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Accelerators in a new light

INSERTION DEVICES

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&

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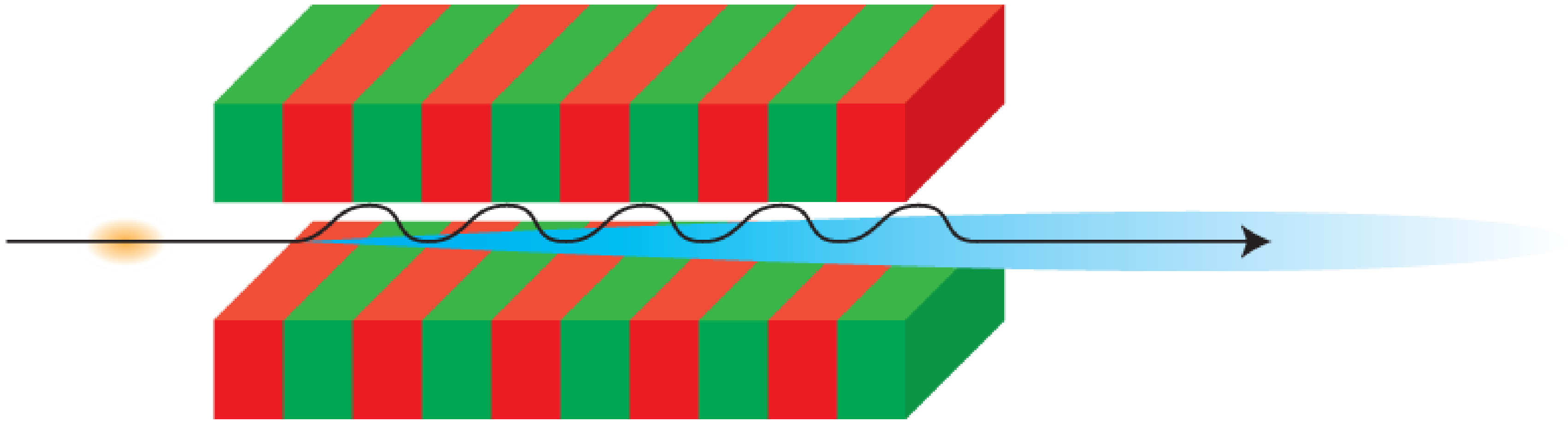
Advanced Accelerator Physics, September 2017, Egham, UK

ROYAL HOLLOWAY UNIVERSITY OF LONDON

What are Insertion Devices?

- Insertion Devices are special magnets that are specifically designed to generate synchrotron radiation
- There are two types; Undulators and Wigglers
- They have a periodic, sinusoidal magnetic field



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Why generate synchrotron radiation?

- Synchrotron radiation can be generated at any wavelength and with any polarization
- It is the brightest source of X-rays on the planet (by far!)
- The purpose of many advanced accelerators is to generate **synchrotron radiation from undulators and wigglers** so it can be used for **science research**
- **Damping rings use wigglers** to reduce the beam emittance for use in particle colliders
- **Undulators** are used in the proposed International Linear Collider to generate **gamma photons** which then create the **positrons**

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X-rays are Vital for Science Research

Paul D. Boyer

John E. Walker

1997

Peter Agre

Roderick MacKinnon

2003

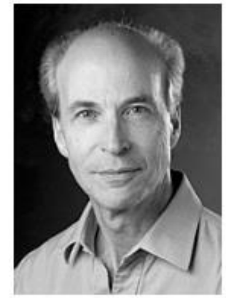

Photo: Stanford University

Roger D. Kornberg

2006

Photo: U. Montan

Venkatraman Ramakrishnan

Photo: U. Montan

Thomas A. Steitz

Photo: U. Montan

Ada E. Yonath

2009

Photo: U. Montan

Robert J. Lefkowitz

Photo: U. Montan

Brian K. Kobilka

2012

Five Nobel prizes have been awarded for research that would not have been possible without synchrotron X-ray sources

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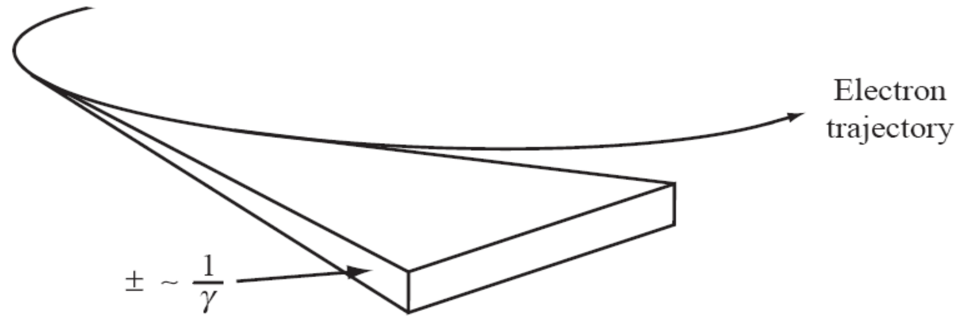
Is Synchrotron Radiation Important to me?

All accelerator scientists and engineers need to understand SR as it impacts directly on many areas of accelerator design and performance

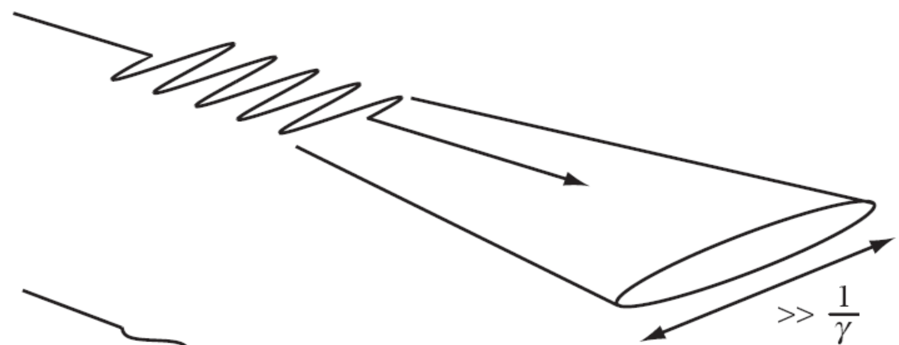
- RF
- Diagnostics
- Vacuum design
- Magnets
- Beam Dynamics
- It affects all charged particles
- Storage Ring Light sources and Free Electron Lasers are a major "customer" of advanced accelerators

Three basic sources of SR

- Dipole

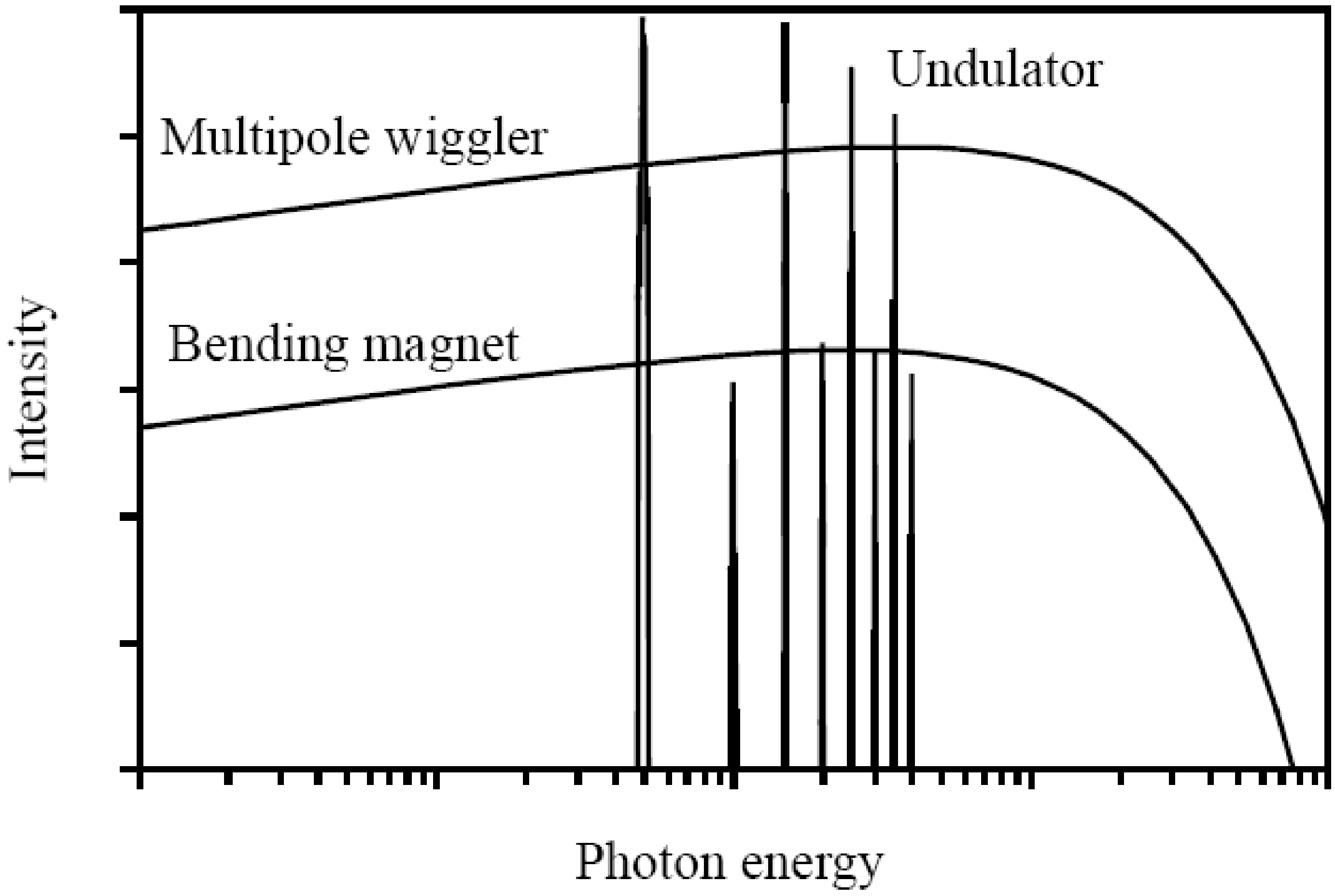


- (Multipole) Wiggler



- Undulator

Typical Spectrum



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Synchrotron Light Sources

The primary light source is the undulator

First built in the late 80’s/early 90’s

~50 user facilities worldwide

Synchrotron Light Sources

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Free Electron Lasers

The most advanced light source is the **X-ray Free Electron Laser**

Requires an undulator ~100 m long

Brighter than a synchrotron by ~1,000,000,000 times

LCLS in USA, the first hard X-ray FEL opened in 2009

Introduction to Synchrotron Radiation

Synchrotron Radiation (SR) is a relativistic effect

Many features can be understood in terms of a combination of two relativistic processes:

