High Performance Insertion Devices (for XFELs)

J. Pflueger, European XFEL

References

H. Onuki. P. Elleaume: “Undulators, Wigglers and their Applications
Taylor & Francis, New York

Referred to as “Onuki”

J. A. Clarke: “The Science and Technology of Undulators and Wigglers”
Oxford University Press, 2004

Referred to as “Clarke”

Tutorial on Undulator Technology: Overview

- Basics
  - Electron Motion in periodic fields
  - Resonance, Slippage
  - Phase Jitter
- Spontaneous Radiation (Single Electron Emission)
- Stimulated FEL Radiation, SASE (Collective Emission)
- Technology
  - Overview: EM, SC, PM
  - Permanent Magnet Undulators Design
- Mechanical Design
  - Design Principles
  - Tolerance Estimation (Example EXFEL)
  - Motion Control
- Undulator Systems for FELs

Basics

Equations of Motion

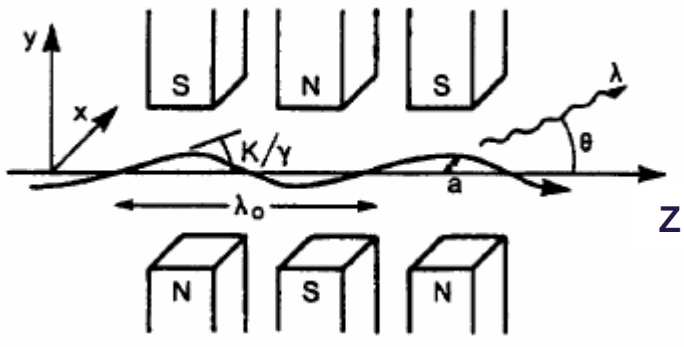
Basic Equations of Motion:

$$\vec{F} = \frac{d\vec{p}}{dt} = m_0\gamma\frac{d}{dt}\vec{v} = e\left[\vec{v} \times \vec{B}\right]$$

Lorentz - Equation

Periodic field:

$$\vec{B} = \begin{pmatrix} 0 \\ B_0 \sin\left(\frac{2\pi}{\lambda_0}z\right) \\ 0 \end{pmatrix}$$



$$\ddot{x} = -\frac{e}{\gamma m_0} v_z B_y$$
$$\ddot{y} = 0$$
$$\ddot{z} = -\frac{e}{\gamma m_0} v_x B_y \cong 0$$

Initial Conditions:

$v_x;\ v_y = 0$

$$v_z = \beta c; \quad \beta = \sqrt{1 - \frac{1}{\gamma^2}} \cong 1 - \frac{1}{2\gamma^2}$$

Beam deflection and excursion

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

Transverse deflection:

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

For pure Sinusiodal Field

$$v_y = 0$$

Longitudinal velocity:

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

Transverse beam excursion:

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

Examples, Practical Formulae

$K = \frac{eB_0\lambda_0}{2\pi m_0 c}$ Undulator K- Parameter

$$K = 0.0933726\, B_0[T] \cdot \lambda_0[mm]$$

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

Relation between 2nd Field Integrals and beam excursions for EXFEL and FLASH

E [GeV]	I_2 [Tmm^2]	X [μm]	
17.5	58	1	EXFEL
17.5	1460	25	÷ RMS beam size
1.2	4	1	FLASH
1.2	140	35	÷ RMS beam size

Practical units :

$$x'[mrad] = 0.3\,\frac{I_1[Tmm]}{E[GeV]}$$

$$x[\mu m] = 0.3\,\frac{I_2[Tmm^2]}{E[GeV]}$$

Max deflection angles and oscillation amplitudes for EXFEL and FLASH Undulators

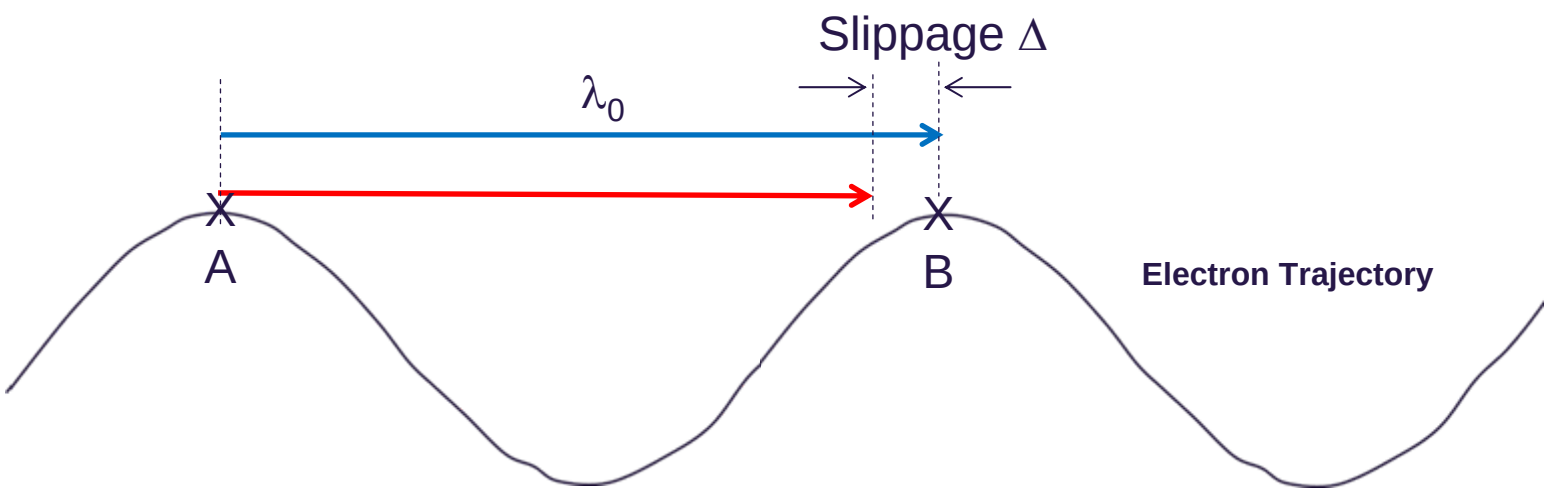
	E [GeV]	λ_0 [mm]	B_{Max} [T]	K_{Max}	K_{Max}/γ [mrad]	$\frac{K_{Max}\lambda_0}{\gamma 2\pi}$ [μm]
SASE1/2	17.5	40	1.19	4.43	0.129	0.82
SASE3	17.5	68	1.7	10.75	0.31	3.35
FLASH	1.2	27.3	0.47	1.2	0.51	2.2

Slippage, Resonance

Light travels at light speed c

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

γ >>> 1; EXFEL@17.5GeV: γ =34247



Travel time for light for λ_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: $\Delta = \lambda_0(1-\bar{\beta}) = \frac{\lambda_0}{2\gamma^2}(1+\frac{K^2}{2})$

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

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

Clarke: p. 53 ff

Optical Phase

Longitudinal Electron Movement

$$v_z(z) = \sqrt{(\beta c)^2 - {v_x}^2} = \beta c \sqrt{1 - \frac{v_x^2(z)}{(\beta c)^2}} \cong \beta c \left\{1 - \frac{1}{2}\frac{v_x^2(z)}{(\beta c)^2}\right\}$$

$$v_x(z) = \frac{ec}{\gamma m_0}\int_{-\infty}^{z} B_y(z')dz'$$

Total slippage = accumulated difference between light and electron speed

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

Optical Phase Advance = 2π x Slippage / λ_{Rad}

$$\varphi(z) = 2\pi\,\Delta(z)/\lambda_{Rad}$$

On resonance i.e. at $\lambda_{Rad} = \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$ $\varphi(z+n\lambda_0) - \varphi(z) = n \times 2\pi$

$$PI(z) = \int_{-\infty}^{z}\left(\int_{-\infty}^{z''} B_y(z')dz'\right)^2 dz''$$

Phase Advance

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

$$= \frac{2\pi}{\lambda_0(1+0.5K^2)}\left[z + \left(\frac{e}{m_0 c}\right)^2 \underbrace{\int_{-\infty}^{z}\left(\int_{-\infty}^{z''} B_y(z')dz'\right)^2 dz''}_{\text{Phase Integral, PI(z), of measured data}}\right]$$

Independent of γ !

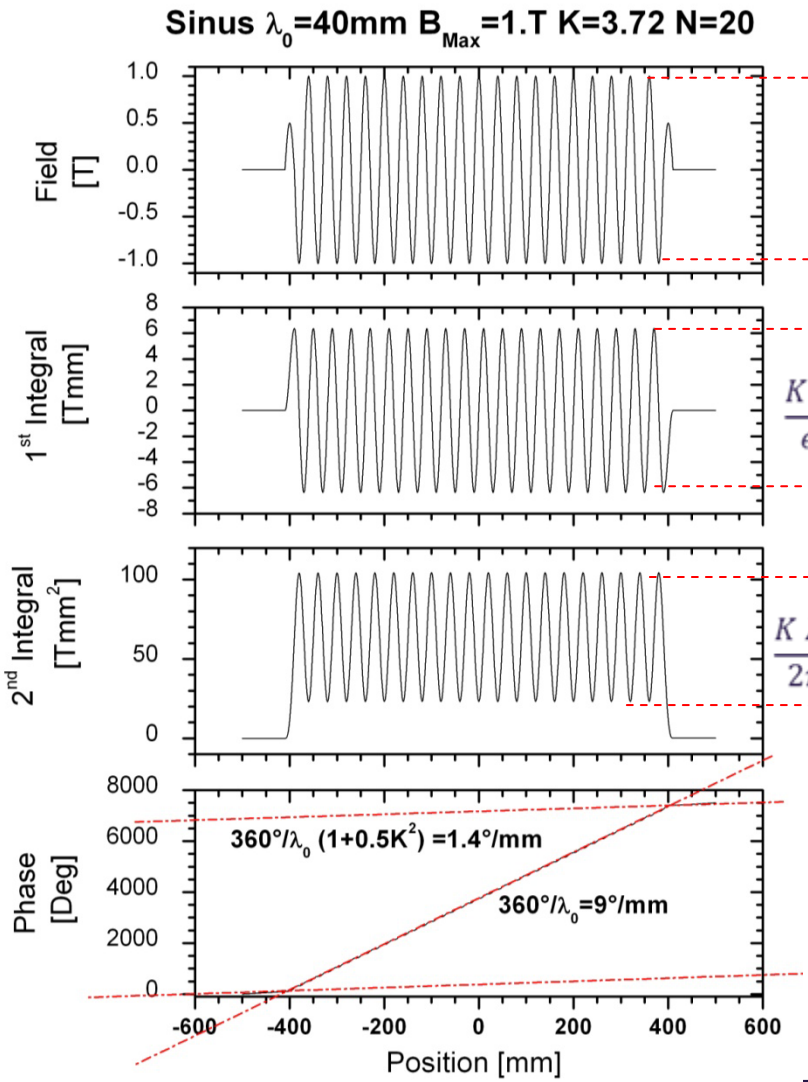
$$\varphi(z + n\cdot\lambda_0) - \varphi(z) = n\cdot 2\pi = \frac{2\pi}{\lambda_0(1+0.5K^2)}\left[n\cdot\lambda_0 + \left(\frac{e}{m_0 c}\right)^2 (PI(z+n\lambda_0) - PI(z))\right]$$

$$K = \frac{e}{mc}\sqrt{\frac{2[PI(z+n\lambda_0) - PI(z)]}{n\lambda_0}}$$

K-parameter for arbitrary periodic field radiates at λ_{Rad} and has phase advance of 2π per period.

Derivation from Radiation Integrals: R.P. Walker NIMA 335, (1993) 328

Demonstration of Field, 1st , 2nd Integral and Phase advance



± 1T

$$\frac{K\, m_0}{e\, c} = \frac{\lambda_0 B_0}{2\pi} = \pm 6.3\ Tmm$$

$$\frac{K\, \lambda_0\, m_0}{2\pi\, e\, c} = B_0 \left(\frac{\lambda_0}{2\pi}\right)^2 = \pm 40.5\ Tmm^2$$

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

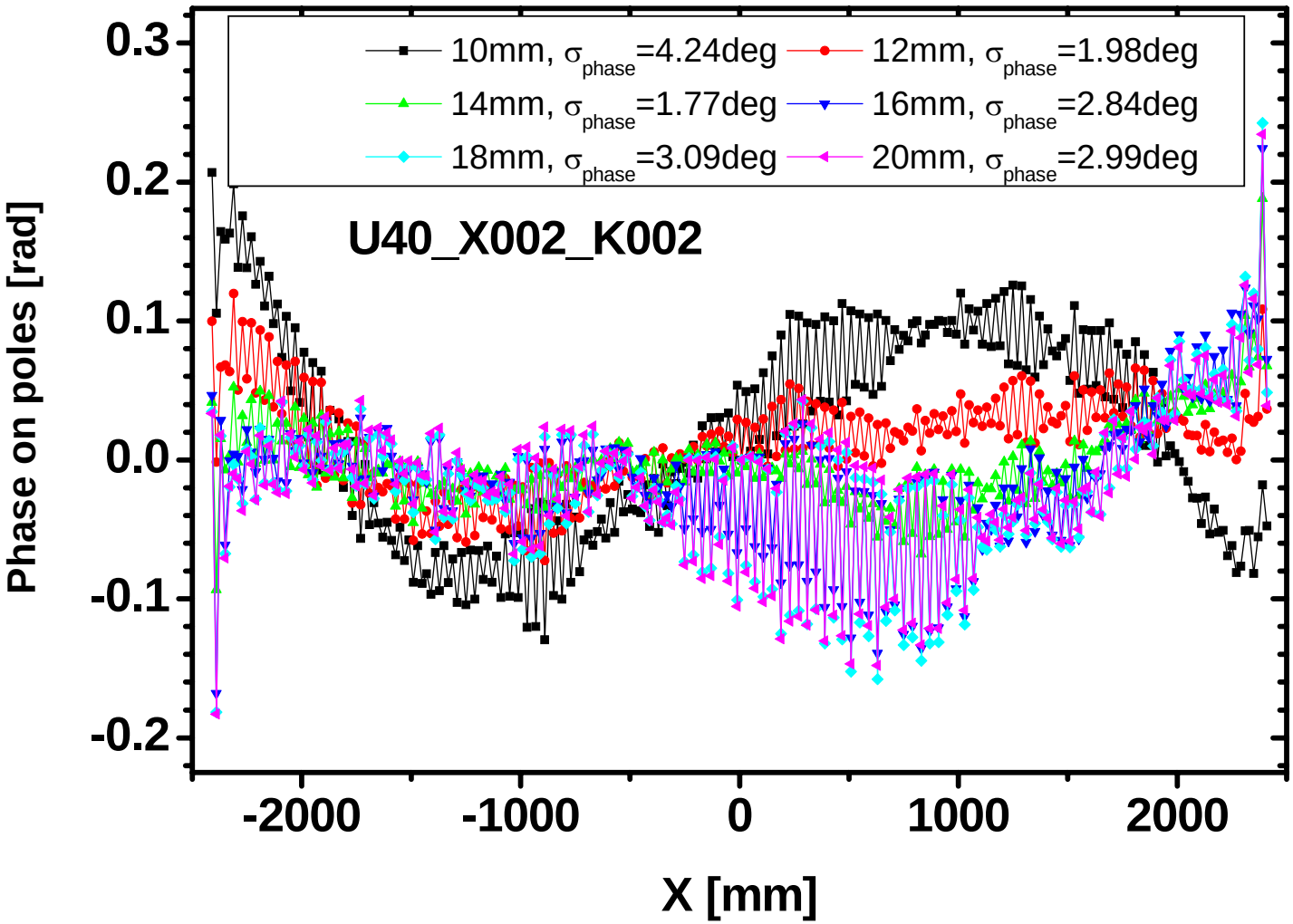
Phase Jitter / Phase Shake

Phase Shake or Phase Jitter is the RMS deviation of the optical phase on the poles with respect to proper 2π advance per period.

$$PJ = \frac{1}{N}\sum_{1}^{N}(i \cdot 2\pi - \varphi(i \cdot \lambda_0)^2$$

The Phase Jitter is a quality criterion for an undulator

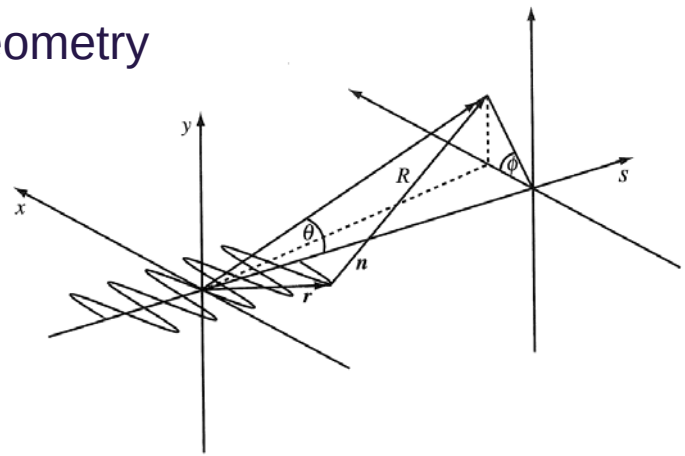
Phase Jitter for a U40 Prototype Structrure



Undulator Radiation

Undulator Brightness

Geometry



Synchrotron Radiation
1.Classical Electrodynamics
2.Single particle theory

J.D. Jackson , “Classical Electrodynamics”, chapter 12
“Clarke”, Chapter 4.3
“Onuki”, Chapter 3

$$\frac{\partial^2 W}{\partial\omega\partial\Omega} = \frac{e^2\omega^2}{16\pi^3 c\epsilon_0}\left|\int_{-\infty}^{\infty}\left(\vec{n}\times\left(\vec{n}\times\vec{\beta}\right)\right)e^{-i\omega\left(t+\frac{\vec{n}\cdot\vec{R}}{c}\right)t}\mathrm{dt}\right|^2$$

$\vec{\beta},\vec{R}$ determined by magnetic field
$\vec{R}$: Circle Dipole Magnet:
Sinus: Undulator Radiation

Calculation of Sychrotron Radiation properties:

❑Numerical: “Clarke”, chapter 5
Free software “SPECTRA” supported by Spring8: http://radiant.harima.riken.go.jp/spectra/index.html
SRW, B2E supported by ESRF: http://www.esrf.eu/Accelerators/Groups/InsertionDevices/Software

❑Analytical Methods using Bessel Functions:

- Dipole Magnets: see for example “Clarke” , section 2
- Planar undulators: Alferov, Bashmakov, Bessonov, Sov. Phys. Tech. Phys 18, 1336 (1974)
- Numerous articles: For example “Onuki” Chapter 3

Practical Formulae

On Axis Brightness

Proportional to Number of Periods squared

$$\left.\frac{\partial \dot{N}}{\partial \Omega}\right|_{\theta=0} = \frac{e^2\gamma^2 N^2}{4\pi c \epsilon_0} L\left(\frac{N\Delta\omega}{\omega_1}\right) F_n(K) \quad = 1.74\times 10^{14} N^2 E[GeV]^2 \mathrm{I[A]} F_n(K) \quad \left[\frac{Photons}{\sec\, mrad^2\ 0.1\%BW}\right]$$

$$F_n(K) = \frac{n^2K^2}{\left(1+\frac{K^2}{2}\right)^2}\left(J_{(n+1)/2}(Y) - J_{(n-1)/2}(Y)\right)^2 \qquad Y = \frac{n^2K^2}{4\left(1+\frac{K^2}{2}\right)}$$

Line Shape Function

$$L\left(\frac{N\Delta\omega}{\omega_1}\right) = \frac{\sin^2\left(\frac{N\pi\Delta\omega}{\omega_1}\right)}{N^2\sin^2\left(\frac{\pi\Delta\omega}{\omega_1}\right)}; \qquad \lim_{\Delta\omega\to 0} L\left(\frac{N\Delta\omega}{\omega_1}\right) = 1$$

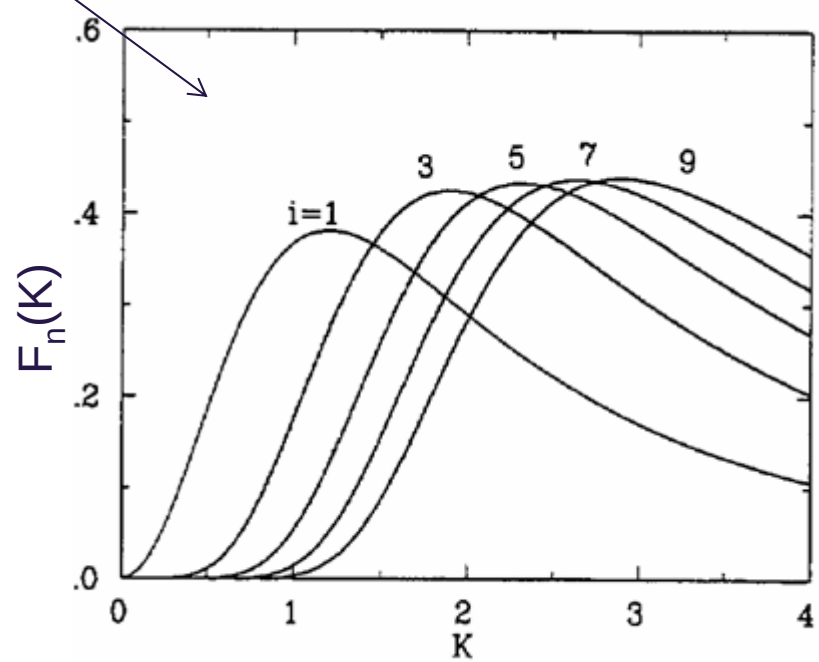
$$\Delta\omega = \omega - n\omega_1$$

$$\frac{\Delta\omega}{\omega_n} = \frac{1}{nN}$$ Spectral Bandwidth

$$\hbar\omega_n[keV] = \frac{9.5094\cdot n\cdot E[GeV]^2}{\lambda_0[mm](1+`0.5K^2+\theta^2\gamma^2)}$$

$$\sigma_{r'} = \sqrt{\frac{\lambda_{Rad}}{L}} = \frac{1}{\gamma}\sqrt{\frac{(1+0.5K^2)}{nN}}$$ Angular width

No even harmonics on axis!



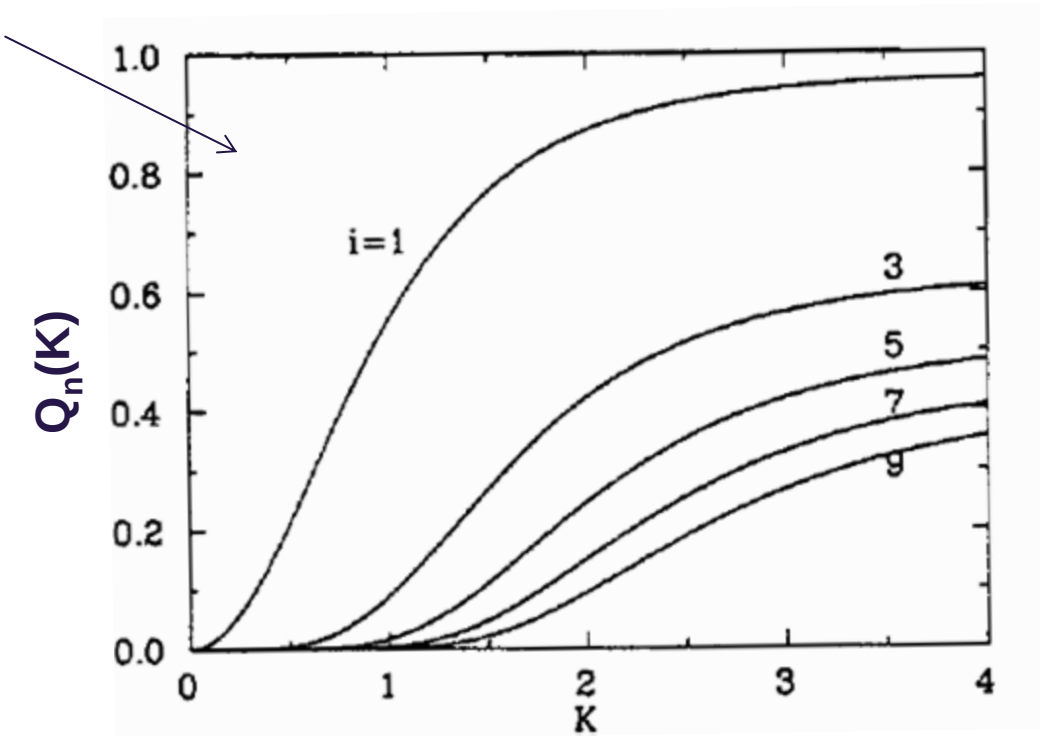
Practical Formulae continued

Flux of an Harmonic

Proportional to Number of Periods!

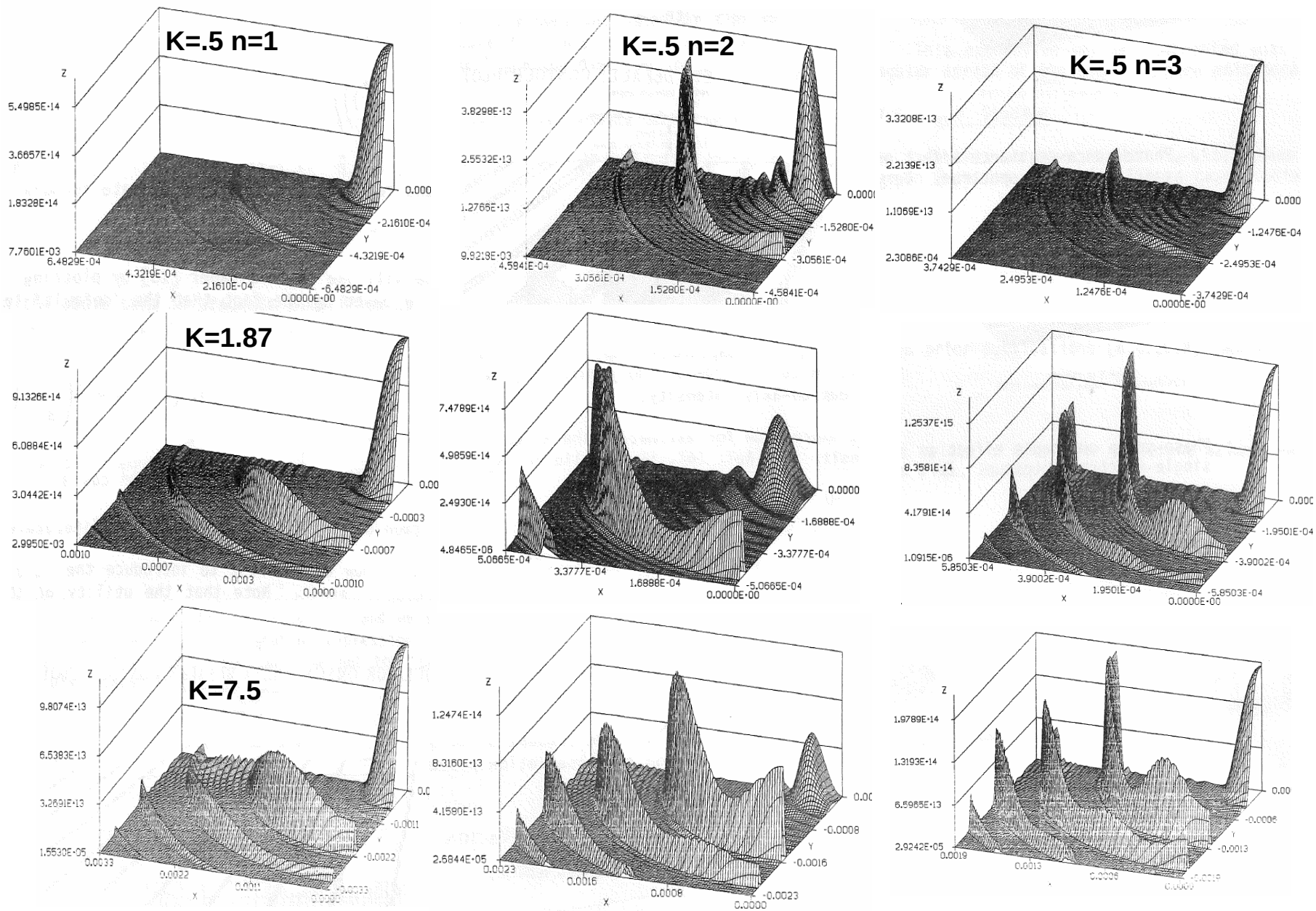
$$\dot{N} = 1.43 \times 10^{14} N I[A] \underbrace{\left(\frac{1+\frac{K^2}{2}}{2}\right) F_n(K)}_{Q_n(K)} \text{ in } \left[\frac{Photons}{\sec 0.1\%BW}\right]$$

Photon number is energy independent!



