Light Source Design – Part 1: Parameters, Metrics and Configurations

Monday 22 Nov 2010 at 15:30 (00h50')

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Co-authors :

Presenter : Dr. HETTEL, Robert (SLAC)

Light Source Design: Storage Ring Technology

(SPEAR3 and elsewhere)

Robert Hettel, SLAC

Mexican Light Source Workshop

November 22-24, 2010

Topics Discussed

- Parameter choices
- Lattice types
- SPEAR3 accelerator physics studies
- Magnets and girders
- Vacuum system
- Power supplies
- RF systems
- Instrumentation and controls
- Photon beam line components
- Insertion devices

Topics Not Discussed

- Injector design
- Kicker magnets and pulsers
- Synchrotron light monitors
- Photon BPMs and misc. other diagnostics
- Transverse/Longitudinal Feedback Systems
- Machine Protection Systems
- Personnel Protection Systems
- Beam Containment Systems
- Radiation shielding
- Tunnel and experimental floor engineering
- Utilities (gasses, water, electricity)
- …..

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Basic Storage Ring Parameters

- Energy
  - critical photon energy ~ E^2
  - photon power density ~ E^4
  - ring circumference ~ E

  photon flux density ~ E^2

  RF voltage ~ E^4/ρ

  cost
- Current
  - Beam power ~ I (absorber and optics design, RF power)
  - Brightness and flux ~ I
- Beam dimensions (size, divergence, bunch length) - emittance

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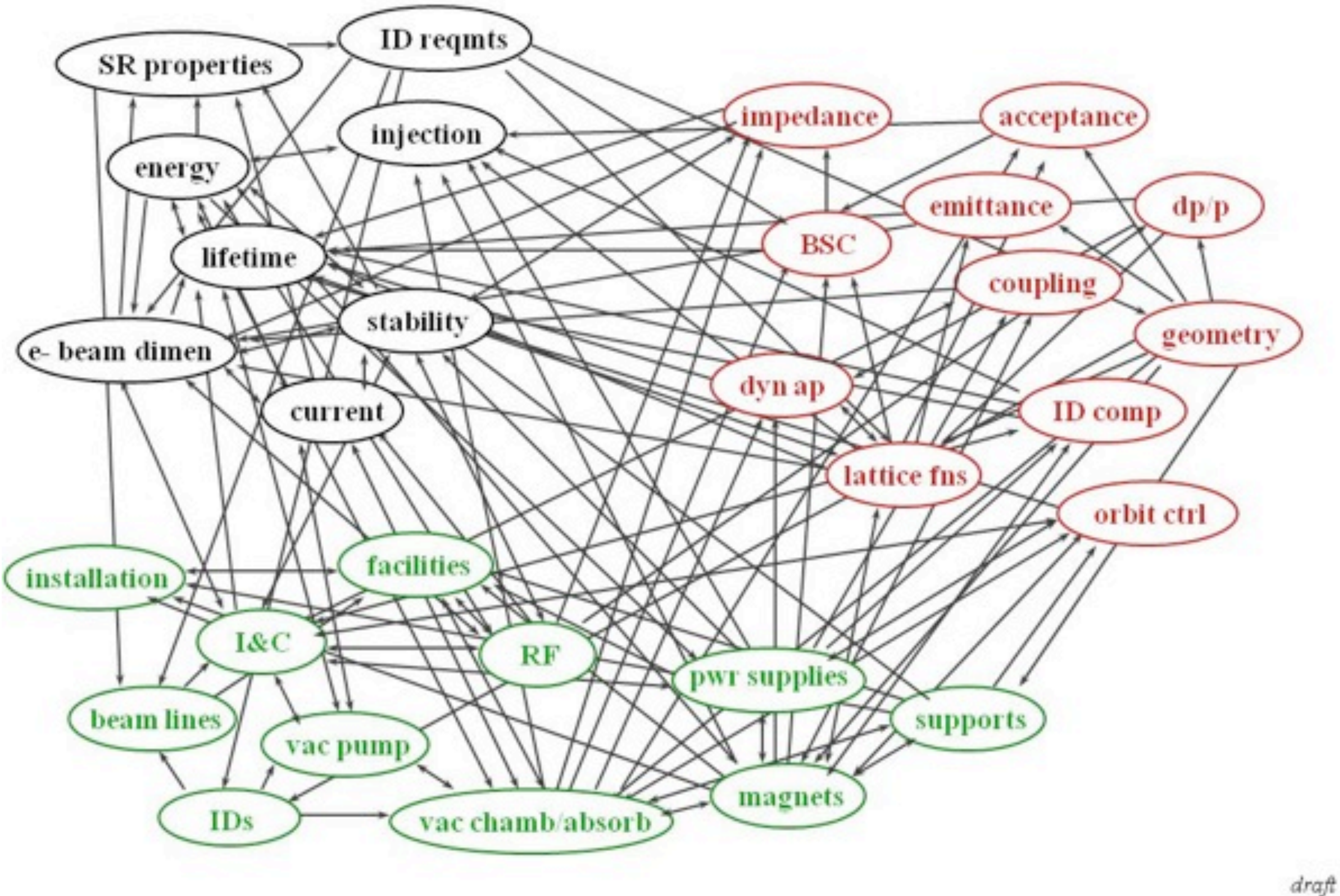
  - Brightness and flux ~ I
- Beam dimensions (size, divergence, bunch length) - emittance
- Site dimensions (available space, cost)
- Number of bend magnet vs. insertion device beam lines
- Number and length of straight sections (for IDs, injection, RF)
- Injector type (linac, booster, top-up capability, cost)
- Other requirements and constraints

Light Source Design



Making Design Choices

- **Management assures options fully considered and optimal choices are made**

NOT EASY!

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- Methods for making design choices:

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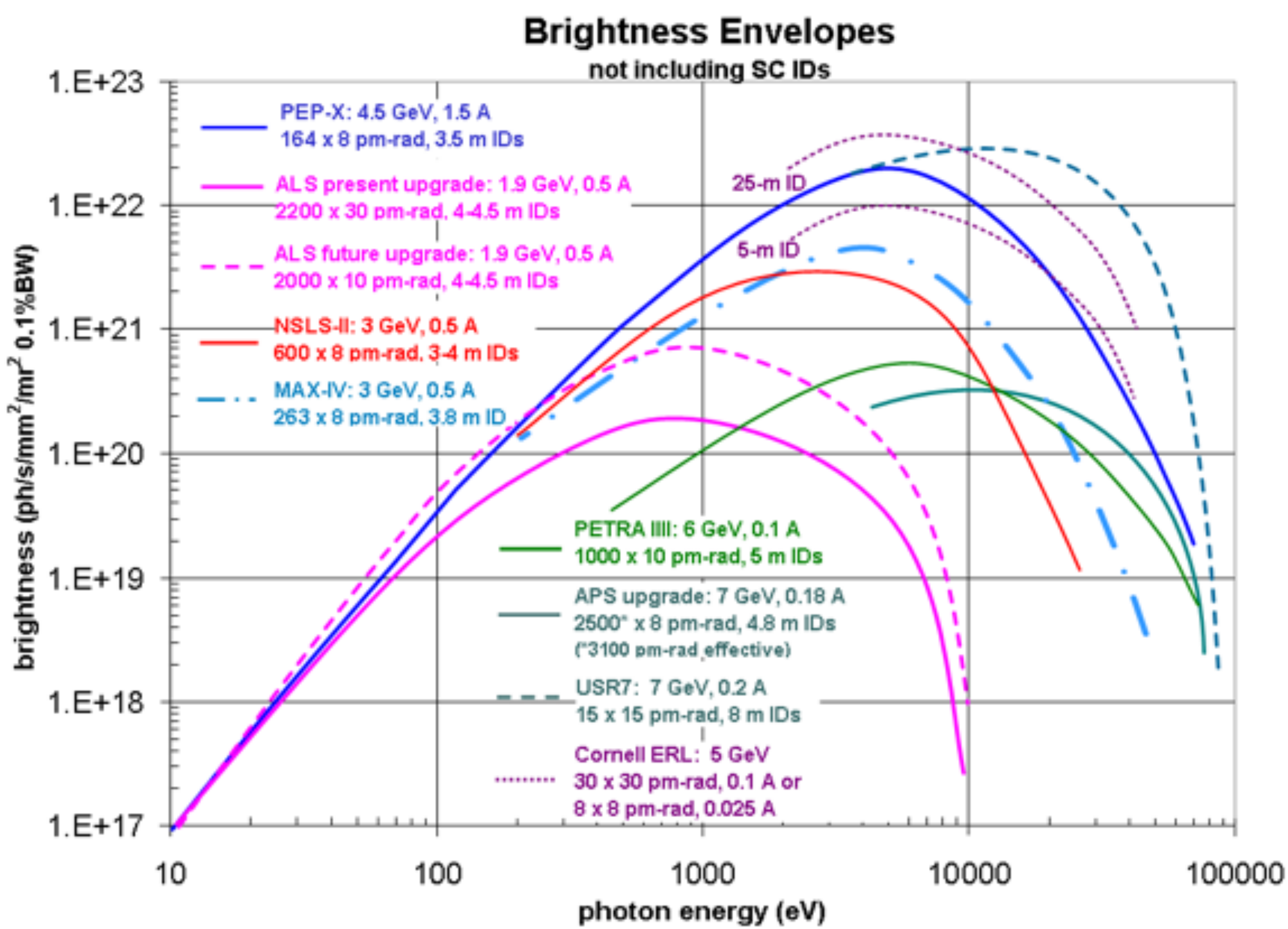
    - convene workshop as needed (e.g. 3 vs. 3.5 GeV decision for SPEAR 3)
  - discussion of options
    - solutions need to be compatible, not interfere with other systems
  - internal and external design reviews
  - parallel/competitive design of critical systems - best solution adopted

Energy



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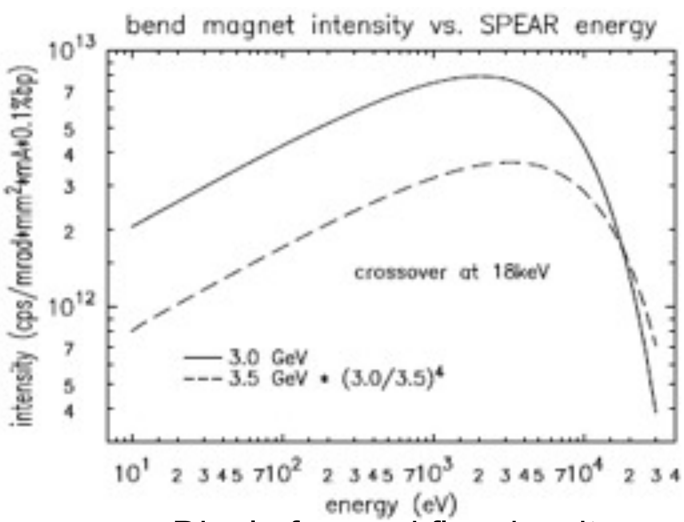
Energy vs. Current

Radiated photon power and power density ~ $E^4\ I/\rho$

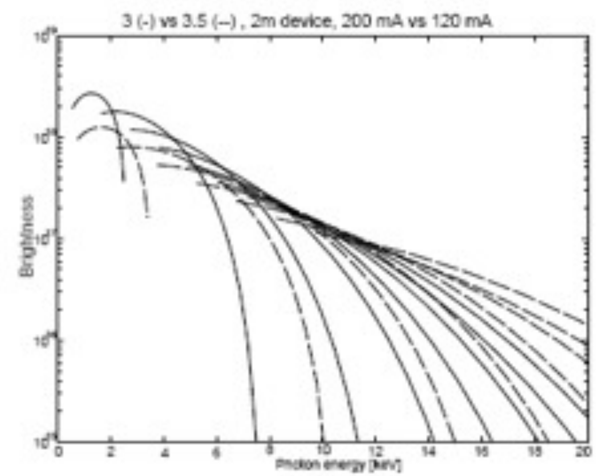
For a ring having fixed circumference (ρ) and photon absorbers operating near maximum rating, or for fixed available RF power:

$$E^4\ I/\rho = \text{constant}$$

SPEAR3: 3 GeV @ 500 mA vs. 3.5 GeV @ 280 mA



Dipole focused flux density



Brightness for 2-m ID

(3 GeV/200 mA vs. 3.5 GeV/120 mA)

Electron Beam Dimensions

e- beam size:

$$\sigma_x(s) = \sqrt{\varepsilon_x \beta_x(s) + \left(\eta(s)\sigma_{E_{e-}}/E_{e-}\right)^2} \qquad \sigma_y(s) = \sqrt{\varepsilon_y \beta_y(s)}$$

e- divergence:

$$\sigma_{x'}(s) = \sqrt{\varepsilon_x \gamma_x(s) + \left(\eta'(s)\sigma_{E_{e-}}/E_{e-}\right)^2} \qquad \sigma_{y'}(s) = \sqrt{\varepsilon_y \gamma_y(s)}$$

$$\varepsilon_y = \kappa \varepsilon_x$$

Dimensions depend on ε, Twiss parameters (β, η, etc), coupling κ

(need good coupling correction)

Photon Spectral Brightness

Spectral brightness: photon density in 6D phase space

$$B_{avg}(\lambda) \propto \frac{N_{ph}(\lambda)}{(\varepsilon_x \oplus \varepsilon_r(\lambda))(\varepsilon_y \oplus \varepsilon_r(\lambda))(s \times \% BW)}$$

$\varepsilon_{x,y}$ = electron emittance

ε_r = photon emittance **= $\lambda/4\pi$**

$$B_{pk}(\lambda) \propto \frac{N_{ph}(\lambda)}{(\varepsilon_x \oplus \varepsilon_r(\lambda))(\varepsilon_y \oplus \varepsilon_r(\lambda))(\sigma_t \times \% BW)}$$

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Coherent fraction:

$$f_{coh}(\lambda) = \frac{\lambda / 4\pi}{(\varepsilon_x \oplus \varepsilon_r(\lambda))} \times \frac{\lambda / 4\pi}{(\varepsilon_y \oplus \varepsilon_r(\lambda))}$$

Storage Ring Emittance

Emittance ε_x results from the balance between radiation excitation S_x and damping τ_x:

$$\varepsilon_x = S_x \tau_x$$

$$S_x \approx E^5 \oint B^3(s)\mathrm{H}(s)\,ds$$

$$\frac{1}{\tau_x} \approx J_x E^3 \oint B^2(s)\,ds$$

$$\mathrm{H}(s) = \eta_x^2(s) + \frac{\left(\beta_x(s)\eta_x'(s) - \frac{\beta_x'(s)}{2}\eta_x(s)\right)^2}{\beta_x(s)}$$

E = electron energy B = vertical magnetic field strength

β_x, η_x = Twiss parameters; $\beta_x' = d\beta_x/ds$, $\eta_x' = d\eta_x/ds$

J_x = horizontal damping partition number (~ 1)

Minimizing Emittance

$$\varepsilon_{x0} = \frac{C_q E^2}{J_x} \theta^3 F_{latt}$$

θ = dipole bend angle

F_{latt} depends on lattice type and is minimum for Theoretical Minimum Lattice (TME)

$$F_{latt}(TME) = \frac{1}{12\sqrt{15}}$$

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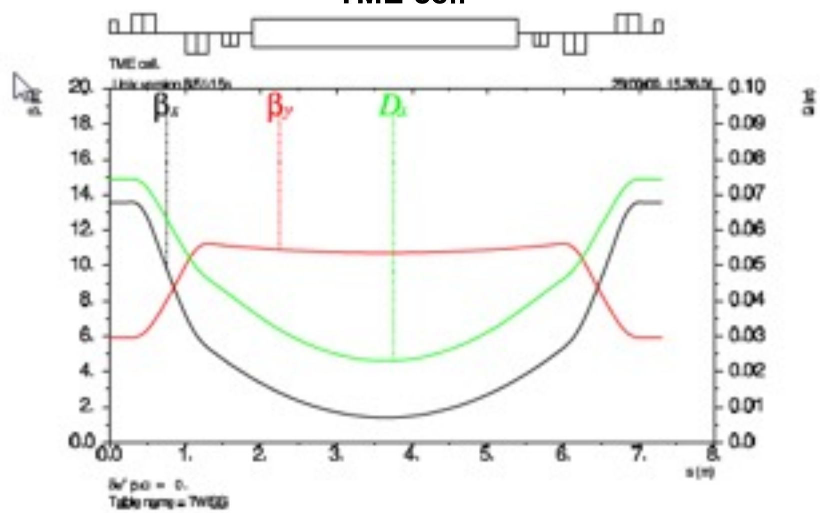
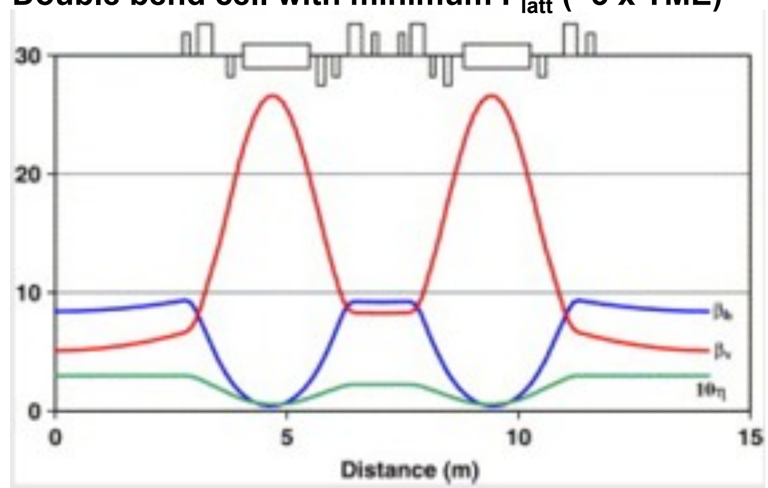
TME cell



Double bend cell with minimum F_{latt} (~3 x TME)



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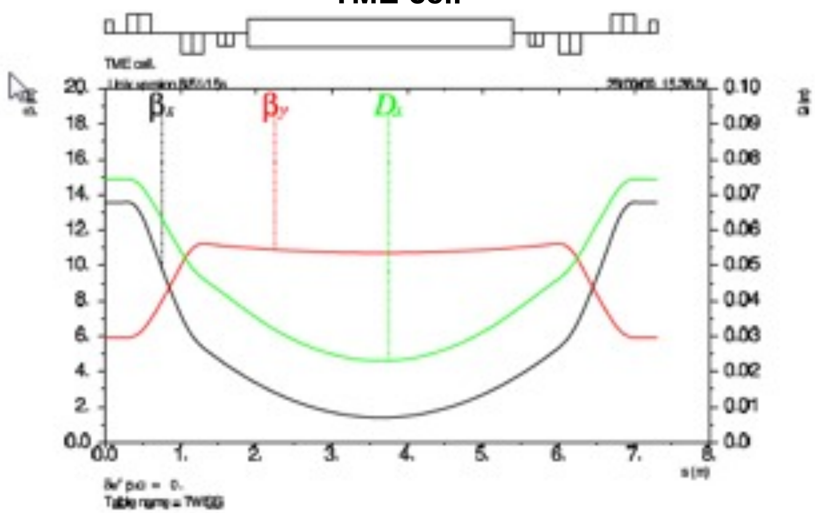

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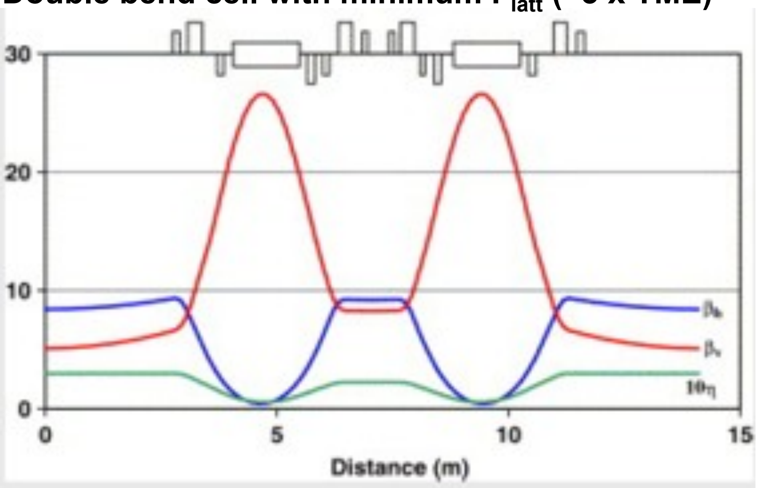
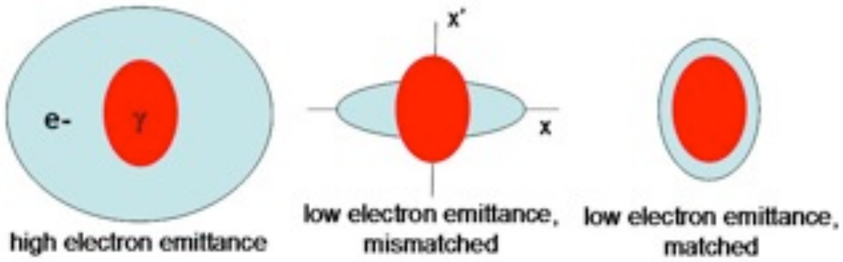


For a given lattice type: $\varepsilon_x \sim C^{-3}$, C = ring circumference

Optimizing Beta Functions for IDs

Electron-photon phase space matching:



$$\frac{\sigma_{ph-ID}}{\sigma'_{ph-ID}} = \frac{\sqrt{\lambda_{ph-ID} 2L_{ID}}}{4\pi\sqrt{\lambda_{ph-ID}/2L_{ID}}} = \frac{\sigma_{e-}}{\sigma'_{e-}} = \frac{\sqrt{\varepsilon\beta}}{\sqrt{\varepsilon/\beta}} \Rightarrow \beta = \frac{L_{ID}}{2\pi}$$

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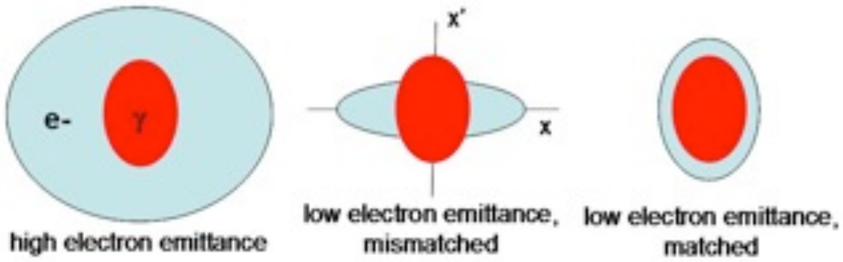

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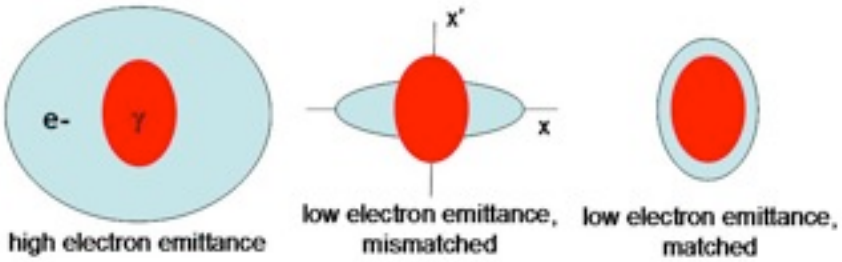

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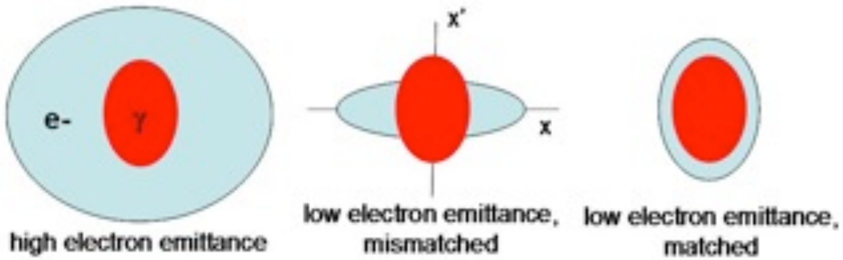

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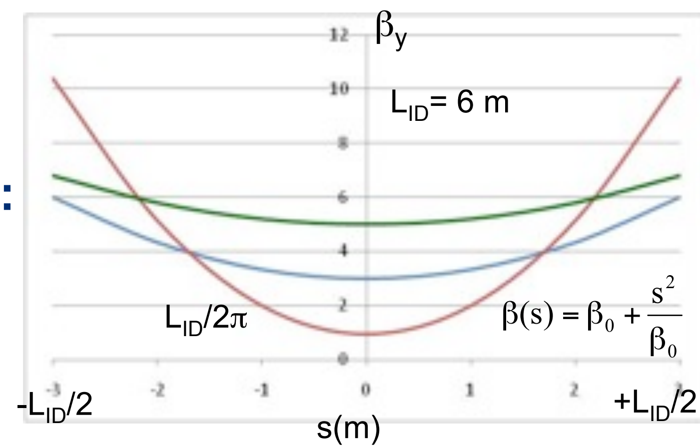
But β_x in injection straight must be large to maximize injection acceptance.

Can reach minimum ID gap when vertical beam size at ID entrance/exit is minimized:

$$\beta_y(s=0) = \frac{L_{ID}}{2}$$



Light Source Parameters

Facility	Energy (GeV)	Circumf (m)	Lattice	# straight sections	Emittance (nm-rad)	Current (mA)
ANKA	2.5	103.2	DDBA	4 4 / 7 m	88/45	200 (400)
SESAME	2.5	124.8	"TME Optic"	16 3 / 3.2 m	24.6 w/o IDs	400
NSLS-I	2.8	170.1	(Chasman/Green) DBA	8 4.5 m	90/45	280
CLS	3	170.9	DBA	12 5 m	18	280
ASP	3	216	DBA	14 5 m	16	200
SPEAR3	3	234.8	DBA	18 3 / 4 / 7m	18/9.8	500
PLS-II	3	281.8	Split DBA	20 3.1 / 6.9 m	5.8/<10 with IDs	400
ALBA	3	268.8	DBA	16 2.6/4.2/8 m	4.3	400

Light Source Parameters – cont.

Facility	Energy (GeV)	Circumf (m)	Lattice	# straight sections	Emittance (nm-rad)	Current (mA)
SLS	2.4	288	TBA	12 4/7/11 m	4.8/4.1	400
Soleil	2.75	354.1	Mod Chas Green	24 3.8/7/12 m	3.7	500
Diamond	3	561.6	DBA	24 5 / 8 m	2.7	300
TPS	3	518.4	DBA	24 7/12 m	1.6	400
LNLS2	3	332	TBA	16 7 m	0.84 (DW)	500
NSLS-II	3	792	DBA	30 6.6 / 9.3 m	0.6 (DW)	500
MAX-IV	3	528	7BA	20 5 m	0.26 (DW)	500
PEP-X	4.5	2200	TME/DBA	32+ 4 /100 m	~0.03	200

Booster-Ring Configurations

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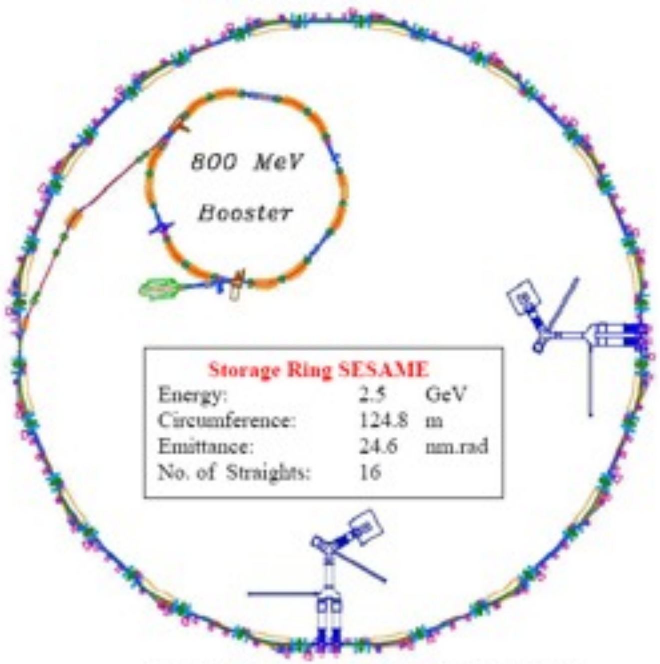
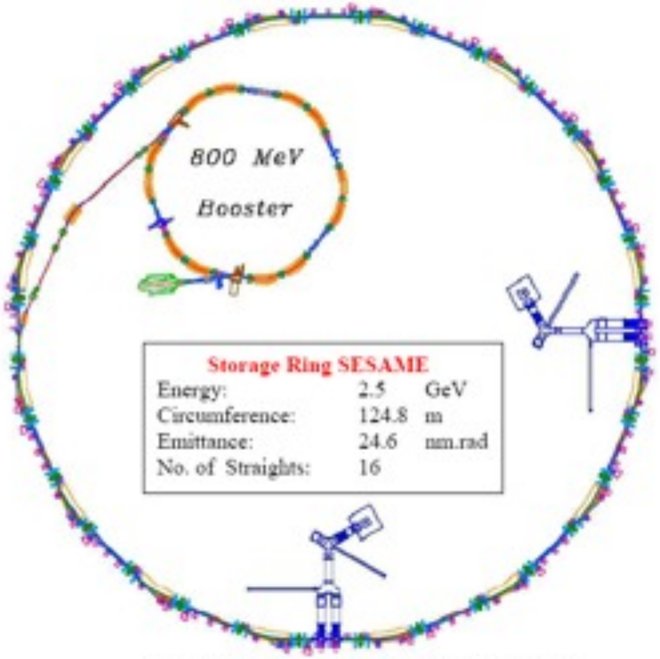


Figure 3: Layout of the 2.5 GeV storage ring of SESAME

ring energy-ramp

Booster-Ring Configurations



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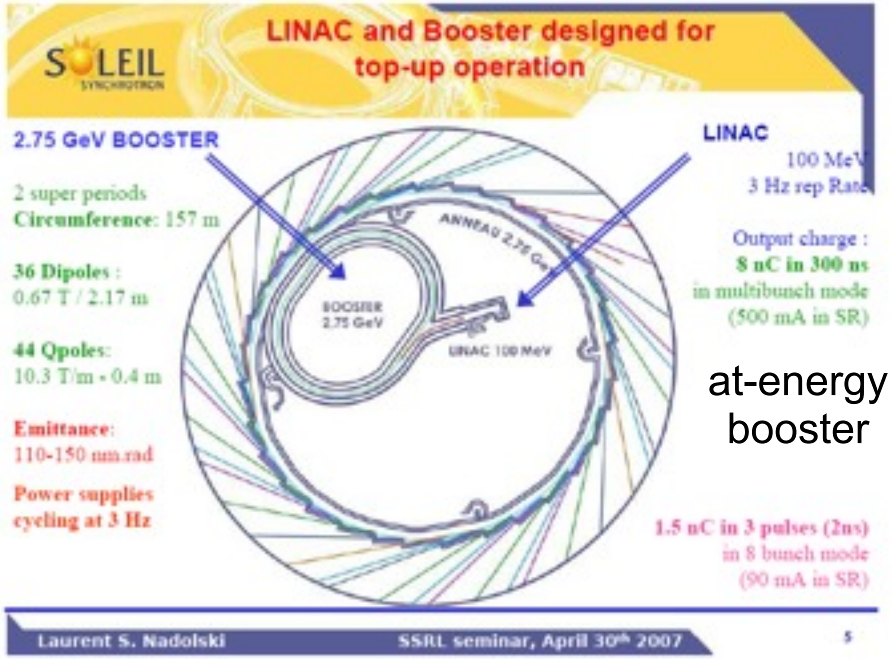

at-energy booster

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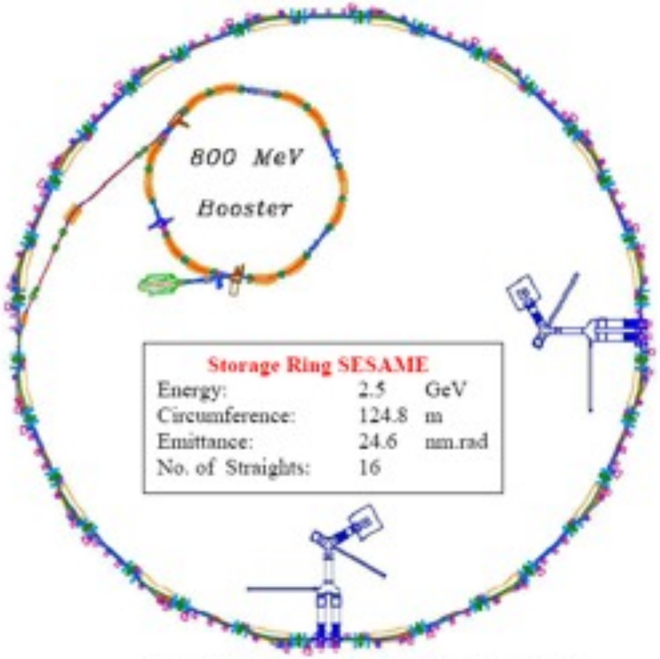

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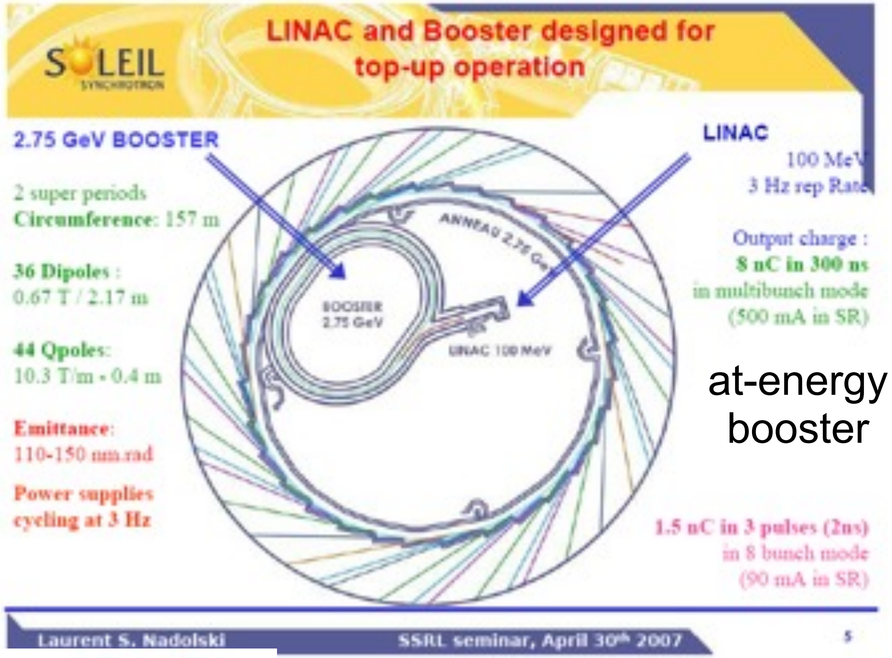

