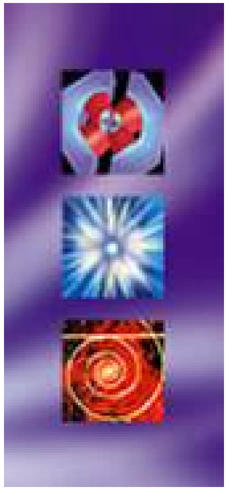
ASTeC Accelerator Science and Technology Centre

Insertion Devices

Jim Clarke
ASTeC
Daresbury Laboratory



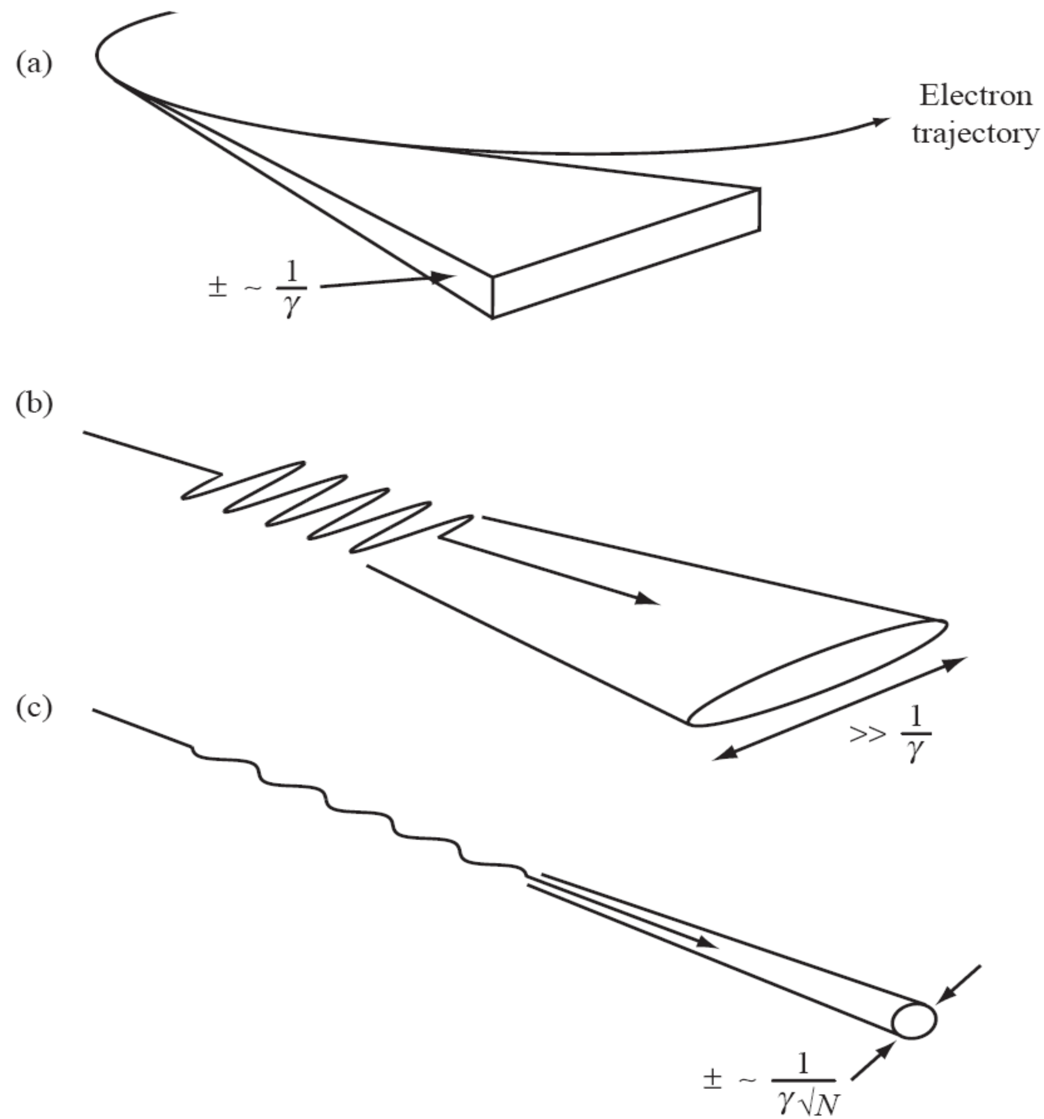
CERN Accelerator School, 16 to 28 September 2007, Daresbury Laboratory

Summary of the Three Basic Sources of SR

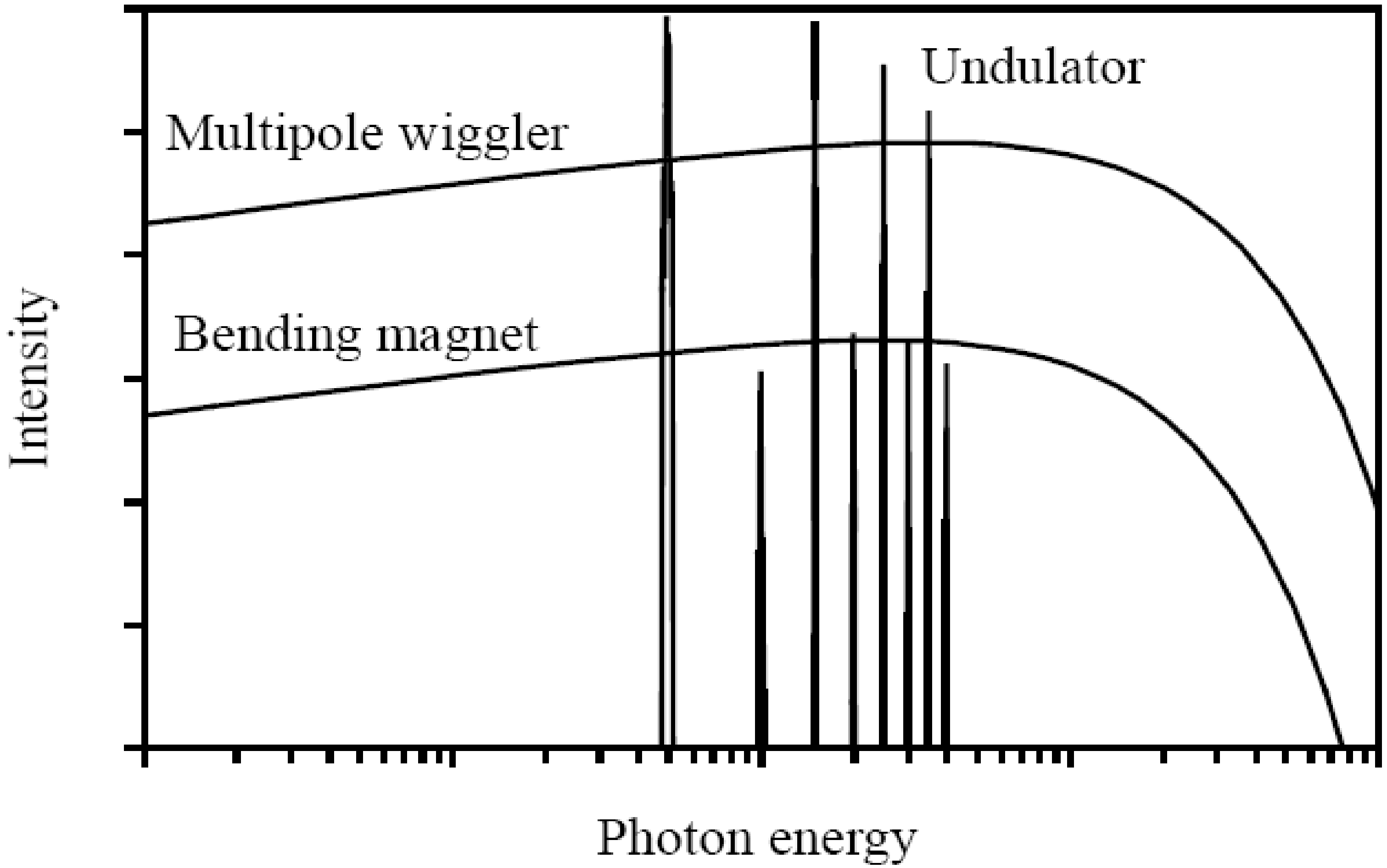
Bending magnet or dipole

(Multipole) Wiggler

Undulator



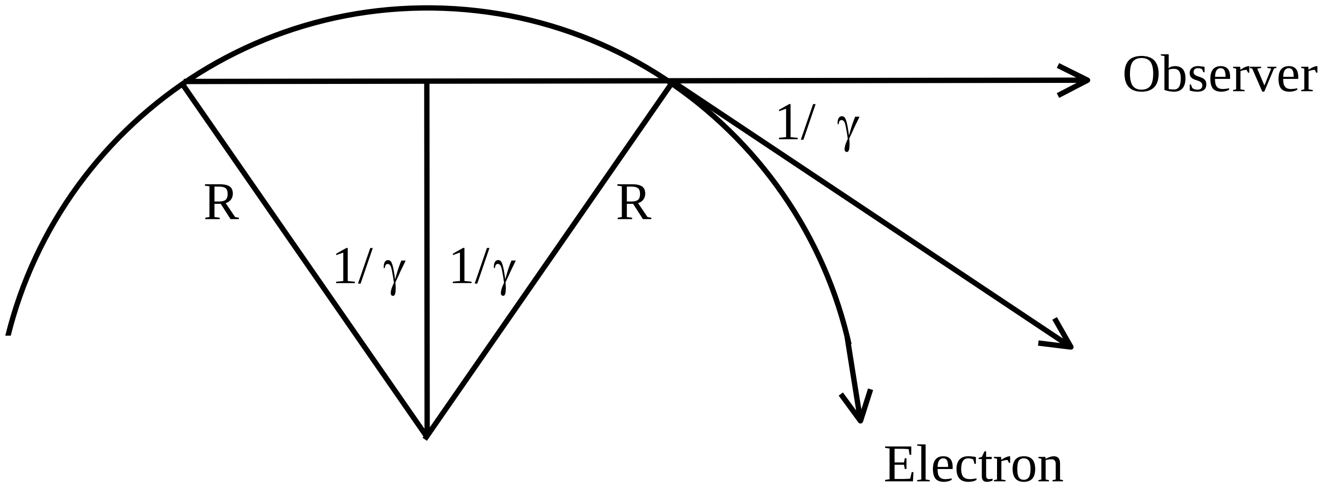
A Typical Spectrum of Synchrotron Radiation



A Brief History of Insertion Devices

1897	Larmor derives expression for total instantaneous power radiated by an accelerated charged particle
1898	Alfred Lienard derives the radiation due to charges moving close to speed of light & energy loss of an electron on a circular path
1947	70MeV electron synchrotron – SR first observed directly
1947	Ginzburg in USSR discusses undulator concept
1951	Motz proposes “undulator” as source of quasi-monochromatic SR
1952	Motz makes experimental demonstration of undulator
1976	SC helical undulator used in first FEL by Madey
1979	First IDs in storage rings
1990s	3rd generation rings built based upon IDs
2000s	Single pass FELs built

SR from Bending Magnets: Simple Recap



The electrons in a synchrotron are accelerated as they are forced to bend along a circular path in a strong magnetic field.

Typical Wavelength

Pulse Length = Time for electron along arc -

Time for photon along chord

$$\approx \frac{4R}{3c\gamma^3}$$

So, Typical Wavelength

$$\approx \frac{4R}{3\gamma^3}$$

For SRS,

R ~ 5.5 m, γ ~ 4000

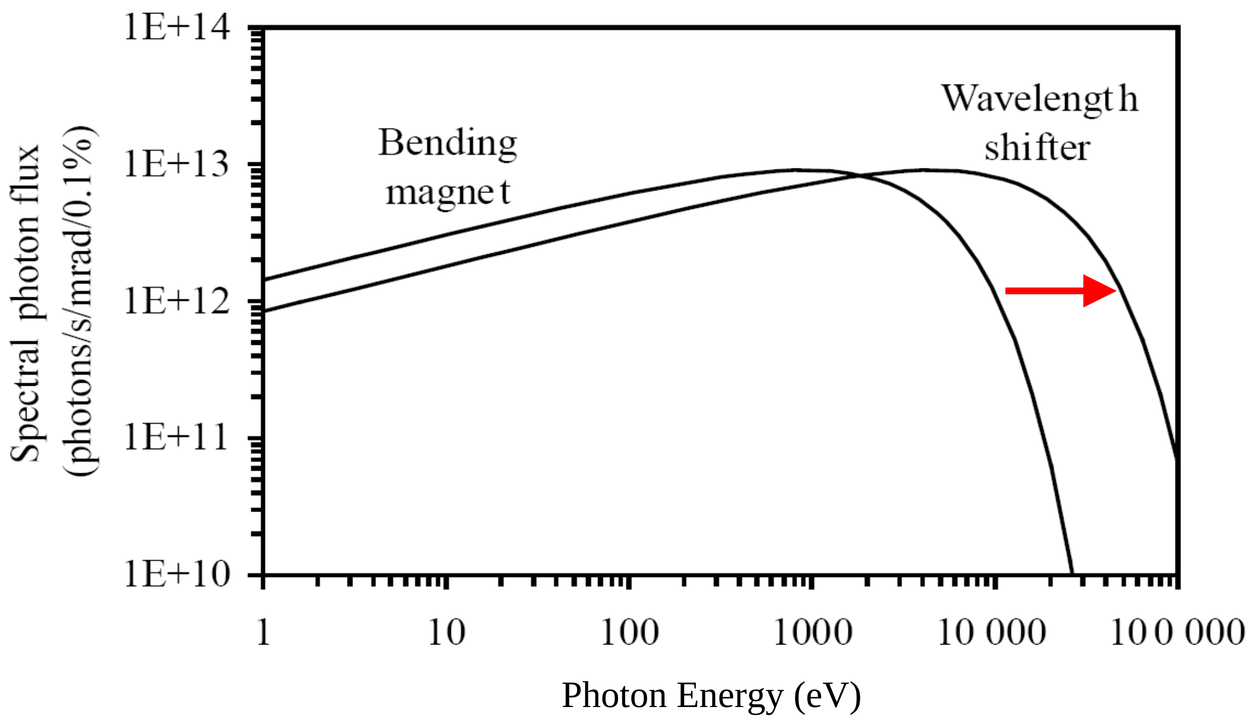
Wavelength ~ 0.1 nm

Wavelength Shifters

Insert high field locally to shift spectrum (change R)

