Undulator magnets for X-ray FELs

SLAC Summer Seminar on Electron and Photon Beams

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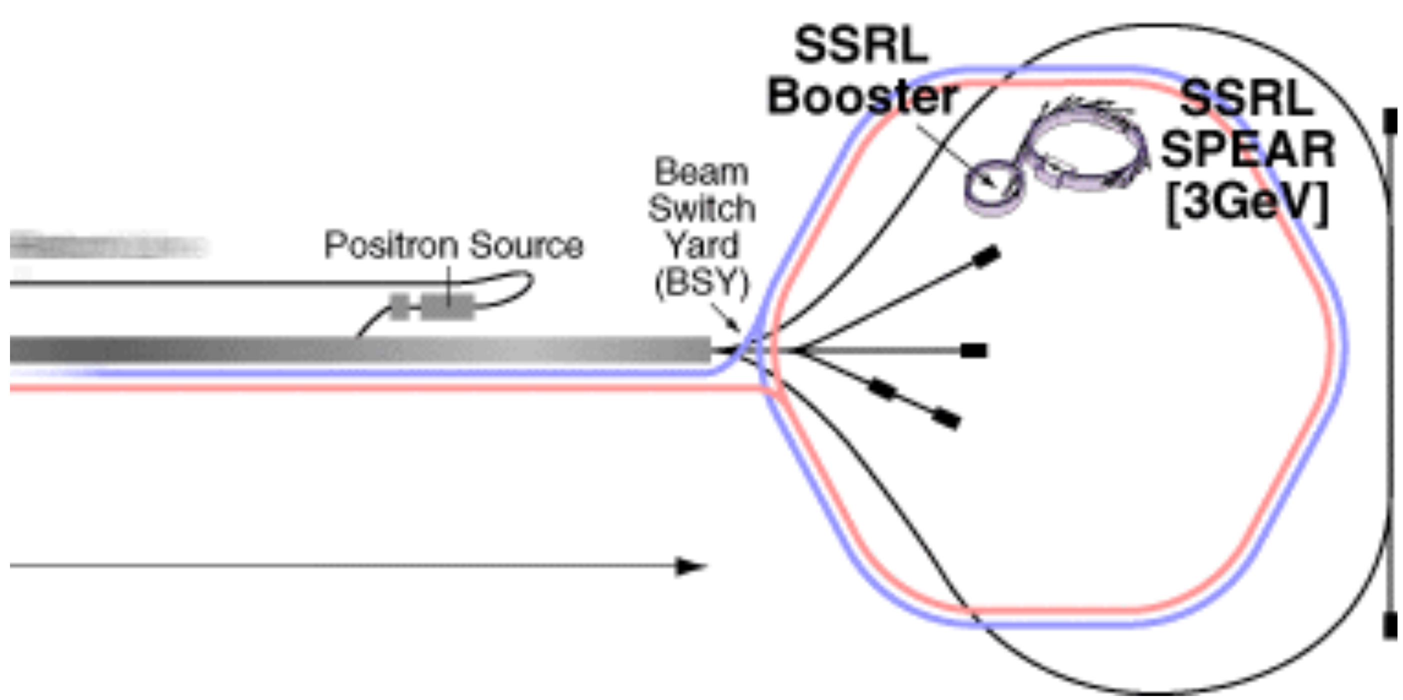
Outline

- Introduction
- Basics of undulators
- Key technologies
- Trajectory considerations
- field correction - shimming
- polarization control
- Future directions

Introduction

Insertion devices as Synchrotron Radiation Sources

- The first storage rings were designed for high-energy physics
  - As energy of electrons was increased, energy was observed to be lost in the form of radiation – synchrotron radiation
  - Key limitation to modern HEP accelerators (one of the motivators for proton rings, and the need to switch to linear colliders for leptons…)
- "2nd generation" sources were rings devoted to SR generation, essentially using the bend magnets as sources (examples: NSLS, ANKA, Spear II, …)



1943: Synchrotron invented by Oliphant
1945: Vekslar, McMillen invent the synchrocyclotron and Betatron
1947: synch. rad. observed at 70Mev GE synchrotron
1949: Wilson et al. first stored beam in a synchrotron
1952: Courant and Snyder develop strong focusing; *already patented by Christofilos!*
1959: CERN PS operational
1960: Brookhaven AGS operational
1972: Spear completed (leads to J/Psi discovery,…)

IEEE Transactions on Nuclear Science, Vol.NS-22, No.3, June 1975

SPEAR II PERFORMANCE*

SPEAR Group†
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305
(Presented by J. M. Paterson)

"… In parallel with the high energy physics program, the Stanford Synchrotron Radiation Project has a large continuing program of ultraviolet and x-ray research.[8] "

1990: SPEAR is used exclusively for SR production

IEEE 1998

SPEAR III – A BRIGHTER SOURCE AT SSRL*

R. Hettel, R. Boyce, S. Brennan, J. Corbett, M. Cornacchia, W. Davies-White, A. Garren, A. Hofmann, C. Limborg, Y. Nosochkov, H.-D. Nuhn, T. Rabedeau, J. Safranek†, H. Wiedemann
Stanford Synchrotron Radiation Laboratory, SLAC, Stanford, CA 94309

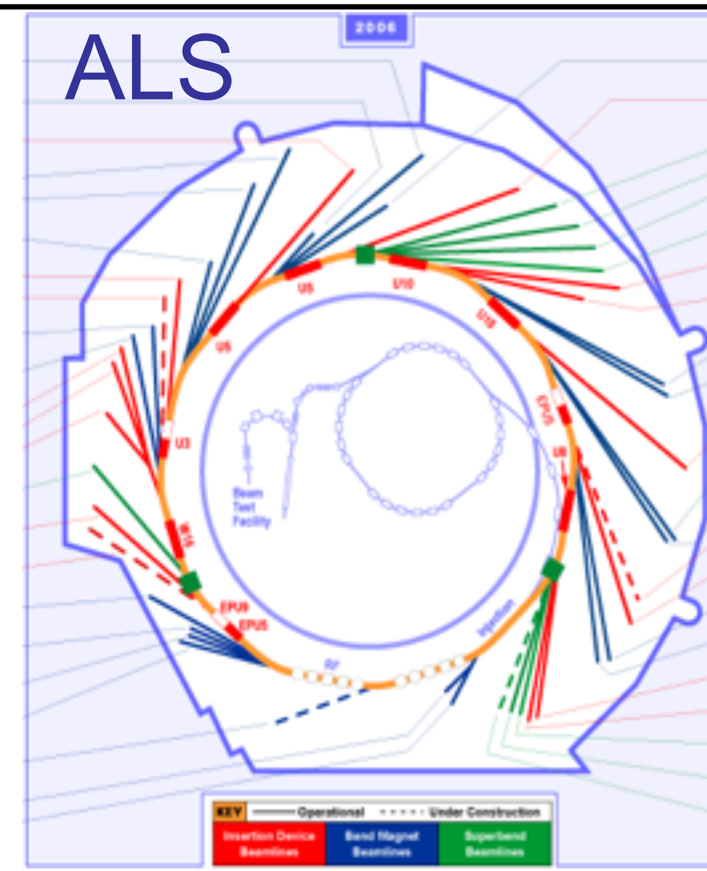
"… By replacing the magnets and vacuum chamber for the 3 GeV SPEAR II storage ring, the natural emittance of the machine can be reduced from 130 to 18 nm-rad and the stored current can be raised from 100 to 200 mA with a 50 h lifetime. This configuration increases focused photon flux for insertion device beamlines by an order of magnitude and the photon brightness for future undulators would exceed 10^{18} at 5 keV. …"

Dedicated SR sources

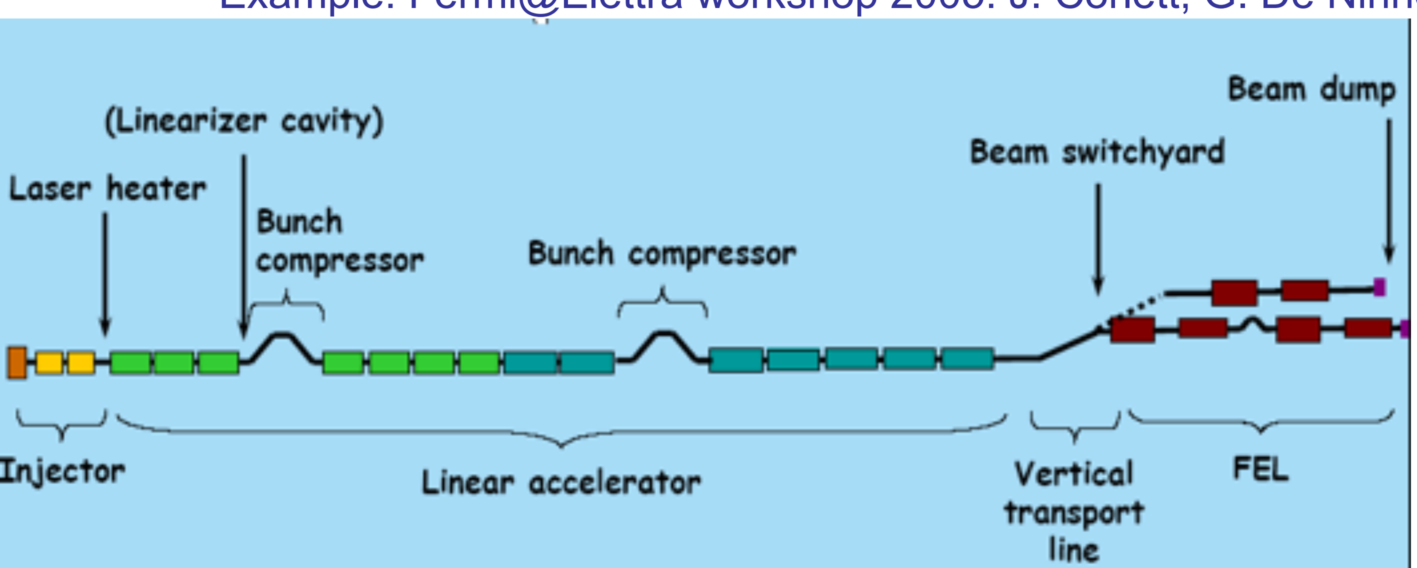
- "3rd generation" sources designed for use of special magnetic systems, "insertion devices", (ID's), into the straight sections of storage rings to generate specific radiation properties tailored to the beamline science needs. (Examples: ALS, Spear III, APS, ESRF, …)
  - Accelerator physics: - ID's should not impact the stored beam – want scalability, ability to exchange devices, etc
  - Scientific users: - ID's tailored to science need, e.g. flux or brightness over a given energy range, polarization control, etc.

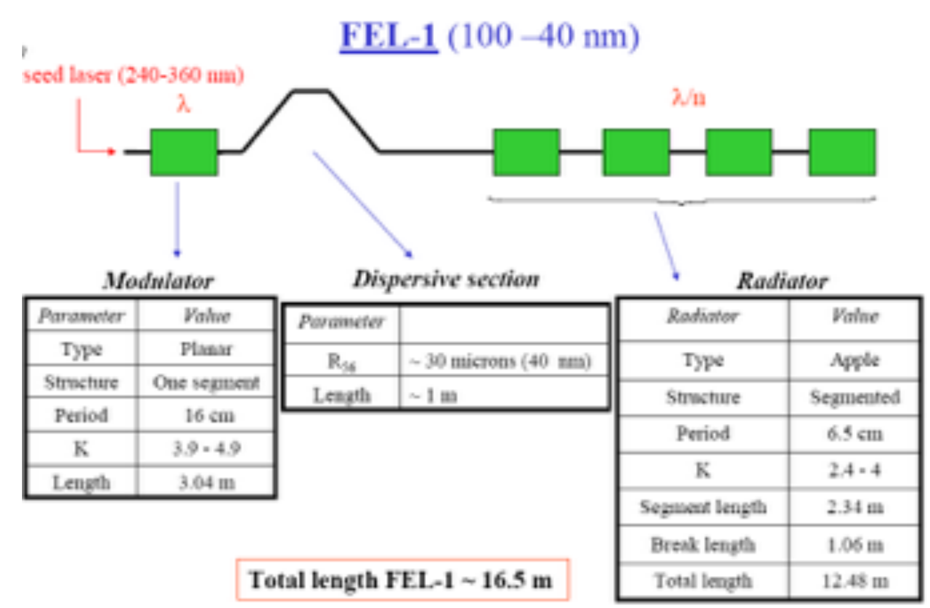
Note: almost all 2nd generation rings now incorporate ID's to enhance their science capabilities

- "4th generation" sources are currently being built – FEL's & ERL's. (examples: LCLS, DESY XFEL, Fermi at Elettra, 4GLS …)
  - Electron bunch passage through "Insertion device" generates synchrotron radiation, which in turn modulates the electron bunch energy; cycle can be repeated down to a final ID section that "radiates" the resulting micro-bunched beam coherently



Example: Fermi@Elettra workshop 2005: J. Corlett, G. De Ninno





Parameter	Value
Type	Planar
Structure	One segment
Period	16 cm
K	3.9 - 4.9
Length	3.04 m

Parameter	
R_{56}	~ 30 microns (40 nm)
Length	~ 1 m

Radiator	Value
Type	Apple
Structure	Segmented
Period	6.5 cm
K	2.4 - 4
Segment length	2.34 m
Break length	1.06 m
Total length	12.48 m

Example applications

- Synchrotron radiation sources for soft / hard x-rays
  - Large number of lights sources worldwide (and quickly growing!)
  - Number of free electron laser projects underway
  - Figure of merit is typically brightness (ph./s/mm^2/mr^2/0.1%bw)

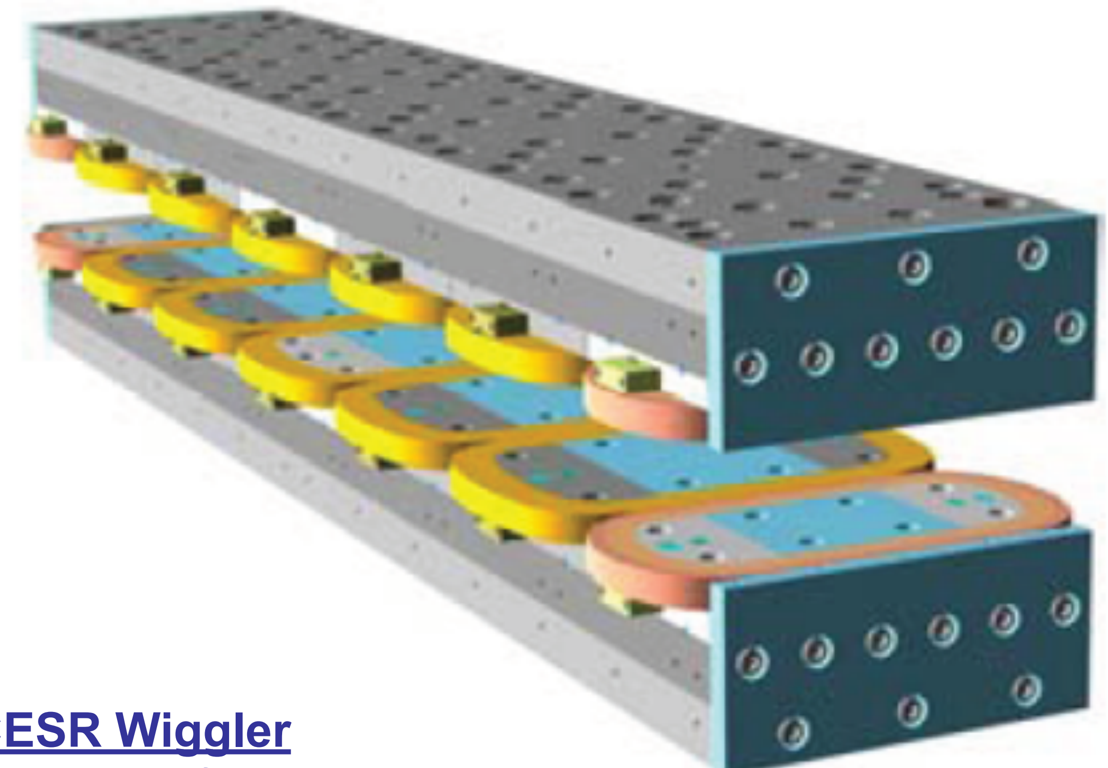
  Higher performance yields higher brightness and/or increased spectral range, or access to higher energy photons
- Damping rings
  - Emittance is reduced proportional to synchrotron radiation power
  - Figure of merit is SR source power => wigglers

  Higher field yields higher power: $P \sim B^2$
- Positron source for ILC
  - Positrons generated from pair-production
  - Polarized positrons from circular pol. radiation
  - Figure of merit is photon flux

  Higher performance yields higher positron production, shorter undulator length

Applications motivating the use of Superconducting insertion devices

- Modulators and radiators for FEL's
  - May serve to shorten length of FEL
  - Access shorter wavelength radiation
  - Main issues:
    - tight requirement on beam trajectory
    - Long lengths overall
- Wigglers for damping rings
  - CESR, ILC, …
- Undulator for ILC positron source



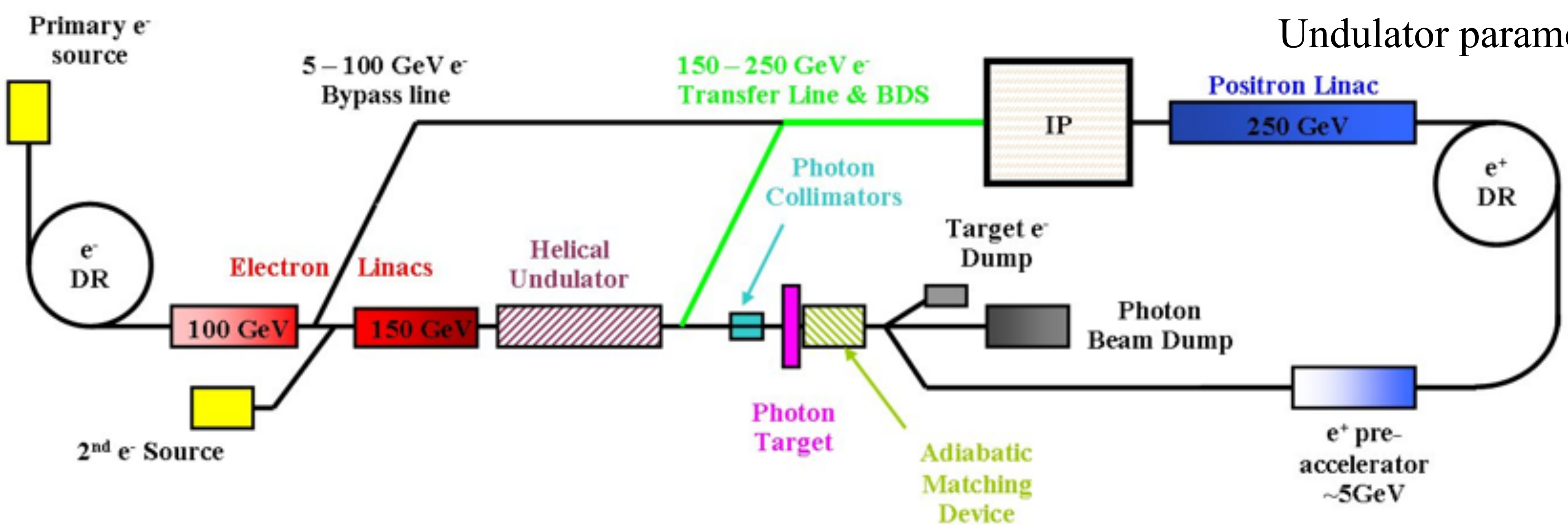
CESR Wiggler
2,1T peak field
9cm horizontal uniform aperture
40cm period
7.62cm pole gap, 5cm vertical beam aperture

Baseline wigglers for ILC damping ring

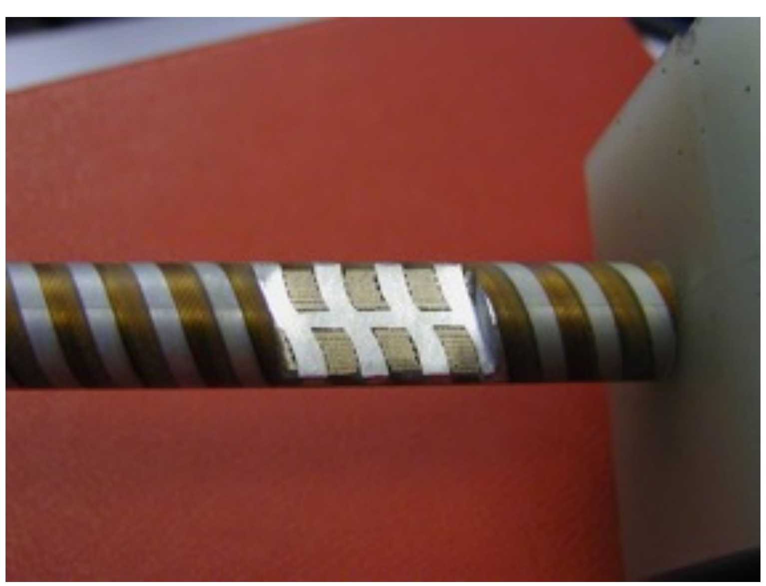
ILC Positron Source

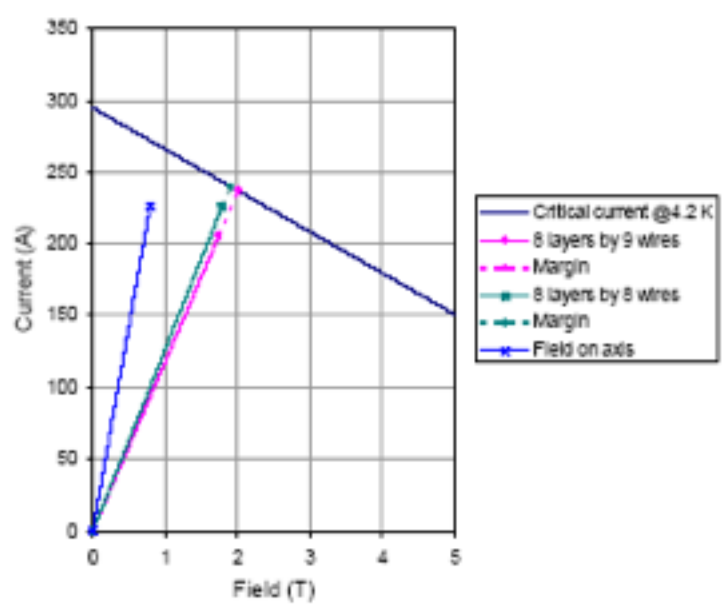
Parameter	Value	Units
Period	10	mm
Peak field	1.1	T
Type	Helical	-
Length	100-200	m
Max Photon Beam Power	95	kW

Undulator parameters (ideal)



First NbTi prototype, EUROTeV-heLiCal collaboration





Magnet features & parameters:

- Conductor: NbTi. 0.44 mm diam.
- Groove size: 4x4 mm
- Test: achieved 0.8 T on axis

References:

1. Y. Ivanyushenkov et al., Proceedings of PAC 2005
2. D. Scott et al, Proceedings of EPAC 2004

A look back in time, to the first FEL undulator…

Ancient history

Superconducting helically wound magnet for the free-electron laser

Rev. Sci. Instr., 1979

L. R. Elias and J. M. Madey

High Energy Physics Laboratory, Stanford University, Stanford, California 94305

(Received 12 April 1979; accepted for publication 18 May 1979)

- The first undulators were superconducting
  - 1975, undulator for FEL exp. at HEPL, Stanford
  - 1979, undulator on ACO
  - 1979, 3.5T wiggler for VEPP

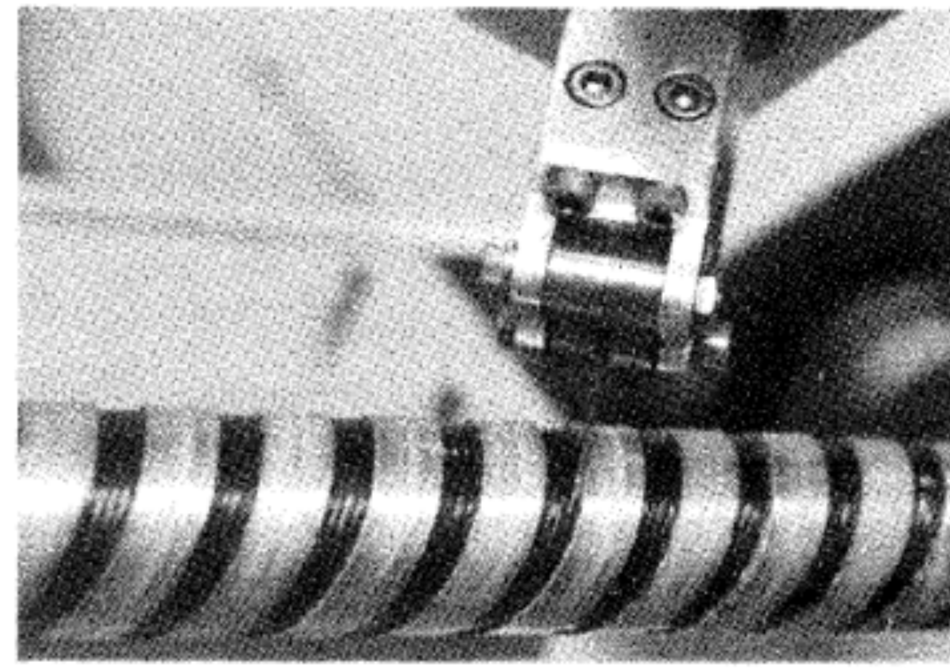


FIG. 5. Wire winding tool and partially completed magnet.

IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

GAIN MEASUREMENT ON THE ACO STORAGE RING LASER

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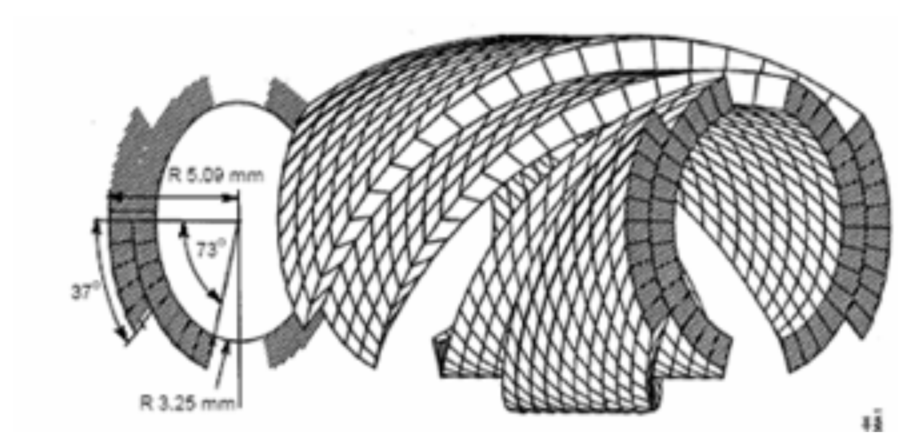
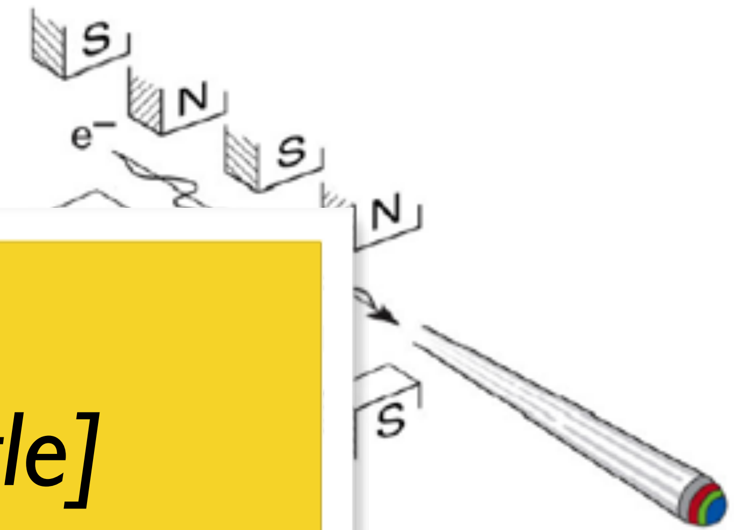


Basics of undulators

Undulator and Wiggler characteristics: Field properties

- These are magnetic devices generating fields transverse to the passing charged particles, usually designed to be inserted into a ring to generate synchrotron radiation
  - Fields can be "planar", helical, or variable
  - Planar devices e
  - ⇒There is always
- Fields are cha
  - Strength para

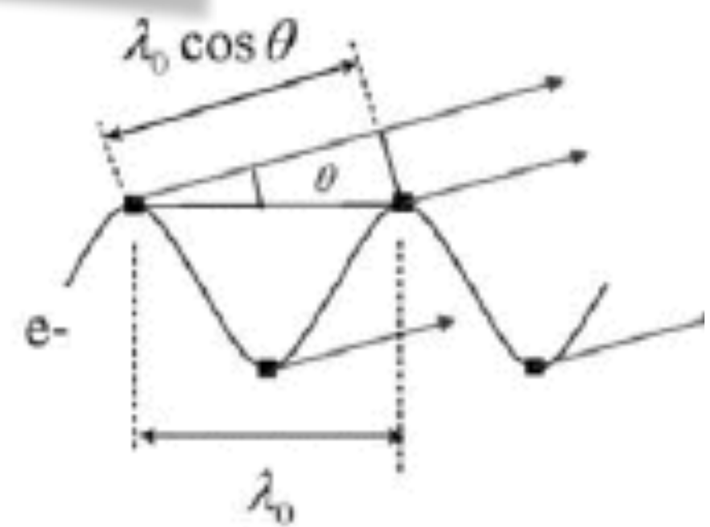


Nomenclature:
"First integral": x'(z) *[angle]*
"Second integral": x(z) *[displacement]*

Electron Equation of Motion. Integrating the equation of motion of a relativistic electron moving with average velocity $\langle v_z \rangle$ perpendicular to a sinusoidal on-axis wiggle field of magnitude $B_y = B_0 \cos k_w z$ and period $\lambda_w \equiv 2\pi/k_w$ gives, for the velocity and trajectory in the direction mutually perpendicular to $\langle v_z \rangle$ and $\vec{B}$:

$$\frac{d\vec{p}}{dt} = d\gamma m\vec{v} = e(\vec{E} + \vec{v} \times \vec{B}) \Longrightarrow \frac{v_x}{c} = \frac{K}{\gamma} \sin k_w z \quad \text{and} \quad x = \frac{K}{\gamma k_w} \cos k_w z, \qquad (14.1)$$

where $\gamma = 1957E[\text{GeV}]$ and deflection parameter $K \equiv eB_0/k_w mc = .934B_0[\text{T}]\lambda_w[\text{cm}]$.



$$\Rightarrow (dx/dz)_{\max} \overset{def}{=} K/\gamma \quad \Rightarrow \quad K = \frac{eB\lambda_u}{2\pi m_0 c} = 0.934\lambda_u[cm]B[T]$$

Brian Kincaid, JAP 1977;
See R. Schlueter, Res. Memo 88-57, LLNL 1988 for wiggler field harmonics and focusing

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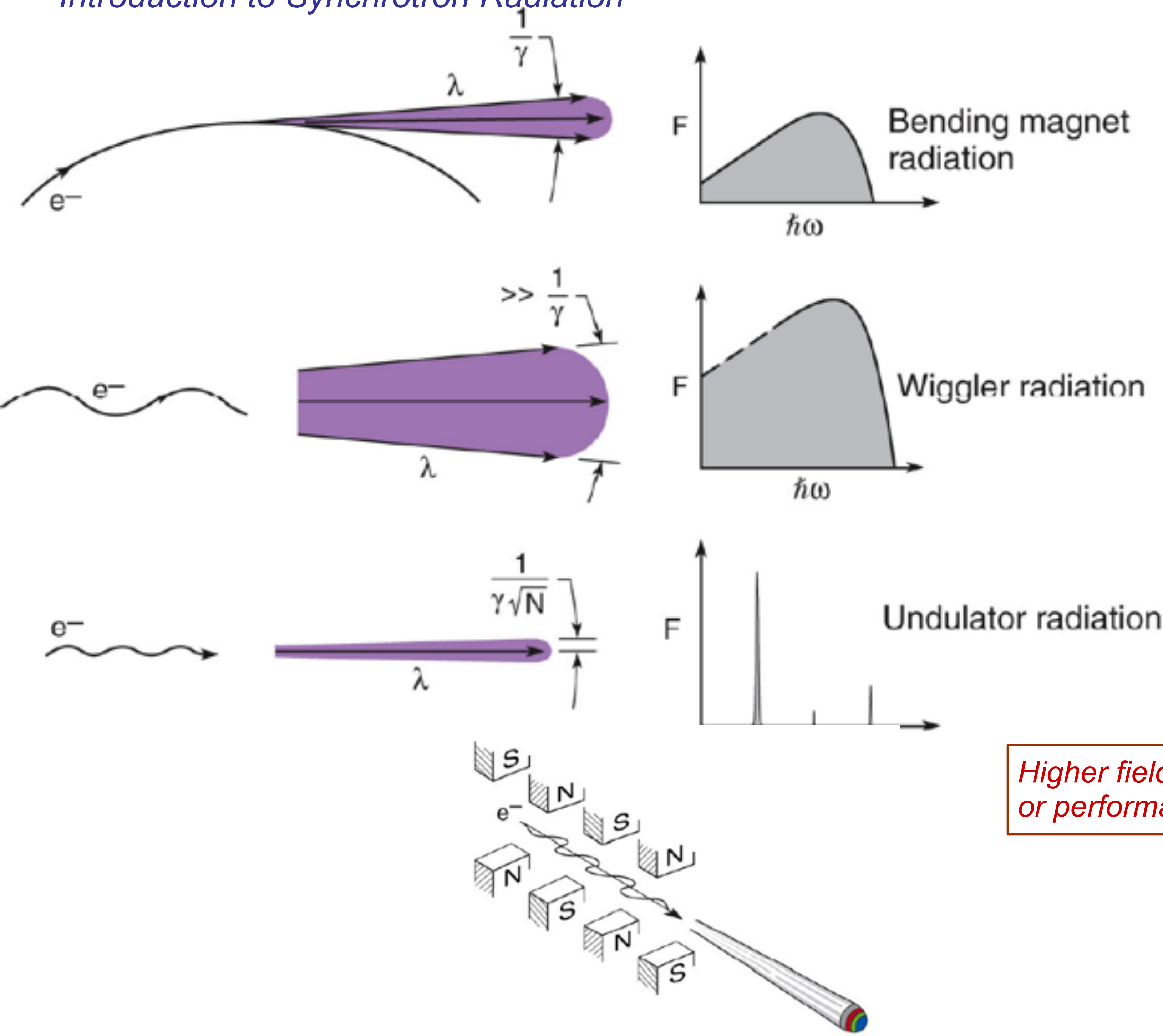
Undulator and Wiggler characteristics: Radiation properties

From David Attwood,
Introduction to Synchrotron Radiation



Continuous spectrum characterized by

ε_c = critical energy

ε_c(keV) = 0.665 B(T)E^2(GeV)

$$P[kW] = 0.633E^2[GeV]\,B^2[T]\,I[A]\,L[M]$$

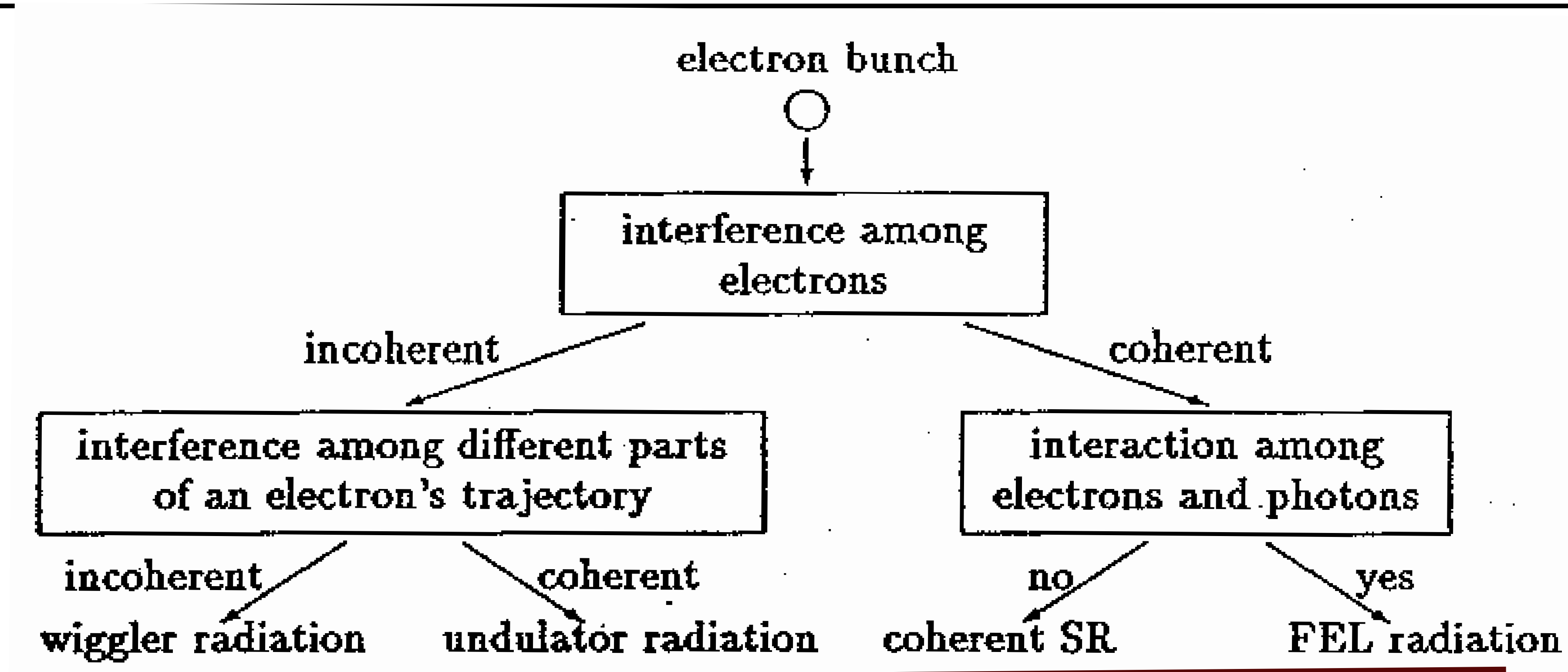
Higher field results in higher critical energy, more power

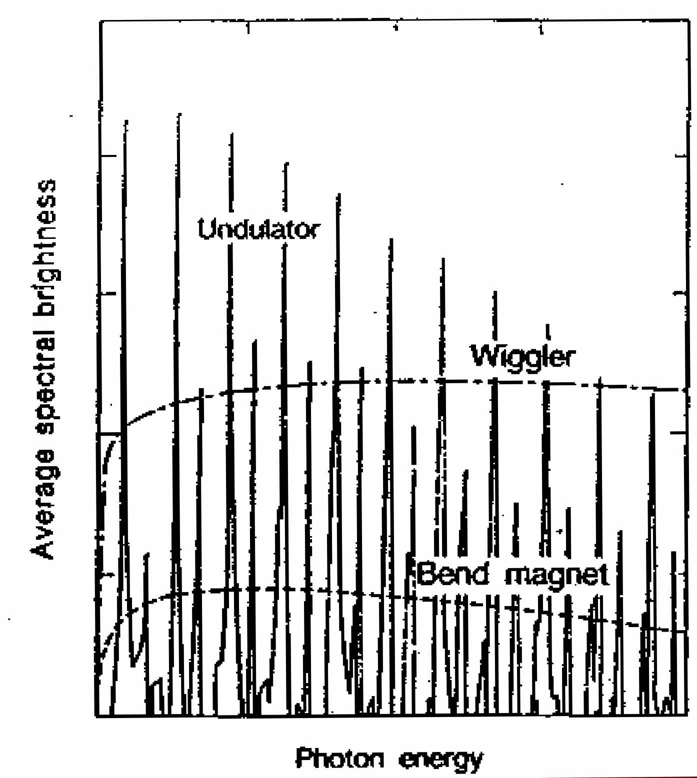
$$\varepsilon_1\ (\text{keV}) = \frac{0.95\ E^2\ [\text{GeV}]}{\lambda_u\ [\text{cm}]\ (1 + \frac{K^2}{2})}$$

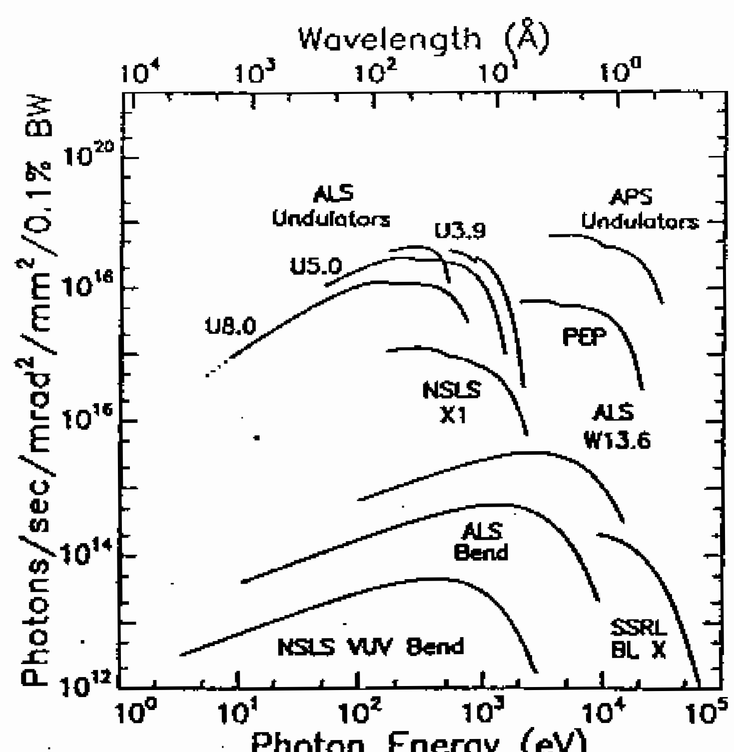
Quasi-monochromatic spectrum with peaks at lower energy than a wiggler

Higher field for same period results in larger spectral range, or performance can be leveraged to increase brightness

Distinguishing sources







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Beam energy, spectral range, and undulator performance

$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1 + K^2/2\right)$$

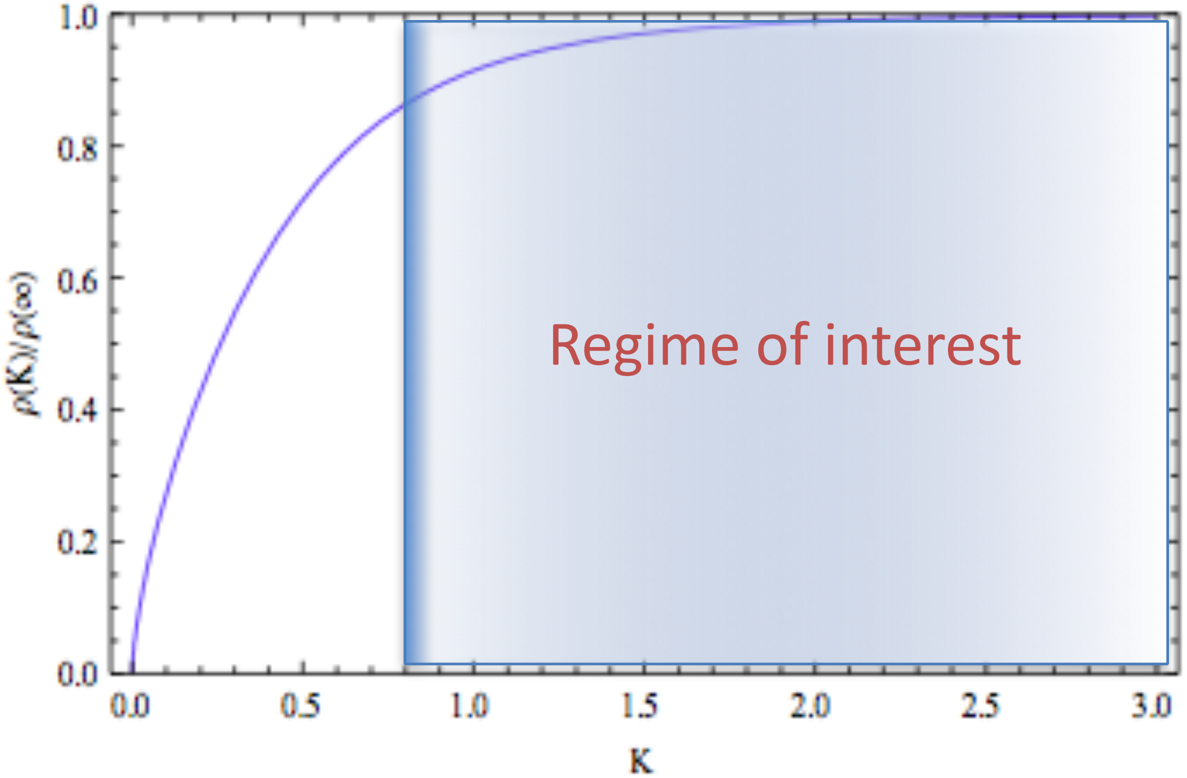
Linac-driven

$$K = \frac{eB\lambda_u}{2\pi mc}$$

Technology-driven

- For any given technology:
  - At fixed gap, field increases with period
  - At fixed period, field drops as gap increases

$$K_{max} = \left[2\left(\frac{\lambda_2 - \lambda_1}{\lambda_1}\right)\left(1 + \frac{K_{min}^2}{2}\right) + K_{min}^2\right]^{1/2}$$



=> Choice of electron energy is closely coupled to undulator technology, allowable vacuum aperture, and spectrum needed

Importance of undulator technology

- Undulator characteristics and beam energy yield photon wavelength

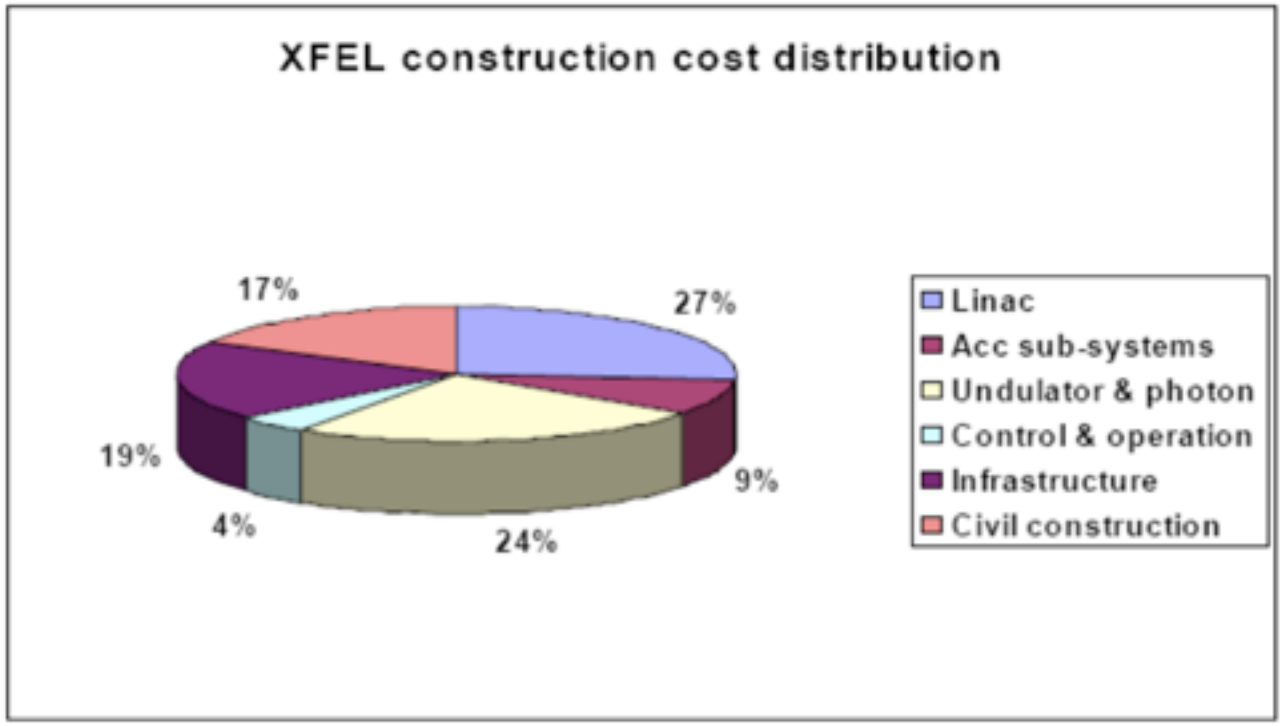
$$\lambda_{1,planar} = \frac{1 + K^2/2}{\gamma^2}\lambda_u$$

$$\lambda_{1,helical} = \frac{1 + K^2}{\gamma^2}\lambda_u$$

- Coupled problem:
  - ***Always*** want tunability
  - ***Sometimes*** want polarization control
  - Different FEL lines will focus on different spectral ranges, with different timing, synchronization etc. needs

- **Cryogenics+linac** and **Undulator** farms are dominant cost drivers

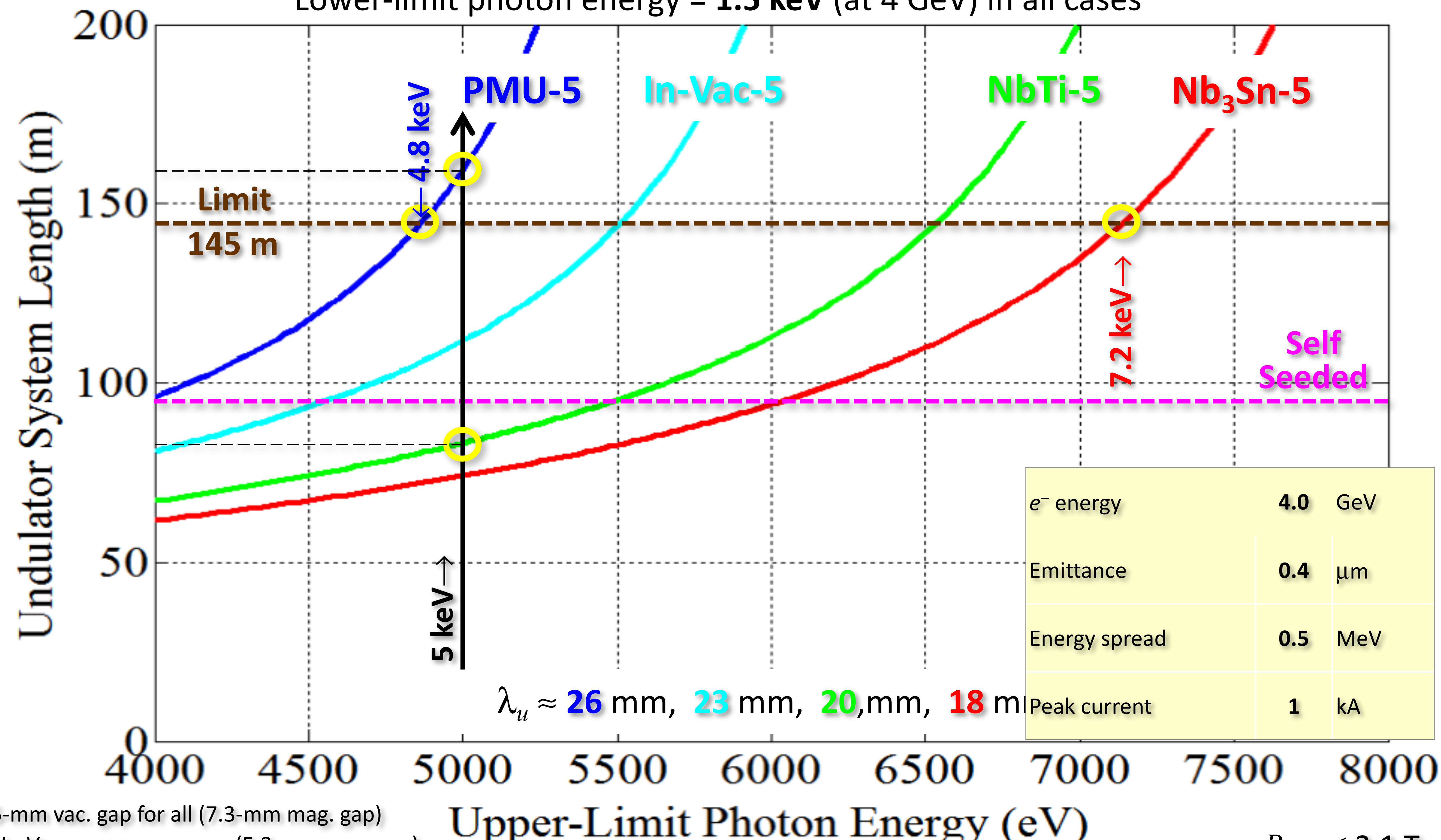
Lei Zang, Cockcroft Institute presentation



SCU Motivation *(Courtesy P. Emma)*

Und. Length (+20%) vs Upper-Limit Photon Energy (*LCLS-II*)

Lower-limit photon energy = **1.5 keV** (at 4 GeV) in all cases



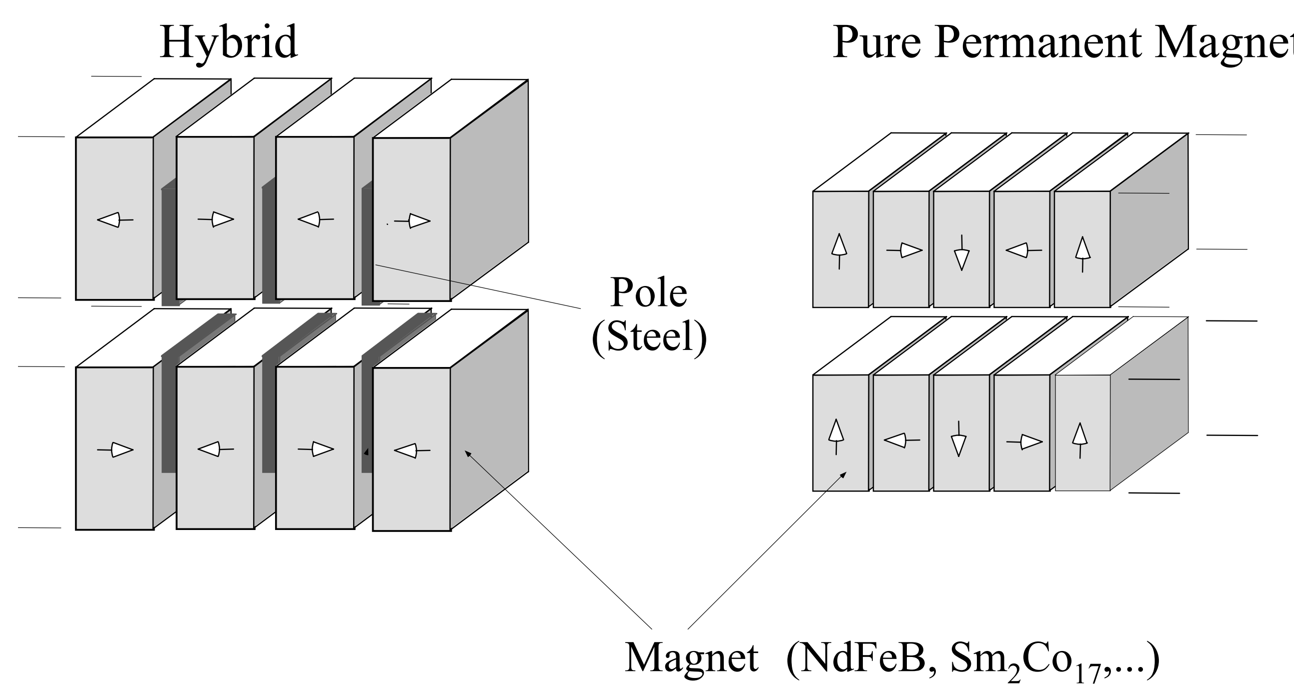
- 5-mm vac. gap for all (7.3-mm mag. gap)
- *In-Vac* → same vac. gap (5.3-mm mag. gap)

