Insertion Devices

CERN Accelerator School, Chios 2011

Intermediate Level Course, 26.09.11

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Outline

- Generation and Properties of Synchrotron Radiation
- Undulator Technology
- Interaction of IDs with e-Beam
- Magnet Measurements and Tuning

HELMHOLTZ | ASSOCIATION

DESY

In memoriam Pascal Elleaume

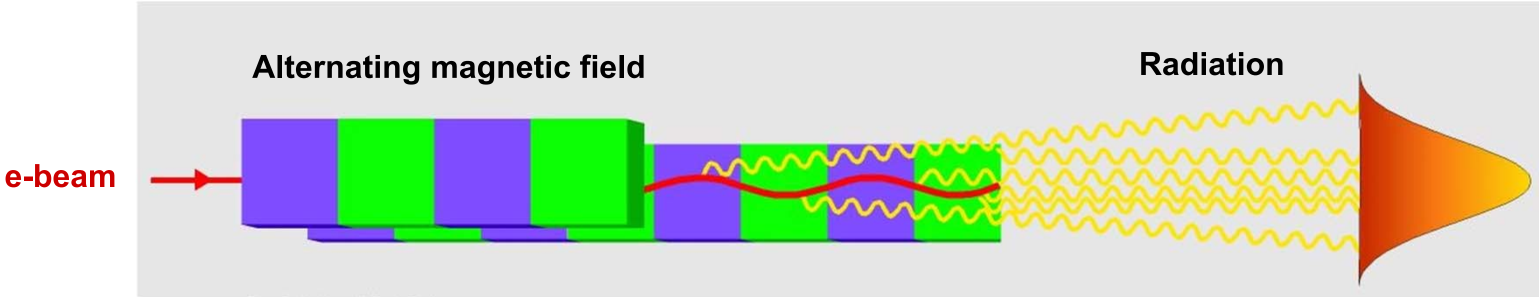
Countless contributions to

FELs … Insertion Devices … Accelerator physics

1956-2011

- Major share in the establishment of permanent magnet based undulators
- Development of several new ID concepts and related components
- Development and refinement of new ID technologies like in-vacuum undulators
- Realization of diverse new measurement and shimming techniques
- Elaboration of various simulation and analysis software
- Investigation of interaction of IDs with the e-beam
- Contributions to SR diagnostics

Insertion Device



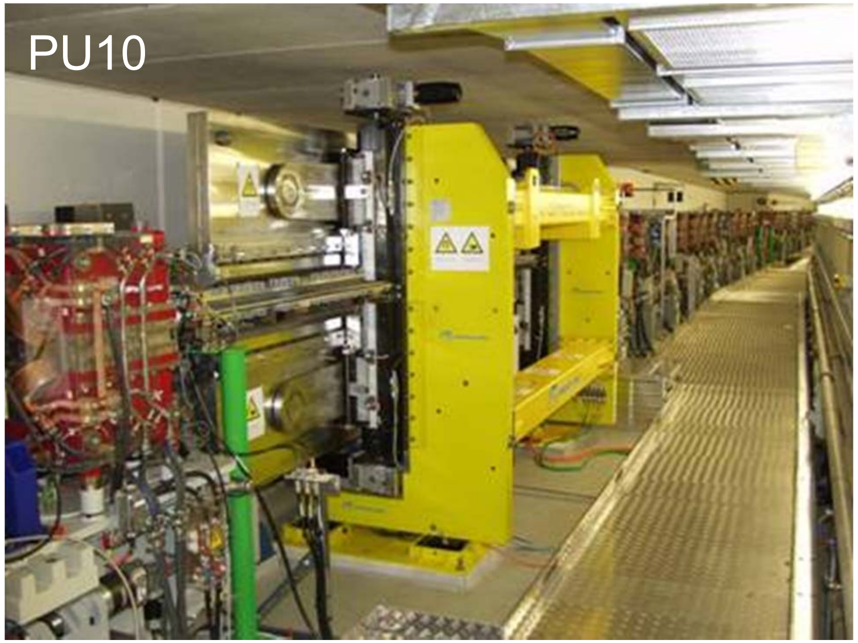
Idea

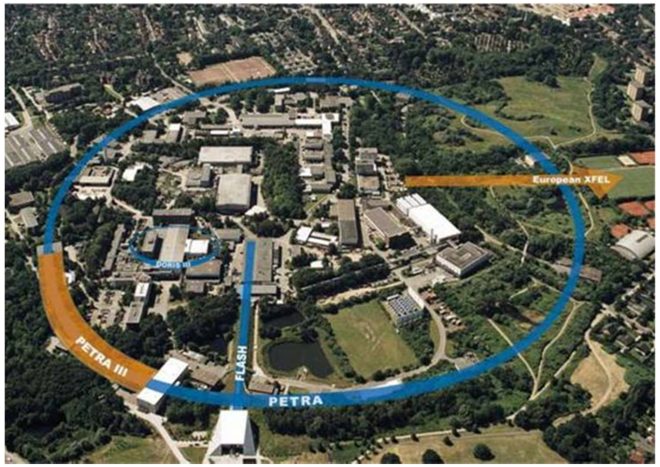
- Oscillating magnetic field causes a wiggling trajectory
→ Emission of synchrotron radiation
- So-called „Undulators“ or „Wigglers“ are often „inserted“ in straight sections of storage rings
→ „Insertion Device“
- Period length ~15 400mm, magnetic gap as small as possible (5 40mm)

Purpose

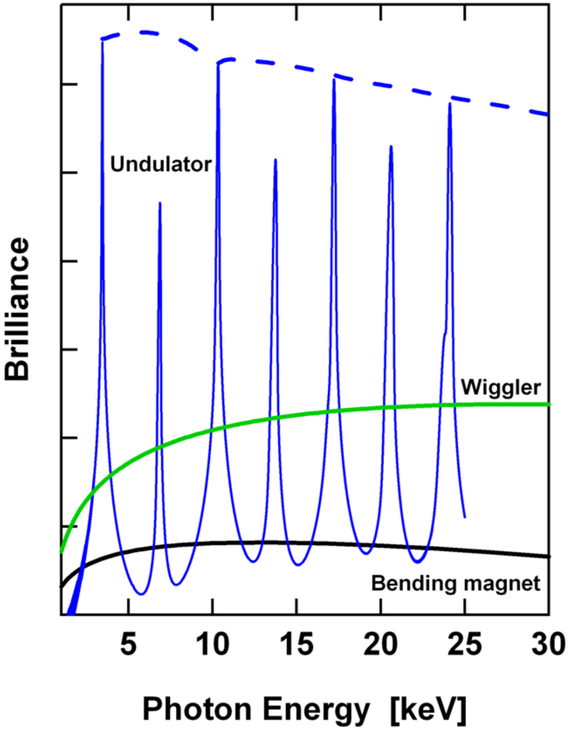
- **Intense synchrotron radiation source in electron storage rings**
- Emittance reduction in light sources (NSLS II, PETRAIII)
- Beam damping in colliders (LEP,)

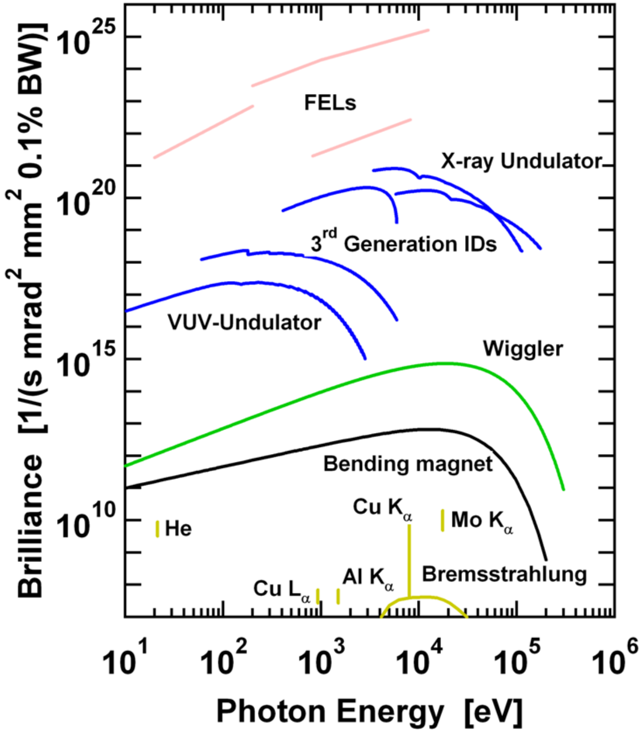
Undulators in PETRA III at DESY





Synchrotron Radiation Sources & Brilliance





Spectral characteristics of different SR-sources

Development of brilliance: 15 orders of magnitude

FEL: Peak-brilliance another ~8 orders ↑

[B] = photons/sec/mm²/mrad²/0.1%bw

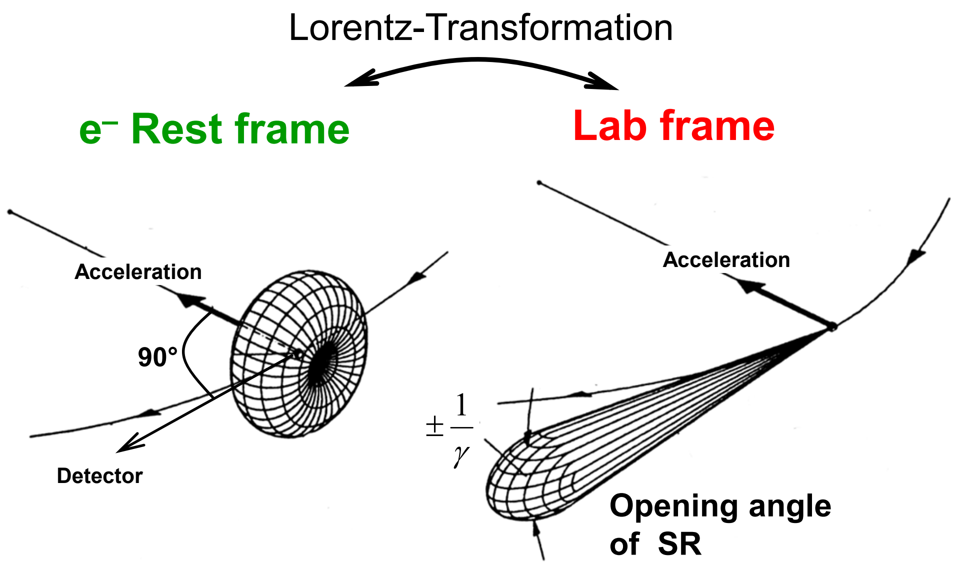
Brilliance = Photon flux at energy E within 0.1% bandwidth normalized to beam size and divergence

$$B = \frac{\mathcal{F}_n}{4\pi^2 \Sigma_x \Sigma_y \Sigma'_x \Sigma'_y}$$

(often used as figure of merit)

Principle of Synchrotron Radiation

Acceleration of charged particle



- **natural opening angle ~1/γ = 0.06-0.5mrad**

  e.g. ESRF, PETRA3: 1/(1957x4.5[GeV]) = 85µrad

- **Accelerated charge emits electromagnetic radiation**
- **Angular distribution like for electric Dipole**

- **Acceleration induced by Lorentz force**

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

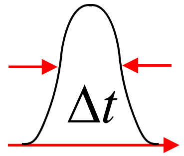
i.e. transverse acceleration in a storage ring

- **Radiated power**

$$P = \frac{e^2 c}{6\pi\varepsilon_0 \left(m_0 c^2\right)^4}\frac{E^4}{\rho}$$

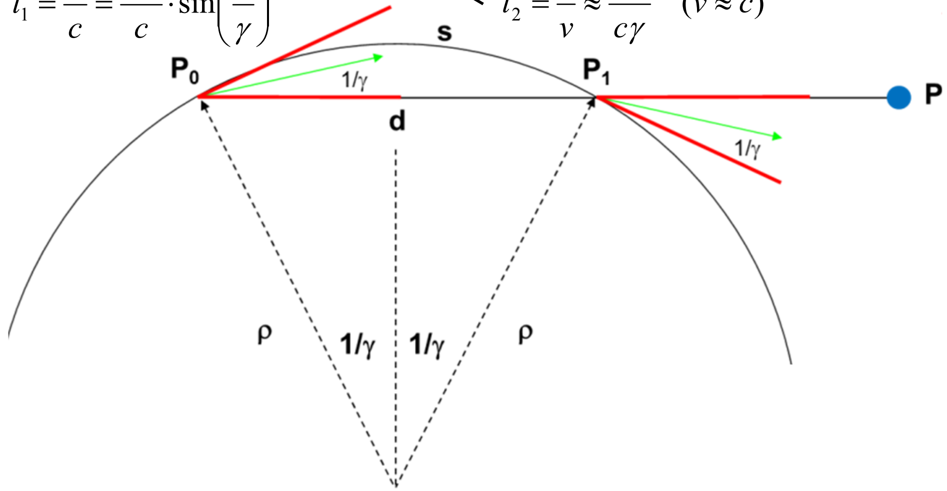
Dipole Radiation

$$\Delta t = t_2 - t_1 \approx \frac{2\rho}{c}\left[\frac{1}{\gamma} - \underbrace{\sin\left(\frac{1}{\gamma}\right)}_{\approx \frac{1}{\gamma} - \frac{1}{6\gamma^3}}\right] = \frac{\rho}{3c\gamma^3}$$



- **Due to the narrow opening cone ($\Theta = 1/\gamma$) the observer will see only a short light pulse with duration $\Delta t \sim \rho / c\gamma^3$**

$$t_1 = \frac{d}{c} = \frac{2\rho}{c}\cdot\sin\left(\frac{1}{\gamma}\right) \qquad t_2 = \frac{s}{v} \approx \frac{2\rho}{c\gamma} \quad (v \approx c)$$



- **This results in a broad continuous Fourier spectrum with a characteristic frequency**

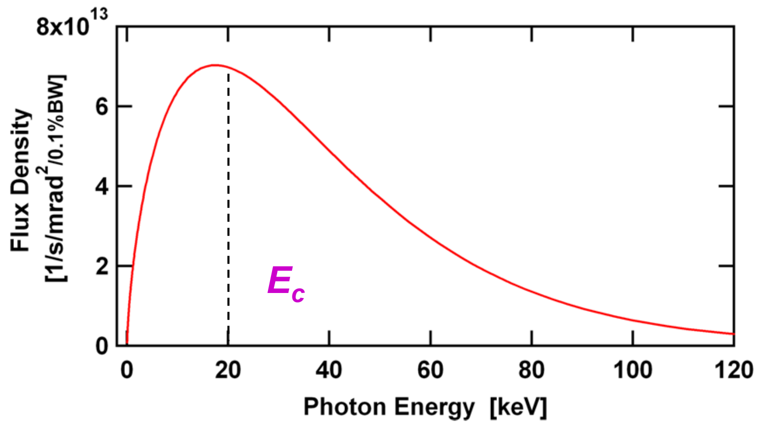
$$\omega_c \sim c\,\gamma^3/\rho \sim E_e^2 \cdot B$$

