OPTIMIZATION OF SUPERCONDUCTING UNDULATORS FOR LOW REPETITION RATE FELS

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Introduction

• Many groups have been developing Superconducting Undulators (SCUs) for a number of years, especially for storage rings
• Successfully implemented now and in routine use on ANKA and APS
• LCLS-II have strongly considered the use of SCUs

• We have worked on SCUs in the UK for about 15 years (Daresbury, Rutherford, Diamond)
• We have now started to look at the implications of an SCU specifically designed for FELs
SCU for Storage Ring

• Most groups have converged on a similar concept for planar SCUs

SC windings (usually NbTi)

Steel former and poles

Electron beam
SCU for Storage Ring

- Most groups have converged on a similar concept for planar SCUs

- SC windings (~4K)
- Steel former and poles (~4K)
- Vacuum Chamber (~15K)
- Separate insulating vacuum
- Electron beam
SCU for FELs

• The constraints are different
  – Vacuum levels are more relaxed
  – Good field region requirement much smaller
  – No significant synchrotron radiation heatload from upstream
  – The energy deposited within the SCU due to wakefields is now under our control – the bunch parameters and repetition rate

• The engineering becomes simplified
  – Common vacuum system
  – No internal vacuum chamber, just thin copper foils (like in-vacuum undulators) when the deposited power is low enough
Resistive Wall Wakefields

- Assuming copper with $\text{RRR} = 10$, circular cross section (parallel plates give similar results)
- Anomalous Skin Effect (ASE) and Extreme ASE regimes considered
- Gaussian bunches

For reference:

**LCLS modes**

- **Nominal**
  - 150 pC, 40 to 300 fs FWHM

- **Short bunch**
  - 20 pC, 3 fs FWHM

Resistive Wall Wakefields

- Power loss per meter depends on number of bunches per second
- 100mW/m comfortable for cryocooler-based system

For reference:
- Diamond Light Source ~1W/m
- Argonne Photon Source ~2.5W/m
Resistive Wall Wakefields

- Maximum bunch repetition rate assuming 100mW/m
- 250pC bunches and 5mm aperture
- >> 100Hz for all scenarios
Magnet Gap

- Storage Ring Example:
  - Beam stay clear = 5.0mm
  - Vacuum chamber wall thickness = 2 x 0.5mm
  - Insulating gap between 15K vac chamber and 4K magnet = 2 x 0.5mm
  - Magnet aperture = 7.0mm
Magnet Gap

- **Storage Ring Example:**
  - Beam stay clear = 5.0mm
  - Vacuum chamber wall thickness = 2 x 0.5mm
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  - **Magnet aperture = 7.0mm**
Magnet Gap

• Storage Ring Example:
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  – Vacuum chamber wall thickness = 2 x 0.5mm
  – Insulating gap between vac chamber and 4K magnet = 2 x 0.5mm
  – **Magnet aperture = 7.0mm**

• FEL Example:
  – Beam stay clear = 5.0mm
  – Vacuum chamber **not required**
  – Copper conducting sheet at 4K = 2 x 0.1mm
  – Insulating gap between vac chamber and 4K magnet **not required**
  – **Magnet aperture = 5.2mm**

• Very significant reduction in magnet aperture
Magnet Modelling

- Example 15mm period undulator

Notes

**SwissFEL Aramis** hard X-ray FEL

In-vacuum hybrid PM undulator

The most advanced undulator type currently in operation on an XFEL
Magnet Modelling

- Example 15mm period undulator

Notes

State of the art cryogenic PMU

Pr$_2$Fe$_{14}$B with a remanent field of 1.57 T at 77 K

(Latest PM grade with Br = 1.7T will increase fields ~8%)
Magnet Modelling

- Example 15mm period undulator
- Magnet modelling using Opera 3D
- Commercially available NbTi at 1.8K with safety margin of 10%
- Note at 4K we typically observe a ~10% reduction in field

Notes

Storage Ring SCU with 7.0mm magnet gap
Includes internal vacuum chamber
Magnet Modelling

- Example 15mm period undulator
- Magnet modelling using Opera 3D
- Commercially available NbTi at 1.8K with safety margin of 10%
- Note at 4K we typically observe a ~10% reduction in field

Notes

FEL SCU with 5.2mm magnet gap

No internal vacuum chamber, only high conductivity copper liner
Impact on FELs

• Use SwissFEL Aramis as an example
  – Wavelength range 1 to 7Å
  – In-vacuum undulator with **15mm period and K = 1.2**
  – Tune wavelength by changing beam energy between **5.8 and 2.2 GeV**

• FEL SCU Option 1
  – **K = 1.2 at period of 10.3mm**
  – Tune wavelength by changing beam energy between **4.8 and 1.8 GeV**

• Impact
  – Maximum electron energy reduced by **1GeV**
  – Saturation length reduced by **~20%**
  – FEL power reduced by **~25%**
Impact on FELs

- Use SwissFEL Aramis as an example
  - Wavelength range 1 to 7Å
  - In-vacuum undulator with **15mm period and K = 1.2**
  - Tune wavelength by changing beam energy between **5.8 and 2.2 GeV**

- FEL SCU Option 2
  - **15mm period and K = 2.9**
  - Tune wavelength by changing K and beam energy between **5.8 and 3.8 GeV**

- Impact
  - Wavelength tuning at fixed energy (e.g. **1 to 3Å at 5.8 GeV**)
  - Saturation length unchanged
  - FEL power increased ~ x2 at long wavelengths
FEL SCU Demo on CLARA

- We are now assembling a 30cm SCU Demo
- 15.5mm period, 7.4mm gap, $B = 1.25T$, $K = 1.8$
- Install and test on CLARA FEL Test Facility at Daresbury
Helical SCU Option

- FELs could instead use the classic bifilar helix undulator which generates a helical field
  - Circular polarisation
  - Increased FEL coupling factor
  - Circular beam aperture
- This type of undulator is very well matched to FEL SCU engineering
- We plan to carefully compare this type with the planar type in the future
Example Helical Undulator

**ILC Positron Source** undulator under test at RAL (2009)

11.5mm period, $B_x=B_y=1.1T$

Successfully demonstrated

4m module contains 2 x 1.75m helical undulators, circular beam aperture diameter = 5.25mm

Summary

- SCUs are already in routine operation in a couple of storage rings
- FELs offer different constraints on the engineering of SCUs
- At lower repetition rates (>>100Hz) much **smaller magnet gaps** are possible
  - No change to electron aperture
  - No fundamental change to SCU design required
  - Much higher magnetic fields than any other technology
- This will positively impact the optimization of new XFELs in terms of beam energy and wavelength coverage
- Helical SCUs are also compatible with these findings
- A demo of this new type of SCU will be tested on CLARA in 2018