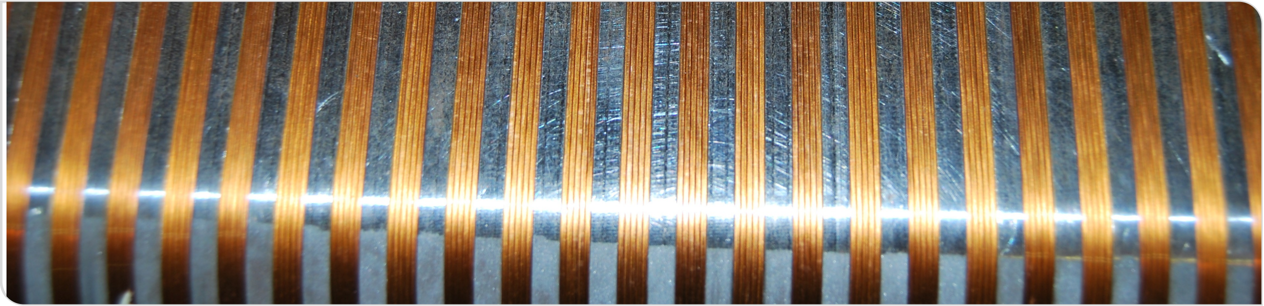
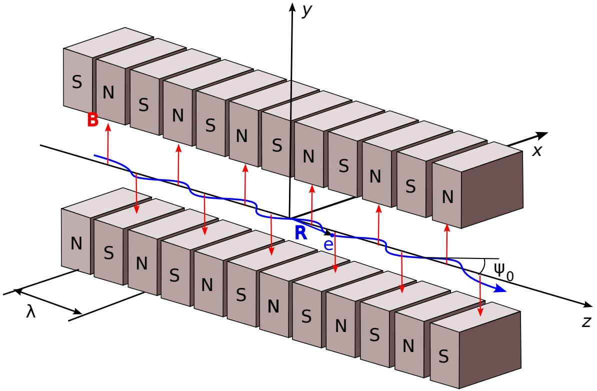
Insertion Devices

Axel Bernhard | 2023-12-01



The basic idea of insertion devices



- Magnet in an insertion
- not being part of the lattice

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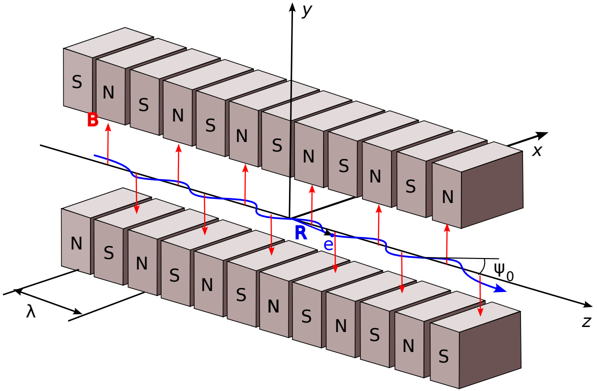

- Magnet in an insertion
- not being part of the lattice
- typically a periodic array with
  - period length λ_u
  - number of periods N_u
  - length $L_u = N_u \lambda_u$
  - zero net deflection: $x'(-L_u/2) = x'(L_u/2)$
  - zero net displacement: $x(-L_u/2) = x(L_u/2)$

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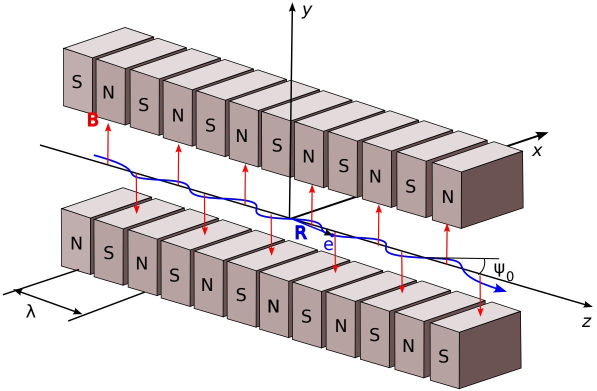

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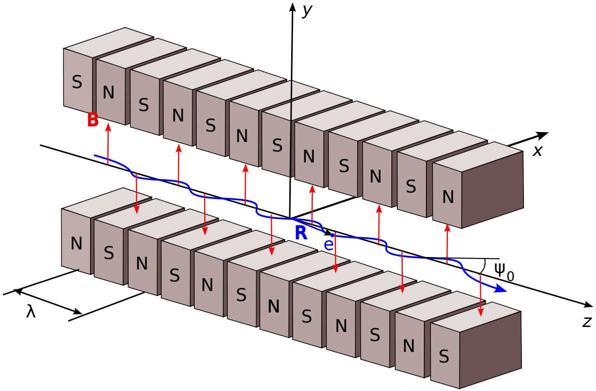
  - zero net displacement: $x(-L_u/2) = x(L_u/2)$
- aim: generate enhanced radiation by multiple deflection

The basic idea of insertion devices



Classification with respect to undulator parameter

$$K_u :\approx \frac{\psi_0}{1/\gamma}$$

- $K_u \gg 1$: *Wiggler*
- $K_u \lesssim 1$: *Undulator*

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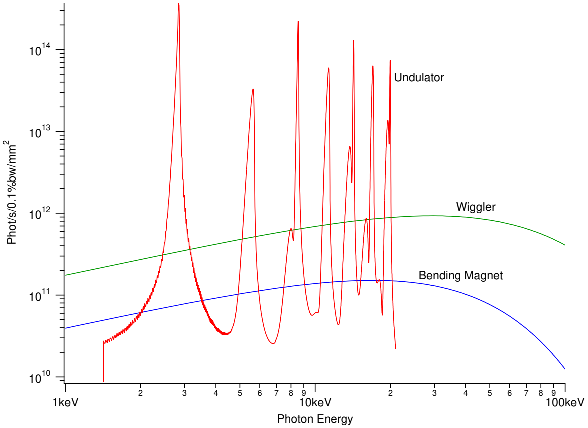

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The purpose of IDs

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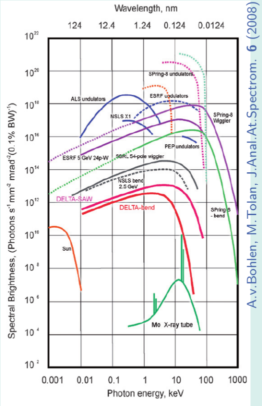
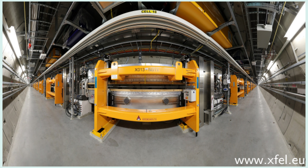
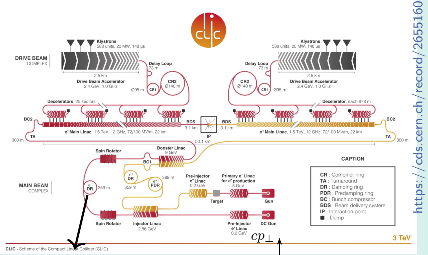
Generation of brilliant synchrotron radiation