($\sim 10^{19}$ Hz → $\lambda \sim 1$Å)

or "critical" energy E_c

$$E_c\,[\text{keV}] = 0.665 \cdot E_e^2\,[\text{GeV}] \cdot B_0\,[\text{T}]$$

(ESRF, PETRA: $E_c \sim 20$keV)



Dipole Radiation

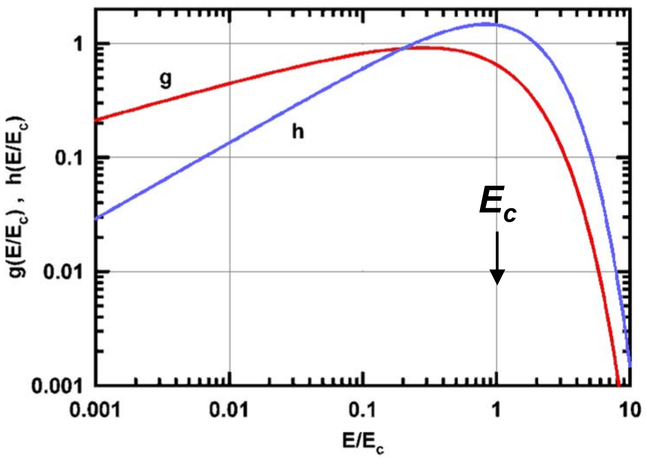
- **Spectral Intensity Distribution**

  (→Schwinger equation)

$$\frac{d\mathcal{F}}{d\Omega}(E,\Psi)=\frac{3\alpha}{4\pi^2}\gamma^2\frac{I_e}{e}\frac{\Delta\omega}{\omega}\left(\frac{E}{E_c}\right)^2\left(1+\gamma^2\psi^2\right)\times\left[K_{2/3}^2(\xi)+\frac{\gamma^2\psi^2}{1+\gamma^2\psi^2}K_{1/3}^2(\xi)\right]$$

with

$$\xi=\frac{E}{2E_c}\left(1+\gamma^2\psi^2\right)^{3/2}$$



- **Flux density**, emitted **in orbit plane** $\psi=0$

  [phot./sec/mrad²/0.1%bw]

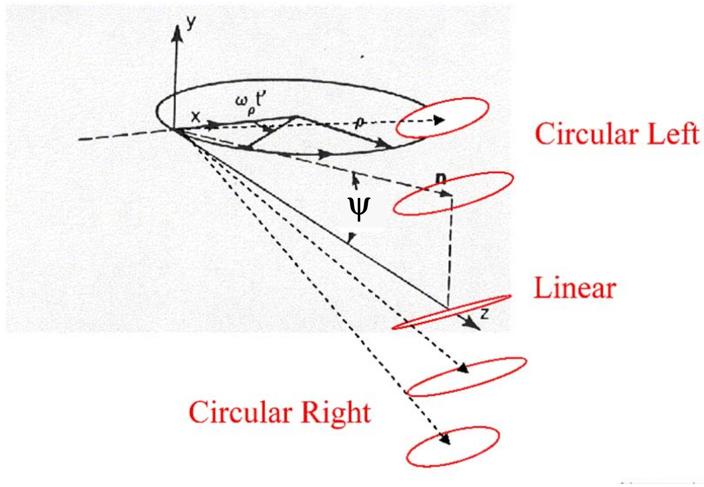
  $d\mathcal{F}/d\Omega(E)|_{\psi=0}$ **= 1.33·10¹³** E_e^2**[GeV] ·** I_e**[A]** $h(E/E_c)$

- **Flux, integrated over all vertical angles** ψ

  [phot./sec/mrad/0.1%bw]

  $d\mathcal{F}/d\theta(E)$ **= 2.46·10¹³ ·** E_e^2**[GeV] ·** I_e**[A] ·** $g(E/E_c)$

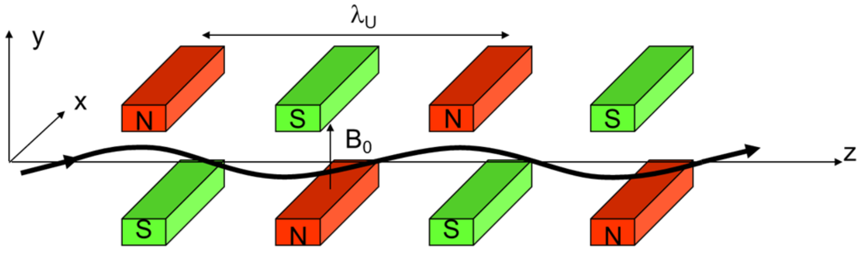
- **Linearly polarised in orbit plane**



Electron Trajectory in an Insertion Device

Lorentz force $\vec{F} = \gamma\, m_0 \frac{d\vec{v}}{dt} = e\vec{v} \times \vec{B}$

with $\gamma = \frac{1}{\sqrt{1-\beta^2}}$, $\beta = \frac{v}{c}$



Assume small angular deflections $v_x,\, v_y \ll v_z \sim c$

Equations of motion:

$$x'' = \frac{d^2x}{dz^2} = -\frac{e}{\gamma\, m_0 c}\left(B_y - y'B_z\right)$$

with $\dot{x} = \frac{dx}{dt} = \frac{dx}{dz}\frac{dz}{dt} = x'\dot{z}\,,\quad \dot{z} = \beta c \approx \text{const},\quad \beta \approx 1$

$$y'' = \frac{d^2y}{dz^2} = -\frac{e}{\gamma\, m_0 c}\left(x'B_z - B_x\right)$$

For a sinusoidal vertical field $(0,\, B_y\,,\, 0)$:

$$B_y = B_0 \sin\left(\frac{2\pi}{\lambda_U} z\right)$$

Angular deflection $x' = \frac{K}{\gamma}\cos\left(\frac{2\pi}{\lambda_U} z\right)$

Displacement $x = \frac{\lambda_U}{2\pi}\frac{K}{\gamma}\sin\left(\frac{2\pi}{\lambda_U} z\right)$

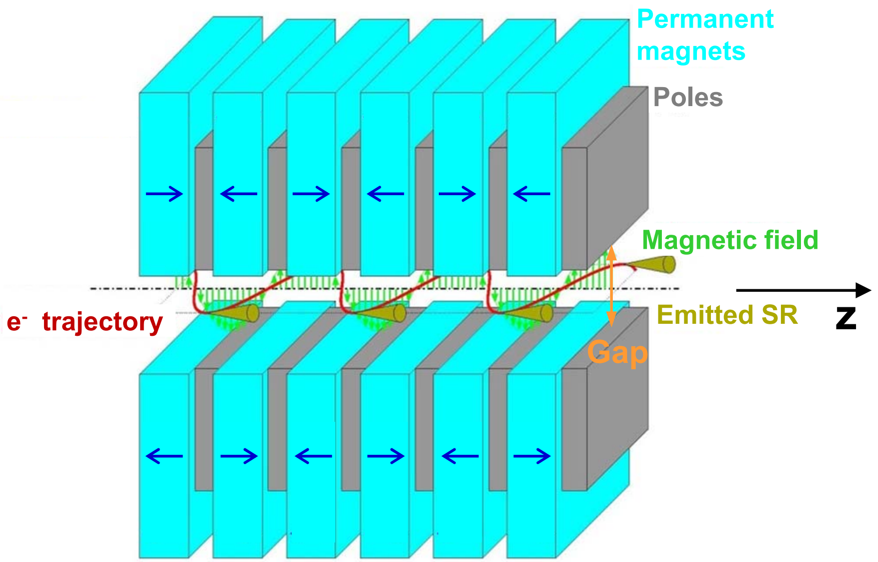
with the so-called **Deflection Parameter *K***

$$K = \frac{e}{2\pi\, m_0 c} B_0\, \lambda_U \quad = \quad 0.934 \;\; B_0\,[\mathrm{T}] \;\; \lambda_U\,[\mathrm{cm}]$$

Maximum angular deflection angle $\delta = \pm K/\gamma$

K is a measure for the strength of the insertion device

Wigglers



- Alternating magnetic field

$$B(z) = B_0 \sin\left(\frac{2\pi}{\lambda_U} z\right)$$

Period length λ_U (typ. 10-30cm)
Peak field B_0 (typ. >1.5T)
Number of periods $N=L/\lambda_U$ (typ. 5-100)

- K-parameter: $K \gg 1$, typ. $K > 10$

  Opening angle of the emitted SR $\delta = \pm K/\gamma$

  → spatial power distribution (typ. ~mrad)

Intensities of all poles add up (incoherently)

$Flux_{Wiggler} = 2 \cdot N \cdot Flux_{Dipole}$ (for equal E_c)

→High intensities

→High photon energies

Critical energy:

E_c [keV] = 0.665$\cdot E_e^2$[GeV] $\cdot$ B_0[T]

Emitted total power of a wiggler or undulator with length $L=N\cdot\lambda_U$: (typ.: 50kW)

P_{tot} = 0.633 $\cdot$ B_0^2 [T] $\cdot$ L [m] $\cdot$ E_e^2 [GeV] $\cdot$ I_e [A]

Polarisation of wiggler radiation:
linearly polarised in the orbit plane ψ=0,
unpolarised out of plane

Undulator Radiation

Consider K<<1:

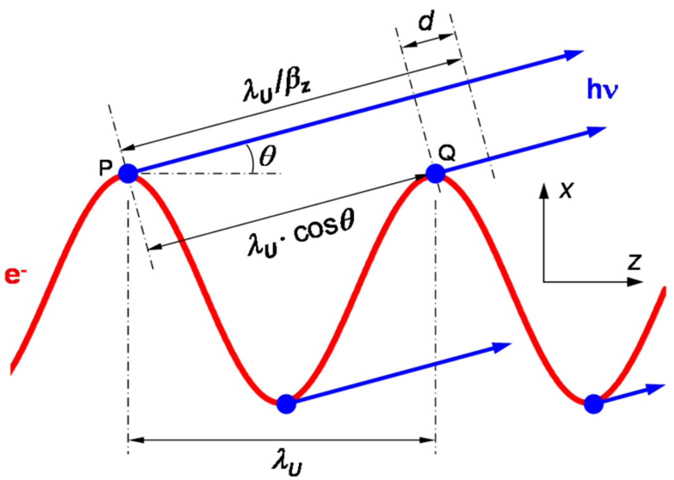
- Maximum angular deflection is much smaller than the opening angle of the radiation cone
- Observer can fully follow the sinusoidal trajectory
- Wavelength of the emitted light $\lambda_R \sim \lambda_U$ is drastically shortened due to relativistic effects:

Lorentz contraction: $\lambda_u \rightarrow \frac{\lambda_u}{\gamma}$

Doppler effect: $\lambda_u \rightarrow \frac{\lambda_u}{2\gamma}(1+\gamma^2\theta^2)$

Combined: $\lambda_R \rightarrow \frac{\lambda_u}{2\gamma^2}(1+\gamma^2\theta^2)$

For ~GeV machines: $2\gamma^2 \sim 10^7$, λ_U ~mm → λ_R ~Å



Time for the e- to travel one period: $\lambda_U / c\overline{\beta}_z$

In this time the wavefront from P will propagate: $\lambda_U / \overline{\beta}_z$

Constructive interference for: $d = \lambda_U / \overline{\beta}_z - \lambda_U \cos\theta \; = \; n\lambda_R$

$$\rightarrow \quad \lambda_R = \frac{\lambda_U}{2n\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\theta_x{}^2+\gamma^2\theta_y{}^2\right)$$

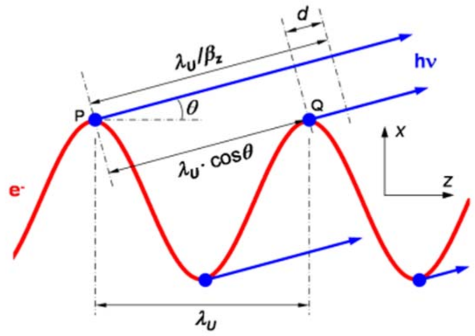
$$\lambda_R\,[\text{Å}] = \frac{13.056\;\lambda_U[\text{cm}]}{E^2[\text{GeV}]}\left(1+\frac{K^2}{2}\right) \quad \text{or} \quad E_1[\text{keV}] = \frac{0.950\;E_e{}^2[\text{GeV}]}{\lambda_U[\text{cm}](1+K^2/2)}$$

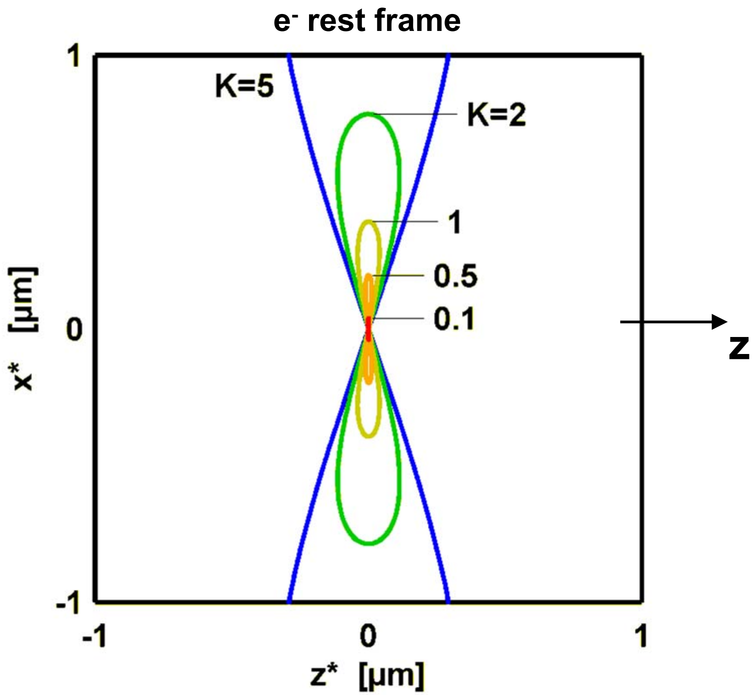
(on-axis)

typically: K = 1 3, λ_U = 1 5 cm → λ_R ~ nm Å

Higher Undulator Harmonics

- Constant propagation velocity along trajectory *s*
- Drift velocity along the averaged propagation direction *z* does vary
- Electron motion in its rest frame corresponds to a figure 8

