Beam Stability at Light Sources

R. Hettel, SSRL

- Beam properties
- Stability requirements
- Noise sources
- Orbit stabilizing technology
- Future directions

Beam Stability Requirements

Want stability of:

- intensity after apertures
  apertures in phase space
- steering accuracy on small samples
  pointing accuracy
- e- trajectory in IDs
  emission pattern, off-axis energy pattern, switched polarization, etc.
- photon energy
- timing
  pump-probe, etc.
- beam lifetime

Stability requirements depend on:

- time scale
- machine properties ????
- photon source phase space and experiment phase space acceptance
  including optics

Electron Beam Properties and Phase Space

Electron beam characterized by conjugate variable pairs in 6-D phase space:

x, x' $\qquad$ y, y' $\qquad$ E, t **(or f)**

-------- transverse ---------- $\qquad$ **longitudinal**

For each conjugate pair, beam occupies phase space ellipse of constant area - or emittance

transverse:

$$\varepsilon = \gamma(s)x^2 + 2\alpha(s)xx' + \beta(s)x'^2 = \text{constant} \qquad \left(\alpha = -\beta'/2 \qquad \gamma = \frac{1+\alpha^2}{\beta}\right)$$

$$\varepsilon_y \cong k\varepsilon \qquad (k = \text{coupling},\ k <\sim 0.1)$$

e- beam size:

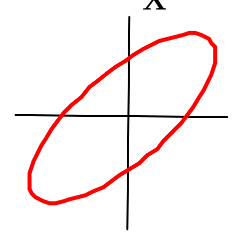
$$\sigma_x(s) = \sqrt{\varepsilon_x\beta_x(s) + (\eta(s)\delta E/E)^2} \qquad \sigma_y(s) = \sqrt{\varepsilon_y\beta_y(s)}$$

e- divergence:

$$\sigma_{x'}(s) = \sqrt{\varepsilon_x\gamma_x(s) + (\eta'(s)\delta E/E)^2} \qquad \sigma_{y'}(s) = \sqrt{\varepsilon_y\gamma_y(s)}$$

longitudinal:

$$\Delta\phi\ (\text{rad}) = \frac{h\alpha_c}{\nu_s}\frac{dE}{E} \qquad \left(= \sim 40\frac{dE}{E} \text{ for SPEAR3}\right)$$



Have coupling between phase space planes (6-D emittance preserved)

- H-V by skew quads, orbit in sextupoles, resonances
- transverse-longitudinal (Touschek scattering, $\Delta x = \eta\Delta E/E$)
- etc.

Photon Beam Properties

Photon beam dimensions (unfocused):

$$\sigma_{ph}(L) = \sqrt{\sigma_{e-}^{\,2} + (L\sigma'_{ph})^2} \qquad\qquad \sigma'_{ph} \cong \sqrt{\sigma'^{\,2}_{e-} + \frac{1}{N\gamma^2}}$$

N = number of undulator periods (= 1 for dipoles and high k wigglers)
γ = E(GeV)/.51 x 10^{-3} (at critical energy; depends on energy)

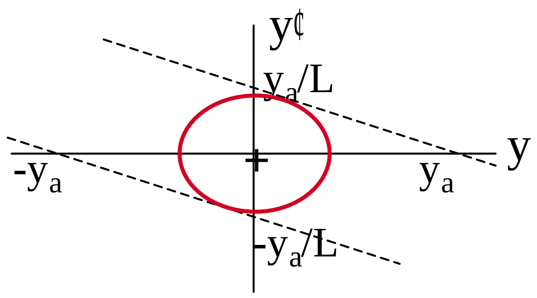
Notes:

σ'_{e-} = order 10-100 μrad horizontally, order 10 μrad vertically

$1/\gamma$ = order 100 μrad ⇒ dominates vertical divergence except for large N

σ'_{ph-} (horiz) = order mrads for dipole and wiggler sources

Translation of photon phase space between source and experiment:

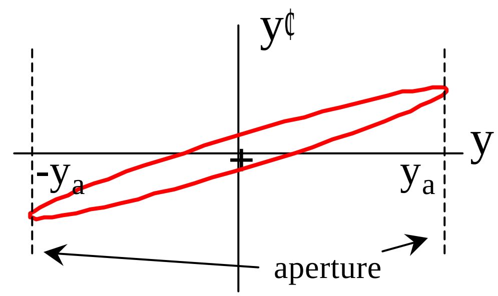


source point

-L ←

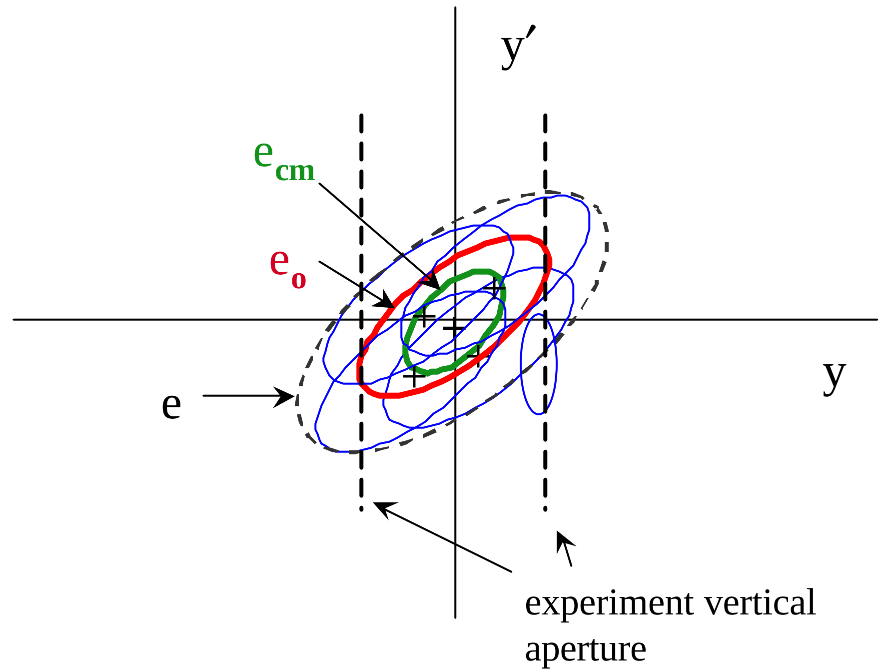
$$y_{exp} = y_{sp} + Ly'_{sp}$$
$$y'_{exp} = y'_{sp}$$

L →



experiment

Beam Position Instability and Emittance Growth from Orbit Motion



For disturbance frequencies >> experiment integration time:

$e = e_o + e_{cm}$ $De/e = e_{cm}/e_o$

For disturbance frequencies < experiment integration time:

e (envelope) $= e_o + 2Ö\, e_o e_{cm} + e_{cm}$ $De/e\ @\ 2\ Ö\ e_{cm}/e_o$

($\varepsilon_{cm} << \varepsilon_o$; L. Farvacque, ESRF)

Note: can apply similar analysis to other conjugate variables

Beam Stability - Time Scales

Disturbance frequencies >> experiment integration time:

Orbit disturbances blow up effective beam s and s¢, reduce intensity at experiment, but do not add noise.

For $\Delta\varepsilon/\varepsilon = \varepsilon_{cm}/\varepsilon_o <$ ~10%: $\quad$ **Dy_{cm}(rms) < ~0.3 s_y** $\quad$ **$Dy¢_{cm}$(rms) < ~0.3 $s_{y'}$**

Note: can have frequency aliasing if don't obey Nyquist….

Disturbance frequencies £ experiment integration time:

Orbit disturbances add noise to experiment.

For $\Delta\varepsilon/\varepsilon =$ ~$2\sqrt{\ }\varepsilon_{cm}/\varepsilon_o <$~10%: $\quad$ **Dy_{cm}(rms) < 0.05 s_y** $\quad$ **$Dy¢_{cm}$(rms) < 0.05 $s_{y'}$**

Disturbance frequencies << experiment time (day(s) or more):

Realigning experiment apparatus is a possibility.

Sudden beam jumps or spikes can be bad (low rms)

Note: peak amplitudes can be > x5 rms level

Intensity Stability

Want high level of flux (I) constancy through aperture or steering accuracy to hit small sample (sample size on order of beam size σ).

$\Delta I/I < 10^{-3}$ (typical)

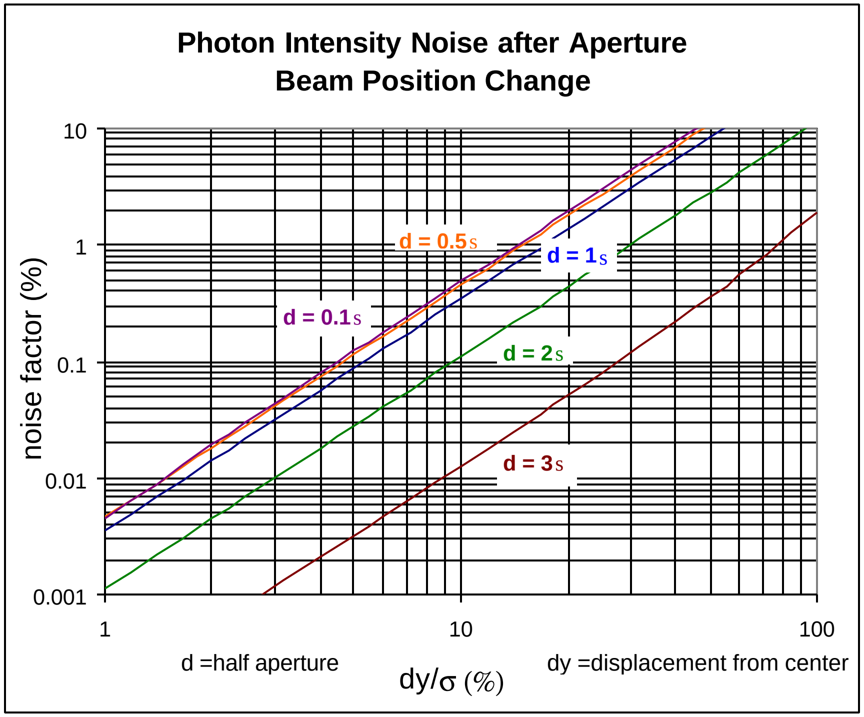
Note: some experiments require **$< 10^{-4}$** flux constancy

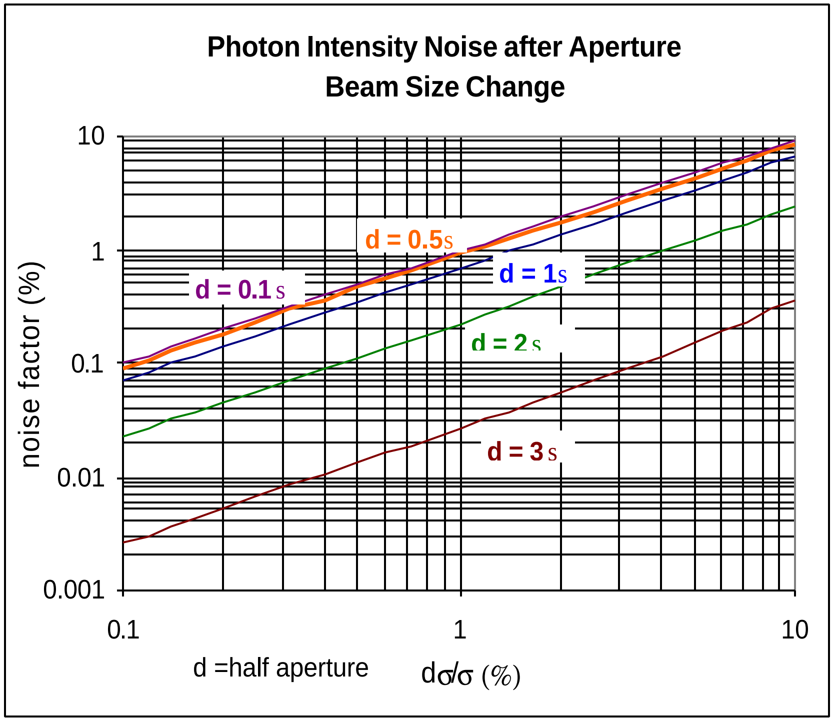
Photoemission electron spectroscopy combined with dichroism spectroscopy (subtractive processing of switched polarized beam signals) (H. Padmore)

Flux variations caused by

- orbit instability
- beam size instability

Beam Stability at Apertures





Intensity variations for beam with Gaussian size σ due to position motion dy from the center and beam size change dσ for various sized apertures.