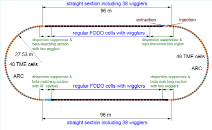
A.v.Bohlen, M.Tolan, J.Anal.At.Spectrom. 6 (2008)



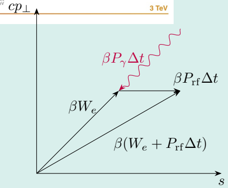
Radiation damping



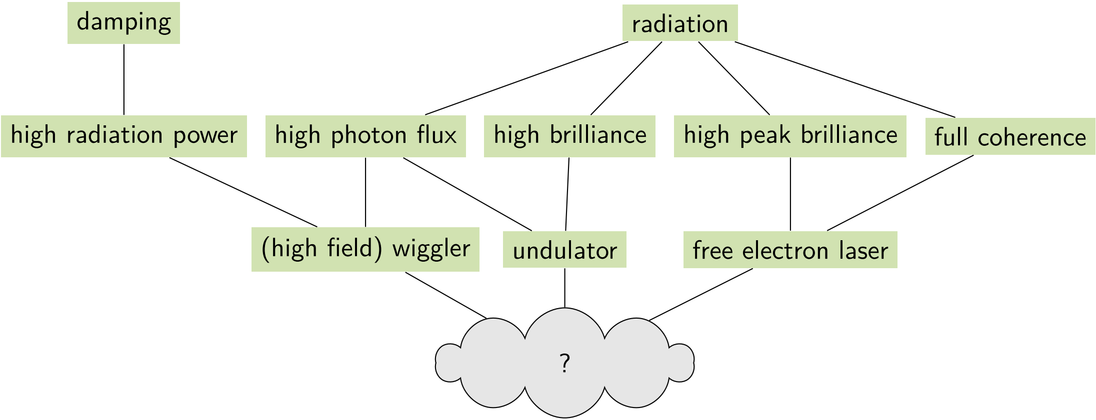
https://cds.cern.ch/record/2655160



M. Aicheler (ed.), CLIC conceptual design report (2012)



From use case to design requirments

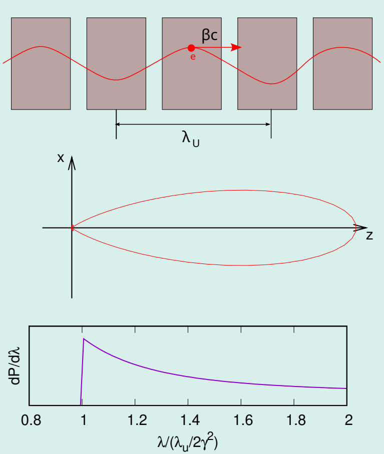


Outline

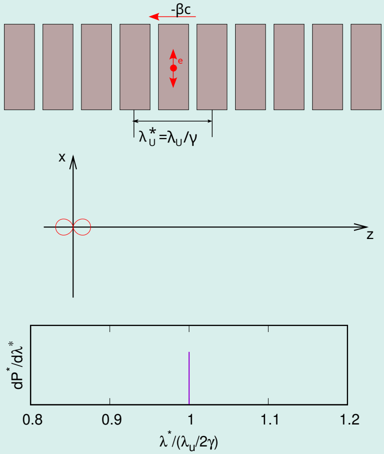
Outline

The basic principle

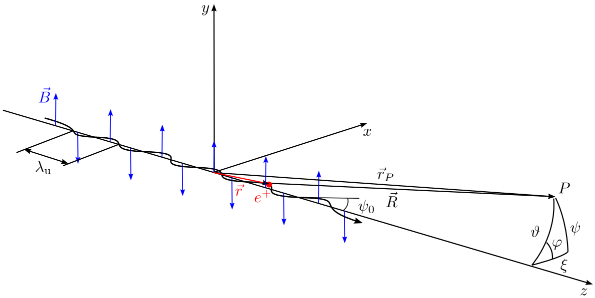
Laboratory frame



Co-moving frame



The particle trajectory I



Ideal planar undulator:

$$\vec{B}(x,0,z) = B_0(0, \cos k_u z, 0)$$

with $$k_u = \frac{2\pi}{\lambda_u}$$

Equations of motion: Lorentz force

$$\vec{F} = m\gamma \begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{pmatrix} = e(\vec{v} \times \vec{B}) = eB_0 \begin{pmatrix} -\cos(k_u z)\dot{z} \\ 0 \\ \cos(k_u z)\dot{x} \end{pmatrix}$$

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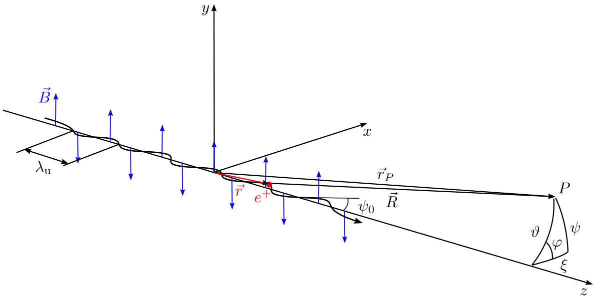

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Integration for x component:

$$\dot{x} = -\frac{eB_0}{m\gamma k_u} \sin(k_u z).$$

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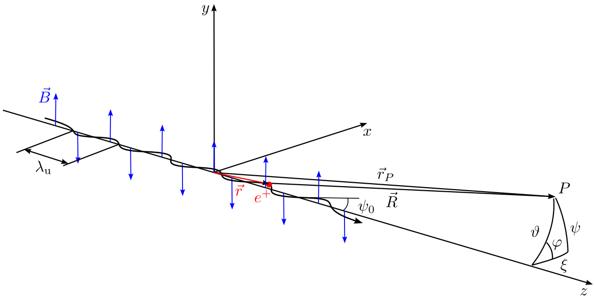

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z-component: energy conservation:

$$\dot{x}^2 + \dot{z}^2 = \beta^2 c^2 \quad \Rightarrow \quad \dot{z} = \beta c \sqrt{1 - \frac{\dot{x}^2}{\beta^2 c^2}}$$

The particle trajectory II

Trajectory as function of time

$$x(t') = \frac{K_\mathrm{u}}{\beta\gamma k_\mathrm{u}} \cos(\Omega_\mathrm{u} t')$$