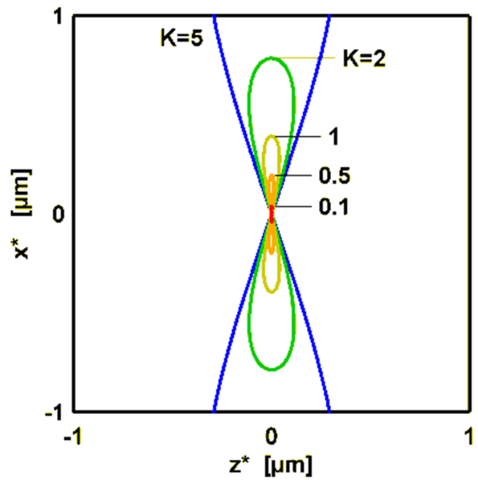


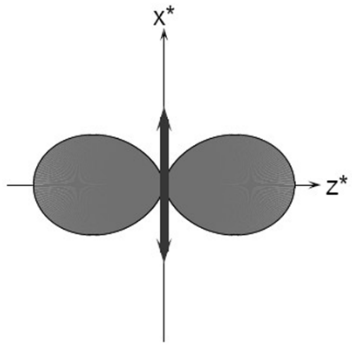
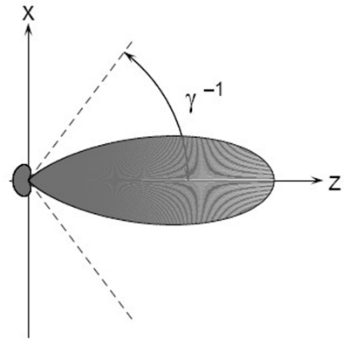
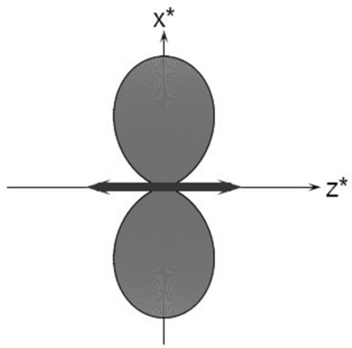
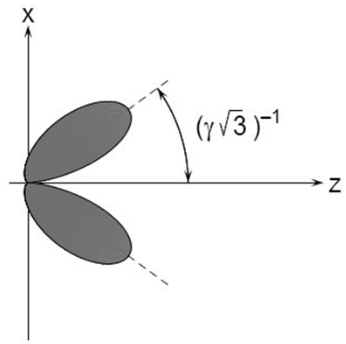


- Larger *K*-parameter → stronger modulation of v_z
- **The modulation of v_z is the reason for the occurance of higher undulator harmonics**

  (usually highly desired!)

Odd and Even Undulator Harmonics



	e⁻ rest frame	laboratory frame
Transverse oscillation ↓ Odd harmonics		
Longitudinal oscillation ↓ Even harmonics		

2 longitudinal oscillations for 1 transverse → twice the frequency

Transverse oscillation → Odd harmonics → on-axis emission

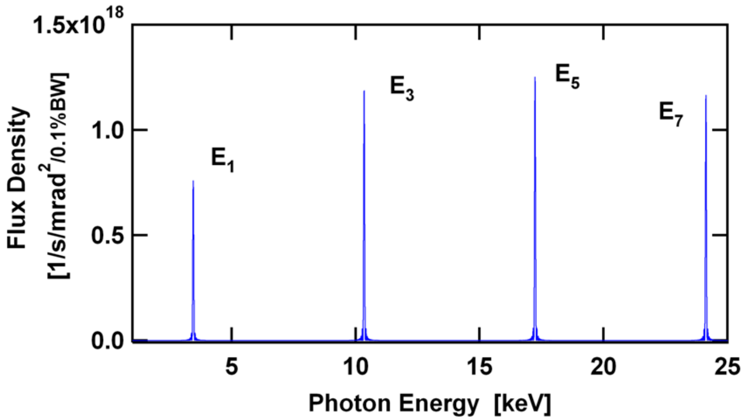
Longitudinal oscillation → Even harmonics → off-axis radiation

Undulator ... → … Wiggler

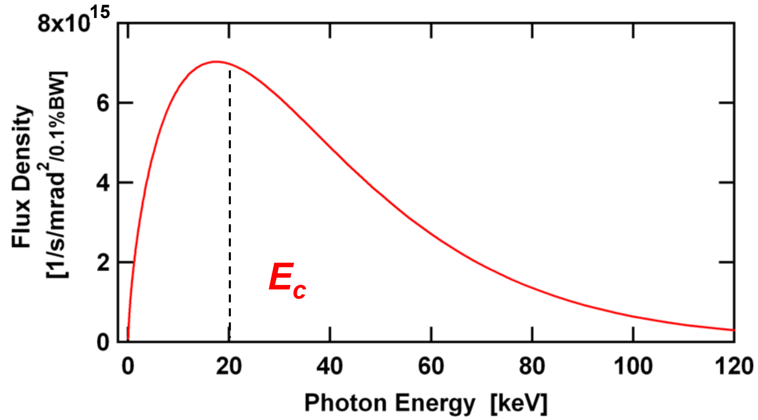
Discrete spectrum
characteristic quantity: E_1

K-parameter →

Continuous spectrum
characteristic quantity: E_c



→



larger K-Parameter ↑↑ → more higher harmonics
→ fundamentale E_1 ↓ → spacing of harmonics ↓

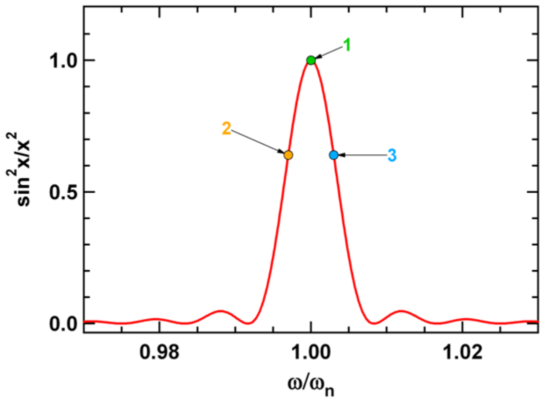
… → overlap of harmonics → quasi-continuous spectrum = wiggler

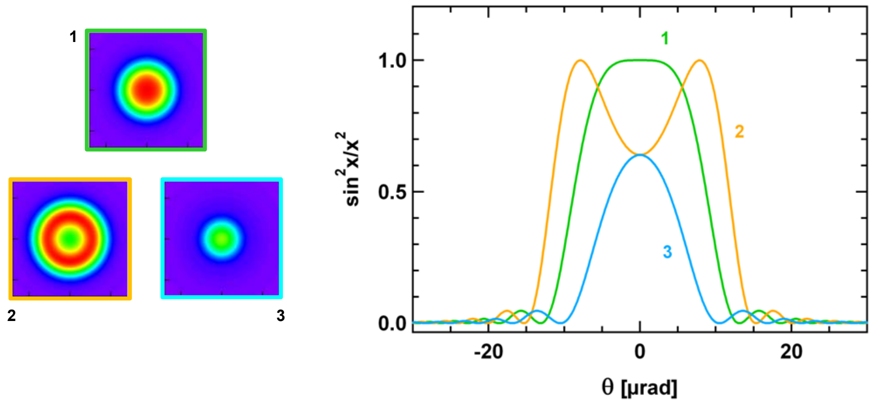
Spectral and Spatial Distribution of SR

(for a filament e-beam)

$$\left.\frac{d^2\mathcal{F}}{d\omega\, d\Omega}\right|_{\theta_{x,y}=0} \propto N^2 \sum_{n=1,3,5\ldots}^{\infty} \boxed{H_n(\omega,\theta)} \cdot \boxed{F_n(K)}$$

$$\boxed{H_n(\omega,\theta) = \frac{\sin^2 x}{x^2}} \quad \text{with} \quad x = N\pi \frac{\Delta\omega}{\omega_1(\theta)} = N\pi\left(\frac{\omega - n\omega_1(0)}{\omega_1(0)} - \frac{\omega}{\omega_1(0)}\gamma^2\theta^2\right)$$





Spectral dependence *H(ω,θ=0)*
(Energy domain)
of an undulator harmonics along beam axis

Angular intensity distribution
(Spatial domain)

Spectral width
(~ 1% ... 0.1%)

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\omega}{\omega} = \frac{1}{nN}$$

Natural source size and divergence

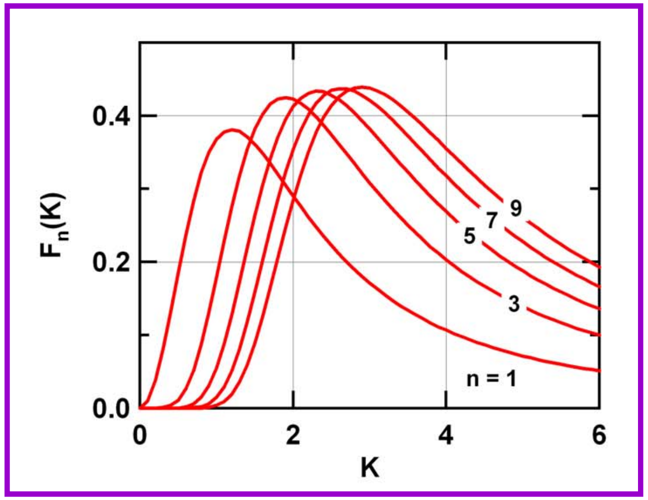
$$\sigma_R = \frac{\sqrt{2\lambda L}}{4\pi}, \quad \sigma'_R = \sqrt{\frac{\lambda}{2L}}$$

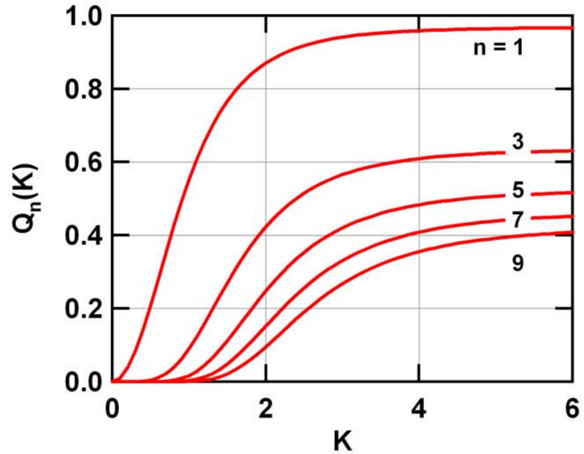
but Gaussian approx.
not always accurate

(typically 1-10μm 1-10μrad)

Undulator: Photon Flux

F_n





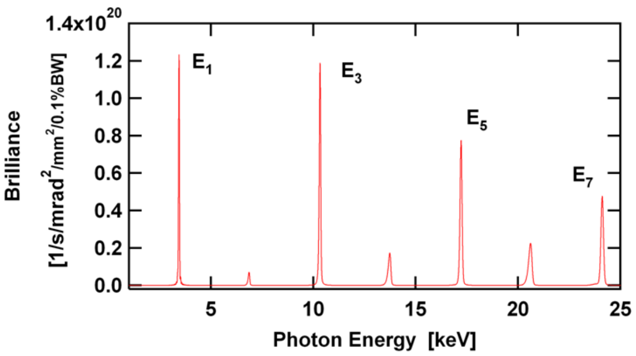
On-axis flux density [*phot./sec/mrad²/0.1%bw*]
in practical units:

$$\left.\frac{d\mathcal{F}_n}{d\Omega}\right|_{\theta_{x,y}=0} = 1.744\times10^{14}\ N^2\ E^2[\mathrm{GeV}]\,I_e[\mathrm{A}]\ F_n(K)\quad,\ (n=1,3,5...)$$

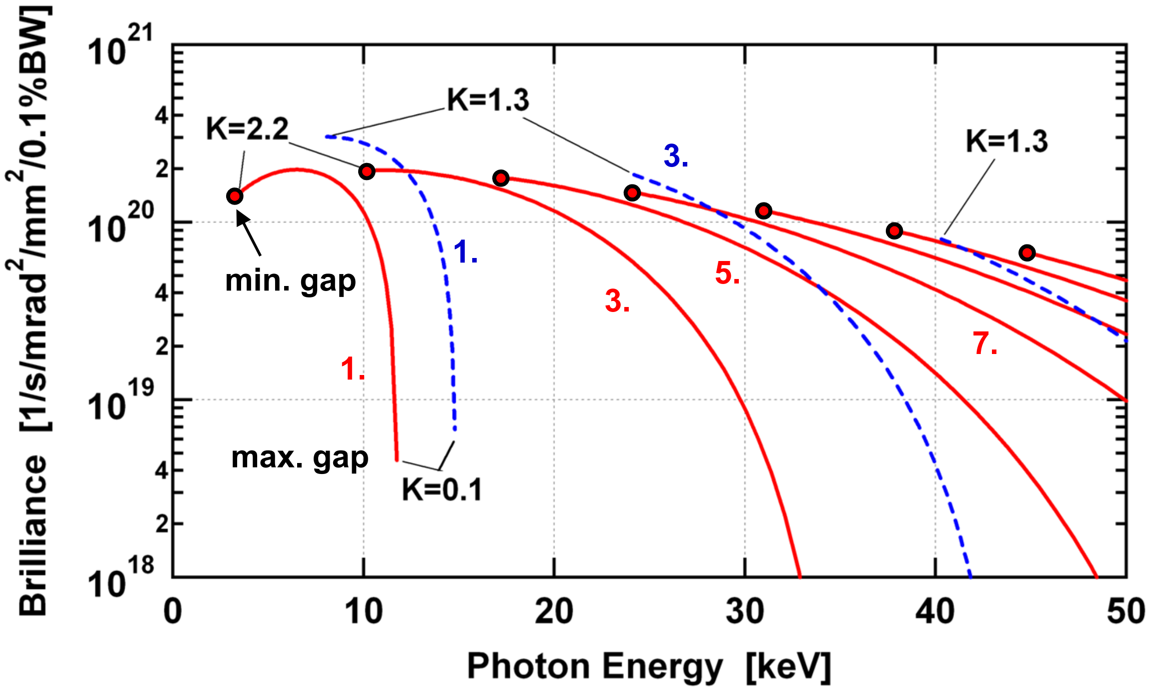
Integrated over the „*central cone*" → Flux
[*phot./sec/0.1%bw*]:

$$\mathcal{F}_n = 1.431\times10^{14}\ N\ I_e[\mathrm{A}]\ Q_n$$

Tuning of Photon Energy



constant Gap!