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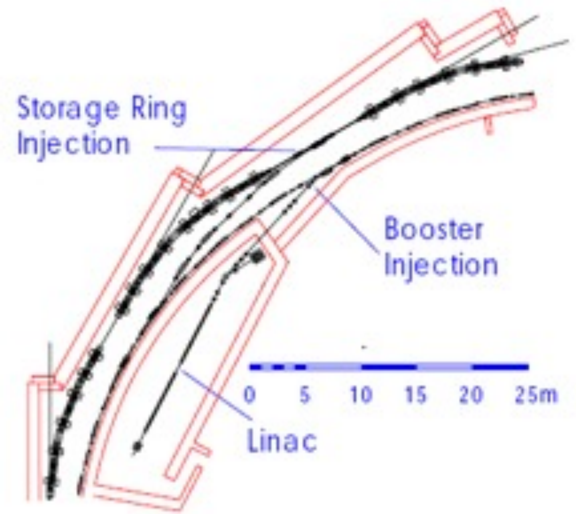
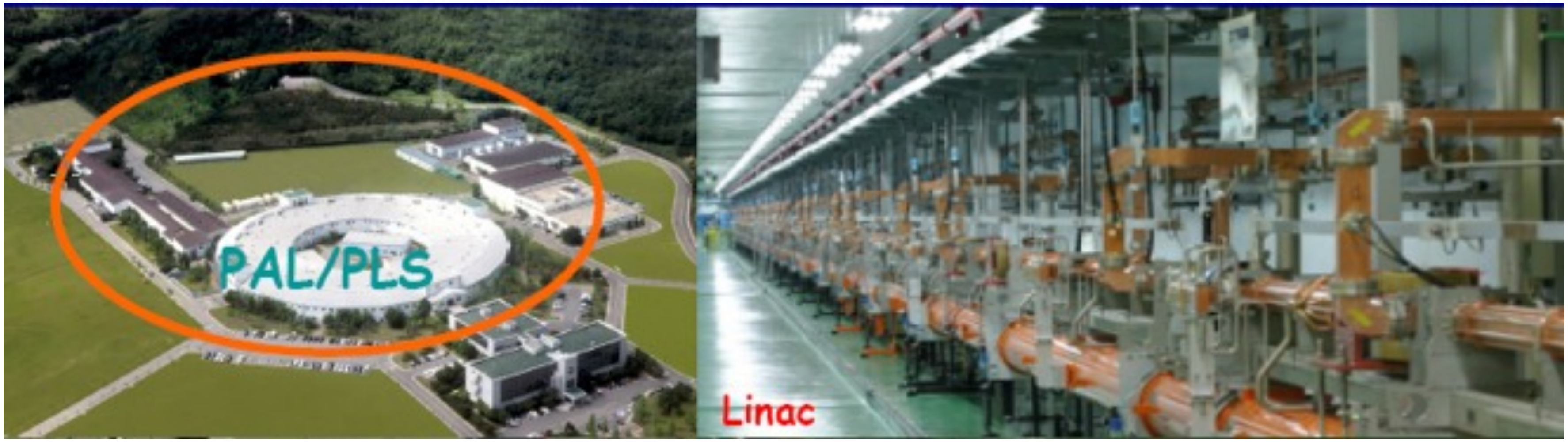


at-energy booster in ring tunnel

At-Energy Linac Injector



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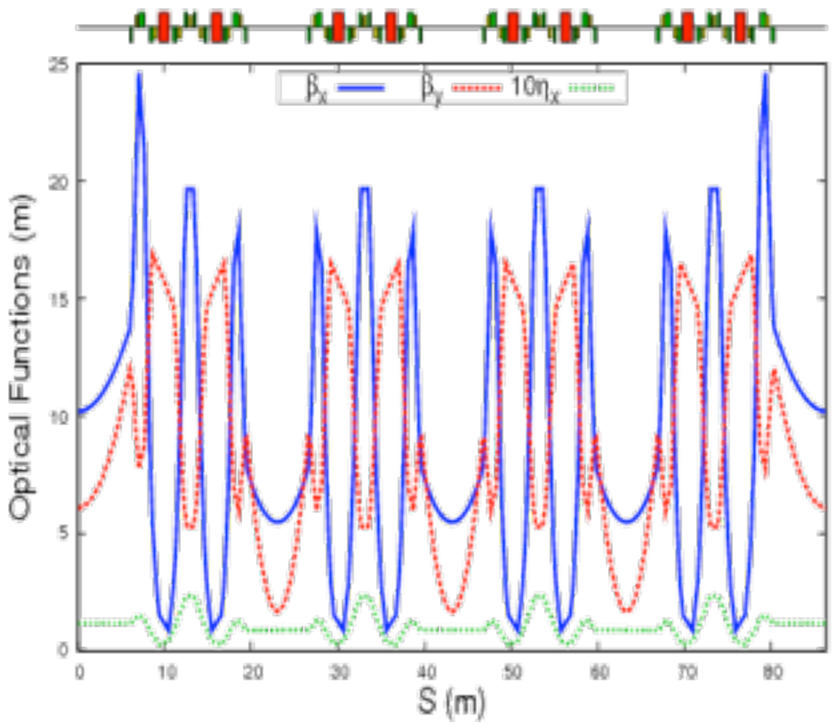
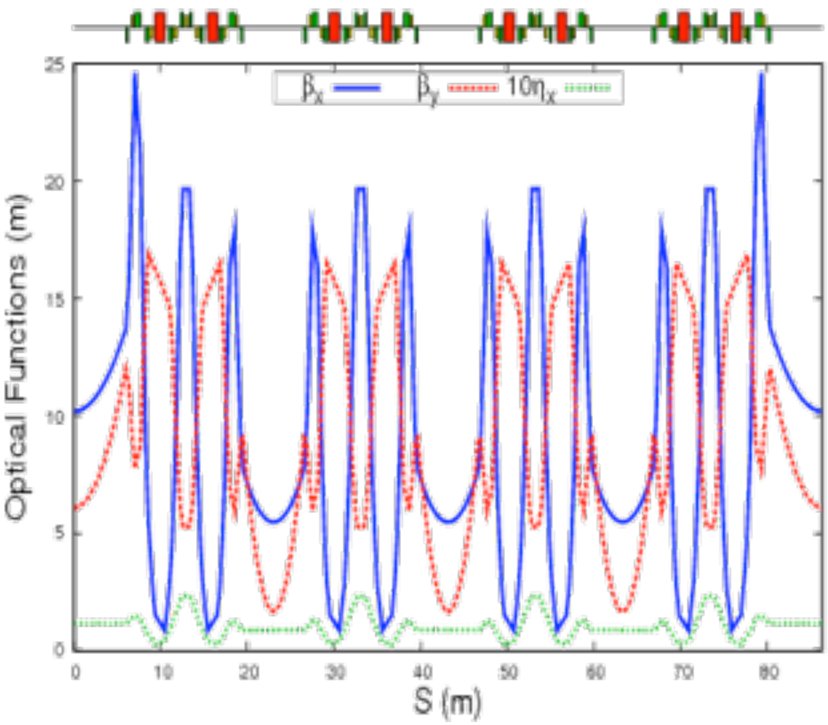
Storage Ring Lattice Types



TPS

Double-Bend Achromat (DBA)

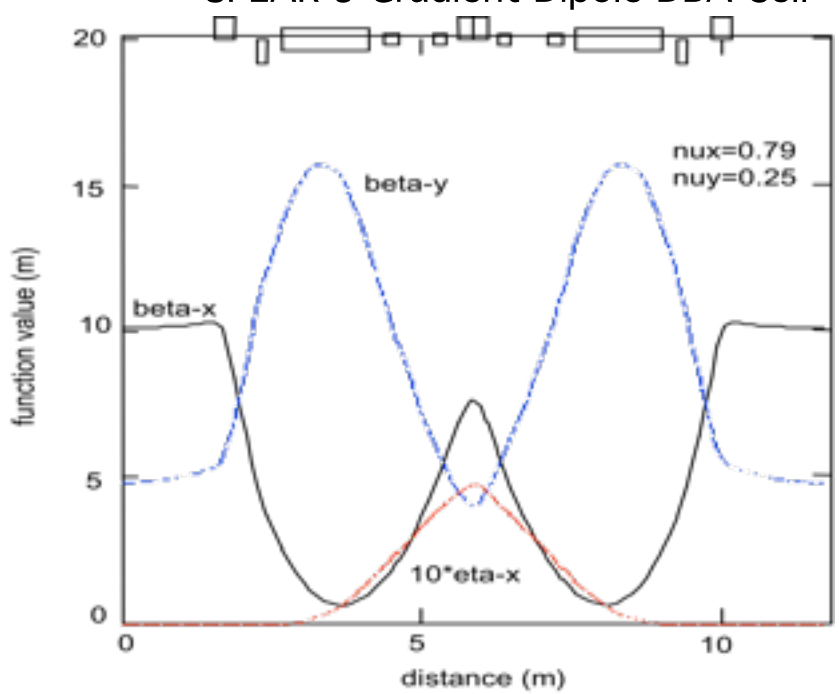
Storage Ring Lattice Types



TPS

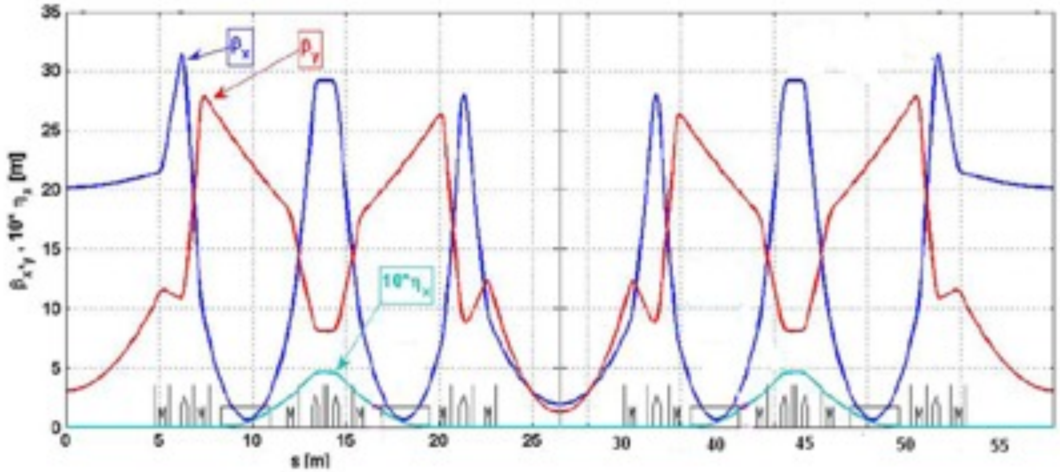
Double-Bend Achromat (DBA)

SPEAR 3 Gradient Dipole DBA Cell



SPEAR3 – gradient dipole

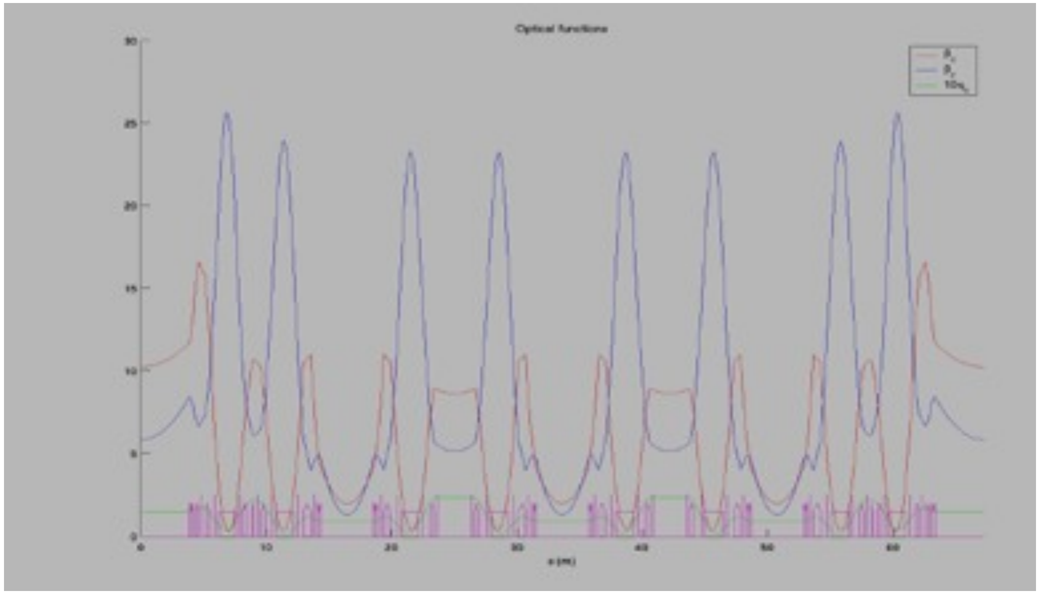
Lattice Types – cont.



NSLS-II Superperiod

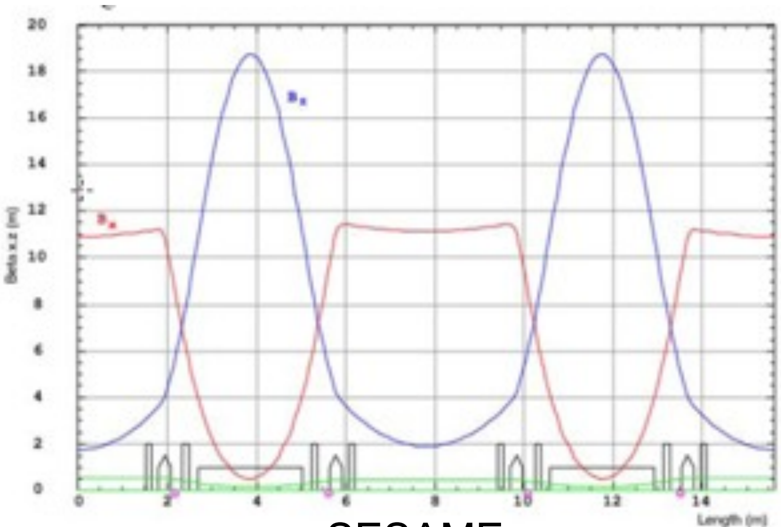
DBA
alternating optics

ALBA



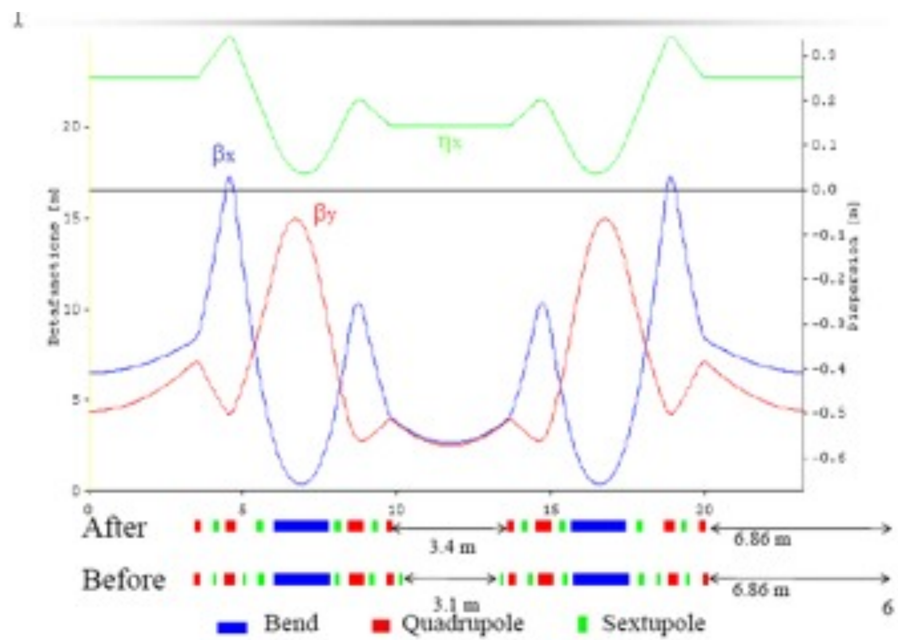
Lattice Types – cont.

Compact lattices



SESAME

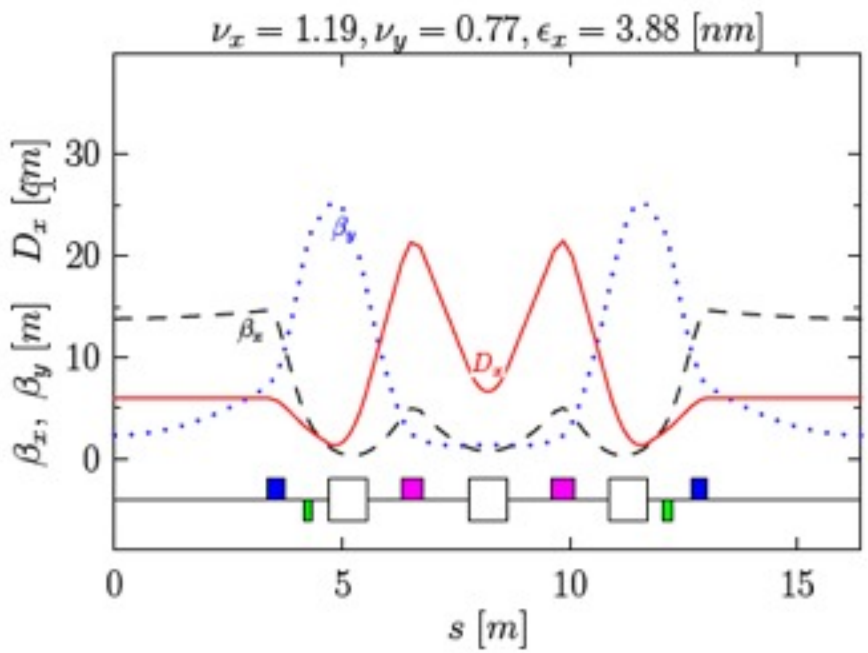
PLS-II



Large non-zero dispersion causes emittance growth with IDs

Lattice Types – cont.

ALS TBA (1.9 GeV)
"superbends" for hard X-rays



Multiple-bend achromat (MBA)

Lattice Types – cont.

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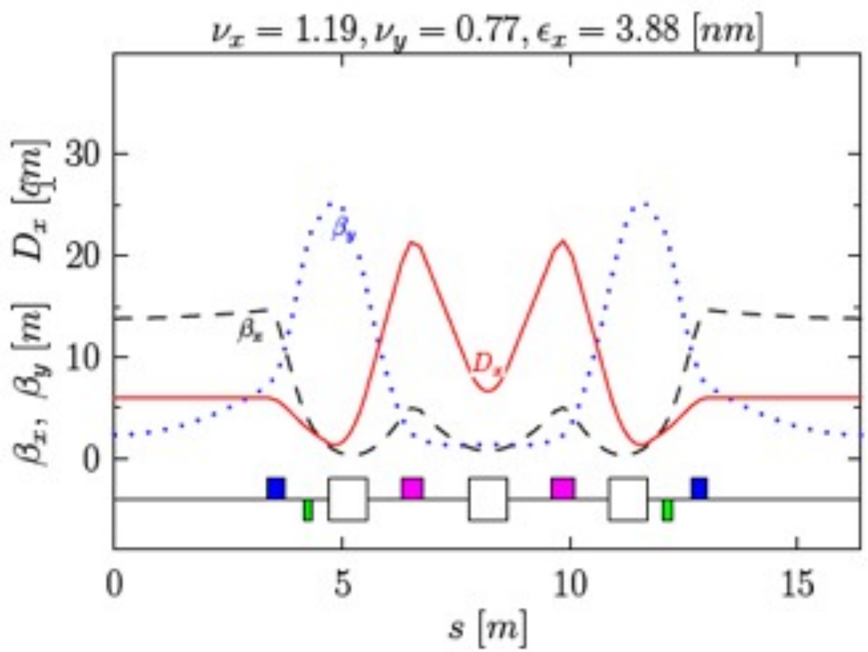
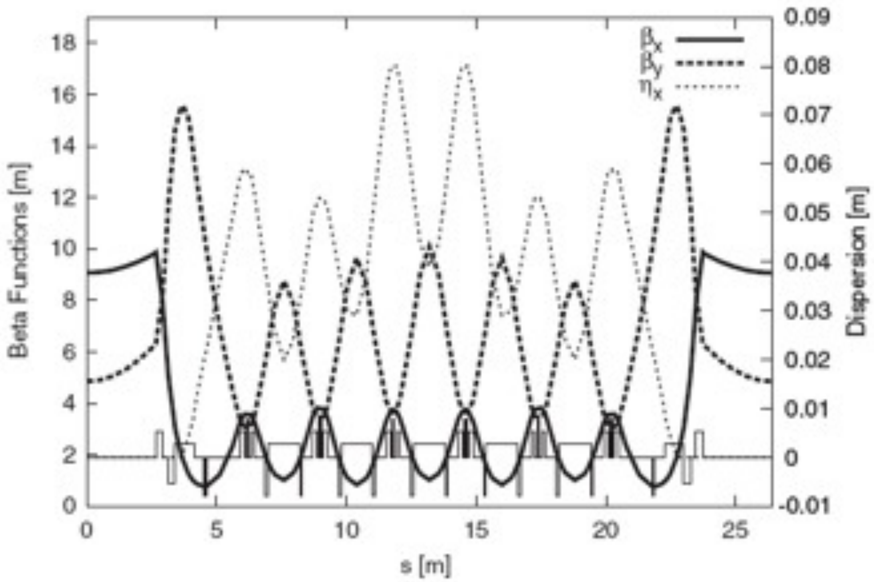


Multiple-bend achromat (MBA)

MAX-IV 7BA



Dispersion Leak to Reduce Emittance

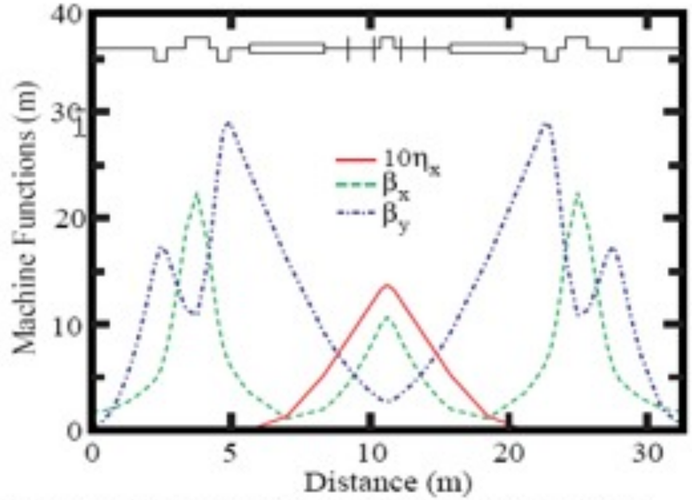


Figure 2. Machine functions in the original lattice.

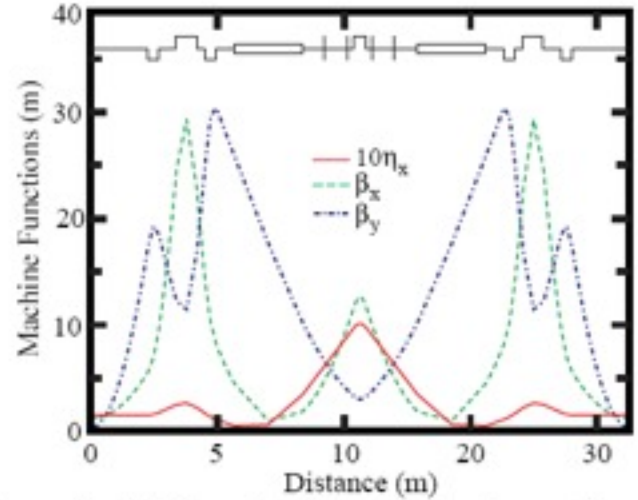


Figure 3. Machine functions in the low emittance lattice.

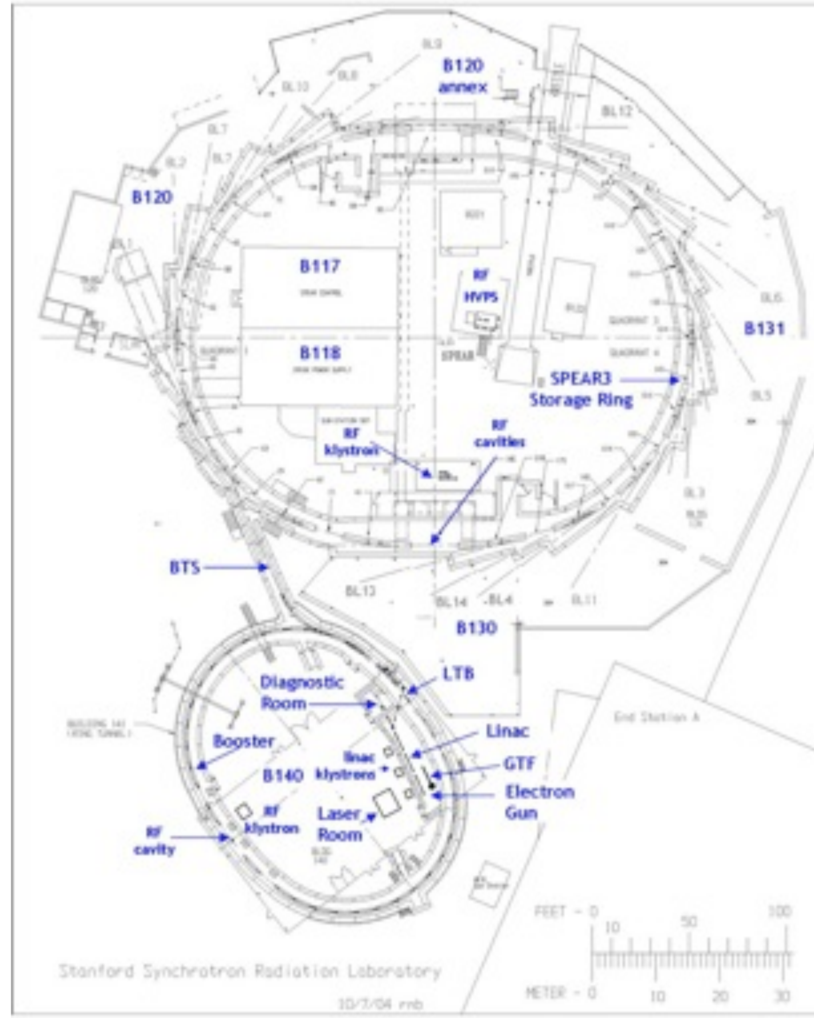
$$\varepsilon_x = S_x \tau_x$$

$$S_x \approx E^5 \oint B^3(s)\mathcal{H}(s)\,ds$$

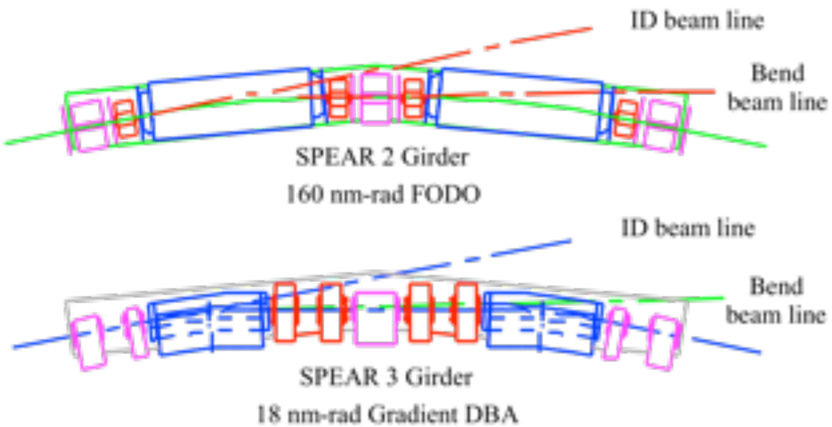
$$\frac{1}{\tau_x} \approx J_x E^3 \oint B^2(s)\,ds$$

$$\mathcal{H}(s) = \eta_x^2(s) + \frac{\left(\beta_x(s)\eta_x'(s) - \frac{\beta_x'(s)}{2}\eta_x(s)\right)^2}{\beta_x(s)}$$

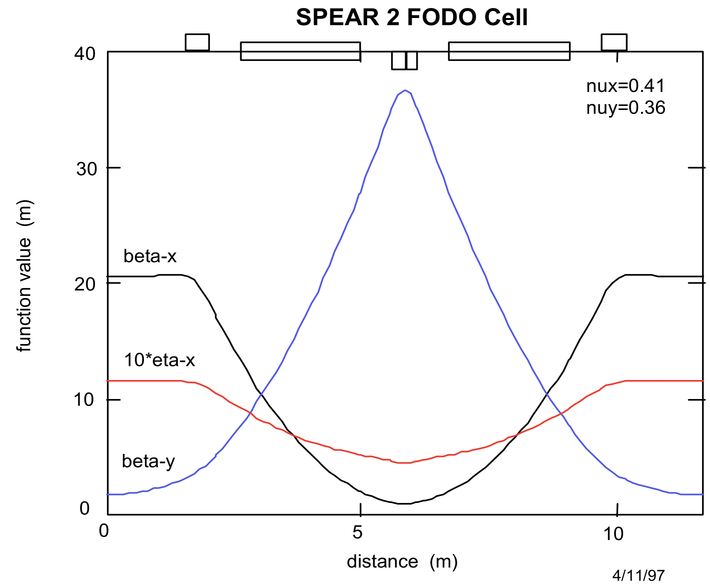
SPEAR3 Design

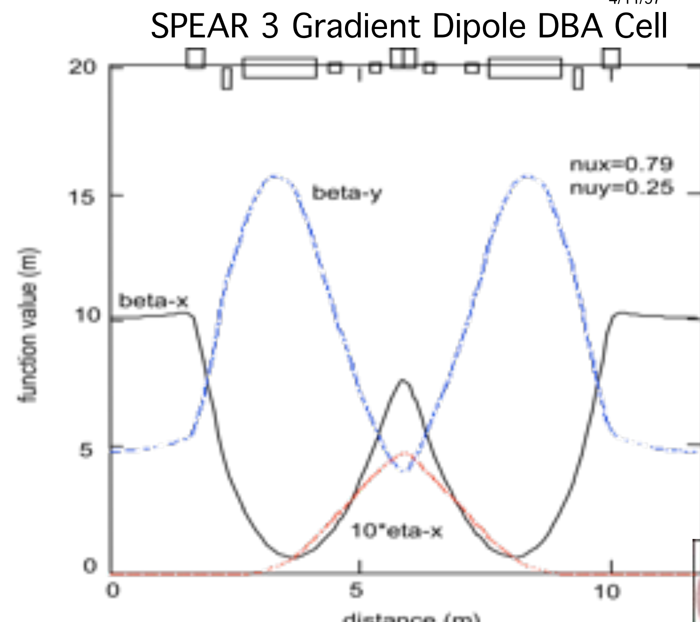


SPEAR3 Lattice Replacement

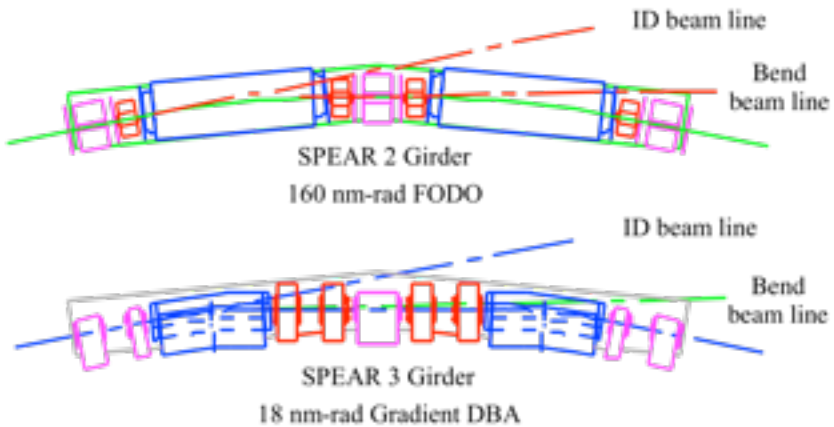


Standard Cells

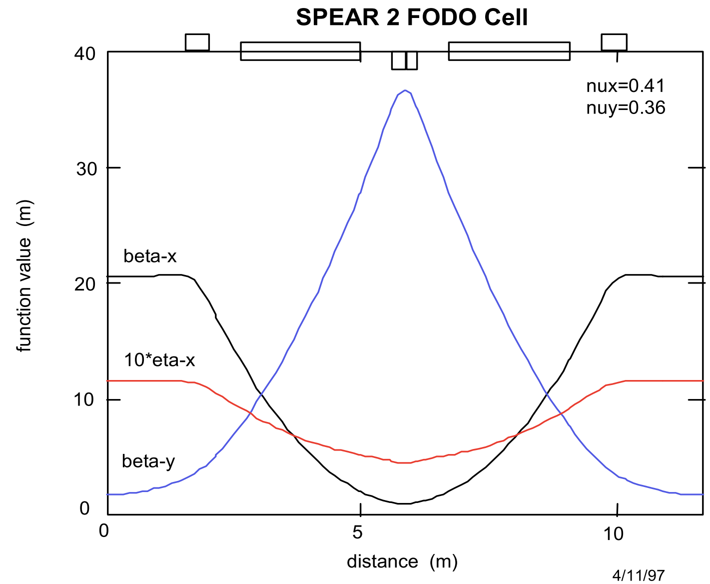


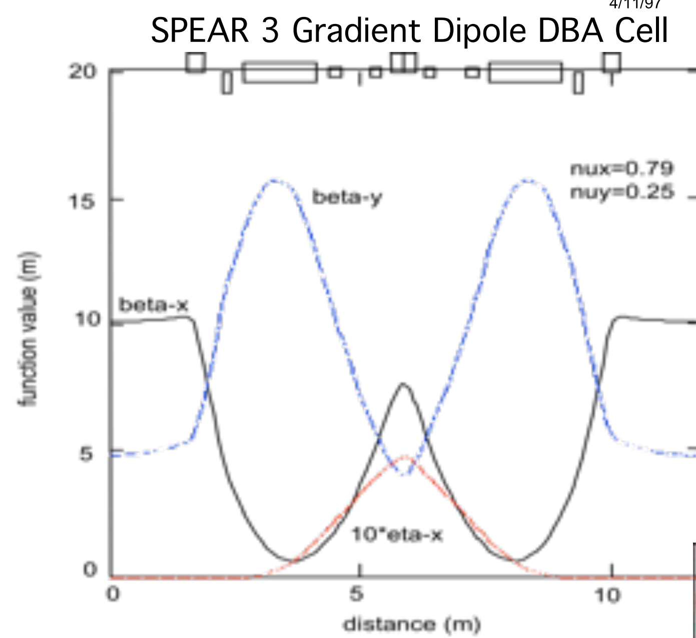


SPEAR3 Lattice Replacement

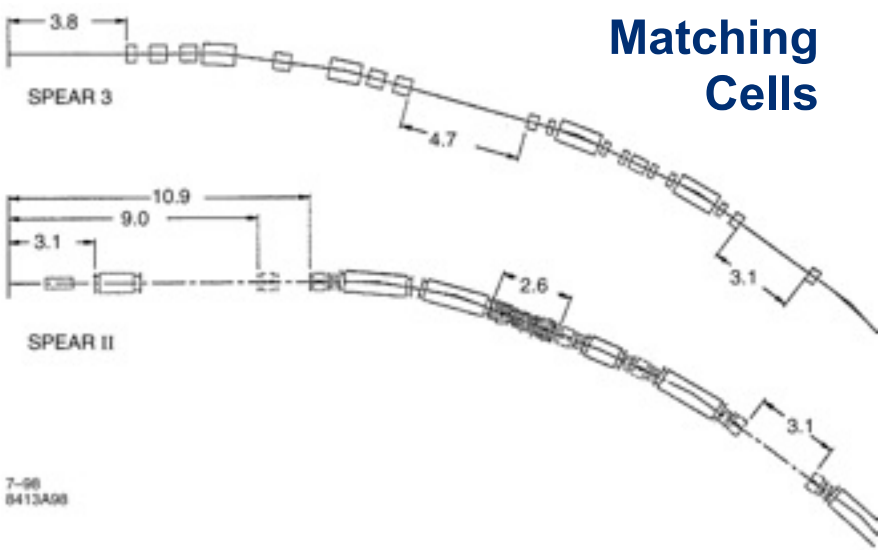


Standard Cells





Matching Cells



SPEAR3 Upgrade - Summary

	SPEAR 2	SPEAR 3
Energy	3 GeV	3 GeV*
Emittance (with IDs)	160 nm-rad	**16 nm-rad**
Current	100 mA	**500 mA** **
Lifetime	40 h @ 100 mA	**>10 h@ 500 mA**
Critical energy	4.8 keV	**7.6 keV**
Circumference	234.126 m	234.126 m
RF frequency/ h	358.5 MHz/280	**476.3 MHz/372**
Injection energy	2.3 GeV	**3 GeV**

9.5 nm-rad with dispersion leak

* 3.3 GeV maximum energy, with current limited to 330 mA.
** 100 mA limit for some beam lines until upgraded for 500 mA.

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9.5 nm-rad with dispersion leak

* 3.3 GeV maximum energy, with current limited to 330 mA.
** 100 mA limit for some beam lines until upgraded for 500 mA.

- Beam line alignment unchanged
- Low impedance, stable vacuum chamber
- < 1.6 nTorr N_2-equivalent pressure at 500 mA

- Mode-damped RF system
- **Stable** beam properties
- Minimal down time for users (< 1 year)

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SPEAR3 Beam Dimensions

	ID Source Point		Dipole Source Point	
	SPEAR 2	**SPEAR 3**	**SPEAR 2**	**SPEAR 3**
σ_x	2000 μm	**427 μm**	790 μm	**160 μm**
$\sigma_{x'}$	2-20 mrad	**2-20 mrad***	mrads	**mrads**
σ_y	53 μm	**30 μm**	200 μm	**50 μm**
$\sigma_{y'}$	142 μrad	**136 μrad***	147 μrad	**136 μrad**
σ_s	23 mm/75 ps	**5.3 mm/19 ps**	23 mm/75 ps	**5.3 mm/19 ps**

* For 100-period undulator: $\sigma_{x'} = 42$ μrad, $\sigma_{y'} = 15$ μrad

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* For 100-period undulator: $\sigma_{x'} = 42$ μrad, $\sigma_{y'} = 15$ μrad

Transverse Stability:

<10% of beam dimensions

⇒ **< 20 μm H, < 5 μm V** at stable BPMs

<1.4 μrad vertical for 100-period ID

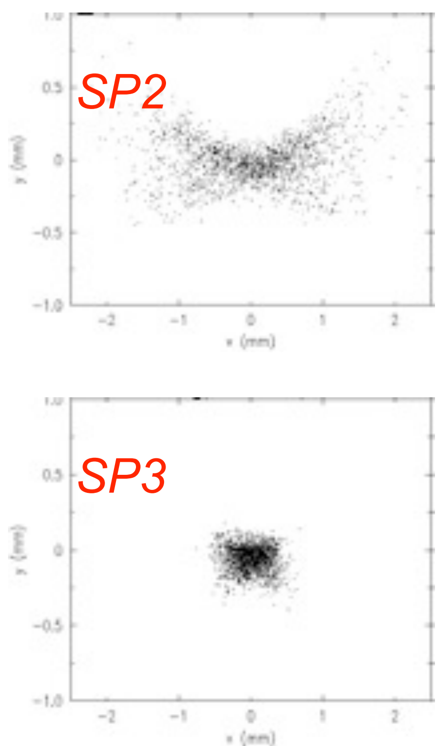
⇒ **< 0.02%** coherent E oscillations (dipole sources)

Longitudinal Stability:

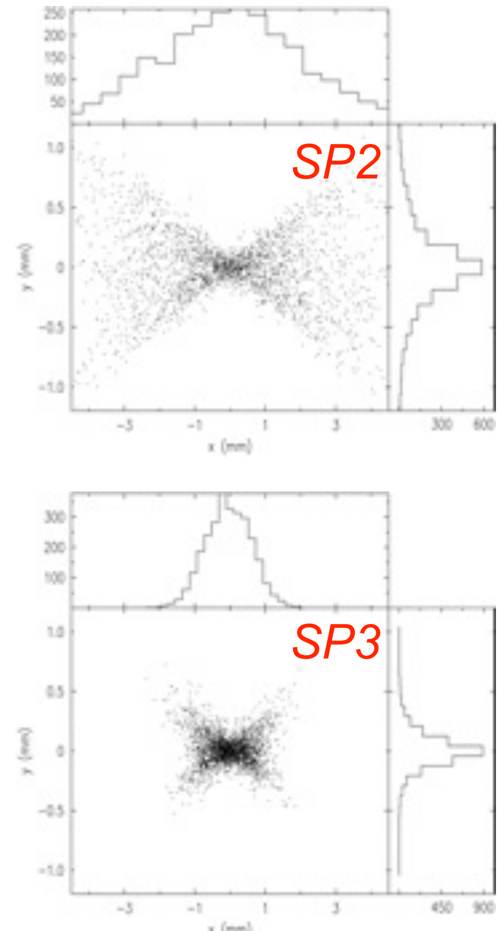
< 0.01% coherent E oscillations ($\Delta\phi < 0.3^o$)
for 10^{-4} stability of 5^{th} undulator harmonic

SPEAR 3 Photon Beam Improvements

	flux		brightness	
beam line	1keV	10keV	1keV	10keV
bend	4.7x	9.9x	89x	188x
BL4/7 ID	13.9x	15.3x	116x	127x
BL9 ID	5x	5x	43x	43x



BL9-2 (1mr accept)



BL4-2 focus w/ 2mr accept.

