Recent Work on Insertion Devices at the ALS

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Input from:

ALS Accelerator Physics group
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AFRD Supercon
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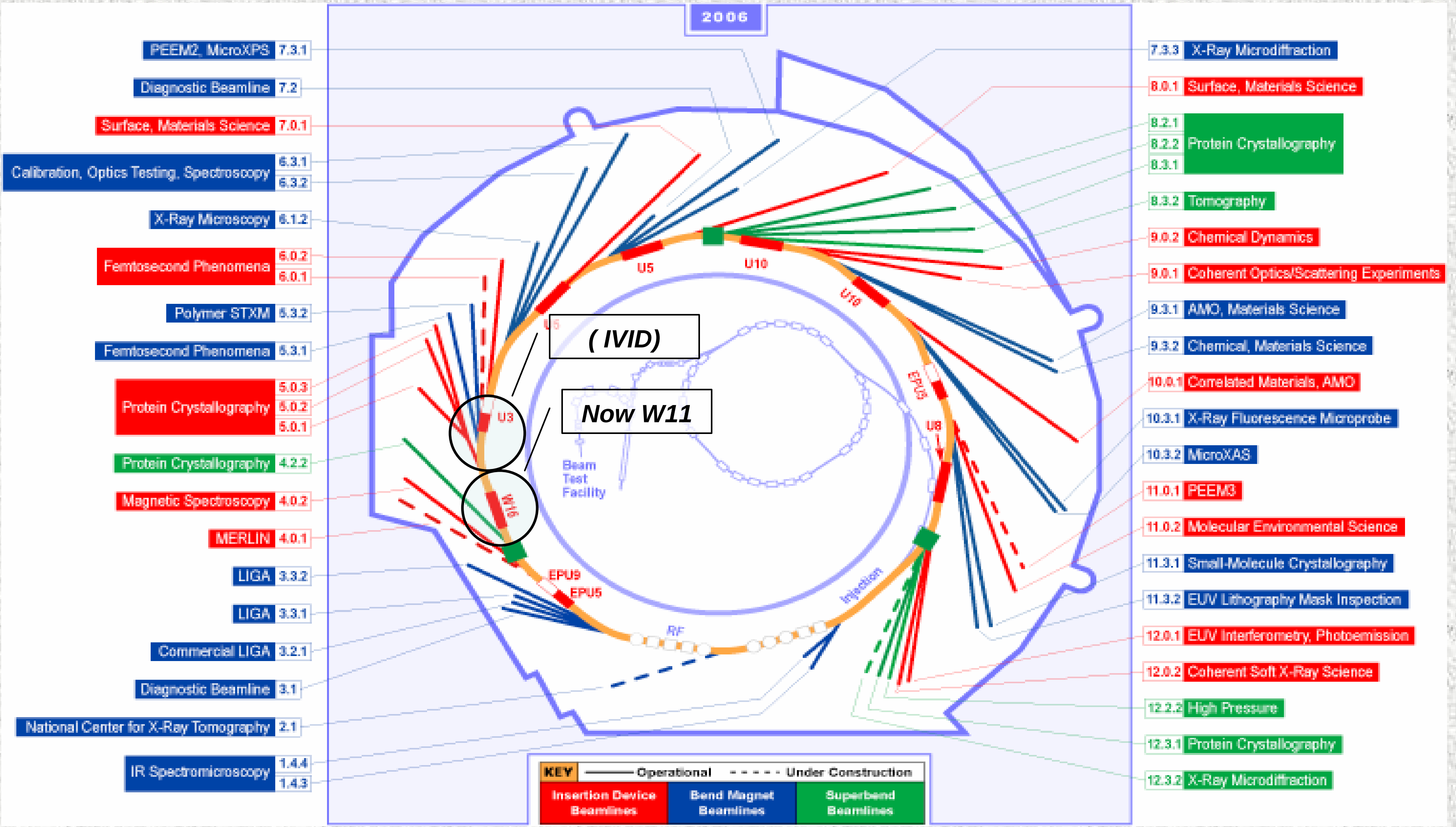
Outline

1. Review of existing insertion devices at the ALS
    - Planned insertion devices - applications and specifications
        - Near term (reasonably well known)
        - Longer term (likely to change…)
2. Details of a device under construction – MERLIN
    - Quasi-periodic magnetic structure
    - Anticipated spectral performance
3. EPU modifications to accommodate top-off operation
    - Dynamic multipoles and compensating shims
4. R&D results on superconducting undulator prototypes

ALS beamline diagram



Review of existing and *future* insertion devices at the ALS

Wave 1*
Wave 2**
Wave 3: SCU's, ultra-fast,…

Beamline	Application	Type	Period, Length	Energy range*	Status
4.0.1	*MERLIN - meV resolution spectroscopy*	*QEPU*	*90mm; 1.8m*	*8-300eV*	*Being fabricated*
4.0.2	Magnetic spectroscopy (MCD, MLD)	EPU	50mm; 1.8m	50-1900eV	1998
5.0.1	Protein crys.; femto modulator	Wiggler	110mm; 3.5m		2004
6.0.1,2	Femto radiator – ultrafast science	IVID	30mm; 1.5m	200-1800 (U) 2keV-10keV (W)	2005
7.0.1	Surface & materials science	Undulator	50mm; 4.5m	60-1200eV	*1993*
*7.0.1**	*COSMIC – coh. scattering & imaging*	*EPU*	*34mm, 1.8m*	*250-1300eV*	~2008
*7.0.2**	*MAESTRO – microscopy & elect. Struct.*	*EPU*	*70mm, 1.8m*	*20-600eV*	~2008
8.0.1	Imaging, x-ray fluorescence	Undulator	50mm; 4.5m	65-1400eV	1993
9.0.1,2	Coh. Scattering; Chem. Dynamics	Undulator	100mm, 4.5m	5-800eV	1995
10.0.1	Photoemission	Undulator	100mm, 4.5m	17-340eV	1997
11.0.1	PEEM	EPU	50mm, 1.8m	100-2000eV	2003
11.0.2	Molecular environmental science	EPU	50mm, 1.8m	95-2000eV	2001
12.0.1,2	EUV, ARPES, Coherent x-ray science	Undulator	80mm, 4.5	60-1000eV	1993
*10.0.1***	*Photoemission HERS*	*EPU*			
*10.1.1***	*Atomic / molecular physics*	*EPU*			
*2.?***	*QUERLIN – Q-res.Inelastic scattering*	*SCU*		*~1keV*	
*12.0.1,2***	*ARPES; coherent science*	*Undulator*	*80mm, 3m*		

* Typically reflects beamline, not ID, energy range

ALS storage ring parameters

(Thanks to David Robin)

Present Operation	After Top-Off
• Injection at 1.5 GeV and then ramp	• Full energy injection (1.9 GeV)
• Inject with insertion devices open	• Inject with insertion devices closed
• Average beam current is 250 mA	• Average beam current is 500 mA
• Vertical emittance is 150 pm rad	• Vertical emittance is 30 pm rad
• Lifetime is 8 hours at 400 mA	• Lifetime is about 3 hours at 500 mA
• Injection period every 2 to 8 hours – 1 Hz injection for 4 minutes • From 200 to 400 mA	• Injection period about every 30 seconds – 1 pulse • From 498.5 to 500 mA
• Photon shutters are closed during injection	• Photon shutters remain open during injection

Top-Off upgrade and ID’s linked

- Can no longer open ID’s for injection
  - Inject every ~30s
  - Beam dynamics concerns
    - Injection efficiency limitations imposed by EPU’s
- Minimum aperture must be set by scrapers
  - Avoid radiation damage to ID’s
  - Safety considerations
    - Possible fault scenario of electrons sent down beamlines must be eliminated

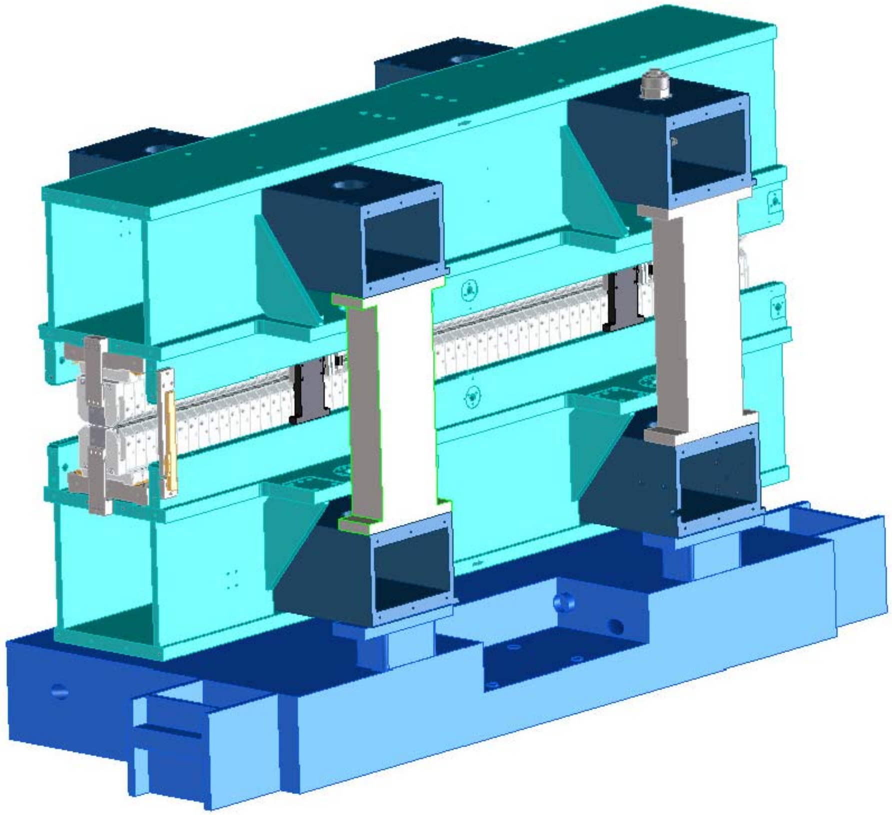
Installed EPUs

Three EPU50s of same Design:

- 4.0.2: MCD, 1998
  - First in a 3rd Gen. ring!
- 11.0.2: MES, 2002
- 11.0.1: PEEM3, 2005

W11: Femto-Slicing Modulator

- Installed 2004
- Replaces W16
- Meets ongoing PX needs
- ~790nm fundamental for femto-slicing
- Re-uses W16 structure and vacuum chamber designs



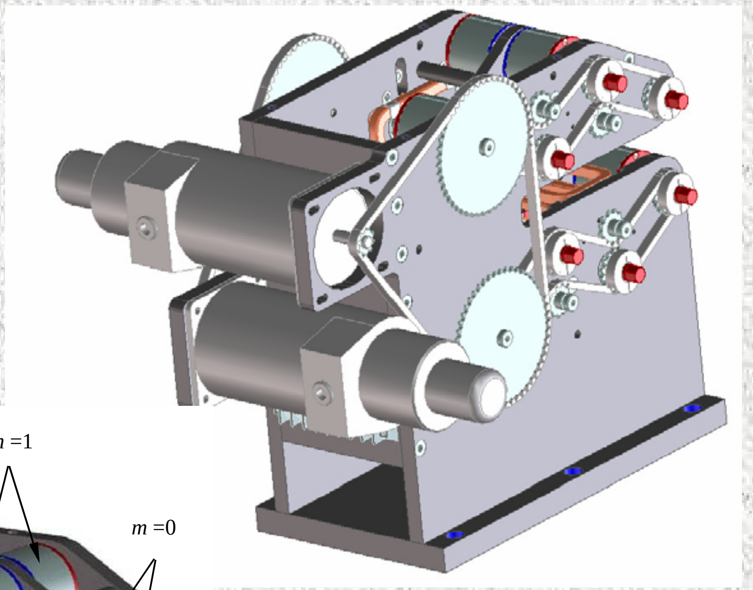
IVID30: Femto-Slicing Radiator

- Installed 2005
- Purchased from Neomax (formerly Sumitomo Special Metals)
- Collaboration with Spring8

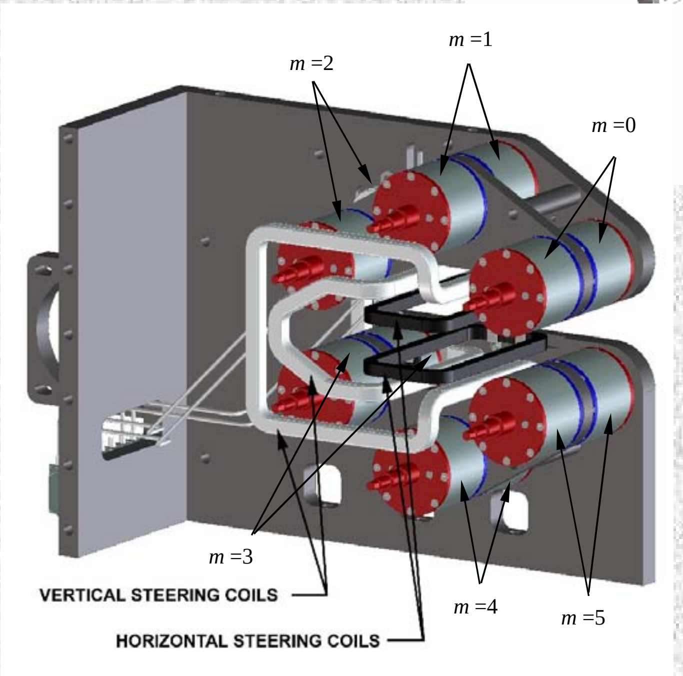
Permanent Magnet Chicane

J. Y. Jung et al., PAC03

- Installed in center of chicaned ID straights
- Objective: eliminate magnetic hysteresis characteristic of iron-core electro-magnets
- Design based upon PM corrector ring concept
- Uses PM rotors to set main field
- Uses air-core coils for fast horizontal and vertical dipole correction