The area under the flux curve is unchanged

Local field (usually) put in 3 magnet bump “insertion device” so not integral part of ring



SRS Example:

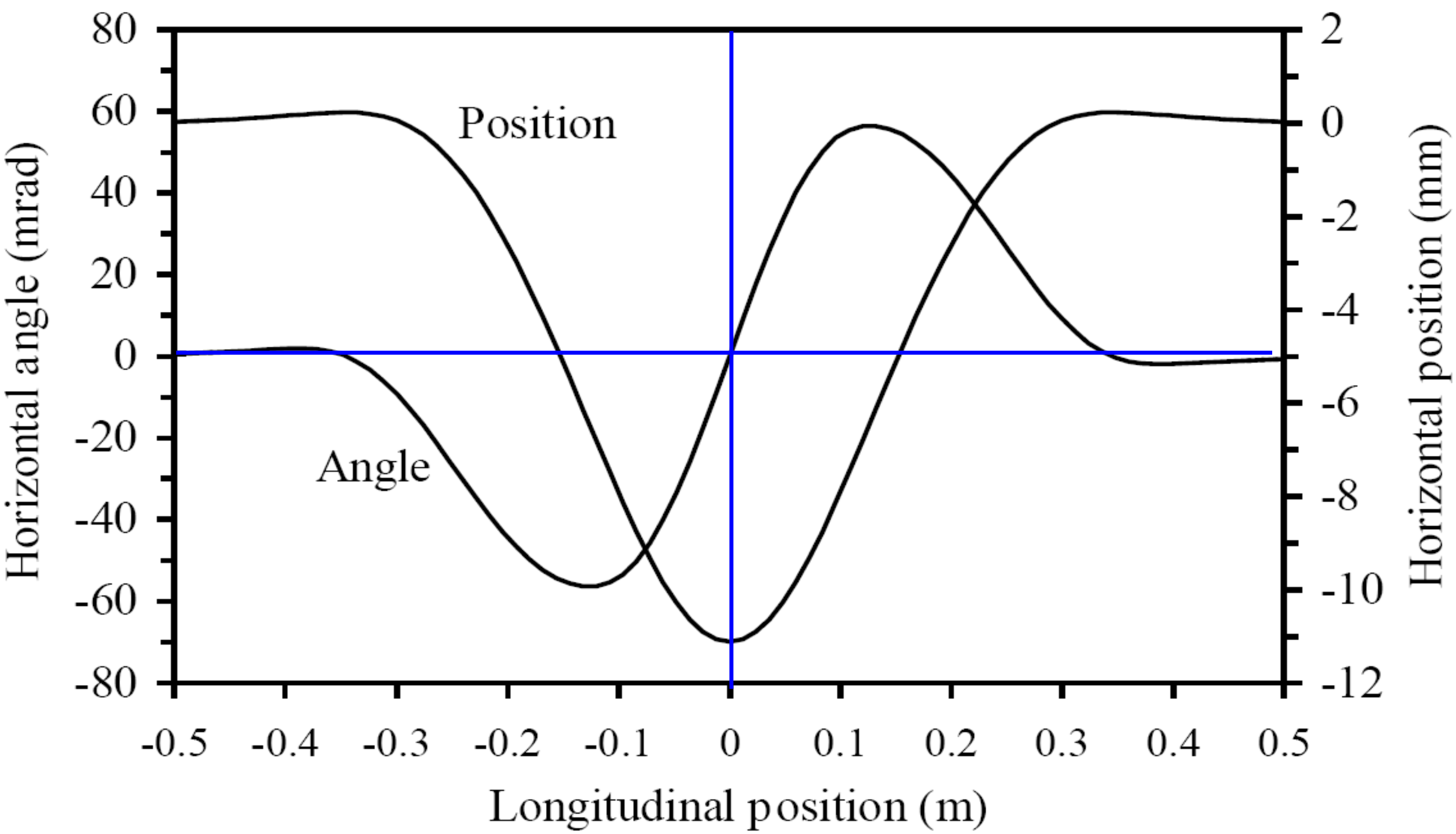
1.2T BM & 6T WS.
2GeV, 200mA.

Electron trajectory in a Wavelength Shifter

Electron enters on axis and exits on axis

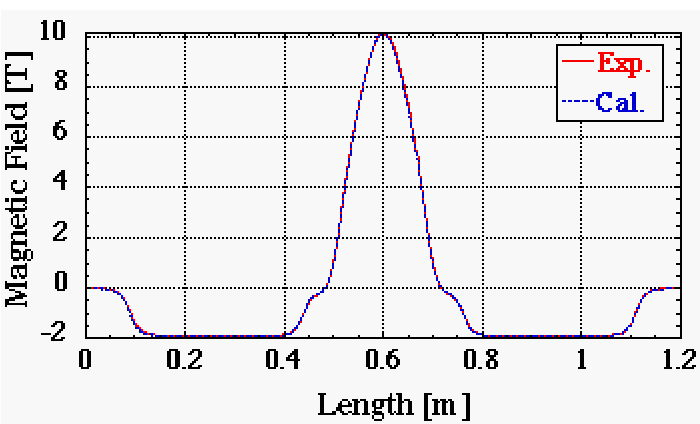
Peak of bump occurs at peak magnetic field – when angle is zero

SR emitted here will travel parallel to axis



Example of Wavelength Shifter

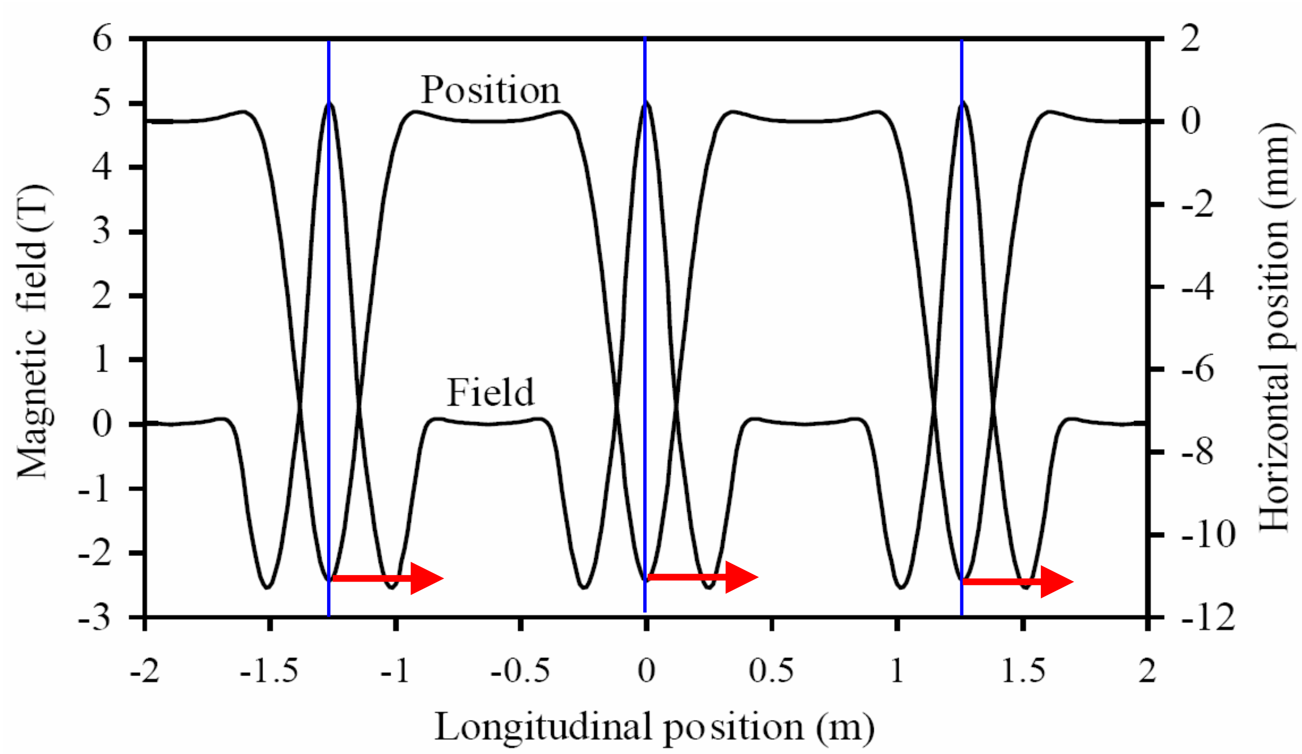
Spring-8 10T superconducting wavelength shifter (or wiggler)



Extension to Multipole Wigglers

One wavelength shifter will give enhanced flux at high photon energies

Imagine many WS installed next to each other in the same straight



Multiple Wavelength Shifters

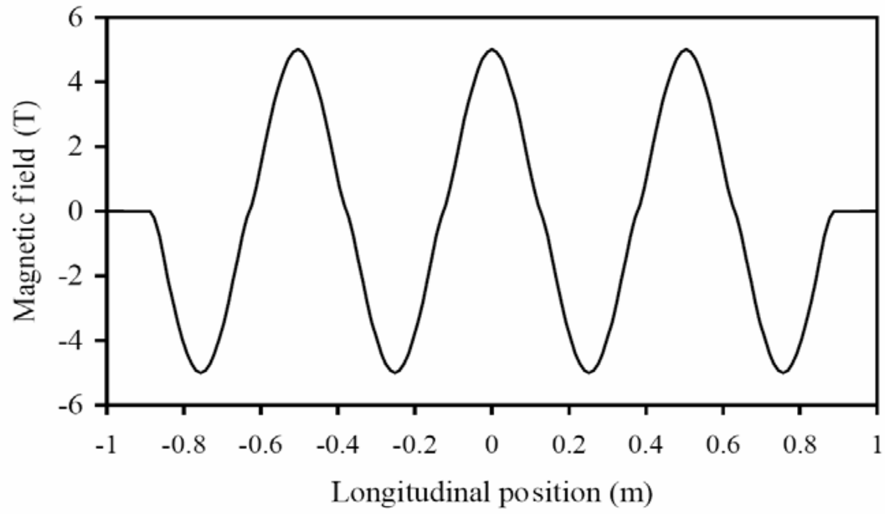
Each WS would be an independent source of SR – all emitting in the forward direction.

The observer on-axis would see SR from all 3 Source points

Observer will see 3 times more flux

This is the basic concept for a multipole wiggler

Three separate WS is not the most efficient use of the space, a better way of packing more high field emitters into a straight is:



B field usually sinusoidal

Multipole Wigglers – electron trajectory

Electrons travelling in s direction

For small angular deflections $(\dot{x} \ll 1, \dot{y} \ll 1)$

The equations of motion for the electron are

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

Assume a MPW which only deflects in the horizontal plane

Only has vertical fields on axis

$$\ddot{x} = \frac{eB_y}{\gamma m_0 c}$$
$$\ddot{y} = 0 \ .$$

Angular Deflection

B field is sinusoidal with period λ_u

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

Integrate 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, peak angular deflection is $\frac{B_0 e}{\gamma m_0 c}\frac{\lambda_u}{2\pi}$

Define the deflection parameter

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

K Parameter

Peak angular deflection is $\dfrac{K}{\gamma}$

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

So if $K < 1$ the electron trajectory will always overlap with the emitted cone of SR – interference effects

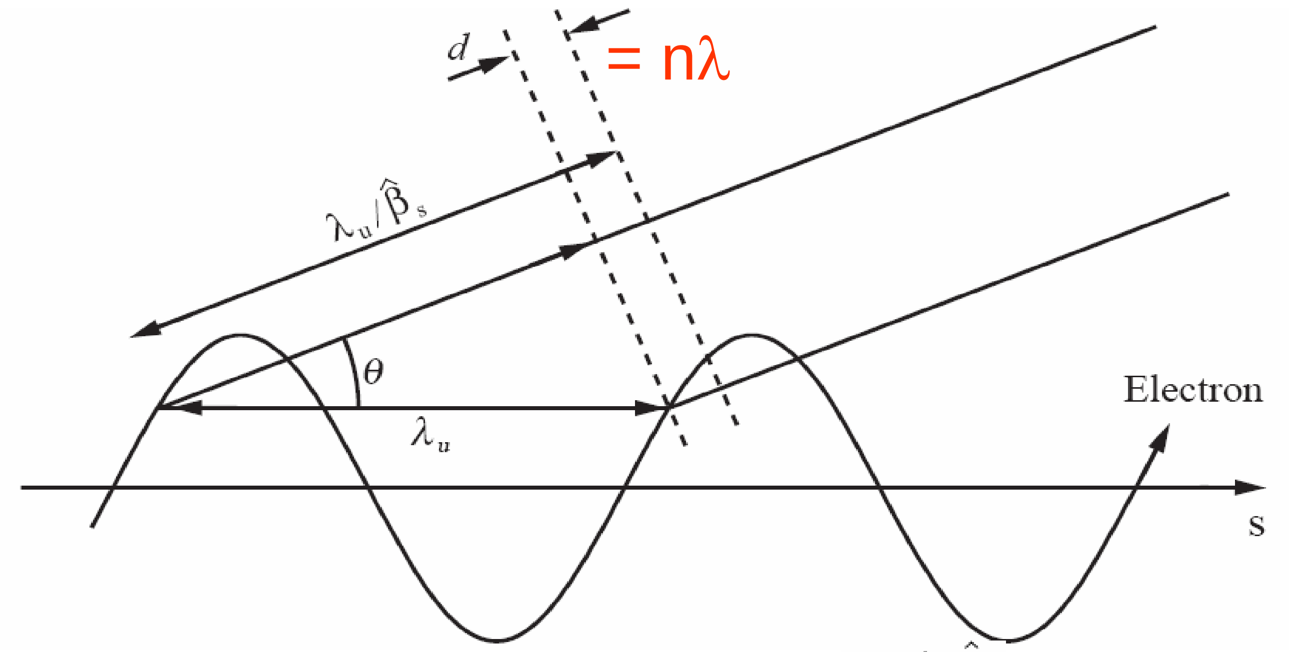
If $K \gg 1$ there will be little overlap and the source points are effectively independent – this is the case for a MPW

The case of $K < 1$ is an undulator

The boundary between an undulator and a MPW is not actually this clear cut!