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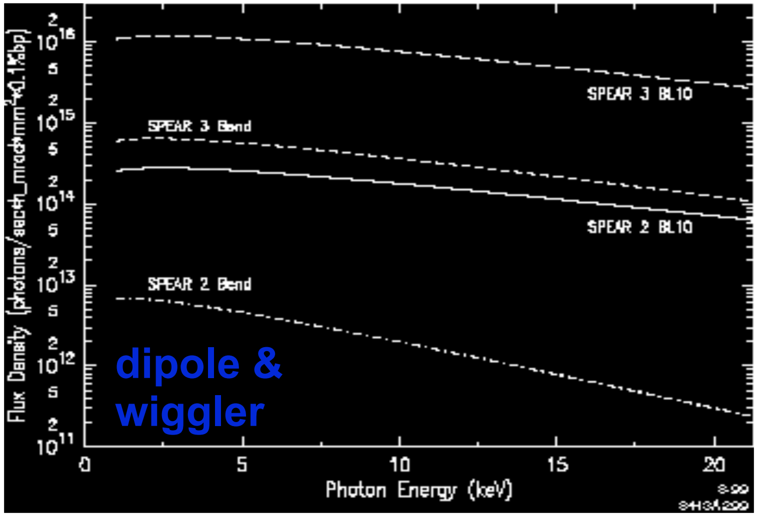
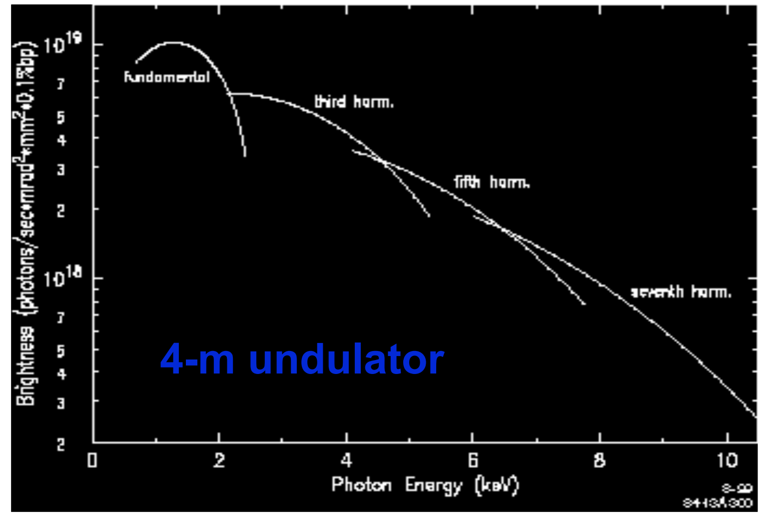
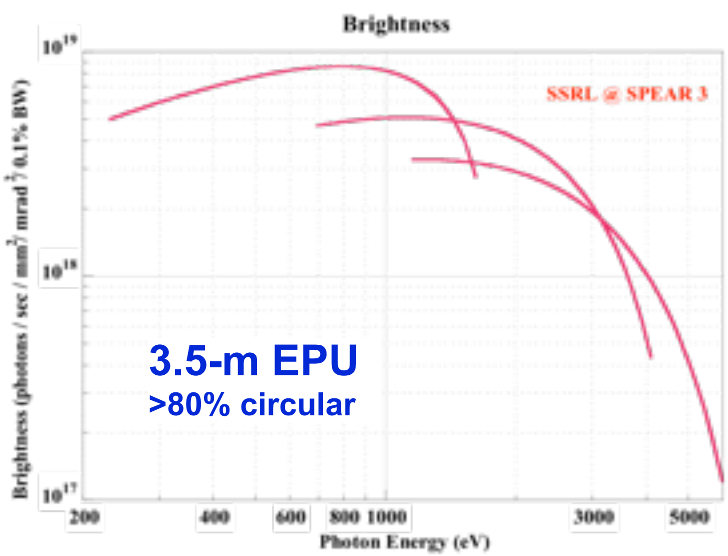
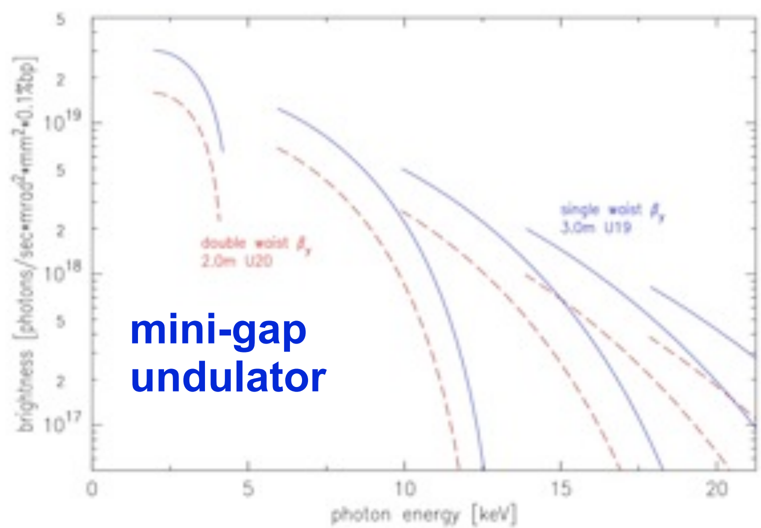
SPEAR 3 Photon Beam Spectra







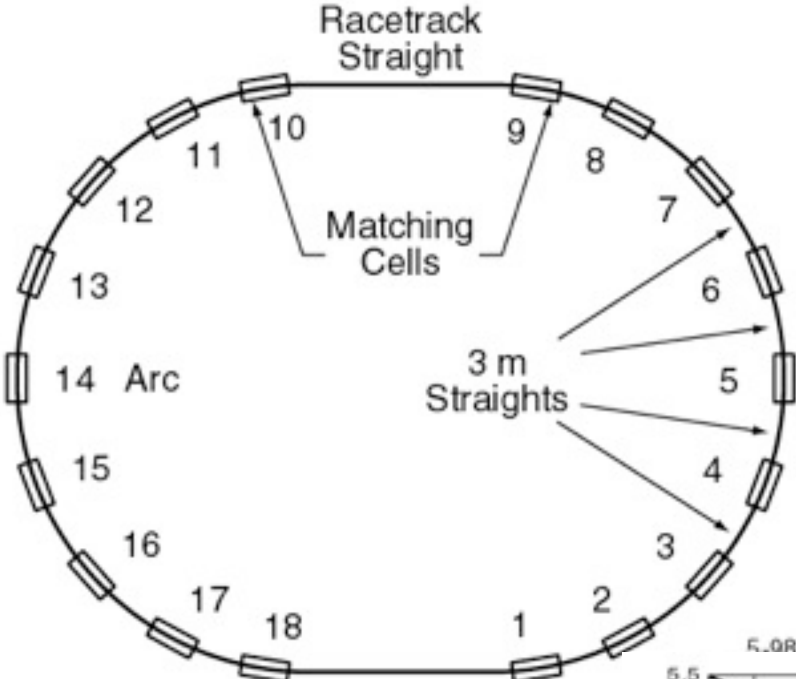


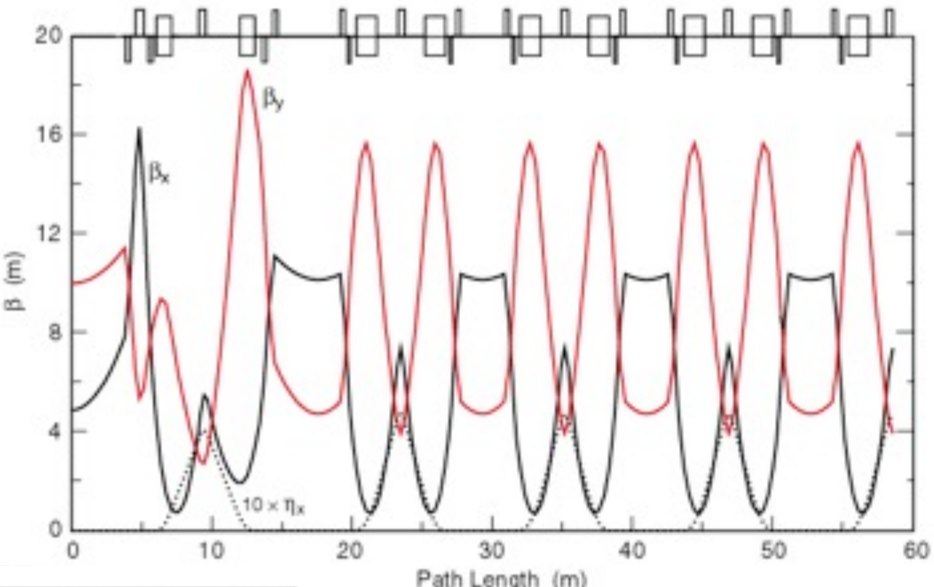
Work Breakdown Structure and Cost Estimate

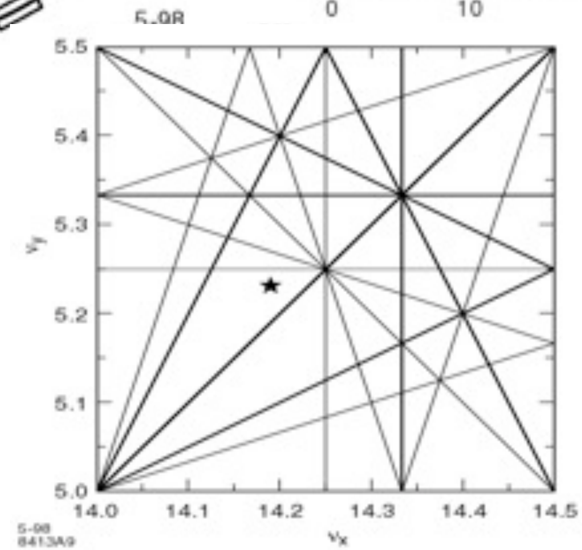
1	SPEAR 3 Project	M$	M$
1.1	Magnet and Supports	6.7	
1.2	Vacuum System	9.1	
1.3	Power Supply System	3.5	
1.4	RF System	0.6	3.1
1.5	Instrumentation, Control and Protection Systems	2.6	
1.6	Injector	0.2	
1.7	Beam line Front Ends	1.0	
1.8	Facilities	1.3	
1.9	Installation and Alignment	4.0	
1.A	Project Physics, Management and Administration	2.7	
	Total Direct in FY'98M$	31.6	34.1
	Indirect Costs	4.7	5.1
	Contingency	9.6	10.3
	Escalation	3.3	3.6
	TOTAL ESTIMATED COSTS (TEC)	49.2	53.1

Accelerator Physics Studies

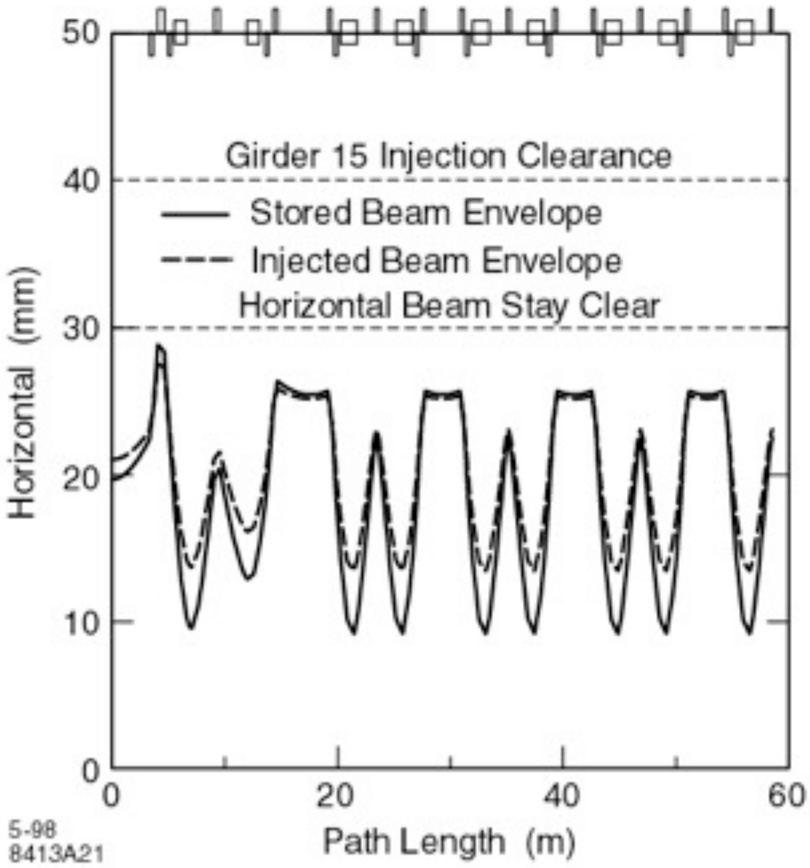
SPEAR3 Lattice

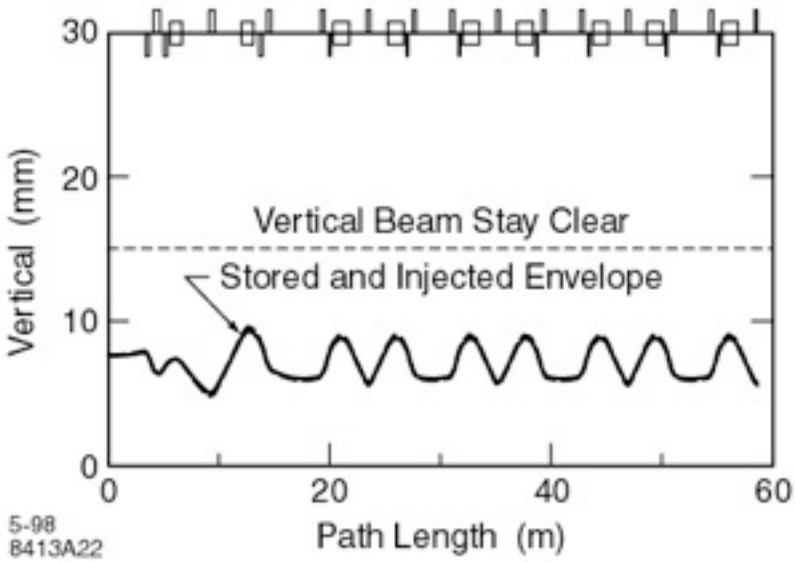






Beam-Stay-Clear





SPEAR3 Lattice – Orbit Correctors and BPMs

Corrector locations

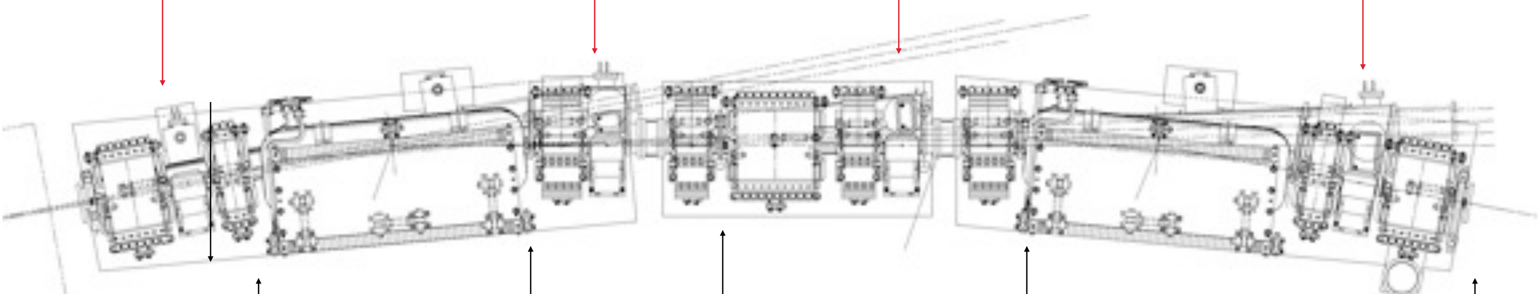
(72 total; 54 H and 54 V correctors used for orbit feedbck)

H/V

V
(H available)

H
(V available)

H/V



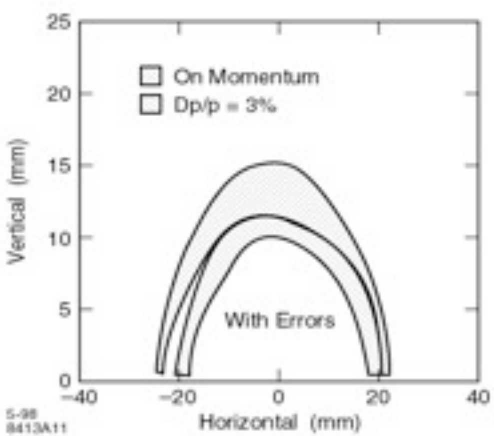
potential problem
with TE_{10} mode
in antechamber

BPM locations

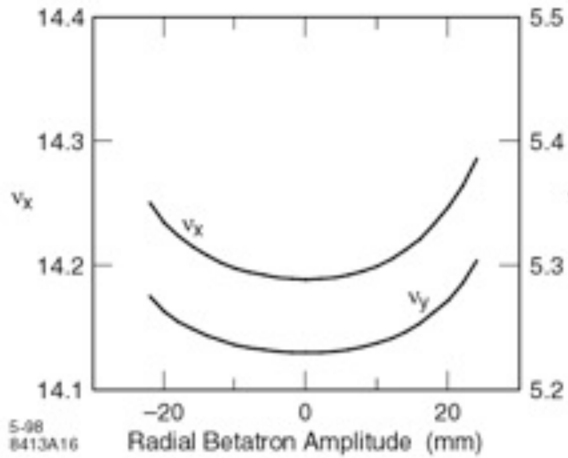
(104 total; 90 used for orbit
feedback)

SPEAR 3 Lattice Properties

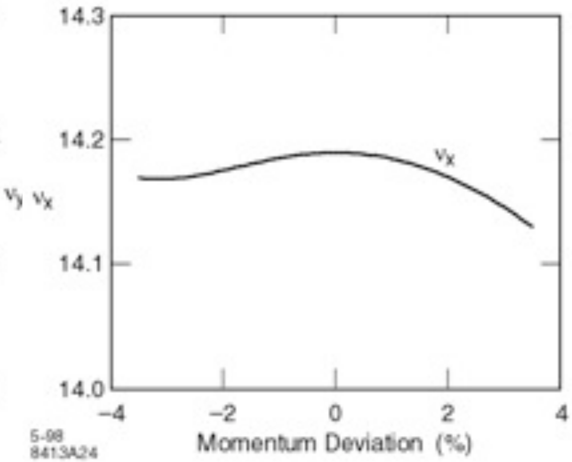
Dynamic aperture:



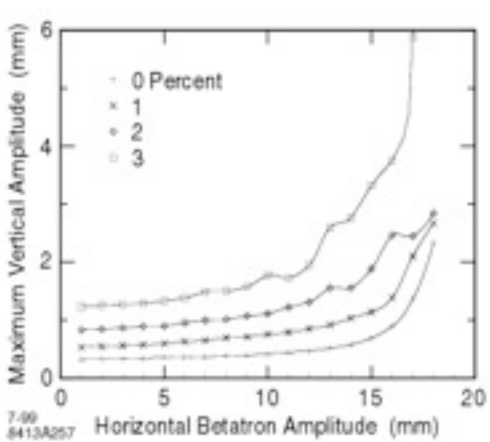
Tune with amplitude:

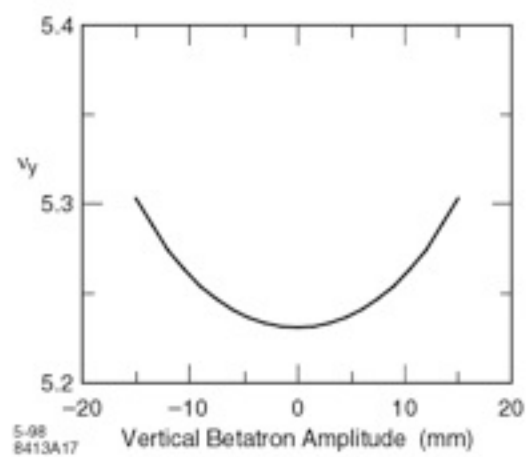


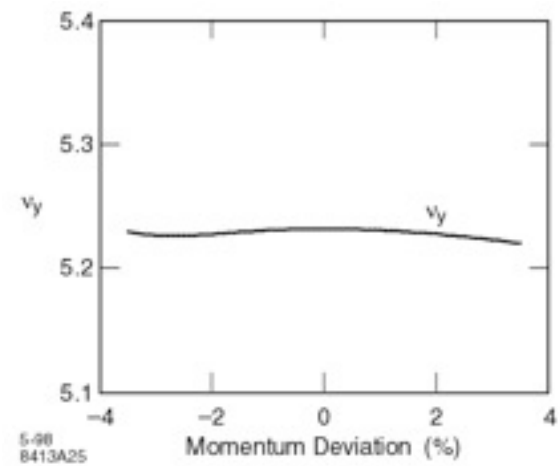
Tune with momentum:



Coupling with amplitude:







Multi-Objective Genetic Algorithms (MOGA, D. Robin et al.)

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Collective Effects - Impedance and Instabilities

Narrowband

No harmful HOMs from PEP-II cavities

No feedback needed for coupled bunch instabilities

Broadband

L_{tot} = ~120 nH   Z/n = ~1 Ω f_R = 15 GHz

I_{th} = 5 mA/bunch for onset of energy widening

~x2 energy and bunch widening at **25mA/bunch**

Resistive Wall

Tunes below half integer

I_{th} @ 0.2 ξ (norm):   **450 mA** for **SS** chamber

(head-tail damping)   **>800 mA** for **Cu** chamber

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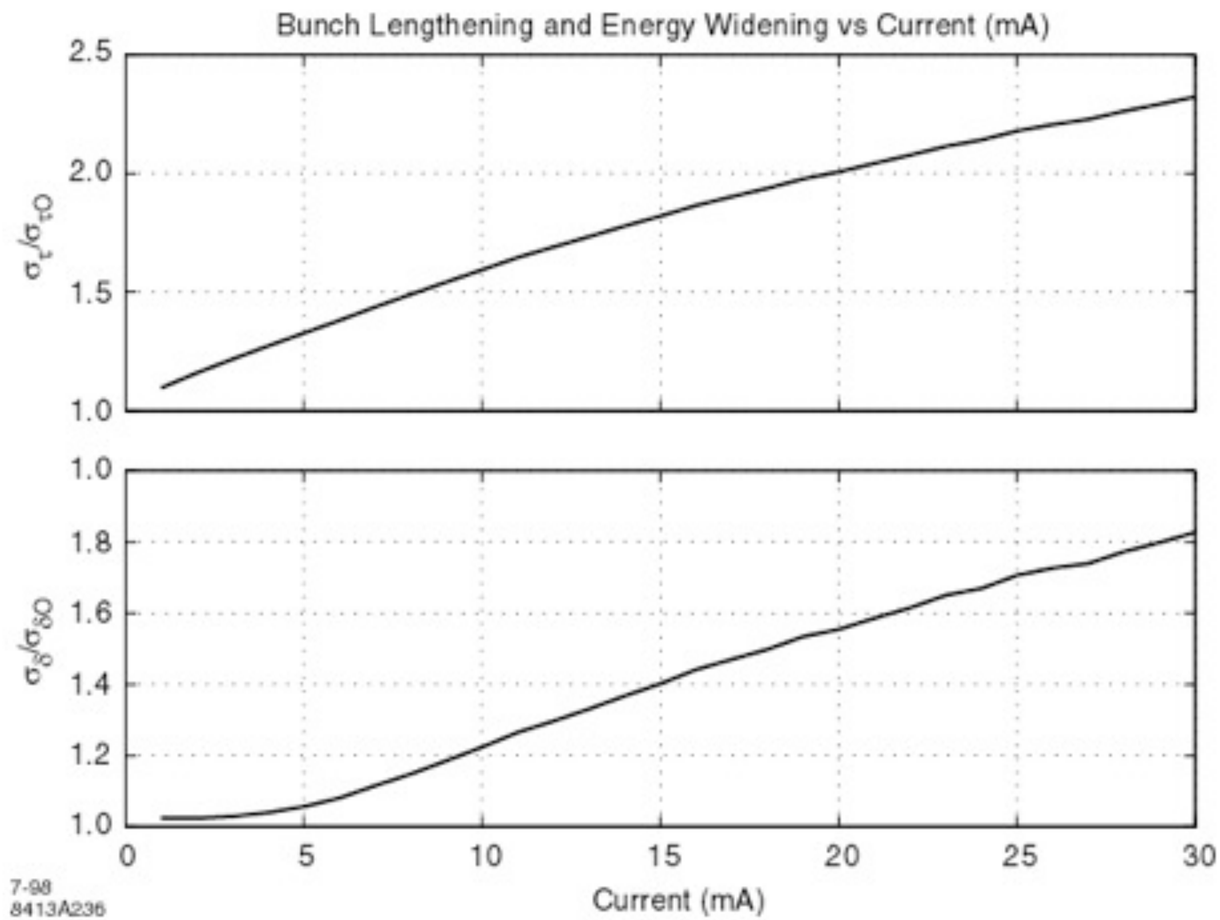
Bunch Length and Energy Spread vs. Current



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Lifetime

Gas Scattering: 28 h @ 500 mA

- Coulomb: **89 h**
- Bremsstrahlung: **41 h**

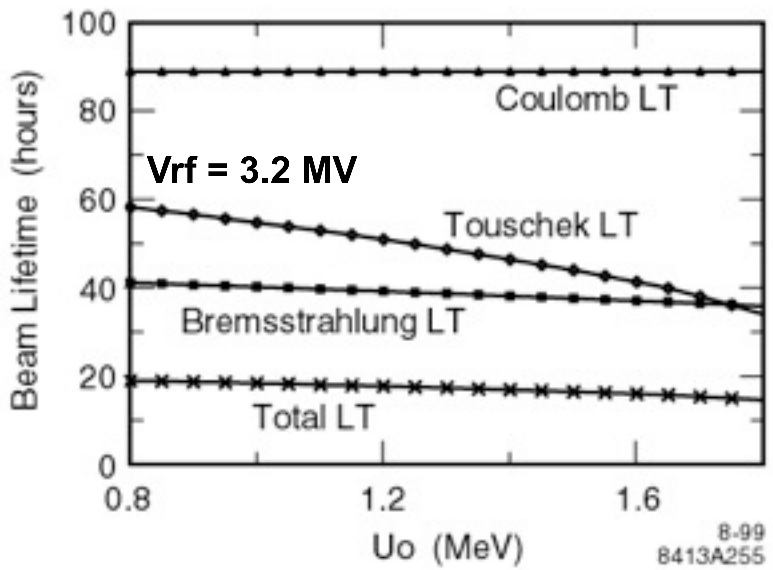
1.8 nTorr N_2-equivalent (conservative), 3% energy acceptance

Touschek: 53 h @ 500 mA

1% coupling, 3.2 MV RF, 3% energy accept, 279 bunches

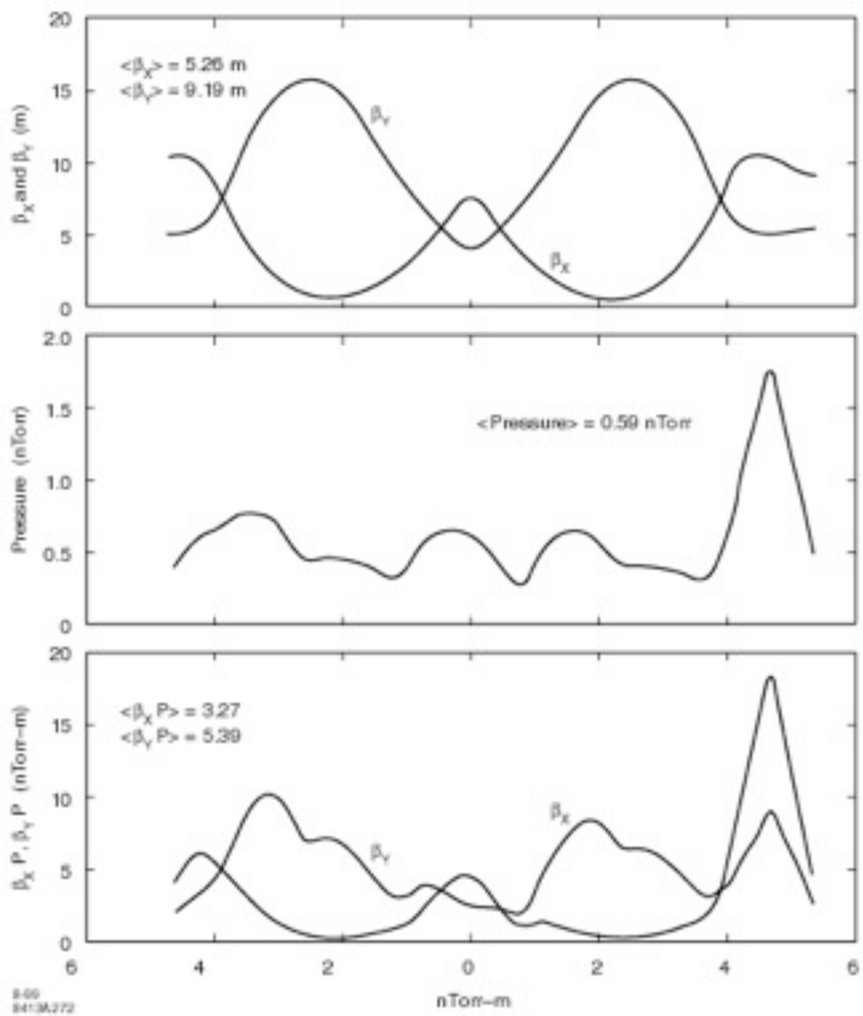
Total: 18 h @ 500 mA

- higher if pressure <1.8 nTorr
- **45 h** @ 200 mA

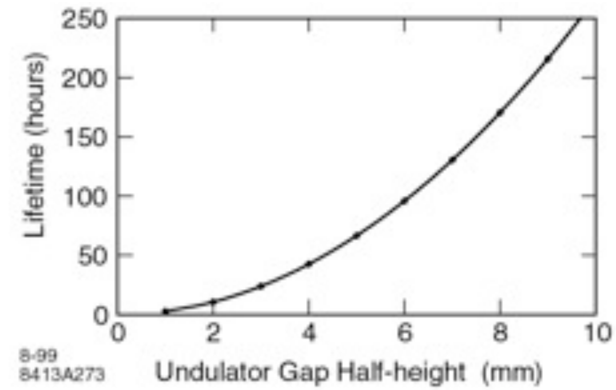


Gas Scattering Lifetime

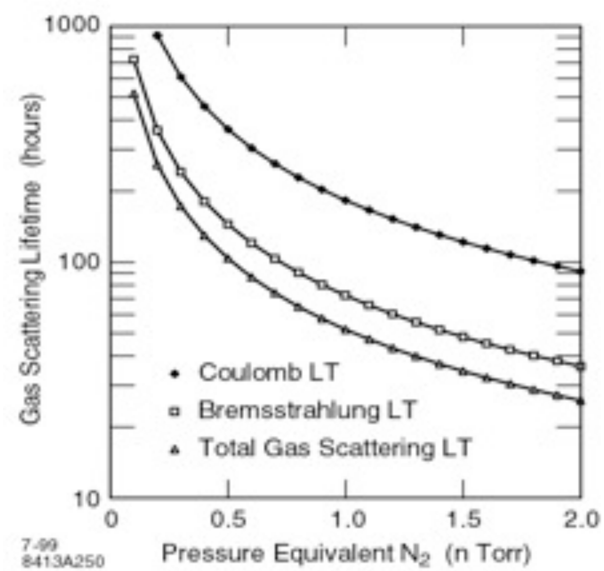
Beta-pressure profile:



Coulomb lifetime and vertical aperture:



Total gas-scattering lifetime:



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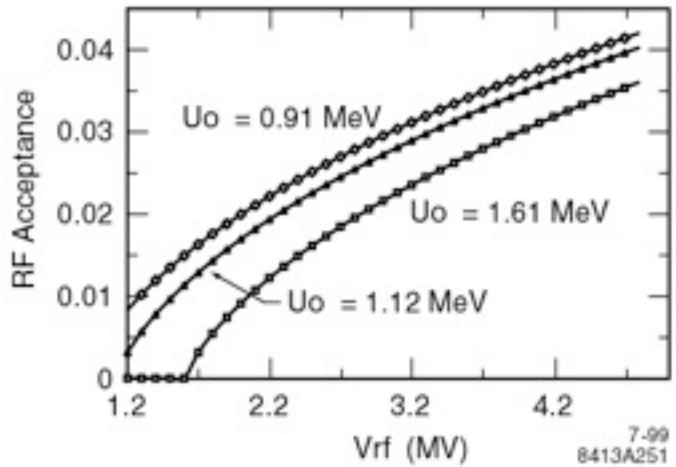
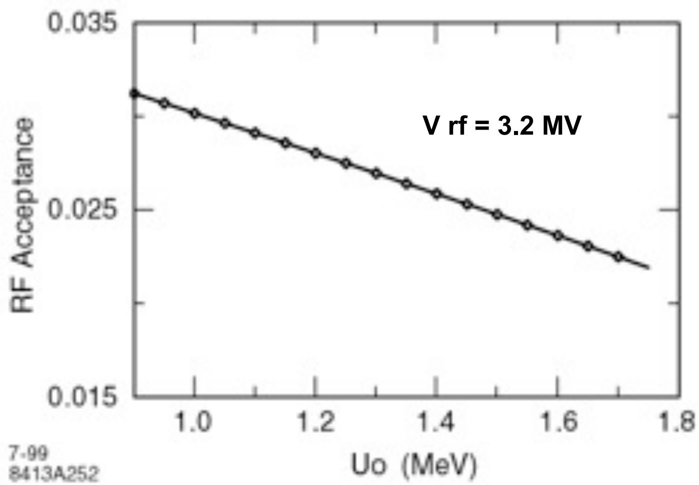
Touschek Lifetime and Momentum Acceptance

Touschek lifetime and RF acceptance:

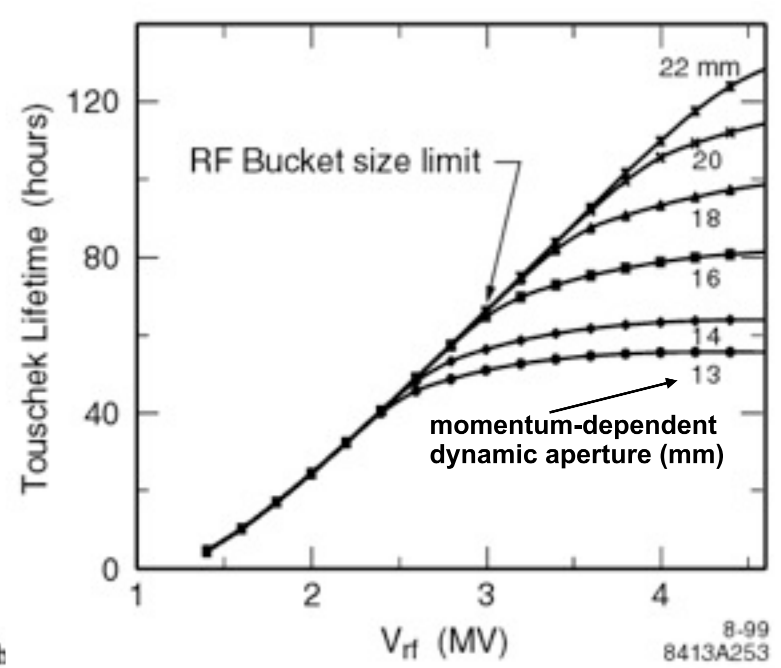




RF acceptance:

$$\frac{\Delta E}{E} = \sqrt{\frac{2U_0\left(\sqrt{q^2-1} - \mathrm{acos}\left(\frac{1}{q}\right)\right)}{\pi \alpha h E}}$$

$q = eV/Uo$
(overvoltage)



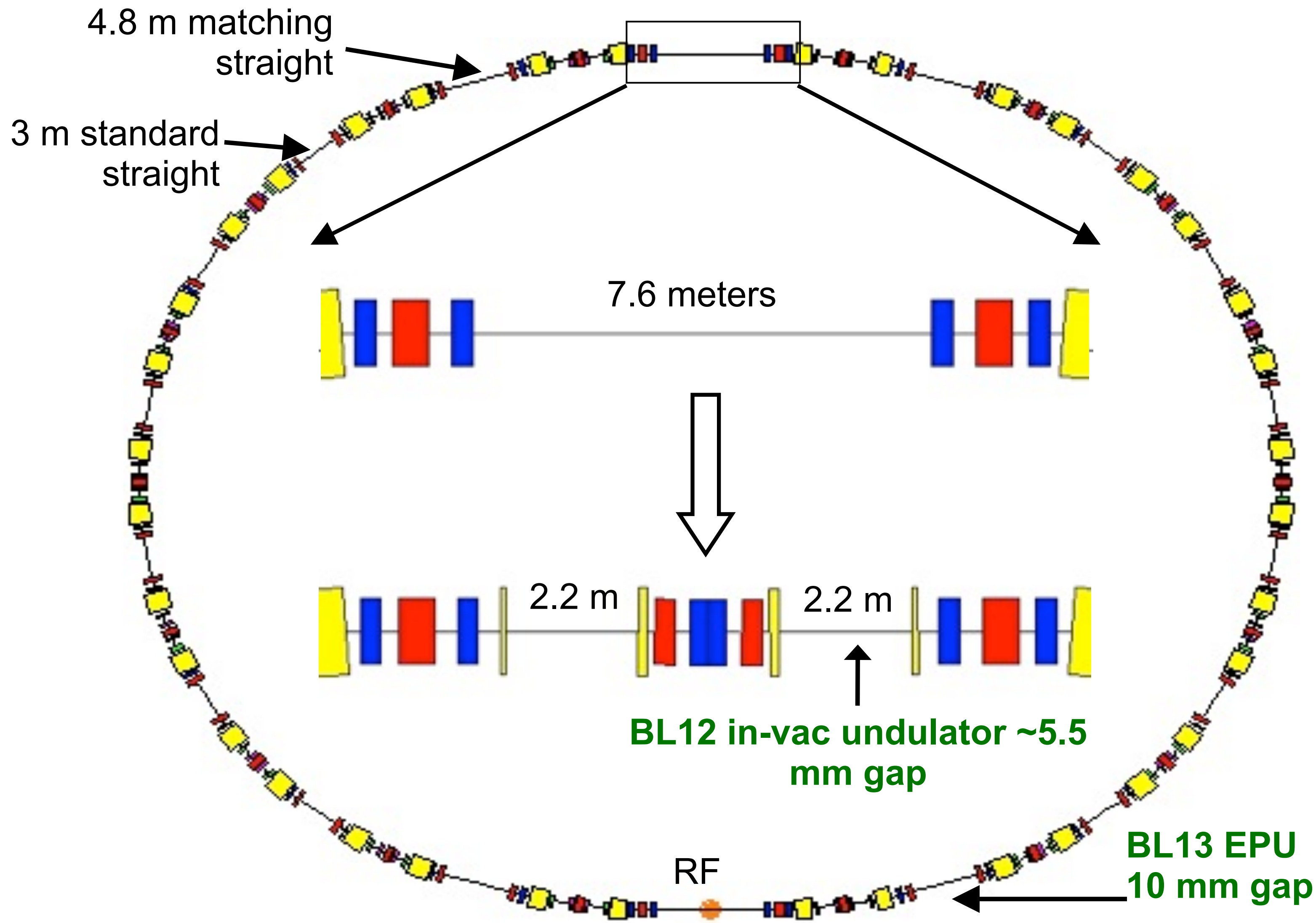
rms bunch

r_0 is the classical electron radius, and c is the speed of light. D(v) is a form fac-

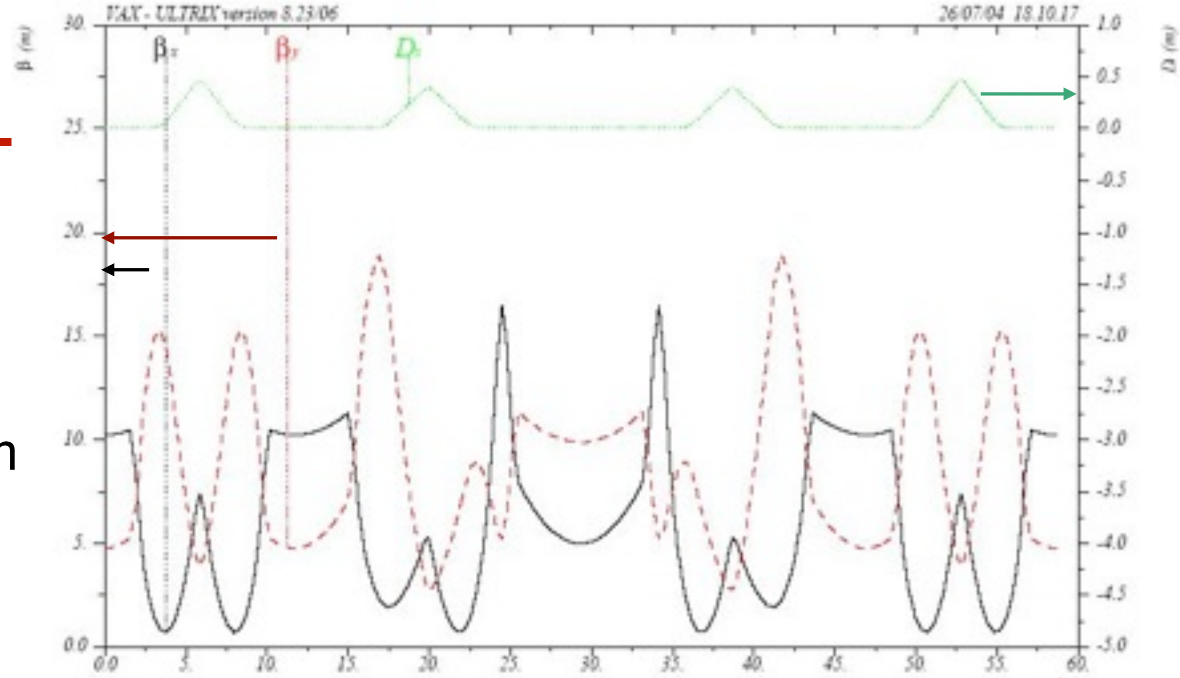
value of 0.2 [REF ???] $\frac{\delta p}{p}\Big|_m$ is the smallest value of the RF acceptance, the

ent dynamic aperture or the physical acceptance.