Change of photon energy by:

- **(variation of electron energy γ)**
- **variation of K-parameter by changing the gap**

  gap↑ → ↓*B* → *K*↓ → λ_R↓ = E_{ph}↑

$$\lambda_R = \frac{\lambda_U}{2n\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

K_{max} > 2 : fully tunable

K_{max} = 1.3 : tunable only above 3rd harmonic

Emittance Effects

e-Beam emittance ε $\varepsilon_{x,y} = \sigma_{x,y} \cdot \sigma'_{x,y}$

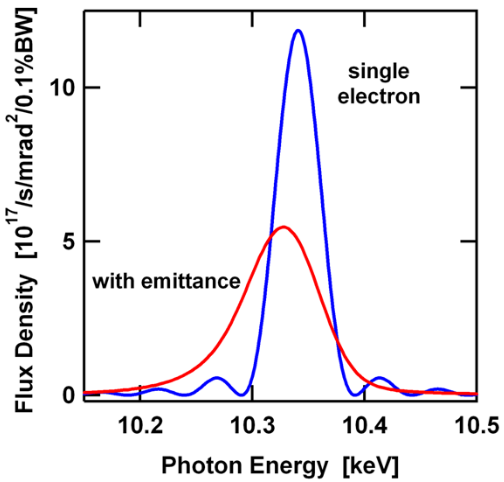
- Broadening of undulator harmonics
- Intensity reduction

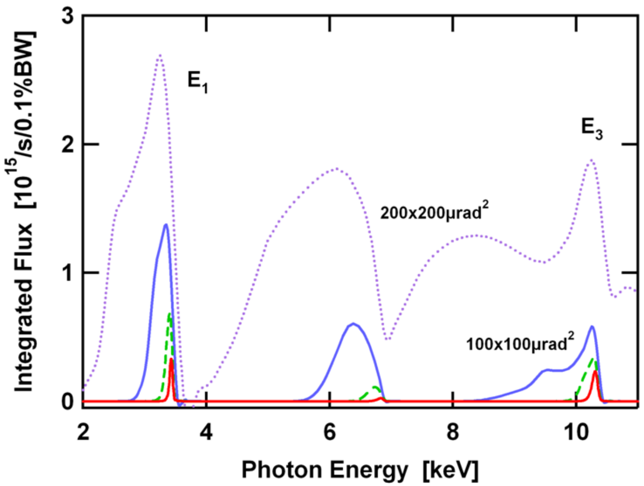
(Light sources: ε_x ~ 1-450 nm rad, coupling $\kappa=\varepsilon_y/\varepsilon_x$ ~1%)

Spatial Effects:

- Enlargement of **size** and **divergence** of the emitted photon beam

$$\Sigma_{x,y} = \sqrt{\sigma^2_{x,y} + \sigma^2_R} \quad , \quad \Sigma'_{x,y} = \sqrt{\sigma'^2_{x,y} + \sigma'^2_R}$$





Spectral Effects:

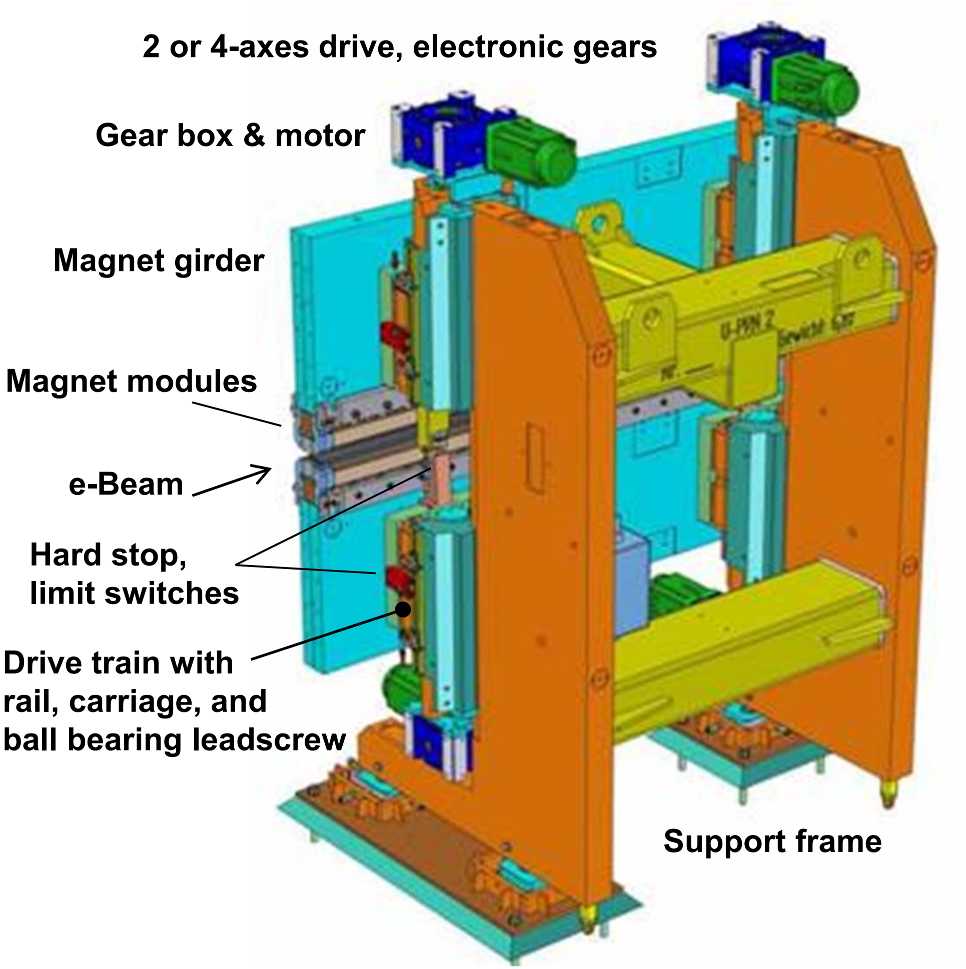
- **Red shift** with a low energy tail
- **Even harm.** of off-axis electrons get visible on-axis

- Symmetric broadening due to **energy spread Δγ/γ** of electrons (typ. ~0.1%)

Spectral intensity distribution (at fixed gap!), integrated over **different apertures:**

25×25µrad², 50×50µrad², 100×100µrad² and 200×200µrad²

Undulator Technology: Support Structure



(installed e.g. at PETRA III or sFLASH)

Various requirements:

Minimum girder deformation

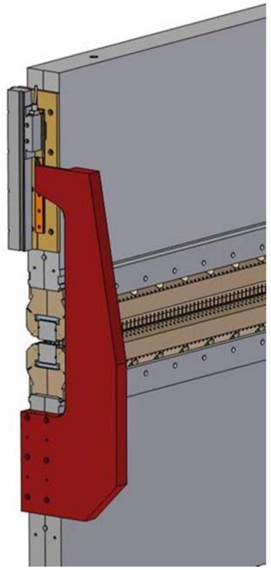
Changing magnetic forces up to ~100kN

Gap accuracy of ~1µm (1µm ≅ 1 Gs)

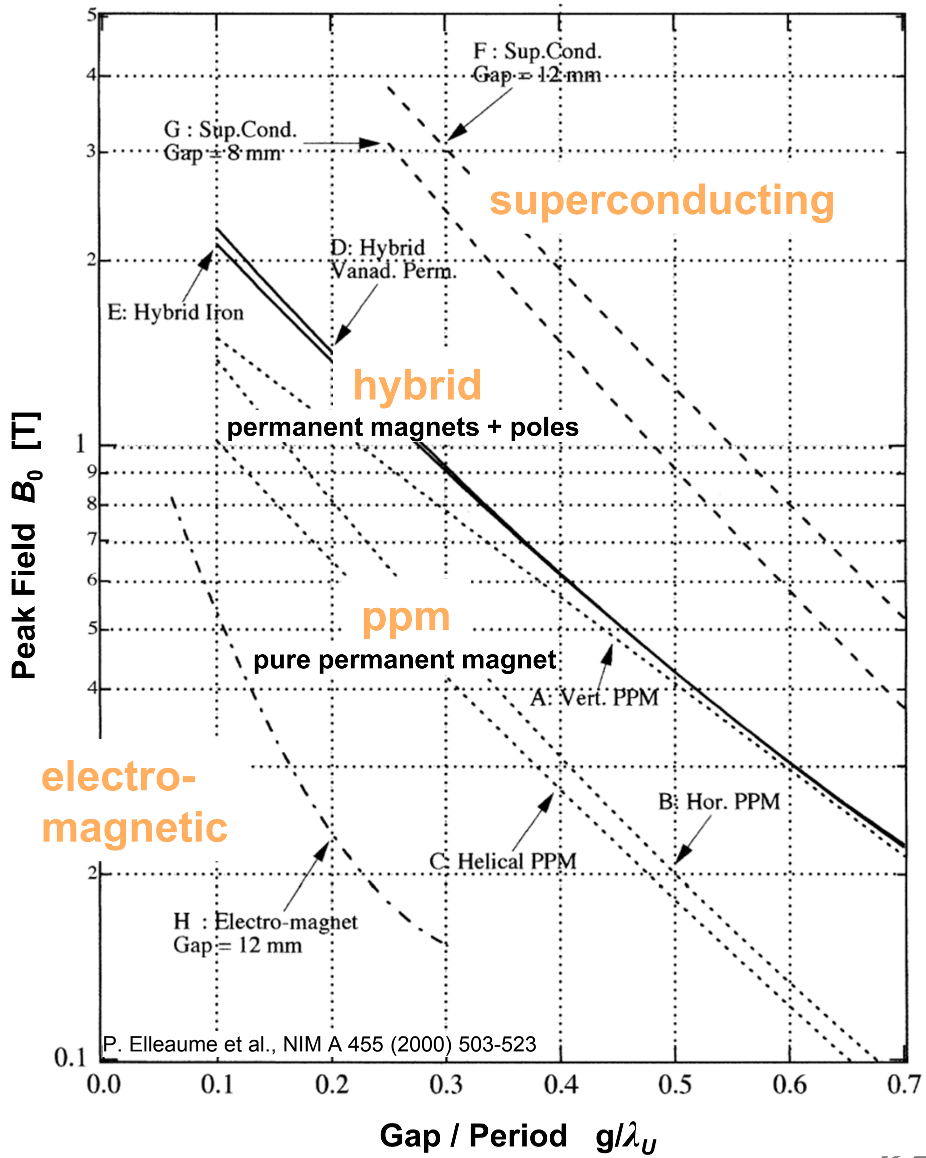
Possibility for taper up to ~1mm

Temperature insensitivity

Gap measurement system fully decoupled from load support



Magnet Technology



Magnetic force

$$F = \frac{B_0^2 \, L \, W}{4\mu_0}$$

Area *L* x *W* of magnet structure

$$F[\mathrm{N}] \approx 2 \cdot 10^5 \; B_0^2 \, [\mathrm{T}] \, L[\mathrm{m}] \; W[\mathrm{m}]$$

Peak field

$$B_0 = a \, e^{\left(b \frac{g}{\lambda_U} + c \left(\frac{g}{\lambda_U} \right)^2 \right)}$$

for ~ 0.1 g/λ_U 1

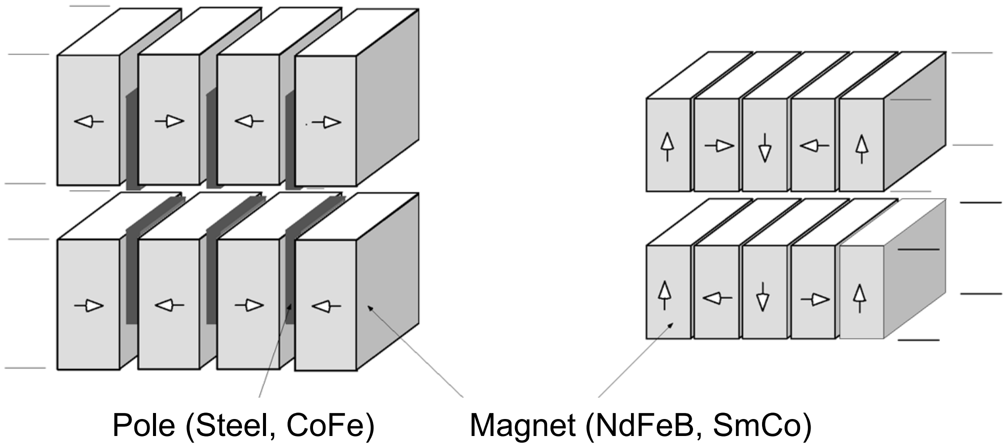
Permanent Magnet Technology

Hybrid design

- higher field
- field quality limited by
  - mechanical tolerance of poles
  - block errors

Pure permanent magnet (ppm)

- simpler to compute and to correct
- field quality limited by
  - block errors



Magnet materials

	Remanence	Permeability		Coercitivity	T-Koeff
Material	B_r [T]	$\mu_{r,\parallel}$	$\mu_{r,\perp}$	$H_{c,j}$ [kA/m]	[%/°C]
$SmCo_5$	0.9–1.01	1.05		2400–1500	–0.04
Sm_2Co_{17}	1.04–1.12	1.05–1.08		2100–800	–0.03
$Nd_2Fe_{14}B$	1.0–1.45	1.03–1.06	1.12–1.17	3000–900	–0.11

Latest development: Vapor diffusion of Dy into grain boundaries of NdFeB → Hcj increase by >300kA/m !

