Insertion Devices for ERL Machines

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What wavelengths of light do the users want?


• Many want from about 3 to 20 keV

• A few want 30 to 70 or 80 keV

• A few want 100 keV

• One wants below 1 keV

• Magnetic studies want variable polarization

This is very similar to the variety of characteristics provided at APS. The proposed ERL energy is 5 to 7 GeV, also similar to the APS 7 GeV.
APS On-Axis Brilliance Tuning Curves

On-Axis Brilliance (ph/s/mrad²/mm²/0.1%bw)

Energy (keV)

UA (3.3 cm)
U2.7 cm
U1.8 cm
U5.5 cm
WA (8.5 cm)
Bending Magnet
Differences from APS undulators

• Smaller emittance beam for the ERL

• Smaller vacuum chamber may be possible, allowing smaller-gap undulators out-of-vacuum

• With the stronger field of an undulator at smaller gap, a shorter period may be preferred.
Present APS parameters ($\varepsilon_x = 7.7$ nm-rad, $\varepsilon_y/\varepsilon_x = 1.0\%$), undulators with 3.3 and 2.7 cm periods.

Original design of APS with larger vertical emittance ($\varepsilon_y/\varepsilon_x = 10\%$) is included for comparison.

The circularly polarizing undulator (CPU) can produce both circular (dots) and linear (dashes) polarized light.
Future APS low-\(\varepsilon_x\) (3.6 nm-rad) low-\(\varepsilon_x/\varepsilon_x\) (0.25%) lattice, 300 mA beam, 7.7-m-long undulators. (2.4-m-long, 3.3-cm period device is for comparison). A superconducting undulator (SCU) is proposed for APS.
Tuning curves using ERL parameters for undulators of different periods. Symbols are for minimum gaps of 4, 6, and 8 mm. End of curve is at 2 mm.

(beam: 5.3 GeV, 100 mA, .043 mm $\sigma$, .0035 $\sigma^*$, .001 $\sigma_E$; undulator: 25 m long)  
(courtesy R. Dejus)
Circularly Polarized Undulator

Shown in cross-section.

• 500 – 3000 eV output
• circular polarization, both left and right
• linear polarization, both vertical and horizontal
• switchable polarization
• compatible with standard ID vacuum chamber, so it can share a straight section
• open along one side for access by magnetic measurement probes
• built-in dipole end correction
The Circularly Polarizing Undulator (CPU) at the measurement bench.
A 1-cm-period undulator?

- The user wants ~30 to 40 keV photons.
- Minimum vacuum chamber size at APS is 7 mm, for a 7.5 mm undulator gap.
- A superconducting device makes up for the longitudinal pole-to-pole spacing being smaller than the gap.

The smaller gap for the ERL might make a standard hybrid device feasible.

Permanent magnets can be thin if they don’t have to be too wide. What are the roll-off requirements for an ERL? The APS requirement is:

\[
\frac{B(x = 0) - B(x = 5\text{mm})}{B(x = 0)} < 0.001 \quad \text{at 11.5 mm gap}
\]
What are some requirements for ERL undulators?

Electron beam will go through multiple undulators before re-entering linac.

Users want freedom to adjust the gap of their undulator at will, and don’t want to be affected by others’ gap changes.

The photon beam will be small, and intense, and sometimes used for microscopy. Users will have demanding requirements for beam stability.

Some users will want to switch the polarization of their light. Even without the lifetime decay in beam current of a storage ring, they will probably want to switch every few seconds or faster.

If the user changes a characteristic of the photon beam (such as wavelength or polarization), the photon beam shouldn’t move.
Those requirements impose demands on the magnetic quality of the undulators.

- Invisibility of others’ gap changes places requirements on the first and second integrals of the field through the undulators.

- Stability of the beam despite gap or polarization changes demands proper correction of the end errors.

- Passive correction is always nice.

The relevant magnetic characteristics are the first and second integrals of the field. The first integral gives an angular deflection, the second integral a lateral displacement.

- The integral through the whole device is important for the overall behavior of the machine.

