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Accelerators in a new light

OPTIMIZATION OF SUPERCONDUCTING UNDULATORS FOR X-RAY FELS

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Diamond Light Source

EuPRAXIA

Compact

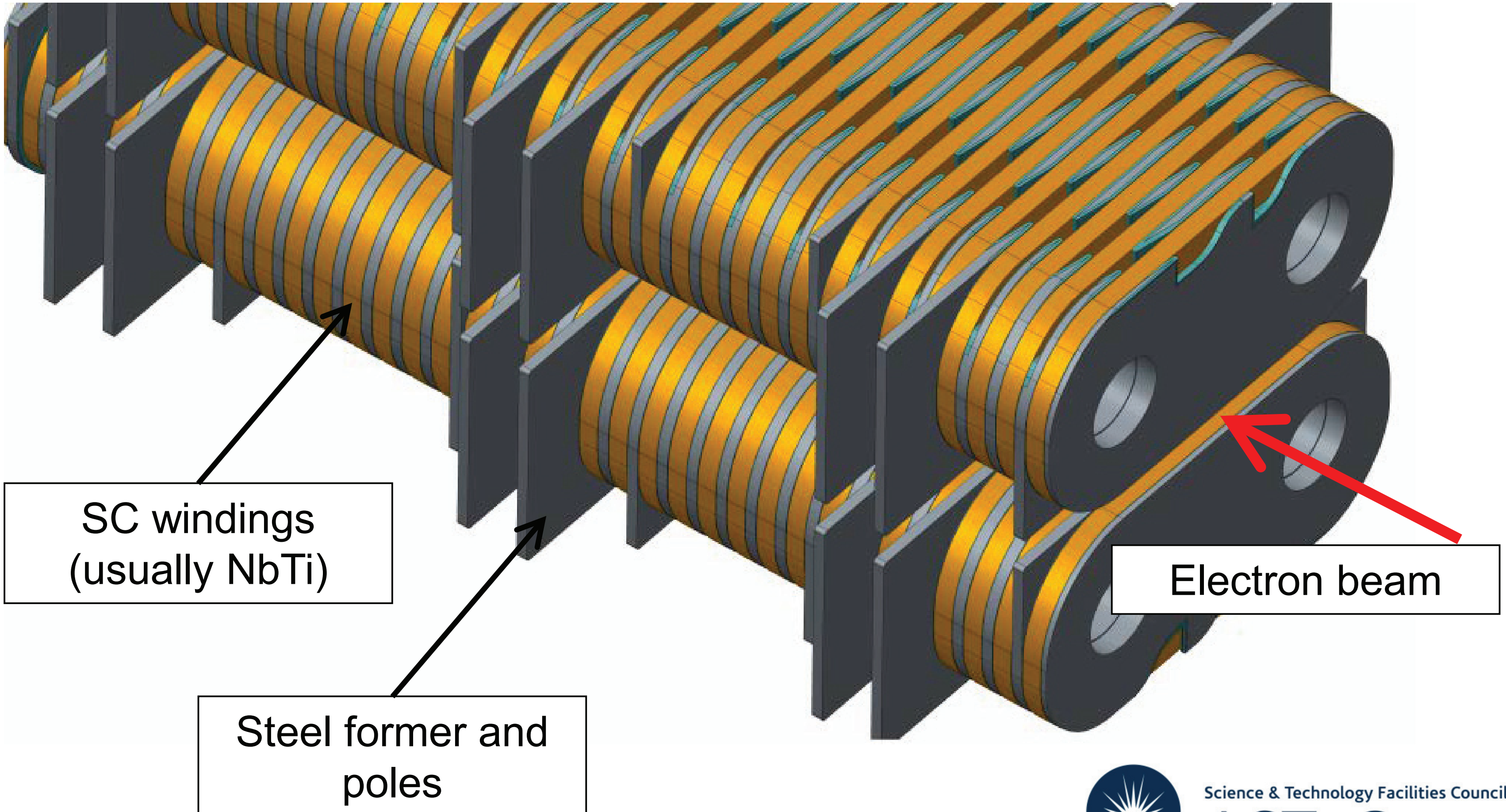
Introduction

- Superconducting Undulators (SCUs) have now reached an impressive level of performance and reliability
  - Successfully implemented and in routine use at KARA (KIT) and APS (Argonnne)
  - See Monday's talk from Joel Fuerst (MOA2PL03), for example
- ***SCUs are now genuine candidates for X-Ray FELs***

- We have worked on SCUs in the UK for about 15 years (Daresbury, Rutherford, Diamond)
- We are now studying in detail the implications of an SCU specifically optimised for X-Ray FELs

SCU Design

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



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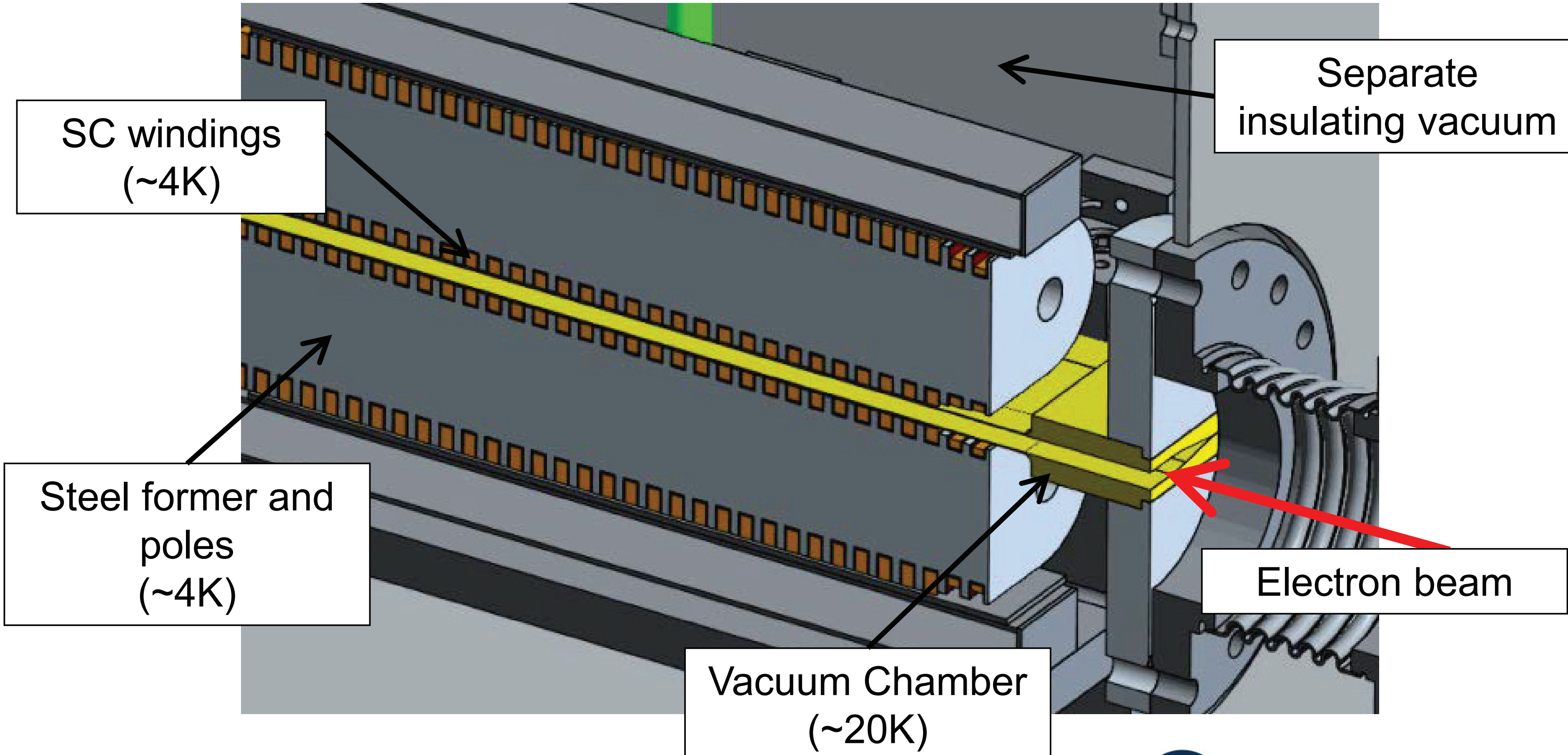
SCU for Storage Ring

