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Status of SC Undulator Studies in the UK

Jim Clarke

ASTeC

on behalf of the Daresbury and Rutherford Appleton Laboratories SCU Team

Contents

Setting the Scene

- **RAL** has a long and distinguished history in the field of SC magnets and more recently with closed loop cryogenic systems
  - SC magnets particularly for particle physics applications
  - Cryocoolers primarily for space applications
- **Daresbury** has a similar position in the field of light sources and undulators
- **Since 2004 the two groups have worked together on SCUs**
- Recently **Diamond** has also joined the team

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Helical SCU Motivation

- The International Linear Collider requires unprecedented numbers of positrons when compared with present day sources
- If the positrons can be **polarised** then the physics reach of the collider can be enhanced
- **ILC Baseline** – Synchrotron radiation from an undulator
  - Very high energy electrons
  - Short period undulator
  - Lots of Periods for high intensity
  - Helical undulator ➔ circularly polarised photons

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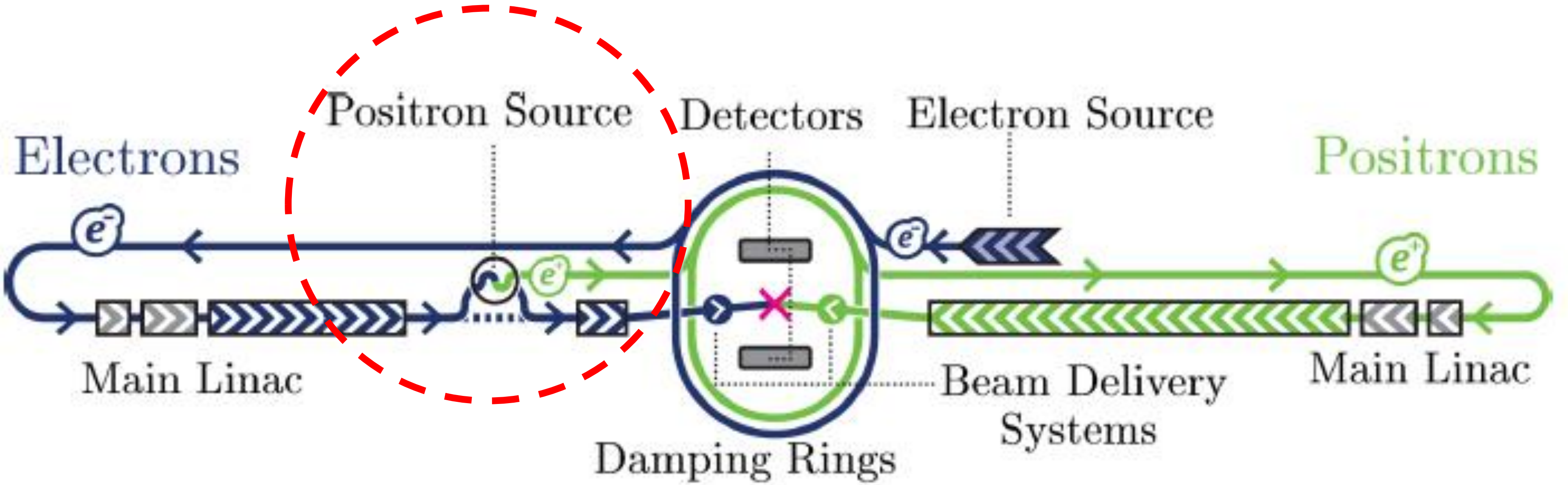
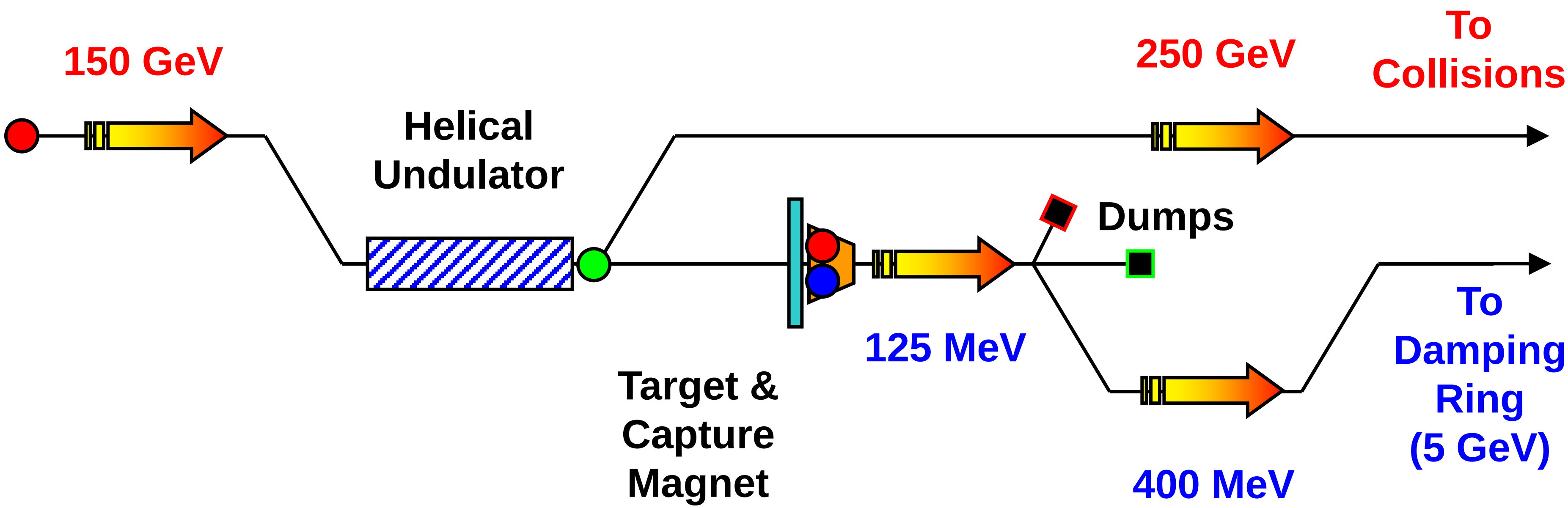
The ILC

- The ILC is a proposed **electron-positron collider**
- Both beams have maximum energy **250 GeV**
- Total length of facility **~35 km**



Positron Source Layout (RDR)



- **10MeV+ photon beam** generated in helical undulator by **150 GeV electrons**
- Photon beam travels ~400 m beyond undulator and then generates e^+e^- pairs in **titanium alloy target**
- Positrons captured and accelerated to 125 MeV
- Any electrons and remaining photons are then separated and dumped
- Positrons further accelerated to **400 MeV and transported for ~5km**
- Accelerated to 5 GeV and **injected into Damping Ring**

The Undulator

- To generate the photons with a high enough energy (>10MeV) need to use **short period, high field**, undulator
- For sufficient positrons undulator must be **~200m**
- Short period, high field, only possible with **narrow aperture**:
  - Resistive wall effects
  - Vessel surface roughness effects
  - Synchrotron radiation power problems
  - Generating a vacuum with difficult aspect ratio
  - Mechanical tolerances
  - Manufacturing issues
- **Superconducting** technology solution chosen after ‘competition’ with permanent magnet

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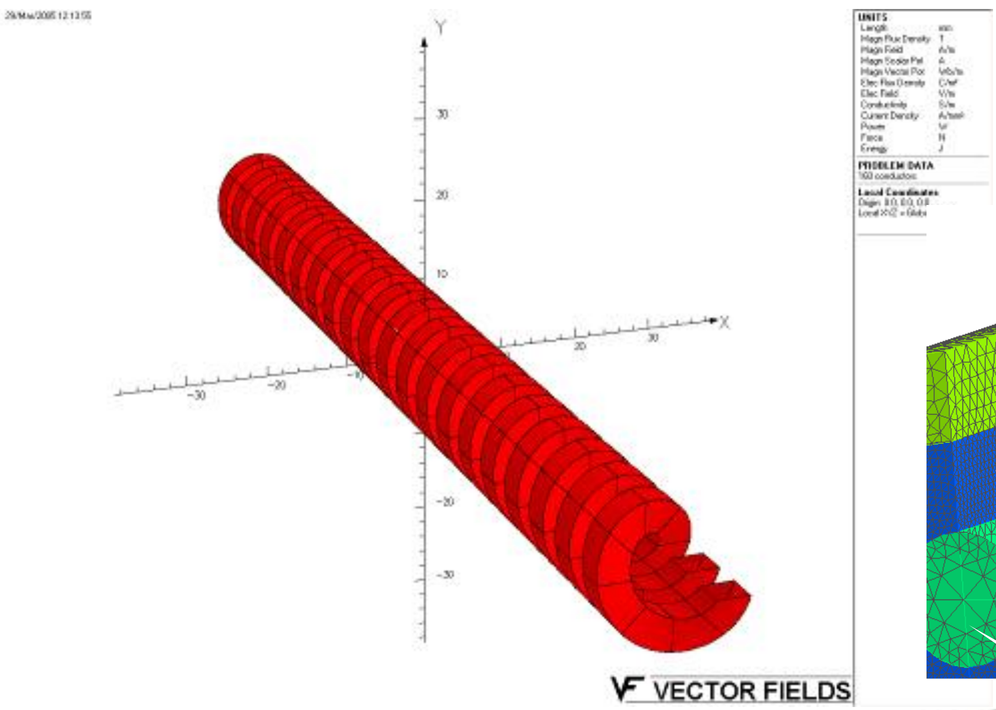
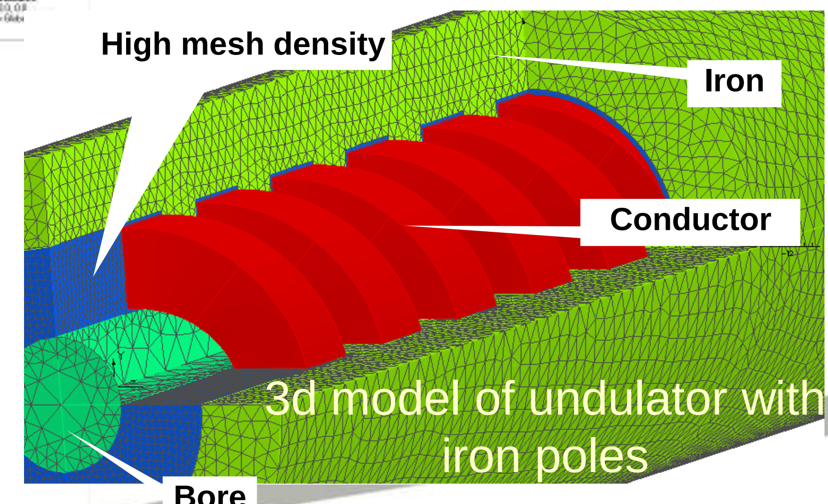
D.J. Scott et al, PR-STAB, 10, 032401 (2007).

Magnet Design

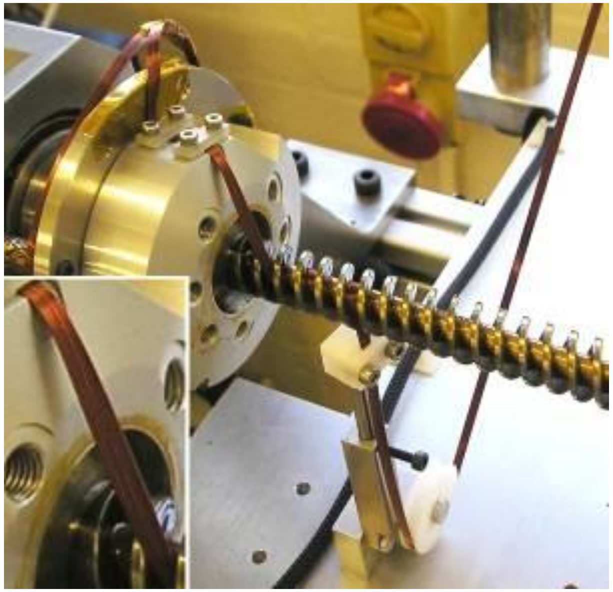
- **Bifilar Helix with iron poles**
- **NbTi wire**
- Non-magnetic vacuum vessel

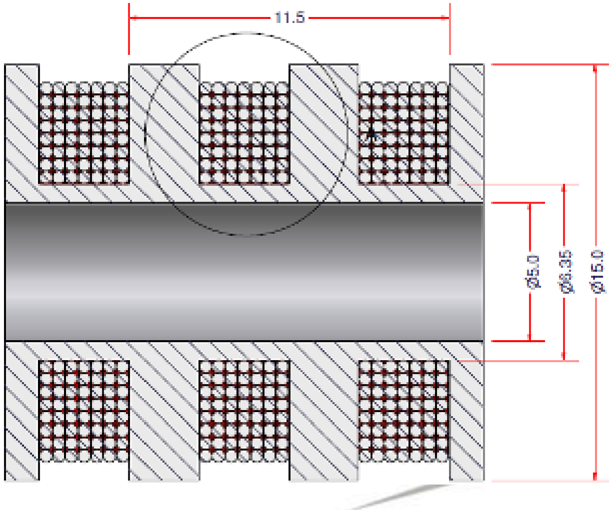


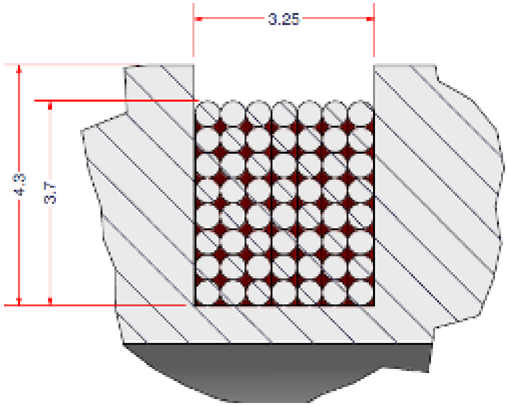


NbTi Winding

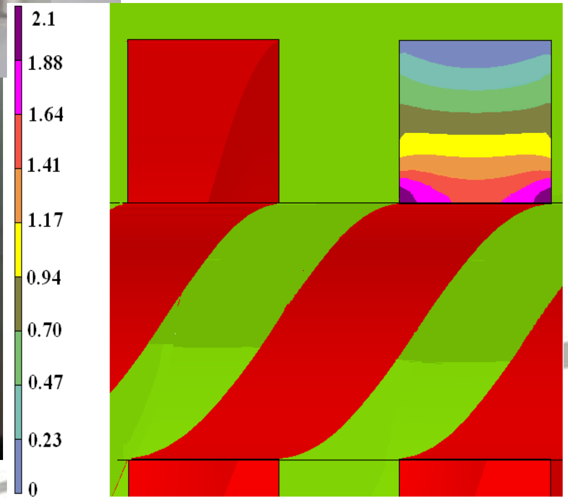
- Wound with **7 wire ribbon**, 8 layers
- Ø0.4 mm NbTi wire, with 25 µm enamel (Ø0.45 mm when insulated)
- 3.25 mm wide winding for 11.5mm period
- Packing factor of 62%







