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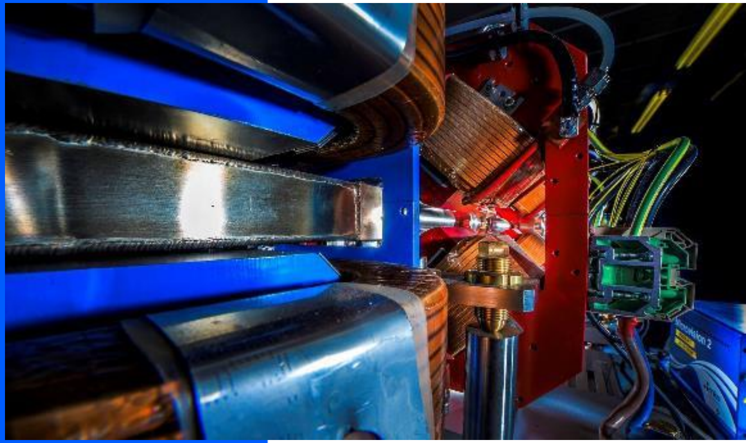
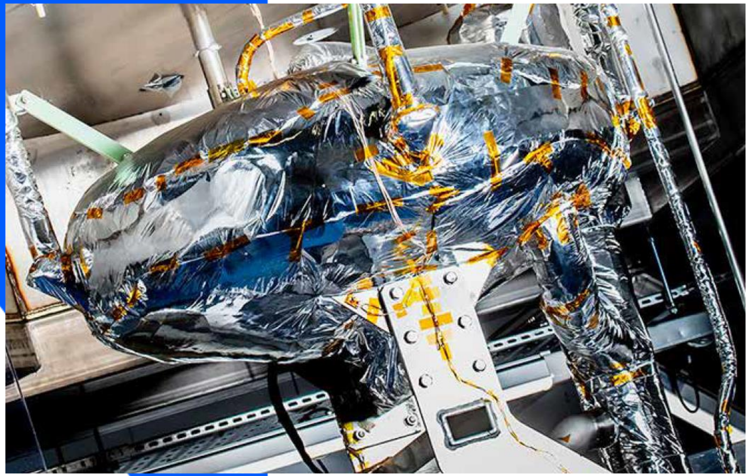
Making a brighter future through advanced accelerators

Insertion Devices
Lecture 2
Technology





Jim Clarke
STFC Daresbury Laboratory
12th November 2022

Introduction

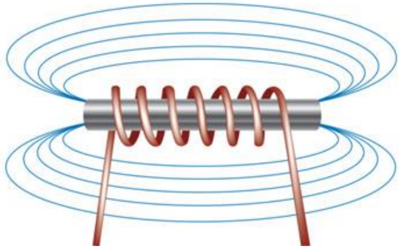
- The first lecture on radiation from Insertion Devices explained that periodic magnetic fields are required by both undulators and wigglers

- In this second lecture we'll look at how the required magnetic fields can be generated, the engineering that enables these to be built, and what the limitations are for the magnet parameters

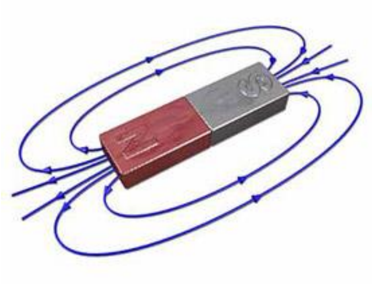
Generating Periodic Magnetic Fields

- To generate magnetic fields we can use:

- Electromagnets
  - Normal conducting or
  - Superconducting



- Permanent Magnets



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

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What is a Permanent Magnet ?

Definition:

A magnet is said to be **Permanent** (or **Hard**) if it will independently support a useful flux in the air gap of a device

A material is magnetically **Soft** if it can only support such a flux with the help of an external circuit (eg iron is soft)

A PM can be considered as a passive device analogous to a spring (which stores mechanical energy)

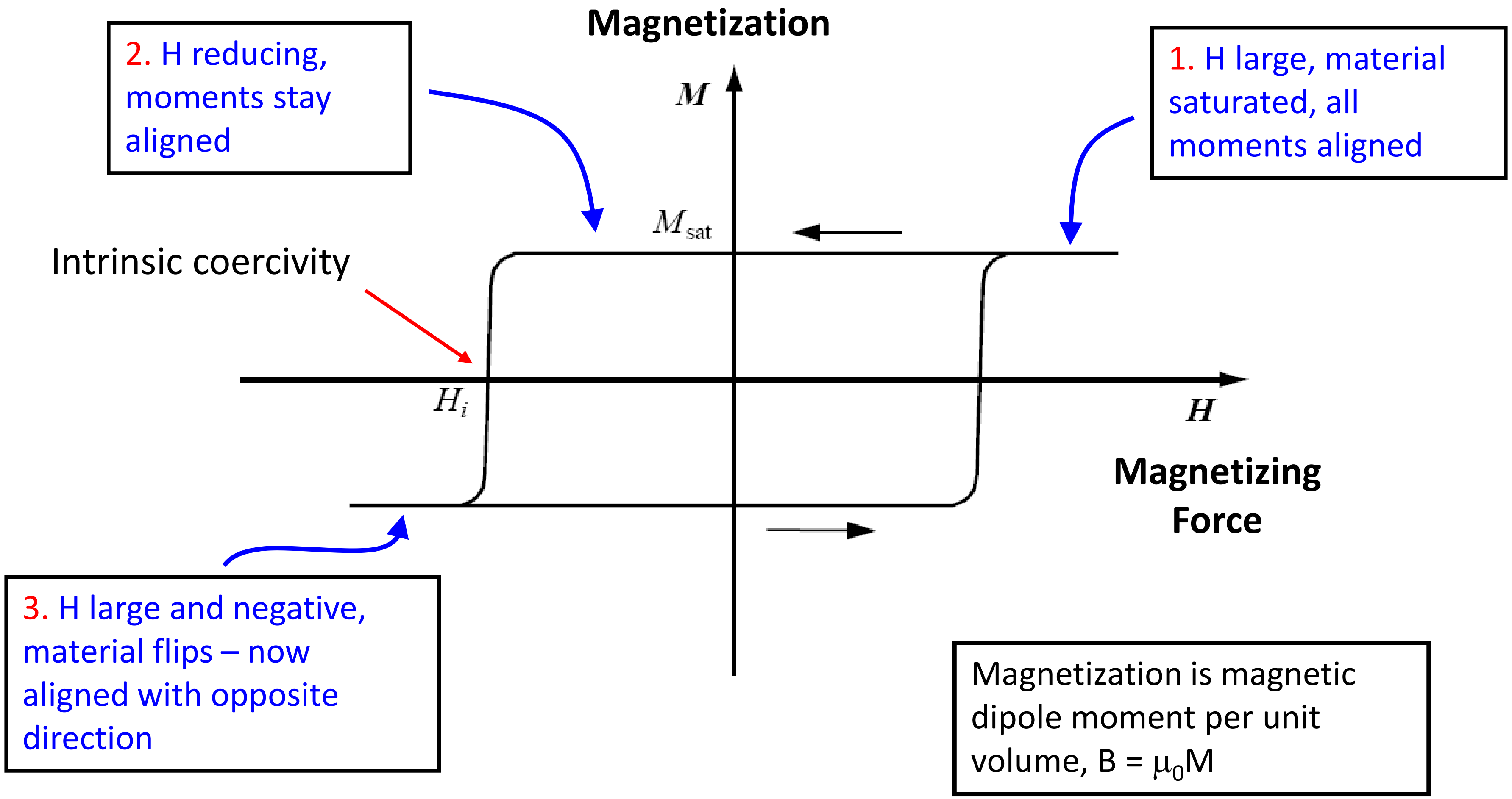
Permanent Magnets

- Permanent Magnet materials are manufactured so that their magnetic properties are enhanced along a particular axis

- When a magnetic field, B, is applied to a magnetic material each dipole moment tries to align itself with the field direction
- When B is strong enough (at saturation) all of the moments are aligned, overcoming other atomic forces which resist this
- **A Permanent Magnet maintains this alignment after the external B is removed**

An Ideal Permanent Magnet

The characteristics of a Permanent Magnet are determined by its behaviour under an external magnetization force H



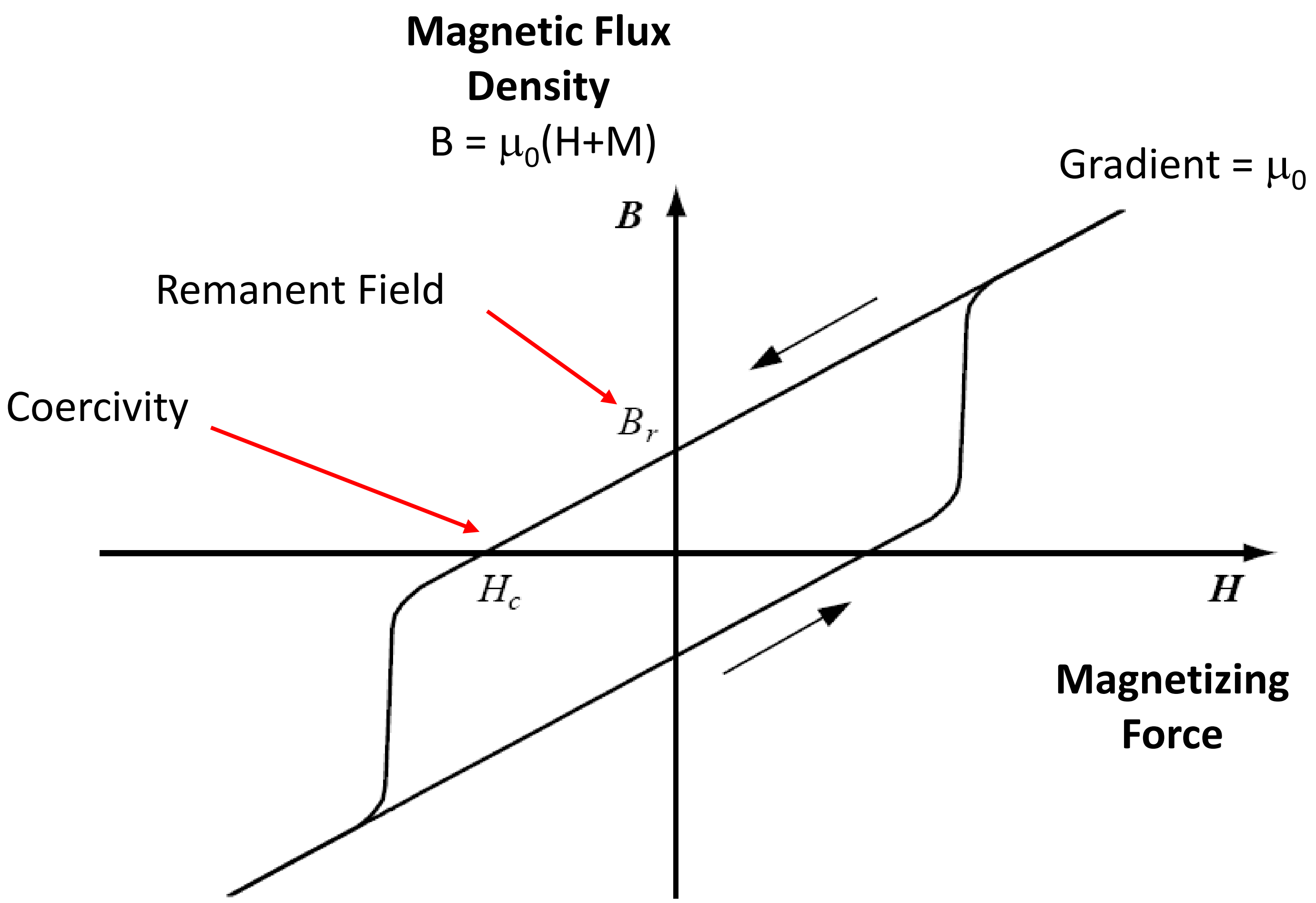
1. H large, material saturated, all moments aligned