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



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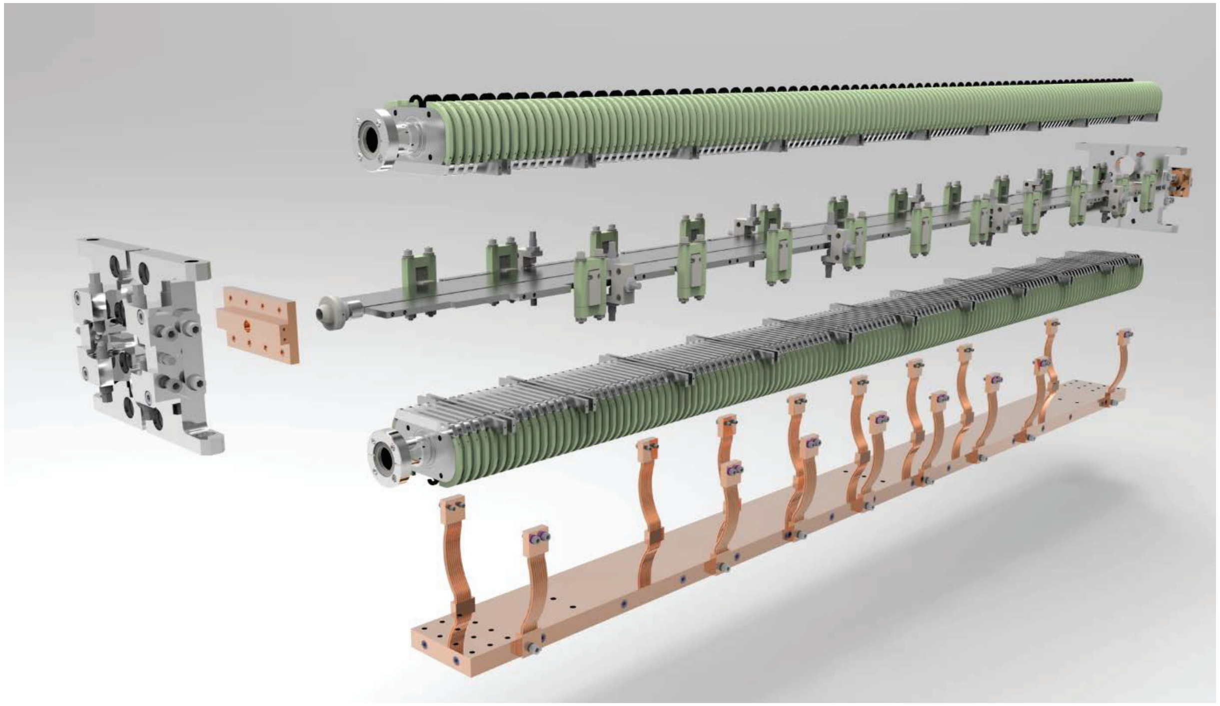
SCU Internal Vacuum Chamber

- Why do SCUs have an internal beam vacuum chamber?
  - To separate the beam vacuum from the SCU thermal insulating vacuum
  - To thermally isolate the 4K magnets from the beam
    - Absorbing any stray synchrotron radiation heatload from upstream
    - Absorbing the heatload due to wakefields

Exploded view of APS SCU showing the internal vacuum chamber
courtesy of J. Fuerst



SCU for FELs

- The constraints are different between Storage Rings and FELs
  - Vacuum levels are much more relaxed
  - No significant synchrotron radiation heatload from upstream
  - No wide aperture for injection needed
  - The average power deposited within the SCU due to wakefields is different

- Can we remove the internal vacuum chamber and instead build **"In-Vacuum SCUs"**?
  - Have a common vacuum system
  - Use thin copper foils for wakefield considerations
  - Analogous approach to that of permanent magnet in-vacuum undulators

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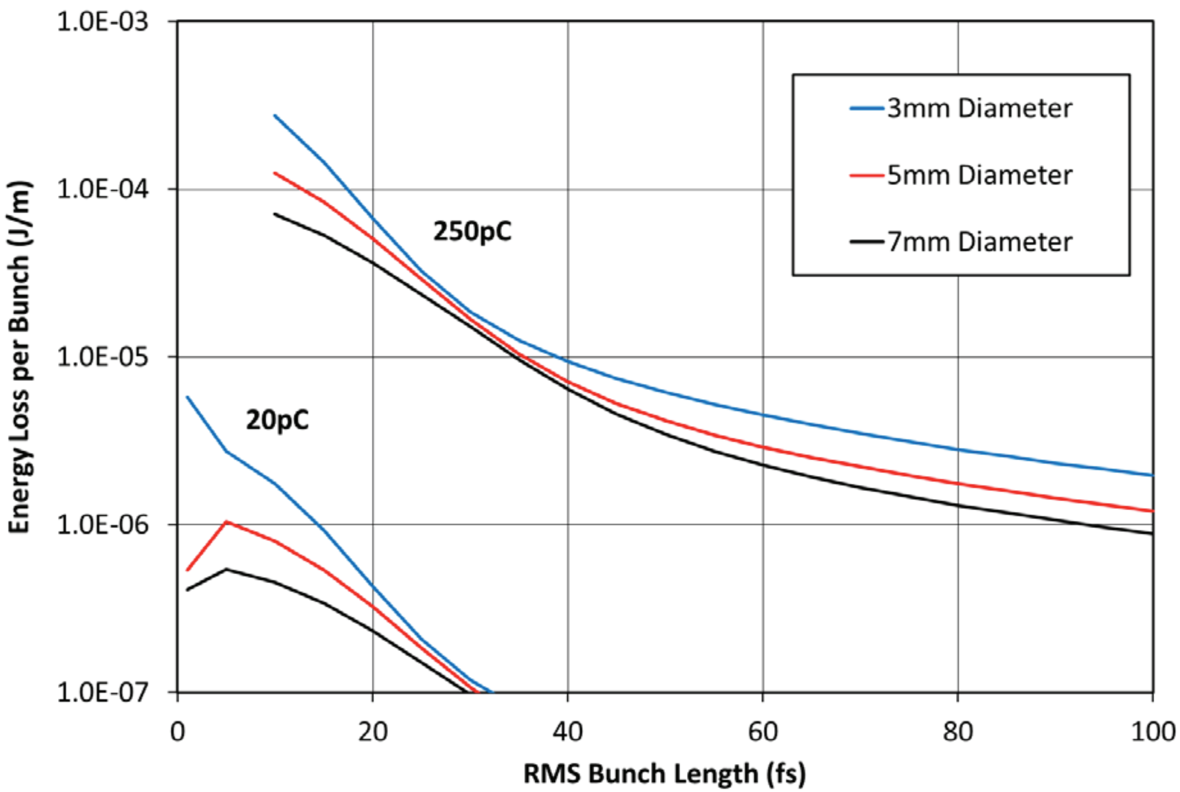
Power from Resistive Wall Wakefields

- Assume copper with RRR = 10 (conservative assumption), 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 300fs FWHM