$B_{max} < 2.1$ T

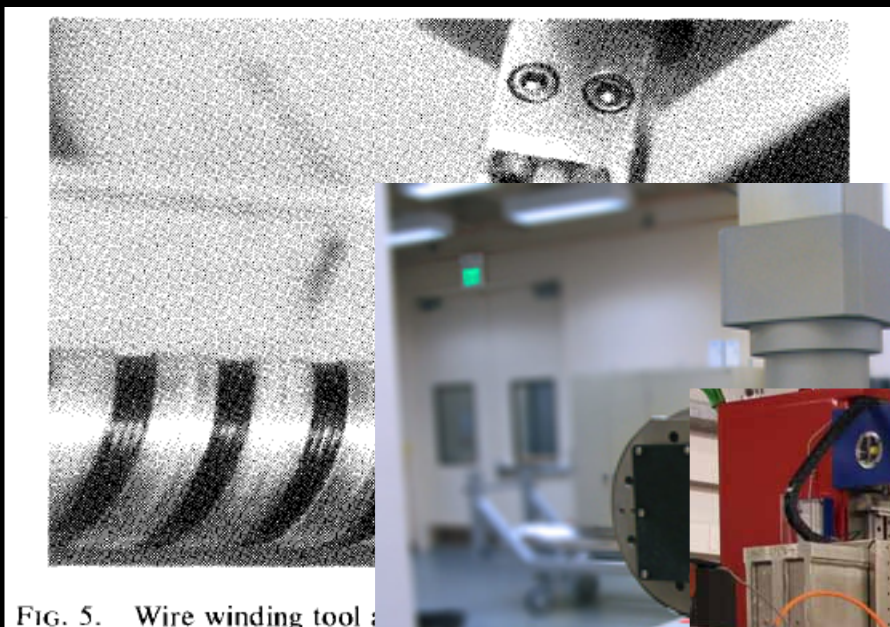
Key Technologies

A variety of technologies exist

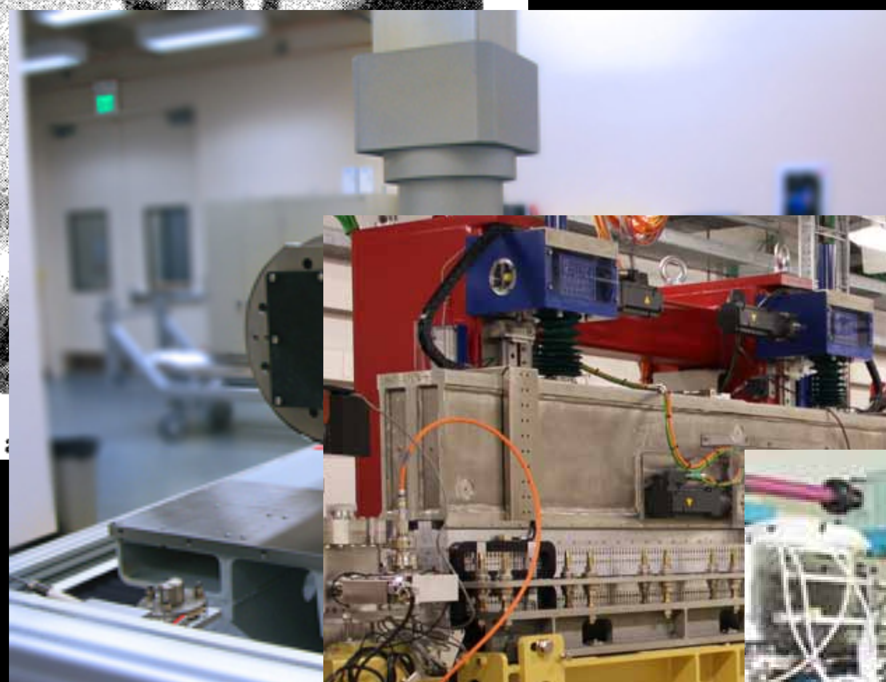
- Pure and Hybrid Permanent magnet devices:
  - "Out of vacuum"
  - "In-vacuum"
  - "Cryogenic in-vacuum"
- Pure variable polarizing undulators
  - Apple-II
  - Delta
- Electromagnet undulators
- Superconducting undulators



A variety of technologies exist to produce undulating fields, with permanent magnet systems serving as the workhorse



Superconducting bifilar,
Stanford, circa 1977



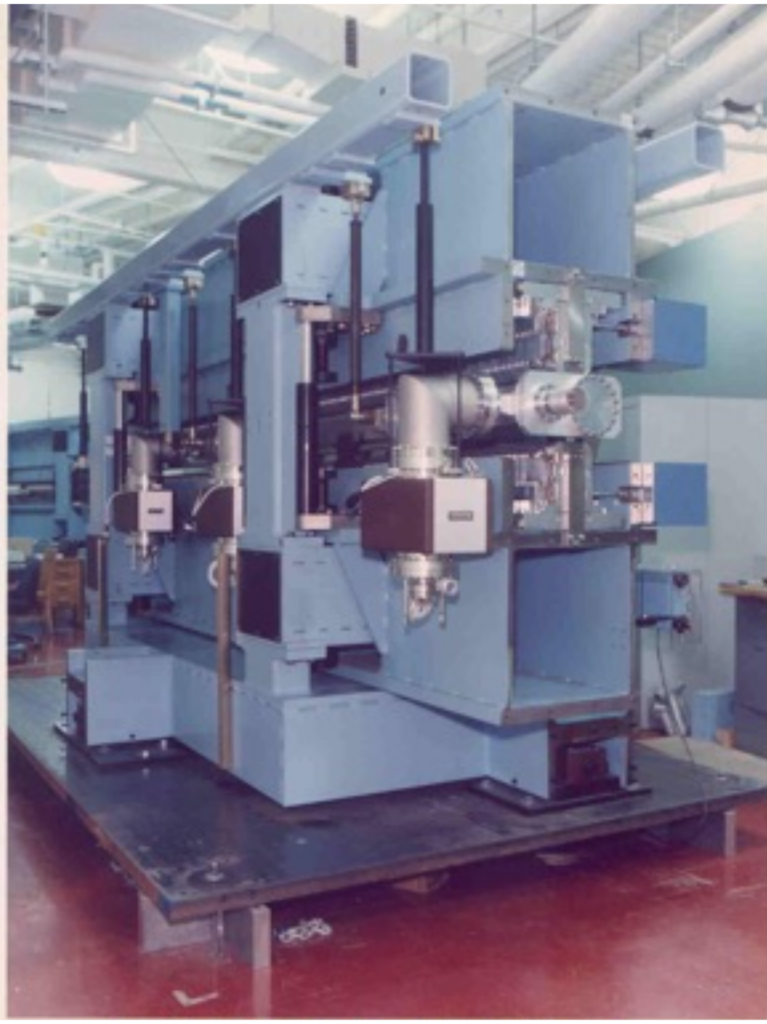
PM hybrid, fixed gap,
LCLS, Slac

PM EPU,
Fermi, Trieste

IVID
XFEL SPring8

PM hybrid, variable gap,
LCLS-II, Slac

Undulator evolution

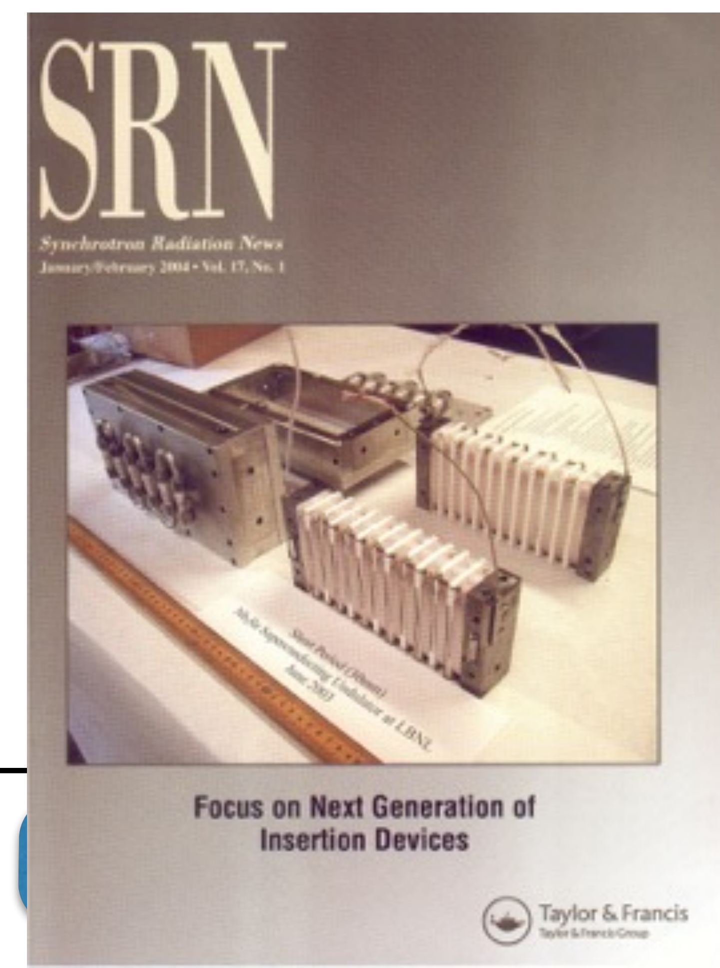


ALS U50 (1993)
Hybrid permanent magnet technology

ALS EPU50 (1998)
Pure permanent magnet technology, Elliptically polarizing capability

Spring8 IVUN (2000)
Small gap In-vacuum device

superconducting undulators



Undulator technologies have evolved to enhance performance

- PM devices have evolved by…
  - ✓ Reducing magnetic gap: in-vacuum device development
  - ✓ Improving PM remanence: materials development, use at cryogenic temperatures
- Alternative approach: revive superconducting undulators to leverage materials improvements over the last couple of decades

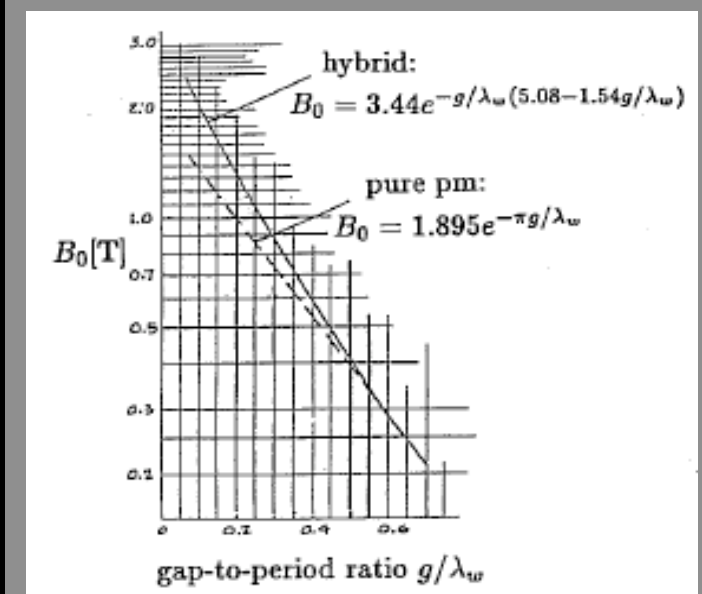
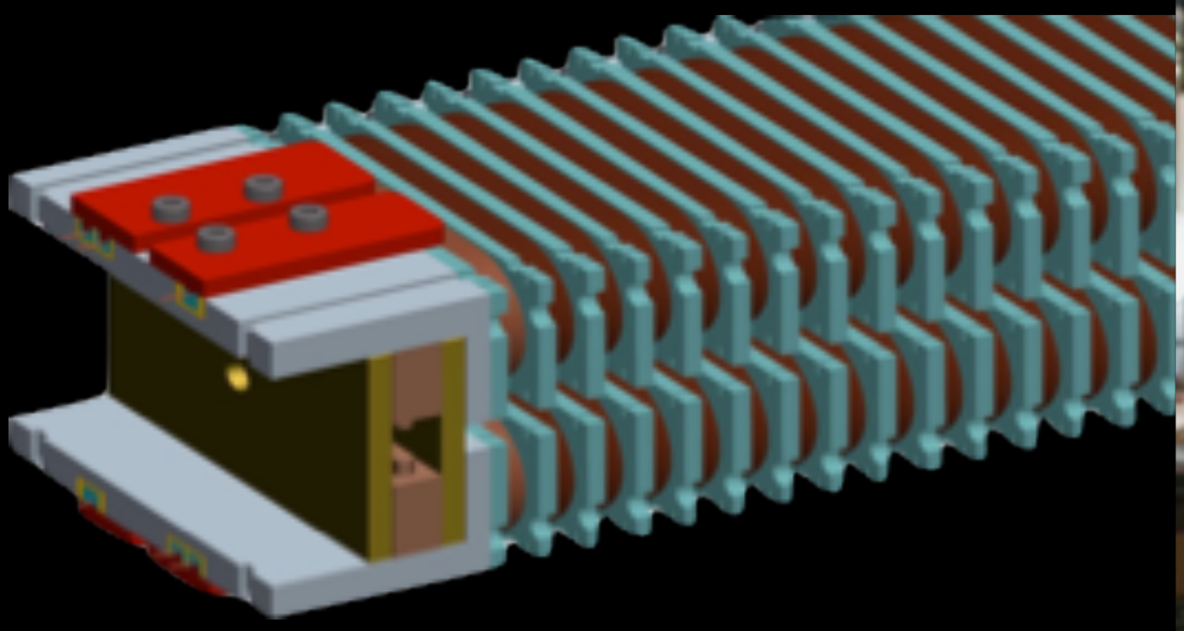
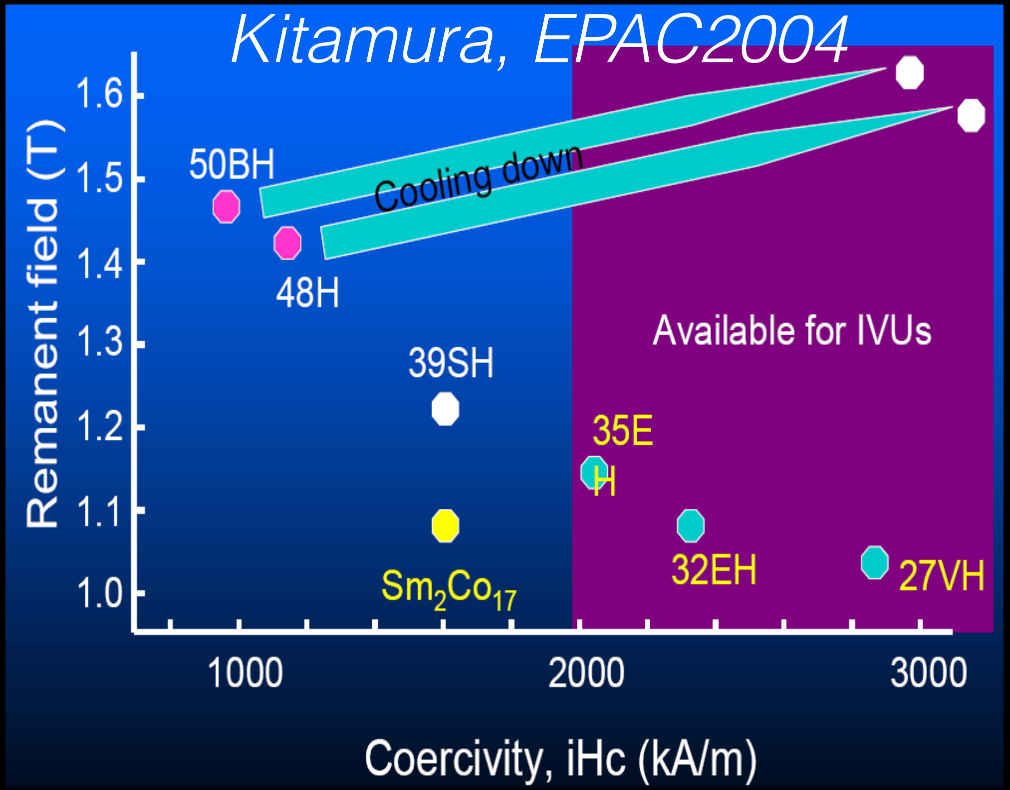


Fig. 14.9 Attainable on-axis field in pure PM and hybrid insertion devices ($B_r = 1.1$T, $H_{pm} = -0.8H_c$).

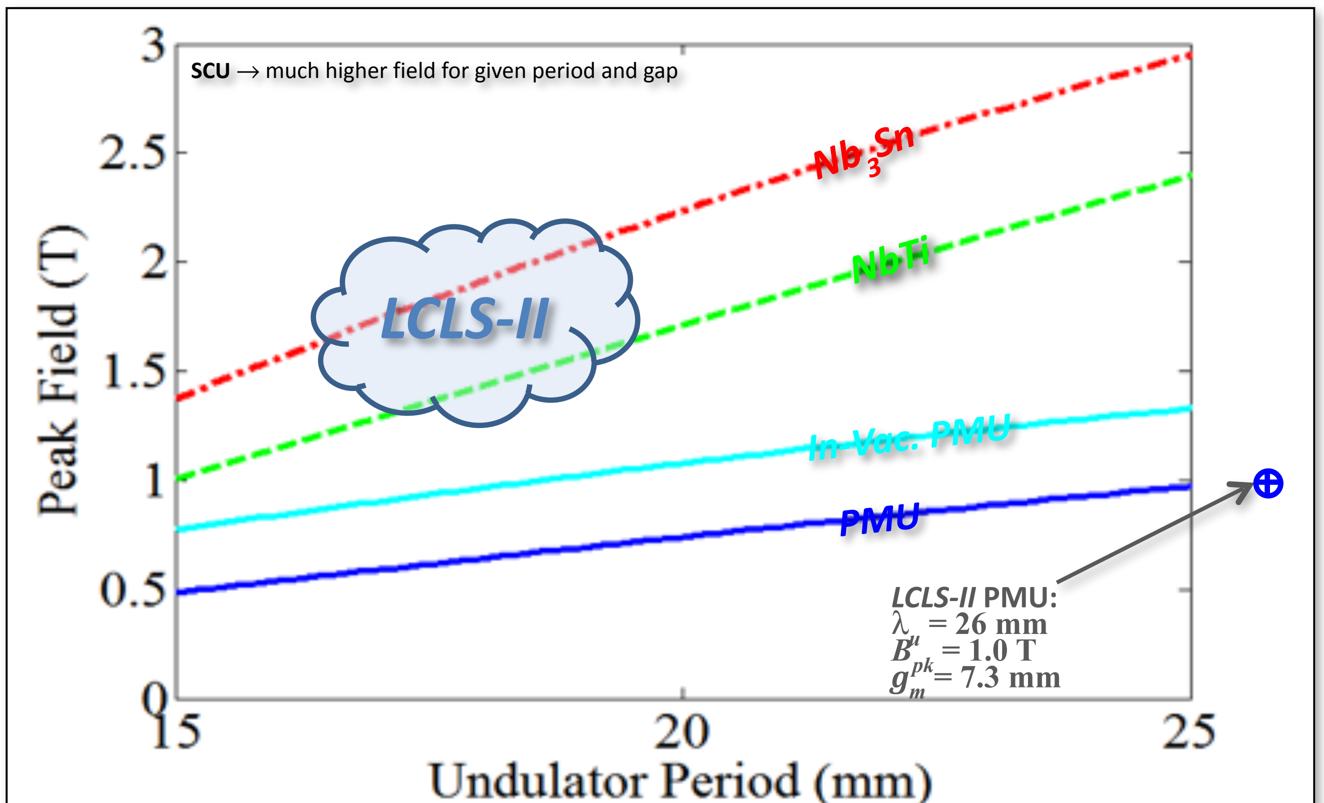


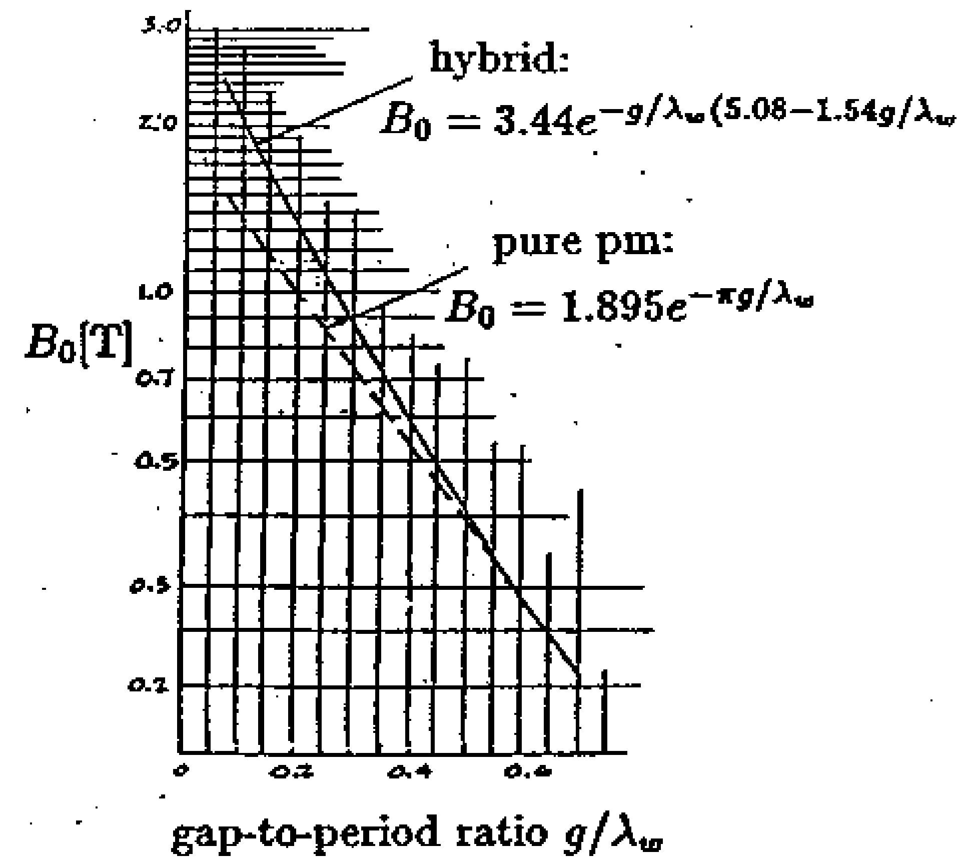


Performance comparison

- PM ⇒ PM Hybrid ⇒ IVID ⇒ CIVID ⇒ SCU

Take advantage of Vanadium Permendur *Reduce gap* *Use Br(T), Hc(T)* *Use superconducting materials*





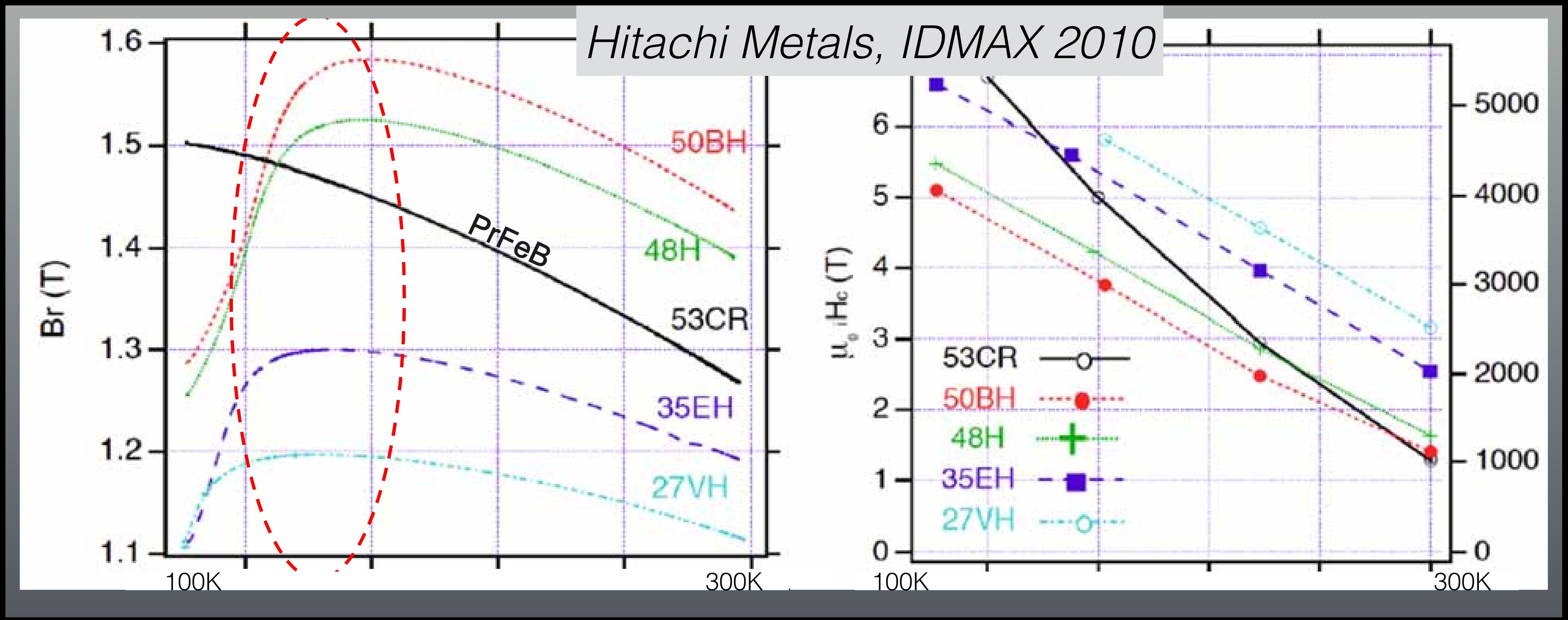
Careful!