2. H reducing, moments stay aligned

3. H large and negative, material flips – now aligned with opposite direction

Magnetization is magnetic dipole moment per unit volume, $B = \mu_0 M$

The Ideal BH Curve



Magnetic Flux Density

$B = \mu_0(H+M)$

Gradient = μ_0

Remanent Field

Coercivity

Magnetizing Force

Available Materials

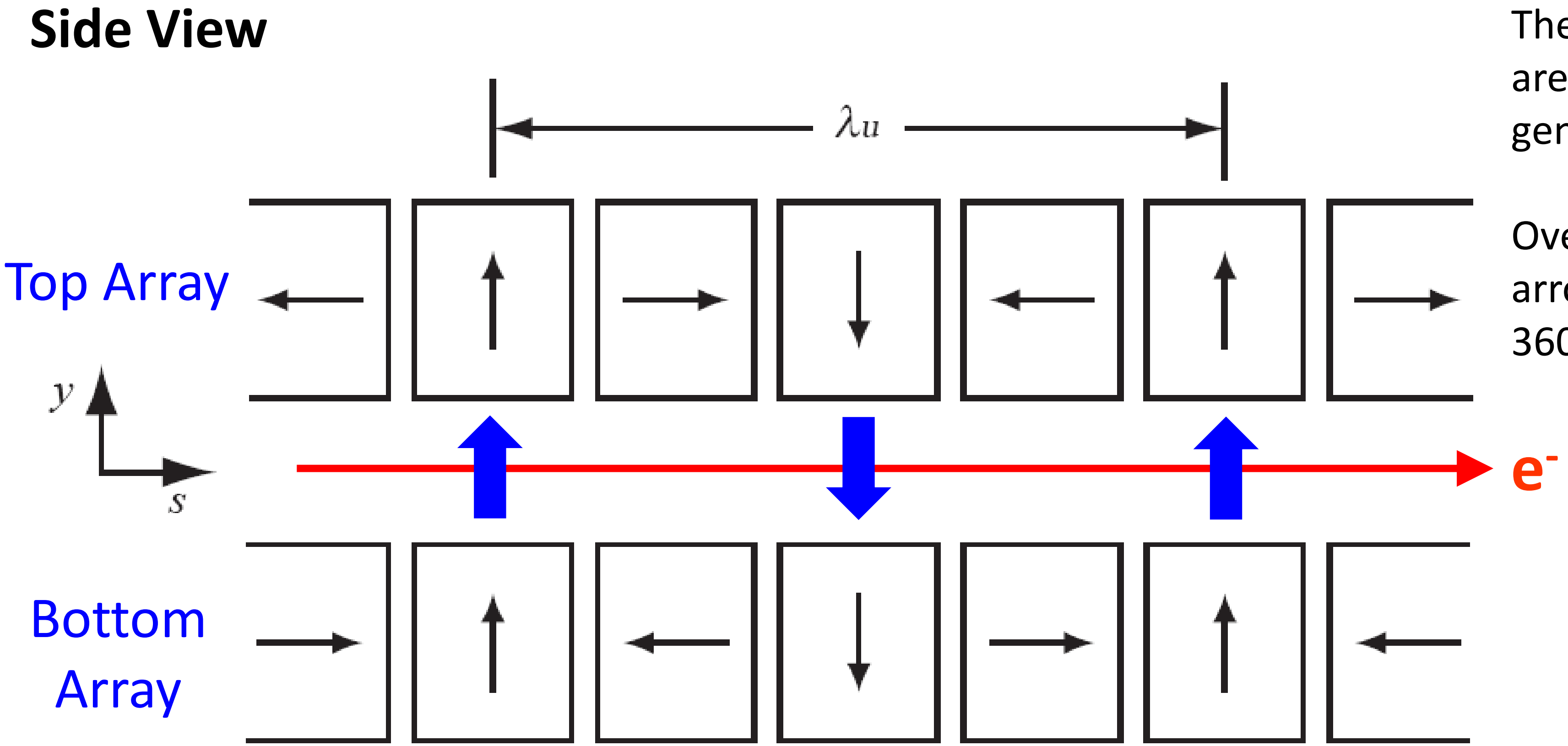
Two types of permanent magnet are commonly used for undulators – Samarium Cobalt (SmCo) and Neodymium Iron Boron (NdFeB), a new type (PrFeB) is also starting to be used for special applications – **these are all very close to ideal in their performance**

	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	~1.03	~1.1
Temperature Coefficient	-0.04 %/°C	-0.11 %/°C
Max operating temperature	~300°C	~100°C
Comment	Brittle, easily damaged, better intrinsic radiation resistance, expensive	Less brittle, easier to machine, expensive

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 (like air) we can just add field contributions from each block linearly – just like we do with fields generated by coils
- We want a sinusoidal magnetic field along the direction of the electron beam
- To generate a perfect sinusoidal field an ideal PPM would have **two sets (arrays)** of Permanent Magnets, one above the beam and one below, 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 arrays into a number of discrete rectangular magnet blocks

Typical PPM arrangement, 4 Blocks per period



The arrows in the blocks are the field directions generated by each block

Over a full period the arrows have rotated by 360°

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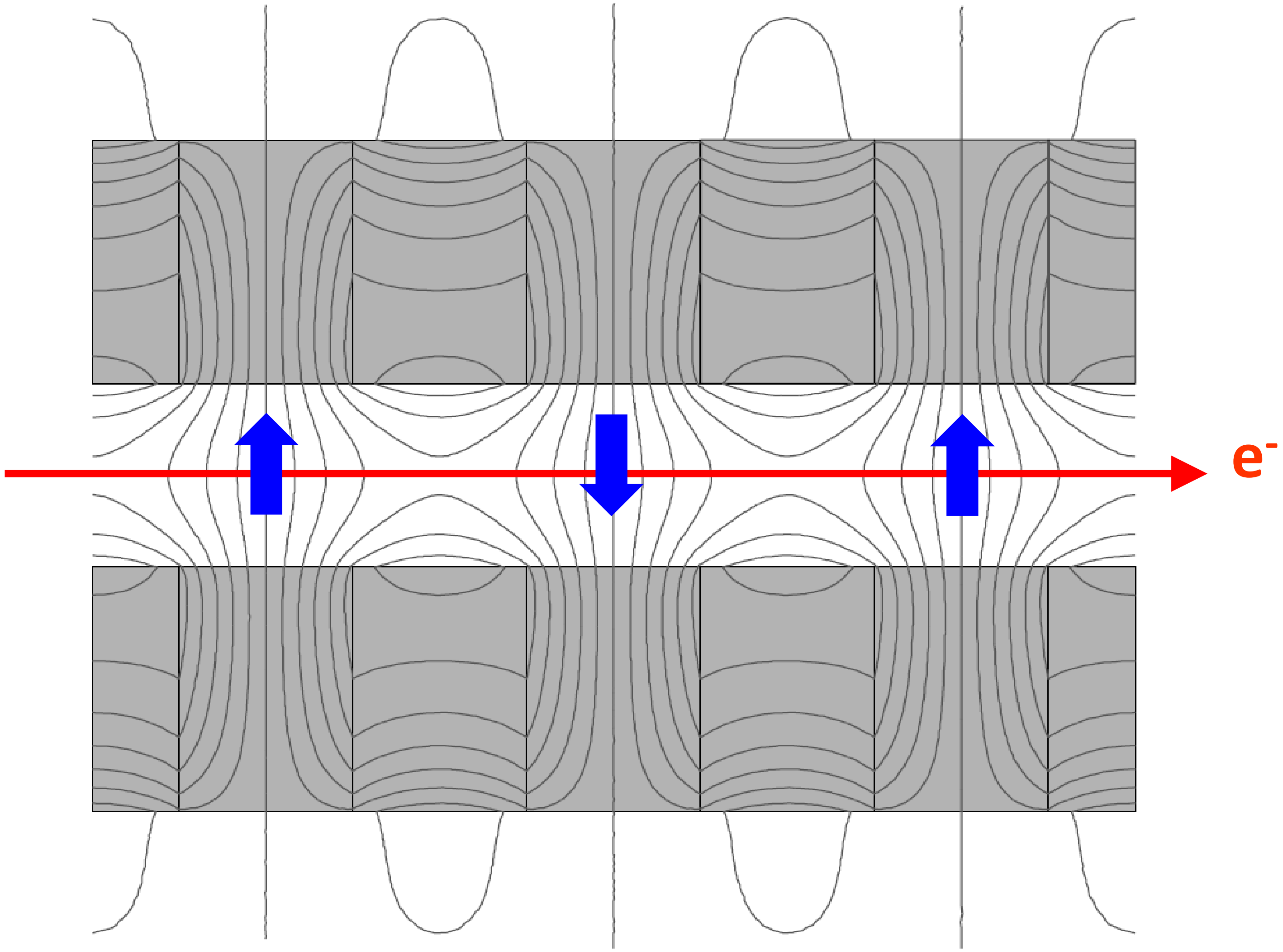
Example PPM arrangement, 4 Blocks per period

Photo of a PPM Array being measured with a Hall probe

SwissFEL Undulator built at DL

Lines of Magnetic Flux



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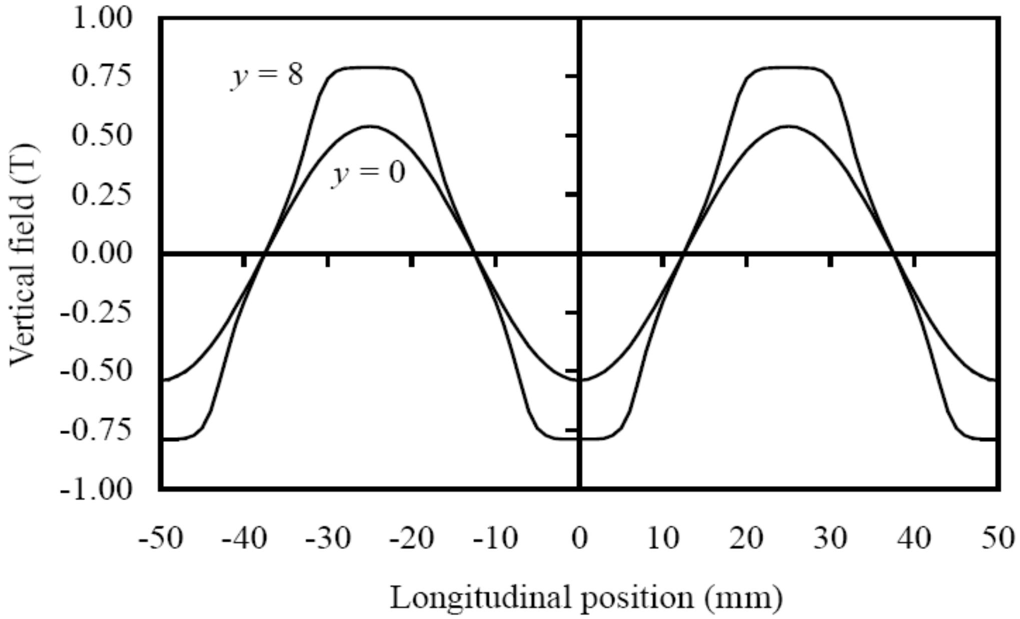
A Practical PPM, 4 Blocks per period

4 blocks per period is a good compromise between on axis field strength and quality vs engineering complexity

The magnetic field on axis is very close to a perfect sine wave

Away from the axis it is definitely **not sine-like** (but it doesn't matter because we make sure the electrons are on-axis!)



