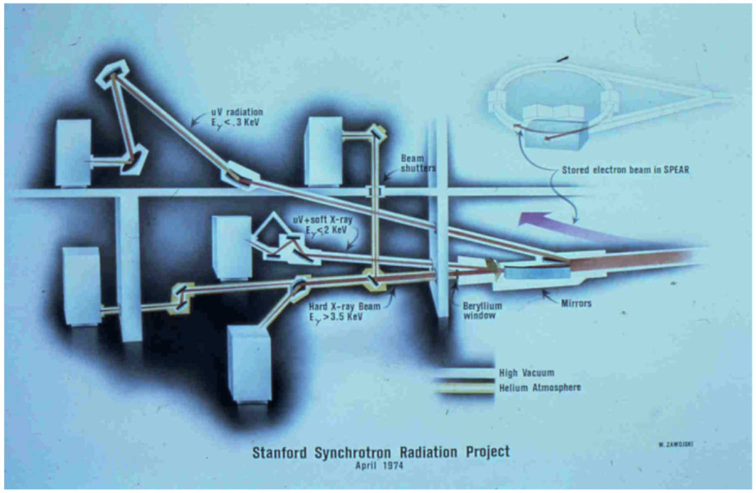


Spectral photon distribution of synchrotron radiation from CEA. Curves ① ② ③ ④ indicate present capabilities with existing damping magnets. Curves ⑤ ⑥ show capabilities that will result when a new wiggler magnet is built and installed. Curves ⑦ ⑧ show capabilities that will result when a 5.0 GeV beam is stored.

SSRP beamlines

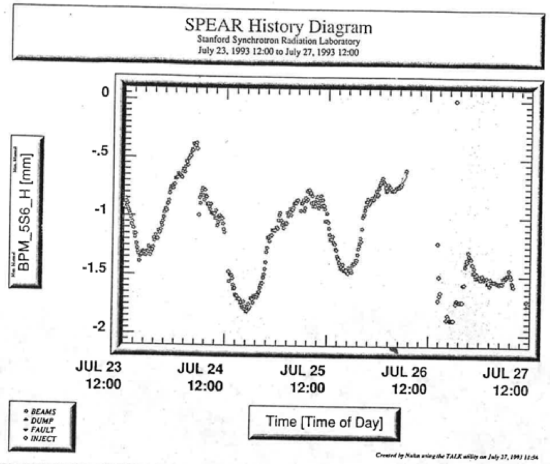
1971

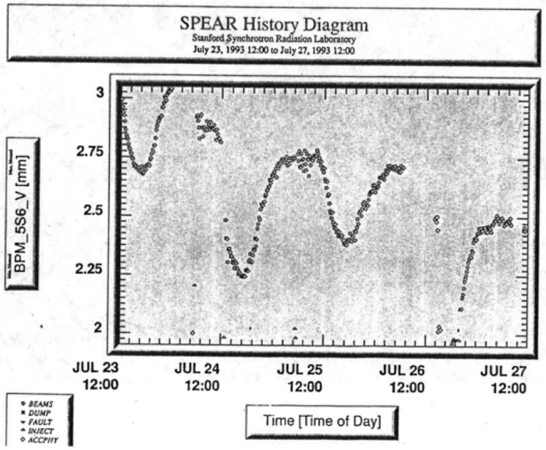
1972

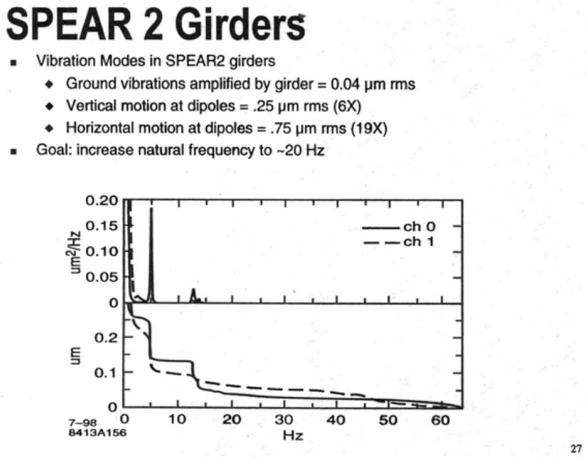


1974

SPEAR II Orbit Instability – ca 1980





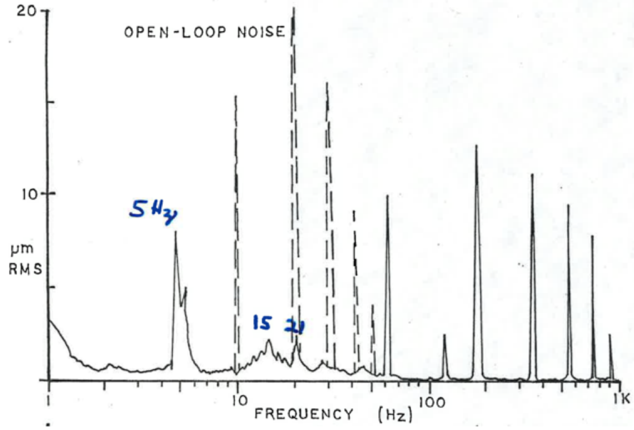


SPEAR 2 Girders

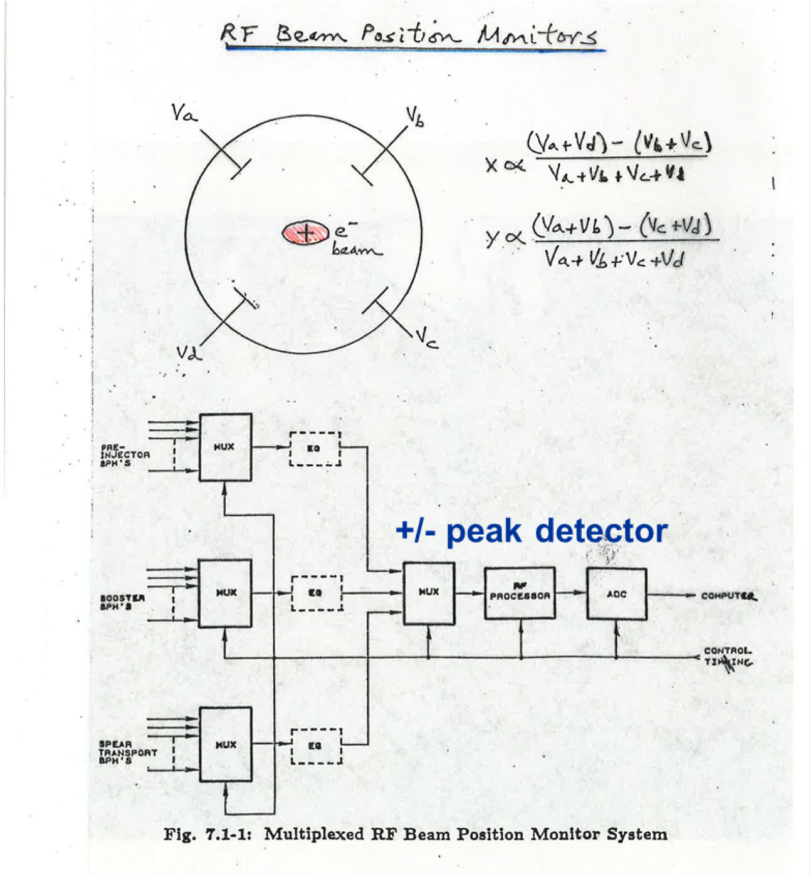
- Vibration Modes in SPEAR2 girders
  - Ground vibrations amplified by girder = 0.04 μm rms
  - Vertical motion at dipoles = .25 μm rms (6X)
  - Horizontal motion at dipoles = .75 μm rms (19X)
- Goal: increase natural frequency to ~20 Hz