Formulas/fits only appropriate under certain conditions: need to look at design closely to assure no demagnetization, saturation, etc. occurs

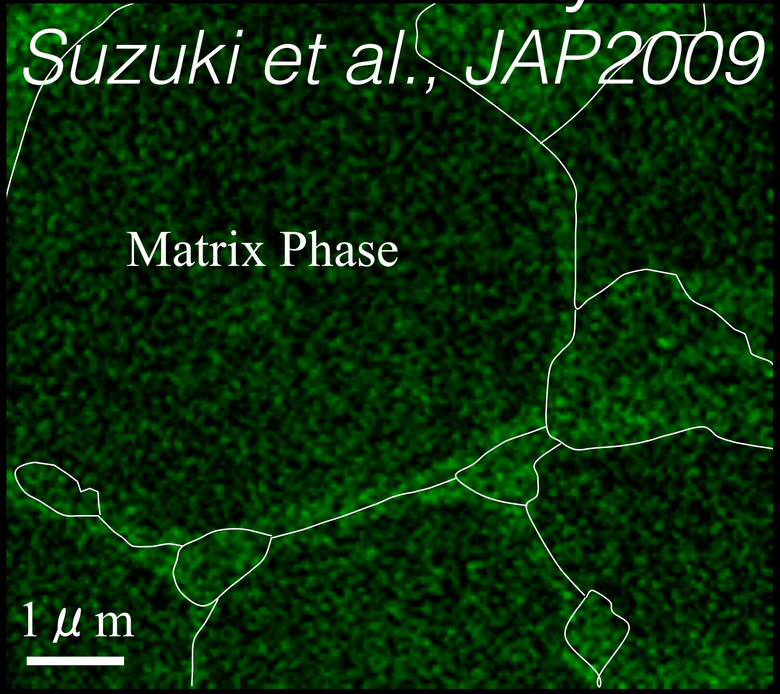
Planar technologies

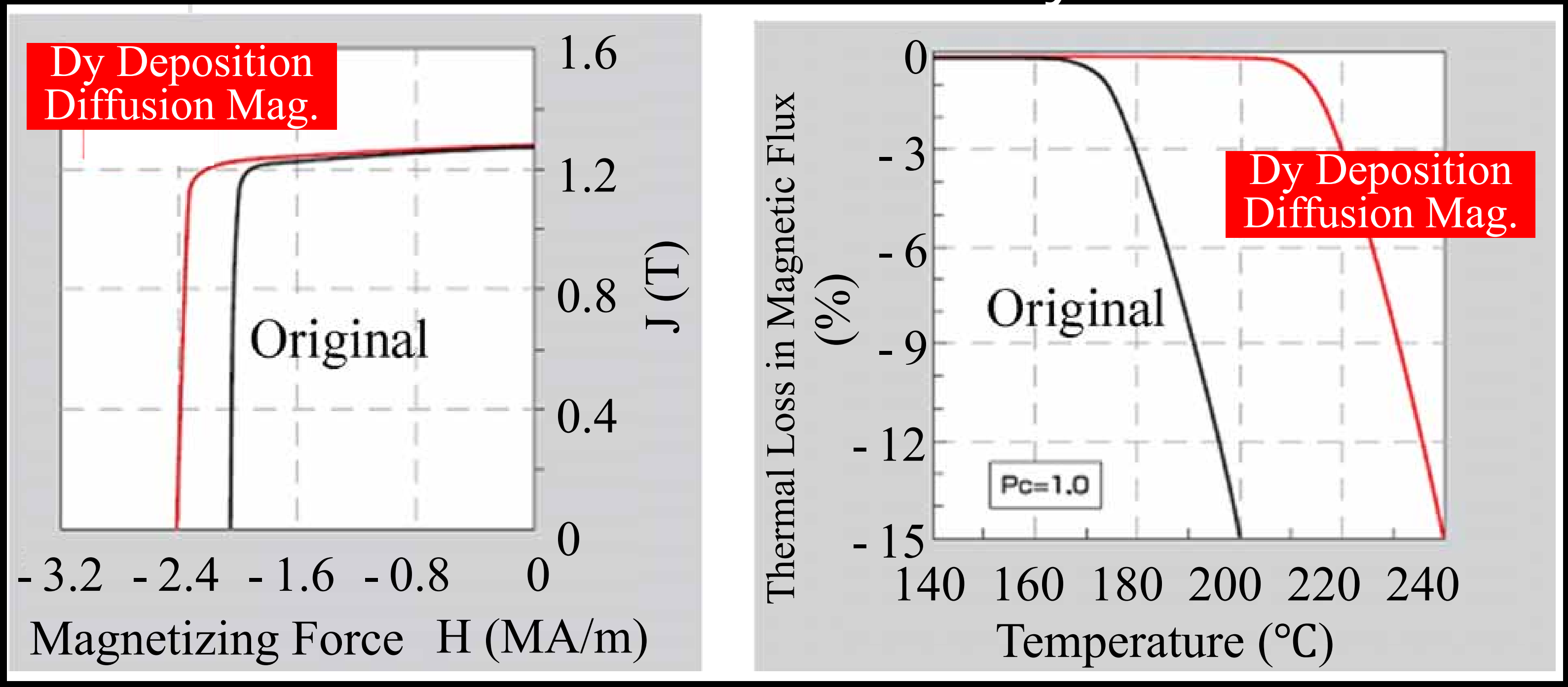
Technology	Strengths	Weaknesses	R&D
Pure and hybrid PM, out of vacuum	*•Performance known* *•Tolerances understood* *•Measureable*	*Field strength* *Gap motion+forces*	*•Gap control* *•Cost reduction*
Hybrid PM, in vacuum	*•Performance known* *•Tolerances (somewhat) understood* *•Measureable*	*•Vacuum considerations* *•Image currents* *•Gap motion+forces*	*•Gap control* *•Image currents* *•Cost reduction*
Cryogenic in-vacuum (hybrid) (CIVID)	*Potential performance*	*•Need to use high Br material – cannot bake* *•Tolerances difficult to control (dT, motion, etc)* *•Measurements*	*•Improve vacuum* *•Material developments* *•Cold measurement system*
NbTi superconducting	*•Potential performance (~CIVID)* *•Well-established material* *•No moving parts*	*•Low Tc (less margin)* *•Jc not "the best"*	*•Cold measurement system* *•Field correction* *•Magnetization effects*
Nb_3Sn superconducting	*•Potential performance (best Ic, "high" T margin)* *• 30-40%>NbTi, CIVID* *•Well-established material* *•No moving parts*	*•Extra "reaction" step* *•Larger filaments in superconductor*	*•Cold measurement system* *•Field correction* *•Magnetization effects*

Advances in PM field performance through technology and materials



Dy diffusion enhances coercivity

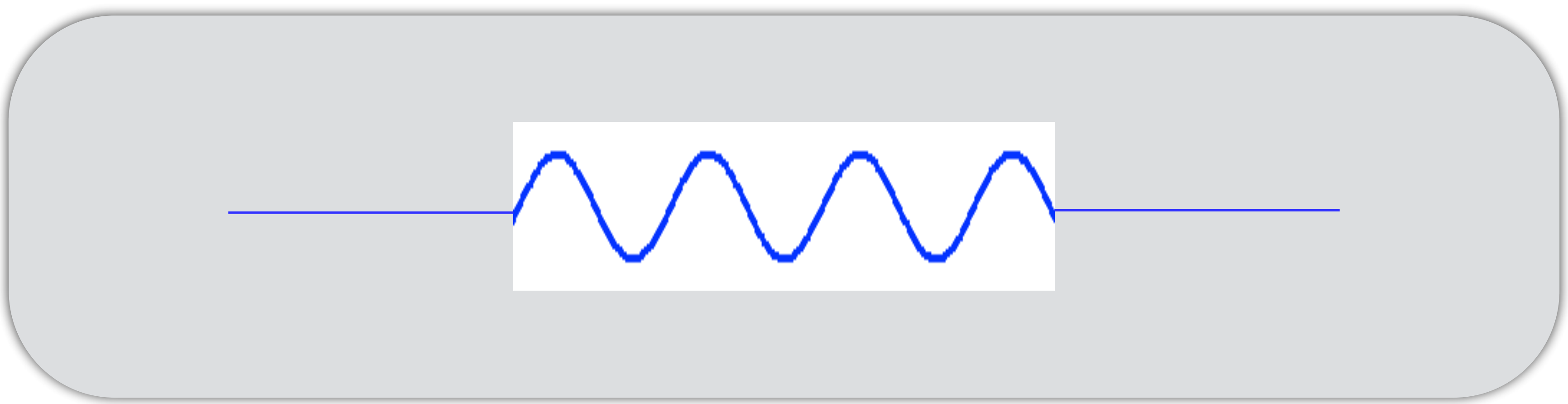




Trajectory considerations

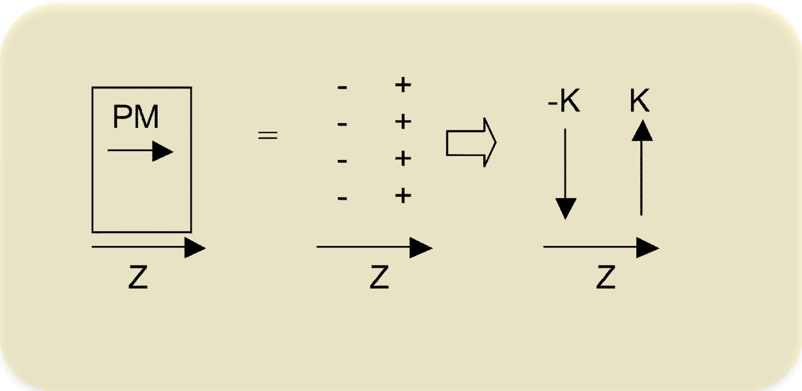
Beam steering considerations

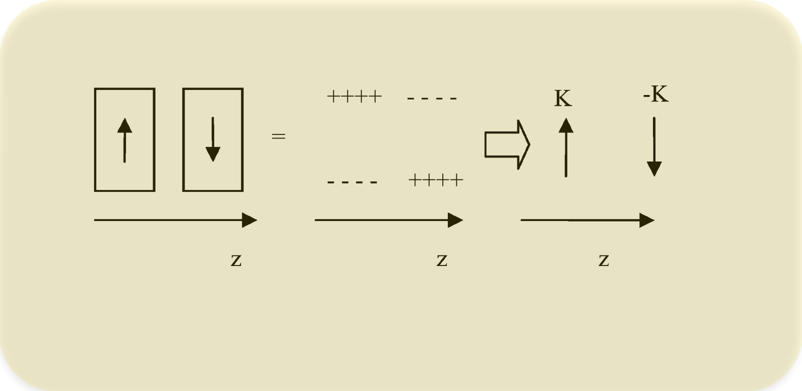
- Ideal condition consists of…
  - Beam arrival on axis
    - ✓ parallel to nominal path (NP), and with no offset
  - Undulator entry results in electron transverse oscillation about NP
  - Periodic section results in identical transverse oscillations
  - Beam exit results in beam on NP (parallel, no offset)

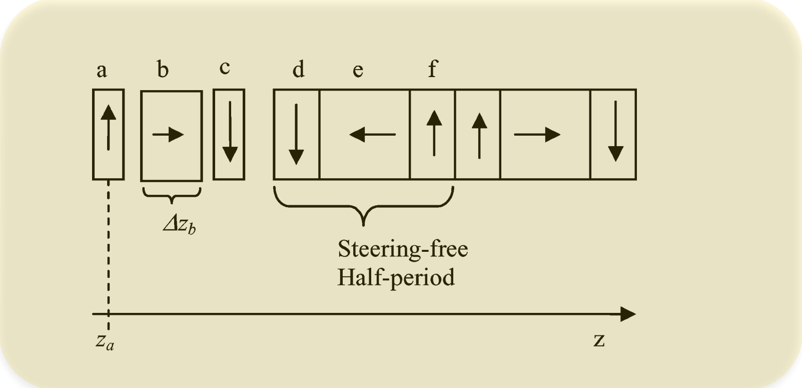


Entrance and exit kicks

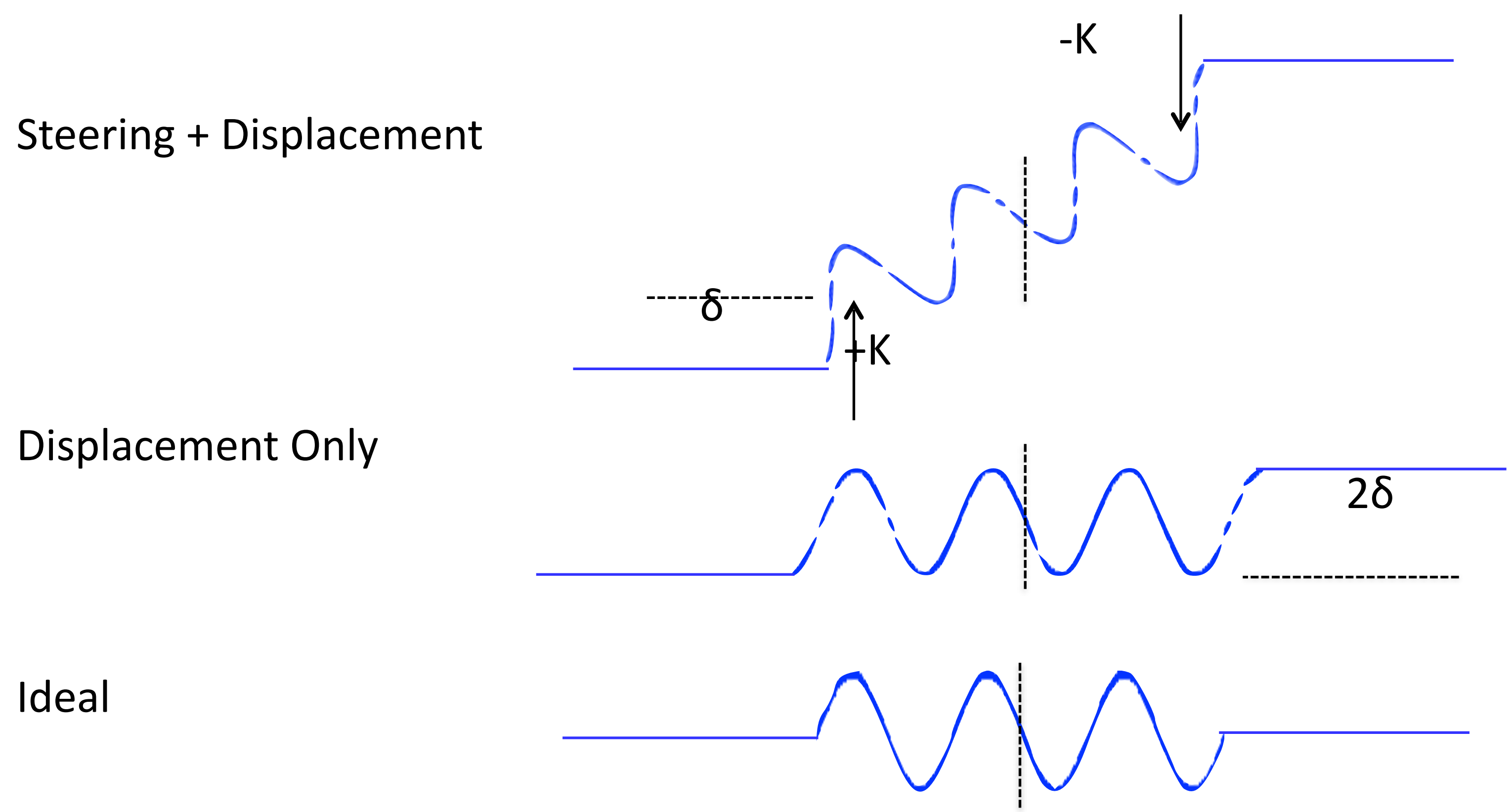
- End design is critical to control trajectory





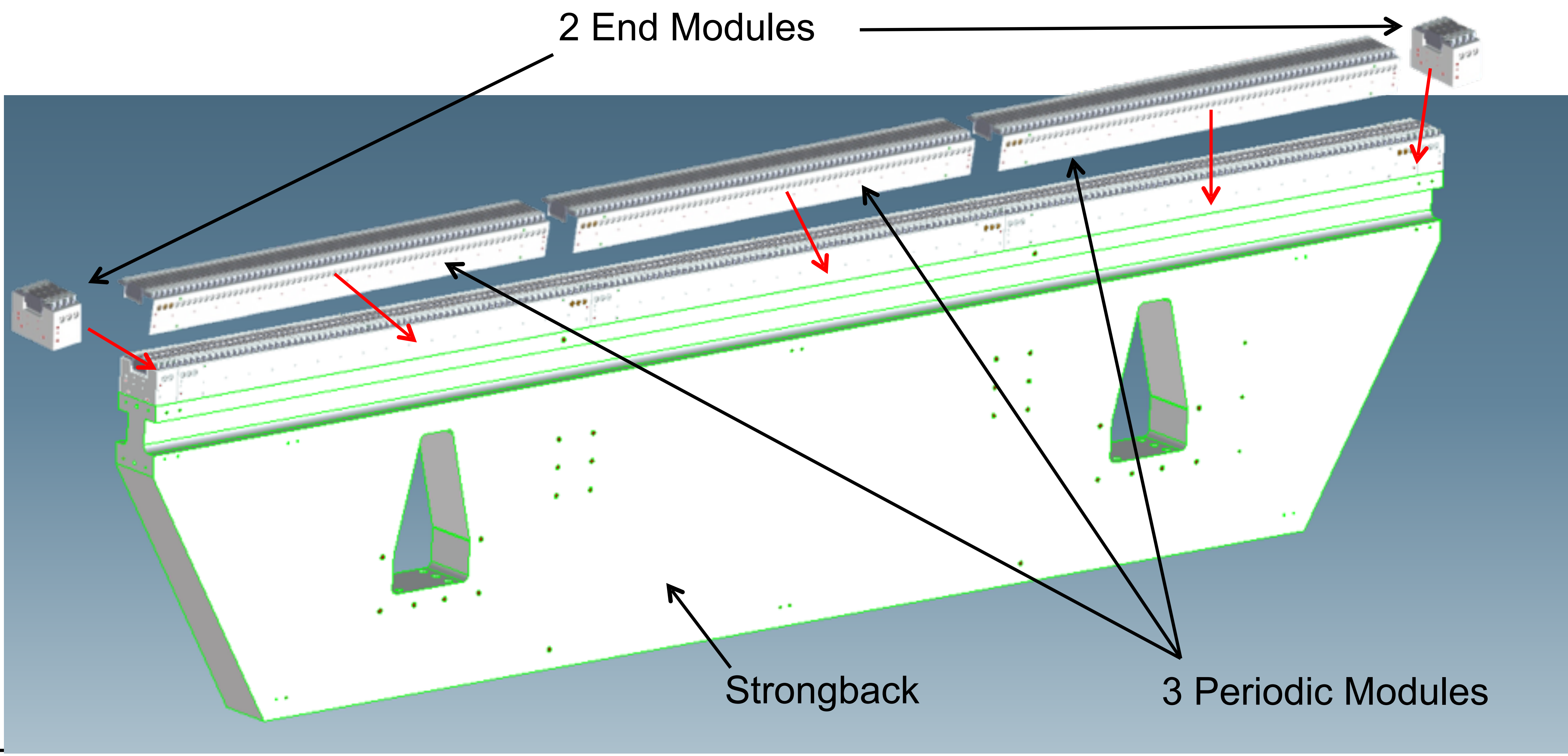


- For μ=1 material, "perfect" ends exist, for all gaps
- For μ>1 material, search solution minimizing end kicks



Modular Magnetic Structure for LCLS-II: ends optimized to minimize end-kick variations with gap

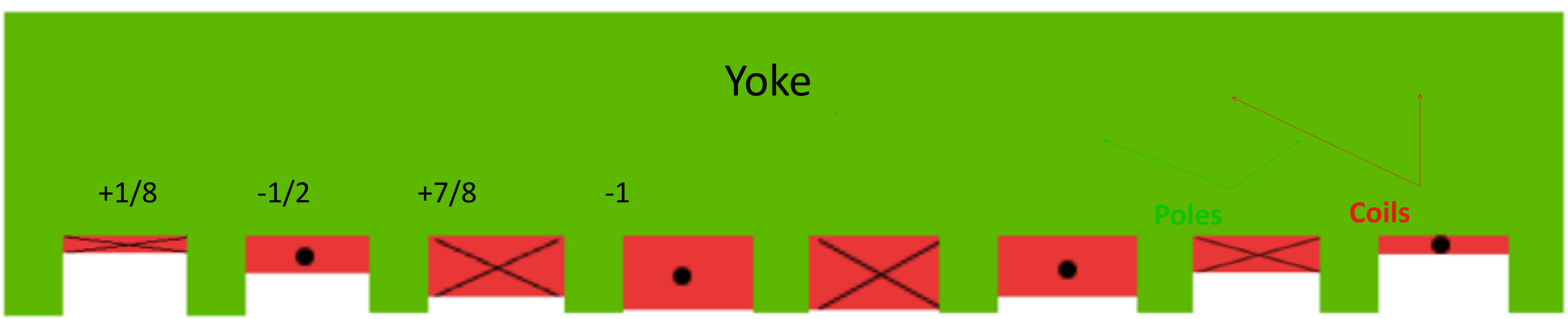
Module Array with Strongback, ~3.4m Long



End design optimization for SCUs

- Odd poles/even coils
- Binomial expansion pattern
  - Poles: 0, +1/4, -3/4, +1, -1,… (scalar potentials)
  - Coils: +1/8, -4/8, +7/8, -1, +1,…
- 7 x 8 turns/pocket:
  - Turns/coil: 7, 28, 49, 56, 56,…

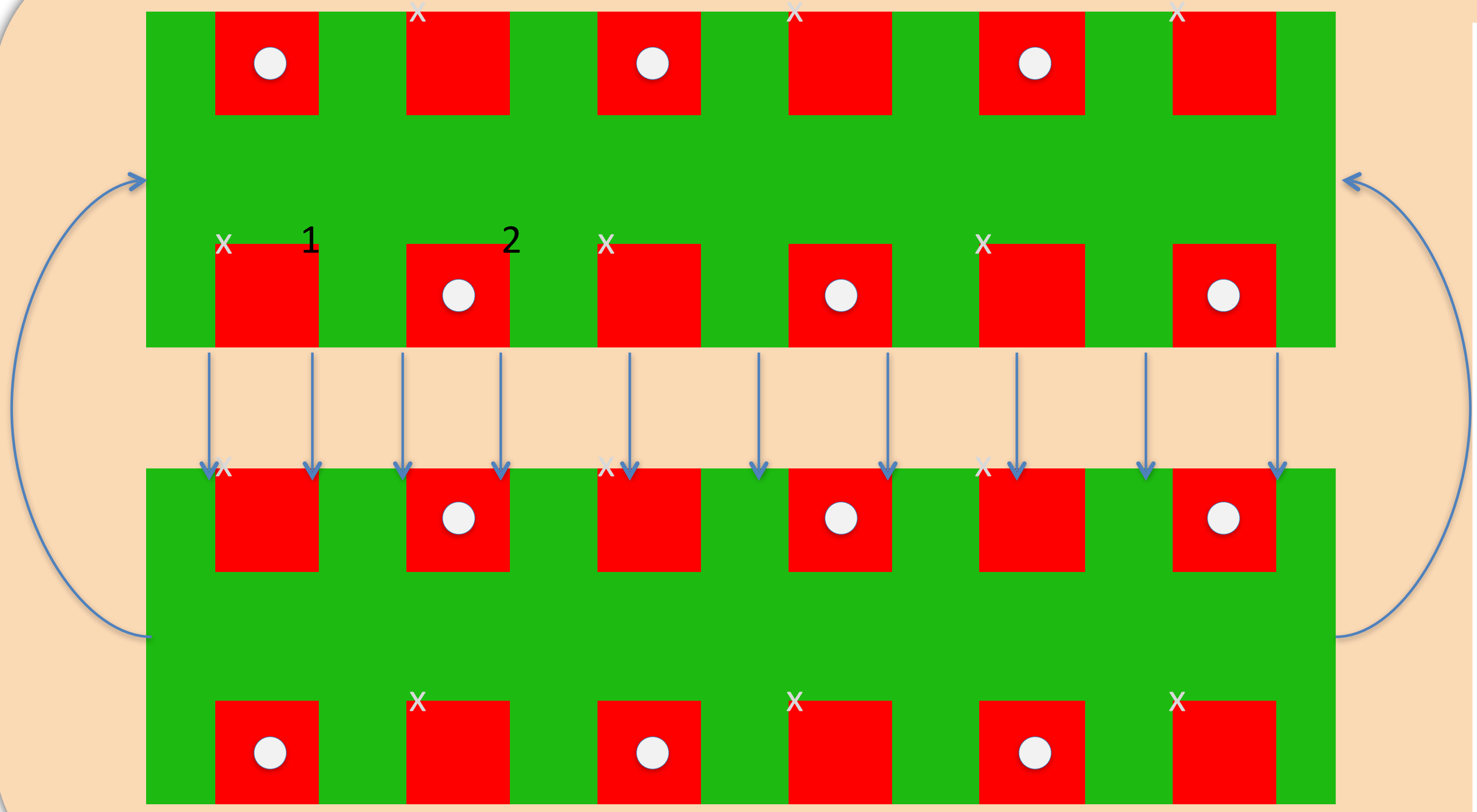
- Example requirements:
  - I1 (end) < 40 μT•m
  - I2 (end) < 50 μT•m2

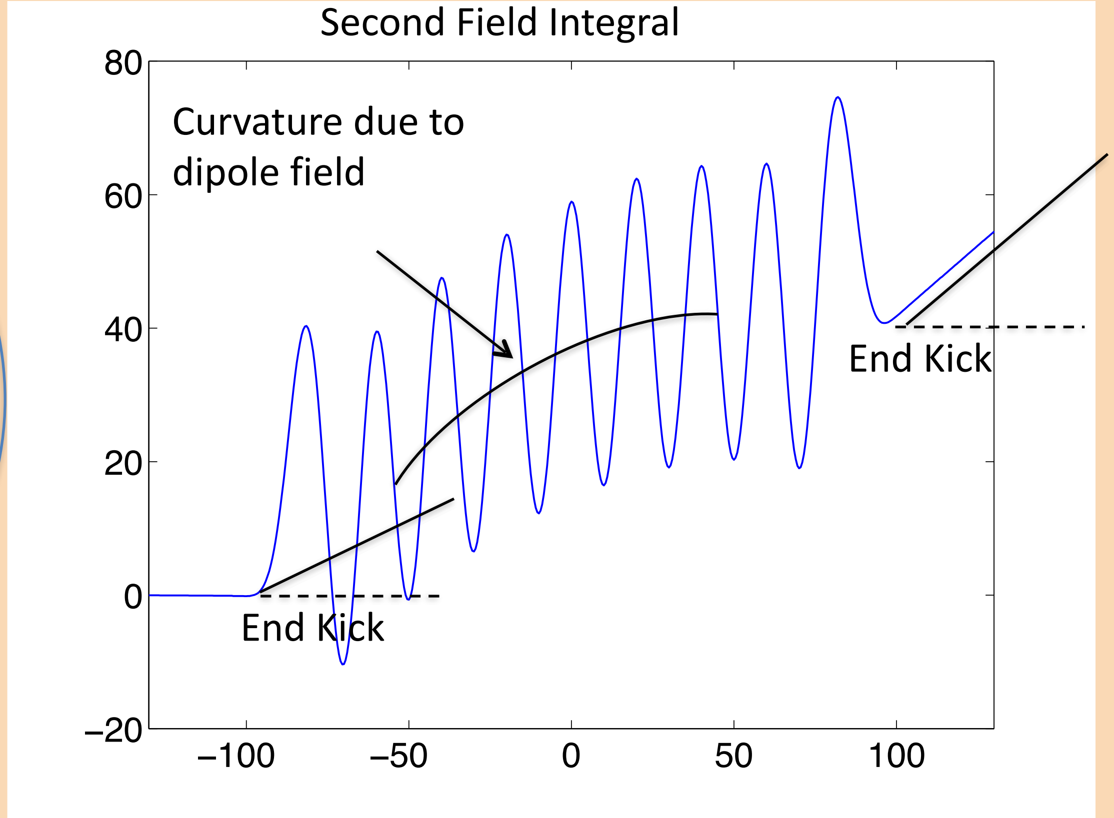


This expansion yields "perfect" beam trajectory (ideally)

