Recent Work on Insertion Devices at the ALS

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Input from:

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AFRD Supercon
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Outline

1. Review of existing insertion devices at the ALS
   • Planned insertion devices - applications and specifications
     • Near term (reasonably well known)
     • Longer term (likely to change…)
2. Details of a device under construction – MERLIN
   • Quasi-periodic magnetic structure
   • Anticipated spectral performance
3. EPU modifications to accommodate top-off operation
   • Dynamic multipoles and compensating shims
4. R&D results on superconducting undulator prototypes
Review of existing IDs...

ALS beamline diagram

Now W11

(IVID)
Review of existing IDs…

Wave 1:
Wave 2:
Wave 3: SCU’s, ultra-fast,…

<table>
<thead>
<tr>
<th>Beamline</th>
<th>Application</th>
<th>Type</th>
<th>Period, Length</th>
<th>Energy range*</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0.1</td>
<td>MERLIN - meV resolution spectroscopy</td>
<td>QEPU</td>
<td>90mm; 1.8m</td>
<td>8-300eV</td>
<td>Being fabricated</td>
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<tr>
<td>4.0.2</td>
<td>Magnetic spectroscopy (MCD, MLD)</td>
<td>EPU</td>
<td>50mm; 1.8m</td>
<td>50-1900eV</td>
<td>1998</td>
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<td>5.0.1</td>
<td>Protein crys.; femto modulator</td>
<td>Wiggler</td>
<td>110mm; 3.5m</td>
<td></td>
<td>2004</td>
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<tr>
<td>6.0.1,2</td>
<td>Femto radiatior – ultrafast science</td>
<td>IVID</td>
<td>30mm; 1.5m</td>
<td>200-1800 (U)</td>
<td>2005</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2keV-10keV (W)</td>
<td></td>
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<tr>
<td>7.0.1</td>
<td>Surface &amp; materials science</td>
<td>Undulator</td>
<td>50mm; 4.5m</td>
<td>60-1200eV</td>
<td>1993</td>
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<td>7.0.1*</td>
<td>COSMIC – coh. scattering &amp; imaging</td>
<td>EPU</td>
<td>34mm, 1.8m</td>
<td>250-1300eV</td>
<td>~2008</td>
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<td>7.0.2*</td>
<td>MAESTRO – microscopy &amp; elect. Struct.</td>
<td>EPU</td>
<td>70mm, 1.8m</td>
<td>20-600eV</td>
<td>~2008</td>
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<tr>
<td>8.0.1</td>
<td>Imaging, x-ray fluorescence</td>
<td>Undulator</td>
<td>50mm; 4.5m</td>
<td>65-1400eV</td>
<td>1993</td>
</tr>
<tr>
<td>9.0.1,2</td>
<td>Coh. Scattering; Chem. Dynamics</td>
<td>Undulator</td>
<td>100mm, 4.5m</td>
<td>5-800eV</td>
<td>1995</td>
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<tr>
<td>10.0.1</td>
<td>Photoemission</td>
<td>Undulator</td>
<td>100mm, 4.5m</td>
<td>17-340eV</td>
<td>1997</td>
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<tr>
<td>11.0.1</td>
<td>PEEM</td>
<td>EPU</td>
<td>50mm, 1.8m</td>
<td>100-2000eV</td>
<td>2003</td>
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<tr>
<td>11.0.2</td>
<td>Molecular environmental science</td>
<td>EPU</td>
<td>50mm, 1.8m</td>
<td>95-2000eV</td>
<td>2001</td>
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<tr>
<td>12.0.1,2</td>
<td>EUV, ARPES, Coherent x-ray science</td>
<td>Undulator</td>
<td>80mm, 4.5</td>
<td>60-1000eV</td>
<td>1993</td>
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<td>10.0.1**</td>
<td>Photoemission HERS</td>
<td>EPU</td>
<td></td>
<td></td>
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<td>10.1.1**</td>
<td>Atomic / molecular physics</td>
<td>EPU</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.7**</td>
<td>QUÆRLIN – Q-res.Inelastic scattering</td>
<td>SCU</td>
<td></td>
<td></td>
<td>~1keV</td>
</tr>
<tr>
<td>12.0.1,2**</td>
<td>ARPES; coherent science</td>
<td>Undulator</td>
<td>80mm, 3m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Typically reflects beamline, not ID, energy range
# ALS storage ring parameters

