The development of a Superconducting Undulator for the ILC Positron Source

James Rochford
On behalf of the HeLiCal collaboration
Introduction

• Helical Collaboration
• ILC requirements

Summary of helical development programme

• Design drivers
• Magnetic modelling
• Prototype research and development
• Manufactured specification

Prototype design and manufacture

• 4m Module design
• Magnet Testing and integration
• Assembly of 4m module
• Testing of the final prototype
Helical collaboration

- Argue physics case for polarised positrons
- Prototype undulator
  - permanent magnet
  - superconducting

Collaboration members
ASTEC:
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RAL:
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University of Durham:
G.A. Moortgat-Pick
Argonne:
Y. Ivansuhenkov

ASTEC
Permanent magnet undulator
Impedance calculations
Wakefield heating
Vacuum considerations
Specification (plus Liverpool and Durham)

RAL Technology dept
Superconducting undulator
Magnetic modelling
Prototyping
Mechanical design
Manufacture
Undulator:

To produce a circularly polarised positron beam

- High energy electron beam through helical undulator
  - emission of polarised photons.
- Downstream high Z target, pair production
- Positrons stripped off to produce polarised positron beam.
Initial goals
• Total undulator length 100-200m
• Undulator Period 10 mm ??
• Beam Stay clear 4.5mm dia
• Module length 2-10m

Field requirements for
• Electron Drive Beam Energy 150 GeV
• Photon Energy (1st harmonic) 10.06 MeV
• Photon Beam Power 131 kW
R&D programme

Goals

• Shortest possible period - Goal 10mm
• Beam stay clear 4.5mm  - Tolerance 250um
  - Bore tube 0.5mm
  - Winding bore ~6mm

Constraints

• Technology – Selection NbTi over NbSn
  - Tight tolerances
  - Small bore
  - Complex winding
  - Relatively small improvement from NbSn

We needed a programme to assess what could be achieved

• Magnetic modelling what's achievable with NbTi
• Prototype research and development
• Manufactured specification
Calculated operating point for 7 wire 9 layer Cu:Sc 1:1 NbTi ribbon

<table>
<thead>
<tr>
<th>period (mm)</th>
<th>Winding bore (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.25</td>
</tr>
<tr>
<td>12.00</td>
<td>49</td>
</tr>
<tr>
<td>11.80</td>
<td>55</td>
</tr>
<tr>
<td>11.50</td>
<td>64</td>
</tr>
<tr>
<td>11.25</td>
<td>72</td>
</tr>
<tr>
<td>11.00</td>
<td>80</td>
</tr>
</tbody>
</table>

Relationship between period and winding bore in terms of operating point
• If we want to operate at 80%
• We constrain the operating space
• For a winding bore of 6mm
• We can reduce the period to 11.5mm

Plots showing realistic bore-period models
The peak conductor field
• No iron present
• Bore field 0.8T
• J\text{required} = 1000A/mm²

Inclusion of iron
• If NbTi is used
• Iron former and poles are essential

Typically
• 0.4 the field from the iron poles
• 0.1 from the iron return yoke

The peak conductor field
• Full iron poles
• Bore field = 0.8T
• J\text{required} = 400A/mm²
### What happens during a quench

#### Simple adiabatic quench model
- Stored energy small only ~250J at nominal current
- Low inductance, high current, rapid quench
- By time current has run down ~15% coil normal
- High temp rise in hot spot can be 150-200K

#### Real coil more complex
- Simple adiabatic quench model pessimistic
- Will have significant quench back in the copper bore tube
- Effectively spreads quench energy very quickly, quenching a much larger portion of the coil

### Magnetic modelling

<table>
<thead>
<tr>
<th>Quench current</th>
<th>A</th>
<th>215</th>
<th>215</th>
<th>300</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection resistance</td>
<td>ohm</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>Total energy dissipated internally</td>
<td>J</td>
<td>253</td>
<td>21</td>
<td>578</td>
<td>131</td>
</tr>
<tr>
<td>Total energy dissipated externally</td>
<td>J</td>
<td>0</td>
<td>232</td>
<td>0</td>
<td>444</td>
</tr>
<tr>
<td>Total energy in system</td>
<td>J</td>
<td>253</td>
<td>253</td>
<td>578</td>
<td>576</td>
</tr>
<tr>
<td>Maximum temp rise</td>
<td>K</td>
<td>126</td>
<td>54</td>
<td>161</td>
<td>109</td>
</tr>
<tr>
<td>Maximum internal voltage</td>
<td>V</td>
<td>86</td>
<td>7</td>
<td>222</td>
<td>47</td>
</tr>
<tr>
<td>Time constant of quench</td>
<td>mS</td>
<td>34</td>
<td>21</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td>Normal part of the coil</td>
<td></td>
<td>17%</td>
<td>11%</td>
<td>18%</td>
<td>16%</td>
</tr>
</tbody>
</table>
Prototype R&D