Double-Waist Chicane Optics (BL 12, BL 13)



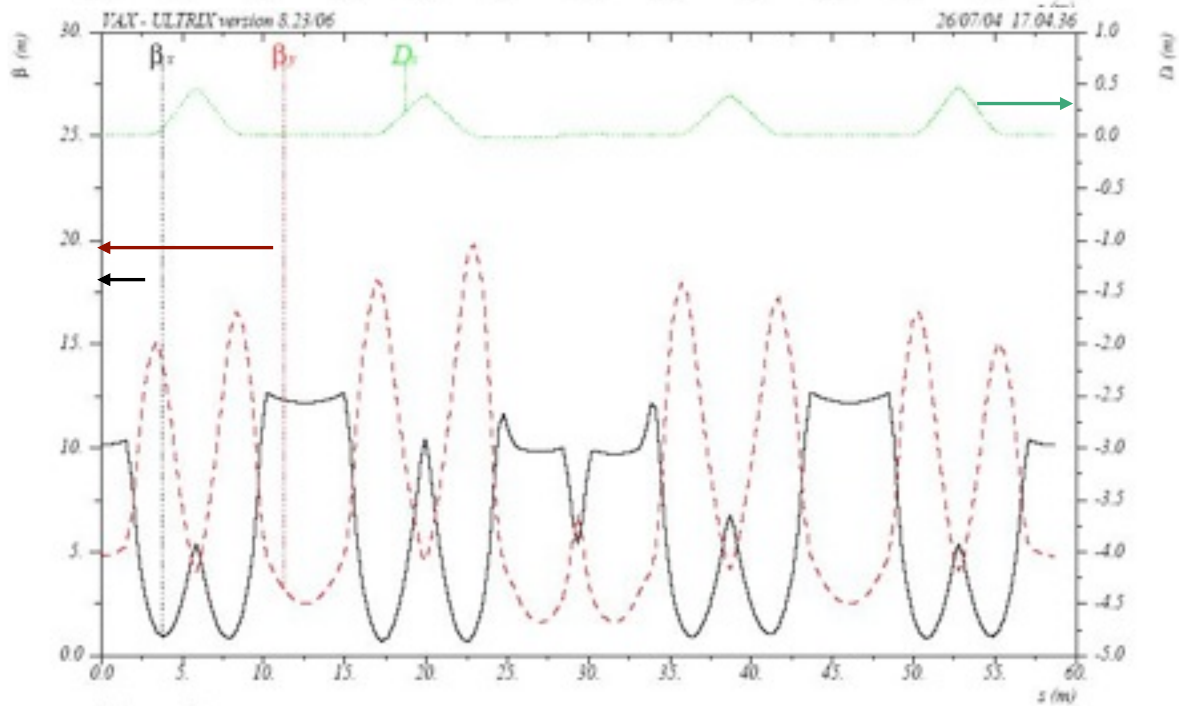
Chicane Optics



Baseline optics

matching straight, β_y = 4.8 m

long straight, β_y = 10 m



Chicane optics

matching straight, β_y = 2.5 m

long straight, β_y = 1.6 m

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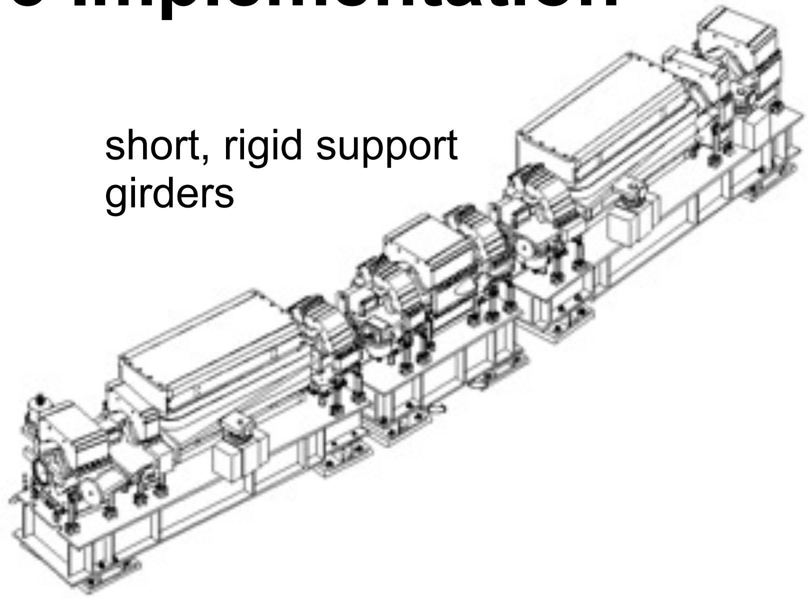
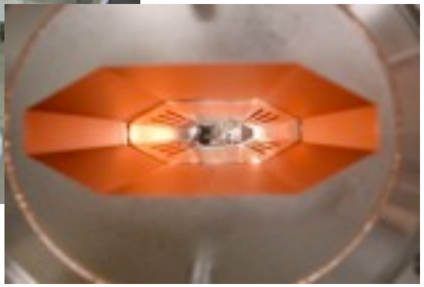
SPEAR 3 Implementation

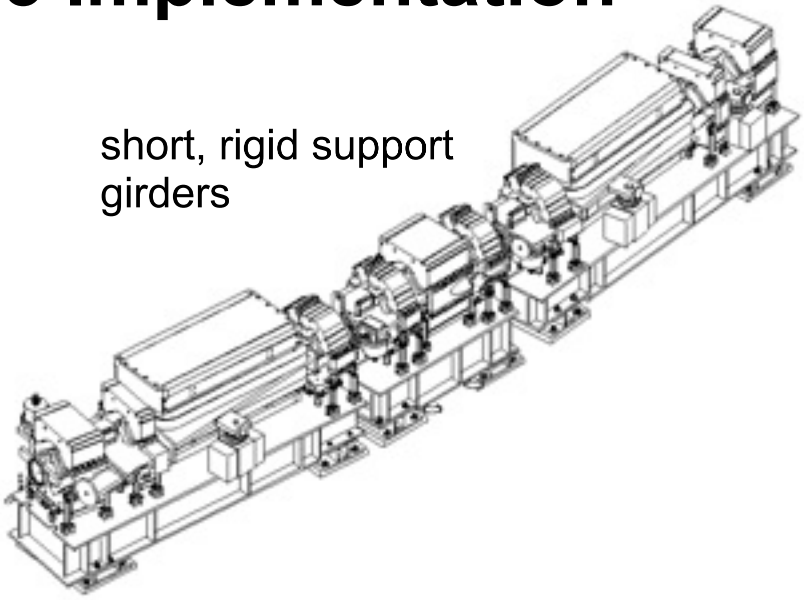
short, rigid support girders



SPEAR 3 Implementation

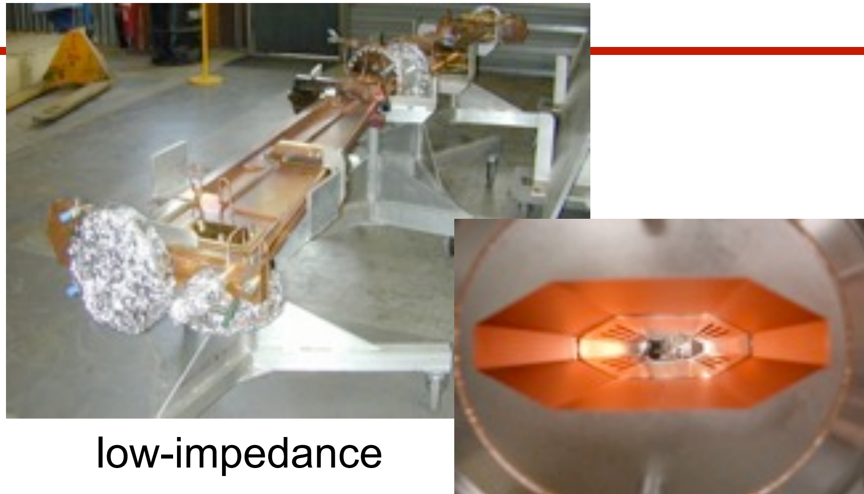


low-impedance chambers

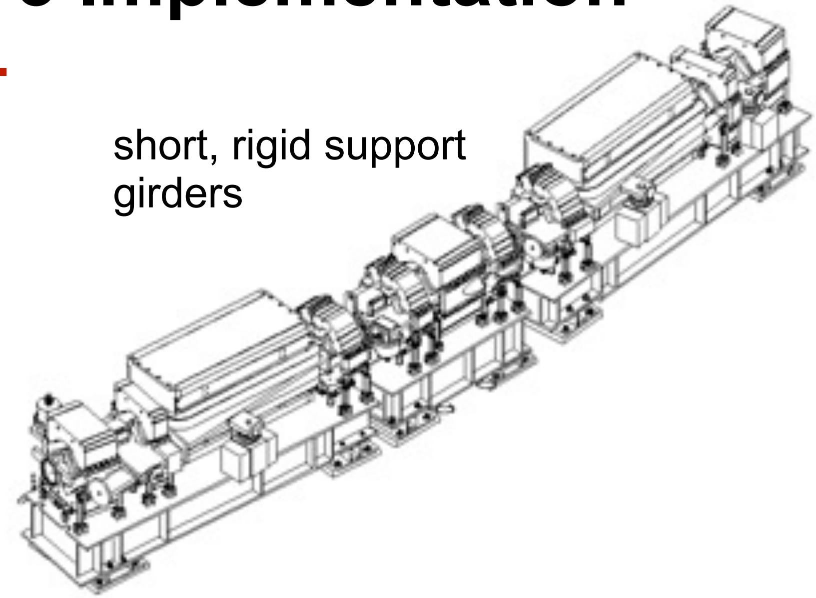


short, rigid support girders

SPEAR 3 Implementation



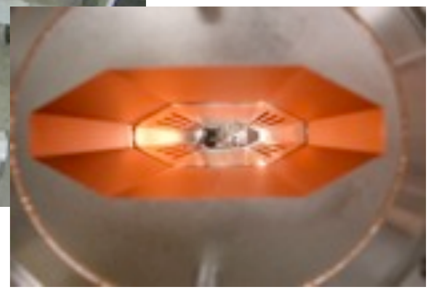
low-impedance
chambers



short, rigid support
girders

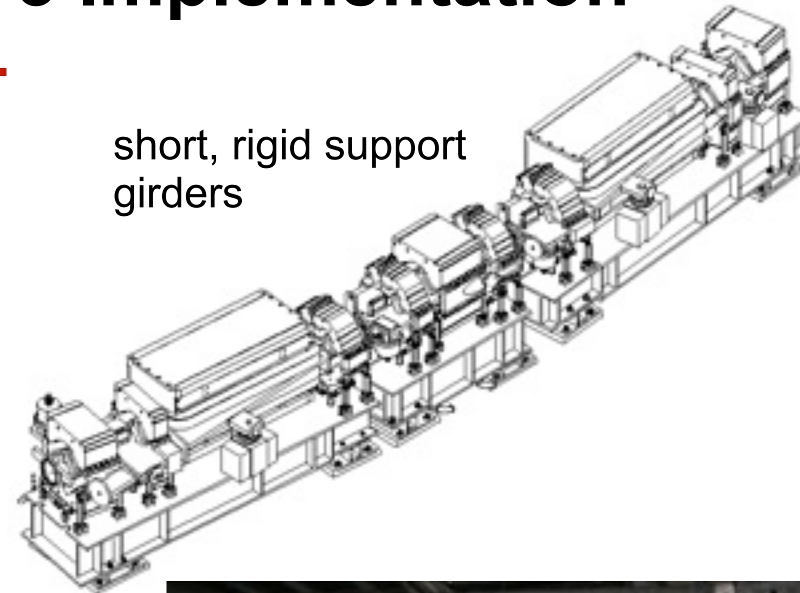
mode-damped rf
cavities

SPEAR 3 Implementation



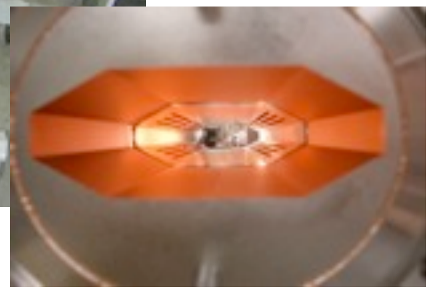
low-impedance chambers

short, rigid support girders



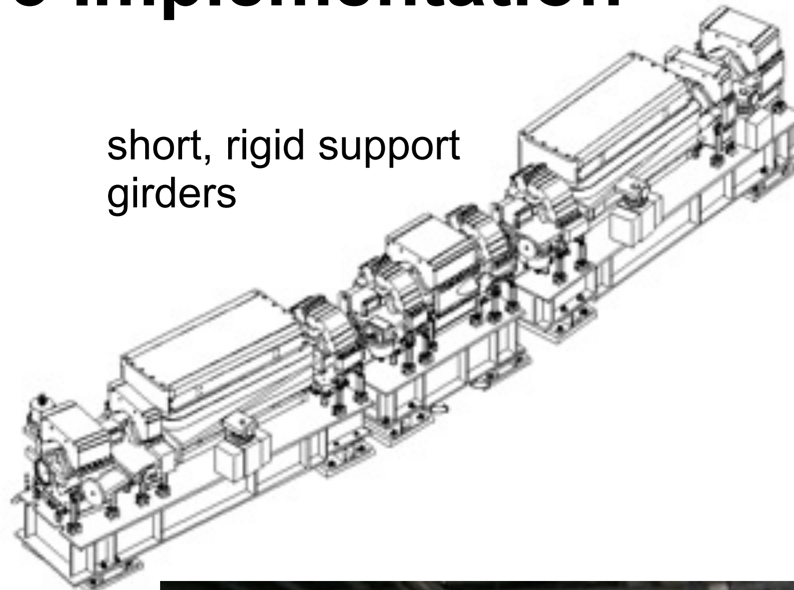
mode-damped rf cavities

SPEAR 3 Implementation



low-impedance chambers

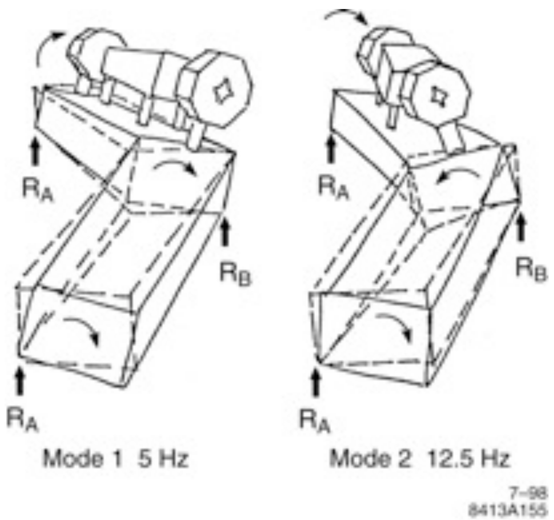
short, rigid support girders

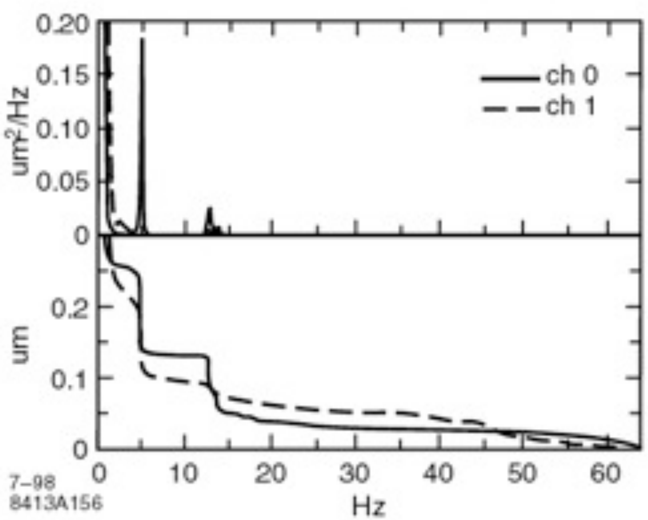


mode-damped rf cavities

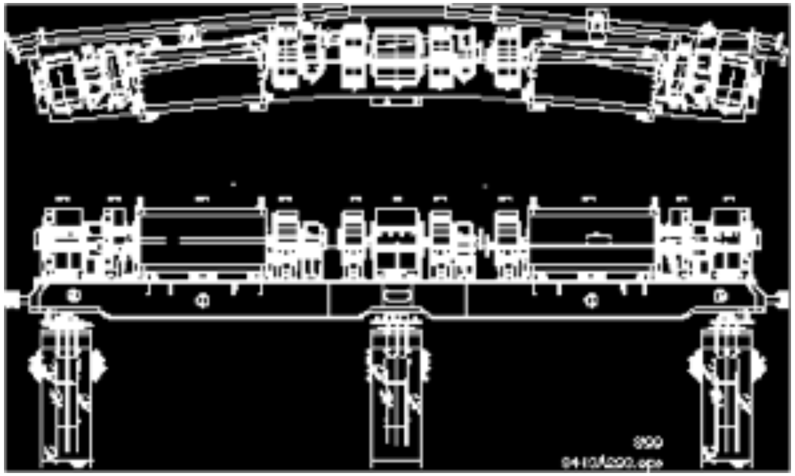
SPEAR 3 Magnet Girders

SPEAR2 girders:

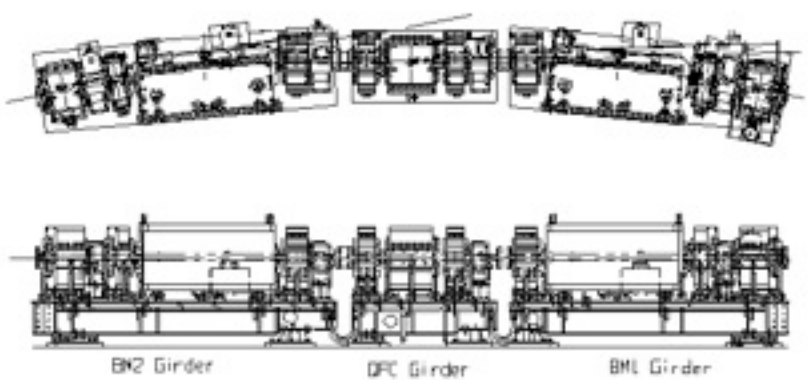




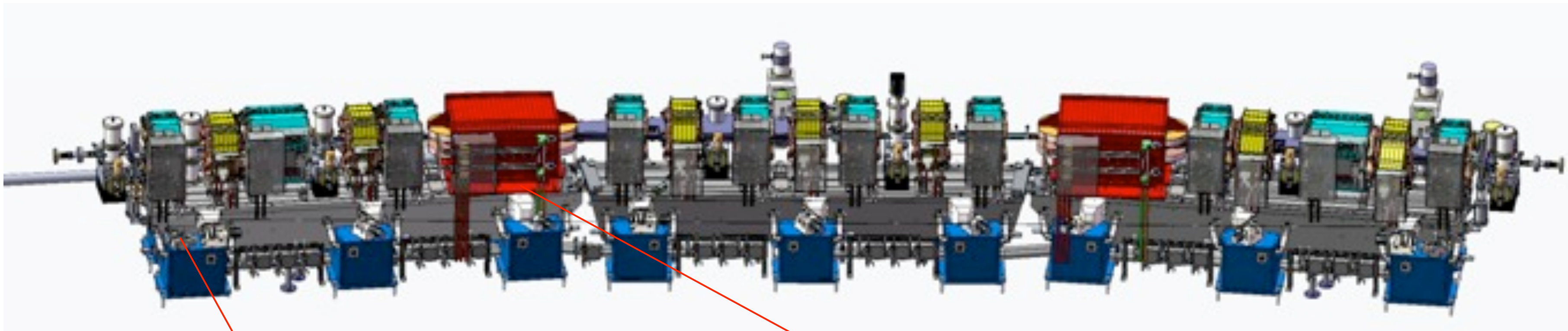
SPEAR 3 option 1:

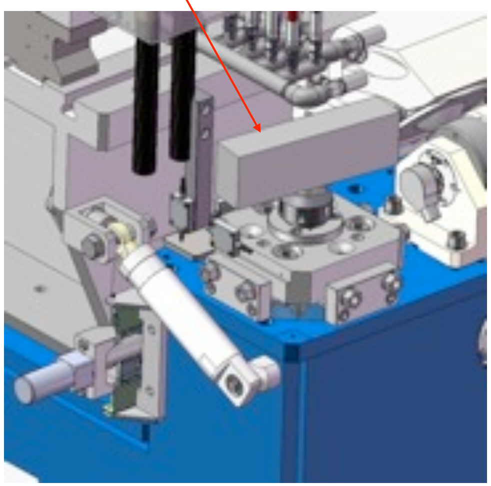


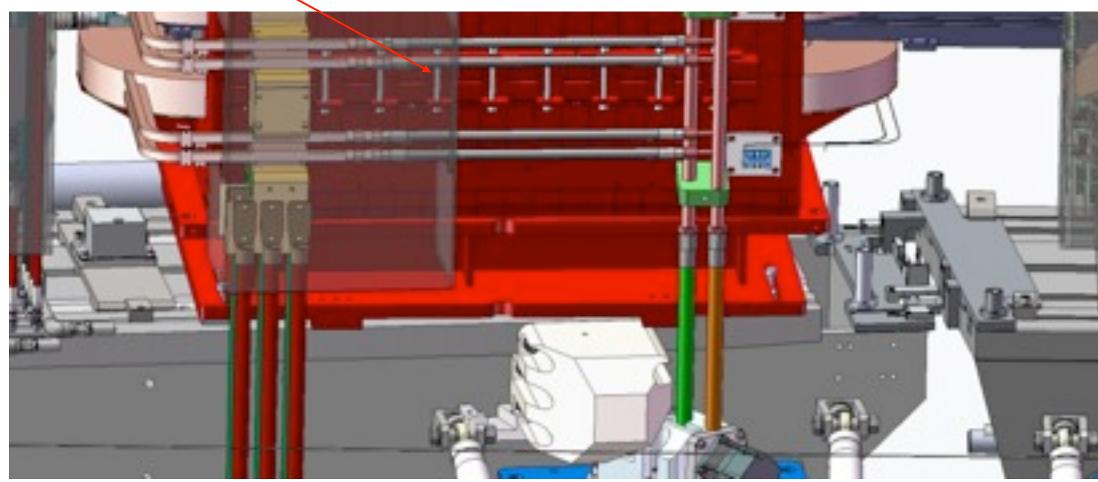
SPEAR 3 option 2 (selected, new concrete floor):



TPS Girder Mover System







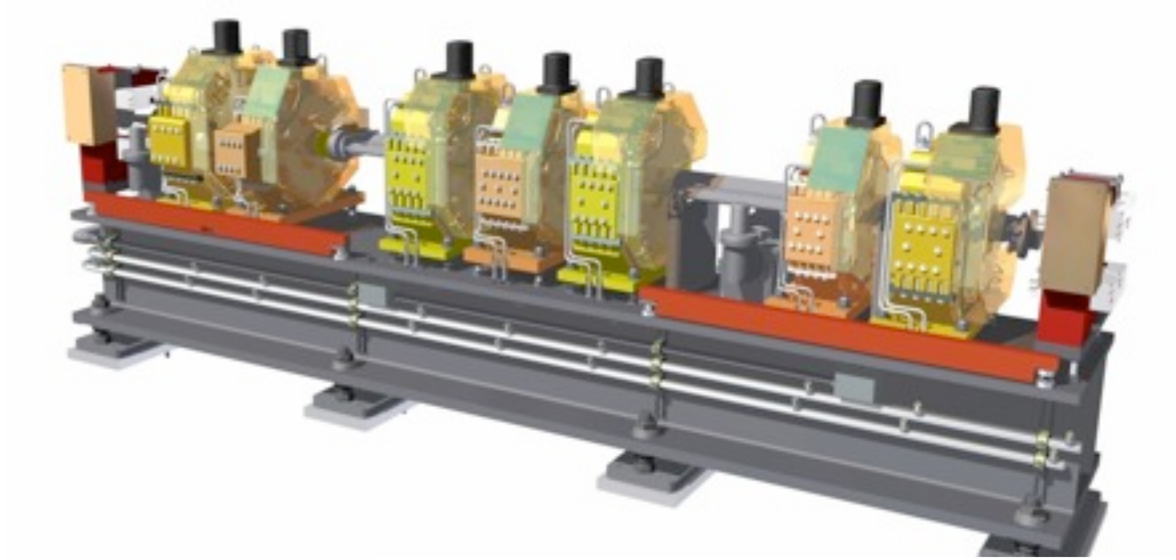
- The side pillar moved to the top of one pedestal to release clumsy space

- Tilting moved to the center area of girder for better reference
- Touching sensors adopting LVDT for cost down and small reference sockets on the sensor modules for better installation accuracy (<10μm)

NSLS-II and MAX-IV Magnet Girders

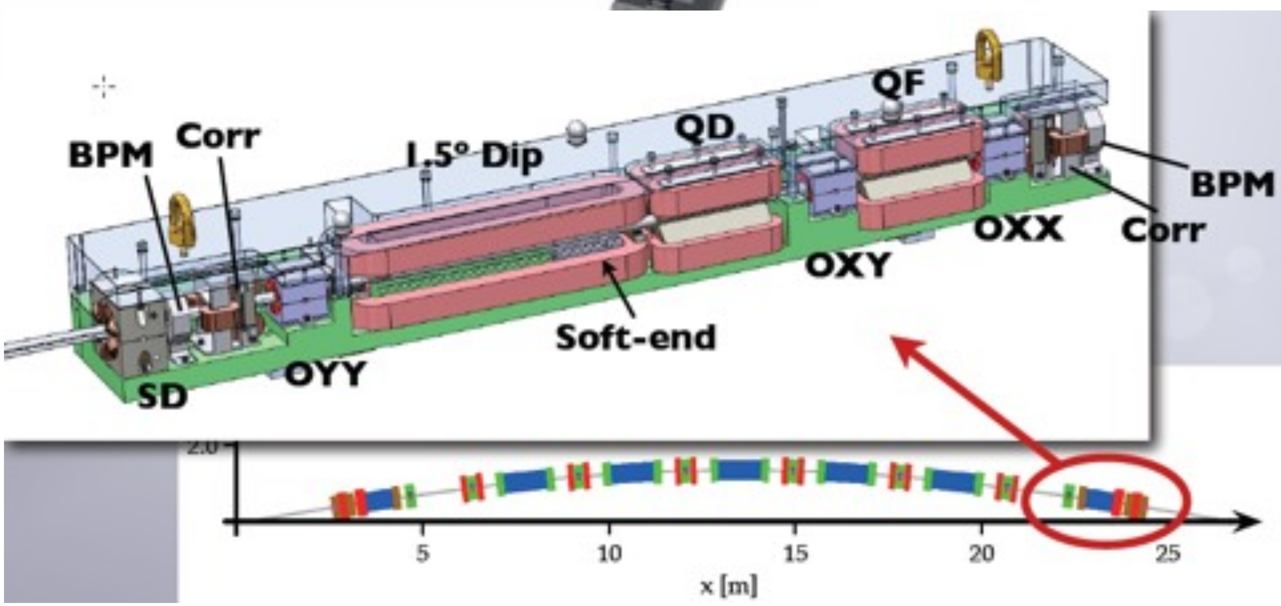
NSLS-II

NSLS-II and MAX-IV Magnet Girders



NSLS-II

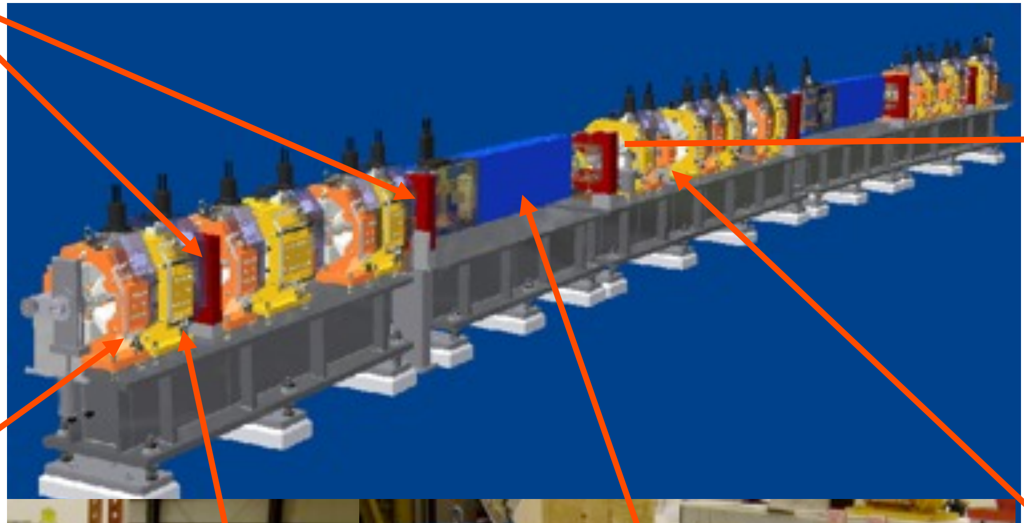
MAX-IV

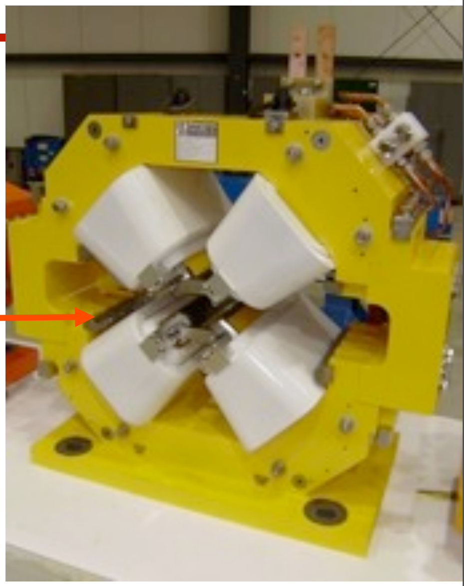


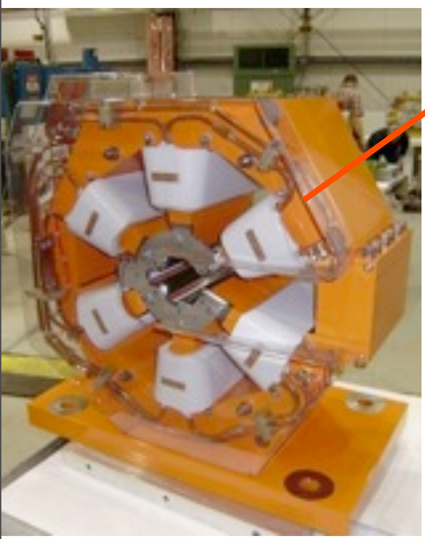
Magnet Types in a Typical Cell

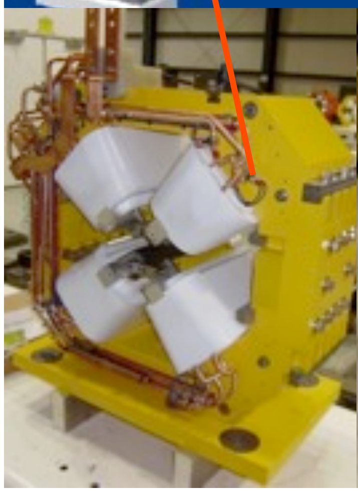
Correctors

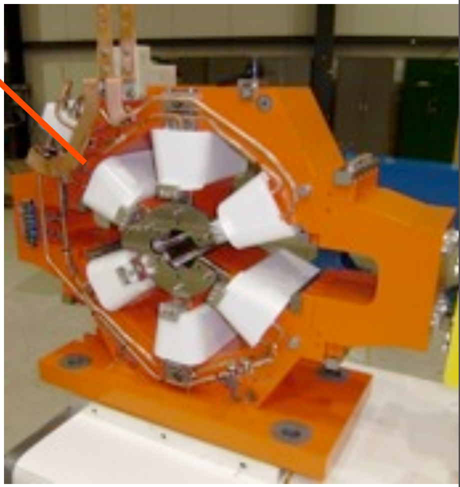
Wide Quadrupoles & Sextupoles to accommodate X-ray transport.