Lorentz contraction and

Doppler shift

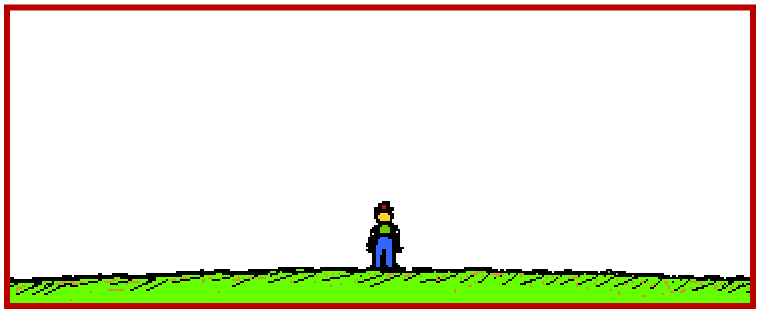
I will talk about electrons but the effect is present for all charged particles

Lorentz Contraction

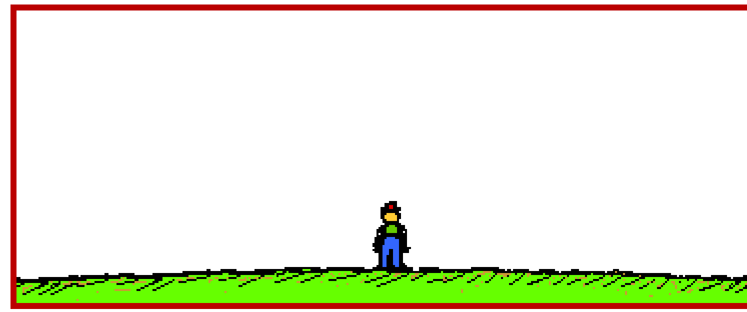
Special Relativity tells us that moving objects shorten in length along their direction of travel.

$$\gamma = \frac{E}{E_0}$$

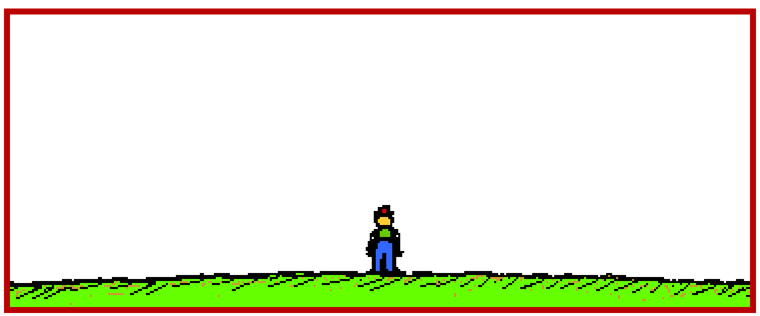
Spaceship Moving at the 10 % the Speed of Light



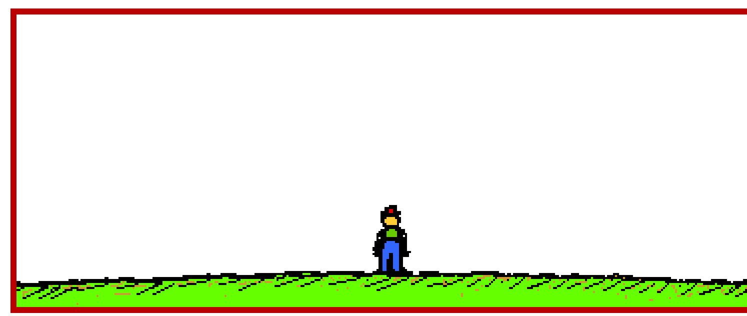
Spaceship Moving at the 86.5 % the Speed of Light



Spaceship Moving at the 99 % the Speed of Light



Spaceship Moving at the 99.99 % the Speed of Light



http://www.physicsclassroom.com

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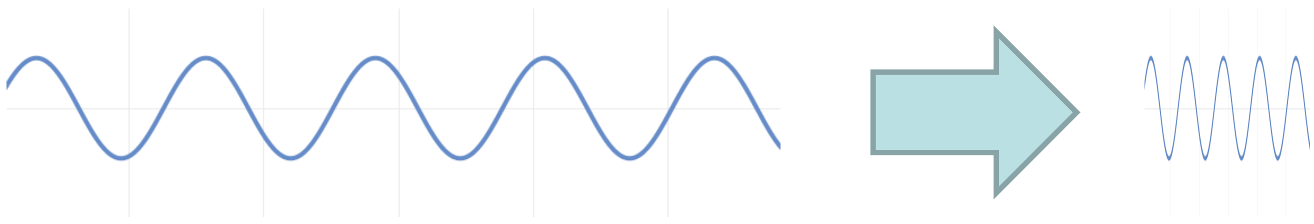
Lorentz Contraction

Imagine that a relativistic electron is travelling through an undulator with a periodic magnetic field (i.e. the field has a sinusoidal variation)

To the electron it seems like a magnetic field is rushing towards it

If in our rest frame the magnet period is λ_u then because of Lorentz contraction the electron sees it as λ_u/γ



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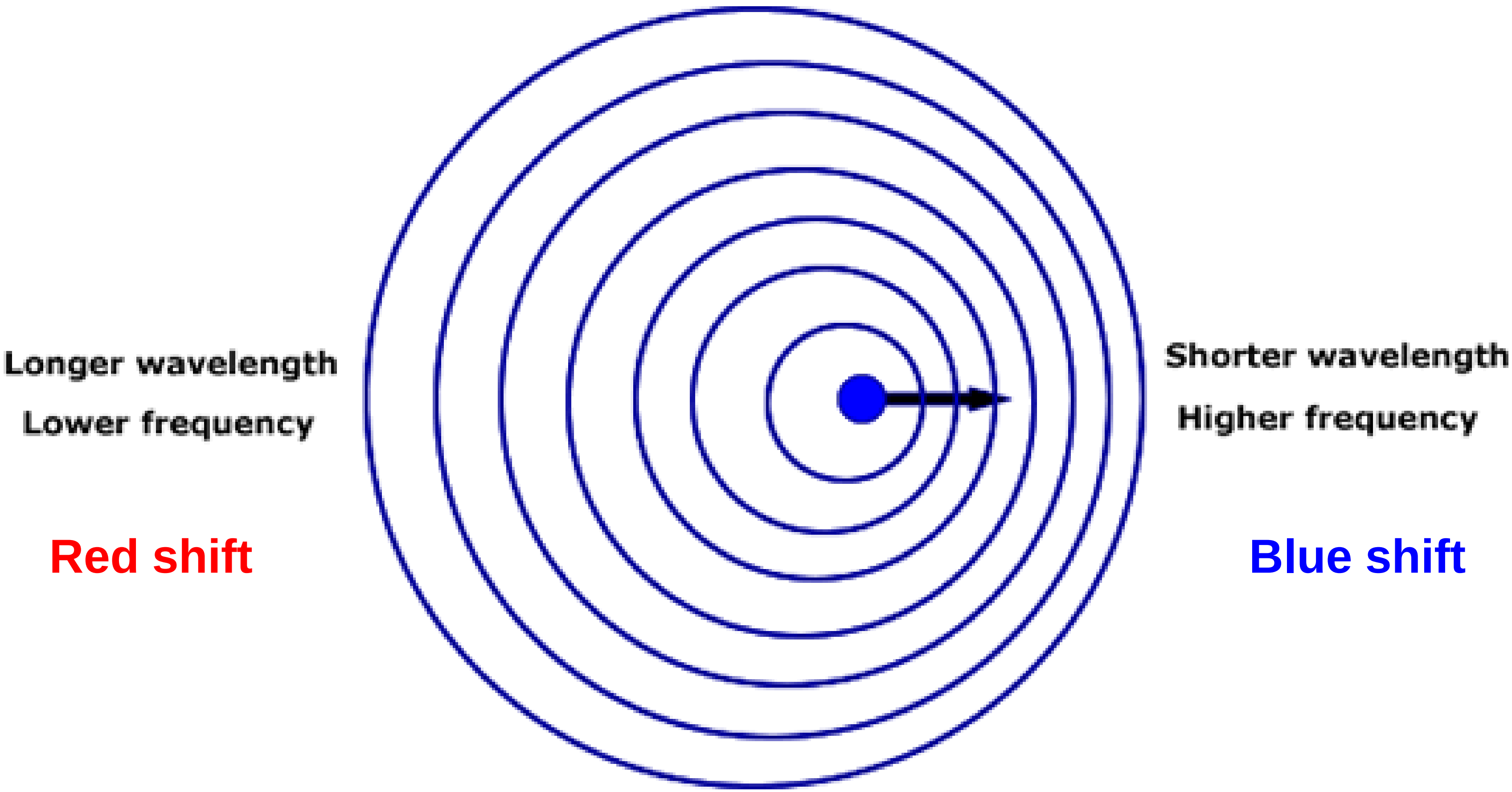
Doppler Shift



Red shift

Blue shift

Relativistic Doppler Shift

In the **relativistic** version of the Doppler effect the ***frequency*** of light seen by an observer at rest is

$$f = \gamma f'(1 + \beta)$$

Source travelling towards the observer

where f' is the frequency emitted by the moving source and β = v/c ~1 when electron is relativistic.