Intensity Stability - Orbit

For 0.1% intensity stability, orbit stability should be

$Dy_{cm} < .05\ s_{y}$ at source point for ***focused*** beams

$Dy¢_{cm} < .05\ s_{y'}$ at source point for ***unfocused*** beams

s_{y} ~ **20-50** m**m,** s_{x} ~ **100-500** m**m** for most 3rd generation sources

$s_{y¢}$ **= ~140** m**rad** @ 3 GeV, N = 1; **= 17** m**rad** @ 3 GeV, N = 100; **= 7** m**rad** @ 7 GeV, N = 100

Þ Dy_{cm} **< ~1-3** m**m,** $Dy¢_{cm}$ **< ~0.5-10** m**rad** for 3rd gen sources

Orbit perturbing mechanisms:

- varying magnetic fields (moving quadrupoles, ID gaps, other field sources)
- coherent electron energy variations in lattice dispersion sections at frequencies < data integration time (synchrotron oscillations, RF)

$\Delta x = h\ D\ E/E < .05\sigma_x = \sim 10\text{-}20\ \mu m$

Þ **DE/E (coherent) < ~10^{-4}** (η_x= ~0.1 m at dipole sources; η_y= ~0.02 m)

($\Delta\phi$ **< 0.2º** for SPEAR 3)

Þ $Df_{RF}/f_{RF} = a_c\ DE/E < \sim 10^{-7}$ (α_c = ~10^{-3})

(Δf_{RF} **< 50 Hz** for f_{RF} = 500 MH); imposes limit on phase noise for RF source ~10 kHz BW)

Intensity Stability - Beam Size

For 0.1% intensity stability, beam size stability should be

$$Ds/s < \sim 10^{-3}$$

Beam size-perturbing mechanisms:

- changes in horizontal-vertical electron beam coupling

  ID gap change, orbit in sextupoles, energy ramp without coupling correction

- collective effects

  coupling resonances, single- and multibunch instabilities in transverse and longitudinal planes, intrabeam scattering

- gas bursts, ions, dust particles

- electron energy variations in lattice dispersion sections at frequencies > data integration time **(synchrotron oscillations, Landau damping mechanisms, etc.)**

$$s^2 = eb + (hdE/E)^2 + (hDE/E)^2$$

($\sqrt{\varepsilon\beta}$ = ~350 μm; $\eta\ \delta E/E$ = ~100 μm for η = 0.1 m and $\delta E/E$ (natural energy spread) = ~ 0.1%; σ_0 = ~360 μm)

$$Þ \quad DE/E\ (rms) < \sim 1.6 \times 10^{-4}$$

Photon Energy Resolution

Photon energy resolution <10^{-4} after monochromator:

Bragg: $$\frac{\Delta E_{ph}}{E_{ph}} = \frac{\Delta\theta}{\theta_B}$$ where θ_B = ~5°-45° (~90-800 mrad)

Þ Dy¢$_{cm}$ < ~10 mrad

Note: some monochromators reaching 10^{-5} resolution Þ Dy¢$_{cm}$ < ~1 mrad

Undulator line energy and width not degraded:

line wavelength = $\lambda_n = n\, \lambda_u(1+k^2/2)/2\gamma^2$

Þ d l$_n$/ l$_n$ = -2 DE/E

natural width = $\delta\, \lambda_n/\lambda_n = 1/Nn$ (N = # periods, n = harmonic

- for **<10%** line width increase (N = 100, n = 10) Þ **DE/E (rms) < ~2 x 10^{-4}**
- for **<10^{-4}** coherent energy shift (N = 100, n = 10) Þ **DE/E (coherent) < ~5 x 10^{-5}**

Note: for 10^{-5} resolution Þ DE/E (coherent) < ~5 x 10^{-6}

(⇒ $\Delta\phi$ < **0.01°** for SPEAR 3 Δf_{RF} < **2.5 Hz** for f_{RF} = 500 MHz)

Timing Stability

Bunch time-of-arrival stability (Δt_{bunch})**:**

Dt_{bunch} **< ~0.1 of critical time scale** in experiment (pump-probe sync, etc.)

- or -

< ~0.1 s_{bunch} (σ_{bunch} = ~5-50 ps)

whichever is larger

Bunch length variations usually not a problem unless Touschek lifetime affected

Time-of-arrival variations caused by energy oscillations:

$$\Delta t_{bunch} = \frac{\Delta\phi \text{ (rad)}}{2\pi f_{rf}} \Rightarrow$$

Dt_{bunch} **= ~1.3 ps** for dE/E (coherent) = 10^{-4} in SPEAR 3

(= ~0.08 s_{bunch}**)**

Lifetime

Lifetime contributors:

- quantum lifetime
- gas scattering lifetime (Coulomb, bremsstrahlung)
- Touschek lifetime
- ions and dust particles

Touschek usually dominant lifetime factor for low E rings (< 3 GeV):

$$\tau_{\text{Touschek}} \propto \frac{\sigma_x \sigma_y \sigma_s \gamma^2 \left({}^{\delta p}\!/_{p} \right)_m}{N}$$

$\delta p/p$ = ring momentum acceptance

N = number of particles in bunch

Þ **control and stabilize bunch volume**

Ion trapping prevented by having gap in bunch fill pattern

Sources of Electron Beam Instability

Long term (weeks-years)

- ground settlement (mm)
- seasonal ground motion (< mm)

Medium term (minutes-days)

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

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 (x10-x40)

  Þ nm level ground motion can be amplified close to mm level

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

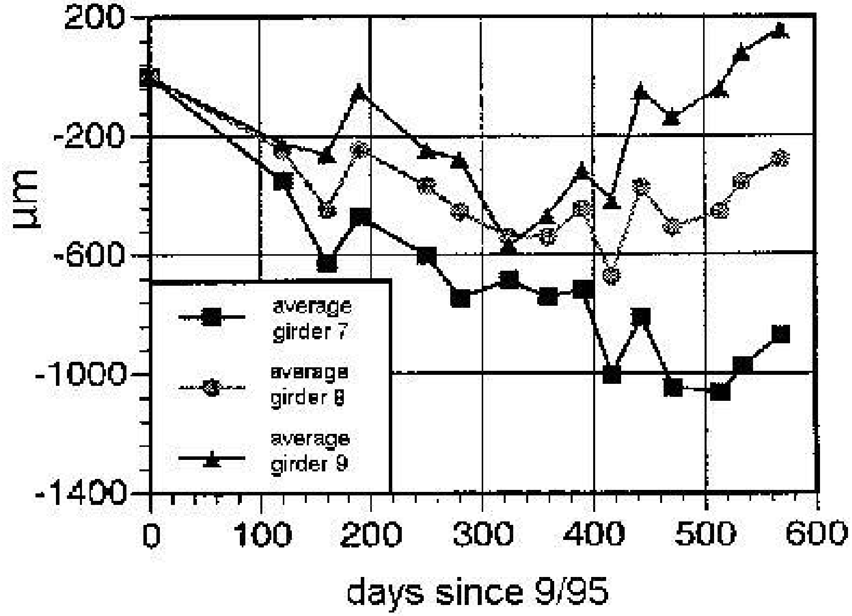
High frequency (sub-millisecond)

- high frequency PWM and pulsed power sources (microns)
- synchrotron oscillations (1-100 μm)
- single- and multibunch instabilities (1-100 μm)

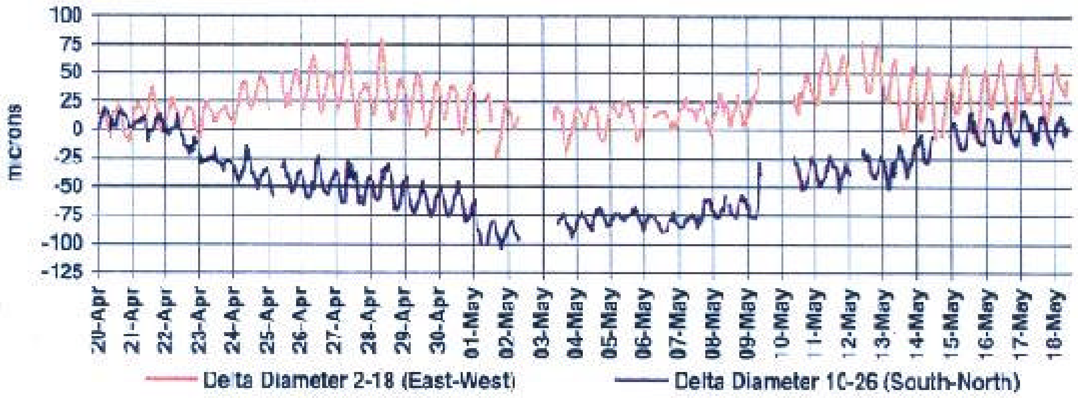
Note: relative component motion more critical than common mode motion

Ground Motion - slow

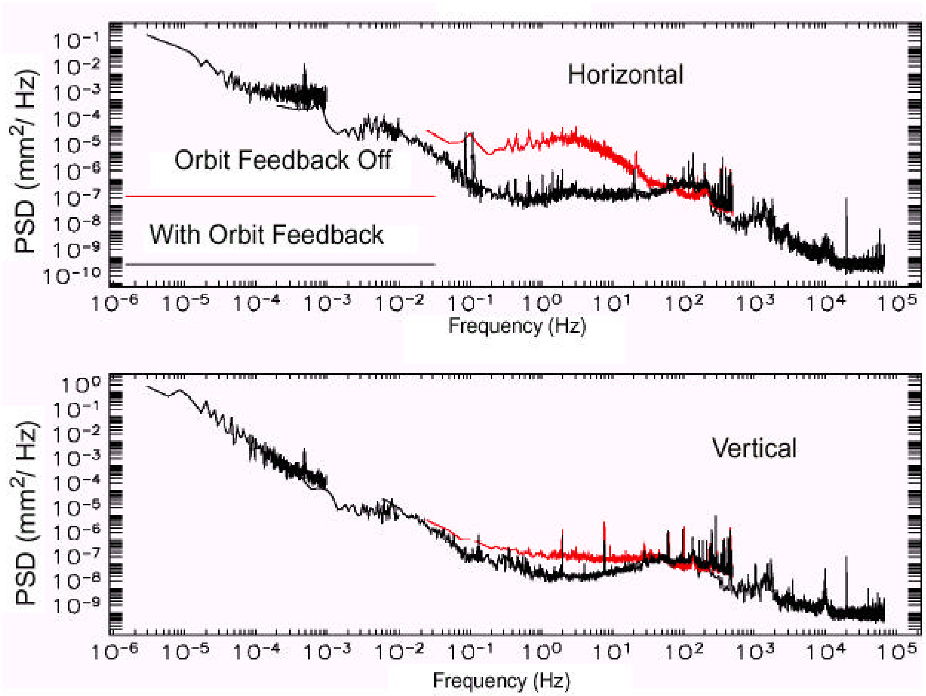
Ground settling (ALS)

