SELECTION OF THE OPTIMUM UNDULATOR PARAMETERS FOR THE NLS: A HOLISTIC APPROACH

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NLS

• 4\textsuperscript{th} Generation Light Source for the UK
  – High repetition rate (kHz initially, MHz later)
  – Ultrashort, high brightness, high coherence X-rays
  – THz to keV available

• Science Case & Outline Facility Design published
  – Available from www.newlightsource.org

• FELs offer complete coverage from 50 eV to 1 keV.
  – FEL-1: 50-300 eV
  – FEL-2: 250-850 eV
  – FEL-3: 430-1000 eV
  – Polarisation control required
Design Philosophy for the Undulators

• Often light source projects are forced to make an early decision on undulator type and gap

• Need this to define electron energy to begin accelerator design

• We have made a rapid second iteration to avoid project being ‘locked-in’ to initial choice

• Second iteration based on start-to-end model bunches (not Gaussian!), resistive wall wakes, FEA of vessel wall thicknesses, etc
  – Try to be as inclusive as possible
Design Philosophy for the Undulators

Initial Selection of Undulator Parameters → Electron Energy Selection → NLS Layout & Design → Start to End Model → Electron Bunch at FELs

Resistive Wall Wakefields in Elliptical Vessel → FEL Output → Minimum Internal Aperture → Magnet Gap

Design Philosophy for the Undulators

1. Initial Selection of Undulator Parameters
2. Electron Energy Selection
3. NLS Layout & Design
4. Start to End Model
5. Add vessel wall thickness and tolerances
6. Magnet Gap
7. Resistive Wall Wakefields in Circular Vessel
8. FEL Output
9. Minimum Internal Aperture
10. Resistive Wall Wakefields in Elliptical Vessel
11. FEL Output
12. Minimum Internal Aperture
13. APPLE-3 & Delta Undulators
14. Compare Magnetic Fields Achievable & Select Undulator
15. APPLE-2 & Crossed Planar Undulators
16. Electron Energy Selection
17. NLS Layout & Design
18. Iterate solution for NLS

Jim Clarke
FEL 2009, Liverpool
Initial Selection

- **APPLE-2 undulators with 8 mm magnet gap and internal aperture of 6 mm**
- From photon energy ranges of FELs we need 2.25 GeV electrons
Wakefields

• Need to consider 3 effects
  – Resistive (image currents)
  – Geometric (changes in vessel cross-section)
  – Surface Roughness (vessel surface finish)

• Resistive is of most concern
  – Other projects have consistently found resistive to be dominant effect
  – Will determine vessel material and inner dimensions
  – Other two can always be made smaller (in principle!)
Elliptical Vessel

- Keep $b$ fixed at 3mm and vary $a$
- As $a$ increases, result tends towards parallel plates result
- Little gain seen when $a \gg 3b$
- So, set $a = 3b$ for this study

Wakes from single particle at $z = 0$
Copper, AC conductivity model
Example Wakefields

- Longitudinal wakefields, AC conductivity model, aluminium vessel (a = 3b), 200pC
Circular and Elliptical Vessels

- Differences between circular and elliptical wakes is strongly correlated with bunch length – which frequencies are excited
- For the NLS with FWHM ~150 fs there is little difference for the same vertical aperture
FEL Performance

- Time dependent modelling carried out for FEL-3 at 1000 eV using Genesis 1.3 – most demanding case
- Resistive wakes were calculated as a function of aperture for circular and elliptical \((a = 3b)\) aluminium vessels, AC model
- Only the radiator section has the wake included
- No efforts have been made to regain any loss in output power (eg by tapering or using a longer radiator section)

Geometric and surface roughness wakes have been neglected, only on axis effects included
FEL Performance

FEL-3 output at 1000eV, seeded by HHG at 100eV
FEL Peak Power

Peak power expressed as a percentage of the value with no wake included

No difference between circular and elliptical vessels for NLS, for same vertical aperture
FEL Peak Power

• If peak power is expressed as a percentage of what is practically realisable (ie relative to the 10 mm internal aperture case):
  – 6 mm would give 87%
  – 8 mm would give 94%

• Assume that a 10% loss is acceptable then internal vessel aperture (circular or elliptical) should be 7 mm

• Need to add allowance for vacuum vessel to understand what the undulator magnet gap can be
Vacuum Vessels

• Assessment has been made of wall thickness required for vacuum load by elliptical vessel with $a=3b$ and also circular vessel (Cu or Al)
  – Elliptical **needs 0.25 mm** thick walls (at thinnest part)
  – Circular **needs 0.1 mm** thick walls
  – Note these are the *maximum* levels required in the gap region of interest for NLS (internal aperture < 10 mm)

• Allowance is added for alignment, vessel straightness, vessel deflection under load
Vacuum Vessels

- Result shown for Al 6061 alloy extrusion

- Analysis also shows that vessel would be robust under handling and from shock loads

- Vacuum porosity would need to be checked

- Stainless Steel vessel coated with Al or Cu is also possible
Vessel Examples

- **Elliptical vessel**, internal height 7 mm
- Width is $3 \times 7 = 21$ mm
- Add vessel walls & allowances
- **Magnet gap is 8.1 mm**
- **Circular vessel** with same impact on FEL output has internal diameter of 7 mm
- Add vessel walls & allowances
- **Magnet gap 7.6mm**
- No difference between Cu or Al
Undulator Options

• Four options have been considered
  
  – APPLE-2
    • Mature solution, many examples, well understood, low risk
  
  – APPLE-3
    • Fields enhanced \( \sim 40\% \), no practical examples, restricted side access
  
  – Delta
    • Fields enhanced \( \sim 70\% \), only short prototype exists, no side access
  