PM issues:

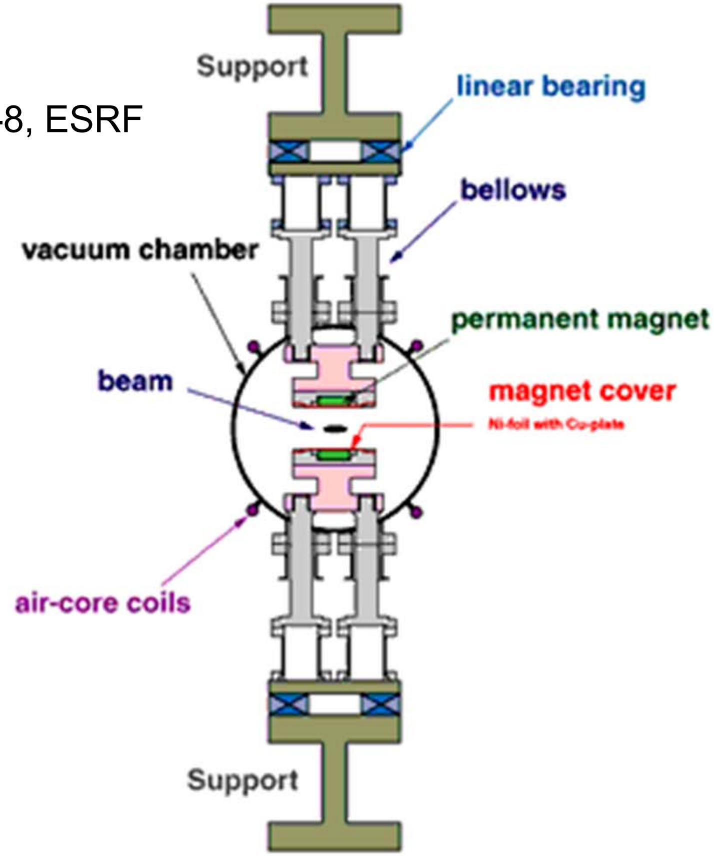
- Magnetic errors imprinted during pressing (Br, angular errors, N/S-effect)
- Radiation hardness
- Temperature resistivity (→ SmCo)
- Machining (NdFeB is a little less brile)
- Expensive (both)

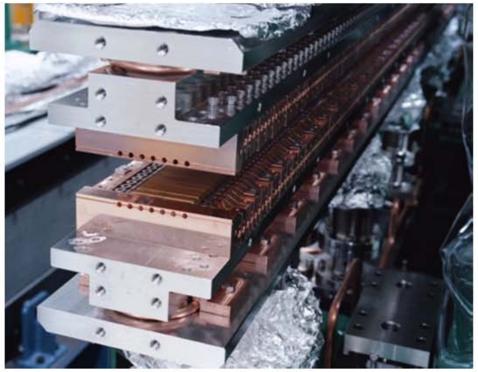
In-Vacuum Undulators

Widely used at many SR sources

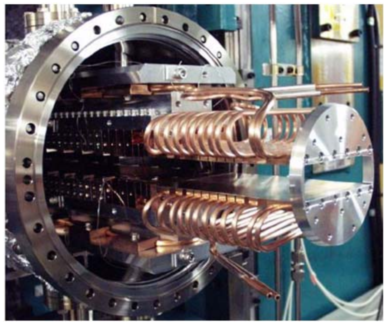
Originally developed at NSLS, SPring-8, ESRF

Minimum magnetic gap of 3-6mm

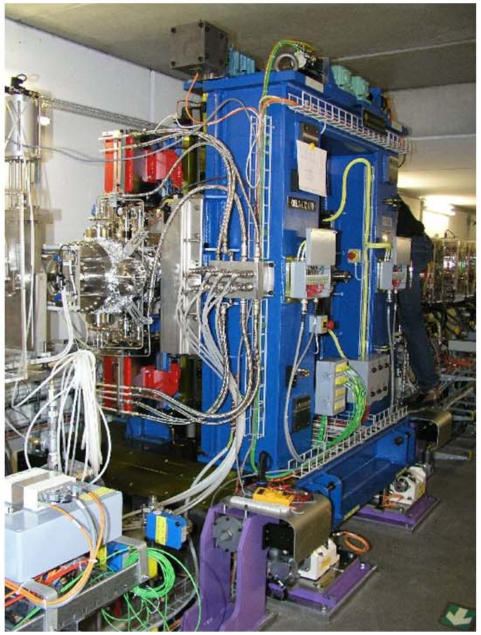




SACLA -XFEL(SPring-8) IVU
L=18x5m, λ_U=18mm

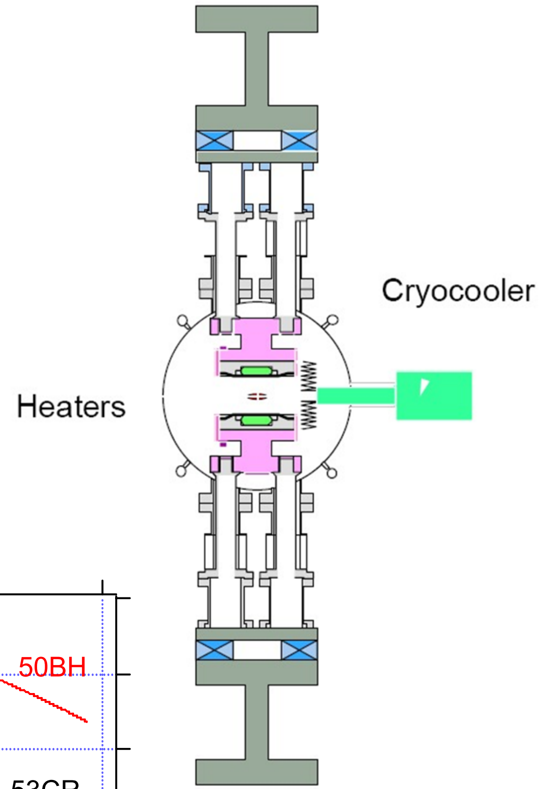


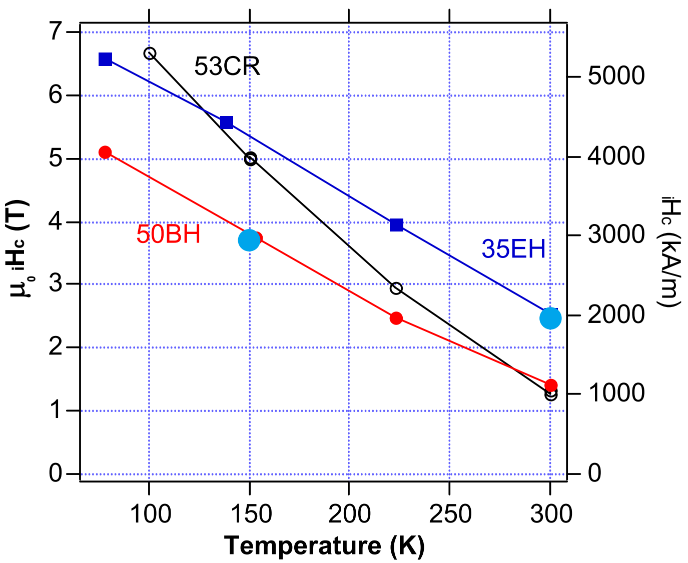
Flexible taper transitions
require careful design

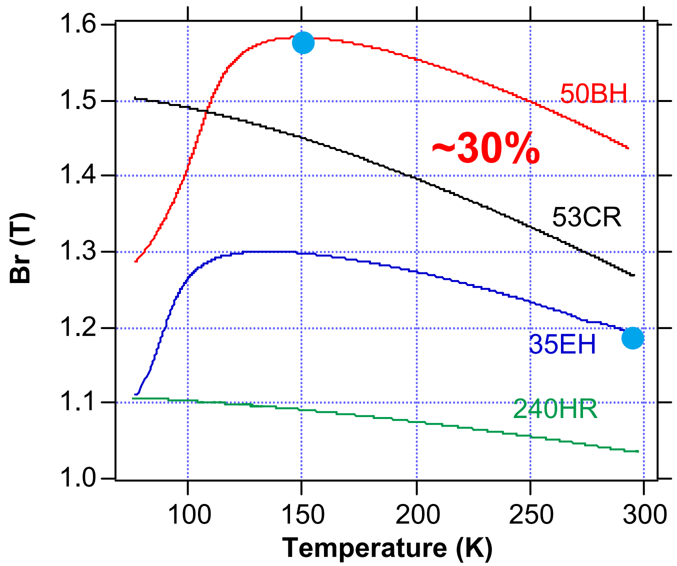


Cryogenic In-Vacuum Undulator

- Increased coercivity at cryogenic temperatures (~130K)
  → choice of high B_r material, high resistance against demagnetization
- Increased remanent field (Br) at low temperatures
  → higher fields at same period length, i.e. larger energy tunability
- Modification of mechanical design (thermal deformation, therm. Isolation), use of cryo-coolers
- Development of magnetic measurements and tuning techniques at cryogenic temperatures
- Some IDs already built or in operation (ESRF, SLS, Diamond, Soleil)



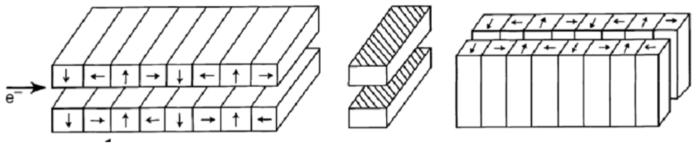




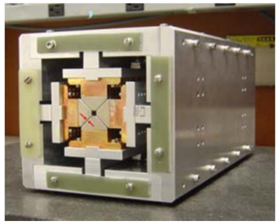
T. Hara, T. Tanaka, SPring-8, PRST-AB 7 (2004)

Helical / Elliptical Undulators

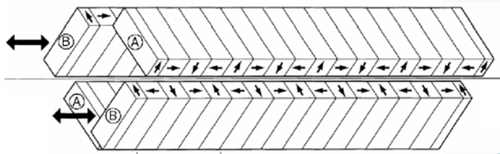
Permanent magnet devices



K.J.Kim

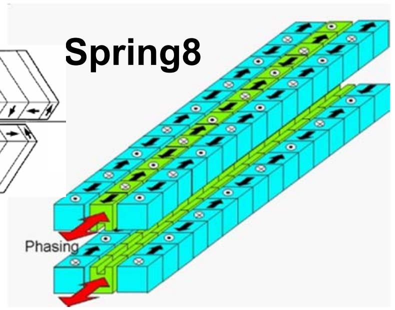


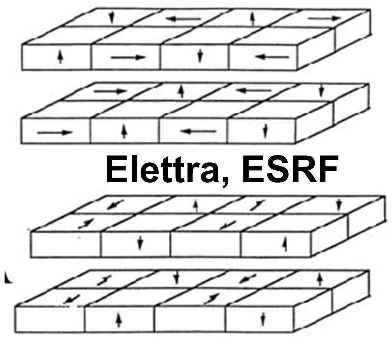
Cornell



H.Onuki

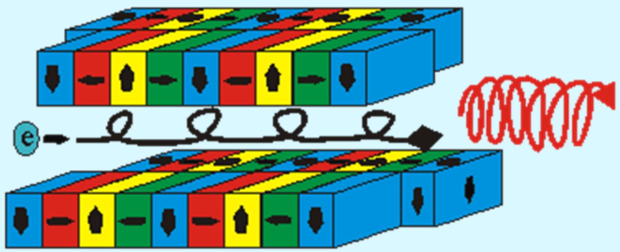
Spring8



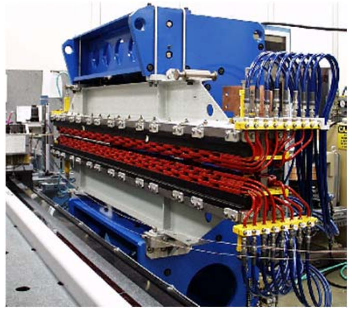


Elettra, ESRF

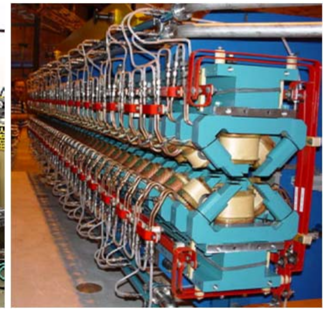
- Apple2 design: highest field
  most popular



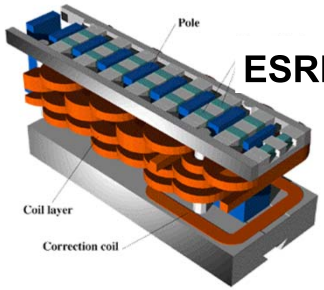
Electromagnetic devices



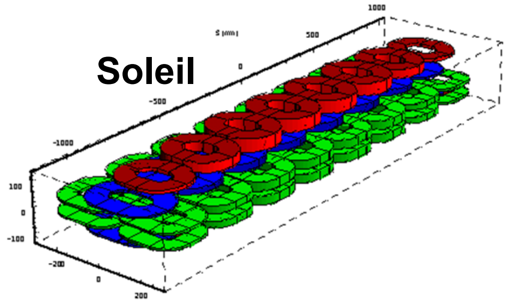
APS



Elettra / SLS



ESRF



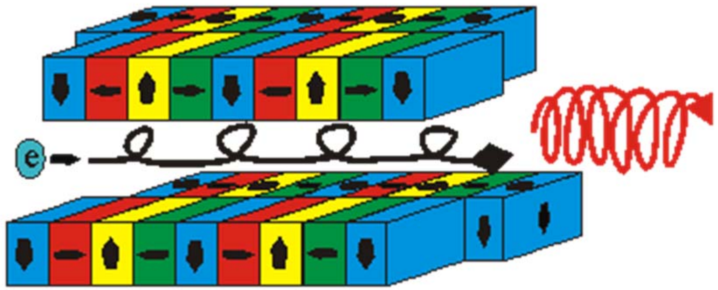
Soleil

- \+ fast helicity change
- \+ mechanically simpler
- – weak fields
- – restricted to long periods
- – not invisible to other users
- – not hysteresis-free

Apple2 Undulator: Principle

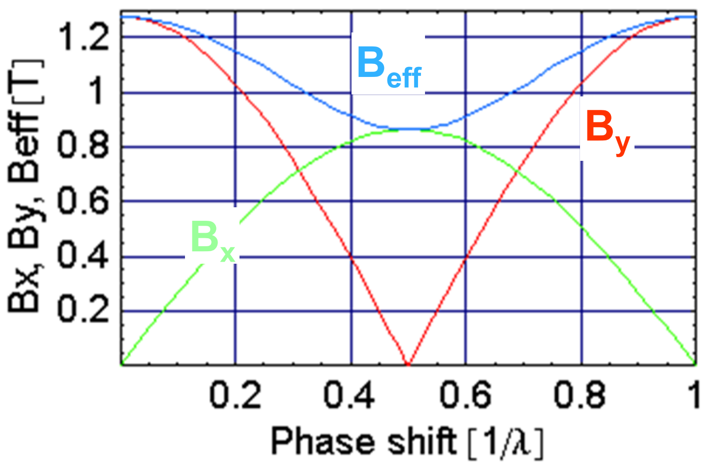
Split magnet rows (movable along the beam)

