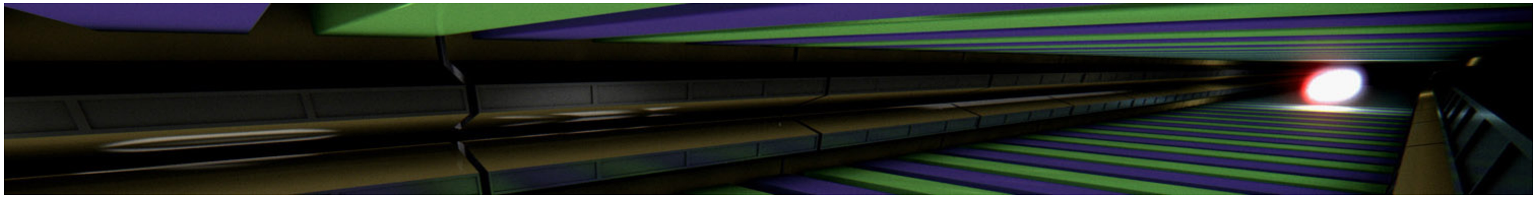


Undulator Technology

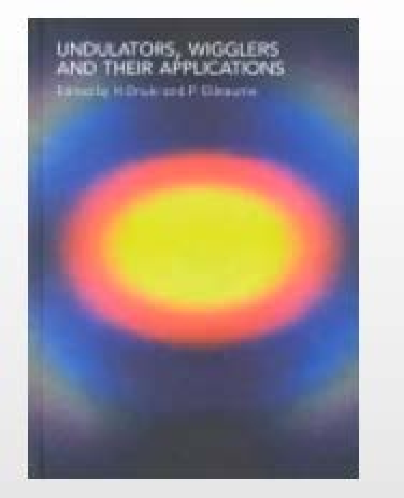
Joachim Pflueger, European XFEL

Overview

Concentration on hardware and technology NOT on theory of SR radiation and FELs!

- Undulator Basics, Key parameters, Field integrals Resonance wavelength, K-Parameter, Phase Jitter etc.
- Technology Overview: EM, SC, PM
  - Electro Magnetic Undulators
  - Super Conducting Undulators
  - Permanent Magnet Technology & Undulator Design
- Mechanical Design Examples
- Undulator Systems for XFELs
- Outlook: Future development

References, Books



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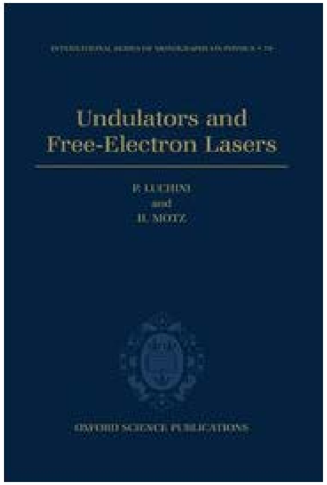

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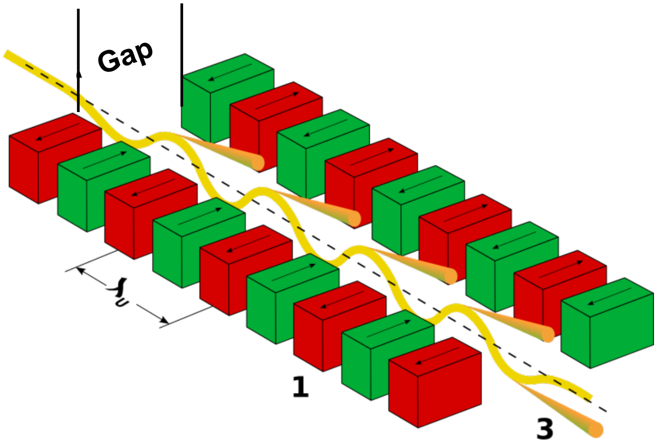
Vol1, Chapter 2 :
North Holland Publishing Company, 1983

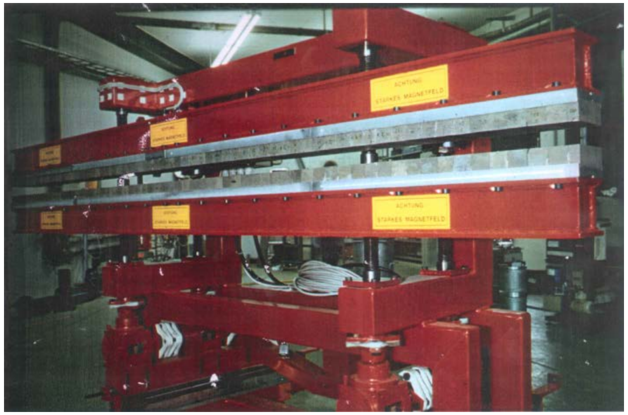
Referred to as “Handbook SR”

Basics

What is an Undulator?

- “Undulator“ from Latin “Unda“ = “Wave“→ “Wave maker“
- Synonyms: “Insertion Device“, “Wiggler“
- Magnetic system, which forces electrons on an oscillating, wiggling but overall <u>straight</u> orbit
- Made from periodically alternating magnets with period length λ
- Typical lengths $\approx$ 1 to 5m
- Core component of ultra bright light sources like FELs and SRs





W1 HASYLAB 1983-2012

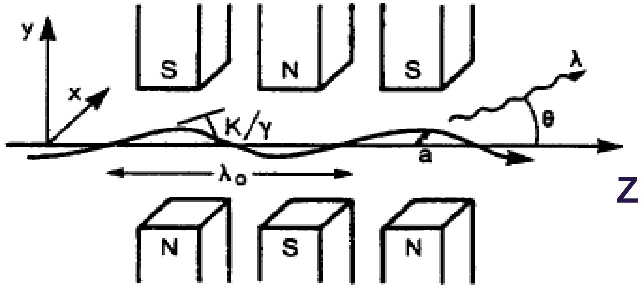
Equations of Motion in an Undulator

Lorenz Equations of Motion:

$$\vec{F} = \frac{d\vec{p}}{dt} = m_0\gamma\frac{d}{dt}\vec{v} = m_0\gamma\begin{pmatrix}\ddot{x}\\ \ddot{y}\\ \ddot{z}\end{pmatrix} = e\left[\vec{v}\times\vec{B}\right] = e\cdot\begin{pmatrix}v_yB_z - v_zB_y\\ v_zB_x - v_xB_z\\ v_yB_y - v_yB_x\end{pmatrix}$$

Planar Periodic field:

$$\vec{B} = \begin{pmatrix}0\\ B_0\sin\left(\frac{2\pi}{\lambda_0}z\right)\\ 0\end{pmatrix} \quad \text{or measured field } \mathrm{B_y(z)}$$



Initial Conditions:

$$B_x, B_z = 0 \qquad v_x, v_y = 0;\ v_z = \beta c;$$

$$\beta = \sqrt{1-\frac{1}{\gamma^2}} \cong 1 - \frac{1}{2\gamma^2}$$

$$\gamma = \frac{E_{Kin}}{m_0c} \gg 1 \qquad m_0c = 511keV$$

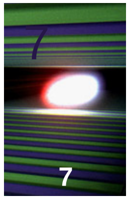
Lorentz Equation

$$\ddot{x} = -\frac{e}{\gamma m_0}v_zB_y$$

$$\ddot{y} = 0$$

$$\ddot{z} = -\frac{e}{\gamma m_0}v_xB_y \cong 0$$

Beam deflection and excursion



Assumptions: 1.) x’, y’ << 1; 2.) $v_z \approx \beta c$; 3.) $z=\beta c\, t$

Transverse deflection:

Measurable!

K

$$x'(z)=\frac{v_x(z)}{c}=-\frac{e}{\gamma m_0 c}\int_{-\infty}^{z}\underbrace{B_y(z')dz'}_{\text{1st Field Integral}}=-\frac{eB_0\lambda_0}{\gamma\, m_0c2\pi}\sin\left(\frac{2\pi}{\lambda_0}z\right)=-\frac{K}{\gamma}\sin\left(\frac{2\pi}{\lambda_0}z\right)$$

For pure Sinusiodal Field

$$v_y=0$$

Total velocity is preserved in magnetic field → $v_y^2+v_z^2=(\beta c)^2$

Longitudinal velocity:

$$v_z=\sqrt{(\beta c)^2-{v_x}^2}\cong c\beta\left[1-\frac{K^2}{4\gamma^2}-\frac{K^2}{4\gamma^2}\cos\left(\frac{4\pi}{\lambda_0}z\right)\right]=\mathrm{c}\left[\bar{\beta}-\frac{K^2}{4\gamma^2}\underbrace{\cos\left(2\cdot\frac{2\pi}{\lambda_0}z\right)}\right]$$

$\bar{\beta}$

Modulation by $2\cdot\frac{2\pi}{\lambda_0}$

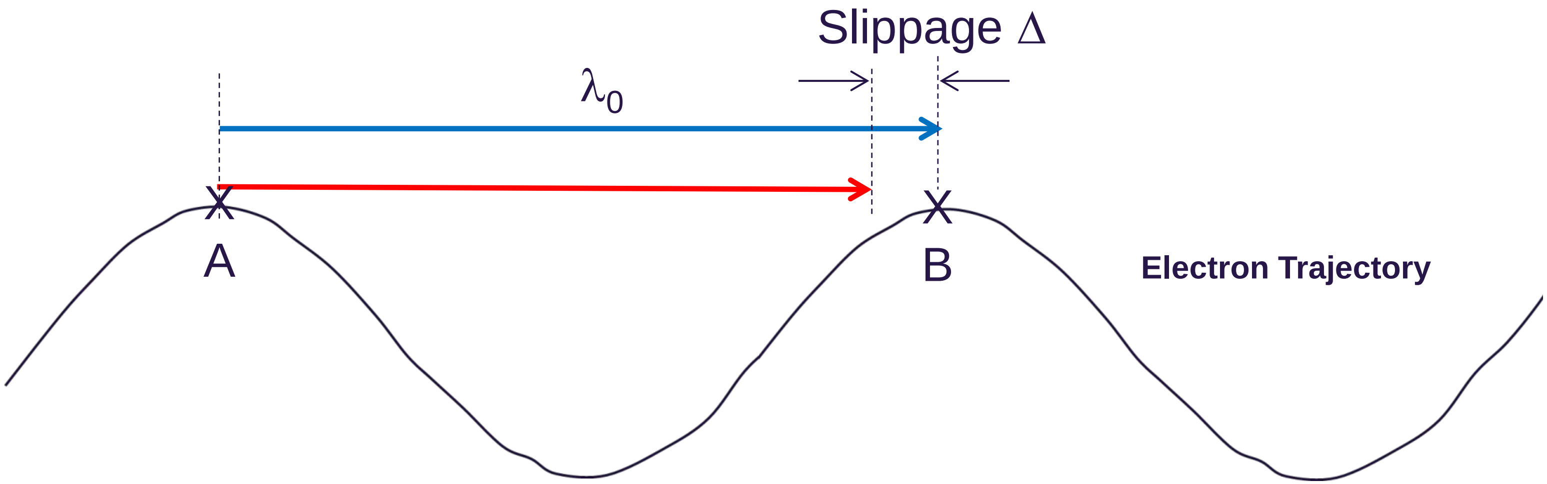
Transverse beam excursion:

$$x(z)=-\frac{e}{\gamma m_0 c}\underbrace{\int_{-\infty}^{z}\left(\int_{-\infty}^{z'}B_y(z'')dz''\right)dz'}_{\text{2nd Field Integral Measurable!}}=-\underbrace{\frac{eB_0{\lambda^2}_0}{\gamma m_0 c\,4\pi^2}\cdot\cos\left(\frac{2\pi}{\lambda_0}z\right)}_{\text{For pure Sinusiodal Field}}=-\frac{K}{\gamma}\,\frac{\lambda_0}{2\pi}\cdot\cos\left(\frac{2\pi}{\lambda_0}z\right)$$

Slippage, Resonance Wavelength

Light travels at light speed c

In undulator electrons travel at average speed $\bar{\beta}c$; $\bar{\beta} \cong 1 - \frac{1}{2\gamma^2} - \frac{K^2}{4\gamma^2}$;



Travel time for light for $\lambda_{0:}$:$t_c = \frac{\lambda_0}{c}$; Distance traveled by electron this time : $\frac{\lambda_0}{c}\bar{\beta}c = \bar{\beta}\lambda_0 < \lambda_0$

Difference = slippage:$\Delta = \lambda_0\left(1 - \bar{\beta}\right) = \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$

Resonance wavelength: $\Delta = \lambda_{Rad} = \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$

Example SASE1/2:
γ =34247, λ_0=40mm, K=4
Δ=1.53 x 10^{-10}m=1.53Å

More in Clarke: p. 53 ff

Optical Phase

Total slippage = accumulated difference between light and electron

$\Delta(z) = \int_{z_0}^{z}\left(c - v_z(z')\right)dz' = \frac{z}{2\gamma^2} + \frac{1}{2}\left(\frac{e}{\gamma m_0}\right)^2 \int_{-\infty}^{z}\left(\int_{-\infty}^{z''} B_y(z')dz'\right)^2 dz''$ using $1 - \beta \cong \frac{1}{2\gamma^2}$

Optical Phase Advance $\varphi = 2\pi$ x Slippage / λ_{Rad}; $\lambda_{Rad} = \frac{\lambda_0}{2\gamma^2}(1 + \frac{K^2}{2})$