So, in terms of wavelength $\lambda \sim \frac{\lambda'}{2\gamma}$

Combining Lorentz and Doppler

So the electron emits light of wavelength λ_u/γ

Lorentz contraction

And since it is travelling towards us this wavelength is further reduced by a factor 2γ

Doppler shift

So the wavelength observed will be ~ $\lambda_u/2\gamma^2$

For GeV electron energies with γ of 1000's, an undulator with a period of a **few cm** will provide radiation with wavelengths of **nm (X-rays)**

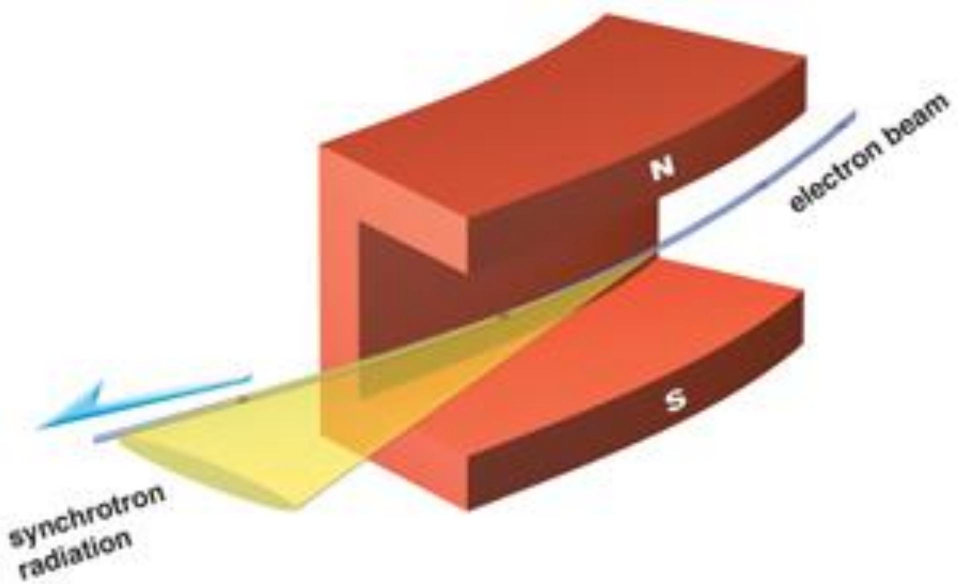
SR from Dipoles

A bending magnet or dipole has a uniform magnetic field

The electron travels on the arc of a circle of radius set by the magnetic field strength

Horizontally the light beam sweeps out like a lighthouse - the intensity is flat with horizontal angle

Vertically it is in a narrow cone of angle typically $\pm 1/\gamma$



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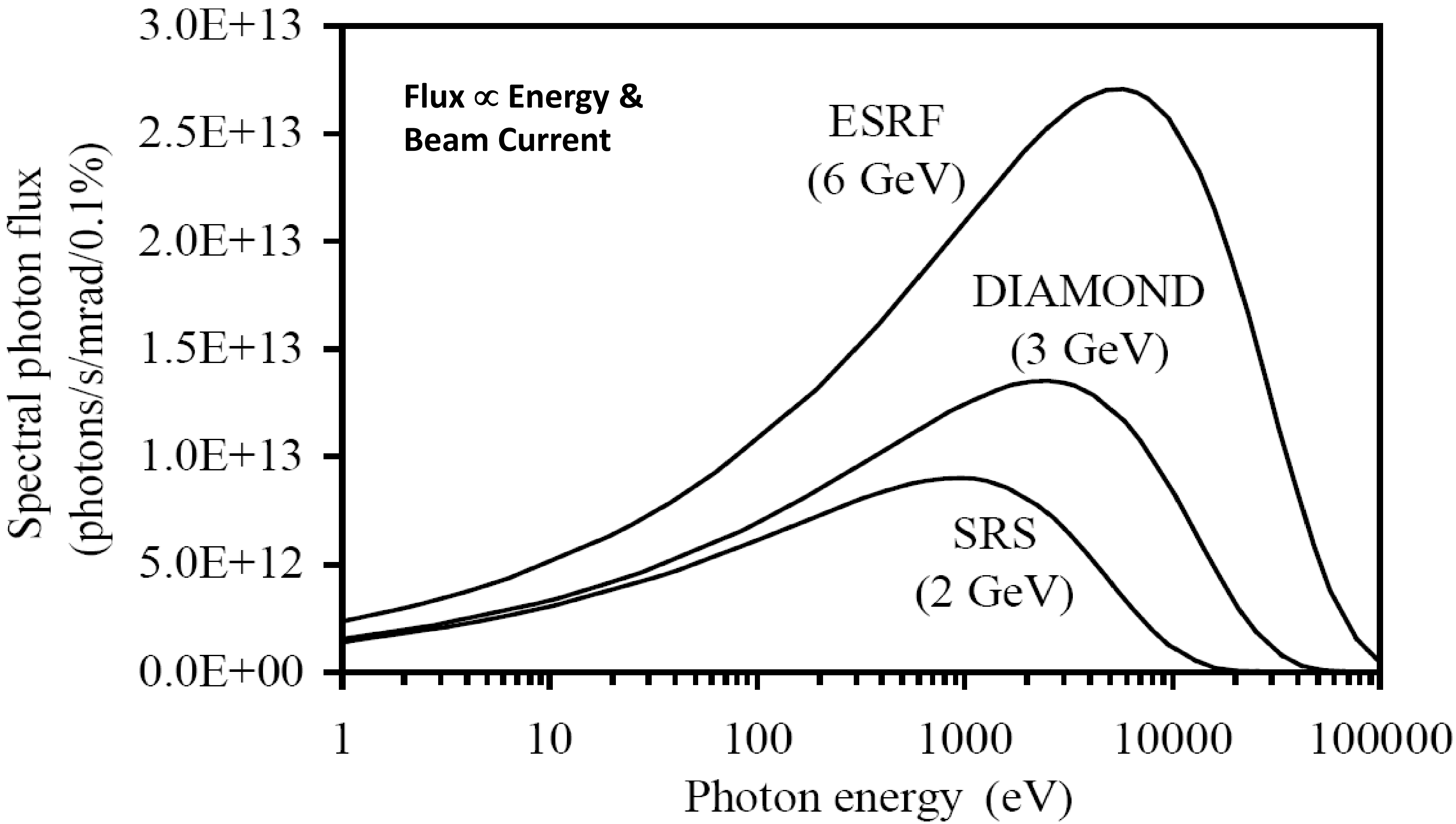
Examples for Photon Flux

log-linear scale, 200mA beam current assumed for all sources



SR Power

Virtually all SR facilities have melted vacuum chambers or other components due to the SR hitting an uncooled surface by accident

The average SR power is very high and the **power density is even higher**

The total power emitted by the electron beam in the dipoles is

$$P_{\text{total}} = 88.46\,\frac{E^4 I_b}{\rho_0}$$

where the power is in **kW**, E is in GeV, I_b is in A, bend radius ρ_0 is in m.

and **power density on axis** (in W/mrad^2)

$$\left.\frac{dP}{d\Omega}\right|_{\psi=0} = 18.08\,\frac{E^5 I_b}{\rho_0}$$

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Examples

Ring	Energy (GeV)	ρ (m)	I_b (mA)	P_{total} (kW)	$dP/d\Omega$ (W/mrad^2)
SRS	2	5.56	200	50.9	20.8
DIAMOND	3	7.15	300	300.7	184.4
ESRF	6	25.0	200	916.5	1124.0

The RF system replaces this lost power continuously and keeps the electrons in an equilibrium state

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Adjusting the Dipole Spectrum

- In a storage ring of fixed energy, the spectrum can be shifted sideways along the photon energy axis if a different bending radius can be generated.
- Requires a different B Field
- Used to shift the rapidly falling edge (high energy photons, short wavelengths)
- Special magnets that do this are called **wavelength shifters**

Multiple Wavelength Shifters?

- If we can fit many wavelength shifters in a straight section then we will get more photons!
- Each Wavelength Shifter would be an independent source of SR – all emitting in the same forward direction.
- The observer will see SR from all the Source points – the flux would just add up linearly

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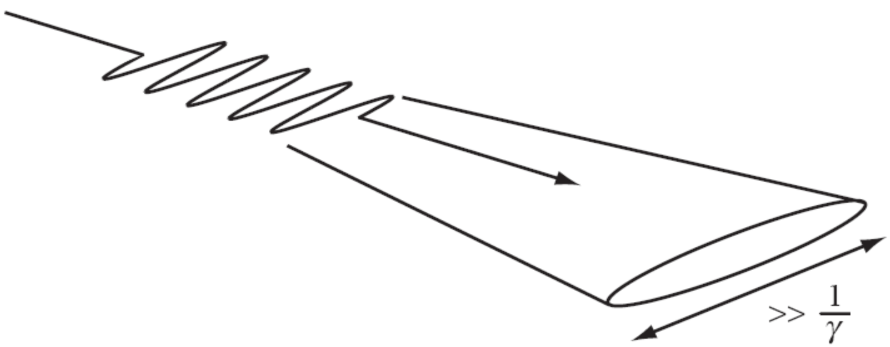
Multipole Wigglers

- This idea is the basic concept for a **Multipole Wiggler**
- A Multipole Wiggler has lots of high field magnets giving both shorter wavelengths and even more photons
- Separate Wavelength Shifters is not the most efficient use of the space! A better way of packing more high field emitters into a straight is a sinusoidal field shape



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Wigglers – Electron Trajectory

Electrons are travelling in the **s** direction

The equations of motion for the electron are

$$\ddot{x} = \frac{d^2x}{ds^2} = \frac{e}{\gamma m_0 c}(B_y - \dot{y}B_s)$$

$$\ddot{y} = \frac{d^2y}{ds^2} = \frac{e}{\gamma m_0 c}(\dot{x}B_s - B_x)$$

If we have a wiggler which only makes the electron oscillate in the horizontal plane (x) (i.e. $B_x = B_s = 0$) then:

$$\ddot{x} = \frac{eB_y}{\gamma m_0 c}$$

$$\ddot{y} = 0 \quad .$$

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Deflection Parameter, K

B_y is **sinusoidal** with period λ_u

$$B_y(s) = -B_0 \sin\left(\frac{2\pi s}{\lambda_u}\right)$$

Integrate once to find $\dot{x}$ which is the ***horizontal angular deflection*** from the s axis

$$\dot{x}(s) = \frac{B_0 e}{\gamma m_0 c}\frac{\lambda_u}{2\pi}\cos\left(\frac{2\pi s}{\lambda_u}\right)$$

Therefore, the maximum angular deflection is $\frac{B_0 e}{\gamma m_0 c}\frac{\lambda_u}{2\pi}$

We define K as the **"deflection parameter"**

$$K = \frac{B_0 e}{m_0 c}\frac{\lambda_u}{2\pi} = 93.36\, B_0 \lambda_u$$

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Trajectory of the Electron

One more integration gives the electron path, which is also a sine wave

$$x(s) = \frac{K}{\gamma}\frac{\lambda_u}{2\pi}\sin\left(\frac{2\pi s}{\lambda_u}\right)$$

The maximum angular deflection is $\frac{K}{\gamma}$

The maximum transverse displacement is $\frac{K}{\gamma}\frac{\lambda_u}{2\pi}$

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Trajectory of the Electron

SR is emitted with a typical angle of $\sim 1/\gamma$

So if $K < 1$ the electron trajectory will always overlap with the emitted SR (**an undulator**)

If $K \gg 1$ there will be little overlap and the source points are effectively independent – this is the case for a **Wiggler**

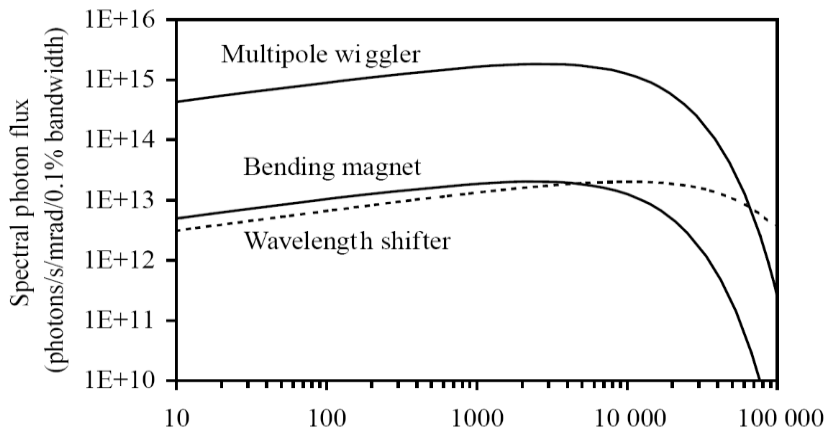
Warning:

Some groups, especially FEL people in the USA, refer to undulators as wigglers!