27

D.Dell'Orco - SLAC - July 28-30, 1998



e-/e+ BPMs for SPEAR II – ca 1980



$$x \propto \frac{(V_a+V_d)-(V_b+V_c)}{V_a+V_b+V_c+V_d}$$

$$y \propto \frac{(V_a+V_b)-(V_c+V_d)}{V_a+V_b+V_c+V_d}$$

+/- peak detector

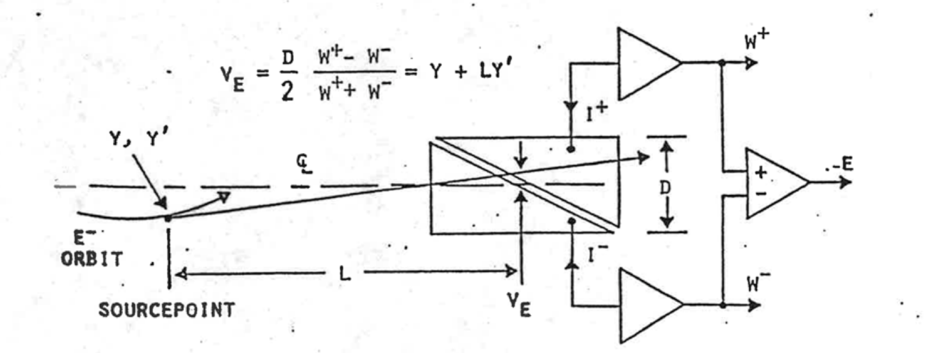
Fig. 7.1-1: Multiplexed RF Beam Position Monitor System

many seconds to acquire an orbit

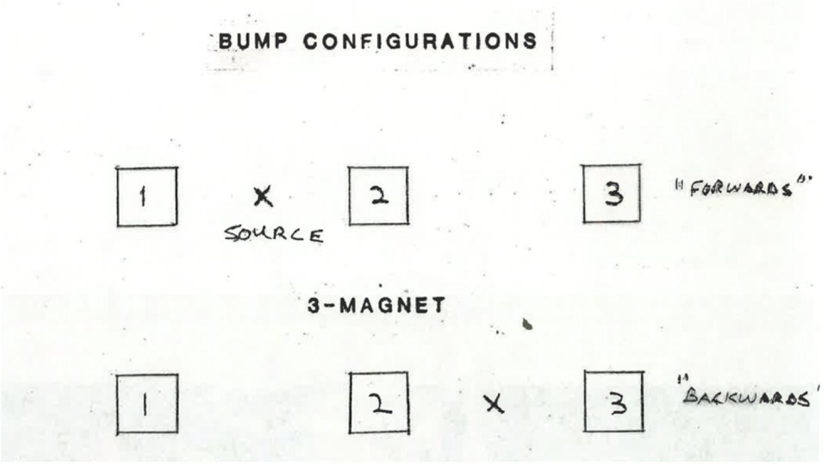
Orbit correction:

- Harmon
- MICADO (most effective corrector – ca 1973)
- Other

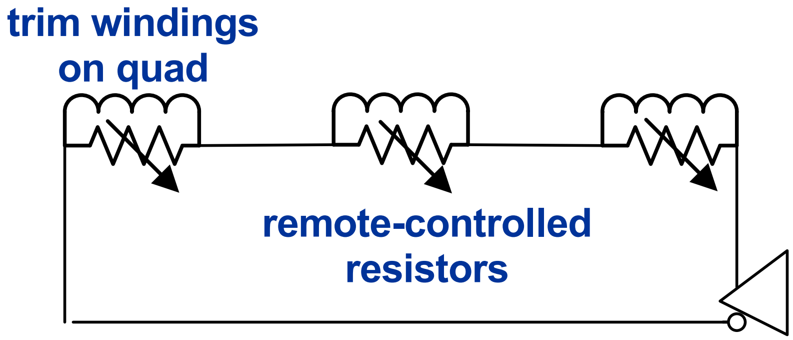
Vertical Beam Steering at SSRL – ca 1980



HELIUM ION CHAMBER POSITION MONITOR



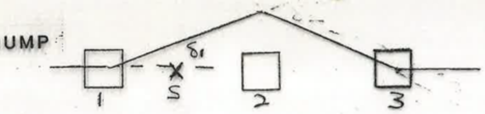
open loop



THE PHYSICS OF ELECTRON STORAGE RINGS
AN INTRODUCTION

MATTHEW SANDS*
UNIVERSITY OF CALIFORNIA, SANTA CRUZ
SANTA CRUZ, CALIFORNIA 95060

3-MAGNET BUMP



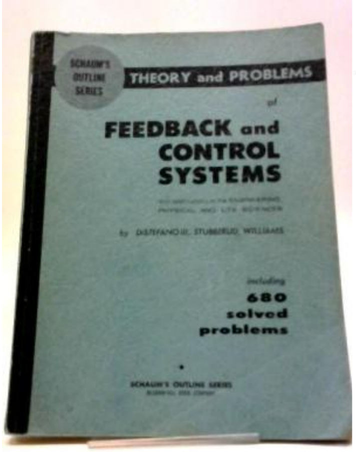
SENSITIVITY COEFFICIENTS

$$\begin{pmatrix} y_c \\ y'_c \end{pmatrix} = \begin{pmatrix} Y \\ Y' \end{pmatrix} \delta_1 = \begin{pmatrix} \sqrt{\beta_1 \beta_s}\,\sin(\varphi_s - \varphi_1) \\ \sqrt{\beta_1/\beta_s}\left[\cos(\varphi_s - \varphi_1) - \alpha_s \cos(\varphi_s - \varphi_1)\right] \end{pmatrix}$$

$$\alpha_s = -\frac{1}{2} \frac{d\,\beta(l)}{dl}\bigg|_{l=s} \qquad (= 0 \text{ FOR SYMMETRY STRAIGHT})$$

$$\begin{pmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \end{pmatrix} = \begin{pmatrix} 1 \\ -\sqrt{\dfrac{\beta_1}{\beta_2}}\,\dfrac{\sin(\varphi_3 - \varphi_1)}{\sin(\varphi_3 - \varphi_2)} \\ \sqrt{\dfrac{\beta_1}{\beta_3}}\,\dfrac{\sin(\varphi_2 - \varphi_1)}{\sin(\varphi_3 - \varphi_2)} \end{pmatrix} \delta_1$$