NbTi Prototypes



Prototypes Summary

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

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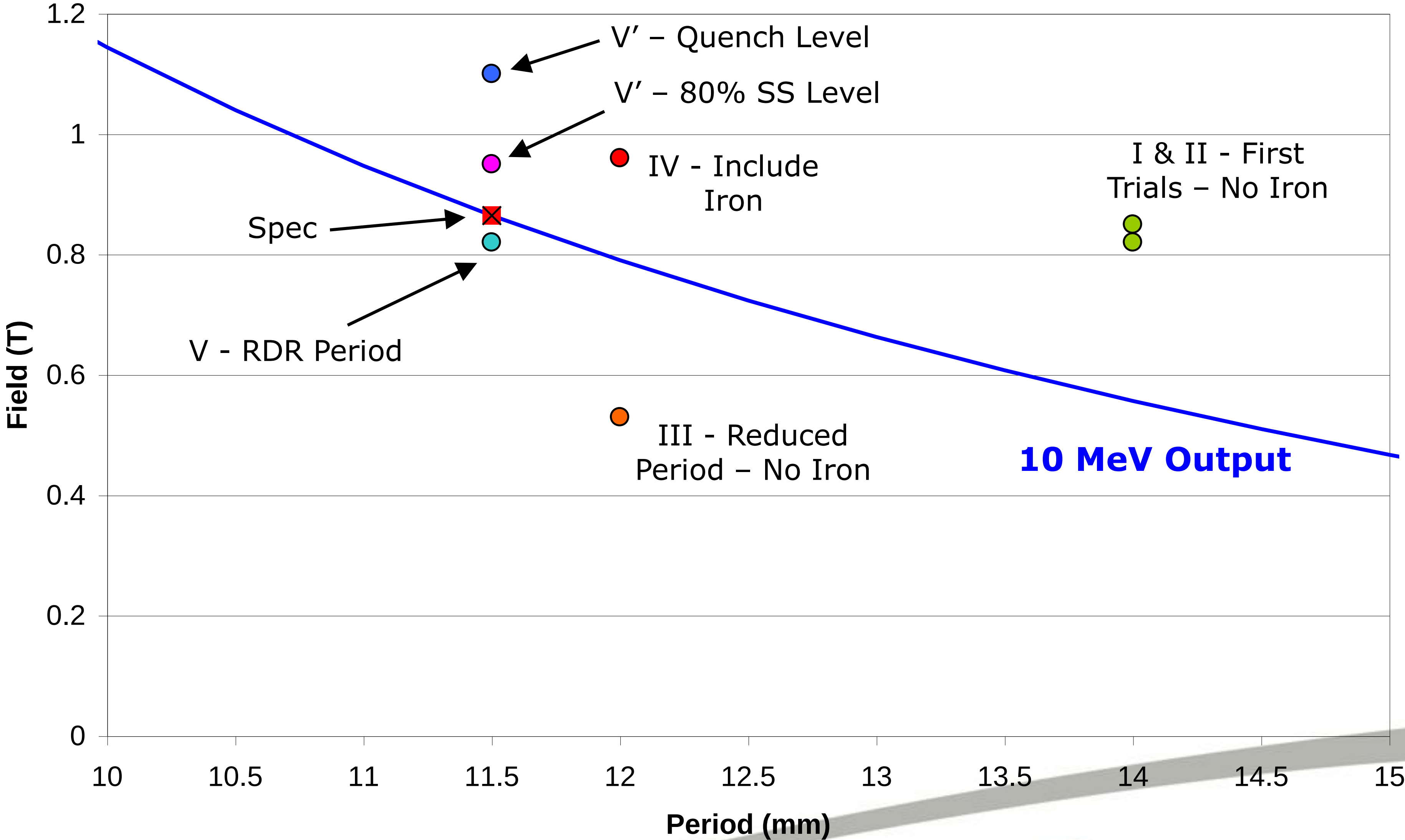
Prototypes Summary



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Full Undulator Parameters

Undulator Parameters	Symbol	Value	Units
Undulator period	λ	1.15	cm
Undulator strength	K	0.92	
Undulator type		helical	
Active undulator length	L_u	147	m
Field on axis	B	0.86	T
Beam aperture		5.85	mm
Photon energy (1^{st} harmonic cutoff)	E_{c10}	10.06	MeV
Photon beam power	P_γ	131	kW

Undulator to be made of 4m long modules

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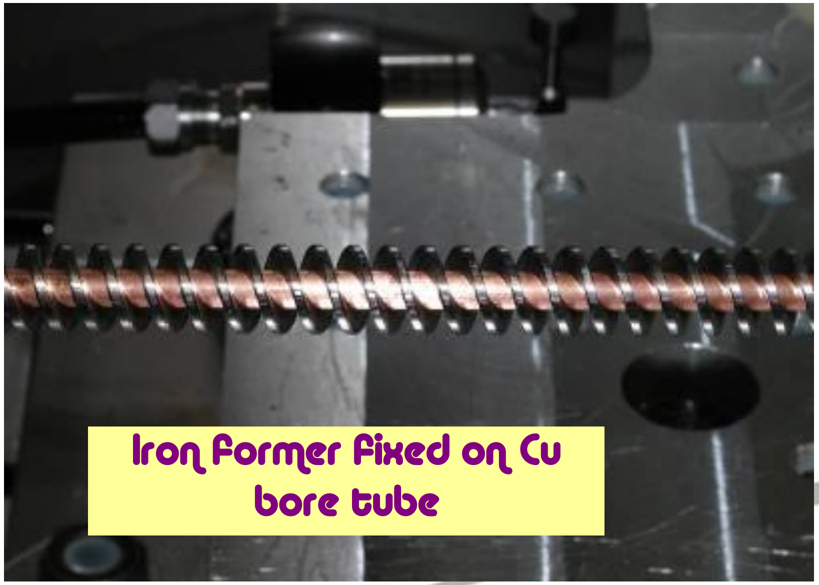
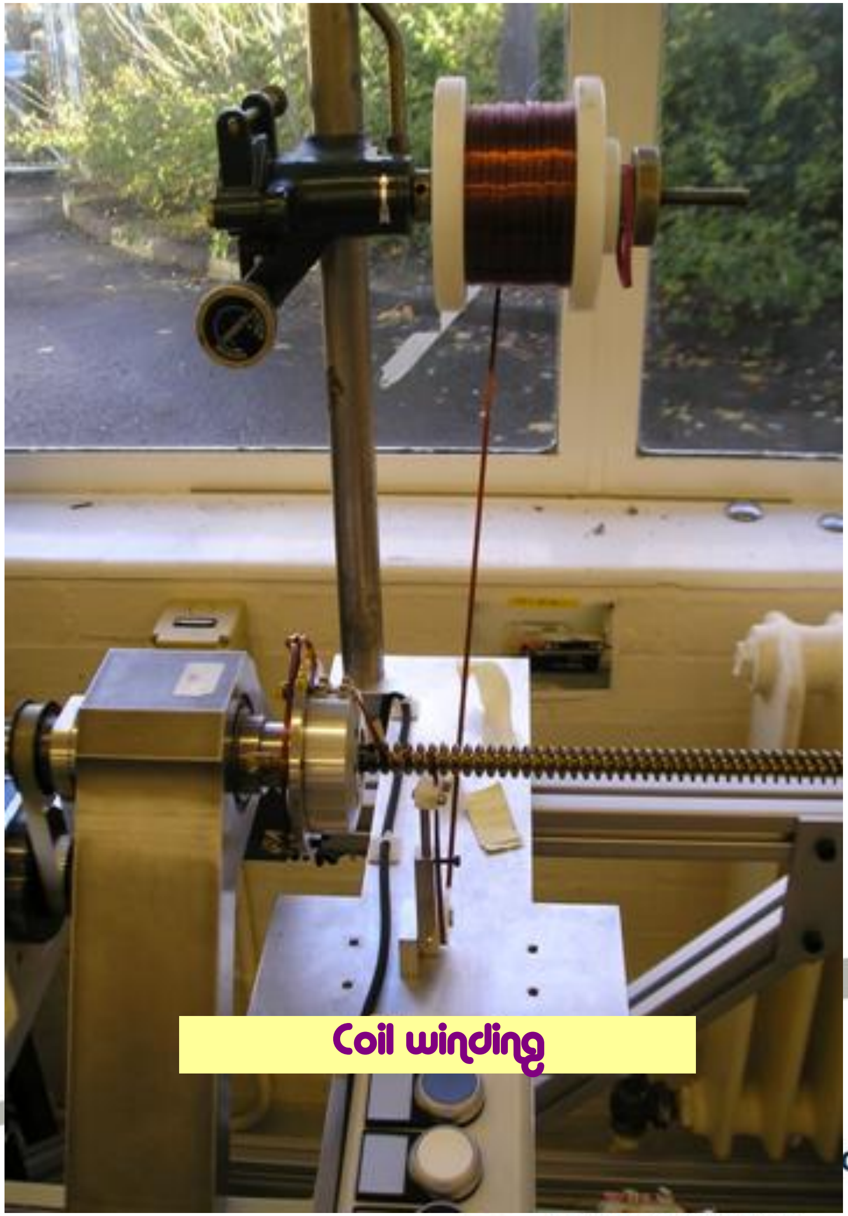
4m Prototype manufacture