Wiggler Flux

- A Wiggler can be considered a series of dipoles one after the other
- There are two source points per period (two poles per period)
- The flux is simply the number of source points times the dipole flux for one pole
- The Wiggler has two clear advantages:
  - **The spectrum can be set to suit the science need**
  - **The Flux is enhanced by the number of poles**

Example
300mA, 3 GeV beam
1.4T dipole
6T WS
1.6T MPW with 45 periods



Wiggler Power

The total power emitted by a beam of electrons passing through **any magnet system** is

$$P_{\text{total}} = 1265.5\, E^2 I_b \int_0^L B(s)^2 ds$$

For a sinusoidal magnetic field the total power emitted is (in W)

$$P_{\text{total}} = 632.8\, E^2 B_0^2 L I_b$$

Power Examples

Dipoles

Ring	Energy (GeV)	ρ (m)	I_b (mA)	P_{total} (kW)	$dP/d\Omega$ (W/mrad^2)
SRS	2	5.56	200	50.9	20.8
DIAMOND	3	7.15	300	300.7	184.4
ESRF	6	25.0	200	916.5	1124.0

Wigglers

Diamond Wiggler, 45 poles at 4.2T, period of 48mm

Power emitted = 33kW

This is equivalent to ~10% all the dipole SR for just one experiment

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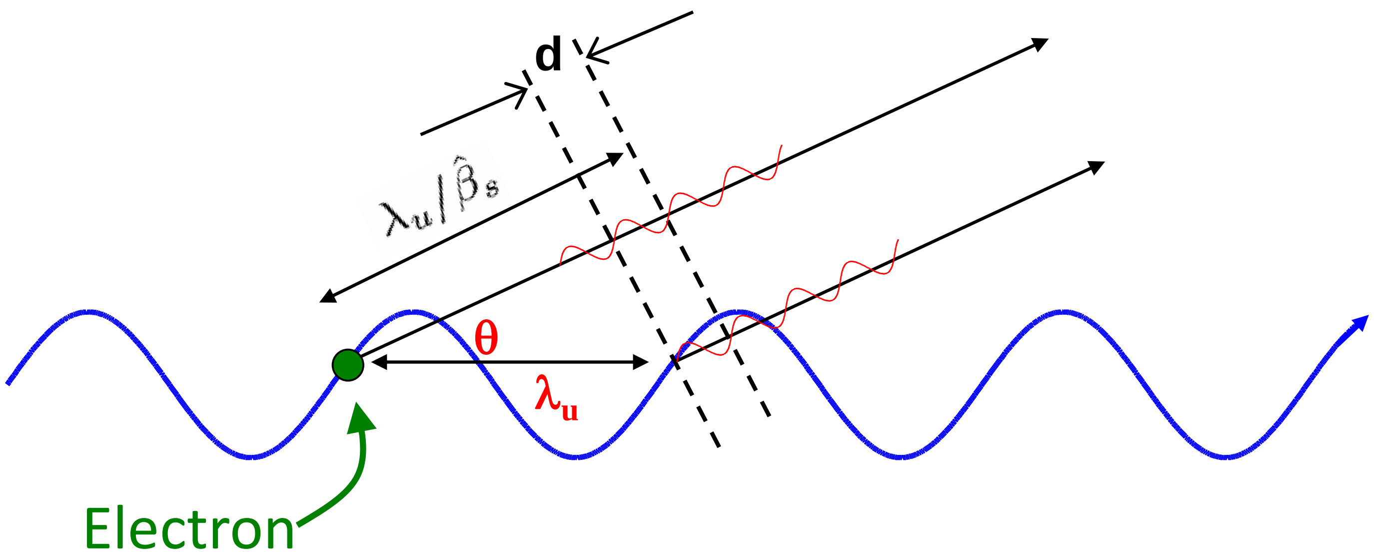
Undulators

- Undulators are very similar magnetically to wigglers
- They are also periodic magnets that make the electrons take a sinusoidal path
- The key difference compared to a wiggler is that the undulator output is due to ***interference of the light*** emitted by a single electron at the poles of the magnet
    - ***A Wiggler is basically just raw power***
    - ***An Undulator is more subtle and precise and ultimately far more popular!***

The Condition for Interference

For constructive interference between wavefronts emitted by the same electron **the electron must slip back by a whole number of wavelengths** over one period



The Undulator Equation

Solving for λ we get **the undulator equation**

$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \theta^2\gamma^2\right)$$

Example, 3GeV electron passing through a 50mm period undulator with K = 3. First harmonic (n = 1), on-axis is ~4 nm.

So **cm** periods translate to **nm** wavelengths because of γ^2 in the denominator

Undulator equation implications

$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \theta^2\gamma^2\right)$$

- The wavelength primarily depends on the **period** and the **energy** but also on K and the observation angle θ.

$$K = \frac{B_0 e}{m_0 c}\frac{\lambda_u}{2\pi} = 93.36\, B_0 \lambda_u$$

- **If we change B_0 we can change λ.** For this reason, undulators are built with adjustable B field. The amount of the adjustability determines the wavelength tuning range of the undulator.

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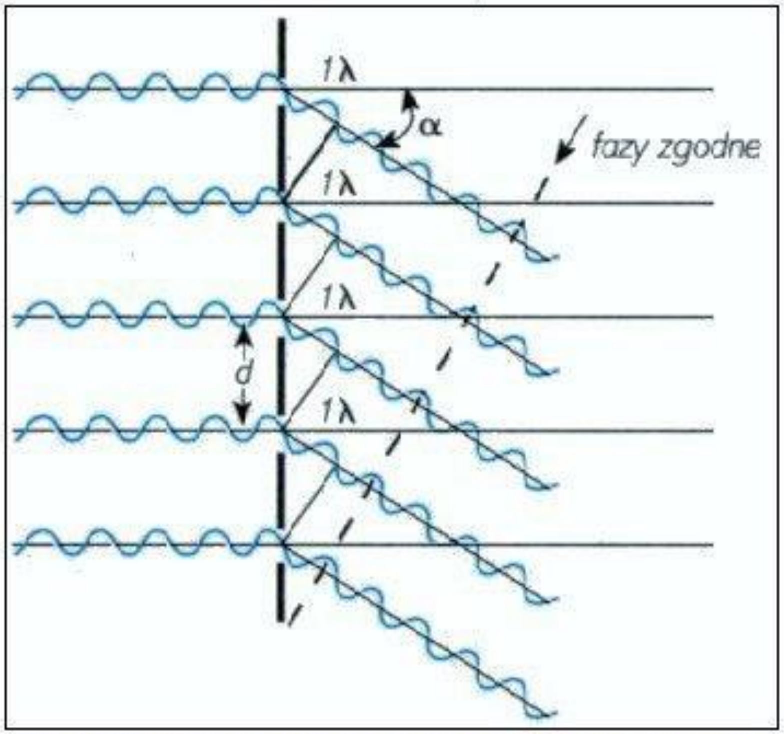
Diffraction Gratings

Undulators and diffraction gratings have much in common

This is because the diffraction grating acts as a large number of periodic sources –
very similar concept to an undulator



The diffraction grating and spectrum on screen
d grating constant, λ wave length, α angle of deflection,

Example Angular Flux Density

- An Undulator with 50mm period and 100 periods with a
- 3GeV, 300mA electron beam will generate:
- Angular flux density of **8 x 10^{17}** photons/sec/mrad^2/0.1% bw

- For a dipole with the same electron beam we get a value of **~ 5 x 10^{13}** photons/sec/mrad^2/0.1% bw

- **The undulator has a flux density ~10,000 times greater than a dipole because it scales with N^2**
- N is the number of undulator periods

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Example Flux

- Undulator with 50mm period, 100 periods
- 3GeV, 300mA electron beam
- Our example undulator has a flux of **4×10^{15}** photons/s/0.1% bandwidth compared with the dipole of **$\sim 10^{13}$**
- **The flux is proportional to N**

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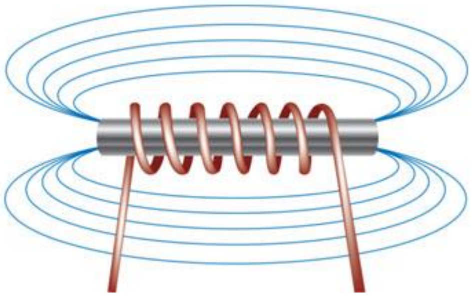
Generating Periodic Magnetic Fields

- To generate magnetic field we can use:

- Electromagnets
- Normal conducting or
- Superconducting



- Permanent Magnets

- **Both types can also include iron to boost and shape the field**

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Pure Permanent Magnet Undulators

- A magnet which contains no iron or coils is said to be a Pure Permanent Magnet (PPM)
- Because the PM relative permeability is ~ 1 we can just add field contributions from each block linearly – just like we do with coils
- We want a sinusoidal magnetic field along the direction of the electron beam
- To generate a sinusoidal field an ideal PPM would have **two sets (arrays)** of Permanent Magnet with their axis rotating smoothly through **360° per period** along the direction of the electron beam
- In practice this ideal situation is approximated by splitting the system into a number of discrete rectangular magnet blocks