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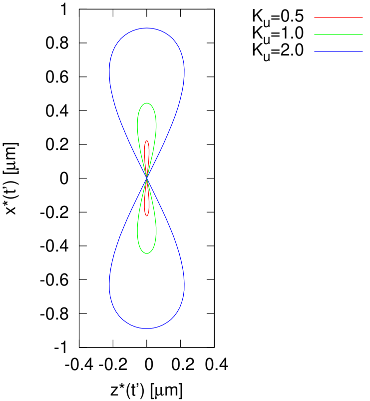
with

$$\beta^* c = \beta c \left(1 - \frac{K_u^2}{4\beta^2\gamma^2}\right) < \beta c!$$

$$2\Omega_u = 2k_u \beta^* c$$

$$K_u := \frac{eB_0}{mck_u}$$



Particle trajectory in the co-moving frame with $v = \beta^* c$; numbers given for $\lambda_u = 14\,\text{mm}$, $W_e = 2.5\,\text{GeV}$.

The radiation field

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Trajectory + Liénard Wiechert potentials:

$$\vec{E}(\vec{r}_P, t) = \frac{e}{4\pi\epsilon_0}\left[\frac{1}{c}\,\frac{\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]}{(1-\vec{\beta}\cdot\vec{n})^3 R}\right]_{\mathrm{ret}}$$

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Consequence of reduced mean drift velocity and figure-8 motion:

complex periodic motion ⇒ line spectrum
with harmonics h of fundamental wavelength

$$\boxed{\lambda_1 = \frac{\lambda_{\mathrm{u}}}{2\gamma^2}\left(1 + \frac{K_{\mathrm{u}}^2}{2} + \gamma^2\vartheta^2\right)}$$

The undulator equation.

The radiation field

KIT Karlsruhe Institute of Technology

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Spectral angular power distribution

$$\frac{\mathrm{d}^2 P_h}{\mathrm{d}\Omega\,\mathrm{d}\omega} = P_\mathrm{u}\gamma^{*2}[F_{h\sigma}(\vartheta,\varphi) + F_{h\pi}(\vartheta,\varphi)]f_N(\Delta\omega_h)$$

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Total power

$$P_\mathrm{u} = \frac{2}{3}\frac{e^4 c^3}{4\pi\epsilon_0}\frac{\langle B^2\rangle W_e^2}{(mc^2)^4}$$

The radiation field

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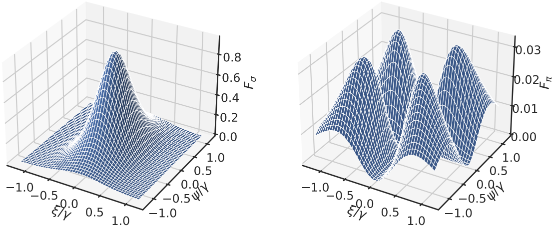
Normalized angular power distribution 1st harmonic for σ and π polarization, respectively:



The radiation field

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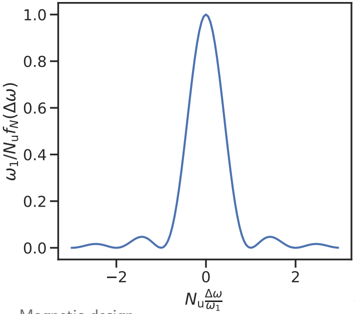
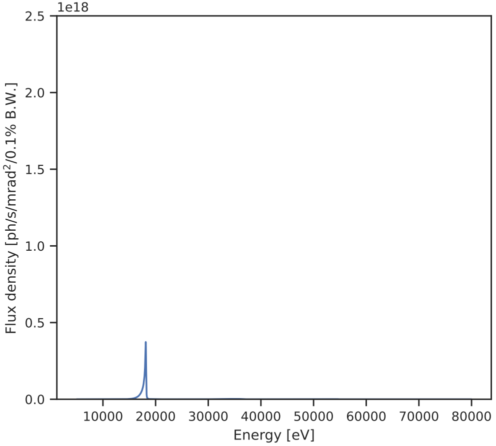
Spectral function 1$^{\mathrm{st}}$ harmonic:



Undulator spectra and tuning



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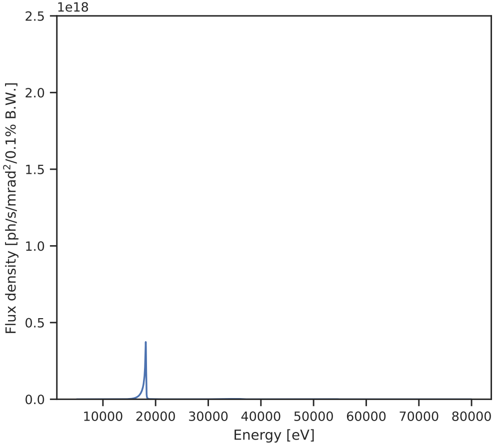

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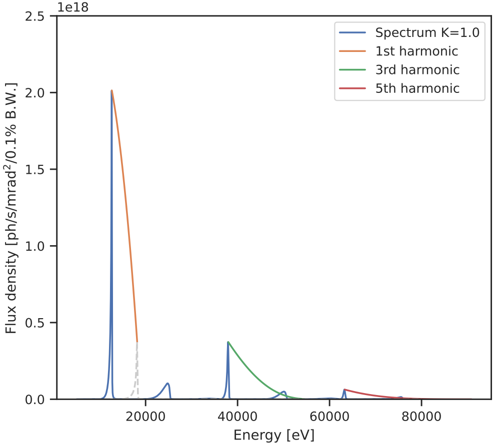

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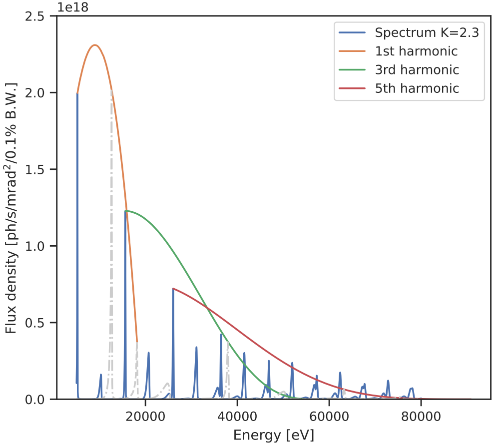

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- $K_\mathrm{u} = 1.0$: higher harmonics appear, intensity increases (power $\propto B_0^2$), lines are shifted to longer wavelengths (lower energies)
- $K_\mathrm{u} = 2.3$: tuning ranges of 1st and 3rd harmonic overlap