Short bunch
20pC, 3 fs FWHM

https://portal.slac.stanford.edu/sites/lcls_public/Lists/machine_faq/FAQ.aspx

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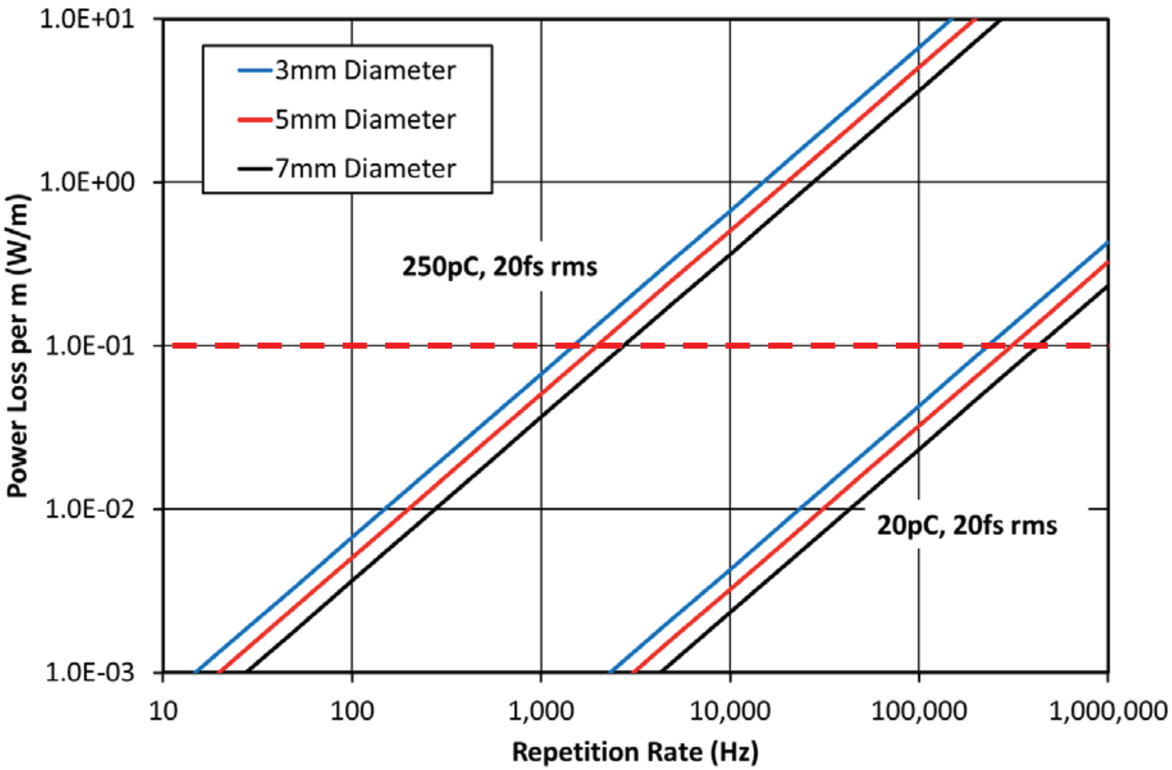
Power from Resistive Wall Wakefields

- Average Power loss per meter depends on **number of bunches per second**
- 100mW/m comfortable for cryocooler-based SCU at 4K



<u>For reference:</u>

Diamond Light Source ~1W/m

Argonne Photon Source ~2.5W/m

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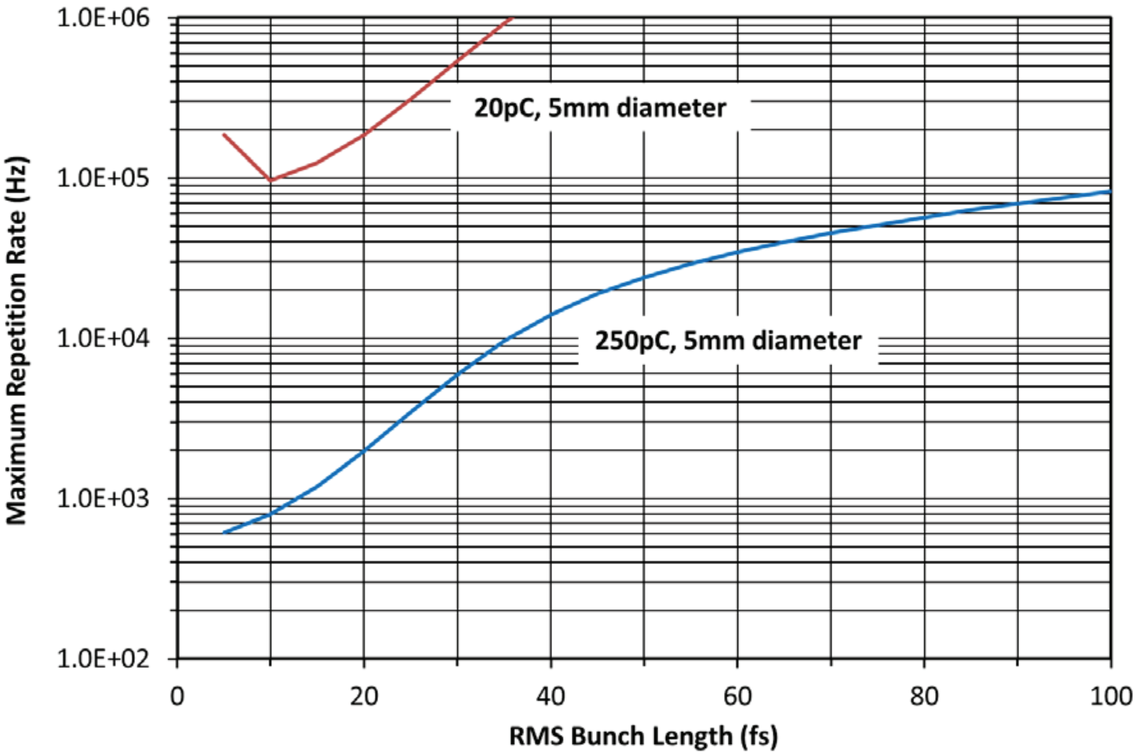
Resistive Wall Wakefields

- Maximum bunch repetition rate assuming 100mW/m limit (conservative assumption for cryocoolers)
- >> 100Hz for all scenarios considered



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Implication of Wakefield Power

- If the power deposited by wakefields is <0.1W/m then this can be absorbed directly by the cryocooled SCU magnet without quenching
  - **No internal vacuum chamber is required in the SCU**
  - The magnet gap can therefore be reduced significantly – just like permanent magnet in-vacuum undulators

- For the wide range of bunches we have studied the power levels are always <0.1W/m in a normal conducting RF X-Ray FEL
  - **All NCRF XFELs can make use of smaller magnet gap In-Vacuum SCU**
  - ***This does not affect the aperture for the beam***

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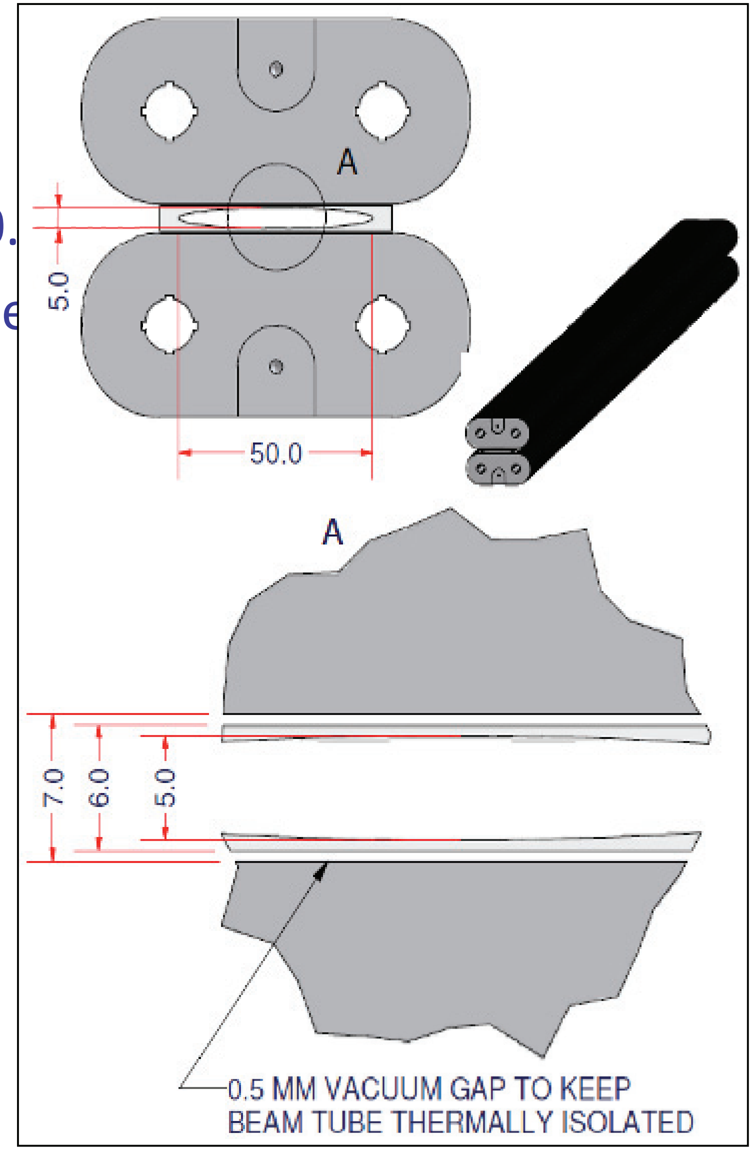
Magnet Gap

- Standard SCU Example:
  - Beam stay clear = 5.0mm
  - Vacuum chamber wall thickness = 2 x 0.5mm
  - Insulating gap between 20K vac chamber and 4K magnet = 2 x 0.5mm
  - **Magnet aperture = 7.0mm**

Magnet Gap

- Standard SCU Example:
  - Beam stay clear = 5.0mm
  - Vacuum chamber wall thickness = 2 x 0.
  - Insulating gap between 20K vac chambe
  - **Magnet aperture = 7.0mm**