For an example PPM with 50mm period, block height of 25mm, magnet gap of 20 mm and remanent field of 1.1 T

Note that the fields increase away from the axis

Peak Field Achievable

- The peak of the sine wave on axis for a 4 block per period device is (g is the gap between the two arrays):

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

- **Important:**
- If all the physical dimensions are scaled together the fields on-axis **do not change**
- Small gaps and small periods can still produce **high fields**
- **This is not true for electromagnets – PM based undulators have a better magnetic performance than EM versions**
- 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

Tuning the Undulator

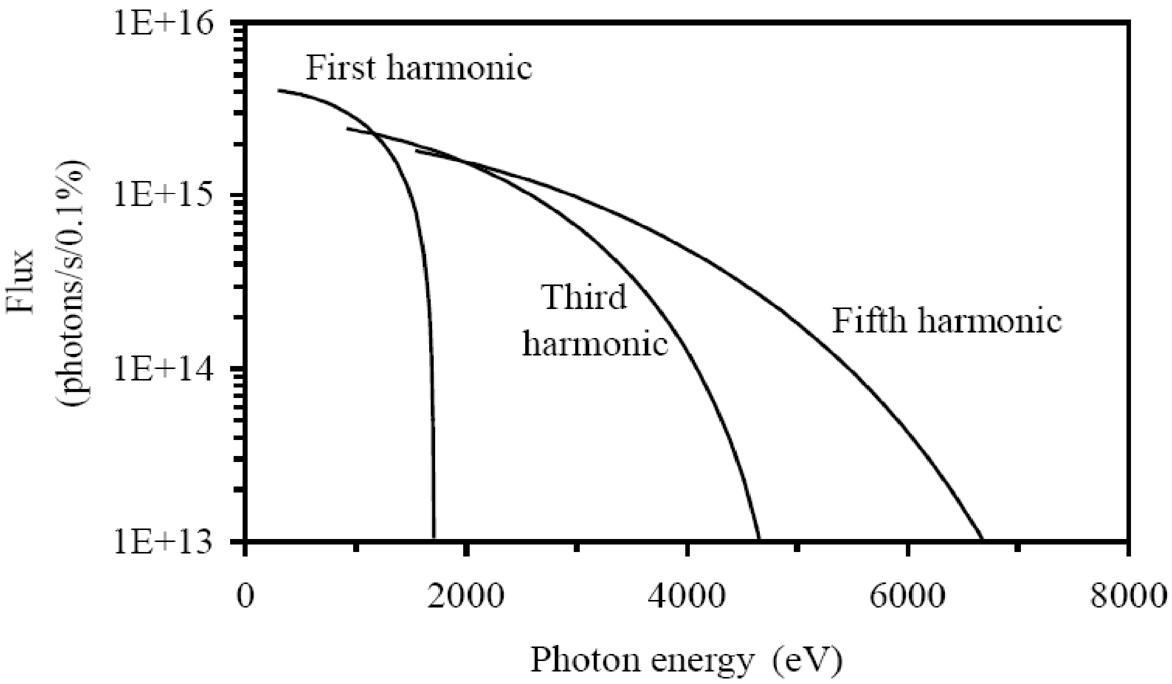
To vary the output wavelength from the undulator – to map out the tuning curves – we need to alter the field level on the axis

We can now see that the only practical way to do this for a permanent magnet device is **to physically change the magnet gap, g**

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

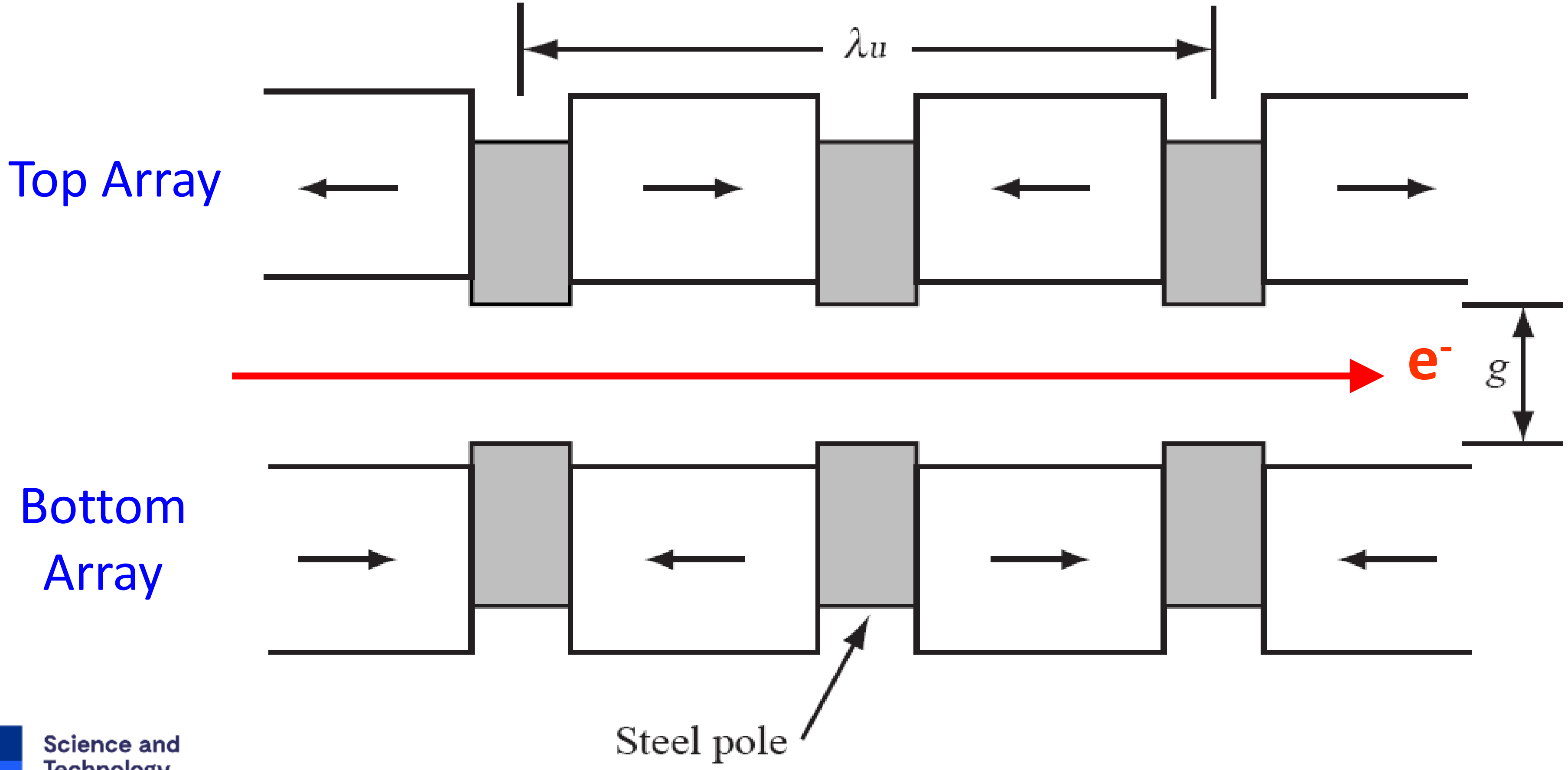
$$K = \frac{B_0 e}{m_0 c}\frac{\lambda_u}{2\pi} = 93.36\, B_0\lambda_u$$

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



Hybrid Undulators – Inclusion of Iron

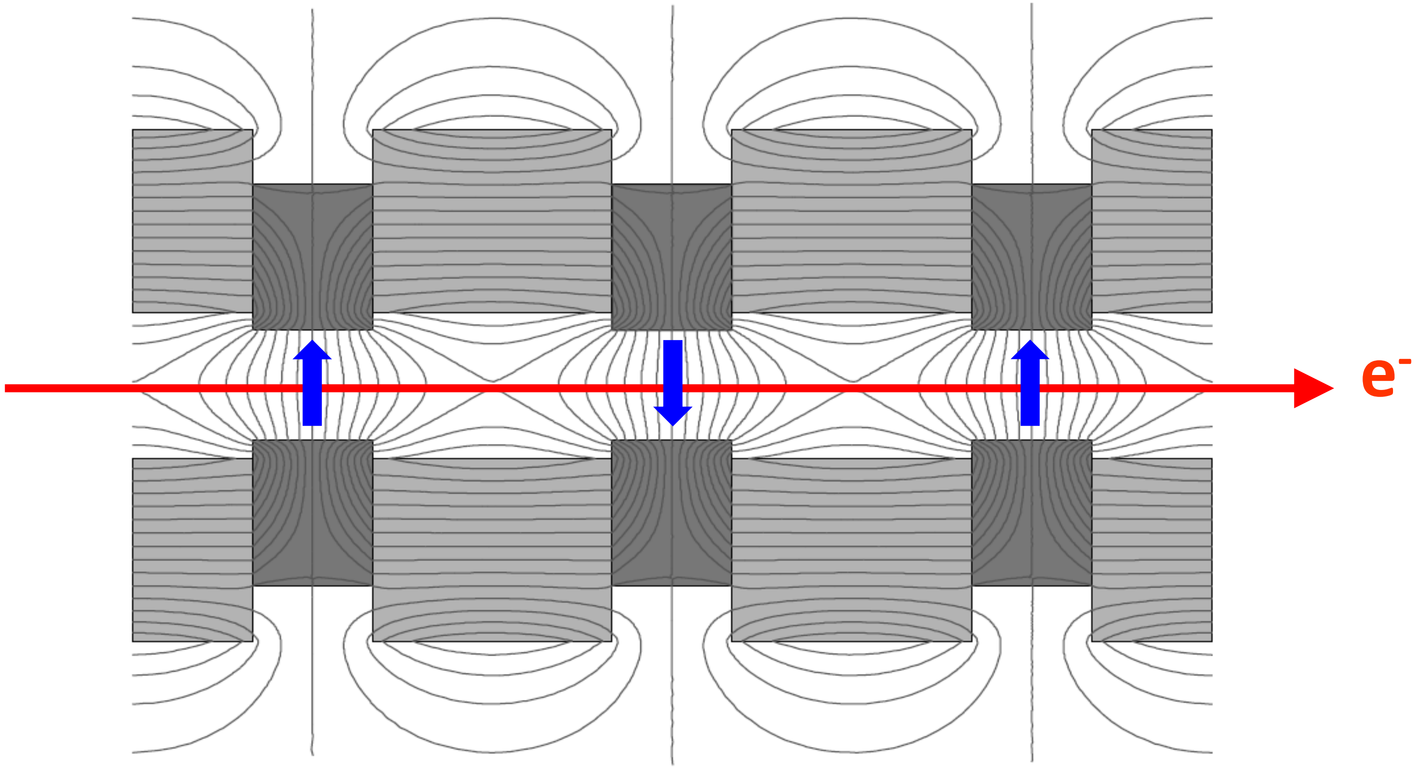
Simple hybrid example



Lines of Magnetic Flux

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

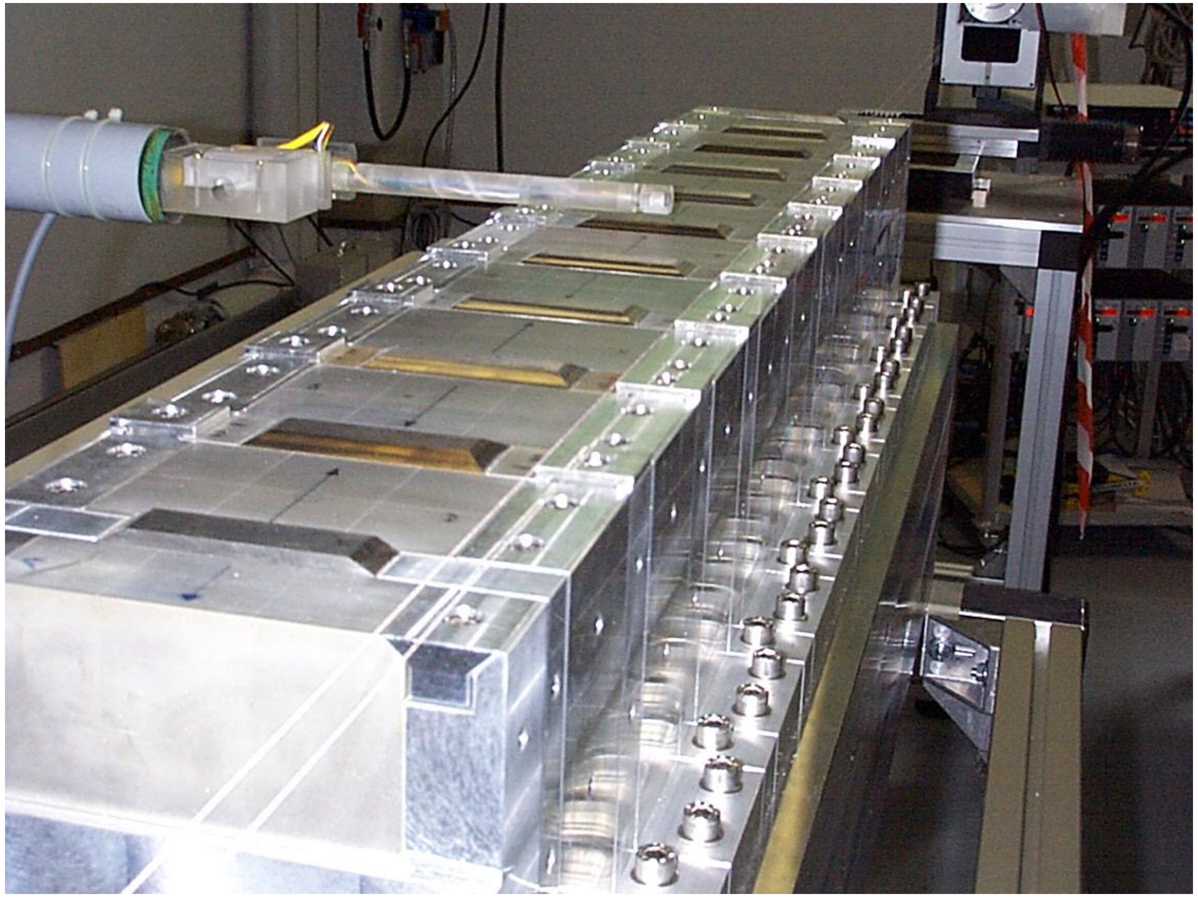
Accurate predictions for particular designs can only be made using specialized magnet software in 2D or 3D