Speeding up Vertical Steering to Suppress 5 Hz and Closing the Loop


SCHAUM'S OUTLINE SERIES

THEORY and PROBLEMS of

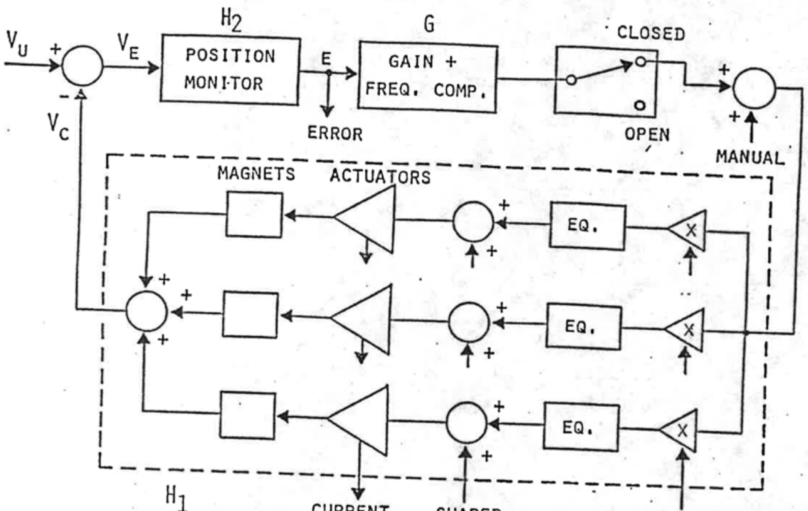
FEEDBACK and CONTROL SYSTEMS

by DiSTEFANO, STUBBERUD, WILLIAMS

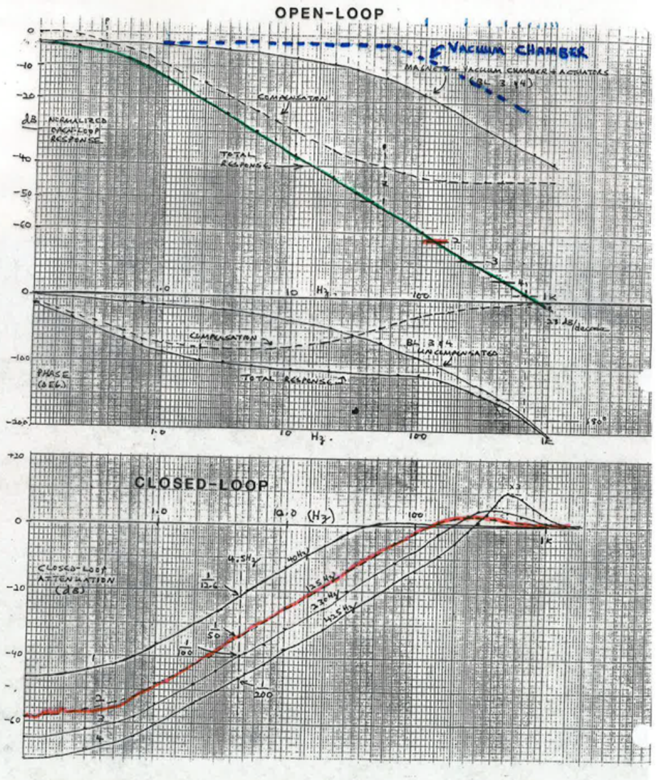
including 680 solved problems

SCHAUM'S OUTLINE SERIES

$$\frac{V_e}{V_u} = \frac{1}{1 + G H_1 H_2 (i\omega)}$$

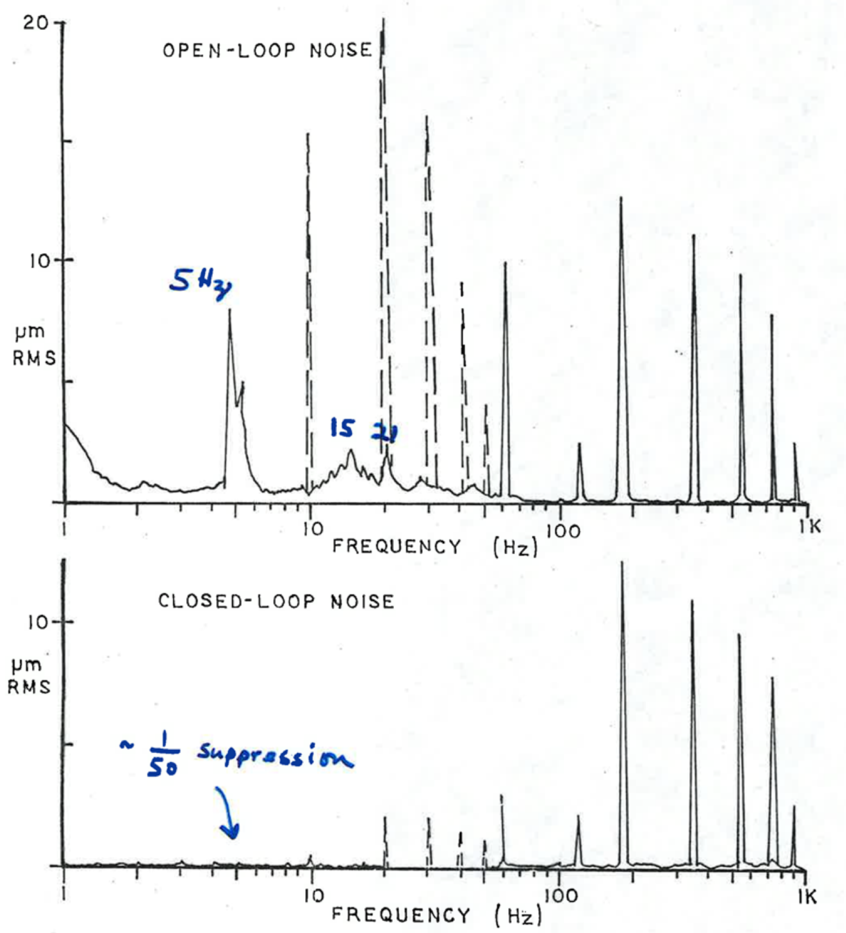


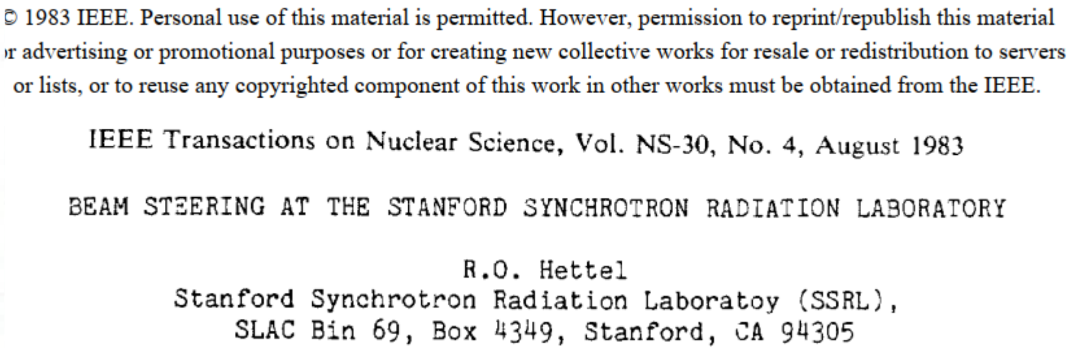
3-MAGNET STEERING SERVO SYSTEM



3-MAGNET STEERING SYSTEM RESPONSE (SPEAR)

Vertical Steering Feedback to Suppress 5 Hz – cont.





IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

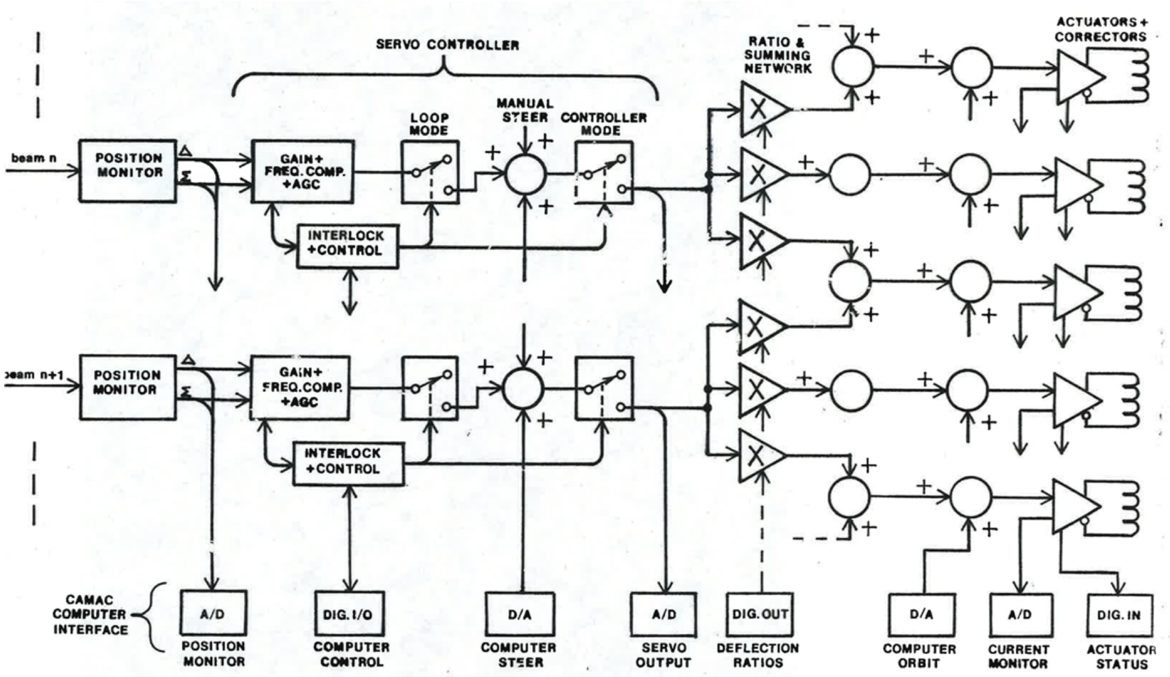
BEAM STEERING AT THE STANFORD SYNCHROTRON RADIATION LABORATORY

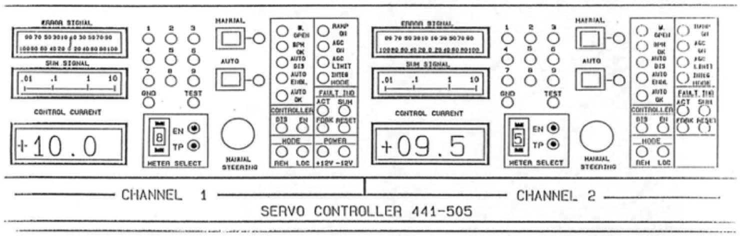
R.O. Hettel
Stanford Synchrotron Radiation Laboratoy (SSRL),
SLAC Bin 69, Box 4349, Stanford, CA 94305

Made Dave Moncton's experiment possible... invited to NSLS in 1984 to implement similar system, working with L-H Yu, J. Galayda, S. Krinsky, R. Nawrocky, etc...