Magnet Gap

- Standard SCU Example:
  - Beam stay clear = 5.0mm
  - Vacuum chamber wall thickness = 2 x 0.5mm
  - Insulating gap between vac chamber and 4K magnet = 2 x 0.5mm
  - **Magnet aperture = 7.0mm**
- In-Vacuum SCU 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!***

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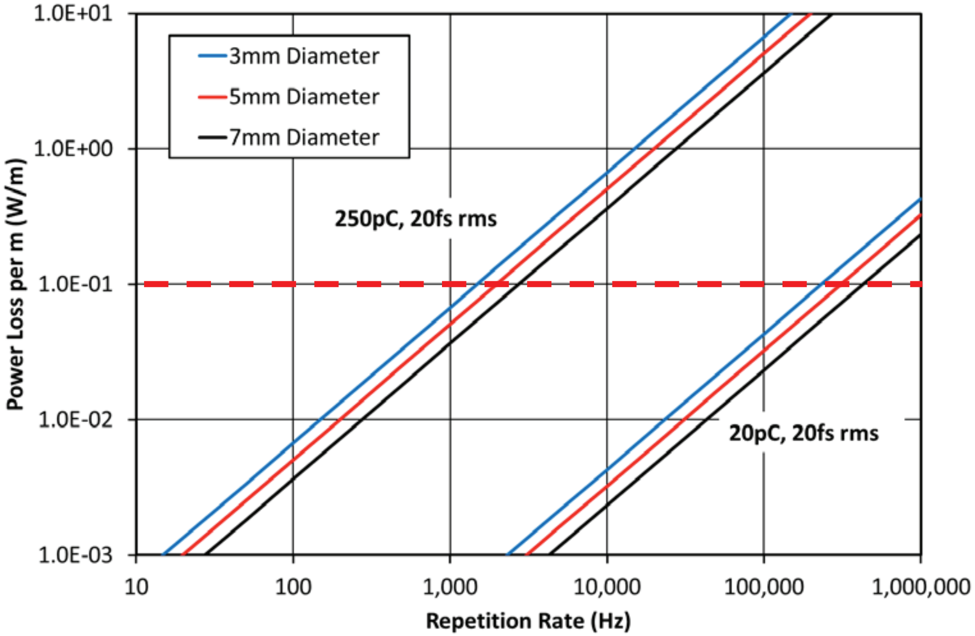
Can CW FELs use In-Vacuum SCU?



- At >>kHz bunch repetition rates the average power load will be >0.1W/m for some parameter sets
  - **Cryo-cooler based In-Vacuum SCU less feasible**
  - **Instead, could use centralized helium cryo-plant for all SCUs**

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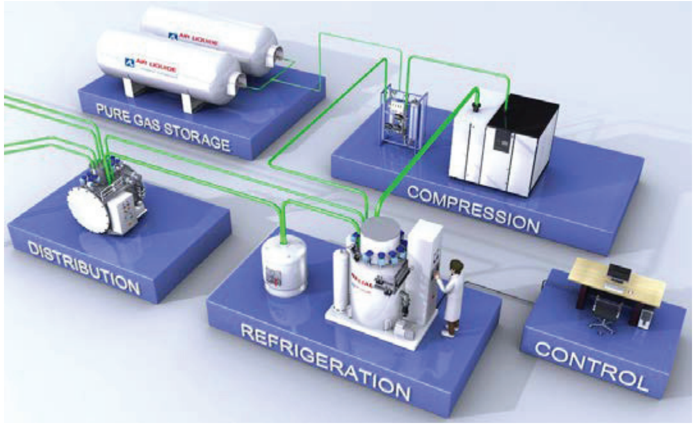
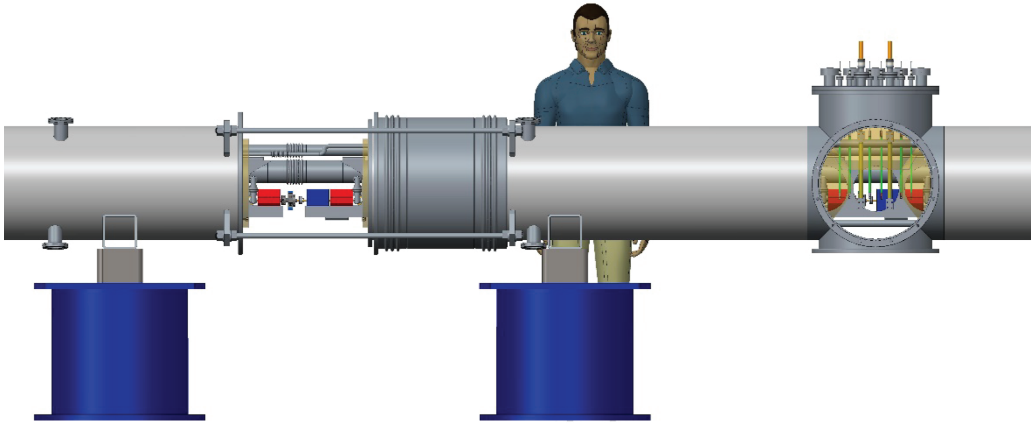
SCU system for FEL

- In fact, the cost effective approach to cooling a string of SCUs for ***any X-ray FEL*** is to ***use a single large cryo-plant, not cryocoolers***
  - See talk of Joel Fuerst (MOA2PL03)
- Heat loads of >1W/m are no problem for a large cryo-plant
  - CW FELs already use 8 to 12kW at 2K for SRF
- ***Therefore, CW FELs could also use In-Vacuum SCUs***



A small helium cryo-plant (Air Liquide)