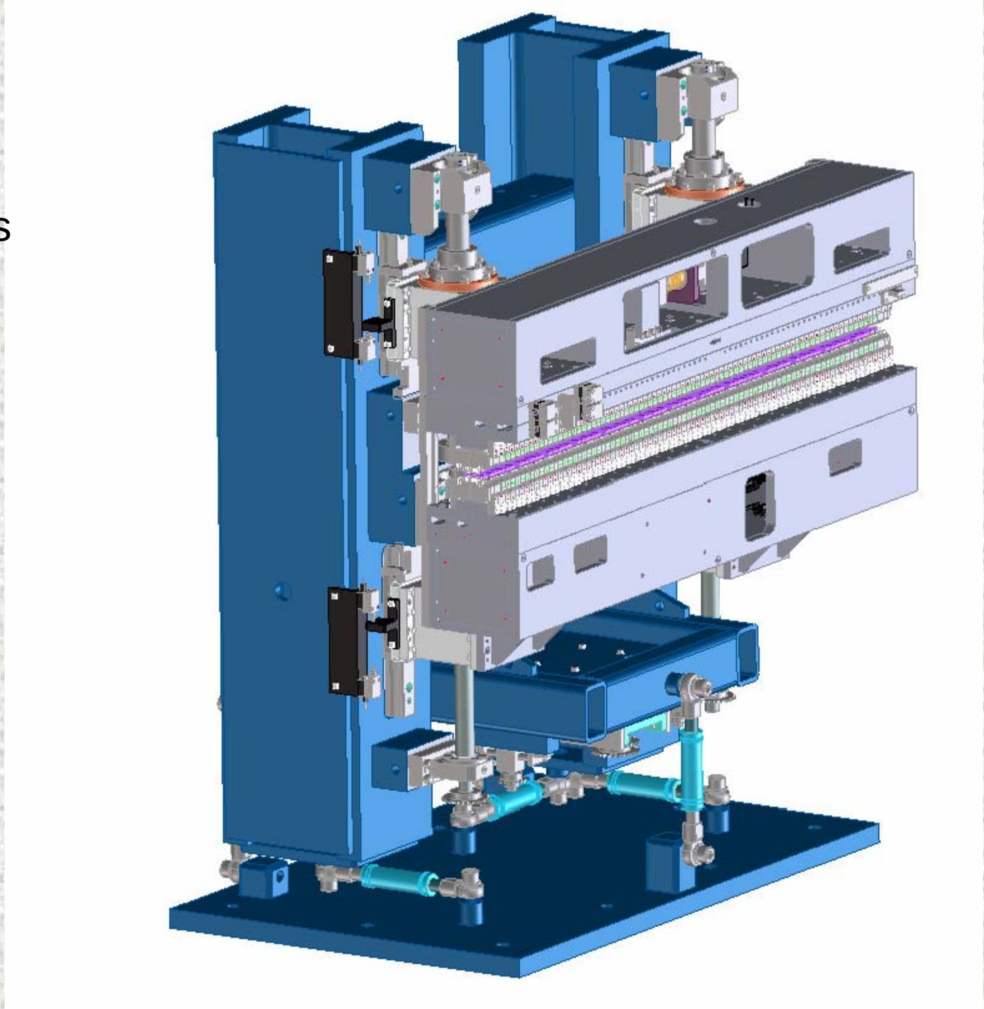


Concept proposed in:
R. Schlueter et al,
NIM Phys Res. A, Vol 395, 1997



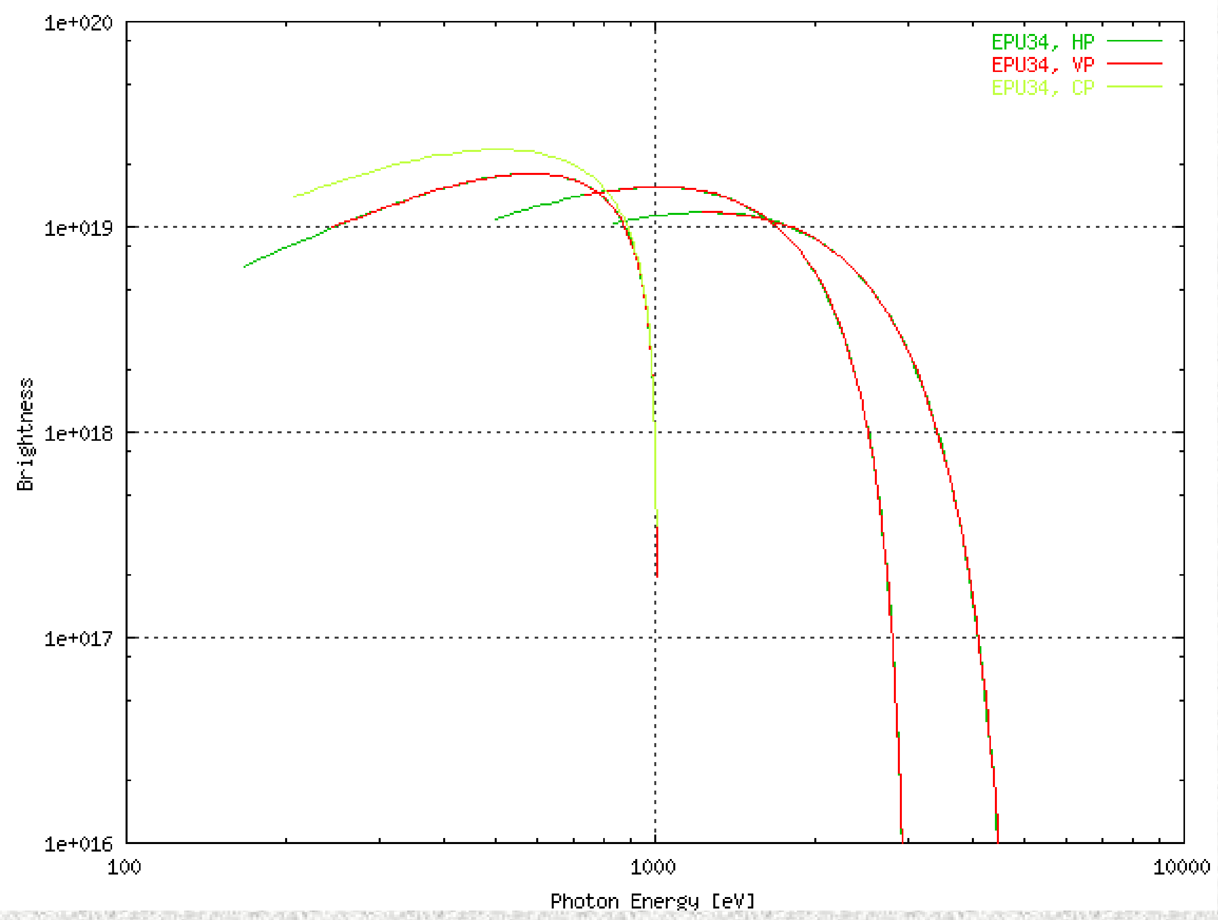
Merlin EPU

- To be installed Spring 2007
- Longer period
  - Higher forces
  - Increased impact on beam dynamics
  - Larger photon fan, increased power
- Quasi periodic
  - Reduce flux from higher harmonics
- New Design Features
  - Stiffer/stronger structure to deal with higher forces
  - New drive system to improve performance
  - Modified magnetic mounting to eliminate systematic relative motion with quadrant shifts



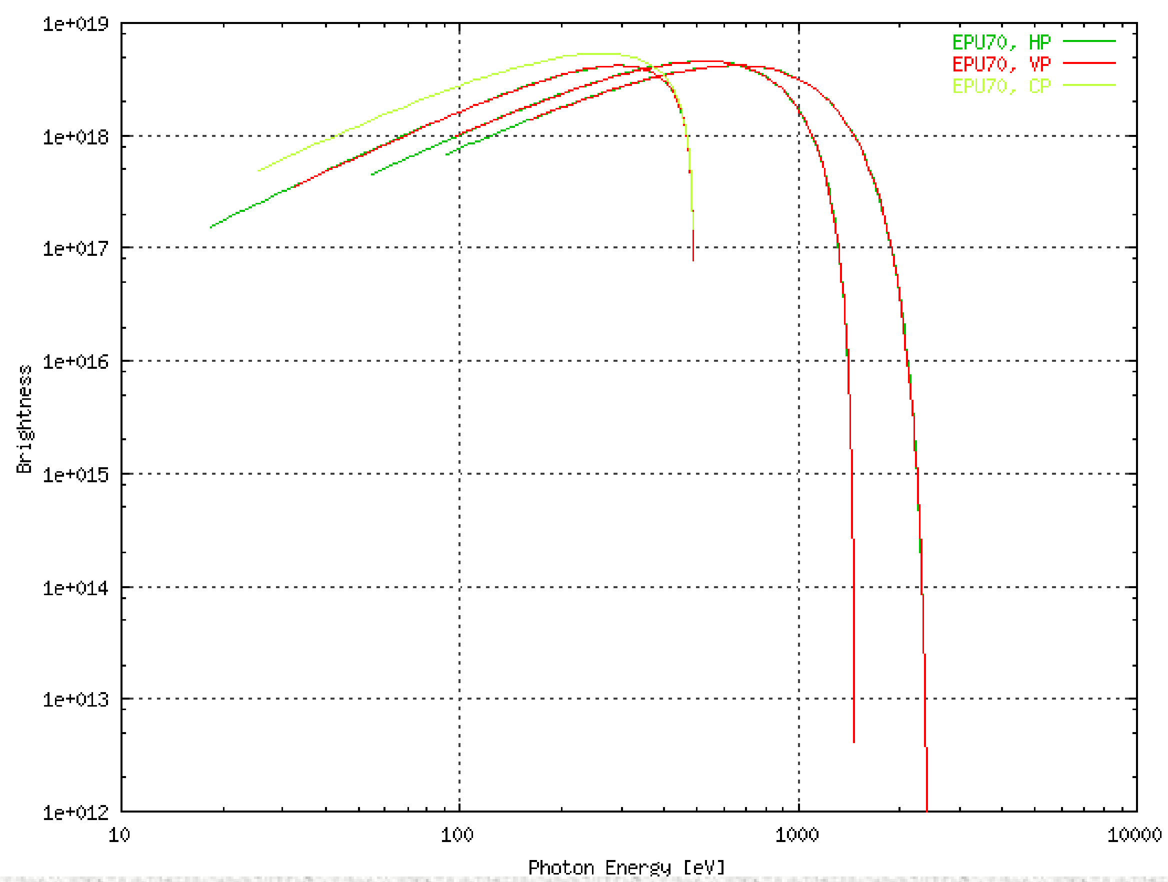
EPU34: Concept for Cosmic

Full Polarization Control E_p > 250 eV



EPU70: Concept for Maestro

- Horizontal Polarization
  E_p > 20 eV
- Vacuum chamber heating limitation:
  - Vertical Polarization
    E_p > 60 eV
  - Circular Polarization
    E_p > 80 eV



Some details of the MERLIN EPU

- Quasi periodic EPU
  - S. Sasaki, NIM Phys. Res. A, 1994; B. Diviacco et al, epac98; J. Chavanne et al, EPAC 1998
  - Optimized spectral properties by varying parameters
    - (e.g. interlattice ratio, block strength)
  - Varying vertical blocks rather than horizontal
    - More effective at generating anharmonic spectrum
    - Individual block perturbations are not self-compensating (steering)
- Blocks mounted on individual keepers
  - Avoid ALS experience with modules (Marks et al, “Shift-dependent Skew Quadrupole…”, MT19, 2005)
- Ends optimized for minimal shift-dependent first integrals
  - Schlueter et al, MT19, 2005; Chavanne et al, PAC 1999

Quasi-periodic synchrotron radiation

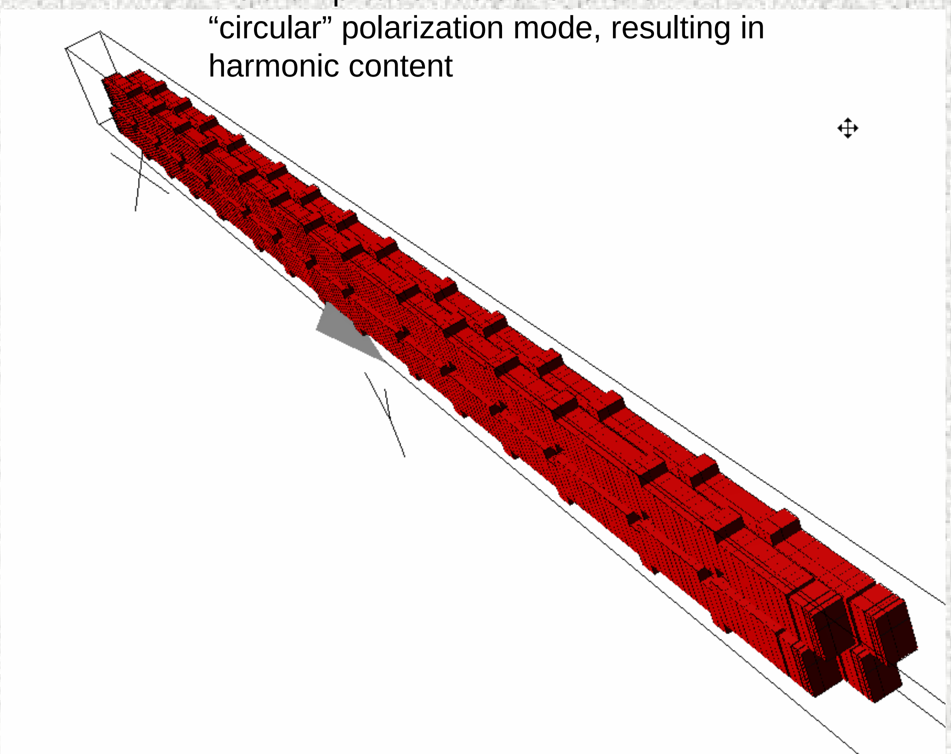
- Idea (introduced by Sasaki): by breaking the periodic magnetic structure in a specific manner, the harmonic structure of the undulator radiation can be modified, yielding "harmonics" at non-integer multiples of the fundamental which are then stopped by the monochrometer
  - Should be particularly useful for low photon energies, where harmonics can excite unwanted electron states;
  - Has been tested on linear undulators at the ESRF, EPU at ELETTRA
  - Currently being investigated by others (Soleil, …) in the case of EPUs

Polarization	EPU90 Fundamental [eV]	QEPU90 Fundamental [eV]
Linear horizontal	8	9
Linear vertical	13	14.7
circular	10.7	12.2

1234 Details of MERLIN QEPU…

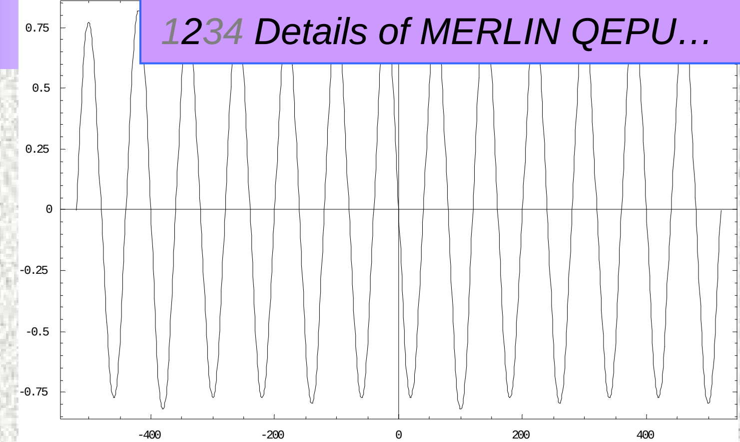
Field components for different polarization modes

- The reduced-strength blocks, when phase-shifted, generate
  - Bz fields
  - By fields even in vertical polarization mode
  - Field-amplitude fluctuations even in “circular” polarization mode, resulting in harmonic content

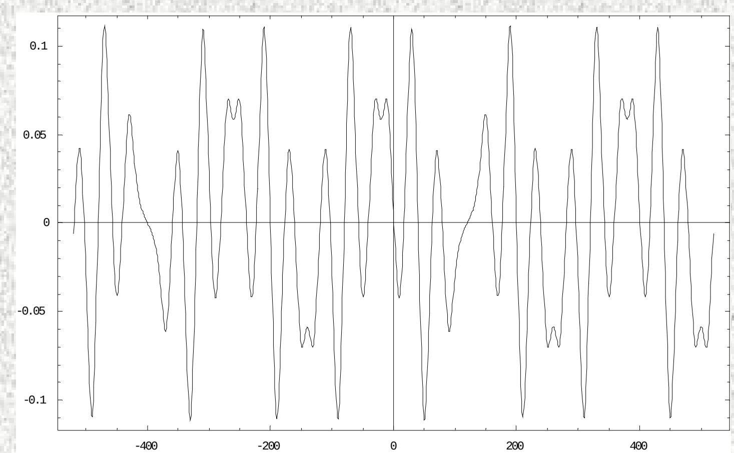


Vertical Polarization mode

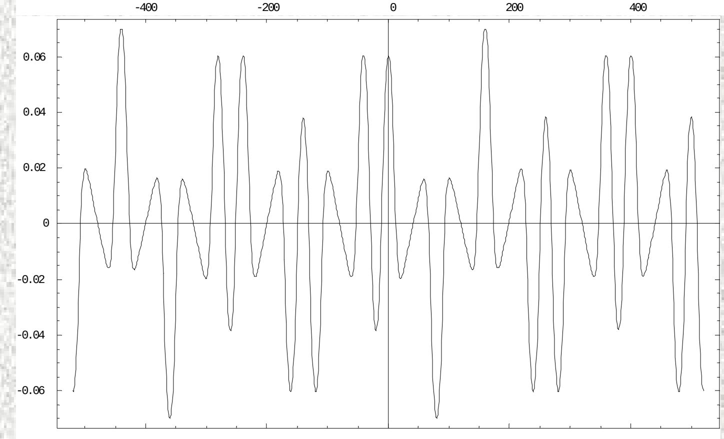
Bx(z)