R&D programme

• Assess different manufacturing methods
• Winding techniques
• Machining techniques
• Promising techniques - prototype undulators
• Bench mark modelling results
**Prototype R&D**

**Short prototypes**
- Family of prototypes
- Each looking at different aspects of manufacture
- Manufacturing concept evolved with the prototypes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prototype 1</th>
<th>Prototype 2</th>
<th>Prototype 3</th>
<th>Prototype 4</th>
<th>Prototype 5</th>
<th>Prototype 5’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prototype goal</td>
<td>Winding Technique</td>
<td>Mechanical tolerances</td>
<td>Reduced period</td>
<td>Check effect of iron</td>
<td>Increased period</td>
<td>improved impregnation</td>
</tr>
<tr>
<td>Length</td>
<td>300 mm</td>
<td>300 mm</td>
<td>300 mm</td>
<td>300 mm</td>
<td>500 mm</td>
<td>500 mm</td>
</tr>
<tr>
<td>Former material</td>
<td>Aluminium</td>
<td>Aluminium</td>
<td>Aluminium</td>
<td>Iron</td>
<td>Iron</td>
<td>Iron</td>
</tr>
<tr>
<td>Bore tube</td>
<td>integral</td>
<td>integral</td>
<td>integral</td>
<td>integral</td>
<td>copper</td>
<td>copper</td>
</tr>
<tr>
<td>Winding period</td>
<td>14 mm</td>
<td>14 mm</td>
<td>12 mm</td>
<td>12 mm</td>
<td>11.5 mm</td>
<td>11.5 mm</td>
</tr>
<tr>
<td>Winding bore</td>
<td>6 mm</td>
<td>6 mm</td>
<td>6 mm</td>
<td>6 mm</td>
<td>6.35 mm</td>
<td>6.35 mm</td>
</tr>
<tr>
<td>Magnet bore</td>
<td>4 mm</td>
<td>4 mm</td>
<td>4 mm</td>
<td>4.5 mm</td>
<td>5.23 mm</td>
<td>5.23 mm</td>
</tr>
<tr>
<td>Superconducting wire</td>
<td>Cu:SC 1.35:1</td>
<td>Cu:SC 1.35:1</td>
<td>Cu:SC 1.35:1</td>
<td>Cu:SC 1.35:1</td>
<td>Cu:SC 0.9:1</td>
<td>Cu:SC 0.9:1</td>
</tr>
<tr>
<td>Winding</td>
<td>8-wire ribbon, 8 layers</td>
<td>9-wire ribbon, 8 layers</td>
<td>7-wire ribbon, 8 layers</td>
<td>7-wire ribbon, 8 layers</td>
<td>7-wire ribbon, 8 layers</td>
<td>7-wire ribbon, 8 layers</td>
</tr>
</tbody>
</table>

Cu:Sc ~0.8
Following a pretty extensive **R&D programme** and **modelling study** the following specification was developed:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undulator Period</td>
<td>11.5 mm</td>
</tr>
<tr>
<td>Field on Axis</td>
<td>0.86 T</td>
</tr>
<tr>
<td>Peak field homogeneity</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Winding bore</td>
<td>6.35mm</td>
</tr>
<tr>
<td>Undulator Length</td>
<td>147 m</td>
</tr>
<tr>
<td>Nominal current</td>
<td>215A</td>
</tr>
<tr>
<td>Critical current</td>
<td>~270A</td>
</tr>
<tr>
<td>Manufacturing tolerances</td>
<td></td>
</tr>
<tr>
<td>winding concentricity</td>
<td>+/-20um</td>
</tr>
<tr>
<td>winding periodicity</td>
<td>+/-50um</td>
</tr>
<tr>
<td>Axial straightness</td>
<td>+/-50um</td>
</tr>
<tr>
<td>NbTi wire Cu:Sc ratio</td>
<td>0.9</td>
</tr>
<tr>
<td>Winding block</td>
<td>9 layers</td>
</tr>
<tr>
<td></td>
<td>7 wire ribbon</td>
</tr>
</tbody>
</table>