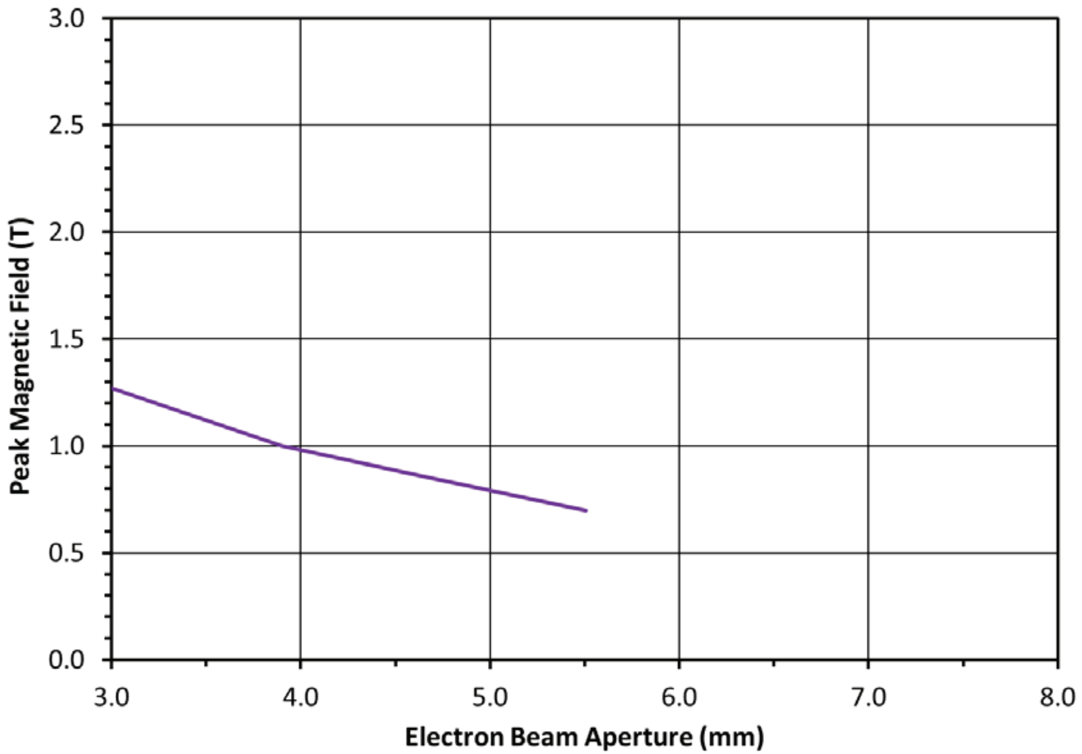


SCU cryostat interconnect showing internal cryogenic distribution

courtesy of J. Fuerst, ANL

Undulator Comparisons

- **Example 15mm period undulator**
- Permanent magnet in-vacuum undulator



Notes

SwissFEL Aramis hard X-ray FEL

In-vacuum hybrid PM undulator

The most advanced undulator type currently in operation on an XFEL

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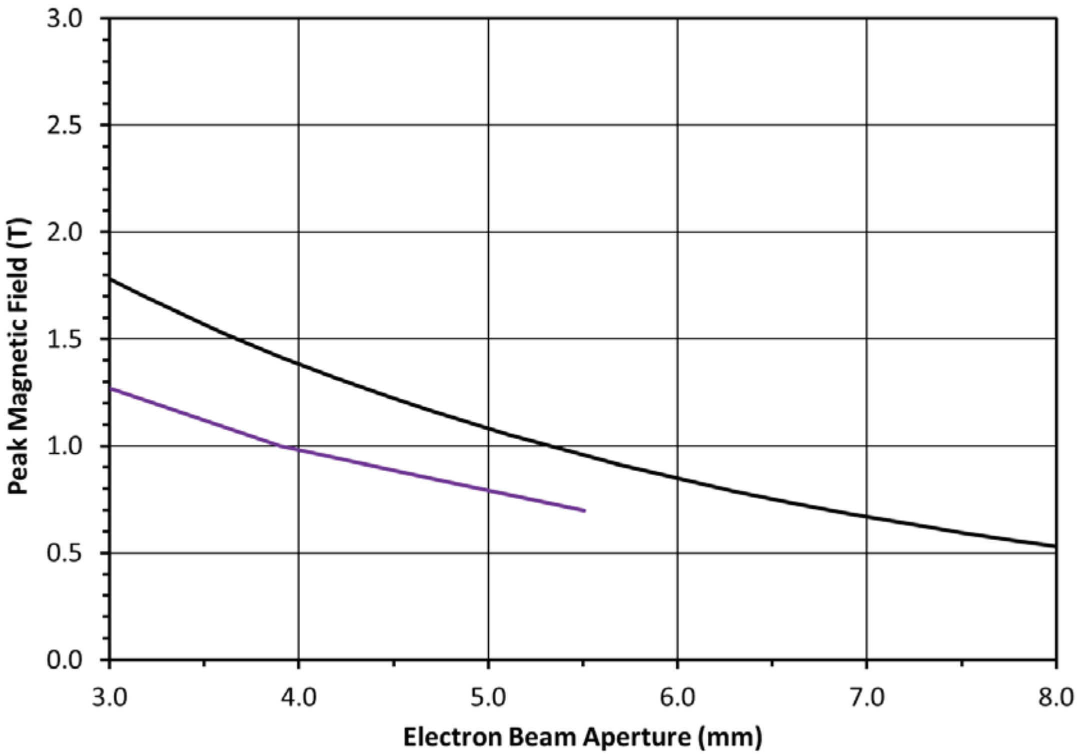
Undulator Comparisons

- **Example 15mm period undulator**
- Cryogenic permanent magnet in-vacuum undulator



Notes

State of the art cryogenic PMU

$Pr_2Fe_{14}B$ with a remanent field of 1.57 T at 77 K

(Recent PM grade with Br = 1.7T will increase fields ~8%)

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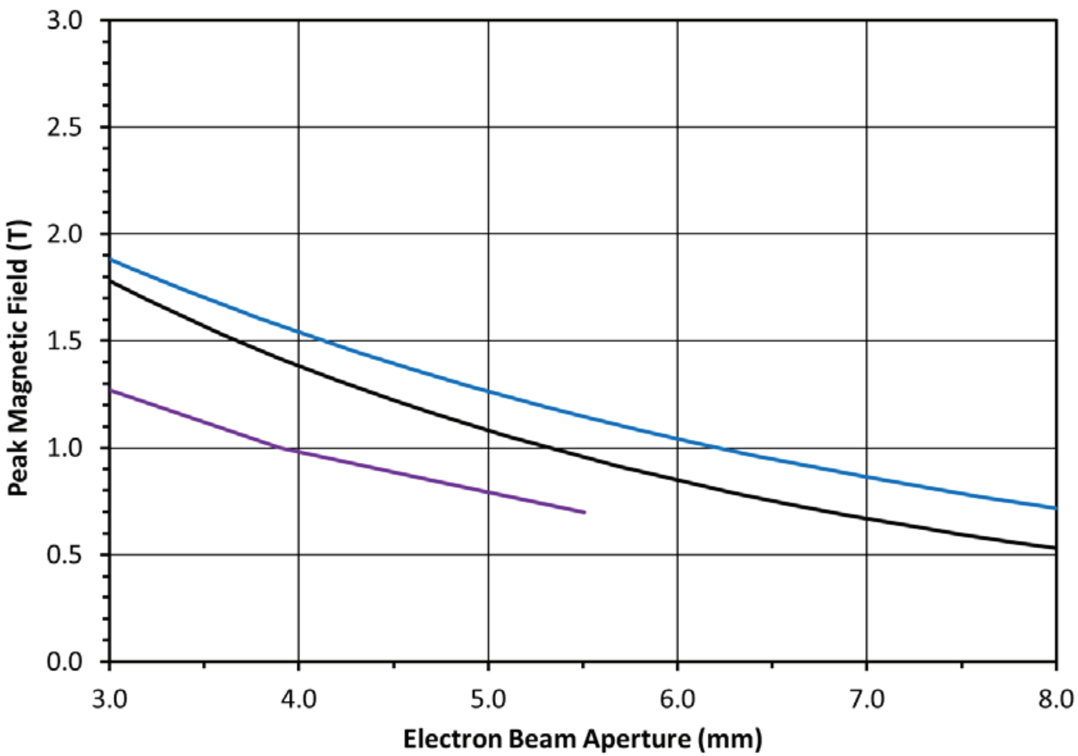
Undulator Comparisons

- **Example 15mm period undulator**
- Standard SCU
  - NbTi at 1.8K
  - Note at 4K we typically observe a ~10% reduction in field



Notes

Standard SCU with magnet gap 2mm larger than electron beam aperture

Includes internal vacuum chamber

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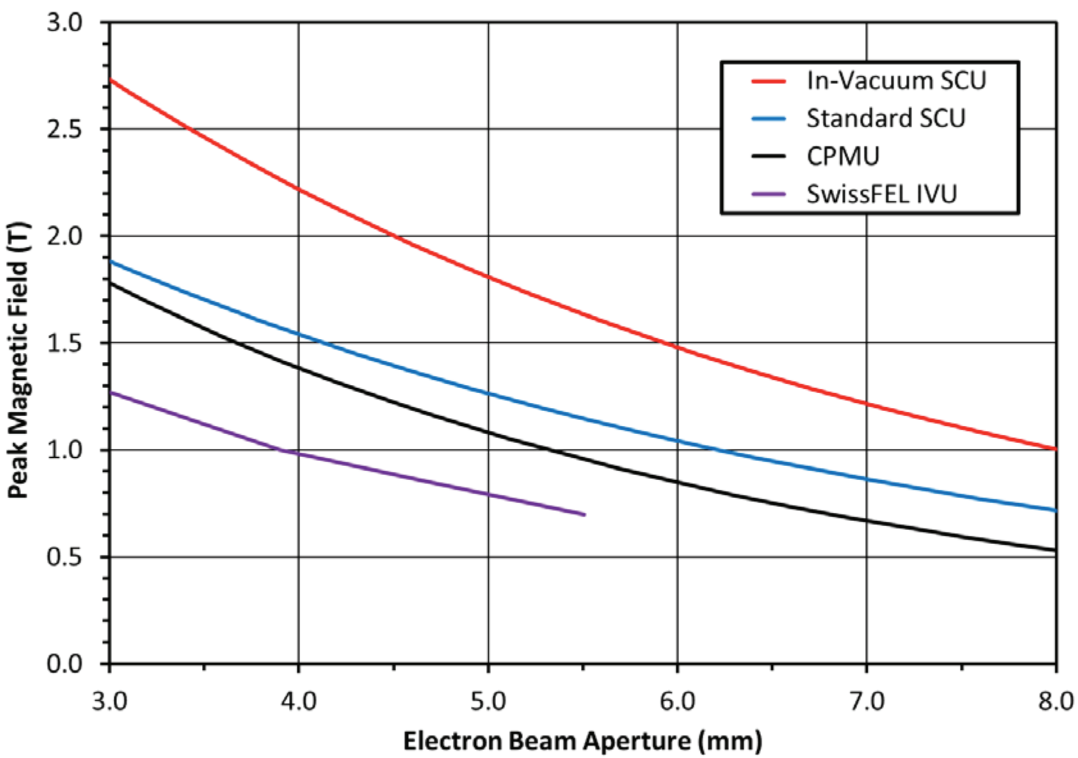
Undulator Comparisons