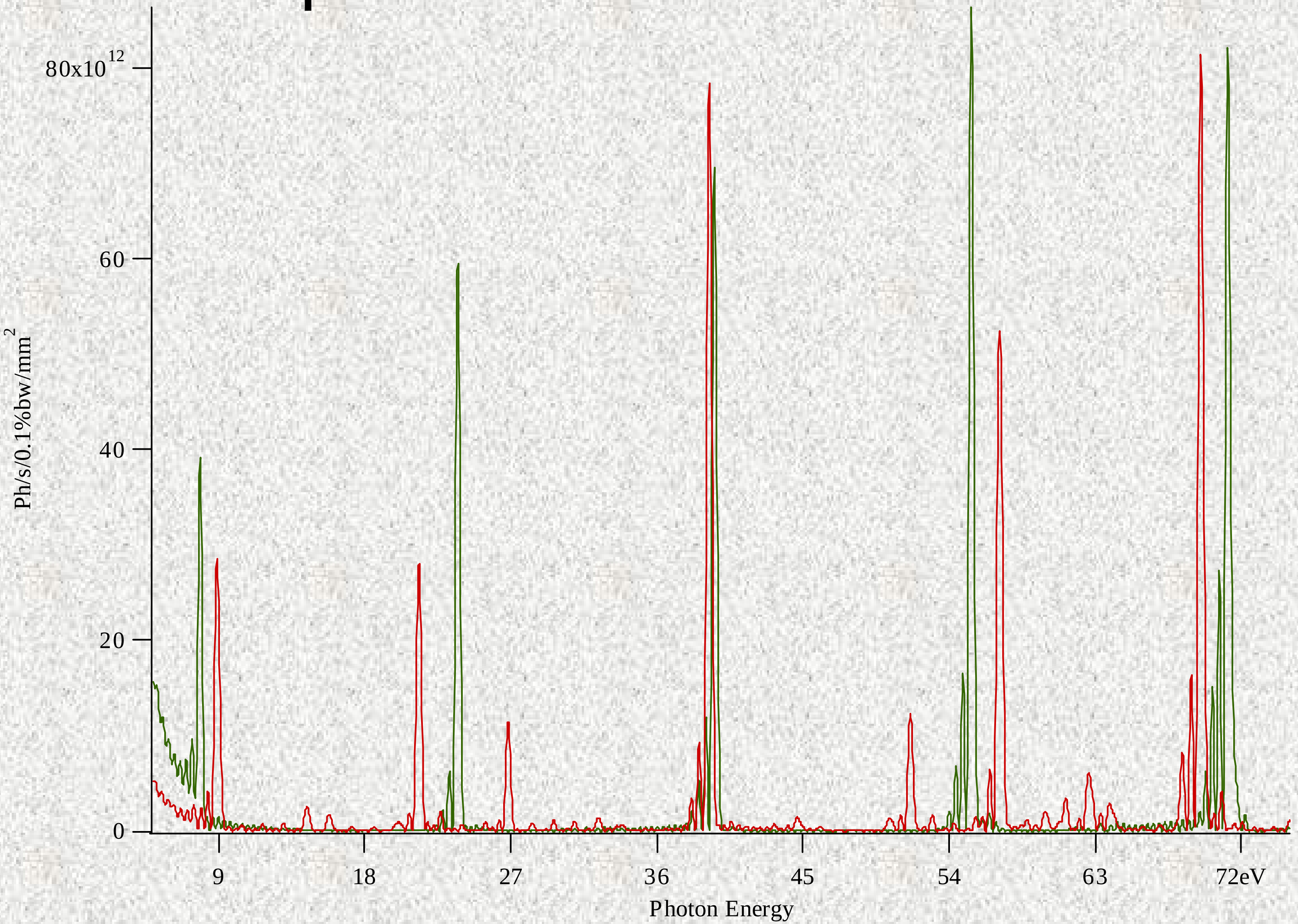
By(z)



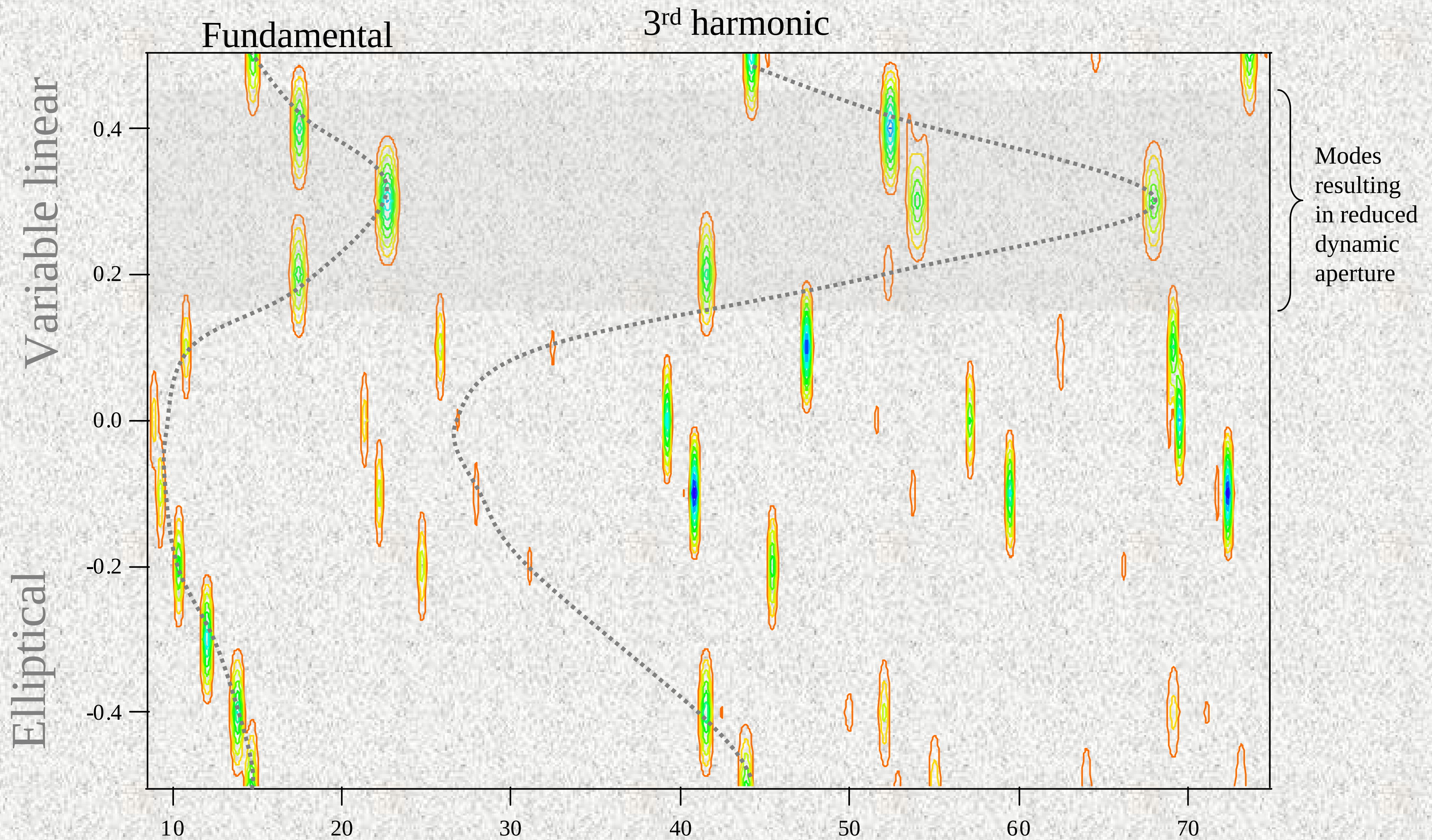
Bz(z)



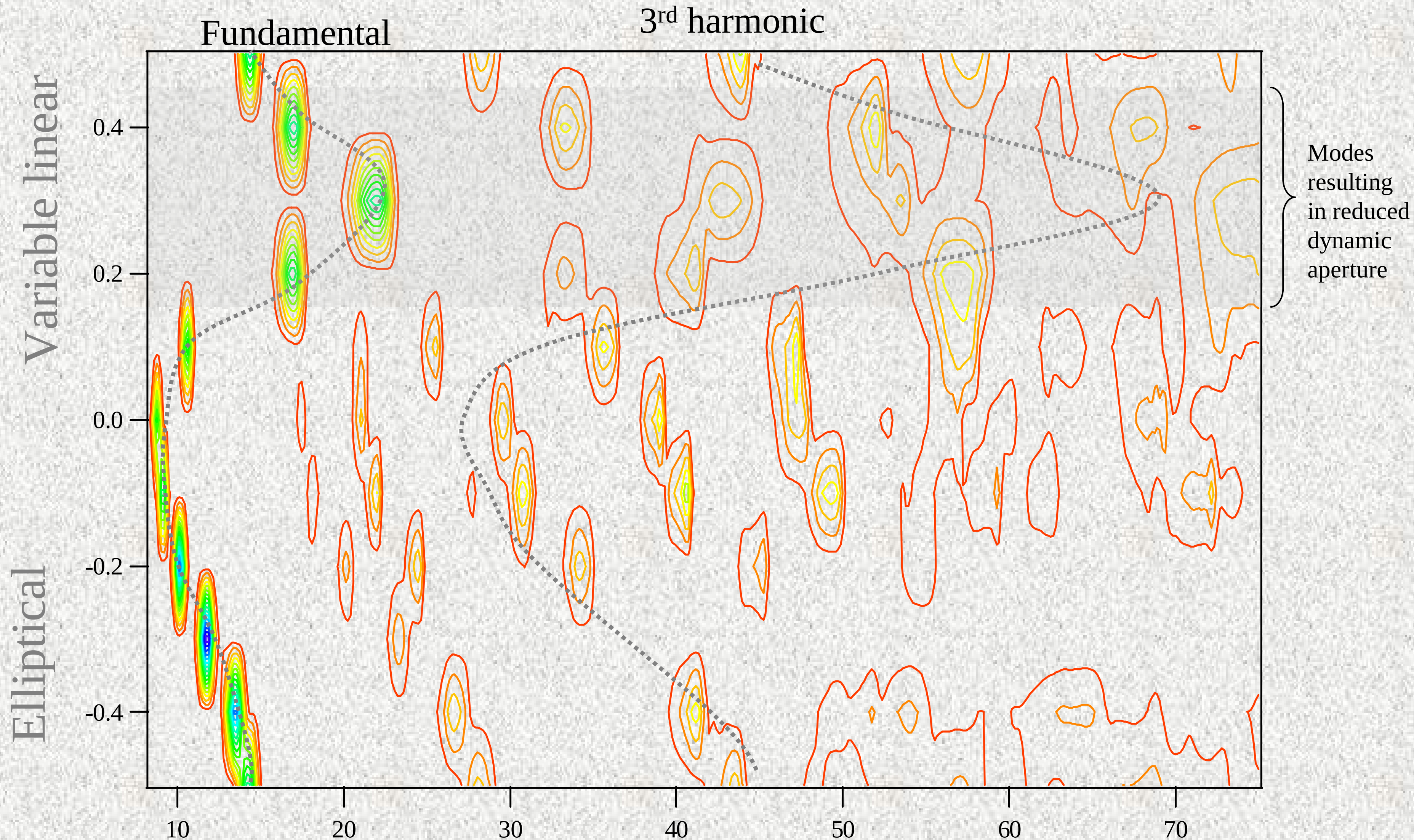
Flux density in horizontal polarization
Comparison with baseline EPU90



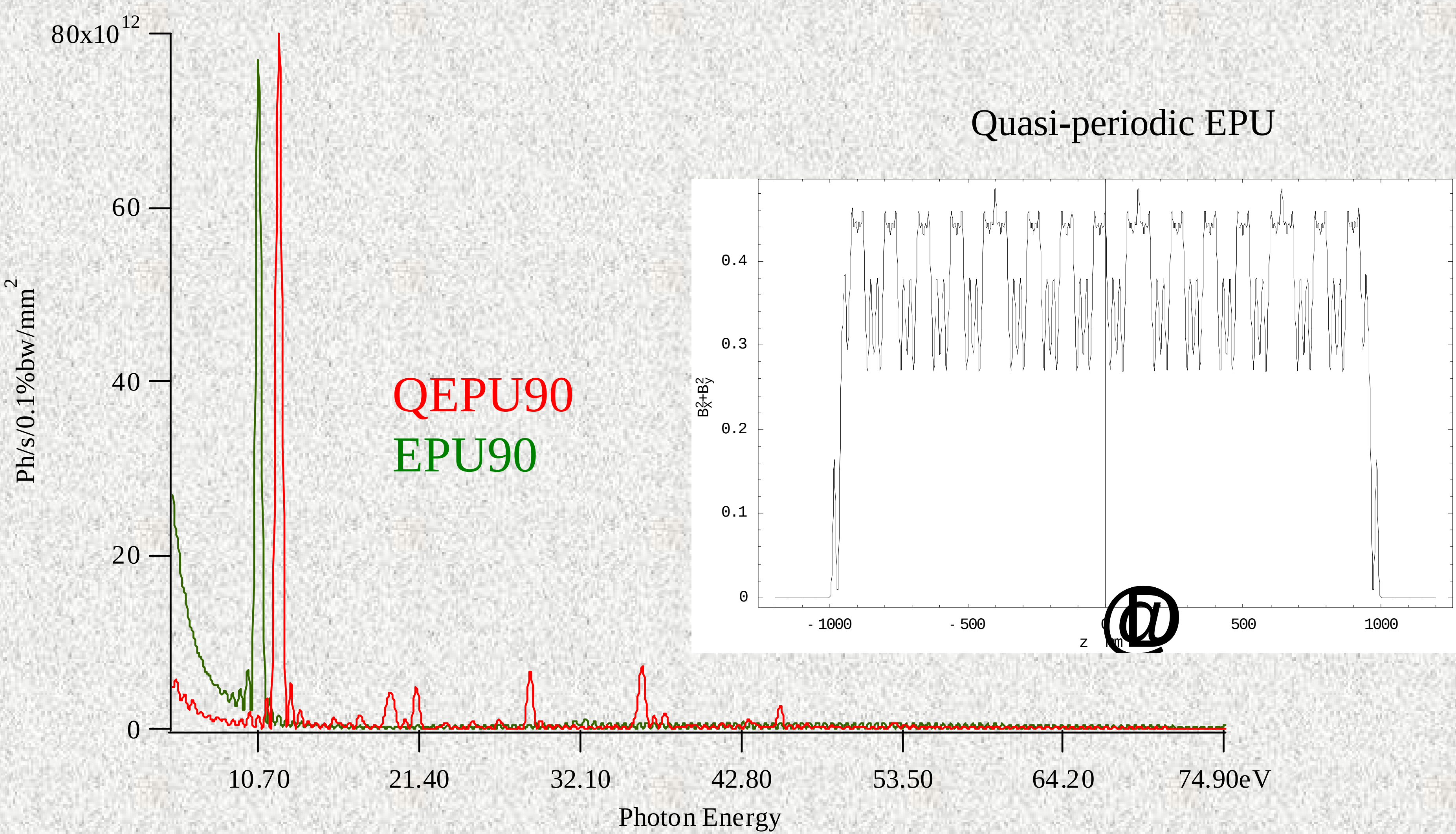
Radiation spectra on axis



Radiation spectra for a (0.6mrad x 0.6mrad) aperture



~Circularly polarized radiation (ds=0.3λ)



Dynamic compensation shims for top-off operation

- Insertion devices typically exhibit natural vertical focusing
  - "Dynamic", i.e. due to particle trajectory coupled to off-axis longitudinal fields (not seen with multipole measurements on the bench)
  - Further "dynamic" defocusing due to field roll-off (see Safranek et al., PAC 2000)
- EPU's have special characteristics:
  - Focus/defocus depending on polarization mode
  - Exhibit strong nonlinear behavior, i.e. (de)focus strength varies with offset
  - Introduces focus/defocus in horizontal plane, where beam dynamics are typically more sensitive

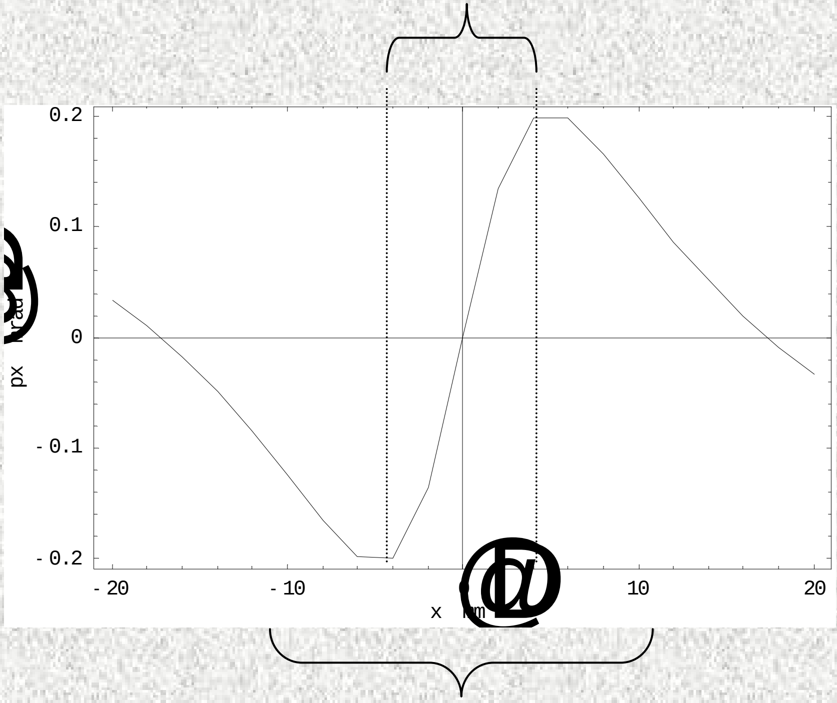
⇒ *Serious impact on lifetime / injection efficiency – tune shift scales with $(\lambda/E)^2$, so problem is worst for low energy rings and long-period EPU's*