- The integral through the upstream end affects trajectory through the undulator and angle of emitted light.
Requirements at APS for integrals through the device are:

<table>
<thead>
<tr>
<th></th>
<th>Vertical</th>
<th>Horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>First integral</td>
<td>100 G-cm</td>
<td>50 G-cm</td>
</tr>
<tr>
<td>Second integral</td>
<td>100000 G-cm²</td>
<td>100000 G-cm²</td>
</tr>
</tbody>
</table>

The integral may not vary by more than this amount over the measured range of gaps.

(Note that the integral of the earth’s field (0.5 G x 240 cm = 120 G-cm) is significant.)

There is no formal requirement for the integrals through just the end of the undulator.

(Yet.)
Higher harmonics will be used, so phase errors must be restricted

- intensity reduction, on average, from an RMS phase error $\phi$ is by $e^{-(n\phi)^2}$, for the $n^{th}$ harmonic

- typical phase error for 3.3-cm-period undulator at 10.5 mm gap is $4^\circ$

Straightness of trajectory is needed, but tuning the phase error takes care of it.
For APS, the integrated multipole requirements are:

<table>
<thead>
<tr>
<th>Integrated moment</th>
<th>Requirement</th>
<th>What it affects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Quadrupole</td>
<td>50 G</td>
<td>Tune, beam size</td>
</tr>
<tr>
<td>Skew Quadrupole</td>
<td>50 G</td>
<td>Coupling, beam size</td>
</tr>
<tr>
<td>Normal Sextupole</td>
<td>200 G/cm</td>
<td>Dynamic aperture, lifetime</td>
</tr>
<tr>
<td>Skew Sextupole</td>
<td>100 G/cm</td>
<td>Dynamic aperture, lifetime</td>
</tr>
<tr>
<td>Normal Octupole</td>
<td>300 G/cm²</td>
<td>Dynamic aperture, lifetime</td>
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</table>

(Chae and Decker, 1995 PAC proceedings.)

(definition: $\int dz(B_y + iB_x) = \sum_{n=0}^{\infty} (b_n + ia_n)(x + iy)^n$ where the $a$ are skew and $b$ normal moments)

These APS requirements are all routinely met.

What are the requirements for ERL?
For a standard planar undulator, the quality of the magnets plays a significant role in how challenging the device is to tune.

We were pleased with the uniformity in a recent shipment of 500 magnets from Shin-Etsu for a prototype undulator for the LCLS.

Although our specification was that they have the same total strength to within ±1%, the magnets that were delivered all fell within ±0.5%.
We also required that the direction of the moment coincide with the geometric axis of the magnet blocks to within 2°.

The axis on the delivered magnets was, on average, 1° off vertically, with a total range from 0.7° to 1.3°. The horizontal (x) component of the magnetization is negligible.
The orientation of the vertical component of the magnetization has a direct effect on the midplane field of the undulator.

We measured the effect using a half-period test fixture. The test magnet is on top, a standard magnet stays on the bottom.
The effect due to the vertical moment was clear.

Results for first magnets to be measured.
Main (z) component of the magnetic moment was in the same direction, but the sign of the vertical component varied.

There may also be an effect on the undulator phase – we are investigating.
Vacuumschmelze is also interested in improving the uniformity of their magnets, with the encouragement of J. Pflueger, for the Tesla magnets.

The hope is to be able to build devices that require no (or minimal) tuning.
Radiation Sensitivity

- NdFeB magnets have been found to be sensitive to radiation-induced demagnetization. Although no damage has yet been seen at APS, there has been significant damage at ESRF.

- With the small beam of the ERL, the radiation spray may be smaller, but

- The undulator gap will be smaller, putting the magnets where the radiation levels are higher.

- The undulator design can improve the radiation resistance of the magnets
  - Use a grade of magnet material with high coercivity
  - Design the magnetic structure to minimize demagnetizing field in high-radiation areas of the magnet block

- Work is ongoing at APS to try to understand what types of radiation the magnets are most sensitive to.