4 axis machining

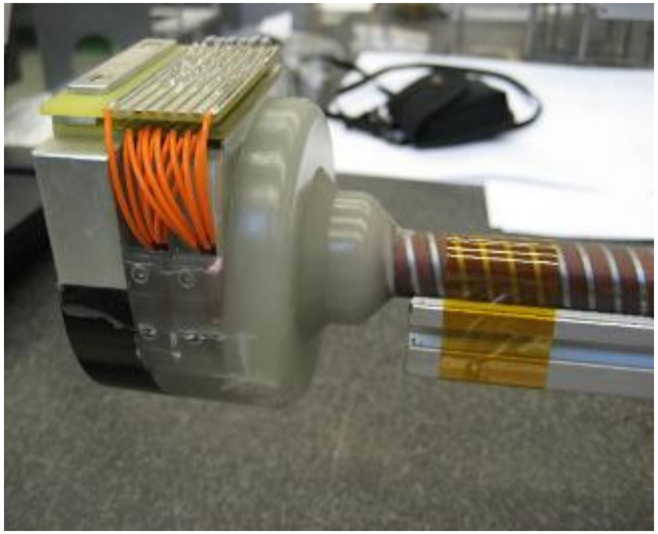


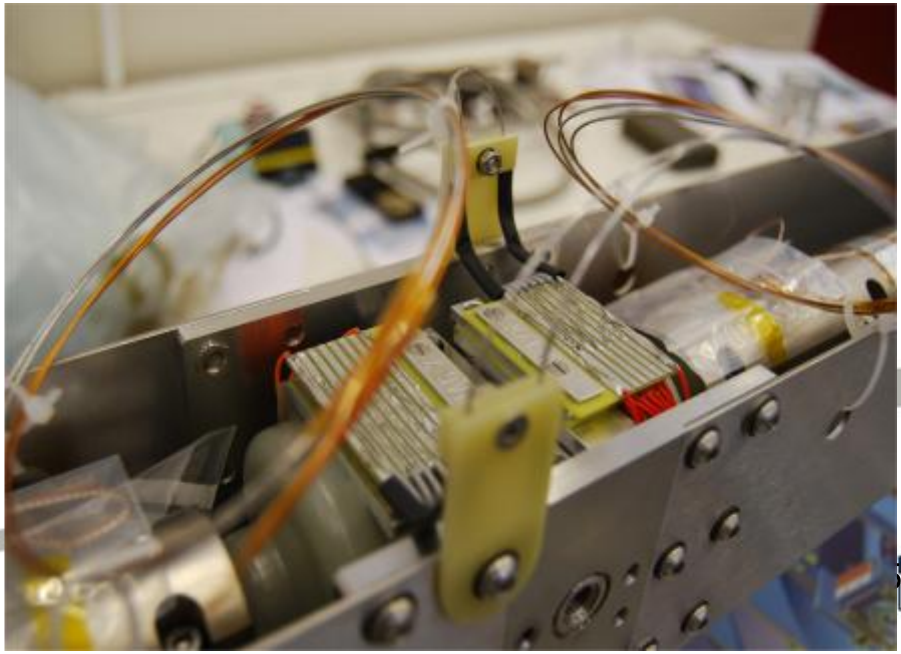
Iron former fixed on Cu bore tube



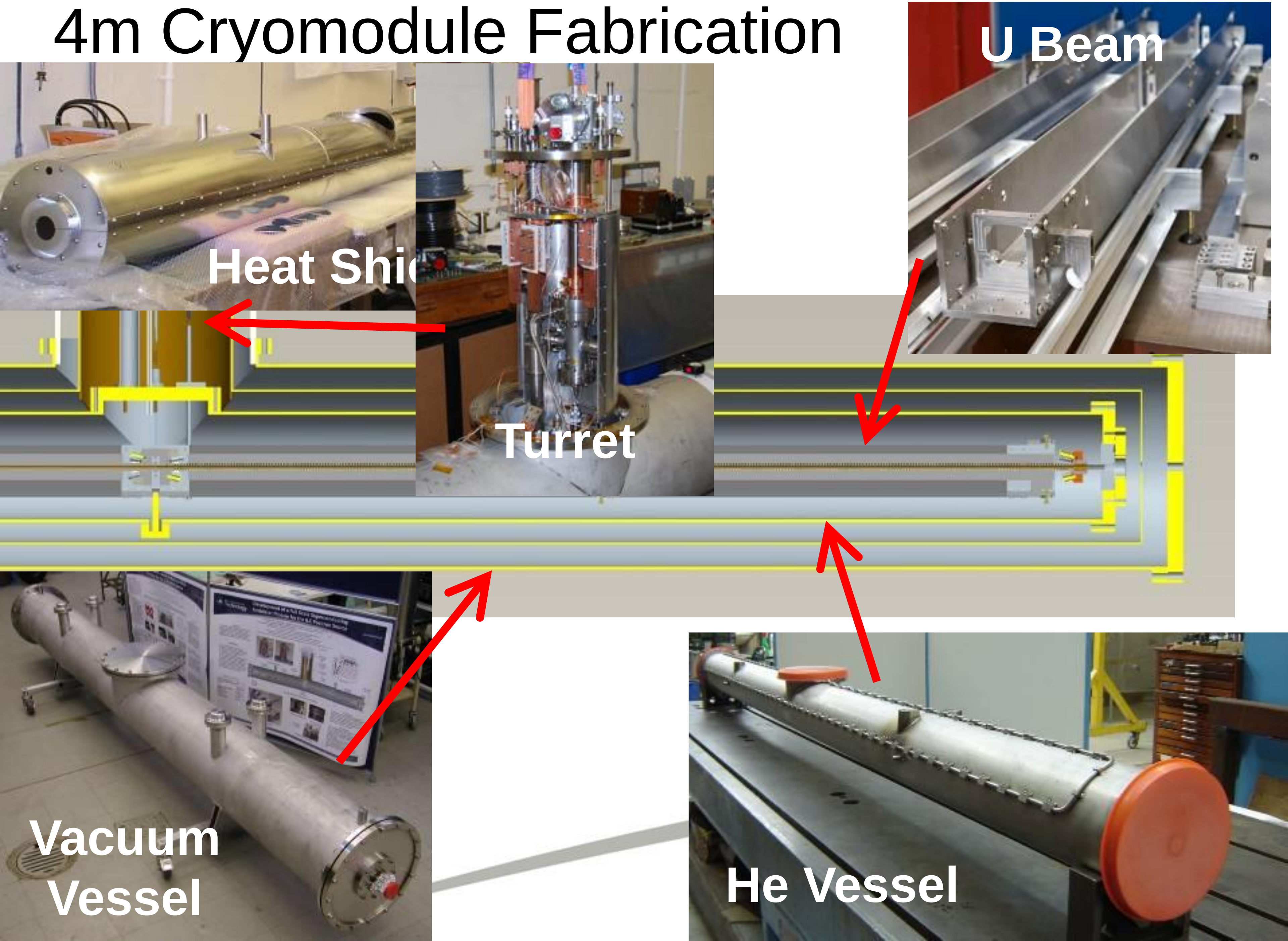
Coil winding

4m Prototype manufacture

4m Cryomodule Fabrication



Cryomodule

- A 4m module containing 2 x 1.75m helical undulators (11.5 mm period) has was constructed
- Closed loop cryo system with cryocooler

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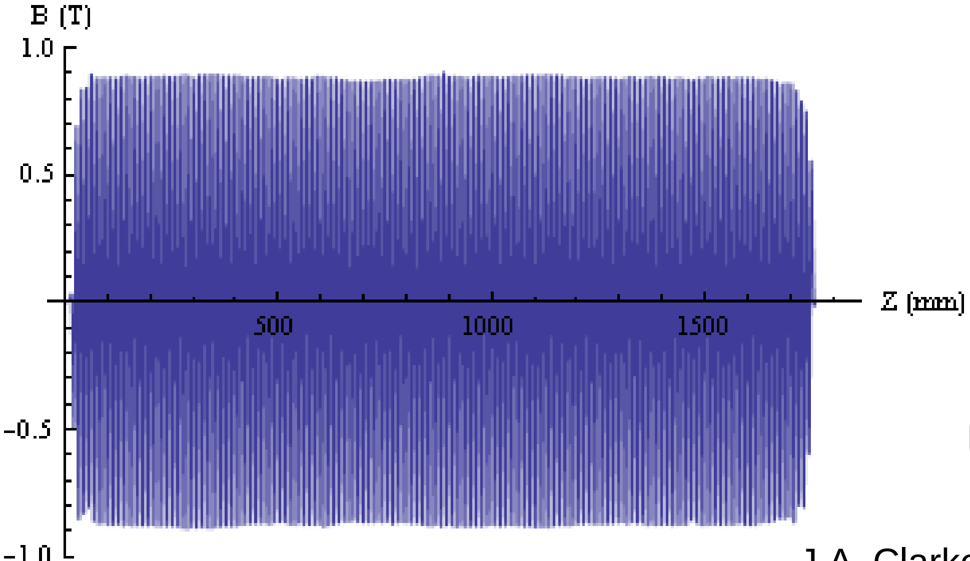
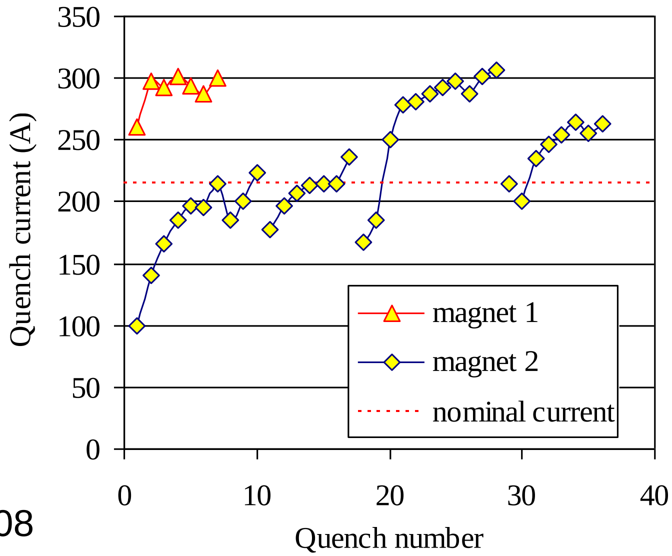
Vertical Tests

- The quench test results show different behaviour between the two identical magnets
- Both do actually reach the same final quench current which agreed well with expectations
- **300A = 1.15T (spec is 0.86T, 215A)**

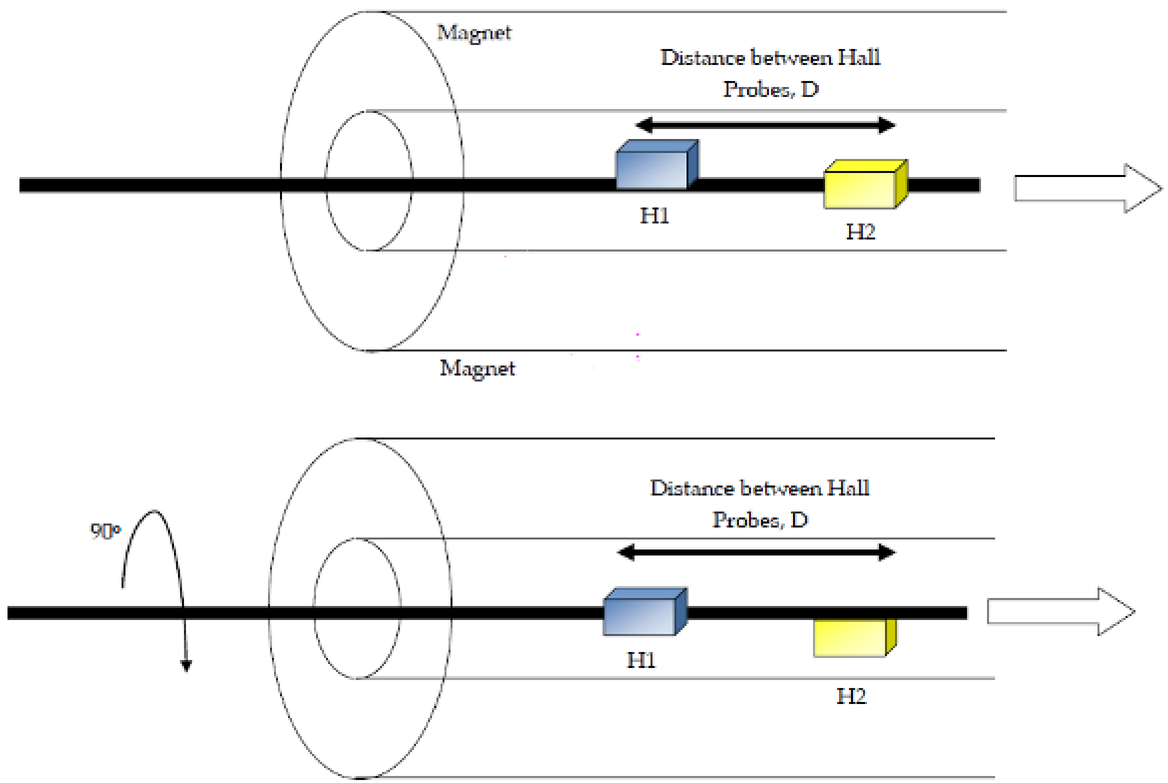




J.A. Clarke et al, EPAC 08

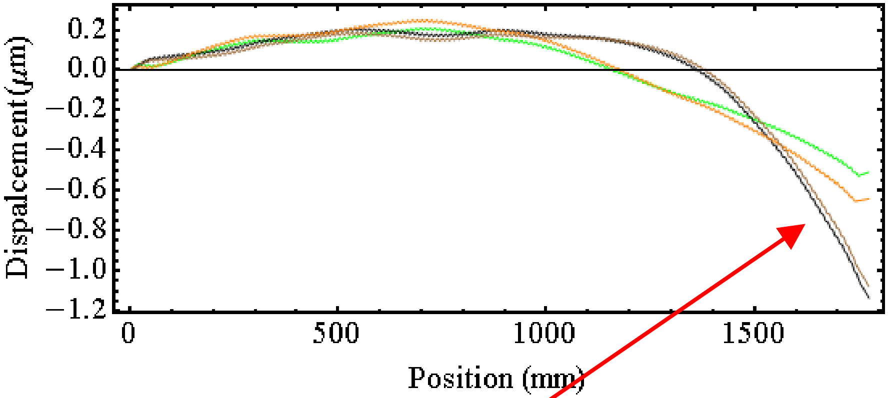
Measurement Details

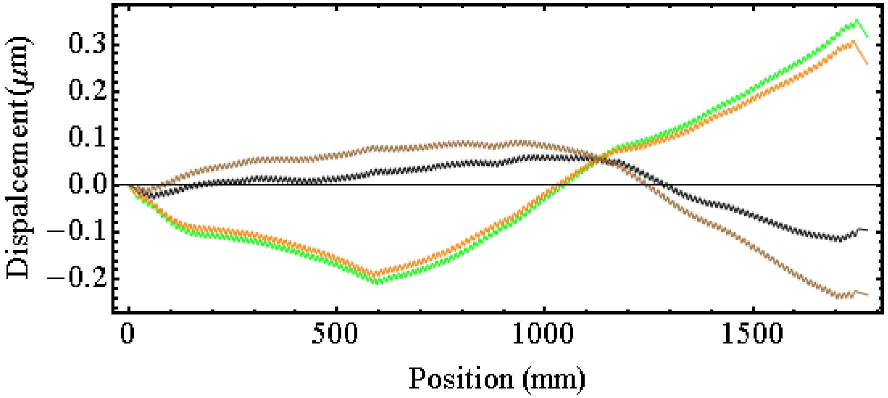
- 2 orthogonal Hall probes x 4 orientations = 8 measurements per magnet



Trajectories

- Combine 180 deg results to cancel planar Hall effect
- H1 and H2 trajectories very similar
- Magnet 1 left, Magnet 2 right