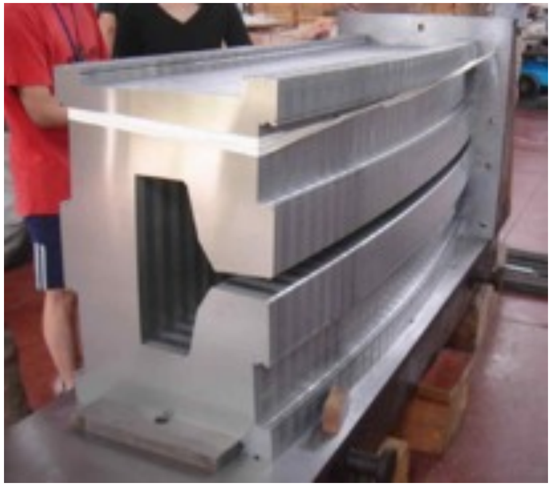
NSLS-II

Dipoles

Dipole Types

- Dipole - straight and curved (more expensive), depending on sagitta
- Gradient dipole (for compact lattices)
- Variable field dipole

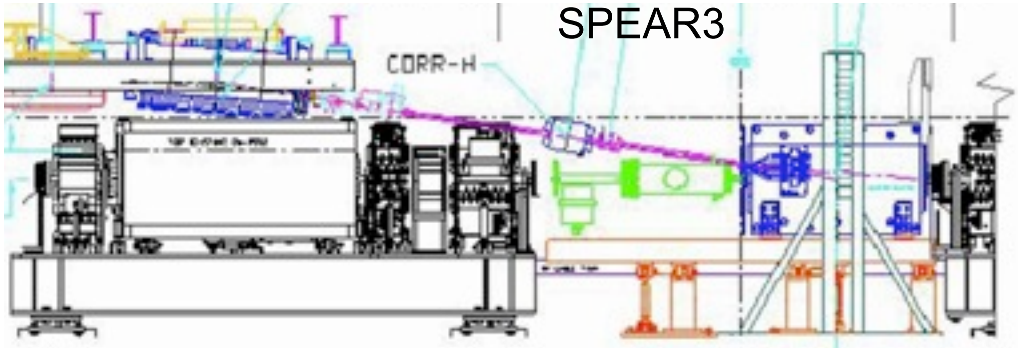
  e.g. LNLS2: low field permanent magnet, high field at beam line source point



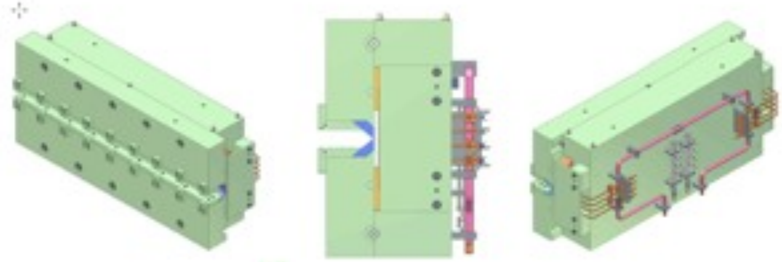
Injection Septum Magnets

- Vertical injection – Lambertson septum magnet

SPEAR3

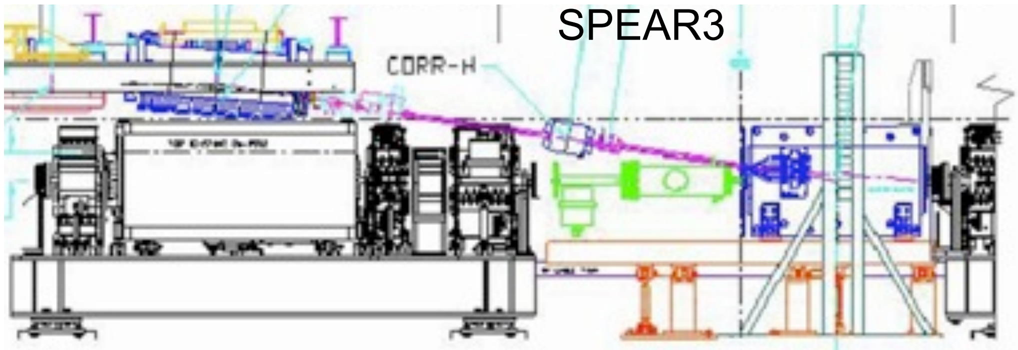


PLS-II septum magnet

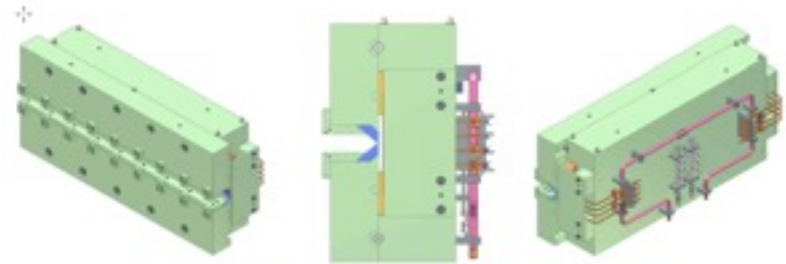


Injection Septum Magnets

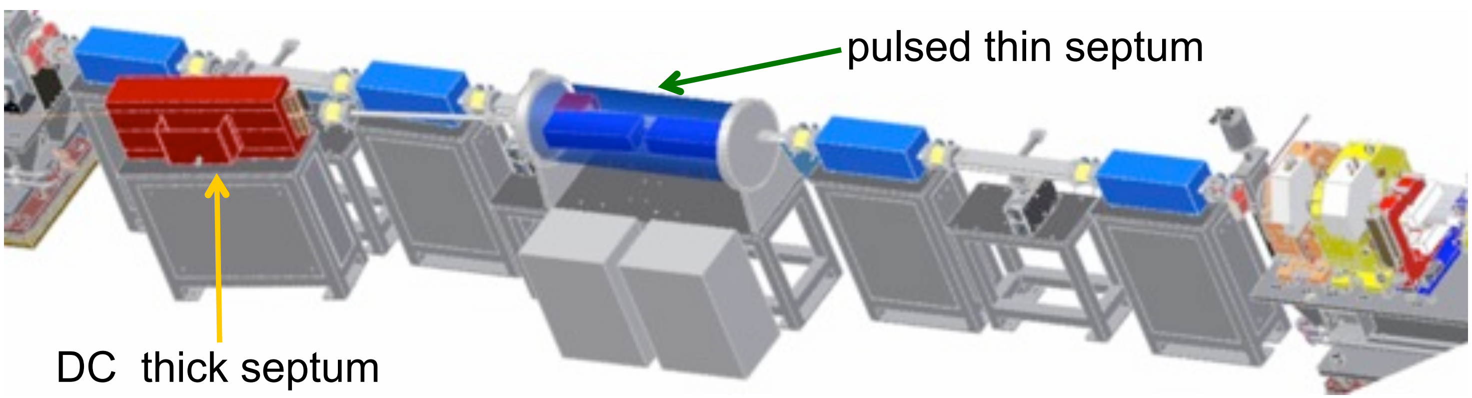
- Vertical injection – Lambertson septum magnet



PLS-II septum magnet

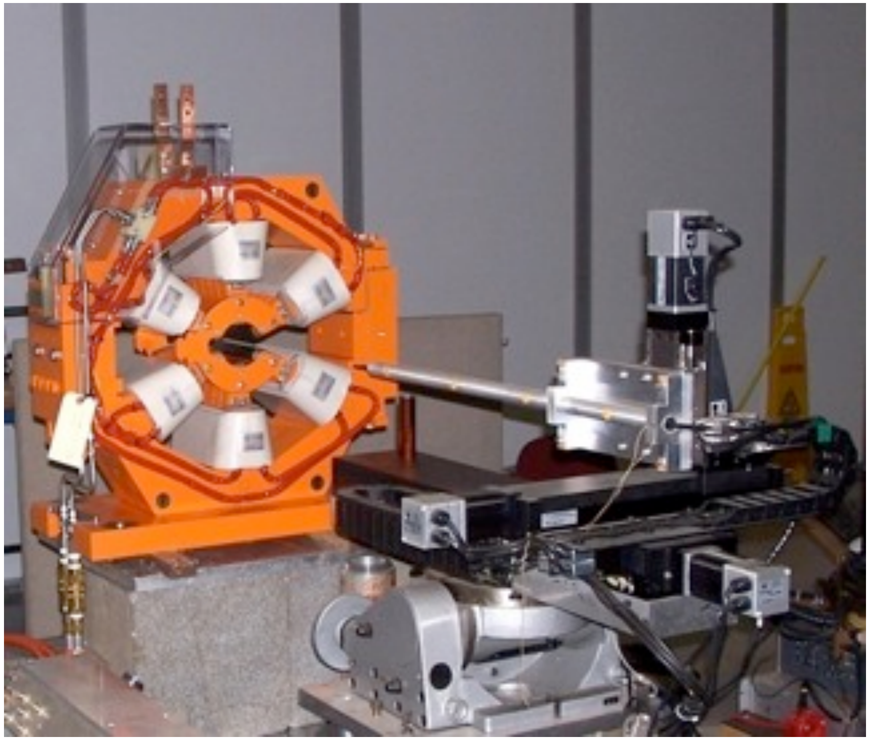


- Horizontal injection – thick and thin septa

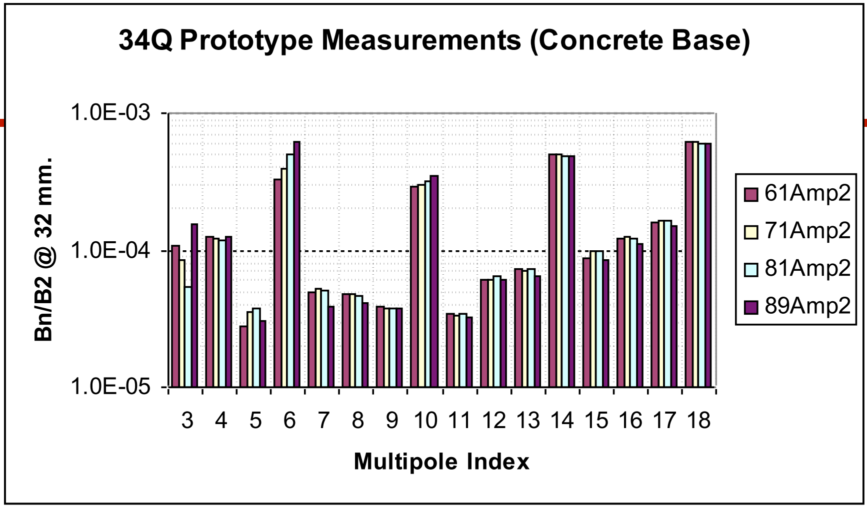


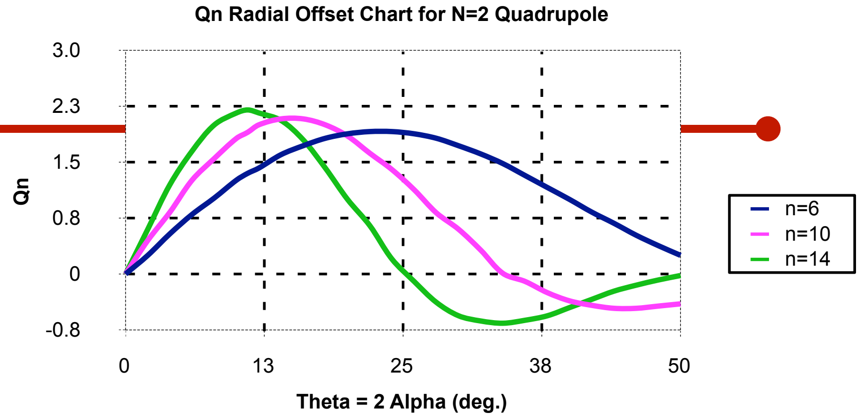
NSLS-II

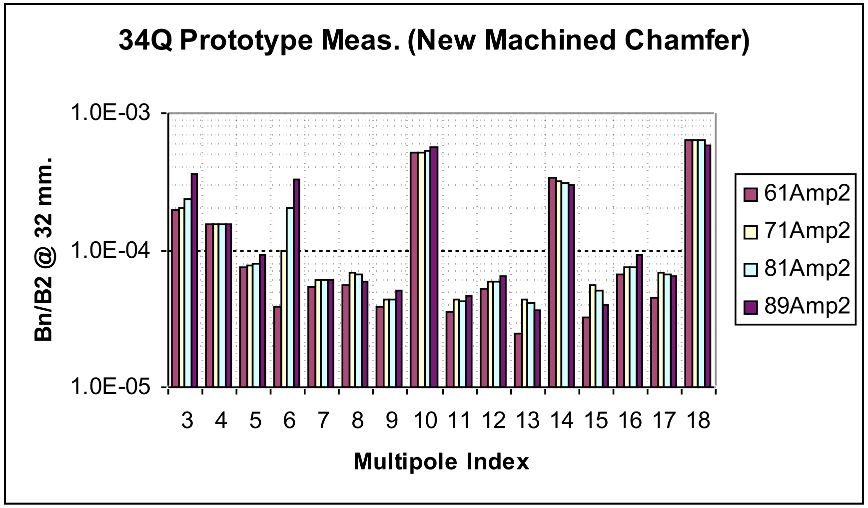
Magnetic Measurement



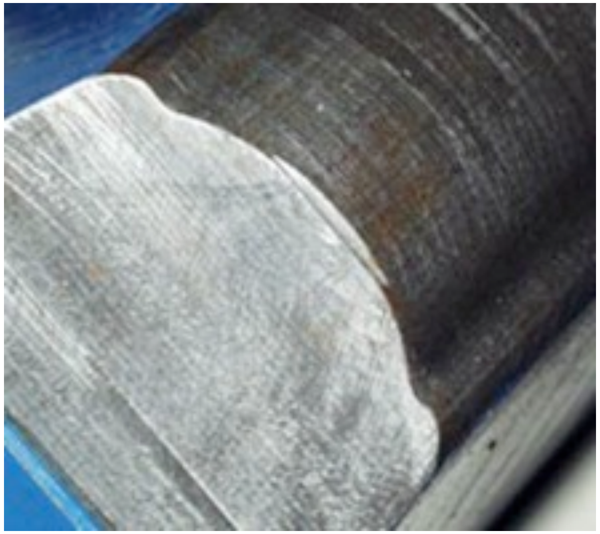
NSLS-II







A curve from **Klaus Halbach's** paper, *First Order Perturbation Effects in Iron-Dominated Two-Dimensional Symmetrical Multipoles*, published in *Nuclear Instruments and Methods – Volume 74 (1969) No. 1* is reproduced above. It describes the effects on the first three *allowed* multipole errors of radial offset portions of a pole for a quadrupole.



$$B(z) = \sum (B_n + iA_n) z^{n-1},\ z = x - iy$$

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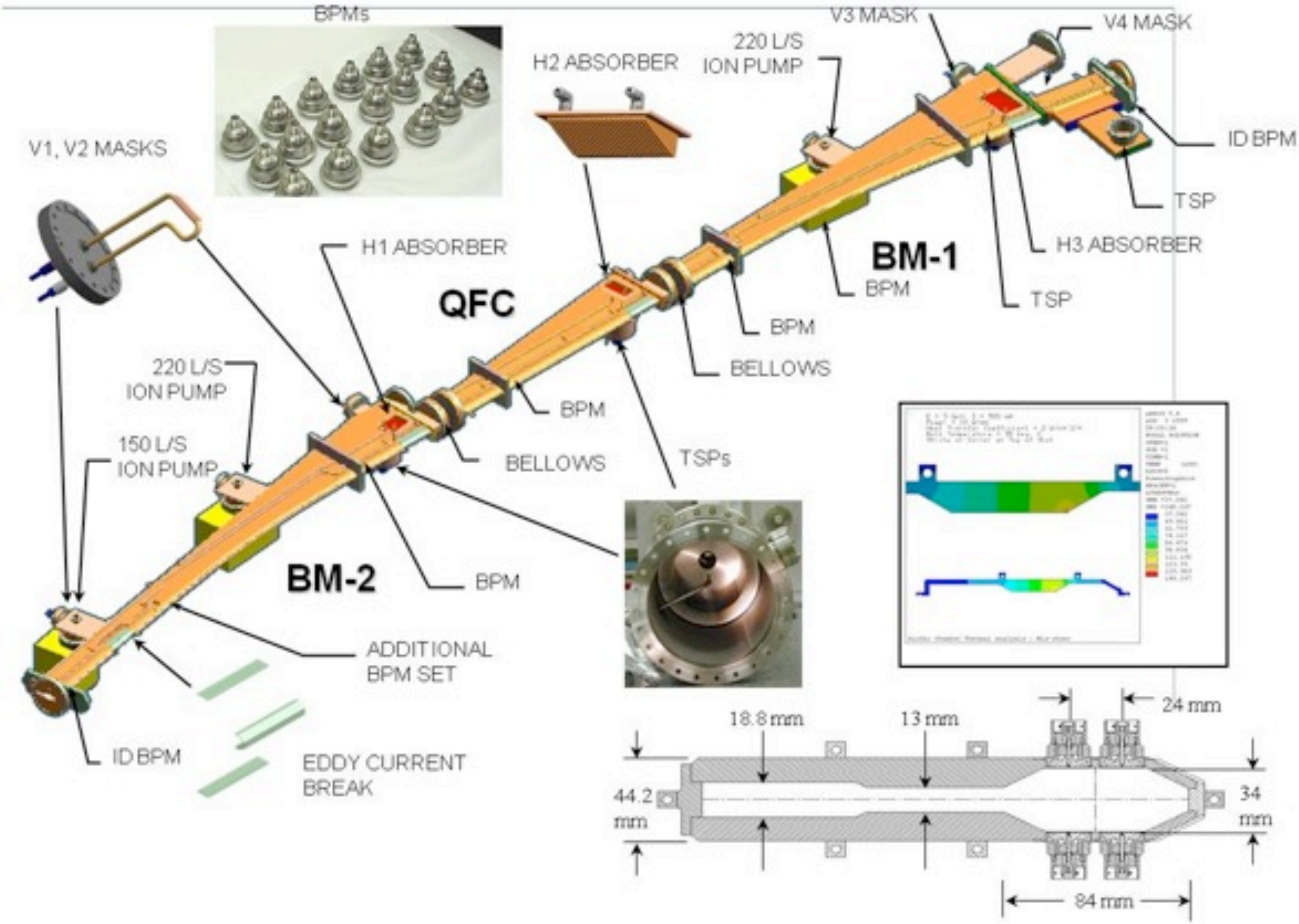
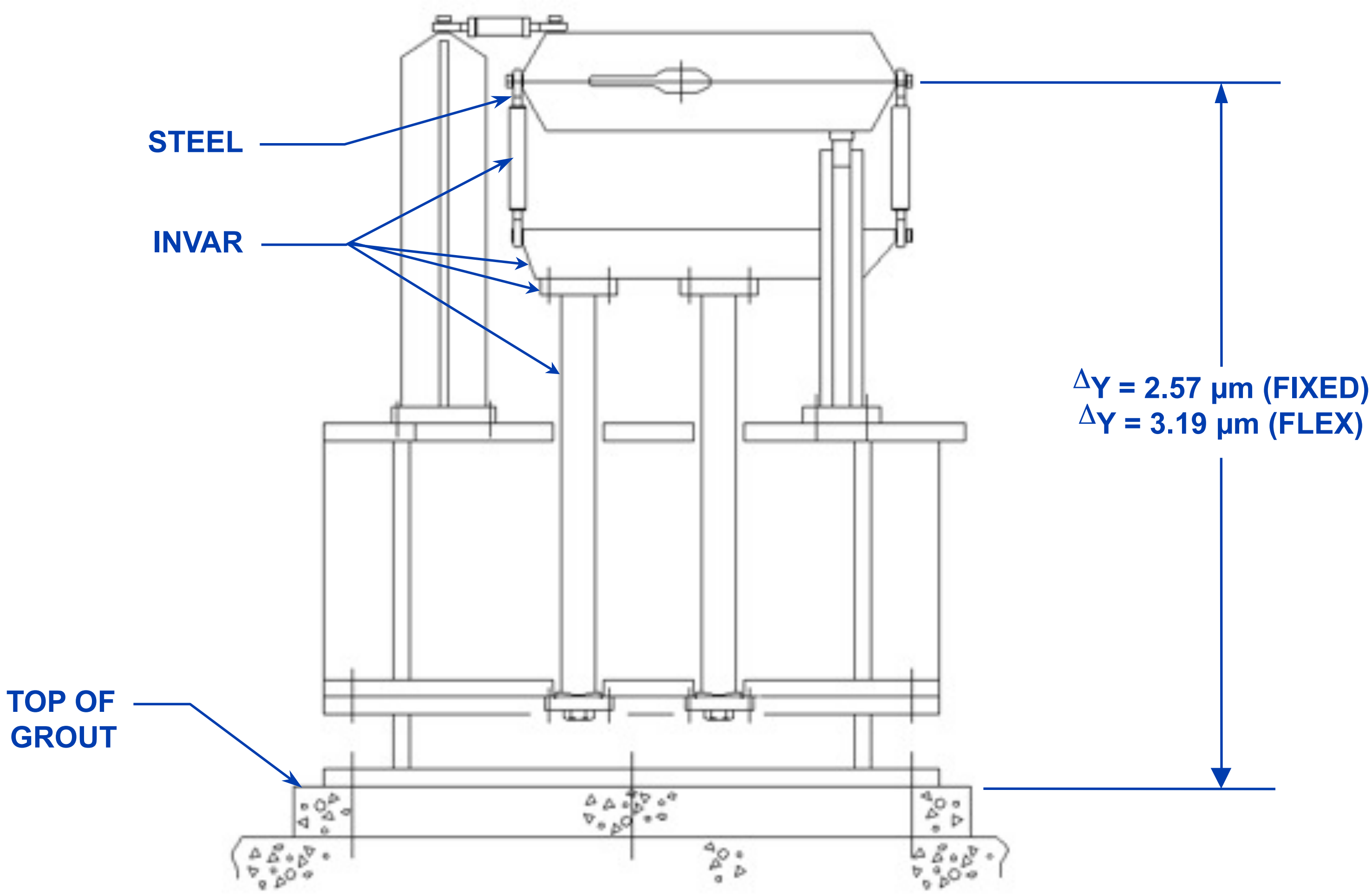
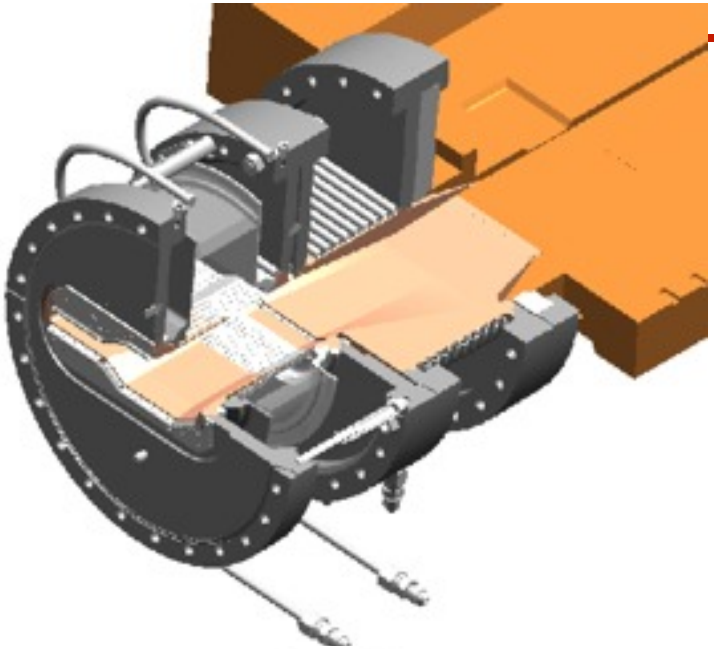
SPEAR3 Vacuum Chamber

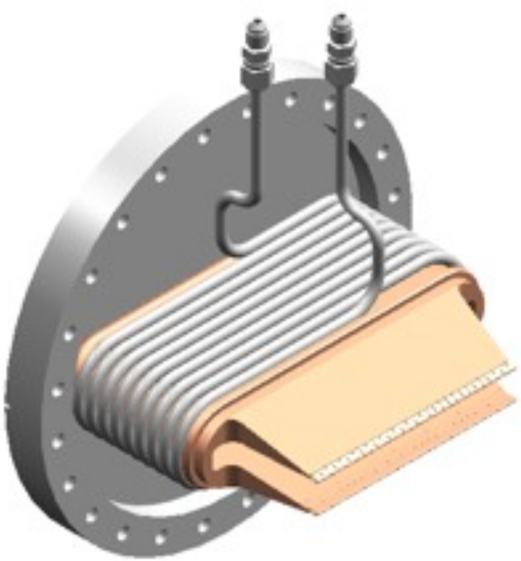


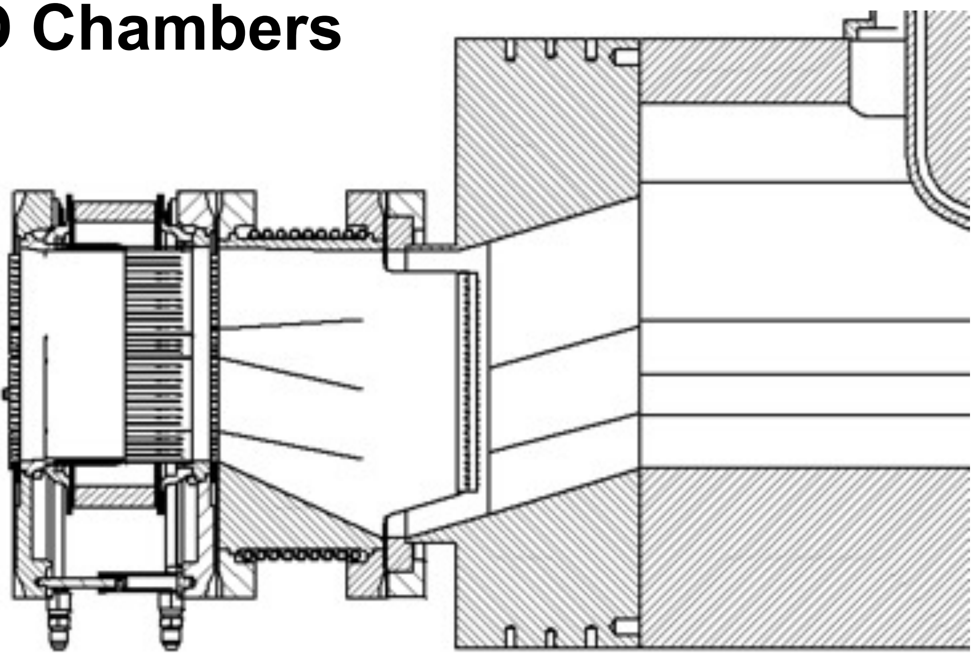
Stable BPM Supports

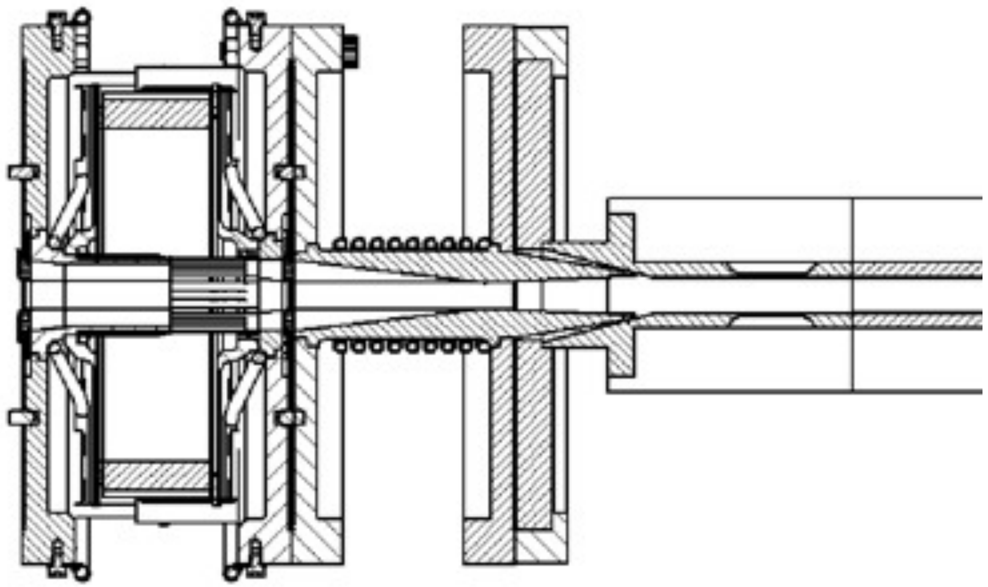


Transitions to Existing ID Chambers

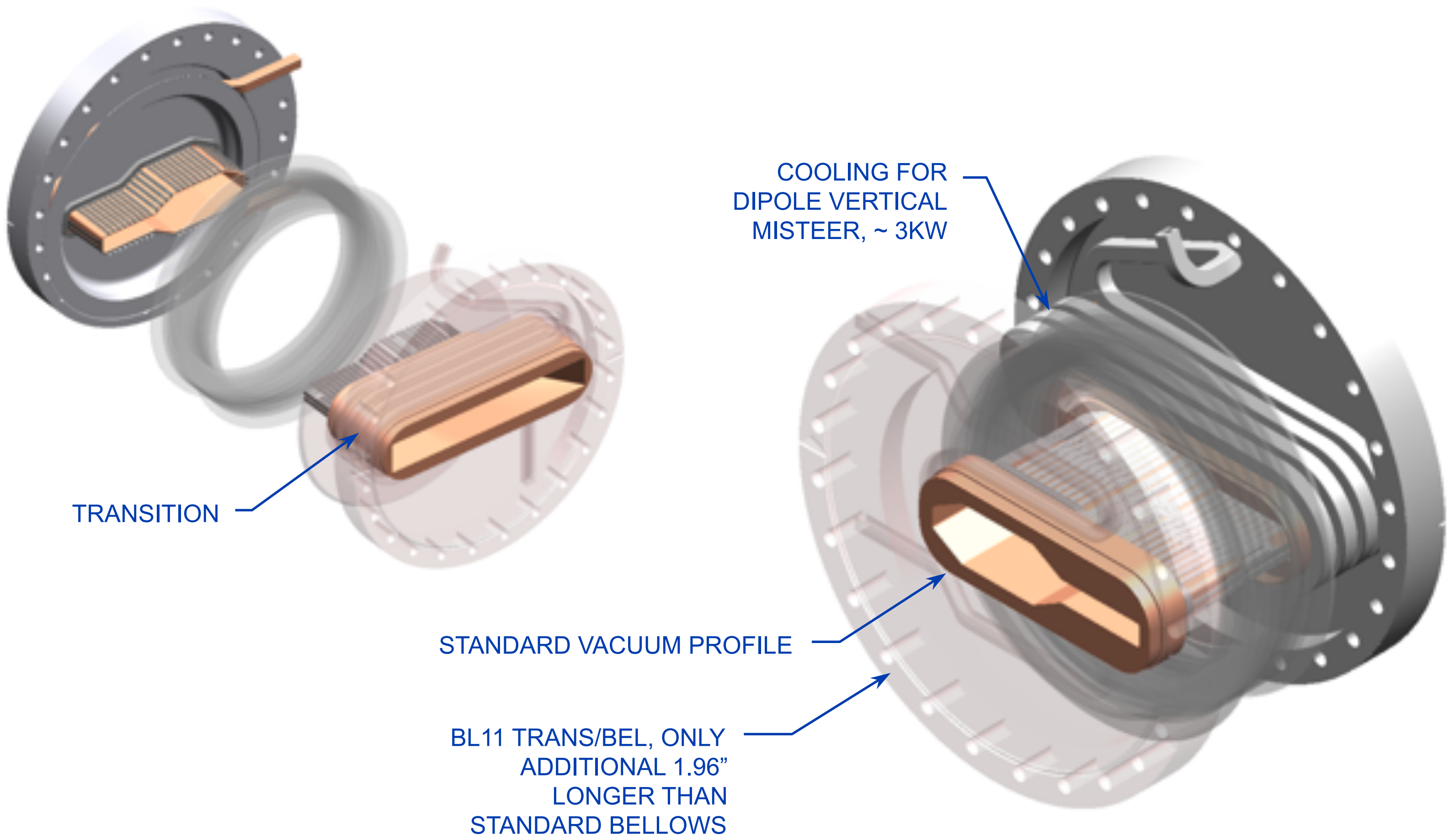








Shielded Bellows



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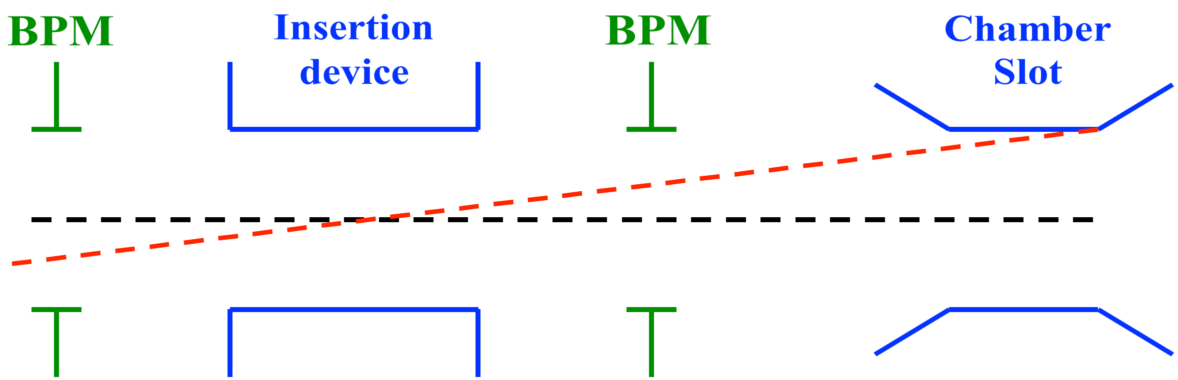
ID Mis-Steer Interlock



$$|\,y + y'L\,| < g/2 - \Delta_{mech.} - \Delta_{\sigma_y}$$

(y,y') = (position,angle) at center of ID

g **= 13 mm** $\Delta_{\mathbf{mech}}$ **= 1.5 mm** $\Delta\sigma_{\mathbf{y}}$ **= 2.2 mm**

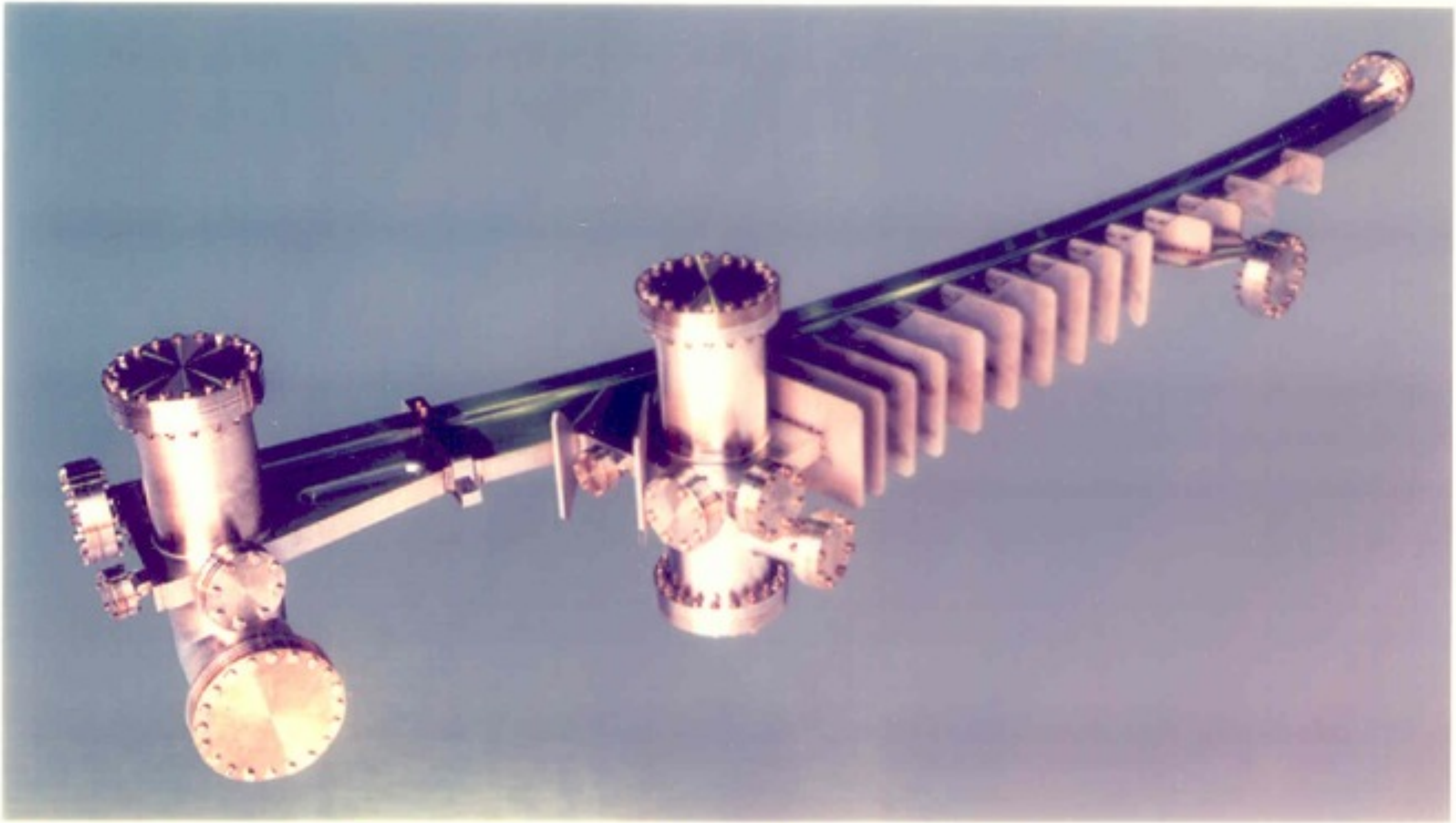
L **= distance at which photons exit slot = 3.9 m**

$$|\,y\,| + |\,y'\,|\,L < g/2 - \Delta_{mech.} - \Delta_{\sigma_y} \quad \Rightarrow \quad \frac{|\,y\,|}{\cancel{2.8}mm} + \frac{|\,y'\,|}{0.72mrad} < 1$$

2.4 mm (accounting for ID focusing)

Aluminum Vacuum Chamber – PLS-II

FMB Feinwerk- und Meβtechnik GmbH
Rudower Chaussee 6, Geb. 19.26/27
D-12484 Berlin (Germany)



Vacuum Chamber - Dipole and Sextupole (ANKA / Karlsruhe)
Radius (Dipol Chamber): 5559 mm
Total length: 2847 mm

Minimal Chambers: NEG-coated (MAX-IV)

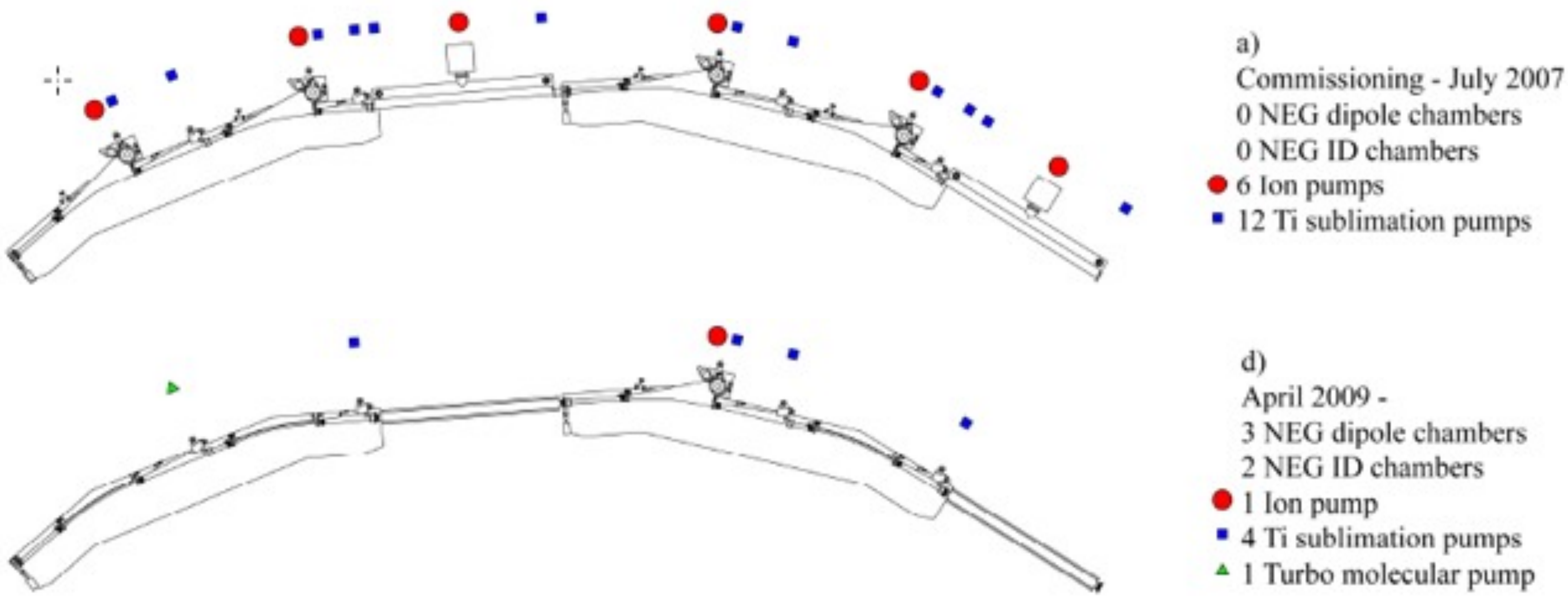
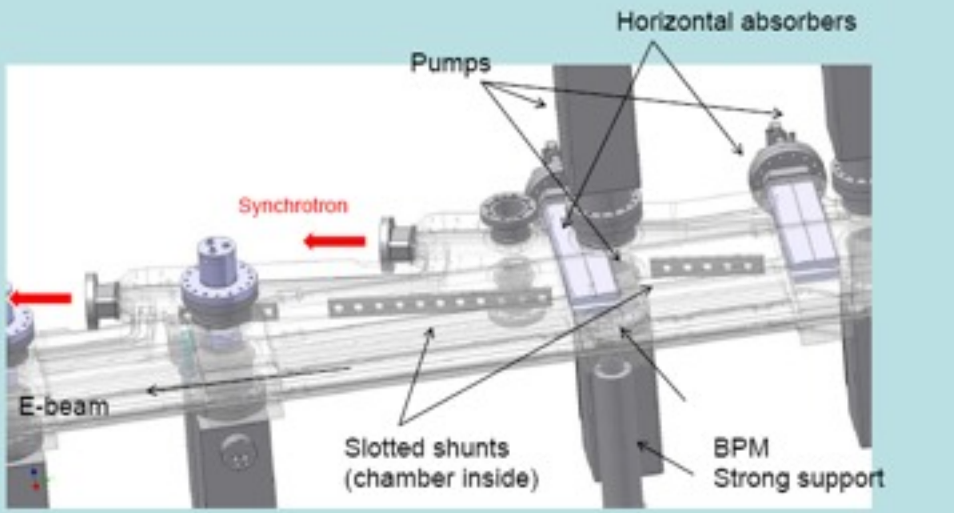


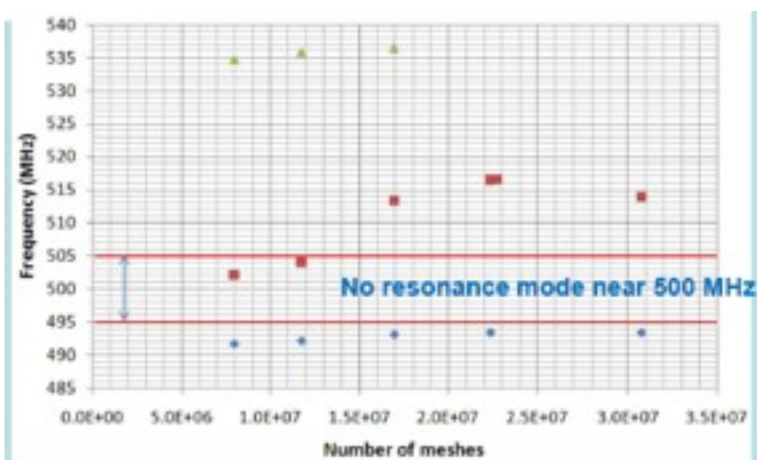
Fig. 1. (Color online) The vacuum system of cell 2 and cell 3 in the MAX II storage ring from a) commissioning to July 2007, b) July 2007 to July 2008, c) July 2008 to April 2009 and d) from April 2009 onwards.

