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

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>1897</td>
<td>Larmor derives expression for total instantaneous power radiated by an accelerated charged particle</td>
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<tr>
<td>1898</td>
<td>Alfred Lienard derives the radiation due to charges moving close to speed of light &amp; energy loss of an electron on a circular path</td>
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<td>1947</td>
<td>70MeV electron synchrotron – SR first observed directly</td>
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<td>1947</td>
<td>Ginzburg in USSR discusses undulator concept</td>
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<td>1951</td>
<td>Motz proposes “undulator” as source of quasi-monochromatic SR</td>
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<td>1952</td>
<td>Motz makes experimental demonstration of undulator</td>
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<tr>
<td>1976</td>
<td>SC helical undulator used in first FEL by Madey</td>
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<td>1979</td>
<td>First IDs in storage rings</td>
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<tr>
<td>1990s</td>
<td>3rd generation rings built based upon IDs</td>
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<tr>
<td>2000s</td>
<td>Single pass FELs built</td>
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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 \sim 5.5 \text{ m}, \gamma \sim 4000

Wavelength \sim 0.1 \text{ 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 ($\dot{x} \ll 1, \ddot{y} \ll 1$)

The equations of motion for the electron are

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

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

Assume a MPW which only deflects in the horizontal plane

Only has vertical fields on axis

\[
\ddot{x} = \frac{e B_y}{\gamma m_0 c}
\]

\[
\ddot{y} = 0 .
\]
Angular Deflection

B field is sinusoidal with period $\lambda_u$

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

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

$$\dot{x}(s) = \frac{B_0e}{\gamma m_0c} \frac{\lambda_u}{2\pi} \cos\left(\frac{2\pi s}{\lambda_u}\right)$$

Therefore, peak angular deflection is

$$\frac{B_0e \lambda_u}{\gamma m_0c 2\pi}$$

Define the deflection parameter

$$K = \frac{B_0e \lambda_u}{m_0c 2\pi} = 93.36 \ B_0 \lambda_u$$
K Parameter

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

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.

\[
\frac{\lambda_u}{\hat{\beta}_s} \times n = d
\]

Time for electron to travel one period is \( \frac{\lambda_u}{c\hat{\beta}_s} \)

In this time the first wavefront will travel the distance \( \frac{\lambda_u}{\hat{\beta}_s} \)

\( \hat{\beta}_s \) 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

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

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: \[ \frac{\Delta \lambda}{\lambda} \sim \frac{1}{Nn} \]

Angular Width:

\[ \sigma_r' = \sqrt{\frac{\lambda}{L}} \]

n = Harmonic order
N = number of periods
L = length of undulator

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

\[ 1.43 \times 10^{14} NI_b Q_n(K) \]

\( I_b \) is average beam current
Undulator Flux Density (On Axis)

In units of photons/sec/mrad²/0.1% 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 the 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)

<table>
<thead>
<tr>
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<th>SmCo</th>
<th>NdFeB</th>
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<tbody>
<tr>
<td>Remanent Field</td>
<td>0.85 to 1.05 T</td>
<td>1.1 to 1.4 T</td>
</tr>
<tr>
<td>Coercivity</td>
<td>600 to 800 kA/m</td>
<td>750 to 1000 kA/m</td>
</tr>
<tr>
<td>Relative Permeability</td>
<td>1.01 parallel, 1.04</td>
<td>1.05, 1.15</td>
</tr>
<tr>
<td></td>
<td>perp</td>
<td></td>
</tr>
<tr>
<td>Temperature Coefficient</td>
<td>-0.04 %/°C</td>
<td>-0.11 %/°C</td>
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</table>
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

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

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

$$B_{y0} = 1.72 \ B_r e^{-\frac{\pi g}{\lambda_u}}$$
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 \( B_r = 1.1 \text{T} \) and \( 0.07 < g/\lambda_u < 0.7 \))
Hybrid vs PPM

Assumes $B_r = 1.1T$ and gap of 20 mm
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 provide control of the polarisation state for experiments.

Fields in circular mode

- $D = 5\,\text{mm}$, $\phi = 36^\circ$
- $D = 16.3\,\text{mm}$, $\phi = 117^\circ$
- $D = 22.5\,\text{mm}$, $\phi = 162^\circ$
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

Upper and lower beams

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 \(~130 \, ^\circ \text{C}\)
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

Diamond U23
Standard planar undulator
In vacuum examples
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

Full undulator system ~130m
European X-FEL

Project based at DESY
5 separate undulator systems
Total undulator length of 652m

Possible extension by 5 more beam lines/10 experimental stations
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, e.g.

- 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