Helical undulators

Undulator field and trajectory

On axis field of an ideal helical undulator:

$$\vec{B} = (B_{x0}\cos(k_\mathrm{u} z - \phi), B_{y0}\cos(k_\mathrm{u} z), 0)$$

$\Rightarrow$ elliptic motion in the transverse plane with

$$\beta_x = -\frac{K_y}{\gamma}\cos(k_\mathrm{u} z), \quad \beta_y = -\frac{K_x}{\gamma}\cos(k_\mathrm{u} z - \phi)$$

and, in particular, for $K_x = K_y, \phi = \frac{\pi}{2}$

$$\beta_z = \beta - \frac{K_y^2}{4\beta\gamma^2} - \frac{K_x^2}{4\beta\gamma^2} = \text{const.}$$

Radiation field

Similar solutions as for the planar undulator with following main differences:

- modified undulator equation

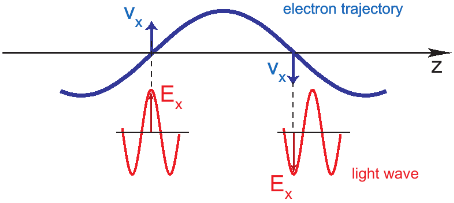
$$\lambda_1 = \frac{\lambda_\mathrm{u}}{2\gamma^2}\left(1 + \frac{K_x^2}{2} + \frac{K_y^2}{2} + \vartheta^2\gamma^2\right)$$

- elliptically, for $K_x = K_y, \phi = \frac{\pi}{2}$ circularly polarized light on axis
- constant $\beta_z \Rightarrow$ virtually no higher harmonics

Outline

The FEL mechanism: resonance condition

Energy transfer particle $\leftrightarrow$ light



P.Schmüser et al., Springer Tracts in Modern Physics (2014)

- oscillatory motion
- $v_x \parallel \vec{E}_{\text{light}}$
- energy transfer possible periodically

Continuous energy transfer

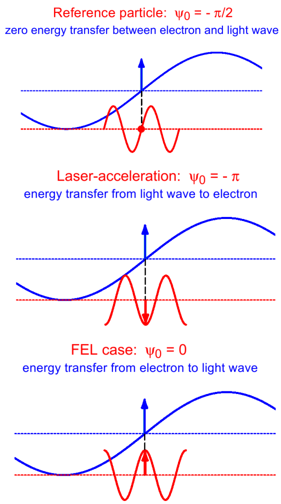
- requires fixed phase relation between electron motion and field oscillation
- that is fulfilled for:

$$\lambda = \frac{\lambda_\text{u}}{2\gamma^2}\left(1 + \frac{K_\text{u}^2}{2}\right)$$

$$\Rightarrow \gamma_r = \sqrt{\frac{\lambda_\text{u}}{2\lambda}\left(1 + \frac{K_\text{u}^2}{2}\right)}$$

with γ_r the resonance energy

The high gain FEL mechanism: microbunching



In a long bunch, given the FEL resonance condition is fulfilled:

- all relative phases present
- periodic particle energy modulation
- periodic drift velocity modulation
- periodic particle density modulation

graphics: P.Schmüser et al., ibid.

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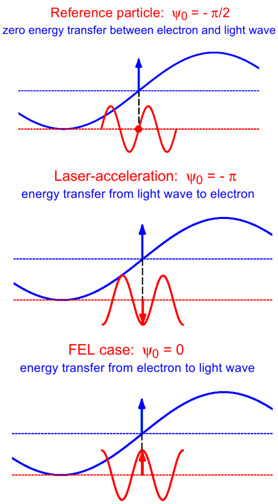

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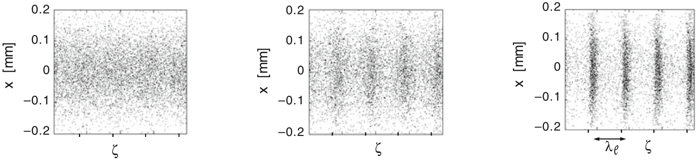
→ Microbunching:



- all particles radiate coherently

graphics: P.Schmüser et al., ibid.

ID field quality: The phase error

Phase relation electron — photon

Phase slip due to different travelling times (over half period):

$$\omega_1 (t_{\text{electron}} - t_{\text{photon}}) = \omega_1 \left(\frac{\lambda_{\text{u}}}{2\overline{v}_z} - \frac{\lambda_{\text{u}}}{2c} \right) ! = \pi$$

Here,

$$\overline{v}_z = \beta^* c = c \left(1 - \frac{1 + \frac{K_{\text{u}}^2}{2}}{2\gamma^2} \right).$$

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Constant phase relation must be maintained along the whole undulator (beamline) for the high gain FEL process to work

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Phase errors

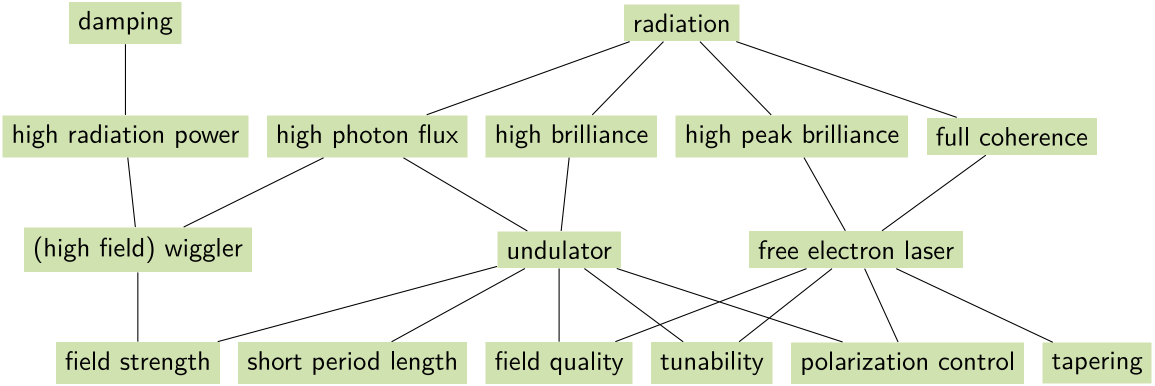
- magnetic field errors $\Rightarrow$ deviations of K_u and $\overline{v}_z$ $\Rightarrow$ local phase deviations ψ_i
- phase error at pole n: accumulated phase deviations of all preceding periods

$$\phi_n = \sum_{i \le n} \psi_i$$

- usual figure of merit for undulator field quality: rms phase error σ_ϕ^2
- target: few degrees