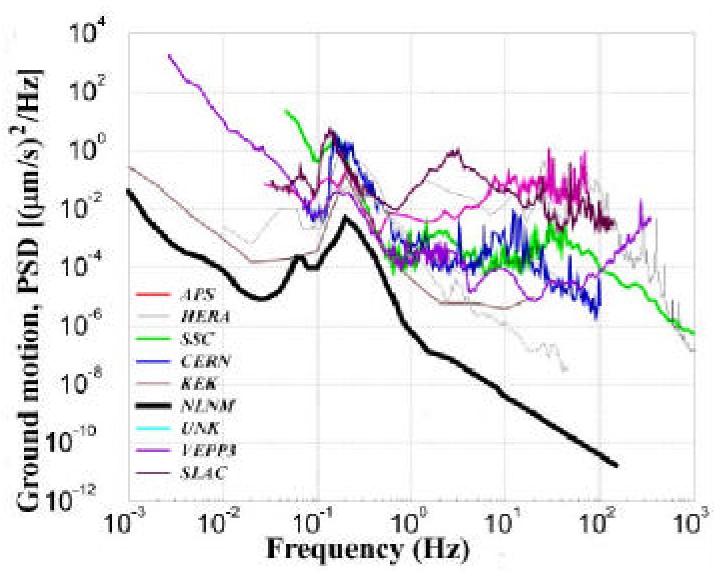


Gravitational earth tides due to sun and moon (ESRF)



Ground Vibration





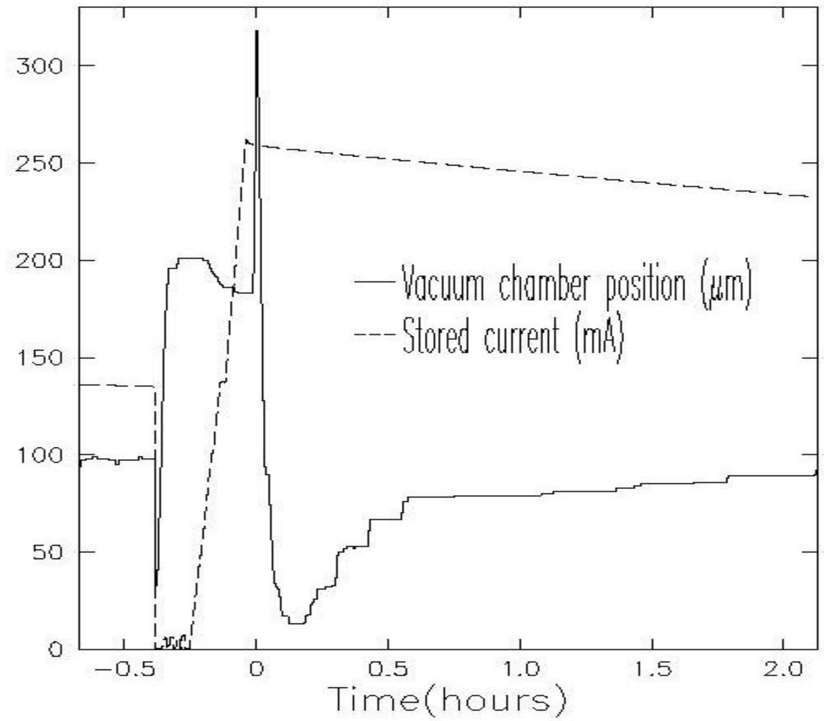
APS

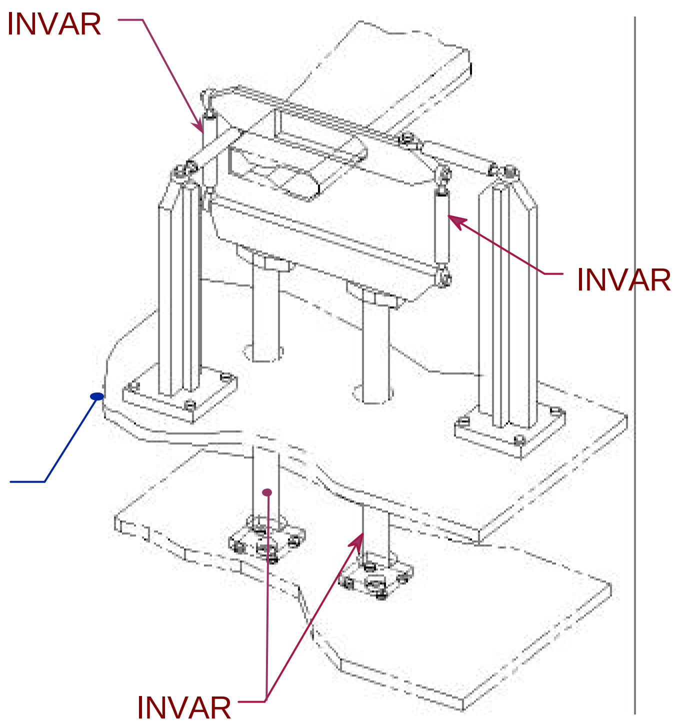
G. Decker

worldwide

V.D. Shiltsev

Vacuum chamber, BPM stability





NSLS chamber motion

J. Safranek

SPEAR 3 chamber/BPM supports

3 μm/°C vert, 15 μm/°C hor

Beam Stabilizing Technology

Accelerator component motion

- short girders, rigid supports (high frequency modes)
- damping materials (visco-elastic double-sided sticky tape, Anocast)
- minimal chamber temp gradients, chamber water cooling, discrete photon stops
- temp-stable BPM supports (Invar, carbon fiber - $<3\ \mu m/^{o}C$ @ 1 m)
- tunnel air and cooling water temperature stabilization ($<0.2^{o}C$)
- reduced vibration from water pipes, machinery, pumps, booster, etc.
- component position sensors (HLS, micron-res encoders, etc.)
- calibration of temperature-induced motion
- at-energy and top-off injection

Corrector magnets

- high frequency, low inductance (kHz)

  strong DC correctors (iron core) + low inductance tweeters (e.g. air core)
- high transverse linearity vs. frequency
- high resistance vac chamber sites (low eddy currents)
- uniform magnetic environment at all sites (field clamps)

Beam Stabilizing Technology - cont.

Power supplies

- low-ripple PWM chopper technology (20 kHz for mains, 40-60 kHz for correctors)
- high stability (transductors, even for correctors)
- high frequency, low quantization noise corrector supplies (≥18-bit DACs)
- digital control and regulation

Orbit monitoring systems

- > kHz orbit acquisition
- 1st turn, turn-turn and narrowband (high resolution)orbit processing modes
- non-multiplexed button processing (calibration tones, hybrid combiners)
- compensation for BPM motion, intensity dependence, etc.
- beam-based offset correction (quadrupole modulation)
- digital processing (including digital receivers)

Beam Stabilizing Technology - cont.

Feedback and other active systems

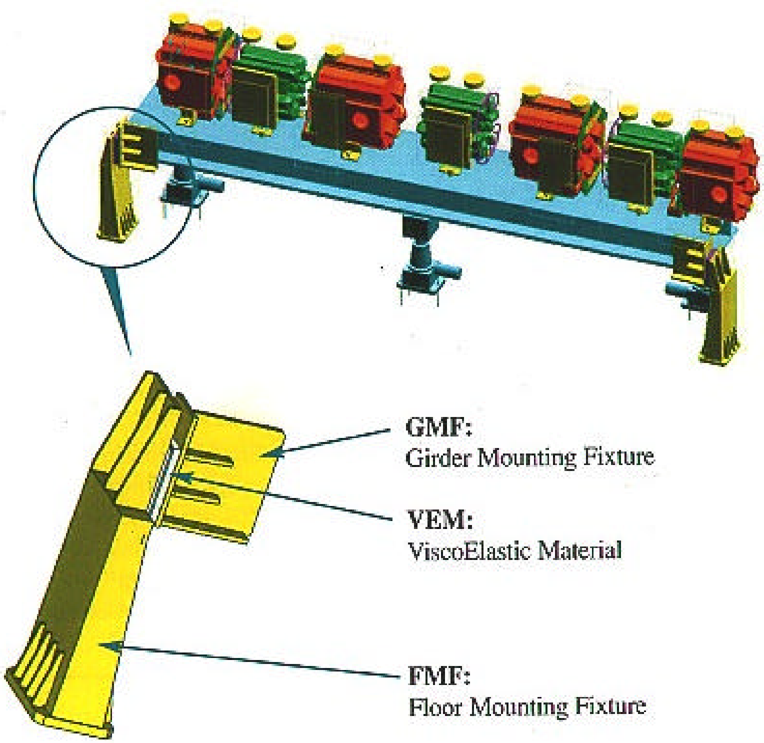
- unified global/local orbit feedback with electron and photon BPMs (up to ~200 Hz BW)
- automatic magnet girder alignment (ESRF, SLS, etc.)
- mode-0 longitudinal feedback through RF system
- multibunch feedback systems (longitudinal and transverse)
- beam line component feedback (mirror, monochromator, etc.)
- harmonic cavities for bunch length control and Landau damping (NSLS, ALS, etc.)
- tune feedback (Aladdin)

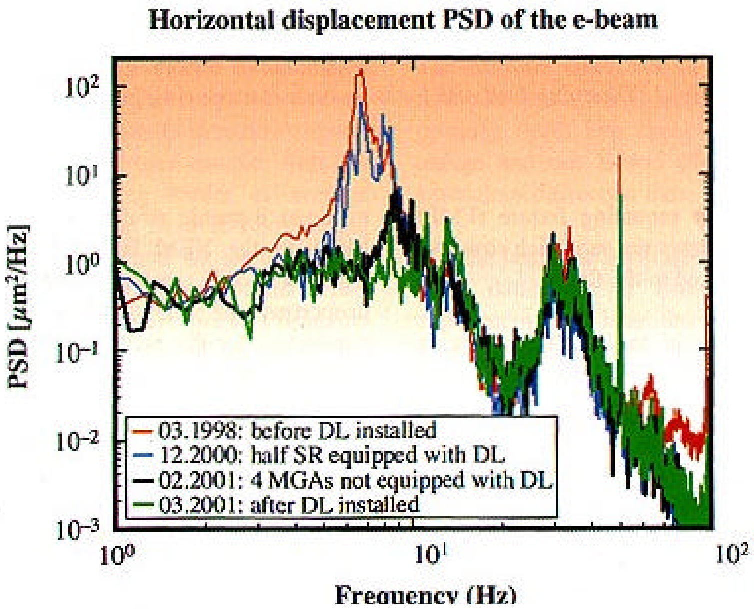
More sophisticated orbit feedback algorithms include:

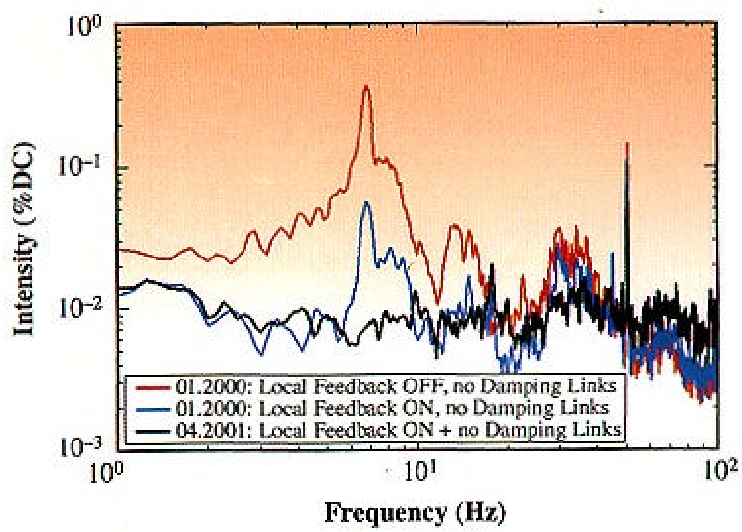
- compensation for ID gap changes
- compensation for accelerator component motion (measured or calibrated)
- real-time digital processing and high speed data links
- RF feedback