Mitigation of Resonance Modes in Chamber – RF Shields

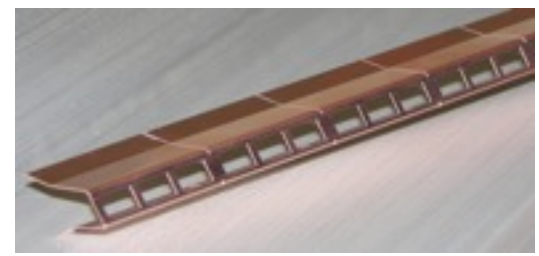
TE_{11} mode in wide chamber near BPM @ ~500 MHz processing frequency

- To increase the cutoff frequency, > 500 MHz
  - ✓ Slotted stiffeners are being installed to minimize conductance reduction





NSLS-II: flexible BeCu RF fingers with 50% of opening space



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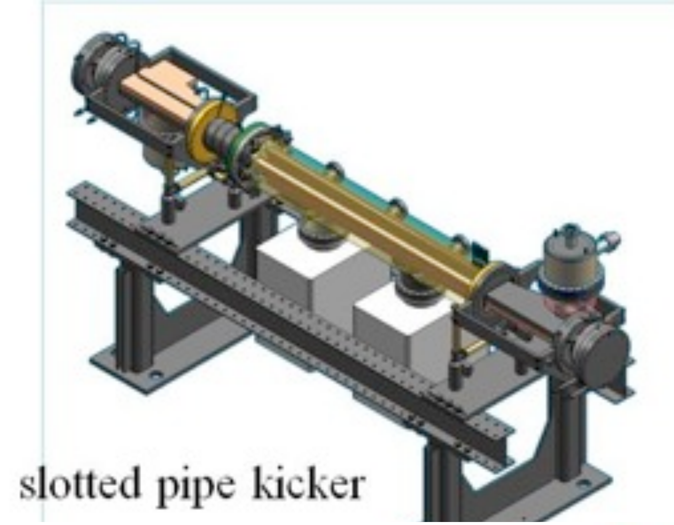
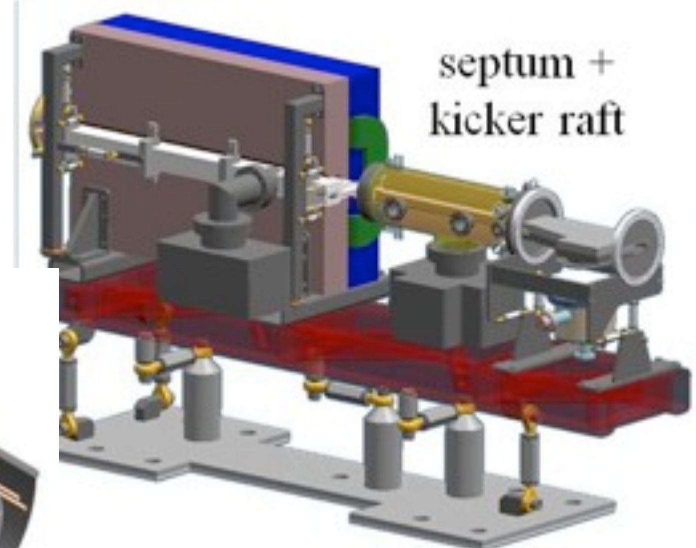
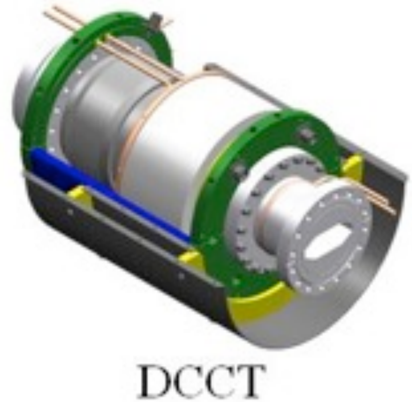
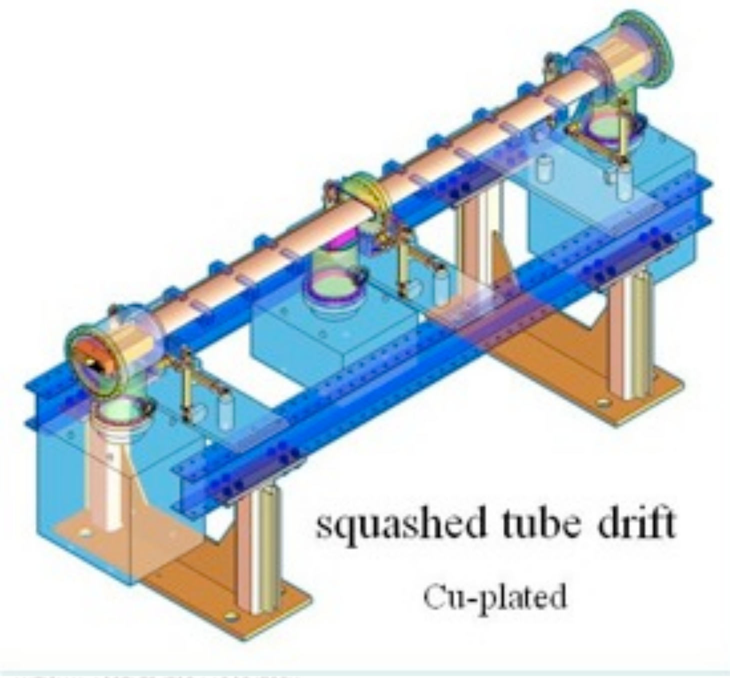
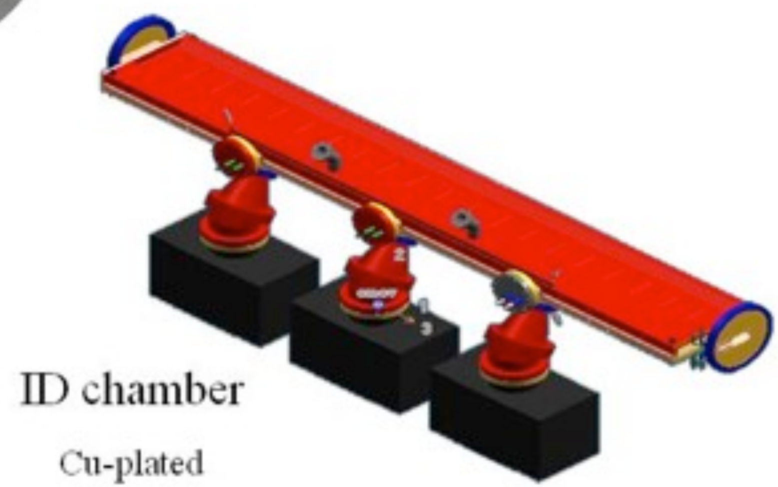
Straight Section Chambers





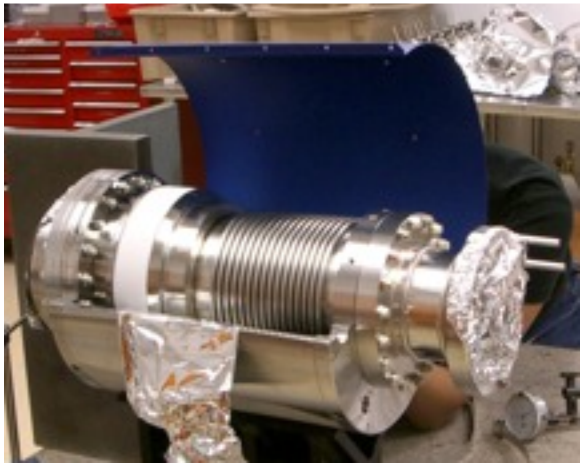


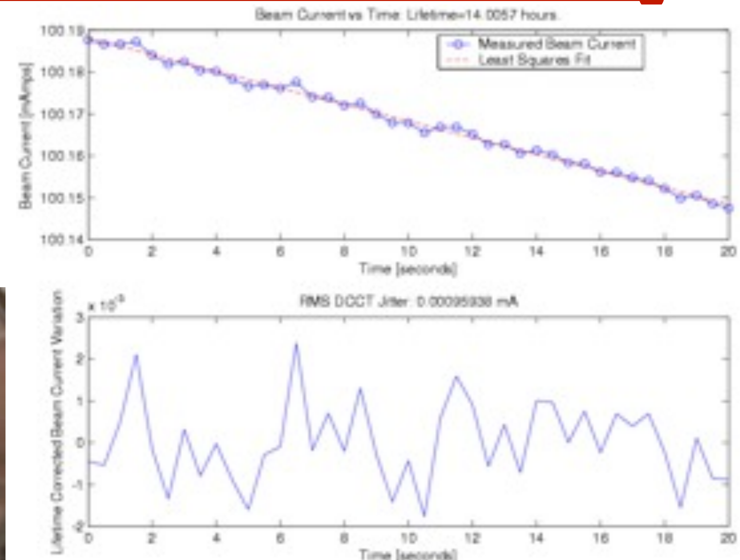




Diagnostics

- Bergoz DCCT, 1 μA in 1 second





0.5 second DCCT data

- Stripline tune driver

Tune measurement

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In-Flange DCCT: Bergoz NPCT


In-flange.NPCT with 96-mm aperture

NSLS-II Diagnostics Systems

Systems	NSLS-II			Vendor		
	SR	BTS	LTB	Booster	Linac	Gun
RF BPM – Single Pass		8	6		5*	
RF BPM – TBT & Stored Beam	180			37*		
ID RF BPM	2 or 3 per ID					
Fill Pattern Monitor (WCM)					3	2
Fill Pattern Monitor (FCT or SL)	1	2	2	1		
Faraday Cup		1	2			1
Beam Charge Monitor (ICT)		2	2			
Fluorescent / OTR Screen	3	9	9	6	6	
Energy Slit		1	1			
Photon BPMs	1 or 2 per ID					
Stored Beam monitor (DCCT)	1			1		
Tune Monitor	1			1		
Top-Off Monitor	2					
X-Ray Diagnostics (BM-A Source)	1					
X-Ray Diagnostics (3PW Source)	1					
VSLM Diagnostics (BM-B Source)	1			1		
Transverse Feedback (H & V)	1+1					
Beam Loss Monitors	TBD					
Beam Scrapers (H & V)	3+2					

*NSLS-II provides BPM Electronics

Power Supplies

large power supplies

intermediate supplies (10-15 kW)

bipolar power supplies

30 A bipolar supply crate

dipole choppers (1

AC motor control center

BT kicker pulser (15 kV)

RF HVPS (15 kV)

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Power Supplies – NSLS-II

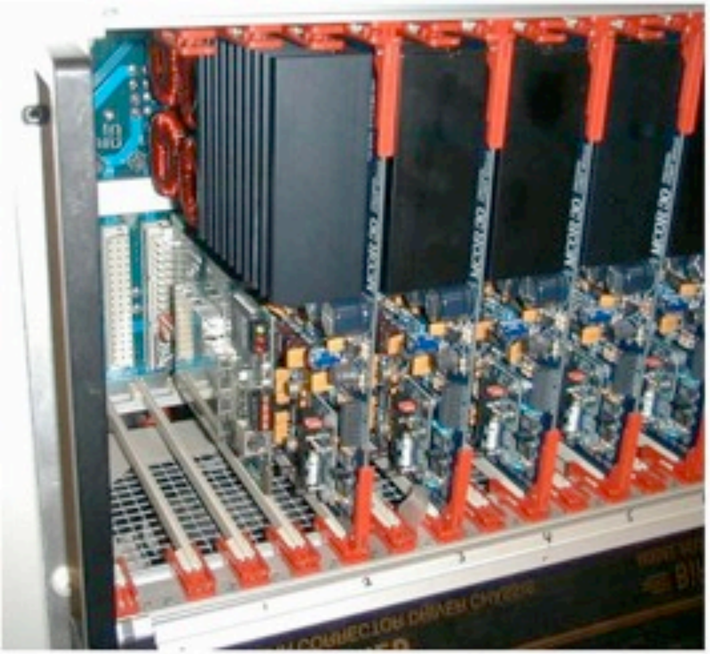
Power Supply -Model	Qty	Max. Voltage	Max Current	Configuration	Stability / Resolution ppm of max I	Operation
Main Dipole	1	1200 V	450 A	Unipolar Switch-Mode , Digital Regulator center point tied to GND	25 3.8	DC 1 Quadrant
Quadrupole -A -B -C -D	60 120 60 60	16 V 22 V 30 V 30 V	175 A 175 A 175 A 200 A	Unipolar Switch-Mode Analog Curr. Regulator – 2 DCCTs 1 PS per Magnet	50 3.8	DC 1 Quadrant
Sextupole -A -B -C	40 5 12	40 V 60 V 16 V	120 A 165 A 120 A	Unipolar Switch-Mode Analog Curr. Regulator- 2 DCCTs Model A & B = 1 PS per 6 Magnets Model C = 1 PS per 2 Magnets	100 15 (3.8)	DC 1 Quadrant
Global Horz. & Vert. Correctors -A	90	24 V	1.25 A	2 Channel Bipolar Linear Analog Curr. Regulator - 4 Shunts	100 15 (3.8)	2000 Hz 4 Quadrant
Insertion Horz. Correctors -B	12	30 V	30 A	Unipolar Switch-Mode Analog Curr. Regulator – 2 DCCTs	50 3.8	DC 1 Quadrant
Skew Quad Corrector-C	30	20 A	20 A	Bipolar Linear Analog Curr. Regulator – 2 DCCTs	100 15 (3.8)	DC 4 Quadrant
Alignment Horz. & Vert. Correctors -D	180	25 V	22A	2 Channel Bipolar Linear / Pre-Regulator Analog Curr. Regulator - 4 DCCTs	25 3.8	3 Hz 2 Quadrant
Dipole Trim – Corrector -E	27	15V	4 A	2 Channel Bipolar Linear / Pre-Regulator Analog Curr. Regulator – 4 DCCTs	100 15 (3.8)	DC 4 Quadrant
Dipole Trim – Corrector -F	3	20 V	10 A	2 Channel Bipolar Linear / Pre-Regulator Analog Curr. Regulator – 4 DCCTs	100 15 (3.8)	DC 4 Quadrant

There is a total of 997 power supply channels used for the NSLS-II storage ring

Magnet family power supplies: “strings” vs. individual

- Quadrupoles need individual tuning to correct for ID focusing effects
- Quadrupole modulation is desired for beam-based alignment and BPM calibration (trim coils can be used for series-powered families)
- Recent studies show that best dynamic aperture may be reached with independently tuned sextupoles (normally powered in families)
- Individual power supplies + cabling usually cost more than strings, but this cost difference can be reduced with modular power systems and short cable distances

Fast Corrector Power Supplies - SPEAR3



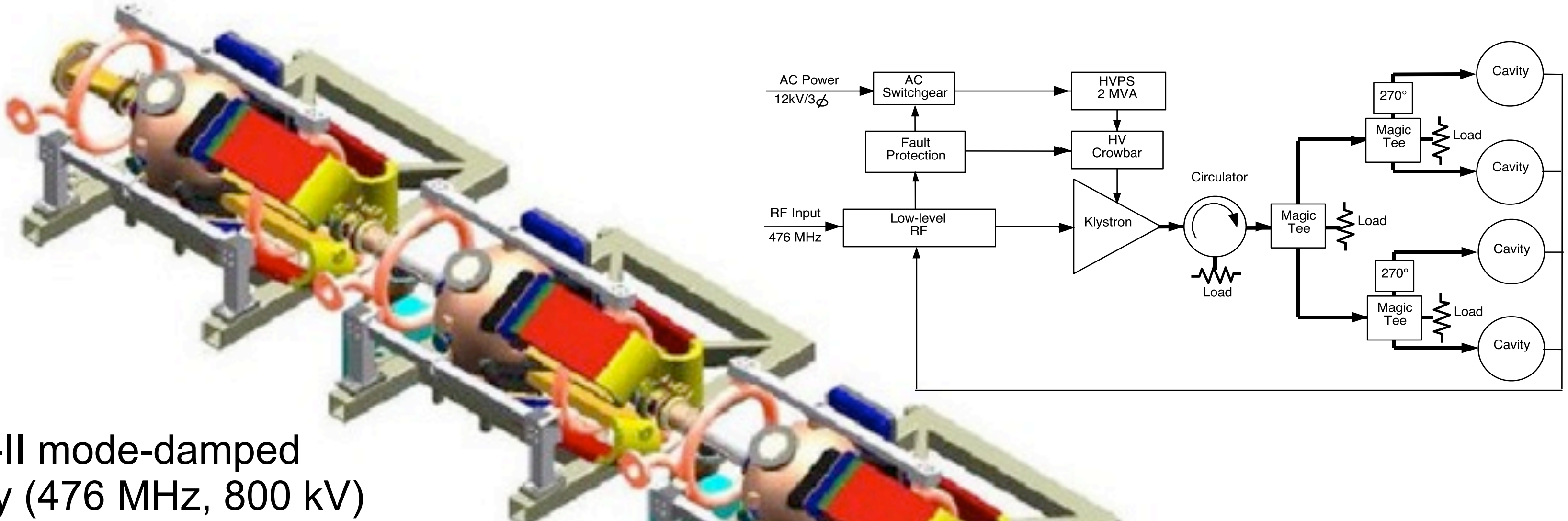
MCOR 30 crate

MCOR 30 and controller daughter card

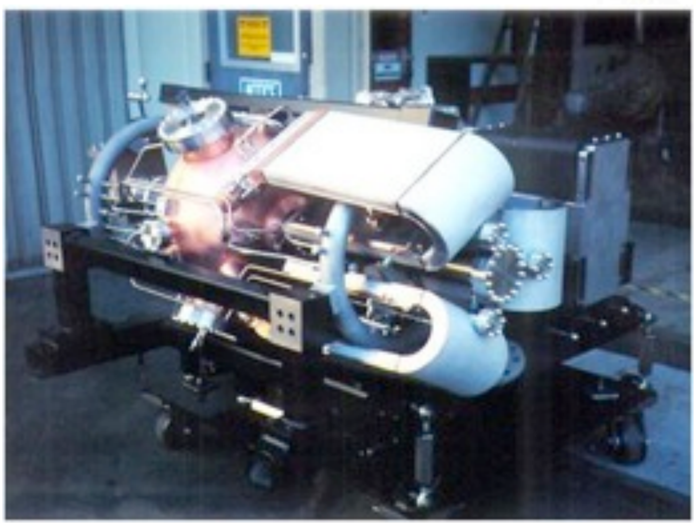
rear panel Frankenbride board

MCOR control Frankenboard + VME CPU

SPEAR 3 RF System



PEP-II mode-damped
cavity (476 MHz, 800 kV)



SPEAR 3 RF System - cont

circulator

waveguide network

installed cavities

low level RF control

SPEAR 3 RF System - cont

circulator

waveguide network

installed cavities

1.2 MW klystron

low level RF control

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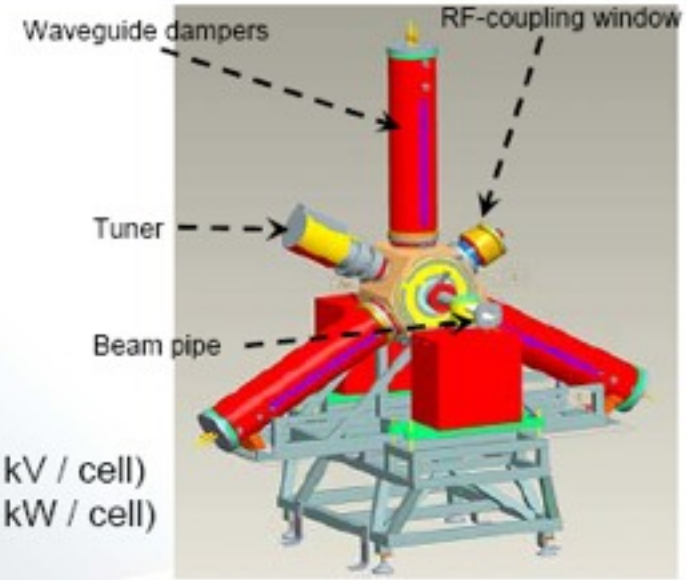
ALBA Mode-damped RF Cavity

ALBA RF

RF Cavity

f	499,654	MHz
Q_0	27000	
Rshunt	3.1	MΩ
R/Q	115	Ω
Cavity power	60	kW
Beam power/cav	87	kW
IPC power	147	kW
Type of cavity	nc (6 Cells/IPC)	
Total Voltage	**3.6**	**MV** (600 kV / cell)
Total Power	**960**	**kW** (160 kW / cell)



- The Call for Tender process is starting now. A prototype with improvements respect the original BESSY design will be first produced.
- A SC third harmonic cavity is planned

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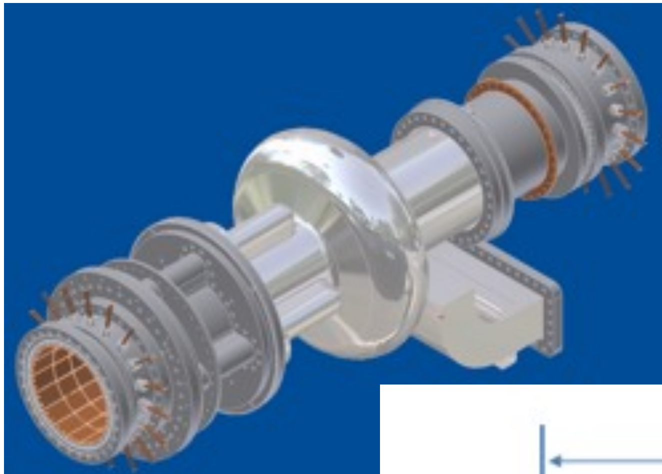
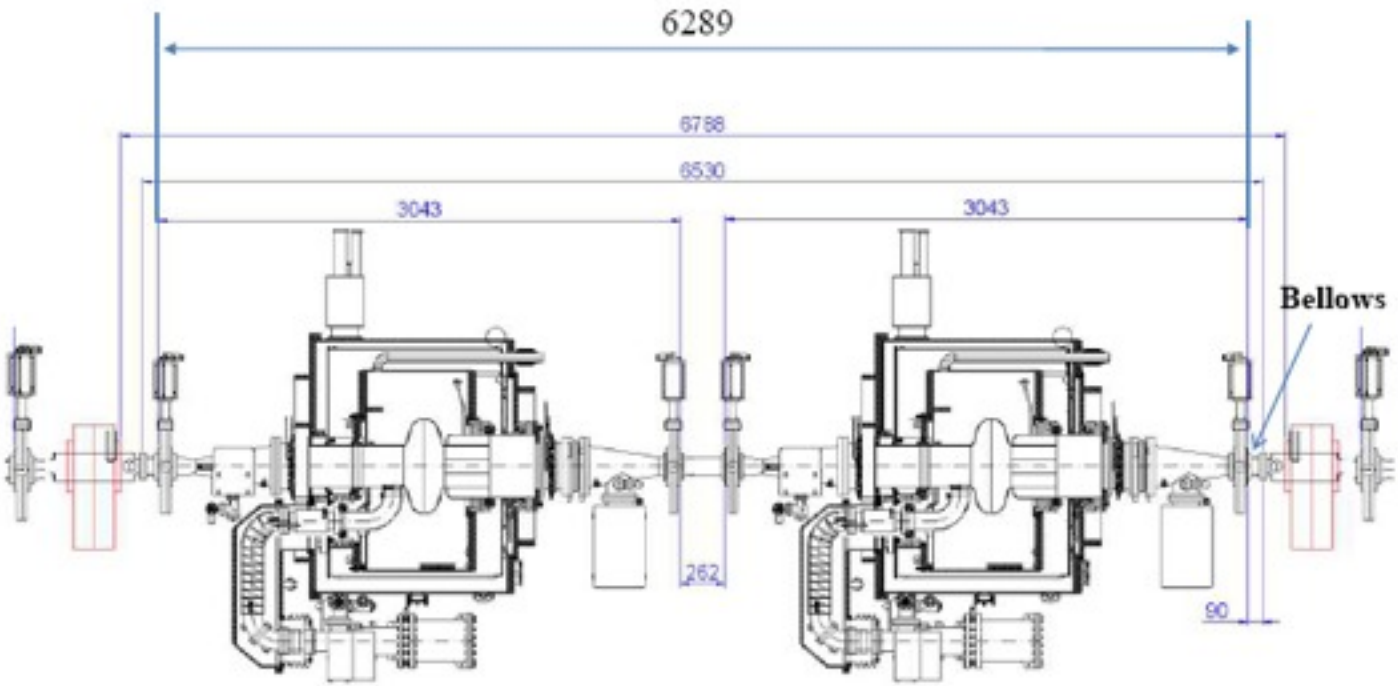
Superconducting RF Cavity



~1.5 MV/cavity



Two CESR-type cryomodules in a long-straight section.

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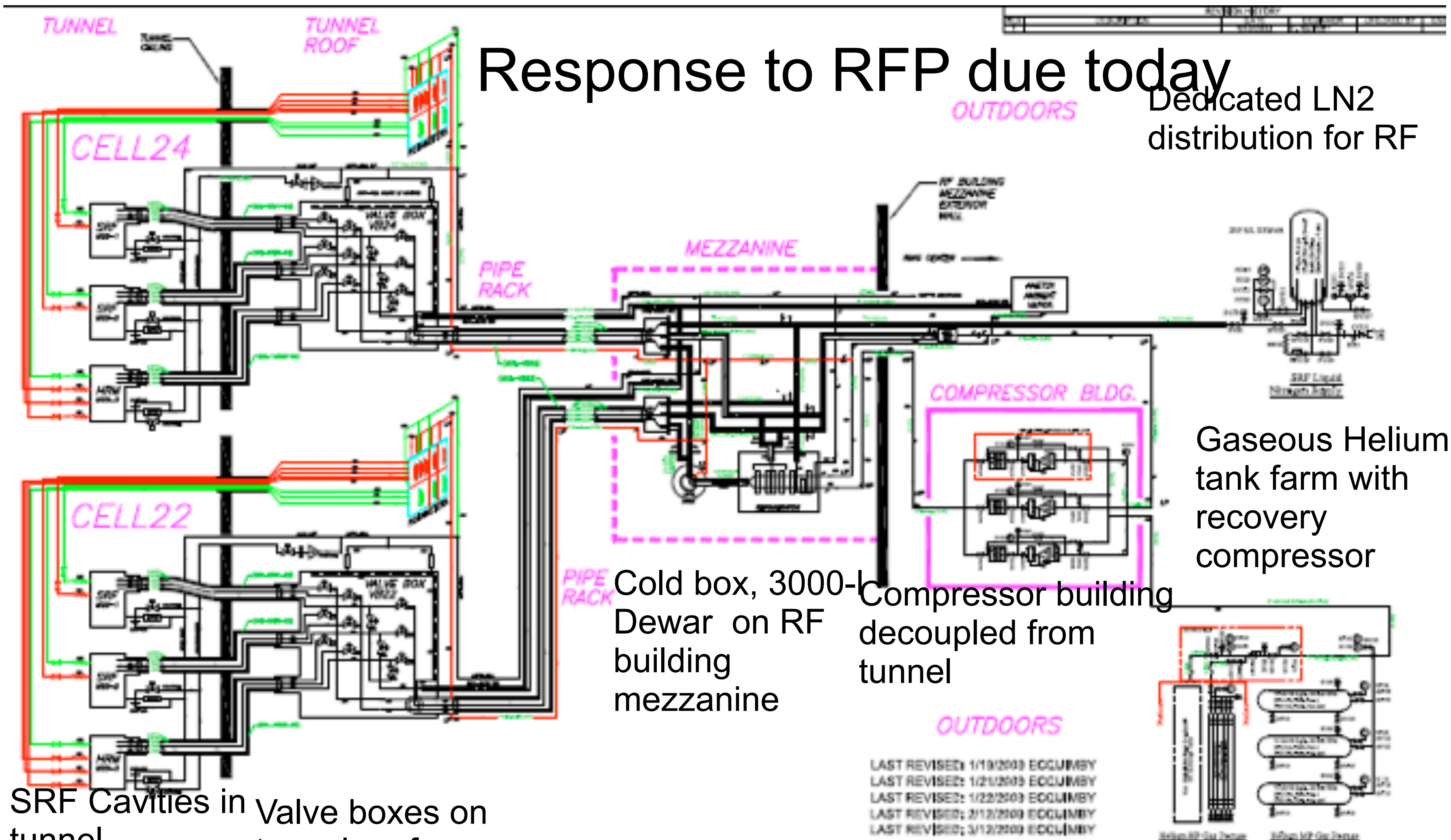
Superconducting RF – Cryogenic System

Response to RFP due today



Dedicated LN2 distribution for RF

Gaseous Helium tank farm with recovery compressor

Cold box, 3000-l Dewar on RF building mezzanine

Compressor building decoupled from tunnel

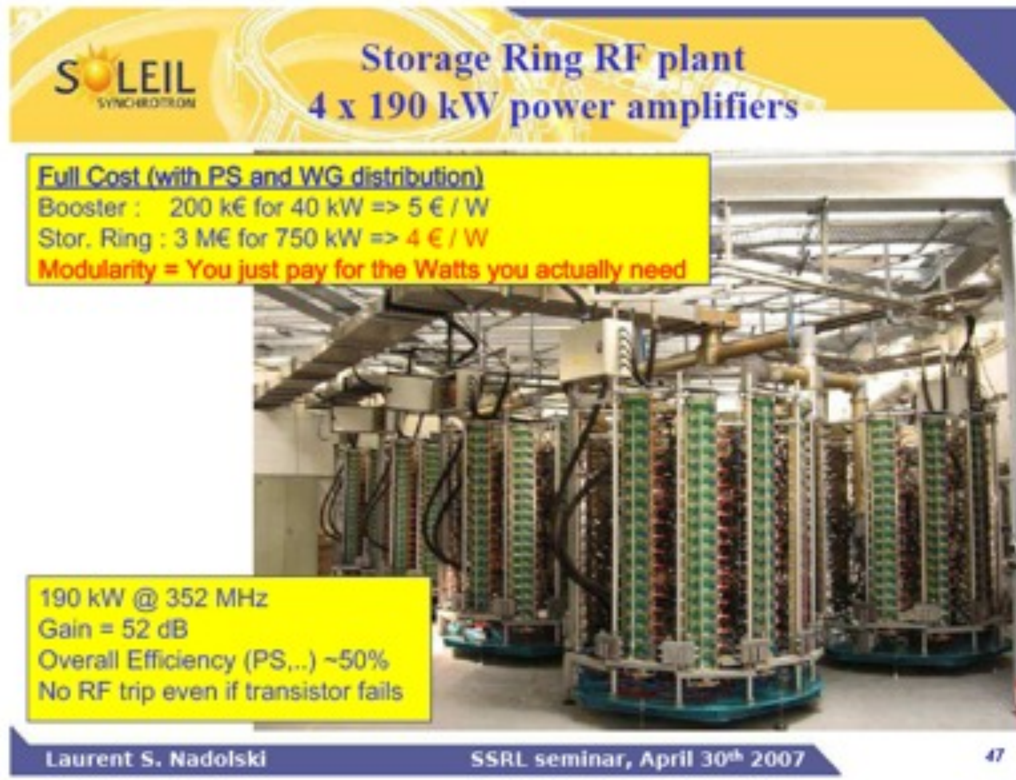
SRF Cavities in tunnel

Valve boxes on tunnel roof

SCRF – Klystrons and Solid State Amplifiers

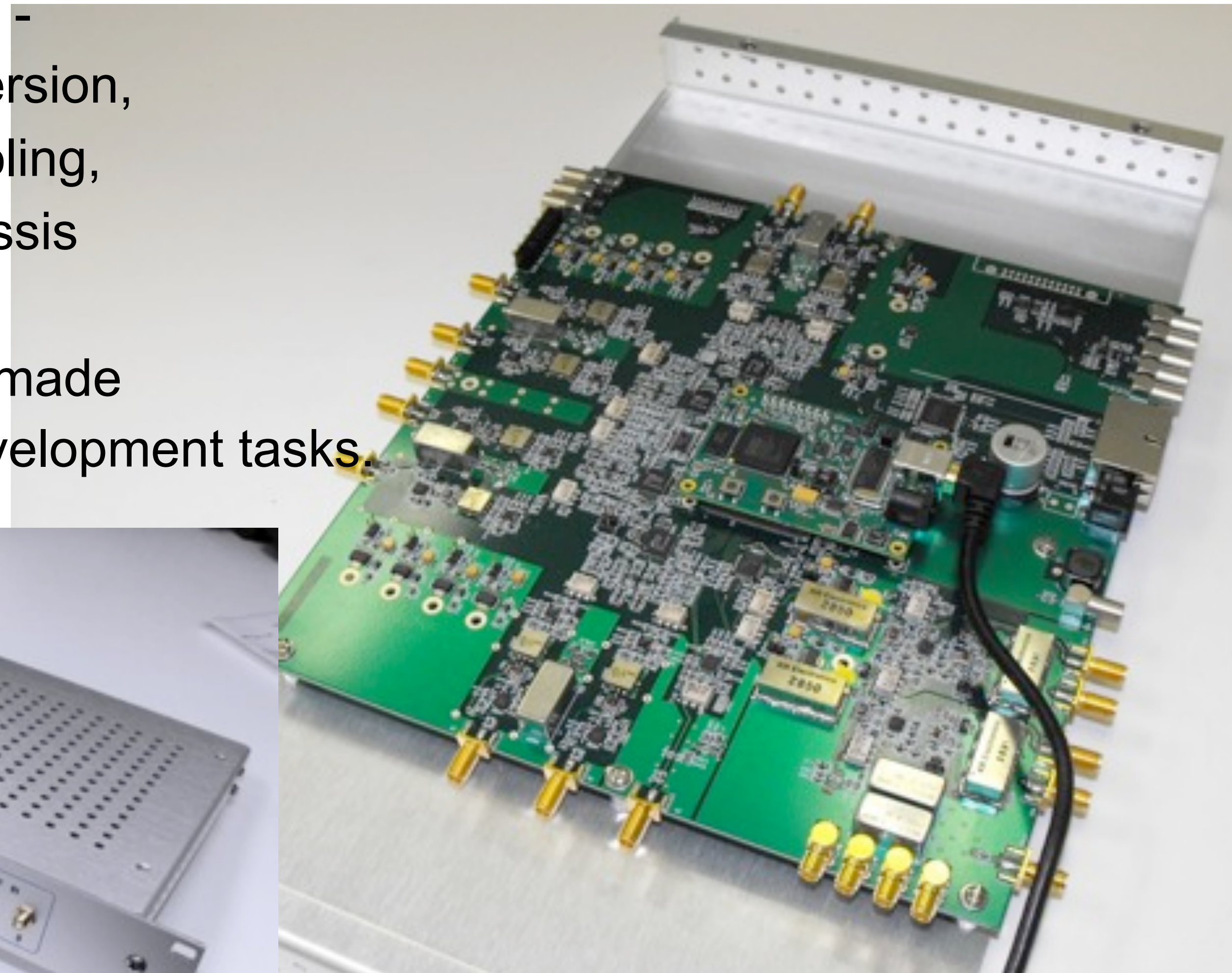
300kW HPRF Klystron-TH2161B

- **Frequency; 500MHz**
- **RF Output(CW); 300kW**
- **Gain; 40dB(min)**
- **Efficiency; 63%(typ)**
- Heater; 10V/30A
- Beam volta
  54kV/10
- Anode volt
- Ion Pump
- Magnet(fo
  100V/1
- Water cooin
  450 liter/
- Water coolin
  10 liter/
- Air cooling f
- Air cooling f