From use case to design requirements

A more complete picture

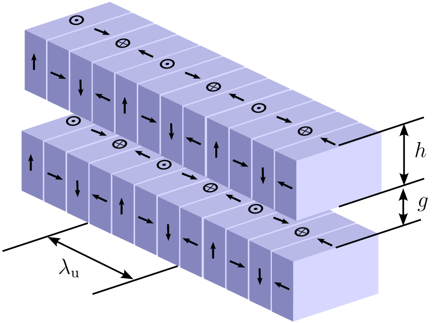


Outline

Magnet technolgy choices for IDs

- Undulator Magnets
  - Permanent magnet (PMU)
    - Pure Permanent Magnet (PPM)
      - planar
      - helical (APPLE, Delta)
    - Hybrid Permanent Magnet (HPM)
  - Electro magnet (EMU)
    - normal conducting
    - superconduct-ing (SCU)
      - planar
        - LTS
        - HTS
      - helical, SCAPE

Pure Permanent Magnet (PPM)



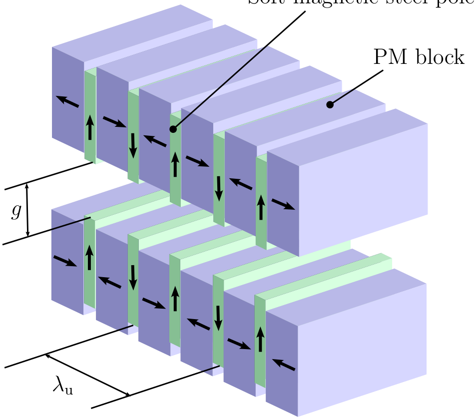
Design principle (K. Halbach NIM 187 (1981))

- permanent magnet blocks
- rotation of easy axis in M steps per period (minimum 4)
- practical scaling law ($M = 4, h = \lambda_u/2$):
  $B_{y0} = 1.72 B_r e^{-\pi g/\lambda_u}$
- amplitude determined by B_r, g and λ_u (H_c)
- tuning by variation of g

Analytic field description (on axis)

$$B_y = -2B_r \sum_{i=0}^{\infty} \cos\left(\frac{2n\pi z}{\lambda_u}\right) \cosh\left(\frac{2n\pi y}{\lambda_u}\right) \frac{\sin(n\pi\epsilon/M)}{n\pi/M} e^{-n\pi g/\lambda_u}(1 - e^{-2n\pi h/\lambda_u}) \quad \text{with} \quad n = 1 + iM$$

Hybrid Permanent Magnet



Design principle (K. Halbach (1983))

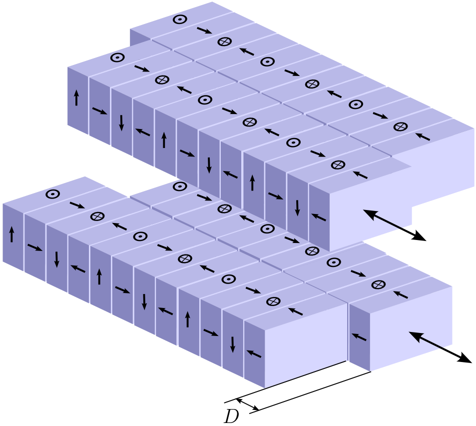
- soft magnetic poles magnetized by permanent magnet blocks
- non-linear material, numeric field calculation required (FEM)
- practical scaling law (Halbach, J. Phys. Col **44** (1983)):

$$B = a \exp\left[b\left(\frac{g}{\lambda_u}\right) + c\left(\frac{g}{\lambda_u}\right)^2\right]$$

a, b, c depending on material choice, compilation to be found in F. Nguyen et al., XLS-Report-2019-004 (2019)

Permanent magnet variable polarization (helical) designs

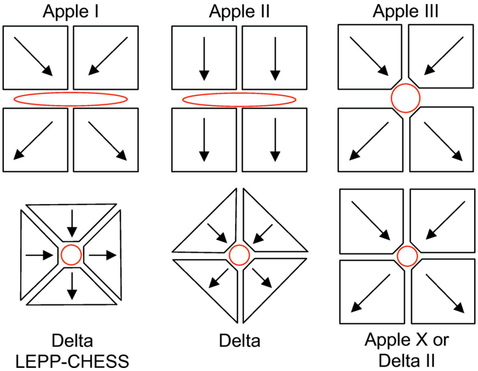
Karlsruhe Institute of Technology



Design principles

- 4 magnet arrays for 2 orthogonal field components
- always fixed phase shift of $\frac{\pi}{2}$ between B_x and B_y
- amplitude ratio varies by longitudinal shifting of arrays

Permanent magnet variable polarization (helical) designs

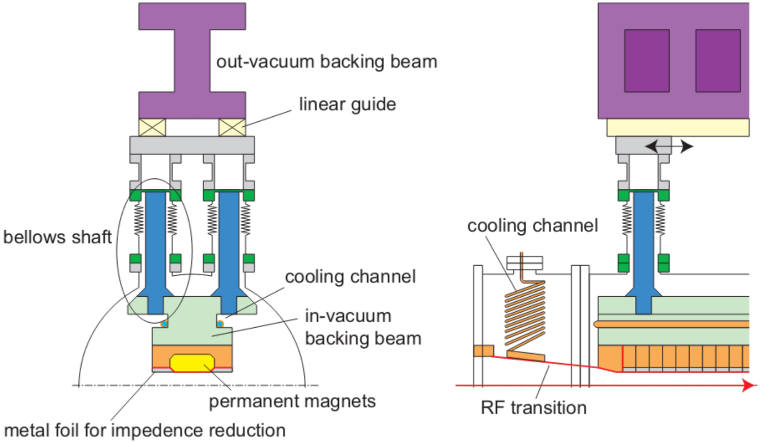


M.Calvi et al., J. Synchrotron Rad. **24** (2017)

Design principles

- 4 magnet arrays for 2 orthogonal field components
- always fixed phase shift of $\frac{\pi}{2}$ between B_x and B_y
- amplitude ratio varies by longitudinal shifting of arrays
- design variations, particularly for round beams
- Scaling law as for planar PMUs, a, b, c additionaly depend on helical undulator design type (see also XLS-Report-2019-004)