(Thanks to David Robin)

<table>
<thead>
<tr>
<th>Present Operation</th>
<th>After Top-Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Injection at 1.5 GeV and then ramp</td>
<td>• Full energy injection (1.9 GeV)</td>
</tr>
<tr>
<td>• Inject with insertion devices open</td>
<td>• Inject with insertion devices closed</td>
</tr>
<tr>
<td>• Average beam current is 250 mA</td>
<td>• Average beam current is 500 mA</td>
</tr>
<tr>
<td>• Vertical emittance is 150 pm rad</td>
<td>• Vertical emittance is 30 pm rad</td>
</tr>
<tr>
<td>• Lifetime is 8 hours at 400 mA</td>
<td>• Lifetime is about 3 hours at 500 mA</td>
</tr>
<tr>
<td>• Injection period every 2 to 8 hours</td>
<td>• Injection period about every 30 seconds</td>
</tr>
<tr>
<td>– 1 Hz injection for 4 minutes</td>
<td>– 1 pulse</td>
</tr>
<tr>
<td>• From 200 to 400 mA</td>
<td>• From 498.5 to 500 mA</td>
</tr>
<tr>
<td>• Photon shutters are closed during injection</td>
<td>• Photon shutters remain open during injection</td>
</tr>
</tbody>
</table>
Top-Off upgrade and ID’s linked

• Can no longer open ID’s for injection
  – Inject every ~30s
  – Beam dynamics concerns
    • Injection efficiency limitations imposed by EPU’s
• Minimum aperture must be set by scrapers
  – Avoid radiation damage to ID’s
  – Safety considerations
    • Possible fault scenario of electrons sent down beamlines must be eliminated
Installed EPUs

Three EPU50s of same Design:

• 4.0.2: MCD, 1998
  – First in a 3rd Gen. ring!
• 11.0.2: MES, 2002
• 11.0.1: PEEM3, 2005
W11: Femto-Slicing Modulator

- Installed 2004
- Replaces W16
- Meets ongoing PX needs
- ~790nm fundamental for femto-slicing
- Re-uses W16 structure and vacuum chamber designs
IVID30: Femto-Slicing Radiator

- Installed 2005
- Purchased from Neomax (formerly Sumitomo Special Metals)
- Collaboration with Spring8
Permanent Magnet Chicane

J. Y. Jung et al., PAC03

- Installed in center of chicaned ID straights
- Objective: eliminate magnetic hysteresis characteristic of iron-core electro-magnets
- Design based upon PM corrector ring concept
- Uses PM rotors to set main field
- Uses air-core coils for fast horizontal and vertical dipole correction

Concept proposed in:
R. Schlueter et al,
Merlin EPU

- To be installed Spring 2007
- Longer period
  - Higher forces
  - Increased impact on beam dynamics
  - Larger photon fan, increased power
- Quasi periodic
  - Reduce flux from higher harmonics
- New Design Features
  - Stiffer/stronger structure to deal with higher forces
  - New drive system to improve performance
  - Modified magnetic mounting to eliminate systematic relative motion with quadrant shifts
EPU34: Concept for Cosmic

Full Polarization Control $E_\rho > 250$ eV
EPU70: Concept for Maestro

- Horizontal Polarization $E_p > 20$ eV
- Vacuum chamber heating limitation:
  - Vertical Polarization $E_p > 60$ eV
  - Circular Polarization $E_p > 80$ eV
Some details of the MERLIN EPU

• Quasi periodic EPU
  – Optimized spectral properties by varying parameters
    • (e.g. interlattice ratio, block strength)
  – Varying vertical blocks rather than horizontal
    • More effective at generating anharmonic spectrum
    • Individual block perturbations are not self-compensating (steering)

• Blocks mounted on individual keepers
  – Avoid ALS experience with modules (Marks et al, “Shift-dependent Skew Quadrupole…”, MT19, 2005)

• Ends optimized for minimal shift-dependent first integrals
  – Schlueter et al, MT19, 2005; Chavanne et al, PAC 1999
Quasi-periodic synchrotron radiation