Undulators: Condition for Interference

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



Time for electron to travel one period is $\lambda_u / c\hat{\beta}_s$

Speed = distance/time

In this time the first wavefront will travel the distance $\lambda_u / \hat{\beta}_s$

$\hat{\beta}_s$ is the average electron velocity in the s direction

Interference Condition

The separation between the wavefronts is $d = \frac{\lambda_u}{\hat{\beta}_s} - \lambda_u \cos\theta$

And this must equal a whole number of wavelengths for constructive interference

$$n\lambda = \frac{\lambda_u}{\hat{\beta}_s} - \lambda_u \cos\theta$$

This leads to

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

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

mm periods translate to **nm** wavelengths.

Harmonic bandwidth

Spectral Bandwidth:

$$\frac{\Delta\lambda}{\lambda} \sim \frac{1}{Nn}$$

n = Harmonic order

N = number of periods

L = length of undulator

Angular Width:

$$\sigma_{r'} = \sqrt{\frac{\lambda}{L}} \ .$$

Very similar results for angular width and bandwidth apply to diffraction gratings.

When does an undulator become a wiggler?

As K increases the number of harmonics increases

At high frequencies the spectrum smoothes out and takes on the shape of the bending magnet spectrum

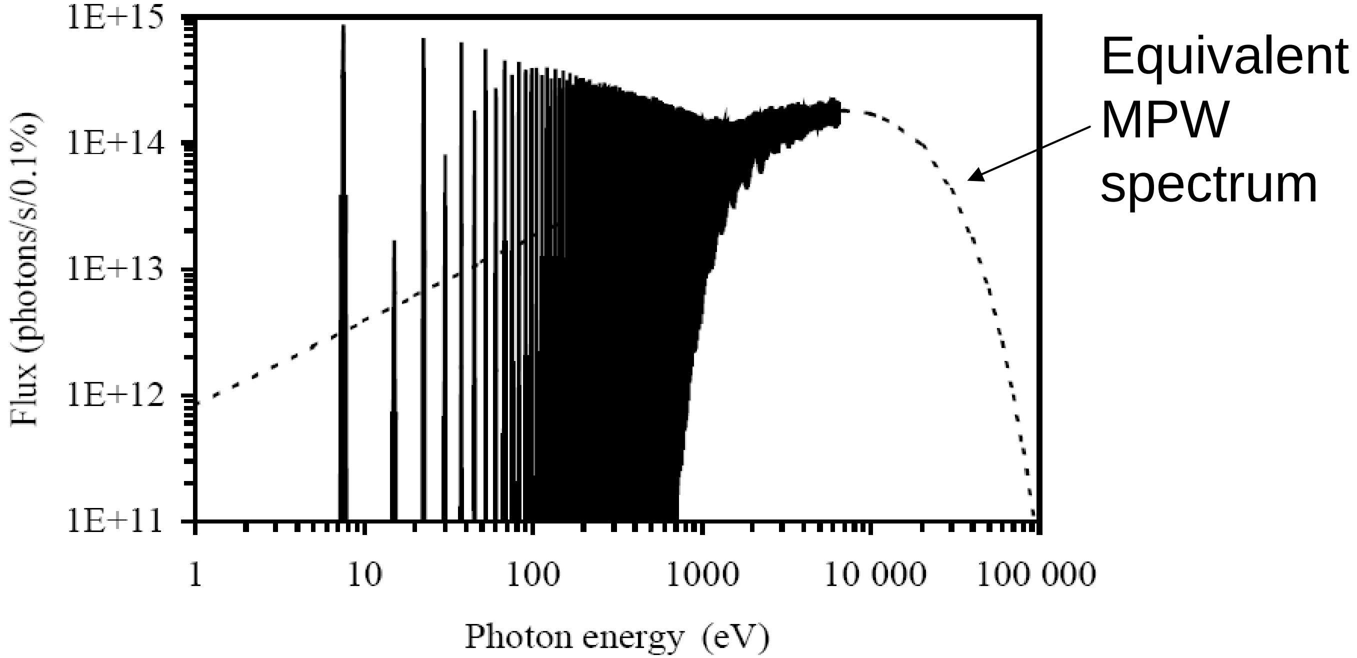
At low frequencies distinct harmonics are still present and visible

There is in fact no clear distinction between an undulator and a wiggler – it depends which bit of the spectrum you are observing

Undulator vs Wiggler

The difference depends upon which bit of the spectrum you use!

Example shows undulator calculation for K = 15. Calculation truncated at high energies as too slow!

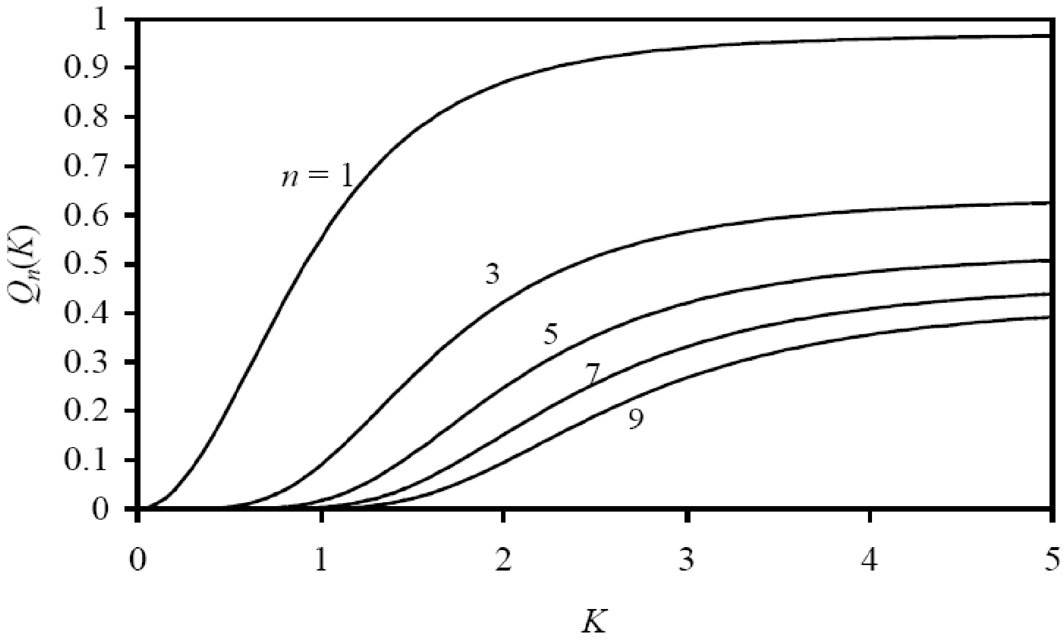


Undulator Flux

In photons/sec/0.1% bandwidth the flux in the central cone is

$$1.43 \times 10^{14} \, N I_b Q_n(K)$$

I_b is average beam current

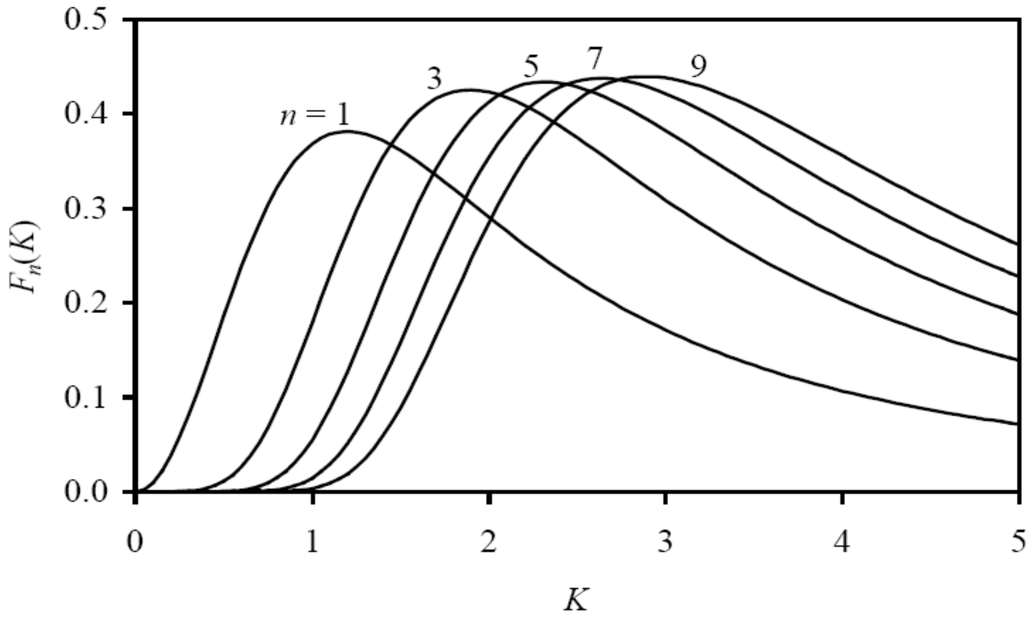


Undulator Flux Density (On Axis)

In units of photons/sec/mrad^2/0.1% bandwidth

$$1.74 \times 10^{14}\, N^2 E^2 I_b F_n(K)$$

As K increases the contribution from the higher harmonics increases

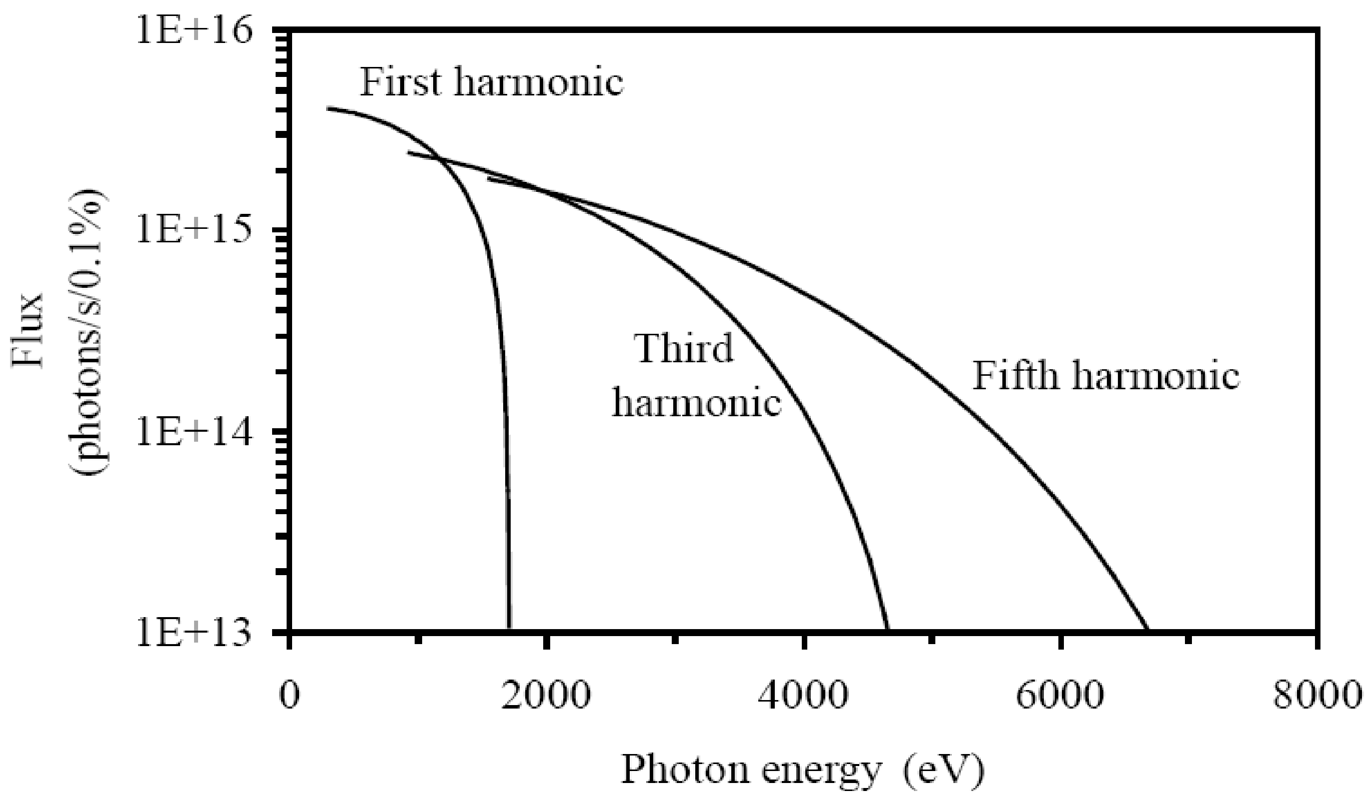


Undulator Tuning Curve

Graph shows flux envelope for example undulator.

K is varied to change photon energy.

Not all of this flux is available at the same time!