⇒ *Nonlinear effects cannot be compensated with other optics; have significant impact on dynamic aperture*

Idea (Chavanne et al., EPAC 2000.;): introduce magnetic shims to compensate for nonlinearity

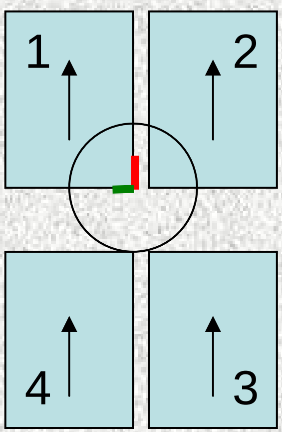
Currently implemented at Bessy (J. Barhdt et al

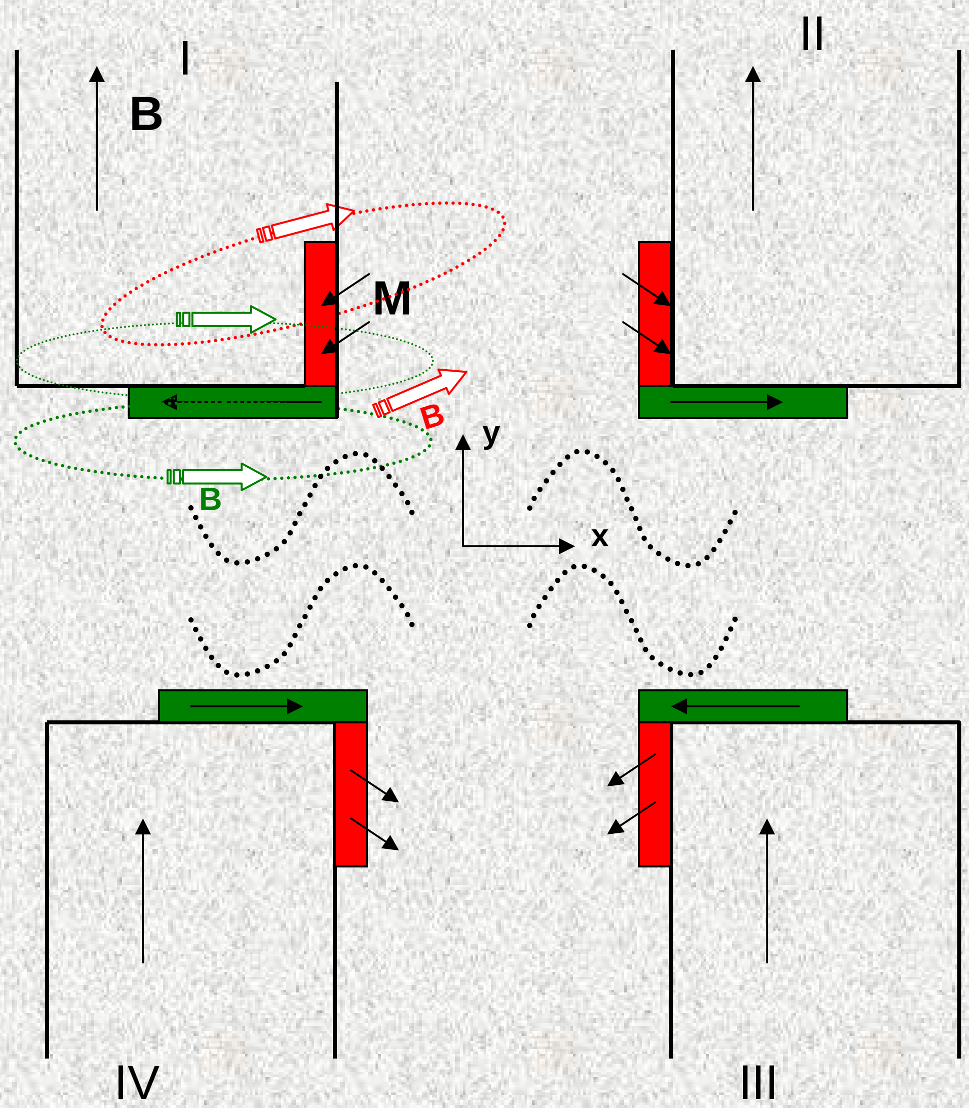
Uncorrected EPU90
Linear defocusing region limited



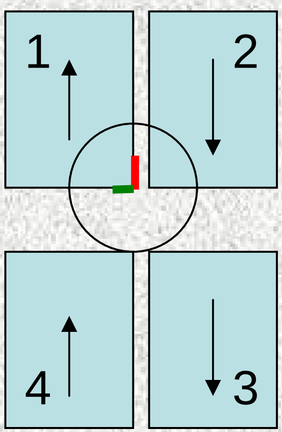
Dynamic aperture needed for top-off

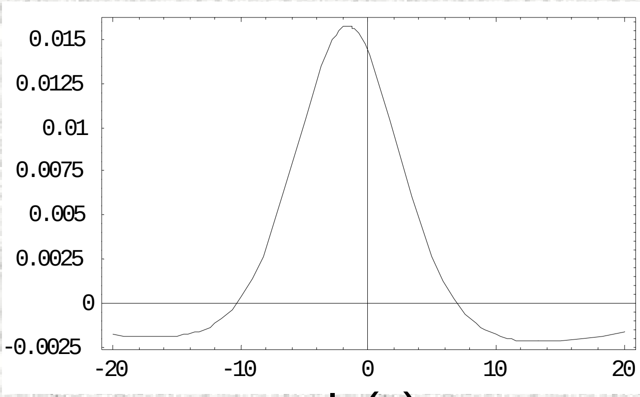
Shim perturbation By(x,y=0)



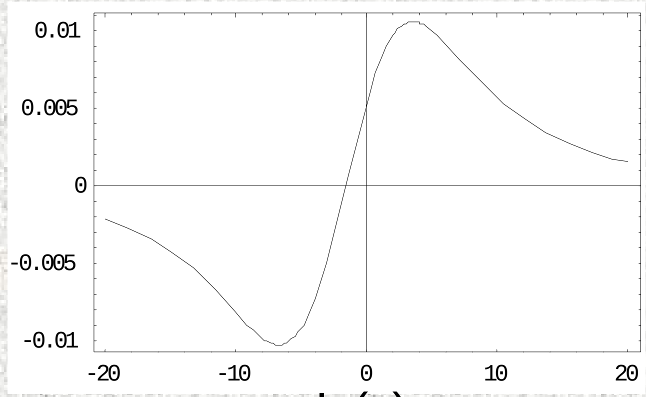


Integrated shim fields and effective focusing



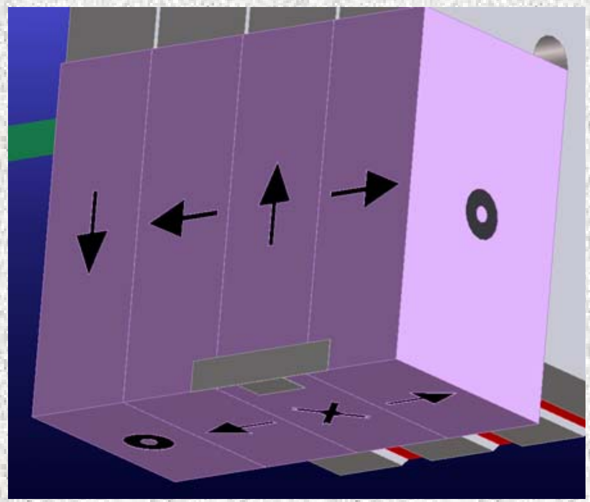


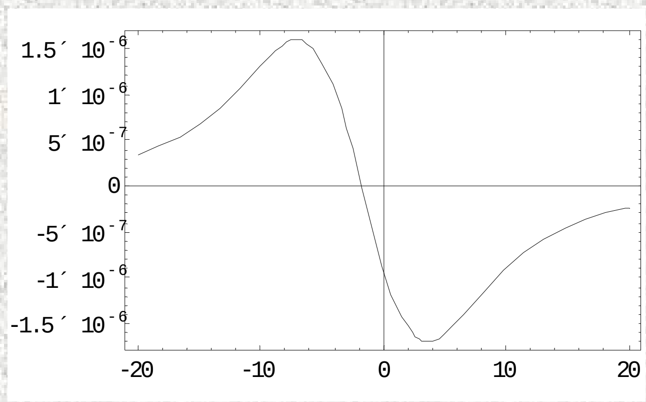
Ix(x)



Iy(x)

Quadrant	Block orientation
Q1	Up
Q2	Down
Q3	Down
Q4	Up

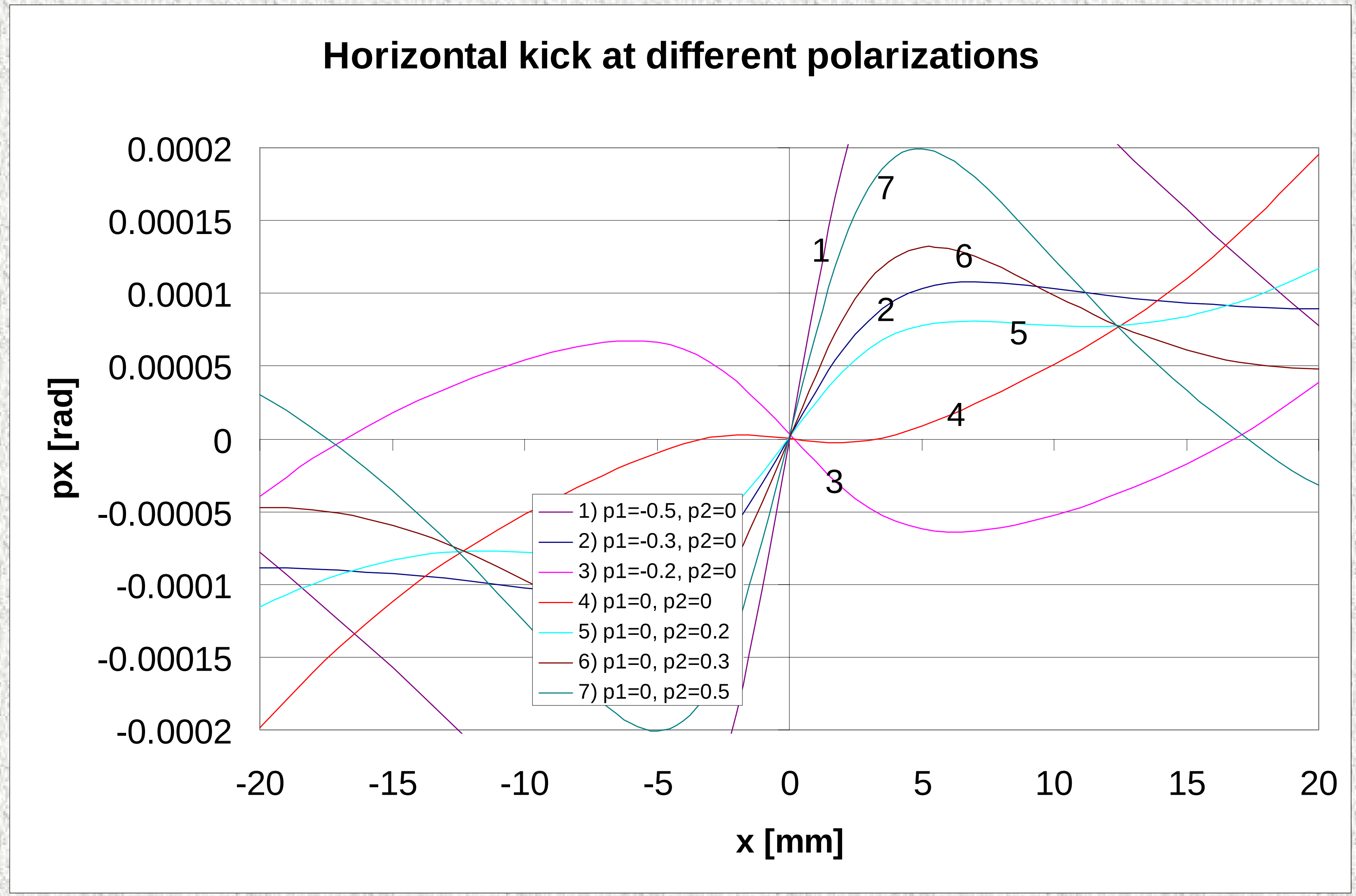




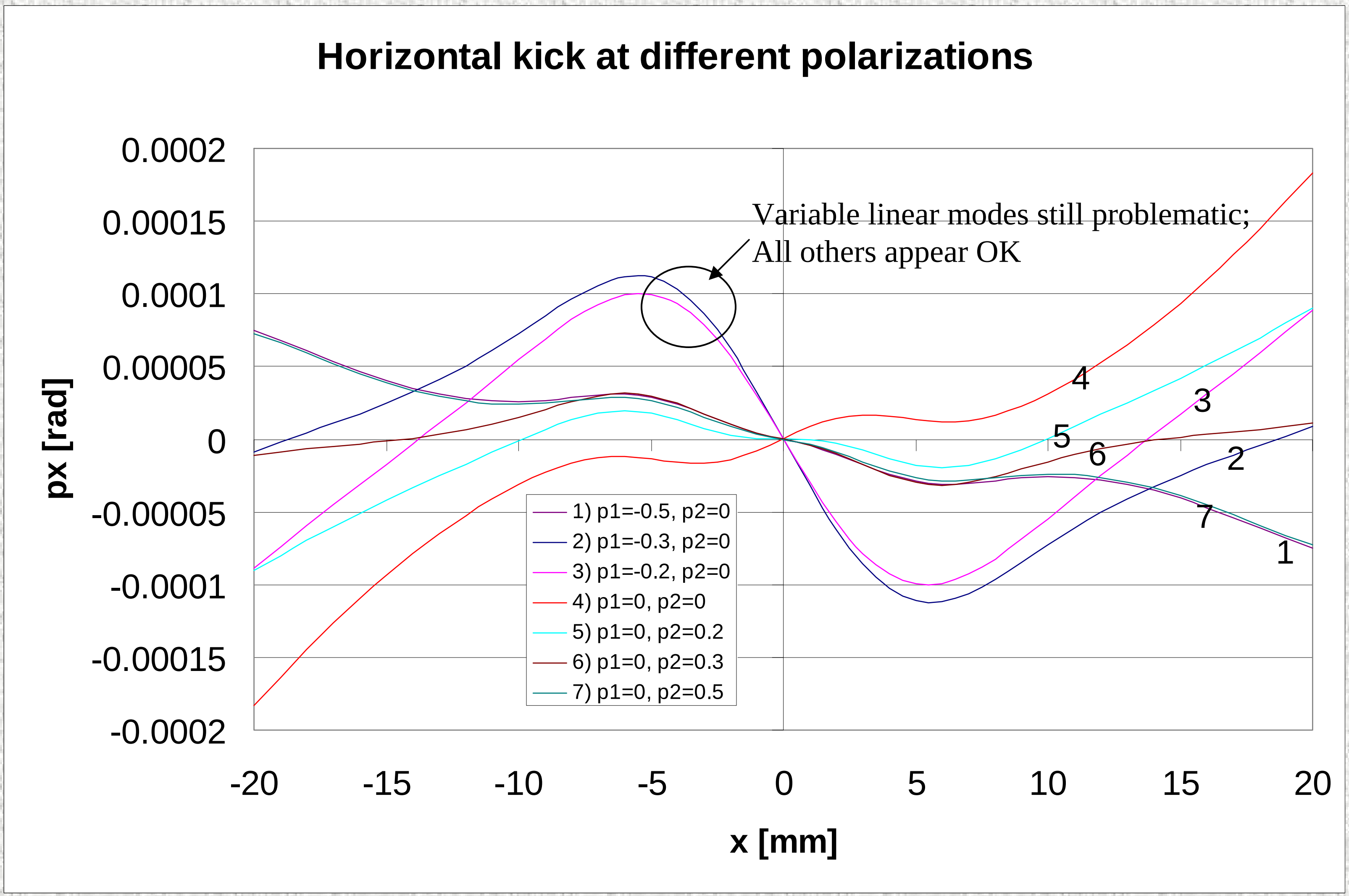
px(x)