Strategies for increasing B

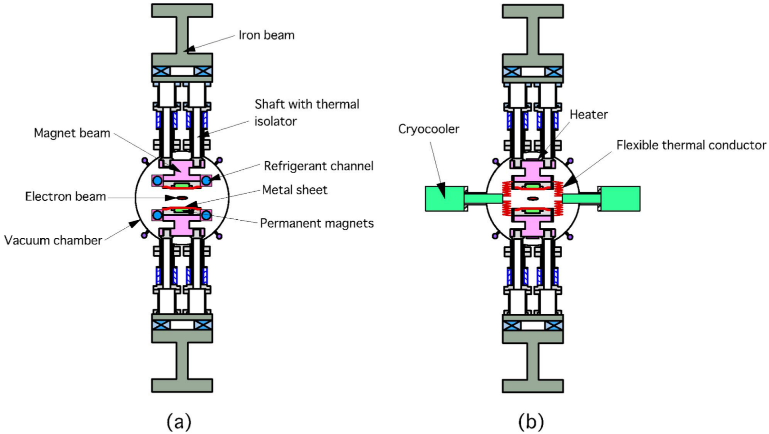


T.Tanaka et al., Proc. FEL 2005

Advanced PMU designs

- In vacuum undulators (IVU)
  - reduce magnetic gap
  - increase ratio B_0/λ_u

Strategies for increasing B

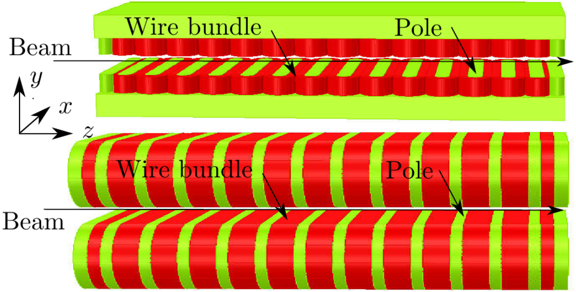


T.Hara et al., PRSTAB **7** (2004)

Advanced PMU designs

- In vacuum undulators (IVU)
  - reduce magnetic gap
  - increase ratio B_0/λ_u
- Cooled PMUs (CPMU) in addition:
  - increase remanent field
  - increase coercive force

Electromagnets: Planar SCUs and SCWs



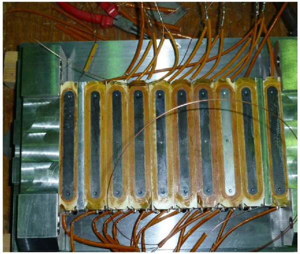
Aiming at very high fields or short periods

Approximating with dipole field, K_u scales like

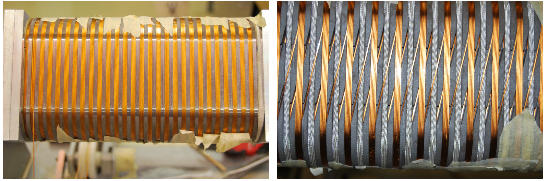
$$K_u = 2.35 \times 10^{-4} NI \frac{\lambda_u}{g} \quad (1)$$

⇒ generally high current densities are required
⇒ SCUs are the mainly relevant EMUs

Electromagnets: Planar SCUs and SCWs



N.Mezentsev et al., CLIC DW Tech. Report (2016)



Undulator short model ‘Undine’, built in-house

State of the art

- low temperature SC, Nb-Ti
- horizontal racetrack
  - simple coil procuction (good)
  - many splices (not so good, but manageable)
- vertical racetrack
  - single wire
  - enabling very short periods

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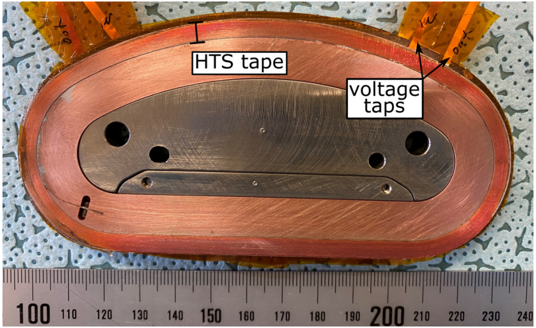


S. Richter, Dissertation, KIT (2023)

HTS vertical racetrack demonstrator coil (1 period)

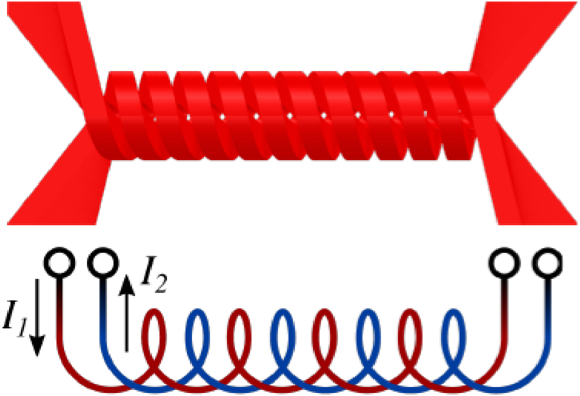
State of the art

- low temperature SC, Nb-Ti
- horizontal racetrack
  - simple coil procution (good)
  - many splices (not so good, but manageable)
- vertical racetrack
  - single wire
  - enabling very short periods

On the horizon

- high temperature SC, ReBCO tape
- unprecedentedly high current densities and field amplitudes

SC helical and variable polarization

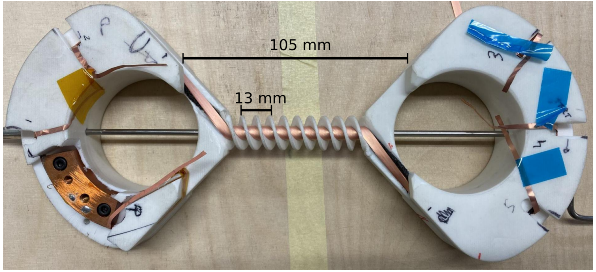


S. Richter, Dissertation, KIT, 2023

Bifilar helix

- bifilar helical coil around beam pipe
- fixed helicity (not changed upon current inversion)
- extremely resource efficient

SC helical and variable polarization



S. Richter, Dissertation, KIT, 2023

Bifilar helix

- bifilar helical coil around beam pipe
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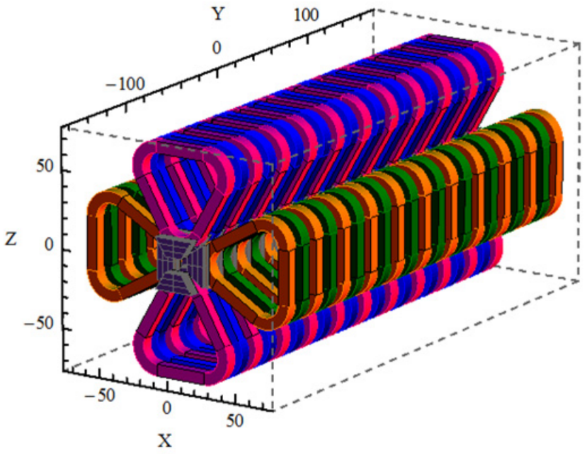
- demonstrated for LTS and HTS