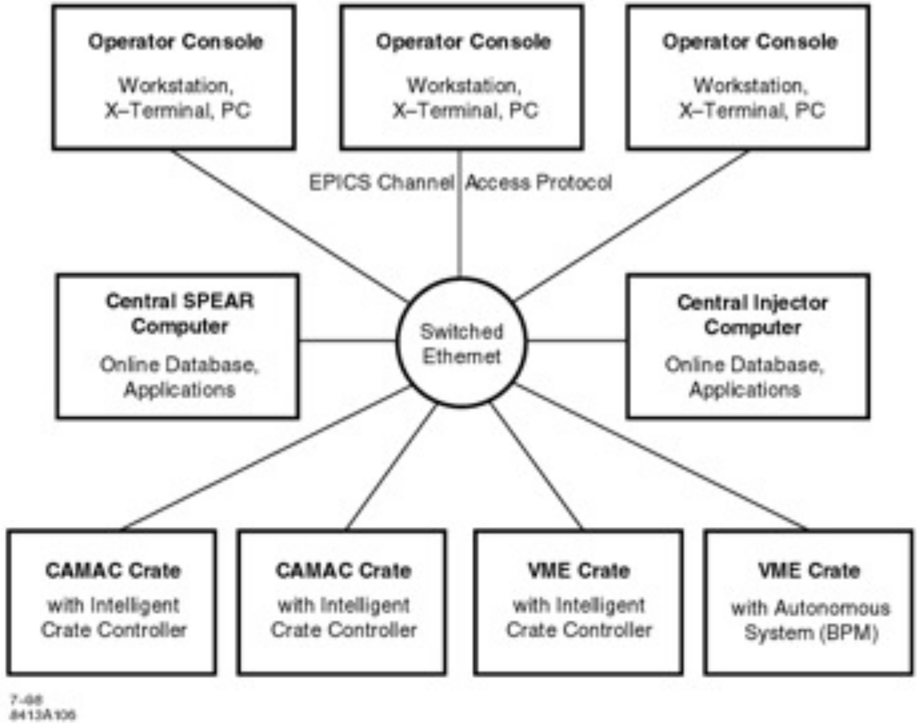


Digital LLRF Control

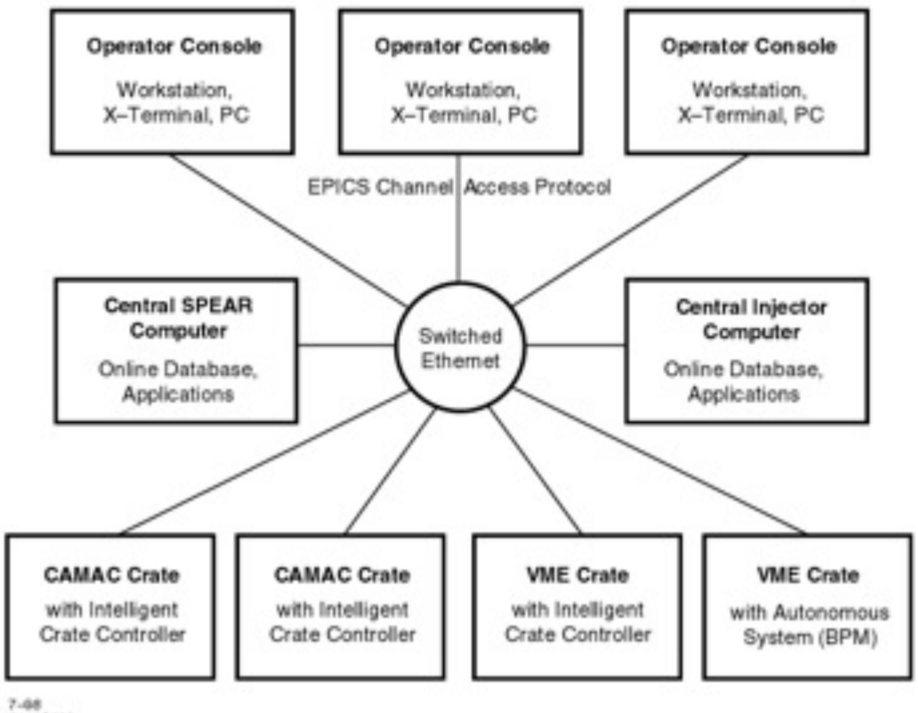
- Gone through 2 revisions
- Addition of integrated - RF-IF up/down conversion,
- Enhanced device cooling,
- Standard 1U 19” chassis packaging,
- 4 samples are being made for supporting RF development tasks.



SPEAR3 Instrumentation and Control

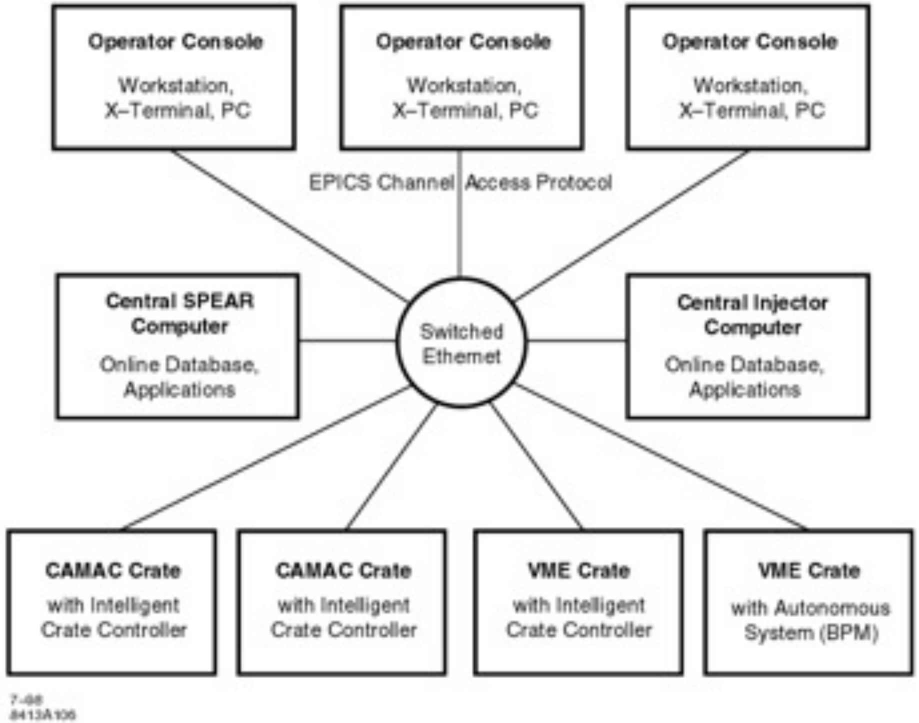


SPEAR3 Instrumentation and Control



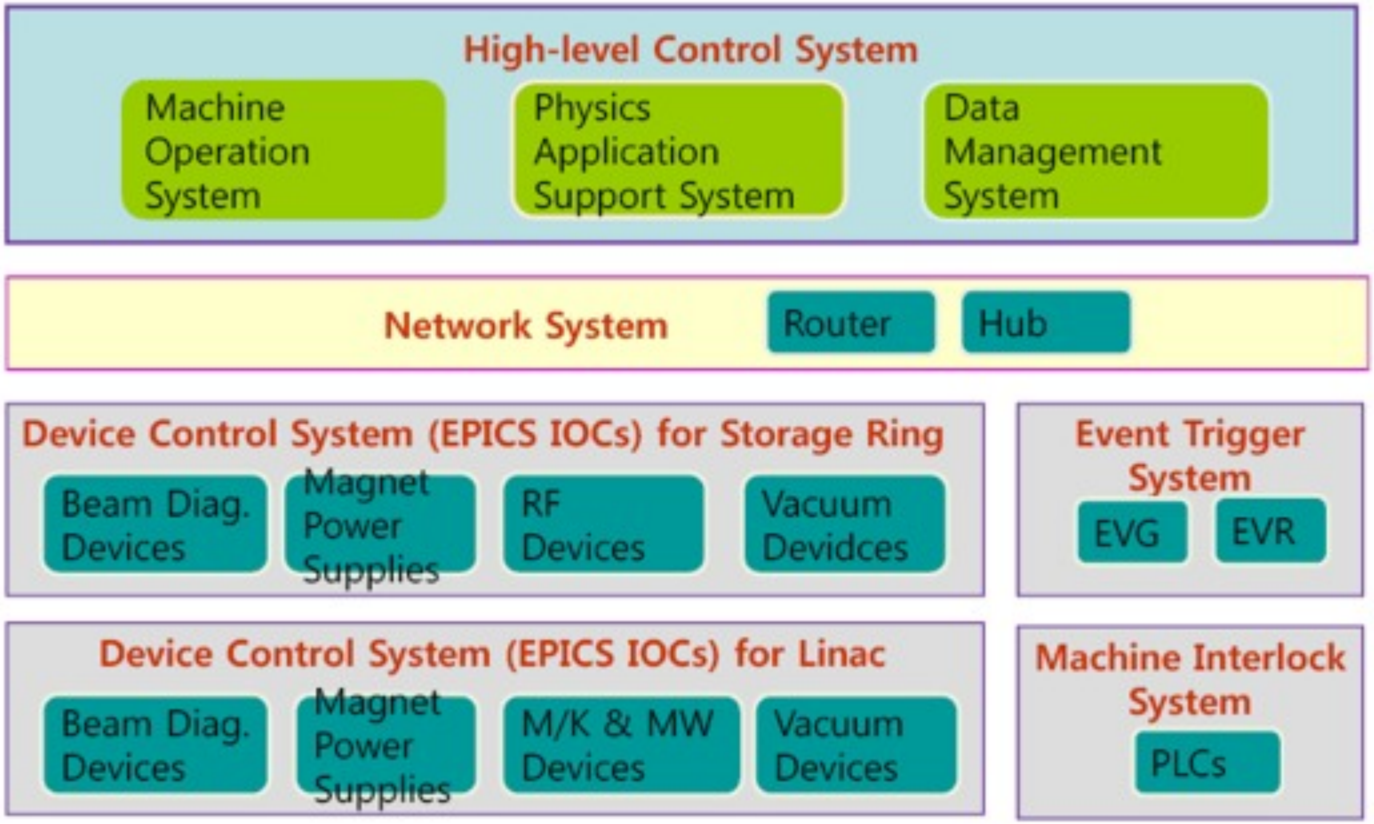
SPEAR3 Instrumentation and Control

- 10^7 bytes/sec real-time data rates
- 10^6 process variables
- 4×10^3 Hz orbit acquisition
- 10^2 Hz orbit feedback
- 10 Hz injection
- $< 5 \times 10^{-3}$ sec protection from beam mis-steer
- $< 10^{-6}$ meter beam position control



Control System Architecture

Configuration Diagram of PLS-II Control



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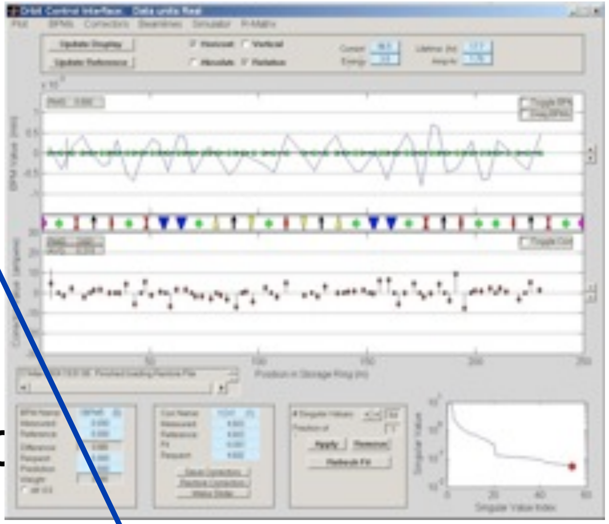
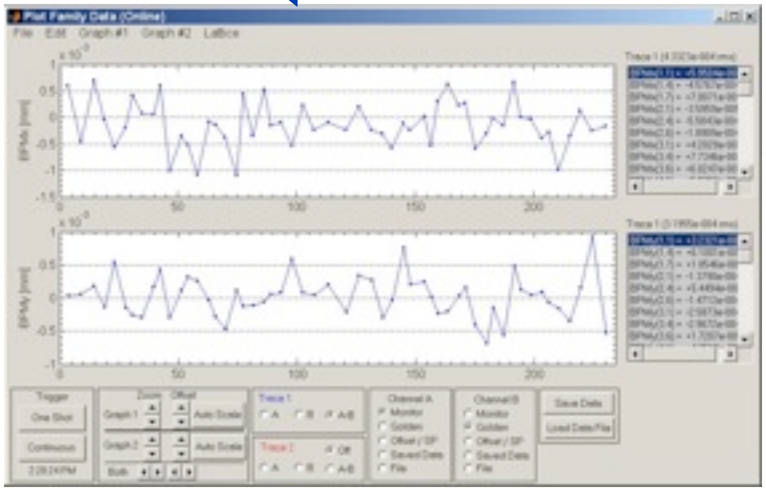
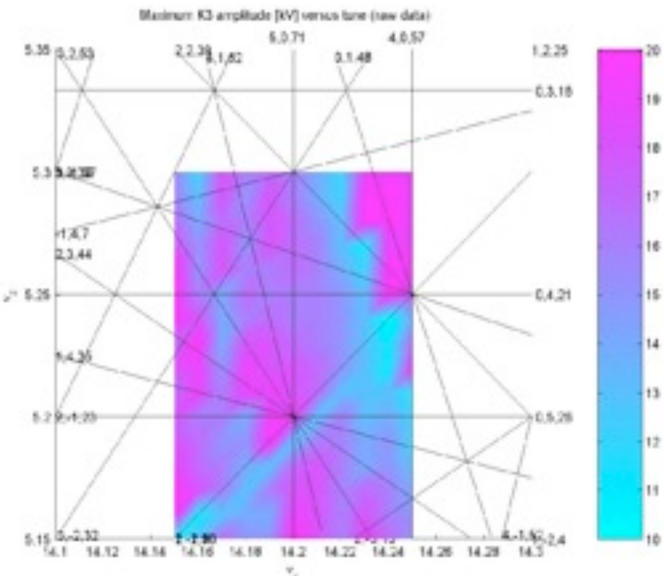
MATLAB Application Programs

- GUIs
  - Orbitgui
  - Plotfamily
- Fast scripting language for commissioning shifts
- Numerical algorithms and graphic for fast data processing

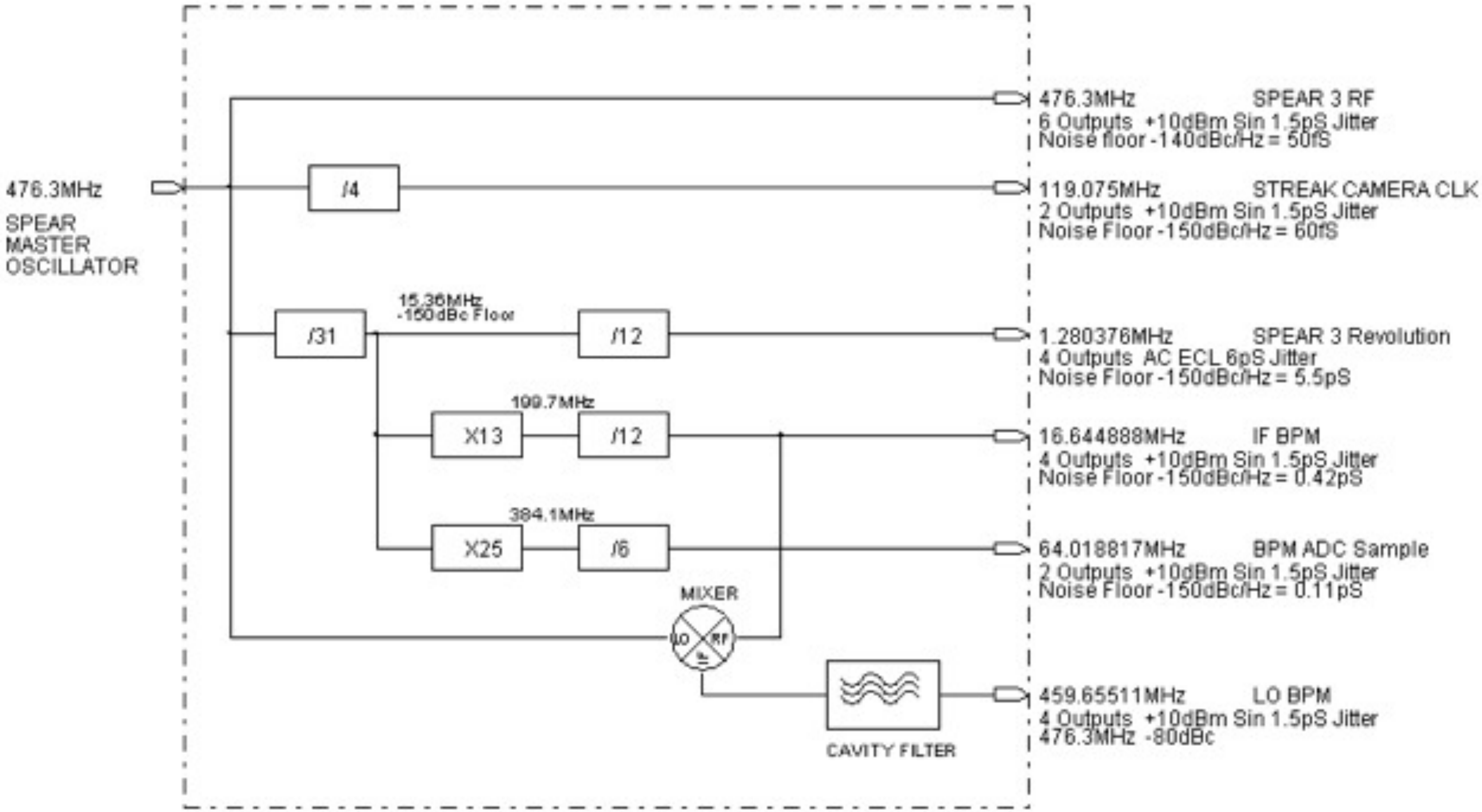






Dynamic aperture vs (ν_x, ν_y)

SPEAR3 Timing and RF Signal Generator System



SPEAR RF:

f_{SPrf} = 372 x f_{SPrev} = 476.300 MHz

Booster RF:

f_{Brf} = 280 x f_{SPrev} = 358.505 MHz

SPEAR revolution freq:

f_{SPrev} = 1.2804 MHz

BPM LO:

f_{LO} = 359 x f_{SPrev} = 459.655 MHz

BPM IF:

f_{IF} = 13 x f_{SPrev} = 16.645 MHz

IF digitizing clk:

f_{IFclk} = 50 x f_{SPrev} = 64.020 MHz

Streak camera clk:

$f_{SC} = f_{SPrf}/4$

= 93 x f_{SPrev}

= 119.075 MHz

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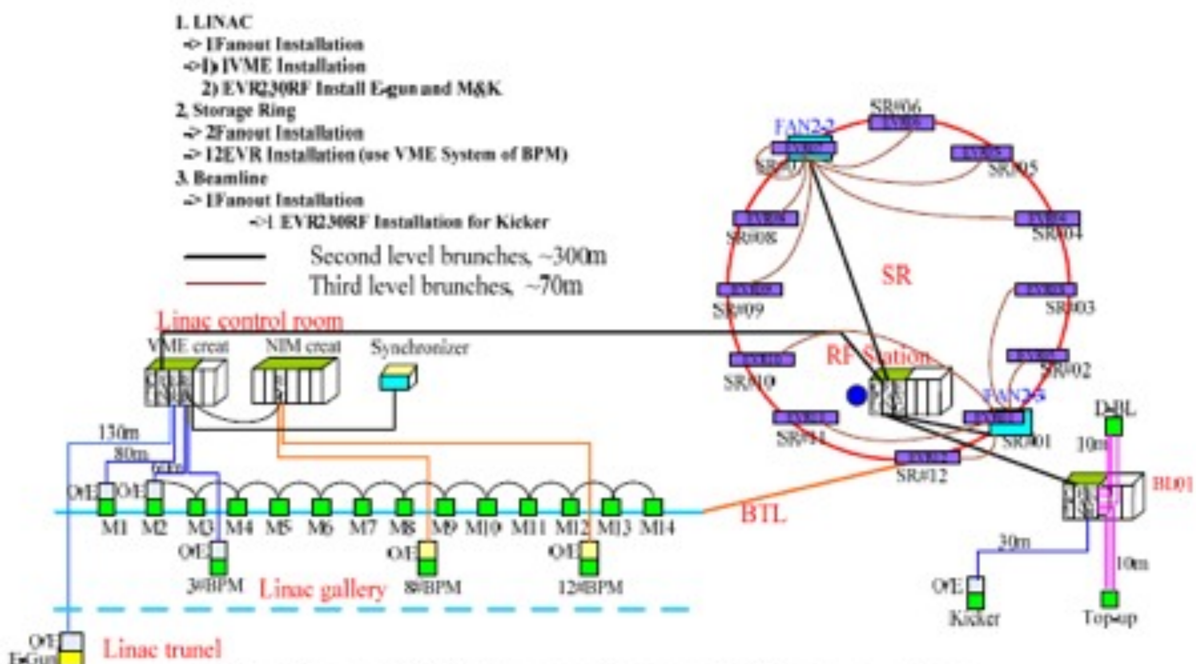
Modern EVG/EVR Timing System

Event Trigger System

- Collaboration with SSRF
- 1 EVG IOC, 15 EVR IOCs
- All hardware modules are under procurement



Structure of PLS-II event-based trigger system

Fast Global Orbit Feedback System

Rate:	4kHz
Bandwidth:	~200 Hz
Number of BPMs:	112 x + 112 y (capable) , 53 x + 53 y now
Number of Correctors:	72 x + 72 y (capable) , 54 x + 54 y now
Control Algorithm:	SVD, PI in the singular vector space of the response matrix

Fast Global Orbit Feedback System

Rate:	4kHz
Bandwidth:	~200 Hz
Number of BPMs:	112 x + 112 y (capable) , 53 x + 53 y now
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Control Algorithm:	SVD, PI in the singular vector space of the response matrix

Static orbit correction

$$\Delta\overline{\mathrm{x}} = \mathrm{R}\Delta\overline{\theta} \qquad R = USV^T$$

$$\Delta\overline{\theta} = \underbrace{V}_{\text{orbit correction eigenvectors}}\underbrace{S^{(-1)}}_{\text{inverse singular values}}\underbrace{U^T}_{\text{orbit BPM eigenvectors}}\Delta\overline{x}$$

orbit correction eigenvectors

inverse singular values

orbit BPM eigenvectors

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Fast Global Orbit Feedback System

Rate:	4kHz
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Number of BPMs:	112 x + 112 y (capable) , 53 x + 53 y now
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Static orbit correction

$$\Delta\overline{\mathrm{x}} = \mathrm{R}\Delta\overline{\theta} \qquad R = USV^{T}$$

$$\Delta\overline{\theta} = VS^{(-1)}U^{T}\Delta\overline{x}$$

orbit correction eigenvectors

inverse singular values

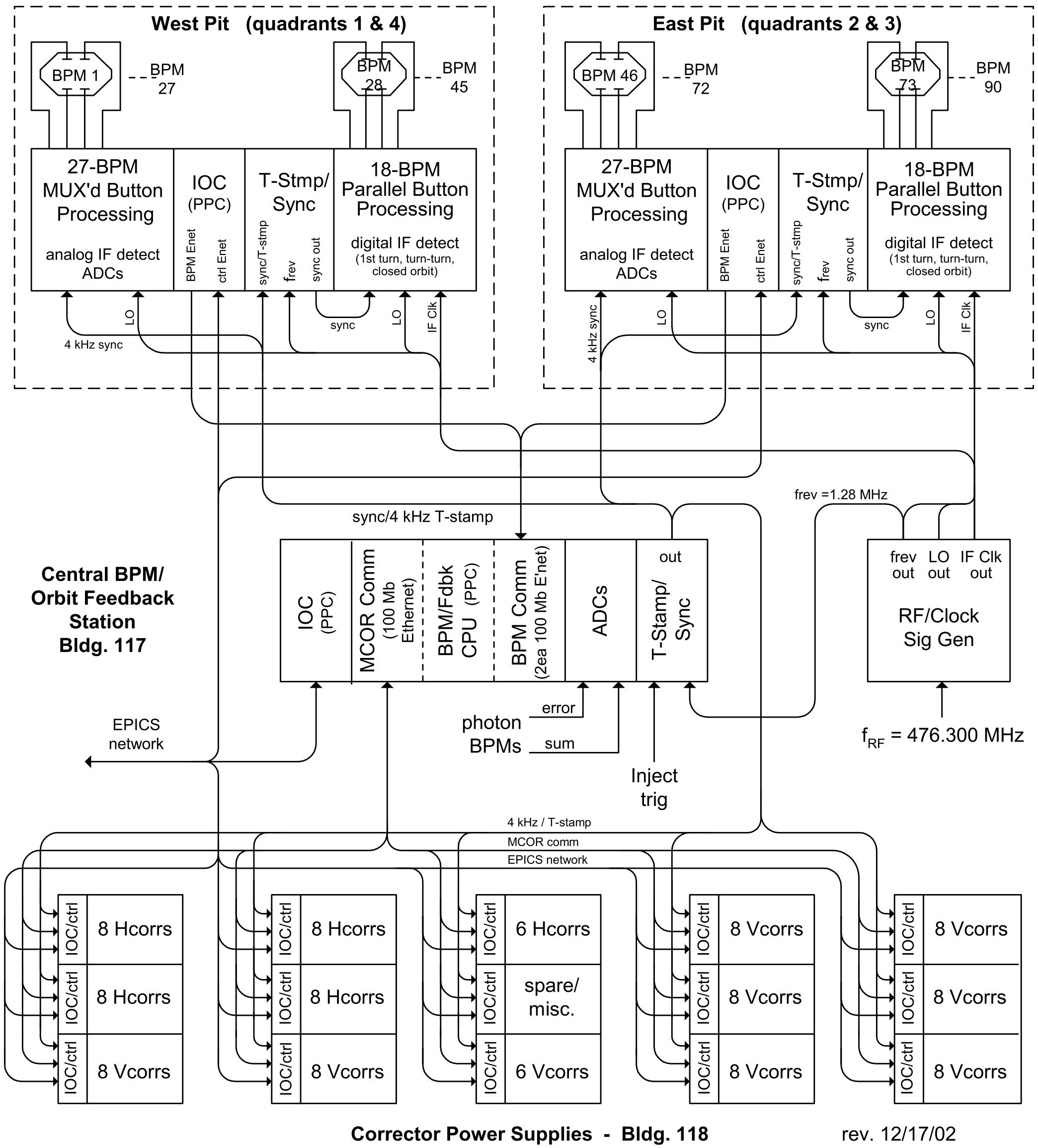
orbit BPM eigenvectors

Dynamic orbit correction

$$\Delta\overline{\theta}(t) = V\hat{K}_{PI}S^{(-1)}U^{T}\Delta\overline{x}(t)$$

$$\hat{K}_{IP}\overline{a}(t) = K_{I}\sum_{n=0}^{\infty}\overline{a}(t-n) + K_{P}\overline{a}(t)$$

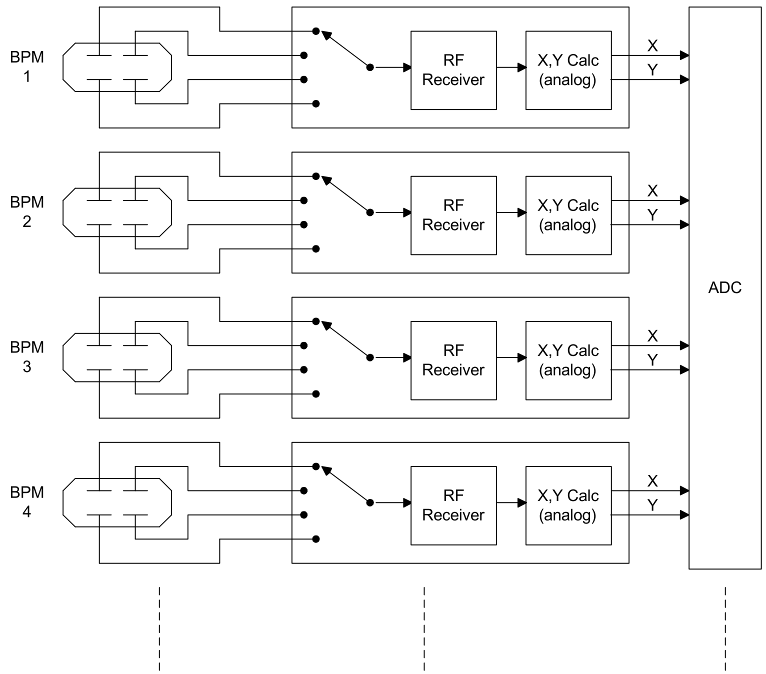
BPM Processing and Orbit Feedback System



SPEAR 3 BPM Processors

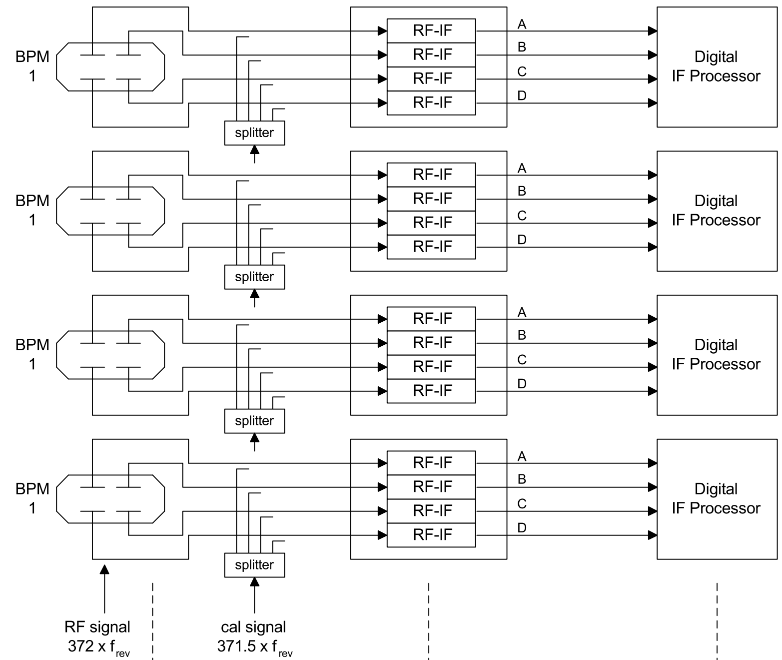
4:1 button MUX (Bergoz)

multi-turn BPM measurement
(~100-200 Hz BW)



parallel processing

1st turn/single-turn/multi-turn
BPM measurement



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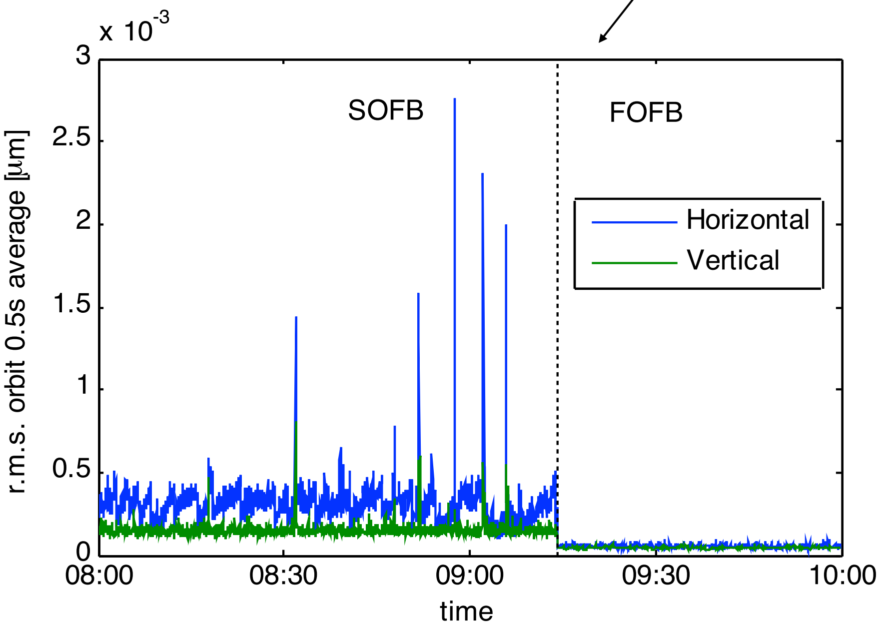
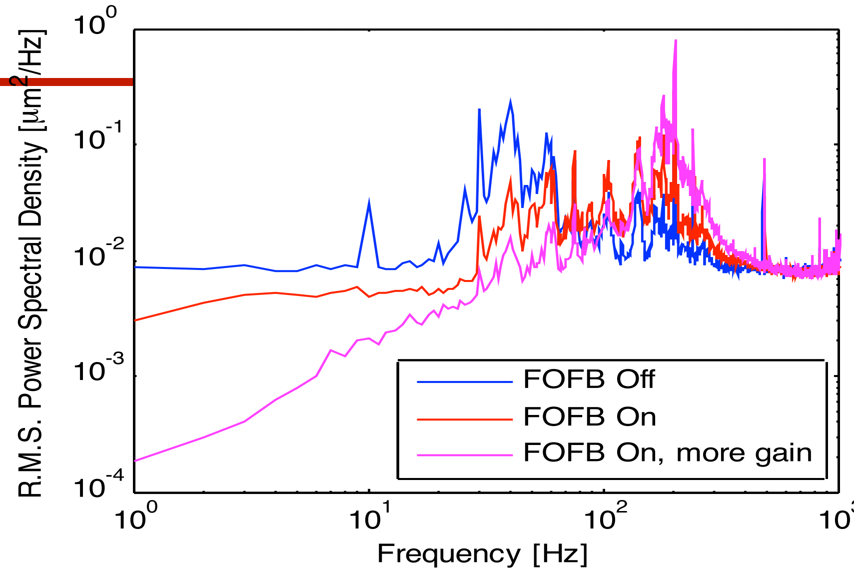
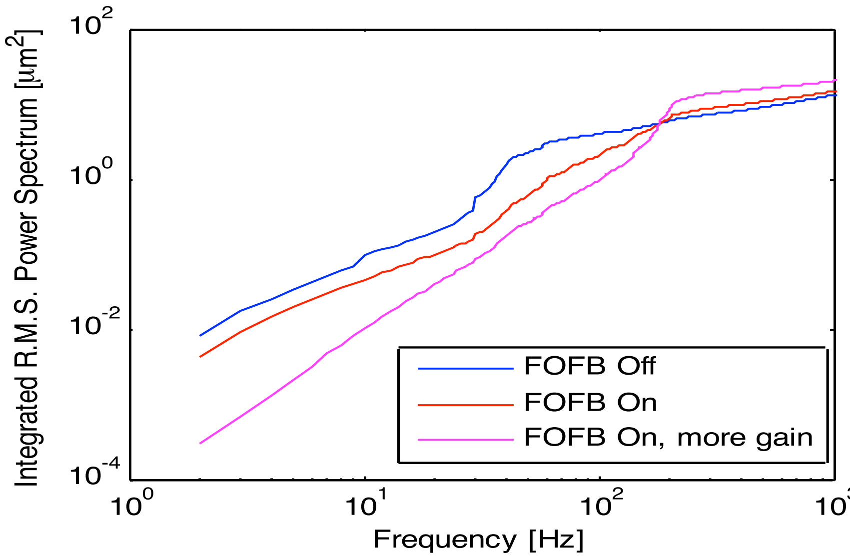
Fast Orbit Feedback Performance

- Large improvement for ½ second averaged BPM data
- ~200 Hz bandwidth.