Permeability effects

- Non-ideal effects due to finite permeability and differential saturation of end poles
  - End kick is dependent on the undulator field
  - Dipole field is generated by unbalanced yoke field

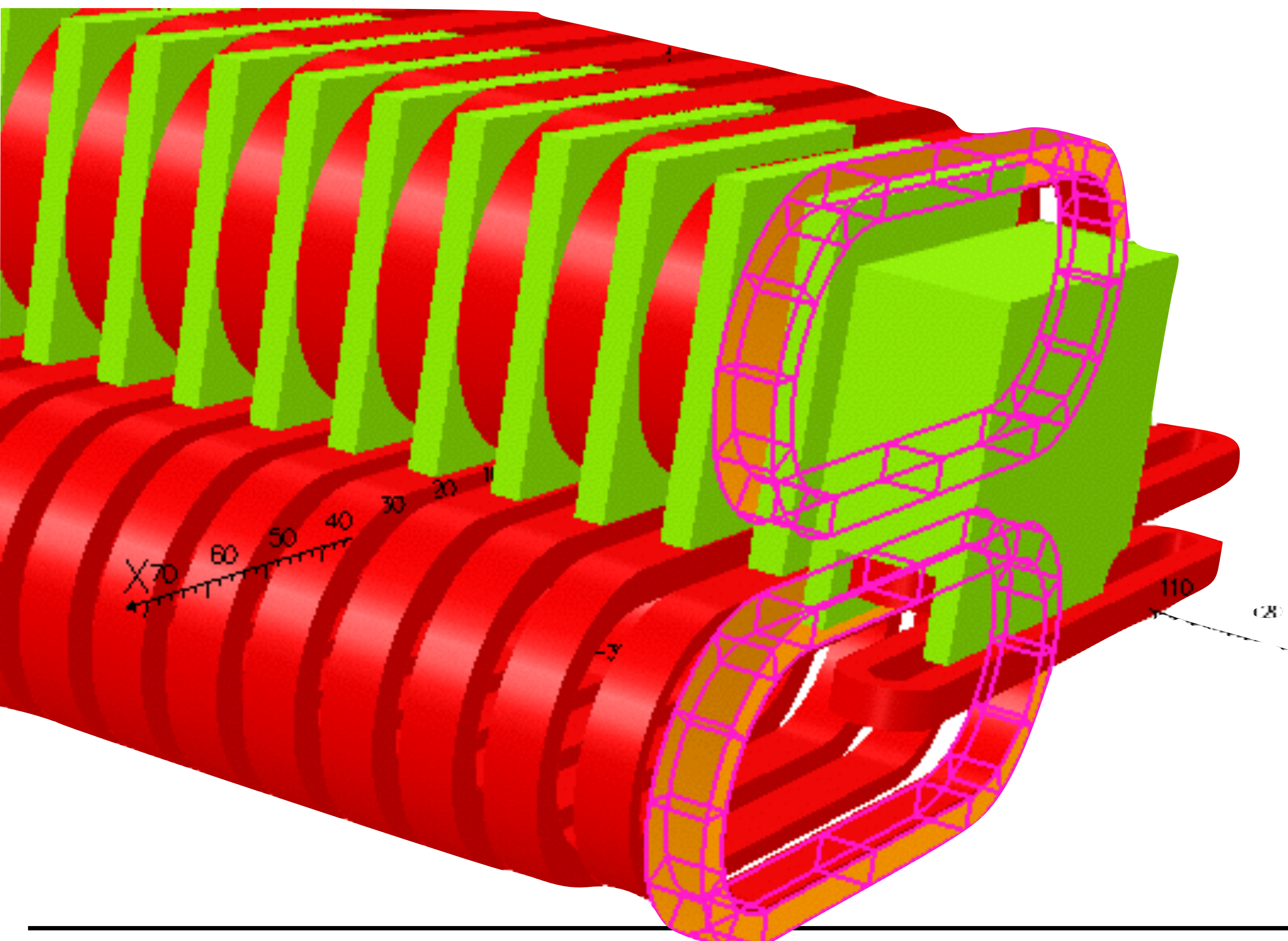


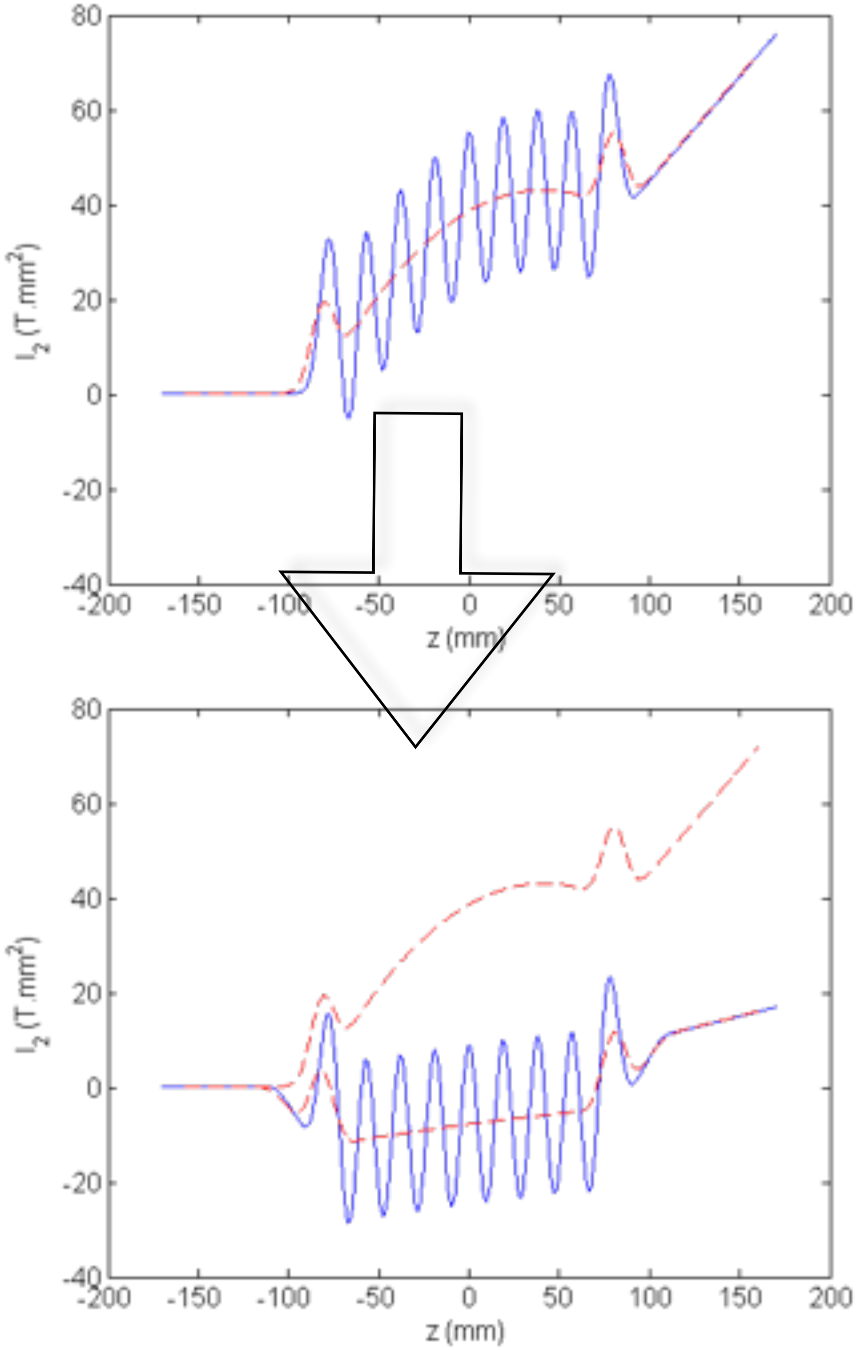


(A different type of signature occurs for even-pole scenario)

End correctors for compensation: *Correction of distributed dipole*

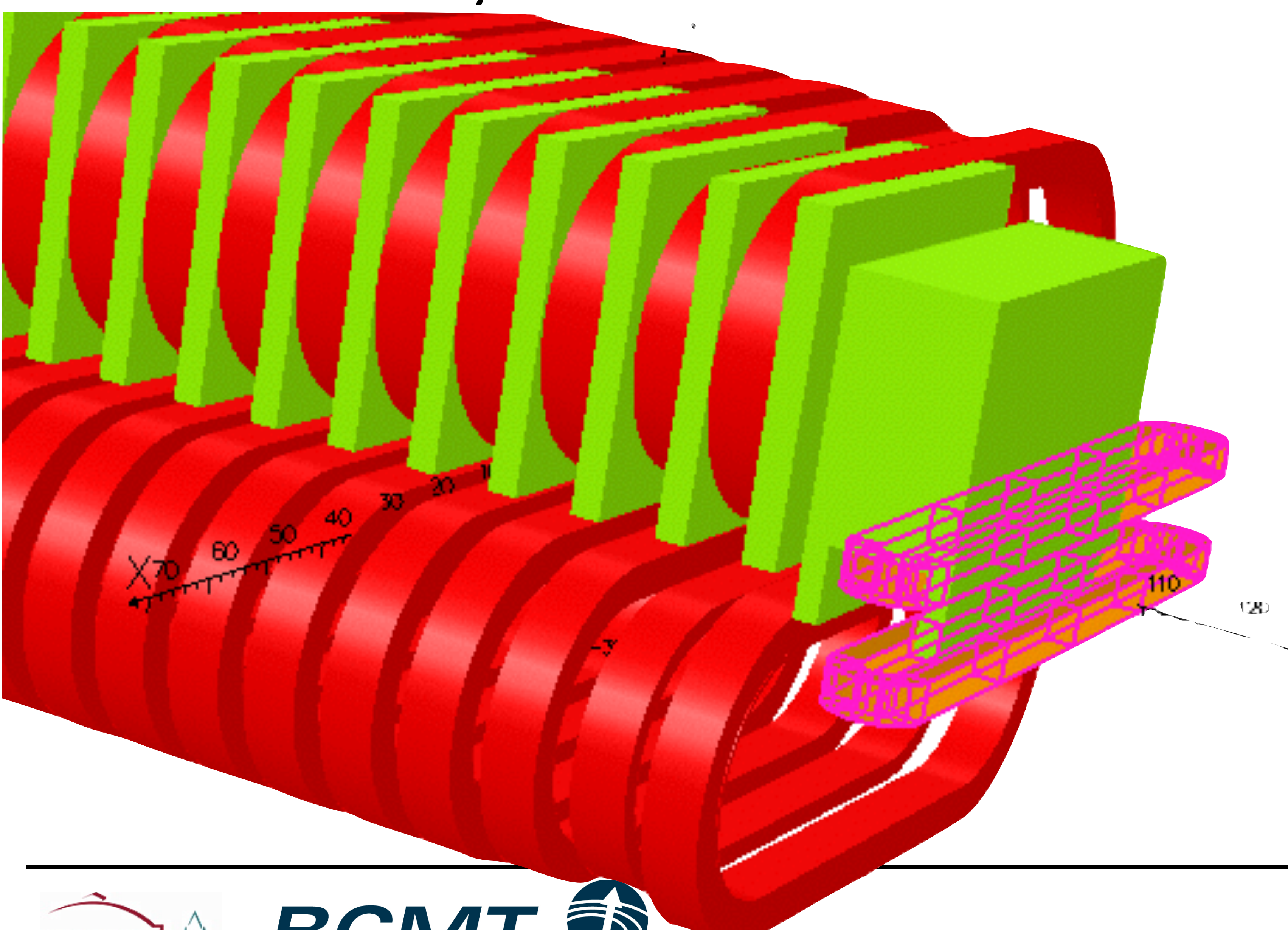
- Wound on top of the main coil in the remaining pocket on each end
- Adds both a *dipole* and *end kicks*

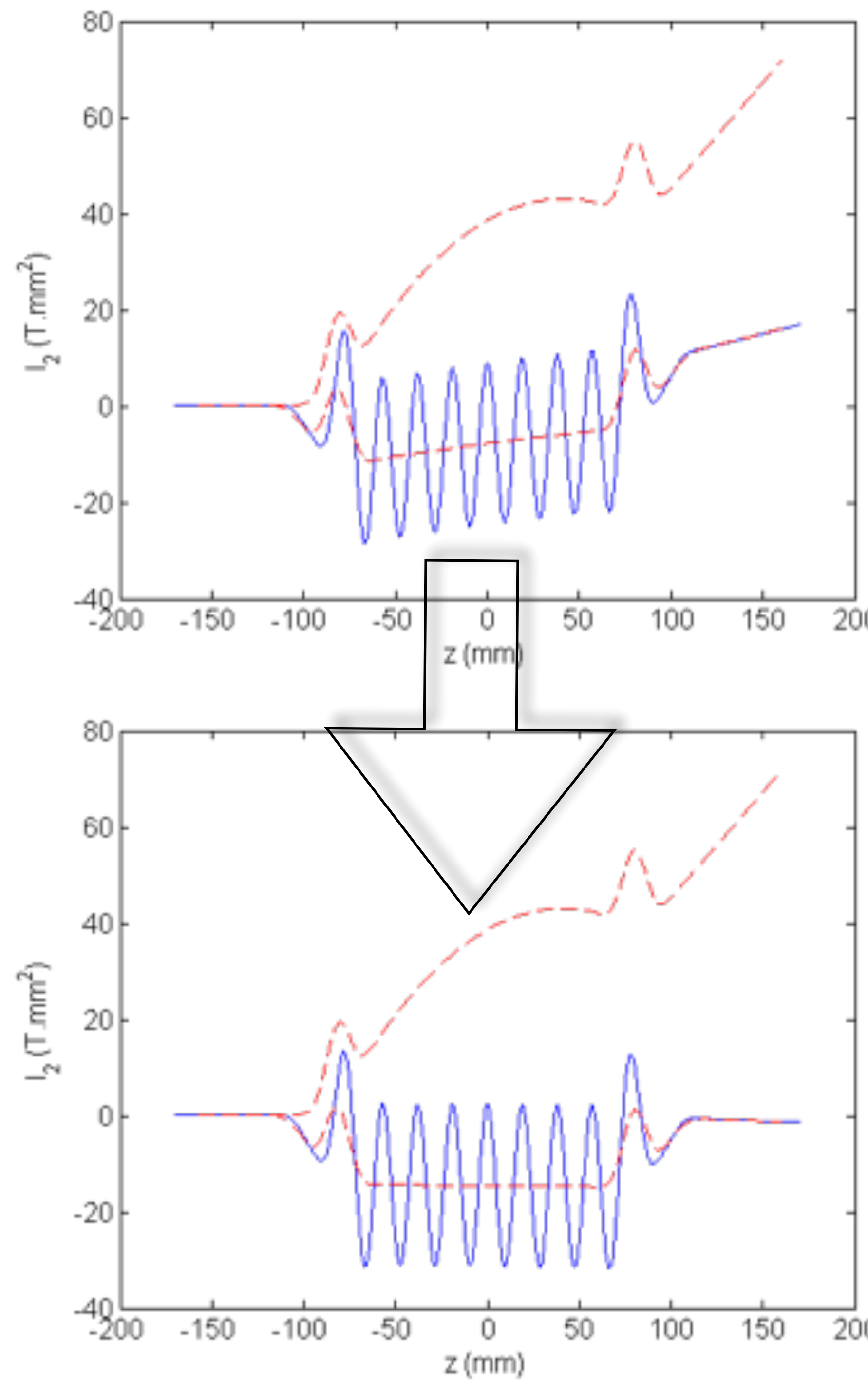




End correctors for compensation:
Correction of end kicks

- Wound in a separate yoke on each end
- Decoupled from the main yoke
  - adds only end kicks

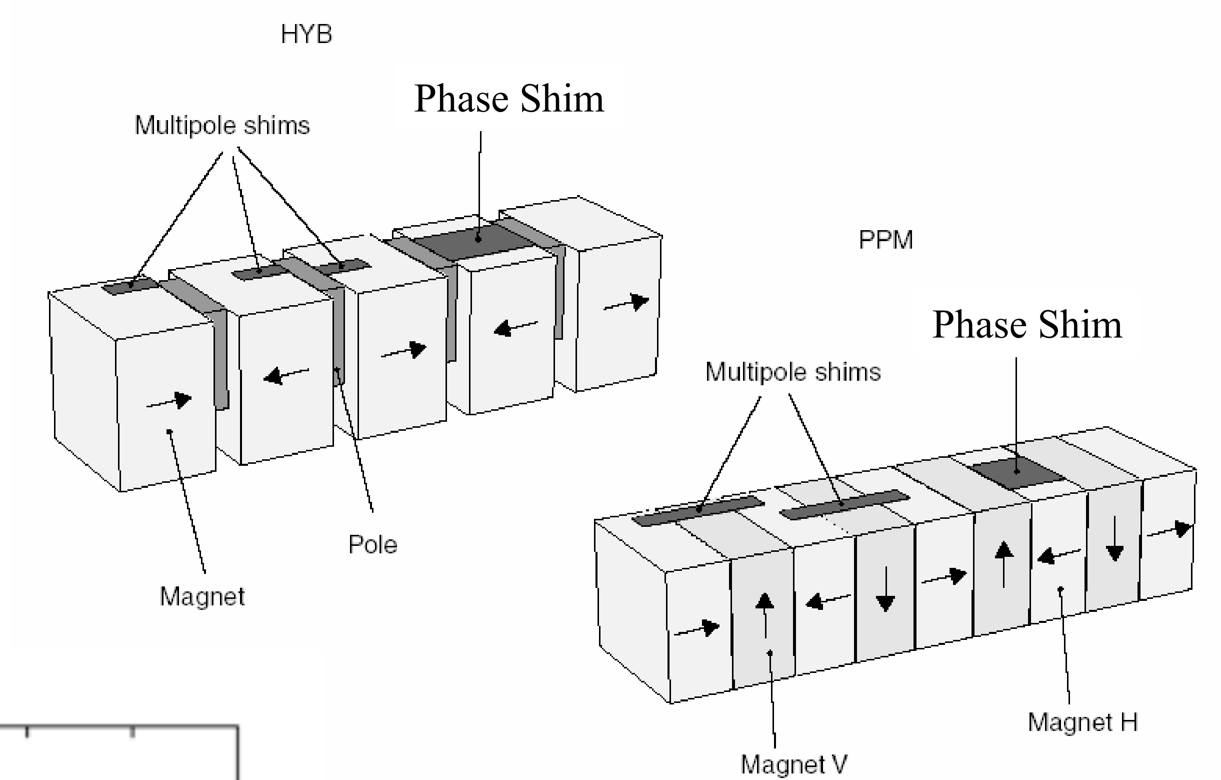


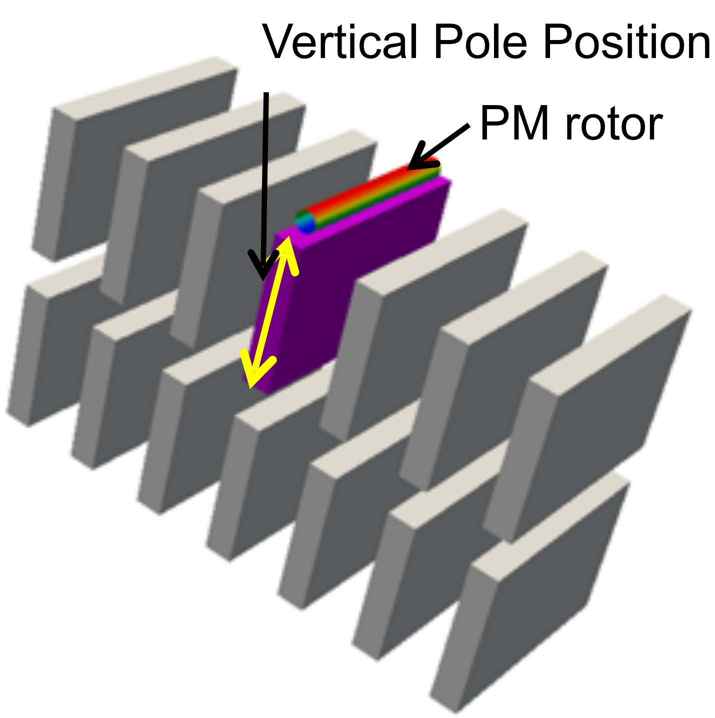


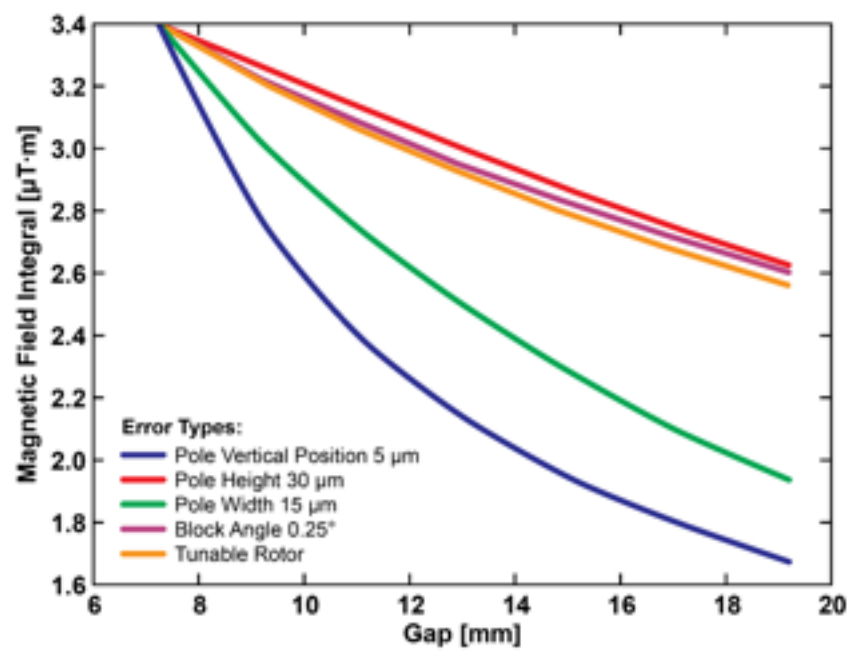
Field correction - shimming

Numerous techniques for shimming

- Pure PM devices:
  - "Virtual shimming": move a block!
- Hybrid PM:
  - magnetic shims
  - PM "rotors"



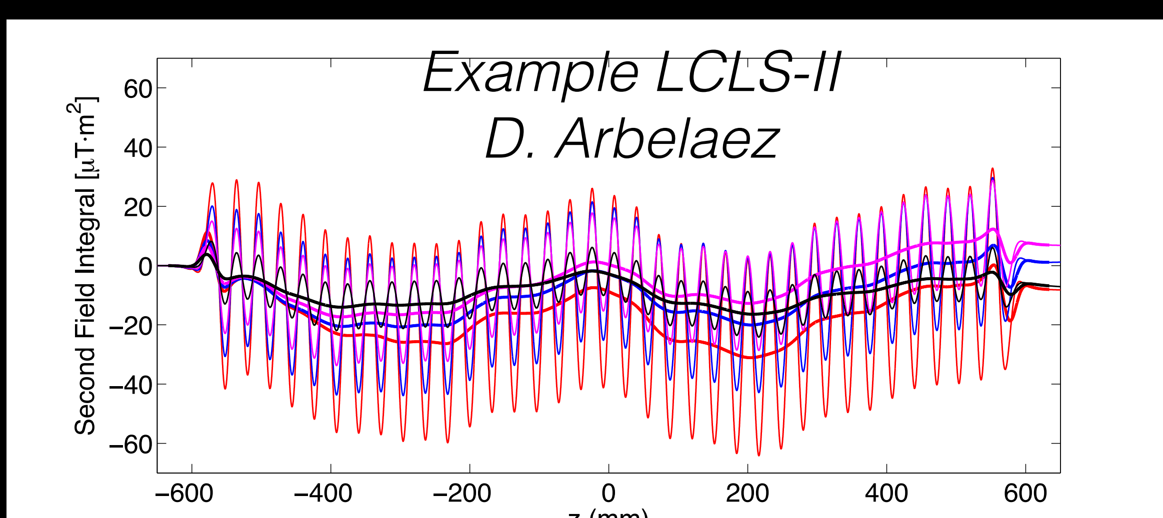


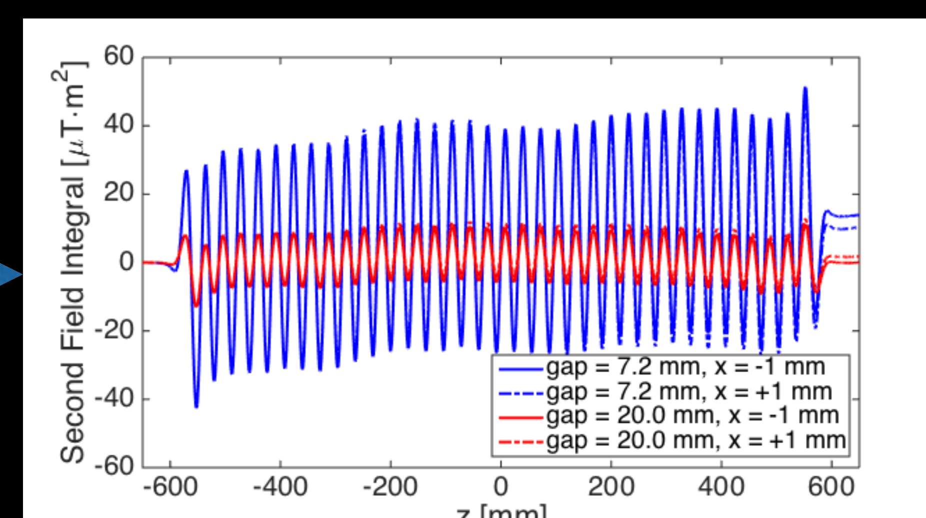


Key point: gap dependence of error sources must be reasonably matched by shimming techniques

Improvements in field quality from detailed understanding of error sources and optimized tuning

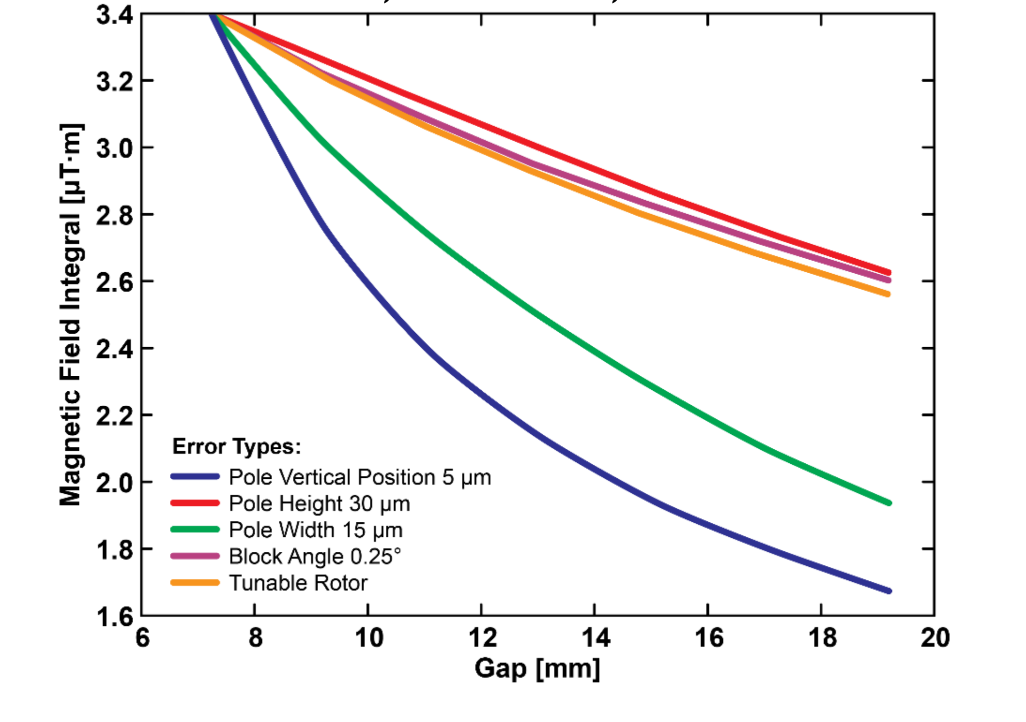
- Undulator field quality dictates electron trajectory wander and phase advance
- Evaluate all error sources:
  - ✓ Amplitudes and distributions
  - ✓ Dependence on field strength
- Identify reliable correction methodology