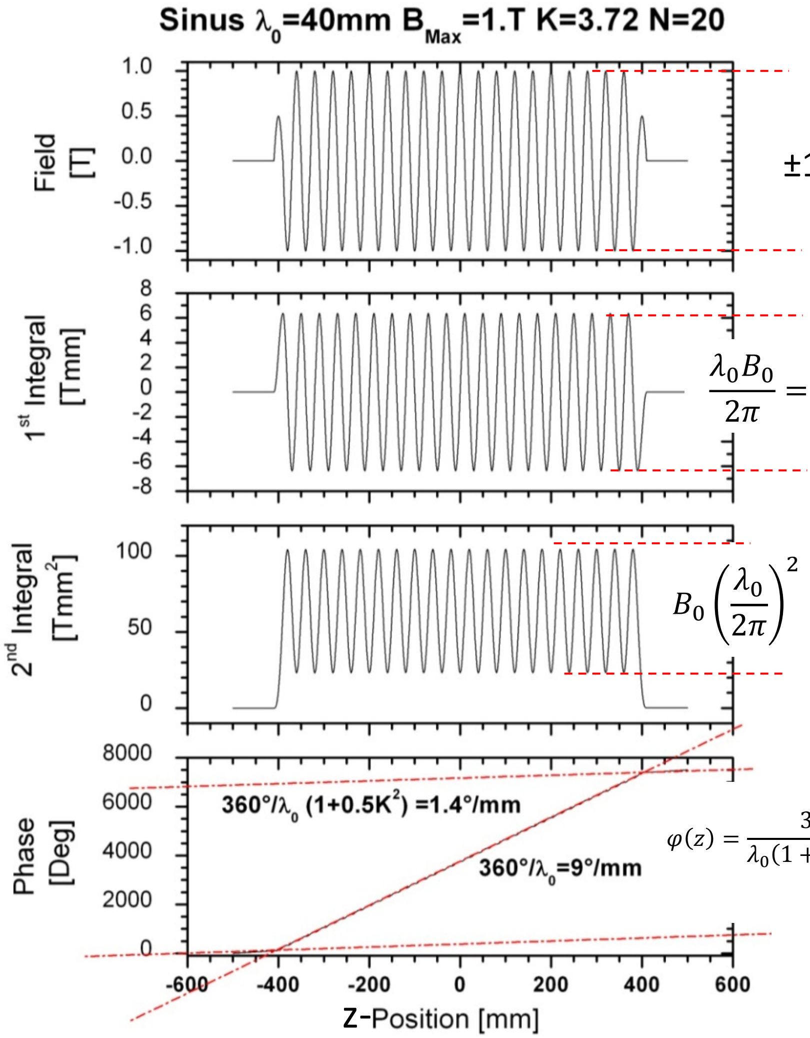
Ideal case: $\varphi(z+n\lambda_0) - \varphi(z) = n \times 2\pi$

$$\varphi(z) = 2\pi\frac{\Delta(z)}{\lambda_{Rad}} = \frac{4\pi\gamma^2}{\lambda_0(1+\frac{K^2}{2})}\left(\frac{z}{2\gamma^2} + \frac{1}{2}\left(\frac{e}{\gamma m_0}\right)^2 \int_{-\infty}^{z}\left(\int_{-\infty}^{z''} B_y(z')dz'\right)^2 dz''\right)$$

$$= \frac{2\pi}{\lambda_0(1+\frac{K^2}{2})}\left(z + \left(\frac{e}{m_0}\right)^2 \underbrace{\int_{-\infty}^{z}\left(\int_{-\infty}^{z''} B_y(z')dz'\right)^2 dz''\right)}_{\text{Phase Integral, PI(z)}} \longrightarrow$$

1. Independent of γ
2. Measurable Quantities!

Example of Field, 1st , 2nd Integral and Phase advance, Phase Error



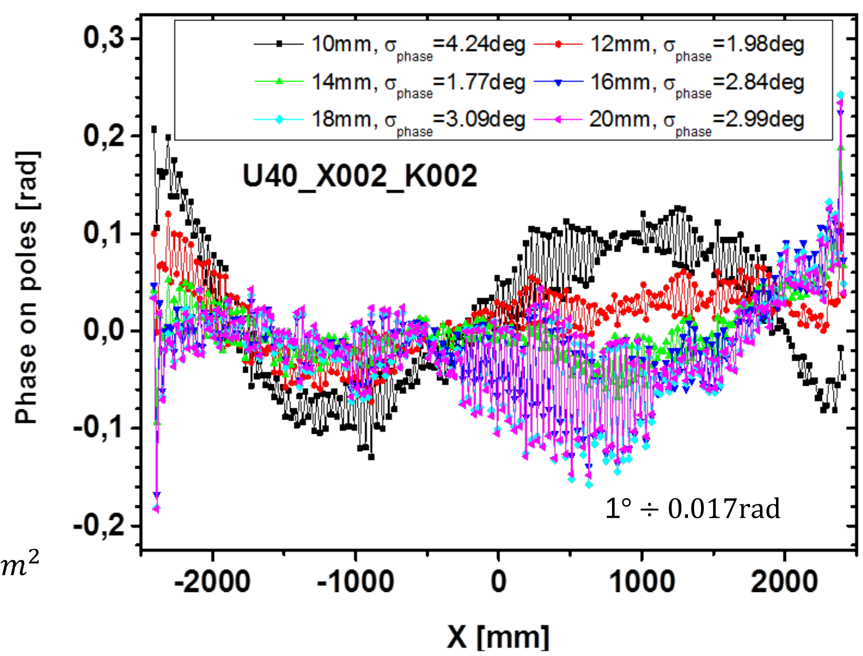
±1T

$$\frac{\lambda_0 B_0}{2\pi} = \pm 6.3\,Tmm$$

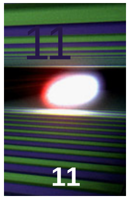
$$B_0\left(\frac{\lambda_0}{2\pi}\right)^2 = \pm 40.5\,Tmm^2$$

$$\varphi(z) = \frac{360}{\lambda_0(1+0.5K^2)}\left[z + \left(\frac{e}{m_0 c}\right)^2 \int_{-\infty}^{z}\left(\int_{-\infty}^{z''} B_y(z')dz'\right)^2 dz''\right]$$

EXFEL U40 : Phase error



1° ÷ 0.017rad



Examples, Practical Formulae

$$K = \frac{eB_0\lambda_0}{2\pi m_0 c} \rightarrow K = 0.0934 \cdot B_0\,[T] \cdot \lambda_0[mm] \qquad Undulator\ \ K - Parameter$$

$$x' = -\frac{e}{\gamma m_0 c} I1 \ \rightarrow x'[mrad] = 0.3\frac{I_1[Tmm]}{E[GeV]} \qquad Deflection\ angle\ \ \leftrightarrow 1.Integral$$

$$x'' = -\frac{e}{\gamma m_0 c} I2 \ \rightarrow x''[mrad] = 0.3\frac{I_1[Tmm^2]}{E[GeV]} \qquad Beam\ excursion\ \ \leftrightarrow 2.Integral$$

e	Elementary charge:	$1.60217646 \times 10^{-19}$ As
m_0	Electron rest mass:	$9.10938188 \times 10^{-31}$ kg
c	Speed of Light:	$2.99\,792\,458 \times 10^{8}$ m / s

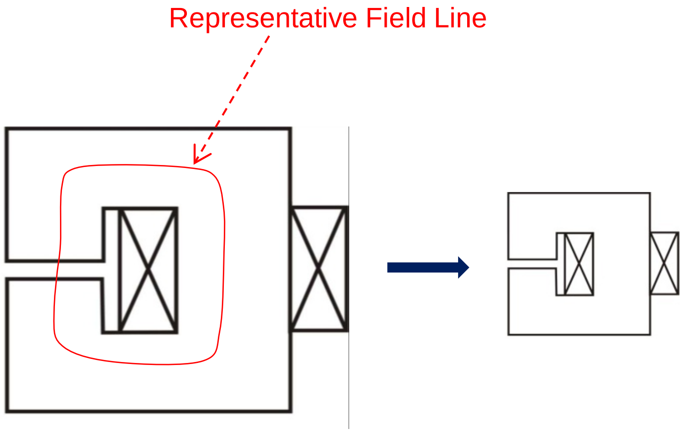
	E [GeV]	λ_0 [mm]	B_{Max} [T]	K_{Max}	K_{Max}/γ [mrad]	$\frac{K_{Max}\lambda_0}{\gamma 2\pi}$ [µm]
SASE1/2	**17.5**	**40**	**1.19**	**3.9**	**0.11**	**0.72**
SASE3	**17.5**	**68**	**1.68**	**9.1**	**0.26**	**2.9**
FLASH	**1.2**	**27.3**	**0.47**	**1.2**	**0.51**	**2.2**

Technical Solutions

Overview:

- Electro Magnetic (EM) Undulators
- Superconducting (SC) Wigglers / Undulators
- Permanent Magnet (PM) Undulators

Scaling Properties of EM and PM Systems



1 : a

$$\oint Hds = \frac{B_{Gap} Gap}{\mu_0} = enclosed\ current = j_{Area} A$$

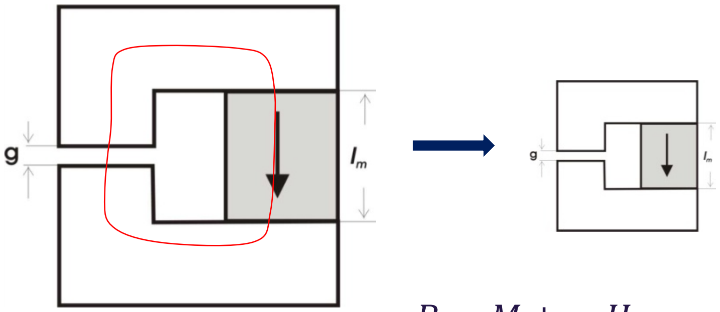
$$B_{Gap} = \frac{j_{Area} A}{Gap} \mu_0$$

$$B'_{Gap} = \frac{j_{Area} A a^2}{a\ Gap} \mu_0$$

$$B_{Gap} = B'_{Gap}\ only\ if\ \ j'_{Area} = \frac{j_{Area}}{a}$$

for a <1 j_{Area} gets higher

Type	j_{Area}[A/mm^2]
Normal Cu	< ~ 10
SC	1500-2000



$$B = M + \mu_0 H$$

$$\oint Hds = \frac{B_{Gap} Gap + l_m B_m}{\mu_0} = j_{Surface} l_m = \frac{M}{\mu_0} l_m$$

$$B_{Gap} = \frac{M l_m}{Gap + l_m} = \frac{M}{\frac{Gap}{l_m} + 1}$$

$M = B_r \approx 1..\ 1.35$ T

$$B_{Gap} = B'_{Gap}$$

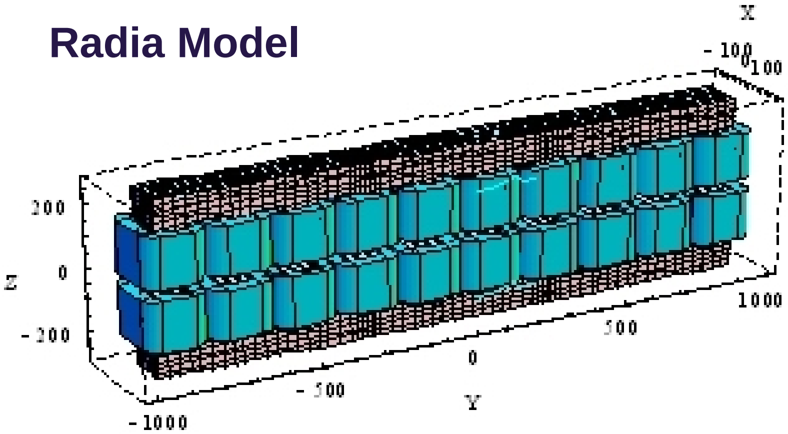
Message:
In EM systems j_{Area} scales inversely with dimensions
PM systems are invariant and can be scaled

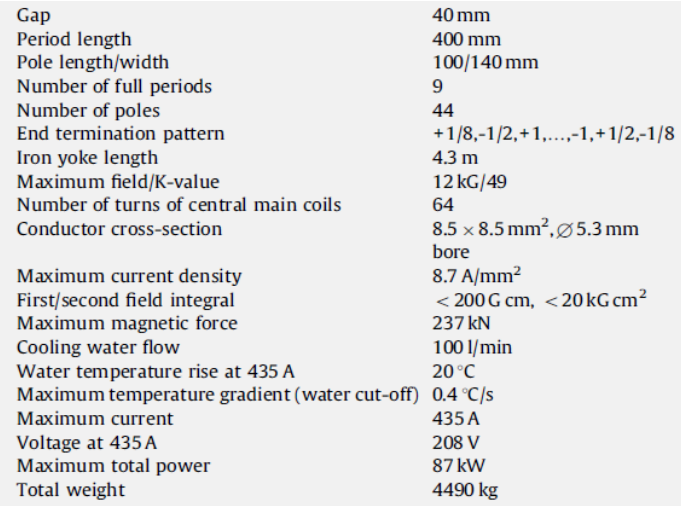
Electro Magnetic Undulators

- Only for large period lengths $\lambda_0 \geq\approx 150$mm → “Wigglers”
- Ineffective for small λ_0
- Conventional technology
- High power demand and costs (Order of 100k€/a)
- AC excitation possible with laminated cores
- Variations:
  - Crossed / Helical undulators (fast switching if AC)
  - Elliptical undulators
  - EM / PM combinations “PM biased EM undulators”
- Speciality devices with limited applications!

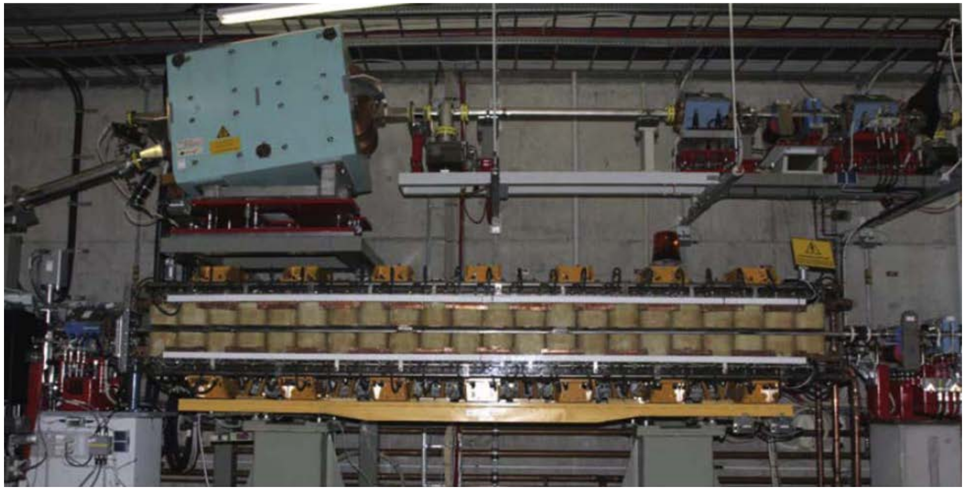
Infrared Undulator in FLASH @ DESY

Radia Model





Gap	40 mm
Period length	400 mm
Pole length/width	100/140 mm
Number of full periods	9
Number of poles	44
End termination pattern	+1/8,-1/2,+1,...,-1,+1/2,-1/8
Iron yoke length	4.3 m
Maximum field/K-value	12 kG/49
Number of turns of central main coils	64
Conductor cross-section	8.5 × 8.5 mm^2, ∅ 5.3 mm bore
Maximum current density	8.7 A/mm^2
First/second field integral	< 200 G cm, < 20 kG cm^2
Maximum magnetic force	237 kN
Cooling water flow	100 l/min
Water temperature rise at 435 A	20 °C
Maximum temperature gradient (water cut-off)	0.4 °C/s
Maximum current	435 A
Voltage at 435 A	208 V
Maximum total power	87 kW
Total weight	4490 kg