ESRF Girder Damping

L. Zhang





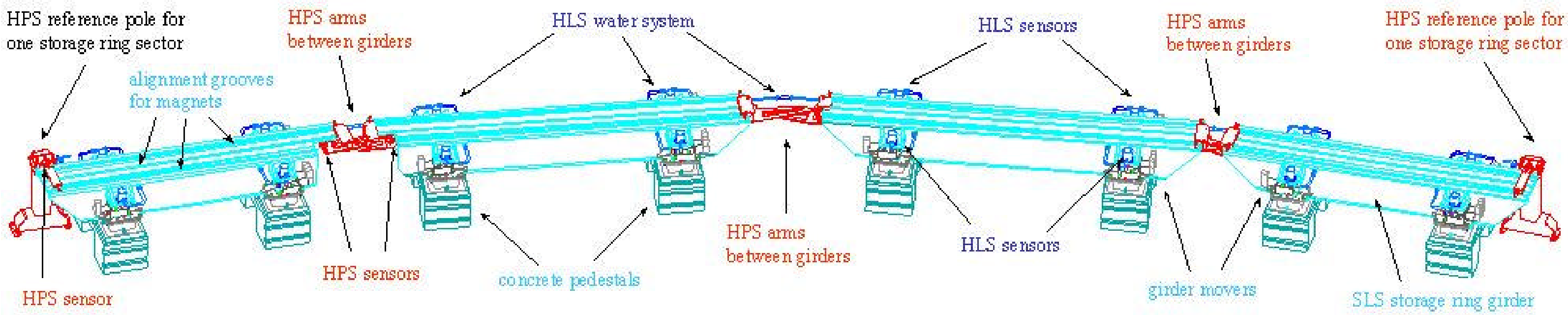


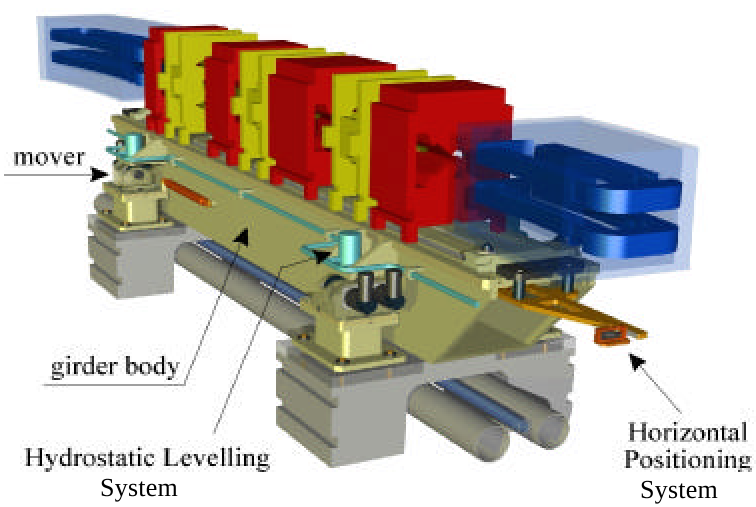
beam line intensity noise

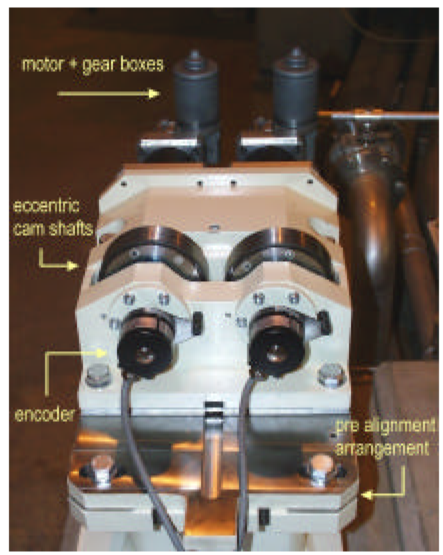
SLS Girder Mover System

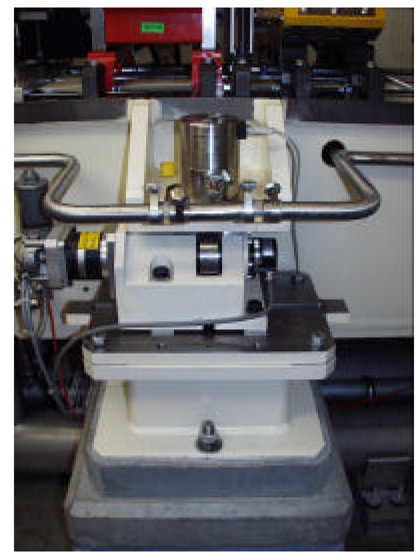
V. Schlott and S. Zelenika et al.

HLS, HPS Systems Overview over one Sector of SLS Storage Ring







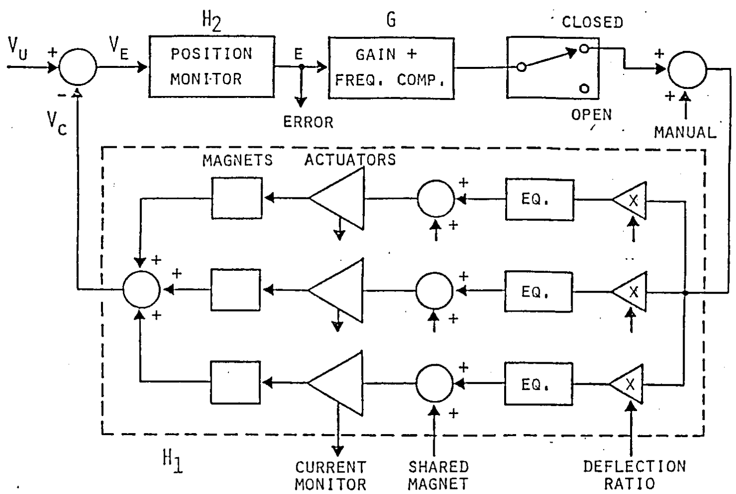


cam mover and hydrostatic level detector (micron res.)

Local 3- and 4-Magnet Feedback Systems

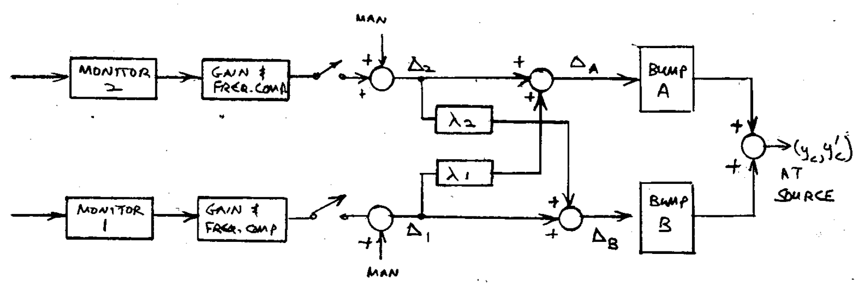
SSRL, 1982-86

$$\frac{V_e}{V_u} = \frac{1}{1 + GH_1H_2\,(i\omega)}$$



3-MAGNET STEERING SERVO SYSTEM

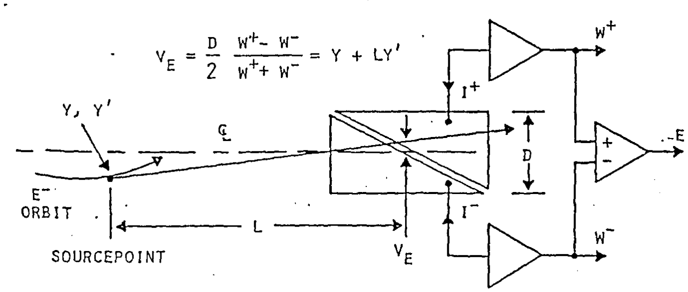
2-MONITOR, 4-MAGNET STEERING SERVO SYSTEM



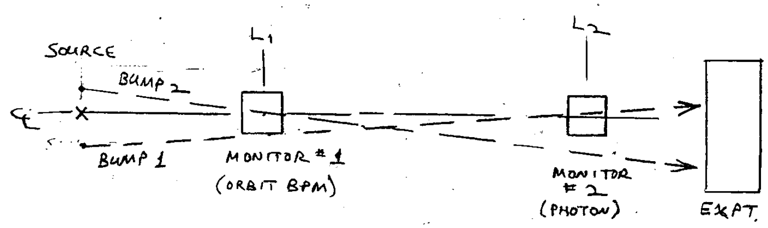
BUMP A & BUMP B ARE LINEARLY INDEPENDENT, COMPENSATED

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

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



HELIUM ION CHAMBER POSITION MONITOR



Global Orbit Feedback Systems

NSLS Harmonic Feedback System 1988

L.H. Yu, R. Biscardi, J. Bittner, E. Bozoki, J. Galayda,
S. Krinsky, R. Nawrocky, O. Singh, G. Vignola

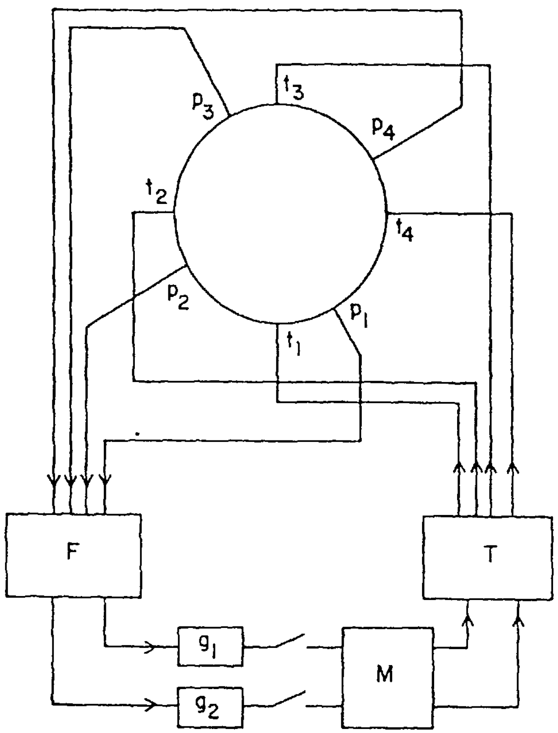
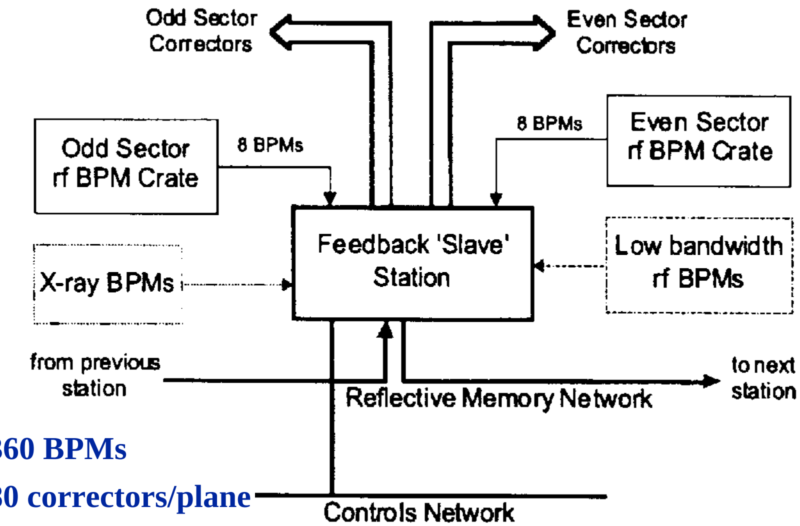


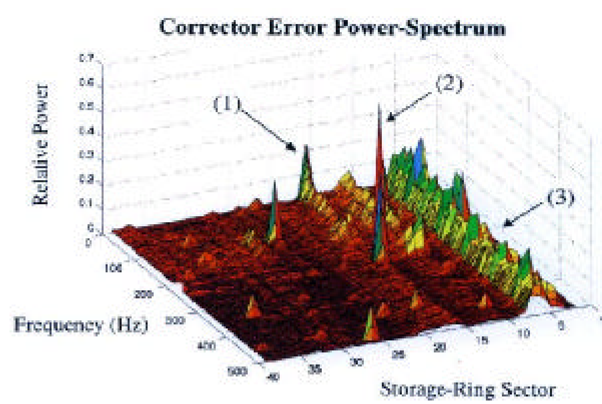
Fig. 1

APS SVD Global Feedback System - 1990s

J. Carwardine, Y. Chung, F. Lenkszus, et al.



- **360 BPMs**
- **80 correctors/plane**
- **BPM de-spiking**



"DSP Scope"