- Idea (introduced by Sasaki): by breaking the periodic magnetic structure in a specific manner, the harmonic structure of the undulator radiation can be modified, yielding “harmonics” at non-integer multiples of the fundamental which are then stopped by the monochrometer
  - Should be particularly useful for low photon energies, where harmonics can excite unwanted electron states;
  - Has been tested on linear undulators at the ESRF, EPU at ELETTRA
  - Currently being investigated by others (Soleil, …) in the case of EPUs

<table>
<thead>
<tr>
<th>Polarization</th>
<th>EPU90 Fundamental [eV]</th>
<th>QEPU90 Fundamental [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear horizontal</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Linear vertical</td>
<td>13</td>
<td>14.7</td>
</tr>
<tr>
<td>circular</td>
<td>10.7</td>
<td>12.2</td>
</tr>
</tbody>
</table>
Field components for different polarization modes

- The reduced-strength blocks, when phase-shifted, generate
  - Bz fields
  - By fields even in vertical polarization mode
  - Field-amplitude fluctuations even in “circular” polarization mode, resulting in harmonic content
Flux density in horizontal polarization
Comparison with baseline EPU90
Radiation spectra on axis

Modes resulting in reduced dynamic aperture
Radiation spectra for a (0.6mrad x 0.6mrad) aperture

Modes resulting in reduced dynamic aperture
Circularly polarized radiation (ds=0.3\(\lambda\))

Quasi-periodic EPU

QEPU90
EPU90

Photon Energy

Ph/s/0.1%bw/mm\(^2\)

0 10.70 21.40 32.10 42.80 53.50 64.20 74.90 eV
Dynamic compensation shims for top-off operation

- Insertion devices typically exhibit natural vertical focusing
  - "Dynamic", i.e. due to particle trajectory coupled to off-axis longitudinal fields (not seen with multipole measurements on the bench)
  - Further "dynamic" defocusing due to field roll-off (see Safranek et al., PAC 2000)
- EPU’s have special characteristics:
  - Focus/defocus depending on polarization mode
  - Exhibit strong nonlinear behavior, i.e. (de)focus strength varies with offset
  - Introduces focus/defocus in horizontal plane, where beam dynamics are typically more sensitive

⇒ Serious impact on lifetime / injection efficiency – tune shift scales with $(\lambda/E)^2$, so problem is worst for low energy rings and long-period EPU’s
⇒ Nonlinear effects cannot be compensated with other optics; have significant impact on dynamic aperture

Idea (Chavanne et al., EPAC 2000.;): introduce magnetic shims to compensate for nonlinearity
Currently implemented at Bessy (J. Barhdt et al)
Shim perturbation $B_y(x,y=0)$
Integrated shim fields and effective focusing

<table>
<thead>
<tr>
<th>Quadrant</th>
<th>Block orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>Up</td>
</tr>
<tr>
<td>Q2</td>
<td>Down</td>
</tr>
<tr>
<td>Q3</td>
<td>Down</td>
</tr>
<tr>
<td>Q4</td>
<td>Up</td>
</tr>
</tbody>
</table>

$I_x(x)$

$I_y(x)$

$px(x)$
Baseline EPU90

Note: p1 controls variable linear polarization modes, p2 controls variable elliptical modes (p2=0.3~circular)

Horizontal kick at different polarizations

-20 -15 -10 -5 0 5 10 15 20

px [rad]

1) p1=-0.5, p2=0
2) p1=-0.3, p2=0
3) p1=-0.2, p2=0
4) p1=0, p2=0
5) p1=0, p2=0.2
6) p1=0, p2=0.3
7) p1=0, p2=0.5

x [mm]
Shimmed EPU90
(Calculated with Radia)

Horizontal kick at different polarizations

Variable linear modes still problematic;
All others appear OK
Shimmed Merlin, vertical polarization (calculated, before and after shimming)
Shimmed Merlin, circular polarization (calculated)
Shimmed Merlin, linear (~45 degrees) polarization (calculated)
Other scenarios evaluated

- Tracking performed at \( g = 14 \), nominal minimum gap
- Checked that the dynamic aperture remains acceptable at \( g = 18, 22 \)
  - Tracking was performed for linear horizontal and linear vertical
  - Tracking also performed for elliptical mode, \( g = 22 \)
  - Kick map evaluated for \( g = 18 \), elliptical mode – appears OK
Combining dynamic multipole correction shims and quasi-periodicity

![Graph showing the effects of combining dynamic multipole correction shims and quasi-periodicity.](chart.png)
LBNL Nb$_3$Sn superconductor Undulator R&D

Collaboration of AFRD & Engineering Div.