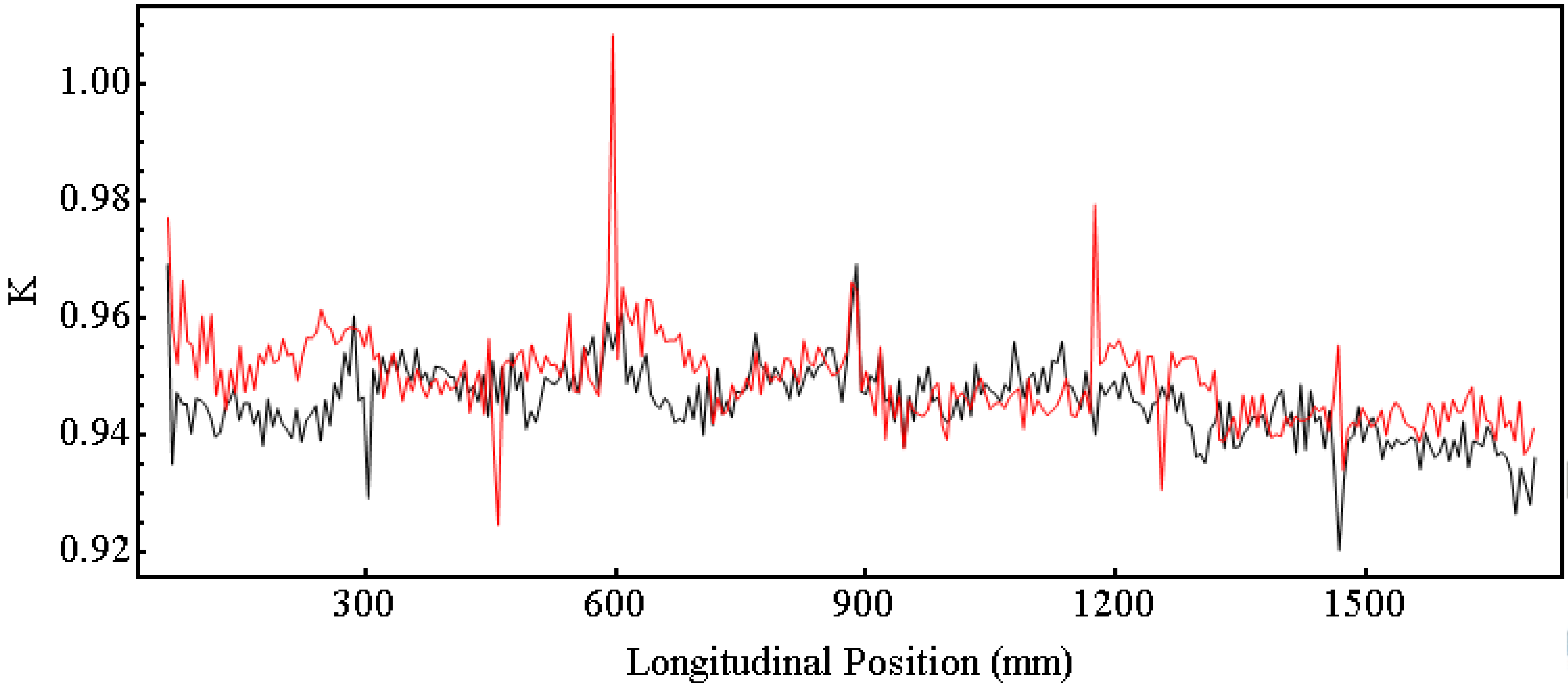




“Dipole field” – very hard to explain!
It is in all the raw data but only in one field component.
Unable to generate in any magnet model including errors

K along length

- M1 black, M2 red
- Spikes are due to “Indexing points” from former manufacture
- Tighter control on former machining would remove these



logy

Phase Error

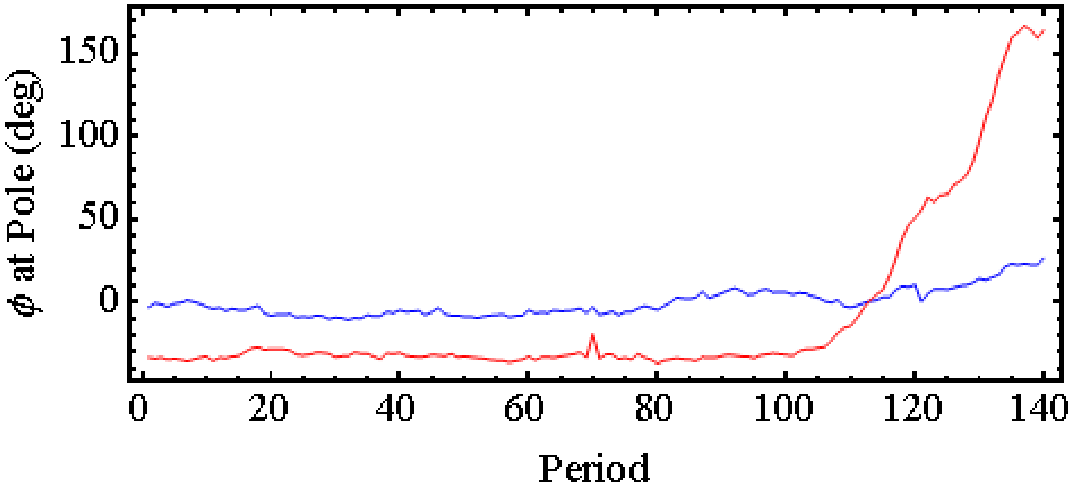
- X (red) and Y (blue) components of the field
- Phase generally very good except dipole part of M1!
- Magnet 1

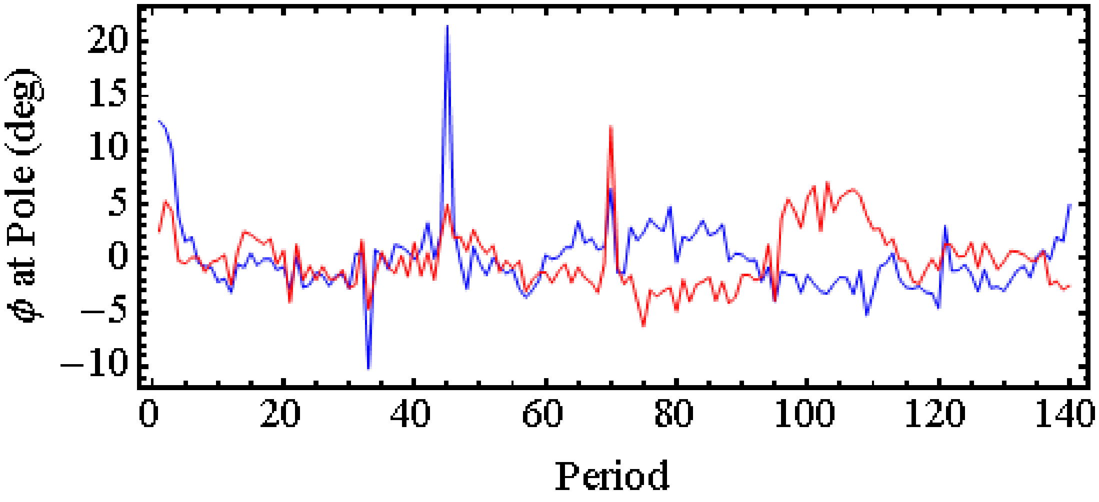
  $\sigma_{\varphi}x = 8.3°$

  $\sigma_{\varphi}y = 53°$
- Magnet 2

  $\sigma_{\varphi}x = 3.4°$

  $\sigma_{\varphi}y = 2.8°$





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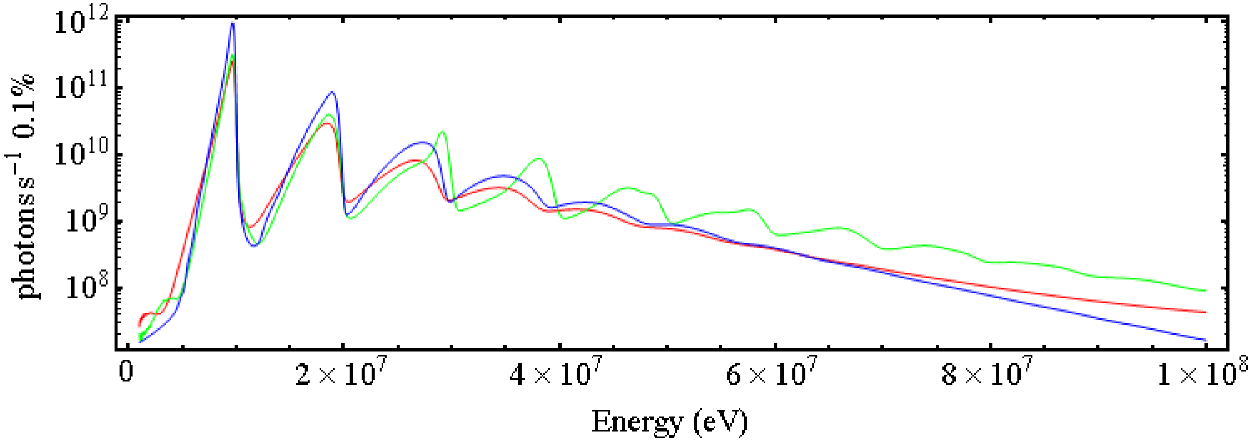
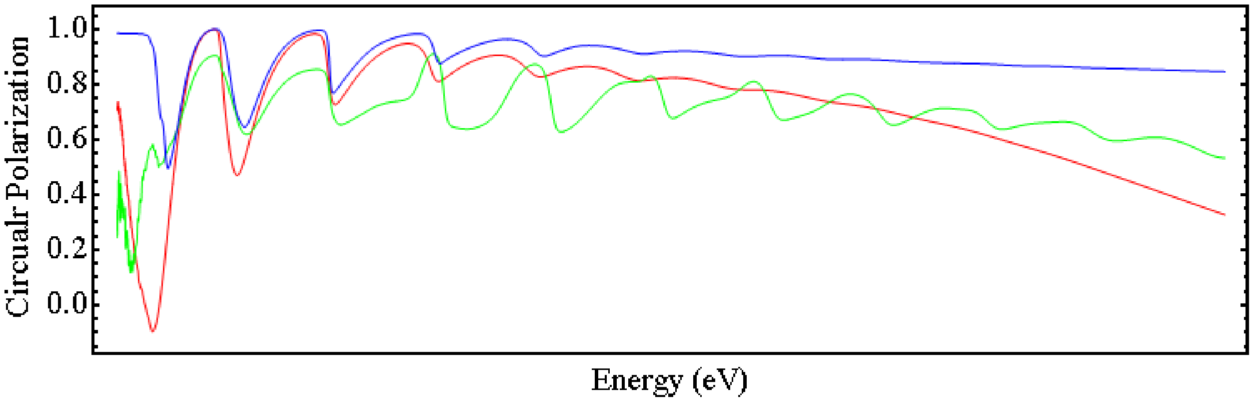
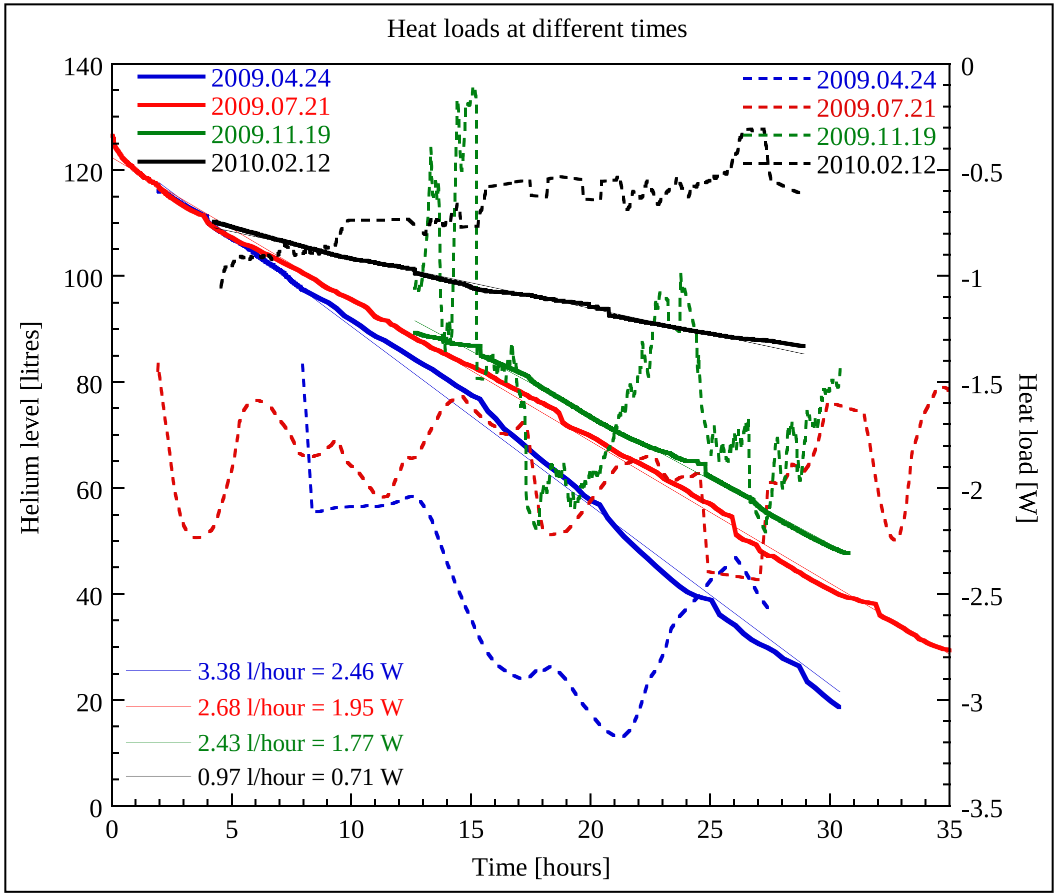
Flux calculated with SPECTRA

- Flux into 1μrad square aperture, red M1, green M2, blue ideal
- Issue – there are more high energy photons than ideal case (although not more total power)
- Investigating this now with our own code and one written in CI





Module Heat Load Problem



- Heat load higher than anticipated
  - System is not recondensing
- Improvements being made slowly with time
  - Main issue is top plate not at **4K**

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Application of Nb_3Sn

- To generate higher fields or to be able to reduce the period we need to use Nb_3Sn
- Goal would be to reduce period to ~9mm
- **Concerns**
  - Packing factor reduced as insulation is thicker
  - Performance of wire at <5T
  - Insulation of former
  - Can no longer wind with ribbon
  - More difficult material to work with (heat treatment)
- Need Nb_3Sn wire to have small diameter for similar filling factor
- Have purchased 1 km of Ø0.5 mm (Ø0.63 mm with glass braid) wire from OST.