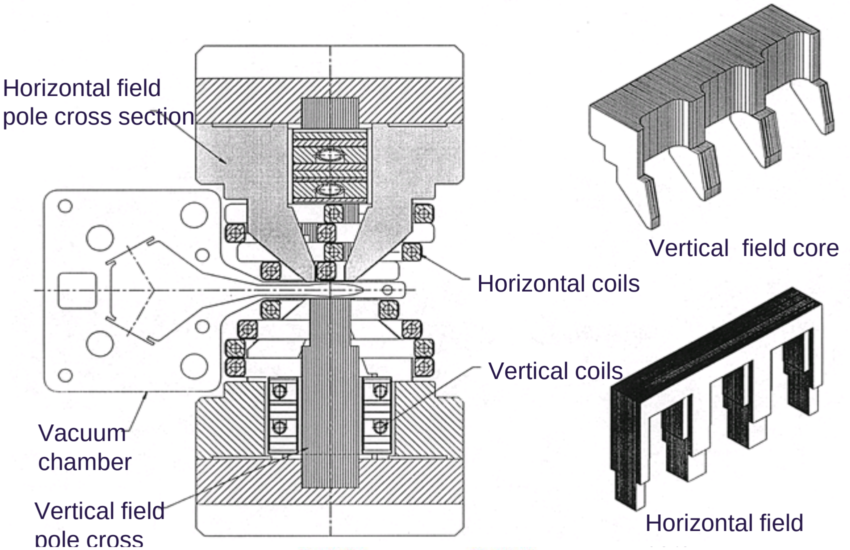


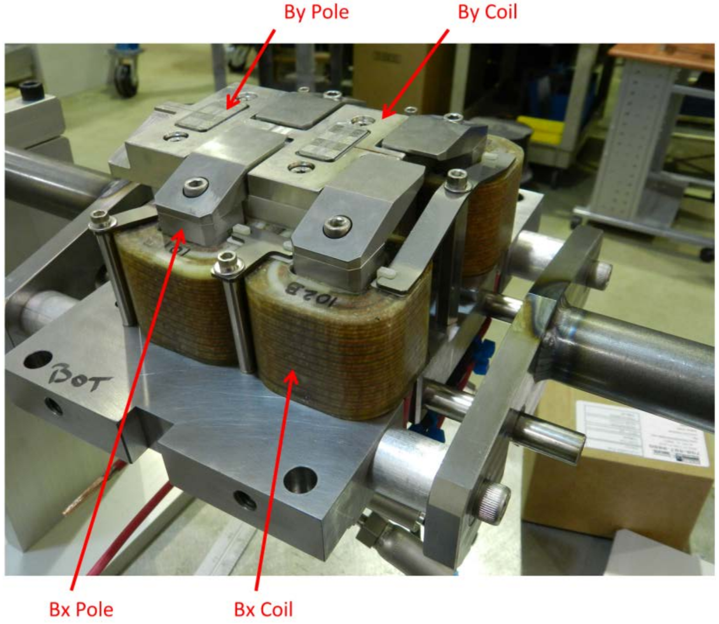
O. Grimm, N.Morozov, A.Chesnov, Y.Holler, E.Matushevsky, D.Petrov, J. Rossbach, E.Syresin , M.Yurkov, NIMA 615 (2010) 105–113

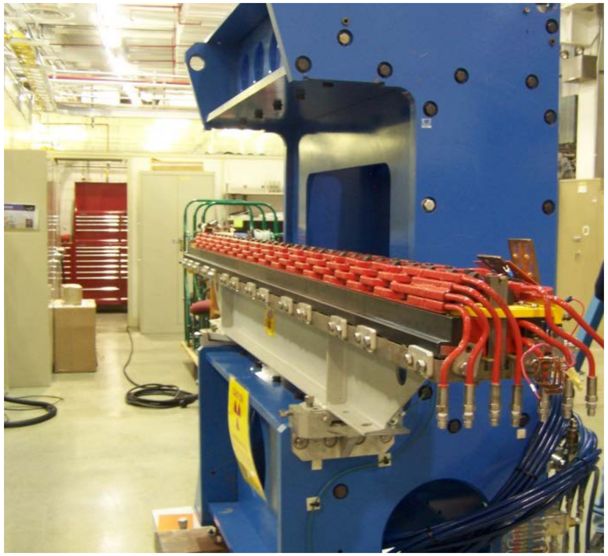
Operation Cost 25% Usage:

80kW * 0.2€/kWh*(356*24)h *0.25=35k€/a

Helical EM Undulator



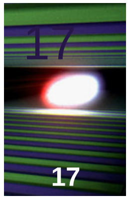




Electromagnetic undulator - APS

Courtesy: Efim Gluskin, APS

Superconducting Insertion Devices



Two Regimes:

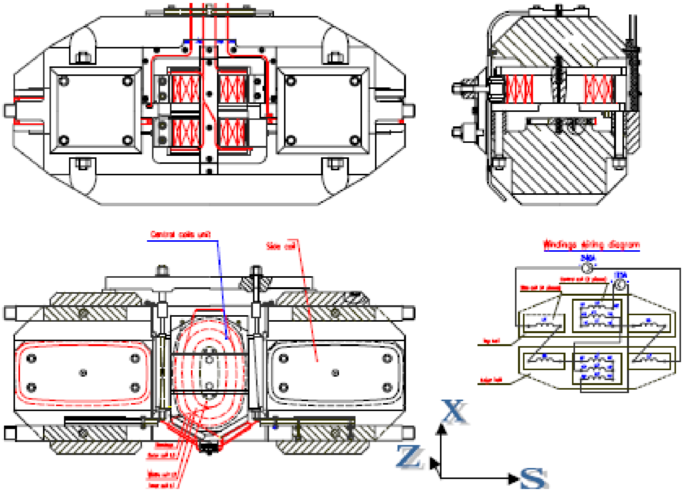
1. Long Periods
   - Few poles, fields 6-10 Tesla and above
   - Wavelength shifters, hard radiation with low energy electrons
   - Used in many SR sources

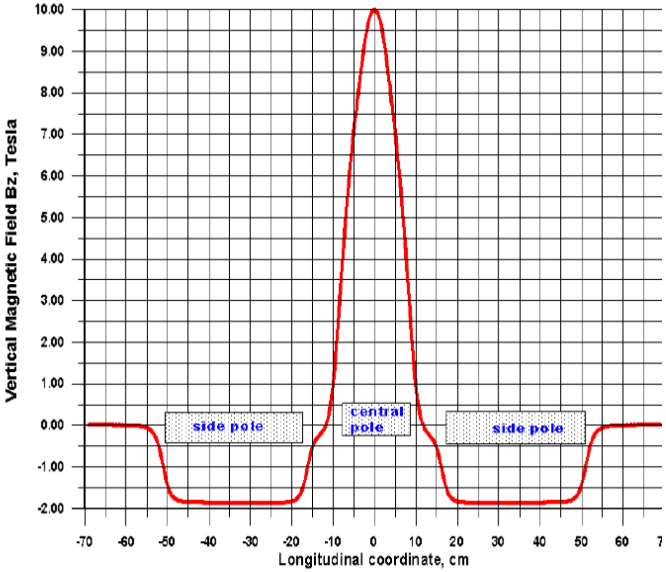
2. (Very) short periods many poles
   - Allows (theoretically) for highest fields at $\lambda_0 \geq\approx 10$mm
   - Technological challenging, ongoing development since the 1970ies – But only few devices were built (ANKA/KIT, APS, LBL)
   - Problems: Field measurement, field error tuning
   - So far: Special applications not for large scale use

Example for a SC wavelength shifter (BINP)

Spring8 Wavelength shifter

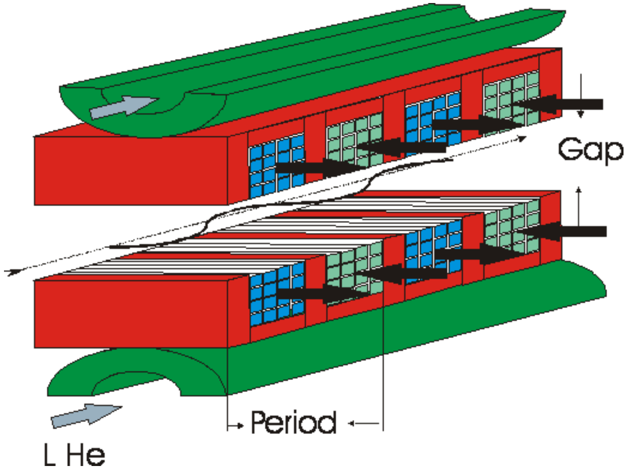
# of poles:	**3**
Max field in central pole:	**10.3 Tesla**
Cold mass:	**~1000kg**
Pole Gap:	**42 mm**
Chamber size:	**100x 20 mm^2**

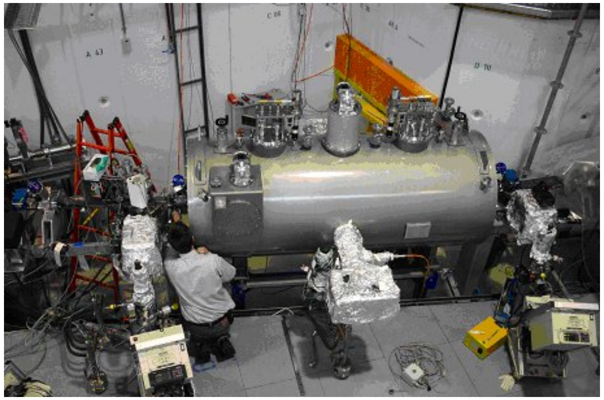




N.Mezentsev, Budker Institute Novosibirsk, Russia

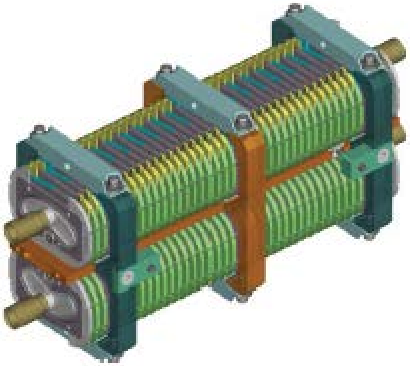
Super Conducting Undulators

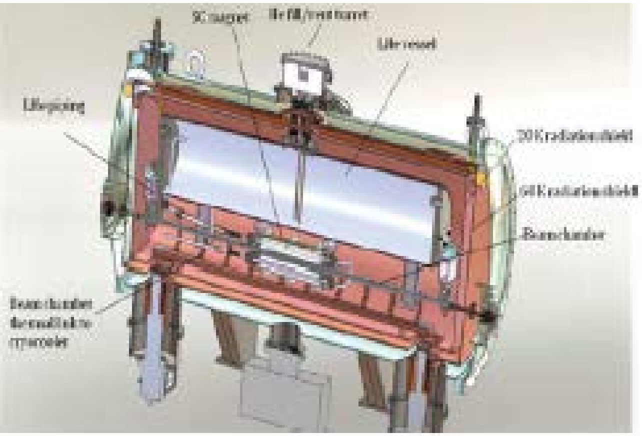




SCU @ ANKA Karlsruhe
in Operation since ≈ 2005

λ_0:	15mm
N:	133
Gap:	7mm
B_{Peak}:	0.98 T
K:	1.37

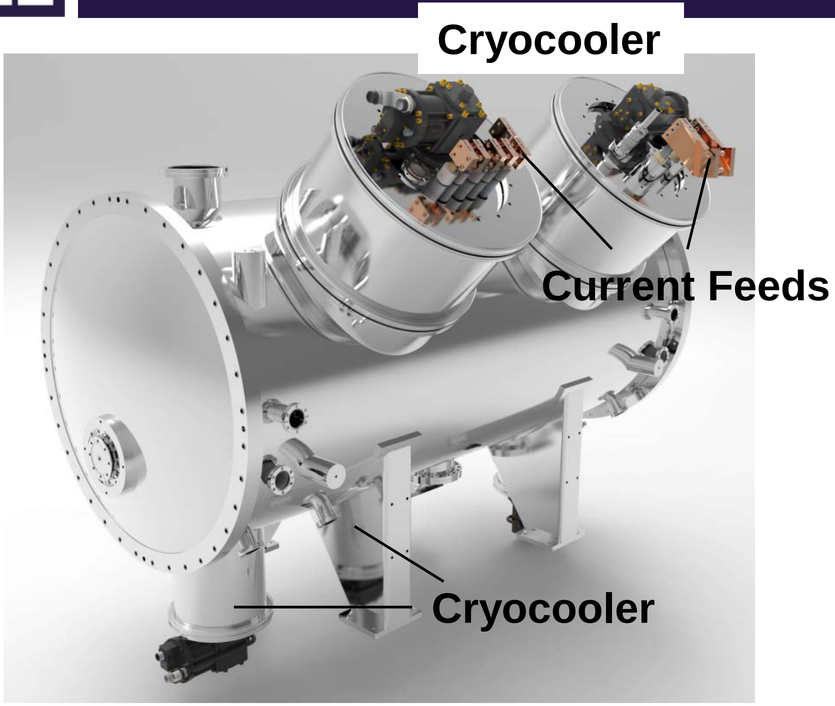


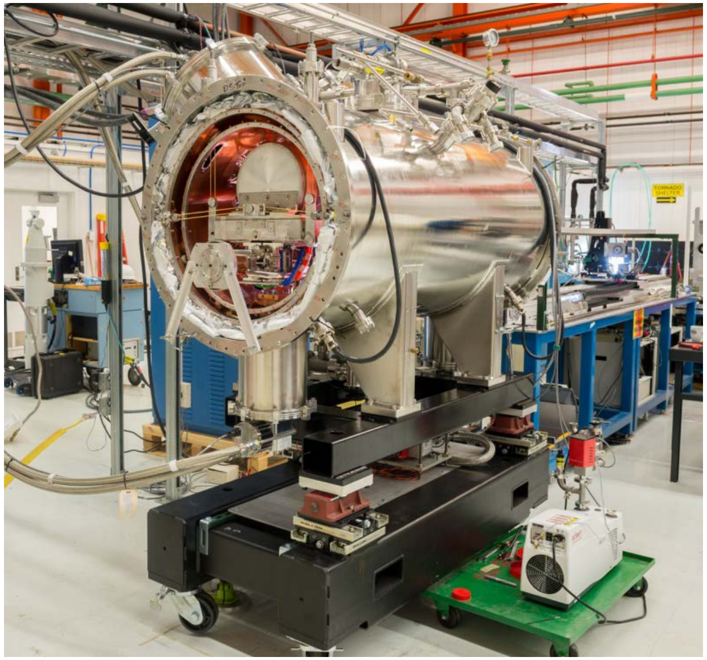


SCU0 (SCU) @ APS Argonne

λ_0:	16mm
N:	20 (70)
L:	330 (1140)mm
Gap:	9.5mm magnetic
B_{Peak}:	0.65T @ 500A
K:	0.97