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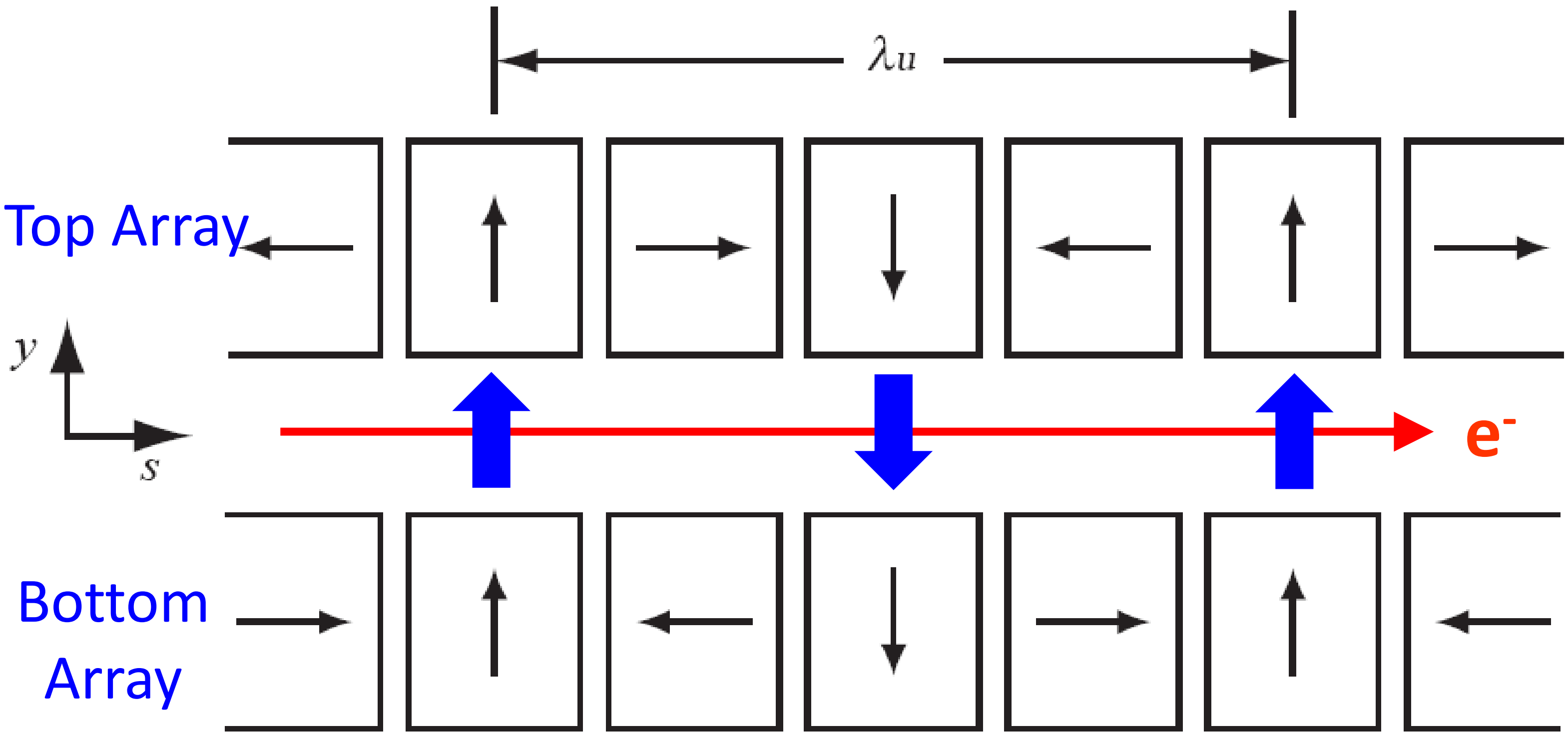
Example PPM arrangement, 4 Blocks per period

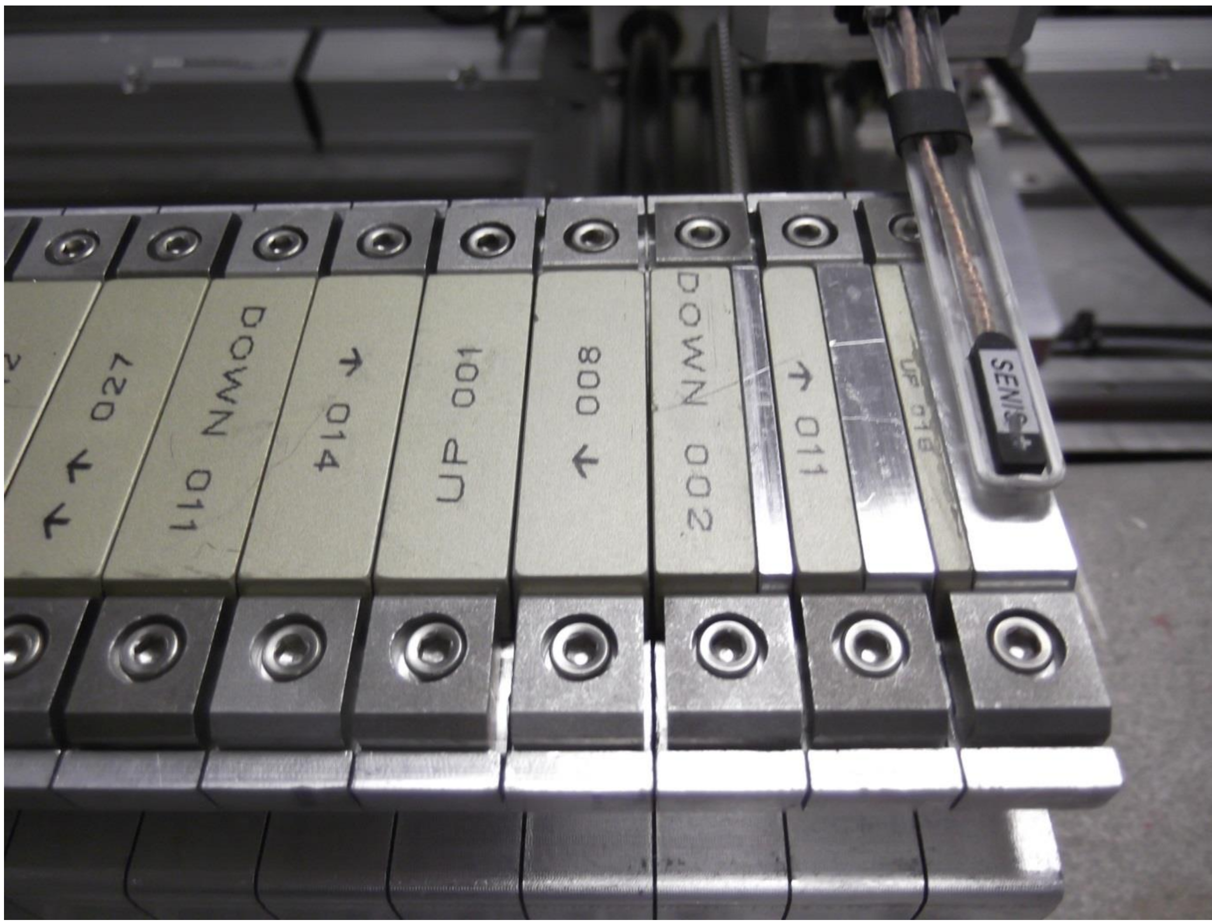
Side View



Example PPM arrangement, 4 Blocks per period

Photo of a PPM Array

SwissFEL Undulator built at DL



Peak Field Achievable

$$B_{y_0} = 1.72\, B_r e^{-\pi g/\lambda_u}$$

- **Important:**
- If all the dimensions are scaled together the fields on-axis **do not change**
- Small gaps and periods can still produce **high fields**
- This is not true for electromagnets

- Even higher fields are possible with permanent magnets if we **include iron in the system**
- Mixing Permanent Magnets and iron poles is called a **hybrid** magnet

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Changing the Wavelength

- To vary the output wavelength from the undulator we need to alter the field level on the axis
- We can now see that the only practical way to do this for a permanent magnet device is **to change the magnet gap, g**

$$B_{y_0} = 1.72\, B_r e^{-\pi g/\lambda_u}$$

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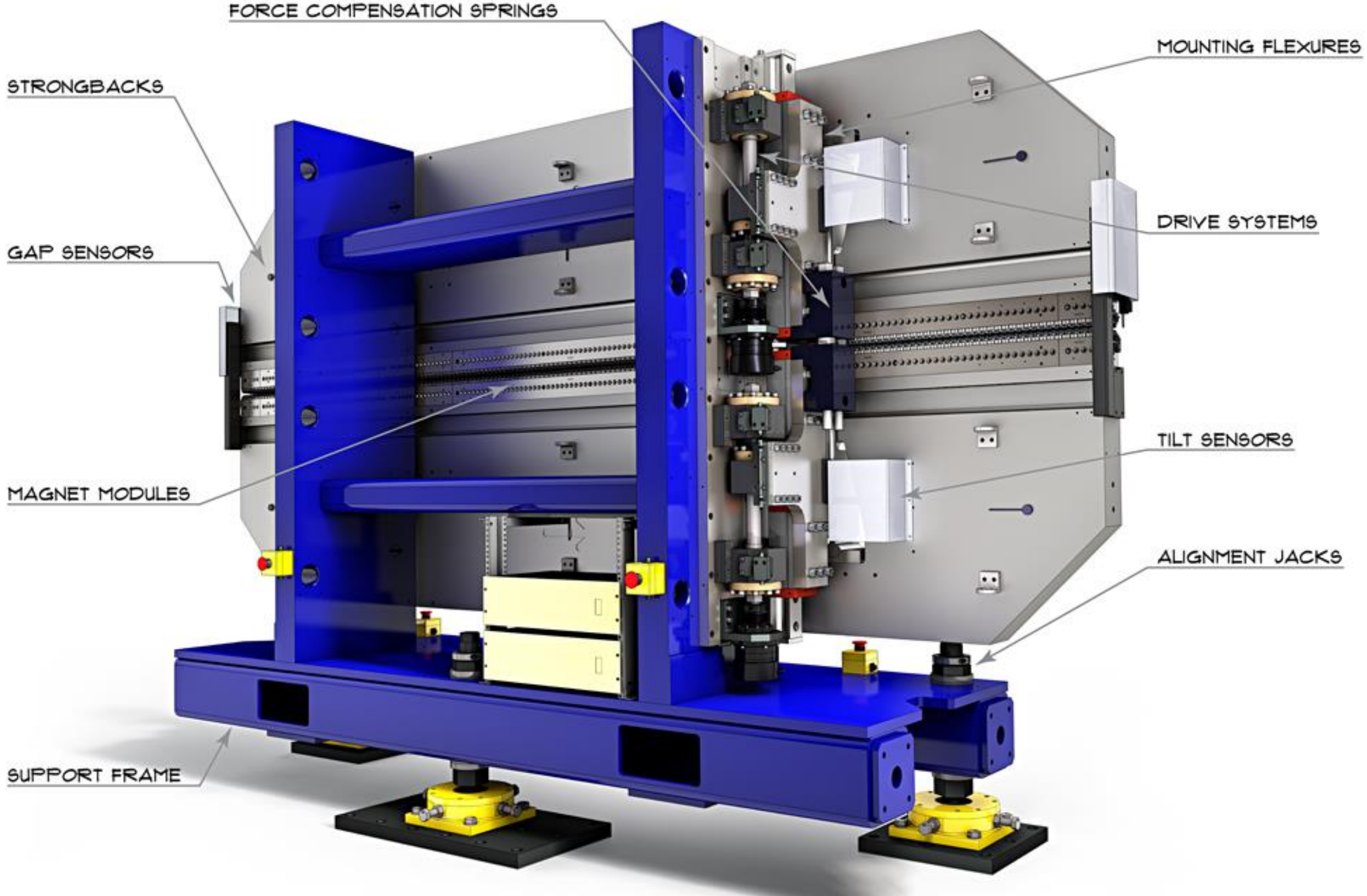
Real Undulator Implementation