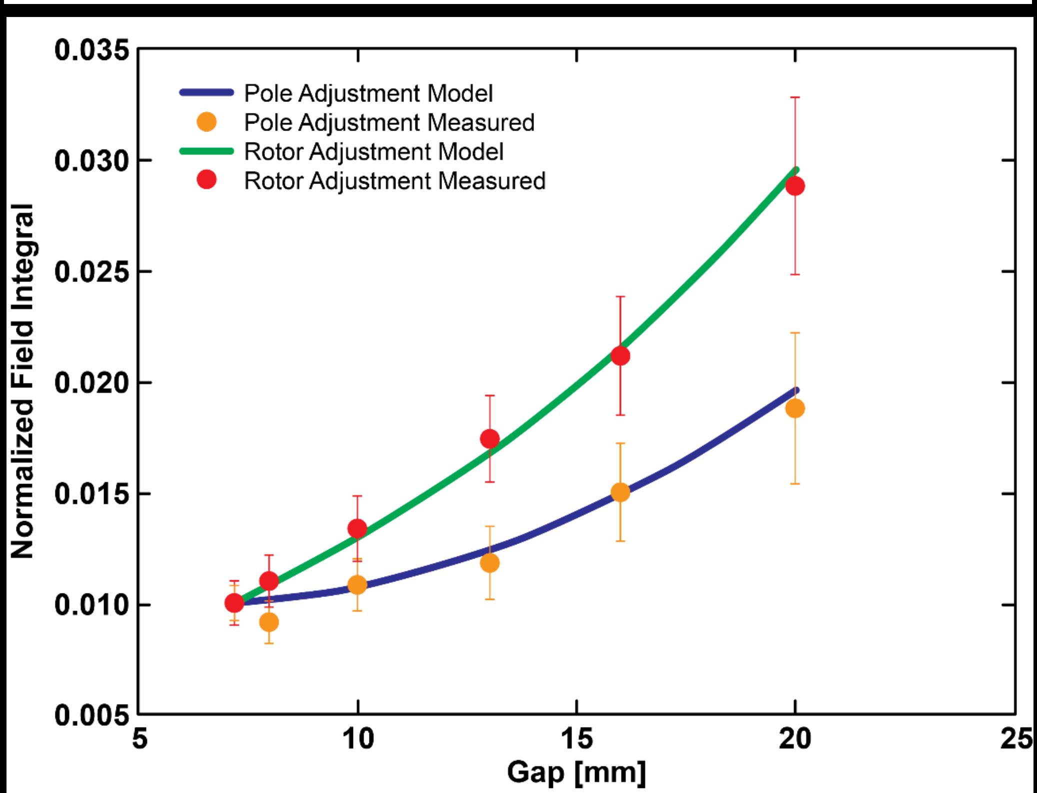




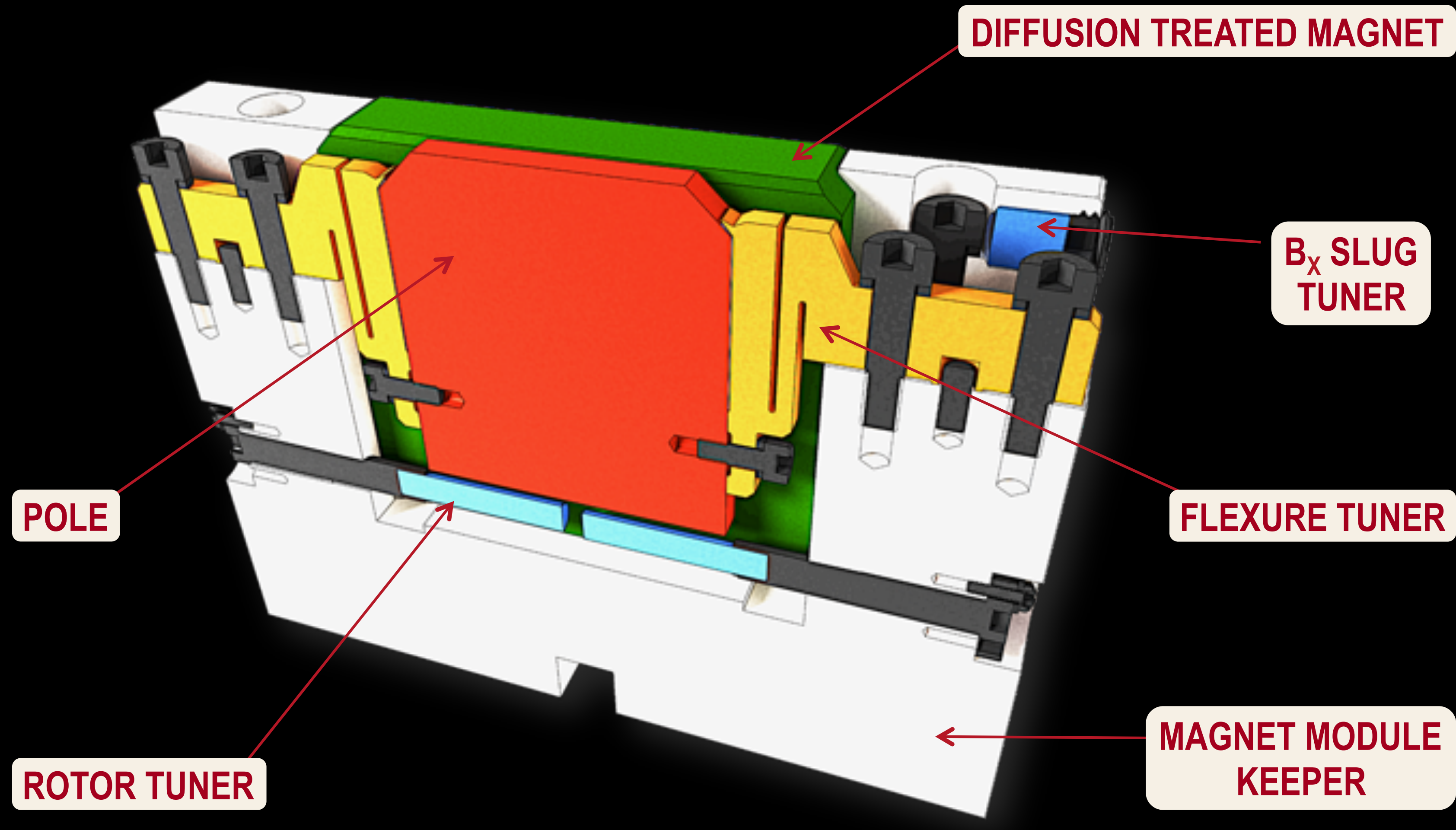
Example of hybrid PM tuning improvements: LCLS-II undulators

Arbelaez, BeMa, PSI 2014

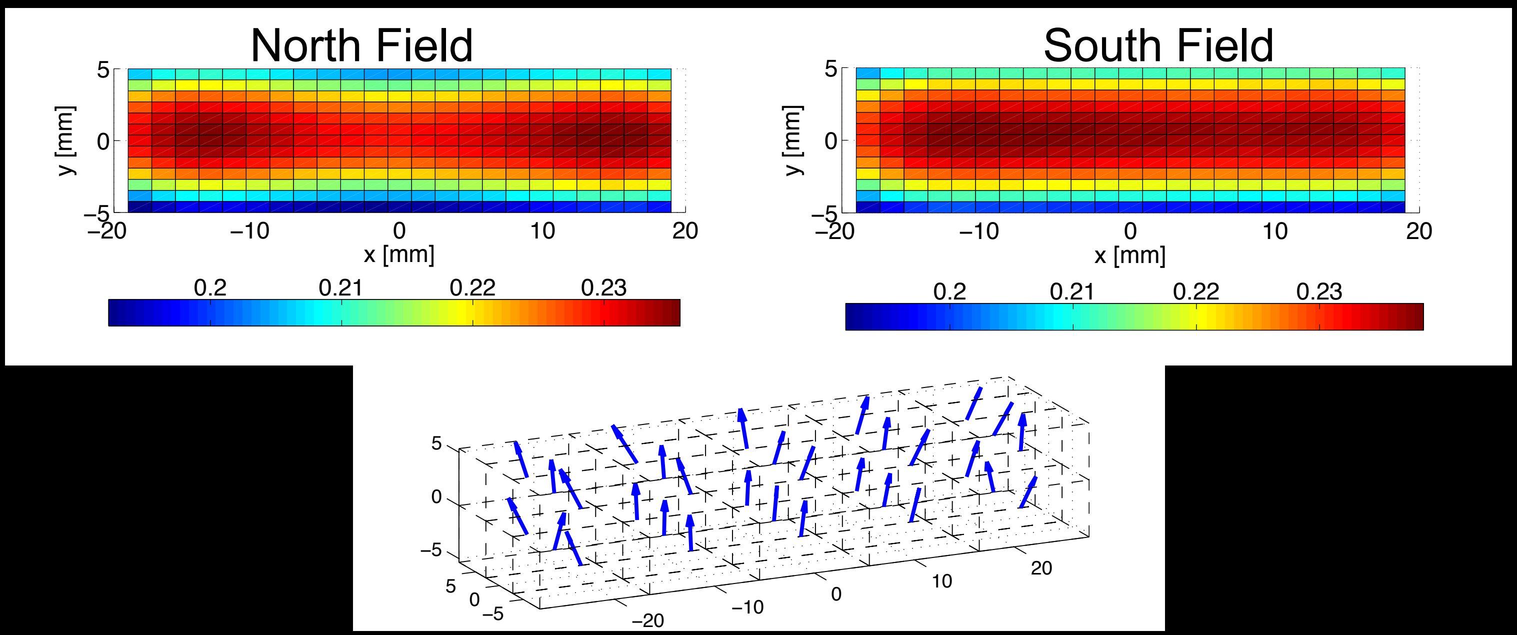


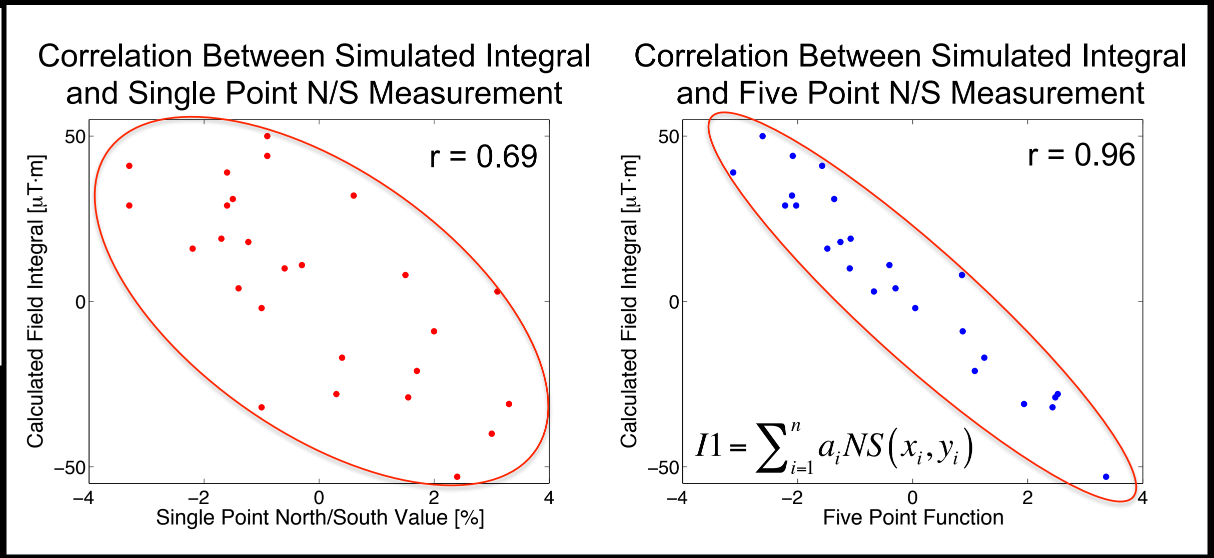


Leitner, LCLS-II review 2015

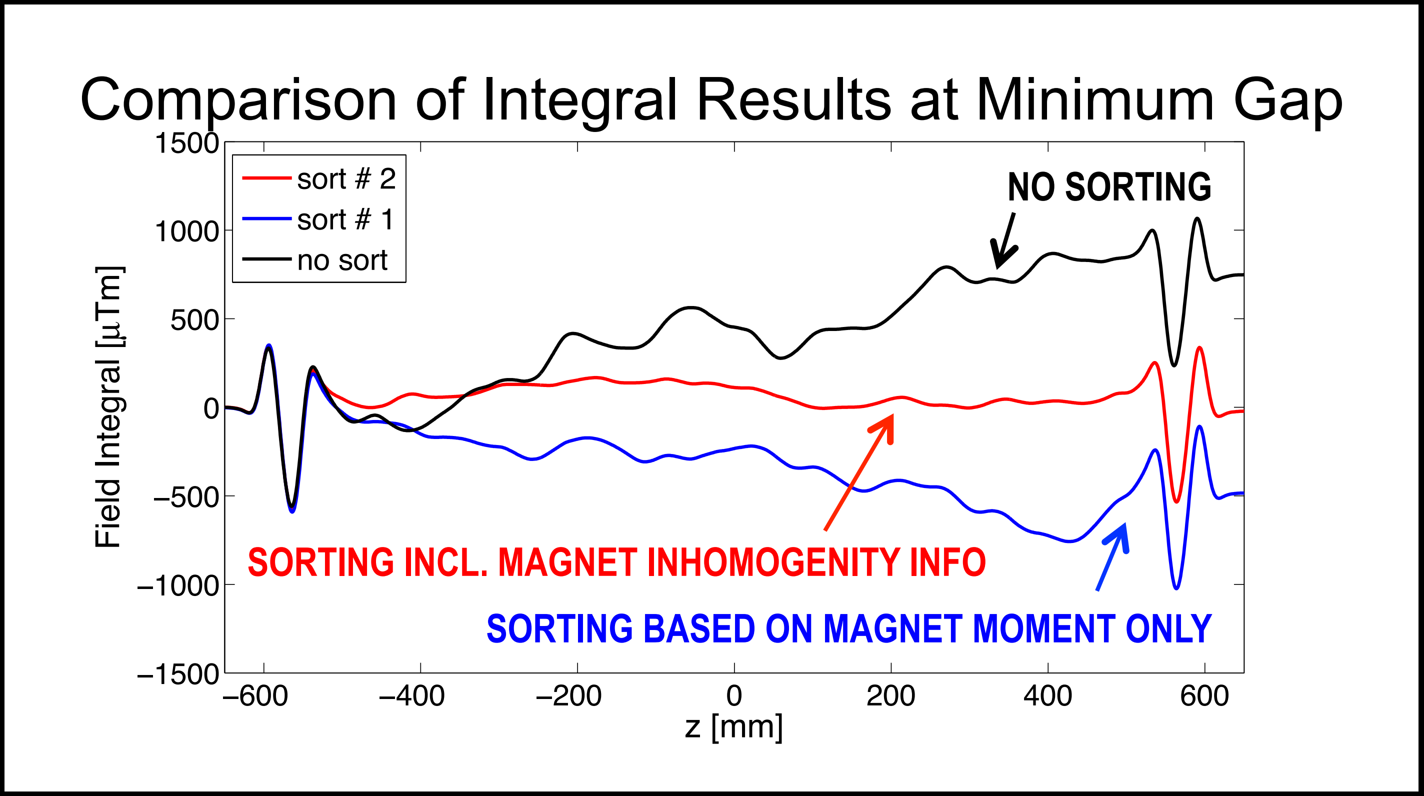


Improved sorting of PM material results in significant reduction in tuning time





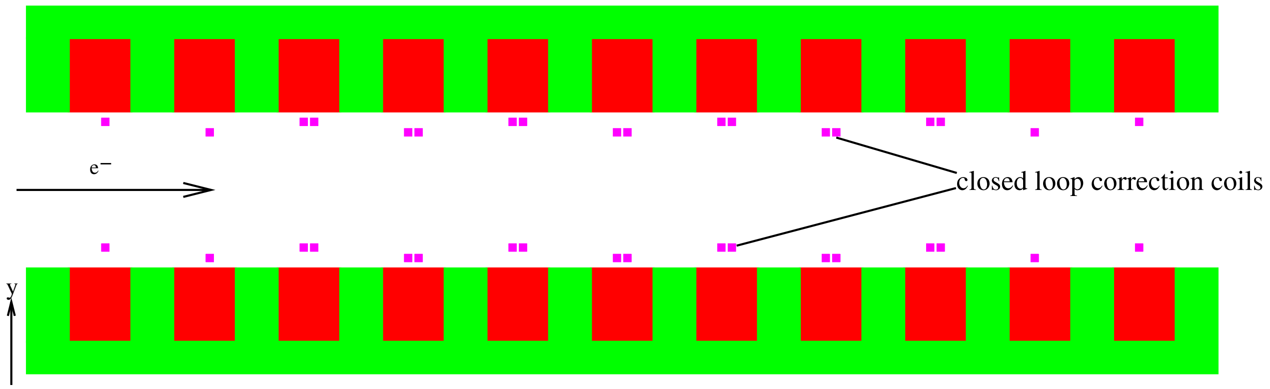
D. Arbelaez, BeMa workshop, PSI, 2014



Field correction

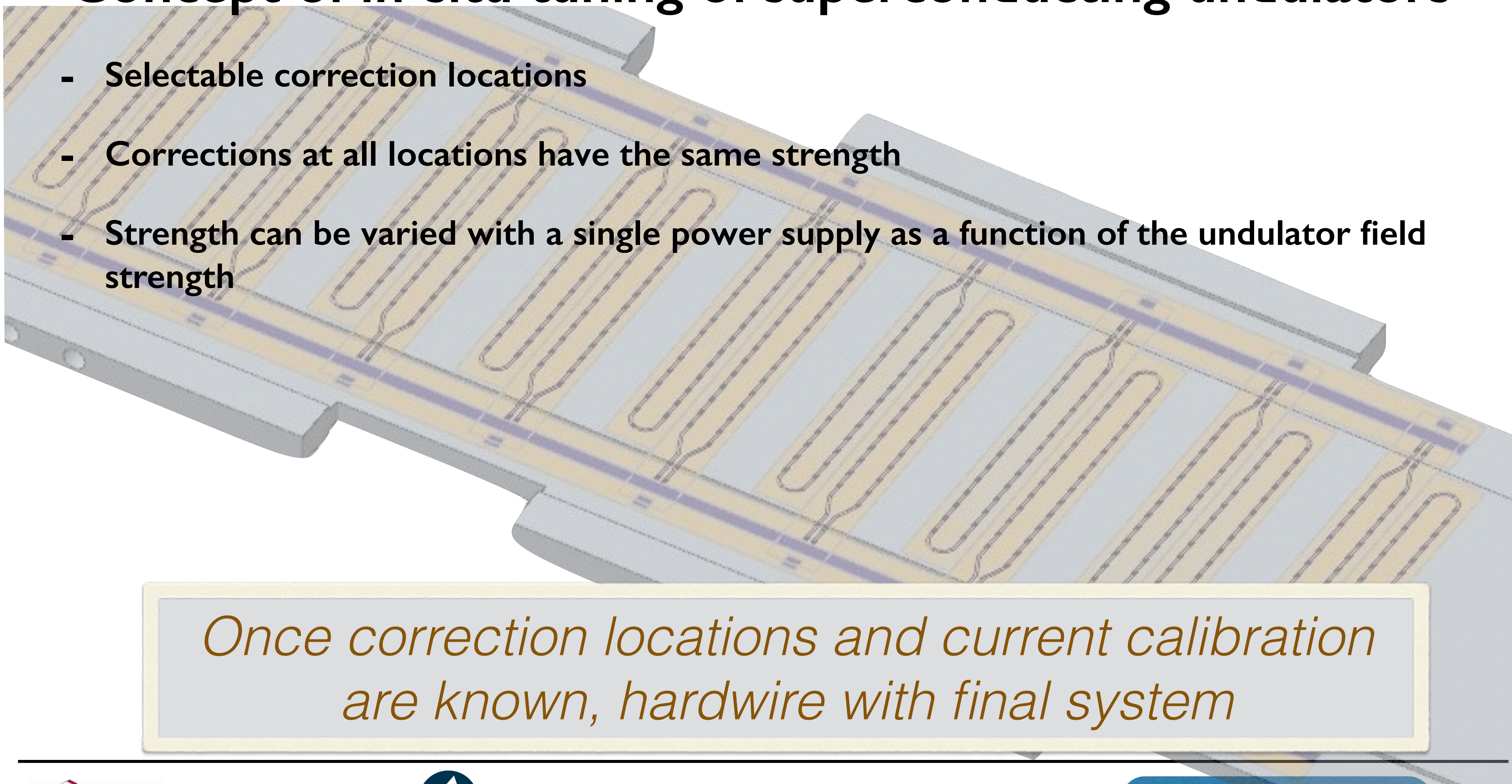
- PM systems use "virtual" or magnetic shims
- SCU correction methods:
  - Trim "coils": located on each/any poles
    - ✓ Amplitude of correction (~1%) has been demonstrated (e.g. at LBL)
    - ✓ Individual control is possible, but becomes complex
    - ✓ Experience with PM devices suggests few "coils" can provide requisite correction => locations of corrections determined during undulator testing off-line
    - ✓ Mechanism to direct current using superconducting switches has been tested
  - Passive "shims" (ANKA): use closed SC loop to enforce half-period field integral
    - ✓ Should significantly reduce RMS of errors
    - ✓ Some residuals will still exist due to fabrication issues
    - ✓ Possibility of hysteretic behavior from pinned flux – needs to be measured under various field cycling conditions

Wollman et al., PRSTAB 2008



Tuning for internal trajectory and phase errors

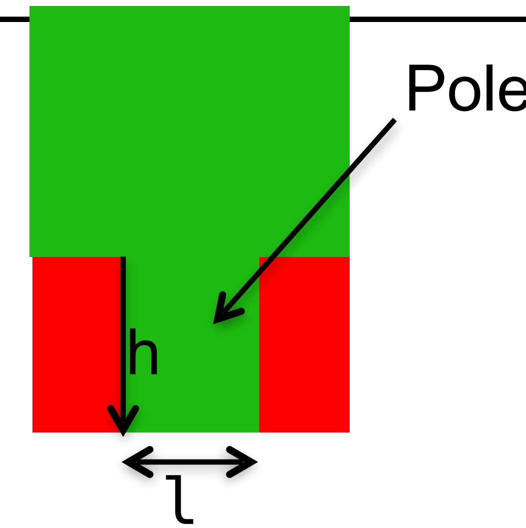
- **Concept of in-situ tuning of superconducting undulators**



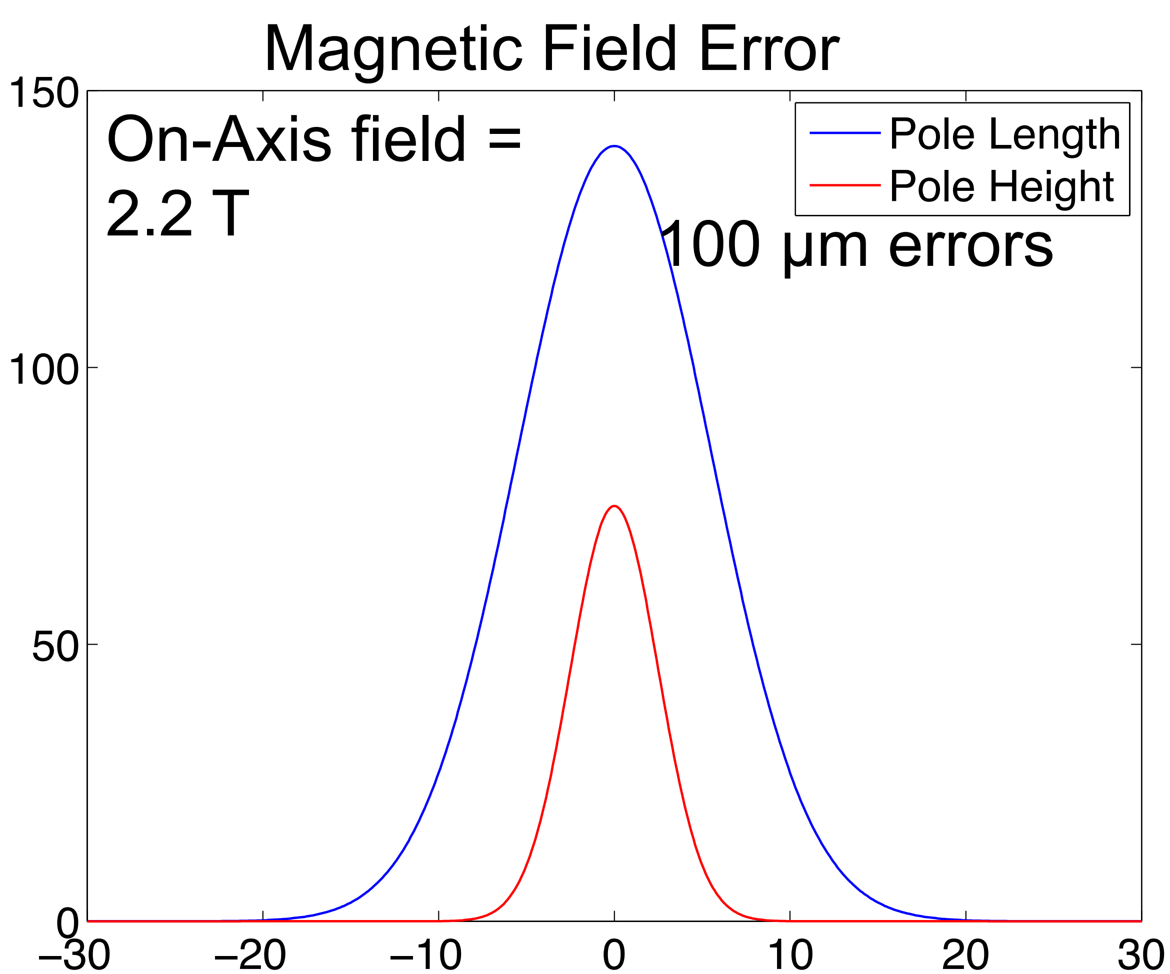
  - Selectable correction locations
  - Corrections at all locations have the same strength
  - Strength can be varied with a single power supply as a function of the undulator field strength