SCU: assembled cryostat

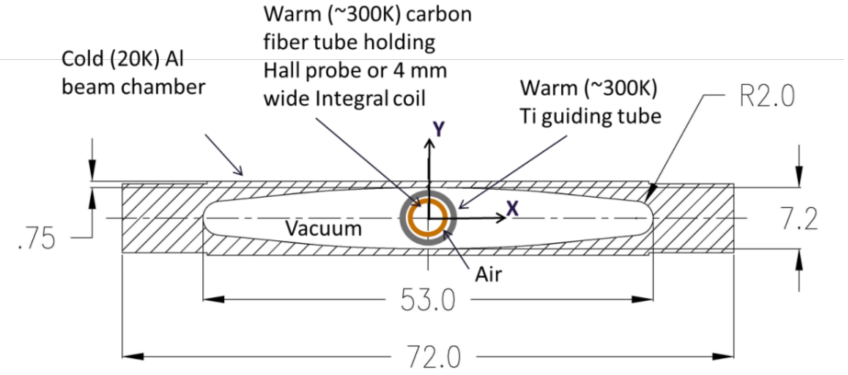




Operational Experience in APS:

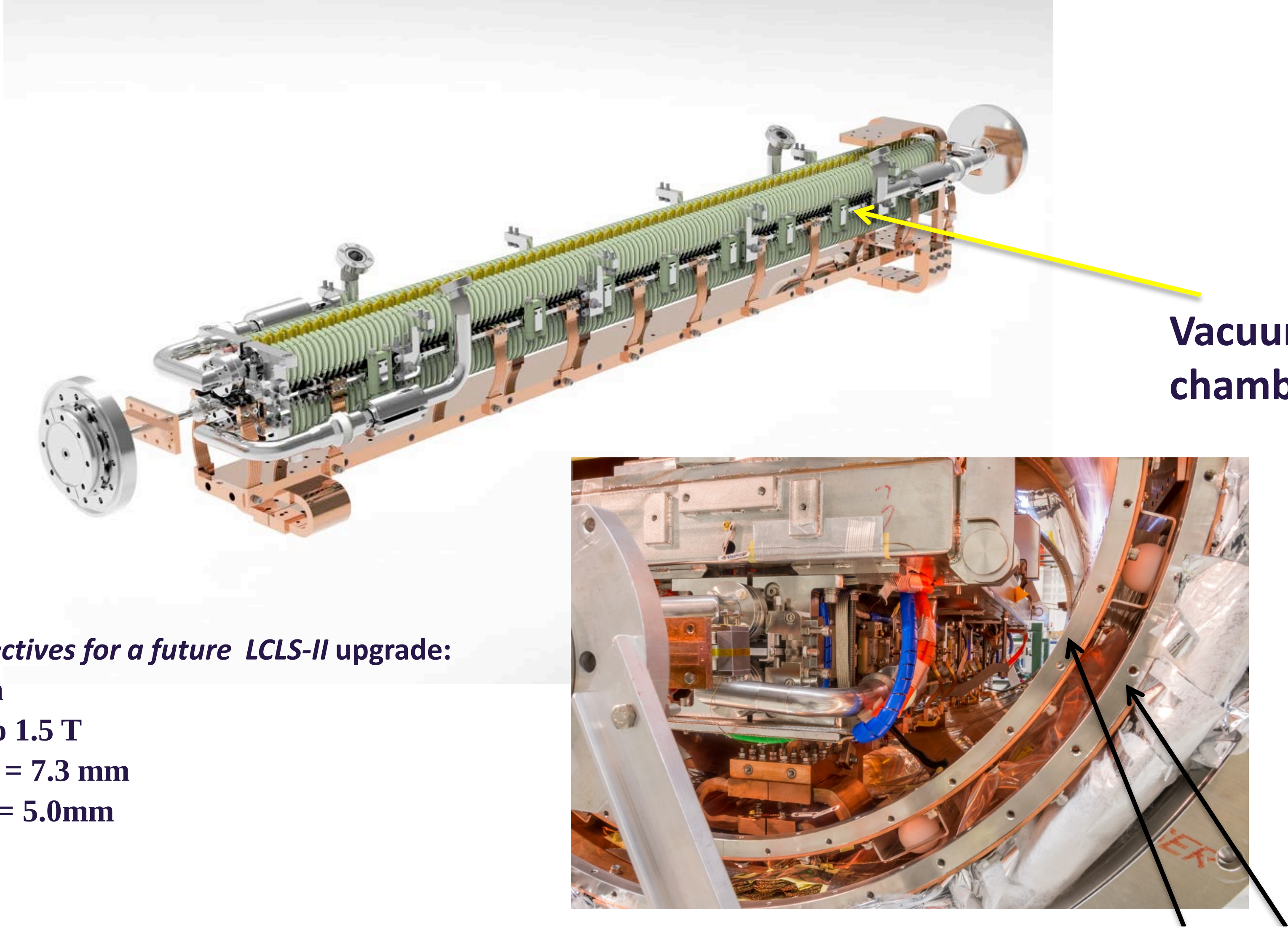
- 3 years with short 0.3m prototype
- 1 year with 1.1m device

1.6m prototype for LCLS II tested, in specs



Courtesy E.Gluskin, APS

SCU: undulator and vacuum chamber



***Target Objectives for a future LCLS-II* upgrade:**

$\lambda_u \approx 15$ mm

$B_{pk} = 1.0$ to 1.5 T

$Gap_{magnetic} = 7.3$ mm

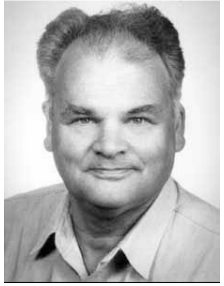
$Gap_{Vacuum} = 5.0$mm

Problems with SC Insertion Devices:

- Heat load by SR, especially in small gap short period devices.
- Shielding reduces usable gap
- Infrastructure and continuous maintenance required: Liquid Helium, or Cryocoolers
- Magnetic measurements
- Error compensation schemes available
- Not yet mature for making high quality undulators

Permanent Magnet Undulators

Permanent Magnet Undulators

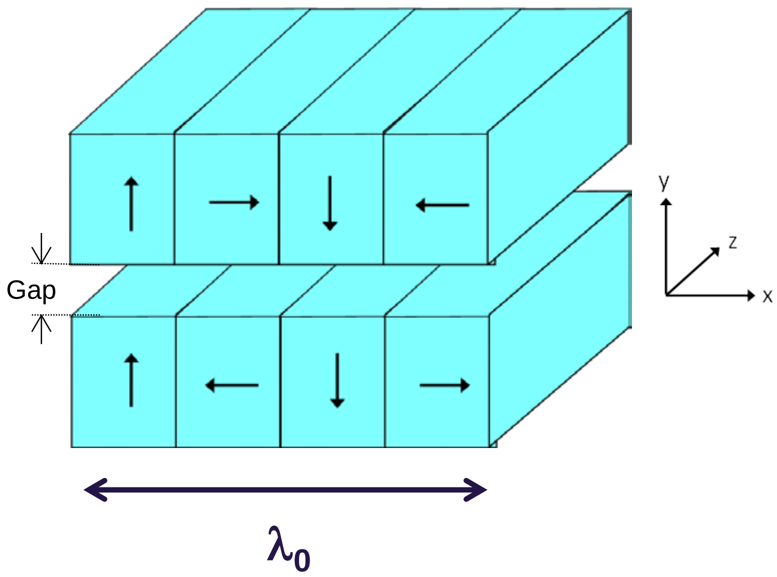


Klaus Halbach
1924-2000

- Pioneered by K. Halbach in the early 1980ies
- Technology widely used for 90-95% of devices
- Most use NdFeB only special applications use SmCo
- PM are best for small dimensions and high fields
- Most advanced technology for Undulators, all problems solved: field measurement, tuning → close to perfect fields
- Two basic design principles:
  1. Pure Permanent Magnet (PPM) without iron:
  2. Hybrid with soft iron
- PPM allows various modifications: Crossed undulators, Apple, Delta….
- In vacuum devices allow for smaller usable gaps
- Cryogenic undulator up to 20% higher fields

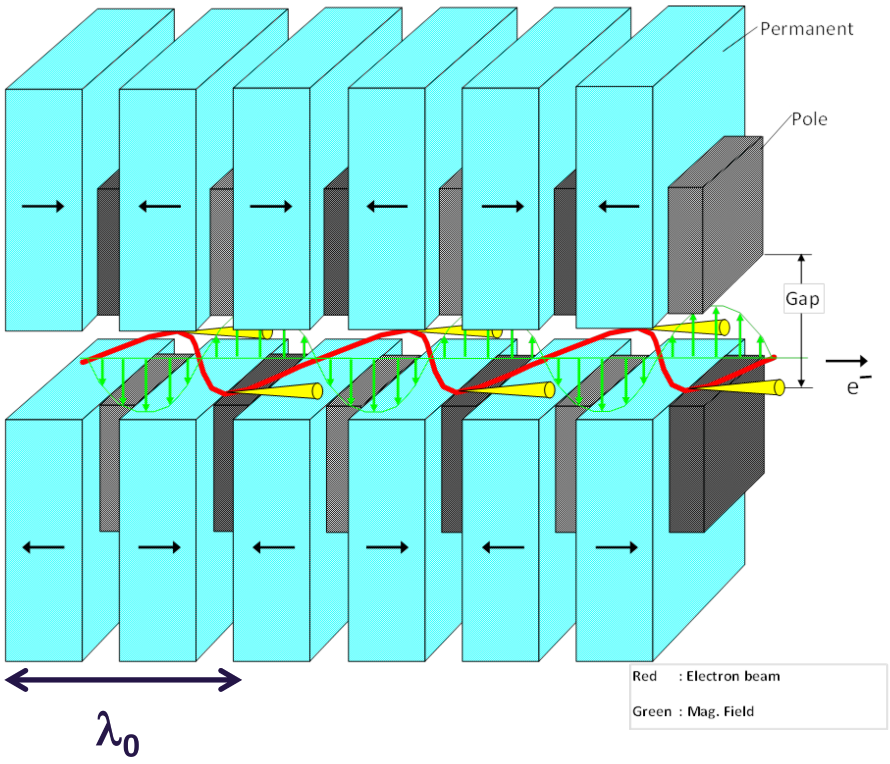
Planar Permanent Magnet Structures

PPM



K. Halbach, NIM 187, (1981) 109

Hybrid



K. Halbach, Journal de Physique 44, Colloque C1, (1983) 211

Field strength controlled mechanically by the gap

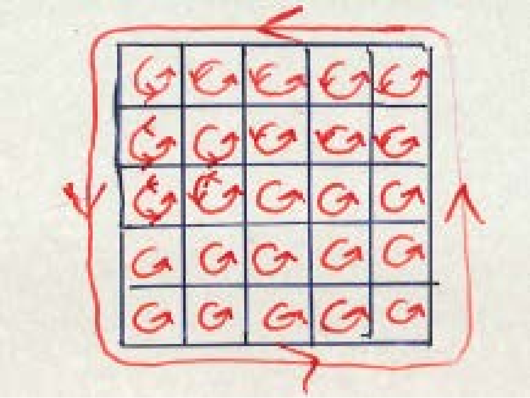
Field Calculation for ironless structures

Current sheet Method :

1. *No Iron*
2. *Homogeneous Magnetization*
3. $\mu_r \simeq 1.0$
4. ***Superposition principle***

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi} \iint_{Surface} \frac{(\vec{M} \times d\vec{a}) \times (\vec{r} - \vec{r'})}{(\vec{r} - \vec{r'})^3}$$

$\vec{j} = \frac{\vec{M} \times \vec{n}}{\mu_0}$ $B_r = 1.2\text{T} \div 9.55 \times 10^5 \frac{A}{m}$



In homogeneous material
all internal currents cancel
Only the surface current remains

Analytic solutions for fields and field integrals for some geometries exist: Parallelepipeds, cylinders…
Example PPM Undulator: Superposition of fields of individual parallelepipeds
Limitations:
NbFeB $\mu_r \approx 1.05\text{-}1.08$ SmCo $\mu_r \approx 1.01\text{-}1.04$

More:
Elleaume & Onuki p. 161
Clarke p. 113

Magnet Design Codes

If $\vec{M}(\vec{H})$ not constant and $\mu_r \neq 1$ analytic solutions do not exist.

→Numeric methods

- Finite Element Methods
  need to mesh out the space
    - 2D Poisson/Superfish/Pandira
      Dates back to Holsinger/ Halbach in the 1980ies was very popular!
      Free download from Los Alamos Lab:
      http://laacg.lanl.gov/laacg/services/
    - Professional 3D Codes TOSCA, OPERA, ANSYS, MAFIA….
      Commercial, not free, expensive!
- Integral Methods
  RADIA: 3-D, meshes out only magnetic relevant parts: Coils, Magnets, Iron
  NOT free space, calculates Field and field integrals at any point is space directly
  Developed at ESRF by O.Chubar, P. Elleaume; Very popular for Insertion Devices.
  Free download but needs MATHEMATICA
  http://www.esrf.eu/Accelerators/Groups/InsertionDevices/Software/Radia

Magnet Design Steps

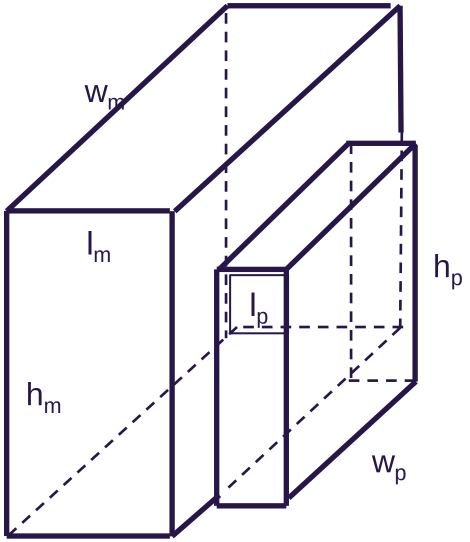
Input: e^- energy, radiation wavelength range

Design Criteria:

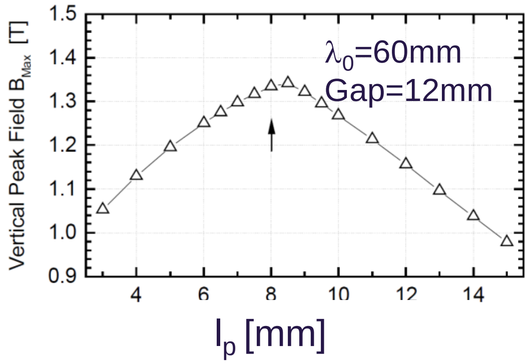
- Gap, Period Length λ_0, Peak Field B_0, K-Parameter
- “Good” Field range → width of poles & magnets
- “Good” range of field integrals (dynamic aperture for injection)
- Gap dependence of field integrals → End pole design
- Properties of Permanent Magnet Material:
  - Balance of B_r vs H_{CJ}
  - Worst case operating temperature (60°C)
  - EXFEL: $B_r \geq 1.26$T; $H_{CJ} \geq 1670$A/m at 20°C