Brightness

All emitted photons have a position and angle in phase space

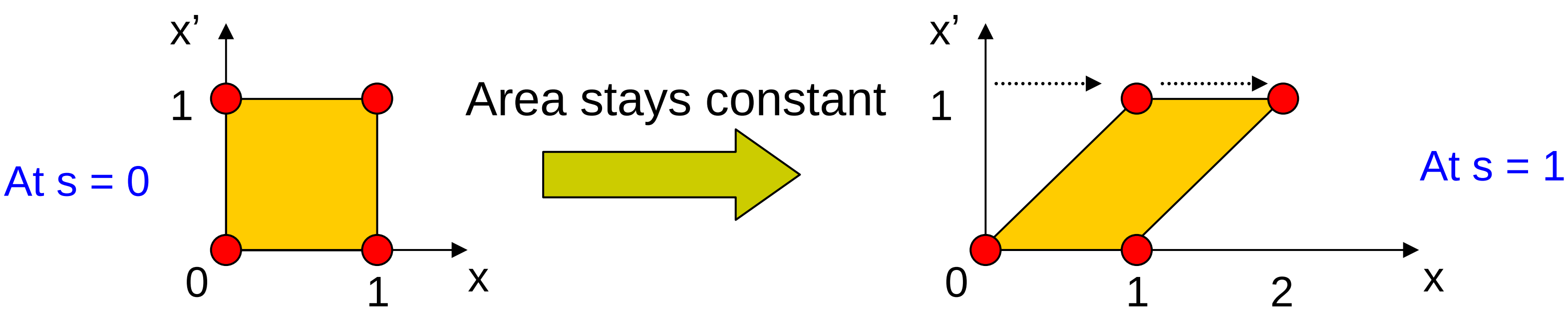
Phase space evolves as photons travel but area stays constant (Liouville's theorem)

Emittance of electron beam governed by same theorem

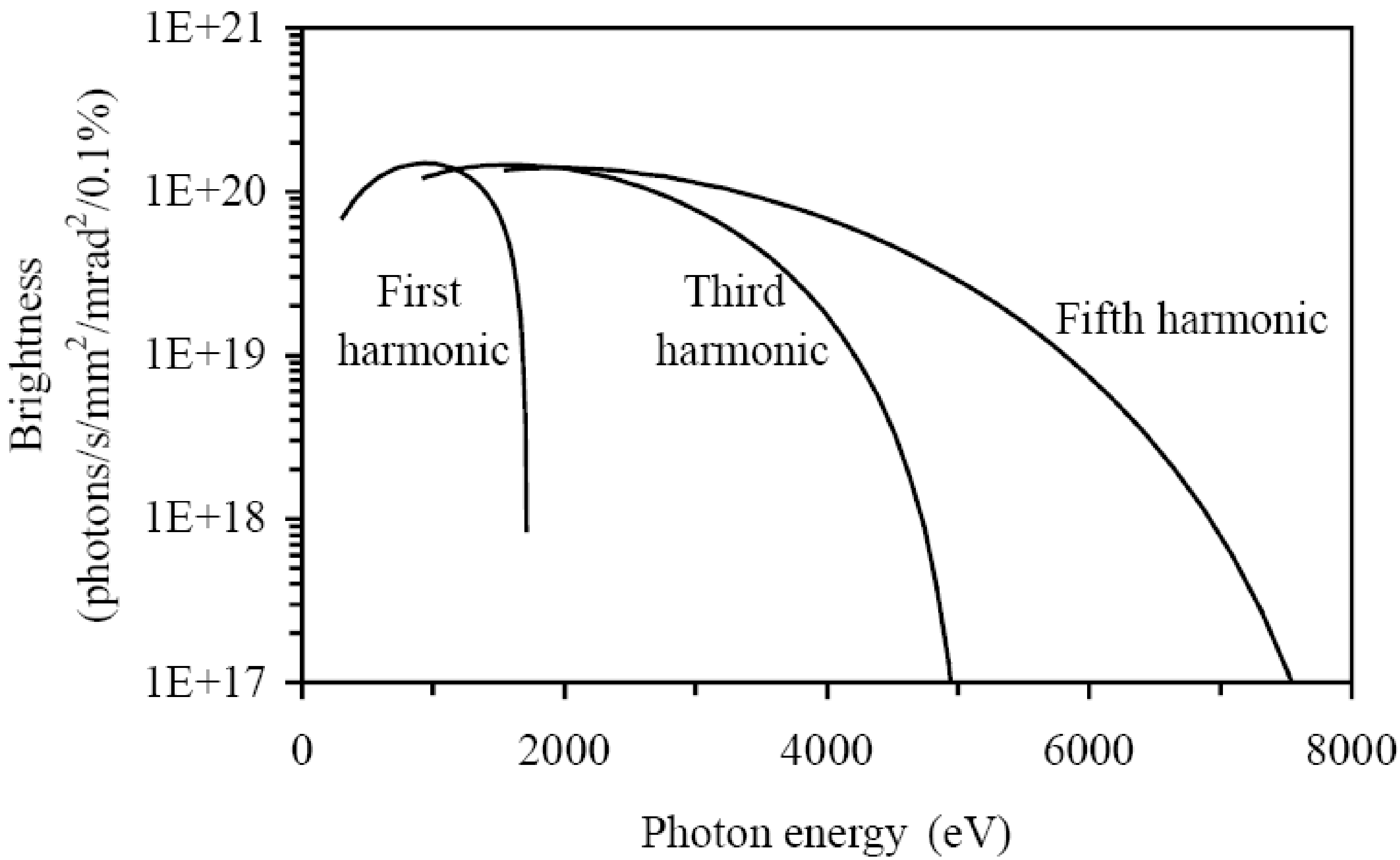
Brightness is the phase space density of the flux – takes account of number of photons and their concentration

Brightness (like flux) is conserved by an ideal optical transport system, unlike angular flux density for instance

Since it is conserved it is a good figure of merit for comparing sources (like electron beam emittance)



Brightness tuning curve

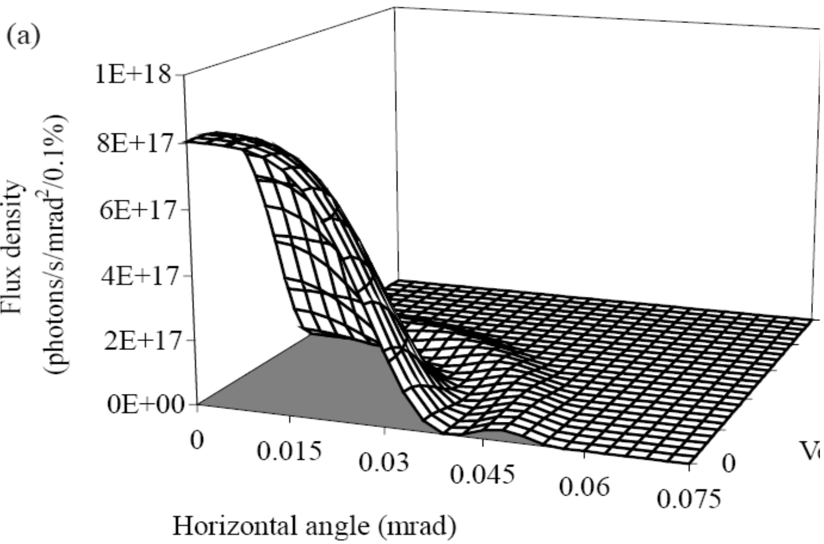


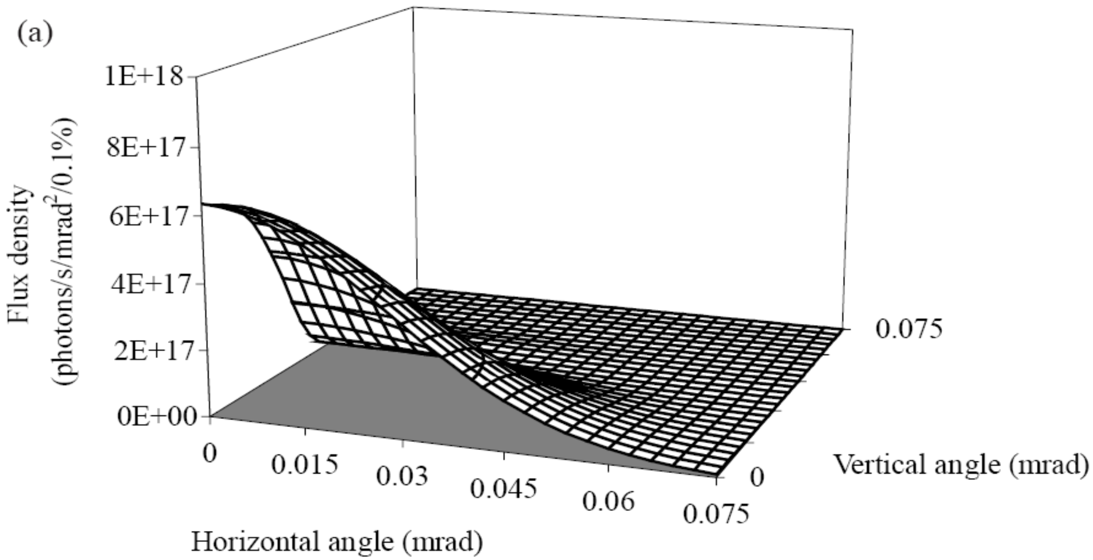
Calculated by dividing flux by effective (combination of electron and photon) source size and divergence in both planes

Undulator Output Including Electron Beam Dimensions

No electron beam size and divergence

Including electron beam size and divergence





Electron beam smears out the flux density

Total flux unchanged

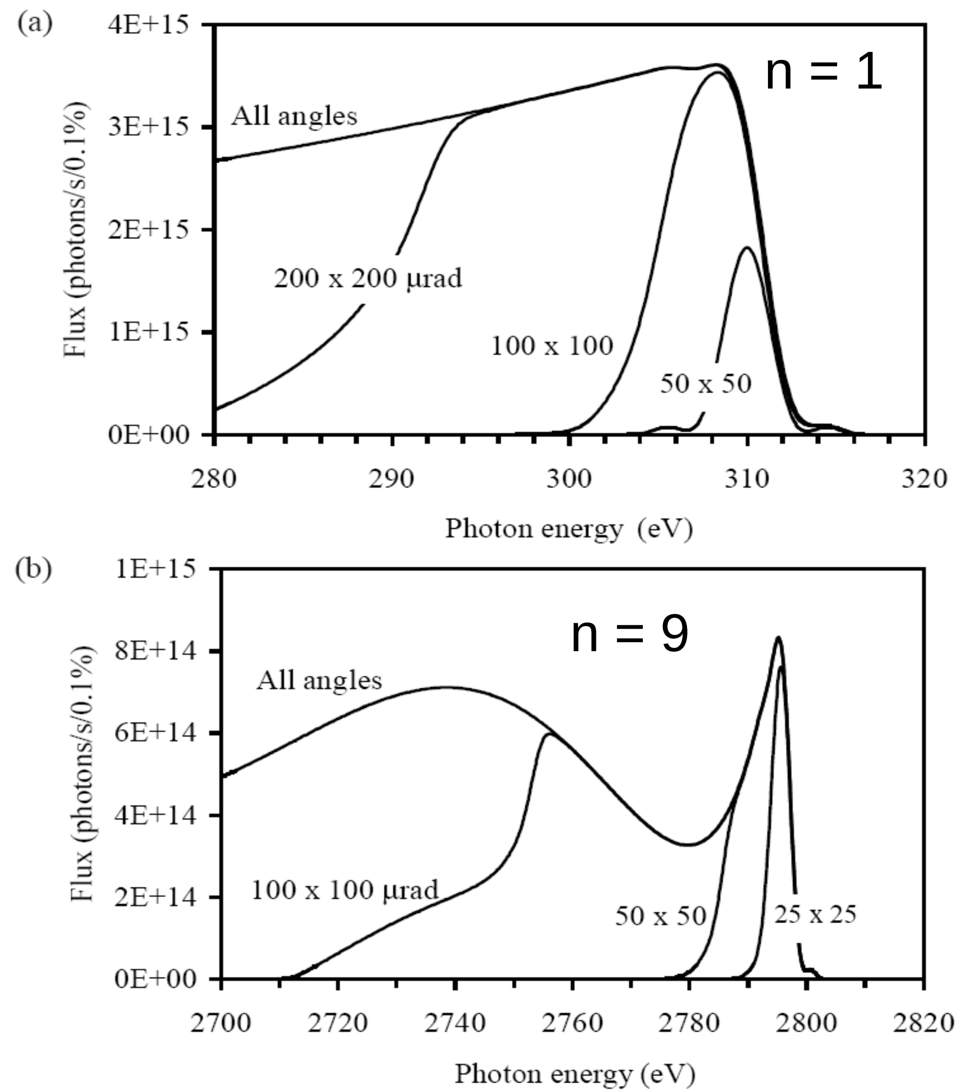
Flux through an aperture

How much total flux is observed depends upon beamline aperture

As aperture increases, flux increases and shifts to lower energy

Can see that higher harmonic has narrower divergence

$$\frac{\Delta\lambda}{\lambda} \sim \frac{1}{Nn}$$



Insertion Device Technology

To generate the magnetic field we can use:

Current carrying coils (Electromagnets)

Normal conducting or superconducting

Permanent Magnets

Both can be with or without iron

Permanent Magnet Materials

Two types are generally used Samarium Cobalt (SmCo) and Neodymium Iron Boron (NdFeB)

	SmCo	NdFeB
Remanent Field	0.85 to 1.05 T	1.1 to 1.4 T
Coercivity	600 to 800 kA/m	750 to 1000 kA/m
Relative Permeability	1.01 parallel, 1.04 perp	1.05, 1.15
Temperature Coefficient	-0.04 %/°C	-0.11 %/°C
Comment	Brittle, easily damaged. Not radiation hard but depends on grade. Expensive. Better at high temperature.	Less brittle but still liable to chip. Not radiation hard but depends on grade. Expensive.