SC helical and variable polarization



Y.Ivanyushenkov et al., Proc.IPAC 2017

Bifilar helix

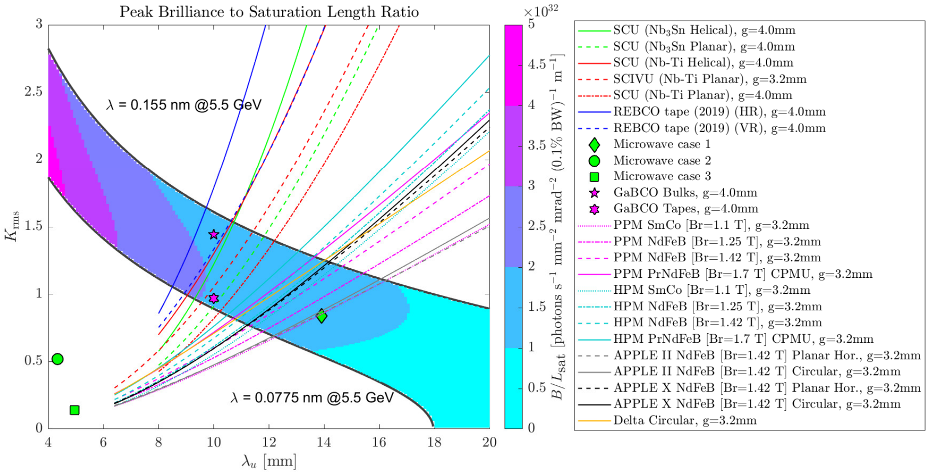
- bifilar helical coil around beam pipe
- fixed helicity (not changed upon current inversion)
- extremely resource efficient
- demonstrated for LTS and HTS

SCAPE

- SC arbitrary polarizing emitter
- full polarization control through two independently powered coil pairs

Comparison of undulator technologies

Example from the CompactLight design study



F. Nguyen et al., XLS Report 2019-004

Outline

Aspects of 3D and technical design

a non-exhaustive list

- **field termination**
  3D design and technical measures to ensure the beam-optical transparency
- **forces, structural mechanics**
  mechanics for taking up and moving against magnetic forces (variable gap, polarization control), thereby maintaining field quality
- **cooling**
  cryo-engineering for CPMUs and SCUs
- **SC magnet protection**
  quench detection and magnet protection, simplified compared to beam transport magnets due to the low field energy
- **fiducialization**
- **field quality measurement and control**

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Field termination

Transparency requirement:

$$x\left(\frac{-L_\mathrm{u}}{2}\right) = x\left(\frac{L_\mathrm{u}}{2}\right) \quad \text{and} \quad x'\left(\frac{-L_\mathrm{u}}{2}\right) = x'\left(\frac{L_\mathrm{u}}{2}\right)$$

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This is equivalent with

$$I_1 := \int_{-\frac{L_\mathrm{u}}{2}}^{\frac{L_\mathrm{u}}{2}} B_y \mathrm{d}z = 0$$

$$\text{and} \quad I_2 := \int_{-\frac{L_\mathrm{u}}{2}}^{\frac{L_\mathrm{u}}{2}} \mathrm{d}z \int_{-\frac{L_\mathrm{u}}{2}}^{z} B_y \mathrm{d}z' = 0,$$

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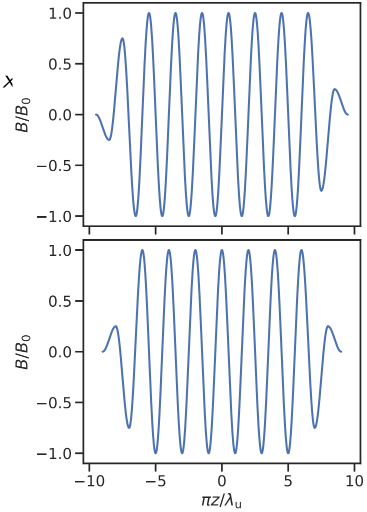
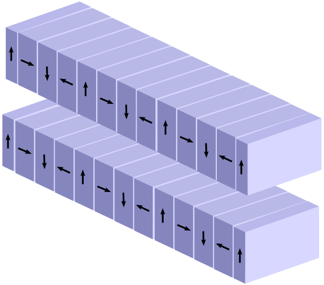
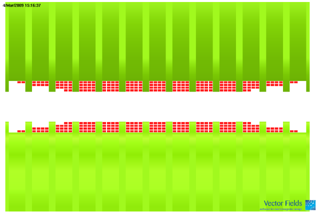
Practically achieved with

$$B_y(z) = -B_y(-z) \quad \text{and} \quad I_2 = 0$$

$$\text{or} \quad B_y(z) = B_y(-z) \quad \text{and} \quad I_1 = 0.$$







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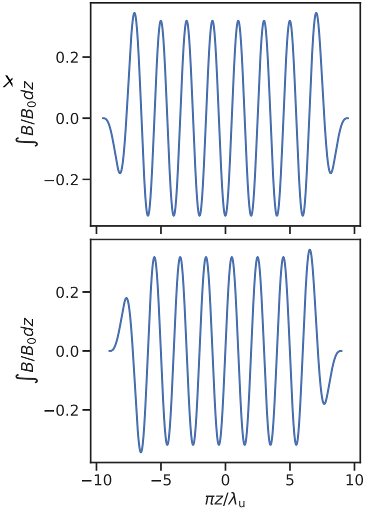