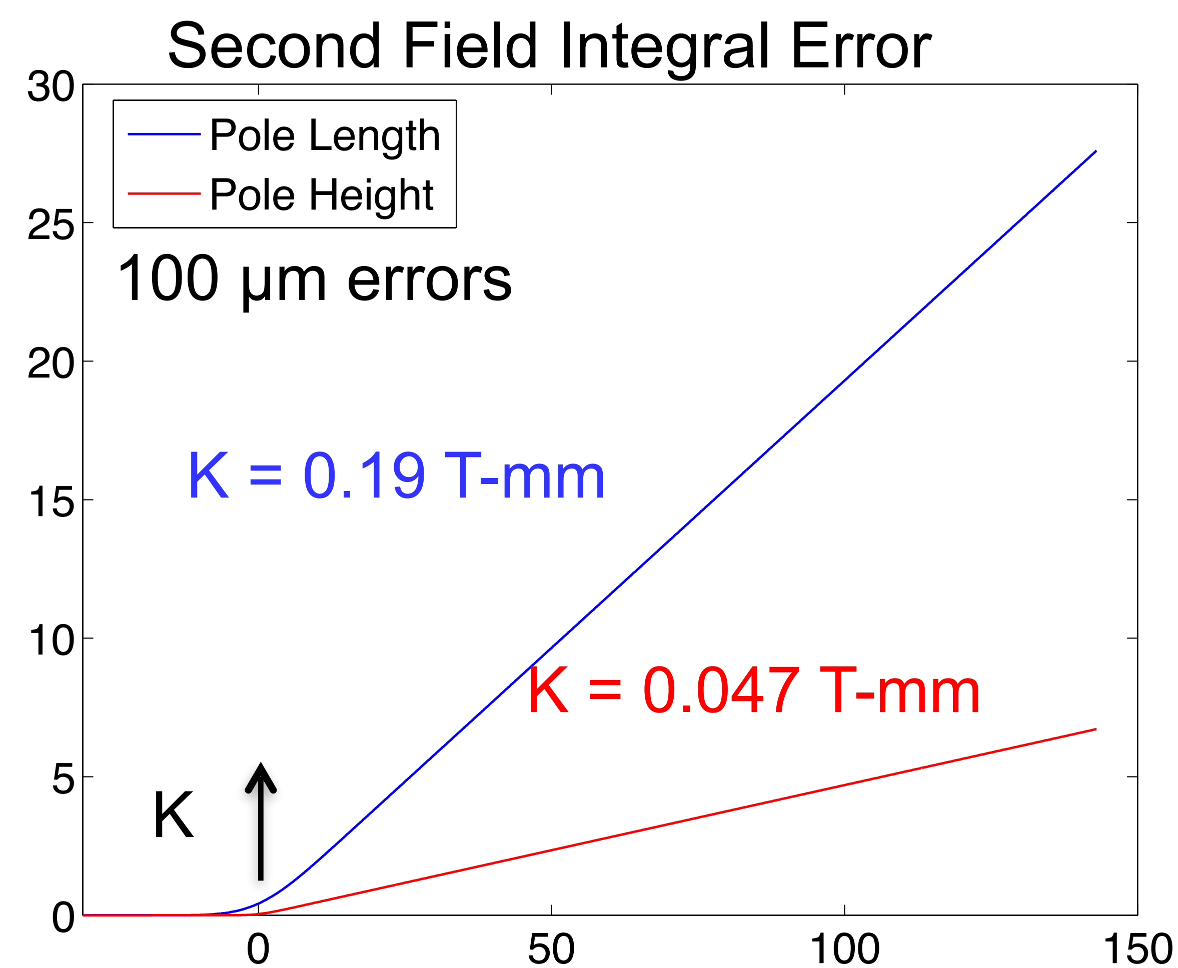
Once correction locations and current calibration are known, hardwire with final system

Pole Errors

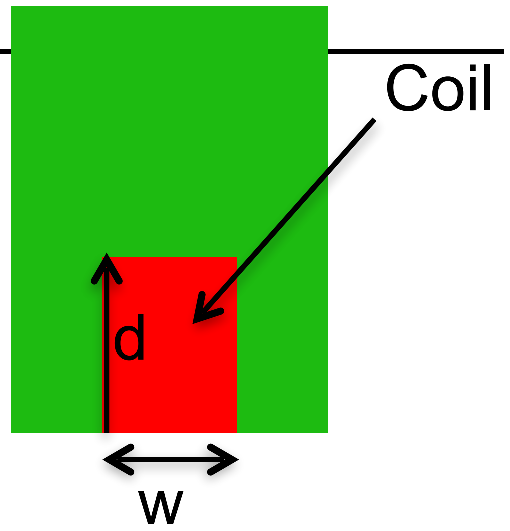


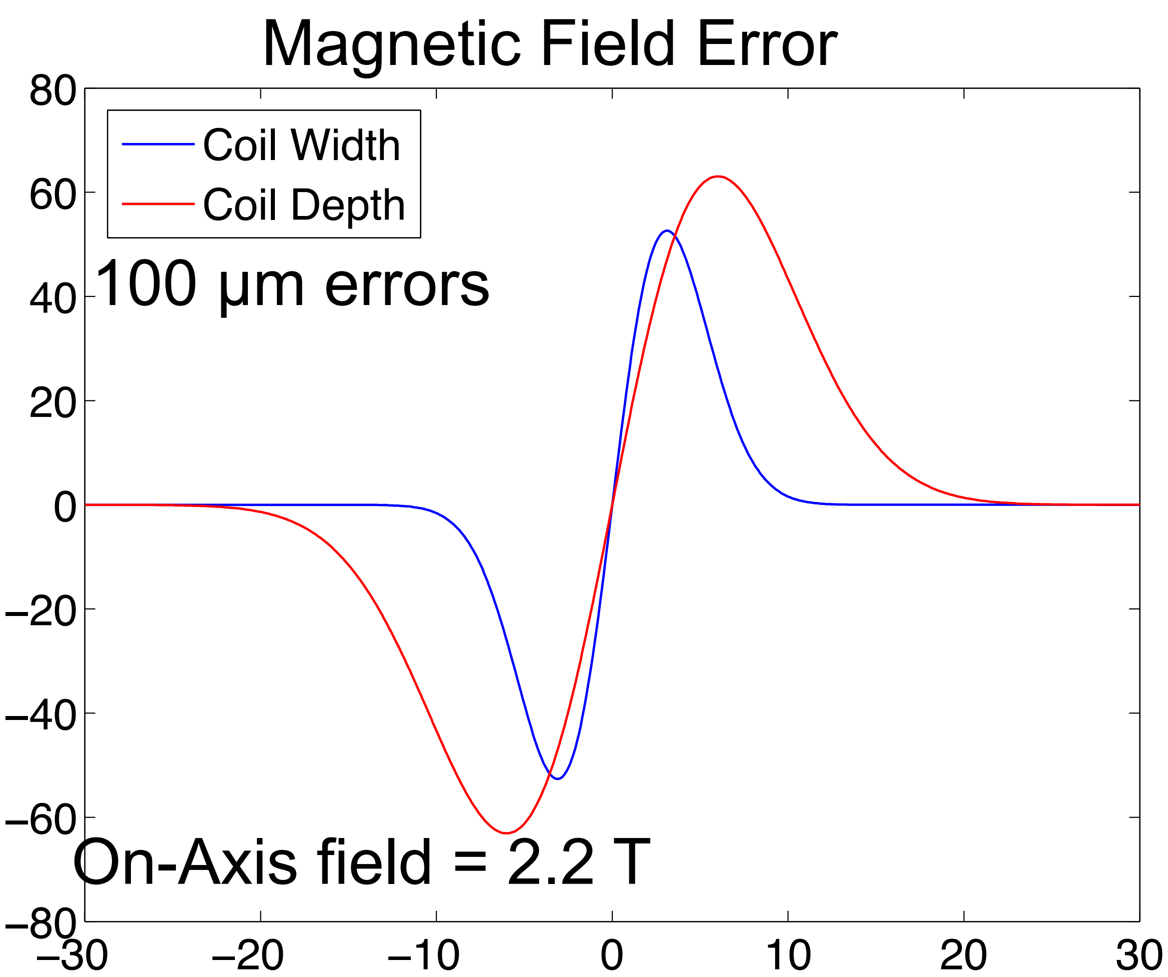
- Field error is maximum at the center of the pole (even function)
  - Produces a net kick
  - Displacement grows linearly with distance
  - Pole height error scales as $\delta h/g$ where g is the gap
  - Pole length error scales as $\delta l/l$ (very sensitive since l is the smallest dimension)

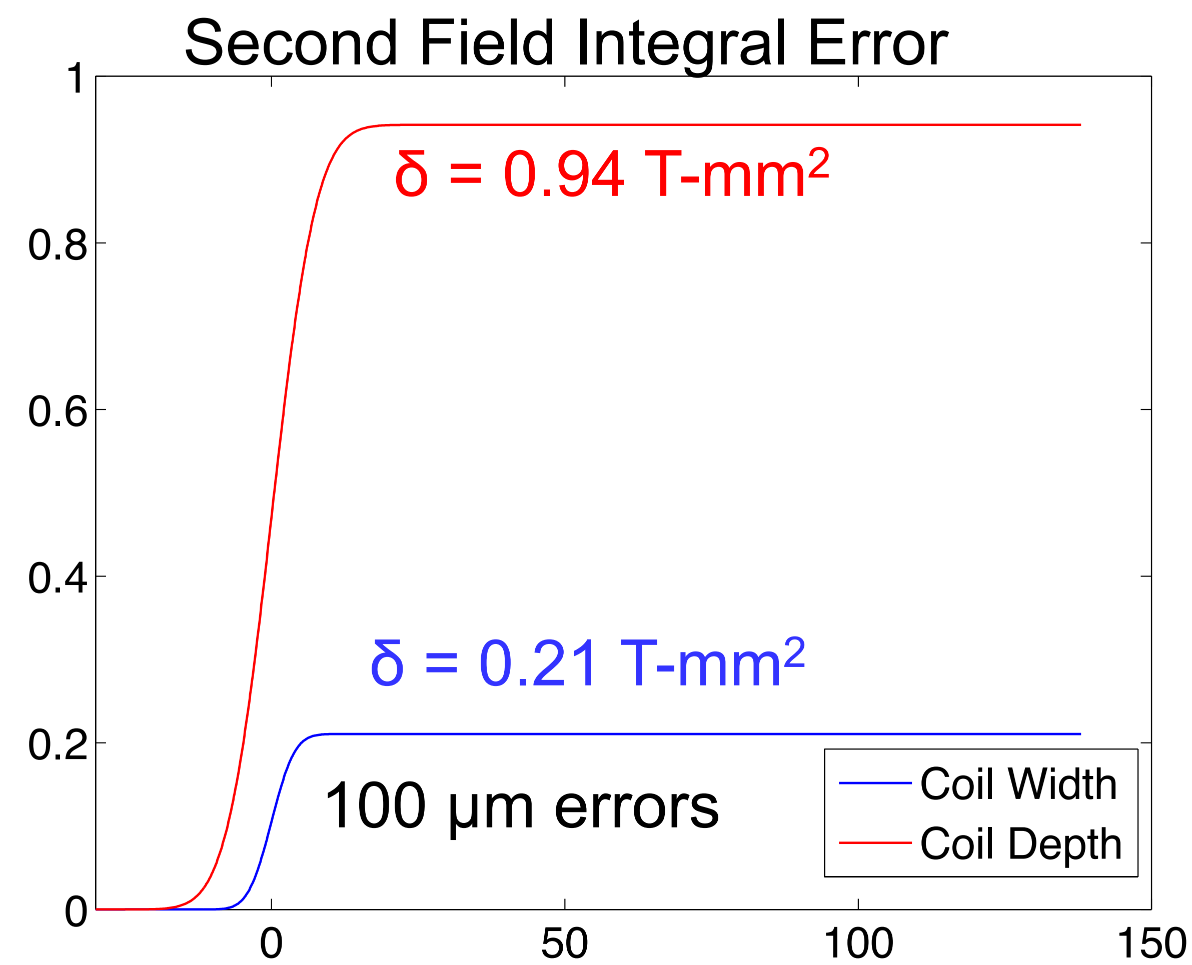




Coil Errors



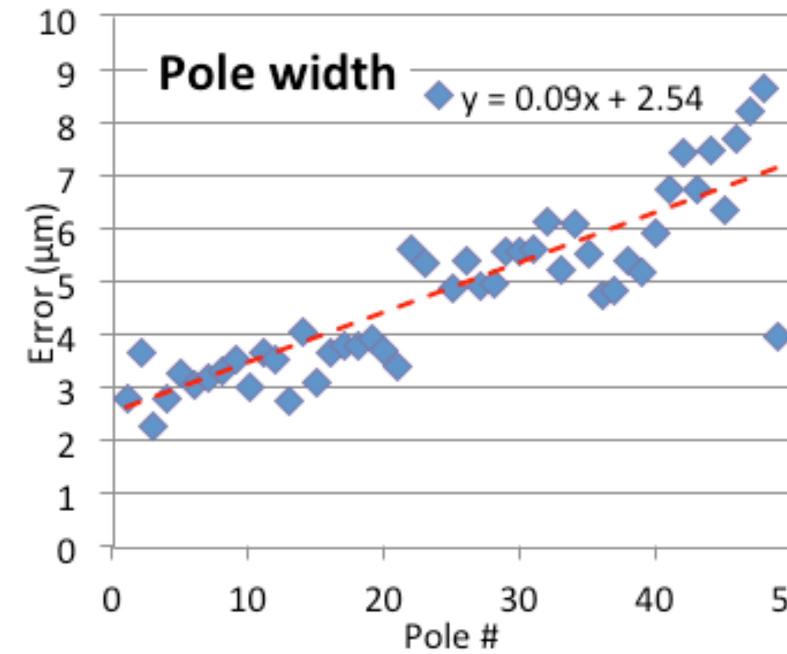




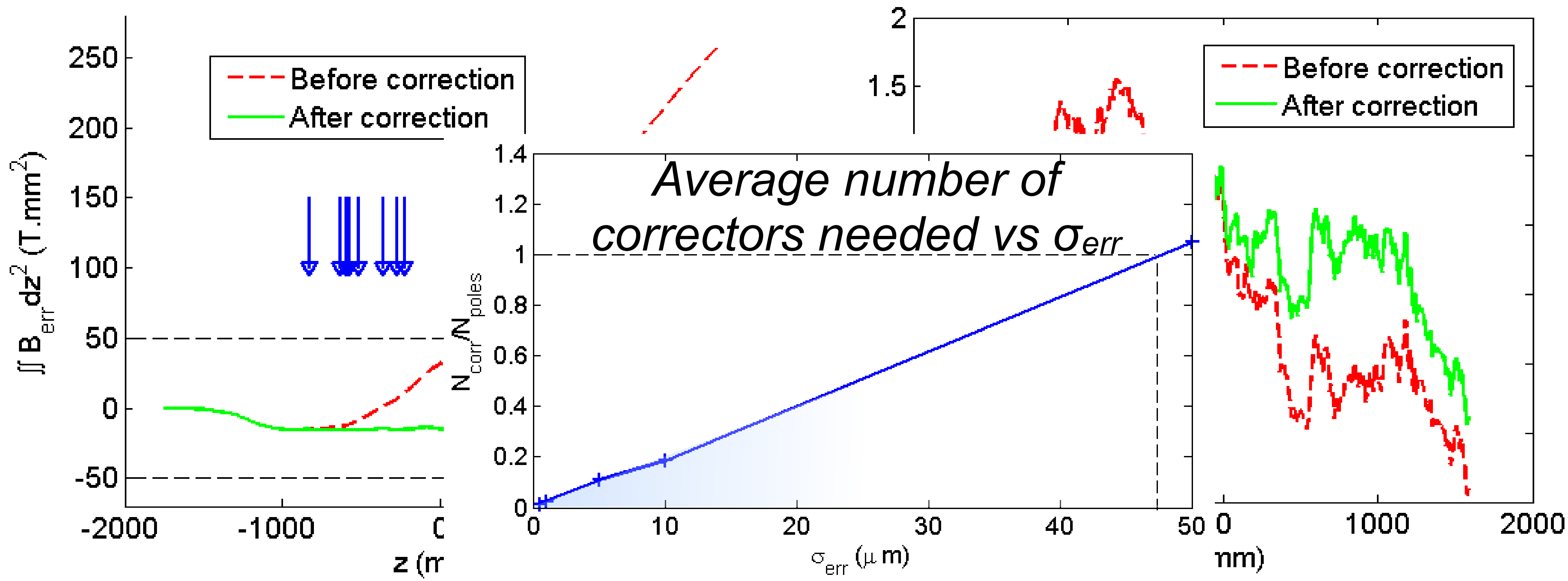
BERKELEY LAB
BCMT
BERKELEY CENTER FOR MAGNET TECHNOLOGY
U.S. DEPARTMENT OF ENERGY Office of Science

Example implementation (simulation)

- Assumes
  - random errors based on measured σ from 0.5m prototype
  - 3.3m device, yielding 331 poles
  - period 20mm, magnetic gap 7.5mm



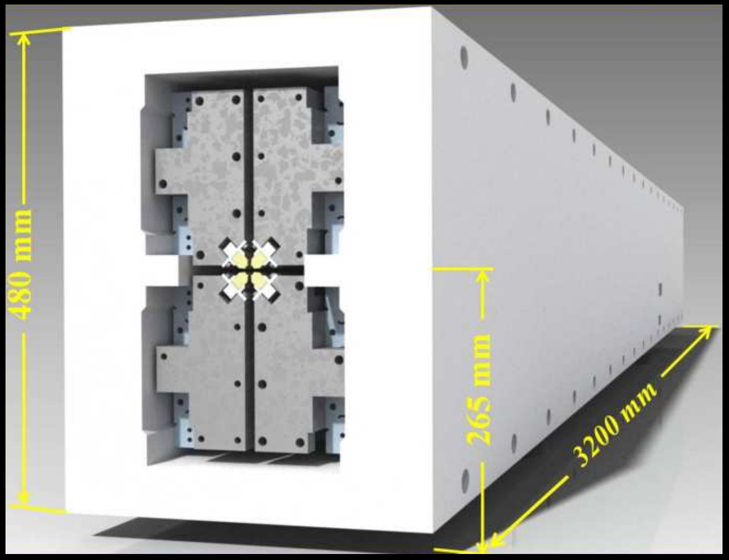
Rochepault,et al. (2014). *IEEE Trans. Appl. Supercond, 24*(3)



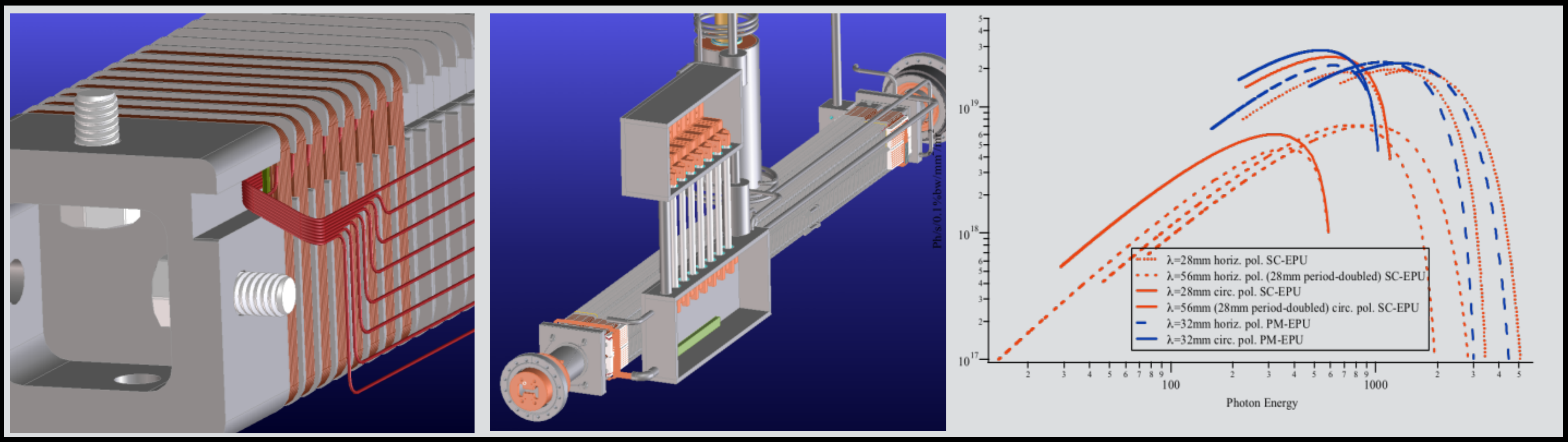
Polarization control

Polarization control adds science possibilities, but comes at a cost

- Cleanest: all undulators variable polarizing
  - ✓ Suffers primarily from VPU strength limitation ⇒Delta undulator is a promising approach
- Less clean: crossed undulator
  - ✓ superposition of radiation fields from different parts of the electron bunch
- Simplest: variable polarizing radiator
  - ✓ Radiation contamination from upstream linear polarizing section
  - ✓ Energy/tunability limited by VPU strength