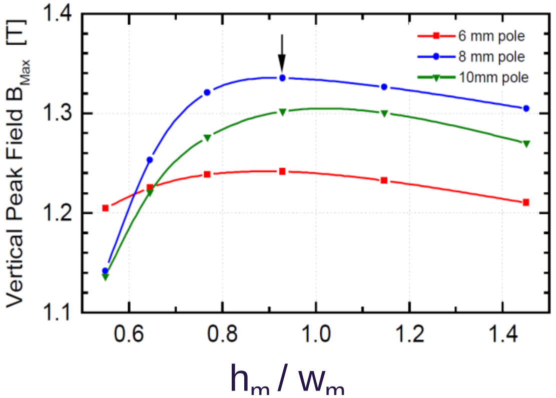
Example: Magnet Design

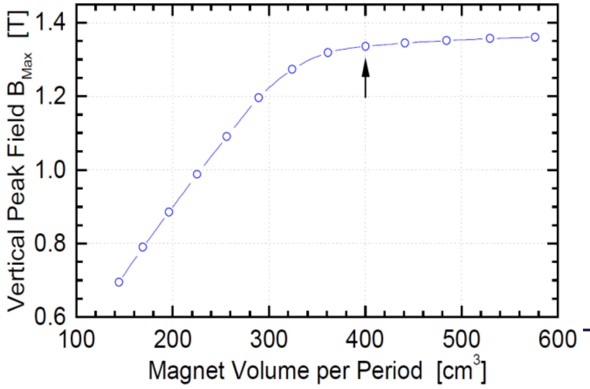
- Optimize dimensions:
  l_m / l_p; $l_m + l_p = \lambda_0$
- h_m / w_m
- h_p, w_p
- Magnet Volume



http://flash.desy.de/reports_publications/tesla_fel_reports/tesla_fel_2000/







Practical Design Formulae

Model for Peak Field:

$$B\left(\frac{g}{\lambda}\right)[T] = a\; e^{b\frac{g}{\lambda}+c\left(\frac{g}{\lambda}\right)^2}$$

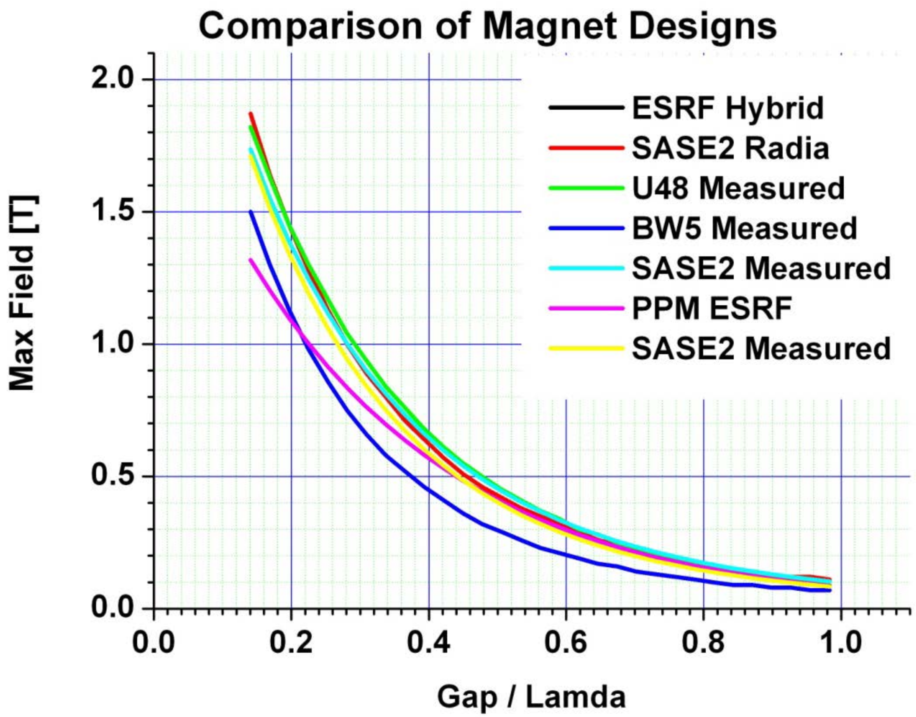
Hybrid FeCo Poles *	3.694	-5.068	1.52
XFEL SASE2 measured **	3.10487	-4.24914	0.80266
XFEL SASE3 measured ***	3.2143	-4.62305	0.92541
HASYLAB BW5 (2T Wiggler)****	3.1852	-5.6036	1.6891
Pure Permanent Magnet *	2.076	-3.24	0.

* see Elleaume et al. NIMA A455 (2000), 503

** EXFEL U40 λ=40mm

*** EXFEL U68 λ=68mm

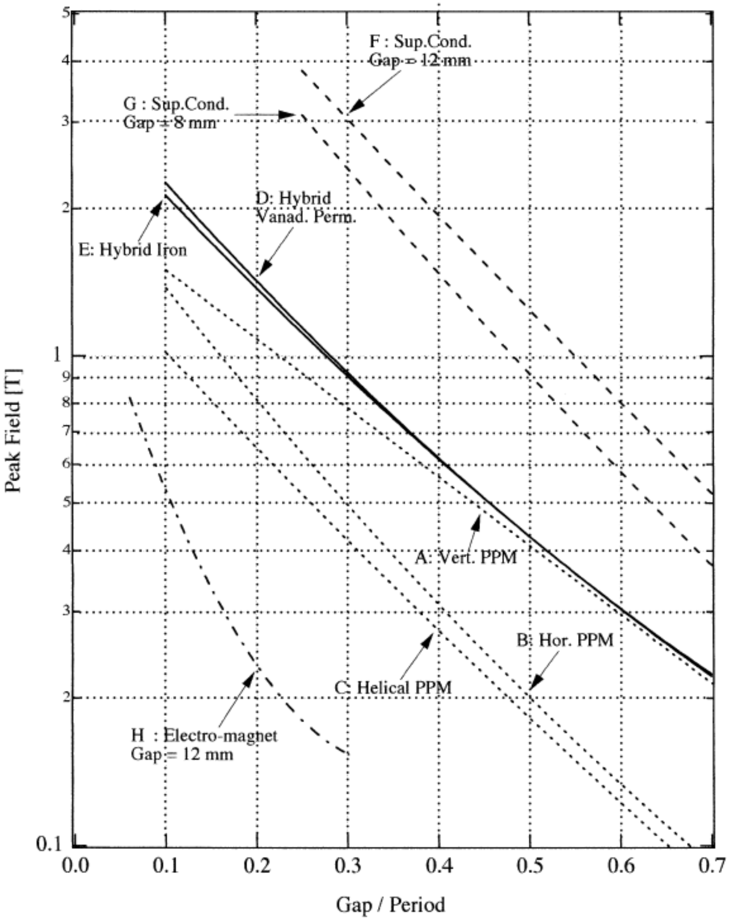
****Large period λ=230mm, Magnet weight: 15kg



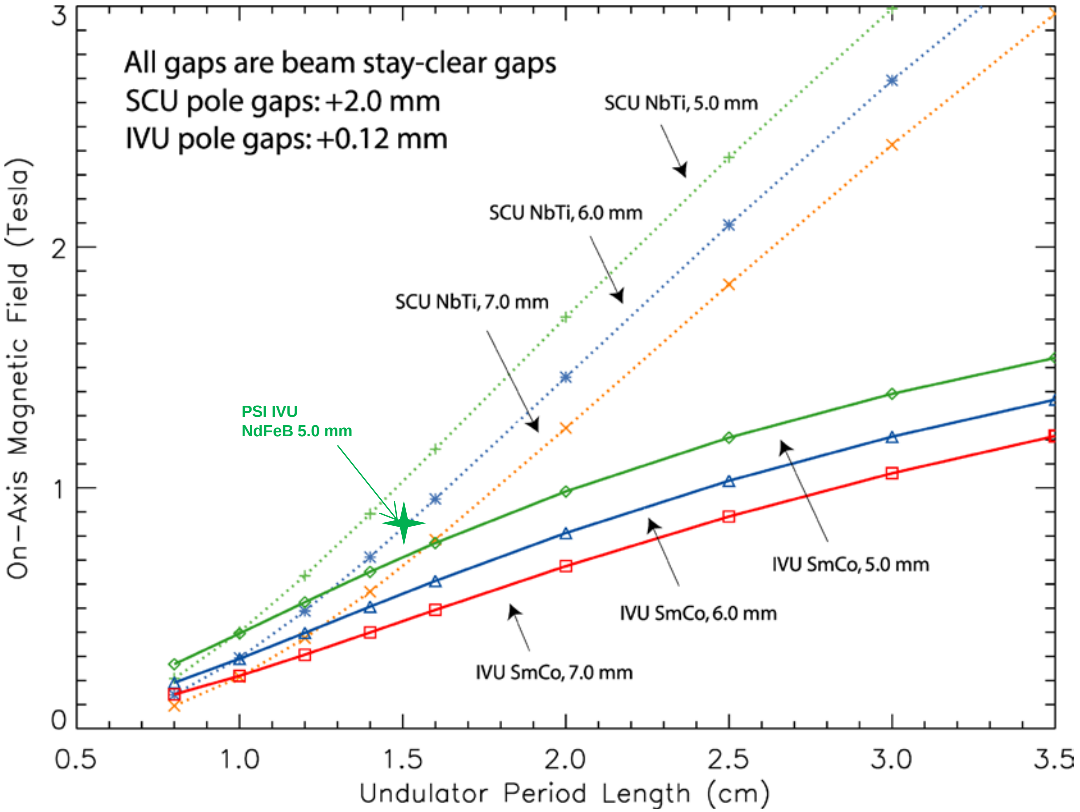
Scaling Example:

	Weight for λ_0=230mm	Weight for λ_0=40mm
BW5 Design	15 kg	0.078 kg
U40 Design	57.3 kg	0.302 kg

Comparison PM - EM - SC



Peak field versus gap/period for EM, PM and SC technology taken from P. Elleaume, J. Chavanne, B. Faatz, A455 (2000), 503

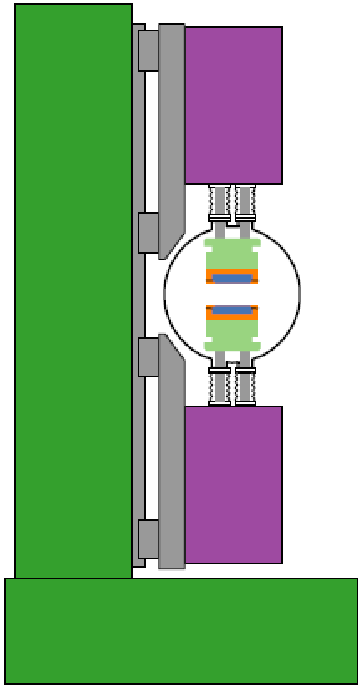


Courtesy: Efim Gluskin APS Aug 2012

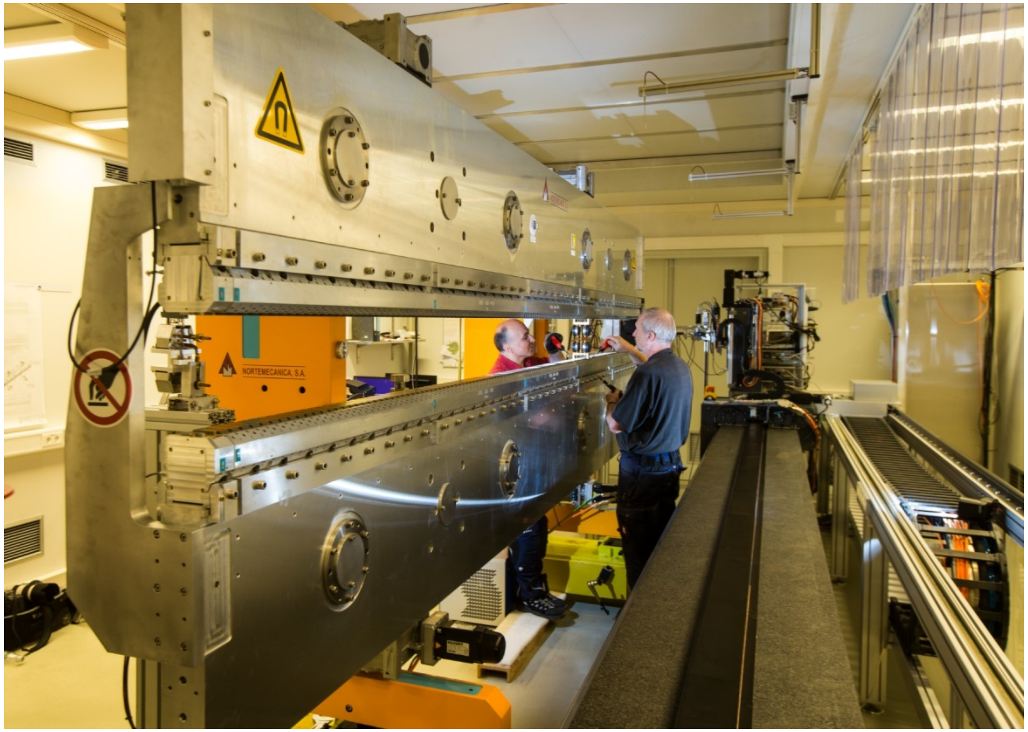
Mechanic Design Principles

C Frame

Pro: Best access for magnetic measurements & Tuning
Con: Non-symmetric, more effort for mechanical stability and rigidity