Considered for ALS applications:
- Radiator for femto-slicing experiment
- Source for protein crystallography

LDRD results (2003-04):
- Two prototypes using 6-strand cable
- 30mm period prototype; 80% of Jc
- 14.5mm period prototype: ~75% Jc

WFO (2005-06, for Argonne Nat. Lab):
- Test single strand conductor
- Design and fabrication improvements
- Reached short sample Jc in 4 quenches
Low-temperature superconductors of interest: 
\(\text{Nb}_3\text{Sn}, \text{NbTi with Artificial Pinning (APC)}\)

\textit{Peter Lee et al, Applied Superconductivity Center, NHMFL, Florida}

See Thesis of Arno Godeke for an excellent review of \(\text{Nb}_3\text{Sn}\)

Oxford MJR strand used for LBNL \(\text{Nb}_3\text{Sn}\) prototypes

Best commercially available APC \(\text{NbTi}\)

See R. Scanlan and D. Dietderich, IEEE Trans. Applied Supercond., Vol. 13, No 2, June 2003 for review of recent improvements in \(J_c\) of \(\text{Nb}_3\text{Sn}\)

Critical Current Density (4.2 K), A/mm²

- \(\text{YBCO: CC in Pancake Coils} (\text{American Superconductor})\)
- \(\text{YBCO: Nb}_3\text{Sn} / \text{ZrO}_{2} = 1\text{ mm thick microbridge, } H|| < 4\text{ K. Folyu et al. (LANL)} \text{ 90}\)
- \(\text{YBCO: } \text{YBCO} / \text{ZrO}_{2} = 1\text{ mm thick microbridge, } H|| < 75\text{ K. Folyu et al. (LANL)} \text{ 90}\)
- \(\text{Nb-Ti: Example of Best Industrial Scale Heat Treated Composites -1990 (compilation)}\)
- \(\text{Nb-Ti: Nb-4}\%\text{Al} \times 41\text{ mm wide, K. Lee, Naux and Laboletier UW-ASC} \text{96}\)
- \(\text{Nb-Sn: Enron route int. stob. - VAC-HP, non-(Cu+Ta) } J_c, \text{ Thoener et al. Erice} \text{96}\)
- \(\text{Nb-Sn: Non-} \text{Cu} J_c, \text{Internal Sn OI-ST RRP #6555-A, 0.8 mm, RTSW} \text{2002}\)
- \(\text{Nb-Sn: Non-} \text{Cu} J_c, \text{Internal Sn OI-ST RRP 1.3 mm, ASC} \text{02/ICMC} \text{03}\)
- \(\text{Nb-Sn: L} \times \text{8 K Non-} \text{Cu} J_c, \text{Internal Sn OI-ST RRP ASC} \text{02/ICMC} \text{03}\)
- \(\text{Nb-Al: JAEKI strand for ITER TF model coil}\)
- \(\text{Nb-Al: RQHT-2 At.\% Cu, 0.4 mm} \text{ (fujimura et al 2002)}\)
- \(\text{Bi-2212: non-Ag } J_c, \text{ 427 fil. round wire, Ag/SiC=5 (Hasegawa ASC-3800/TNT1-2001)}\)
- \(\text{Bi 2223: Rolled 85 Fil. Tape (AmSoc) B}, \text{ UW-6.96}\)
- \(\text{Bi 2223: Rolled 85 Fil. Tape (AmSoc) B}, \text{ UW-6.96}\)
- \(\text{MgB}_2: 10\%\text{wt SiC doped (Don et al APL 2002, UW measurements)}\)
Superconducting undulator R&D at LBNL

• Issues addressed:
  – Conductor stability and magnet protection under extremely high current operation
  – Demonstrated ability to provide field kick for phase-error correction
  – Demonstrated fabrication techniques to yield peak conductor performance in a real magnet configuration

• Remaining issues
  – Field measurement system for phase-error determination
  – Full phase-error correction scheme
  – Calorimetric measurements of beam-based heating on real rings
  – For SC-EPU:
    • demonstrate reasonable ramp-rates for field (photon energy) variation
    • Demonstrate switching network for period-doubling operation
Prototype III undulator quench performance

- Five quenches:
  - 585A, 585A, 635A, 717A, 714A
  - At 717A:
    - $J_{sc} = 8250\text{A/mm}^2$
    - $J_{cu}\text{ (quench)} = 7600\text{A (self-protected)}$
    - $J_{av} = 1760\text{A/mm}^2$ (using full pocket size)

$J_c (12\text{T}, 4.2\text{K})$
Old generation $\sim 2000\text{A/mm}^2$
(This was used for all of the LBL prototypes)
New generation $\sim 3000\text{A/mm}^2$
(just need to get the filament size down...)