Hybrid Undulators – Inclusion of Iron

Photo of a Hybrid Array

SRS Wiggler being measured with a Hall probe



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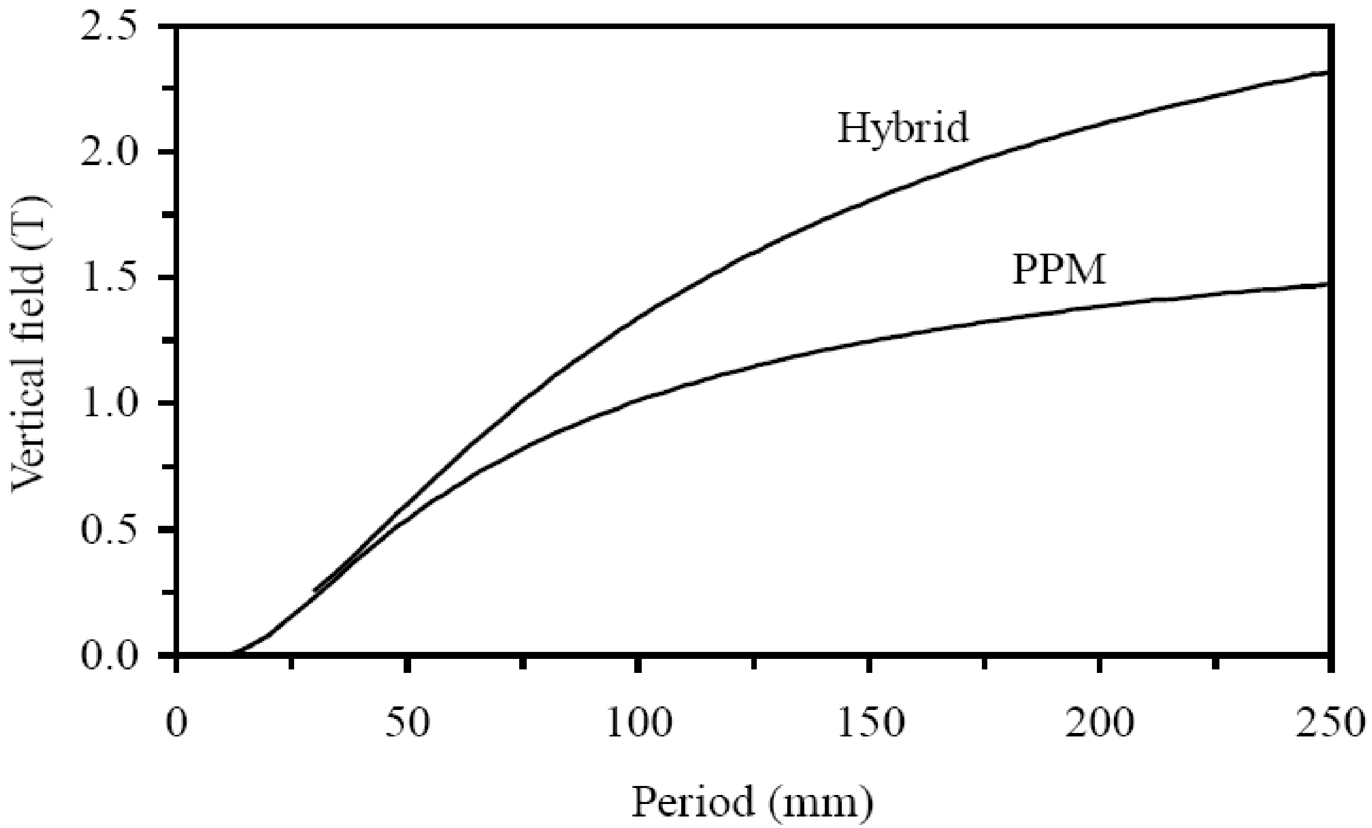
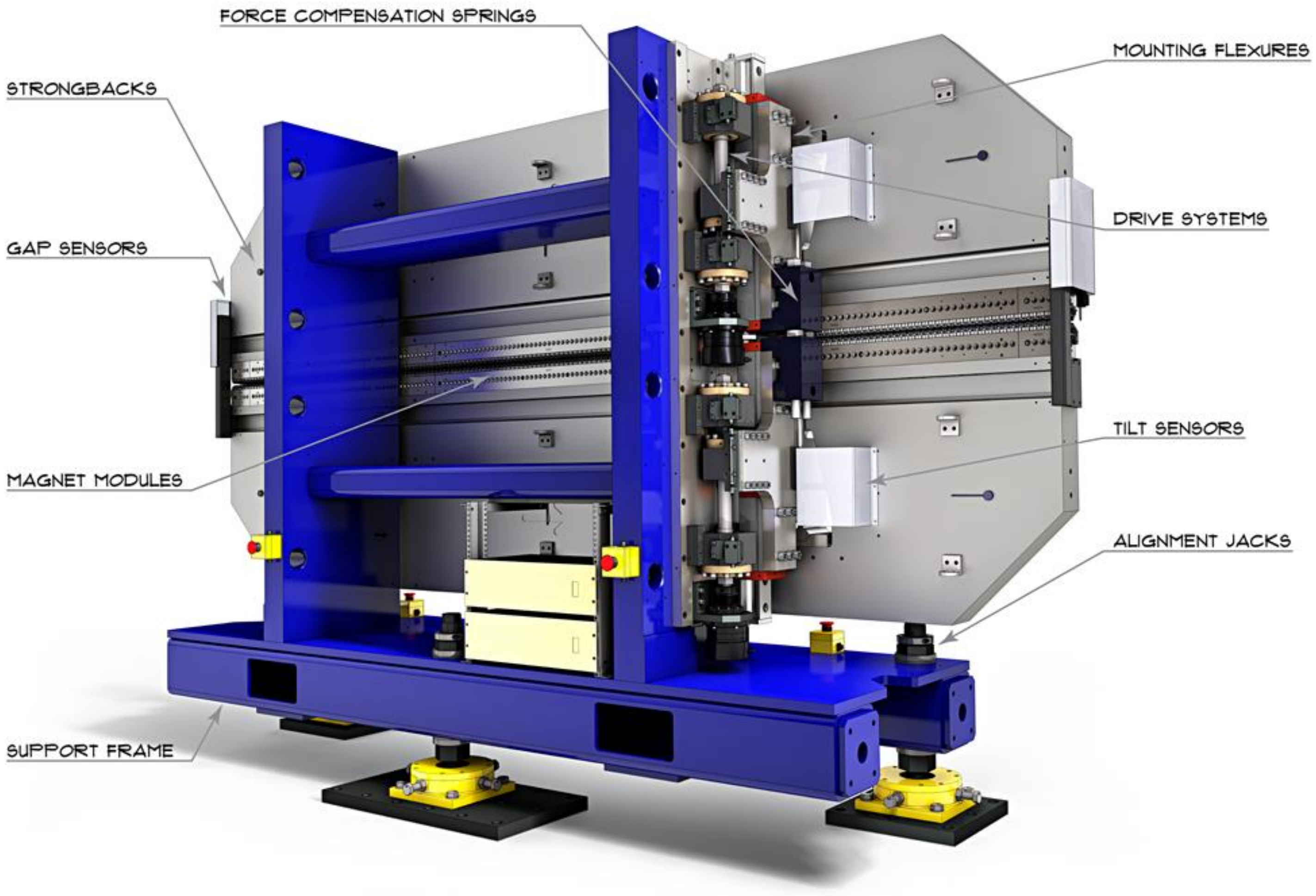
Hybrid vs PPM Undulators

Assuming Br = 1.1T and gap of 20 mm



Real Undulator Implementation

Although the permanent magnet blocks are themselves physically small, the engineering arrangement needed to generate high quality fields and to change the magnet gap in a precise and controlled way means undulators are large and challenging engineering systems



LCLS-II Undulator, LBNL

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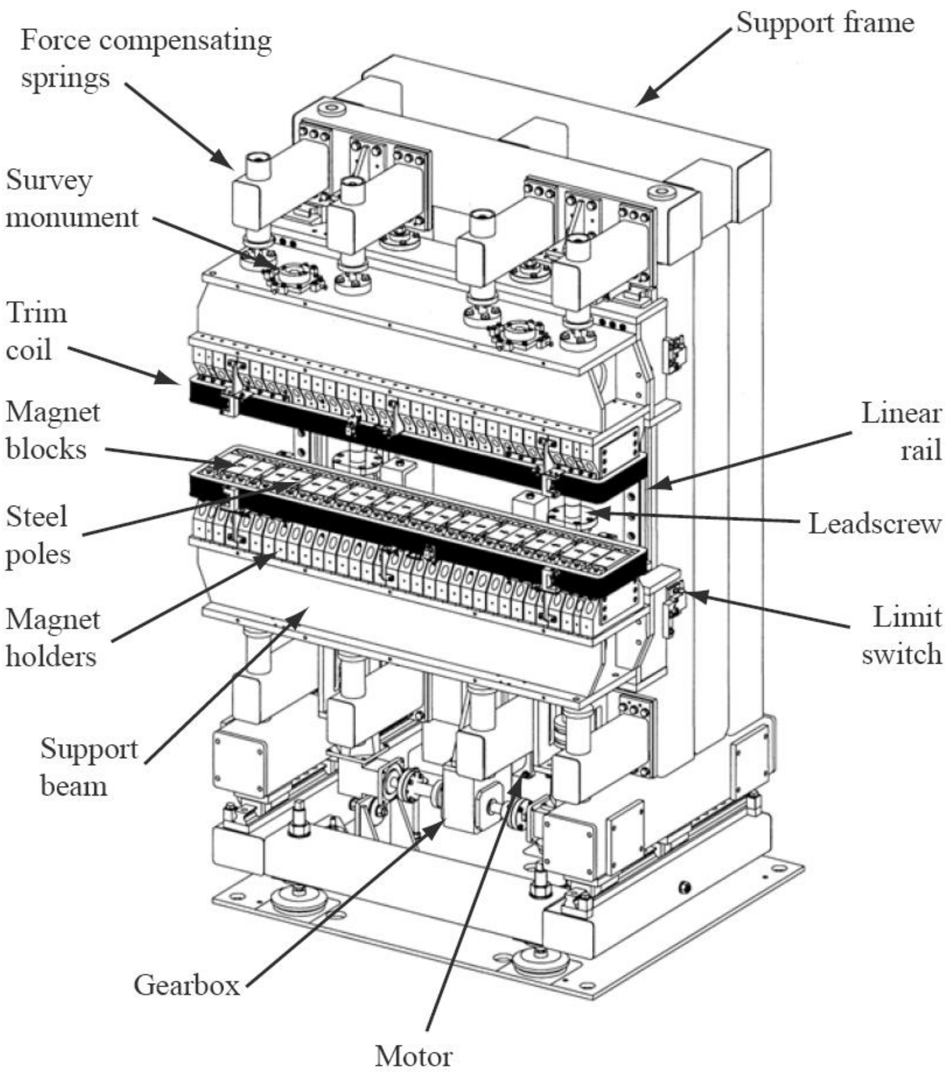
Engineering Issues for all PM Undulators