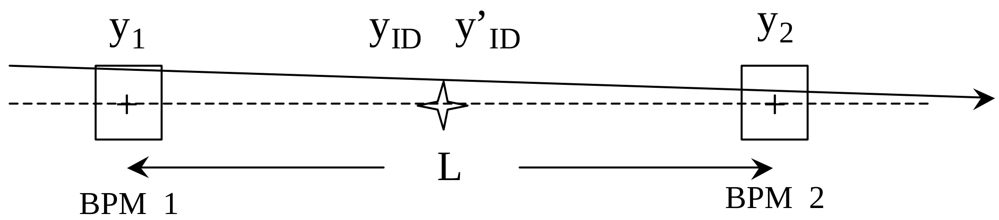
1) Poor regulation of sextupole supply

2) Steering supply oscillating at 248 Hz

3) Bad BPM with broadband noise

Local vs. Global Feedback

Local correction:



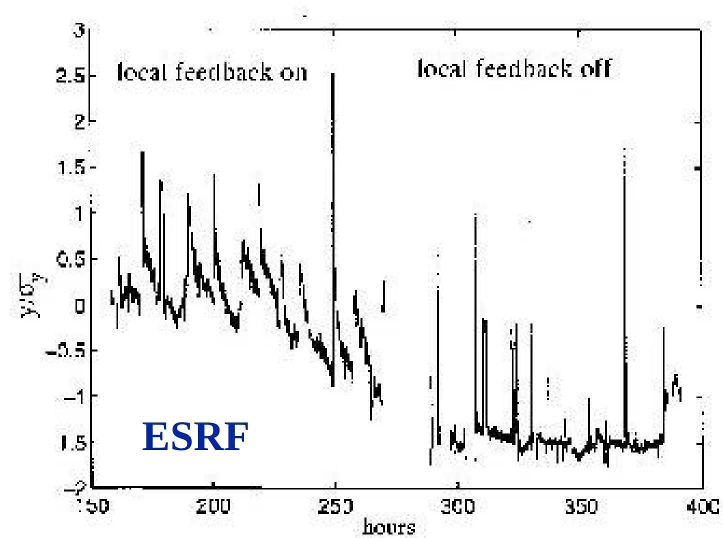
$y_{ID} = (y_1 + y_2)/2$ $\langle y^2_{ID} \rangle = \Delta y^2/2$ $y'_{ID} = (y_1 - y_2)/2L$ $\langle y'^2_{ID} \rangle = \Delta y^2/2L^2$

Δy = measurement error

e.g., $\Delta y = 10\ \mu m$, L = 3 m Þ **7 mm rms** position error, **2.4 mrad rms** angle error

Þ **want L to be large**

Multi-loop crosstalk Þ reduced performance



Global correction:

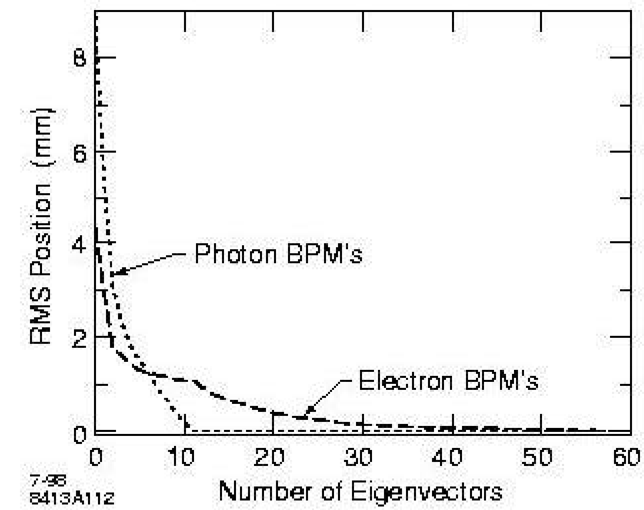
- reduced set of correction eigenvectors filters response to BPM noise

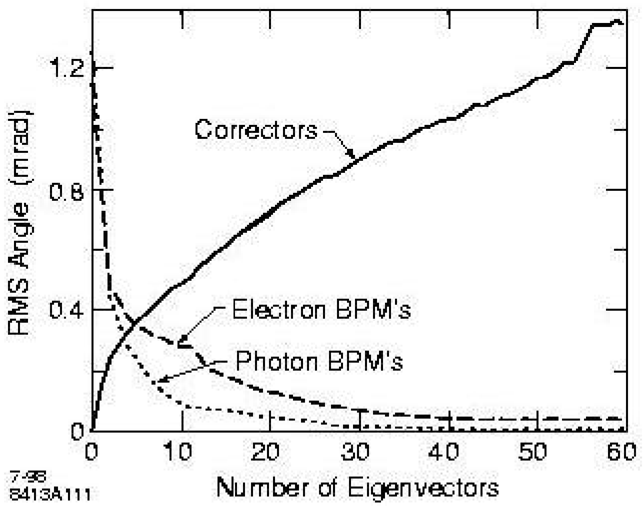
  lower spatial BW, more BPMs in average

- correction matched to most likely disturbances

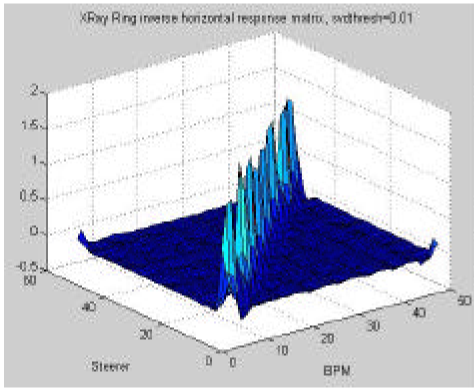
SVD Orbit Correction

SPEAR (J. Corbett)

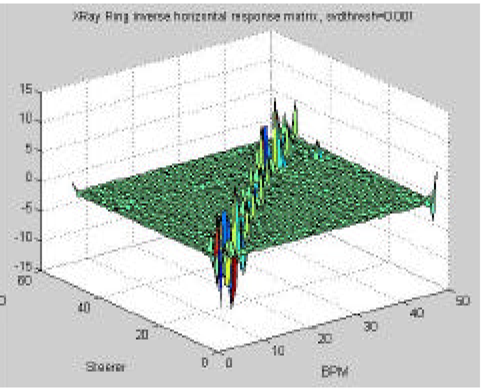




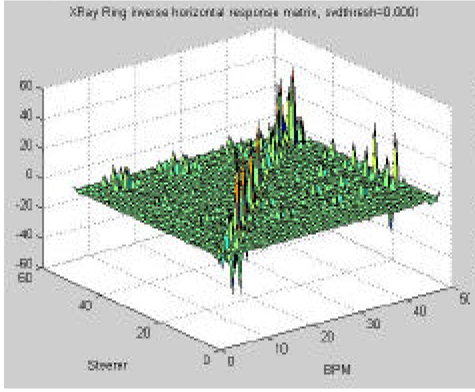
NSLS X-Ray ring inverse response matrix with different SVD thresholds (J. Safranek)



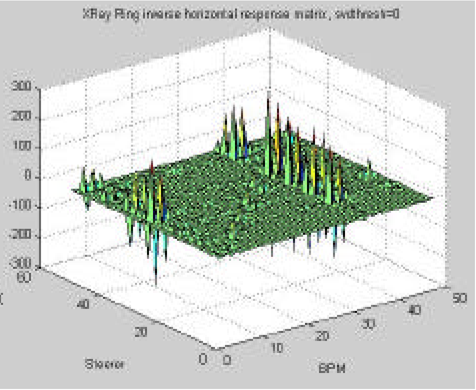
SVD threshold = 0.01



SVD threshold = 0.001



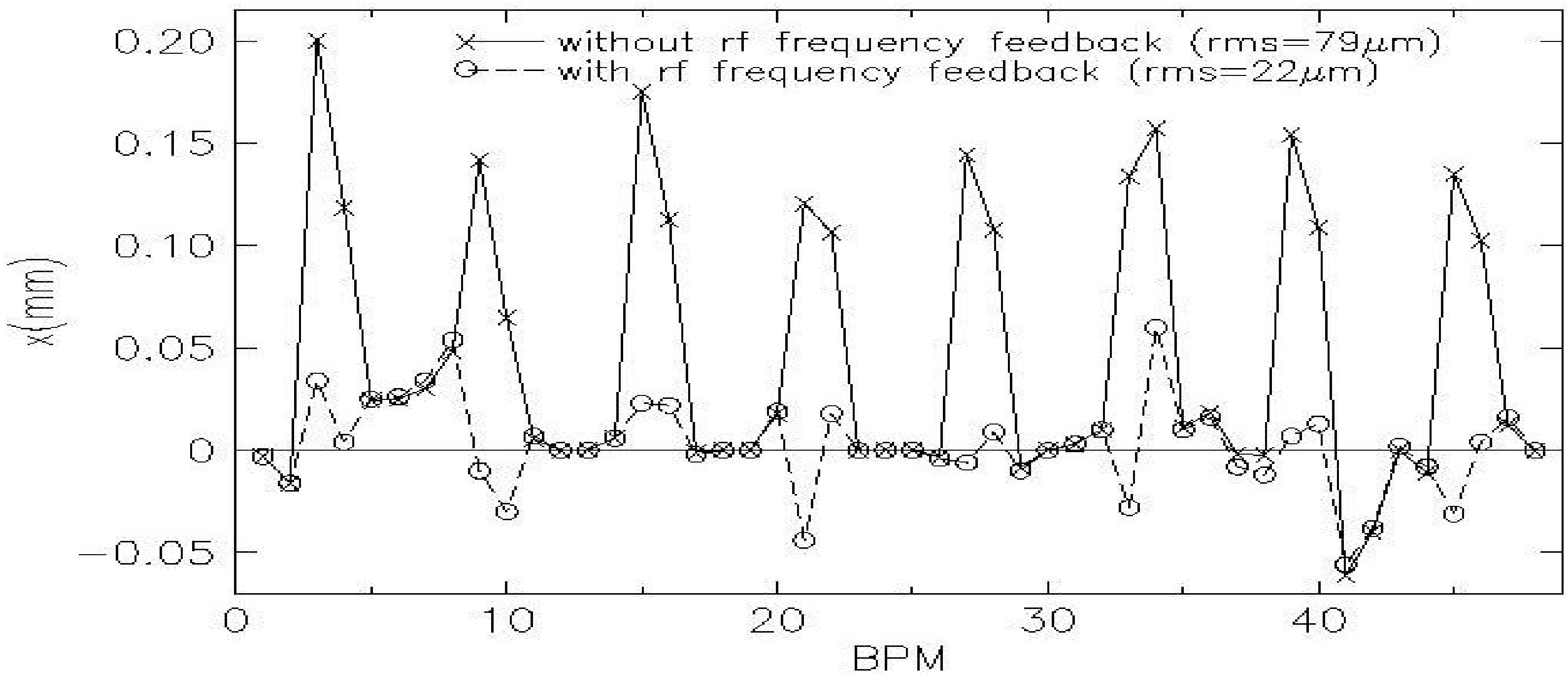
SVD threshold = 0.0001



SVD threshold = 0

RF Feedback

NSLS



Orbit Feedback - Performance Limitations

Electron BPMs (electron)

- BPM mechanical motion (thermal)
- intensity or fill pattern dependence
- TE_{10} mode in antechamber
- local position/angle calculation errors
- orbit acquisition rate (rate ~10x fdbk BW ⇒ 1 kHz for 100 Hz BW; rate ~2 kHz to avoid 720 Hz alias)
- BPM muxing (switch rate > ~10x orbit acq BW to avoid H-V coupling; limited by switch settling time)