Suggested further reading:
"Clarke", "Onuki"
CERN Acceleratos schools:
CERN 2010-04, 98-04, 95-06

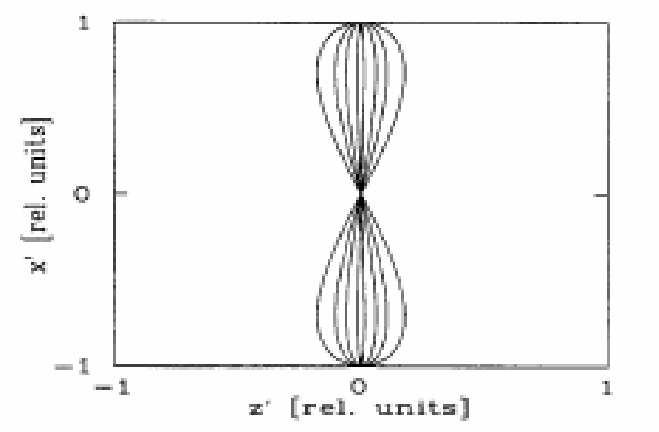
Spatial Distribution of 1st, 2nd and 3rd Harmonic

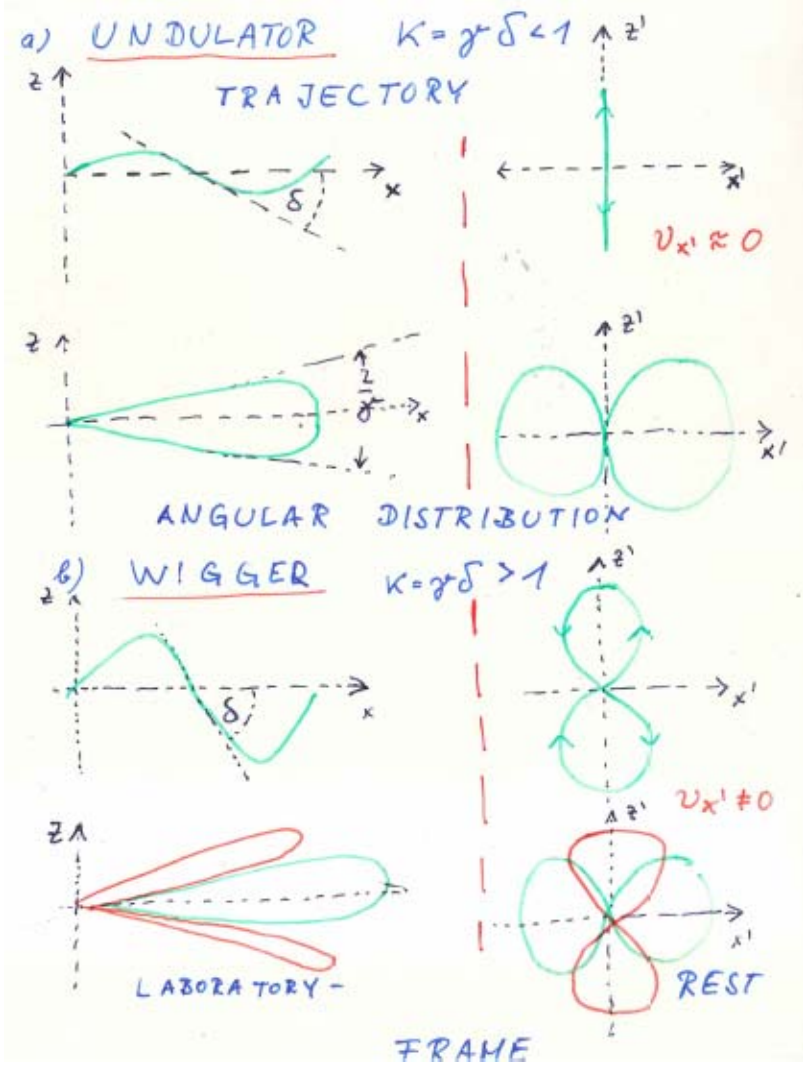


Taken from: R.Tatchyn, A.D. Cox, International Conference on Insertion Devices Oct. 27-30, 1985, Stanford, Ca, USA

Alternative qualitative explanation

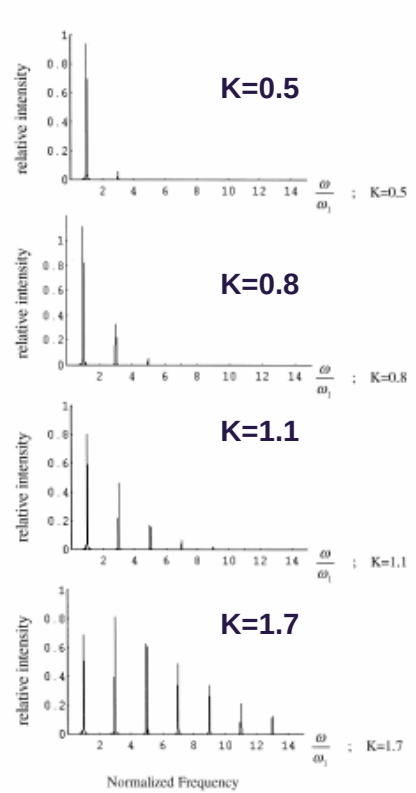
Motion in the electron rest frame moving with speed $\bar{\beta}c$ for different K

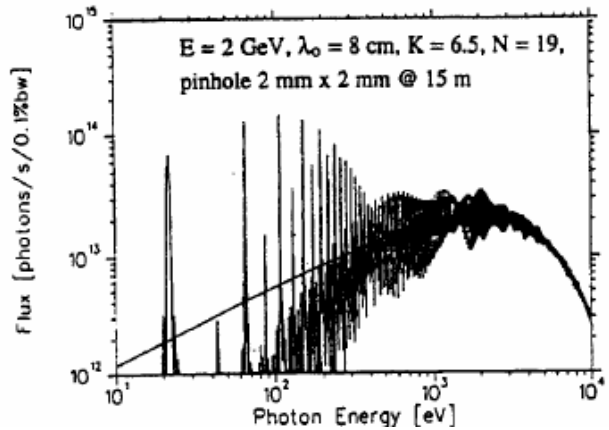


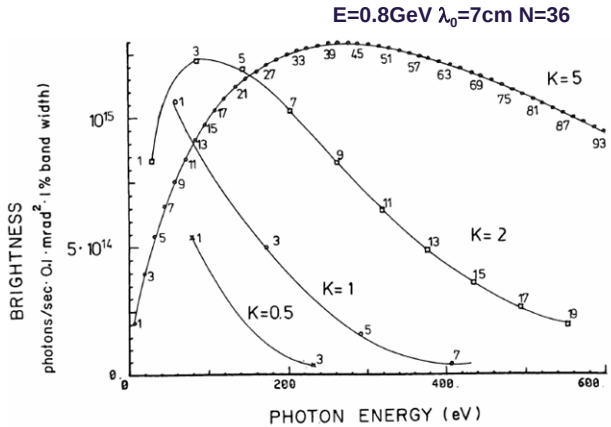


Wiggler Radiation

Wiggler Radiation







With increasing K harmonics get closer
On axis harmonic n overlaps with off axis harmonic n+1 if:

$$\gamma\theta^2 \geq \frac{1+0.5K^2}{n} \qquad \text{n large}$$

Interference effects disappear

Bend Source Approximation:
Brightness 2N times that of a dipole magnet:

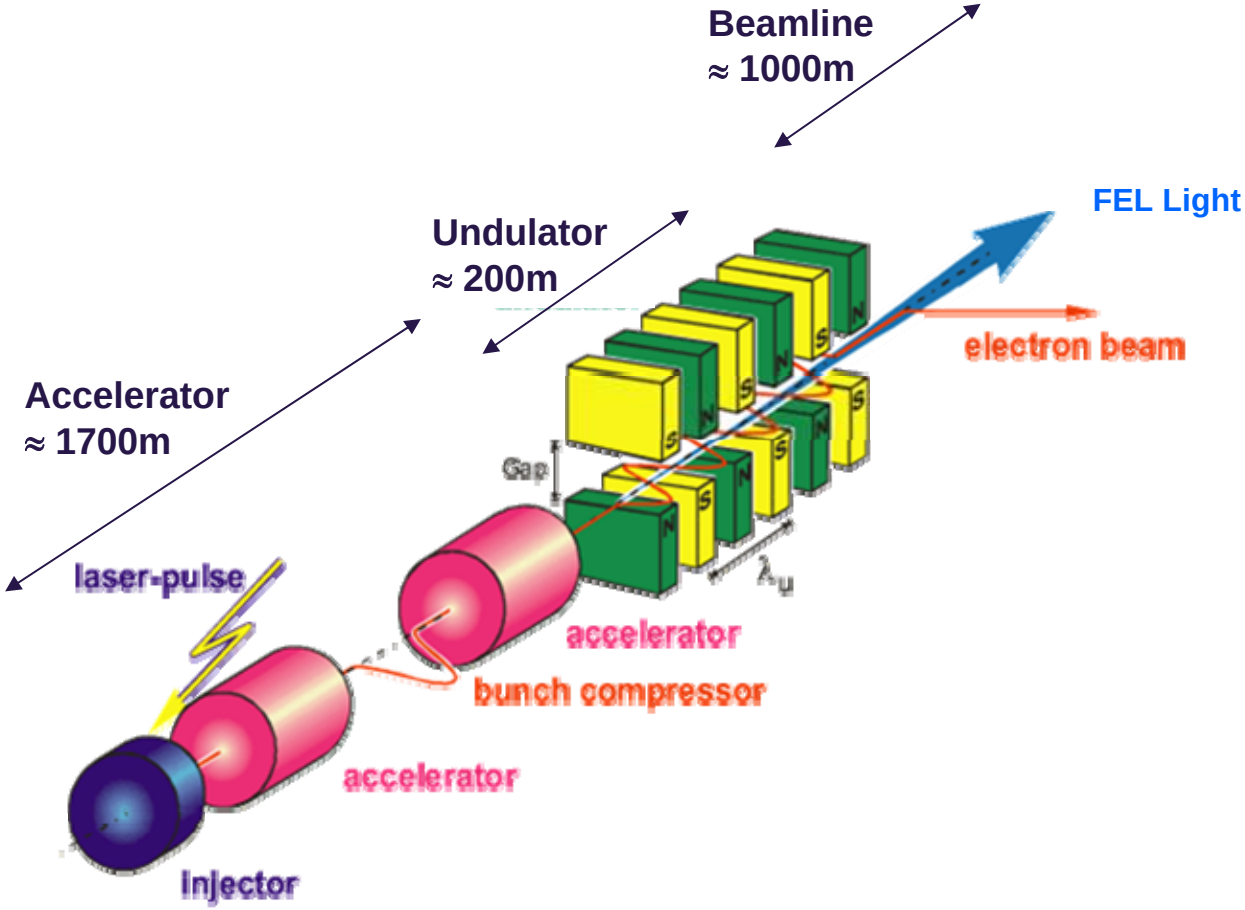
$$\left.\frac{\partial \dot{N}}{\partial \Omega}\right|_{\theta=0} = 2N \cdot E[GeV]^2 I[A] \left(\frac{E}{E_c}\right)^2 K_{\frac{2}{3}}{}^2\left(\frac{E}{E_c}\right)$$

$$E_C[keV] = 0.665 E[GeV]^2 B[T]$$

$K_{2/3}$: Modified Bessel function

FEL Radiation

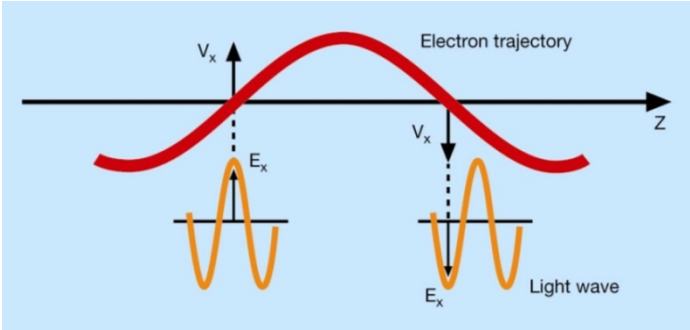
Schematic of a SASE FEL

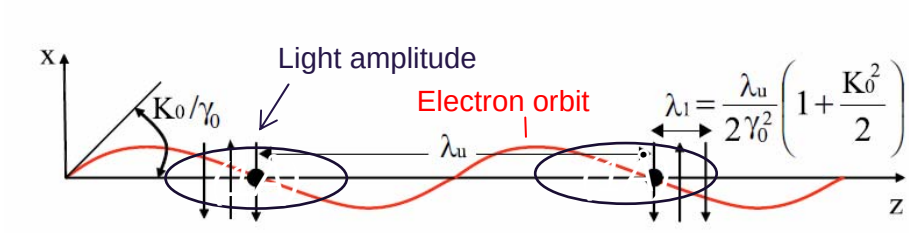


Key Elements of an Ångstroem SASE FEL

1. Accelerator
   - Ultra low emittance $\varepsilon_n < \approx 10^{-6}$m i.e. low divergence (1-2µrad), small beam size (≈20µm) and low energy spread ($\Delta E/E \leq 10^{-4}$)
   - Bunch compressors for extremely high peak currents (up to 5000A) and short bunch lengths typically < 100fs (1 -30µm)
   - An accelerator for 10-17GeV preserving emittance and low energy spread
2. Undulator System
   - Very long (≈200m for 0.5Å)
   - "perfect" fields leading to
     - Straight trajectory
     - Low phase error
3. Suitable X-Ray Optics
   - Transport the light to the experimental stations
   - Must withstand extreme power densities
   - Extreme requirements to preserve coherence properties

SASE FEL Principle





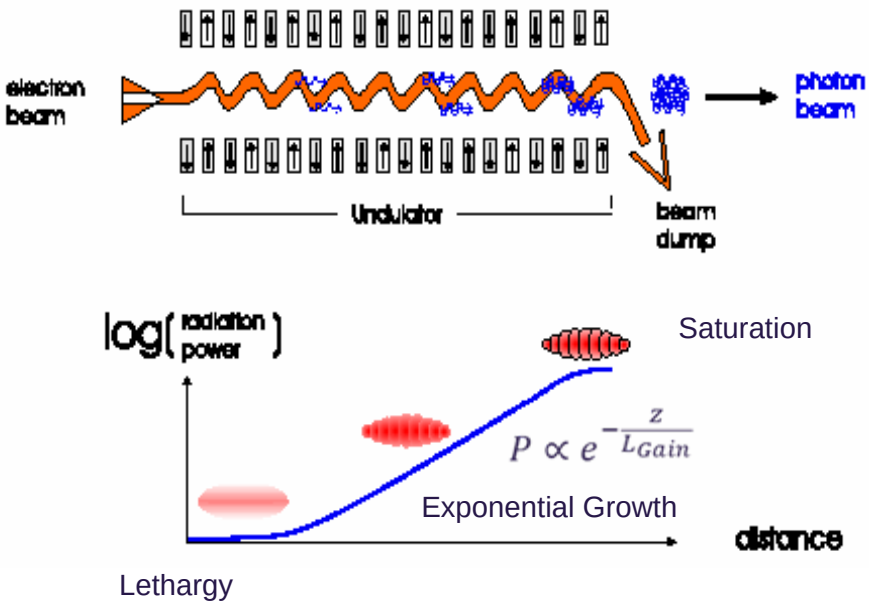
From: Z. Huang und K. Kim, Phys. Rev. ST Acc.B. 10, 034801 (2007)

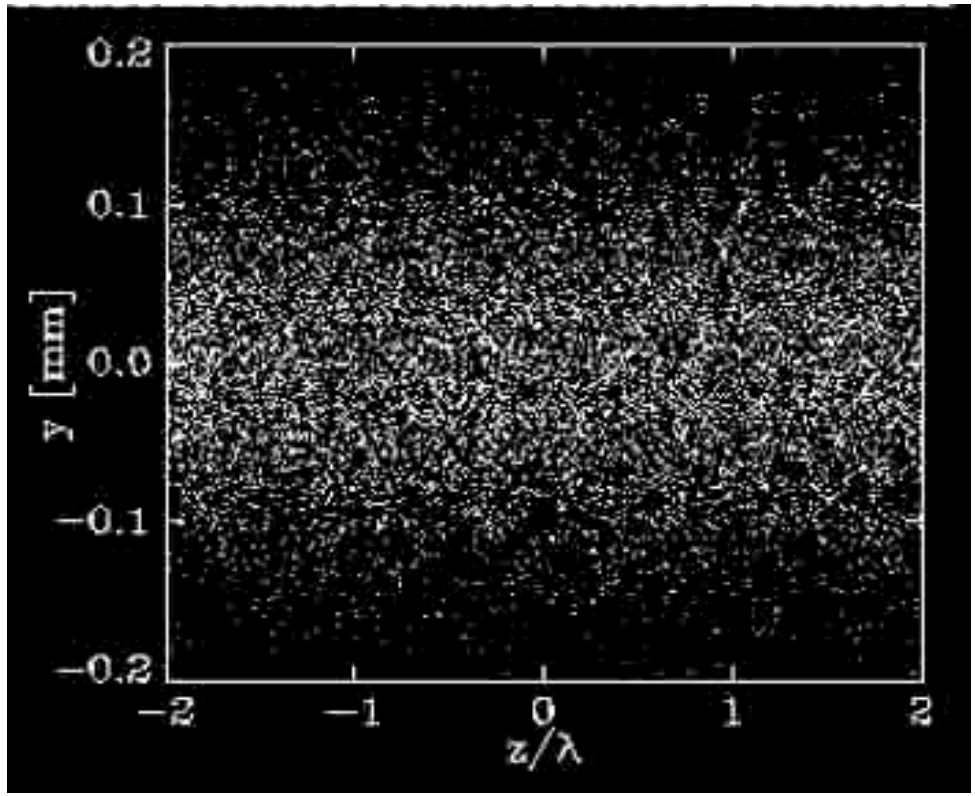
- The FEL effect is a collective effect of many electrons in a bunch
- The undulator provides transverse velocity component to electrons→coupling to the transversal Laser field
- Slippage: In XFEL undulator light slips one λ_{Rad} (1Å) per λ_0 (40mm)
- Energy transfer ΔW between electron and Laser Field over long distances
- Sign depends on relative position in the bunch:

$$\Delta W = -e\int \vec{v}\cdot\vec{E}dt$$

- Some electrons gain some loose energy → bunching
- Bunching leads to increased radiation → exponential growth
- If all electrons are bunched saturation occurs

Evolution of Microbunching





Courtesy: Sven Reiche, PSI

Typical European XFEL Parameters

ε_n:	$\leq 1\mu m$
I_p:	3000A
$\Delta E/E$:	10^{-4}
E:	10-17.5 GeV
λ_{Rad}:	<1……50Å

For 1Å

l_{Gain} :	$\approx 10m$
L_{sat} :	$\approx 112m$ (10 to12 l_{Gain})
ρ :	3×10^{-4}
P_{rad} :	11 GW ($\rho \times P_{beam}$)

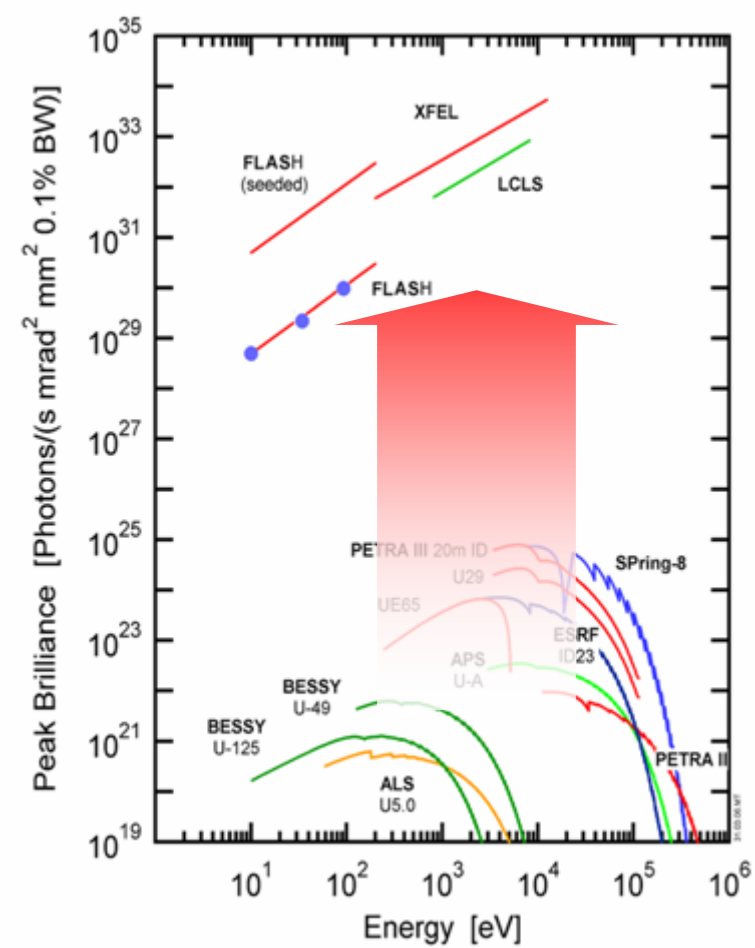
Photons/Puls: 1.3×10^{11}

Pulse Duration: $\approx$ 90 fs

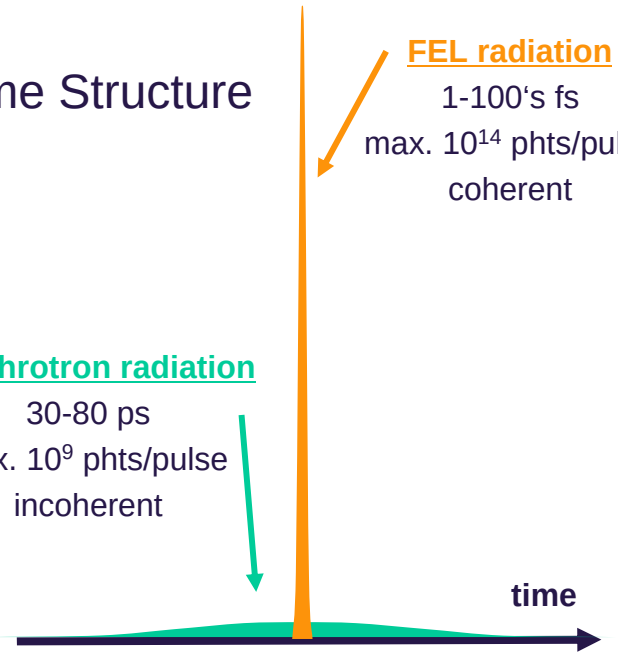
FEL radiation properties

Peak brilliance

Photons per phase space volume and bandwidth element



Time Structure



- 1,000,000,000 higher peak brilliance
- 1,000 shorter light flashes (ps → fs!)
- High transverse coherence

- A revolutionary tool for the research with (X-ray) photons

Courtesy A. Schwarz

Undulator Technology

Overview:

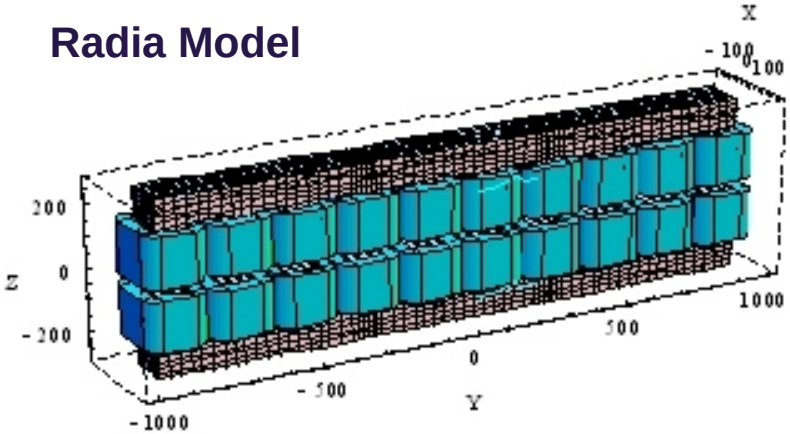
- Electro Magnetic (EM) Undulators
- Superconducting (SC) Wigglers / Undulators
- Permanent Magnet (PM) Undulators