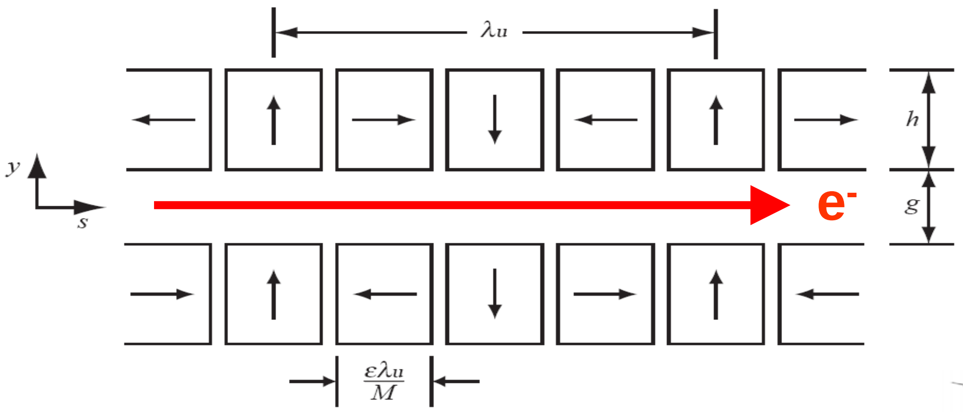
Pure Permanent Magnet Undulators

A magnet which contains no iron or current carrying coils is said to be a pure permanent magnet (PPM)

To generate a sinusoidal field an ideal PPM would have two arrays of PM with the easy axis rotating through 360° per period along the direction of the electron beam

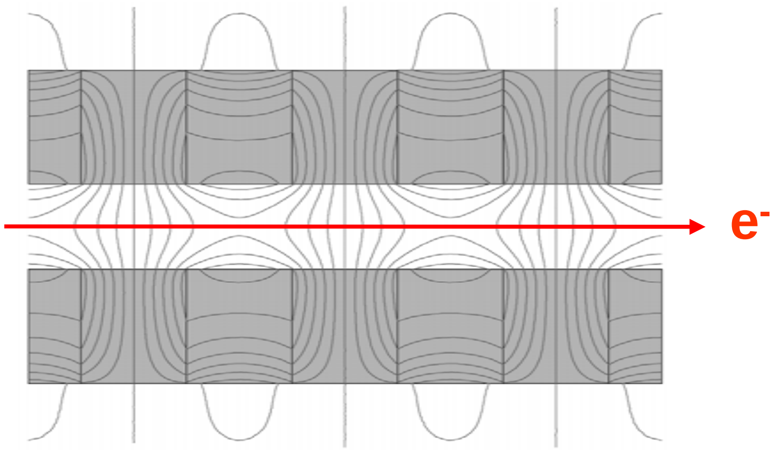
In practice this ideal situation is approximated by splitting the system into rectangular magnet blocks, M per period

Example PPM arrangement, M = 4



With M = 4 and h = $\lambda_u/2$ peak on axis field is:

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



Important:

So long as all the block dimensions scale together the fields on axis do not change

This is not true for electromagnets – there the current densities have to increase to maintain the same field levels

Hybrid Magnets

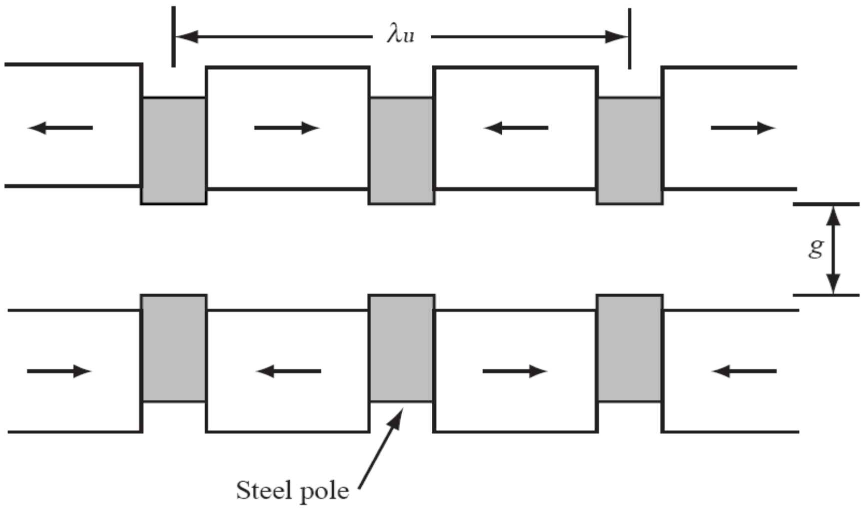
Including a non-linear material like iron means that simple analytical formulae can no longer be derived

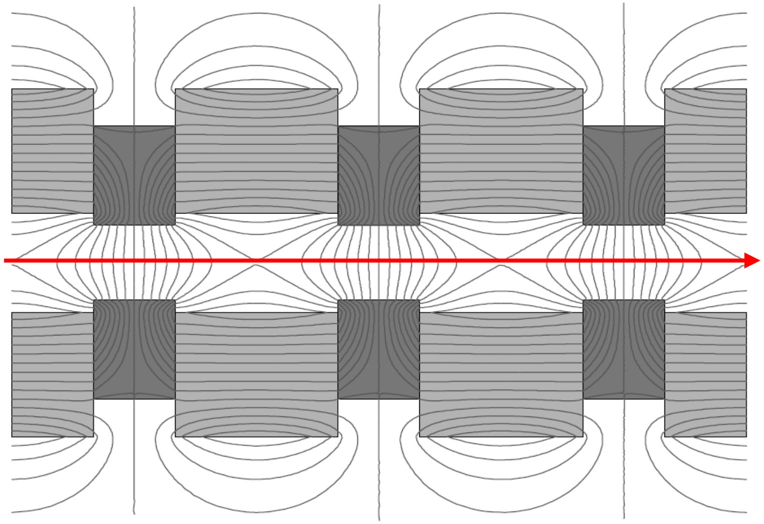
Empirical result:

$$B_{y0} = 3.44 \exp\left(-5.08 \frac{g}{\lambda_u} + 1.54 \frac{g^2}{\lambda_u^2}\right)$$

(for B_r = 1.1T and $0.07 < g/\lambda_u < 0.7$)

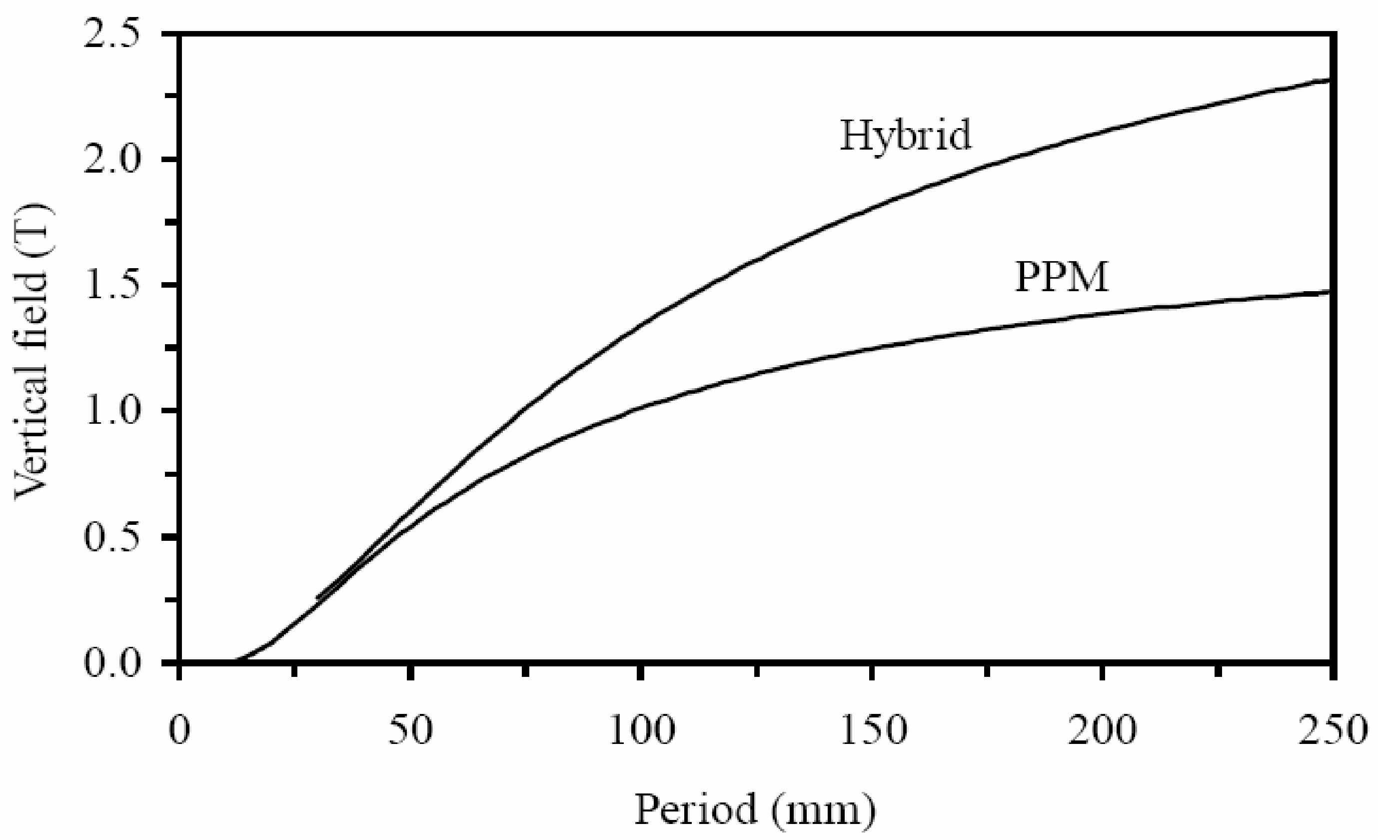
Alternative equations available for different B_r





Hybrid vs PPM

Assumes B_r = 1.1T and gap of 20 mm



Engineering Issues for all PM undulators & wigglers

Engineering demands very high:

Very strong forces during assembly and when complete

Must have high periodicity

Arrays must be parallel to μm precision and must stay parallel at all gaps

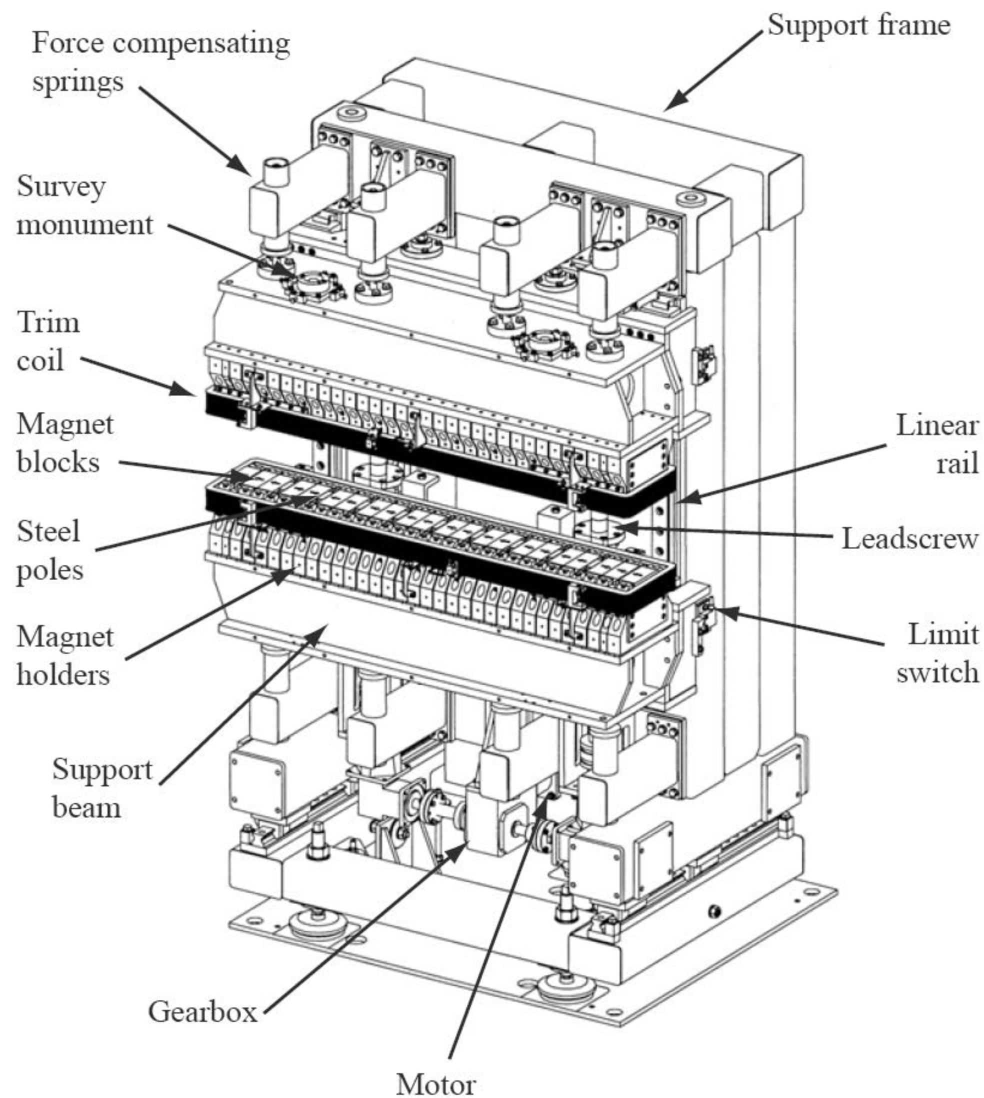
General design themes:

Blocks held in individual holders – glued or clamped

Fastened to backing beam

C shaped support frame

Very long magnets (>5m) split into shorter modules (2 – 3m)