C-shape

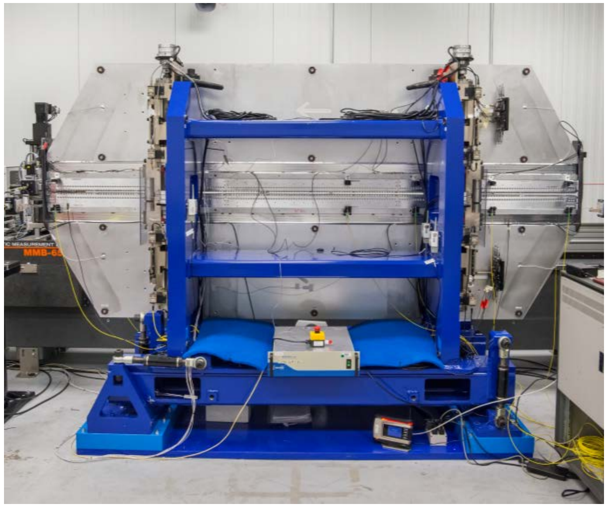


Pole Tuning of an EXFEL 5m U40 while on the 6.5m magnetic bench

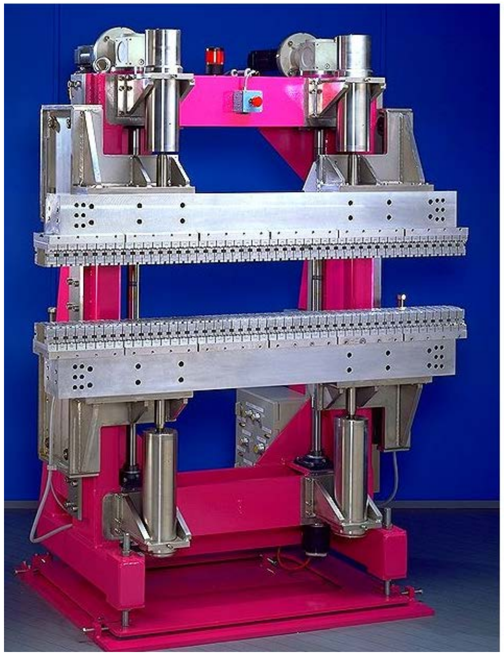
C-Type with guide rails

EXFEL 5m U40
4 Motors/4 Spindles

Petra III 2m U29



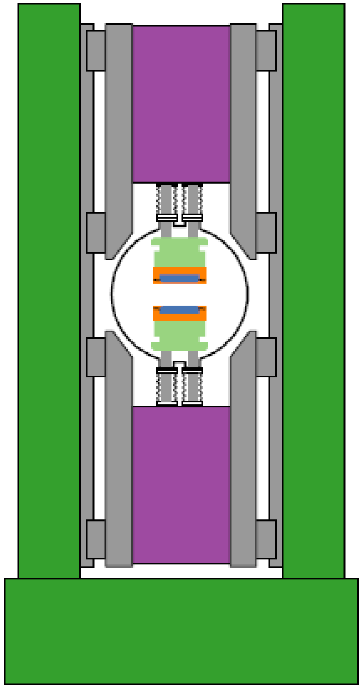
LCLS II Prototype L=3.3m
4 Motors/4 Spindles



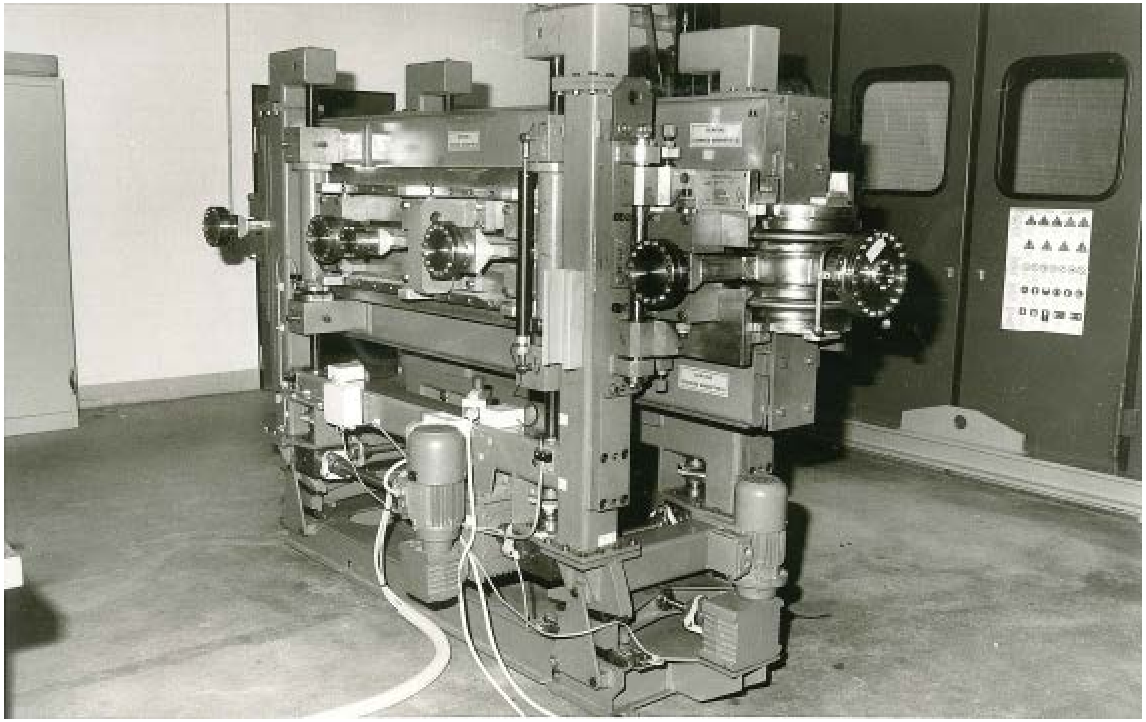
ESRF Standard Carriage;
2Motors & 2 right left spindles
L=1.6m

H-Frame

Pro: Compact, symmetric support, stable
Con: Accurate magnetic measurements and tuning difficult

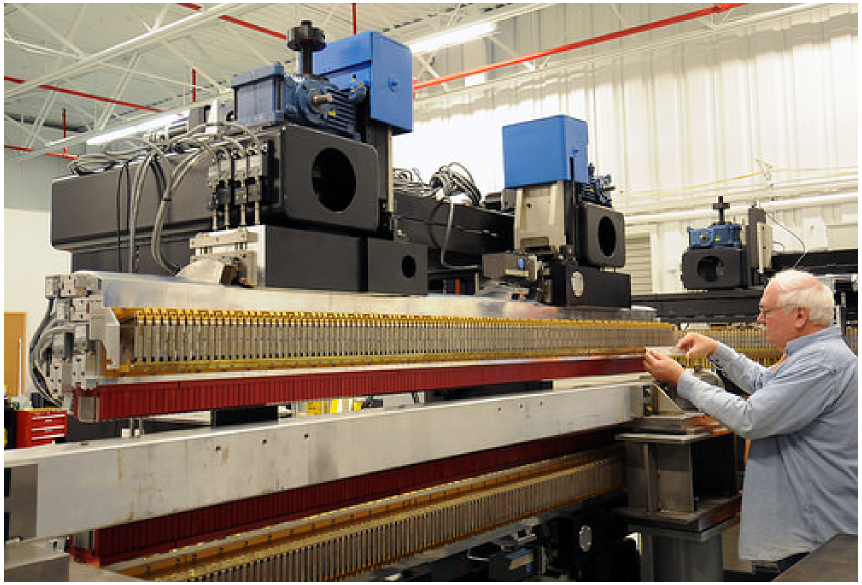


H-Frame

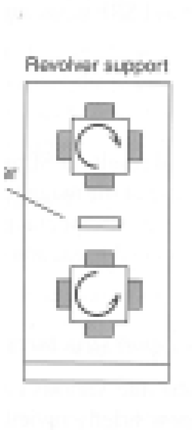


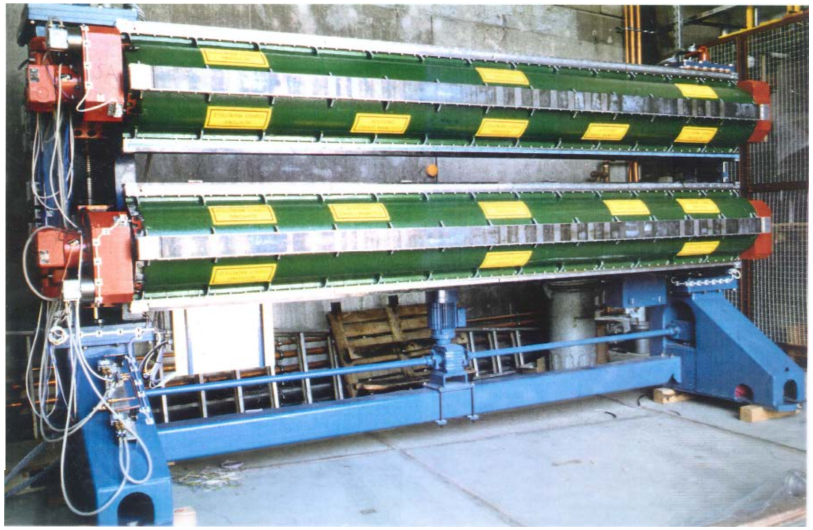
DESY/HASYLAB Hard X-ray Wiggler for
Coronary Angiography 1987-2004

C- Frame Revolver Undulators



APS Revolver 2014
2 Positions



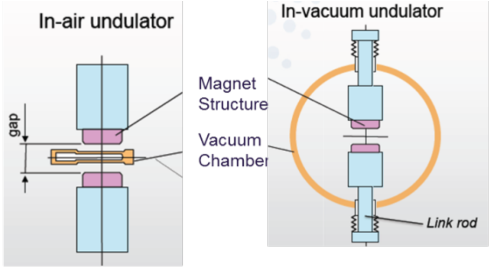


DORIS III Revolver: In Operation since 1991: 4 Positions, only 3 used. In use until 2012.

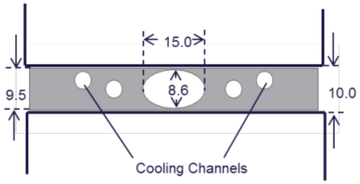
In Vacuum Undulators (IVUs)

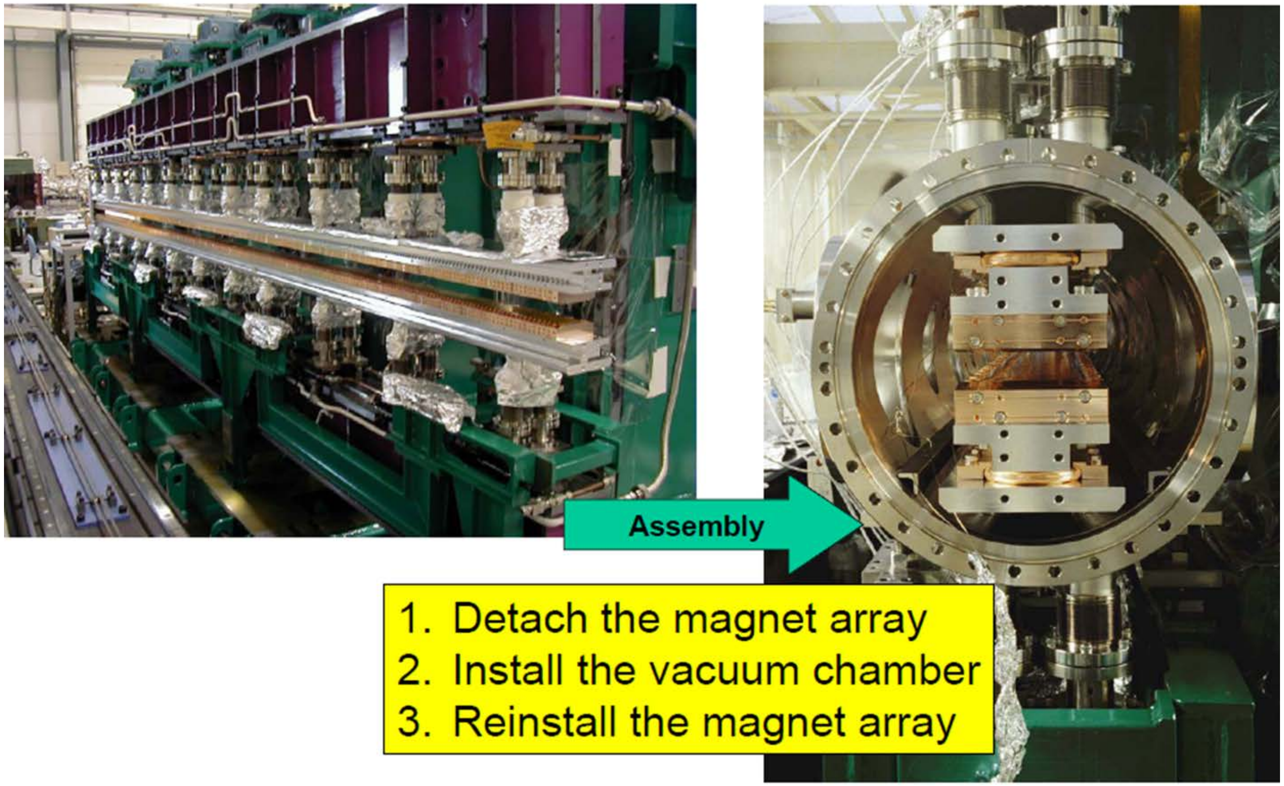
Idea: No vacuum chamber: Magnet gap = Vacuum gap → higher field

Allows for smallest periods and gaps



EXFEL 9.5mm Vacuum Chamber



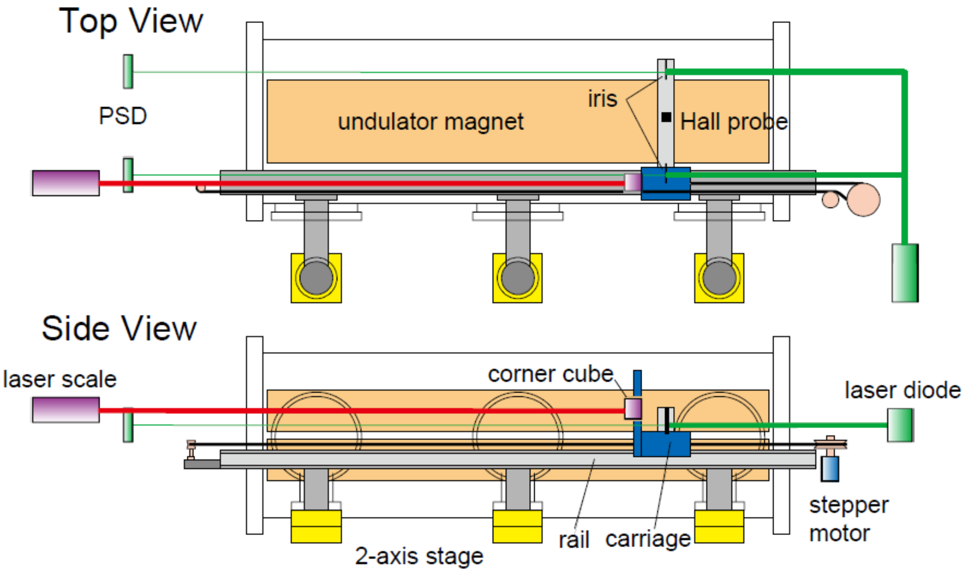


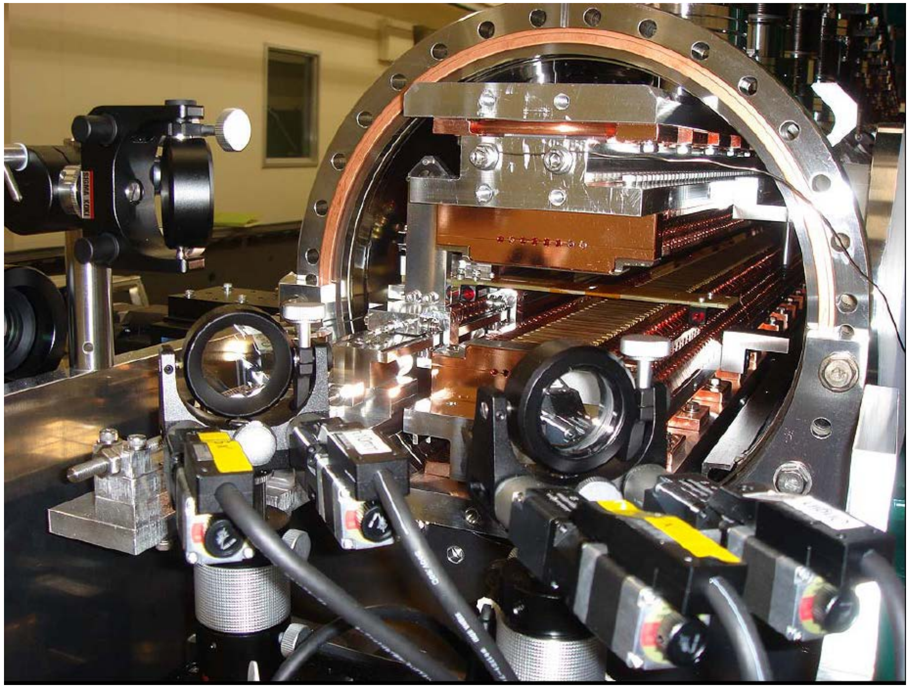
1. Detach the magnet array
2. Install the vacuum chamber
3. Reinstall the magnet array