Electro Magnetic Undulators

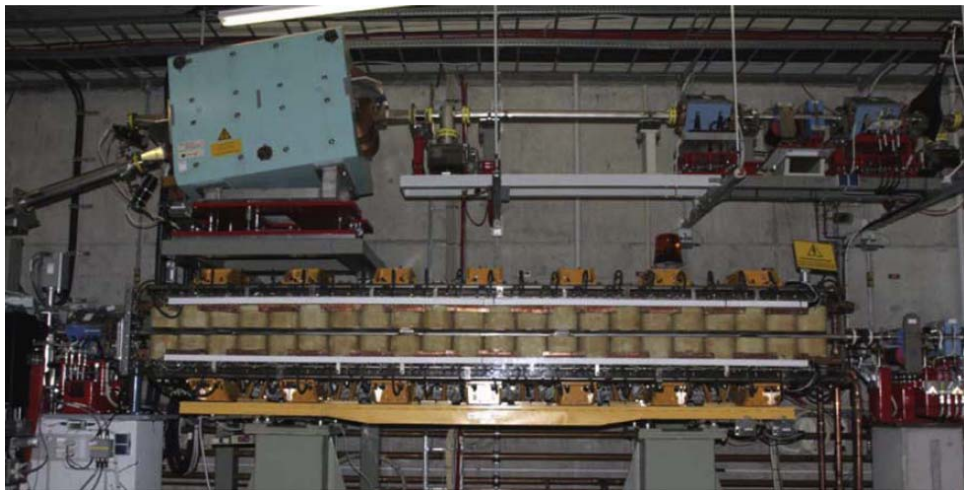
- Only for large period lengths $\lambda_0 \geq\approx 150$mm → "Wigglers"
- Ineffective for small λ_0
- Conventional technology
- High power demand and costs (Order of 100k€/a)
- AC excitation possible with laminated cores
- Variations:
  - Crossed / Helical undulators (fast switching if AC)
  - Eliptical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

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	$8.5 \times 8.5\,mm^2$, $\varnothing$ 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

Superconducting Insertion Devices

Two Regimes:

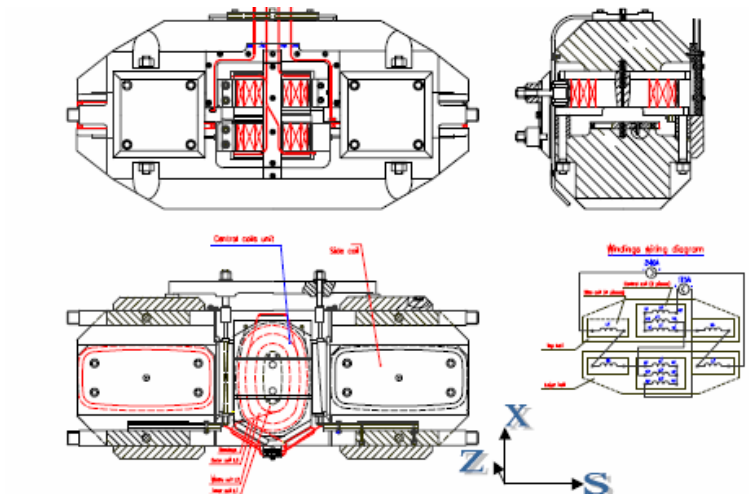
1. Long Periods
   - Few poles, fields 6 Tesla and above
   - Wavelength shifters, hard radiation with low energy electrons
   - Used in many SR sources

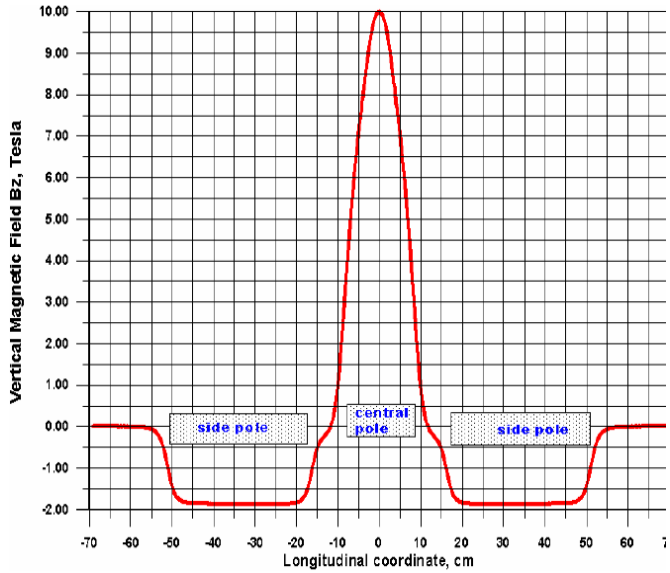
2. (Very) short periods many poles
   - Allows (theoretically) for highest fields at $\lambda_0 \geq\approx 10$mm
   - Technological challenging, ongoing development since the 1970ies.
   - Only few devices were built (ANKA/KIT, APS, LBL)
   - Requires cryogenics at 4.2K or below
   - Unsolved: Field measurement, field error tuning
   - Only for very special applications not for large scale use

Example for a SC wavelength shifter

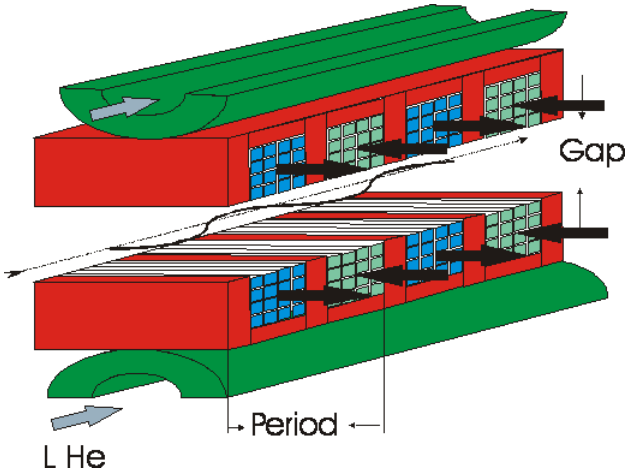
Spring8 Wavelength shifter

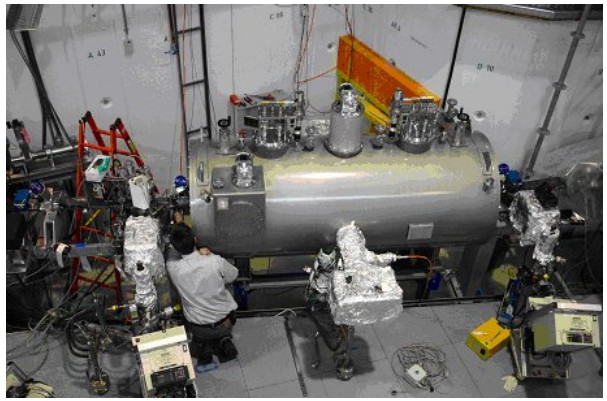
# of poles:	3
Max field in central pole:	10.3 Tesla
Cold mass:	~1000kg
Pole Gap:	42 mm
Chamber size:	100x 20 mm^2





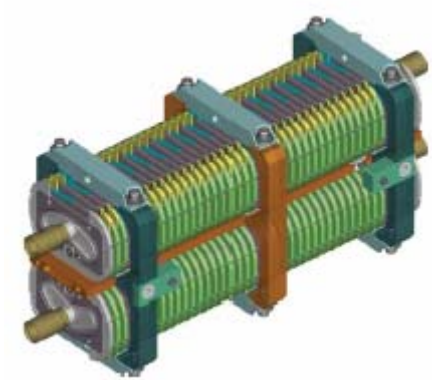
N.Mezentsev, Budker Institute Novosibirsk, Russia

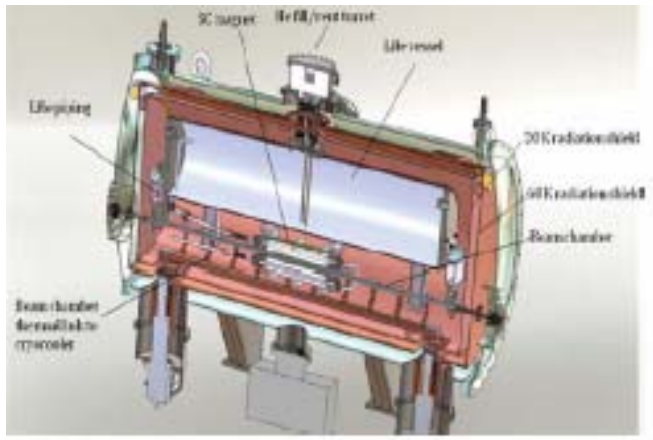




SCU @ ANKA Karlsruhe in Operation

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





SCU0 (SCU) @ APS Argonne

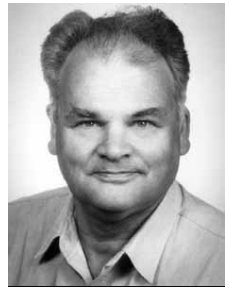
λ_0:	16mm
N:	20 (70)
L:	330 (1140)mm
Gap:	9.5mm magnetic
B_{Peak}:	0.65T @ 500A
K:	0.97

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 cryo coolers
- Limited magnetic measurement accuracy
- No practical error compensation schemes available
- Not yet mature for making high quality undulators

Permanent Magnet Undulators

Permanent Magnet Undulators

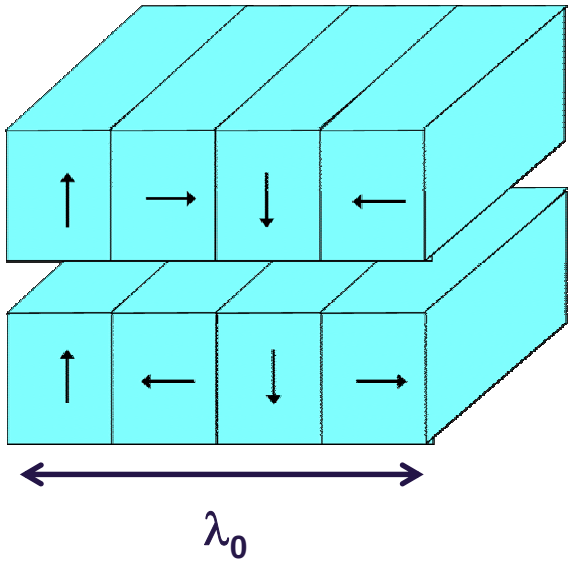


Klaus Halbach
1924-2000

- 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 → see below
- 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

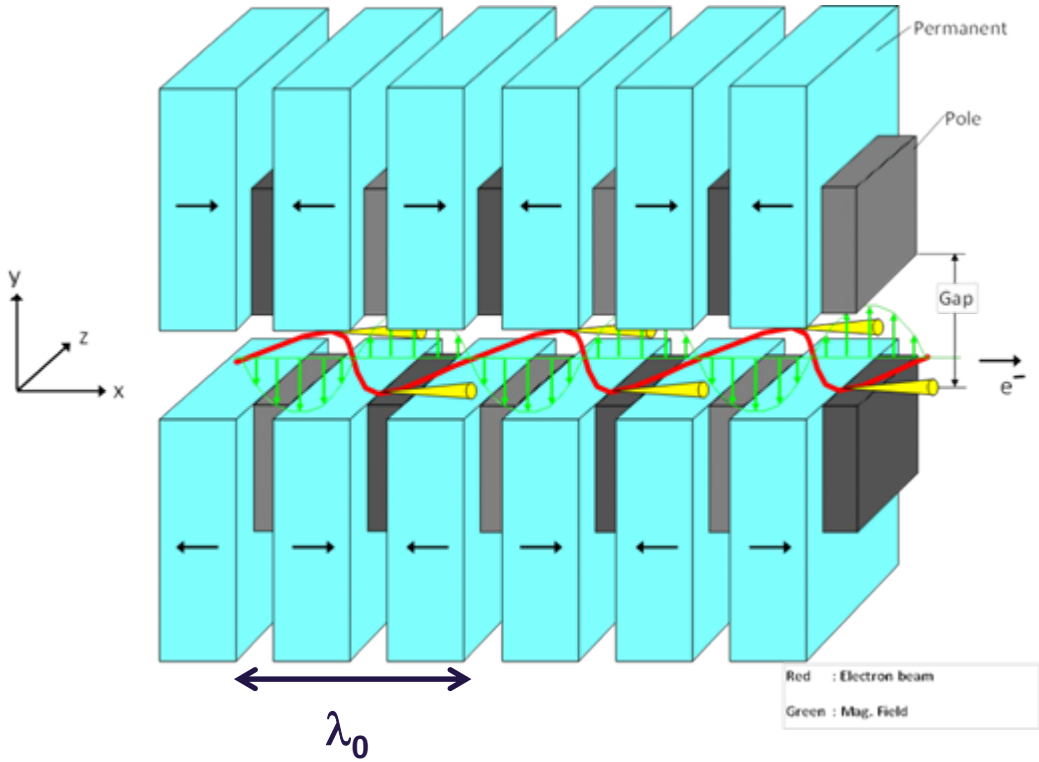
Planar Permanent Magnet Structures

PPM



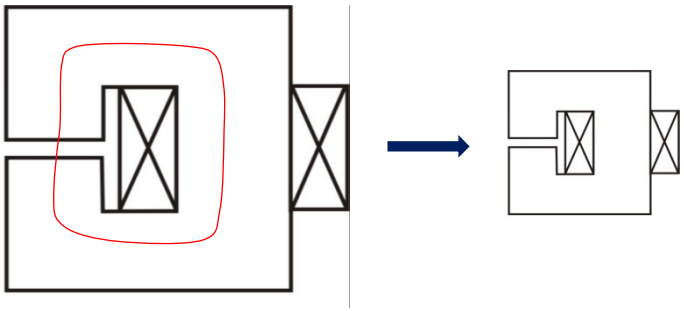
K. Halbach, NIM 187, (1981) 109

Hybrid



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

Scaling Properties of EM and PM Systems



1 : a

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

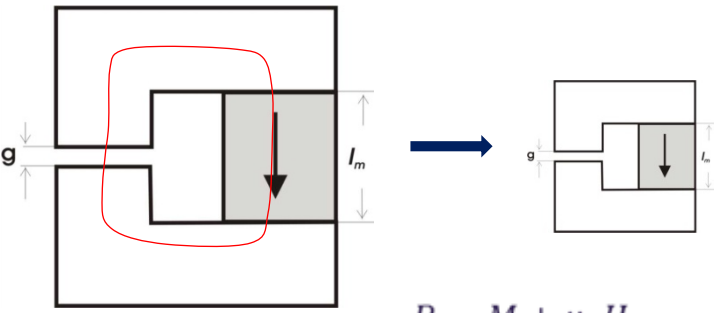
$$B_{Gap} = \frac{j_{Area} A}{Gap} \mu_0$$

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

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

for a <1 j_{Area} gets higher

Type	j_{Area}[A/mm²]
Normal Cu	< ~ 10
SC	1500-2000



$$B = M + \mu_0 H$$

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

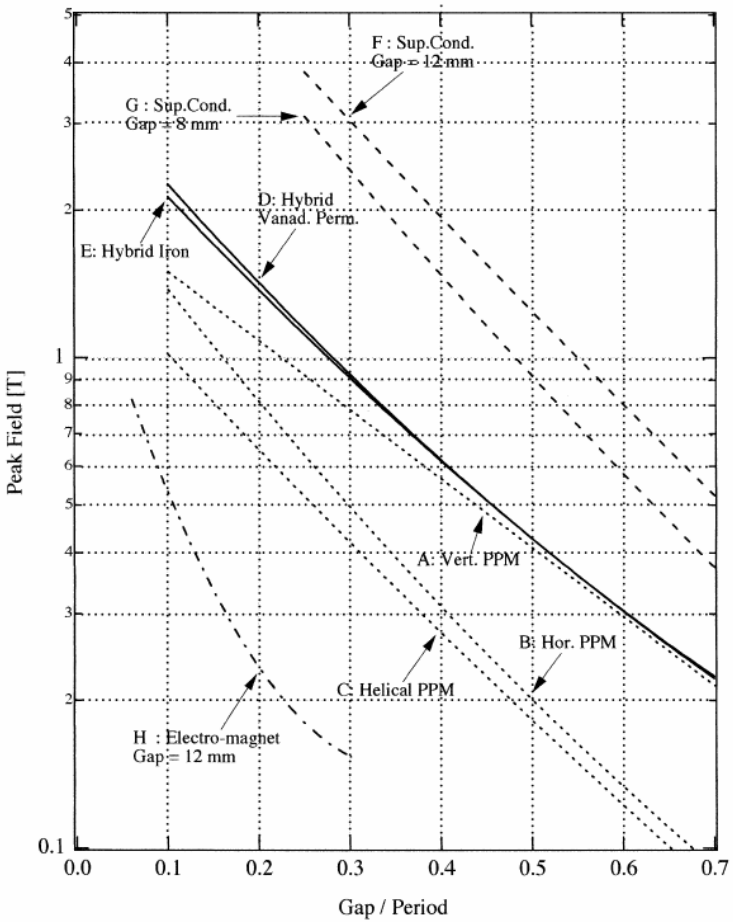
$$B_{Gap} = \frac{M l_m}{Gap + l_m}$$

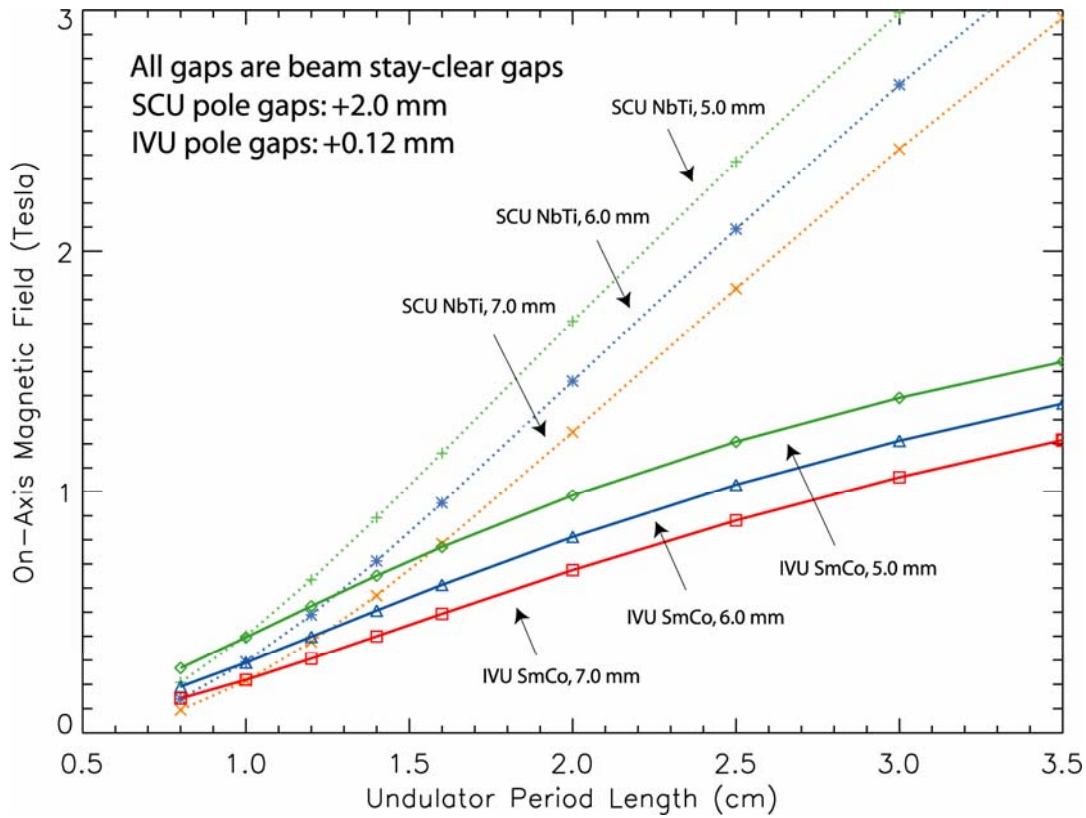
$$B_{Gap} = B'_{Gap}$$

M =B_r ≈1.. 1.35 T

Message:
EM systems j_{Area} scales inversely with dimensions
PM systems are invariant

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

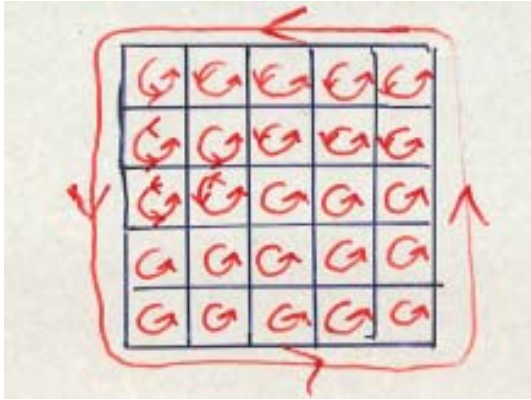
Permanent Magnet Design

Field Calculation for ironless structures

Current sheet Method:

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

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



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

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

Analytic solutions for fields and field integrals for a number of geometries exist: Parallelepipeds, cylinders…
Example PPM Undulator: Superposition of fields of individual parallelepipeds

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://laacg1.lanl.gov/laacg/services/
  - Professional 3D Codes TOSCA, OPERA, ANSYS, MAFIA….
    Commercial, not free, expensive!

- Integral Method(s)
  RADIA: 3-D, meshes out only magnetic relevant parts: Coils, Magnets, Iron NOT free space, directly calculates Field Integrals
  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

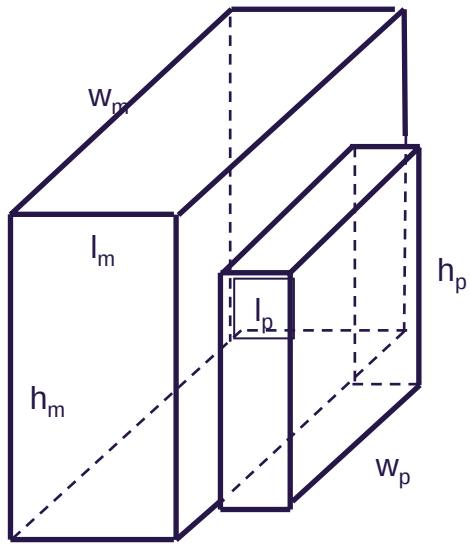
Magnet Design Steps

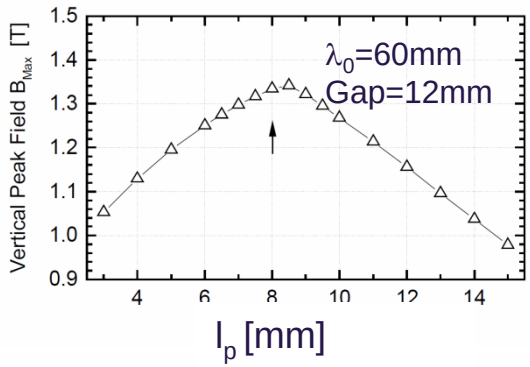
Design Criteria:

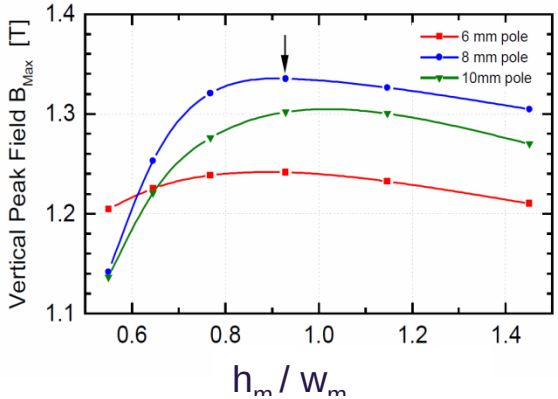
- Gap, Period Length λ_0, Peak Field B_0, K-Parameter
- "Good" Field range → width of poles & magnets
- Termination, end sections
- 1st and 2nd Field Integrals
- "Good" range of field integrals (dynamic aperture for injection)
- Gap dependence of field integrals
- Worst case temperature
- Properties of Permanent Magnet Material

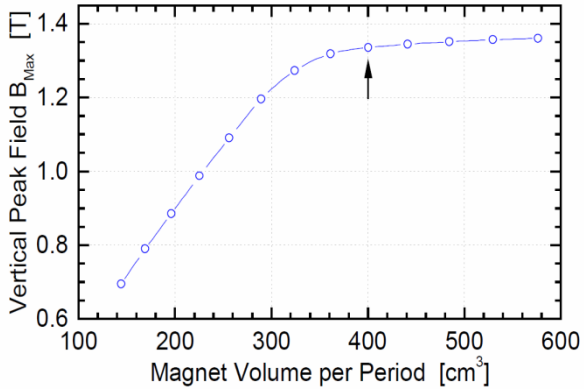
Example: Magnet Design

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









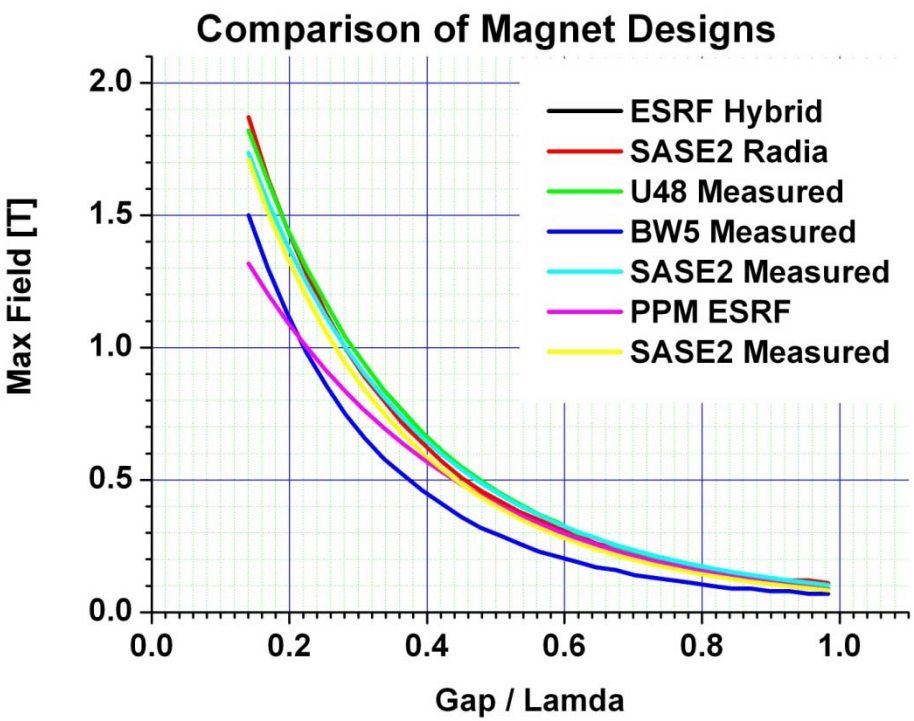
http://flash.desy.de/reports_publications/tesla_fel_reports/tesla_fel_2000/

Practical Design Formulae

Model for Peak Field:

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

Description	a	b	c
Hybrid FeCo Poles *	3.694	-5.068	1.52
XFEL SASE2 measured **	3.10487	-4.24914	0.80266
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
***Large period λ=230mm, Magnet weight: 15kG

$$K = 0.0993\lambda_0[mm]B(g,\lambda_0)$$

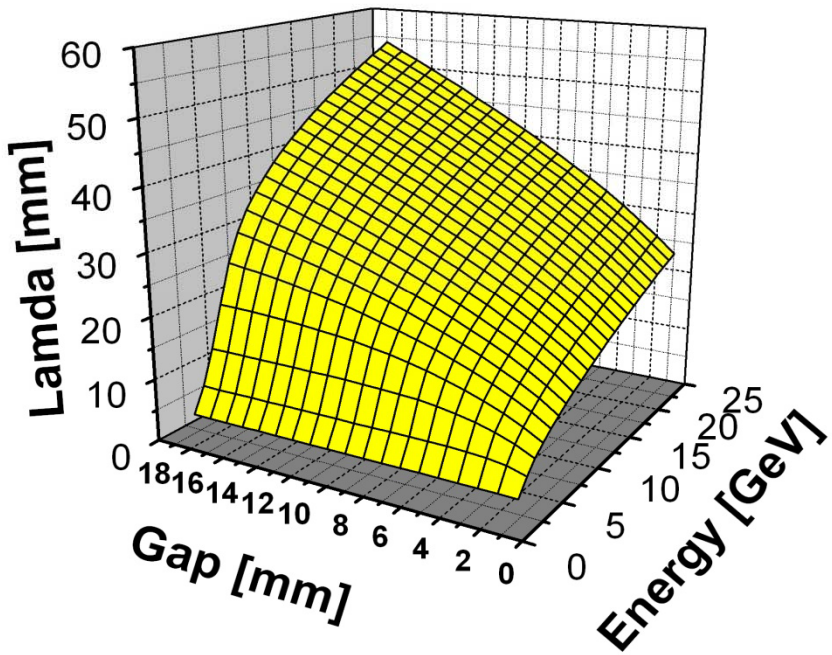
$$\lambda_{Rad}[nm] = \frac{\lambda_0[mm]}{2\gamma^2}10^6(1+0.5K(g,\lambda_0)^2)$$

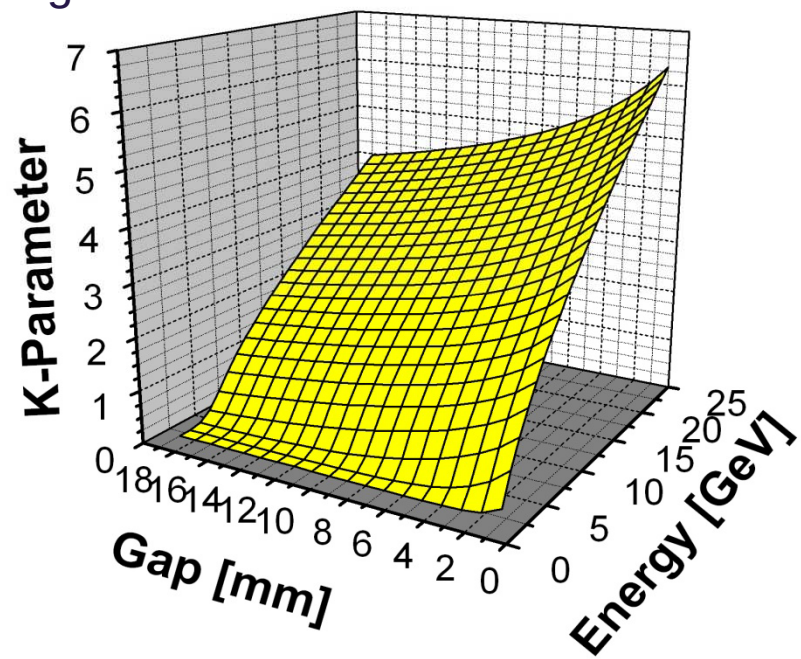
→ *Solve implicitly*

$$\lambda_{Rad}[nm] = \frac{\lambda_0[mm]}{2\gamma^2} 10^6 (1+0.5K(g,\lambda_0)^2) \qquad K = 0.0993\lambda_0[mm]B(g,\lambda_0)$$

→ *Solve implicitly*

λ_{Rad}= 1Å
U40 Design

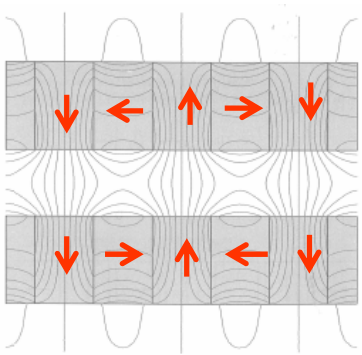


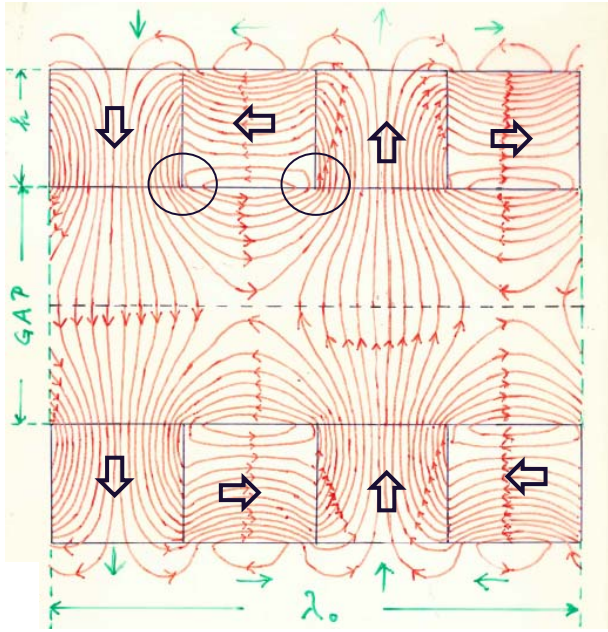


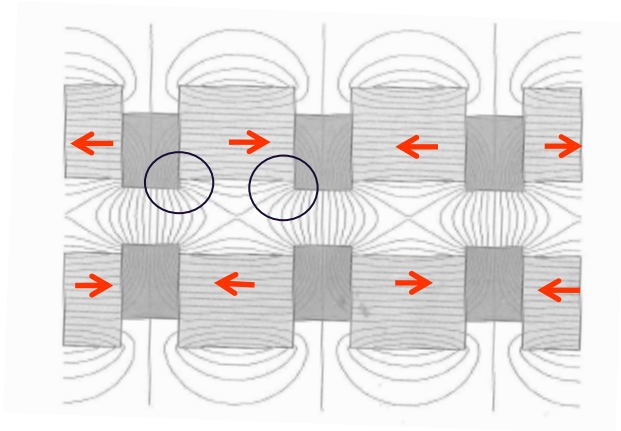
Demagnetization / Selection of PM Material

PPM

Hybrid







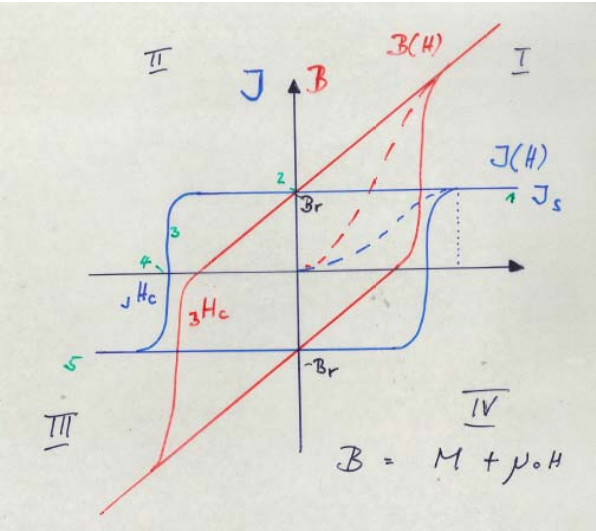
$$B = M + \mu_0 H$$

$-\mu_0 H$ in magnet > M!

Demagnetization:
Dangerous areas beneath poles:
Highest at large gap lowest at closed gap

Magnetic Material Properties

Typical Properties of NdFeB and Sm_2Co_{17} used for Insertion Devices

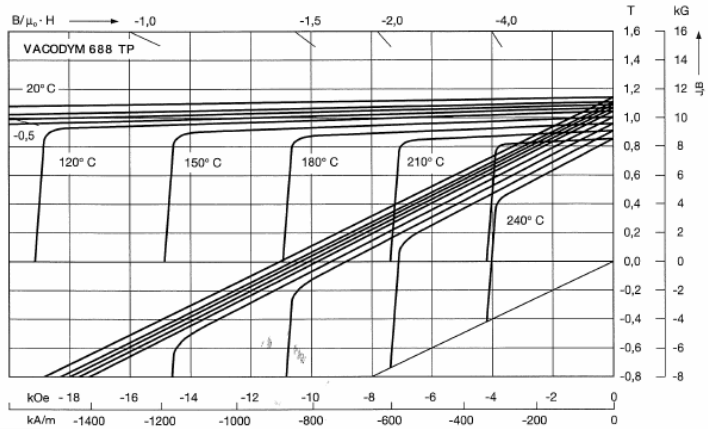


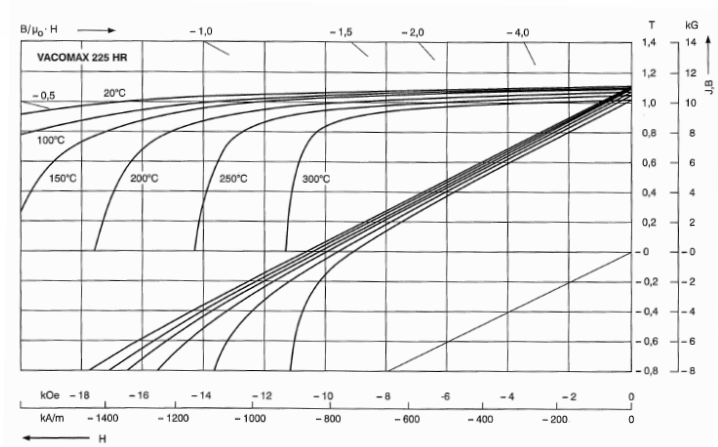
$$B = M + \mu_0 H$$

	Ideal	Real
$\frac{\Delta J}{\mu_0 \Delta H}$	0	0…08
$\frac{\Delta B}{\mu_0 \Delta H}$	1	1 …1.08

Temperature Dependence of B_R and $H_{C,J}$ for NdFeB and Sm_2Co_{17}

	NdFeB	Sm_2Co_{17}
B_r 20° C [T]	1.20	1.05
$H_{C,J}$ 20° C [kA/m]	2000	1590
TK(B_R) [%/° C]	-.1	-.03
TK(H_{cJ}) [%/° C]	-.7	-.2





1T ÷ 795.8 kA/m

Selection of Material

- Determine max $H_{c,J}$ → RADIA or any other software
- Determine worst case temperature= temperature where no irreversible damage occurs >> Operational temperature
- $H_{c,J}$, B_r are competitors: High B_r implies reduction in $H_{c,J}$ and vice versa. Materials with highest B_r are not useful since $H_{c,J}$ too low.
- $H_{c,J}$ and B_r are temperature dependent η_{Br} =-.001/° ; η_{HC}=-.007/°
- At 60° C $H_{C,J}$ is reduced by 30% or more!
- No compromise on $H_{c,J}$!
- Must be taken into account

Example EXFEL Undulators

H_{max}=-1190kA/m

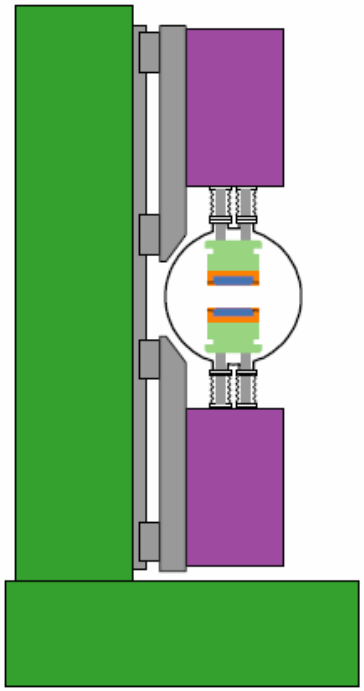
T_{max}= 60° C →28% reduction

$B_r \geq 1.26T$; $H_{CJ} \geq 1670A/m$ at 20° C. Test 1670(1- 0.28)=1200kA/m ok.

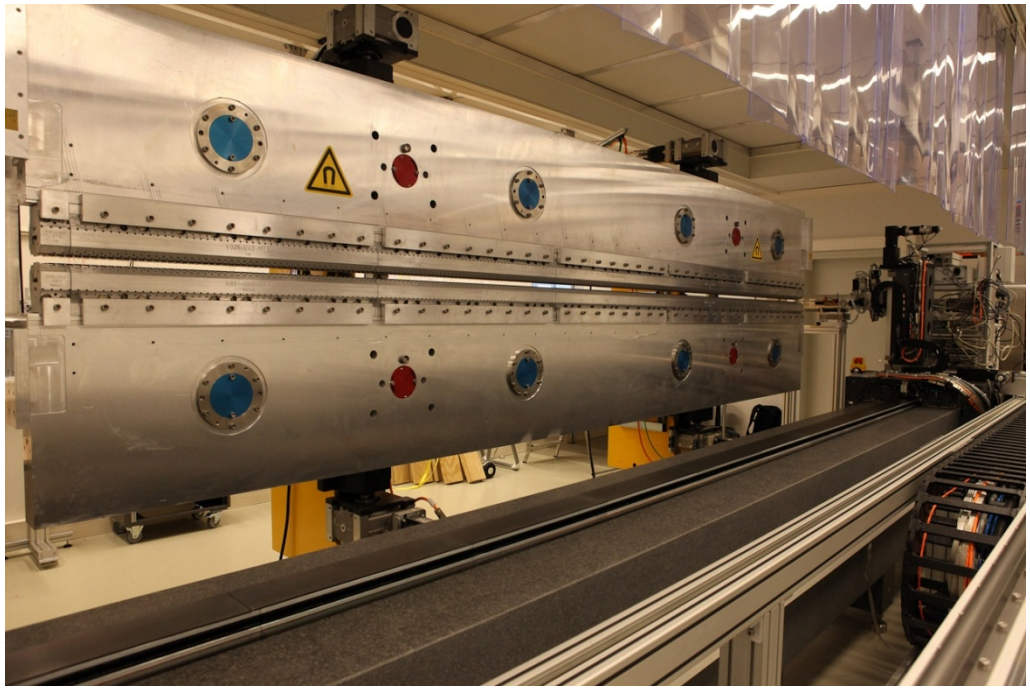
Mechanic Design: Principles and Types

C Frame

Pro: Best access for magnetic measurements
Con: Unsymmetric, more effort for mechanical stability and rigidity



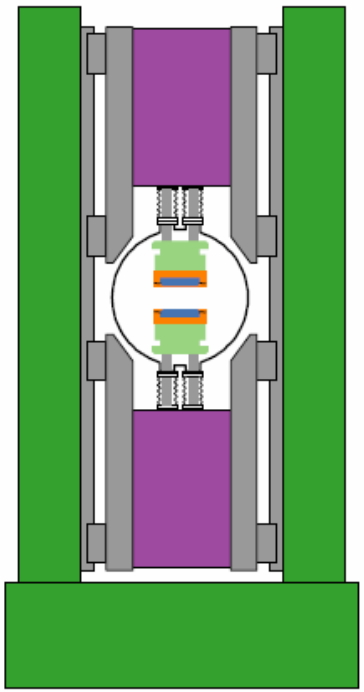
C-shape



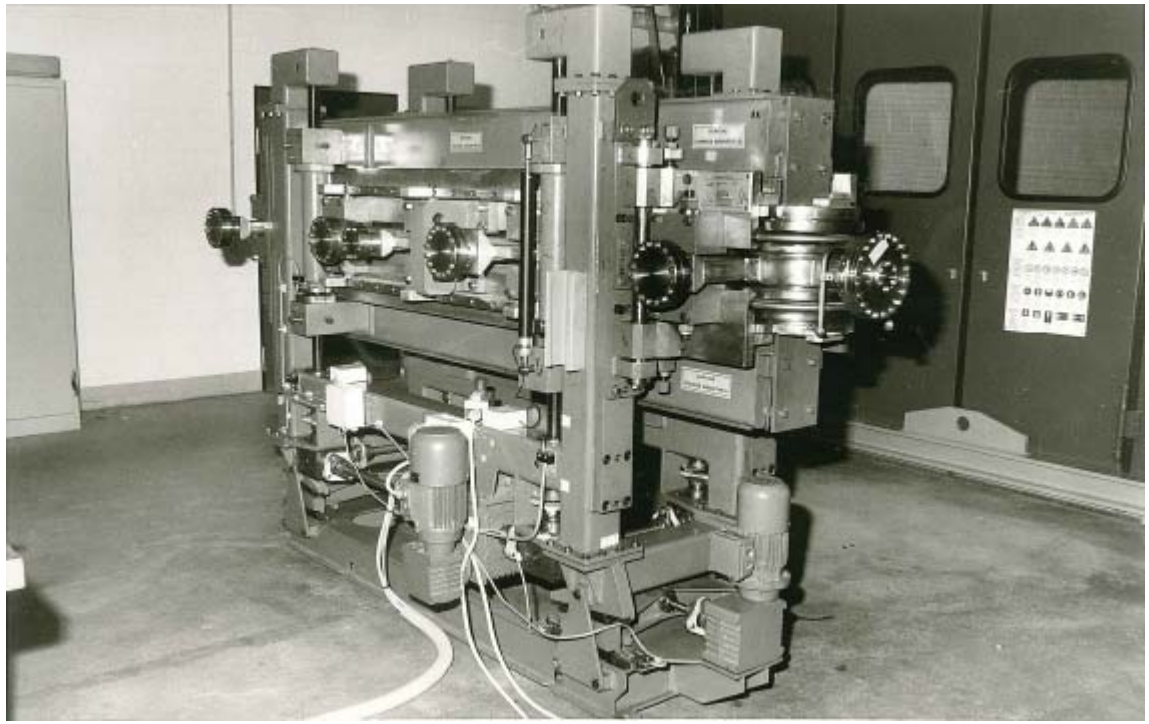
EXFEL 5m U40 on the 6.5m magnetic bench

H-Frame

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



H-Frame



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

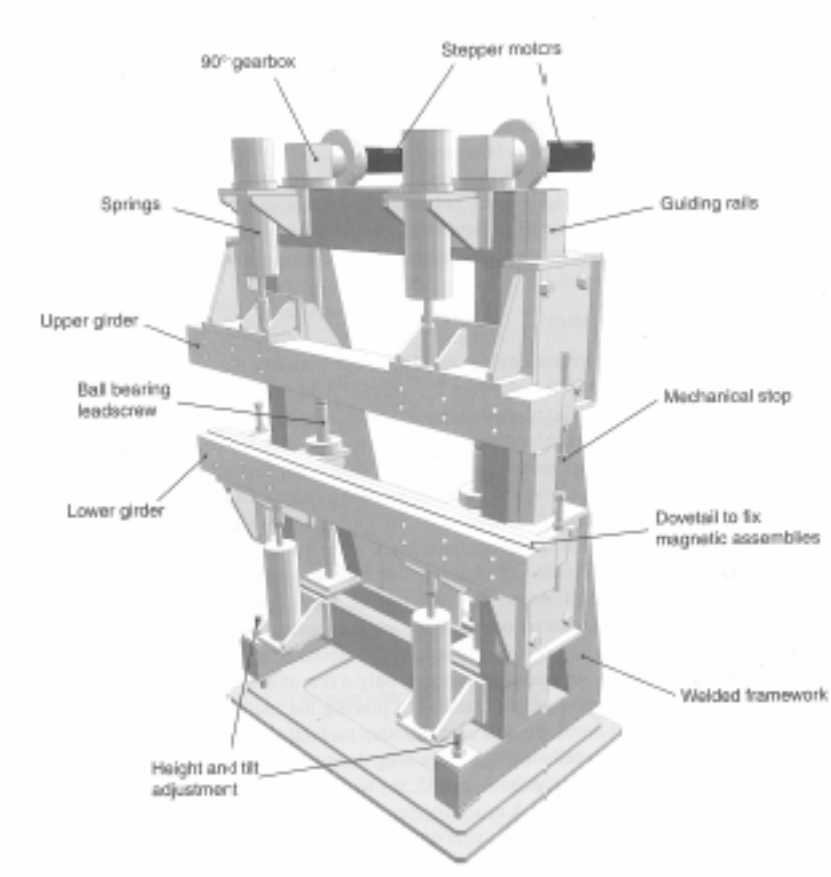
DESY / EXFEL: C-Type with guide rails

4 Motors, 4 spindles

Petra III 2m U29

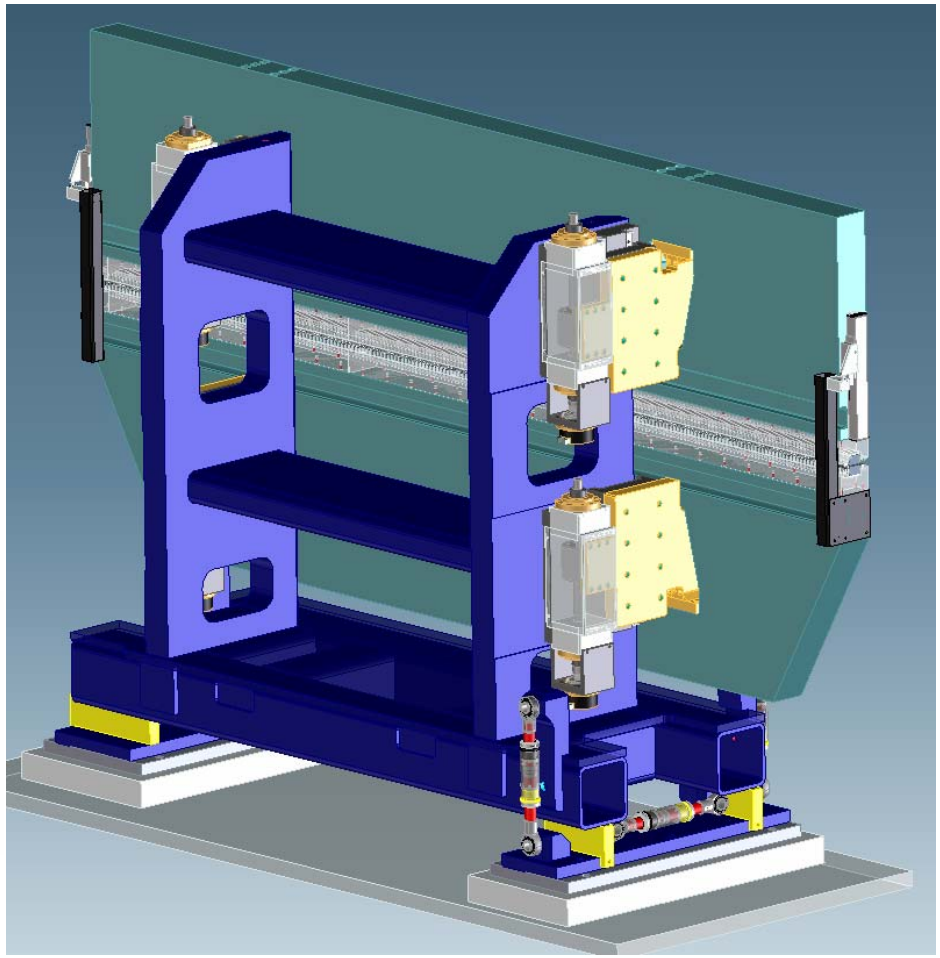
EXFEL 5m U40

More C-Frames:



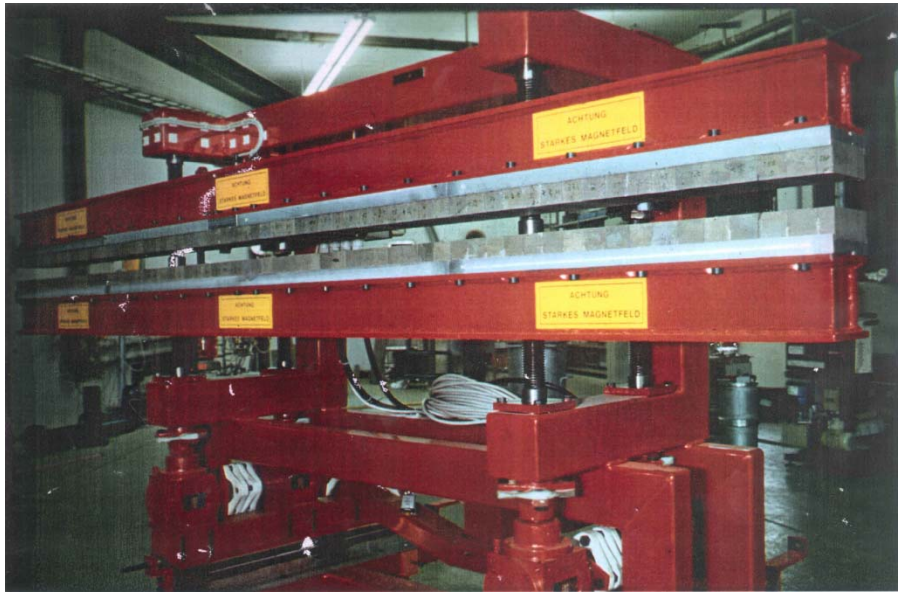
ESRF Standard Carriage;
2Motors & right left spindles

From 'Onuki'

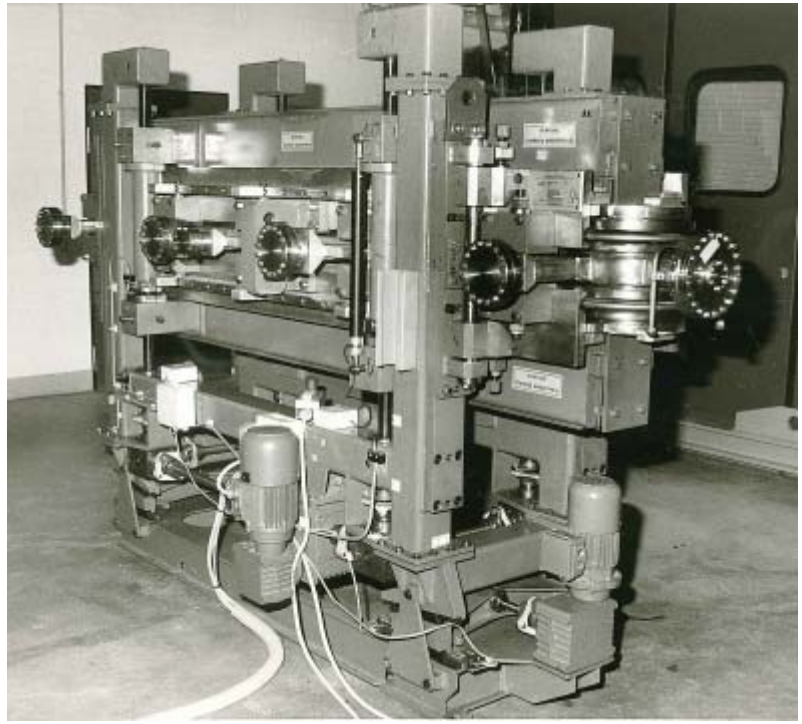


LCLS II Plans: 4 Motors & spindles

Speciality: No guide rails only spindles



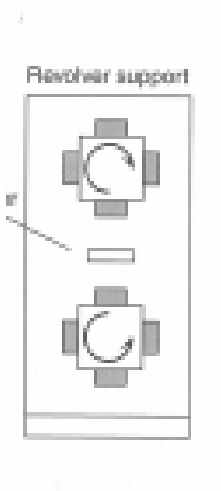
C-Frame Hasylab W1 Wiggler 1984.
Spindle guided.
Still in use since 28 Years!