- **variable polarization**
- **high field**
- **planar structure**

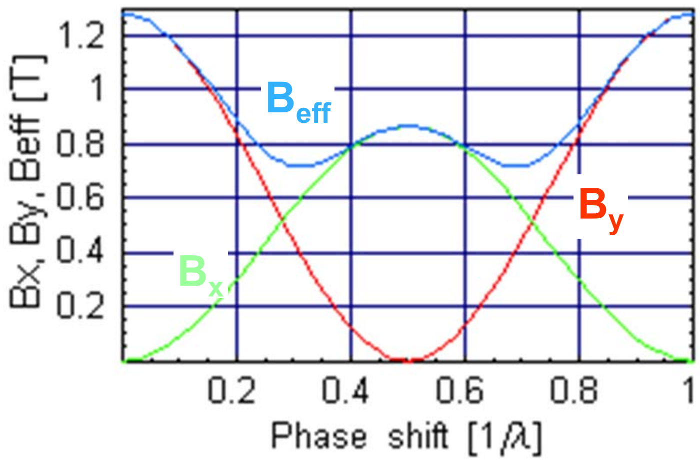


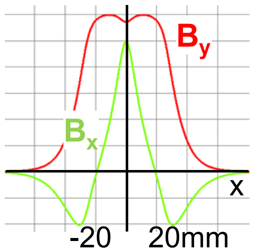
Shift = 0 horizontal linear polarization
Shift = $\lambda/2$ vertical linear polarization

Parallel motion → circular/ellipt. polarization



Antiparallel motion → 45deg linear polarization





But: Transverse field profiles have a large horizontal field roll-off with significant impact on beam dynamics

APPLE2 – UE65 at PETRA III

L = 5 m, λ_U = 65.6 mm, gap = 11 mm

B_{eff}=1.04T, K_{eff}=6.4 (circ.mode)

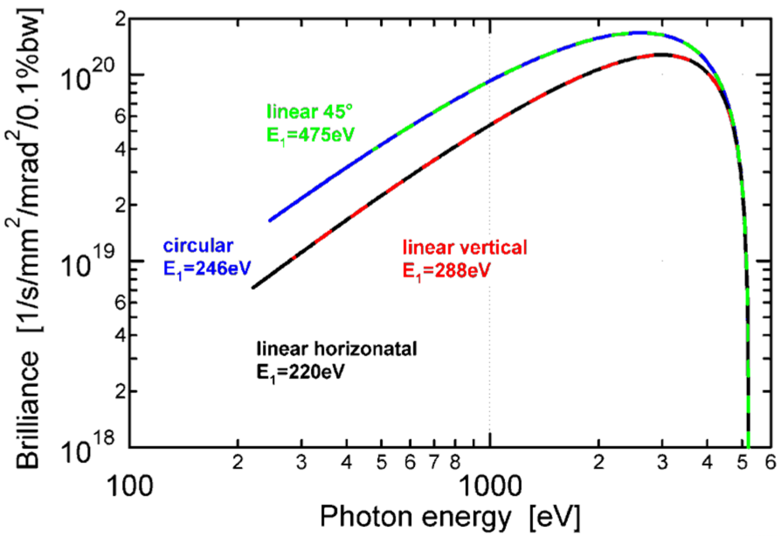
E_1^{circ} = 245eV ~ C K-edge

P_{tot} = 13 kW, dP/dΩ = 0.12 W/μrad² (very low!)

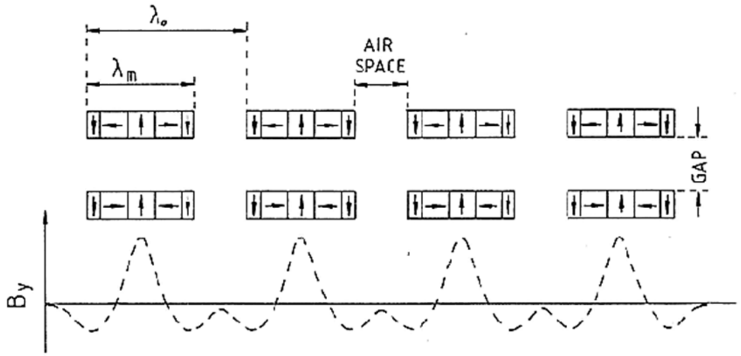
- Additional large transverse and longitudinal magnetic forces in antisymm. mode
- Requires detailed optimization of mechanical support
- with 4-axes drive: → deformation can be partly compensated (J.. Bahrdt et al., conf. proc. SRI09)

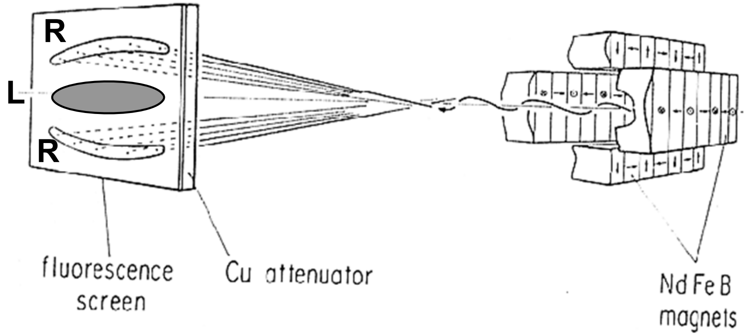
Maximum forces and torques

units: kN, kNm	F_x	F_y	F_z	T_x	T_y	T_z
hor. linear	0	73	0	0	0	0
inclined, 16.4 mm	54	≈ 0	12	6.4	0.75	22.5

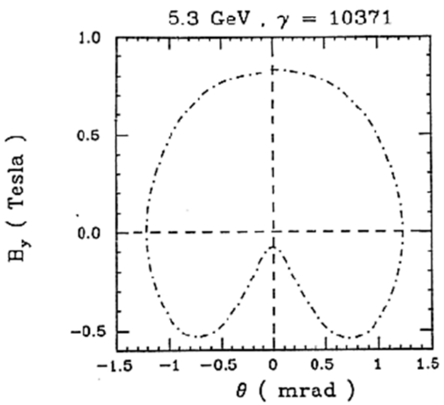


Asymmetric & Elliptical Wiggler

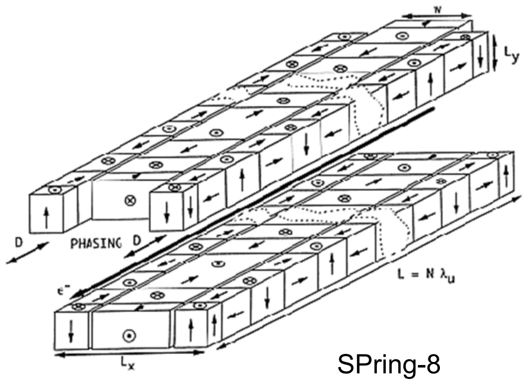




Photon Factory / KEK



DESY, ESRF



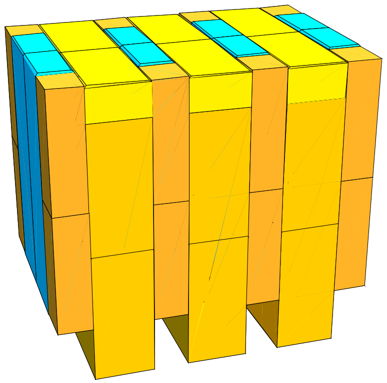
SPring-8

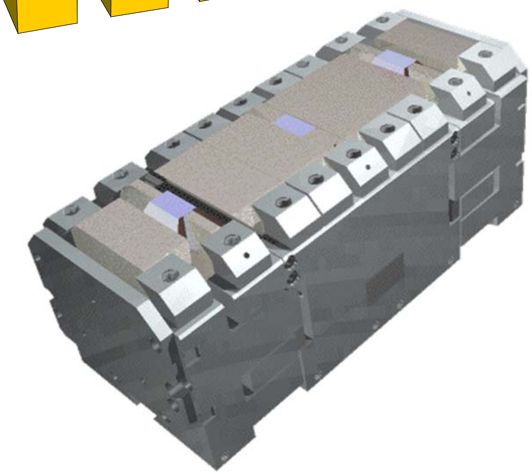
- **mechanically simpler**
- **magnetically delicate** **(large field integrals)**
- **2 source points (on-axis: 1)**

High Field Devices

Permanent magnet devices

- **Hybrid Wiggler** (DESY)
  B=2T, λ_U=11cm, K=21, L=4m, E_c=27keV,





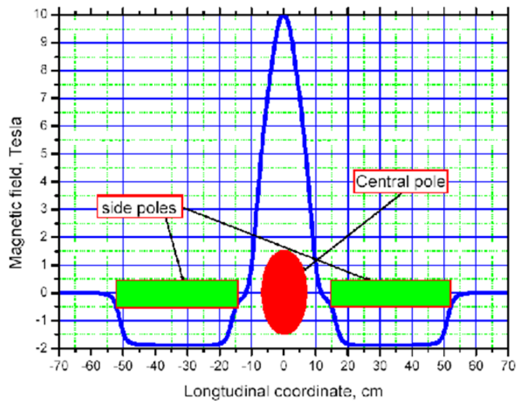
- **Asymmetric Wiggler** (ESRF)
  B=3.1T, λ_U=378mm, 11mm gap

Superconducting devices

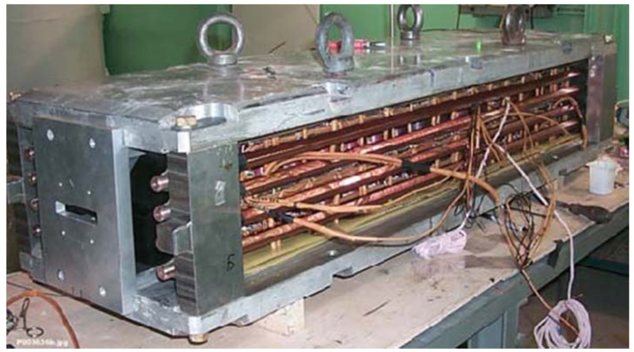
- **3.5T Wiggler** (Elettra, MAX-Lab)
  λ_U=61mm, gap=10.2mm, 46 poles

- **Superbends** (ALS, BESSY, SLS) : B=3-9T

- **10T Wavelength Shifter** (Spring8)



- **Multipole Wiggler** (HMI, BESSY)
  B=7T, K=92, 13 poles,
  P=56kW !



Superconducting Undulators

Goal: Short period, higher field, harder X-ray spectrum

Technology: NbTi or Nb_3Sn, cold bore, cryo-coolers

iron poles contribute to the field by ~1/3

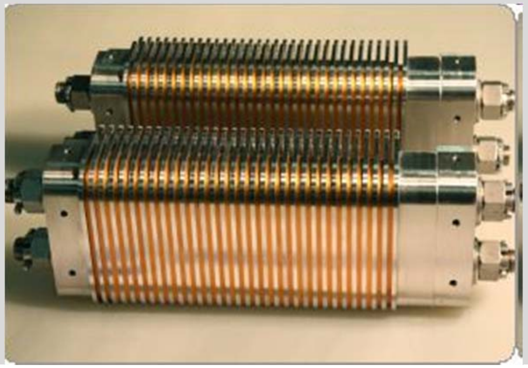
Challenges:

- **Preservation of accuracies towards low temperatures**
  field errors due to therm. expansion, winding errors and large forces on conductor
- **Magn. measurements & tuning mechanisms**
- **Cryo losses**
  development of special diagnostics for SR and image current effects

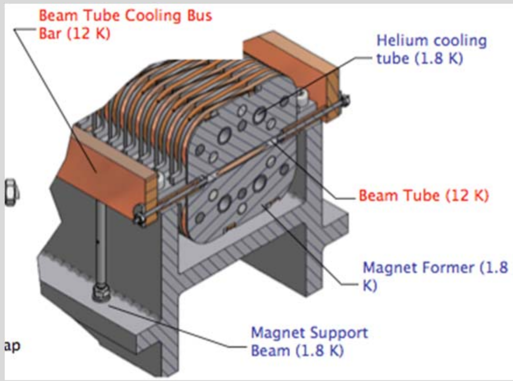
	IVU	CPMU	SCU
λ_u (mm)	21	18	15
N	95	111	133
gap (mm)	6	6	7
B (T)	.75	.88	.98
K	1.47	1.48	1.37

Developments at various labs

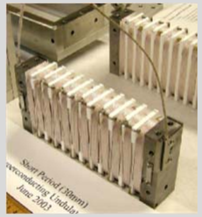
ANKA: NbTi
full devices (1.5m) built, to be installed
shimming strategies, „cold bench"
diagnostics built to study cryo losses



Daresbury: NbTi
helical prototypes and full length device, planar prototypes



LBNL: Nb_3Sn
λ_U=30mm, gap~10mm,
j=6.1kA/m^2, B=3.2T
pushing new technologies,
study YBCO