- **Example 15mm period undulator**
- In-Vacuum SCU
  - NbTi at 1.8K
  - Note at 4K we typically observe a ~10% reduction in field



Notes

In-Vacuum SCU with magnet gap 0.2mm larger than electron beam aperture

No internal vacuum chamber, only high conductivity copper liner

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Helical SCU Option

- FELs could instead use the classic bifilar helix undulator which generates a helical field
  - Circular polarisation
  - Increased FEL coupling factor – more compact FELs
  - Circular beam aperture
  - Very efficient design magnetically
- The same in-vacuum SCU advantages apply to the helical SCU

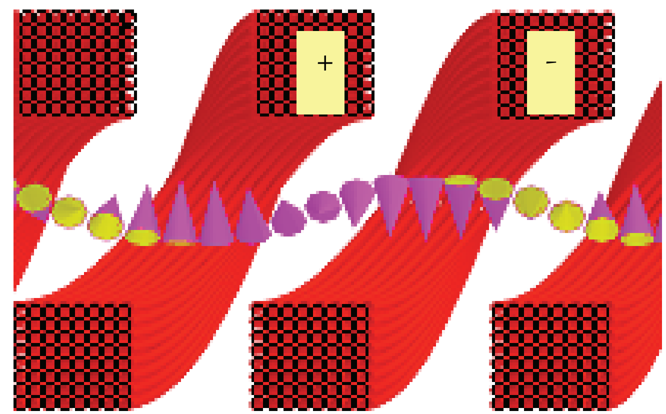
Example Helical SCU

D J Scott et al, Phys Rev Lett, 107, 174803 (2011)

ILC Positron Source undulator under test at RAL (2009)

11.5mm period, Bx=By=1.1T successfully demonstrated

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



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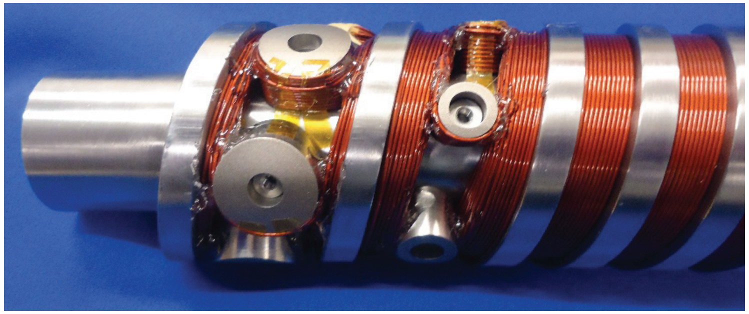
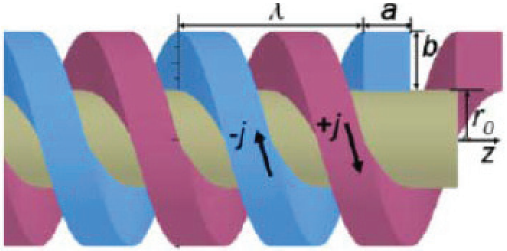
CIRCULAR POLARIZING: HELICAL SCUs

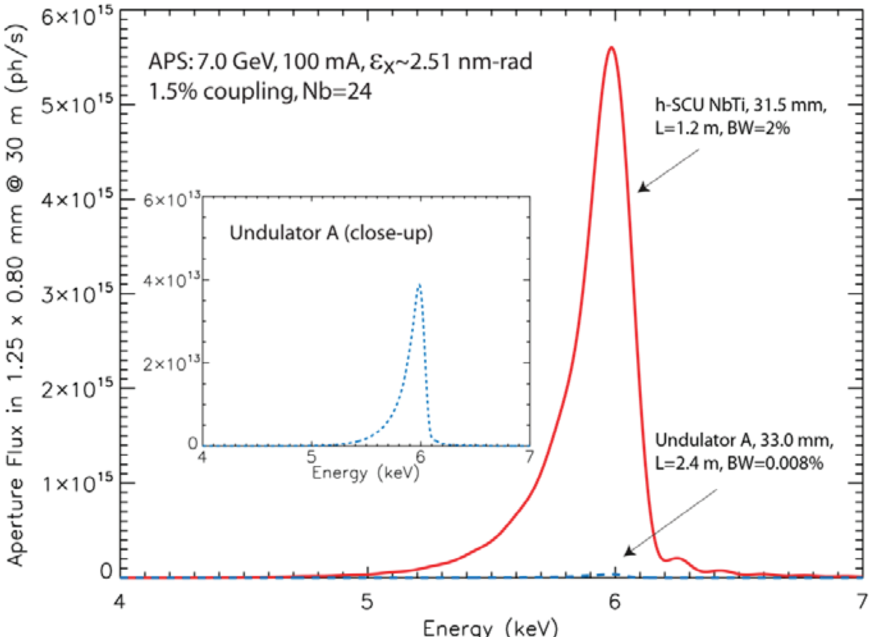
- SCU technology offers the possibility of building circular polarizing helical undulators.
- We have recently completed a helical SCU (HSCU) for the APS.
- X-ray photon correlation spectroscopy program at the APS will benefit from the increased brilliance provided by an HSCU.
- Future helical SCUs may be optimized for FEL applications.

Parameters for APS HSCU	
Cryostat length (m)	1.85
Magnetic length (m)	1.2
Undulator period (mm)	31.5
Magnetic bore diameter (mm)	29.0
Beam vacuum chamber vertical aperture (mm)	8
Beam vacuum chamber horizontal aperture (mm)	26
Undulator peak field Bx=By (T)	0.42
Undulator parameter Kx=Ky	1.2


HSCU prototype coil winding showing end detail.



Magnetic model of HSCU.

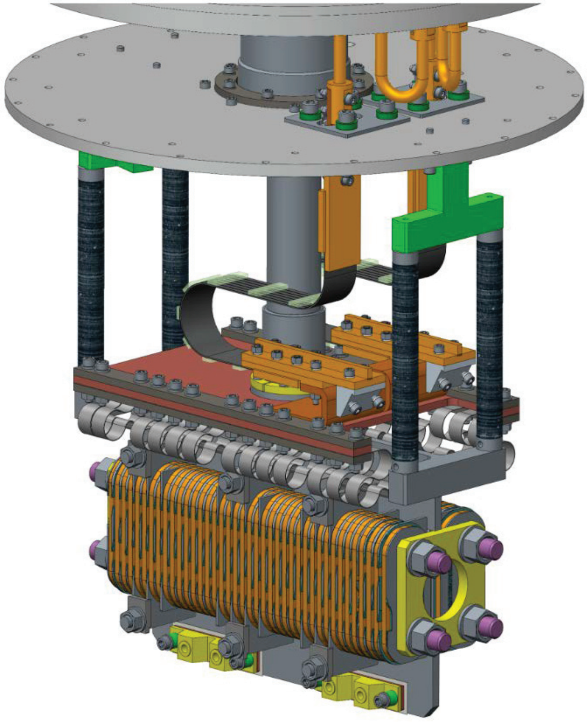


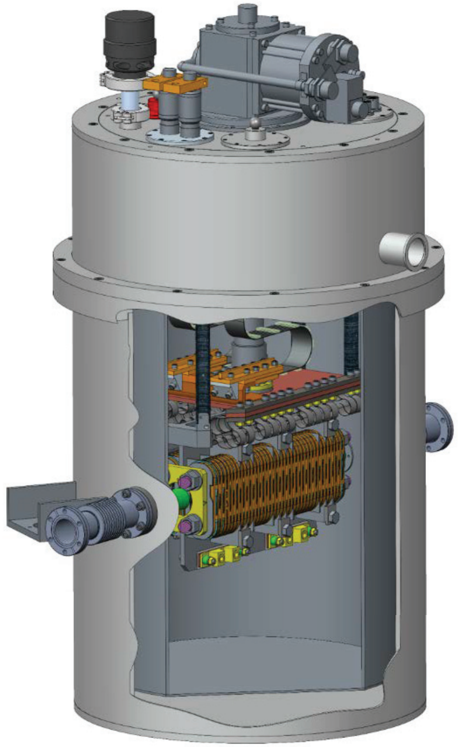
Calculated photon spectrum of helical SCU.