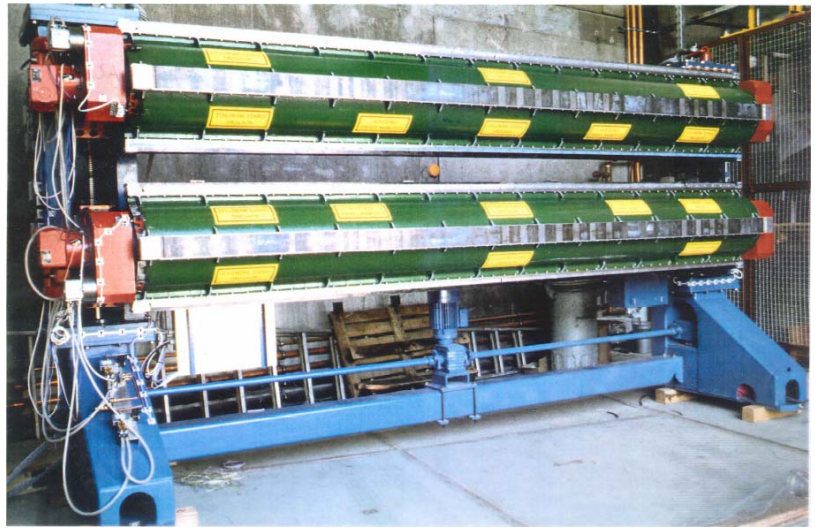


H-Frame: HASYLAB Hard X-ray Wiggler for Coronary Angiography 1987-2004.

C- Frame Revolver Undulator

Spring8 Revolver





DORIS III Revolver: In Operation since 1991: Three Magnet Structures one empty. Still in use!

Undulator minimum Gap

Determined by:

- Beam size, β-Function
- Lifetime in Storage Rings
- Dynamical aperture for injection
- Wake Fields in Linacs/FELs
- Operational safety philosophy
- Radiation Damage in PM Material

} machine dependent

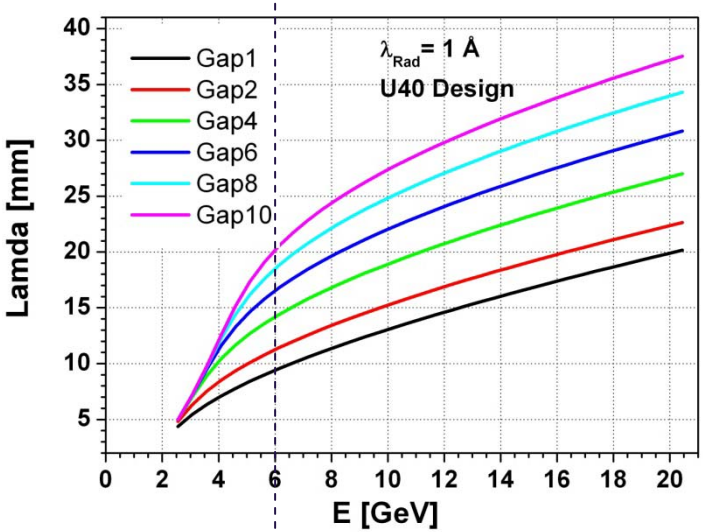
$$\lambda_{Rad}(g,\lambda_0,\gamma) = \frac{\lambda_0[mm]}{2\gamma^2} 10^6 (1+0.5K(g,\lambda_0)^2)$$

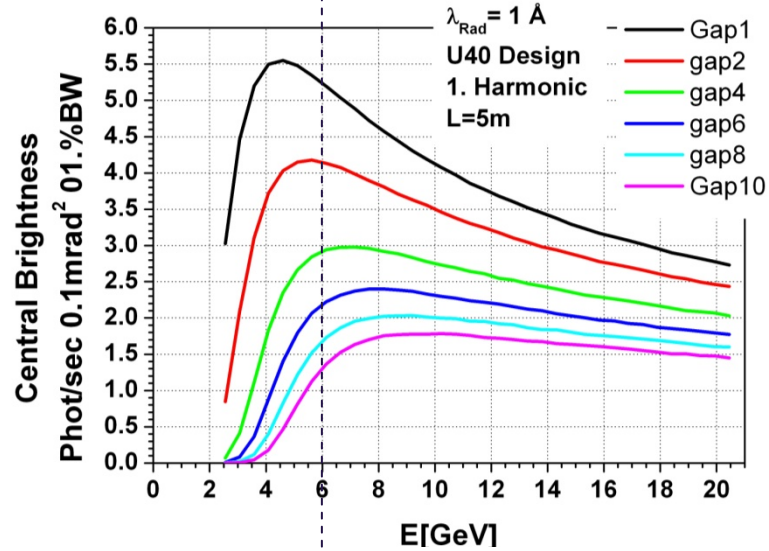
$$K(g,\lambda_0) = 0.0993\lambda_0[mm]B(g,\lambda_0)$$

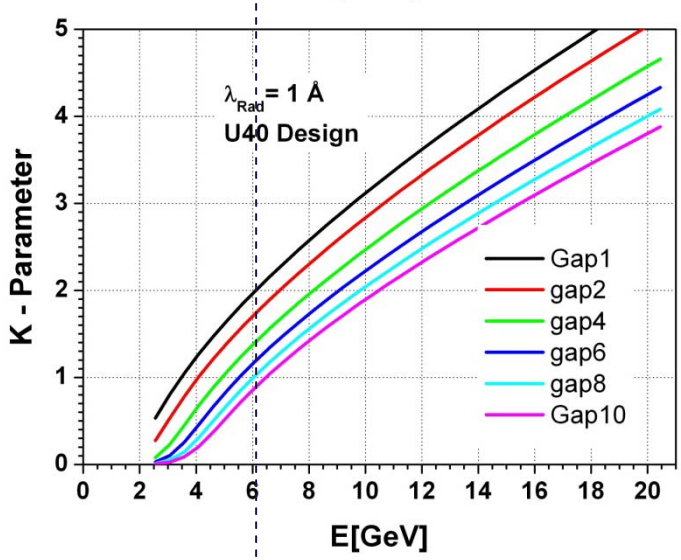
$$B(g,\lambda_0) = a\, e^{b\frac{g}{\lambda_0}+c\left(\frac{g}{\lambda_0}\right)^2}$$ U40: a=3.10487; b=-4.24914; c=0.80266

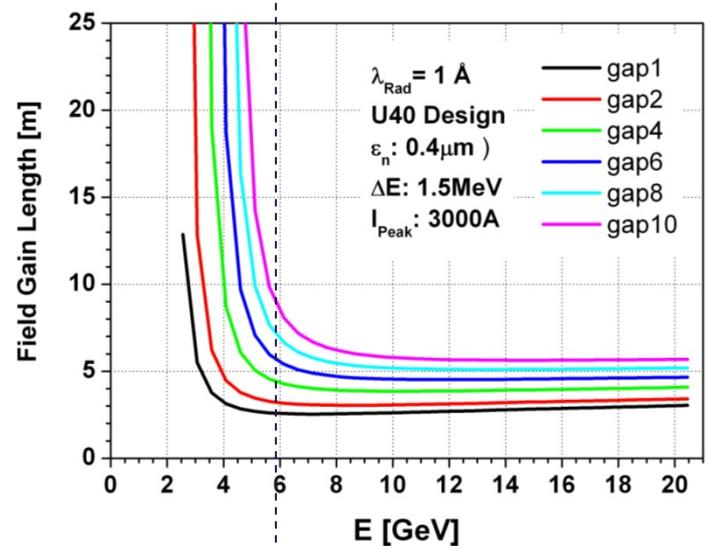
→ *Solve implicitly*

Example: 1Å radiation at different Gaps and Energy





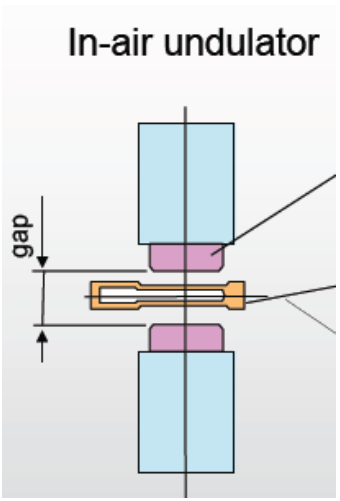


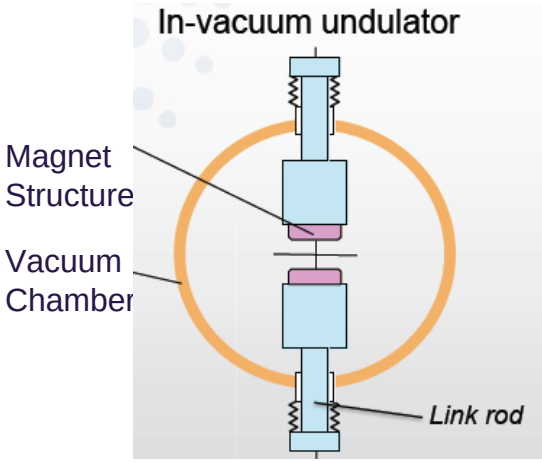


Smaller gap means:
- more periods, shorter λ_0
- higher K
- Shorter λ_{Rad} become accessible
- Better performance

Saldin, Schneidmiller and Yurkov Opt. Comm. 235 (2004) 415

Vacuum Chambers I



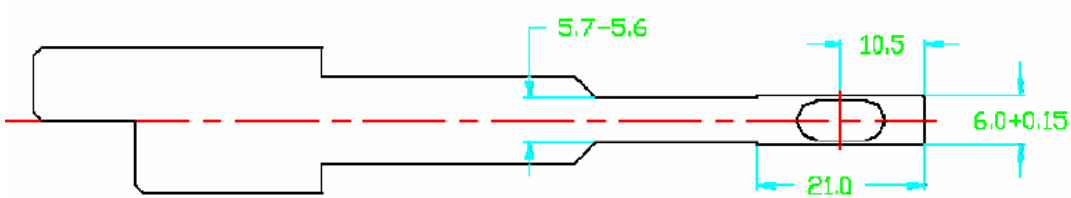


APS 7.5mm Gap Chamber Al-Extrusion

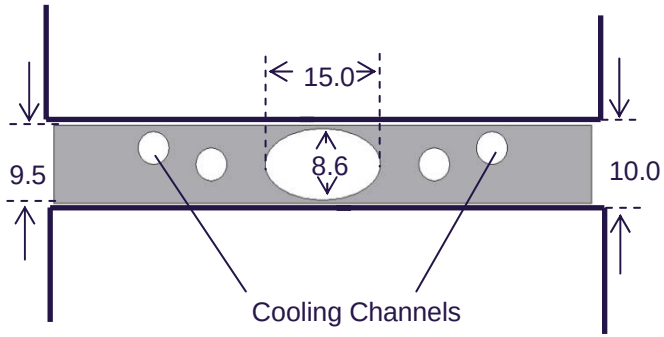
Vacuum Chambers:

- Min Magnetic Gap =Vacuum Aperture + 1 to 2 mm
- Storage Rings: 10mm (special optics, low β etc.)
- EXFEL: 10mm
- LCLS 1: 6.3mm

LCLS I 6.0mm Vacuum Chamber



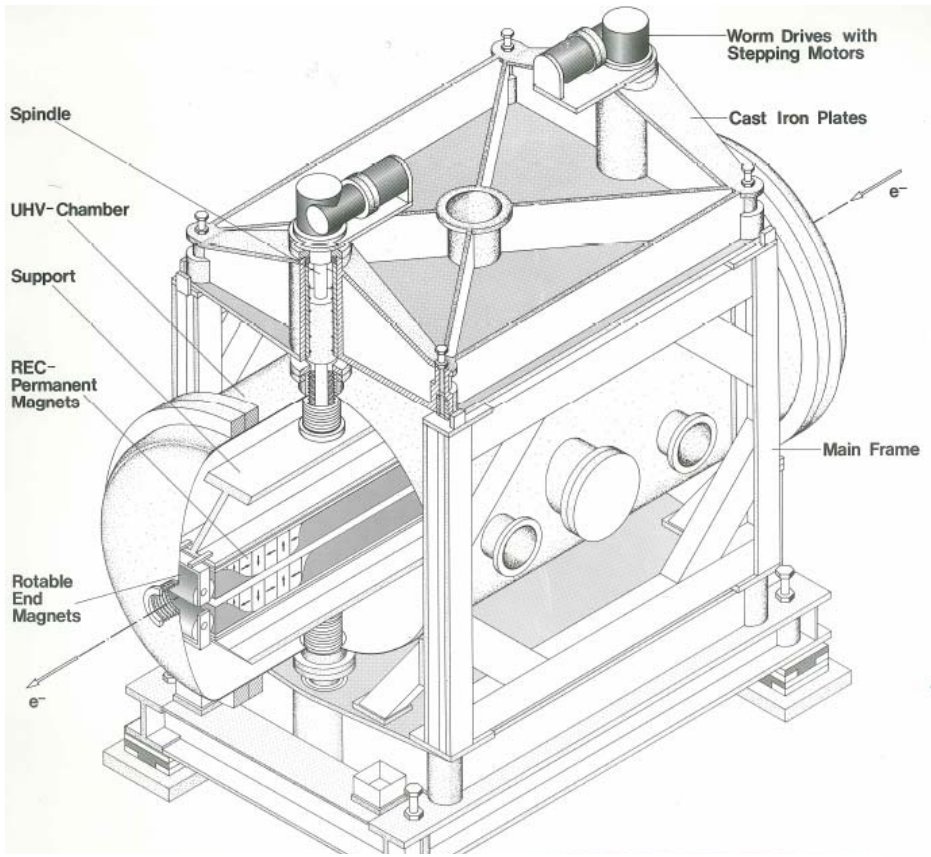
EXFEL 9.5mm Vacuum Chamber



In Vacuum Undulators

Properties
- PM technology
- Magnets in Vacuum
- PPM or Hybrid design
- Ideal: Small gap small λ_0
- Undulator gap = vacuum gap
- Adjustable vacuum aperture
- More expensive
- Pioneered at Spring8 since 90ies

Challenges:
- Vacuum, outgassing etc.
- Magnetic measurements
- Magnets are close to beam → Radiation damage
- Surface roughness and quality
- Wake fields
- RF Impedance / transitions

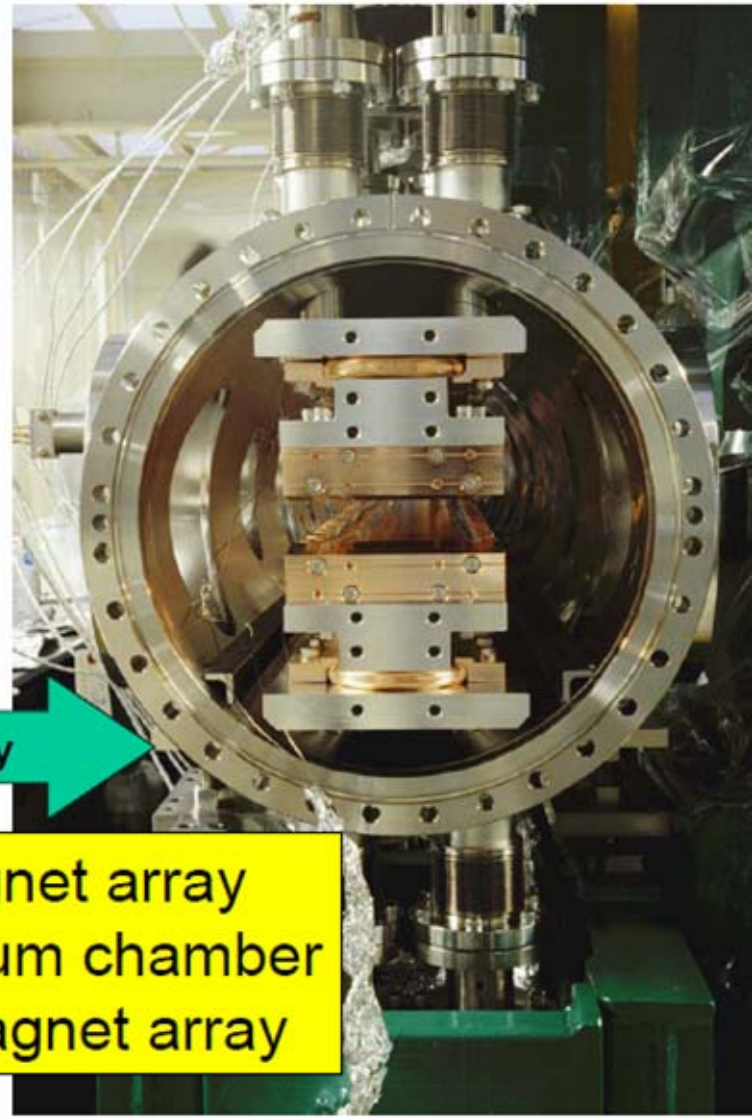


1st Undulator for BESSY I 1986

W. Gudat, J. Pflüger, J. Chatzipetros, W. Peatman
NIMA 246 (1986) 50

Magnetic Reproducibility in IVU?

Assembly

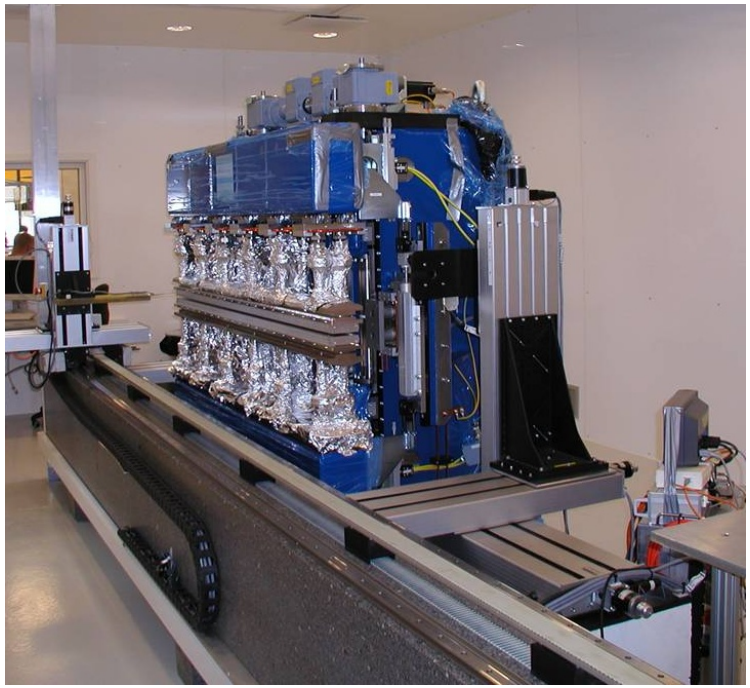


1. Detach the magnet array
2. Install the vacuum chamber
3. Reinstall the magnet array

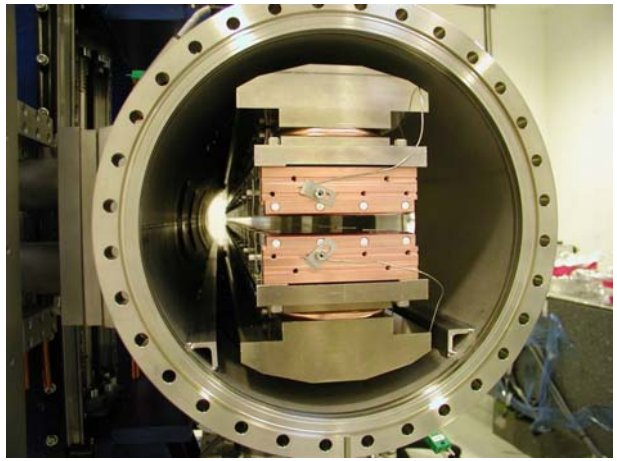
Courtesy: T. Tanaka, Spring8 EFST on Insertion Devices Workshop, Dec 3-4, 2009, Shanghai, China

In Vacuum Undulator by Danfysik 2005

Technology developed at Spring8 spread all over the world



During magnetic measurements

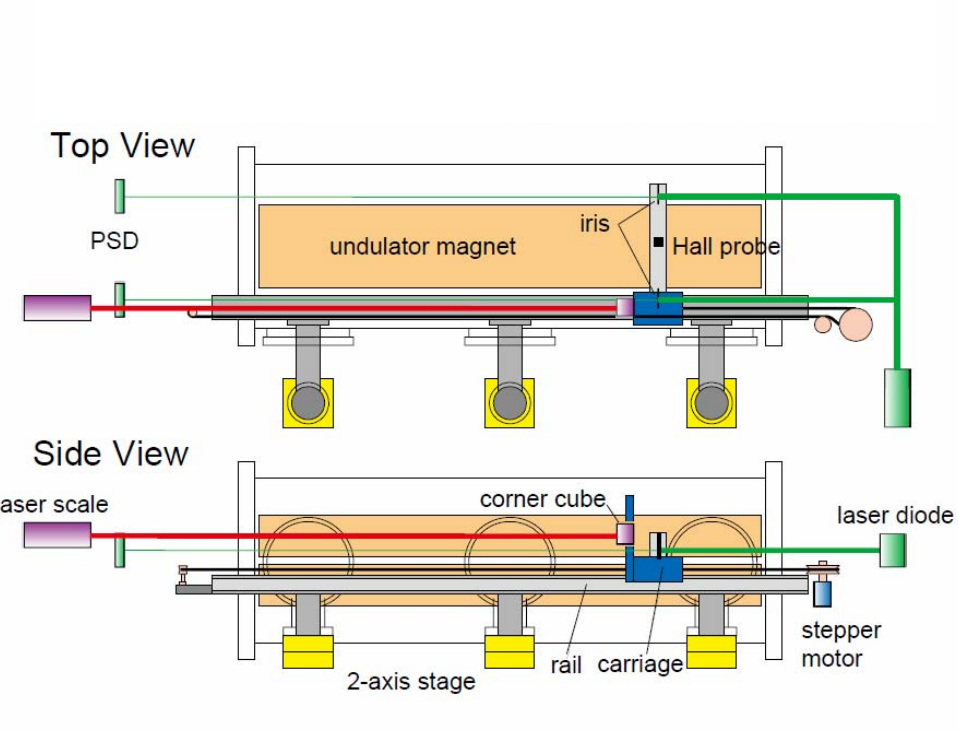


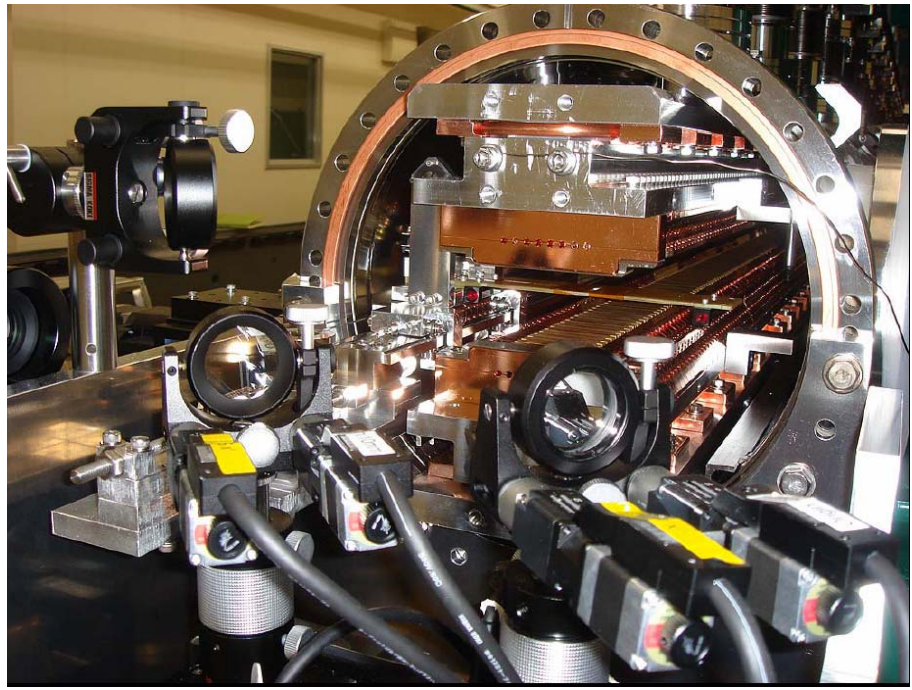
Assembled in vacuum vessel

Device complete

Magnetic Measurements in IVUs using SAFALI

Self Aligned Field Analyzer with Laser Instrumentation





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

SACLA in Vacuum Undulator System during Installation 2009

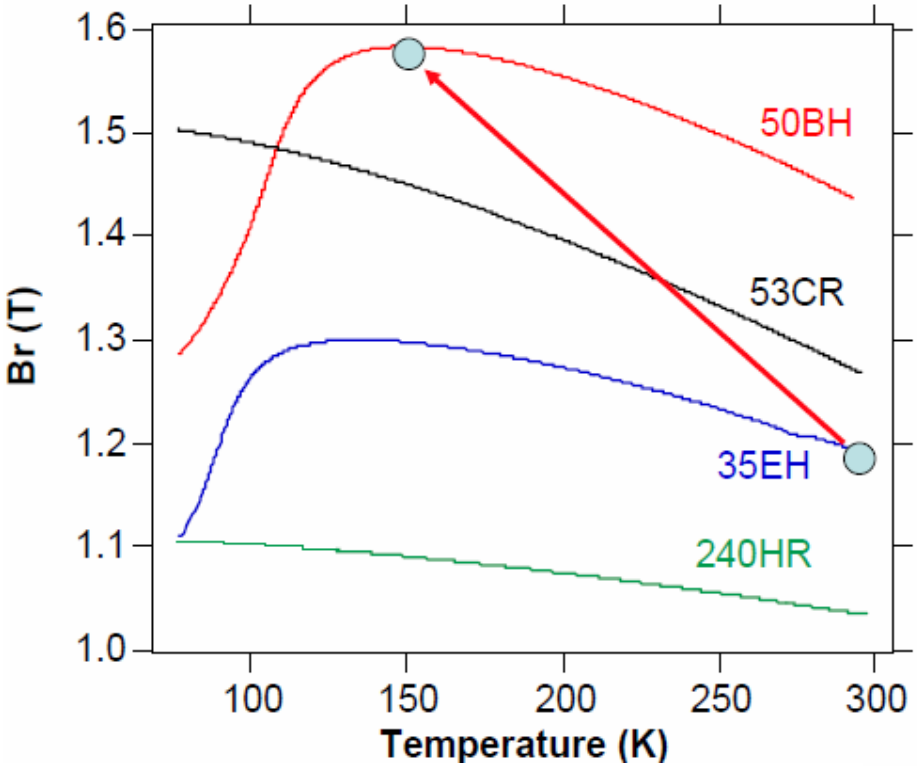
Period		15 mm
Length		4.5 m
# Periods		300
Gap	Minimum	2 mm
	Maximum	25 mm
	Nominal	3.5 mm
K Value	Maximum	1.8
	Nominal	1.3