APS: NbTi
large R&D program, several prototypes

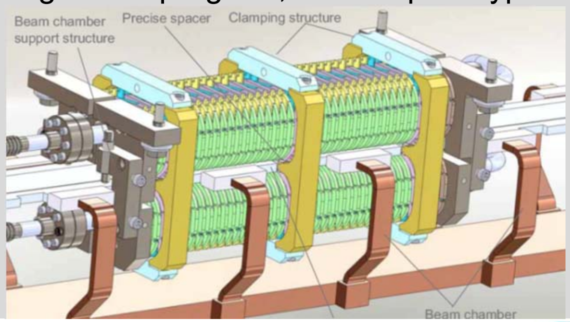


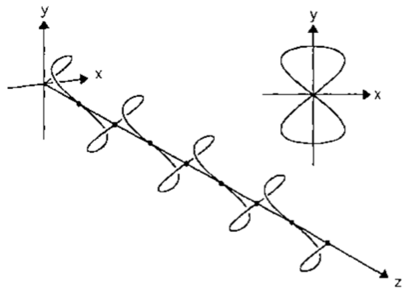
Figure-8 Undulator

Goal: Reduction of high on-axis power density

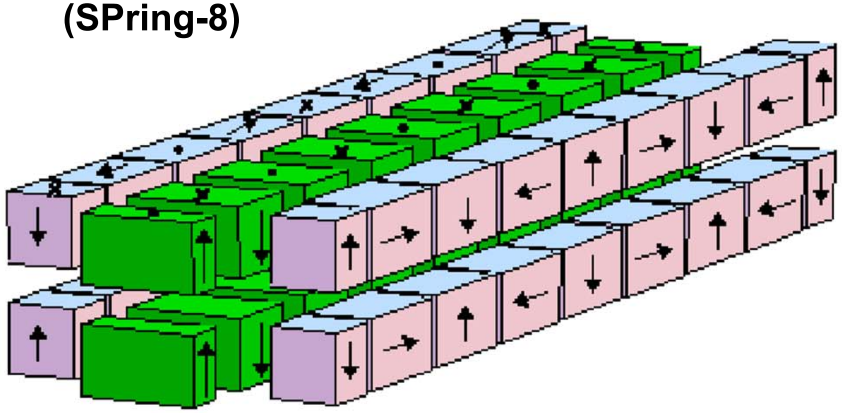
Other alternative:
Helical undulator

$$B_y = \; B_{y0}\,\sin\left(\frac{2\pi}{\lambda_U}z\right)$$

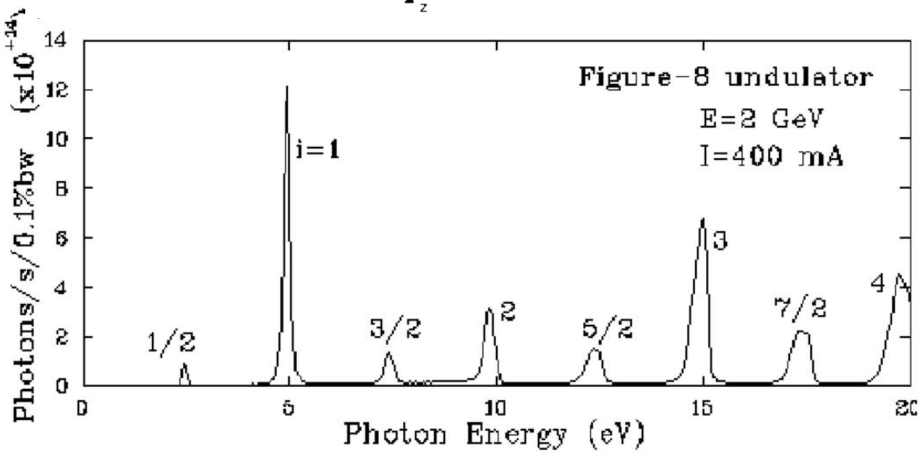
$$B_x = -B_{x0}\,\sin\left(\frac{\pi}{\lambda_U}z\right)$$



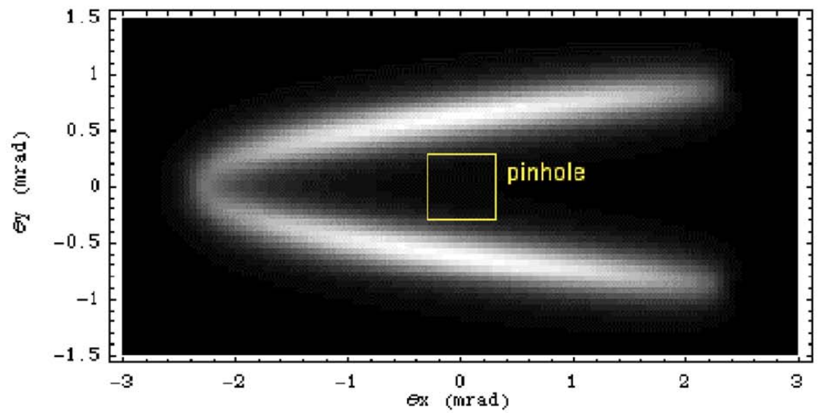
(SPring-8)



Reduction of on-axis power density to ~few %
for only ~30% decrease in 1st harm. flux



(Occurence of half integer odd harmonics)



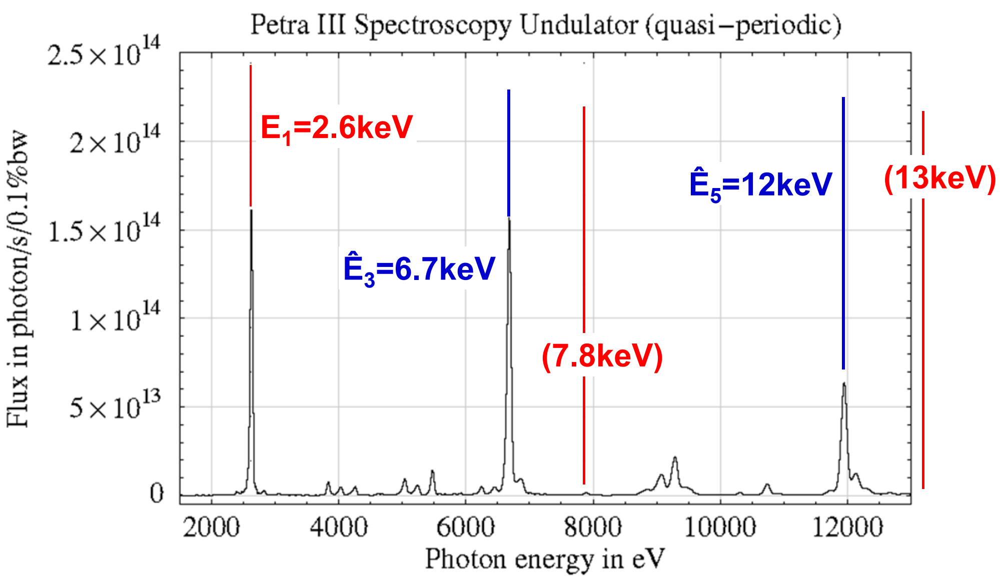
Quasi-Periodic Undulator

Shift of the higher harmonics towards non-integer multiples

S.Sasaki et al., Rev. Sci. Instrum. 66 (1995) 1953

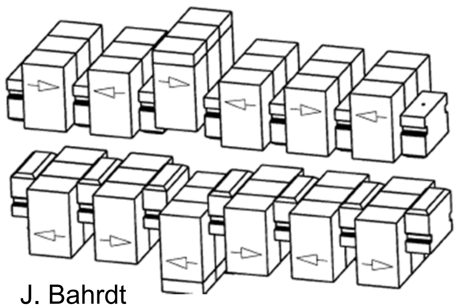
- Suppression of higher order radiation
- realized by modification of distinct magnets
- cleaner photon spectrum !
  (because monochromator usually transmits higher harmonics)
- In operation at various SR facilities

Example: λ_U=31.4mm, gap=9.5mm, L=2m

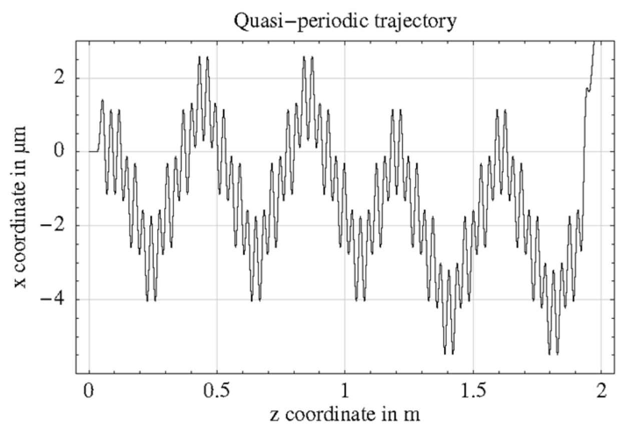


Concept

- Like for diffraction from a quasi-crystal
- Position of poles follow a so-called Fibonacci sequence
- Easier realized by vertical pole displacements at destinct locations



J. Bahrdt



Interaction of IDs with e-Beam

- In terms of beam dynamics, an insertion device should be “transparent” to the machine, i.e. behave like drift space. But there are
- Intrinsic effects
  - Betatron tune shifts, focusing effects induced by the nominal field of the ID
  - For high field devices: Change of emittance, energy spread growth, reduction of damping time
- Effects due to field errors of the ID
  - Closed Orbit Distortions (by dipole errors, gap dependent)
  - Coupling (induced by skew-quad errors)
  - Reduction of dynamic aperture (decrease of life time and injection efficiency)
- Most of these effects can be avoided or corrected by careful design and manufacture, passive field shimming and active adjustments

---

just as a remark

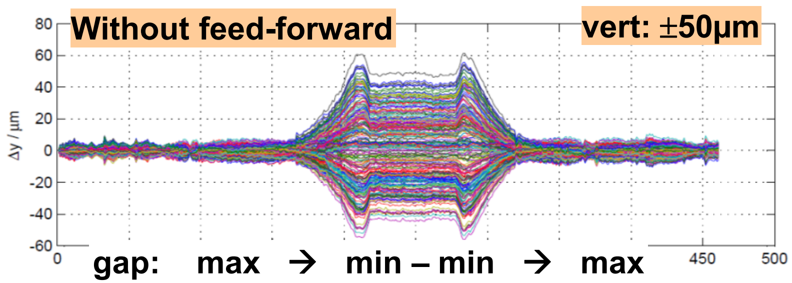
- Also vice versa: The ID might be affected by radiation background in the tunnel
  - Any electronics must be shielded
  - Permanent magnets may partly be demagnetized
  - Corrosion of permanent magnets or poles due to radio chemistry

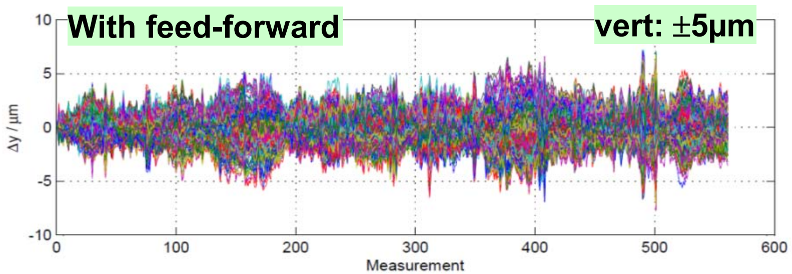
Impact of IDs: COD, Tune shift

COD are caused by gap-dependent residual field integrals (kick and displacement)

Compensation by feed-forward of small corrector coils at the ends of the ID

Example: Read-out of all BPMs around the machine while closing the undulator gap





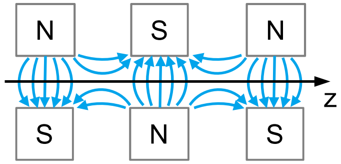
Additional contributions to COD:

- local distortions of the ambient field by adjacent accelerator components in the tunnel
- shielding effects of the support structure

Focussing properties of an ID

$$x'' = \frac{d^2x}{dz^2} = -\frac{e}{\gamma\, m_0 c}\left(B_y - y' B_z\right)$$

$$y'' = \frac{d^2y}{dz^2} = -\frac{e}{\gamma\, m_0 c}\left(x' B_z - B_x\right)$$



Close to the mid plane: $B_z \approx \left(B_z / dy\right) y = \left(B_y / dz\right) y$

Vertical focussing: Any vertically displaced e⁻ will experience a longitudinal field which bends it back towards the horizontal plane.
The vertical focussing parameter is given by

$$k_y = \left(\frac{e}{\gamma\, m_0 c}\right)^2 \frac{B_y^2}{2} = \frac{1}{2\rho^2}$$

$$\frac{1}{F_y} = \int k_y dz = \left(\frac{e}{\gamma\, m_0 c}\right)^2 \frac{B_y^2}{2} L$$

This causes a **tune shift**

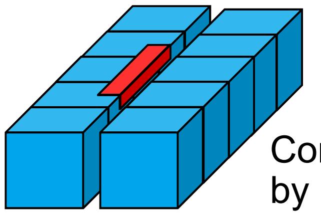
$$\Delta\nu_y = \frac{1}{4\pi}\int \beta_y\, k_y dz \approx \frac{\overline{\beta}_y}{4\pi\, F_y}$$

Non-linear Focusing Effects

Example: **APPLE2** UE65 at PETRA III in **vertical mode**

Strong roll-off of the horizontal field causes dynamic multipole errors.

Magnetic measurement is performed along a straight line but the field integral along the oscillating electron trajectory is not zero.



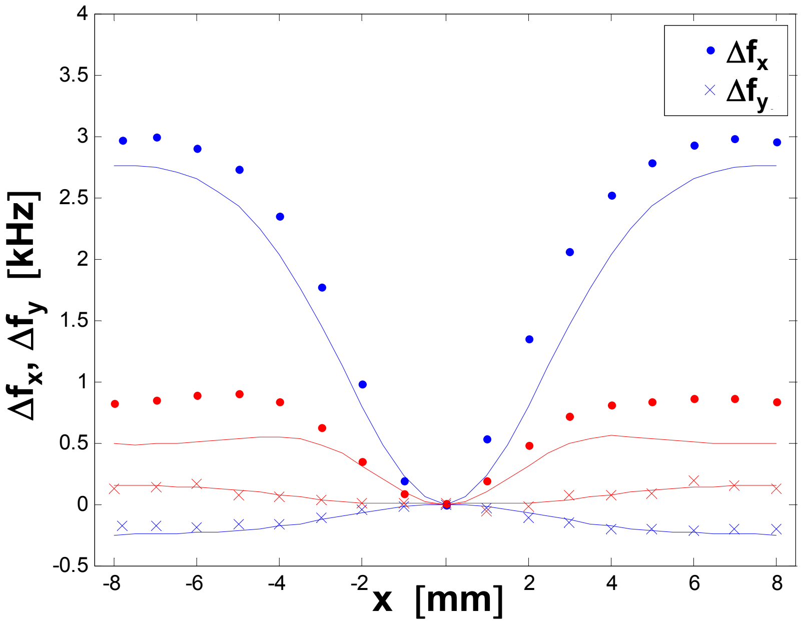
(J. Chavanne et al., Proc. of EPAC 2000 conf.)

Dynamic kicks of a periodic magnet structure:

$$\theta_x = \frac{L}{2(B\rho)^2}\frac{\lambda_U^2}{(2\pi)^2}\left(B_x^0\cdot\frac{\partial B_x^0}{\partial x}+B_y^0\cdot\frac{\partial B_y^0}{\partial x}\right)$$

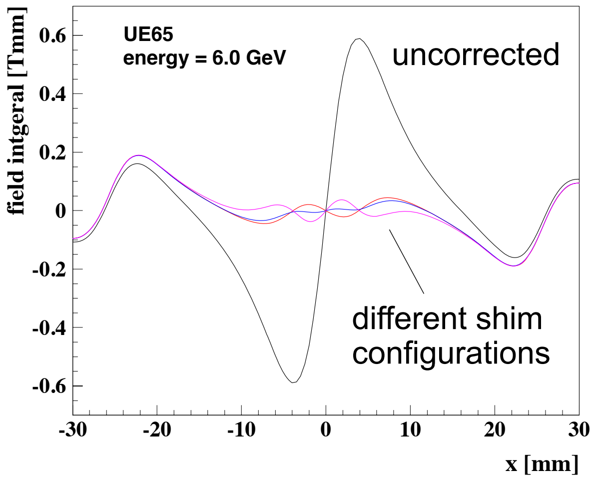
$$\theta_y = \frac{L}{2(B\rho)^2}\frac{\lambda_U^2}{(2\pi)^2}\left(B_x^0\cdot\frac{\partial B_x^0}{\partial y}+B_y^0\cdot\frac{\partial B_y^0}{\partial y}\right)$$

Measurements of the horizontal (•) and vertical (x) **tune shifts** as function of horizontal beam position before (blue) and after (red) placement of L-shims. Theoretical calculations (lines) for comparison..