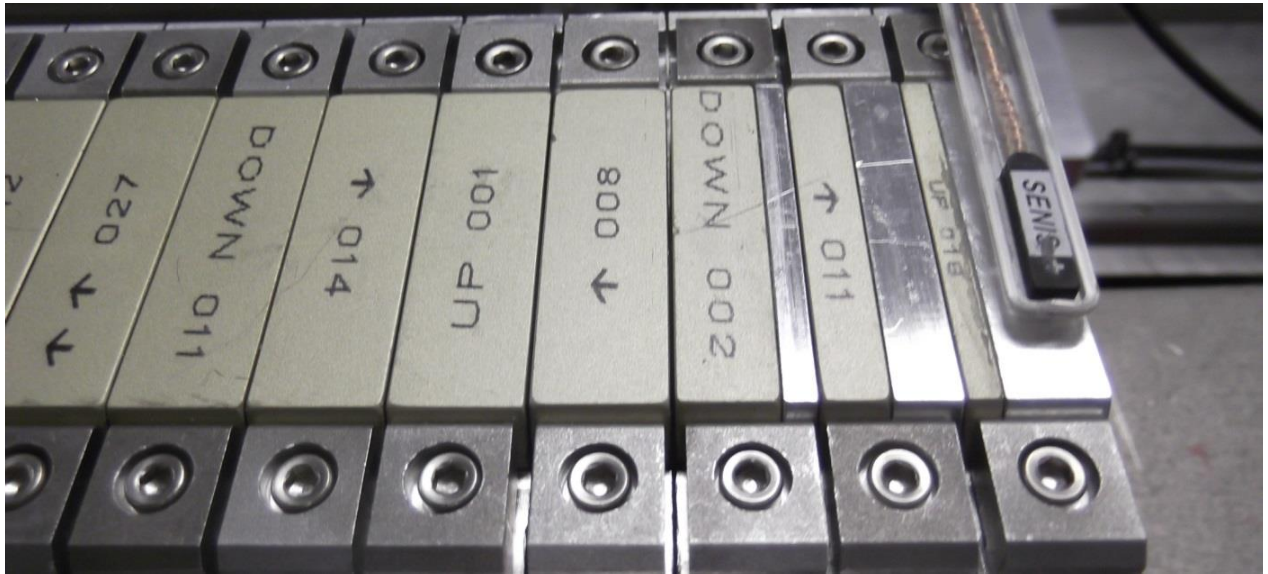
- **Engineering demands are very high:**
- Very strong magnetic forces are present during assembly and when complete
- Must achieve very high periodicity
- Arrays must be parallel to μm precision and must stay parallel at all gaps

- **Typical design themes:**
- Blocks are held in individual holders – usually clamped
- These holders are fastened to a backing beam
- C shaped support frame to allow side access to vacuum chamber and for magnetic measurements
- Very long magnets (>5m) are split into shorter modules (typically 2 – 3m)



Working with Permanent Magnets

- PMs cannot be switched off so there are always magnetic forces that must be dealt with at all times – during assembly and once fully assembled
- Building a PM undulator 'by hand' is not possible – the forces are too strong to hold the blocks in position whilst they are fastened
- Special assembly fixtures, tools and procedures must be followed
- PM blocks are not identical from block to block – they can have different amplitude and direction of magnetization, as well as physical size tolerances
- PM manufacturers will measure every individual block and the undulator designer will decide the precise location of every block in the arrays to maximise field quality as far as possible



Example Undulator Forces

- For a sinusoidal field of length **L** where the **vertical field is constant in x over a width W** (and zero outside of this width) then the **total force between the two arrays is**

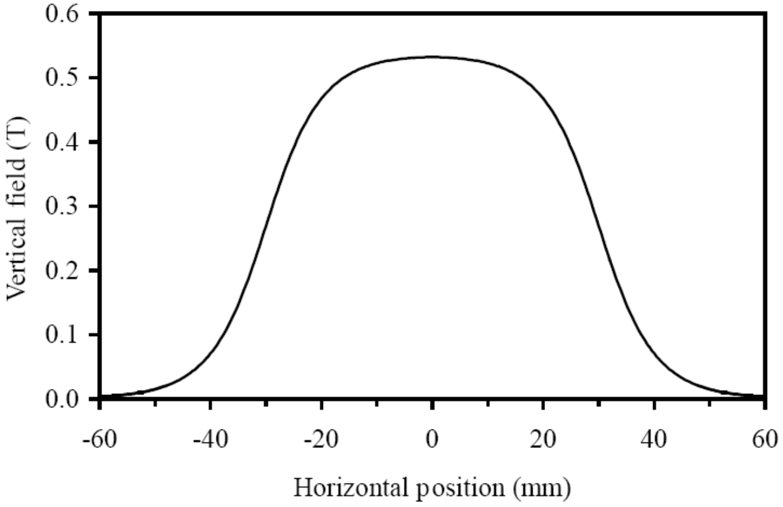
$$F = \frac{B_{y0}^2 LW}{4\mu_0}$$

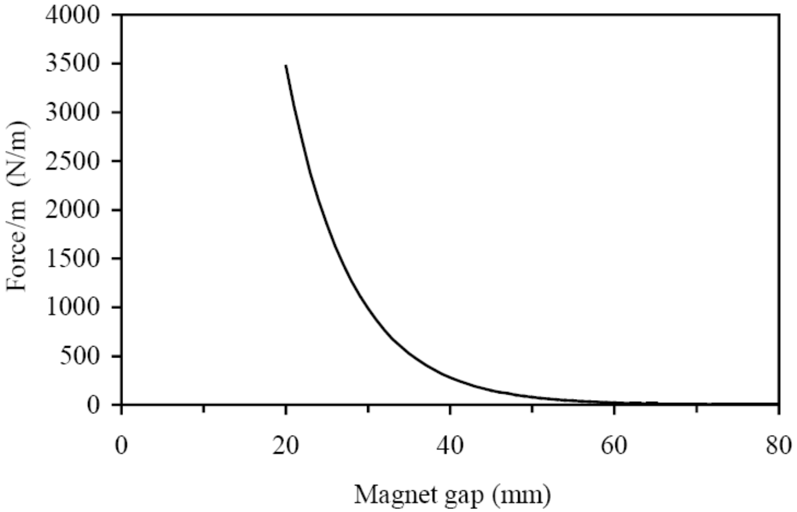
- For a 50 mm period and 20mm gap undulator with a permanent magnet remanent field of 1.1T and a horizontal field width of ~60mm

- The attractive force between the two arrays is ~3500N per meter of length

- Note that this force changes rapidly with gap since the field changes exponentially

$$B_{y0} = 1.72\, B_r e^{-\pi g/\lambda_u}$$





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Correcting Magnetic Field Imperfections

- Precise magnetic measurements of the undulators are (often) made during assembly as well as of the fully assembled device (over the full gap range)
- Small imperfections in the local magnetic fields are corrected to ensure the field quality of the undulator meets the specification required
- **Shimming** is a general term which means making small modifications to the magnet locally so as to optimise the magnet performance
- Magnet block positions may be slightly adjusted by ~0.1mm displacements
- Small pieces of thin iron sheet (shims) are fastened on top of the arrays to slightly modify the field in that location
- The exact dimensions and location of the iron pieces is selected to have the required effect upon the field level
- Although shimming is a time consuming task, it is a very important step, since the magnetic errors will be significantly reduced.

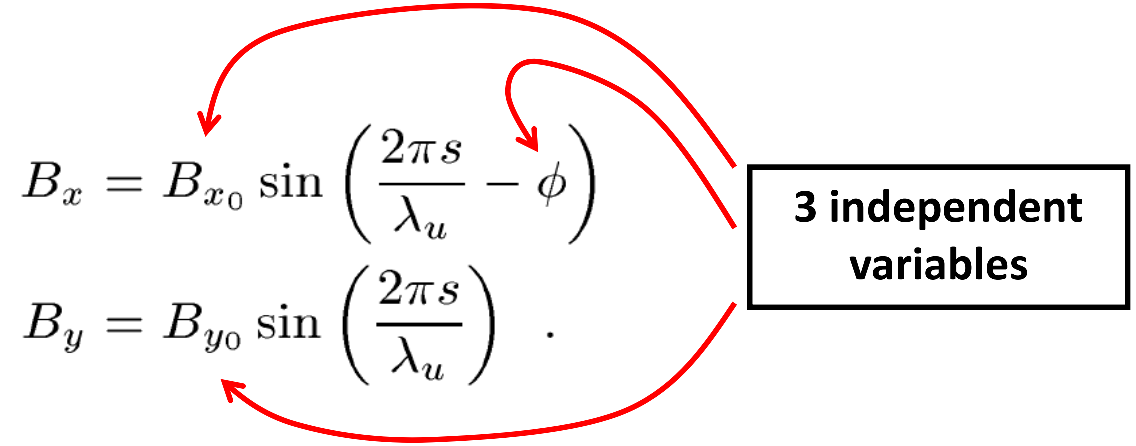
Specific FEL Undulator Challenges

- FEL undulator systems ("radiators") are very long and so are made up of a number of discrete undulator modules (each typically a few m long) which are more manageable and allow for focussing, steering, diagnostics, vacuum pumps etc between modules
- All of the undulator modules need to emit the same wavelength which sets tight limits on reproducibility of period and K
- Want high K (B field) at small periods to minimize the electron beam energy required
- This is contrary to physics which reduces K as the period reduces (if gap fixed) – compromise to be reached
- B will increase if the gap is decreased (for a fixed period) so narrow gaps are preferred by the magnet designer
- But narrow gaps increase the wakefields which can disrupt lasing, increase the risk of radiation damage to the PMs, and make vacuum harder to achieve – compromise has to be reached

Elliptical Undulators

If we also generate a horizontal field of the same period as the vertical one then the electron takes an **elliptical path** when viewed head on

Two fields (B_x and B_y) of equal period but of different amplitude and phase



$$B_x = B_{x0} \sin\left(\frac{2\pi s}{\lambda_u} - \phi\right)$$
$$B_y = B_{y0} \sin\left(\frac{2\pi s}{\lambda_u}\right) \quad .$$

3 independent variables

Only 3 independent variables are needed to define the polarisation so an elliptical undulator can **generate any polarisation state** (linear, circular, or elliptical)

Elliptical Undulators

Pure helical fields are suited to a **circular magnet geometry** (magnets surrounding the vacuum chamber) but these are not always very practical

A planar geometry is better suited to light sources (all of the magnets in the planes above and below the axis)

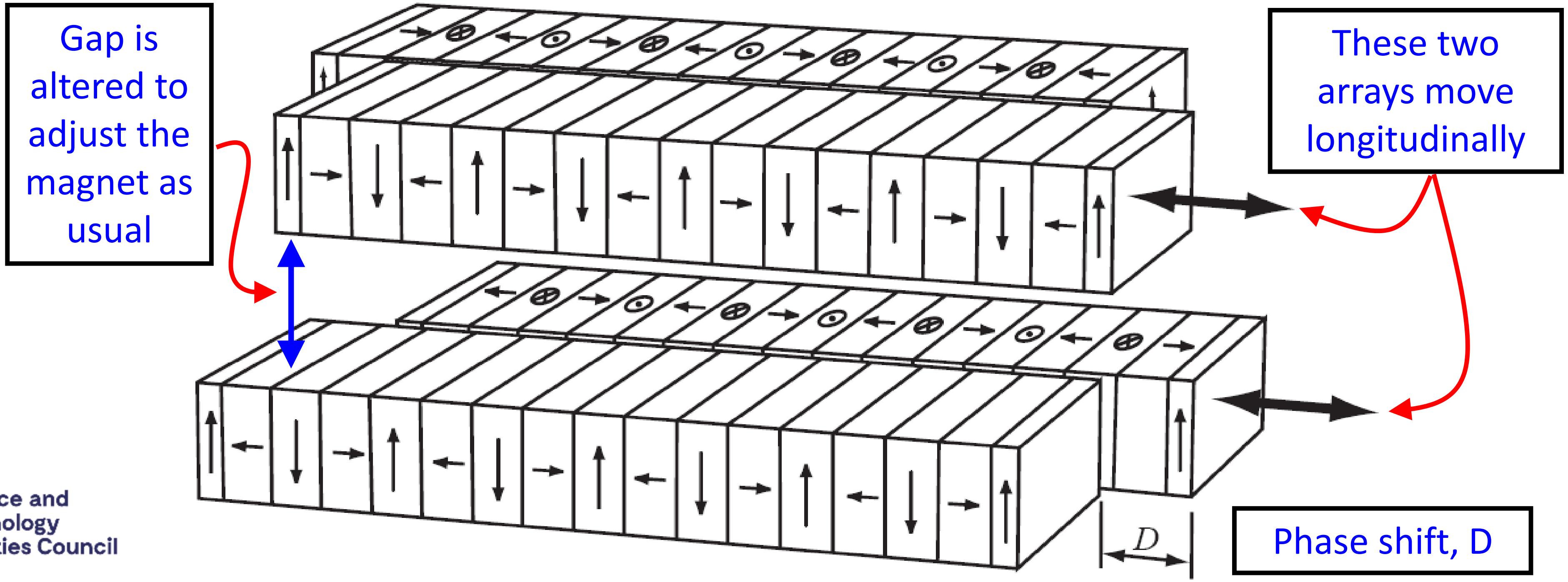
- This allows the machine to have a narrow vertical gap and a wide horizontal gap – as required for injection in storage rings or for magnet measurements
- But, it is not so easy to generate H and V fields (but it is possible!)
- Two degrees of freedom are needed to control the H & V fields independently, ideally three so you can control the phase as well
- Hence two (or three) independent motion systems are needed