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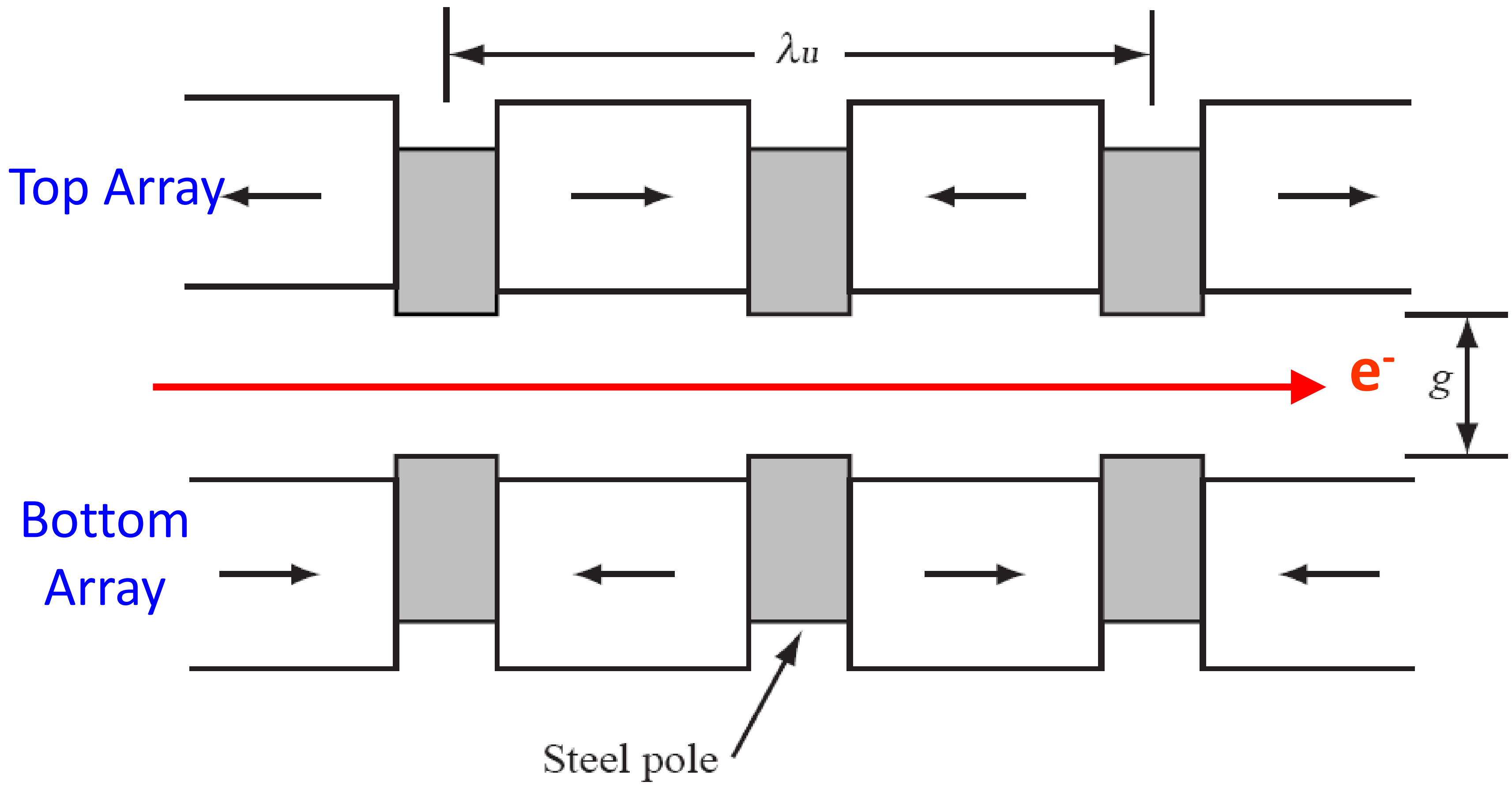
LCLS-II Undulator, LBNL