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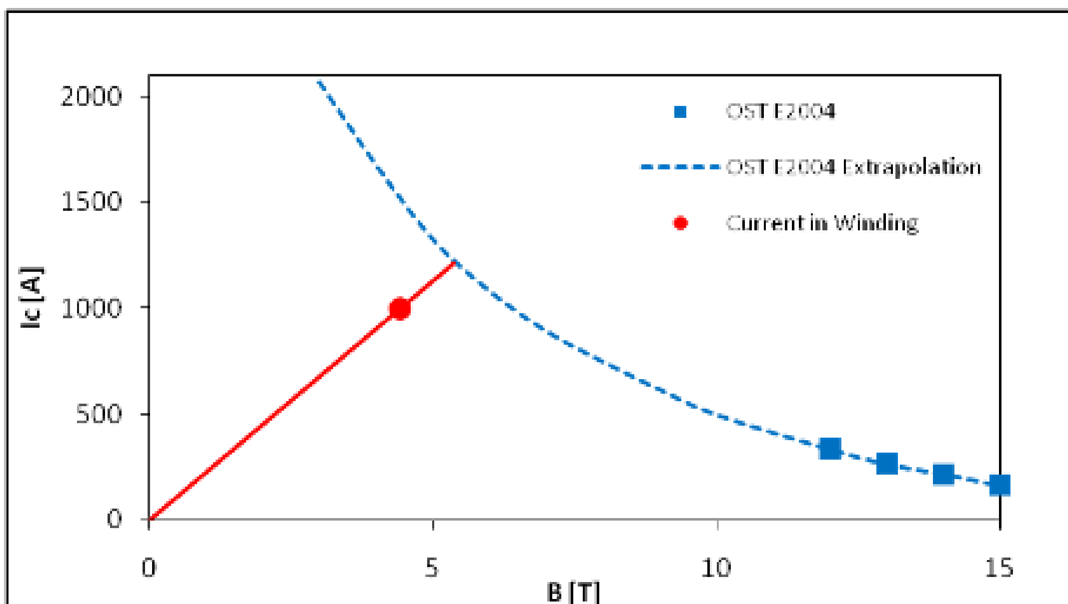
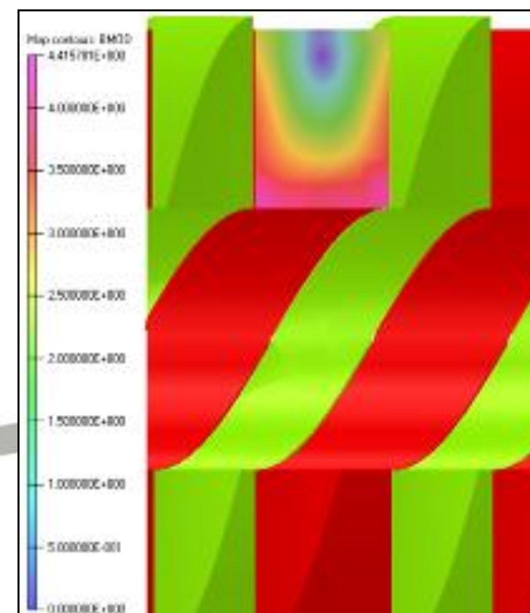
FEA Modelling

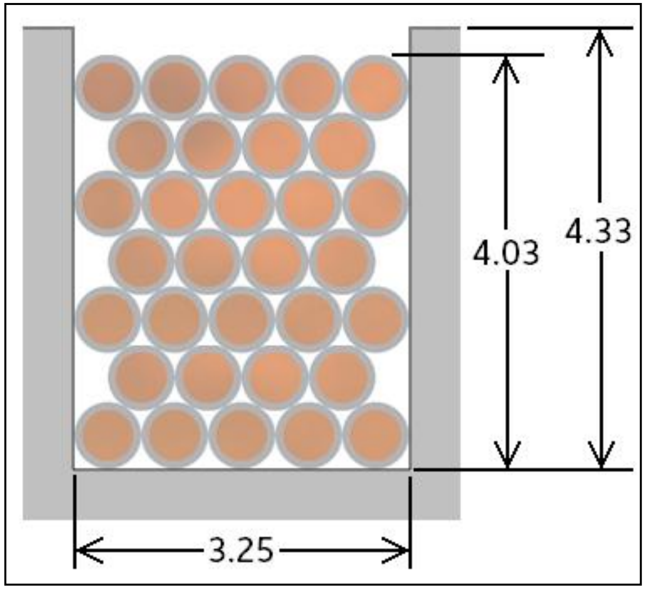
- Winding ID: Ø6.35 mm as before
- Field on axis: 1.54 T for 11.5mm period (cf 0.86T)
- Peak field in conductor: 4.4 T
- Operating at 82% of I_c
- Wire performance to be measured at <5T by KIT





Trial Winding

- Need to do a trial winding to confirm groove dimensions
- Aluminium former has been made with the dimensions shown
- Will be 32 wires in winding
- 11.5 mm period
- Will be wound, potted and sectioned to check groove width etc



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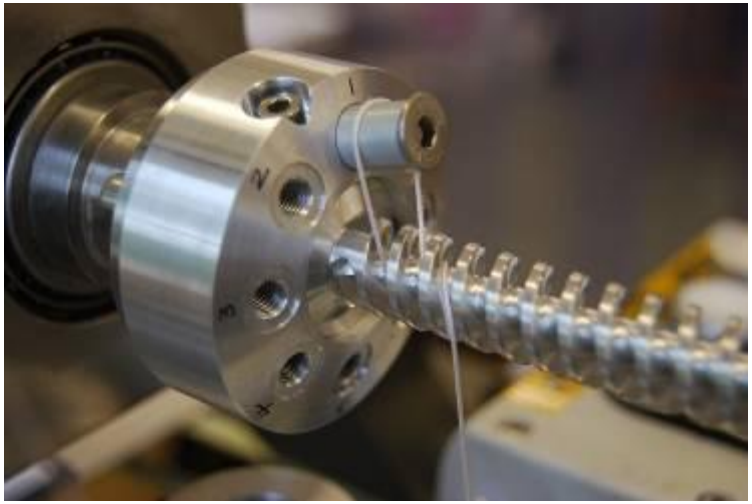
Trial Winding



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Planar SCU for Light Sources

- Successful helical undulator project helped secure funding for planar studies
- Same team of people
- Diamond has recently joined project
- It is anticipated that the first planar SCU will be installed into Diamond (~2012)

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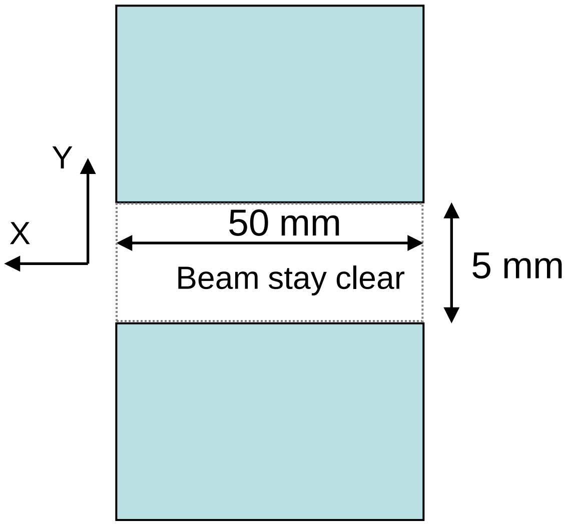
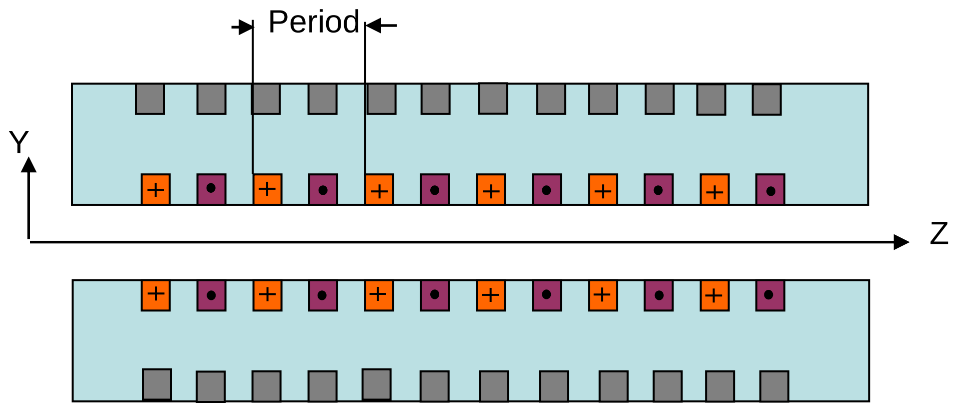
Undulator Specifications

Magnetic length:	2 m
Period :	15 mm
Field on axis:	1.4 T
K	2.0
Beam stay clear:	5 mm (Vert.) x 50 mm (Horiz.)
rms phase error:	< 3 degrees
Trajectory straightness:	+/- 0.5 micron





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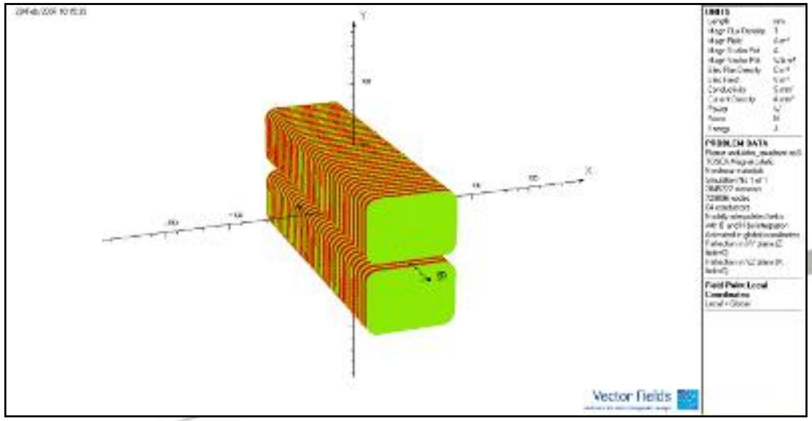
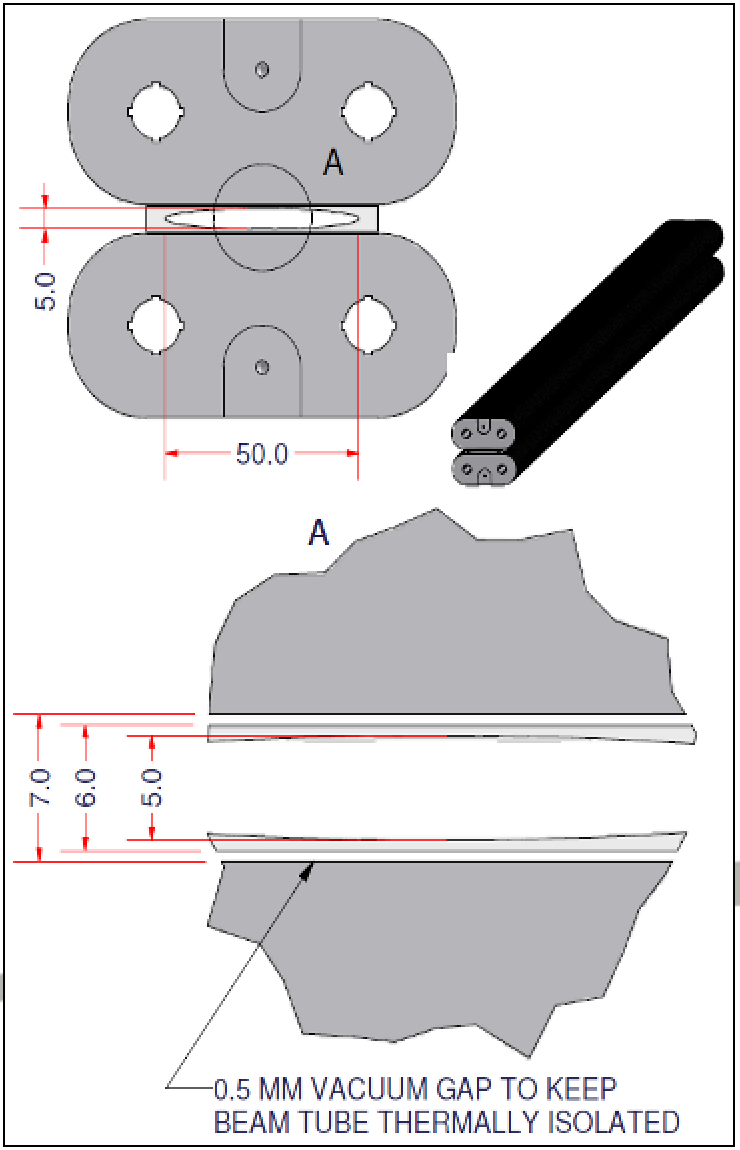
Design Features

- Cold bore magnet with **5mm** aperture vacuum vessel at **~12K**
- Magnet gap **7mm** to allow vacuum gap between vessel and magnet poles
- Magnet to operate at **~1.8K** in order to reach desired field level on axis
- Closed cycle pumped cryo system to achieve 1.8K

Technical Specifications

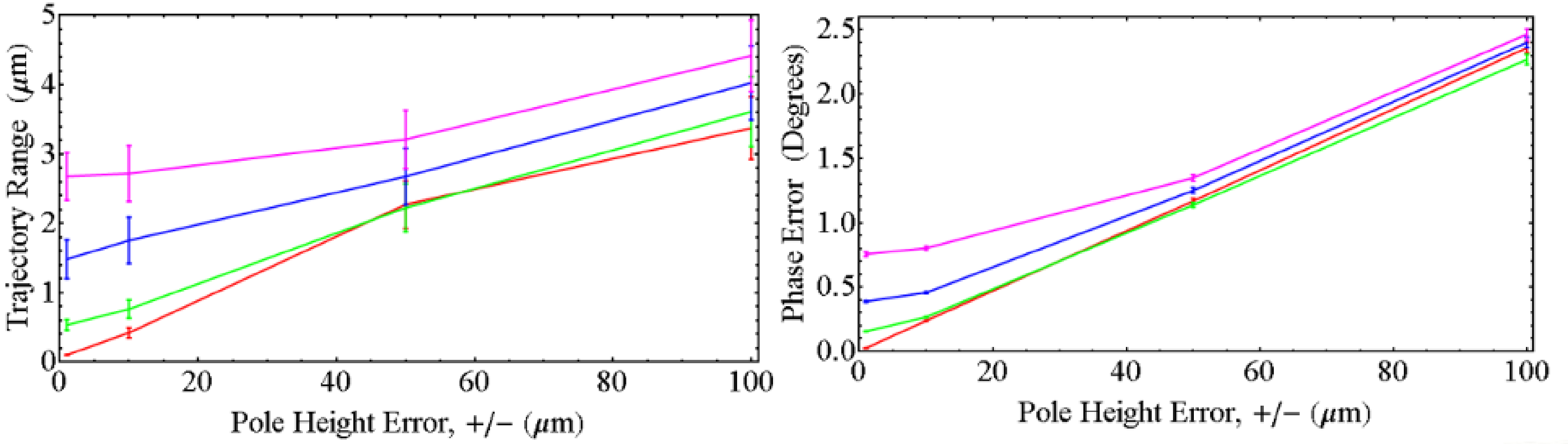
- Peak field in winding ≈ 3.5 T
- Operating current ≈ 450 A
- Operating margin at 1.8 K ≈ 10%
- Av. Current density ≈ 1800 A/mm^2
- Gap = 7 mm
- Rectangular NbTi wire – 0.66 x 0.37 mm
- Winding: 6 wide by 11 deep
- Winding tolerance = ±50 μm longitudinally and ±10 μm depth
- No in-built local correction system