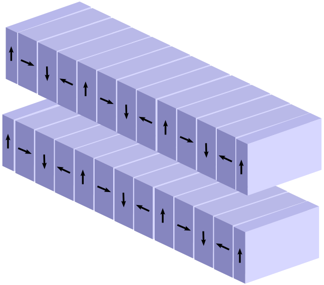

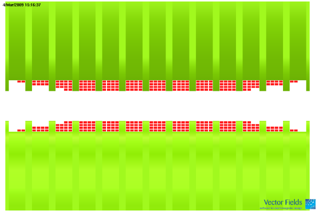

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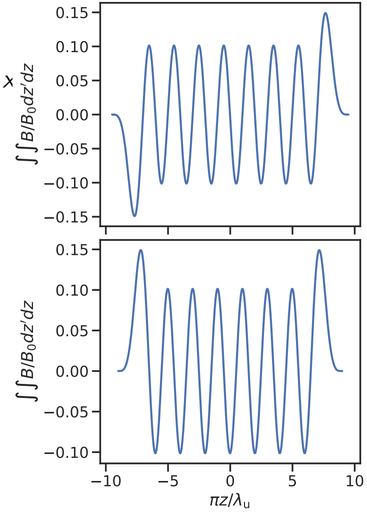
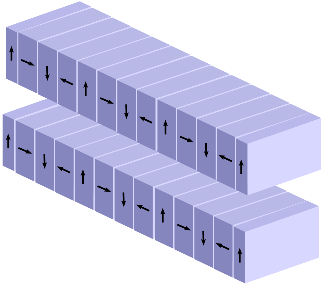
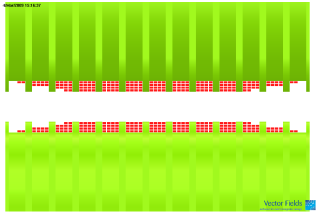
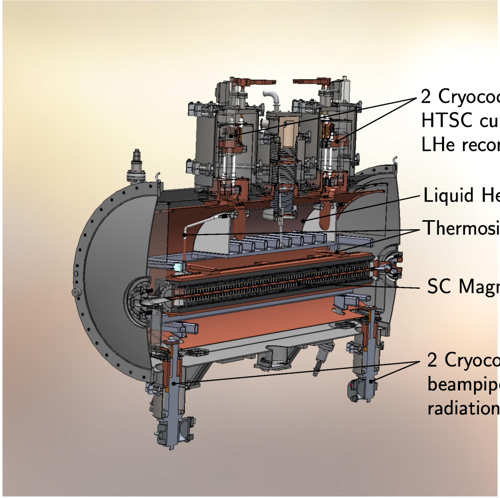






Cooling



N.Mezentsev et al., CLIC DW Tech. Report (2016)

Requirements and techniques

- **SCU**: operating temperature ~ 4 K
- **CPMU**: operating temperature ~ 150 K
- **HTSCU**: operating temperature 4 K to 10 K, still to be investigated and optimized
- Operation in light sources
  - light sources: stand-alone, closed cycle preferred
  - bath or contact cooling with liquids or/and cryocoolers
- Operation in FELs and damping rings
  - foced flow cooling
  - central cryoplant more efficient than local cryocoolers

Field quality measurement and control

Karlsruhe Institute of Technology

Field quality control techniques

- measurement techniques in general
  - Hall probe (, pulsed wire)
    $\rightarrow$ local field, phase error
  - flipping coil, stretched wire, pulsed wire
    $\rightarrow$ field integrals

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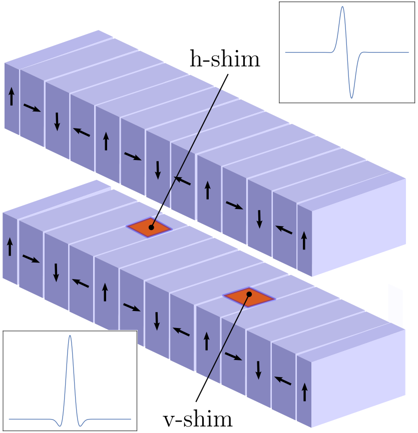

Basic idea of local field correction by shimming

Field quality measurement and control

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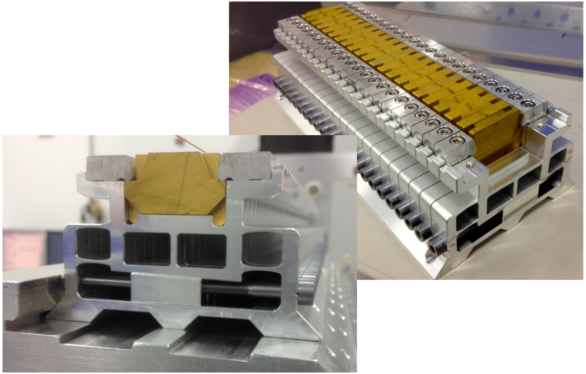

C.J. Milne et al., Appl. Sci. **7** (2017)

Magnet assembly and adjustment system of the Swiss-FEL ARAMIS undulators

Field quality measurement and control

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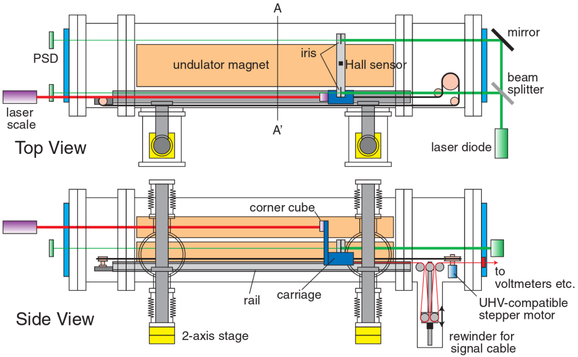

T. Tanaka et al. PRSTAB **12** (2009)

Self-aligned field analyzer with laser instrumentation (SAFALI), UHV compatible.

Field quality measurement and control

Karlsruhe Institute of Technology

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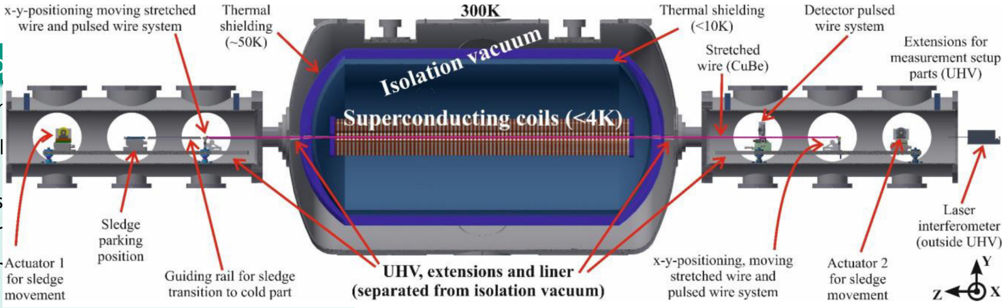
- SCUs specialized cryogenic and in-situ set-ups



A. Grau et al., Proc. IPAC 2019

In-vacuum, cryogenic magnetic measurement setup for magnetic qualification of SCUs in the final cryostat

Summary

- Insertion device design is mainly driven by synchrotron light users' demands in terms of
  - Photon flux and brilliance
  - Polarization control
  - Coherence
  - but also: availability, sustainability
- general trend: towards shorter periods, yet maintaining the tunability range up to $K = 2$
- Permanent magnets are the state of the art, still improving
- Superconducting magnets as an alternative are becoming increasingly relevant, in particular in view of the trend towards more compact light sources
- HTS technology bears a large potential for future short-period high-field insertion devices