Baseline EPU90

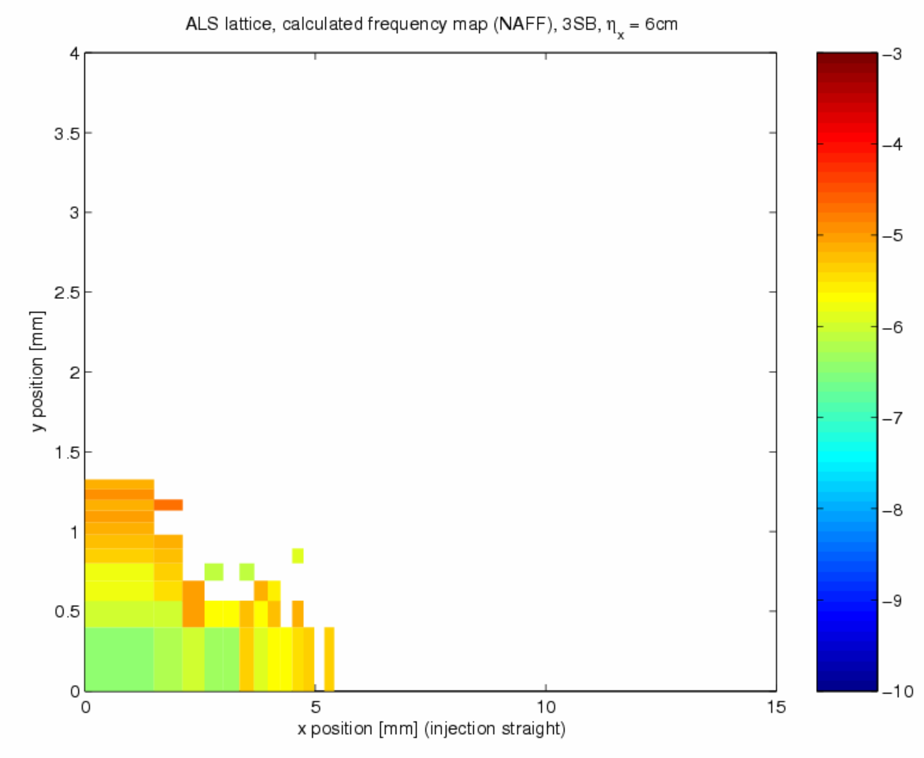
Note: p1 controls variable linear polarization modes,
p2 controls variable elliptical modes (p2=0.3~circular)

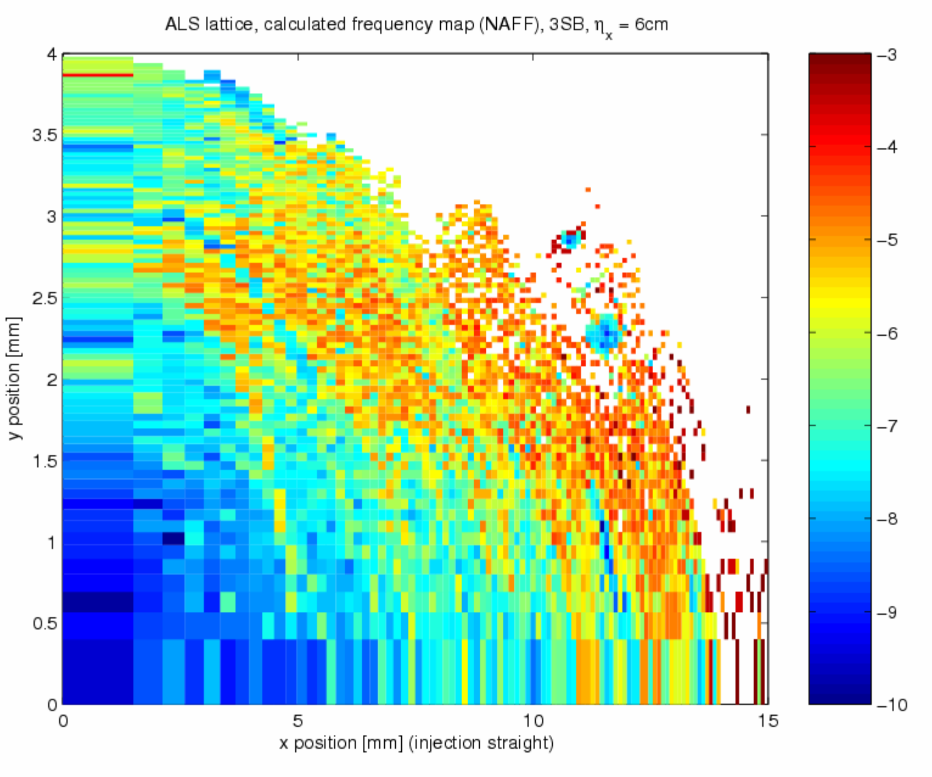


Shimmed EPU90
(Calculated with Radia)

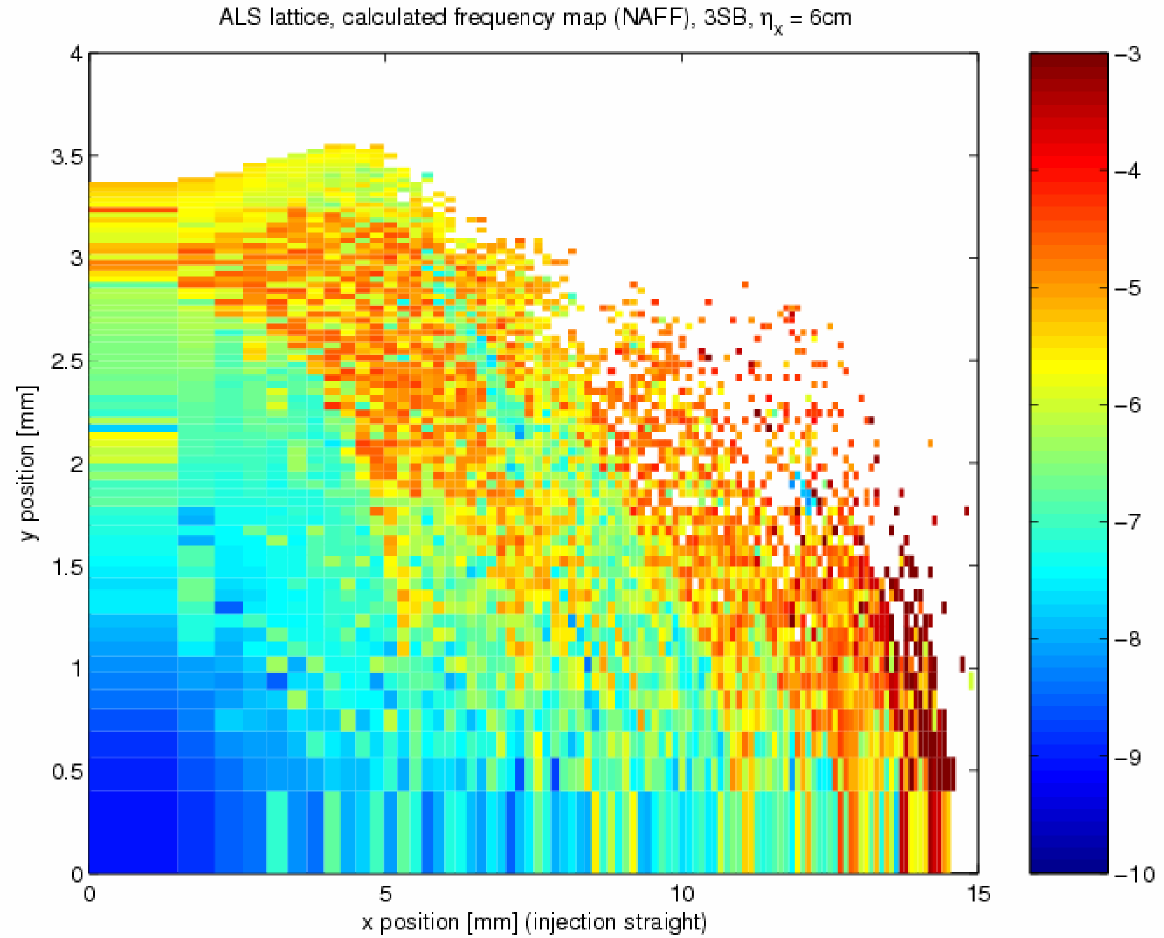


Shimmed Merlin, vertical polarization (calculated, before and after shimming)

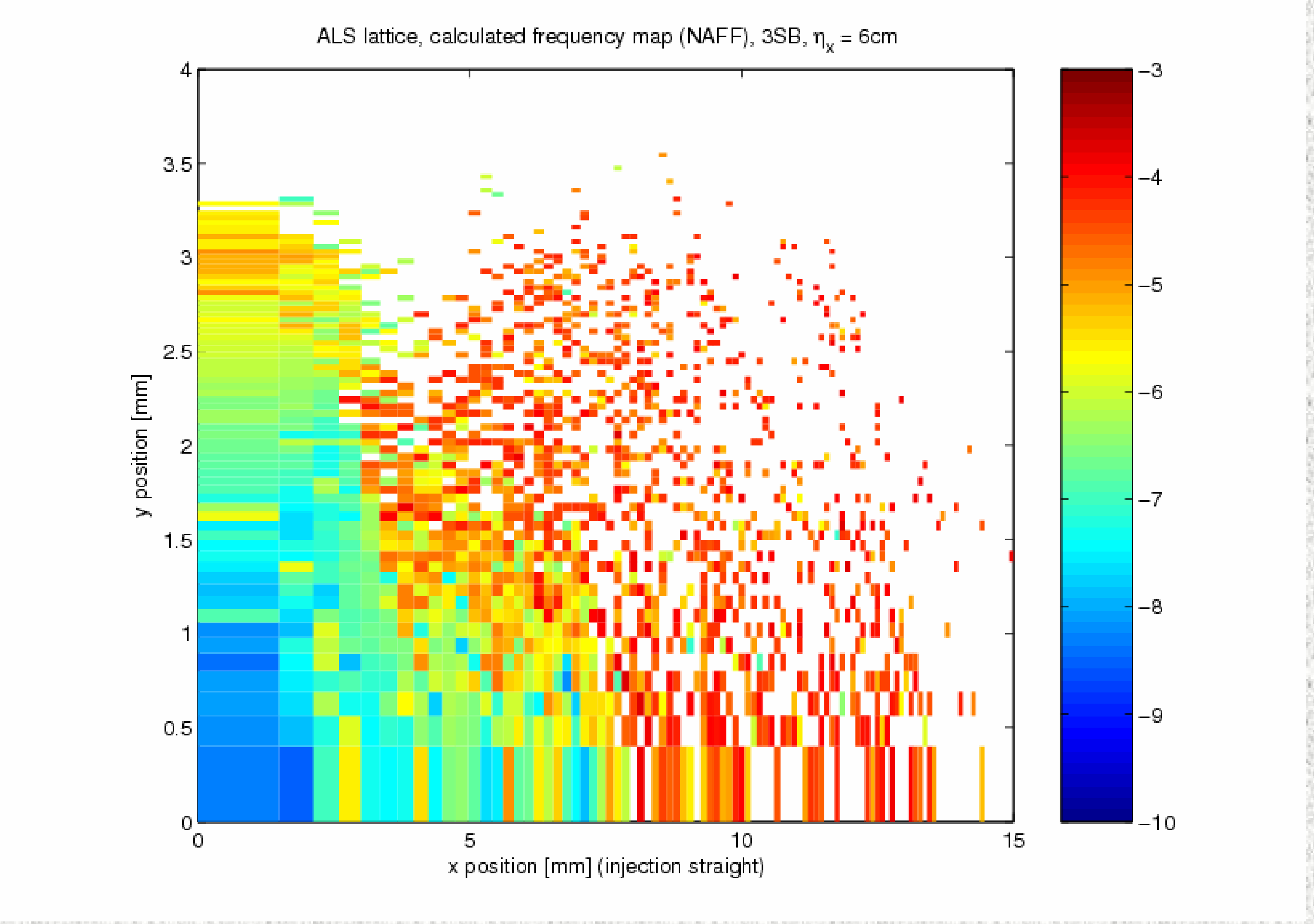




Shimmed Merlin, circular polarization (calculated)

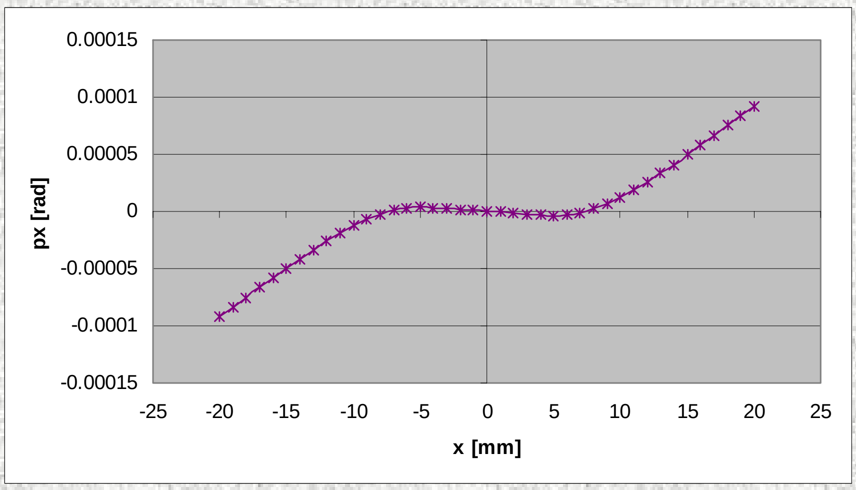


Shimmed Merlin, linear (~45degrees) polarization (calculated)

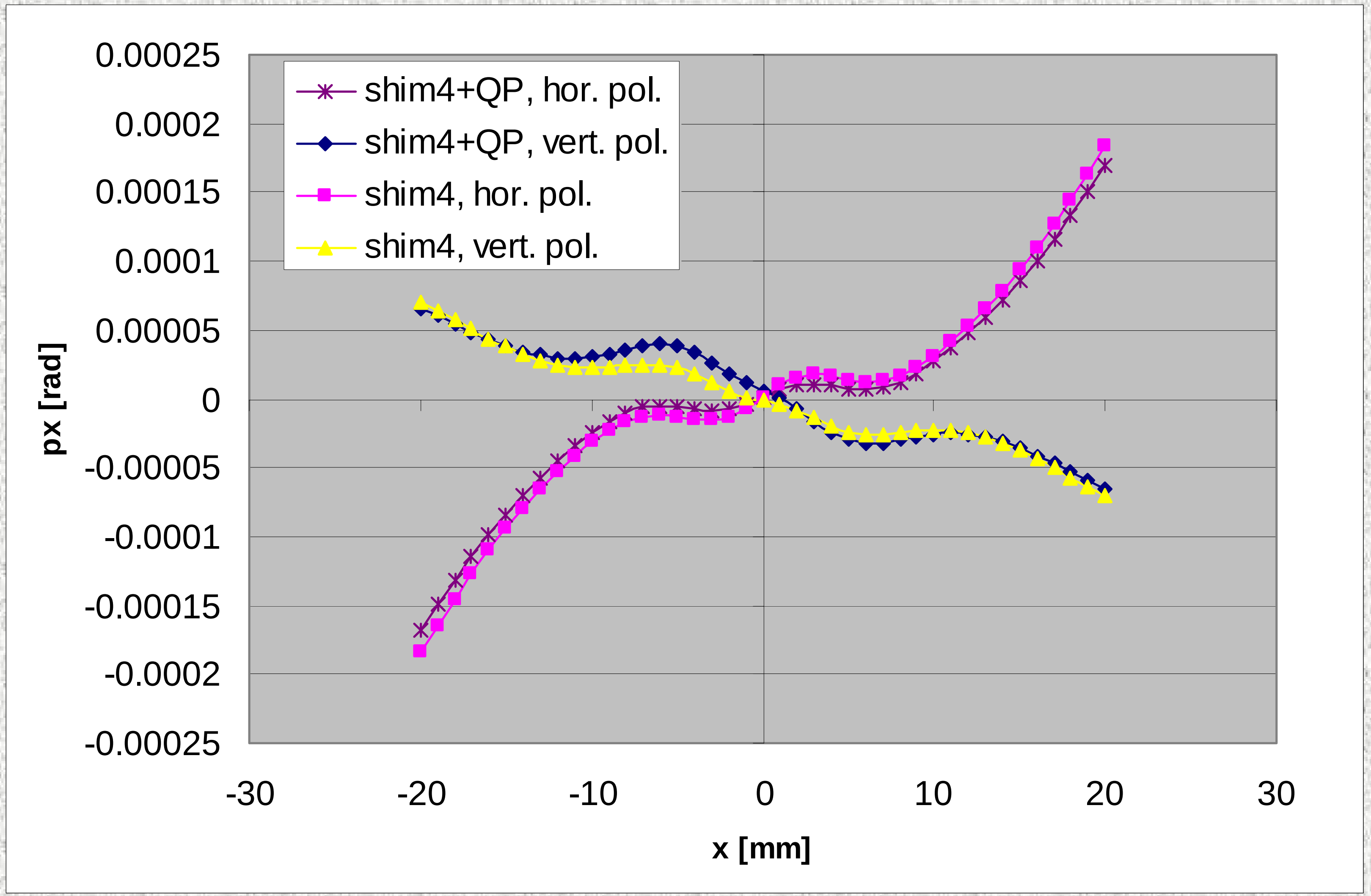


Other scenarios evaluated

- Tracking performed at g=14, nominal minimum gap
- Checked that the dynamic aperture remains acceptable at g=18, 22
  - Tracking was performed for linear horizontal and linear vertical
  - Tracking also performed for elliptical mode, g=22
  - Kick map evaluated for g=18, elliptical mode – appears OK



Combining dynamic multipole correction shims and quasi-periodicity



LBNL Nb_3Sn superconductor Undulator R&D

Collaboration of AFRD & Engineering Div.