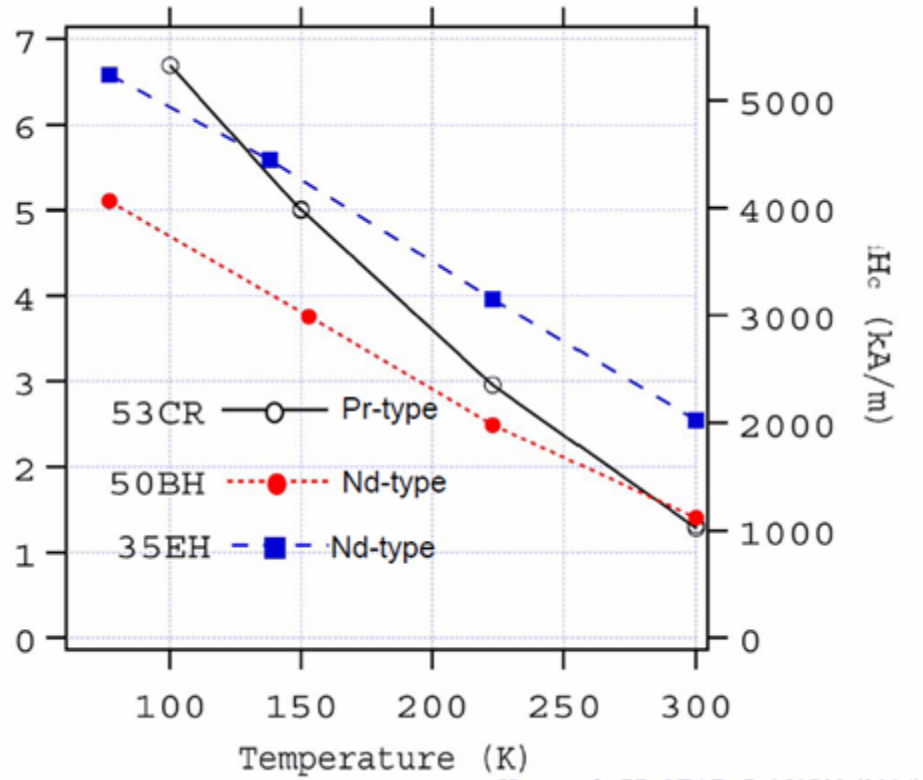
Courtesy: T. Tanaka, Spring8 EFST on Insertion Devices Workshop, Dec 3-4, 2009, Shanghai, China

Cryogenic In Vacuum Undulators (CIVUs

- CIVUs are close relatives to IVUs
- Operated at temperatures -150° C and below
- Higher B_R by $\eta * \Delta T \approx$ 15-20%
- Higher Coercive field by factor 2-3

Temperature Dependence of PM Material





Hara et al., PR-STAB, 7, 050702 (2004)

VACOMAX 240HR
NEOMAX 50BH, 35EH
NEOMAX 53CR

Sm_2Co_{17} magnet
NdFeB magnet
PrFeB magnet (good for high T_c SU)

H. Kitamura, T. Hara, Spring8 WUS2005 Workshop June 6-8, 2005, Hamburg, Germany

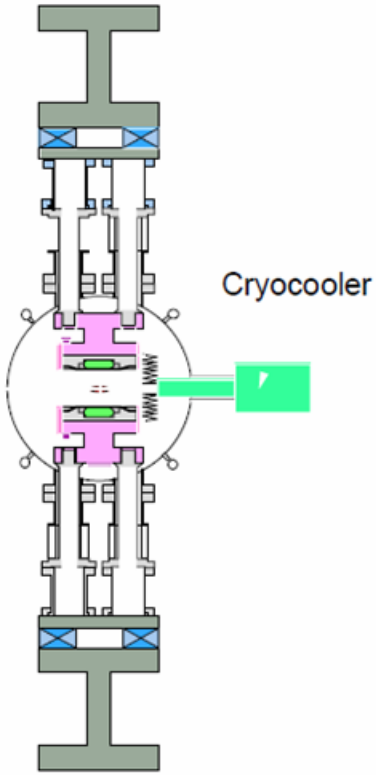
CIVU Summary

Pro:

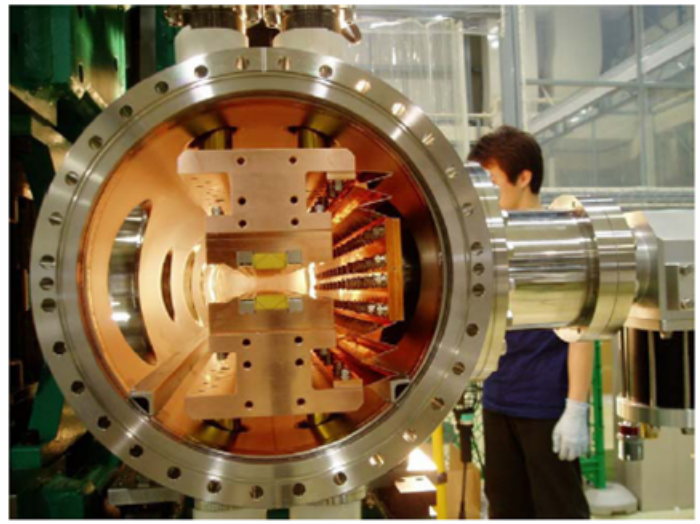
- Technology similar to IVU
- Highest $H_{C,J}$, B_R, values
- Use of High B_R grade with low RT $H_{C,J}$
- High resistance to radiation damage

Challenges

- Magnetic measurements and tuning
- Temperature gradients influence field homogeneity
- Requires cryogenic infrastructure



Undulator period	15 mm
Type	halbach ppm
Length	~ 0.6 m
Material	NdFeB 50BH
Temperature controled by heaters	



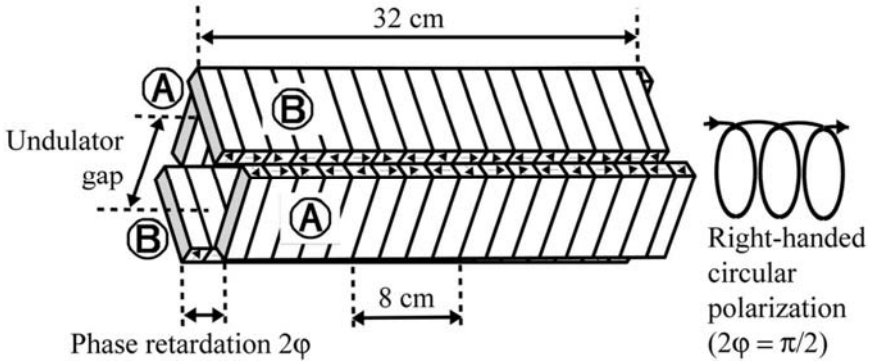
- Cryocooler installation with flexible Cu plate.
- Improvement of thermal isolation at magnet beam supports.

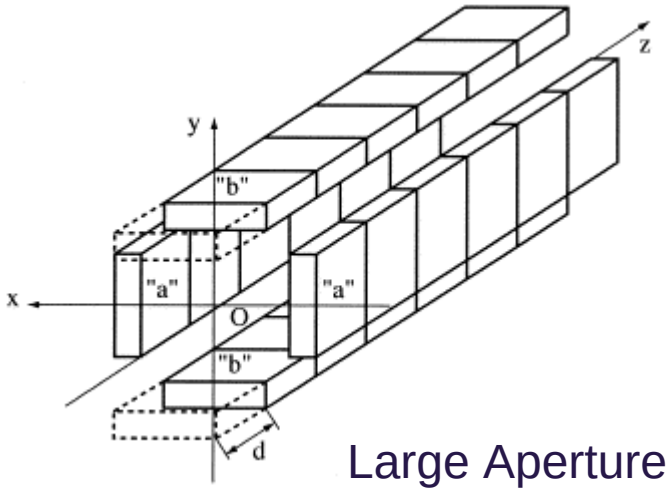
T. Hara, Spring8 WUS2005 Workshop June 6-8, 2005, Hamburg, Germany

Special Insertion Devices

Insertion Devices for Circular Polarized Radiation

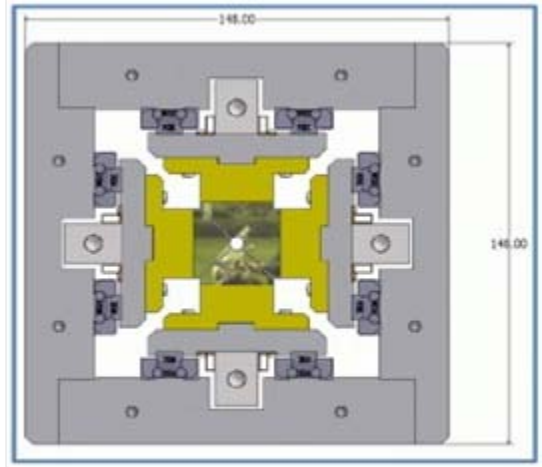
Helical Undulator
For Storage Ring

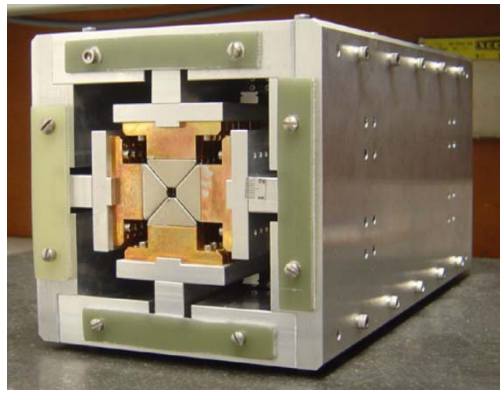




Large Aperture & Gap!

Delta Undulator
for Linacs an ERLs

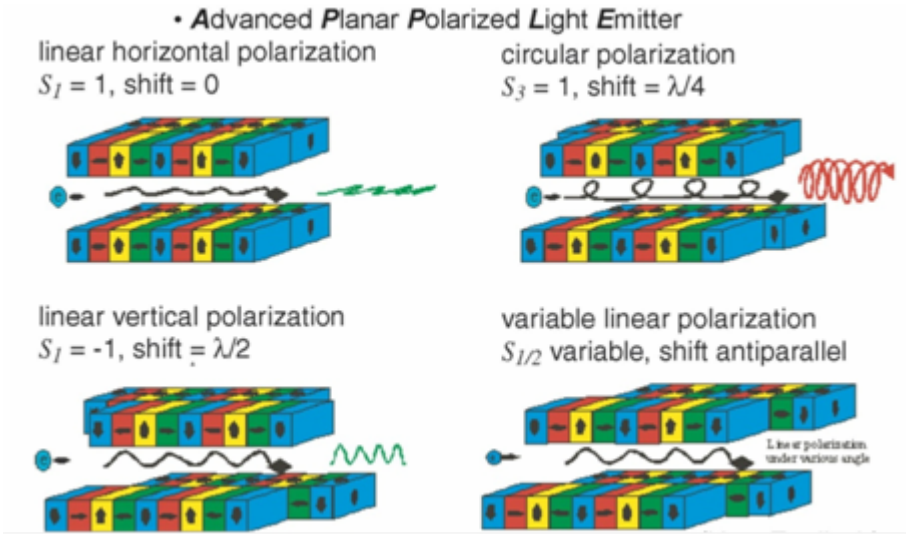


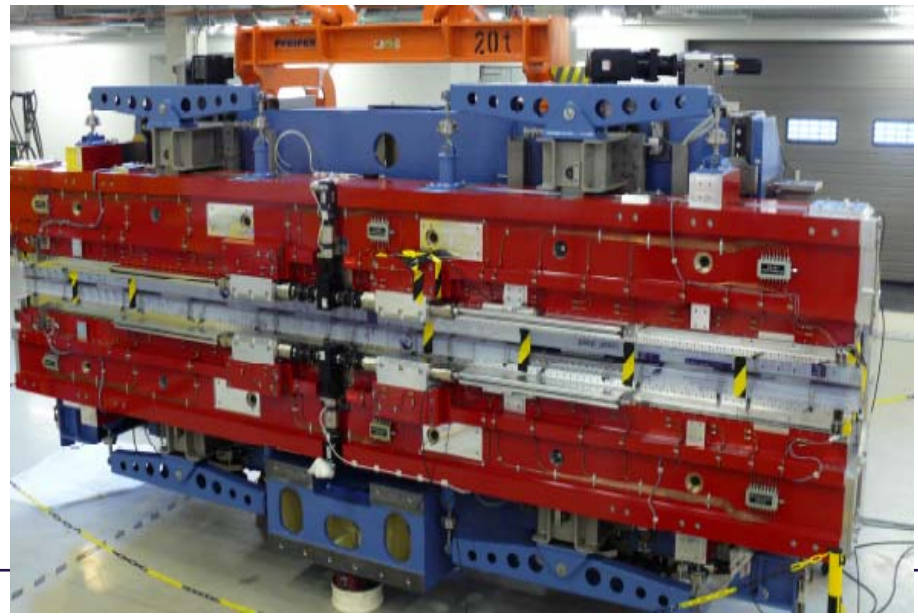


H. Onuki, NIMA 246 (1986) 94

A. Temnykh, PRSTAB 11, 120702 (2008)

APPLE II Undulator





APPLE Undulator for PETRA III
λ_0=60mm
L= 5m

Tolerance Requirements

Tolerance Budget

Key requirement: $\boxed{\frac{\Delta\lambda}{\lambda} \leq \rho}$

ρ :

- For FEL Pierce Parameter of order 10^{-4}
- Spontaneous Emission:
  $\rho = \frac{1}{nN}$ of order 10^{-3}

Radiation Wavelength $\lambda = \frac{\lambda_0 \cdot \left(1 + 0.5 \cdot K^2\right)}{2\gamma^2}$ depends via the K-Parameter

$K = \frac{e \cdot \lambda_0 \cdot B}{2\pi \cdot m \cdot c_0}$ on the magnetic field $B = B(\frac{g}{\lambda_0})$ of an undulator segment

Error sources for the Magnetic field

1. Temperature Changes

$$\Delta B_{Temperature} = B \cdot \eta \cdot \Delta T \; ; \Rightarrow \Delta T = \frac{\Delta B_{Temperature}}{B \cdot \eta}$$

η : Reversible Temperature coefficient of Magnet material
η = -0.1% / ° C for NdFeB -.03%/° C for SmCo

2. Undulator mis-alignment

$$B_y = B_0 \cosh(\frac{2\pi}{\lambda_0}\Delta y)\sin(\frac{2\pi}{\lambda_0}z); \;\Rightarrow\; B \cong B_0(1 + \frac{(\frac{2\pi}{\lambda_0}y)^2}{2}\Delta y + \ldots)$$

$$\Delta B_{Alignment} = \frac{B}{2} \cdot \left(\frac{2\pi}{\lambda_0}\right)^2 \cdot \Delta y^2 \;\; ; \Rightarrow \;\; \Delta y = \frac{\lambda_0}{2\pi}\sqrt{2 \cdot \frac{\Delta B_{Alignment}}{B}}$$

3. Gap distortion: by taper and deformation

$$B(g/\lambda_0) = a \cdot \exp\left[b \cdot (g/\lambda_0) + c \cdot (g/\lambda_0)^2\right]$$

a-c Empirical constants: a=3.44; b= -4.67; c=0.62

$$\Delta B_{Gap} = B \cdot \left(b + 2c\left(\frac{g}{\lambda_0}\right)\right) \cdot \frac{\Delta g}{\lambda_0}; \;\Rightarrow\; \Delta g = \frac{\Delta B_{Gap} \cdot \lambda_0}{B \cdot \left(b + 2c\left(\frac{g}{\lambda_0}\right)\right)}$$

4. Short range field error

Plays special role → later

Total Error

Same weight for all errors:

$$\Delta B \cong \Delta B_{Temperature} \cong \Delta B_{Alignment} \cong \Delta B_{Gap} \cong \Delta B_{Girder}$$

$$\Delta\lambda = \left|\frac{\partial\lambda}{\partial B}\right| \sqrt{\Delta B_{Temp}^2 + \Delta B_{Align}^2 + \Delta B_{Gap}^2 + \Delta B_{Flat}^2} = \frac{\lambda_0}{2\gamma^2} \cdot \frac{K^2}{B} \sqrt{\Delta B_{Temp}^2 + \Delta B_{Align}^2 + \Delta B_{Gap}^2 + \Delta B_{Flat}^2}$$

$$\frac{\Delta\lambda}{\lambda} = \frac{K^2}{\left(1+0.5\cdot K^2\right)} \cdot \frac{\Delta B}{B} \cdot \sqrt{4} \le \rho \qquad \frac{\Delta B}{B} \le \frac{\left(1+0.5\cdot K^2\right)}{\sqrt{4}\cdot K^2} \cdot \rho$$

Example: XFEL SASE1 Undulator: $\rho \approx 3 * 10^{-4}$ @ 1 Å; $K \approx 4$; λ_0=40mm; $B \approx$ 1T; N=120; L=5m; n=5; g=10mm;

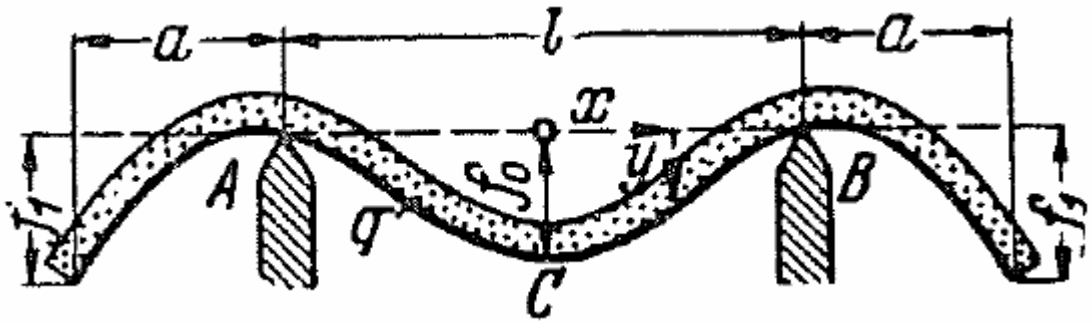
	FEL	Spontaneous
ρ	4×10^{-4}	1.7×10^{-3}
$\Delta B/B$	$8 * 10^{-5}$	4.8×10^{-4}
Temperature : Δ T [K]	0.08	0.5
Alignment: Δy[μm]	100	200
Taper: Δg [μm]	$\approx$ 1	$\approx$ 6
Gap Control Δg [μm]	$\approx$ 1	$\approx$ 6

Deformation

- Deformation proportional to support distance ** 3
- Four points are preferable
- Deformation leads to Variation of the K Parameter, which leads to Variation of Resonance Wavelength leading to increased Phase Jitter.
- But which tolerance needs the FEL process really? Simulations using FEL codes such as GENESIS 1.3 Acceptance Limit: 10% Power Degradation

Girder Deformation

Conventional: Transversal Strain



Dubbel, “Taschenbuch für den Maschinenbau”, Springer, Heidelberg

$$y = \frac{F_1 l^3}{16 E I}\left[1 - \frac{4x^2}{l^2}\right]\left[\left(\frac{5}{24} - \frac{a^2}{l^2}\right) - \frac{1}{6}\frac{x^2}{l^2}\right].$$

Deformation ~ l^3 !!

$$f_0 = \frac{F_1 l^3}{16 E I}\left(\frac{5}{24} - \frac{a^2}{l^2}\right); \qquad f_1 = \frac{F_1 l^3}{24 E I}\frac{a}{l}\left(3\frac{a^3}{l^3} + 6\frac{a^2}{l^2} - 1\right)$$

~ l^3

$f_0 = f_1 \;\; at \; \frac{a}{l} = 0.2232$ Bessel’s Points

Warning:

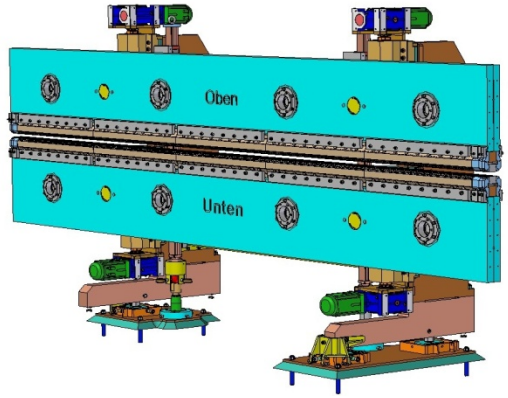
Shear Strain neglected!

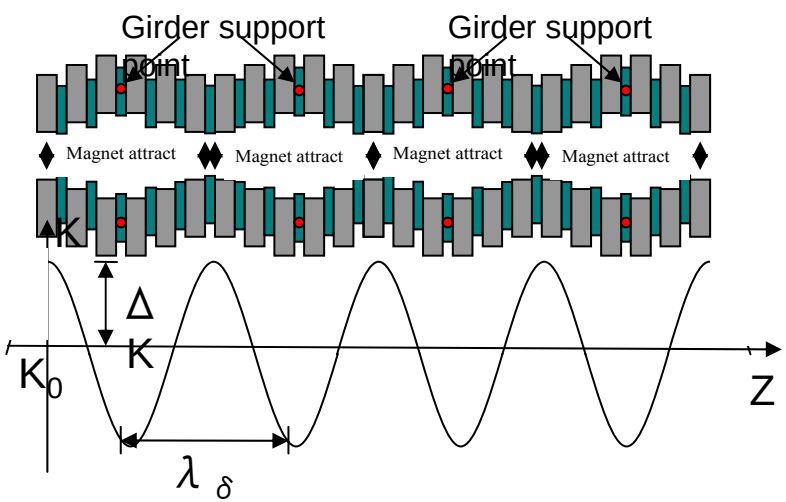
Makes significant contribution for small ≈few μ deflection

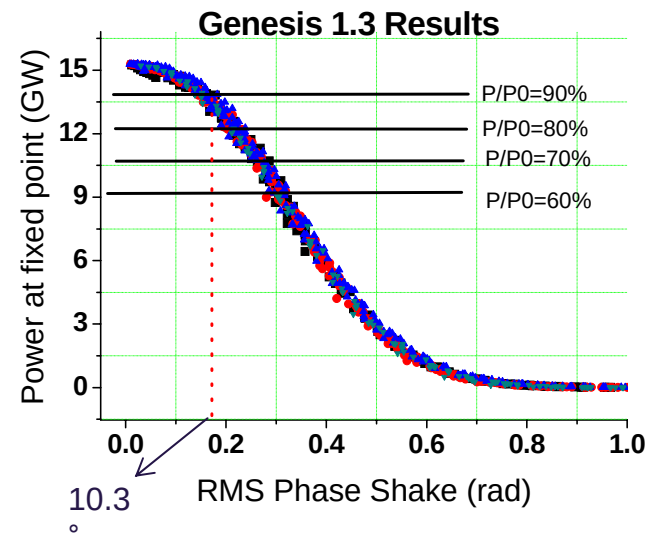
→Theory of Timoshenko Beams ……

Fortunately FEM codes consider!

Deformation and Phase Jitter





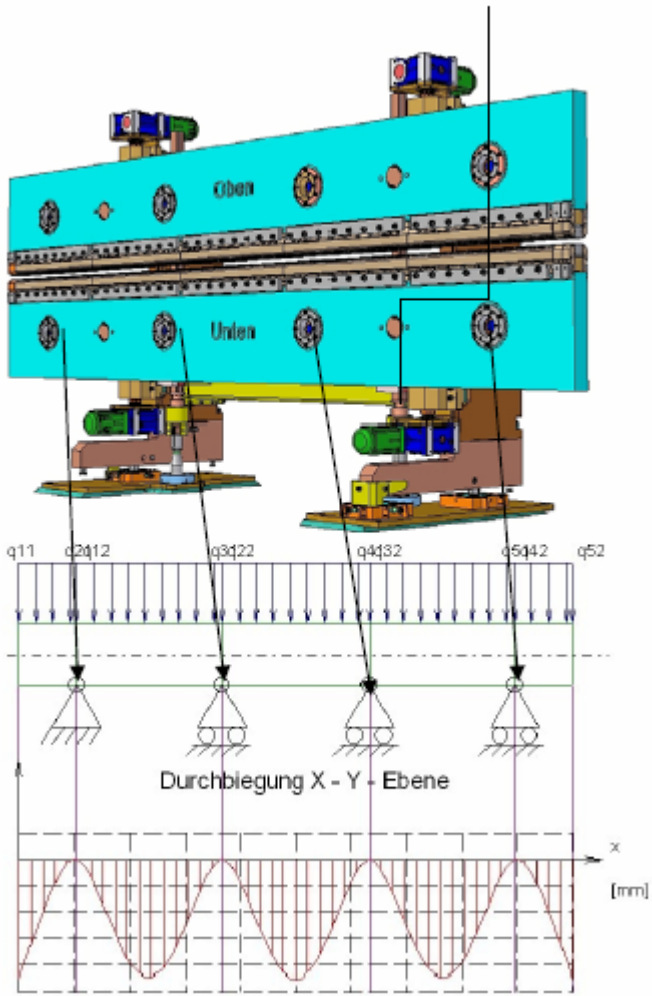


$$\sigma_{\Delta\varphi} = \alpha \cdot \frac{\Delta K}{K_0} \cdot \lambda_\delta; \quad \alpha_{\sin us} = A \frac{1}{2\sqrt{2}\pi}; \quad A = \frac{4\pi K_0^2}{\lambda_u (1 + K_0^2)} \approx 2k_u$$

Results: SASE1 at 1 Å
For $\Delta P/P = 10^\circ$
$\Delta K/K = 0.0037$
$\sigma_{\Delta\varphi} = 0.146$ (8.4°)
Δgap = 30μm

- Y. Li, B. Faatz, J. Pflueger, “Undulator system tolerance analysis for the European x-ray free-electron laser”, Phys. Rev STAB 11, 100701 (2008)

Four Point Support for EXFEL Undulators



Total Magnetic Force: 170kN

Material	E-Modul [kN/mm²]	Deformation [mm]
Stainless Steel	210	.003
AlMg	70	.01

Shear Deformation included!