Record performance
Magnetic gaps and lengths for future insertion devices at the ALS

- Gaps, assuming 5mm vacuum aperture:
  - PM, PM-EPU: 7.3mm (1mm wall thickness, existing controls spacings; could be reduced, but risk increases – no hard stops, chance of hitting chamber…)
  - IV, **IV-EPU**: 5.4mm (0.4mm needed for controls, RF foil)
  - **SCU, SC-EPU**: 6.6mm (0.75mm wall thickness)

- Lengths:
  - PM: 2m (extend devices from current 1.85m by eliminating end chicanes & chambers)
  - IV: 1.62m (lose 360mm compared to PM on each side due to RF transitions)
  - **SCU, SC-EPU**: 1.6m (“cold-bore” operation; RF transitions do not move, but need space for thermal transitions; this is a reasonable estimate)
  - **IV-EPU**: 1.55m (RF transitions are a definite concern; this is an optimistic guess)

- To avoid heating vacuum chamber/magnets with SR, the estimated peak vertical $K$ value for a 2m device is $\sim 4.5$. For PM, PM-EPU one could consider cooling the vacuum chamber, but the risks/issues have not been evaluated.
Review of LBNL interest/effort in superconducting undulators

**Nb$_3$Sn SCU performance curves**

- 24% superconductor in coilpack, $J_c(4.2K,6T)=6800A/mm^2$
- $g=$magnetic gap

- $g=4\text{mm}$
- $g=6\text{mm}$
- $g=8\text{mm}$
- $g=10\text{mm}$
- $g=12\text{mm}$
- $g=14\text{mm}$

**ALS upgrade parameters**

- U50: 50mm period, 4.5m length, $K=3.97$
- SCU22: 22mm period, 1.5m/4.5m length, $K=6.49$

**Papers:**

- S. O. Prestemon et al., IEEE Transactions on Applied Superconductivity, June 2005
- S. Prestemon, R. Schlueter, S. Marks, D. Dietderich, presented at MT19, Sep. 18-23, 2005, Genoa, Italy
ALS performance enhancement, Application Protein Crystallography

Figure of merit: flux at 12.6 keV accepted into 50 µm x 50 µm x .25 mrad x .25 mrad phase space [photons/sec/0.1% bw]. Undulator values assume 4.5 m lengths.

<table>
<thead>
<tr>
<th>Device</th>
<th>Fig. of merit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCU13</td>
<td>39.0 x 10^{12}</td>
</tr>
<tr>
<td>IVU17</td>
<td>3.09 x 10^{12}</td>
</tr>
<tr>
<td>SCW70</td>
<td>6.7 x 10^{12}</td>
</tr>
<tr>
<td>W11</td>
<td>1.2 x 10^{12}</td>
</tr>
<tr>
<td>Sbend</td>
<td>0.34 x 10^{12}</td>
</tr>
</tbody>
</table>
Polarization control
Generating variable linear polarization

- A coil as shown generates antisymmetric $B_x$ and $B_y$ field profiles in $z$ about the coil. The fields are largely on a plane of angle $\psi$ that is a function of the coil gap and $x$-offset.

- A series of such coils in $z$, separated by $\lambda/2$ with alternating current directions, generates $B_x(z)$ and $B_y(z)$ fields that are periodic with equal phase shift.
Polarization control
Generating variable linear polarization

- Consider a 4-quadrant array of such coil-series.
  - If \( I_C = -I_A \), Coils A and C generate additive fields.
  - Set \( I_C = -I_A, I_D = -I_B \); Independent control of \( I_A \) and \( I_B \) provides full linear polarization control.