Considered for ALS applications:

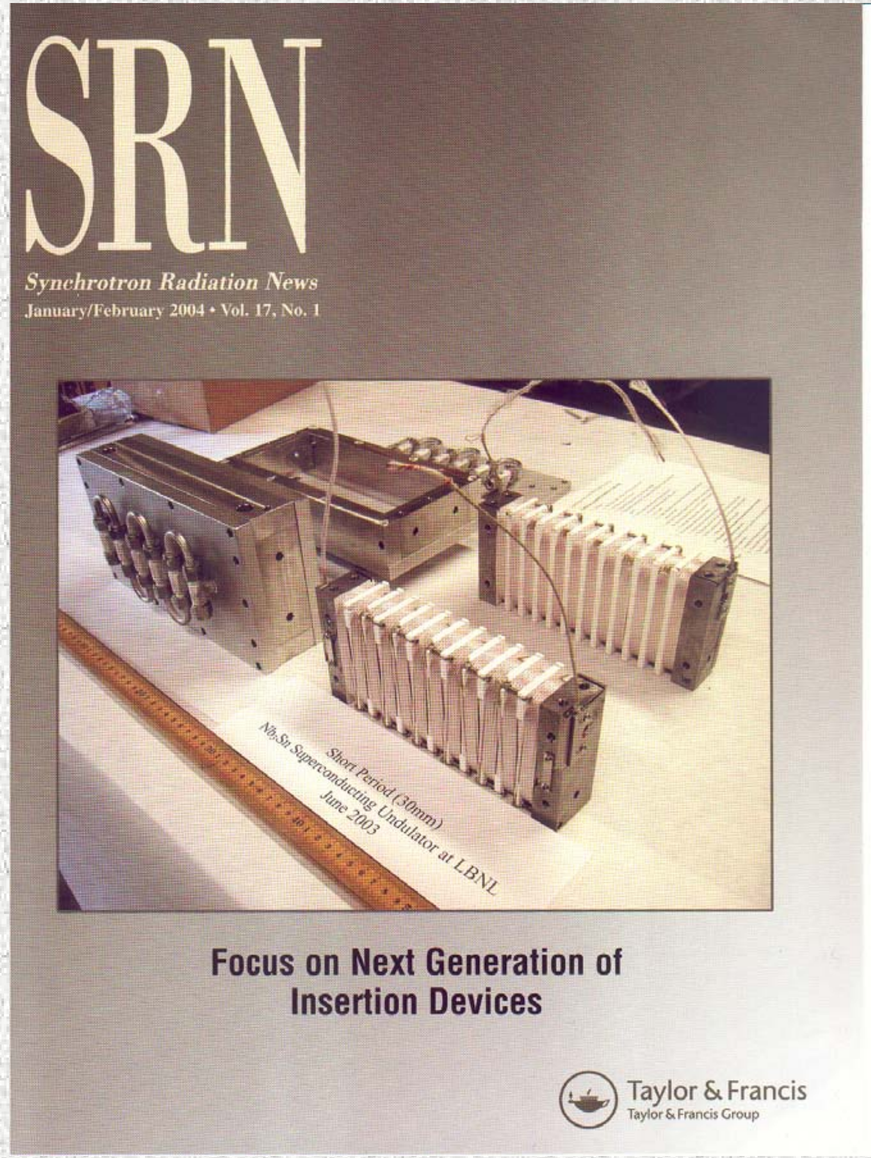
- Radiator for femto-slicing experiment
- Source for protein crystallography

LDRD results (2003-04):

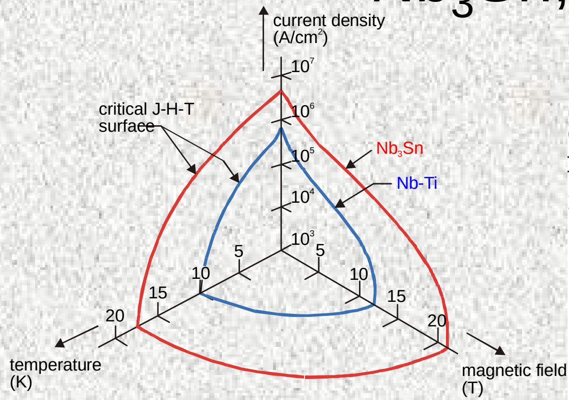
- Two prototypes using 6-strand cable
- 30mm period prototype; 80% of Jc
- 14.5mm period prototype: ~75% Jc

WFO (2005-06, for Argonne Nat. Lab):

- Test single strand conductor
- Design and fabrication improvements
- Reached short sample Jc in 4 quenches



Low-temperature superconductors of interest: Nb_3Sn, NbTi with Artificial Pinning (APC)

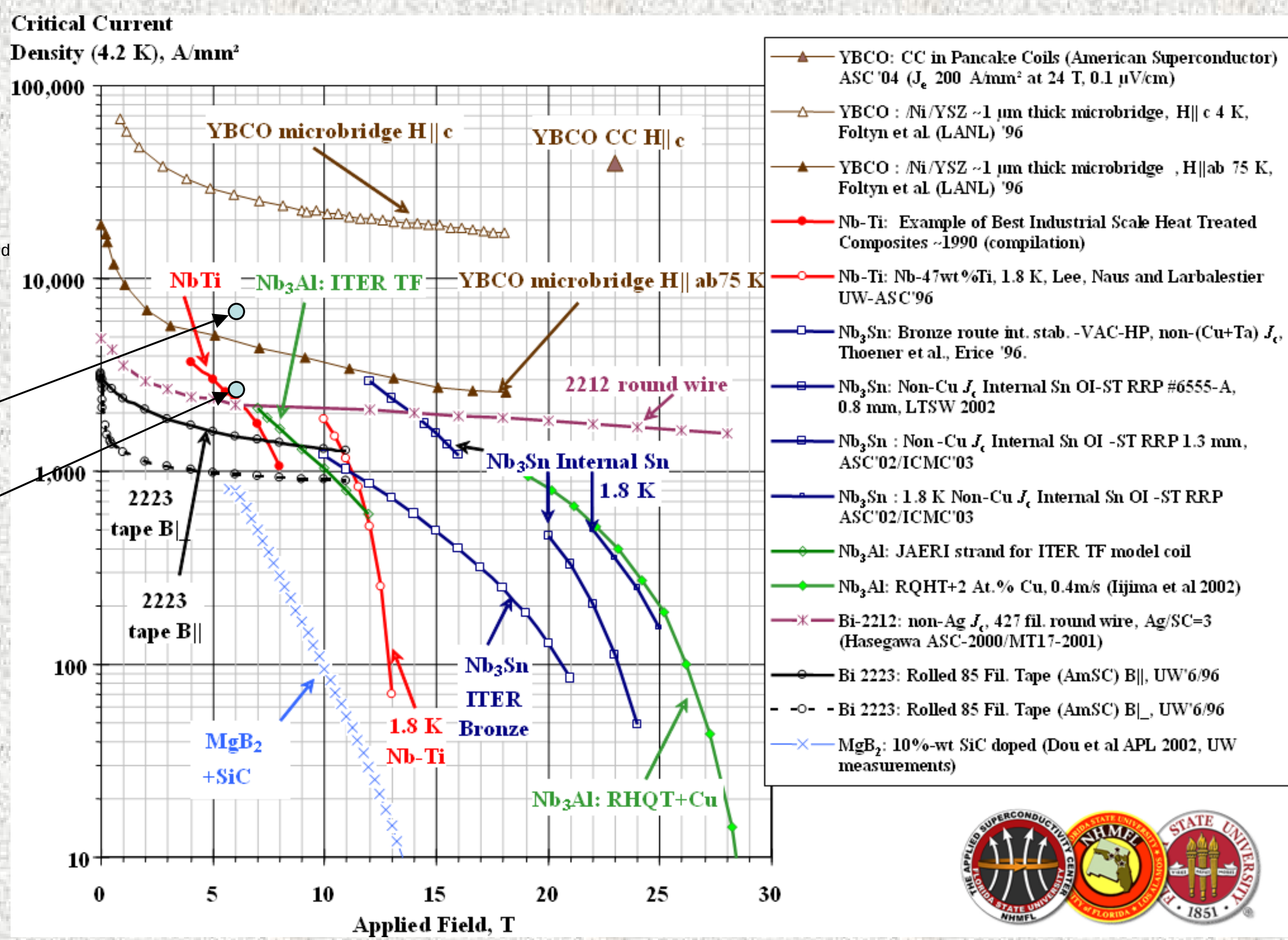


See Thesis of Arno Godeke for an excellent review of Nb_3Sn

Oxford MJR strand used for LBNL Nb_3Sn prototypes

Best commercially available APC NbTi

Peter Lee et al, Applied Superconductivity Center, NHMFL, Florida



See *R. Scanlan and D. Dietderich, IEEE Trans. Applied Supercond., Vol. 13, No 2, June 2003* for review of recent improvements in Jc of Nb_3Sn

Superconducting undulator R&D at LBNL

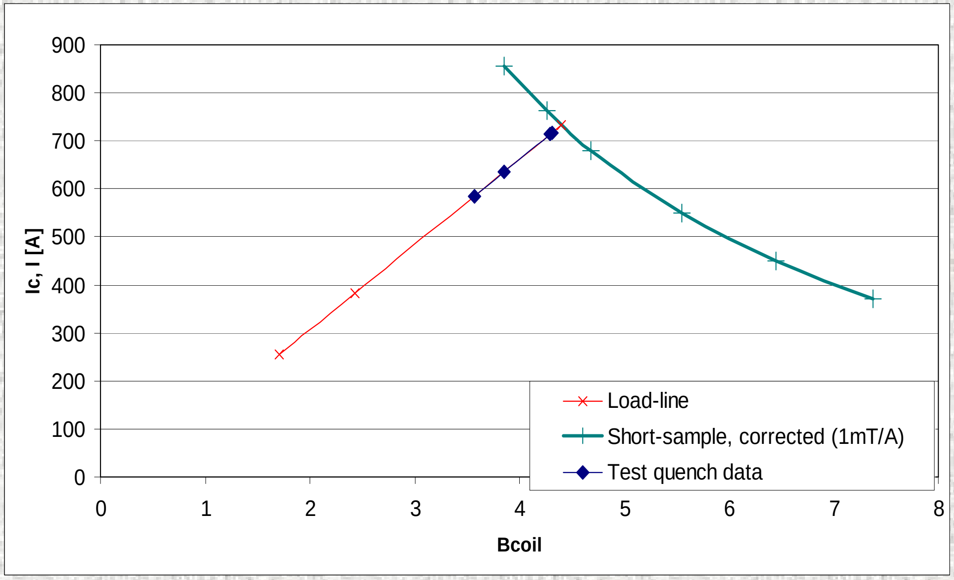
- **Issues addressed:**
  - Conductor stability and magnet protection under extremely high current operation
  - Demonstrated ability to provide field kick for phase-error correction
  - Demonstrated fabrication techniques to yield peak conductor performance in a real magnet configuration
- **Remaining issues**
  - Field measurement system for phase-error determination
  - Full phase-error correction scheme
  - Calorimetric measurements of beam-based heating on real rings
  - For SC-EPU:
    - demonstrate reasonable ramp-rates for field (photon energy) variation
    - Demonstrate switching network for period-doubling operation

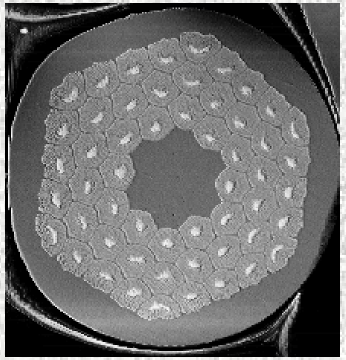
Prototype III undulator quench performance

- Five quenches:
  - 585A, 585A, 635A, 717A, 714A
  - At 717A:
    - Jsc=8250A/mm2
    - Jcu (quench)=7600A (self-protected)
    - Jav = 1760A/mm2 (using full pocket size)

Record performance

Jc (12T, 4.2K)
Old generation ~2000A/mm^2
(This was used for all of the LBL prototypes)
New generation ~3000A/mm^2
(just need to get the filament size down…)





Magnetic gaps and lengths for future insertion devices at the ALS

- Gaps, assuming 5mm vacuum aperture:
  - PM, PM-EPU: 7.3mm (1mm wall thickness, existing controls spacings; could be reduced, but risk increases – no hard stops, chance of hitting chamber…)
  - IV, *IV-EPU:* 5.4mm (0.4mm needed for controls, RF foil)
  - *SCU, SC-EPU*: 6.6mm (0.75mm wall thickness)
- Lengths:
  - PM: 2m (extend devices from current 1.85m by eliminating end chicanes & chambers)
  - IV: 1.62m (lose 360mm compared to PM on each side due to RF transitions)
  - SCU, SC-EPU: 1.6m (“cold-bore” operation; RF transitions do not move, but need space for thermal transitions; this is a reasonable estimate)
  - IV-EPU: 1.55m (RF transitions are a definite concern; this is an optimistic guess)

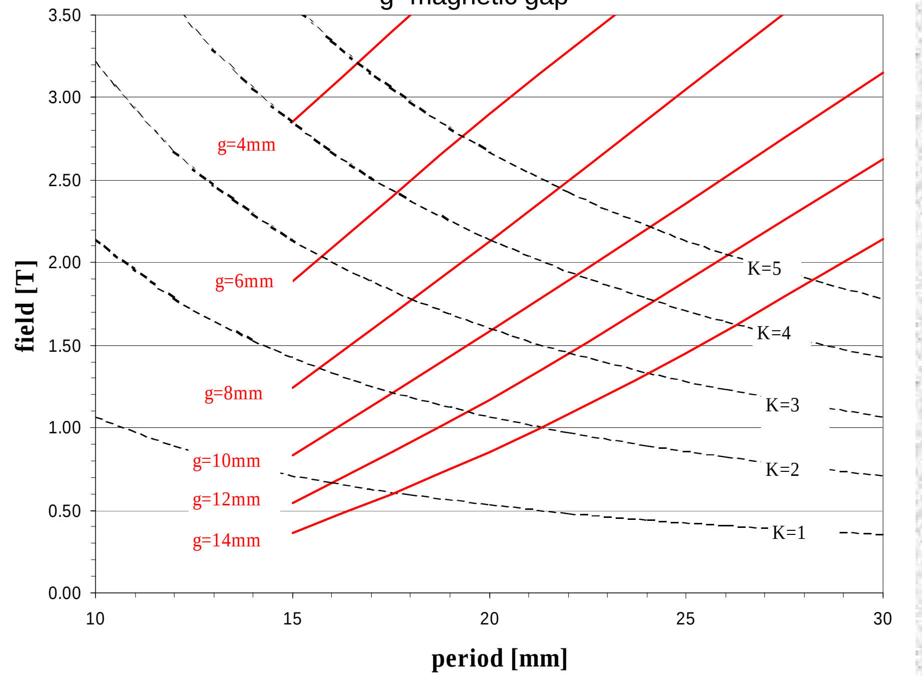
- To avoid heating vacuum chamber/magnets with SR, the estimated peak vertical K value for a 2m device is ~4.5. For PM, PM-EPU one could consider cooling the vacuum chamber, but the risks/issues have not been evaluated.