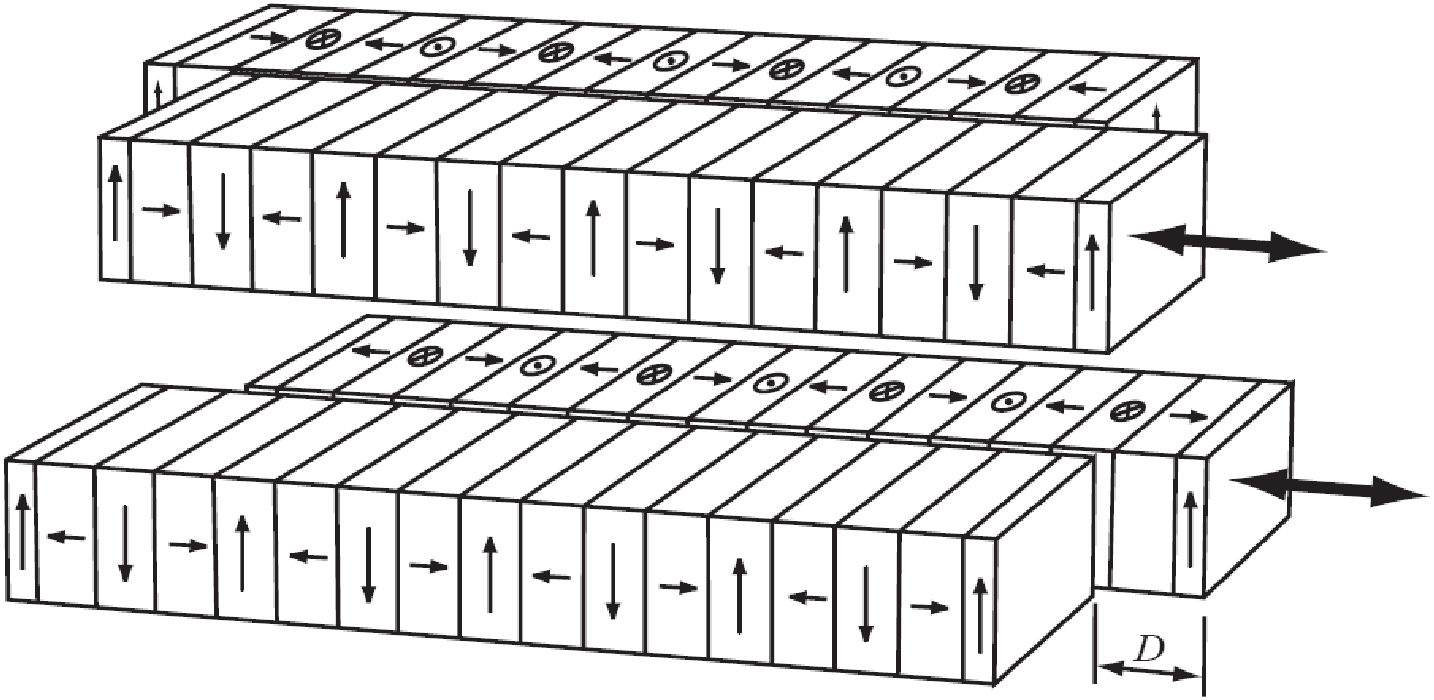
Helical Planar Undulators: APPLE-2 Design

Four standard PPM arrays

Diagonally opposite arrays move longitudinally

All arrays move vertically like conventional undulator

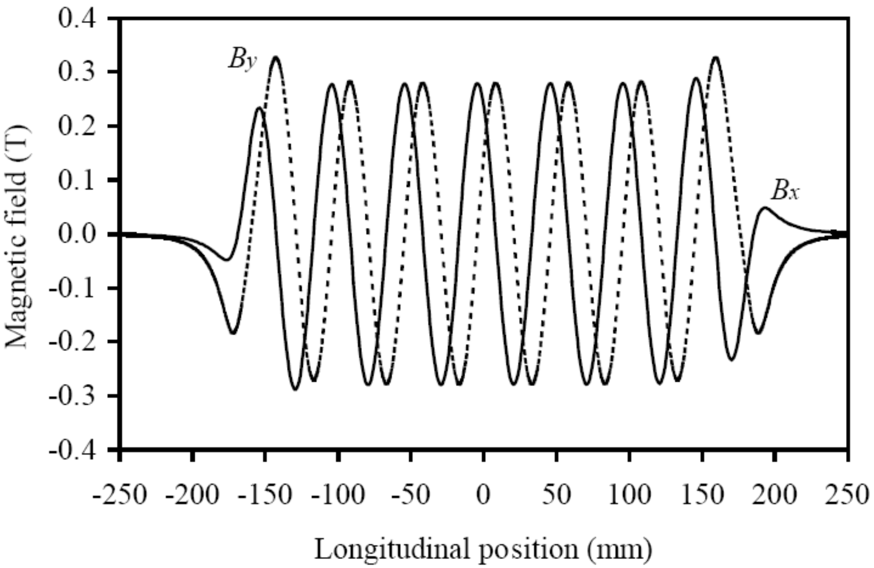
Electron beam travels through centreline of magnet

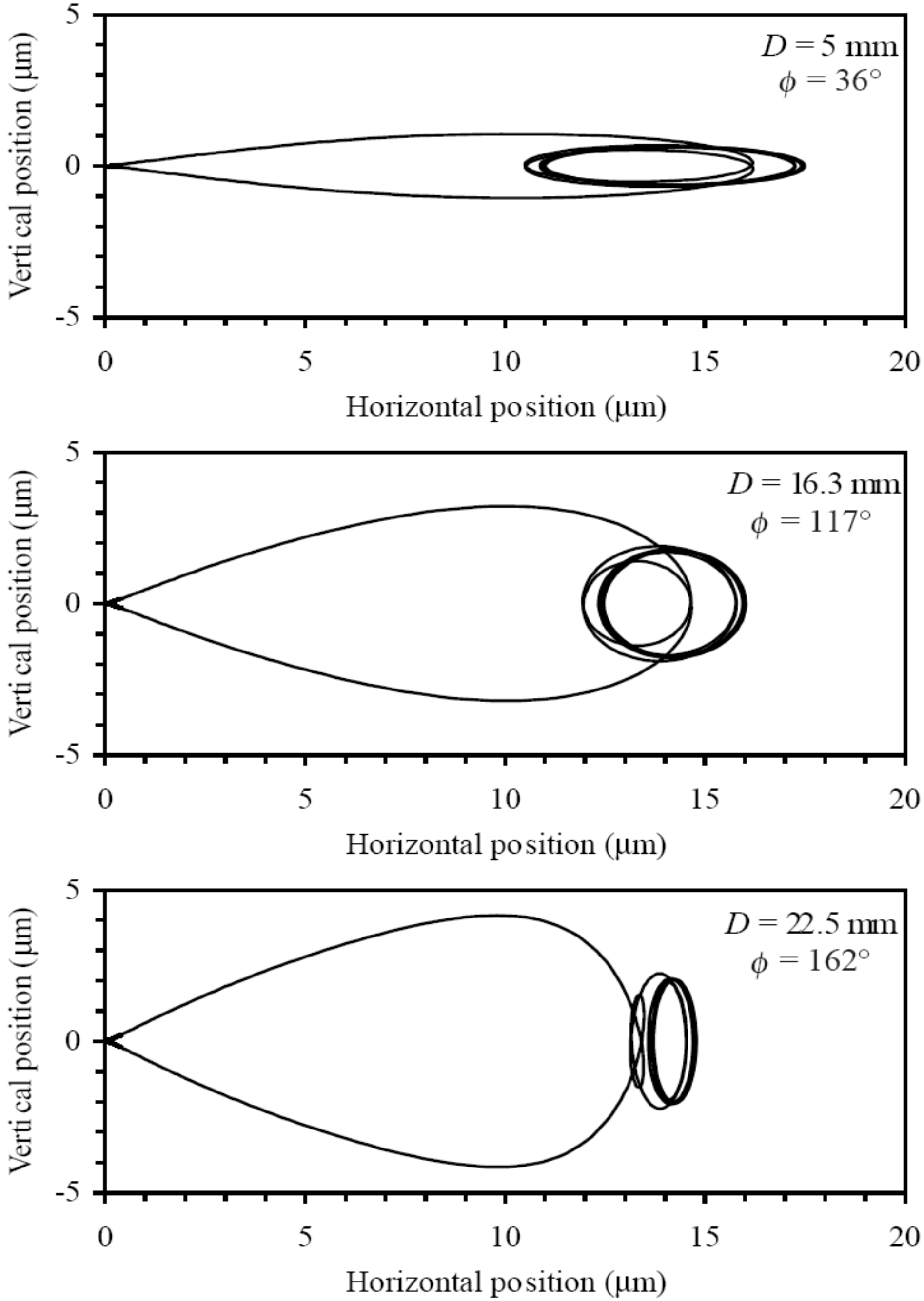


Example head on trajectories

Motivation for this type of undulator is to provides control of the polarisation state for experiments

Fields in circular mode

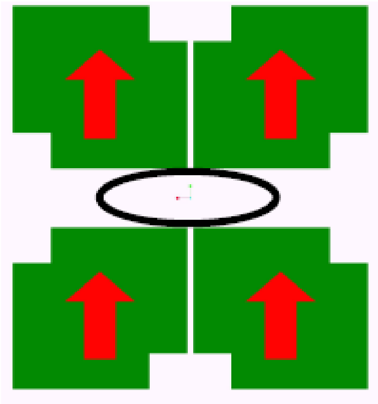




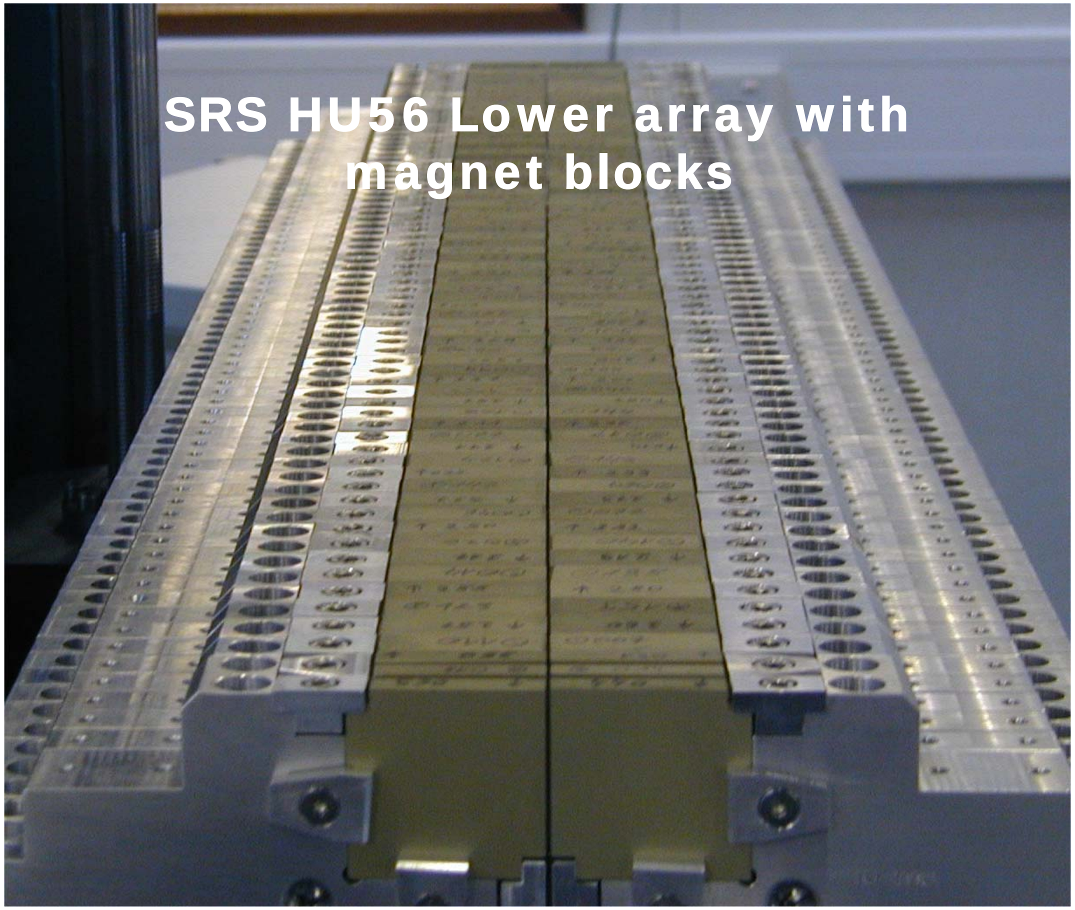
APPLE-2 examples

Typical block shape

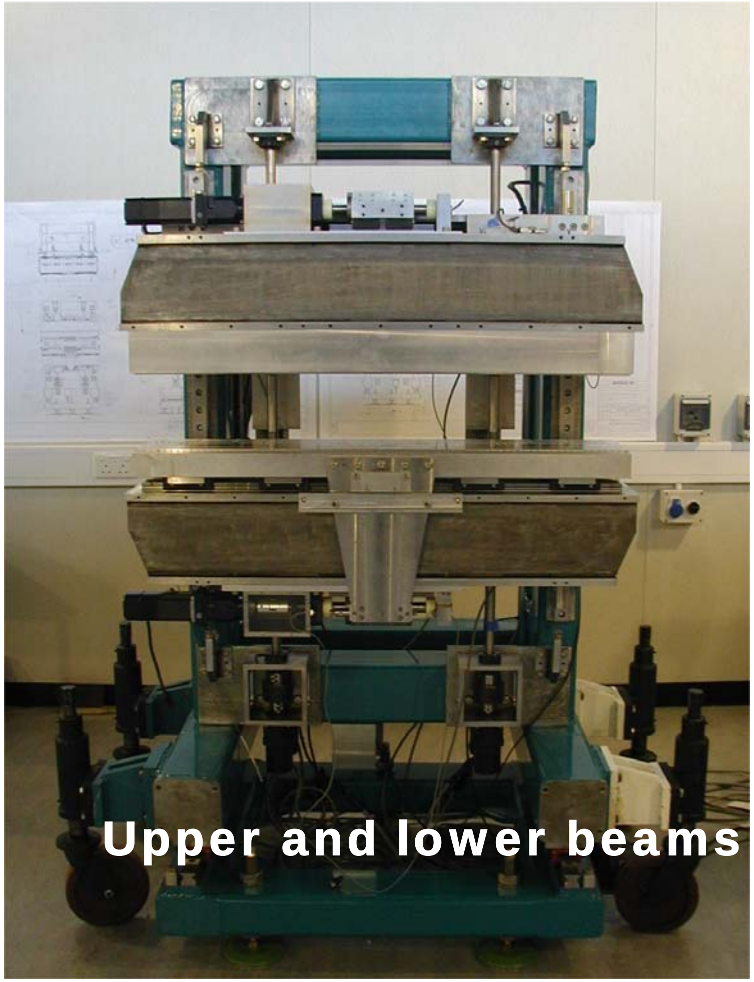
Cut outs are to hold the blocks but are well away from the electron beam