Photon BPMs

- corruption of undulator photon monitor signal by dipole radiation
- dependence on ID gap (emission pattern) and beam intensity
- blade surface contamination

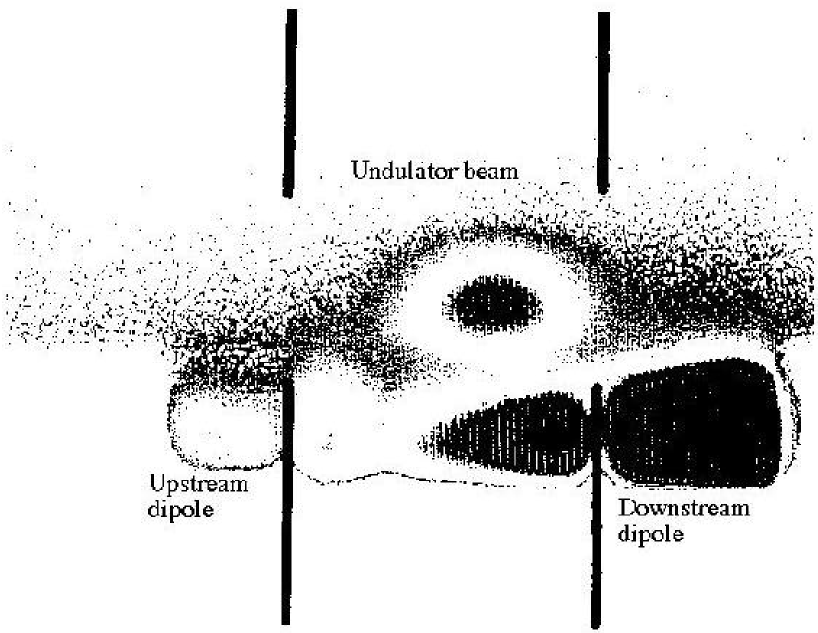
Orbit corrector system

- transverse field uniformity: orbit-dependent response matrix
- field uniformity vs. frequency: freq-dependent response matrix
- vacuum chamber BW
- hysteresis
- quantization noise and step resolution

Response matrix

- inadequate BPM and/or corrector quantities (>4 per β period desirable)
- inefficient BPM and/or corrector placement (low orthogonality)
- non-optimized eigenvector cut-off for R^{-1} (trade-off between azimuthal correction resolution and corrector strengths, sensitivity to BPM noise)

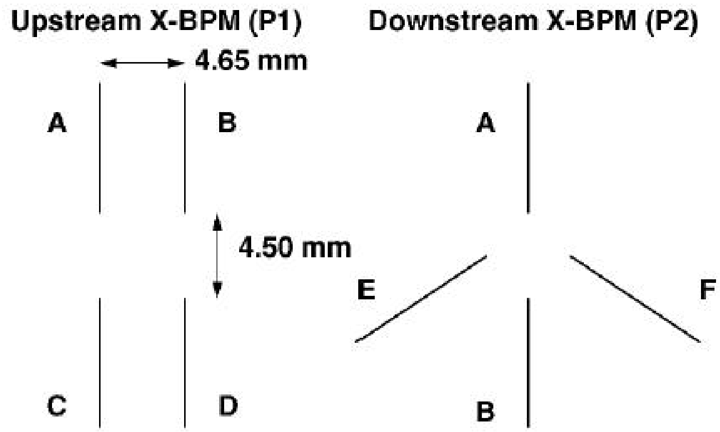
Undulator Photon Monitor Limitations



ESRF

- ID photon emission pattern (flux and energy) changes with ID gap
- Causes apparent beam motion of **~1-100 mm**, which can propagate around ring if photon monitors used in feedback.
- Can compensate for gap changes with calibrated feedforward orbit and tune corrections + feedback to correct residual perturbations.
- Blade monitors work better for low-E rings (photon spectrum better matched to blade photoemission properties) **- K. Holldack et al., BESSY II)**

Photon Monitors - Blade Geometries



APS

O. Singh

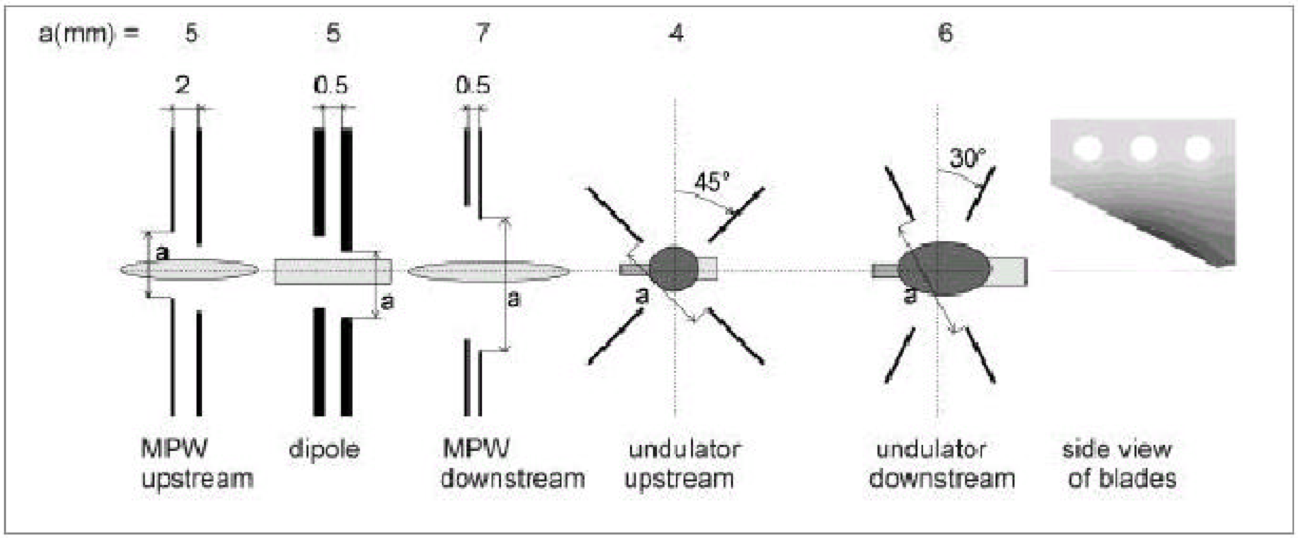


Fig. 2 Blade geometries for staggered pair monitors (SPMs) for dipoles and multipole wigglers as well as XBPMs in undulator frontends. (light shading:dipole and wiggler fans; dark shading:undulator radiation).