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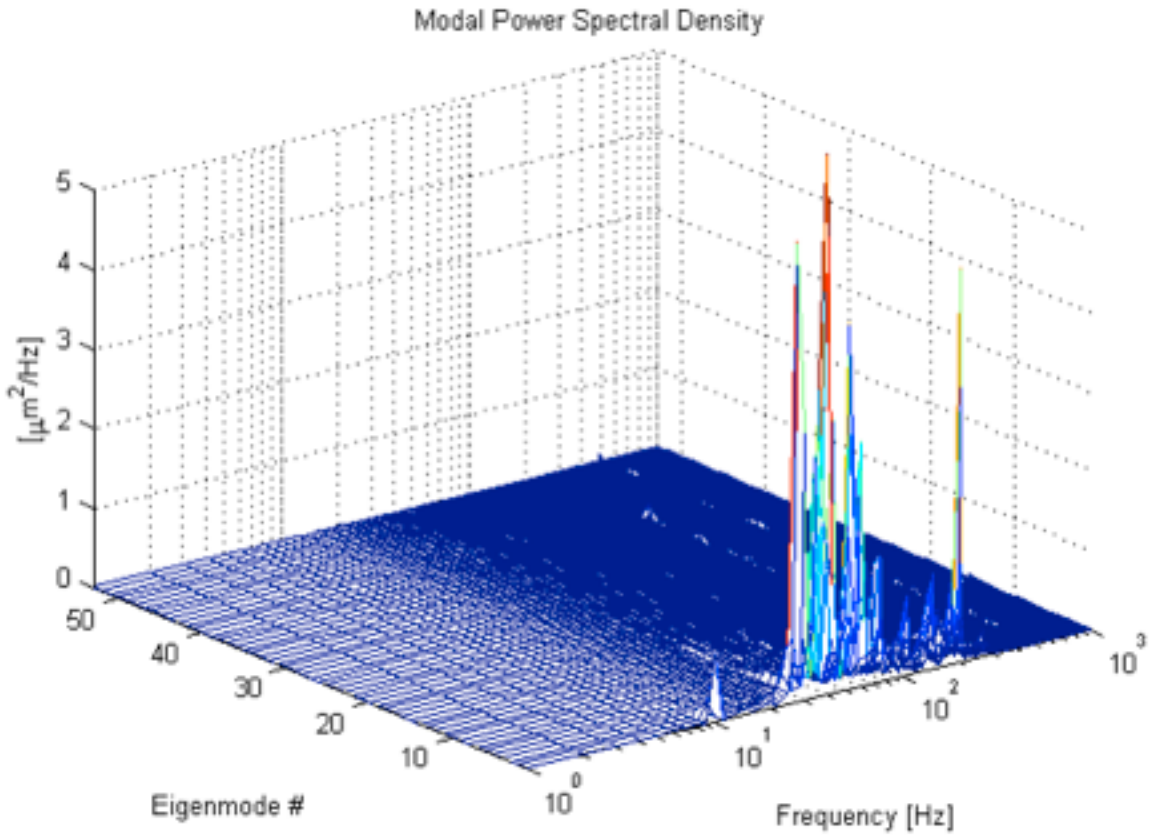
SPEAR Orbit Distortion

Distributed perturbations from small uncorrelated (~1μm) vibrations of individual magnets and supports cause orbit distortions that are concentrated in the eigenmodes having large singular values



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Dispersion Orbit Correction with RF Feedback

$$\frac{\Delta C}{C} = \kappa \Delta T = \alpha_c \frac{\Delta p}{p}$$

$$\frac{\Delta C}{C} = \frac{\Delta f_{rf}}{f_{rf}}$$

$$\Delta x_D(s) = \eta(s)\frac{\Delta p}{p} = \frac{\eta(s)\kappa\Delta T}{\alpha_c}$$

$$\Delta f_{rf} = \frac{\alpha_c f_{rf} \Delta x_D(s)}{\eta(s)}$$

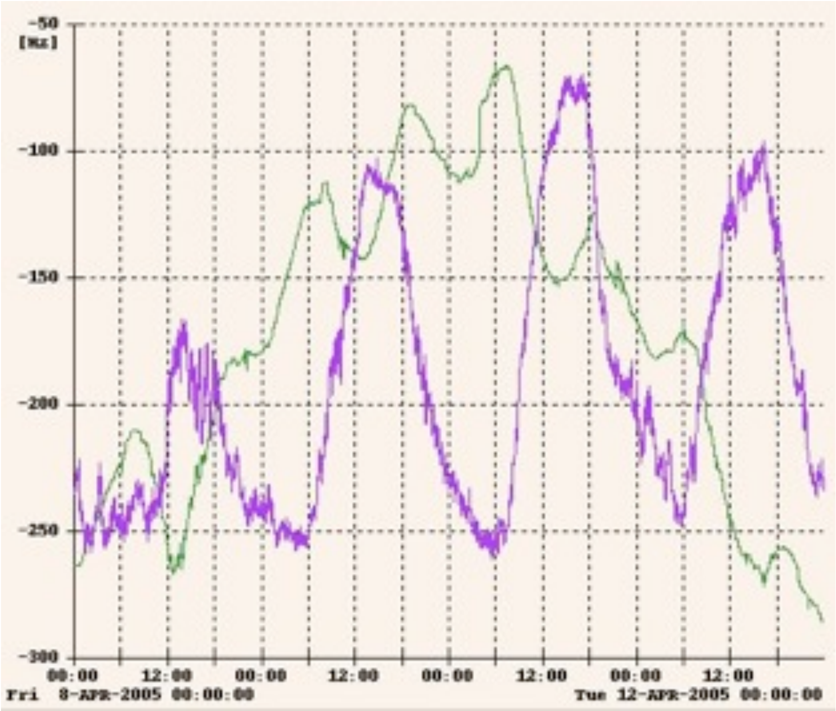

Table 3.28 Effect of circumference change induced by 1° C temperature rise in various materials.

Material	κ [°C^{-1}]	ΔL [mm]	Δp/p [%]	Δx [mm]	Δf [kHz]
Copper	16×10^{-6}	3.75	1.411	6.69	-5.726
Stainless steel	7×10^{-6}	3.98	1.465	6.96	-6.076
Aluminum	24×10^{-6}	5.85	2.205	10.45	-8.932
Iron	12×10^{-6}	2.81	1.058	5.01	-4.290

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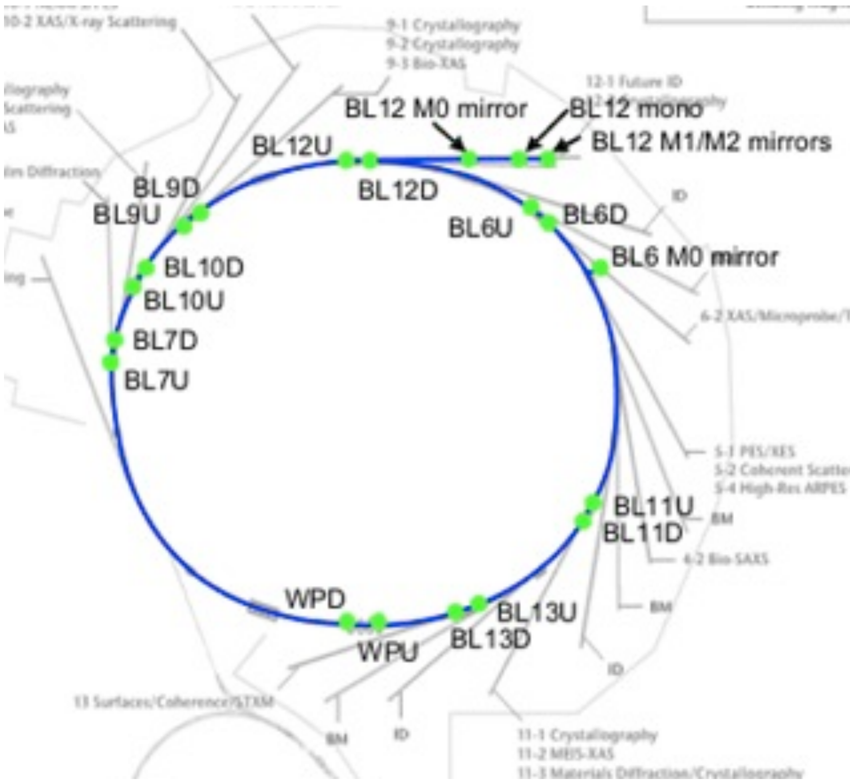
Floor Motion Study - Hydrostatic Level System

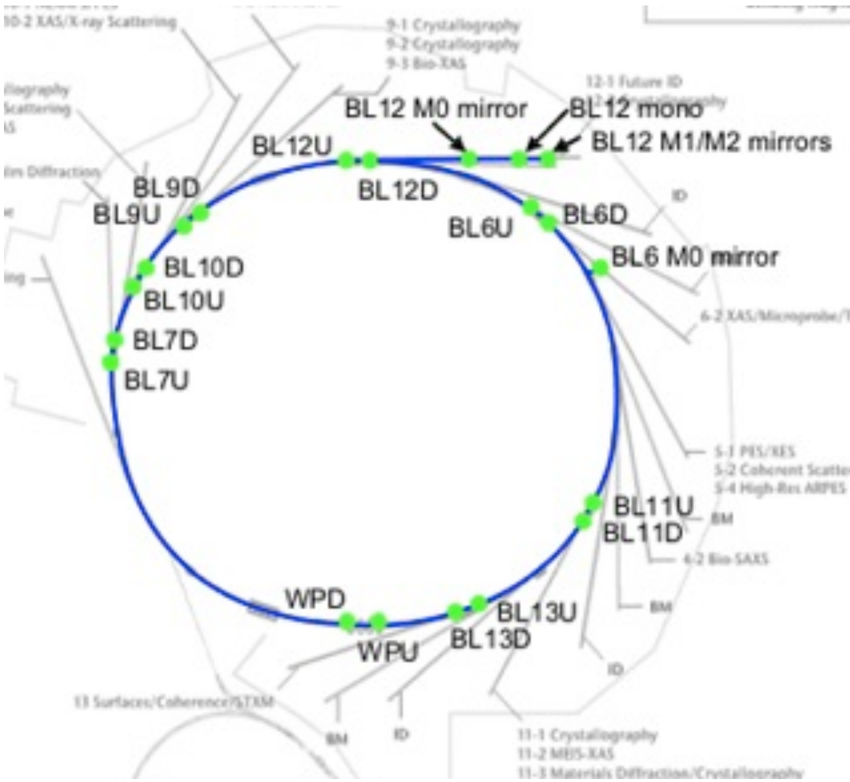
(G. Gassner – SLAC, http://www-group.slac.stanford.edu/met/Align/Spear3/SPEAR_WWW/nov05/autoplot.html)



18 HLS sensors in tunnel, 2 on experimental floor (BL12)

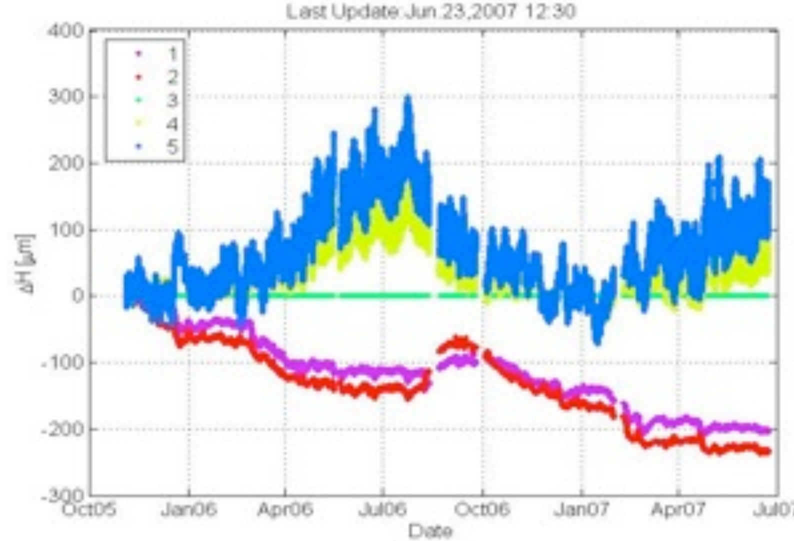
Floor Motion Study - Hydrostatic Level System

(G. Gassner – SLAC, http://www-group.slac.stanford.edu/met/Align/Spear3/SPEAR_WWW/nov05/autoplot.html)

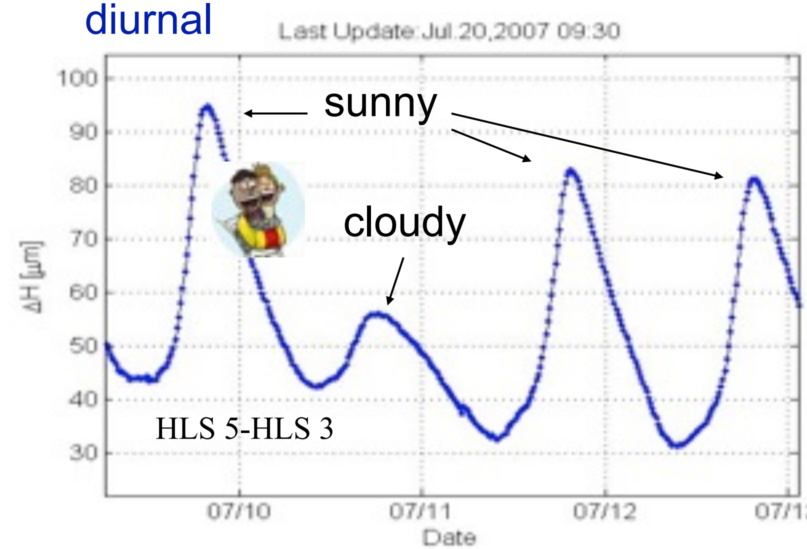


18 HLS sensors in tunnel, 2 on experimental floor (BL12)

seasonal



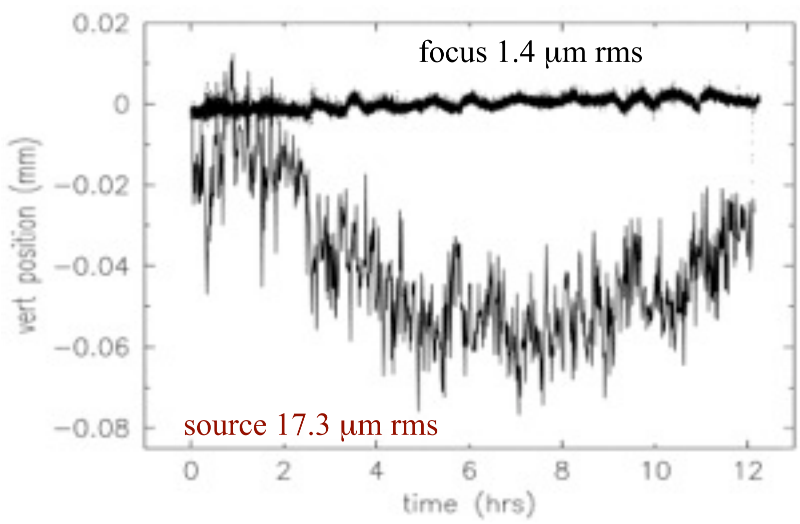
diurnal

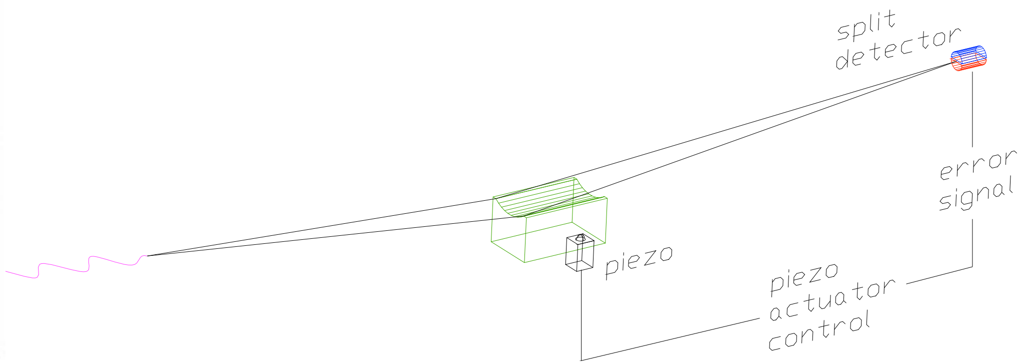


- Tunnel floor moves daily, seasonally, and fr rainfall

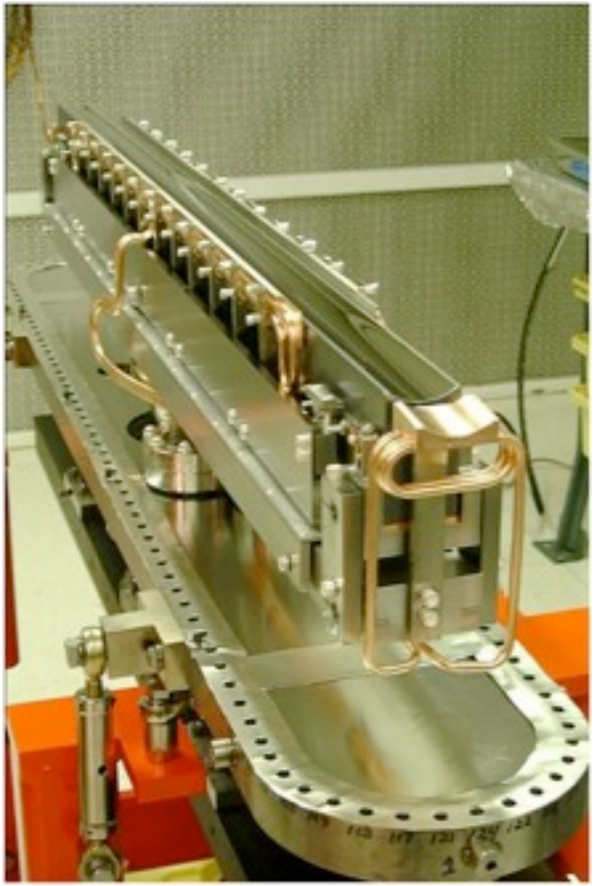
Mirror Pitch Feedback (SSRL, T. Rabedeau)

- error signal obtained from position sensitive (split) detector located near beam focus
- error signal used to control piezo high voltage via PI algorithm
- piezo provides mirror fine pointing control with typical full range of motion +/-~30 μrad





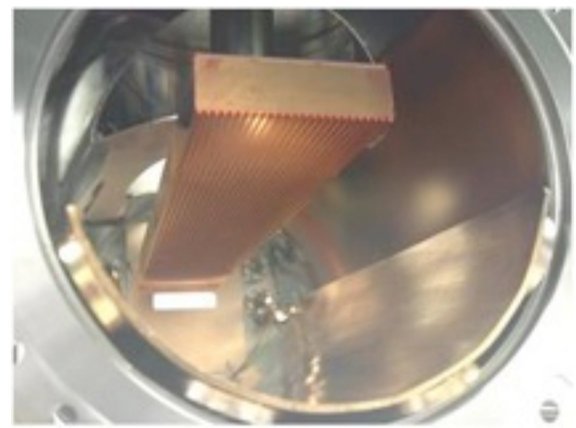
SPEAR 3 Beam Line Components



1.2m toroid mirror for BL10-2

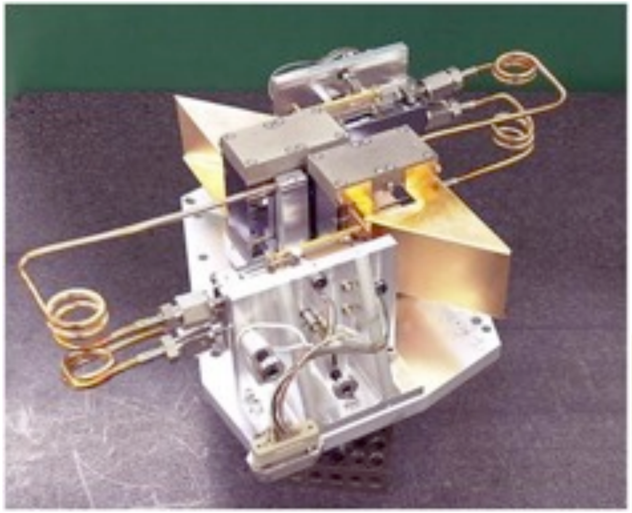
insertion device (Danfysik)

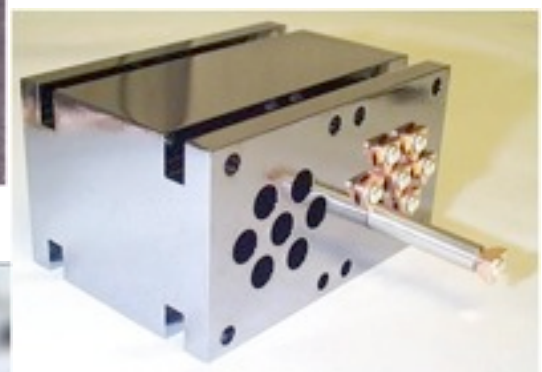
wheel-in BL front end

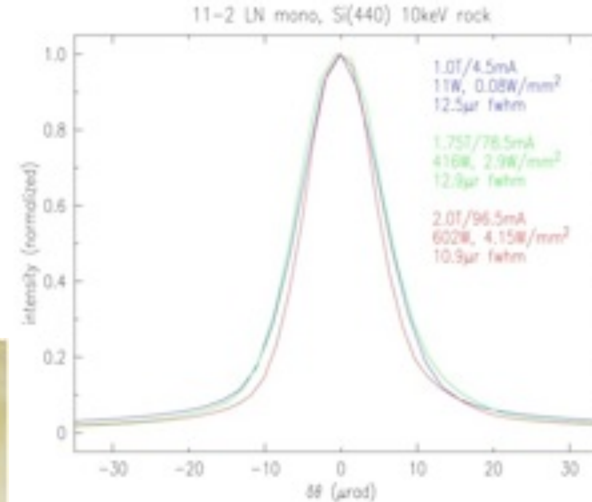


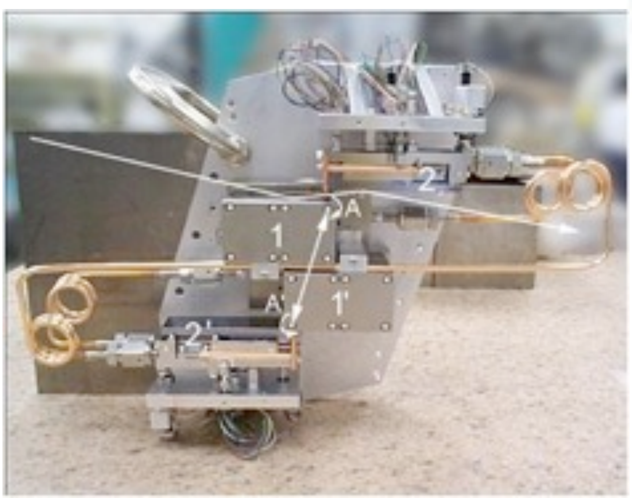
BL front end mask

SPEAR 3 LN Monochromator + Crystal Exchange









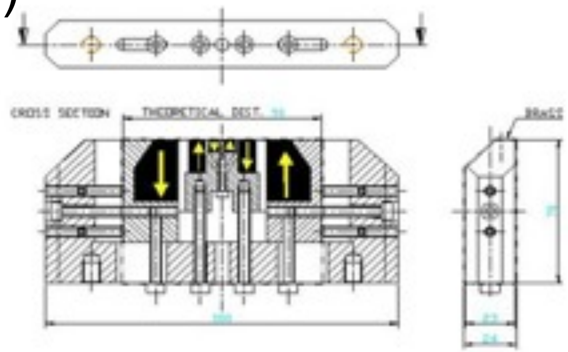
SPEAR3 Insertion Devices

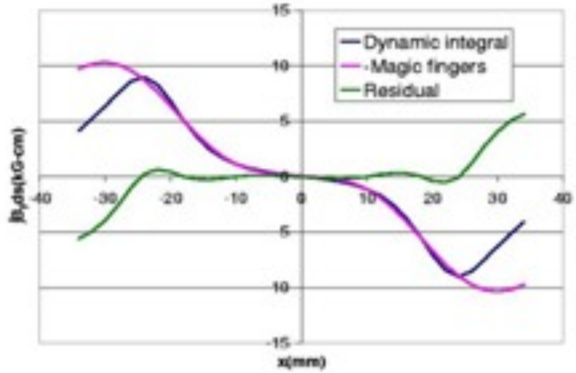
Beam Line	Device	Periods	Field (T)
4	PMW	10	2 @ 16 mm
5	EPU	26	0.7 @ 18.6 mm
6	PMW	27	0.9 @ 16 mm
7	PMW	10	2 @ 16 mm
9	PMW	8	1.9 @ 24 mm
10	PMW	15	1.3 @ 24 mm
11	PMW	13	2 @ 16 mm
12-2	IVUN	67	1.1 @ 5.5 mm
13	EPU	65	0.8 @ 13.5 mm
12-1(future)	TBD		
future (4)	TBD		

Insertion Device Characterization

Insertion Device Characterization

- “Magic fingers” used to correct dynamic integrals for BL11 ID (poles too narrow)





Insertion Device Characterization

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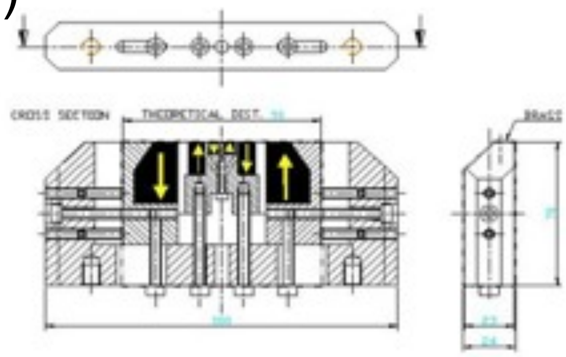
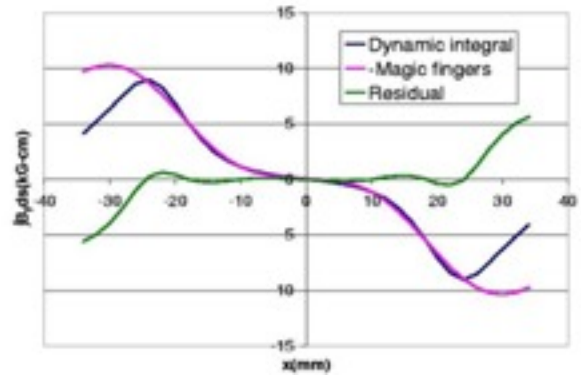
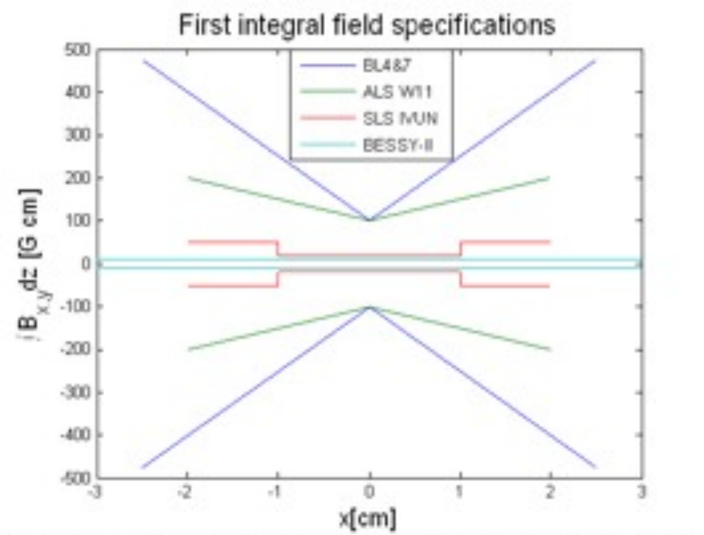




- 1st and 2nd second integrals, transverse field roll-off now fully specified for ID vendors



For BL12 & 13: 100 + 50*|x| G*cm, |x|<2.5 cm; (ALS extended to 25 mm)

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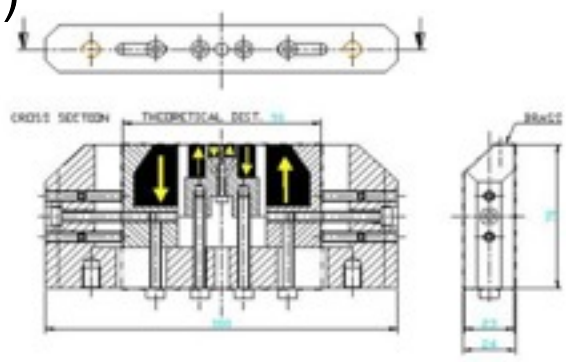
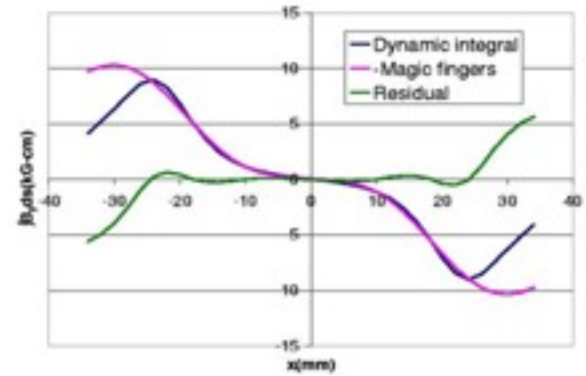
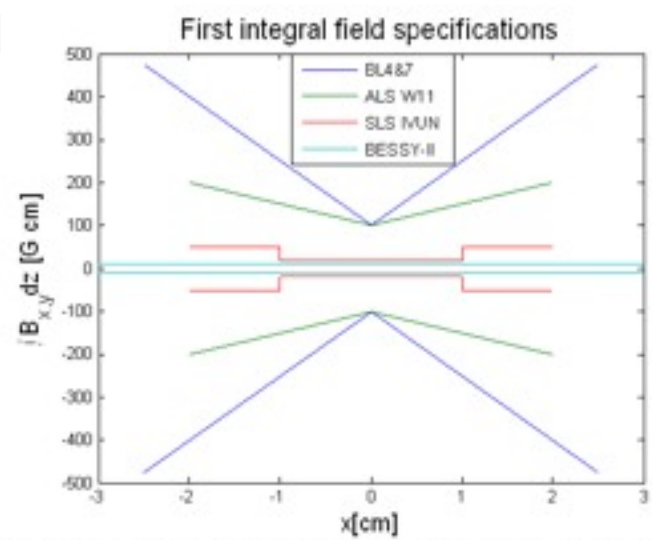
Insertion Device Characterization

- “Magic fingers” used to correct dynamic integrals for BL11 ID (poles too narrow)





- 1st and 2nd second integrals, transverse field roll-off now fully specified for ID vendors
- Skew quad errors found in EPUs - corrector coils added to BL5 and BL13 EPUs



For BL12 & 13: 100 + 50*|x| G*cm, |x|<2.5 cm; (ALS extended to 25 mm)

Insertion Device Characterization

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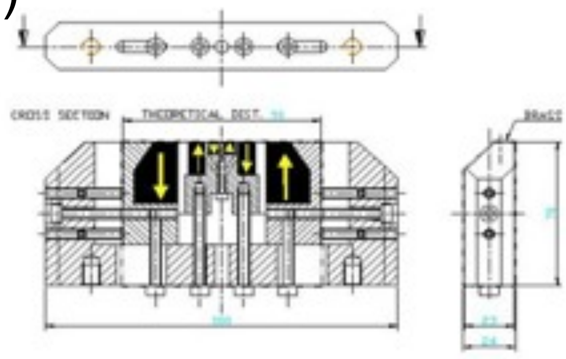
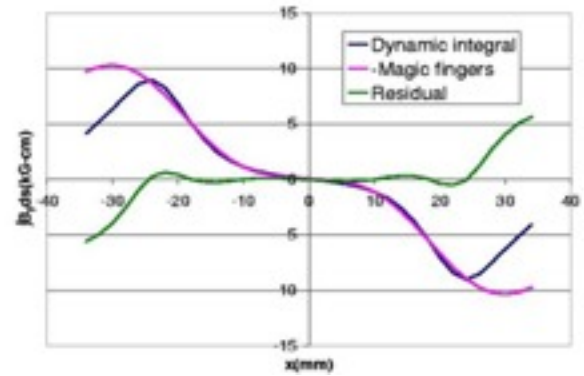
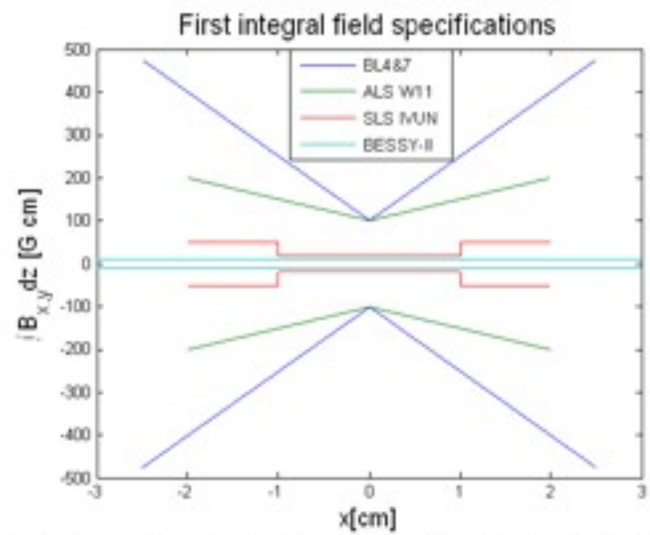




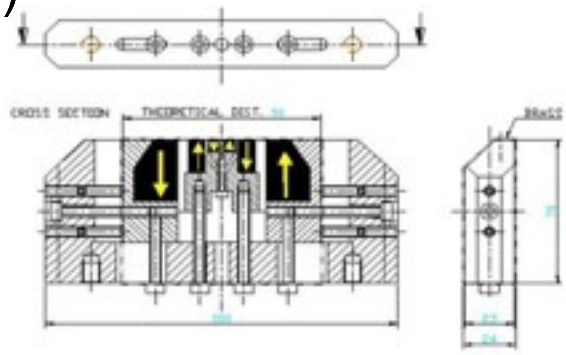
- 1st and 2nd second integrals, transverse field roll-off now fully specified for ID vendors
- Skew quad errors found in EPUs - corrector coils added to BL5 and BL13 EPUs
- EPU field integrals partially corrected by shimming

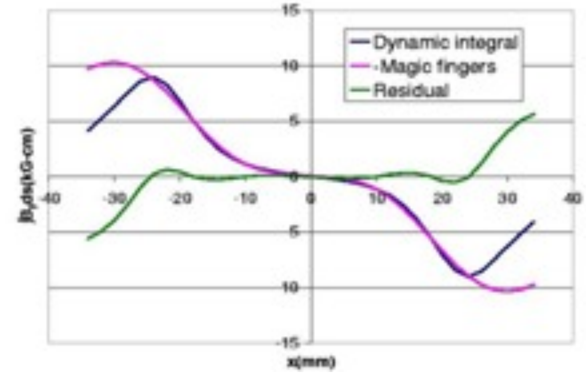


For BL12 & 13: 100 + 50*|x| G*cm, |x|<2.5 cm; (ALS extended to 25 mm)

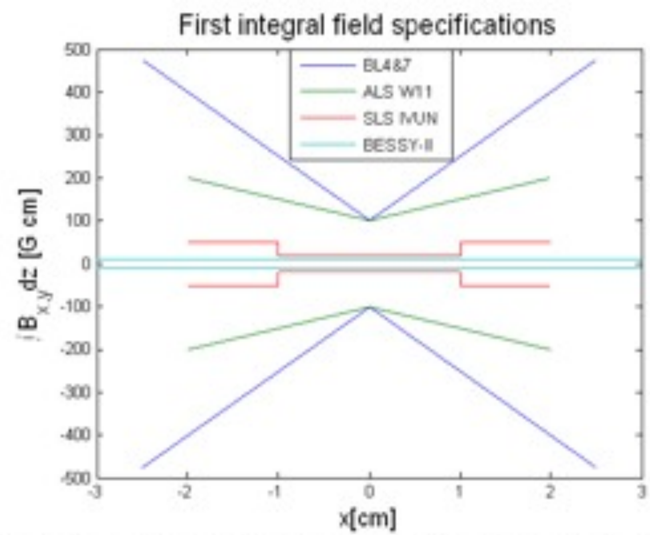
Insertion Device Characterization

- "Magic fingers" used to correct dynamic integrals for BL11 ID (poles too narrow)





- 1st and 2nd second integrals, transverse field roll-off now fully specified for ID vendors
- Skew quad errors found in EPUs - corrector coils added to BL5 and BL13 EPUs
- EPU field integrals partially corrected by shimming
- IDs symplectic integrator included in AT accelerator modeling (Wu et al., Phys. Rev. E, 2003)



For BL12 & 13: 100 + 50*|x| G*cm, |x|<2.5 cm; (ALS extended to 25 mm)

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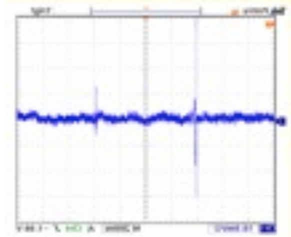
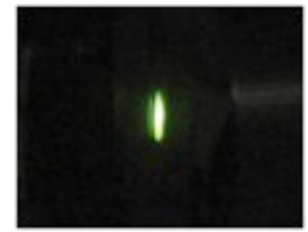
SPEAR 3 Commissioning

First beam to SPEAR3:	Dec. 10. 2003
First turn:	Dec. 12
First stored beam:	Dec. 15
100 mA:	Jan. 22, 2004
First beam seen in beam line:	Mar. 8
First users:	Mar. 15





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Topics Not Discussed

- Injector design
- Kicker magnets and pulsers
- Synchrotron light monitors
- Photon BPMs and misc. other diagnostics
- Transverse/Longitudinal Feedback Systems
- Machine Protection Systems
- Personnel Protection Systems
- Beam Containment Systems
- Radiation shielding
- Tunnel and experimental floor engineering
- Utilities (gasses, water, electricity)
- …..

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Beam energy	3 GeV
Injection energy	3 GeV
Current	100-500 mA
Fill pattern	280 bunches, 93-bunch gap, camshaft bunch in gap (6-bunch timing mode @ 100 mA available)
Circumference	234.144 m
Radio frequency	476.315 MHz
Bunch spacing	2.1 ns
Horizontal emittance	10 nm*rad
Vertical emittance	14 pm*rad
Critical energy	7.6 keV
Energy spread	0.097%
Lifetime	~50 h @ 100 mA, ~14 h @ 500 mA
e- size (x,y)	Dipole: 140, 14 μm rms Standard ID: 310, 8 μm rms Chicane ID: 300, 5 μm rms
e- divergence (x,y)	Dipole: 180, 2.9 μrad rms Standard ID: 33, 1.7 μrad rms Chicane ID: 34, 2.9 μrad rms
Bunch length	20 psec rms (6.7 mm rms)
Straight sections for IDs (available ID length)	9 x 2.3 m 4 x 3.7 m 2 x 1.5 m (Chicane)

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