courtesy of J. Fuerst, ANL

SCU Demonstration on CLARA

- We have assembled a 30cm in-vacuum SCU Prototype
- 15.5mm period, 7.4mm gap, Bmax = 1.25T, Kmax = 1.8
- It will soon be installed and tested on the CLARA FEL Test Facility at Daresbury





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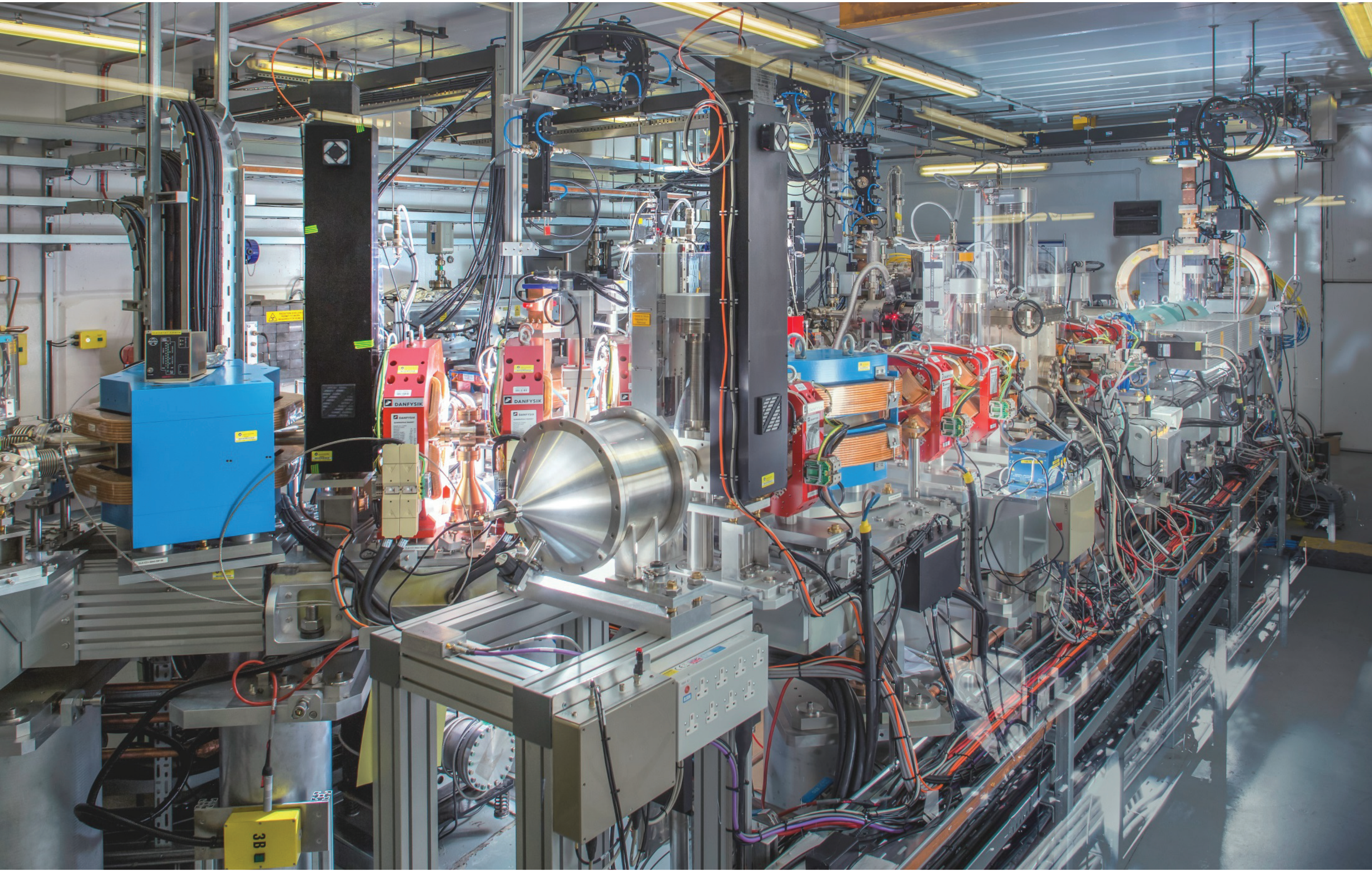
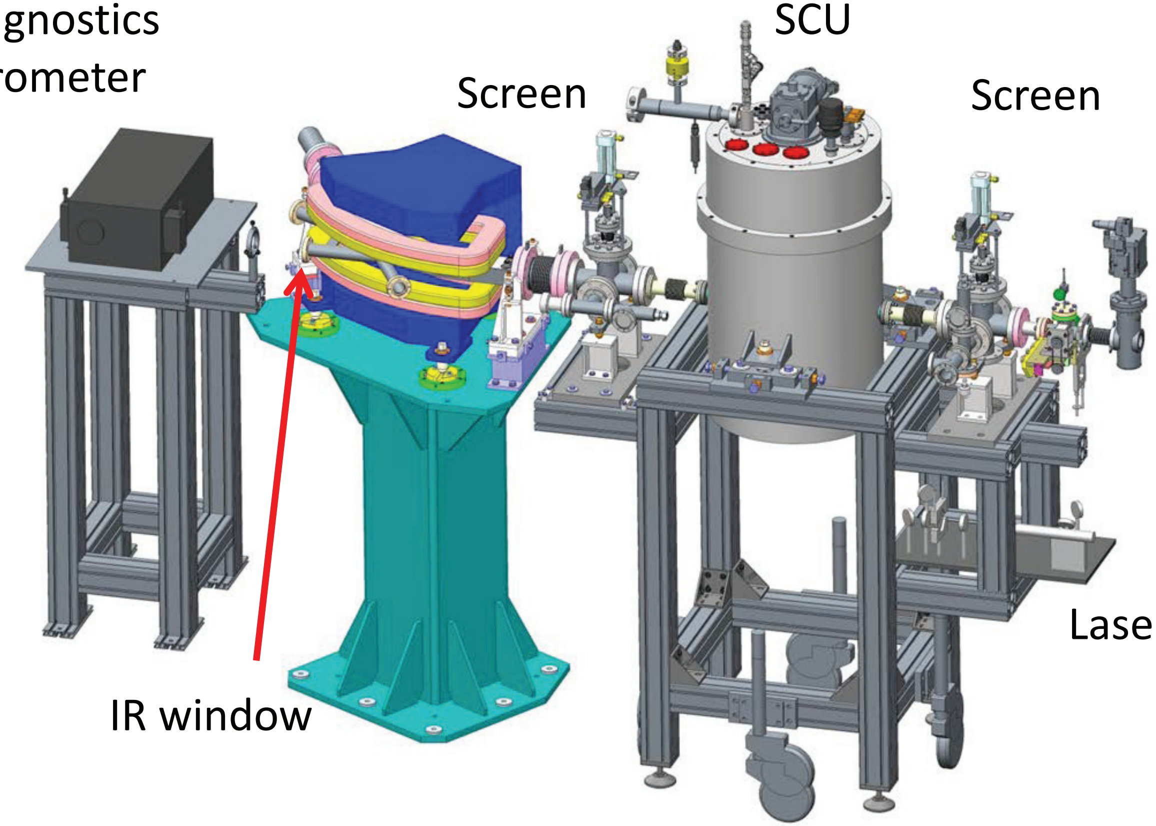
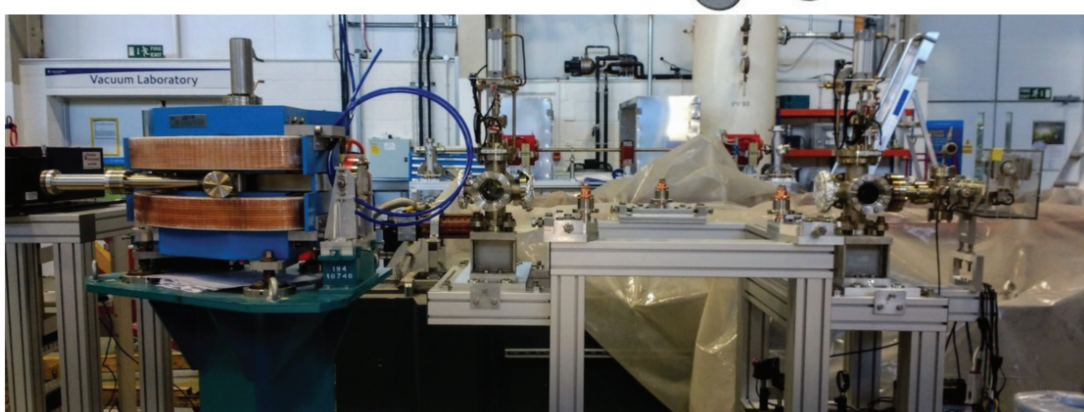
CLARA Phase 1: 50 MeV