Review of LBNL interest/effort in superconducting undulators

Nb_3Sn SCU performance curves

24% superconductor in coilpack, J_c(4.2K,6T)=6800A/mm^2

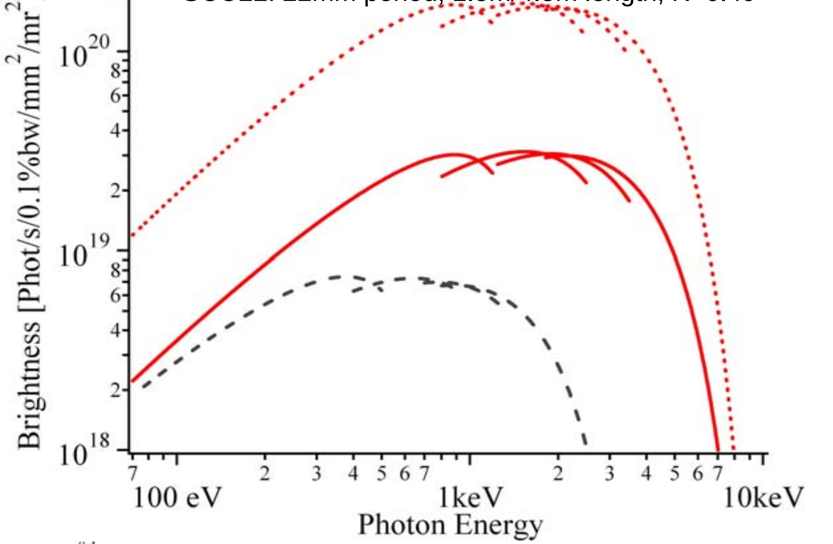
g=magnetic gap

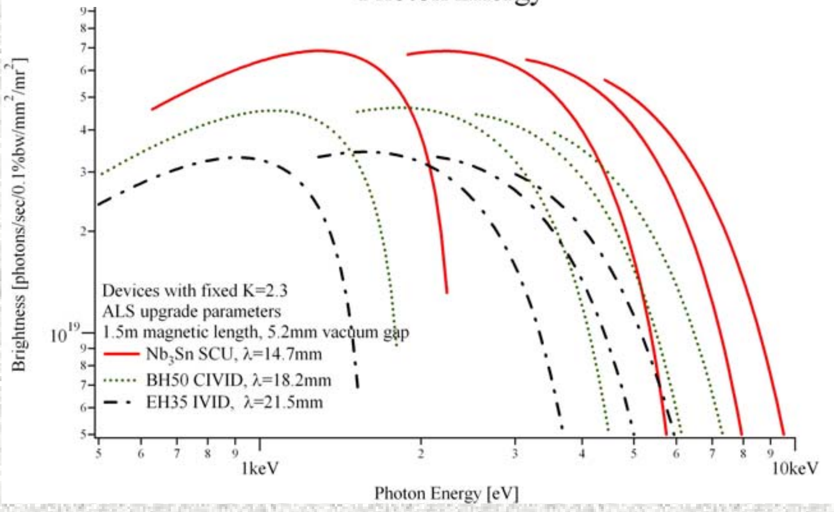


ALS upgrade parameters

U50: 50mm period, 4.5m length, K=3.97

SCU22: 22mm period, 1.5m/4.5m length, K=6.49





Papers:

- Prestemon, S. et al. Proceedings, PAC2003
- M. A. Green, D. R. Dietderich, S. Marks, S. O. Prestemon, Advances in Cryogenic Engineering, AIP, Vol. 49, p 783-790., 2004
- Prestemon, S.; Dietderich, D.;Marks, S. ; Schlueter, R. Synchrotron Radiation Instrumentation, AIP, vol. 705, p 294, 2004.
- Ross Schlueter, Steve Marks, Soren Prestemon, and Daniel Dietderich, Synchrotron Radiation News, January/February 2004, Vol. 17, No. 1.
- S. O. Prestemon et al., IEEE Transactions on Applied Superconductivity, June 2005
- S. Prestemon, R. Schlueter, S. Marks, D. Dietderich, presented at MT19, Sep. 18-23, 2005, Genoa, Italy
- D. R. Dietderich et al., Presented at ASC2006, Seattle, Wa.

ALS performance enhancement, Application Protein Crystallography

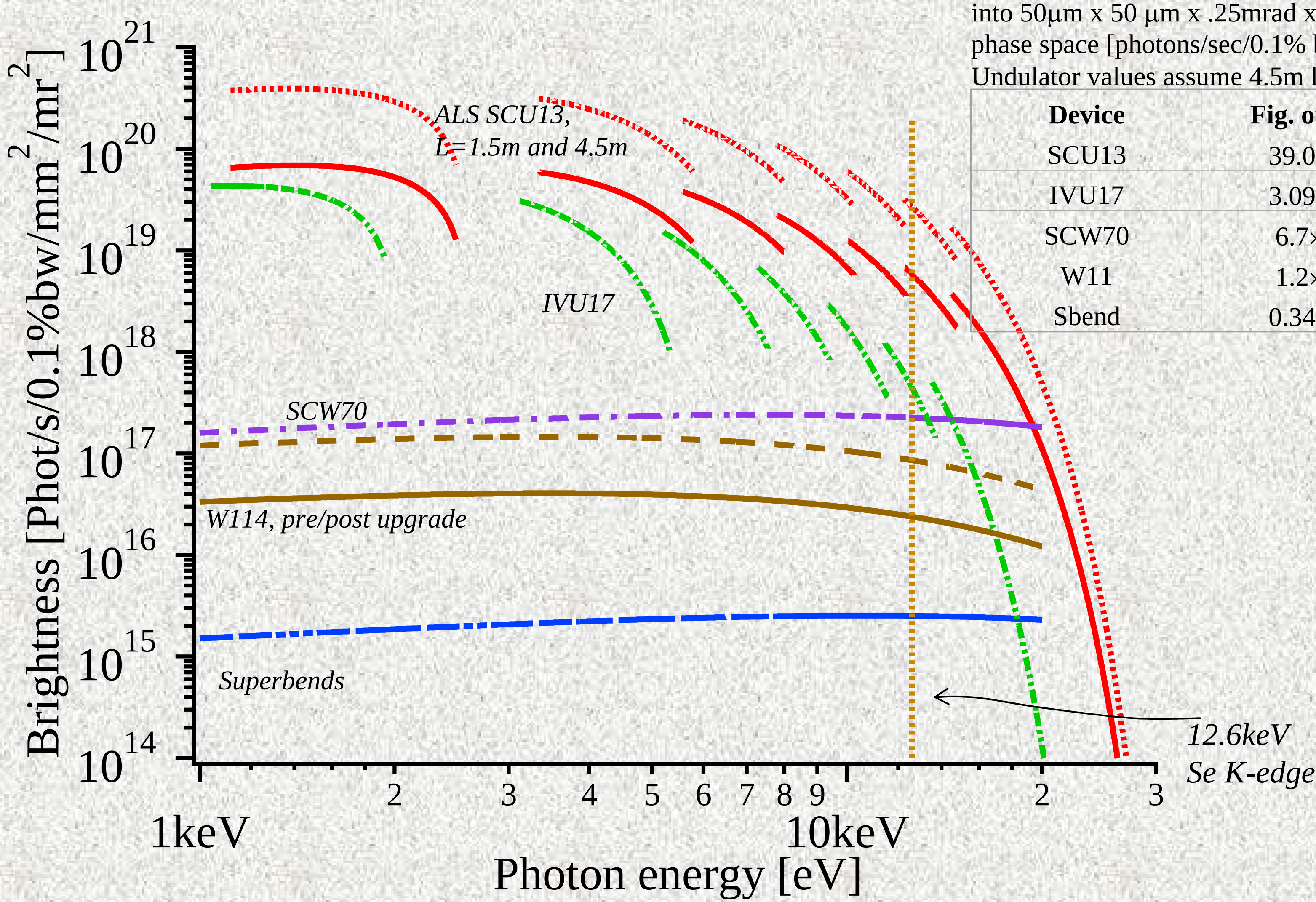


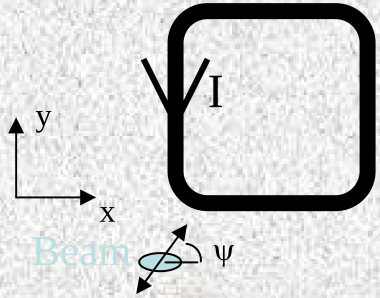
Figure of merit: flux at 12.6keV accepted into 50μm x 50 μm x .25mrad x .25mrad phase space [photons/sec/0.1% bw] . Undulator values assume 4.5m lengths.

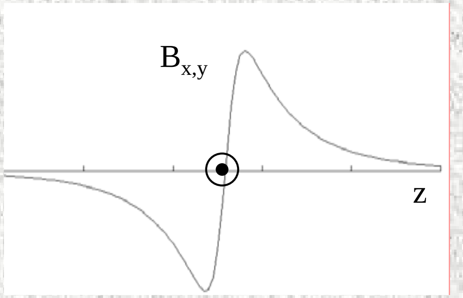
Device	Fig. of merit
SCU13	39.0×10^{12}
IVU17	3.09×10^{12}
SCW70	6.7×10^{12}
W11	1.2×10^{12}
Sbend	0.34×10^{12}

Polarization control

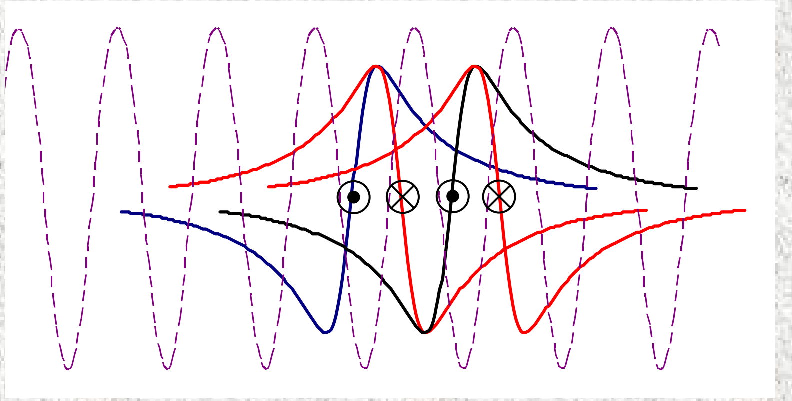
Generating variable linear polarization

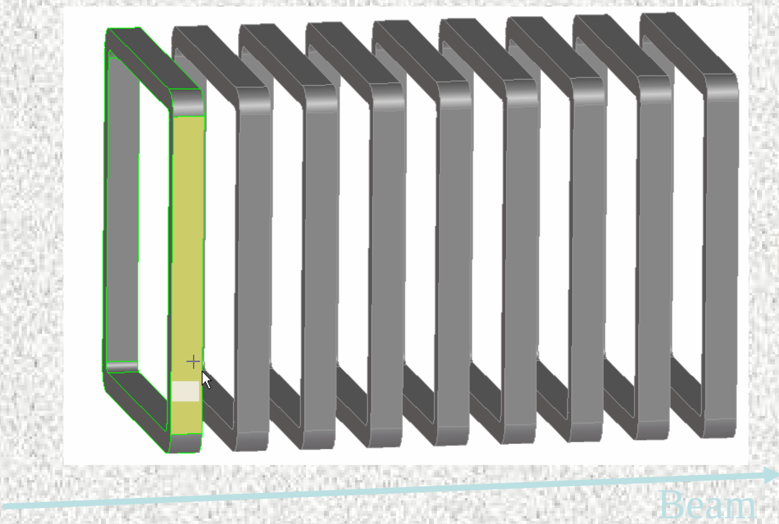
- A coil as shown generates antisymmetric B_x and B_y field profiles in z about the coil. The fields are largely on a plane of angle ψ that is a function of the coil gap and x-offset.





- A series of such coils in z, separated by $\lambda/2$ with alternating current directions, generates $B_x(z)$ and $B_y(z)$ fields that are periodic with equal phase shift.

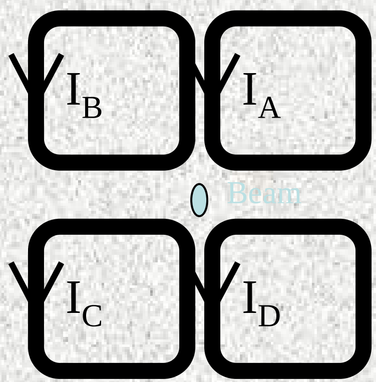




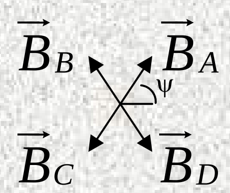
Polarization control

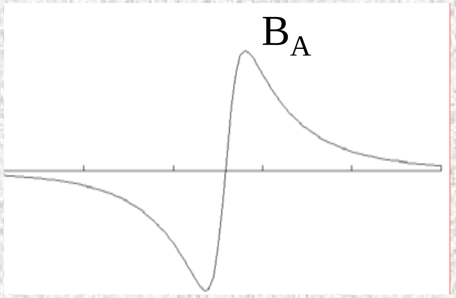
Generating variable linear polarization

- Consider a 4-quadrant array of such coil-series.
  - If $I_C=-I_A$, Coils A and C generate additive fields.
  - Set $I_C=-I_A$, $I_D=-I_B$; Independent control of I_A and I_B provides full linear polarization control.



For $I_A=I_B=I_C=I_D$:





Independent control of I_A and I_B provides variable linear polarization control

- If $I_A=I_B$, vertical field, horizontal polarization
- If $I_A=-I_B$, horizontal field, vertical polarization

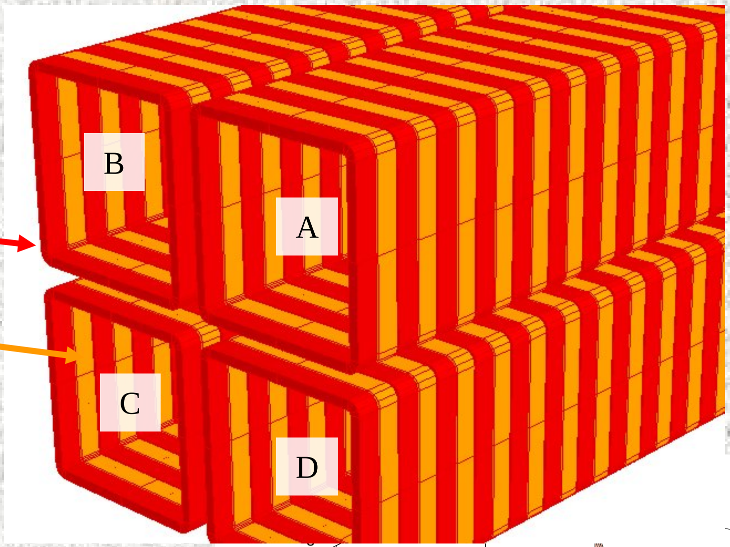
Polarization control

Generating variable elliptic polarization

- Add a second 4-quadrant array of such coil-series, offset in z by λ/4 (coil series α and β)
- With the following constraints the eight currents are reduced to four independent degrees of freedom:

$$I_C^\alpha = -I_A^\alpha, \quad I_D^\alpha = -I_B^\alpha$$

$$I_C^\beta = -I_A^\beta, \quad I_D^\beta = -I_B^\beta$$



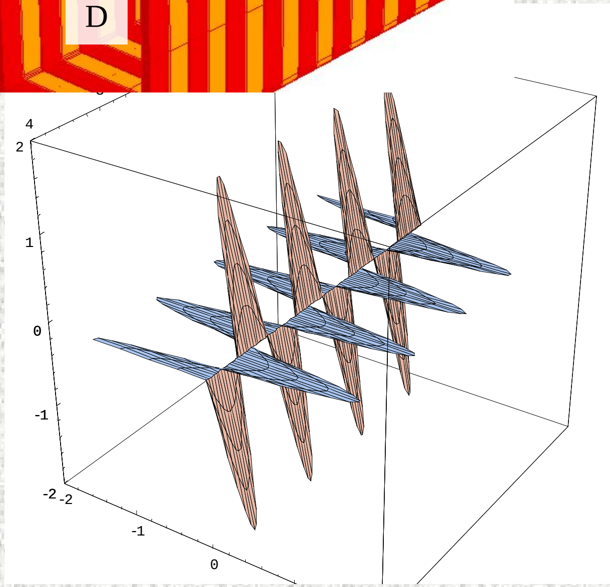
- The α and β fields are 90° phase shifted, providing full elliptic polarization control via

$$\vec{B}^\alpha(I_A^\alpha, I_B^\alpha; z), \quad \vec{B}^\beta(I_A^\beta, I_B^\beta; z):$$