(J. Bahrdt et al., Proc. of IPAC 2011 conf.)

Calculated dynamic multipoles:



Magnetic Measurements and Tuning

Magnetic Measurements and Tuning

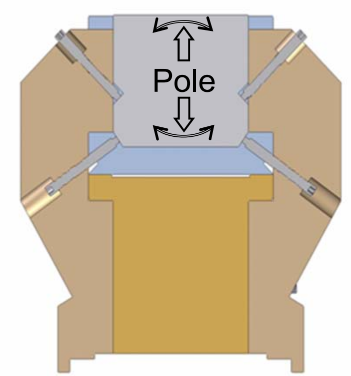
Purpose:

Measure and remove errors in the magnetic field distribution for all gaps

- Optimize the SR emission characteristics → flatten the trajectory inside the undulator and minimize the phase error
- Make the ID „transparent“ for machine operation → remove residual field integrals and multipoles of the device for all gaps

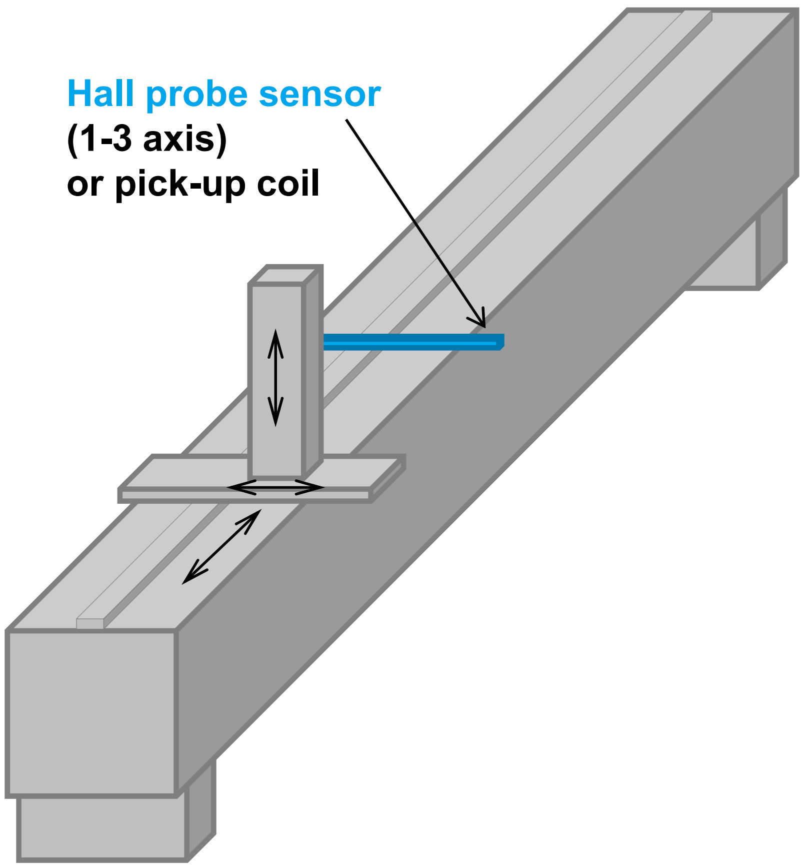
Various Field Correction Mechanisms:

- Initial sorting of magnets, dedicated magnet flipping or swapping
- Magnet or pole height adjustment,
- Application of Fe shims or small corrector magnets
- Local corrector coils



Individual pole adjustment:
height by ±0.1mm
pole tilt by ±1mrad

Hall Probe Measurement Bench



Purpose:
Fast longitudinal field mapping of vertical and horizontal fields

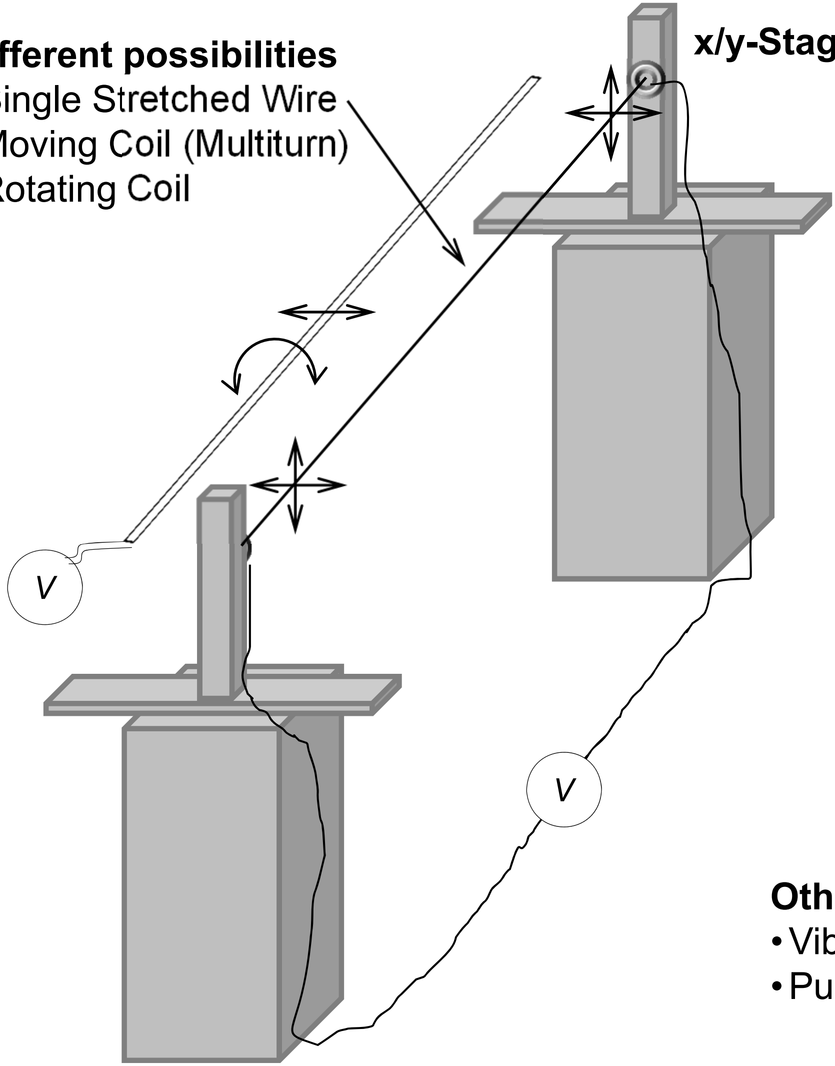
Important for optical phase and trajectory shimming

Hall probe requires calibration, temperature stabilization

- platform on air bearings, driven by linear motor, servo drives for x, y, z axes, reproducibility ~µm
- on-the-fly measurements, max. sampling ~ 200Hz
- temperature controlled environment (<0.5K)

Field Integral Measurements

Different possibilities
- Single Stretched Wire
- Moving Coil (Multiturn)
- Rotating Coil



Purpose: Measurement of longitudinally integrated field integrals, i.e. transverse dependence of vertical and horizontal 1st and 2nd field integrals

Important for determination and shimming of multipoles

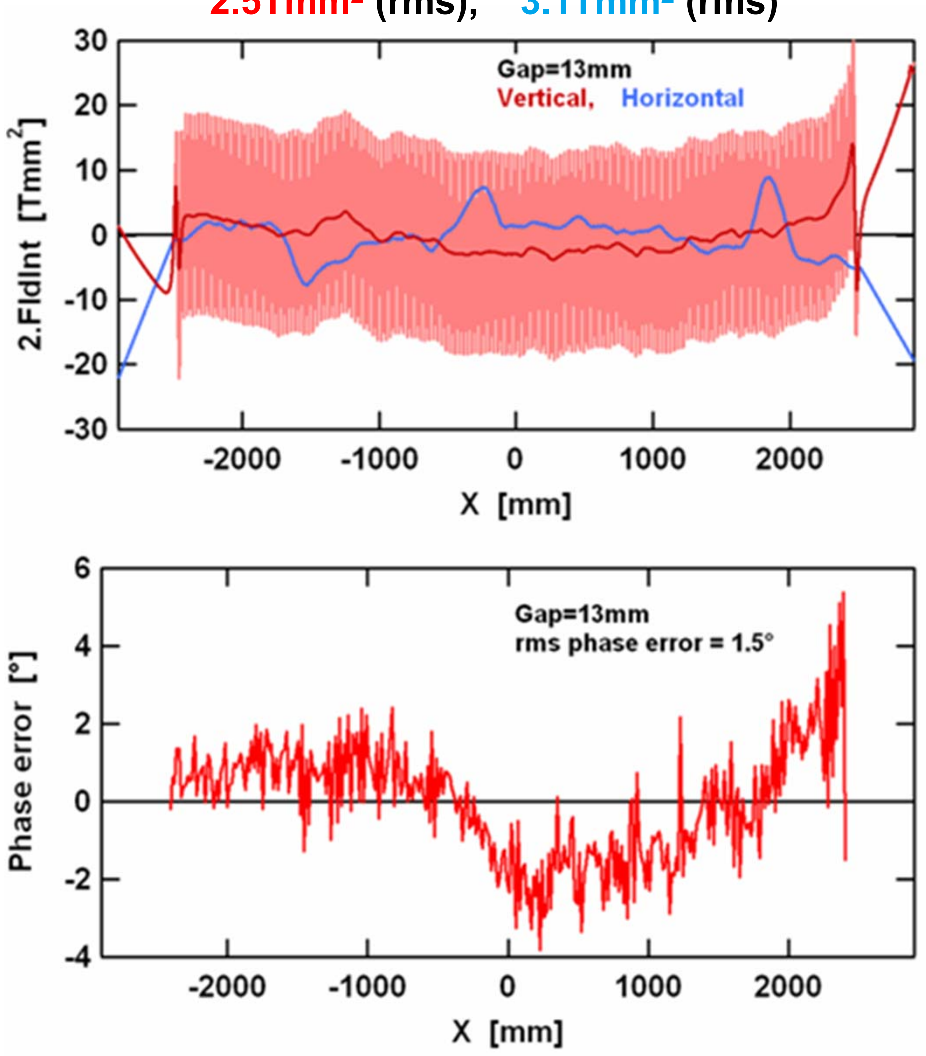
Much more accurate than Hall probes for determination of field integrals

$$\int V dt = -N\,\Delta\Phi \sim \int B_{x,y}\,dz$$

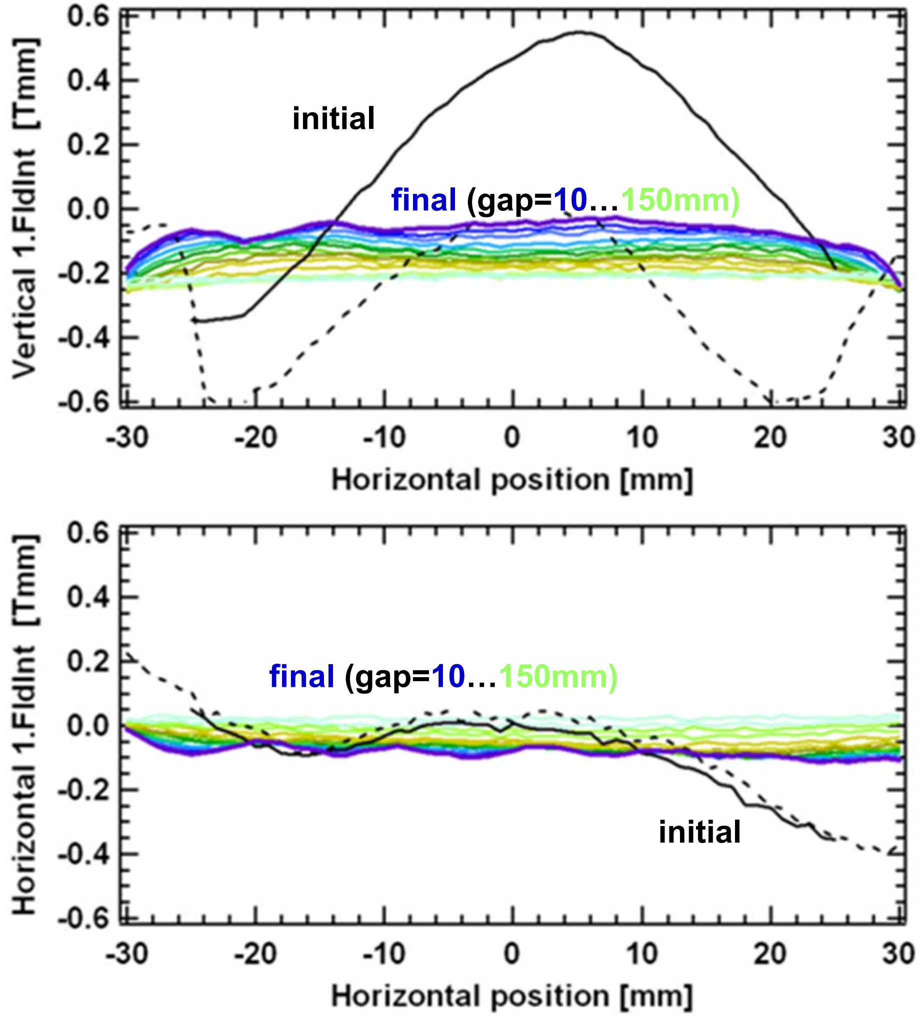
Other techniques
- Vibrating Wire → accurate determination of magnetic axis
- Pulsed Wire → longitudinally resolved field integrals

Example: Measurement &Tuning Results

Trajectory straightness
2.5Tmm² (rms), 3.1Tmm² (rms)



Multipoles tuned with magic fingers
Variation of I1 within ±25Gcm



PETRA III: U32, L=5m

Literature

> Books

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  and other volumes from this series

> Previous CAS Summer Schools

- See previous contributions e.g. from R. Walker, P. Elleaume, J. Clarke, J. Bahrdt