1986: Invited to Photon Factory for same purpose

Shared Magnet Steering

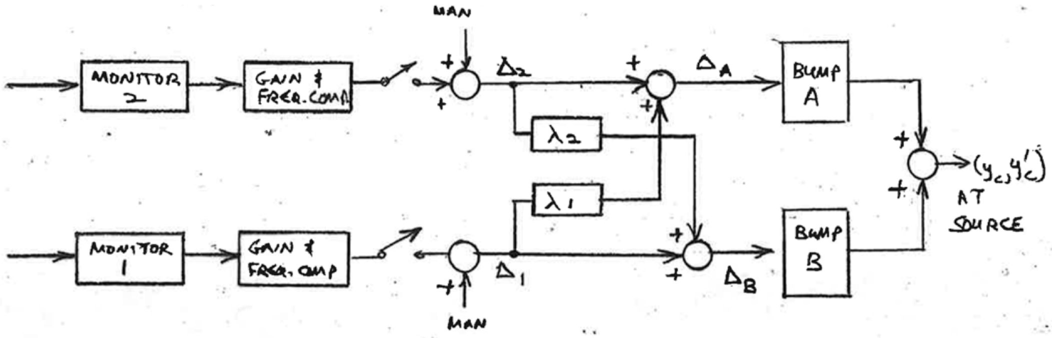




limit system crosstalk to few %.

more stringent decoupling required as # of lines increases
to avoid multi-loop instability

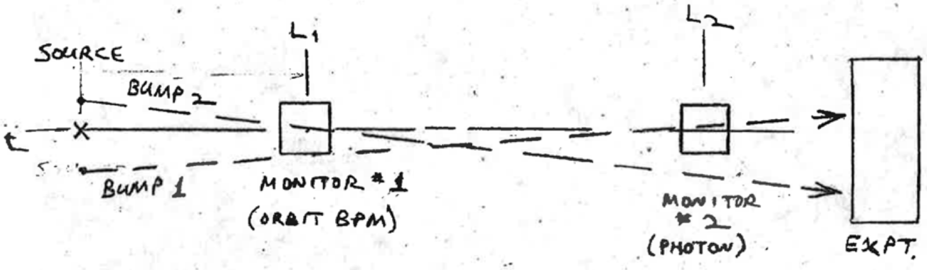
2-monitor, 4-magnet steering – ca 1986



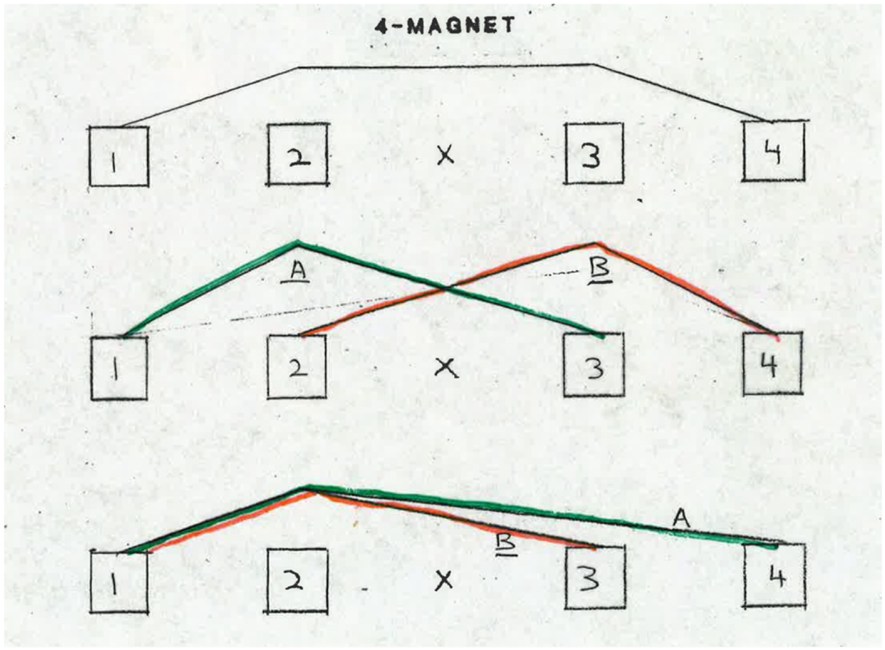
BUMP A & BUMP B ARE LINEARLY INDEPENDENT, COMPENSATED

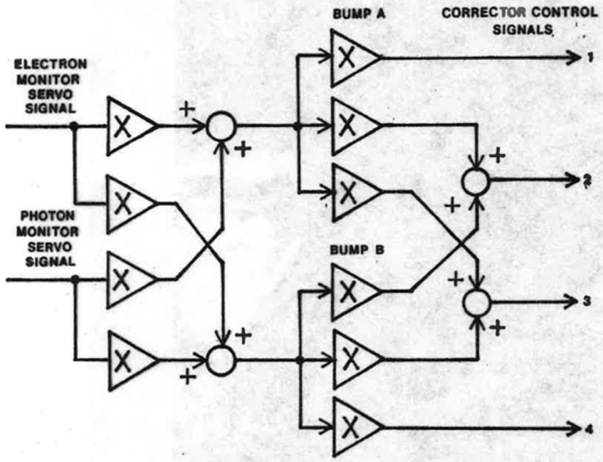
Δ_1 DRIVES BUMP 1. THAT CAUSES NO DISPLACEMENT AT MONITOR 2.

Δ_2 DRIVES BUMP 2 THAT CAUSES NO DISPLACEMENT AT MONITOR 1.