Courtesy: T. Tanaka, Spring8

IVUs : SAFALI

Self Aligned Field Analyzer with Laser Instrumentation



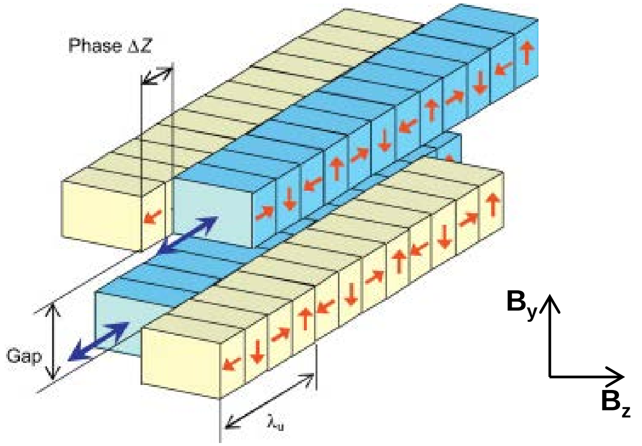


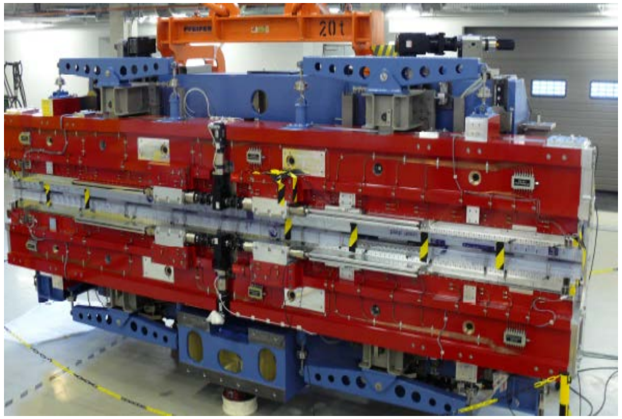
SAFALI measurement of an IVU for SACLA

Courtesy: T. Tanaka, Spring8 EFST on Insertion Devices Workshop, Dec 3-4, 2009, Shanghai, China

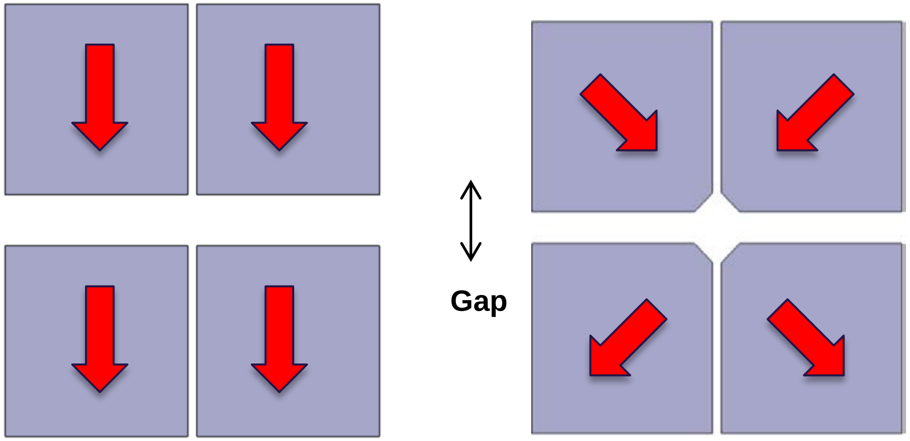
PPM Undulators for variable Polarization I
APPLE (Advanced Polarized Light Emitter)

Advanced Planar Polarized Light Emitter





5m APPLE II for PETRA III



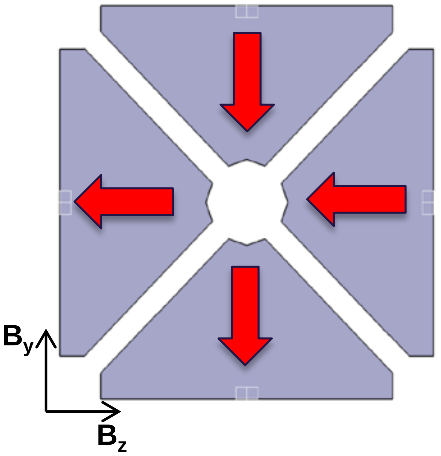
APPLE II

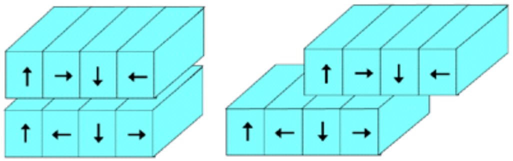
- Large horizontal Gap
- Field adjustable via Gap
- standard for storage rings, widely used
- Lateral access for measurements
- By > Bz

APPLE III

- Reduced horizontal Gap
- Field adjustable via Gap
- Higher Fields than APPLE II
- Optimized for Round Beam pipes in FELs
- Reduced lateral access for measurements
- By > Bz

PPM Undulators for variable Polarization: More devices

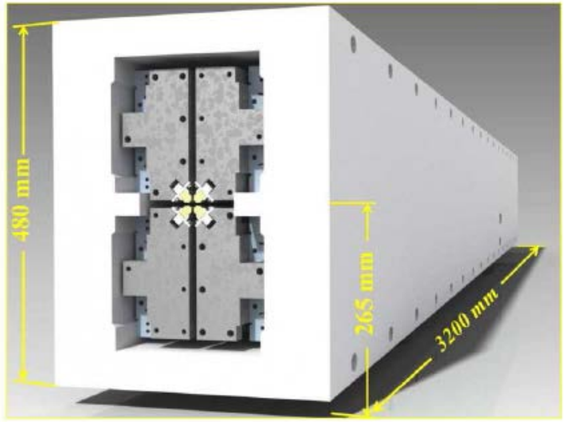




Max. Field
Zero Gradient

Zero Field
Max. Gradient

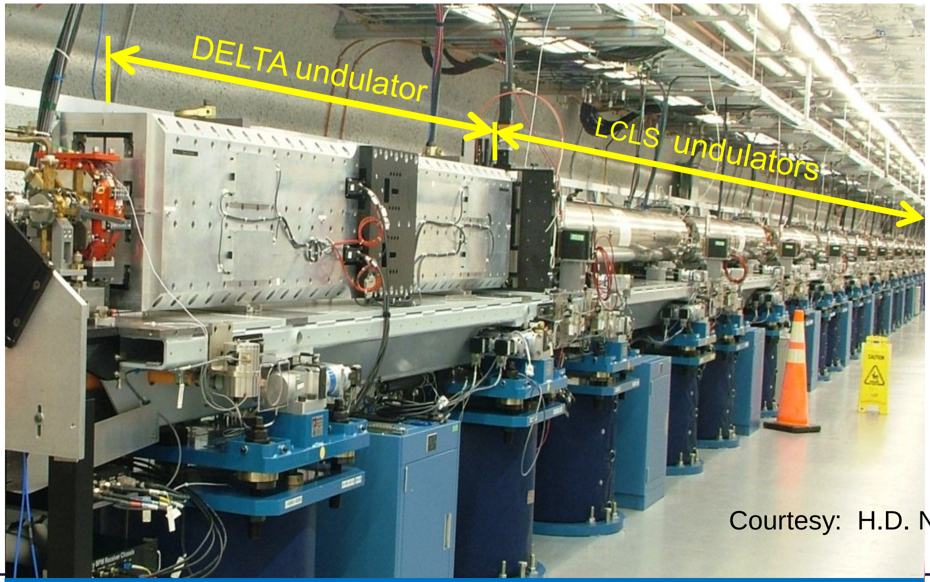
Field Amplitude Change of a Delta



Delta in LCLS I

DELTA

- Fixed gap
- Field change by longitudinal shift
- Compact, symmetric Design
- No lateral access for magnetic measurements
- Problem: Strong field gradients

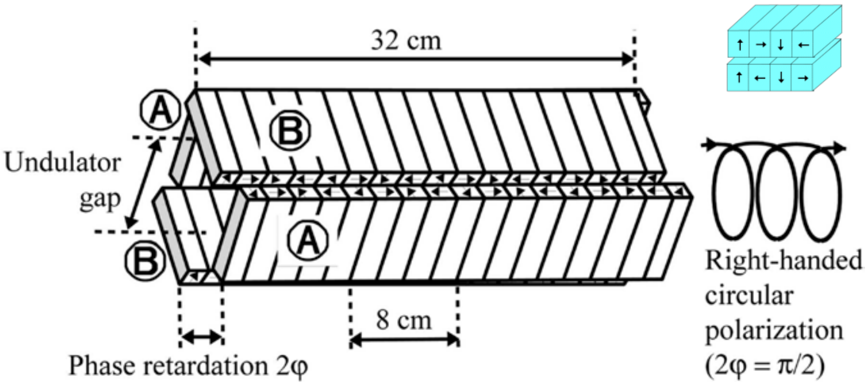


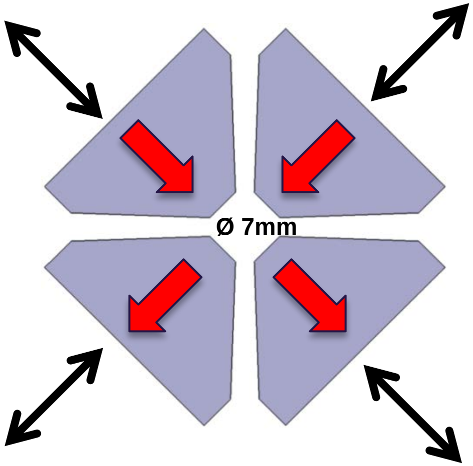
Courtesy: H.D. Nuhn, SLAC

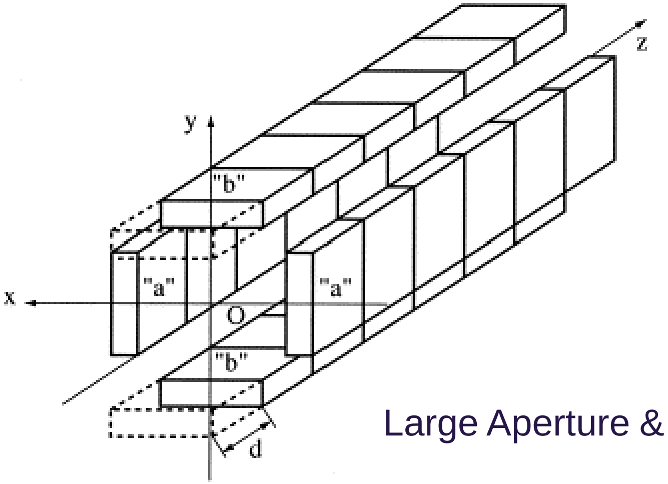
X-ray beam polarization controllable from circulator through elliptical to linear

Radial Gap adjustable polarized Light emitter

Delta + Gap Adjustment





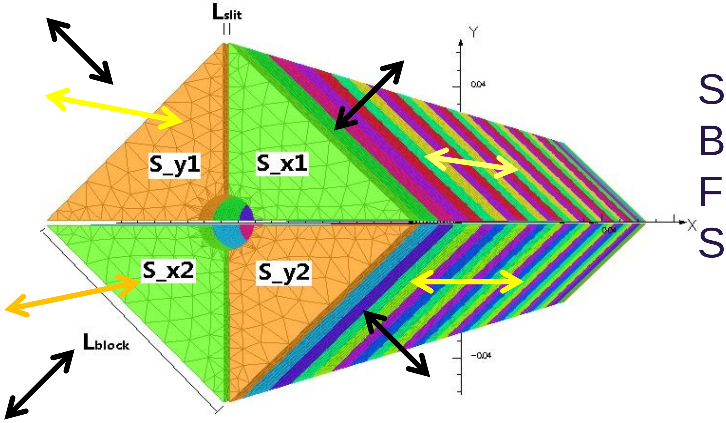


Optimized Geometry

Requires 8 Degrees of Freedom

Large Aperture & Gap!

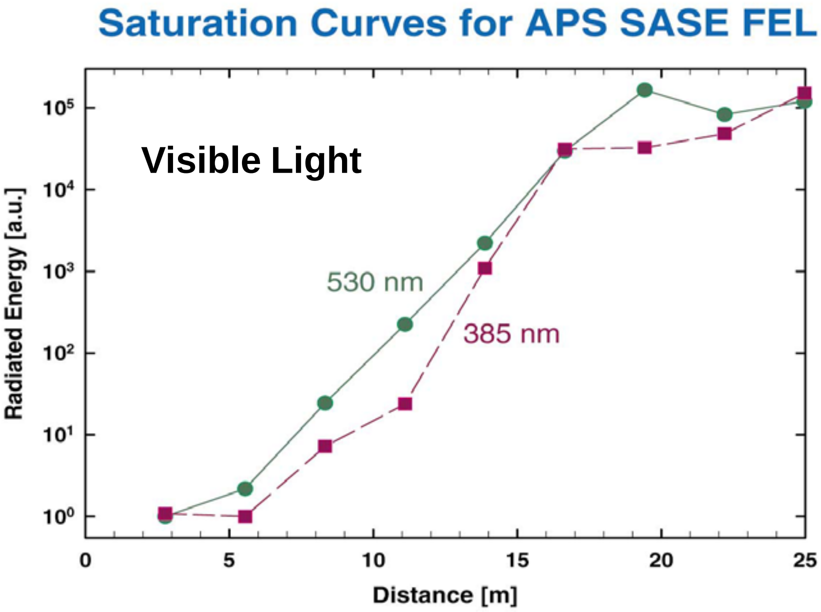
H. Onuki, NIMA 246 (1986) 94



Symmetric
By = Bx
Field adjustable
Substantial effort!