Elliptical Undulator Example: APPLE-2

This is the most popular elliptical undulator and it consists of **four standard** PPM arrays

It has two or three degrees of freedom (motion systems) depending upon the photon output requirements

The electron beam travels along the central axis of the magnet between the arrays



Gap is altered to adjust the magnet as usual

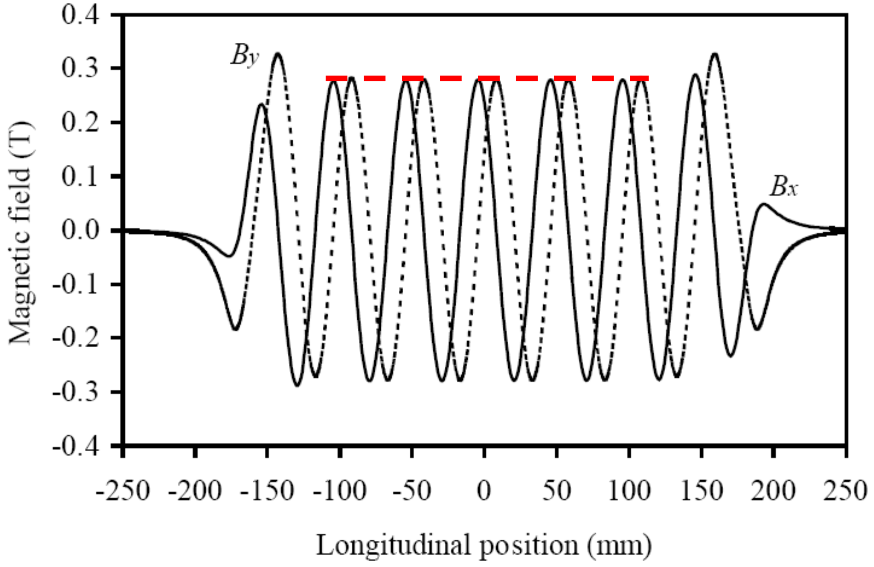
These two arrays move longitudinally

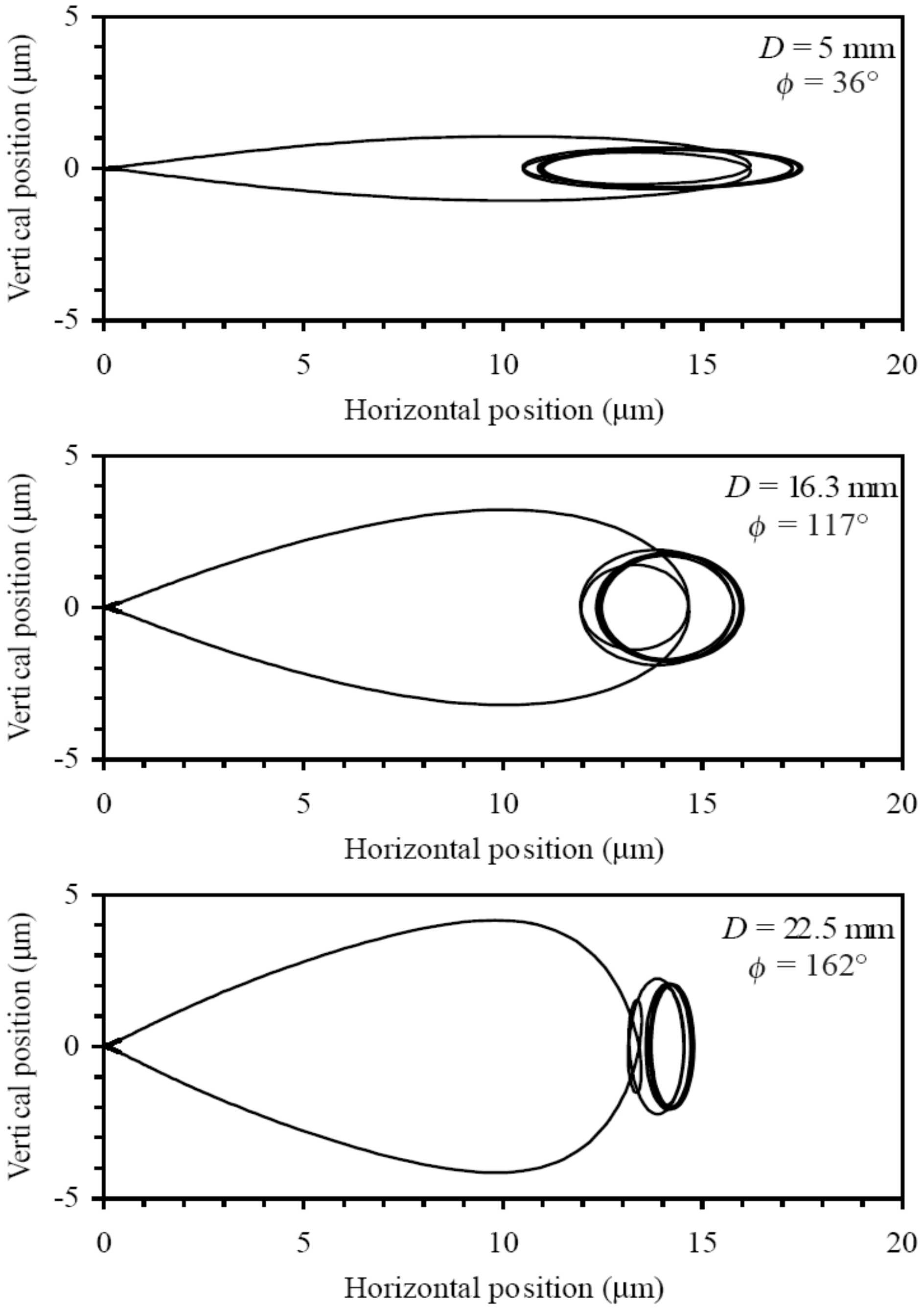
Phase shift, D

Example Trajectories

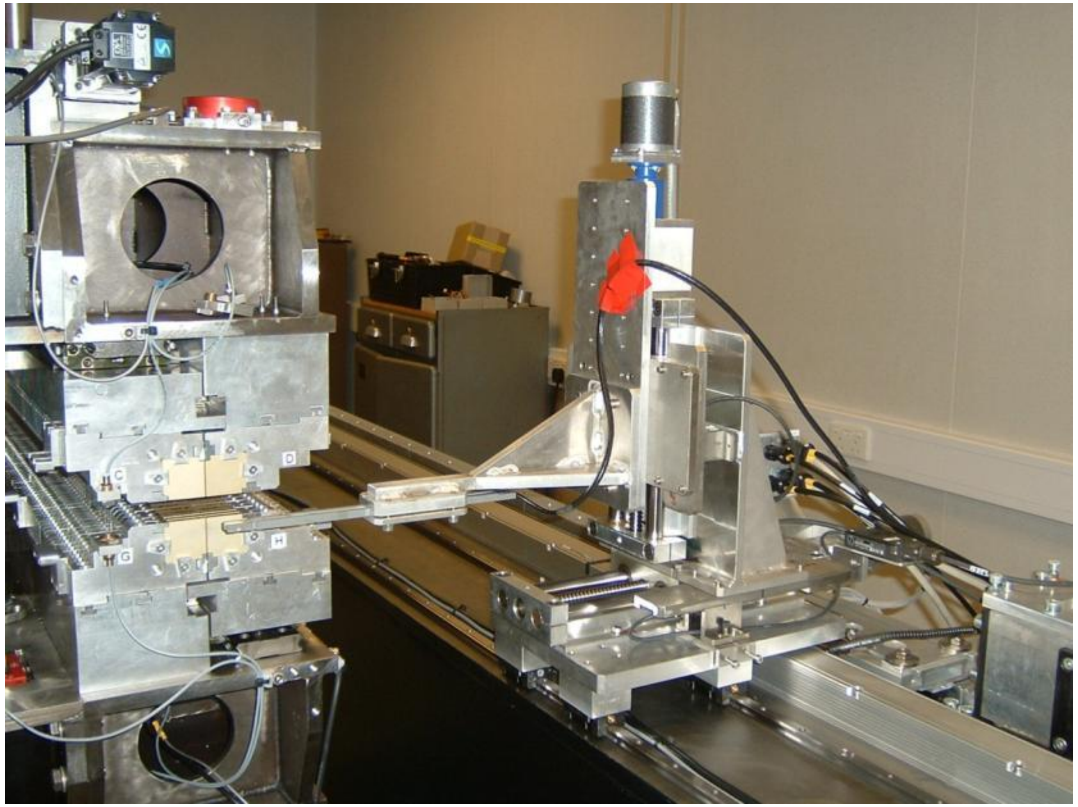
- Trajectories viewed head on – as the observer sees them
- 3 GeV electron beam
- Undulator period is 50 mm
- Magnet gap is 20 mm

H and V Fields in circular polarisation mode





APPLE-2 Examples



SRS HU56
being measured with a Hall probe

In-Vacuum Undulators

- The minimum magnet gap limits the peak field 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 as far as the magnet is concerned***
- Another option is to put the undulator inside the vacuum chamber
  - The physics design of the magnet is the same but the engineering is more challenging

In-Vacuum Examples

Diamond U23

In-vacuum undulator – Before vacuum chamber is fitted

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In-Vacuum Examples

SACLA in-vacuum undulators (Japan XFEL)

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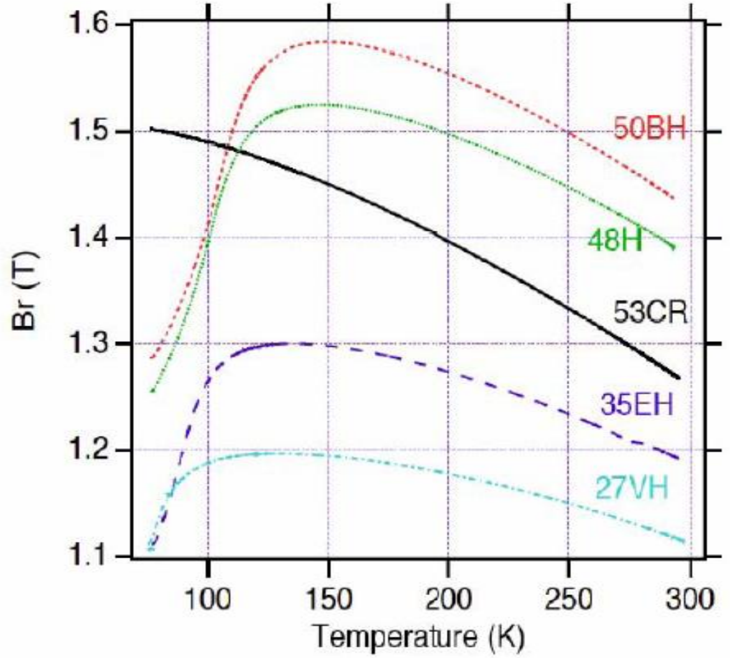
Cryogenic Undulators (CPMUs)

These are a natural evolution of in-vacuum undulators that take advantage of the variation of remanent field with temperature