4-Magnet Bumps: Superposition of 3-Magnet Bumps





Ratio & Summing Network
4-magnet steering

2-Monitor, 4-Magnet Feedback for PEP Beamline

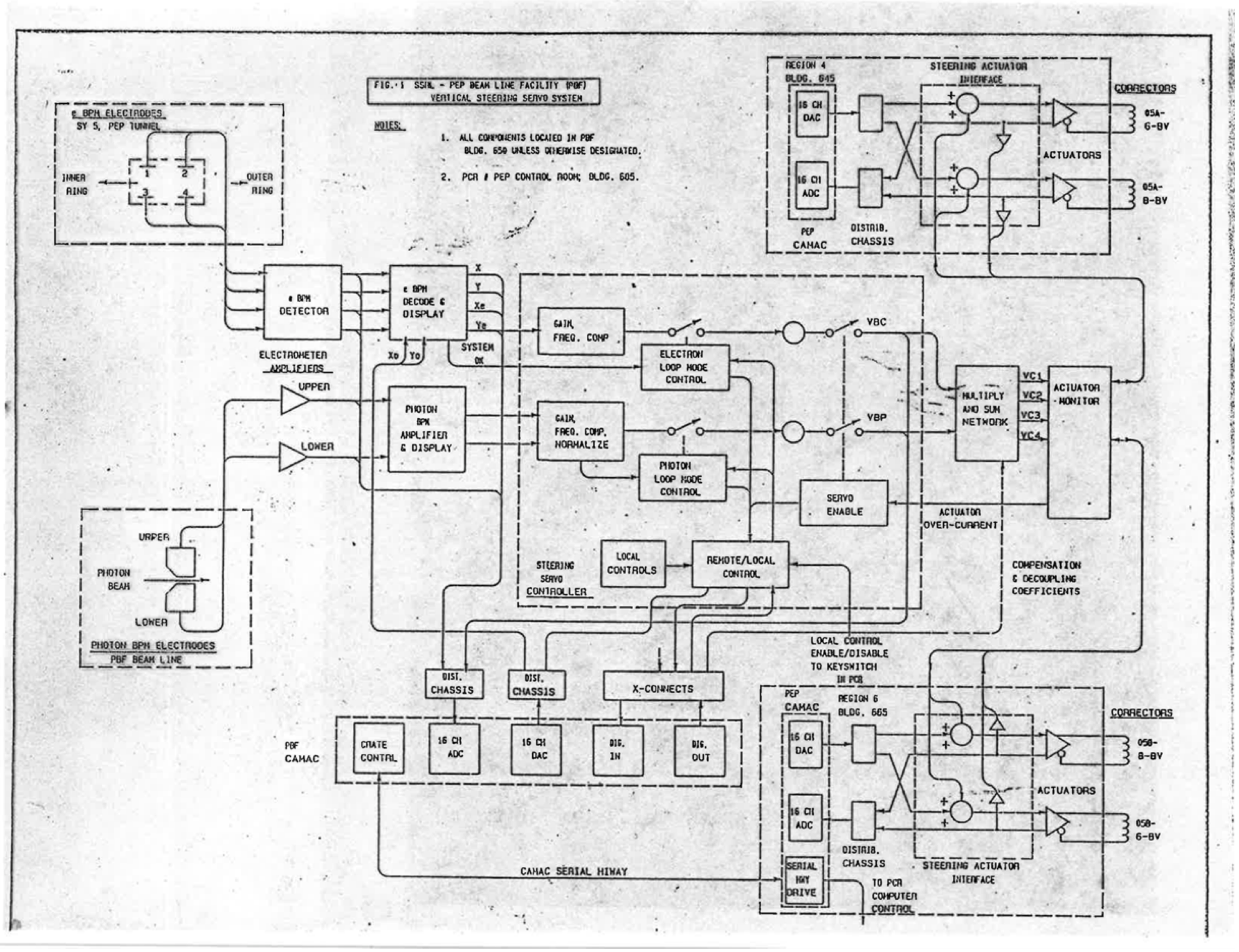


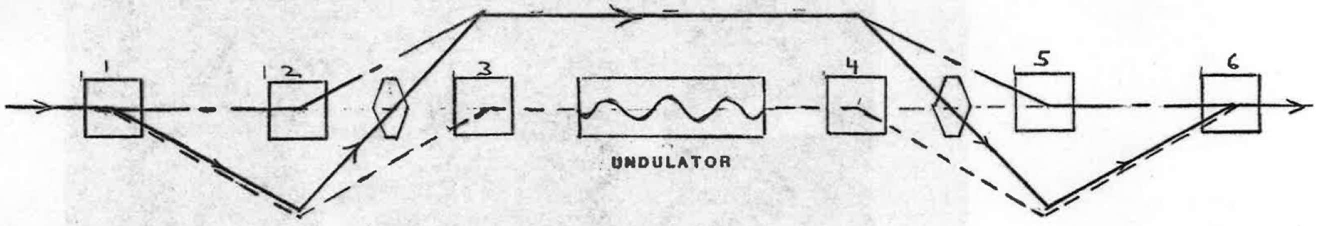
FIG. 1 SSRL - PEP BEAM LINE FACILITY (PBF) VERTICAL STEERING SERVO SYSTEM

NOTES:

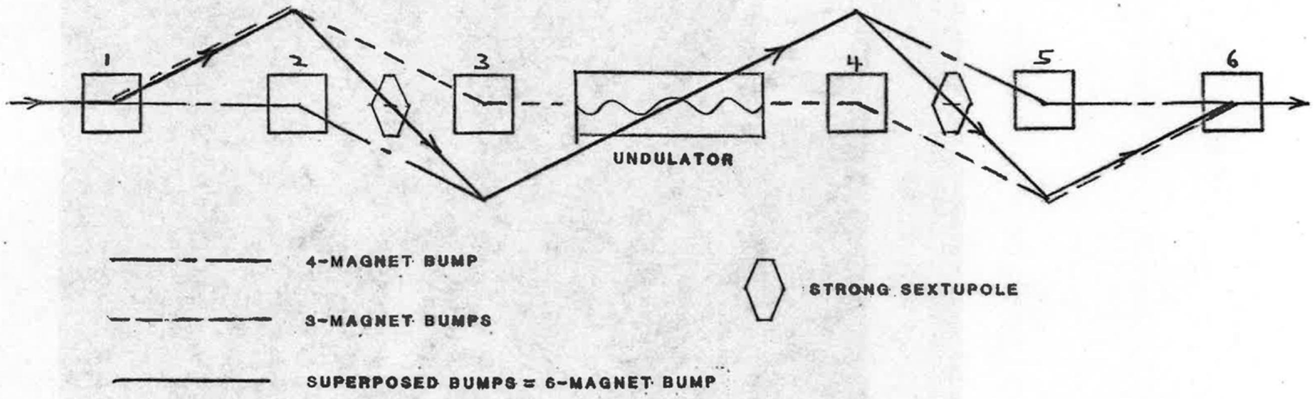
1. ALL COMPONENTS LOCATED IN PBF BLDG. 650 UNLESS OTHERWISE DESIGNATED.
2. PCR = PEP CONTROL ROOM; BLDG. 605.