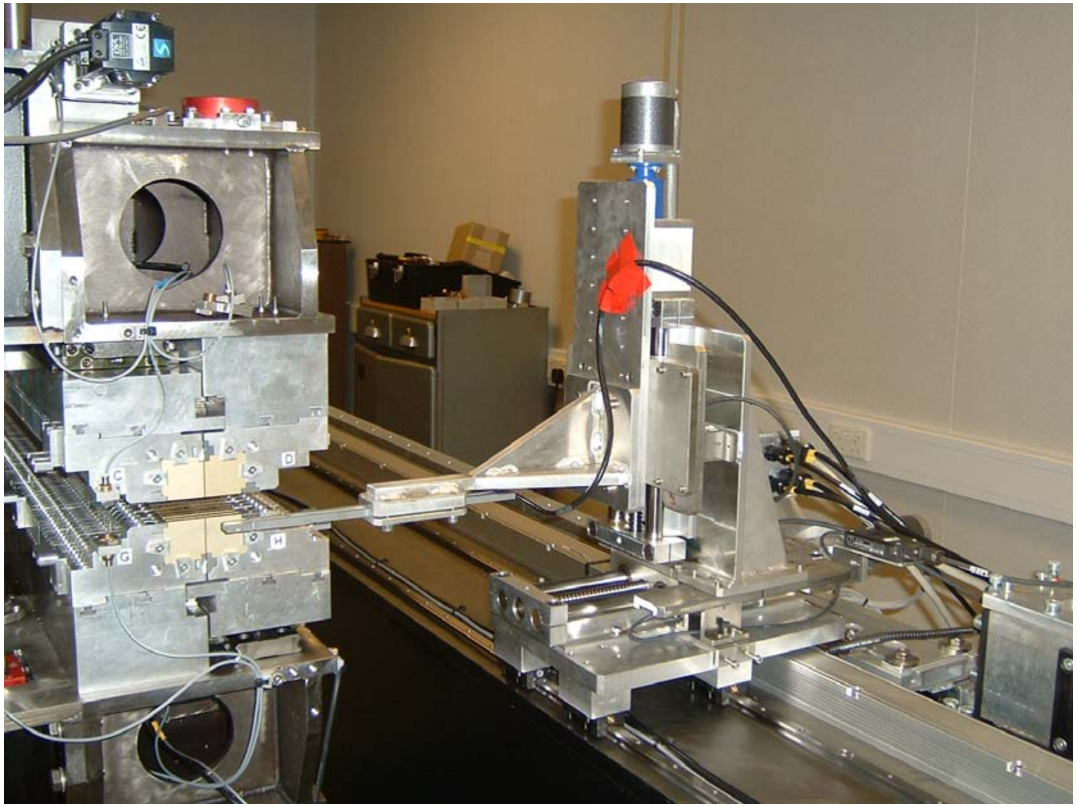


Johannes Barhdt, BESSY



APPLE-2 examples





SRS HU56 being measured

In Vacuum Undulators

Minimum Magnet gap sets performance of device

Magnet gap set by needs of electron beam

In practice set by vacuum chamber

Example:

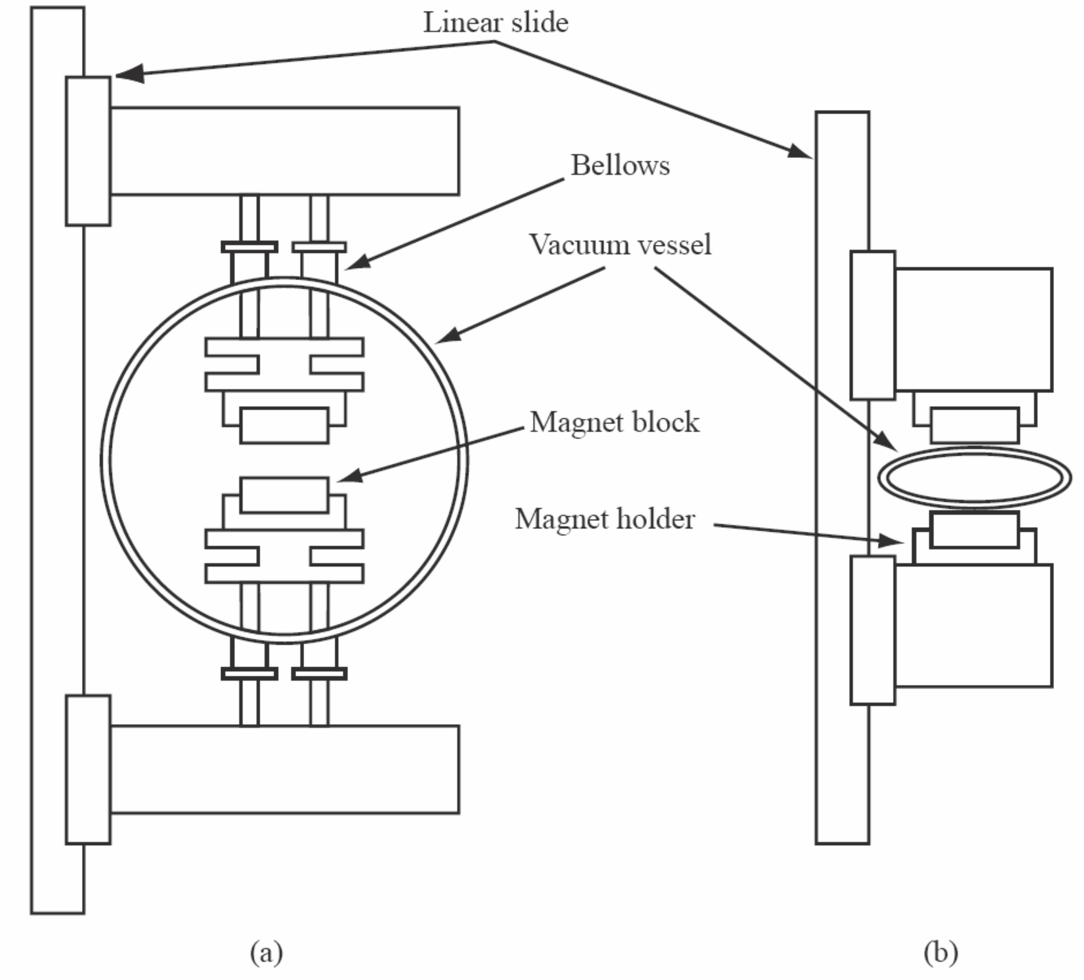
- electron beam needs 10mm vertical space
- vacuum chamber walls 2mm thick
- allowance for alignment tolerances etc 1mm
- Minimum magnet gap 15mm

One solution is to put magnets inside the vacuum system

Vacuum pressure must be maintained otherwise electrons will be lost – affects all users

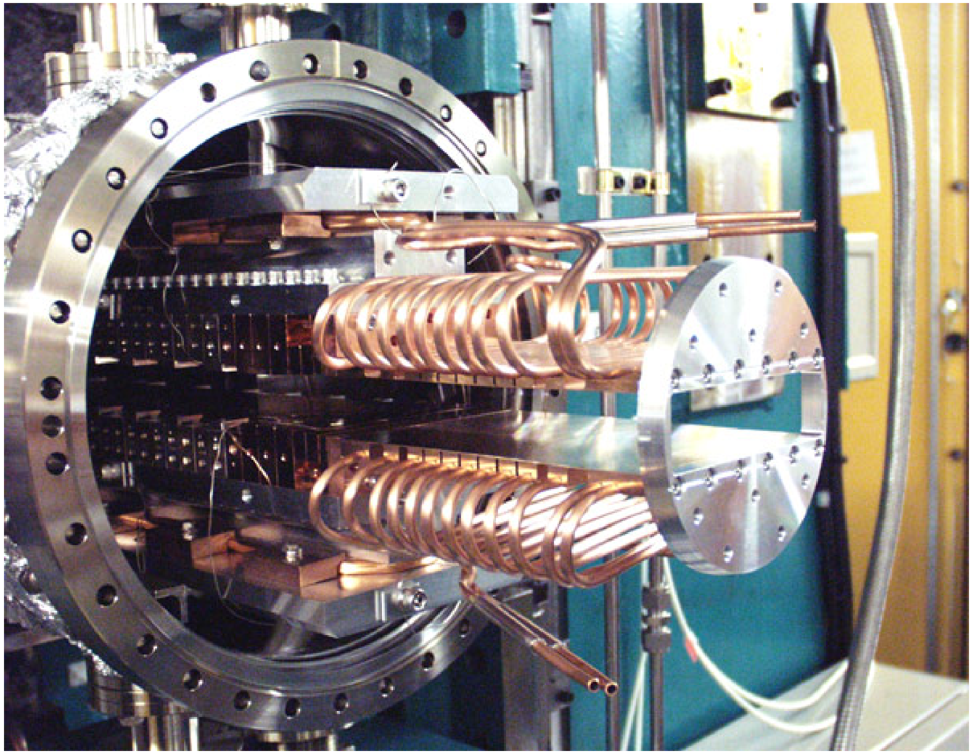
In vacuum undulators

- Magnet blocks not ideal for use within vacuum system
- Must be coated to prevent outgassing (TiN or Ni)
- Must be baked to reach good vacuum - affects magnet performance (irreversible losses?)
- Only bake at ~130 °C
- Surface resistance of blocks high – need sheet of copper to provide path for image currents
- Magnet measurements only possible before full assembly
- Flexible vacuum chambers are an alternative solution



In vacuum examples

In vacuum examples



ALS in vacuum undulator

The Future …

The field of insertion devices continues to evolve:

Higher fields are being proposed by the use of cold permanent magnets

New challenges are presented by the fourth generation light sources – single pass free electron lasers

Insertion Devices are not just used in light sources:

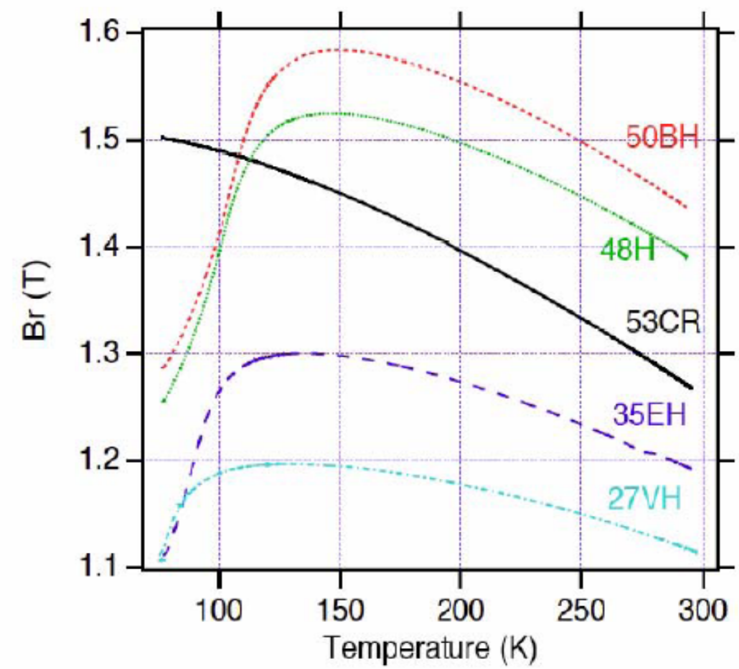
The proposed International Linear Collider relies on ~400m of superconducting wiggler and ~200m of superconducting undulator

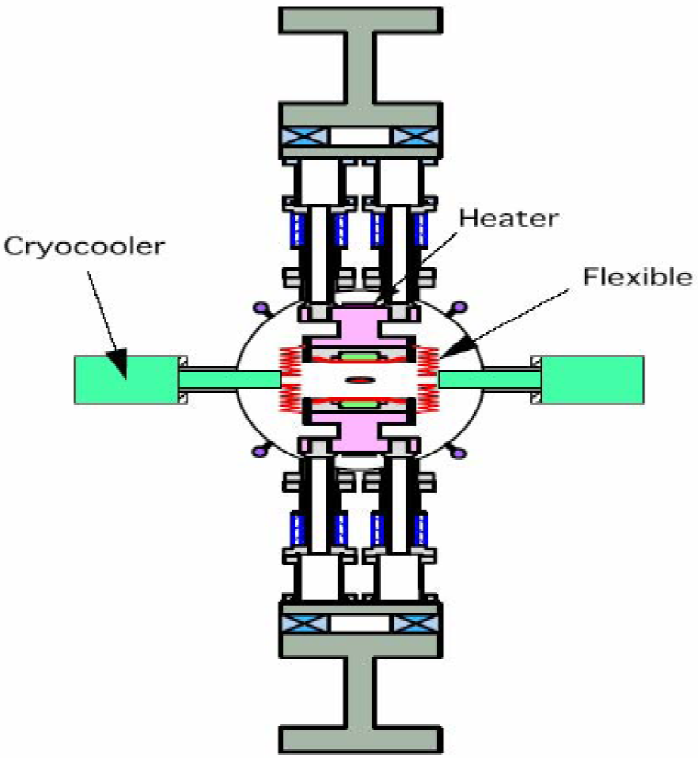
The LHC uses undulators to generate SR for diagnostic purposes