WUS June 6-8, 2005
Münch, Nawrath, Pflüger, Rüter

XFEL Tolerances and Requirements

Max. magnetic force (SASE3)	kN	150
Girder Deformation @ 150 kN magnetic force	μm	<20
Gap accuracy	μm	±1
Taper control	μm	±1
Device length	m	5
Beam Height	M	1.4
Max. gap speed	mm/s	10
Beam Material		AlMg
Magnet support structure		AlMg
Tolerable max. Deformation @ 150 kN, 4 fold support	μm	30
Differential expansion between support and girder		
Four synchronized Motors – No Gears		
Gap measurement	μm	±1
Wedge control	mrad	< ±0.1

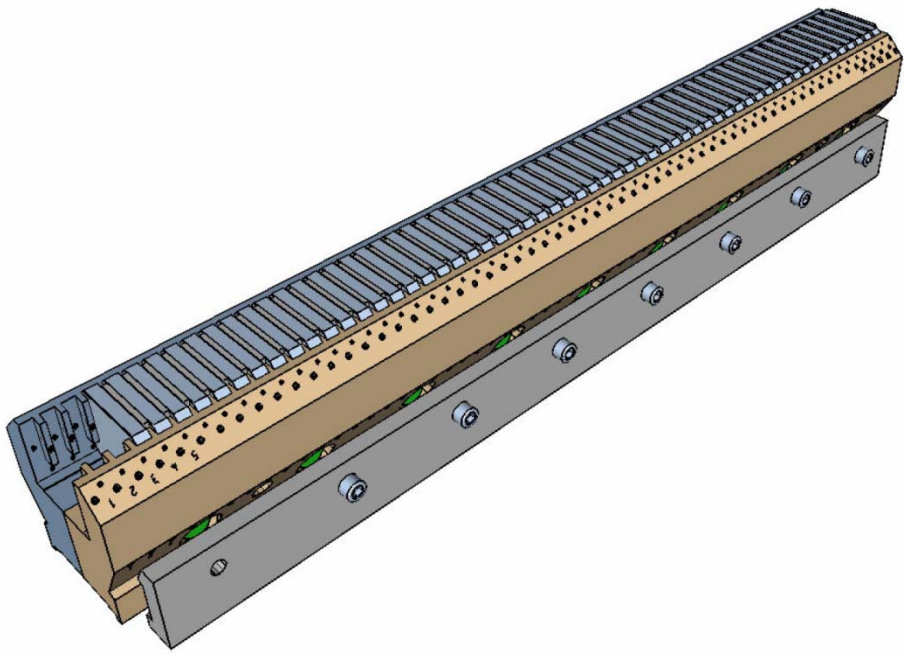
Design of Magnet Structure

Design targets at EXFEL:

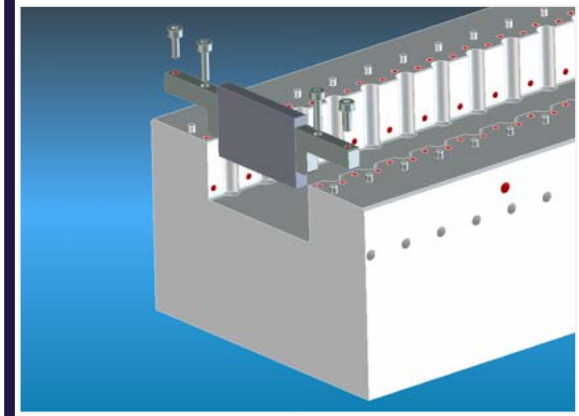
- Compatible with Supports
- Flexible Design adaption of period lengths
- Material is AlMg
- Pole Height Tuning
- Segmentation into ≈ 1m long modules

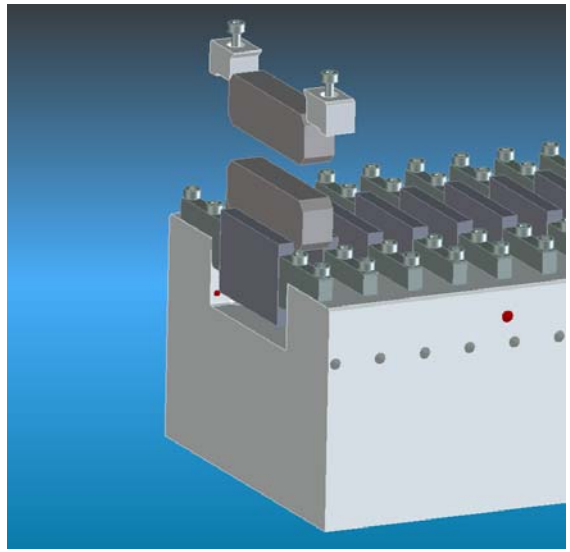
Magnet Module Assembly Procedure

EXFEL Design



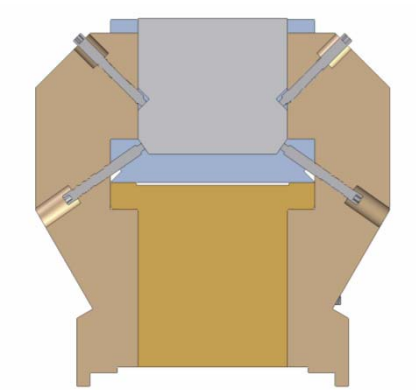
LCLS II Plans





Pole Height Adjustment

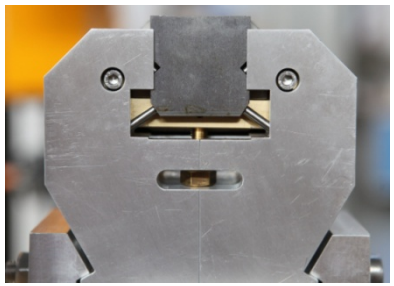
EXFEL Design



Adjustment Range:

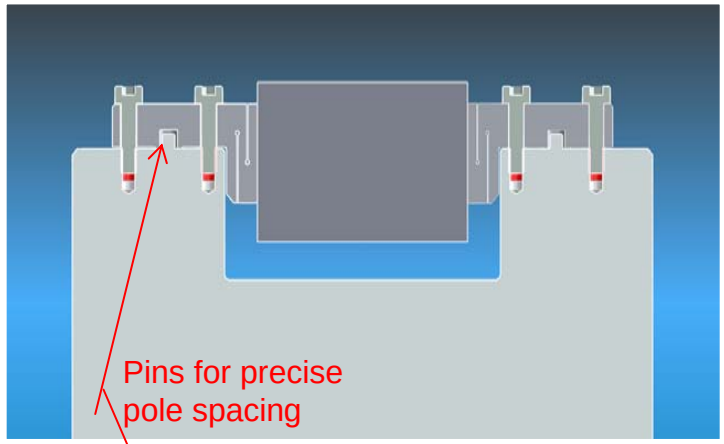
Pole Height : ± 0.3mm

Pole Tilt : ± 4mrad

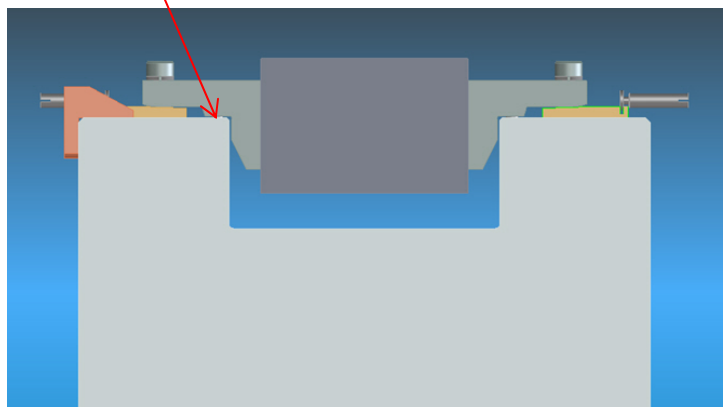


LCLS II Plans

Flexure



Wedge



Drives, Controls and Control Systems

Motors and Drives

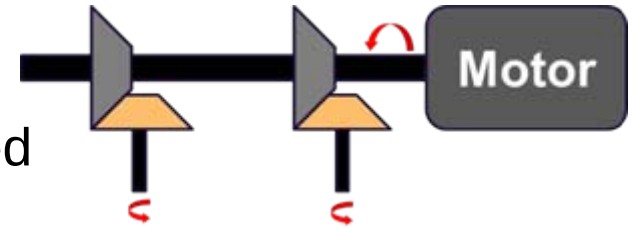
Gap Drive Alternatives:

- Central Motor, T-gears, 90° -gears, four spindles
- Central Motor, T-gear, two right/left spindles
- Two motors with two right/left spindles
- Four motors

Motor Types used for Insertion devices

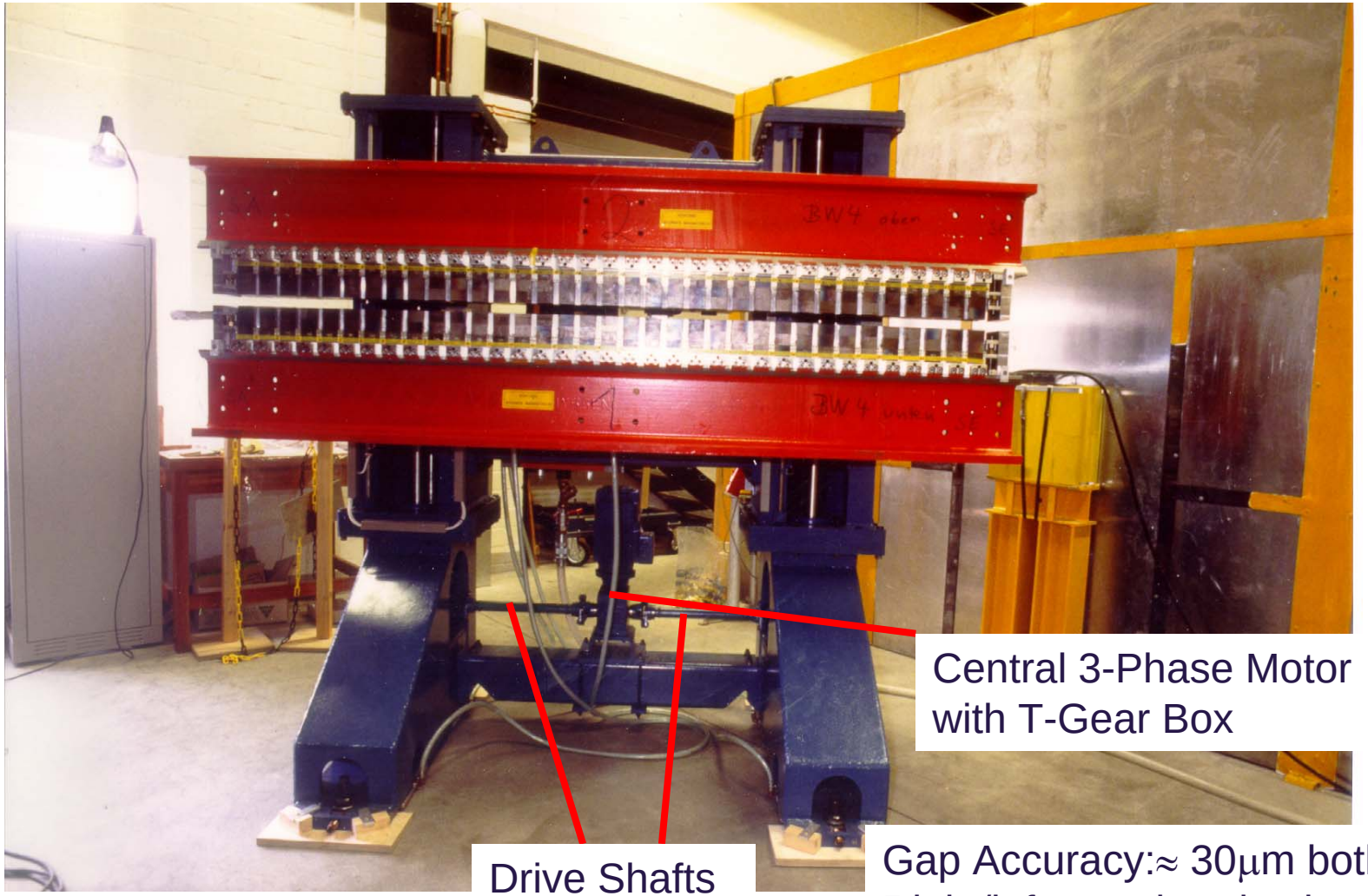
- 3-Phase 2-3 speed motors (historic)
- Stepper Motors (limited torque)
- DC/AC Servo systems (compact, high power)

Traditional Drive Concept



- One central Motor
- One Master Drive Shaft (“Königswelle”)
- T-Gears, 90° Gears for distribution as needed
- **Pro:**
  - Motion control easy –just one single axis
  - Robust
  - Reliable, high operational safety
- **Con:**
  - Accuracy of synchronization limited by: tooth pitch tolerance, play, accumulation in the drive chain.
    Not good for demanding applications in FELs or long undulators
    Examples
    1. 2 x 5 mm right left roller spindle:
       360° ÷ 10.0mm 1μm ÷ .036° or 2 arcmin
    2. DORIS III X-Ray Wigglers: Right / Left difference ≈ 15-20μm

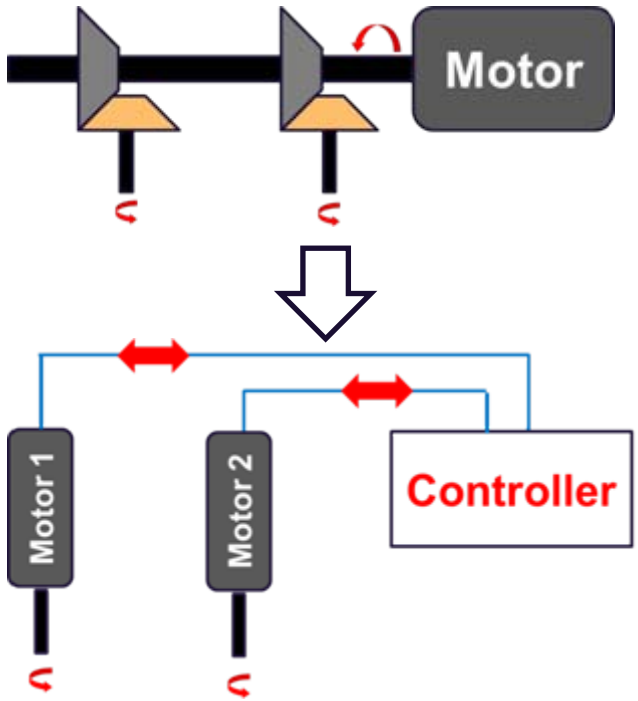
Example: DORIS III X-Ray Wiggler for BW4 (1990) …..still in Use!



Gap Accuracy:≈ 30μm both sides
Right/left synchronization: 15-20μm

State of the Art Motion Control concept

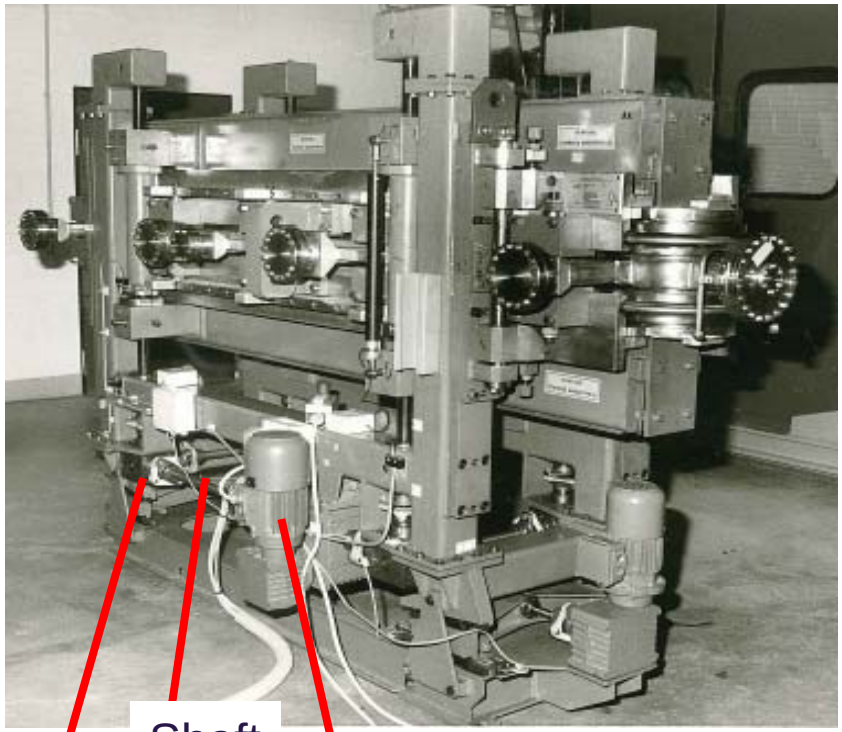
- General Trend:
  Synchronization of individual motors
- Each axis has a motor and position feedback.
- There is a central controller for synchronization and operational safety
- **Pros:**
  - Mechanically simple and economic
  - High accuracy: µm gap control
  - Additional functions can be integrated:
    - Correction tables
    - electronic precision alignment
    - External synchronization (i.e. monochromators)
    - Camming
    - More…
- **Challenges:**
  - Quite sophisticated, requires expertise – dedicated experts
  - Operational safety depends on software!

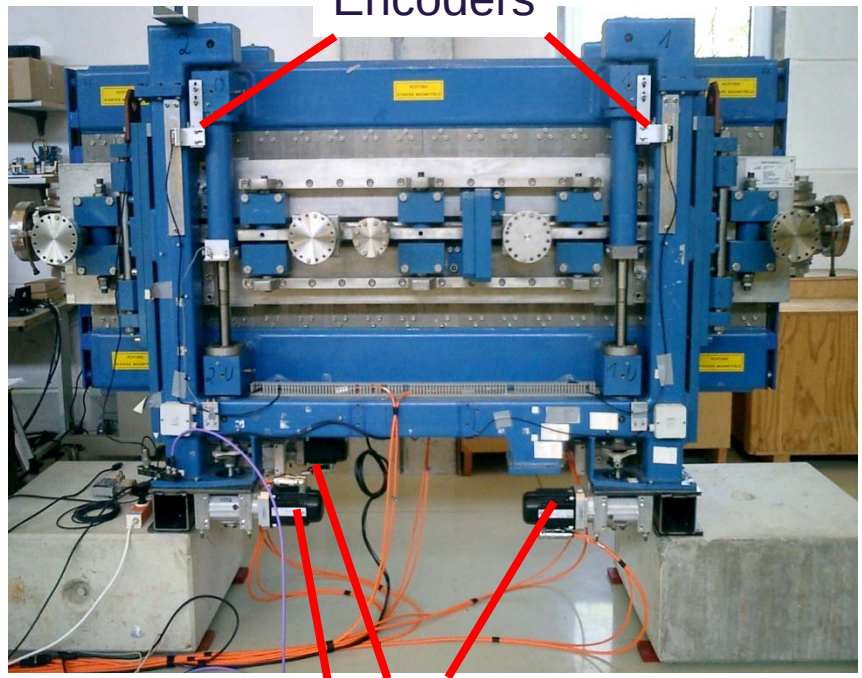


4 Axis Motion Control Test Undulator (MTU)

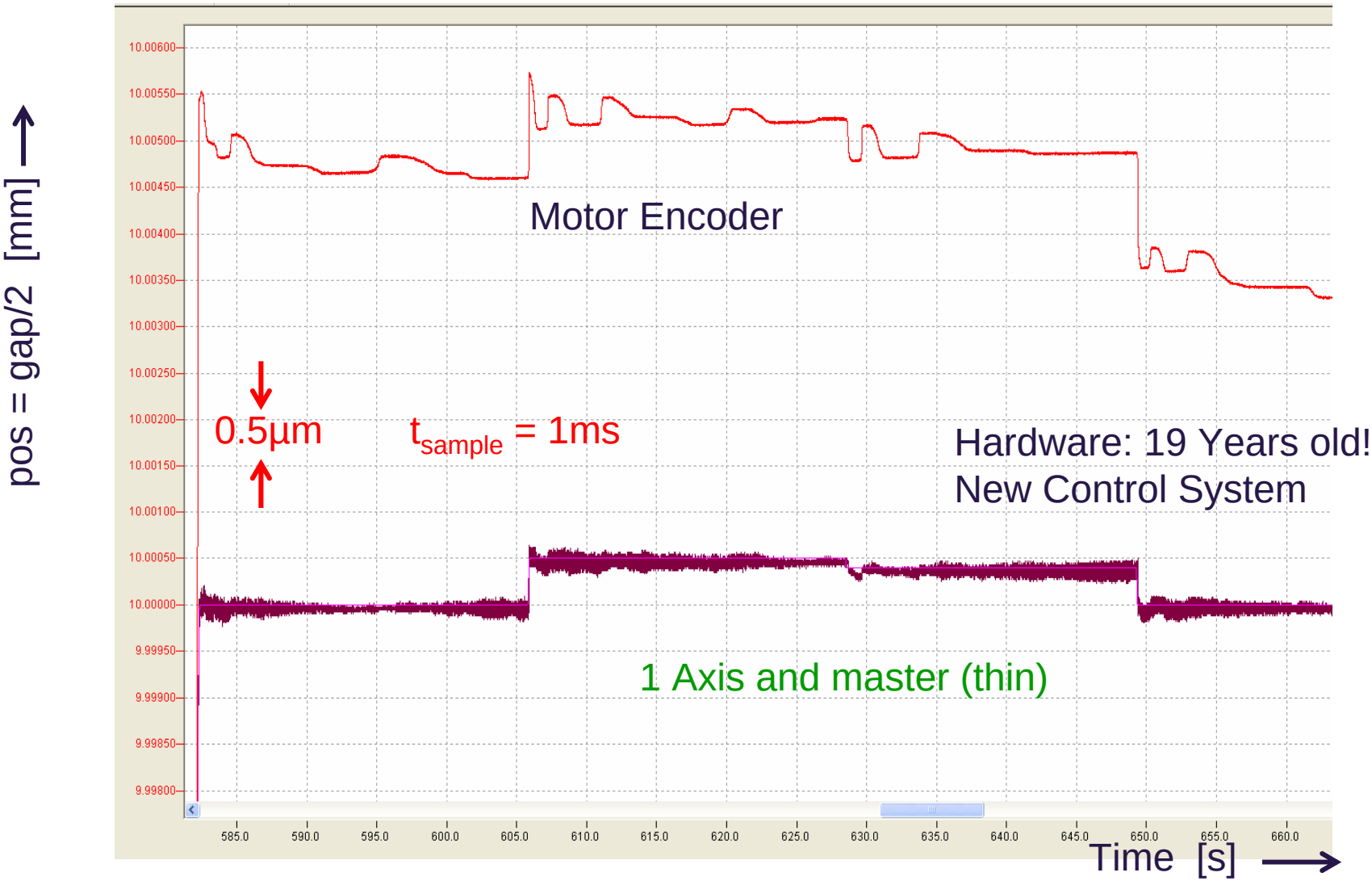
Objectives:
1. Learn operation and commissioning
2. Learn µm gap control

Old HARWI Wiggler 1992 → MTU 2005/6





Gap adjustment accuracy: < 1 μm demonstrated on 20 year old undulator



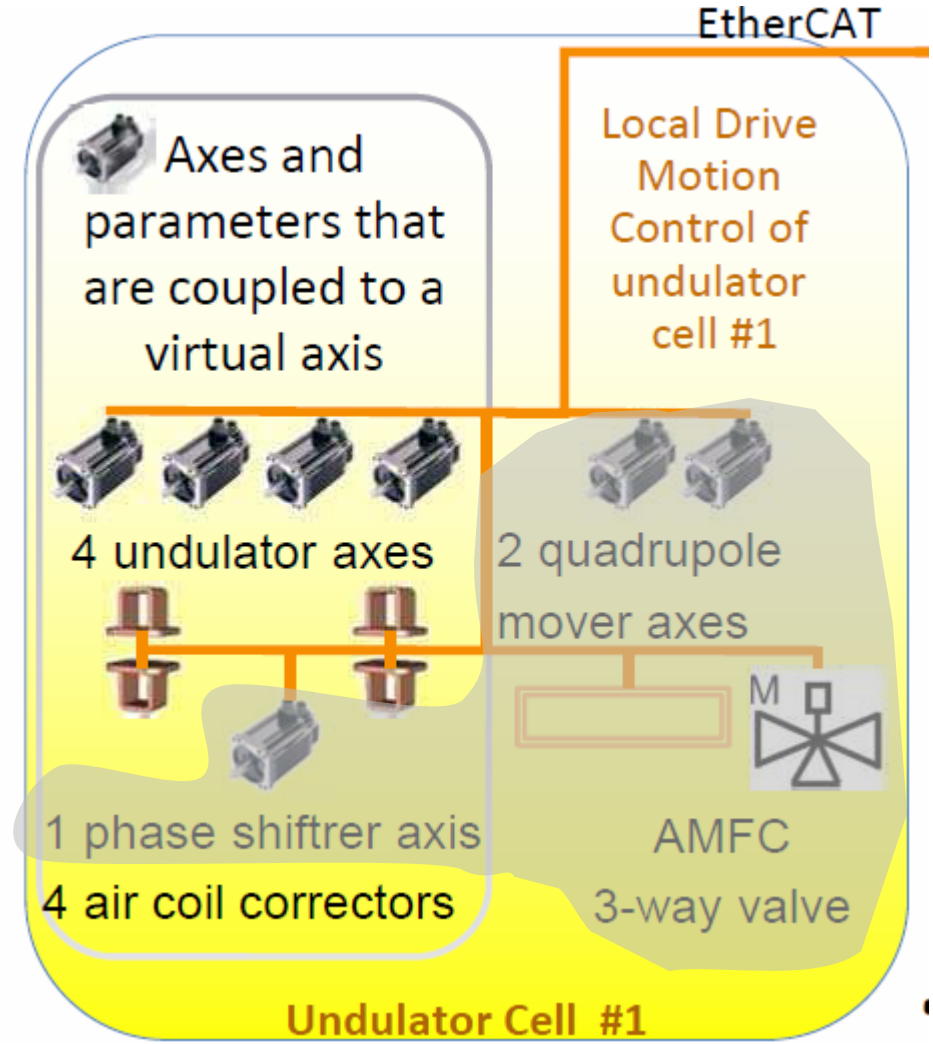
XFEL/Petra III Local Control System

Undulator Segment Control

- Four Servo Motors, encoder feedback
- electronic synchronization, no gears
- µm gap control
- Synchronization of Air Coil Correctors
- Beckhoff Hardware, software PLC, TwinCAT

Extensions for EXFEL

- Phase Shifter
- Quadrupole Mover
- Ambient Magnetic Field Corrector
- 3-Way valve