Never built because of SPEAR Injector project with Helmut Wiedemann

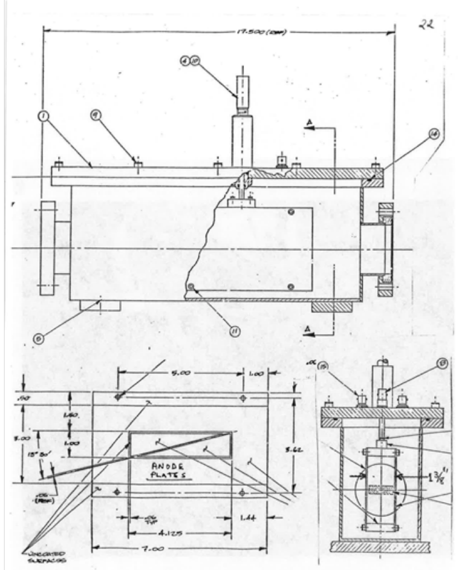
6-Magnet Bumps for PEP



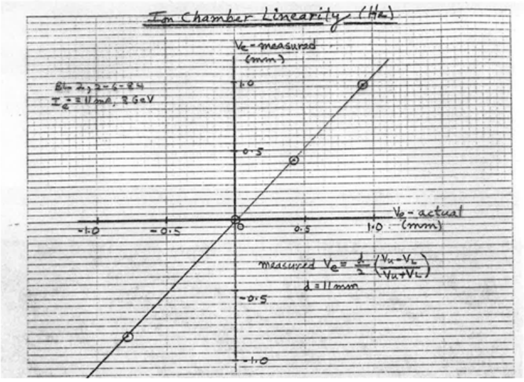
BUMP CONFIGURED TO AVOID ORBIT DISPLACEMENT IN STRONG SEXTUPOLES

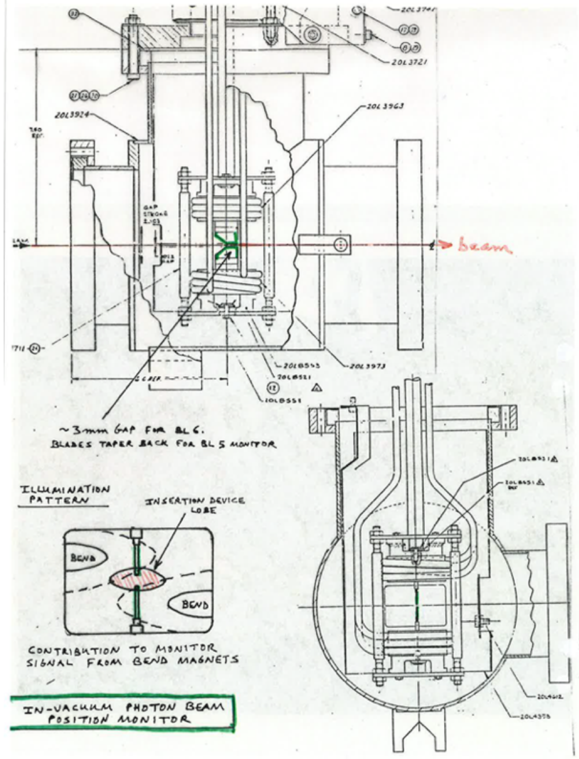


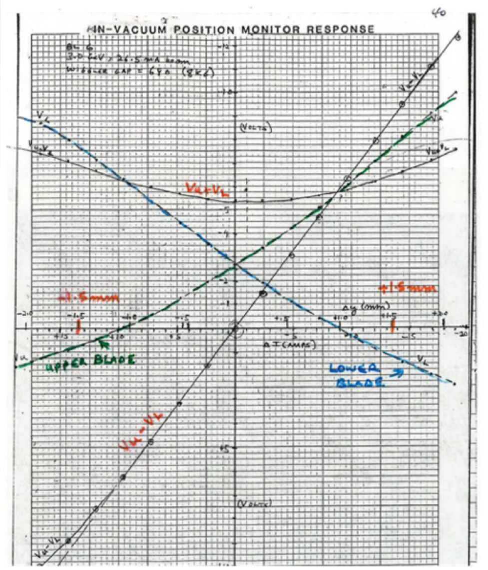
X-ray BPMs at SSRL



SPLIT ANODE HELIUM ION CHAMBER POSITION MONITOR



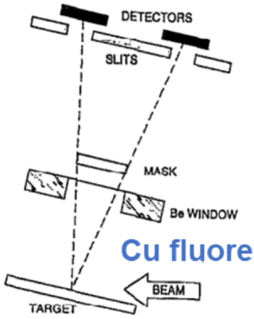




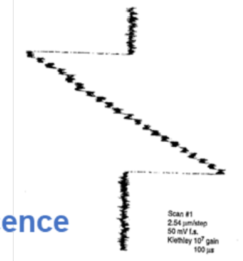
Photon beam position monitor for SSRL Beamline 9

John A. Cerino, Thomas Rabedeau, and William Bowen
Stanford Linear Accelerator Center, Stanford Synchrotron Radiation Laboratory, Stanford,

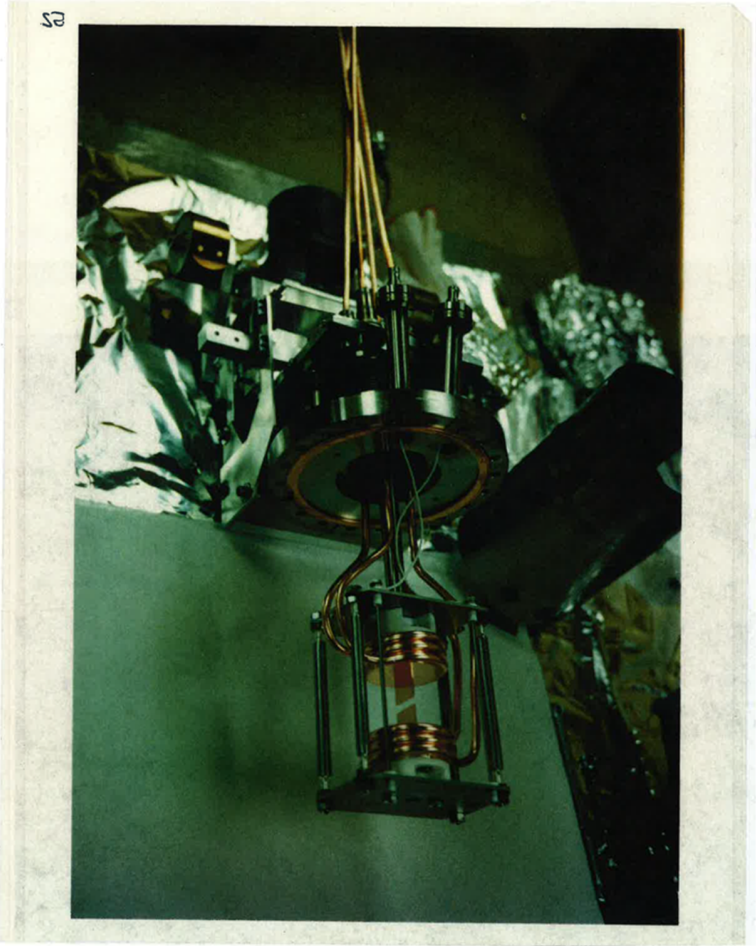
(Presented on 19 July 1994) **Rev. Sci. Instrum. 66 (2), February 1995**

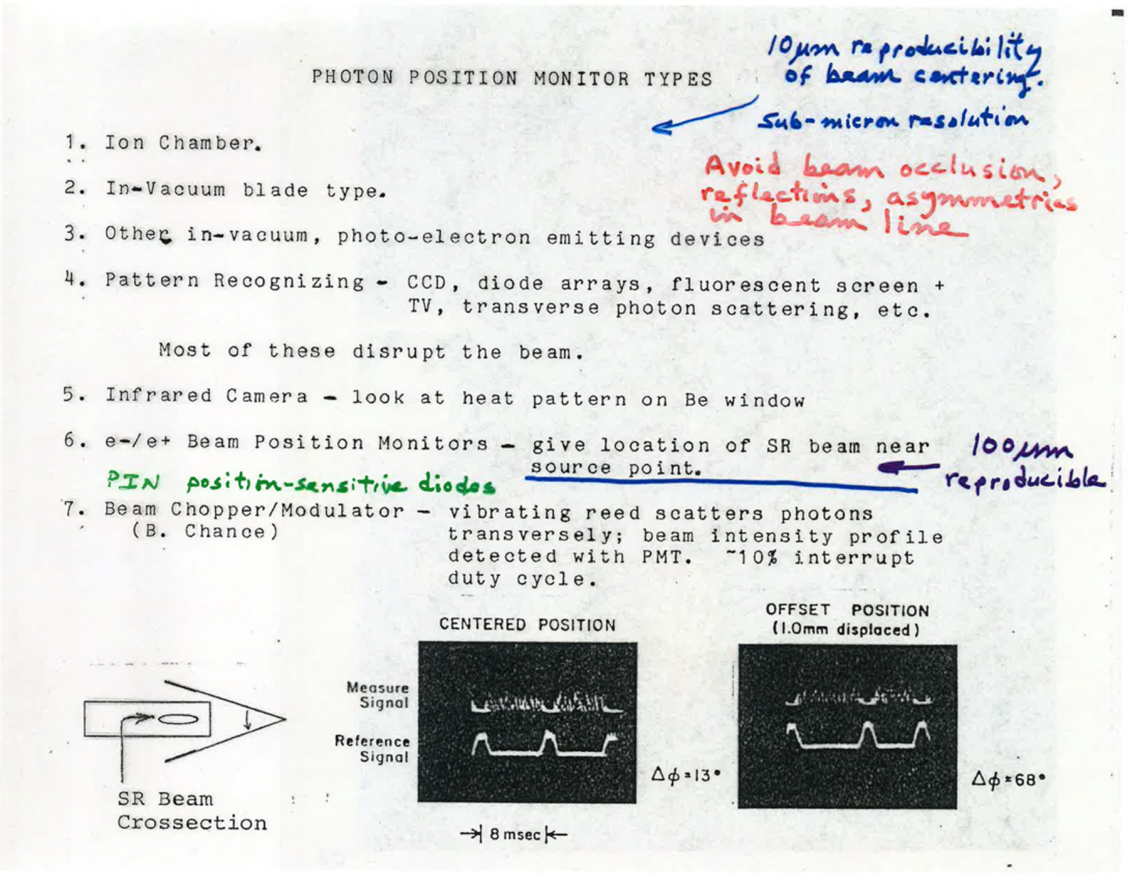


Cu fluorescence



X-ray BPMs at SSRL – cont.





PHOTON POSITION MONITOR TYPES

10μm reproducibility of beam centering.

Sub-micron resolution

Avoid beam occlusion, reflections, asymmetries in beam line

1. Ion Chamber.
2. In-Vacuum blade type.
3. Other in-vacuum, photo-electron emitting devices
4. Pattern Recognizing - CCD, diode arrays, fluorescent screen + TV, transverse photon scattering, etc.

   Most of these disrupt the beam.

5. Infrared Camera - look at heat pattern on Be window
6. e-/e+ Beam Position Monitors - give location of SR beam near source point.