Hybrid Undulators – Inclusion of Iron

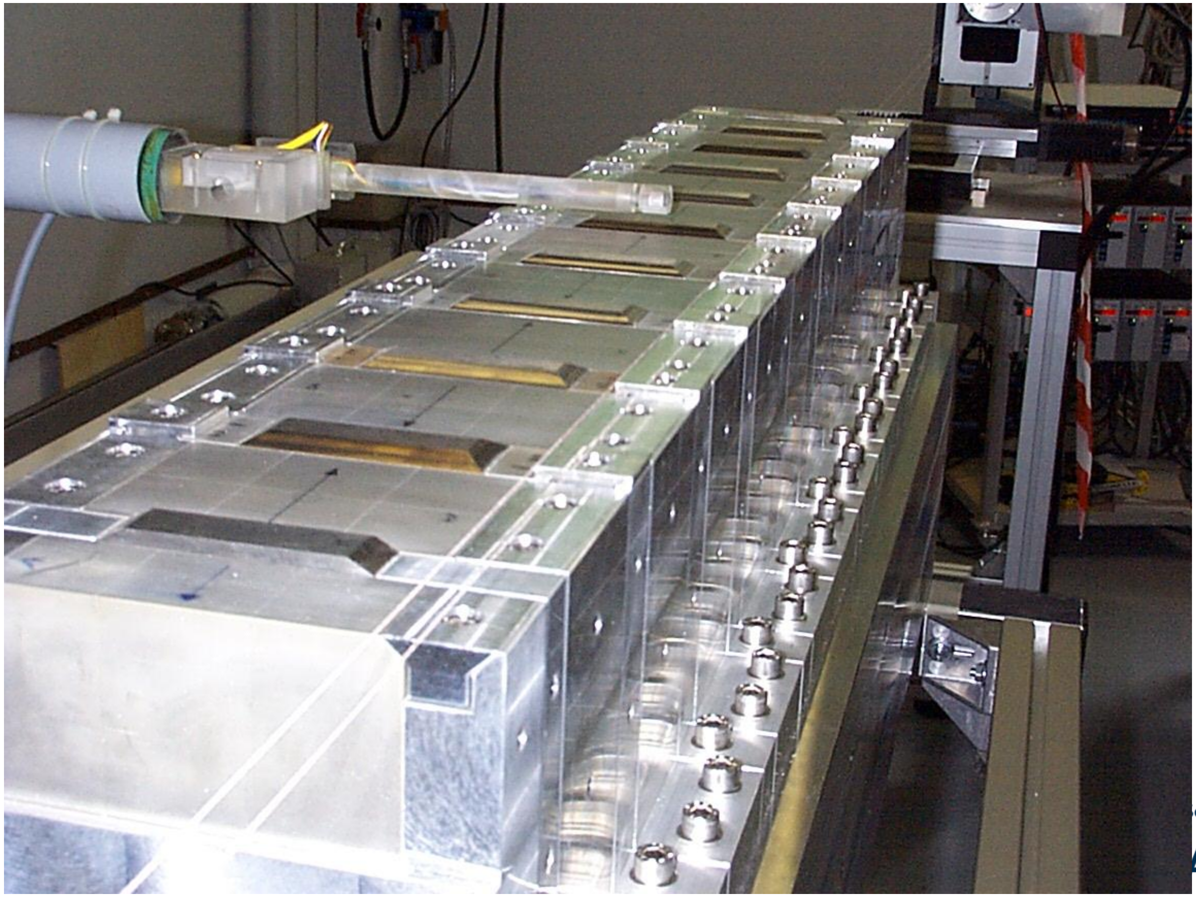
Simple hybrid example



Hybrid Undulators – Inclusion of Iron

Photo of a Hybrid Array

SRS Multipole Wiggler being measured



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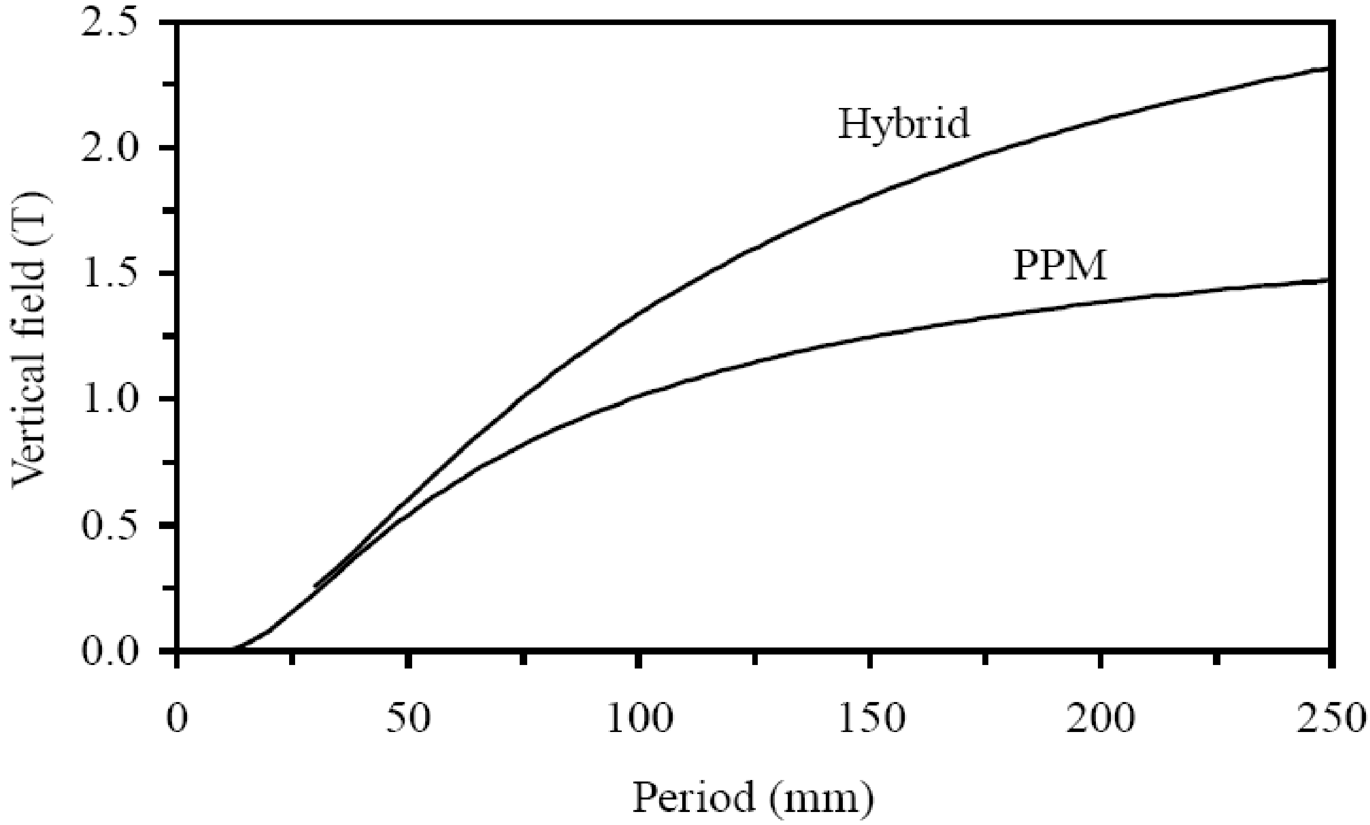
Hybrid vs PPM Undulators

Assuming Br = 1.1T and gap of 20 mm



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In-Vacuum Undulators

- The minimum magnet gap limits the performance of an undulator
- The magnet gap is determined by the needs of the electron beam
- In practice this is set by the vacuum chamber
- **For example:**
  - If an electron beam needs **10mm** of vertical space
  - And the vacuum chamber walls are **2mm** thick
  - With an allowance for mechanical tolerances of **1mm**
  - The minimum magnet gap will be **15mm**
  - *So 5 mm is effectively wasted*
- An option is to put the undulator inside the vacuum chamber

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In-Vacuum Examples

Diamond U23

In-vacuum undulator – Before vacuum chamber is fitted

In-Vacuum Examples

SACLA in-vacuum undulators (Japan XFEL)

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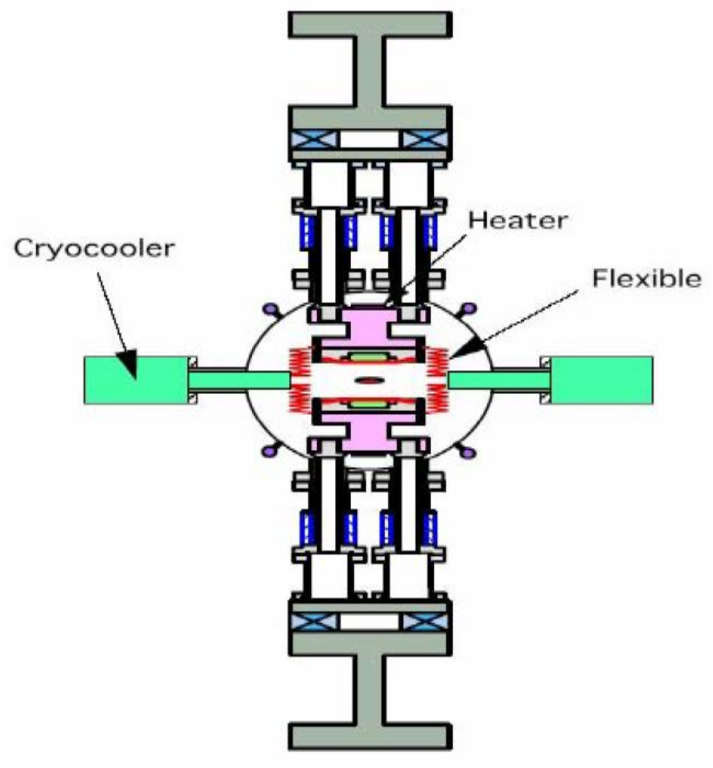
Cryogenic Undulators (CPMUs)

- These are a natural evolution of in-vacuum undulators that take advantage of the variation of remanent field with temperature
- Operational experience with CPMUs on storage rings has been positive
- PrFeB is now the material of choice as it is strong (B_r up to ~1.7T) and works at 77K



H Kitamura, Spring-8

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Superconducting Magnets

- For fields greater than ~3T superconductors are the only real option
- For intermediate fields (~1 to ~3 T) they can have much **shorter periods** than Permanent Magnets
- The materials used are only superconducting below ~10K

Superconducting Wigglers

- Superconducting Wigglers are popular in the intermediate energy light sources (~3GeV) because the high field enhances the flux in the hard X-ray region
- Diamond Examples
- **3.5 T, 60 mm** period, 45 poles
- **4.2 T, 48 mm** period, 45 poles

Superconducting Undulators

- The motivation of using superconductivity is to generate higher fields on axis than are presently available from the best permanent magnet systems
- They have to have a *significantly better* performance to make them worthwhile
- The key region of interest is in **short period** systems, typically ~15mm
- The field quality has to be as good as existing undulators

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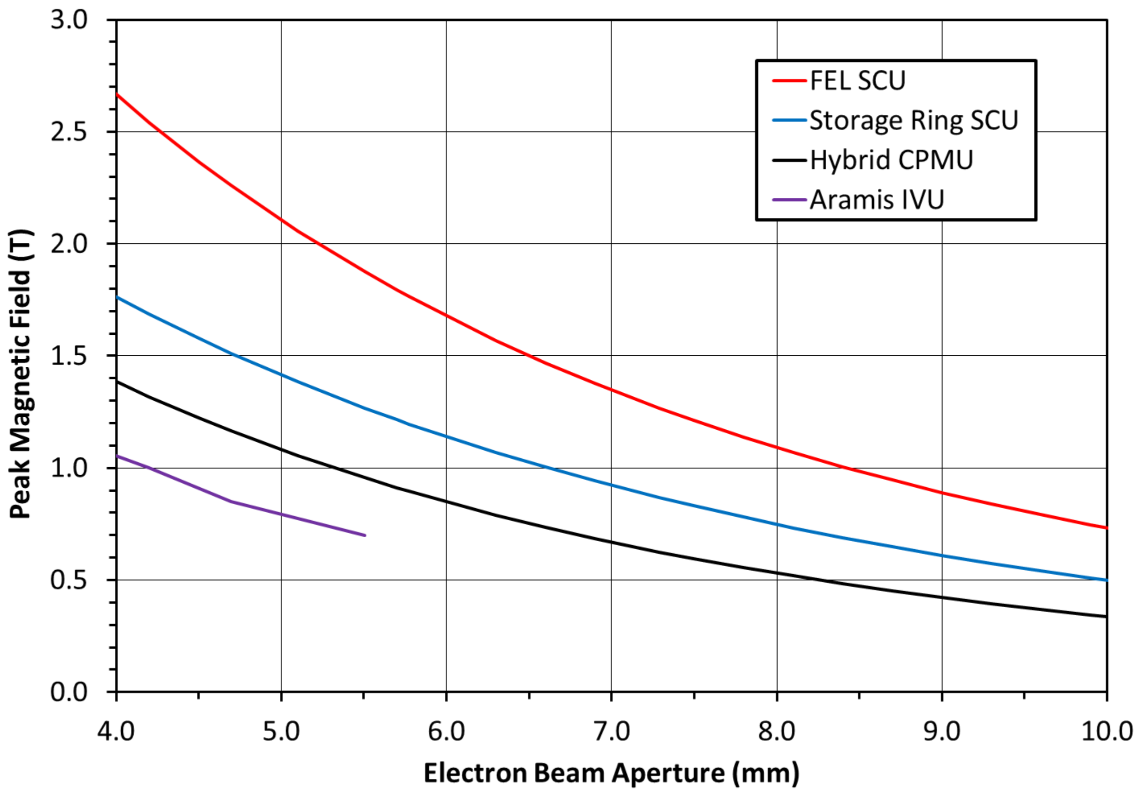
Undulator Comparisons

- **Example 15mm period and 5mm beam aperture**
- These are all State of the art examples for their own particular technology



JA Clarke, FEL 2017

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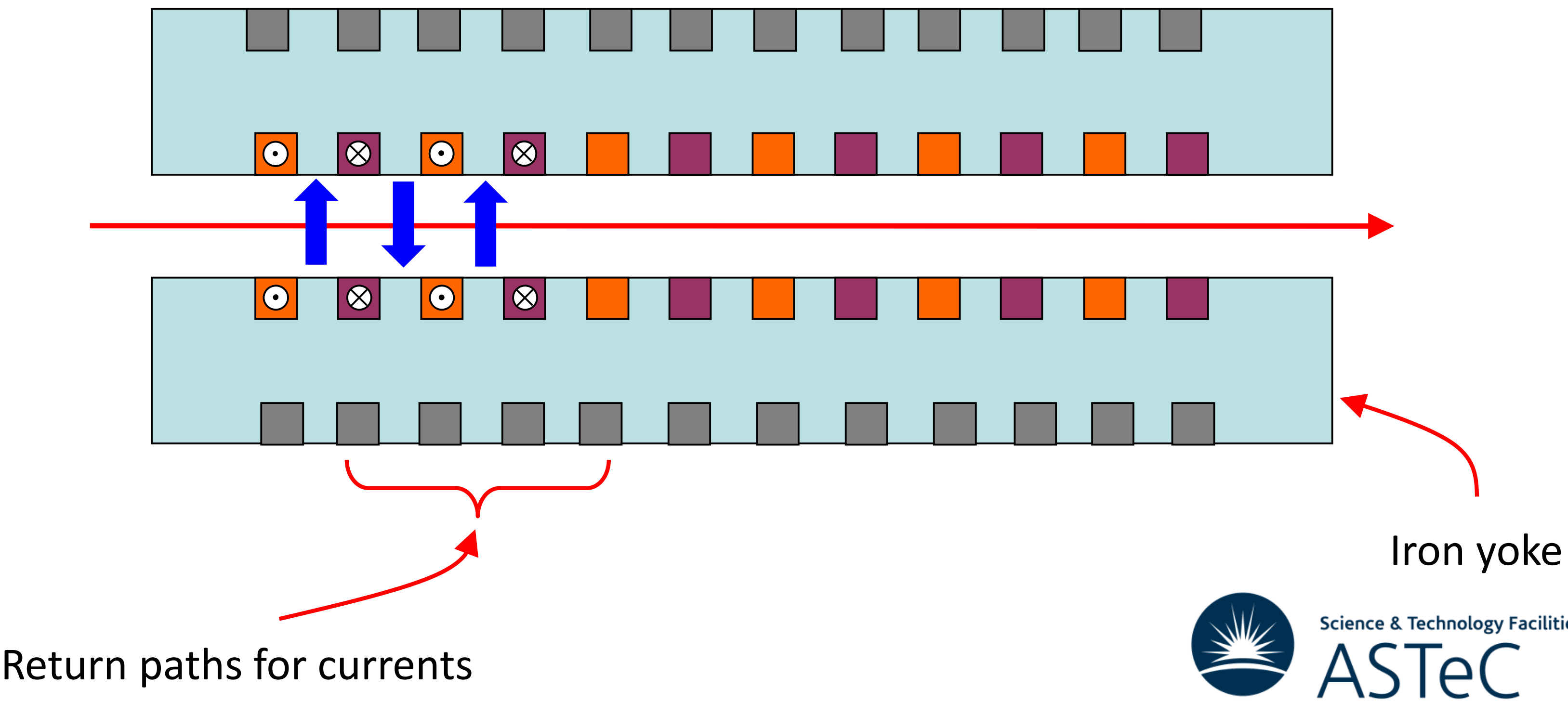
Undulator Design