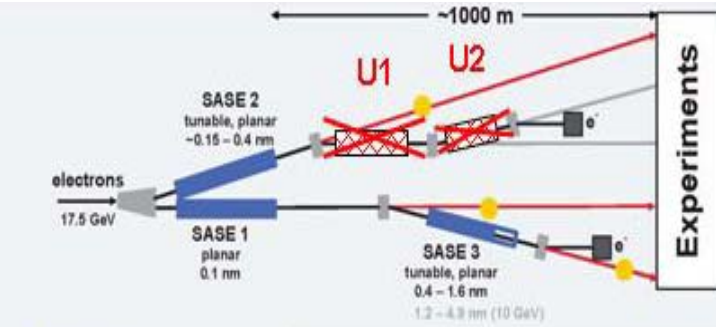


Undulator Systems for FELs

Undulator Systems

- SASE FEL need long undulators→ ≈ 200m for EXFEL
- Segmentation into shorter 5m long Undulator Segments and 1.1m long intersections (EXFEL)
- No new technology use exsting
- Intersection need Phase Shifters to match optical Phasing at any gap
- System is composed of individual components – challenge is their control

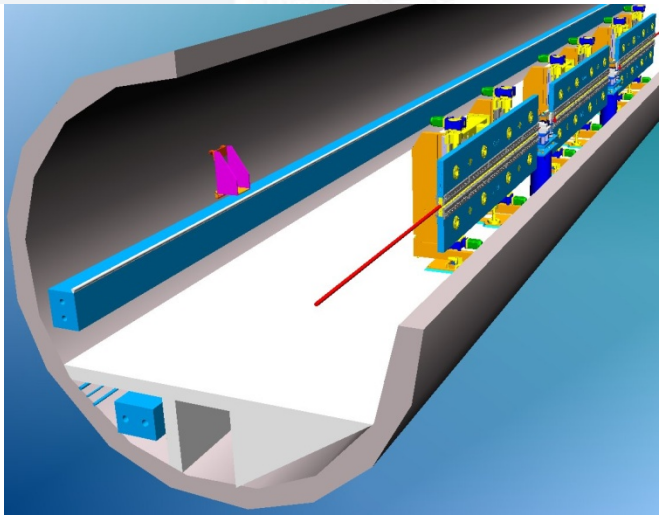
Overview over Undulator Systems



3 Undulator systems
3 Photon diagnostics
3 Photon beamline
6 Instruments

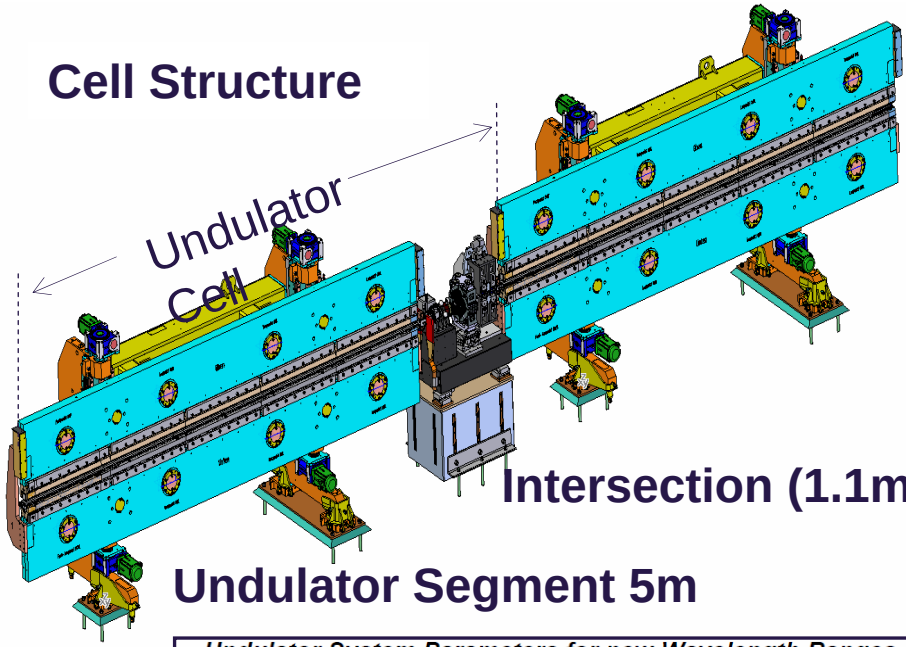
Startup Scenario

SASE1: Full
SASE2: Shortened by 5 Seg
SASE3: Linear



Undulator System in Tunnel

Cell Structure



Intersection (1.1m)

Undulator Segment 5m

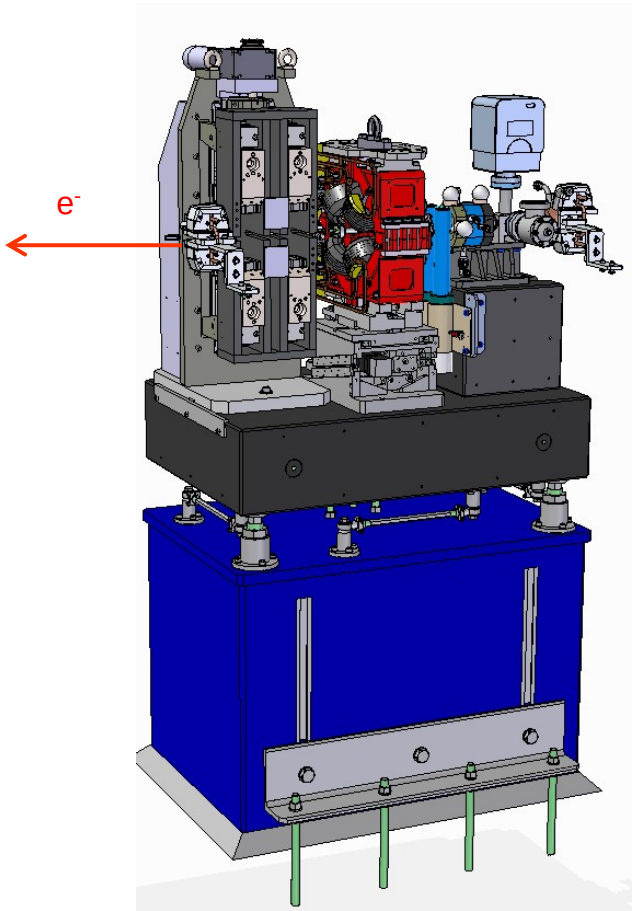
Undulator System Parameters for new Wavelength Ranges

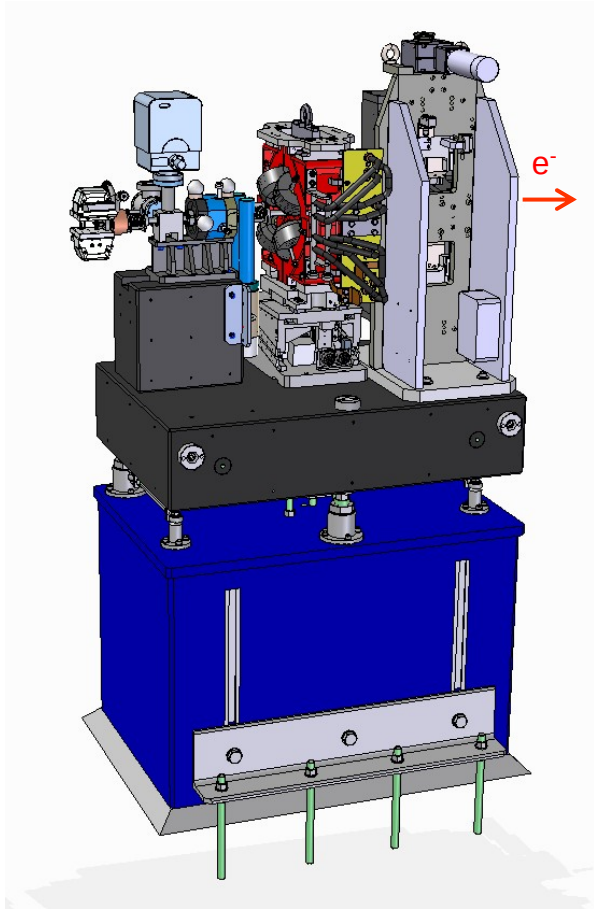
Beam Parameters: E=17.5, 14, 10 GeV, ε_n=0.6μm; ΔE=2.6MeV; I_p=3.0kA, Q=0.25nC

		λ_R* [Å]	λ_0 [mm]	Gap* [mm]	B_{Max} [T]	K_{Max}	β_0+ [m]	N_{Tot}	L_{Mag}** [m]	L_{Tot}++ [m]
SASE1	10	1.1 - 5.7	40	22 - 10	1.2	4.43	32 - 15	35	175	213.5
	14	0.75 - 3		19 - 10						
	17.5	0.72 - 1.9		15.5 - 10						
SASE2	10	1 - 5.7	40	23 - 10	1.2	4.43	46-15	35	175	213.5
	14	0.65 - 3		20 - 10						
	17.5	0.55 - 1.9		17.5 - 10						
SASE3	10	2.5 – 52	68	40 - 10	1.7	10.75	15	21	105	128.1
	14	2 - 26		33 – 10						
	17.5	2- 17		29 - 10						
							Total	**91**	**455**	**555.1**

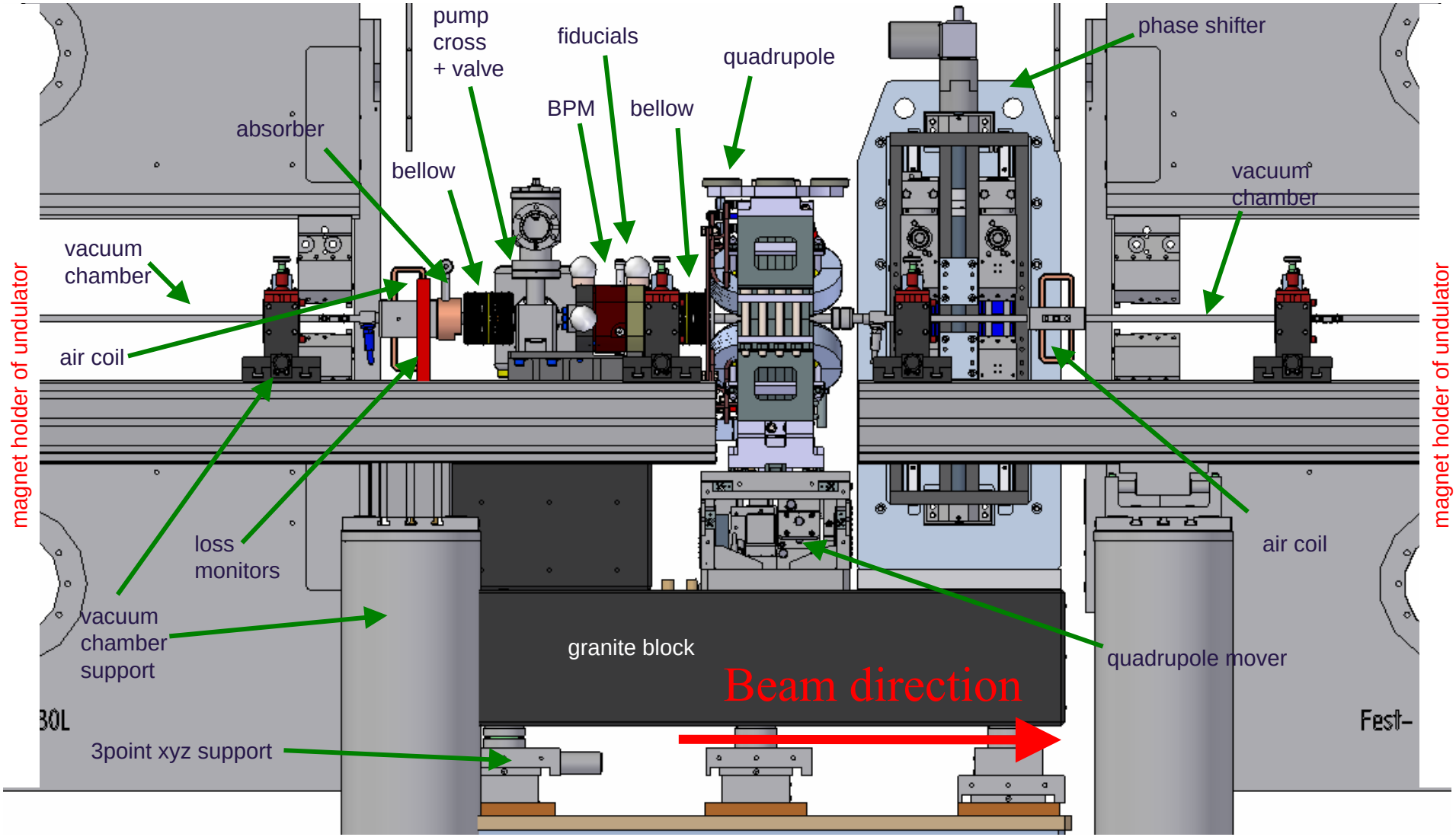
Undulator parameters for SASE1 and SASE2 are identical, but different total numbers are used
SASE3 uses planar undulator segments
* Values are given for 10, 14 and 17.5 GeV (top to bottom)
** Required net magnetic length (= 5m times the number of segments) in order to reach the short wavelength s. It contains NO contingency
+ The beta function is adjustable, minimum value is 15m
++ Total system length including intersections

Sase1/3 Intersection





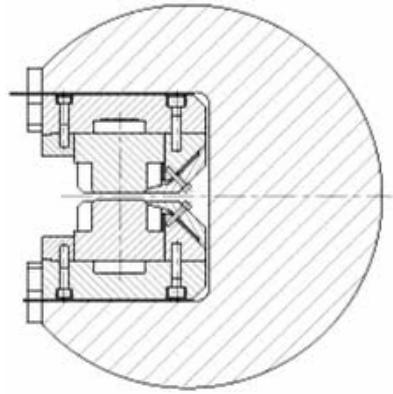
Intersection for XTD1 / SASE 2



wall side

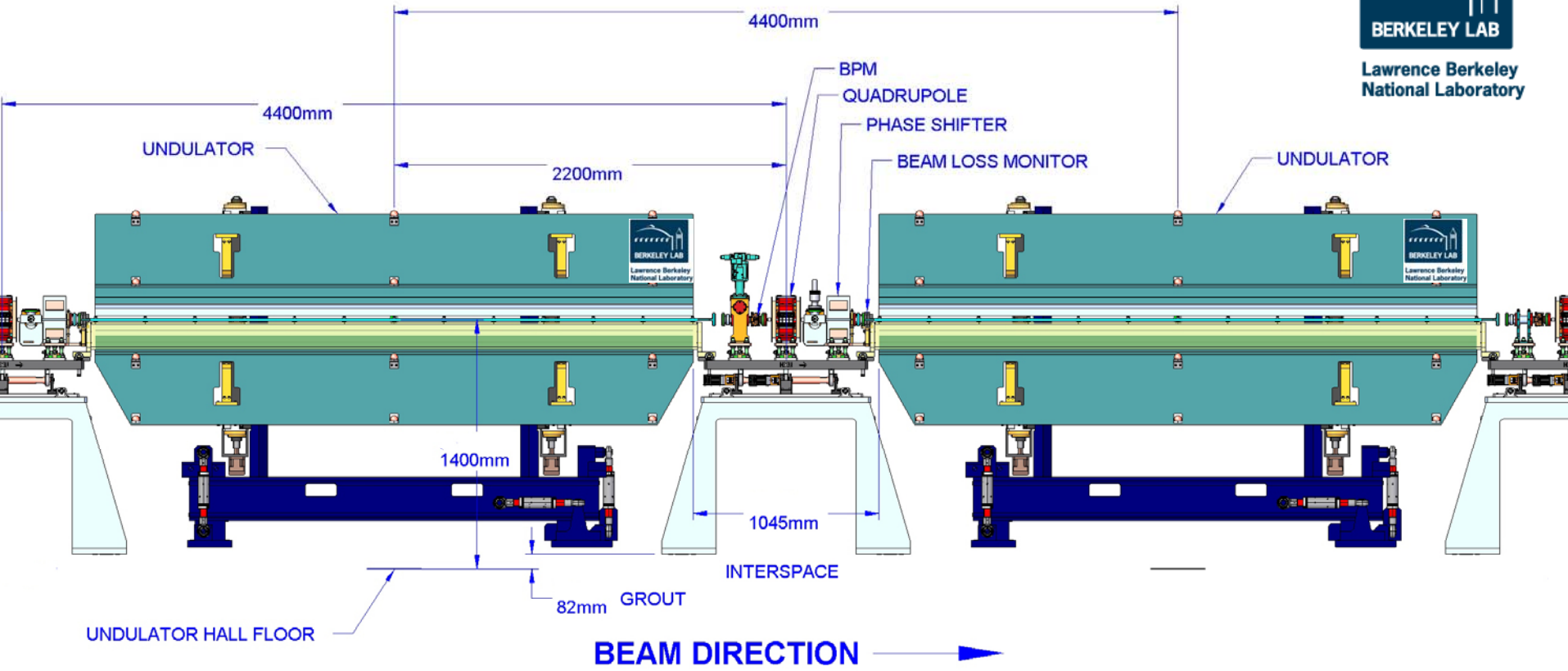
LCLS I Undulator Hall Operational XFEL!

LCLS Undulator System



System Parameters		
Period length λ_0	30	mm
Gap (fixed)	6.3	mm
B_0	1.32	Tesls
K	3.7	
Segment Length	3.4	M
N	112	
# of Segments	33	
System Length	100	m

Segment and Interspace Layout



Courtesy: H.D. Nuhn, SLAC, LCLS-II Project, Aug. 2012

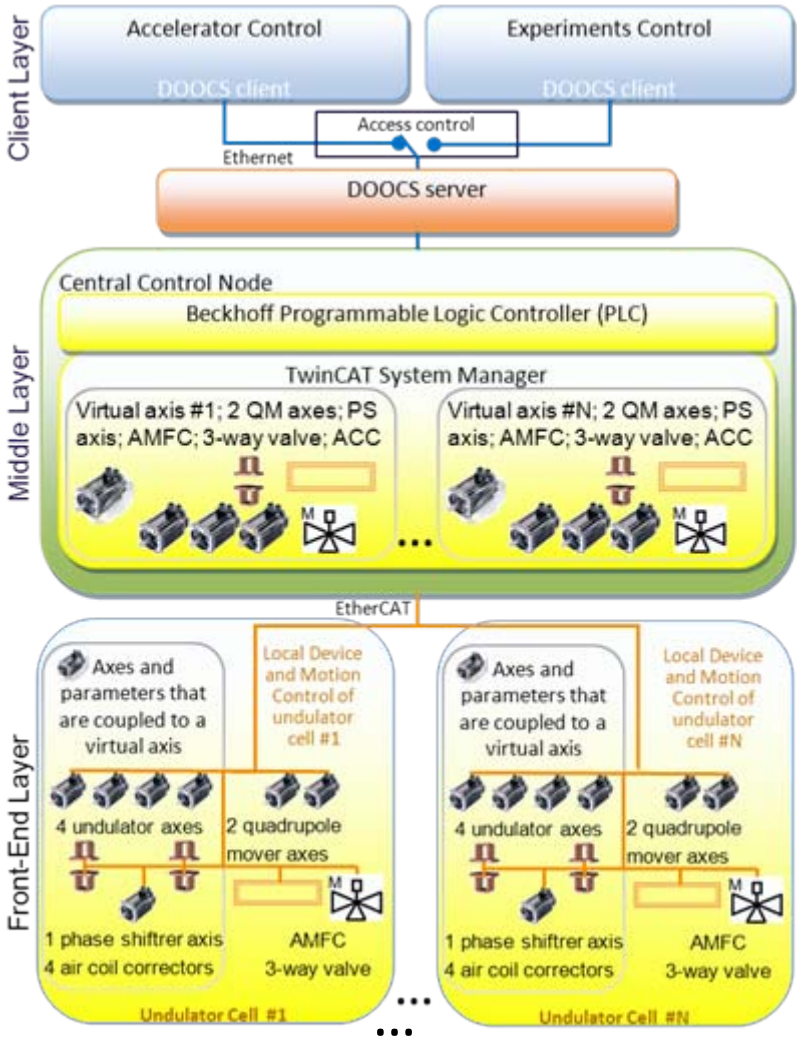
LCLS-II Undulator Dimensions and Ranges

Undulator period length	32	55	mm
Number of periods per strongback	106	61	
Total segment length	3.4	3.4	m
Undulator operational gap range	7.2 – 20.1	7.2 – 25.1	mm
Undulator parameter range (K)	0.83 – 3.76	2.56 – 9.90	
Electron energy range	7 – 13.5	7 – 13.5	GeV
X-ray energy range (required)	2.0 – 13.0	0.250 – 2.0	keV
X-ray energy range (total)	1.8 – 15.4 (40.2)	0.169 – 3.2 (7.4)	keV
Maximum gap	200	200	mm
Tuning gap	~9	~10	mm

Courtesy: H.D. Nuhn, SLAC, LCLS-II Project, Aug. 2012

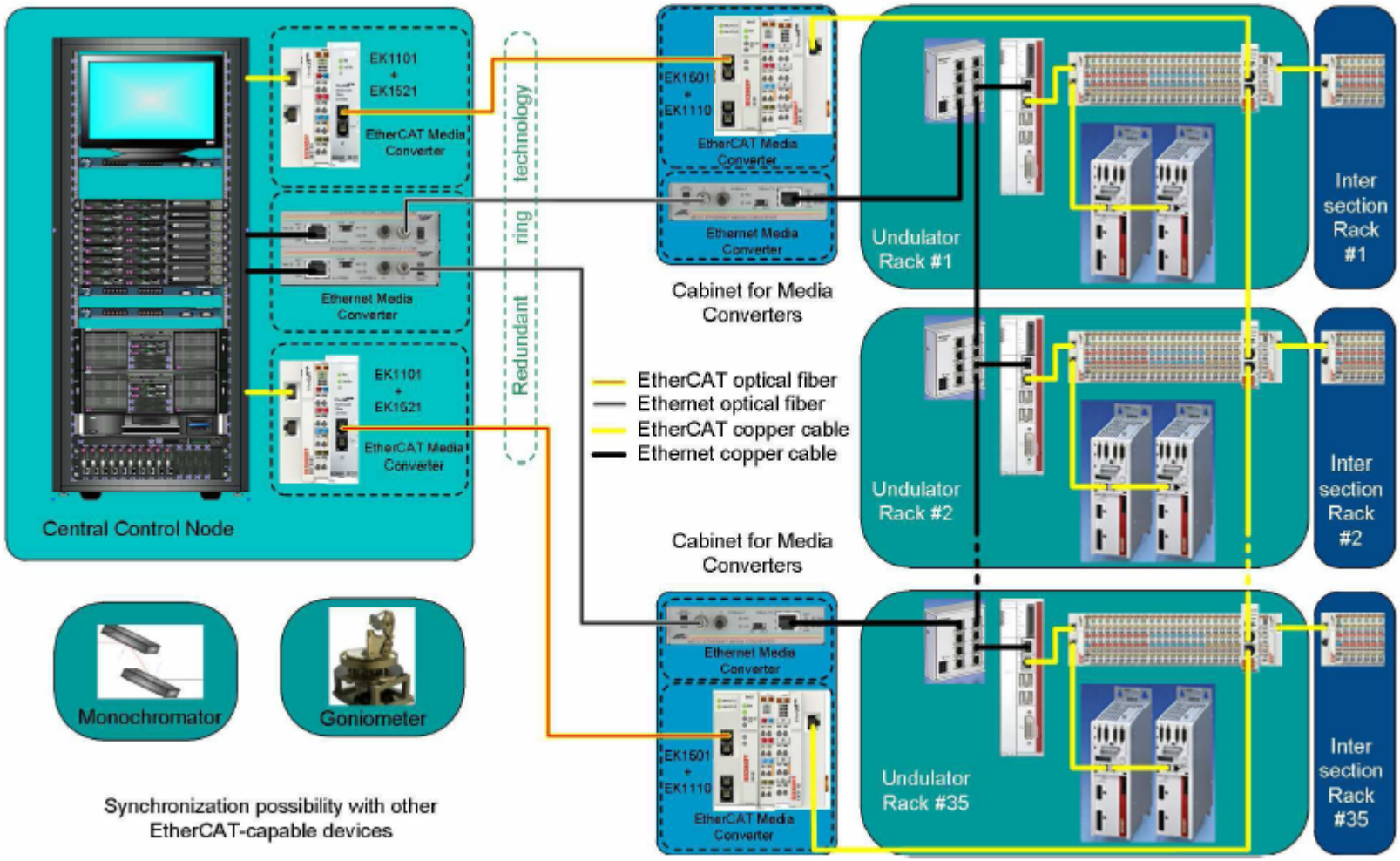
Control of Undulator Systems

Control System Architecture of EXFEL Undulator Systems



Central Control Node (CCN)

- Runs Beckhoff (PLC) and TwinCAT System Manager as well.
- Provides unrestricted access to all components
- Coordination and synchronization of individual cells
- Synchronization with external sources: Monochromators
- Status and error information
- Provides the interface to the DOOCS (Distributed Object Oriented Control System) server.
- The DOOCS server controls the access by the machine/experiment controls. (DOOCS clients)


EK1101
+
EK1521
EtherCAT Media Converter
Ethernet Media Converter
EK1101
+
EK1521
EtherCAT Media Converter
Central Control Node
Redundant ring technology
EK1501
+
EK1110
EtherCAT Media Converter
Ethernet Media Converter
Cabinet for Media Converters
EtherCAT optical fiber
Ethernet optical fiber
EtherCAT copper cable
Ethernet copper cable
Cabinet for Media Converters
Ethernet Media Converter
EK1501
+
EK1110
EtherCAT Media Converter
Undulator Rack #1
Undulator Rack #2
Undulator Rack #35
Inter section Rack #1
Inter section Rack #2
Inter section Rack #35
Monochromator
Goniometer
Synchronization possibility with other EtherCAT-capable devices

Summary I

- Light Generation is described by Classical Electrodynamics
  - SR single particle emission → handy formulae for estimates
  - FEL multi electron effect.
  - SASE FELs need very long undulators
- Technology
  - EM good for long wavelength $\lambda_0 > \approx 160$mm or/and AC
  - SC used for wavelength shifters $B_{max} >= 10T$
    Highest possible field for short periods, but under strong development. Field performance is problem
  - PM widely used since 30 years. Highly developed. Field measurement & tuning perfectly solved
  - IVU and CIVUs extend range
  - Modification & variations: Crossed undulators, Delta, APPLES

Summary II

- Tolerances
  - Undulators for FELs have tighter tolerances than for SR
  - Phase Jitter is a good criterion for FEL performance
- Undulators for FEL applications need accurate motion control systems
- Undulator Systems for XFELs are long 100-200m and make use of many single 4-5m long segments.
  More hardware is needed.
- Controls for XFEL undulators is a special challenge

The End