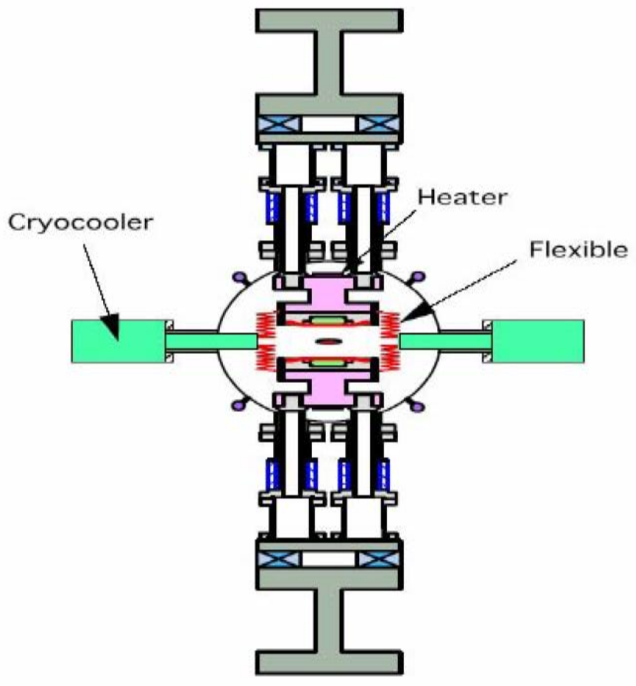
If the undulator can operate at ~150K then there will be a significant field increase with NdFeB

NdFeB grades



The intrinsic coercivity increases also which helps with radiation resistance and allows selection of stronger grades

Basically an in-vacuum device with cryogenic cooling attached

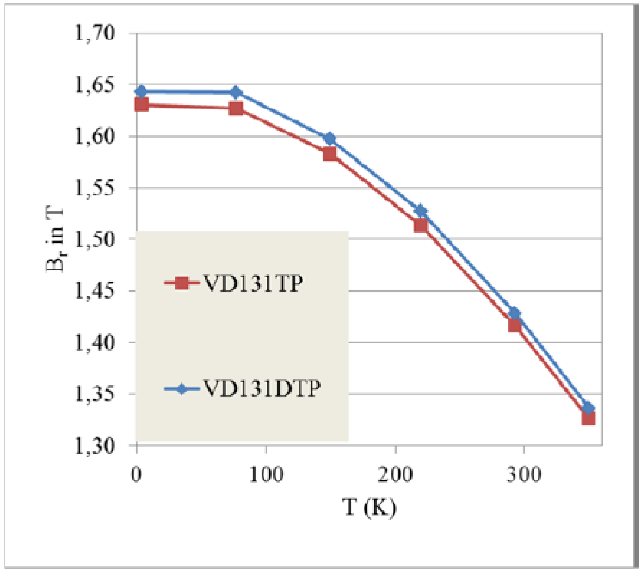


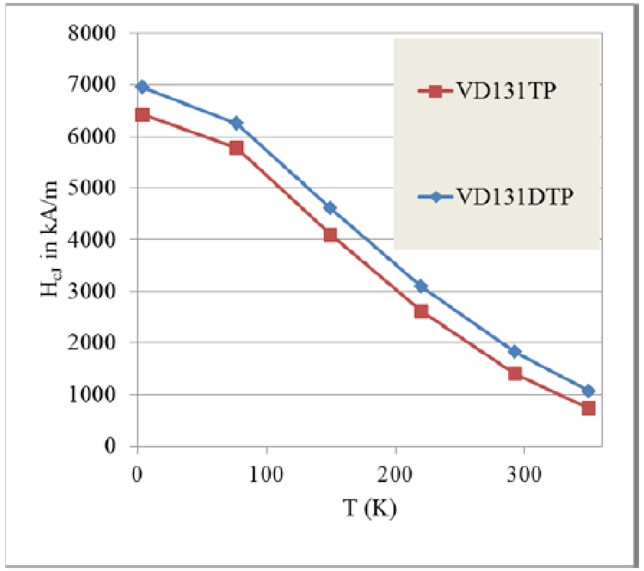
H Kitamura, Spring-8

Cryogenic PM undulators

- **PM Magnetisation increases as temperature decreases, coercivity increases even more** – ***selection of stronger grades of PM possible***
- Better magnetic performance, better vacuum performance because cold, better radiation damage resistance – lots of advantages, just more challenging engineering and more expensive!
- PrFeB is now the material of choice as it is strong (B_r up to ~1.7T) and works at 77K which is a very easy temperature to achieve and maintain with liquid nitrogen

PrFeB grades





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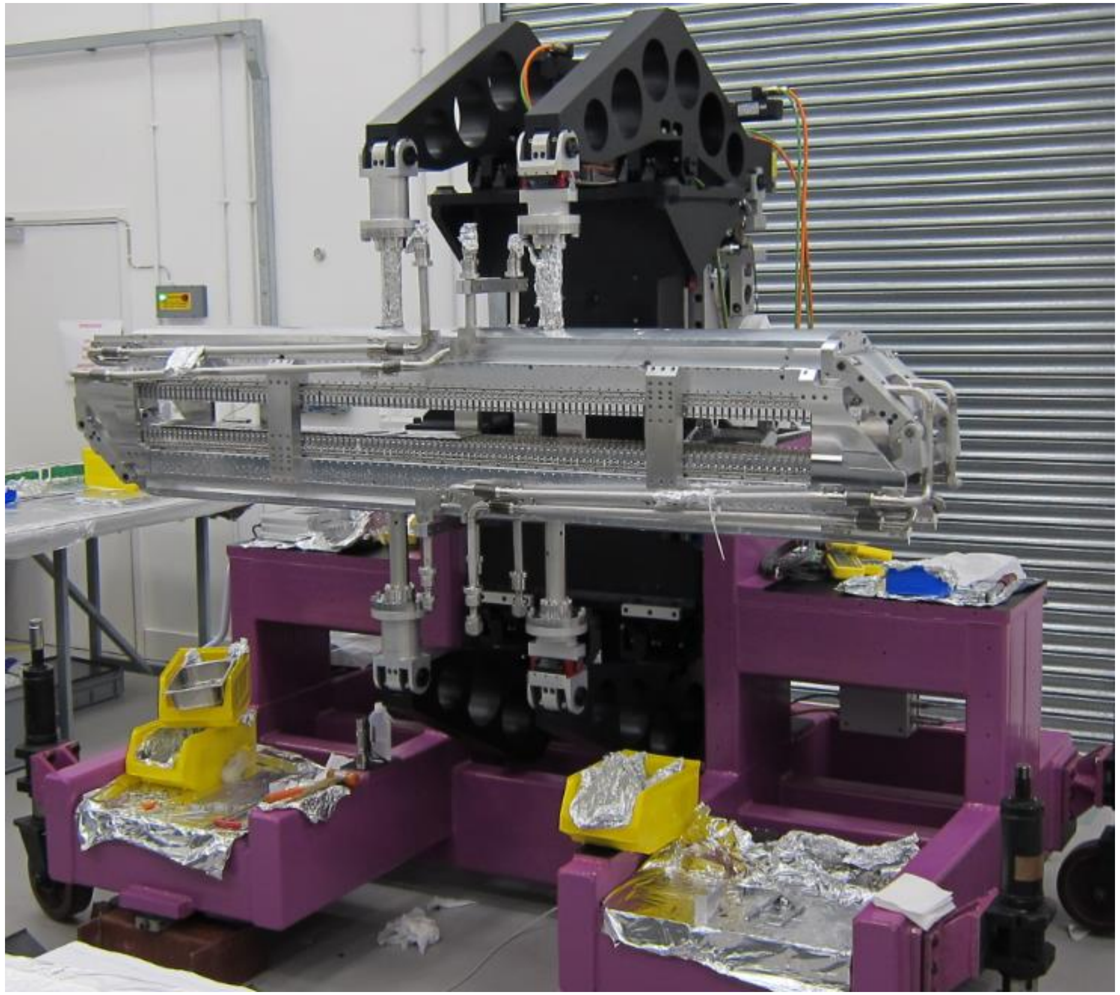
Cryogenic PM undulators

- CPMU being assembled at Diamond – ready for measuring and shimming
- Essentially an in-vacuum undulator with liquid nitrogen cryogenics added (extra complexity!)



S Milward, DLS

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 so far are only superconducting below ~10K but groups are developing high temperature SC undulators
- Hence the magnets always sit inside a cryostat
- In the past they would have a closed loop liquid Helium refrigerator permanently connected to them
- The development of closed cycle cryocoolers has enabled a more 'stand alone' approach to be used in some applications – liquid helium baths are not necessarily required and so not always used

Superconducting Wigglers

- Superconducting wigglers are popular in the intermediate energy light sources (~3 GeV) because the high field enhances the flux in the hard X-ray region
- A key advantage over permanent magnet hybrid wigglers is not just the higher field but also the **reduction in period**
- This lowers the K value and so the radiation is emitted over a narrower horizontal angle (±K/γ) – making it easier to manage the cooling arrangement within the facility
- Note that the majority of the radiation generated by a MPW will **not be transported** down the beamline to the sample and so it must be **absorbed** by cooled surfaces

Superconducting Wiggler Examples

Diamond Light Source

3.5 T

60 mm period, 45 poles

K = 19.6

4.2 T

48 mm period, 45 poles

K = 18.8

For comparison:

SRS ***Hybrid PM*** *Wiggler*

2.4 T

220mm period, 9 poles

K = 49.3

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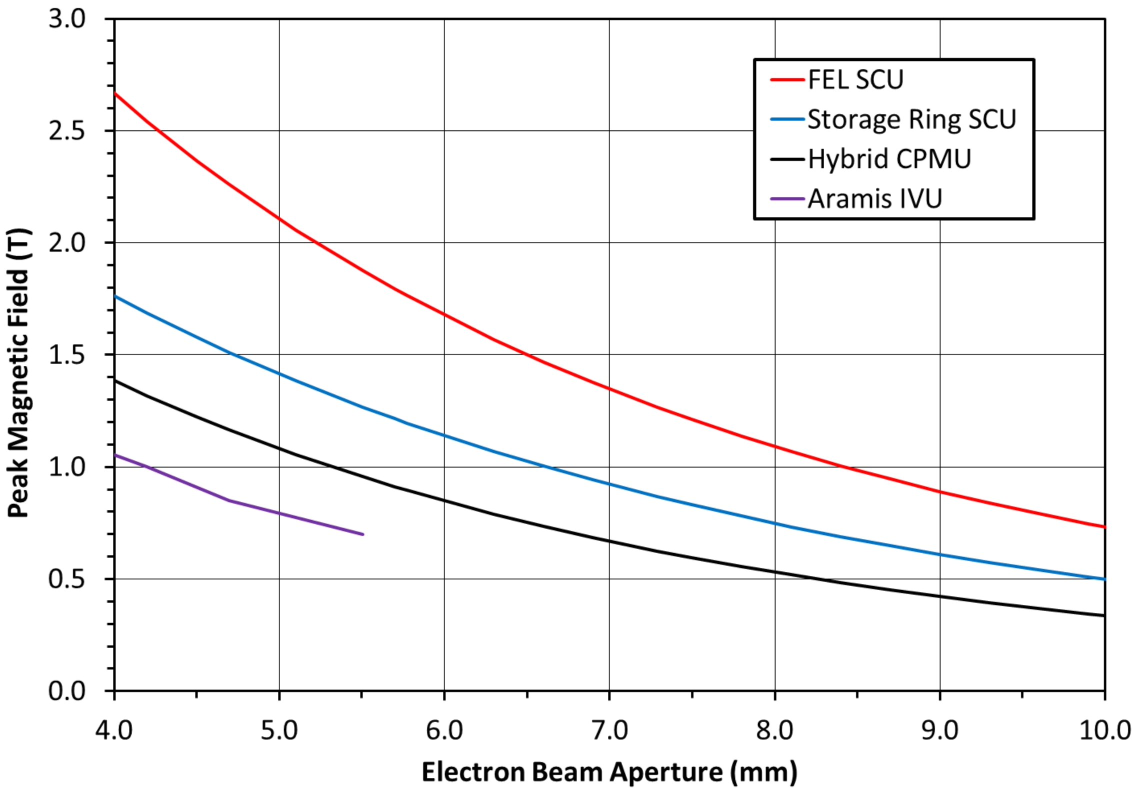
Superconducting Undulators

- The prime motivation for using superconductivity has been to generate higher fields on axis than are presently available from the best permanent magnet systems
- An additional motivation now, for high repetition rate XFELs, is their higher radiation resistance in comparison to permanent magnet alternatives
- The key region of interest for SC Undulators is in **short period** systems, typically ~15 to 20 mm with magnet gaps ~5 to 8 mm
- The field quality has to be as good as existing undulators and most SC undulator groups do not use any field shimming so the engineering tolerances need to be very precise