Radia Modelling

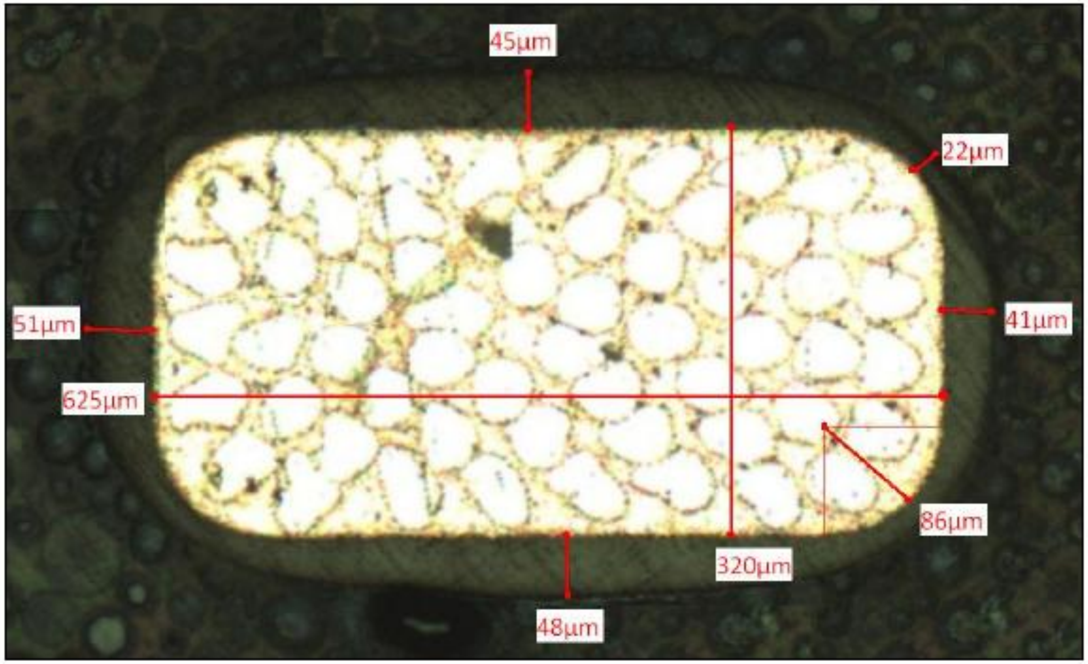
- Effect of errors in pole dimensions suggest that with ±10 μm in height and ±50 μm in length the specification can be met



Effect of pole height error for a pole length error of ±1μm (red), ±10 μm (green), **±50 μm (blue)** and ±100 μm (magenta)
Error bars define 99% confidence levels

SC Wire

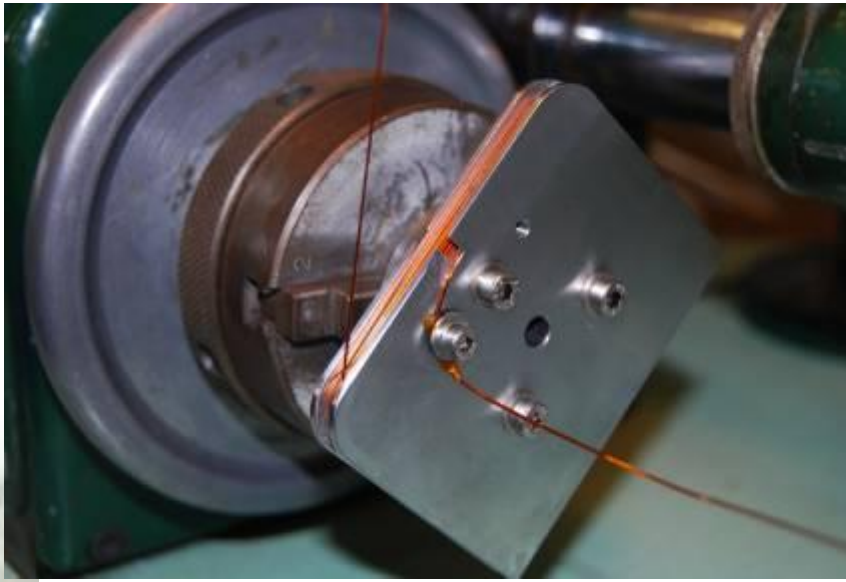
- NbTi procured from Supercon
- Cu:SC of 0.9:1.0
- 0.5mm diameter round wire has been rolled to rectangular to improve packing factor

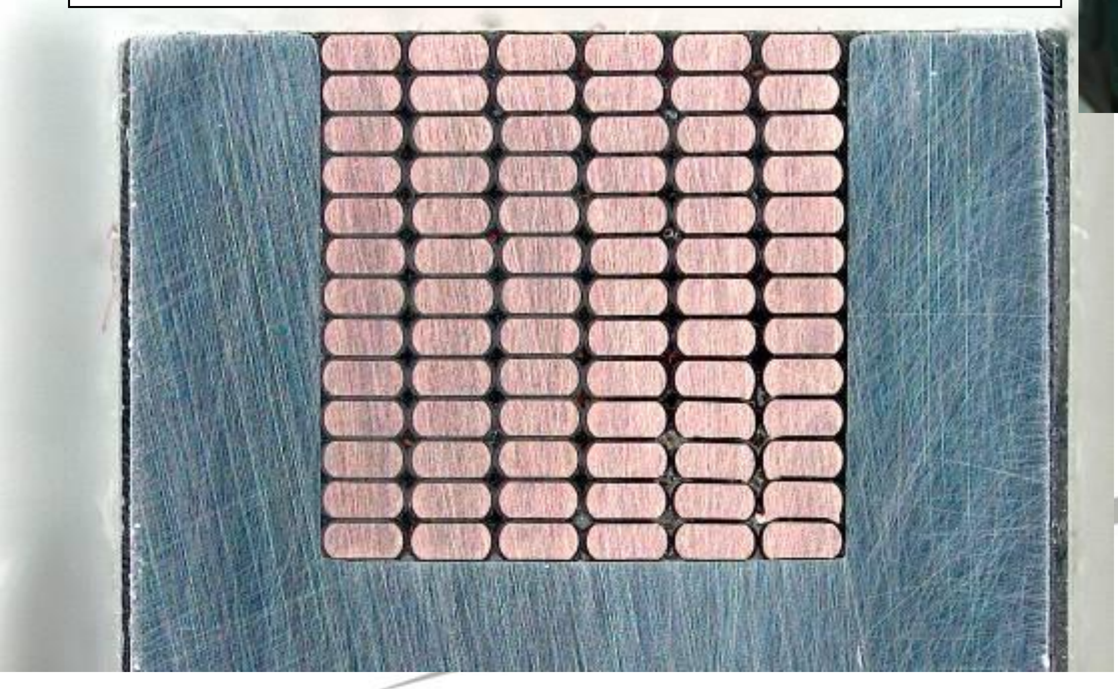


Winding and Former Trials

Initial winding trials have been done with a single coil former and rectangular section (0.635mm x 0.305mm) insulated Cu wire.

Objective was to devise a winding/potting procedure which would position/align the wires to within 10 microns in y.





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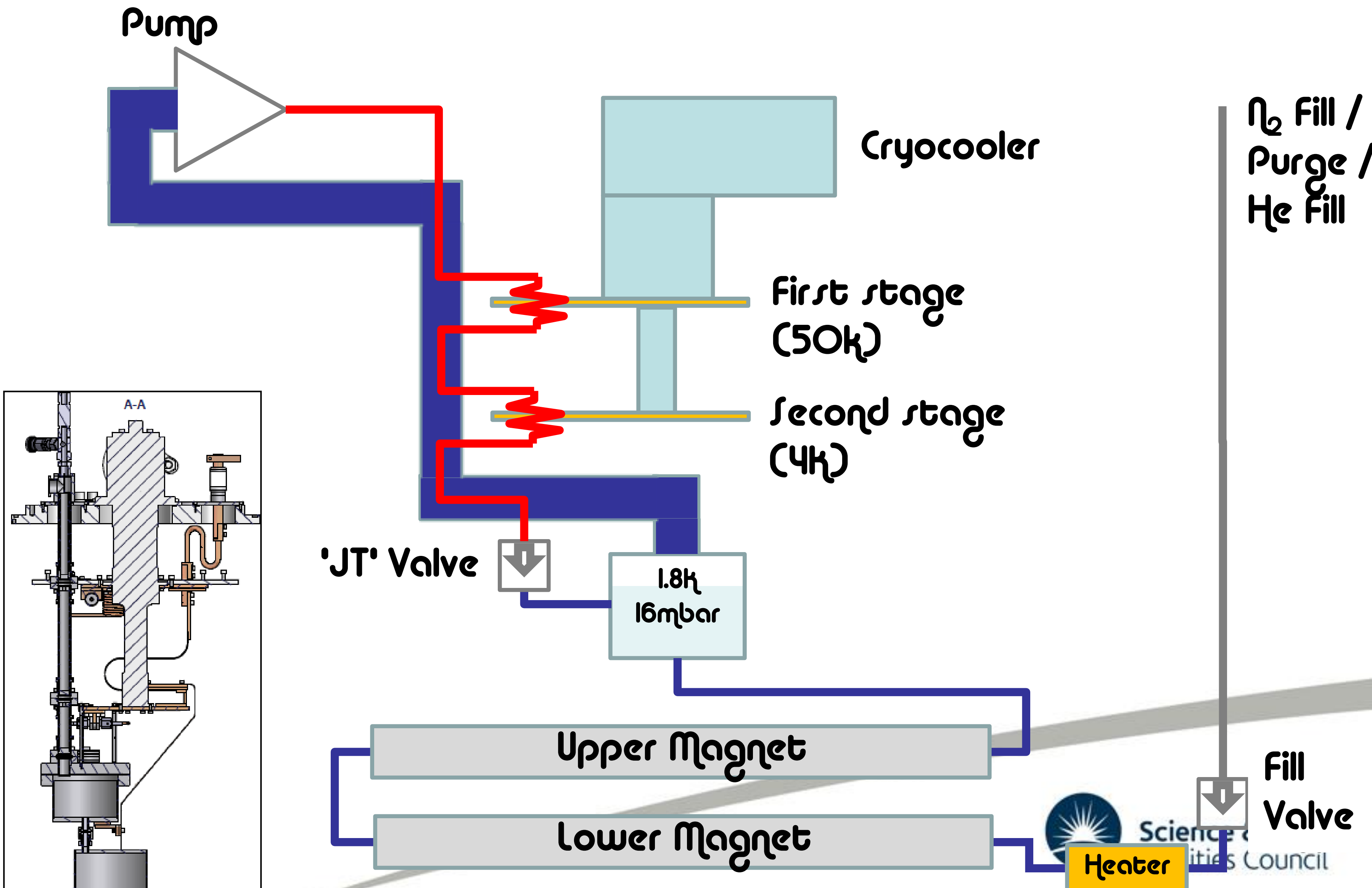
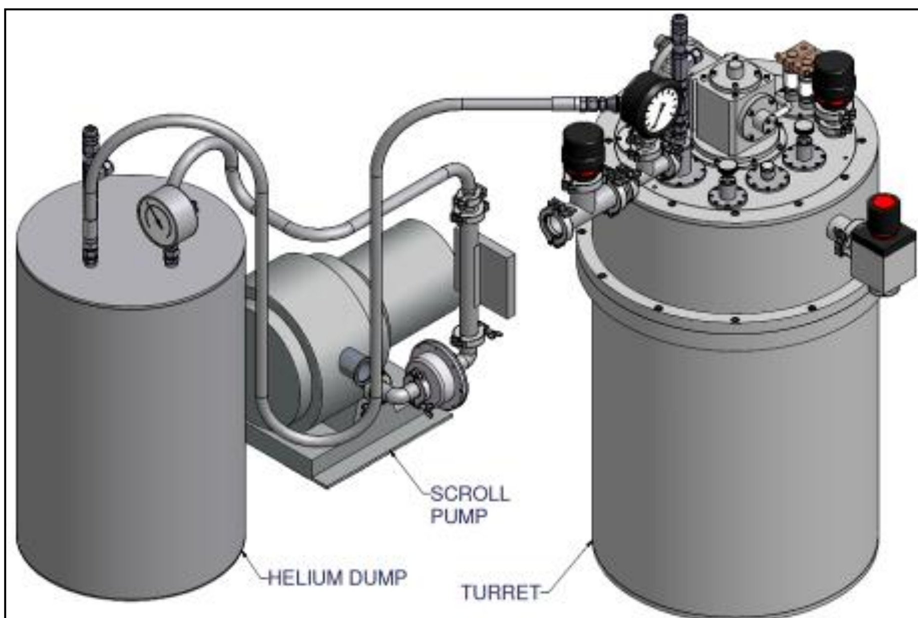
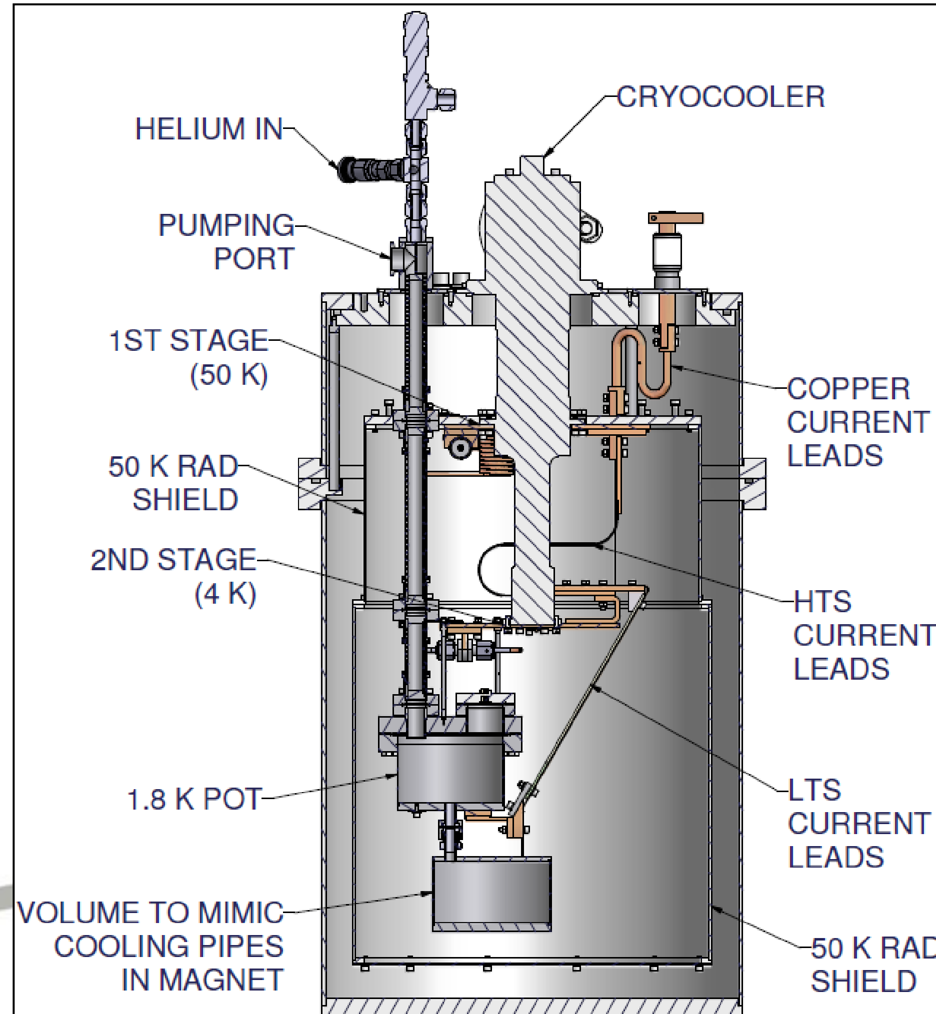
Conceptual Layout of Turret