This defines the shortest period undulator we could reliably build as a prototype with a realistic operating margin. The now the baseline for the ILC RDR.
Key features of prototype

- Magnet rigidity – iron yoke
- Magnet suspension Bessel points in Ubeam
- Alignment between U-beam and He vessel
- Anchored at the midpoint
- Keys allow movement in X and Y
- 4 HTSC current leads
  - independent powering
- Independent beam vacuum
Cryogenic system
• Magnets Bath cooled
• Re condensing system
• Utilising a thermo siphon
• Sumitomo RDK4150
• In principle zero boil off
• Weak thermal link between bath and condenser
• Ln2 pre cooling for He vessel –expedites cooling.
• Final stage charge system with liquid

Heat load inventory
• 50 watts 1st stage
• 1 watt 2nd stage

1st stage 55K
2nd stage 4.5K
0.5W contingency
Prototype manufacture

4 axis machining

Iron former fixed on Cu bore tube

Coil winding
Prototype manufacture

Following winding
- Potting
- Connections to ribbon
- Insertion in Yoke
- Align and clamp in Ubeam

Axis alignment
Magnet straightness

• Prototype alignment
  +/-200um in X
  +/-170um in Y

• Not adequate to deliver a straightness of +/-50um

• Developed an active alignment Yoke

• Allows the straightness of the magnet to be aligned to better than 50um.

• In principle the prototype can be retrofitted with this system at a later date.
Active alignment system

• Flexibility of the magnet
• Over sized magnet aperture - 100um clearance
• Periodically placed adjustors in X and Y
• Adjustors locked off, a small spring maintains alignment takes up the thermal contraction when cold
• Small contact pads - spread contact pressure and avoid damage to winding
• All components are magnetic steel - minimise losses

Manufactured 1/2 meter long test section

• Obtaining some metrology data with this at present
• Our initial tests shows we can position the magnet axis to within +/- 10um at the actuator adjustment point
Field maps along the length of the undulator

- Mapping $B_r$ along the axis
- At 4 points around the azimuth; 0, 90, 180 & 270 degrees
- At magnet ends more detailed maps at 45° intervals around the azimuth
- Also carried out a Quench study
Particle trajectories calculated from measured field data

- Plots show different trajectories calculated from different profiles around azimuth 0°, 90°, 180°, 270°
- Trajectories calculated using SPECTRA
- Trajectories pessimistic limited by hall probe resolution and offset
- These are worst case and easily corrected
Magnet testing
• Quench testing of both Magnets
• 1\textsuperscript{st} magnet went straight to field
• 2\textsuperscript{nd} magnet repetitive training
• Reasons for this are not understood

Both magnets can deliver nominal field with a good margin!
Prototype manufacture

Cold mass integration

 Alignment scope

Alignment ~+/−200μm

Mag 2 connection

Mag 1 connection

Alignment 0.5mm
Prototype manufacture

Final bore leak check following insertion

• System cooled to 77K
• No He leaks above 1e-12mb/ls
• ILC operational pressure ~1e-7mb
• With a small 20l/s ion pump near to each module
• This system can reach pressures <1e-11mb

Ln2 precooling
Powering of magnets in prototype this April
• Each magnet powered independently to ~100A
• We are having problems
• With the current leads
• Bad thermal contact
• Conductor tails are normal
• In process of fixing this at the moment
“Beam heating” test planned
• Simulate beam heating effects
• Resistors in evacuated bore
• Assess how much beam heating magnets can sustain

Collimation in undulator half-cell.

<table>
<thead>
<tr>
<th></th>
<th>Peak</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchrotron load per module RDR (W)</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Wake field heating per module RDR (W)</td>
<td>fill pattern 1</td>
<td>0.6</td>
</tr>
<tr>
<td>Mean beam load</td>
<td>0.4</td>
<td></td>
</tr>
</tbody>
</table>
In coming weeks
Finish commissioning tests
• Recool system
• Run magnets up to nominal current
• Perform bore heating test
• Run magnets up to critical current
• Perform some thermal stability tests on cooler
A prototype helical undulator has been built for the ILC

• The system is capable of fulfilling the ILC positron source requirements

• The magnets have demonstrated that they can meet the field requirements

• They are now integrated in the final module

• The system is now being commissioned

• Tests to see how much beam heating the module can sustain are underway