  – Crossed-Planar
    • Lowest risk magnet, altered FEL configuration, polarisation level vs undulator length for seeded FEL to be studied, fast switching of polarisation
Undulator Options

APPLE-2

APPLE-3

Crossed Planar Schemes

K-J Kim, NIMA 445, p329

Y Ding, PRST-AB 030702 (2008)

Delta

A. B. Temnykh, PRSTAB 11, 120702, 2008

Y Li, EPAC08, p2282
Undulator Comparisons

• Assume $B_r = 1.2T$ and Period = 32mm

<table>
<thead>
<tr>
<th></th>
<th>APPLE-2</th>
<th>APPLE-3</th>
<th>Delta</th>
<th>Planar (Hybrid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet Gap (mm)</td>
<td>8.1</td>
<td>7.6</td>
<td>7.6</td>
<td>8.1</td>
</tr>
<tr>
<td>Vertical Field (T)</td>
<td>0.85</td>
<td>1.09</td>
<td>1.23</td>
<td>1.05</td>
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<tr>
<td>Helical Field (T)</td>
<td>0.51</td>
<td>0.68</td>
<td>0.86</td>
<td>NA</td>
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<tr>
<td>Horizontal Field (T)</td>
<td>0.63</td>
<td>0.87</td>
<td>1.23</td>
<td>1.05</td>
</tr>
<tr>
<td>Min Photon Energy (eV) (circular polarisation)</td>
<td>452</td>
<td>293</td>
<td>198</td>
<td>254</td>
</tr>
</tbody>
</table>

Results are from empirical equations except Delta which is from RADIA Model.
Undulator Comparisons

• FEL-3 photon energy range determines the NLS electron energy (430 to 1000eV)
• Re-optimise electron energy for these apertures
  – Change undulator period

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<th>APPLE-3</th>
<th>Delta</th>
<th>Planar (Hybrid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Aperture (mm)</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Magnet Gap (mm)</td>
<td>8.1</td>
<td>7.6</td>
<td>7.6</td>
<td>8.1</td>
</tr>
<tr>
<td>Energy (GeV)</td>
<td>2.25</td>
<td>2.1</td>
<td>1.9</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Summary

• NLS currently assumes the use of APPLE 2 undulators with an 8 mm magnet gap
• The impact of the resistive wall wakefield has been calculated as a function of aperture and vessel shape using a ‘real’ start to end bunch
• There is negligible difference between circular and elliptical vessels
• A 10% loss in practically realisable power corresponds to a 7 mm internal aperture (relatively slow variation here)
• Four undulator options have been studied
  • The APPLE-3 and crossed planar scheme would allow the beam energy to decrease from 2.25 GeV to 2.1 GeV
  • The Delta undulator would allow the beam energy to fall to 1.9 GeV
Next Steps

• Study wakes in more detail
  – Look at effect of timing jitter on output
  – Include modulator sections
  – Look at strategies to recover power loss (e.g., tapering, longer undulator sections)

• Model the crossed planar scheme for FEL-3
  – Polarisation rate as a function of output power
  – Higher harmonic polarisation
  – Optimum configuration

• Carry out a detailed assessment of the Delta design including magnetic forces, support structure, measurement procedure, shimming ideas, etc.

• The vacuum chamber selected must be prototyped to check that the wall thickness, straightness, smoothness, porosity, etc., can be achieved
Extra Slides
## Magnet Gap Comparisons

<table>
<thead>
<tr>
<th>Project</th>
<th>Minimum Magnet Gap (mm)</th>
<th>Vertical aperture for electron beam (mm)</th>
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</thead>
<tbody>
<tr>
<td>XFEL</td>
<td>10.0</td>
<td>7.6</td>
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<tr>
<td>LCLS</td>
<td>6.8</td>
<td>5.0</td>
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<tr>
<td>SCSS</td>
<td>4.0 nominal (in-vac)</td>
<td>4.0 nominal (in-vac)</td>
</tr>
<tr>
<td>PAL FEL (2008)</td>
<td>5.0 nominal (in-vac)</td>
<td>5.0 nominal (in-vac)</td>
</tr>
<tr>
<td>FERMI</td>
<td>10.0</td>
<td>6.0</td>
</tr>
<tr>
<td>BESSY FEL</td>
<td>10.4 on-axis (circular pipe),</td>
<td>9.0 (diameter)</td>
</tr>
<tr>
<td></td>
<td>5.4 off-axis</td>
<td></td>
</tr>
<tr>
<td>FLASH</td>
<td>12.0</td>
<td>9.5</td>
</tr>
<tr>
<td><strong>NLS (initial working assumption)</strong></td>
<td><strong>8.0</strong></td>
<td><strong>6.0</strong></td>
</tr>
</tbody>
</table>
Comparing Elliptic and Circular Vessels

• Want to compare elliptical result against “equivalent” circular vessel

Wakes from single particle at $z = 0$
Copper, AC conductivity model
Comparing Elliptic and Circular Vessels

- Adjust diameter of circular vessel to give same field observed by particle (self-field).

Same field at $z = 0$ but some variation after. This “equivalence” is clearly an approximation but helps develop understanding of how vessel geometries can be compared.
Variation with Aspect Ratio

- Graph shows how effective circular radius varies with elliptical vessel half height, $b$, as a function of elliptical vessel aspect ratio $(a/b)$
- For $a = 3b$, radius = $1.25 \times b$
Circular vs Elliptical

- Gaussian bunch, AC, Cu
- $R_L =$ Radius of circular vessel which gives same average energy loss per bunch
- $R_S =$ Radius of circular vessel which gives same average energy spread per bunch
- Effect of different vessel shape dependent upon bunch length