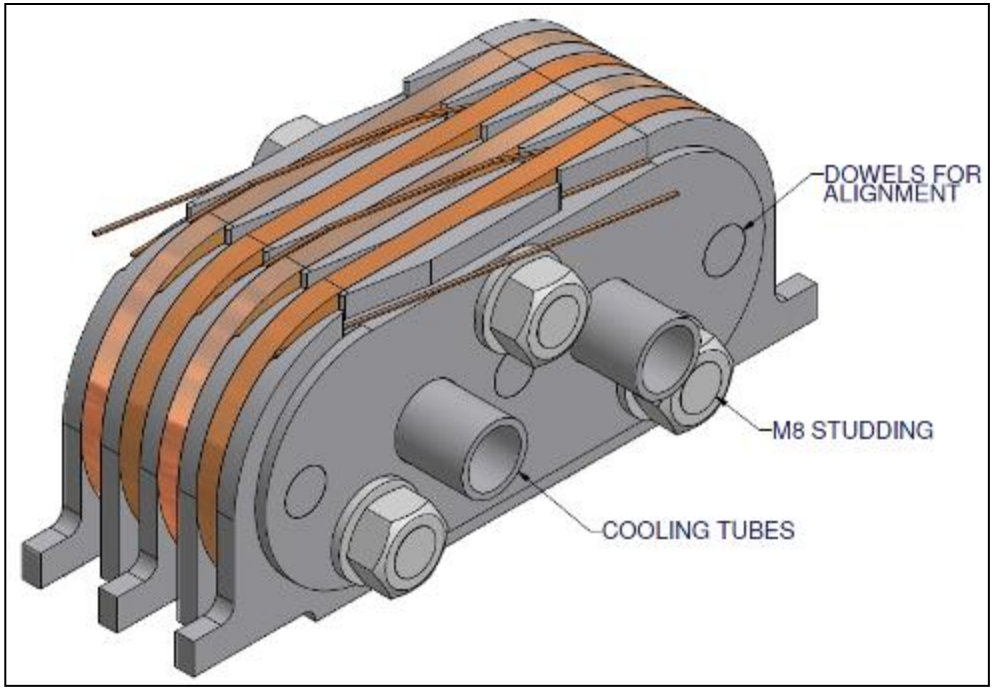
Cryogenic Turret

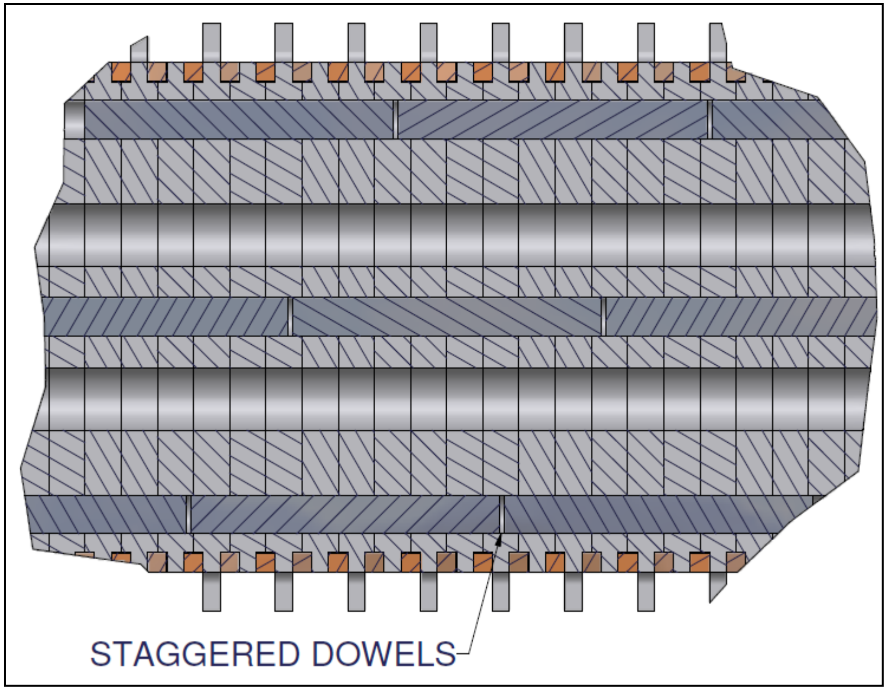
- 200 mW of cooling power at 1.8 K with only 0.68 W load on Cryocooler 2nd stage
- Most parts now delivered
- Will be tested in isolation prior to full magnet construction
- Contains dummy load with heater