- The standard solution is very simple – currents flowing perpendicular to the beam axis with iron poles
- The challenge is the engineering



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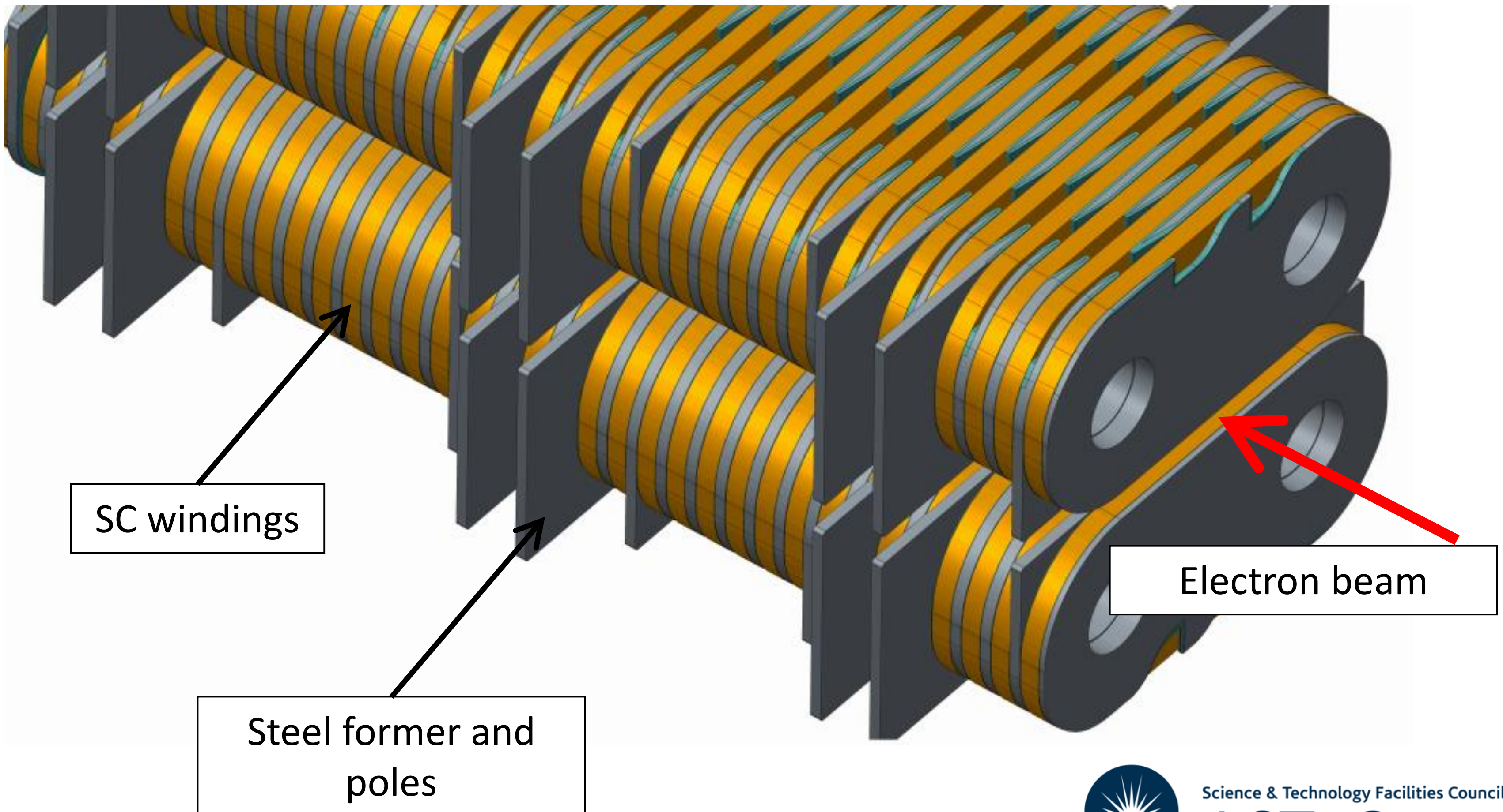
SCU for Storage Ring

- Most groups have converged on a similar concept for planar SCUs



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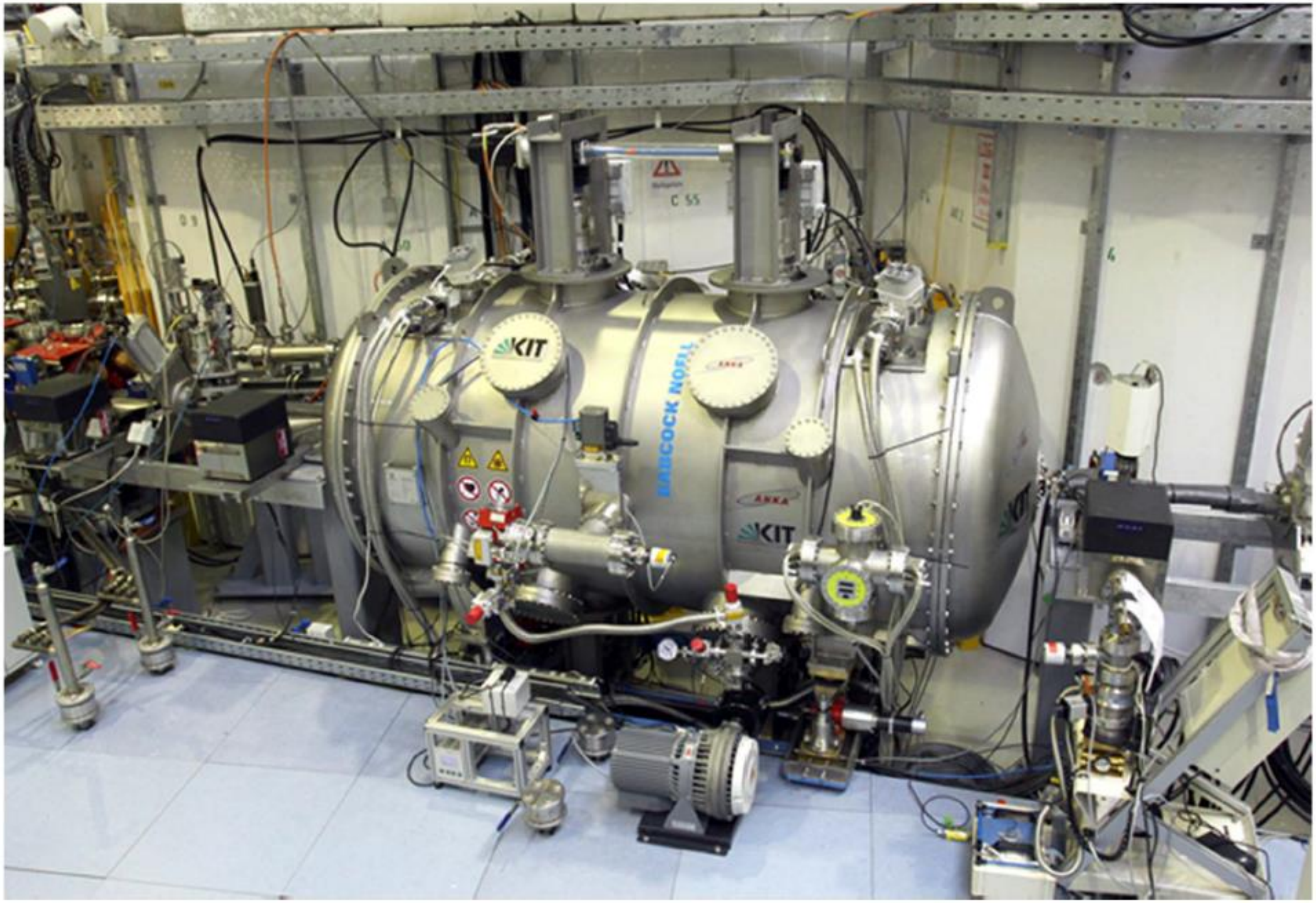
SCU15 installed in ANKA

Babcock Noell GmbH

KIT Karlsruhe Institute of Technology



Summary

- Synchrotron Radiation is emitted by accelerated charged particles - the brightest source of X-rays available
- The combination of Lorentz contraction and the Doppler shift turns the **cm length scale into nm wavelengths**
- Wigglers are periodic, high field devices, used to generate broadband SR at short wavelengths
- Undulators are periodic, lower field, devices which generate radiation at specific harmonics – similar conceptually to diffraction gratings
- To generate a sinusoidal field we can use two arrays of PM blocks – one above and one below the electron beam
- The field limit for a PPM is ~1.5T but if we include iron (hybrid magnet) then >2 T is easily achievable
- In-vacuum solutions allow for smaller magnet gaps but more complex engineering
- Cryogenic PM undulators generate higher field levels and these are installed in several storage rings now
- Superconducting undulators are also being installed on storage rings and they offer the highest possible fields

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