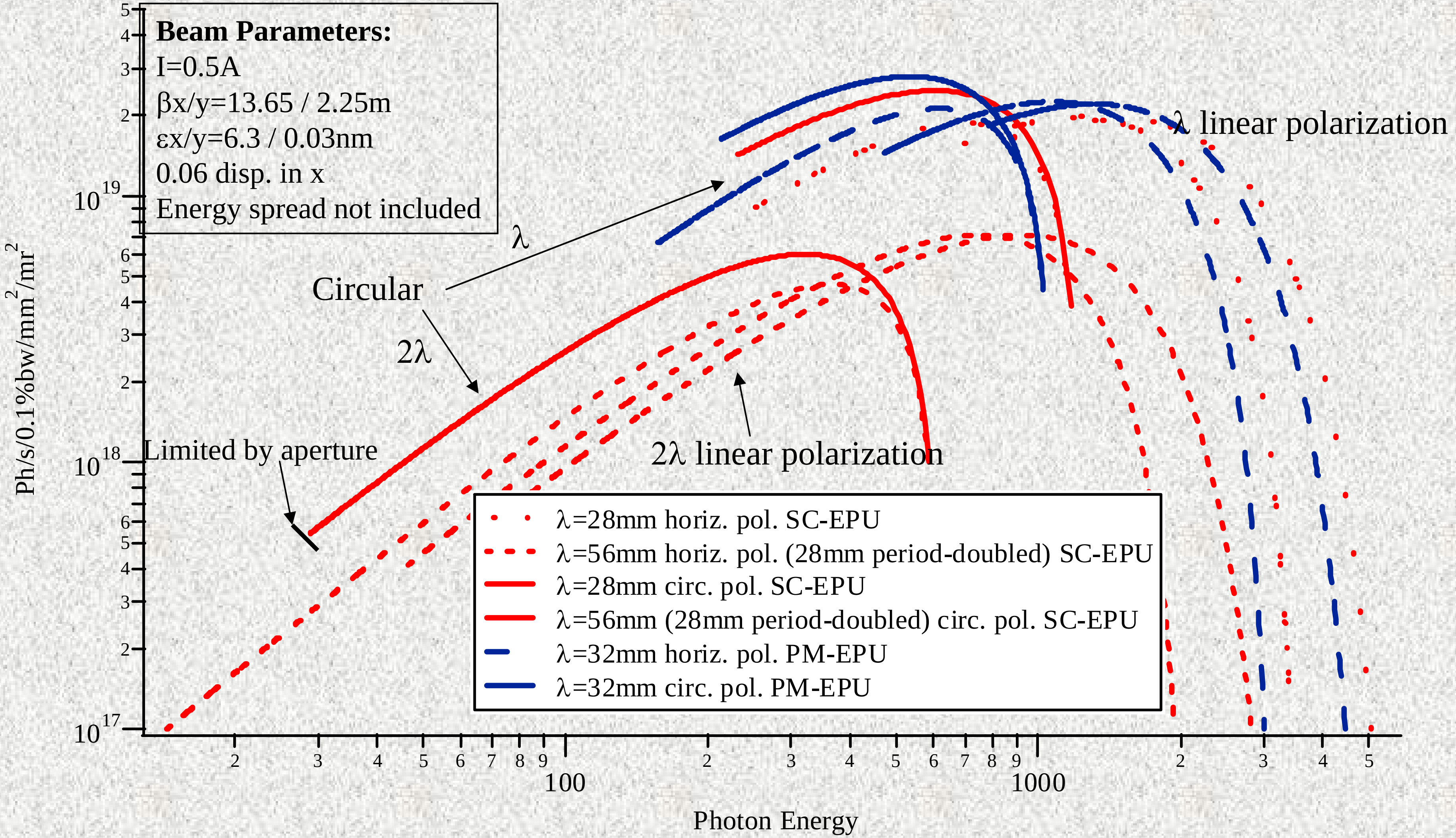
$$\begin{pmatrix} B_x^\alpha \\ B_y^\alpha \end{pmatrix} = \eta \left\{ \begin{pmatrix} \mathrm{Cos}(\psi) & -\mathrm{Cos}(\psi) \\ \mathrm{Sin}(\psi) & \mathrm{Sin}(\psi) \end{pmatrix} \begin{pmatrix} I_A^\alpha \\ I_B^\alpha \end{pmatrix} \right\} \mathrm{Sin}\left(\frac{2\pi z}{\lambda} \right)$$

$$\begin{pmatrix} B_x^\beta \\ B_y^\beta \end{pmatrix} = \eta \left\{ \begin{pmatrix} \mathrm{Cos}(\psi) & -\mathrm{Cos}(\psi) \\ \mathrm{Sin}(\psi) & \mathrm{Sin}(\psi) \end{pmatrix} \begin{pmatrix} I_A^\alpha \\ I_B^\alpha \end{pmatrix} \right\} \mathrm{Sin}\left(\frac{2\pi z}{\lambda} - \frac{\pi}{2} \right)$$

Note: $B_{x,y}^\alpha = \sum_n a_{n;x,y} \sin\left(\frac{2\pi n x}{\lambda} \right)$; typically $\frac{a_3}{a_1} < 2\%$

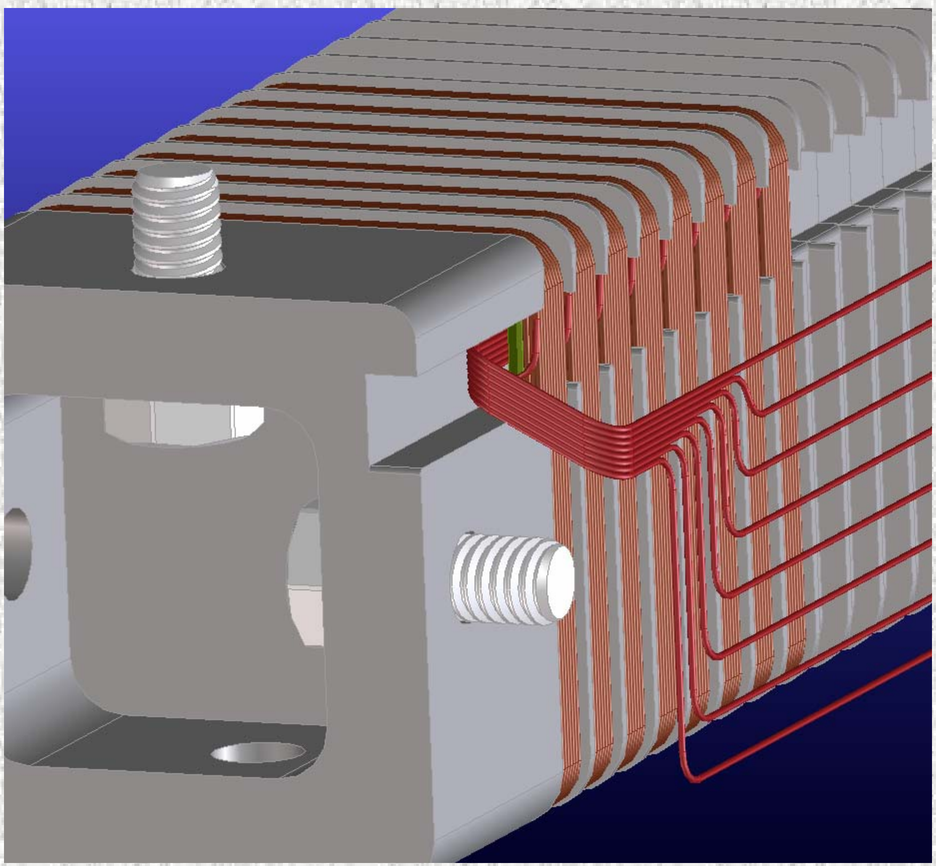


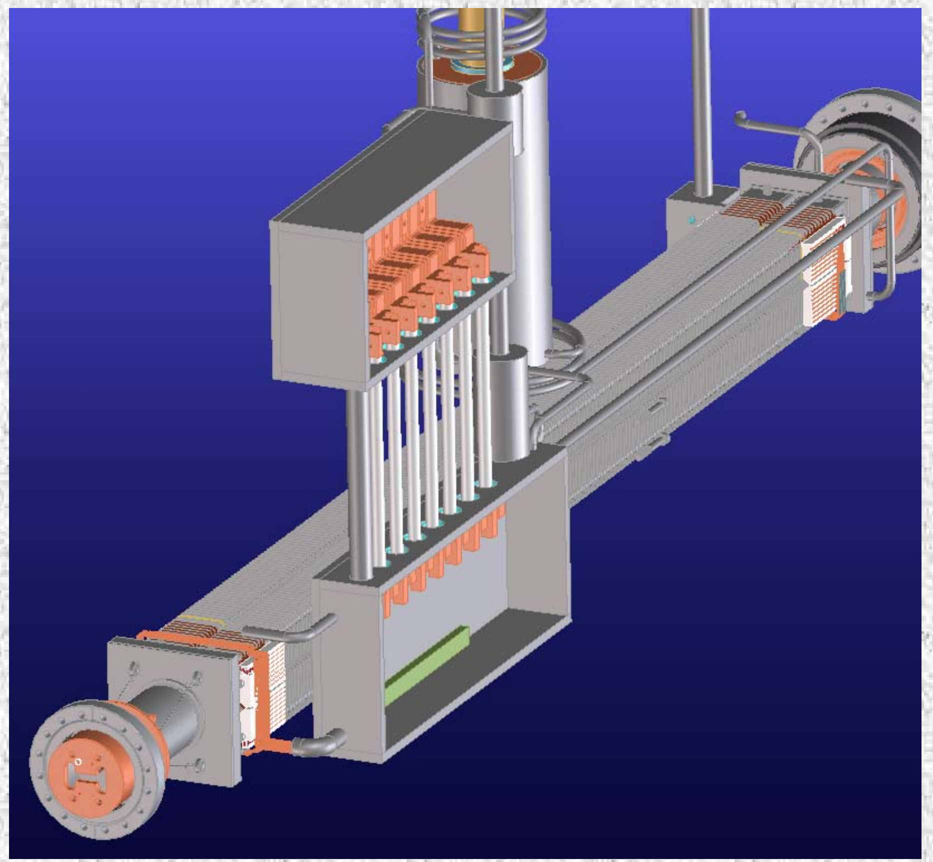
Spectral range and Brightness of example SC-EPU λ=28mm device and PM-EPU λ=32mm



A conceptual design for the LBNL SC-EPU with minimal joints

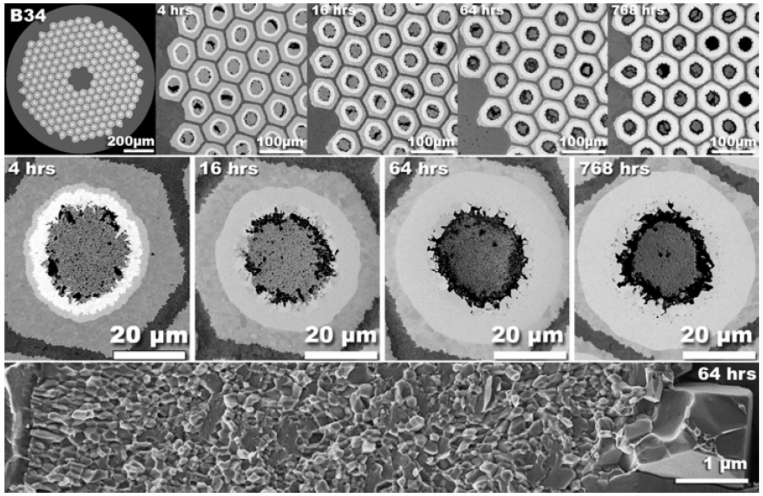
- Four-quadrant, iron-free design
- Cryocooled using heat-pipe approach
- Performance limited by AC losses (dB/dt-induced heating) of coil
- Period halving/doubling requires “switchyard” – superconducting switch needs to be demonstrated





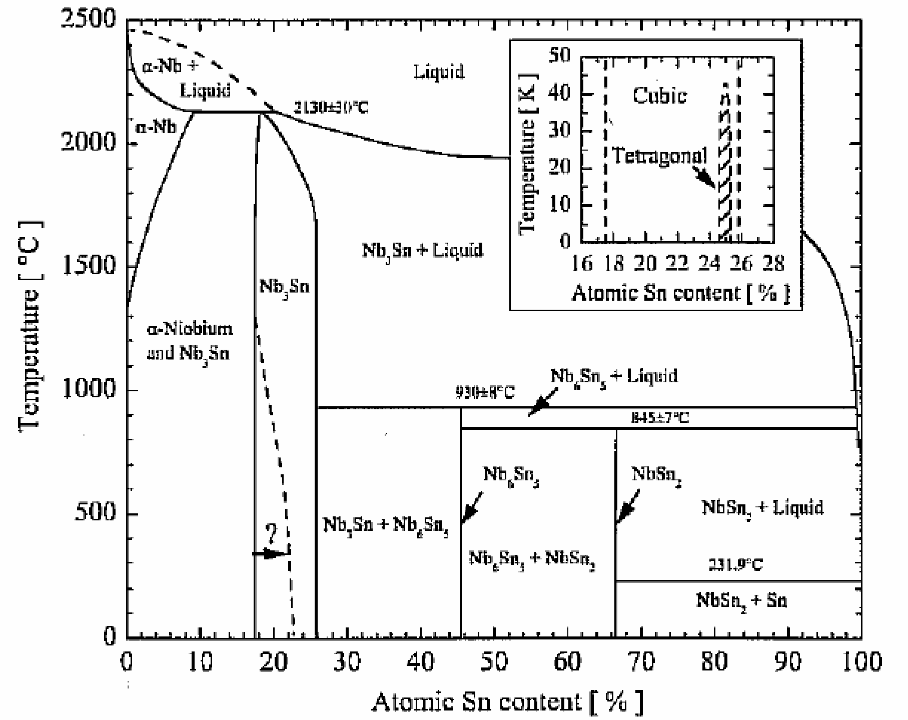
Nb_3Sn superconductors

Highest (Jc, Tc) of all commercially available superconductors in the field range of interest to SCU's

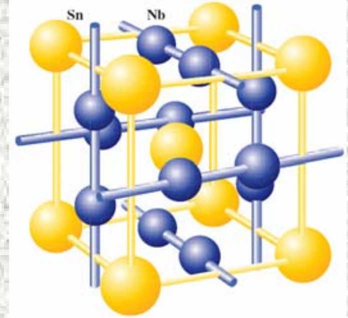


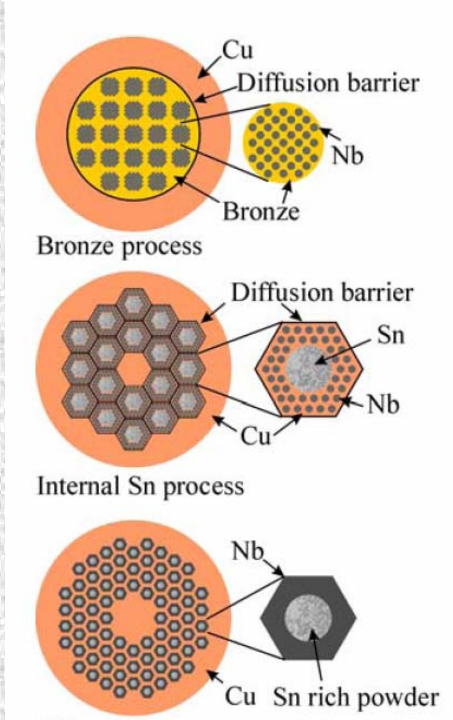
- These are intermetallic compounds, in an A15 structure; A15 is a **brittle** crystal structure
- Requires a fabrication process providing the appropriate composition and A15 development
- Process must not jeopardize **quality of stabilizer** in conductor (typically Cu)
- Requires heat treatment to **~650C**

=> Have significant impact on magnet design and fabrication!



See Thesis of Arno Godeke for an excellent review of Nb_3Sn (source of these plots)





Comparison of QEPU and EPU