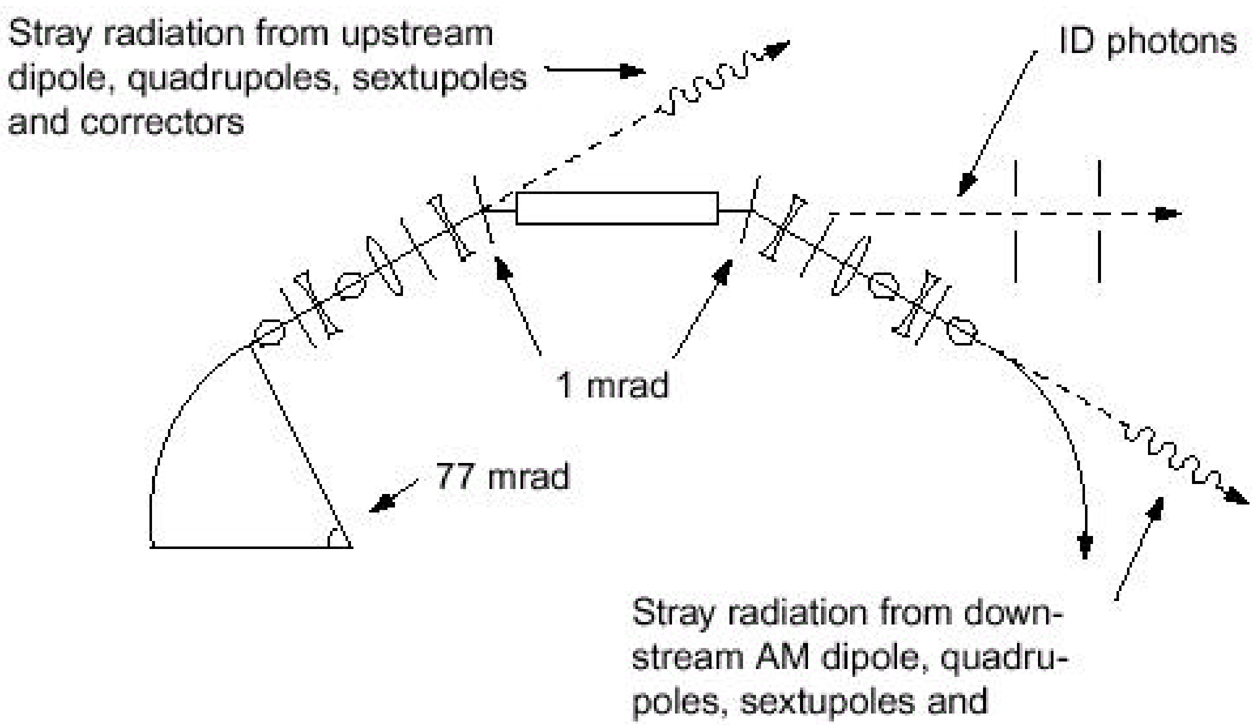
BESSY II

K. Holldack

APS Undulator Soft-Bend Chicane

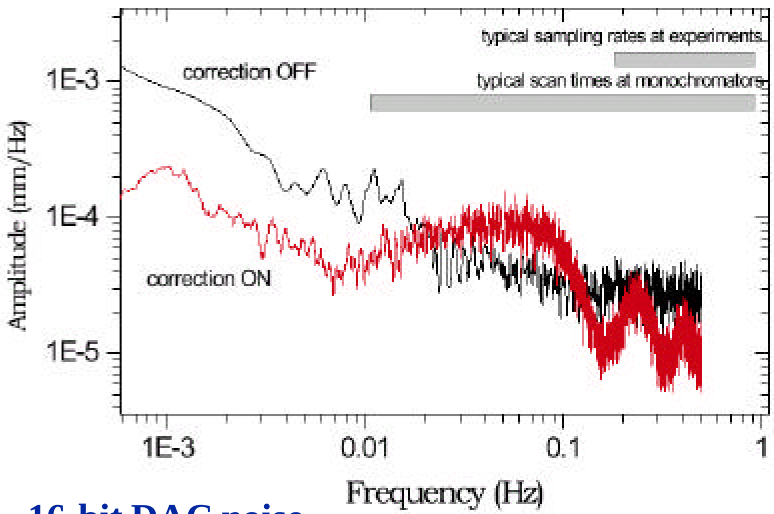
G. Decker

Concept for Reduction of ID X-bpm Stray Radiation Background Signals

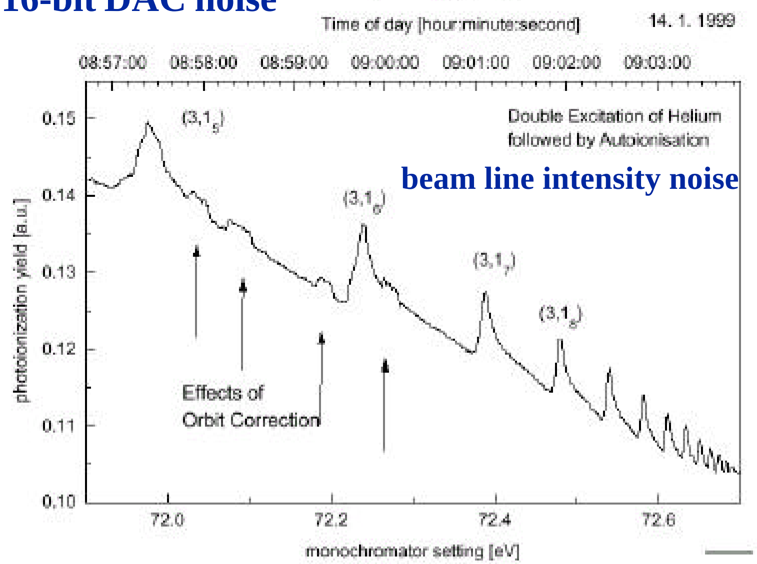


Orbit Feedback - Corrector Resolution

R. Mueller et al., BESSY II



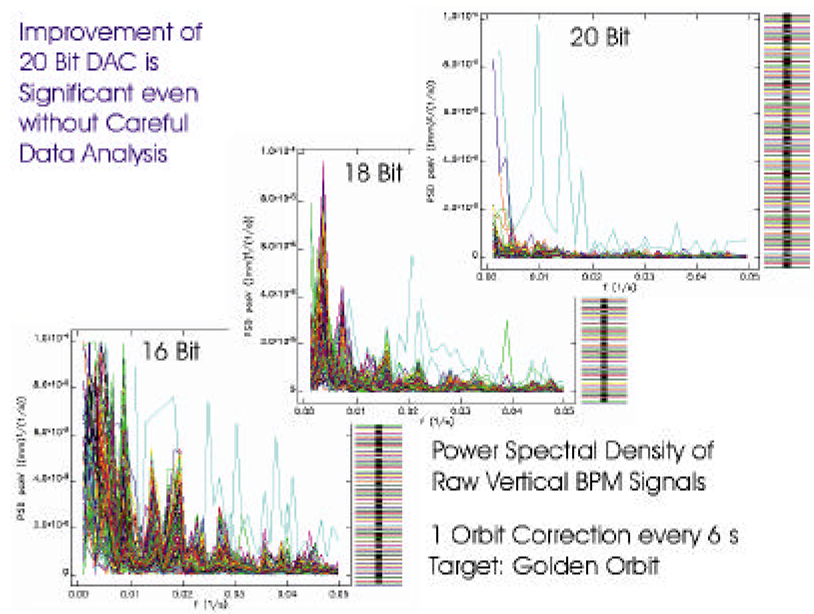
16-bit DAC noise



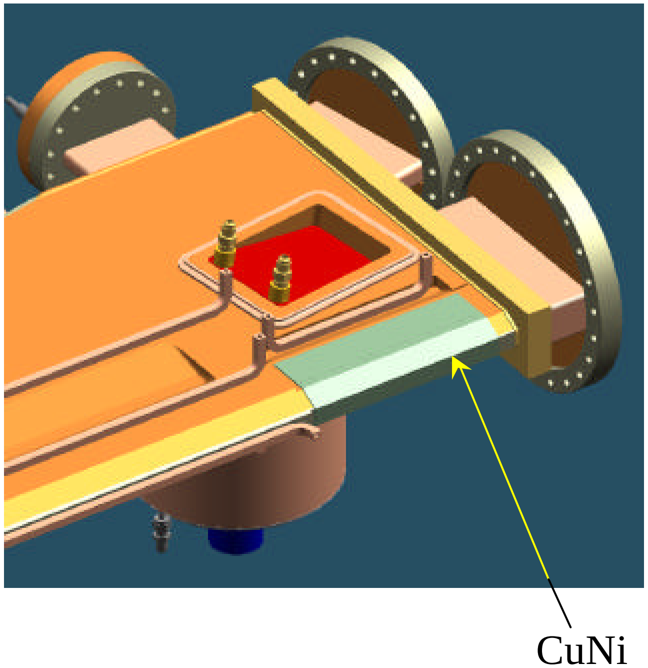
beam line intensity noise

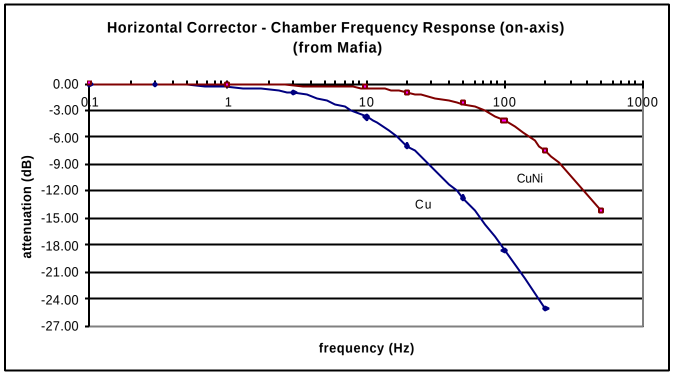
Noise from 16-bit DACs solved with 24-bit DACs (~20-bit ENOB)

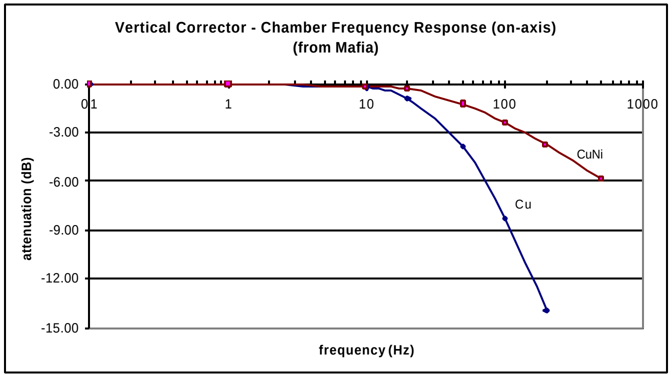
(feedback cycle rate = 0.2 Hz)

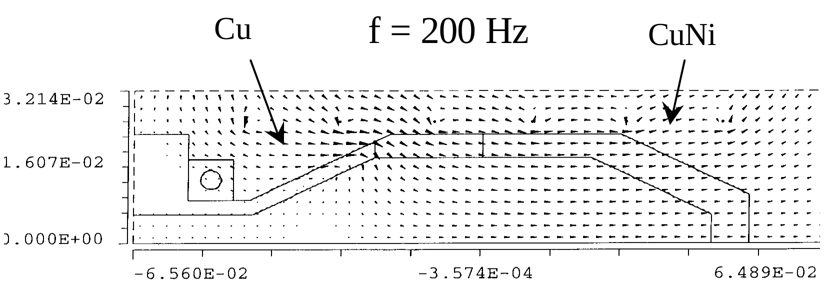


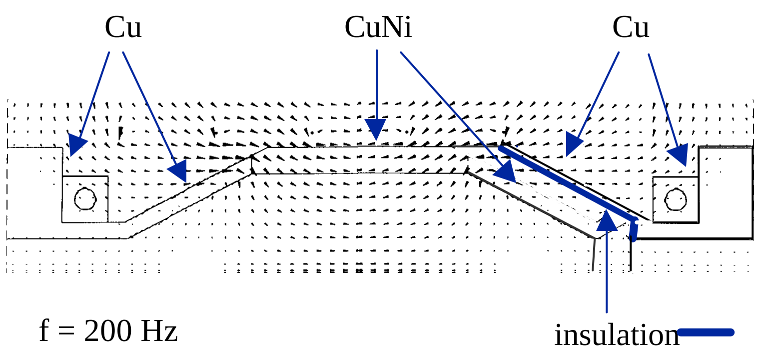
SPEAR 3 Cu Chamber Eddy Current Break



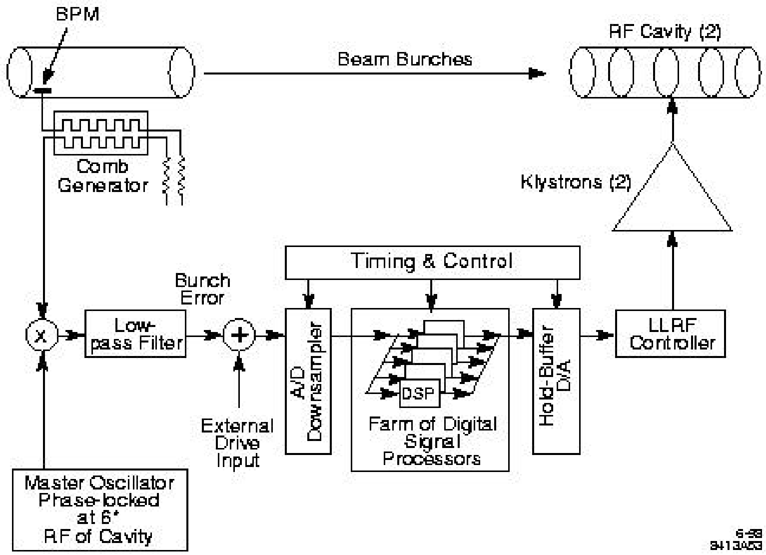




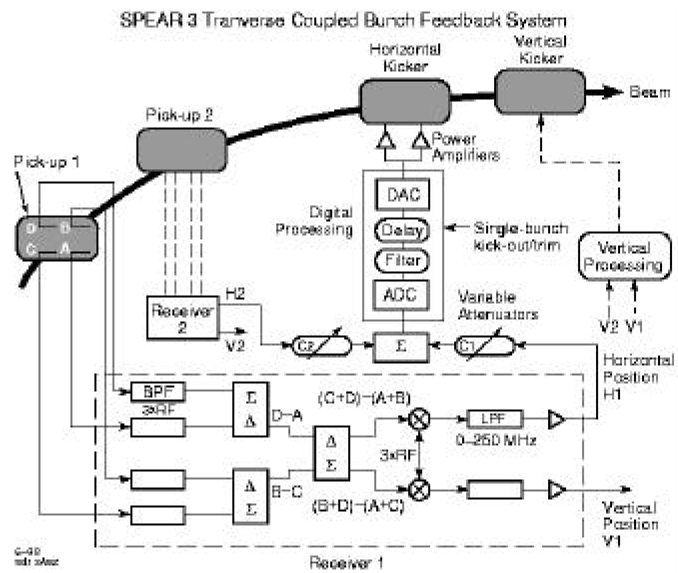




Multibunch Feedback



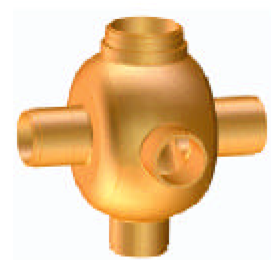
Longitudinal J. Fox et al., SLAC



Transverse W. Barry et al., ALS

Harmonic Cavities

- increase bunch length and Touschek lifetime
- induce tune spread to damp multibunch instabilities **(Landau damping)**

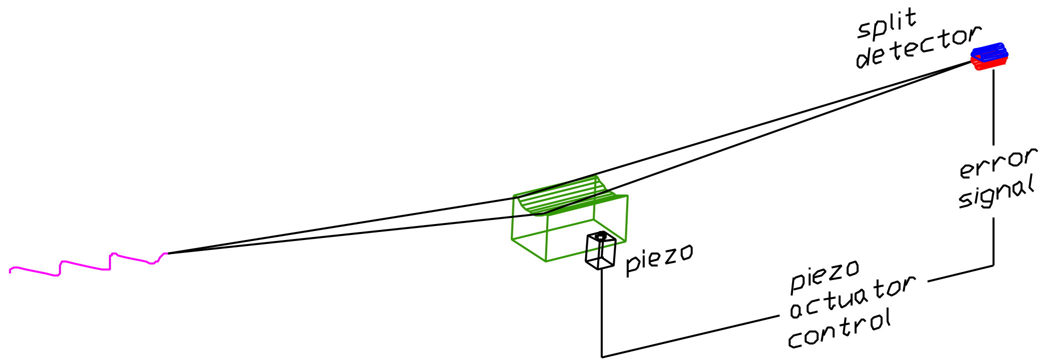


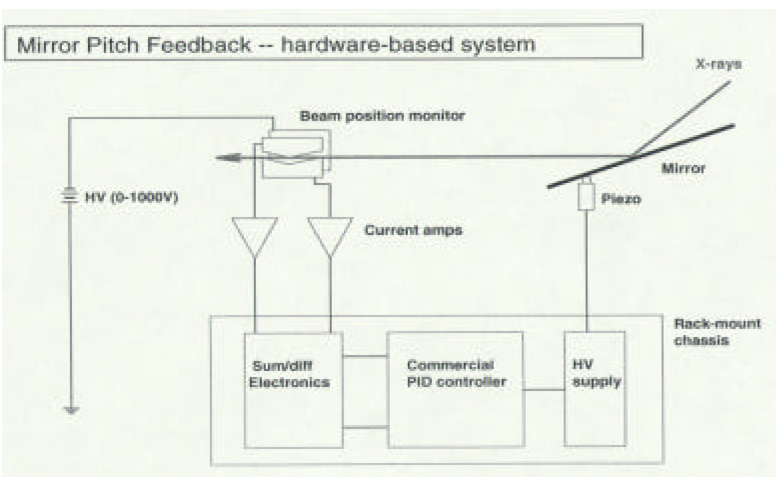
ALS 1.5 GHz cavity
J. Byrd, R. Rimmer et al.