Cryo-undulators

Variation of remanent field with temperature

If can operate ~150K then can gain significantly

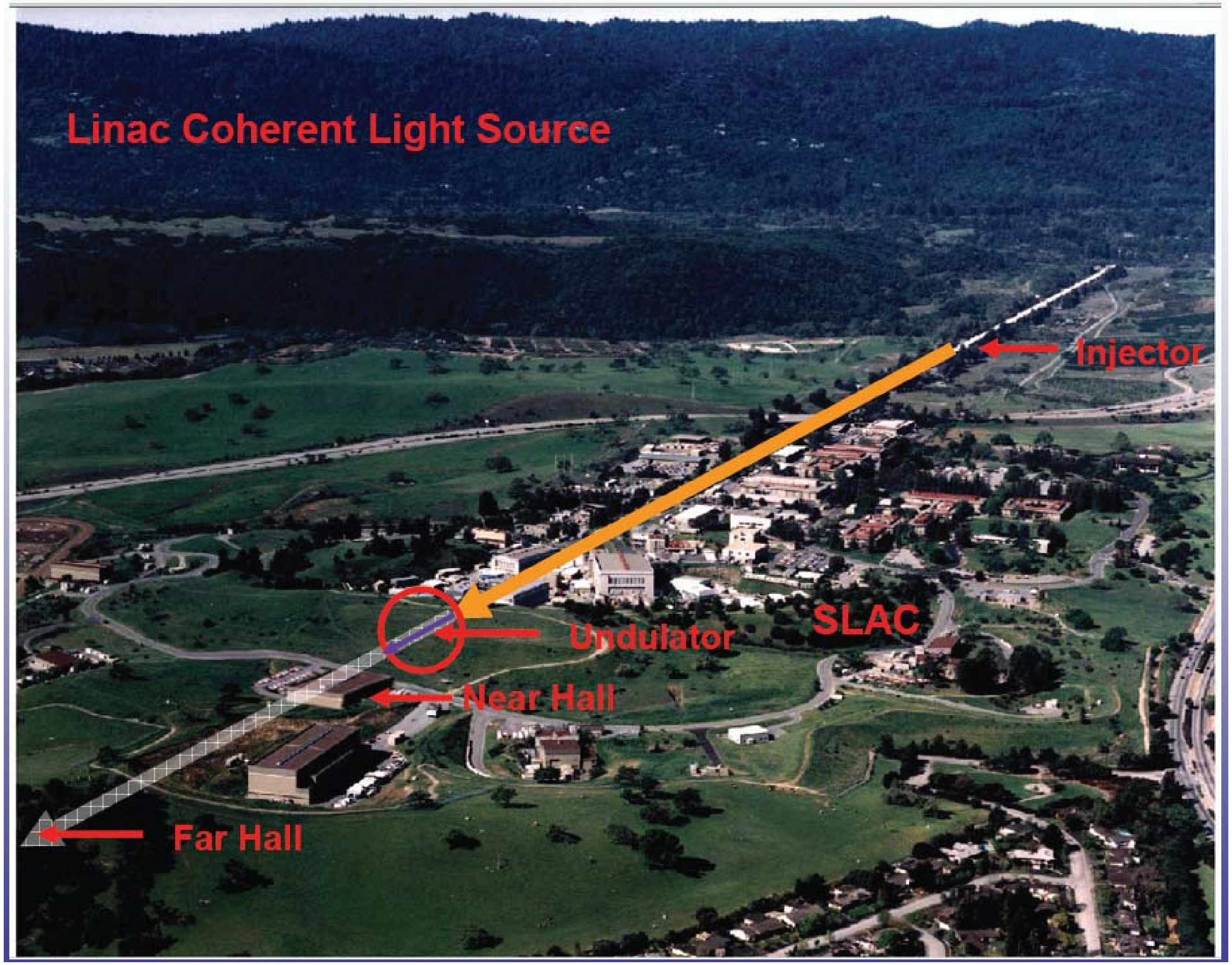




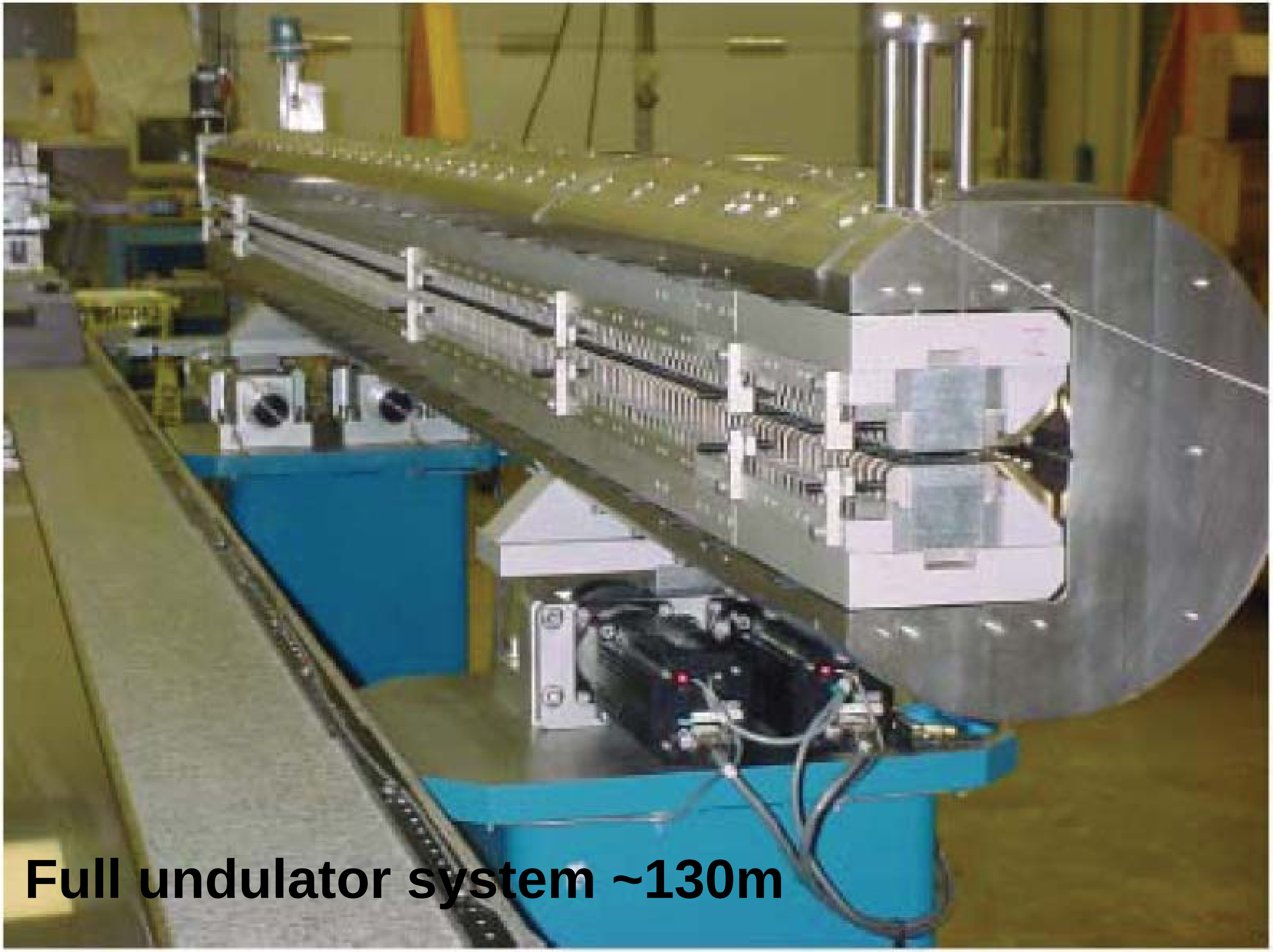
In vacuum undulators are being adapted to try out this novel idea

H Kitamura, Spring-8

Undulators for Free Electron Lasers



LCLS Undulator Prototype

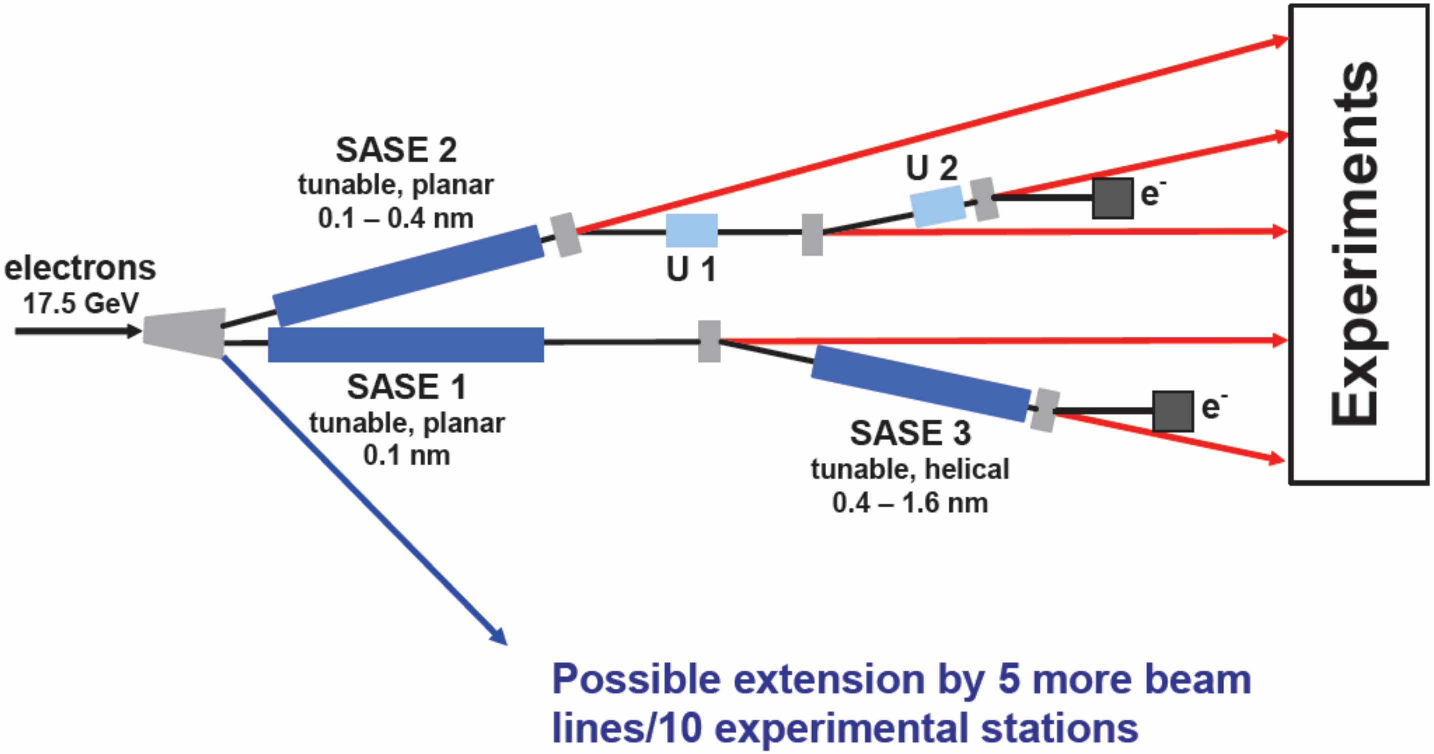


European X-FEL

Project based at DESY

5 separate undulator systems

Total undulator length of 652m

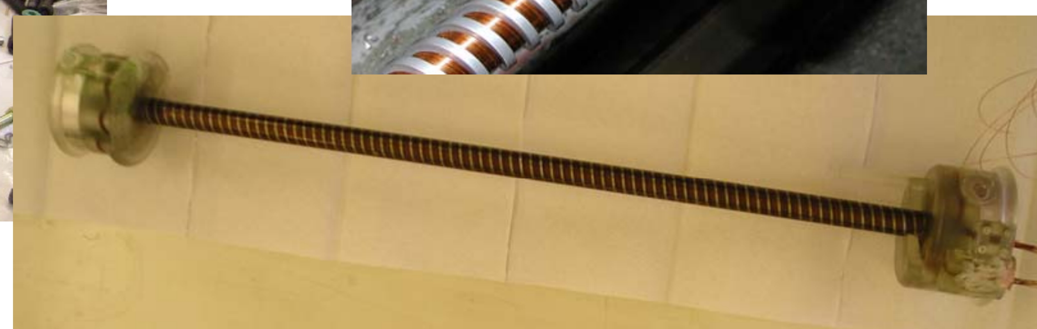


International Linear Collider Positron Source

ILC will generate e^-/e^+ pairs by firing multi-MeV photons into a titanium target.

Photons are generated by passing 150 GeV electrons through a helical undulator ~200m long, ~6mm aperture.

Undulator will be superconducting with ~10 mm period, K ~1.



Summary

This has been a very brief summary of some of the features & issues associated with insertion devices

Many items have not been covered, eg

- magnet measurements
- field quality correction
- beam dynamics effects of IDs
- many novel designs for altering the photon output to suit the experimental requirements

Insertion Devices are now a mature subject but new technologies and innovative designs continue to emerge to push the subject forward

Further Reading

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

H Onuki & P Elleaume, “Undulators, Wigglers and their Applications”, Taylor and Francis, 2003.

R P Walker, “Insertion Devices: Undulators and Wigglers”, CAS 1996, Report CERN 98-04.