   100μm reproducible

   PIN position-sensitive diodes

7. Beam Chopper/Modulator - vibrating reed scatters photons transversely; beam intensity profile detected with PMT. ~10% interrupt duty cycle. (B. Chance)

NSLS Global Harmonic Feedback

PAC '89: 1 harmonic for VUV ring

REAL TIME CLOSED ORBIT CORRECTION SYSTEM

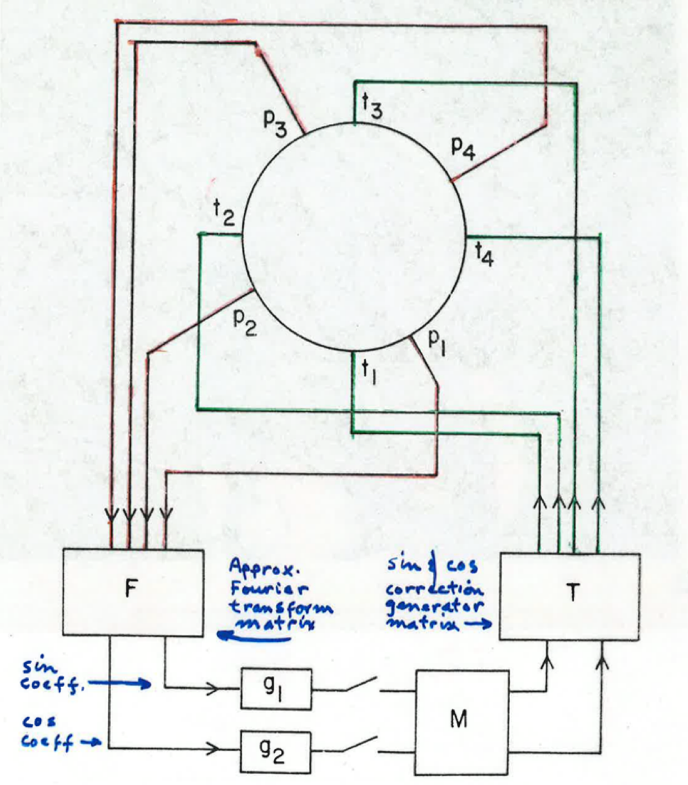
L.H. Yu, R. Biscardi, J. Bittner, E. Bozoki, J. Galayda,
S. Krinsky, R. Nawrocky, O. Singh and G. Vignola
National Synchrotron Light Source
Brookhaven National Laboratory
Upton, New York 11973

PAC '91: 3 harmonics for X-ray ring

Real Time Global Orbit Feedback System for NSLS X-Ray Ring*

L. H. Yu, R. Biscardi, J. Bittner, A. M. Fauchet, S. Krinsky,
R. J. Nawrocky, J. Rothman, O. V. Singh, K. M. Yang

~$\frac{1}{4}$ suppression globally

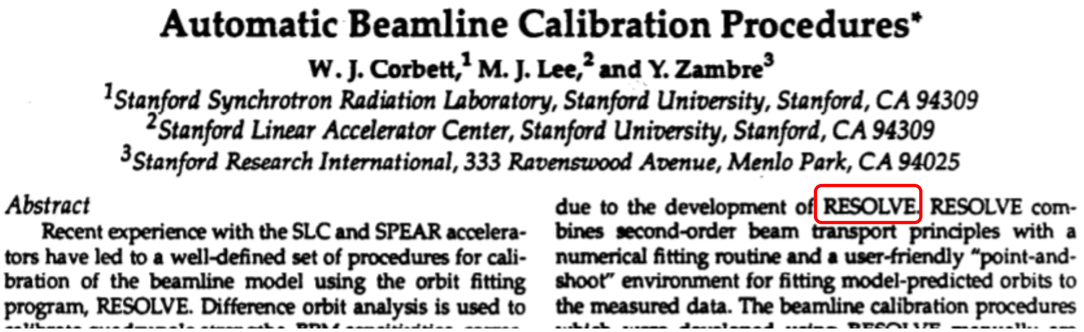


4-monitor, 4-corrector harmonic feedback – for single harmonic x ν

NSLS VUV Ring   L.H.Yu, E.Bozoki, J.Galayda, S.Krinsky, G.Vignola

SPEAR Global Feedback

EPAC '92



Automatic Beamline Calibration Procedures*

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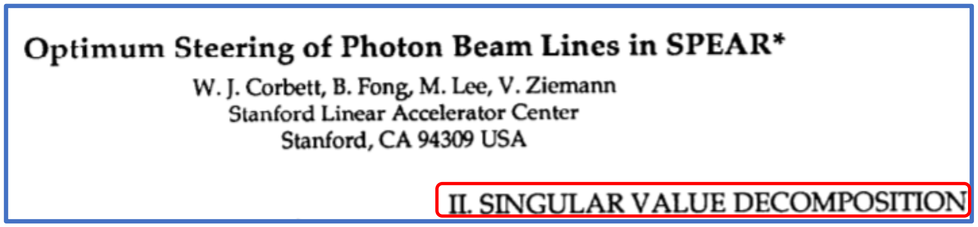
Abstract

Recent experience with the SLC and SPEAR accelerators have led to a well-defined set of procedures for calibration of the beamline model using the orbit fitting program, RESOLVE. Difference orbit analysis is used to due to the development of RESOLVE. RESOLVE combines second-order beam transport principles with a numerical fitting routine and a user-friendly "point-and-shoot" environment for fitting model-predicted orbits to the measured data. The beamline calibration procedures

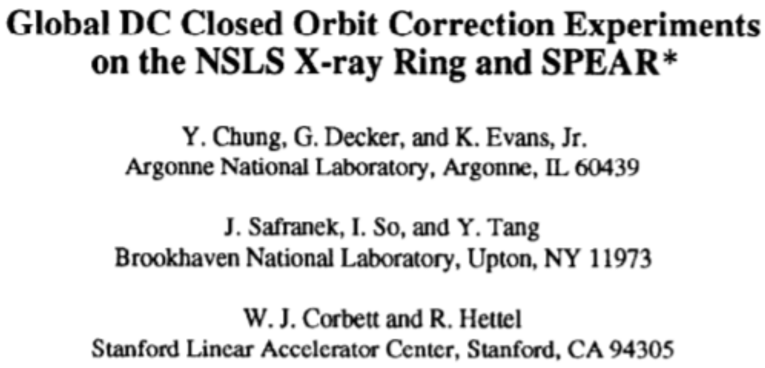
PAC '93



Optimum Steering of Photon Beam Lines in SPEAR*

W. J. Corbett, B. Fong, M. Lee, V. Ziemann
Stanford Linear Accelerator Center
Stanford, CA 94309 USA

II. SINGULAR VALUE DECOMPOSITION



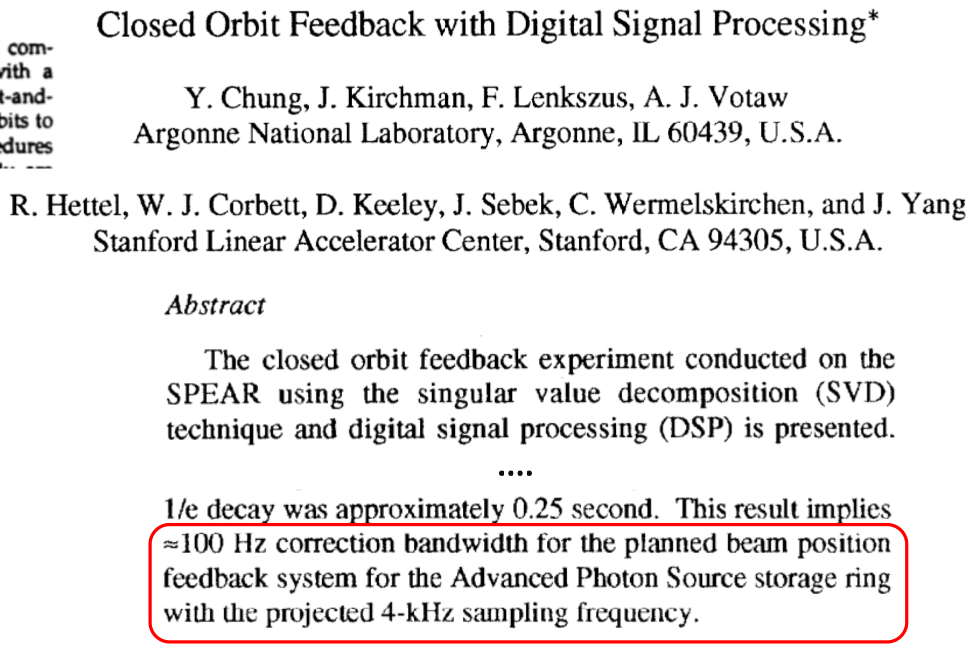
Global DC Closed Orbit Correction Experiments on the NSLS X-ray Ring and SPEAR*

Y. Chung, G. Decker, and K. Evans, Jr.
Argonne National Laboratory, Argonne, IL 60439

J. Safranek, I. So, and Y. Tang
Brookhaven National Laboratory, Upton, NY 11973

W. J. Corbett and R. Hettel
Stanford Linear Accelerator Center, Stanford, CA 94305

EPAC '94



Closed Orbit Feedback with Digital Signal Processing*

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Argonne National Laboratory, Argonne, IL 60439, U.S.A.