CLARA Experiment





Offline Assembly

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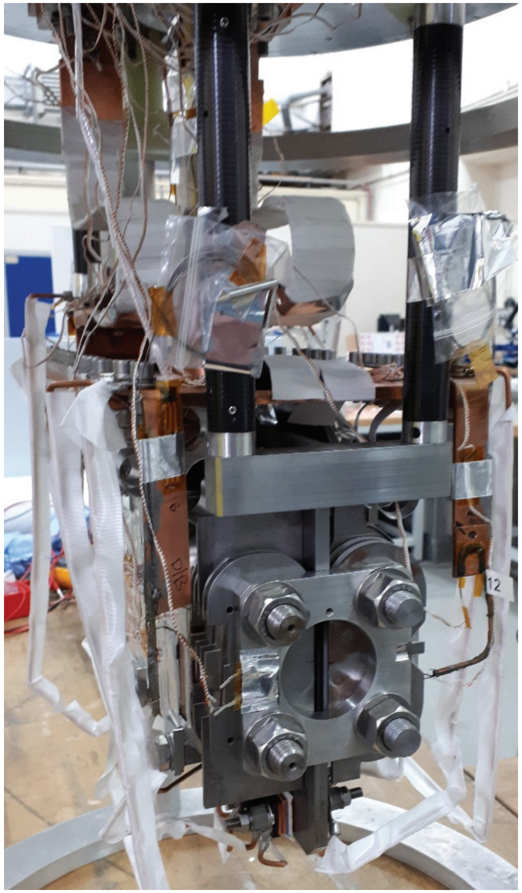
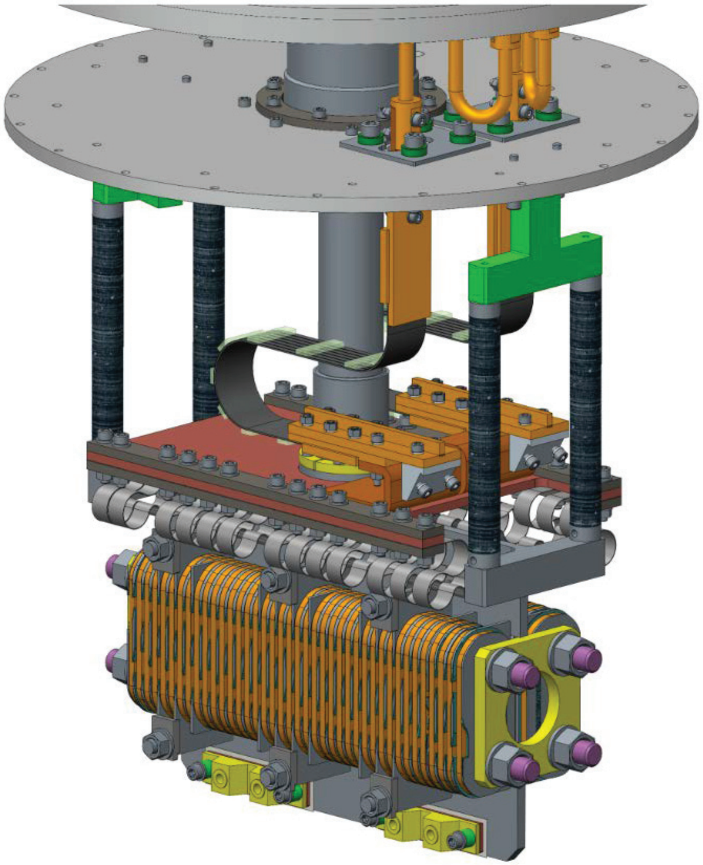
In-vacuum SCU Prototype





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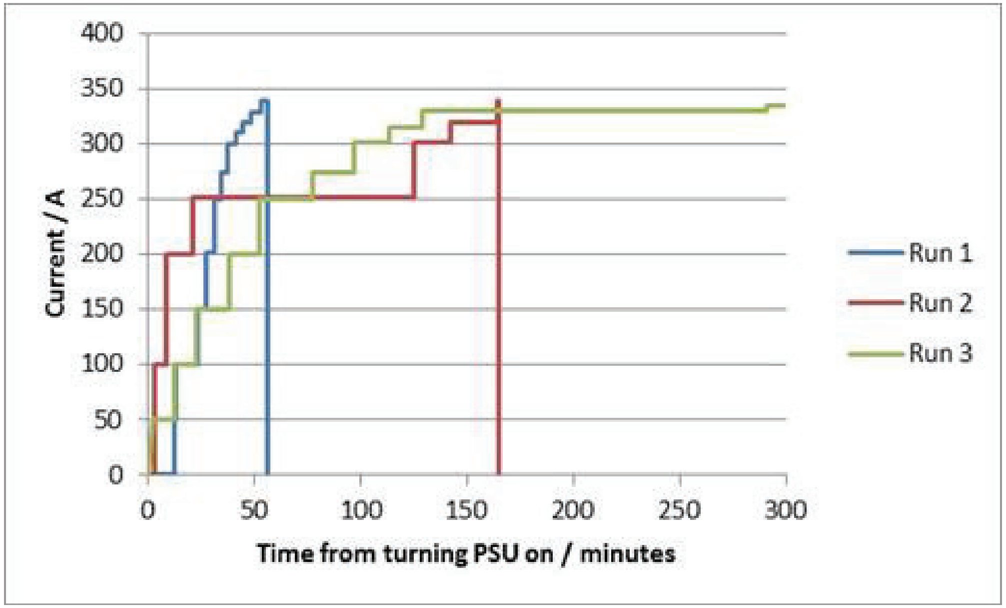
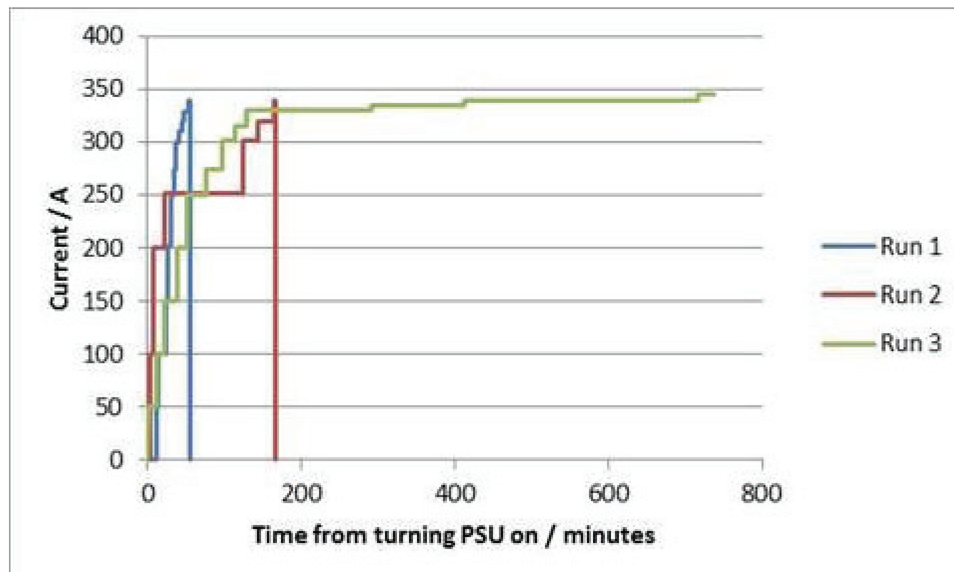
SCU Offline Tests



Operating Current 340A

Max Current during training 380A



Summary

- SCUs are already in routine operation in a couple of storage rings
- FELs offer different constraints on the engineering of SCUs
- The **In-Vacuum SCU** makes much **smaller magnet gaps** possible
  - **No change to electron aperture**
  - **No fundamental change to proven SCU designs required**
  - **Much higher magnetic fields than any other technology – approximately *double* the current PM in-vacuum undulators**
- Helical in-vacuum SCUs should also be strongly considered by XFELs
- A demo of this new type of SCU will be tested on CLARA in 2018
- The results presented here assume **NbTi**, the application of **Nb_3Sn** could provide another step change in performance
- There is no *fundamental* reason why in-vacuum SCUs could not be used on storage rings also