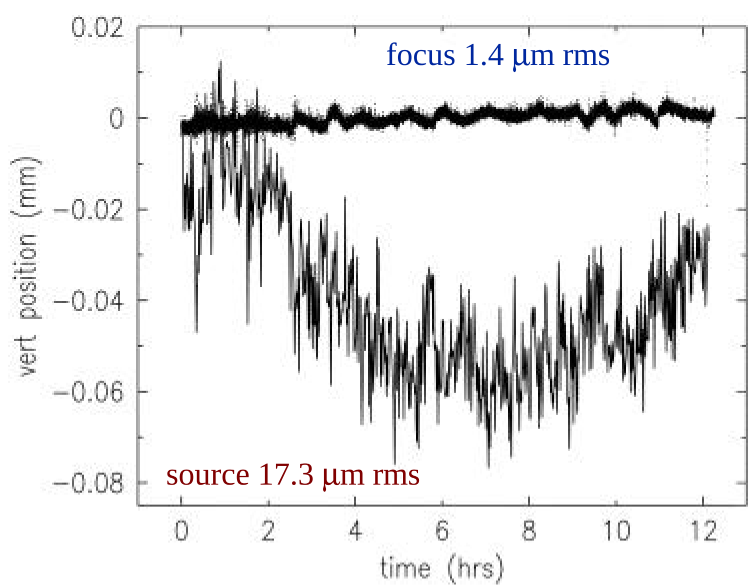
Mirror Feedback

T. Rabedeau, SSRL

- error signal obtained from position sensitive detector near beam focus
- error signal used to control piezo high voltage
- piezo provides mirror fine pitch control with typical full range of motion **+/- 30 mrad** or **+/- 0.6mm** or more focus motion.







Future Light Sources

Energy Recovery Linac (MARS, G. Kulipanov (Budker Inst.); ERL, S. Gruner et al. (Cornell, JLab), PERL, J. Murphy et al. (NSLS); Ultrafast Light Source, A. Zholents et al. (LBNL)

ε_x = ~0.15 nm-rad @ 5-7 GeV $\sigma_{x,y}$ = 3-40 µm $\sigma_{x',y'}$ = 3-10 µrad σ_s = 100 fs - 10 ps

Þ ~ 0.1 mm, 0.1 mrad, <100 fs stability

Challenges: • energy stability • bunch charge stability • pump-probe timing sync • other

LCLS (& SPPS)

ε = ~0.05 nm-rad @ 15 GeV $\sigma_{x,y}$ = ~30 µm $\sigma_{x',y'}$ = ~0.4 µrad σ_s = 85 fs

Þ micron, 10s nrad, <100 fs stability

Challenges:
- < 0.9 ps gun timing jitter
- < 0.07 S-band klystron phase stability
- <0.05% klystron voltage stability
- pump-probe timing sync
- other

Diffraction-limited storage rings (J.-L. Laclare)

ε_x = ~0.1 nm-rad ε_y = ~8 pm-rad (1Å diffraction limit)

σ_x = ~100 µm σ_y = ~10 µm $\sigma_{y'}$ = <10 µrad σ_s = ~10 ps

Þ ~ 0.1 mm, 0.1 mrad stability

Beam Stability Requirements - Summary

(subject to change after SRI 2001 Stability Workshop)

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	<0.1% σ_{ph}	<0.01% σ_{ph}
energy resolution	10^{-4}	10^{-5}
timing stability	<10% bunch length	<10% bunch length
min data avg time	order 1 ms	order 0.1 ms (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	~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	<~5 x 10^{-5} ($\Delta\phi < 0.1^{o}$)	<~5 x 10^{-6} ($\Delta\phi < 0.01^{o}$)

Beam Stability Requirements

DRAFT rev. 8/27/01

	Parameter	Present sources (rings)	Future sources (ring, ERL, FEL)
user stability need	intensity (shot-shot with normalization)	<0.1%	<0.01%
	steering accuracy	<5% σ_{e-}, σ'_{ph}	<2% σ_{e-}, σ'_{ph}
	beam size stability	<0.1% σ_{ph}	<0.01% σ_{ph}
	energy resolution/accuracy	10^{-5}-10^{-4}	10^{-5}
	timing stability	<10% bunch length	<10% bunch length
	polarization stability (switched)	10^{-3} (?)	10^{-4} (?)
	expt data acquisition rate	~10^{-2}-10^{5} Hz	~10^{-2}-10^{6} Hz
	stability period (w/o realignment)	secs-hours	secs-days
	beam availability	>90%	>90%
beam param	emittance	~5-20 nm-rad	~0.05-0.2 nm-rad
	ph beam size (vert)	~30-300 μm	~3-30 μm
	ph beam divergence	~10-200 μrad	~0.5-10 μrad
	H-V emittance coupling	<0.1-10%	<0.01-100%
	e- beam rotation	<?? mrad	<?? mrad
	e- bunch length	~10-100 ps	~10 ps (ring); ~100 fs (ERL,FEL)
e- stability need	position stability (vert)	~1-5 μm	~0.1-1 μm
	angle	~1-10 μrad	~0.05- 0.5 μrad
	coupling	<0.1%	<0.01%
	rotation	<?? mrad	<?? mrad
	bunch-bunch / turn-turn charge	~10^{-2} / 10^{-11}	~10^{-2}/10^{-11}(ring); ~10^{-2}/10^{-2} (FEL, ERL)
	bunch length	~1-10 ps	~1 ps (ring); ~10-100 fs (FEL)
	energy	<~2-5 x 10^{-5} ($\Delta\phi < 0.04$-0.1^{o})	<~5 x 10^{-6} ($\Delta\phi < 0.01^{o}$)
	stability bandwidth	1/hrs - 10^{5} Hz	1/hrs - 10^{6} Hz

Summary

Stability requirements are stringent:

- intensity stability < 0.1%
- photon energy resolution < 10^{-4}
- pointing accuracy < 5% beam dimensions
- timing stability < 10% bunch length

Þ **orbit < 1-5 mm, <1-10 mrad** **beam size < 0.1 %** **e- energy < 5 x 10^{-5}**

Requirements are becoming more stringent:

- x 5-10 more stringent stability with beam source and beam line development

Þ **orbit < .1-1 mm, <.05-.5 mrad** **beam size < 0.01 %** **e- energy < 5 x 10^{-6}**

- faster data acquisition time-scales
- fast-switched polarization, ID changes
- short bunch machines present pump-probe timing sync challenge: **<100 fs**

Stabilizing technology development:

- control noise sources
- motion sensors, calib
- faster orbit feedback
- temp-stable materials
- automatic alignment
- beam line signal processing, component feedback
- vibration-damping materials
- better BPMs (e- and photon)

What matters: relative motion between accelerator and beam line

- integrate beam line and orbit feedback systems (?)

may relieve need for absolute accelerator stability

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ALS/LBL	J. Byrd, D. Robin, C. Steier
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BESSY II	K. Holldack, R. Mueller
Daresbury	C. Nave
ESRF	L. Farvacque ("Beam Centre of Mass Stability",1996)
NSLS	R. Biscardi, S. Krinsky, L.H. Yu
SLS	M. Boge, S.Zelenika, V. Schlott, A. Wrulich
SSRL	J. Corbett, J. Galayda, T. Rabedeau, J. Safranek


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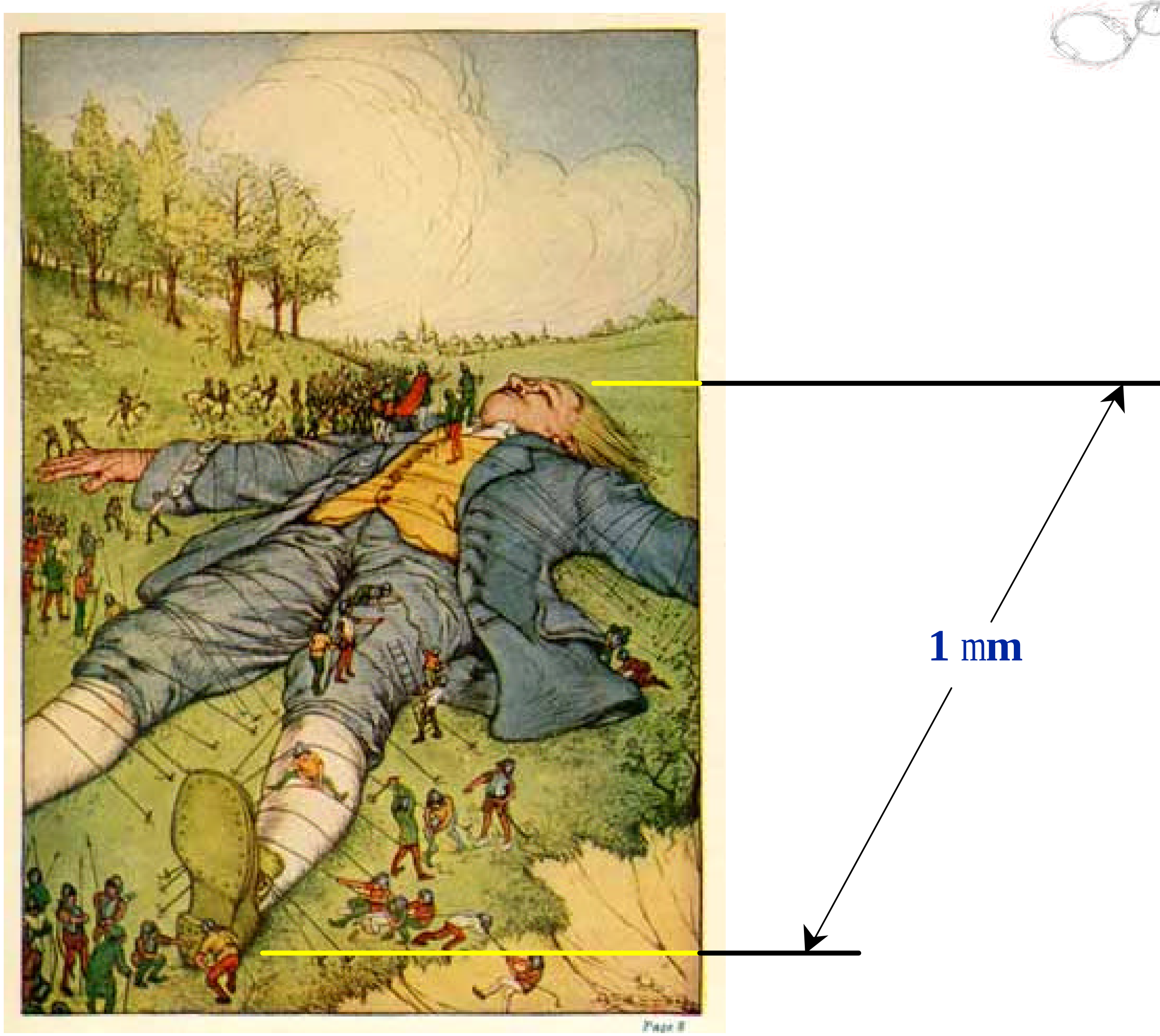
1 mm