R. Hettel, W. J. Corbett, D. Keeley, J. Sebek, C. Wermelskirchen, and J. Yang
Stanford Linear Accelerator Center, Stanford, CA 94305, U.S.A.

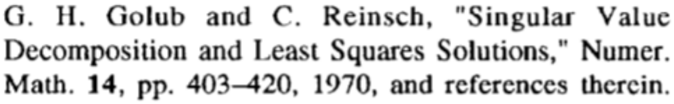
Abstract

The closed orbit feedback experiment conducted on the SPEAR using the singular value decomposition (SVD) technique and digital signal processing (DSP) is presented.

....

1/e decay was approximately 0.25 second. This result implies ≈100 Hz correction bandwidth for the planned beam position feedback system for the Advanced Photon Source storage ring with the projected 4-kHz sampling frequency.

APS-U: 1 kHz BW with 22.6 kHz sampling rate



G. H. Golub and C. Reinsch, "Singular Value Decomposition and Least Squares Solutions," Numer. Math. **14**, pp. 403–420, 1970, and references therein.

Harmonic vs. SVD orbit correction for SPEAR

W.J Corbett et al.

ORBIT CORRECTION

- 30 correctors per plane
- Horizontal: trim windings on main bend cores

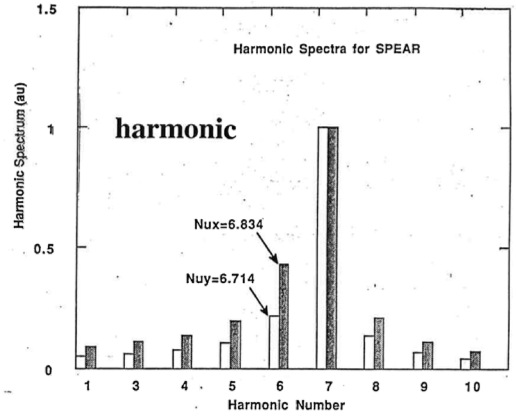
  ⇒ hysteresis; ~2 Hz BW (with chamber)
- Vertical: trim windings on quad cores

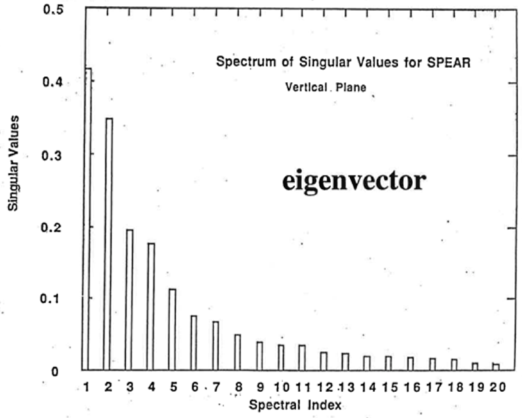
  ⇒ hysteresis; 30 Hz BW (with chamber)
- Correction algorithms:

  1) Harmonic: 10 harmonics detectable (20 BPMs); uses ring model (h = 5,6,7,8 dominant)

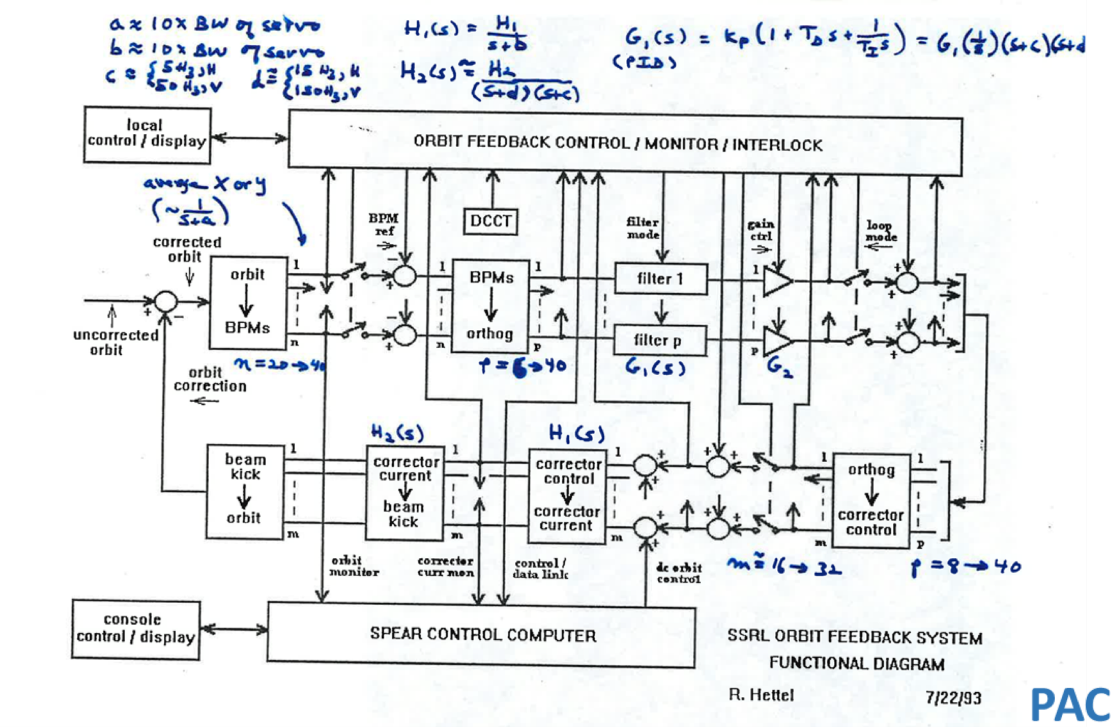
  2) Eigenvector/SVD: 20 eigenmodes detectable; bypasses ring model

  Both use corrector-BPM response matrix



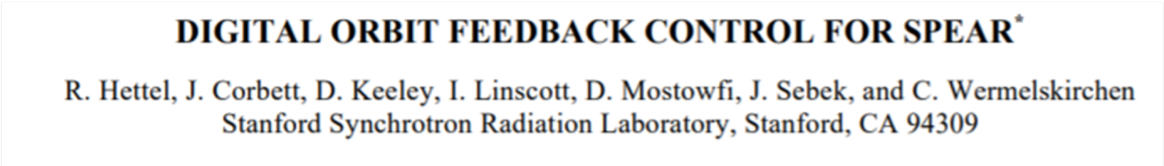


SVD global orbit feedback for SPEAR



PAC ‘95

X-ray BPMs included with superposed local bumps



DIGITAL ORBIT FEEDBACK CONTROL FOR SPEAR*

R. Hettel, J. Corbett, D. Keeley, I. Linscott, D. Mostowfi, J. Sebek, and C. Wermelskirchen
Stanford Synchrotron Radiation Laboratory, Stanford, CA 94309

The past and the future, not to mention the present

SRI 2001

REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 73, NUMBER 3

Beam stability at light sources (invited)

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- With stability requirements increasing by an order of magnitude, feedback systems on beam line components, such as the mirror-tilt feedback implemented at SSRL will become increasingly important.
- These might be integrated with accelerator stabilizing systems to maintain relative alignment between accelerator and experiment.
- New beam line technology, including adaptive optics and photon parameter monitors used to compensate for beam fluctuations, improved measurement methods (e.g., lock-in signal modulation and sample–sample signal normalization, and robust experiment design (i.e., where photon and experiment acceptance phase spaces are well-matched).
- Demands will increase even more for the next generation of diffraction limited light sources (ε ~0.1 nm-rad) which include storage rings, energy recovery linacs, and linac-driven free-electron lasers having 100 fs bunch lengths.

- **Integrated solutions are needed from both accelerator and beam line staff**