XFEL Undulator Systems

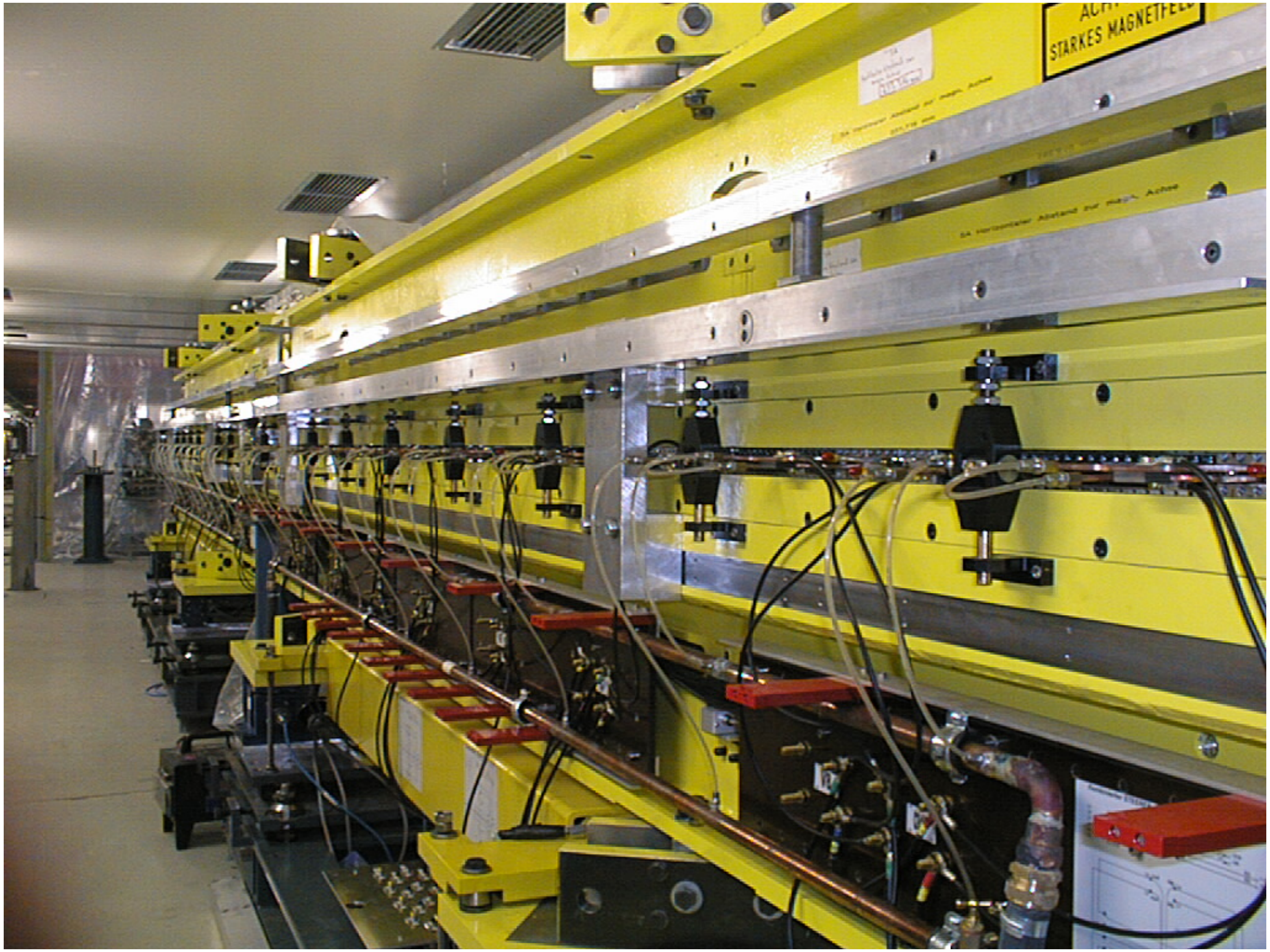
LEUTL Undulator Line



Length	9 x 2.4 m
Period	3.3 cm
Gap	9.4 mm
Field	1 T
K	3.1
Intermodule gap	33 cm

Advanced Photon Source, 2000

DESY TTF1 1999 -2004



First SASE VUV FEL

λ_0=27.2mm

Gap= 12mm, fixed

B_0= 0.497T

K=1.3

L_{tot}=15m

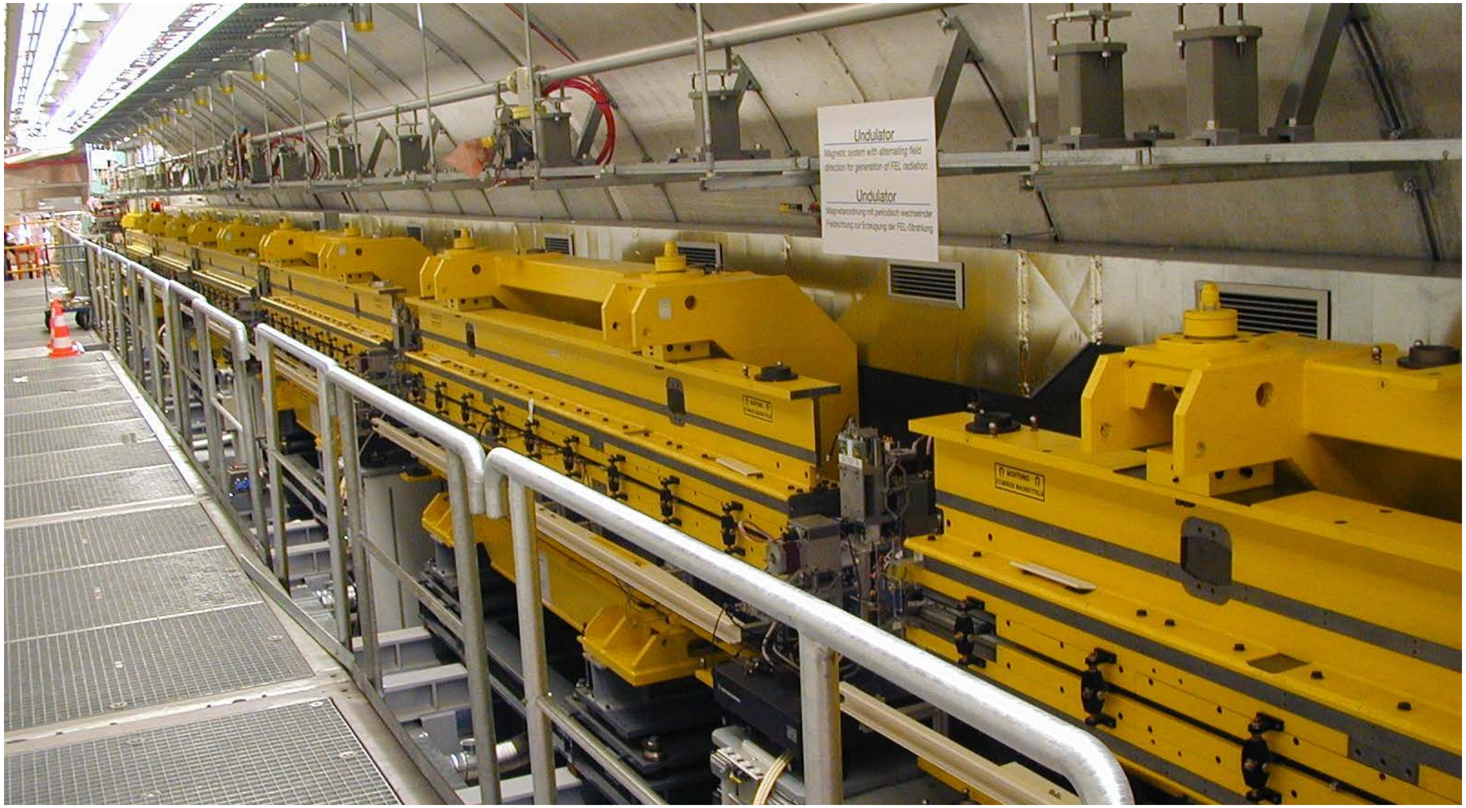
E=0.3GeV

λ_{Rad}= 70nm

Combined Function Focusing

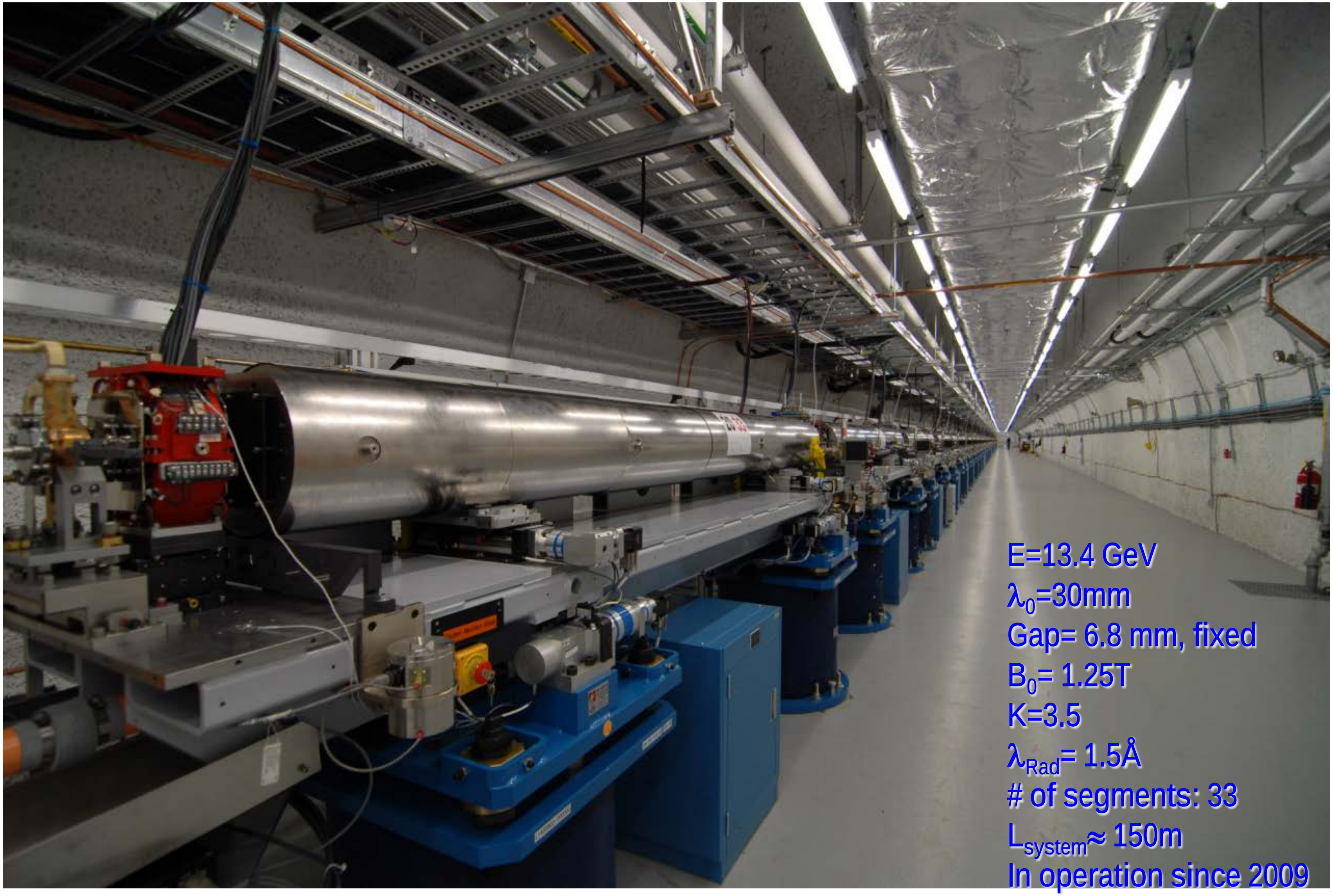
1st Lasing: 2000

DESY FLASH I User Facility 2004



E=1.2GeV; λ_0=27.2mm; Fixed gap= 12mm; K=1.3; λ_{Rad}= 6nm
System length: 30m
In operation since 2005

LCLS-I 84m long Undulator Line



E=13.4 GeV

λ_0=30mm

Gap= 6.8 mm, fixed

B_0= 1.25T

K=3.5

λ_{Rad}= 1.5Å

# of segments: 33

L_{system}≈ 150m

In operation since 2009

SACLA

In Vacuum Undulator

E=8GeV

λ_0=18mm IVU

Gap= $\geq$ 3.7mm

B_0= $\leq\approx$1.2T

K=$\leq$2.1

$\lambda_{Rad}\geq$1Å

Segment Length: 5m

# of Segments: 18

System Length: 110m

In operation since 2010

High density of in-vacuum undulators!

FERMI FEL @ Elettra

E= 1.5GeV
FEL1: APPLE II var. Polarization
λ_{Rad} = 400-1000 Å ;
L= 2.34m; λ_0=65mm; 6 Segments

FEL2: APPLE II var. Polarization
λ_{Rad}= 100-400 Å
L= 2.40m; λ_0=50mm; 10 Segments

In Soft X-Ray FELs undulator lines are relatively short,

Control of radiation polarization is preferred

European XFEL / SASE1

During construction April2016

With Air Condition Enclosure 20.5.2016

E=17.5GeV

λ_0=40mm

Gap= ≥ 10mm

B_0= ≤≈1.2T

K=≤3.9

λ_{Rad}≥0.5Å

Segment Length: 5m

# of Segments: 35

System Length: 220m

Planned Start 1.4.2017

PAL – XFEL Pohang Korea Hard X-ray Line

In Soo Ko, AAPPS Bulletin Vol 26,1

E=10 GeV

λ_0=26mm

Gap= $\geq$ 8.3mm

B_0= $\leq\approx$1.2T

K=$\leq$1.97

$\lambda_{Rad}\geq$0.6Å

Segment Length: 5m

# of Segments: 20

System Length: 125m

Start late 2016

Summary & Outlook

- Three technologies are used for Undulators
  - SCUs made progress: Once mature may deliver shorter periods higher field. → shorter λ_{Rad} at given γ
  - EM technology only for niche applications: Very long λ_0, moderate fields, AC excitation
  - PM technology is most advanced and used on a large scale worldwide for 90%+ of the devices
    Pure PM devices offer options for variable polarization
- Potential for further developments: IVUs, variable polarization
- Future challenges: Long term operation in SC accelerators: EXFEL, LCLSII Radiation damage ↔ small gap
- Not touched: Drive & motion Control; Control systems