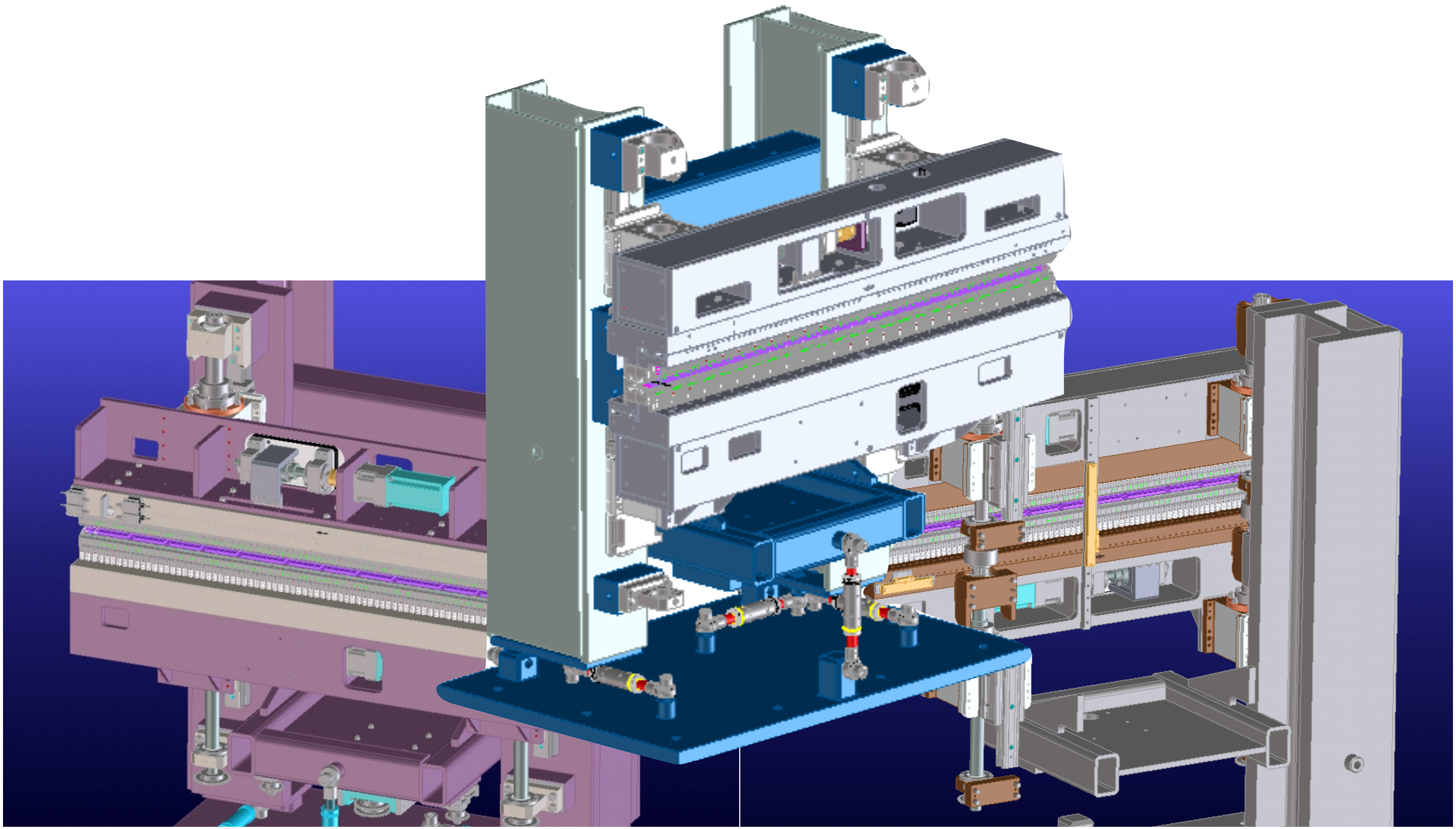


Nuhn, FEL2013



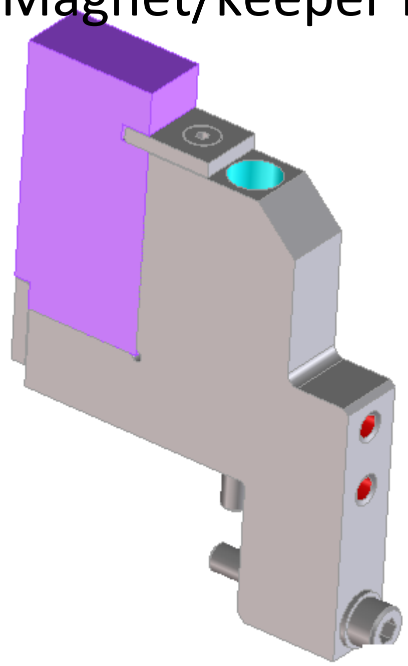
Prestemon, FEL2009

Elliptically polarizing undulators

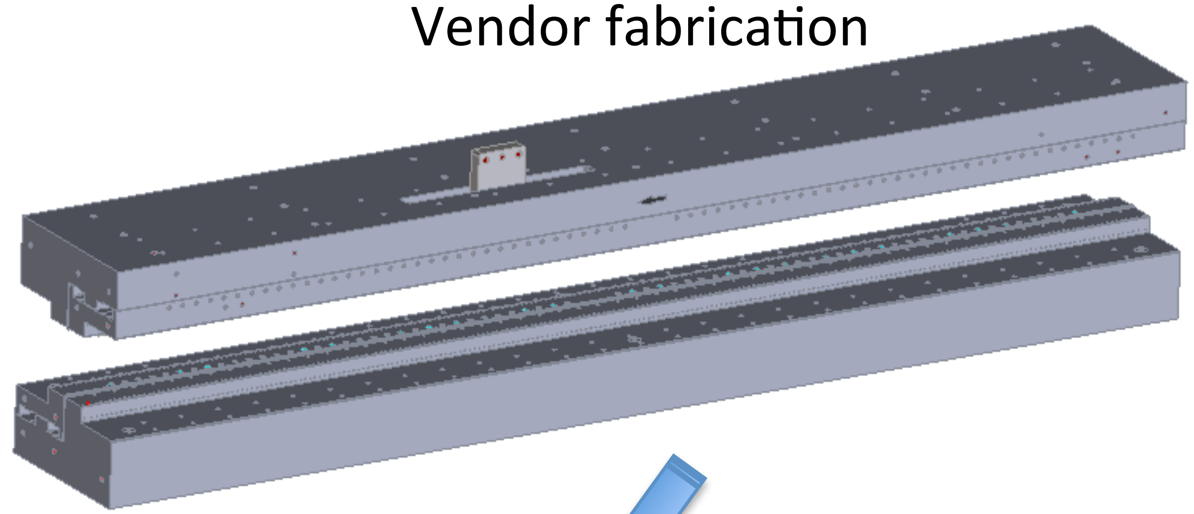


Components of an EPU

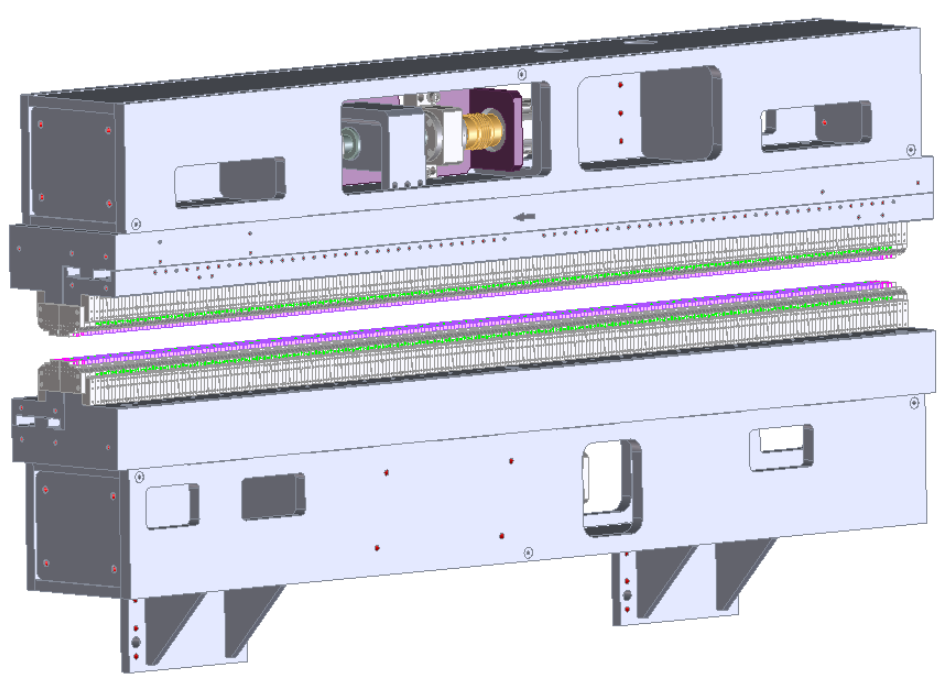
Magnet/keeper from vendor

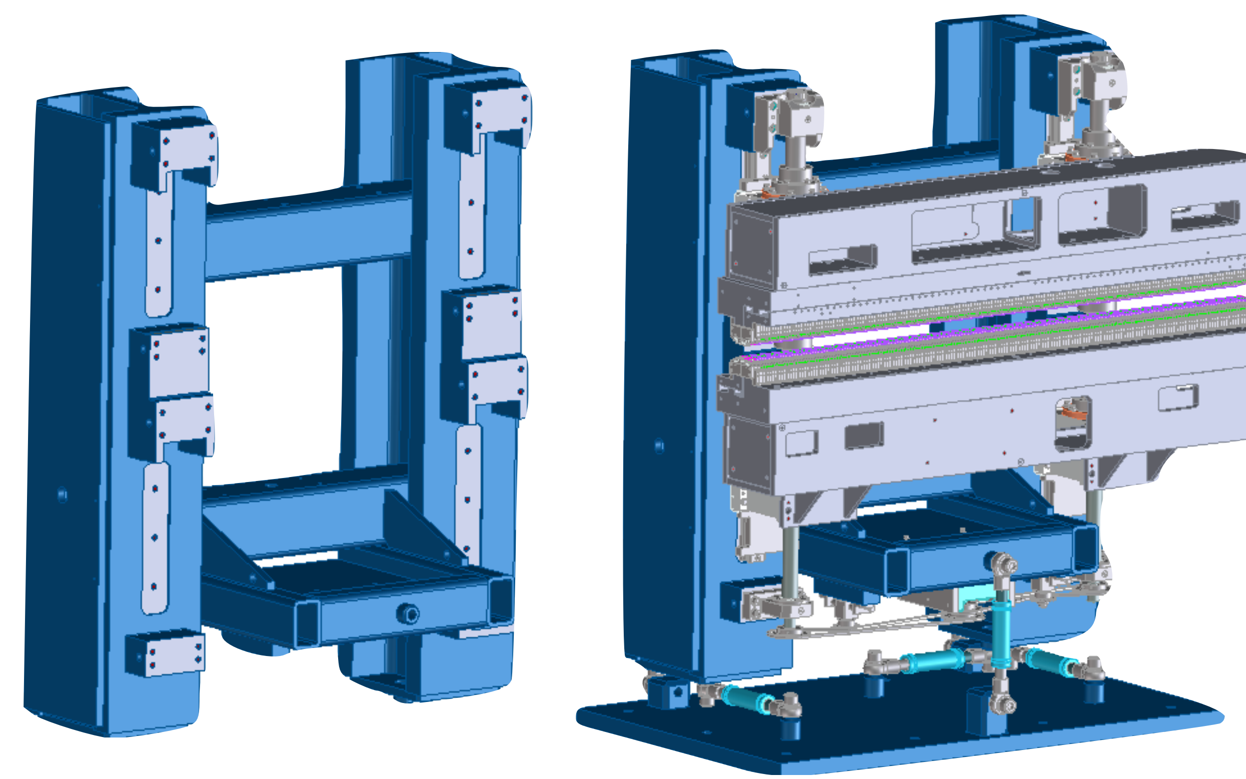


Vendor fabrication

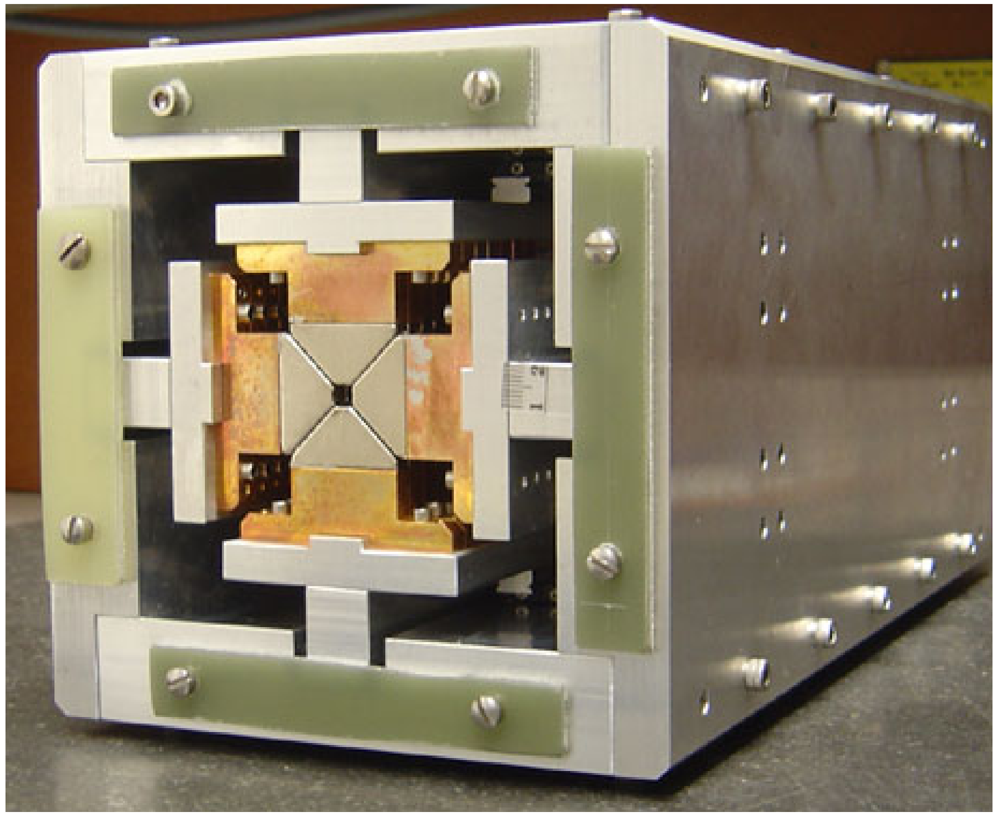


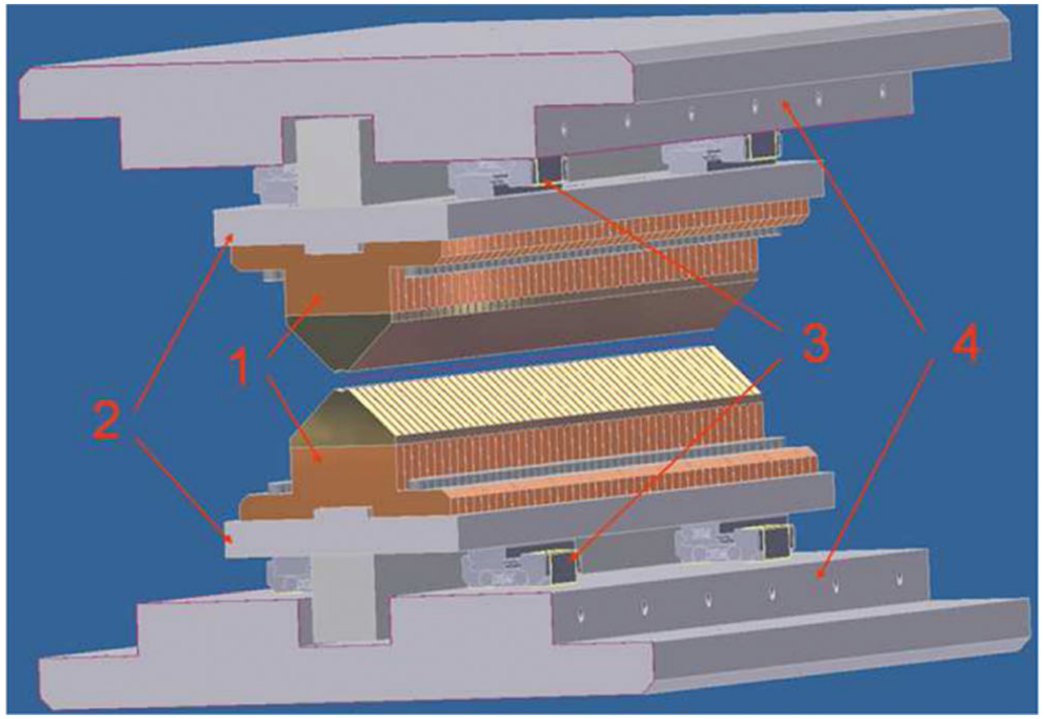
Vendor assembly

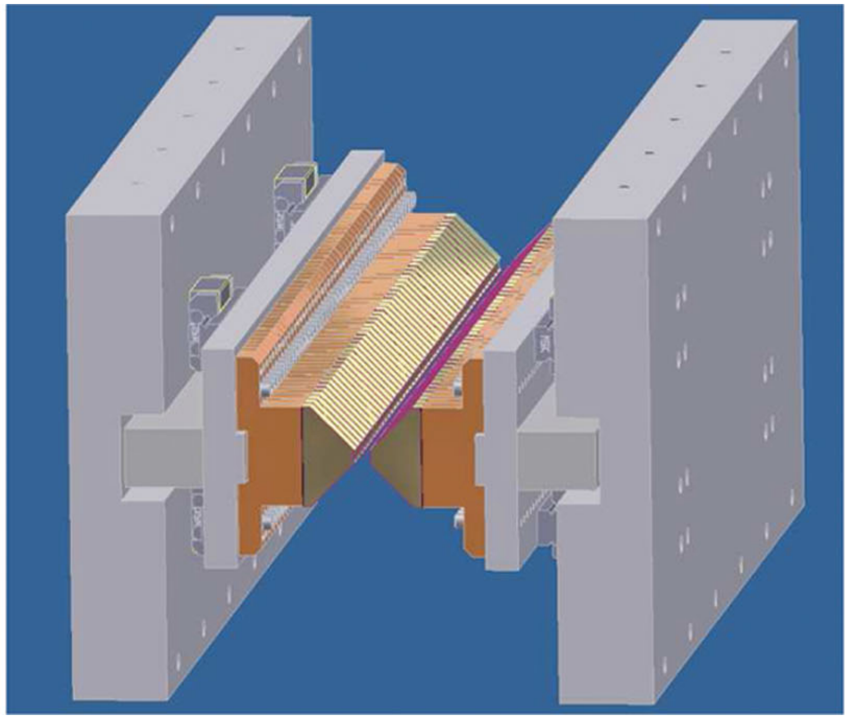




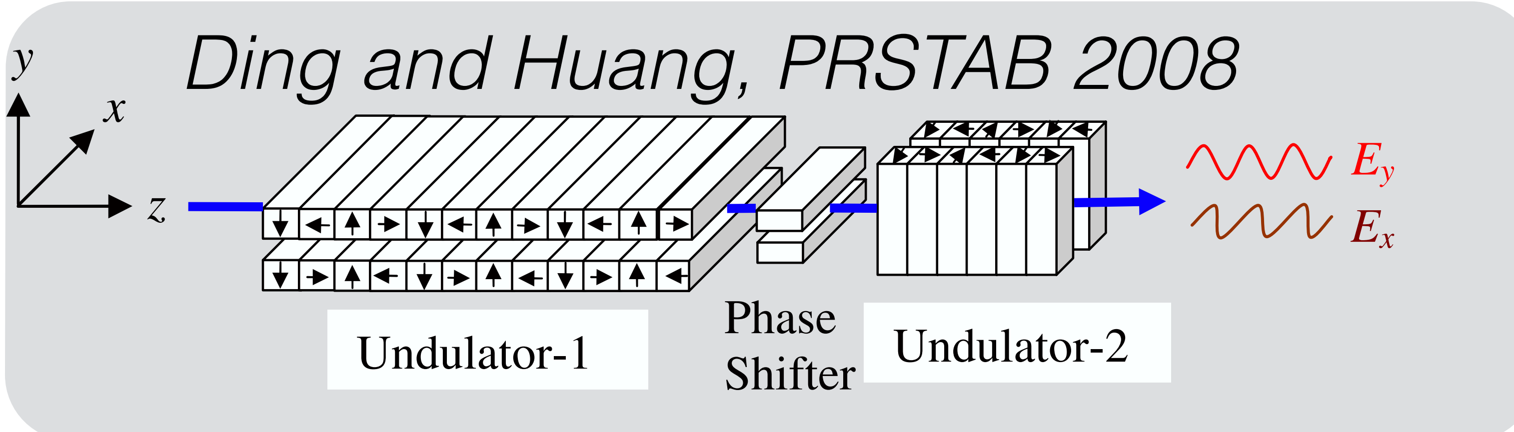
Delta EPU concept







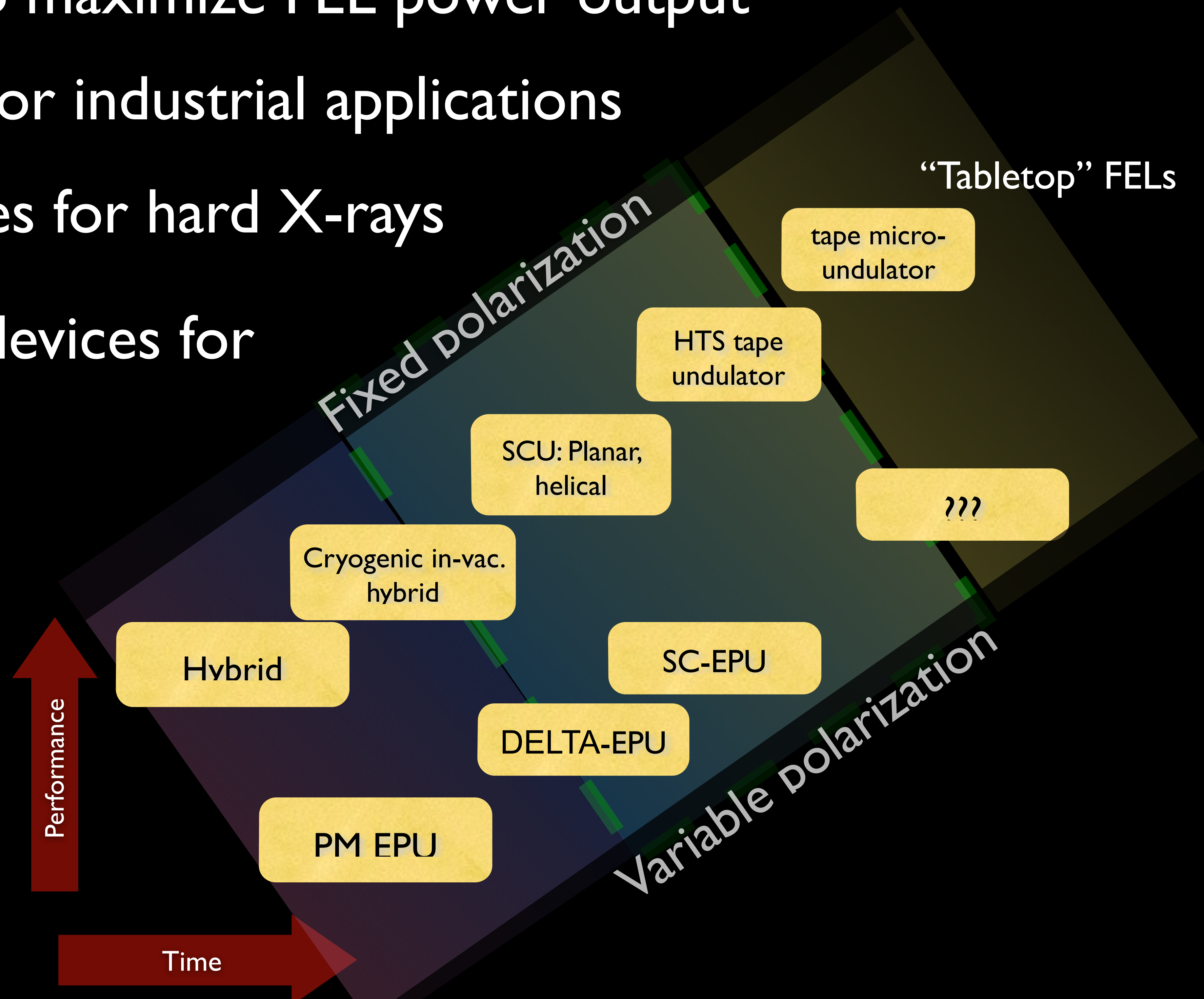
Polarization via crossed (linear polarizing) undulators has potential for FELs



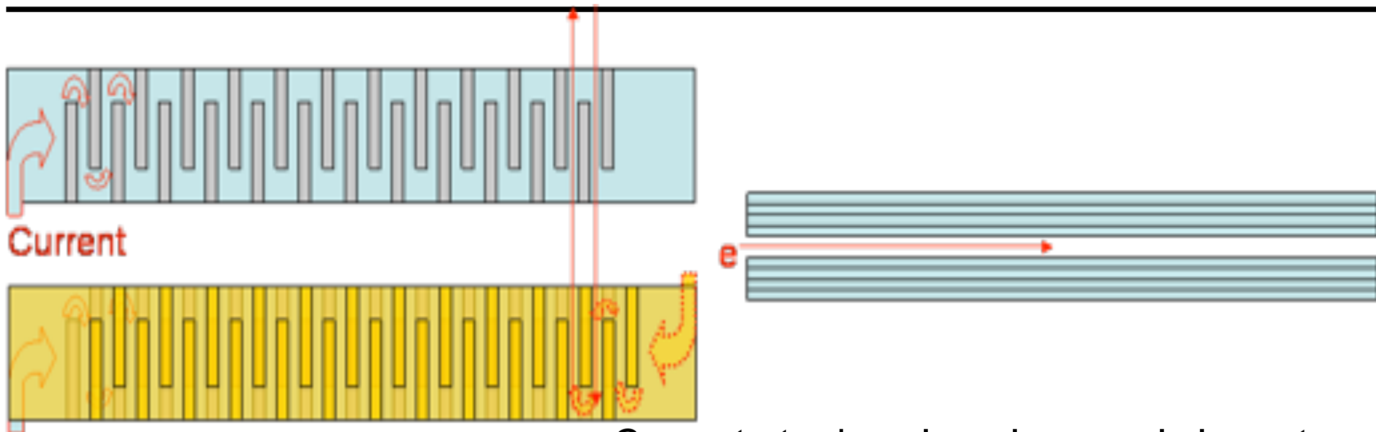
- First proposed by Kwan-Je Kim (NIM 1984); put in context of FEL by Tanaka and Kitimura (SRI2004)
- Each undulator section must be (significantly) shorter than the coherence (*Geloni et al., FEL2011*)
- Comments…
  - ✓ Requires electron bunch coherence for high polarization (e.g. not storage rings)
  - ✓ Polarization angle will fluctuate with micro bunch charge distribution

Future directions:
Tailoring undulator characteristics to the science application

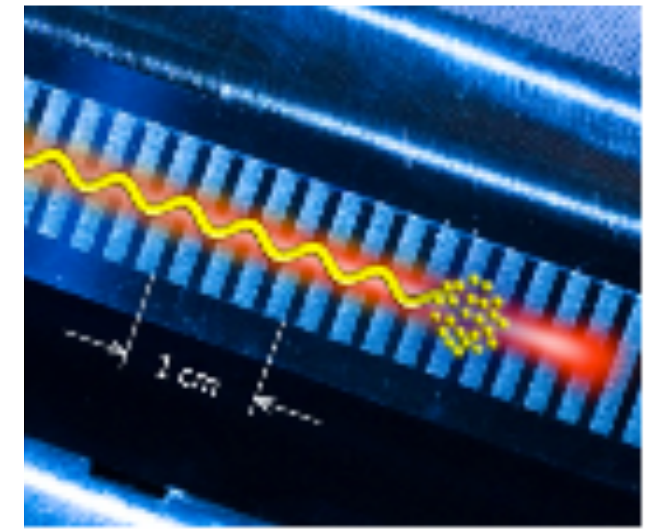
- Optimal tapering to maximize FEL power output
- Improve efficiency for industrial applications
- Short-period devices for hard X-rays
- ultra-short period devices for tabletop FELs



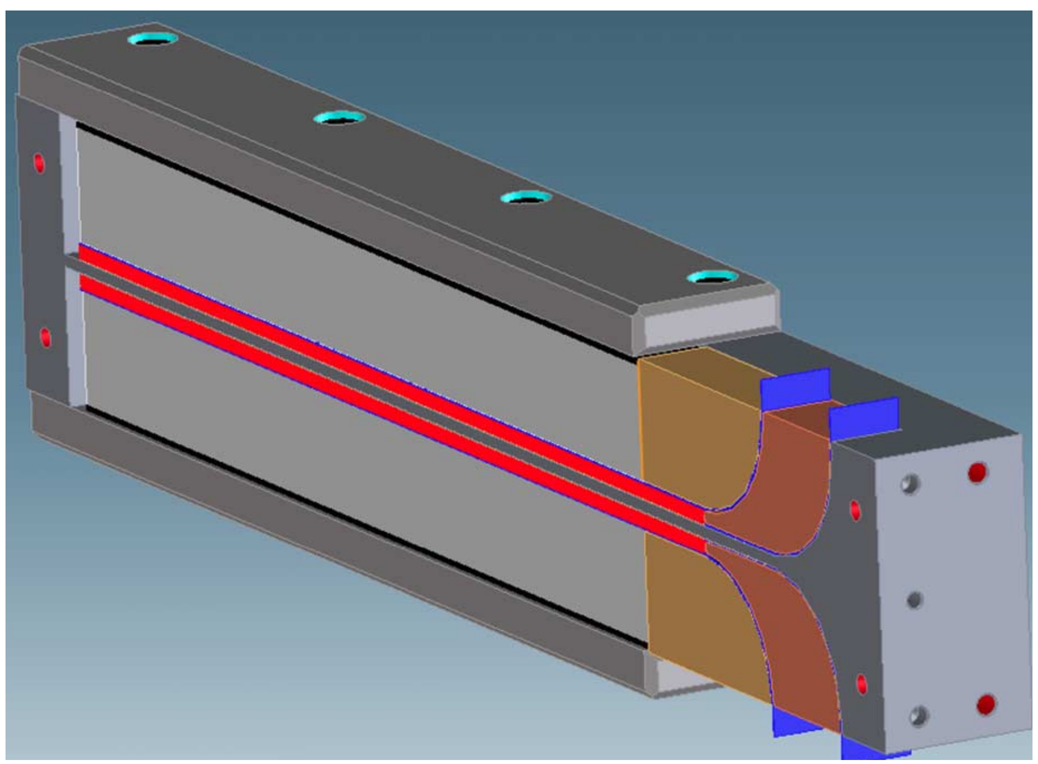
Examples



- Current at edges largely cancels layer-to-layer; result is “clean” transverse current flow



M. Fuchs, MPQ – λ=5mm(?)
Also Shea et al. PRSTAB 2010 (λ=9mm)



Prestemon, PAC 2009, TAS 2011
Yoon et al., NIMS 2011

Tartawi, PRL 2014

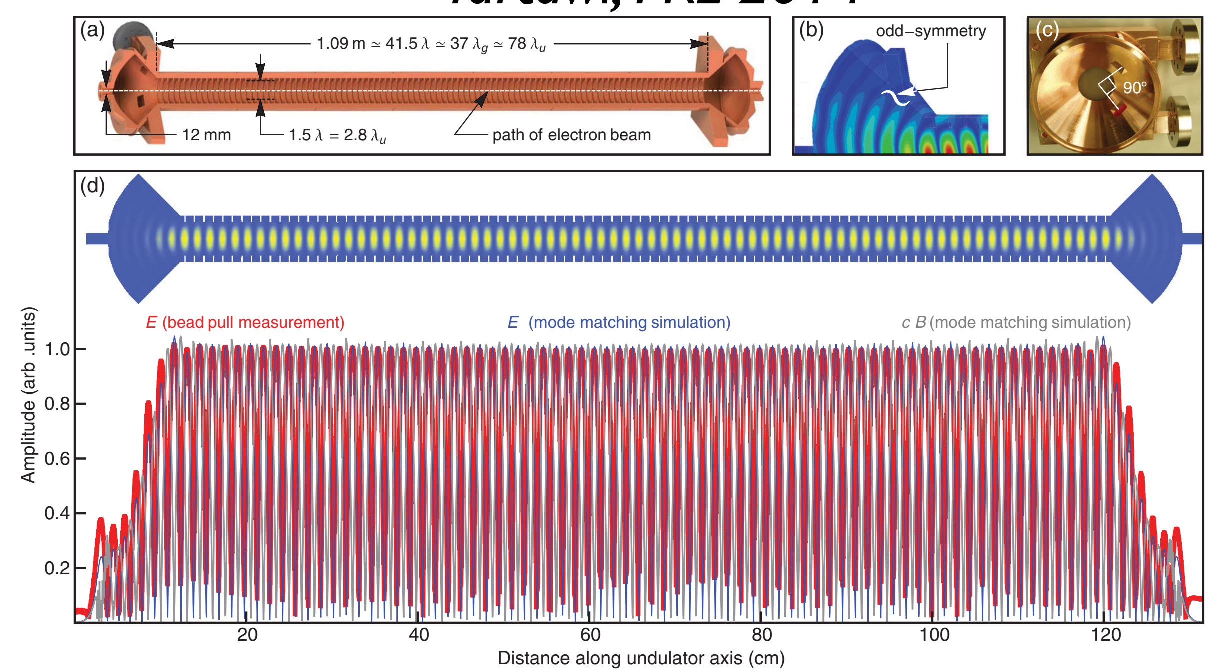


FIG. 1 (color). Design of the undulator with simulated and measured field profiles. (a) Cut-away view of the undulator cavity. (b) Field distribution near a coupling port (simulation with HFSS®, a commercial electromagnetic solver by Ansoft). (c) Implementation of two orthogonal coupling ports. (d) Measured and simulated profiles of the on-axis fields. The inset shows the density plot of the magnitude of the electric field.

Lots more to talk about…

- Analysis methods…
- Materials…
- Radiation damage…
- Beam focussing…
- Magnetic measurements…
- Mechanical systems…
- Etc!

Questions?