For \( I_A = I_B = I_C = I_D \):

- Independent control of \( I_A \) and \( I_B \) provides variable linear polarization control
  - If \( I_A = I_B \), vertical field, horizontal polarization
  - If \( I_A = -I_B \), horizontal field, vertical polarization
Polarization control
Generating variable elliptic polarization

- Add a second 4-quadrant array of such coil-series, offset in z by $\lambda/4$ (coil series $\alpha$ and $\beta$)
- With the following constraints the eight currents are reduced to four independent degrees of freedom:
  \[
  I_C^\alpha = -I_A^\alpha, \quad I_D^\alpha = -I_B^\alpha \\
  I_C^\beta = -I_A^\beta, \quad I_D^\beta = -I_B^\beta
  \]
- The $\alpha$ and $\beta$ fields are $90^\circ$ phase shifted, providing full elliptic polarization control via
  \[
  \vec{B}^\alpha(I_A^\alpha, I_B^\alpha; z), \quad \vec{B}^\beta(I_A^\beta, I_B^\beta; z): \\
  \begin{pmatrix}
  B_x^\alpha \\
  B_y^\alpha
  \end{pmatrix} = \eta \begin{pmatrix}
  \cos(\psi) & -\cos(\psi) \\
  \sin(\psi) & \sin(\psi)
  \end{pmatrix} \begin{pmatrix}
  I_A^\alpha \\
  I_B^\alpha
  \end{pmatrix} \sin\left(\frac{2\pi z}{\lambda}\right)
  \]
  \[
  \begin{pmatrix}
  B_x^\beta \\
  B_y^\beta
  \end{pmatrix} = \eta \begin{pmatrix}
  \cos(\psi) & -\cos(\psi) \\
  \sin(\psi) & \sin(\psi)
  \end{pmatrix} \begin{pmatrix}
  I_A^\beta \\
  I_B^\beta
  \end{pmatrix} \sin\left(\frac{2\pi z}{\lambda} - \frac{\pi}{2}\right)
  \]
  Note: $B_{x,y}^a = \sum_n a_{n;x,y} \sin\left(\frac{2\pi nx}{\lambda}\right)$; typically $\frac{a_3}{a_1} < 2\%$
Spectral range and Brightness of example SC-EPU $\lambda=28\text{mm}$ device and PM-EPU $\lambda=32\text{mm}$

**Beam Parameters:**
- $I=0.5\text{A}$
- $\beta x/y=13.65/2.25\text{m}$
- $\varepsilon x/y=6.3/0.03\text{nm}$
- 0.06 disp. in $x$
- Energy spread not included

**Graphical Representation:**
- $\lambda=28\text{mm}$ horiz. pol. SC-EPU
- $\lambda=56\text{mm}$ horiz. pol. (28mm period-doubled) SC-EPU
- $\lambda=28\text{mm}$ circ. pol. SC-EPU
- $\lambda=56\text{mm}$ (28mm period-doubled) circ. pol. SC-EPU
- $\lambda=32\text{mm}$ horiz. pol. PM-EPU
- $\lambda=32\text{mm}$ circ. pol. PM-EPU

**Ph$/\text{s}/0.1\%\text{bw/mm}^2$ vs. Photon Energy**

**Legend:**
- $\lambda=28\text{mm}$ linear polarization
- $2\lambda$ linear polarization
- Limited by aperture
A conceptual design for the LBNL SC-EPU with minimal joints

- Four-quadrant, iron-free design
- Cryocooled using heat-pipe approach
- Performance limited by AC losses (dB/dt-induced heating) of coil
- Period halving/doubling requires “switchyard” – superconducting switch needs to be demonstrated
Nb$_3$Sn superconductors

*Highest (Jc, Tc) of all commercially available superconductors in the field range of interest to SCU’s*

- These are intermetallic compounds, in an A15 structure; A15 is a brittle crystal structure
- Requires a fabrication process providing the appropriate composition and A15 development
- Process must not jeopardize quality of stabilizer in conductor (typically Cu)
- Requires heat treatment to ~650°C

=> Have significant impact on magnet design and fabrication!

See Thesis of Arno Godeke for an excellent review of Nb$_3$Sn (source of these plots)
Comparison of QEPU and EPU

Performance
At minimum gap
ALS upgrade parameters

Photon energy [eV]

Ph/s/0.1%bw/mm²