Undulator Comparisons

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



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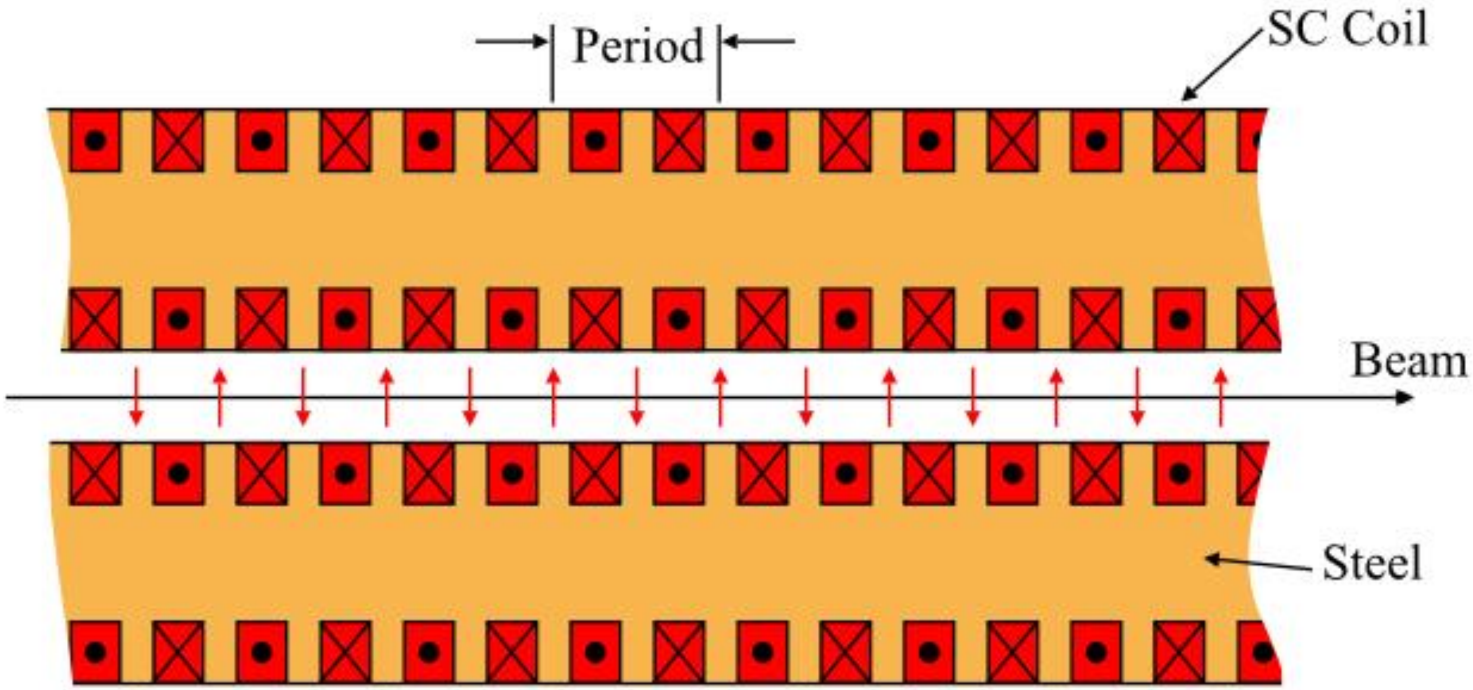
JA Clarke, FEL 2017

Undulator Design

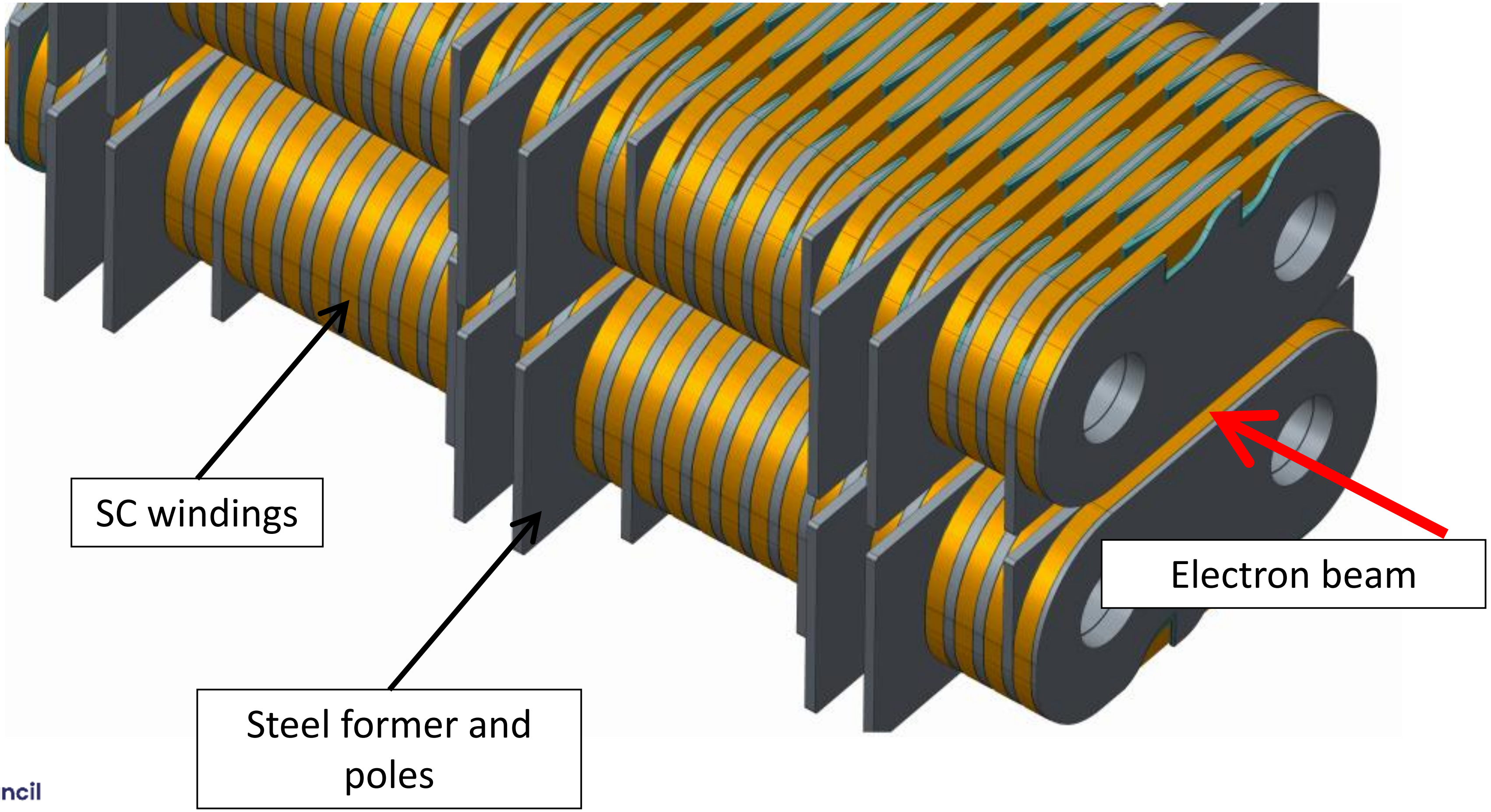
The standard solution is very simple – currents flowing perpendicular to the beam axis with iron poles

The challenge is the engineering



SCU for Storage Ring

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



SCU LAYOUT

Assembled cryostat.

Inside the SCU vacuum vessel.

SCU cold mass.

- SCU cryostat consists of vacuum vessel, thermal shield and a cold mass
- Cooling is provided by cryocoolers
- Closed-loop LHe circuit

Operating SCUs

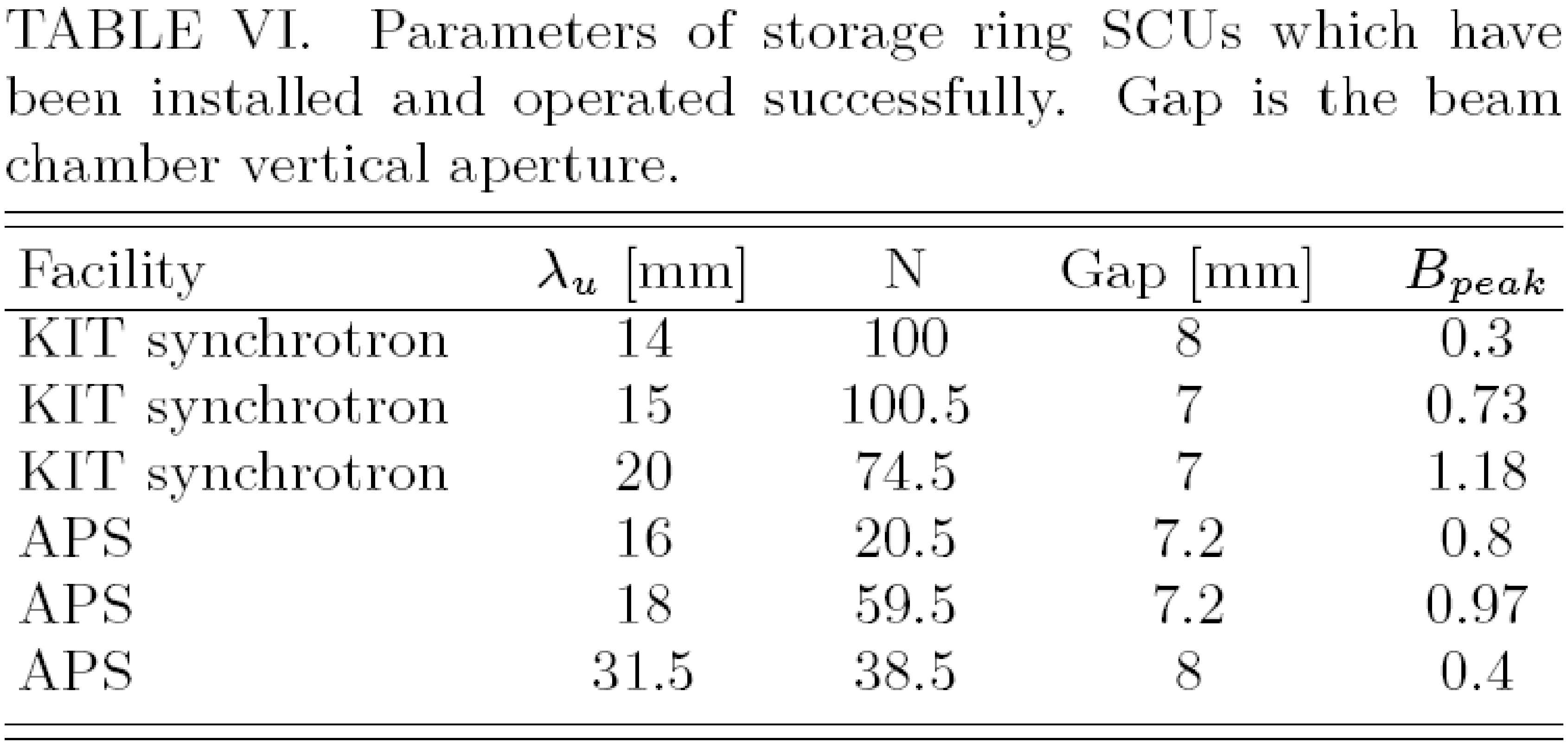


TABLE VI. Parameters of storage ring SCUs which have been installed and operated successfully. Gap is the beam chamber vertical aperture.

Facility	λ_u [mm]	N	Gap [mm]	B_{peak}
KIT synchrotron	14	100	8	0.3
KIT synchrotron	15	100.5	7	0.73
KIT synchrotron	20	74.5	7	1.18
APS	16	20.5	7.2	0.8
APS	18	59.5	7.2	0.97
APS	31.5	38.5	8	0.4

Summary

- To generate a sinusoidal field we 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 at longer periods
- The APPLE-2 is the most popular elliptical undulator design for generating variable polarisation states
- In-vacuum solutions allow for smaller magnet gaps but more complex engineering
- Cryogenic PM undulators at 77K generate higher field levels and these are operational in several storage rings now
- Superconducting undulators are also operational on at least two storage rings, they are being actively developed by several groups for XFELs as well