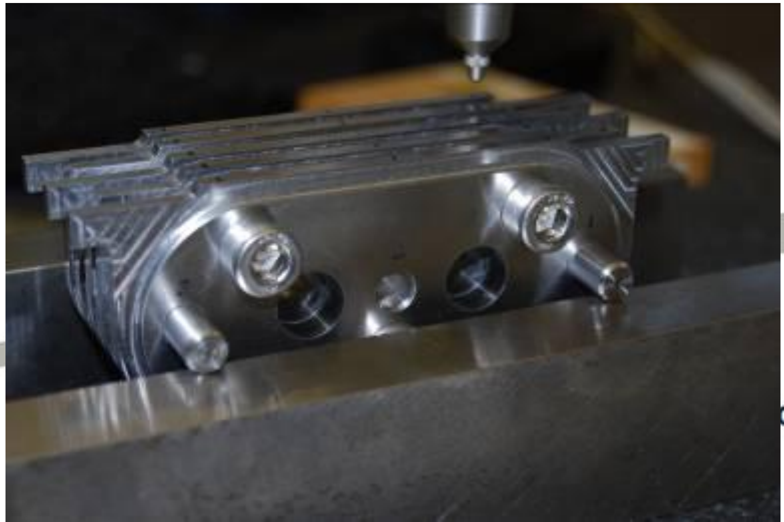




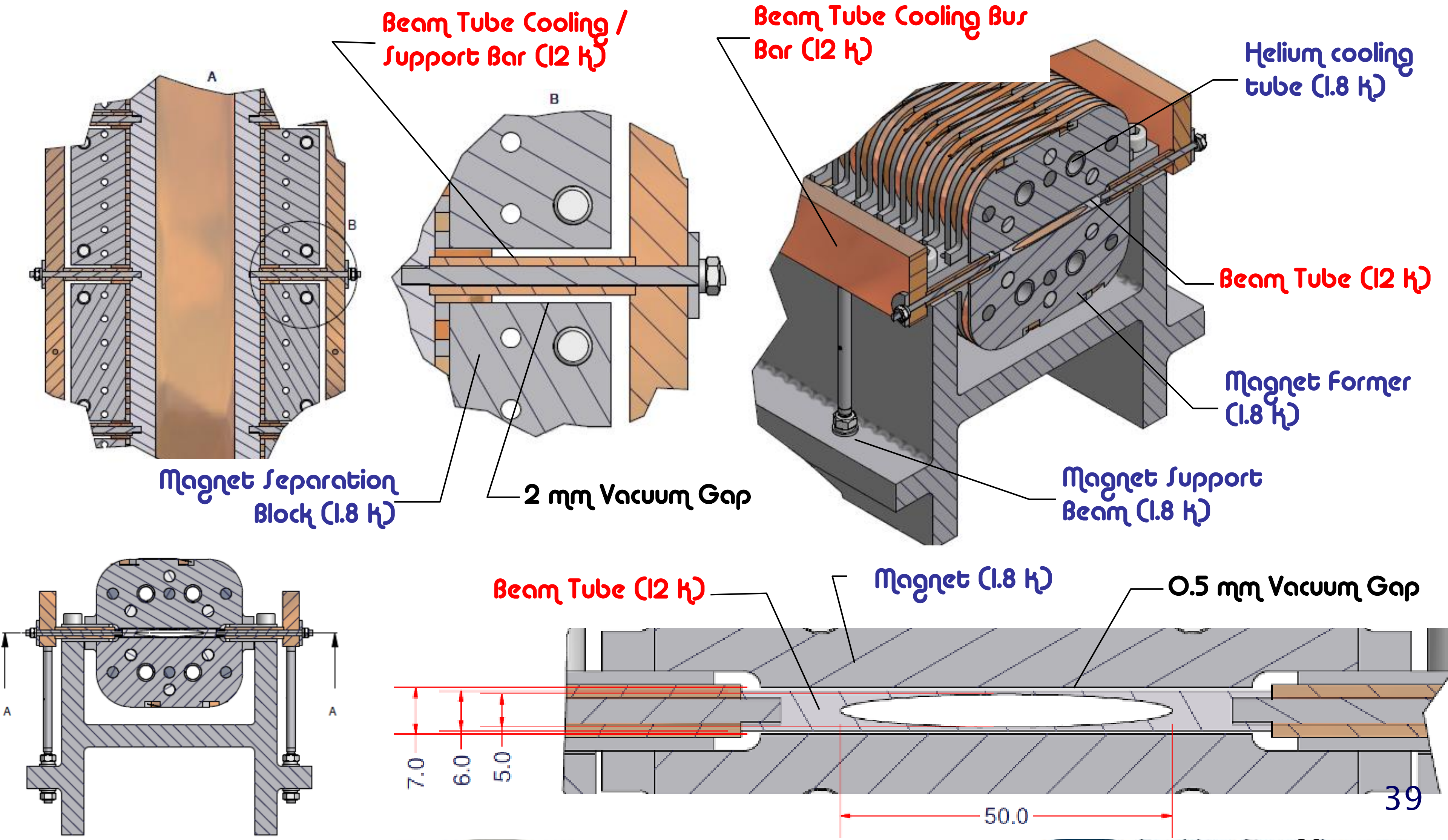
Undulator Magnet







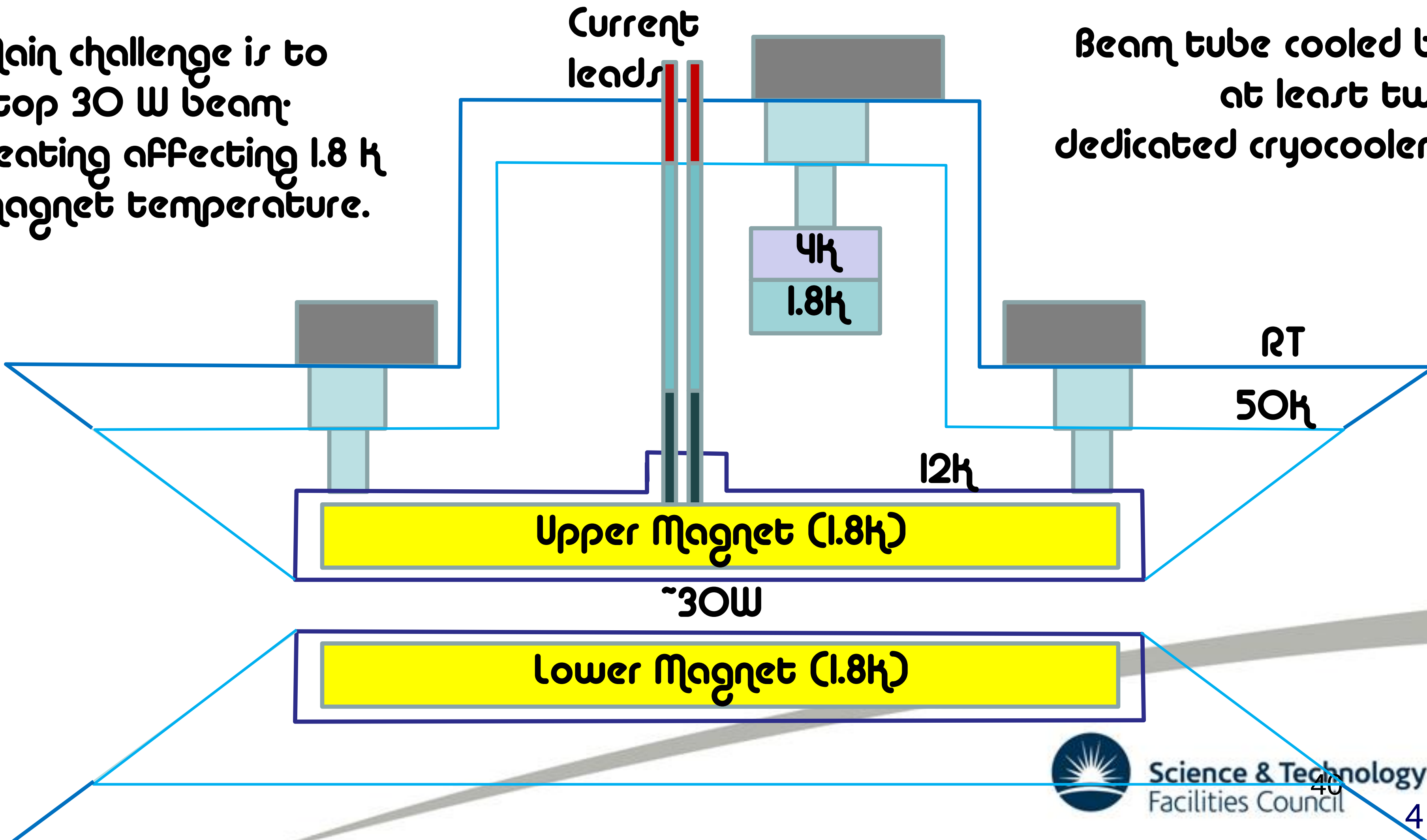
Undulator Assembly



Conceptual Layout of Cryostat

Main challenge is to stop 30 W beam: heating affecting 1.8 K magnet temperature.

Beam tube cooled by at least two dedicated cryocoolers.



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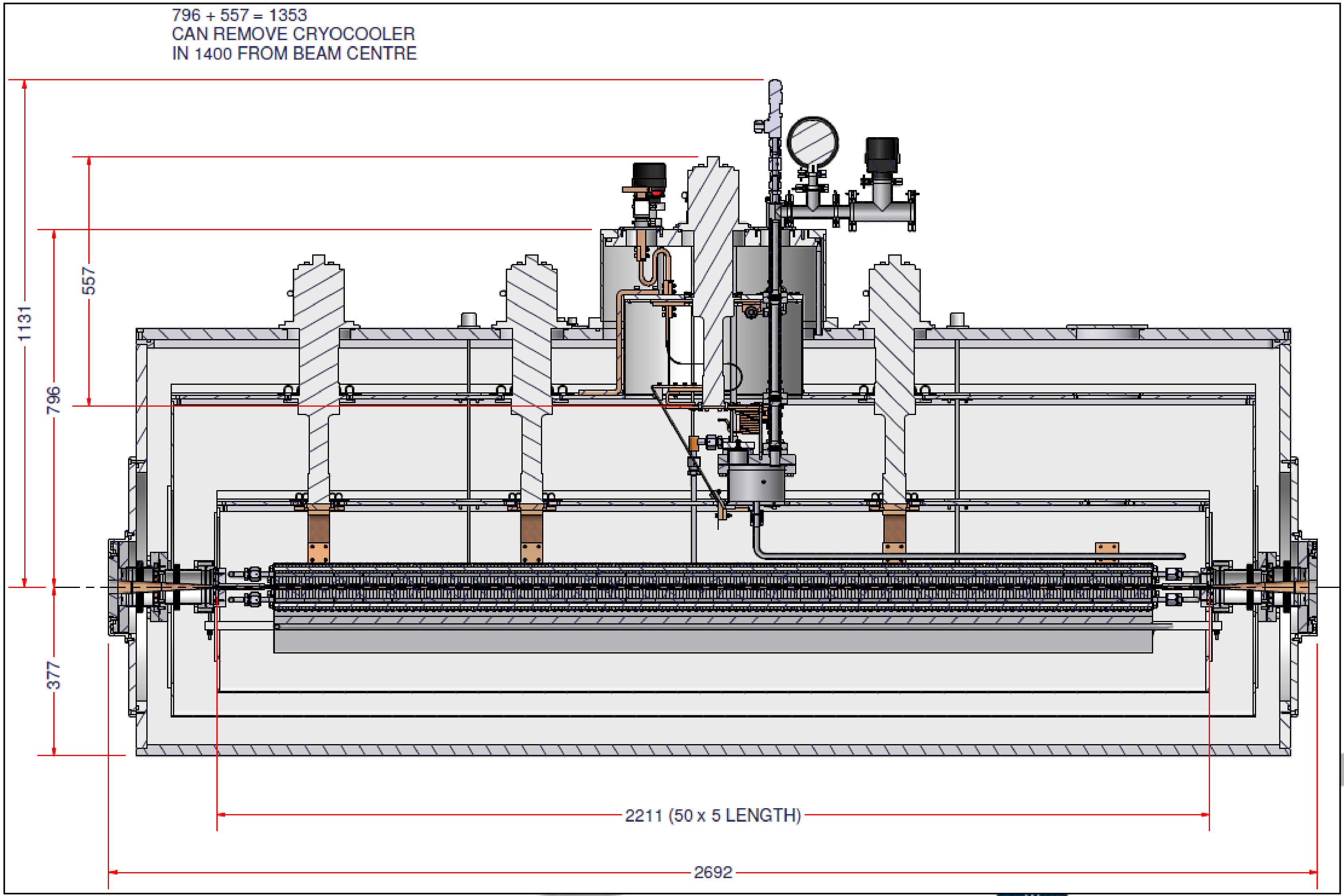
Complete Undulator



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Planar Future Steps

- Assemble the turret test rig and confirm the cooling powers expected are achieved
- Construct a short magnet array to confirm tolerances are achieved
- Construct and vertically test full length magnet
- Assemble and test complete undulator
- Install into Diamond and confirm cryo and magnetic performance

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Resistive Wakefields

- Resistive Wakefields rely on computing the interaction of an external field with the “electrical properties” of the environment
  - External field – electron bunch
  - Environment – Conductivity & shape of vessel
- Different conductivity models are used:
  - DC Conductivity
  - AC Conductivity
    - frequency dependant
  - Anomalous Skin Effect
    - The skin depth is small compared to the mean distance between collisions
  - Extreme Anomalous Skin Effect
    - Behaviour at very low temperatures (<4K)

$$\sigma_{AC} = \frac{\sigma_0}{1 - i\omega\tau}$$

Mean time between collisions for an electron

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Simulations

- The resisitive wakefield is often the limiting factor for how narrow the magnet aperture can be
- Especially important for predicting heat load on cold bore SCUs
- Simulations can only be as accurate as the material properties entered into the codes
- Material properties are not well known, especially at 4K
- Effect of coatings (eg copper or NEG) not clear

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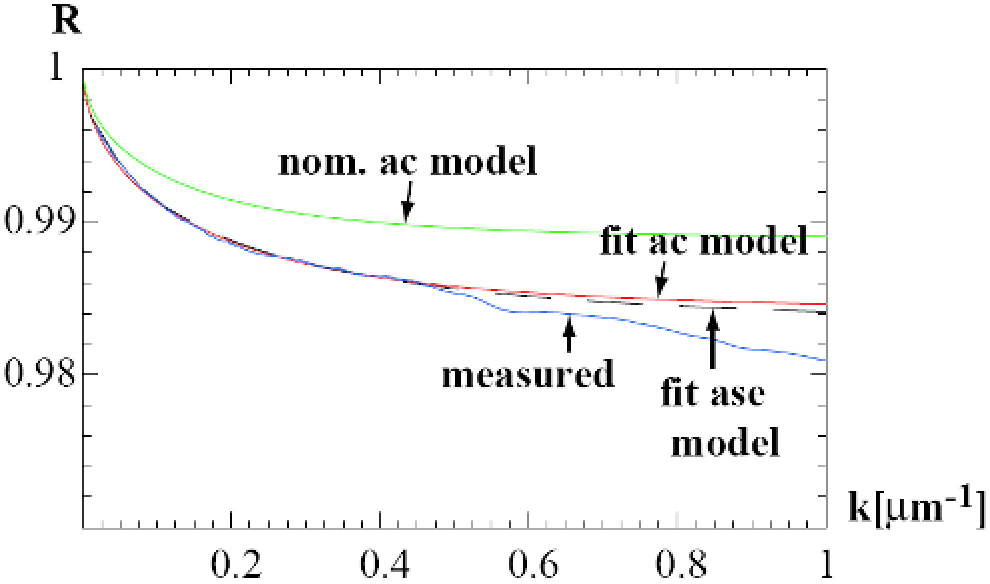
Measurements

- To accurately model the conductivity we need to accurately measure it
- Optical properties of metals:
  - From a measurement of the reflectivity of a metallic surface the conductivity can be inferred
  - Difficult to measure accurately



(Bane, Stupakov & Tu)

Measurements

- Measure the attenuation and dispersion of EM THz signal passing through the vessel – which acts as a waveguide.
  - Signal to noise ratio much higher
  - Can measure the actual beam pipe that will be used
  - Waveguide theory enables us to calculate the mode structure of the THz and the mode propagation
  - Cylindrical vessels, rectangular vessels, elliptical vessels, etc
  - Compare theory to experiment
  - Warm or cold vessels possible

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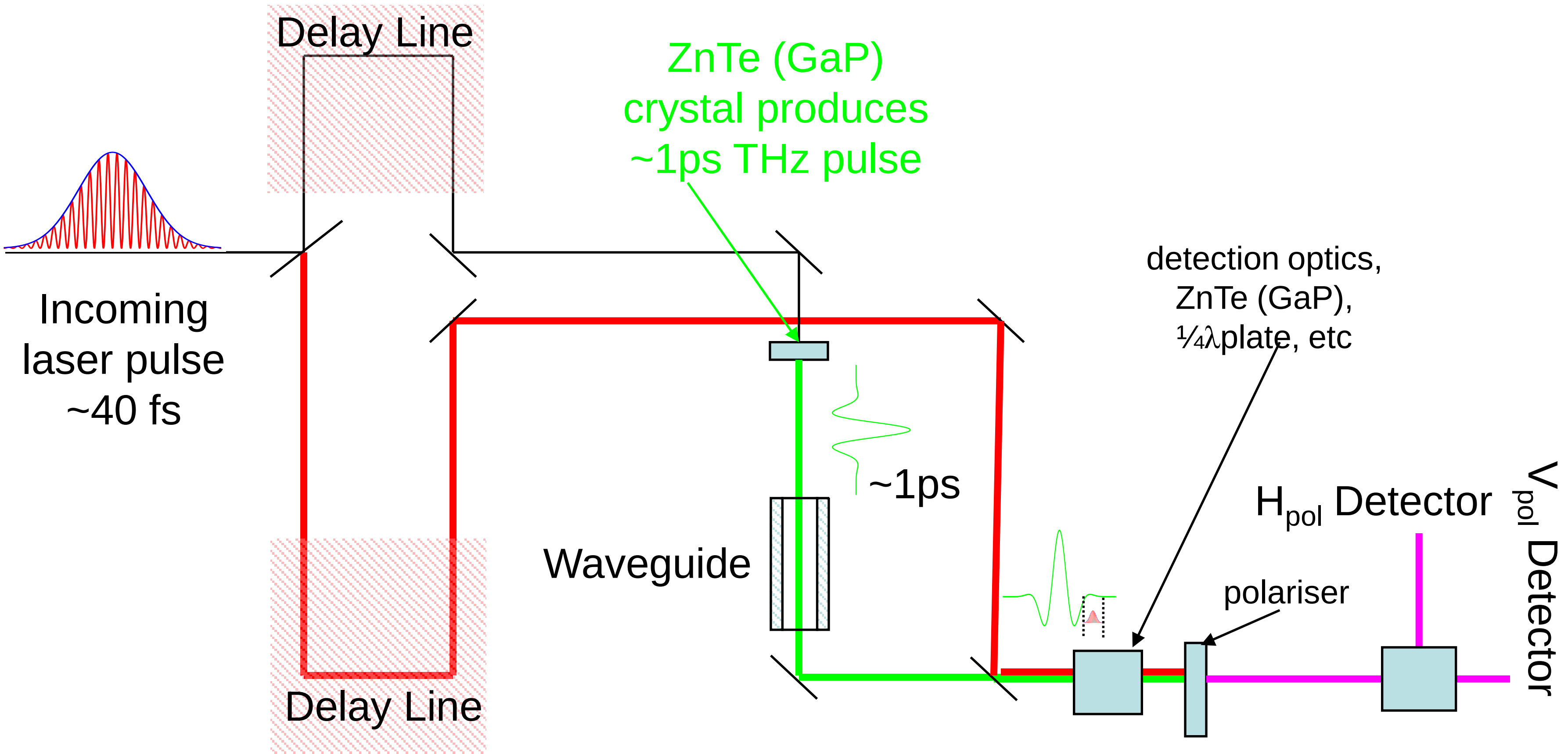
Experimental set-up

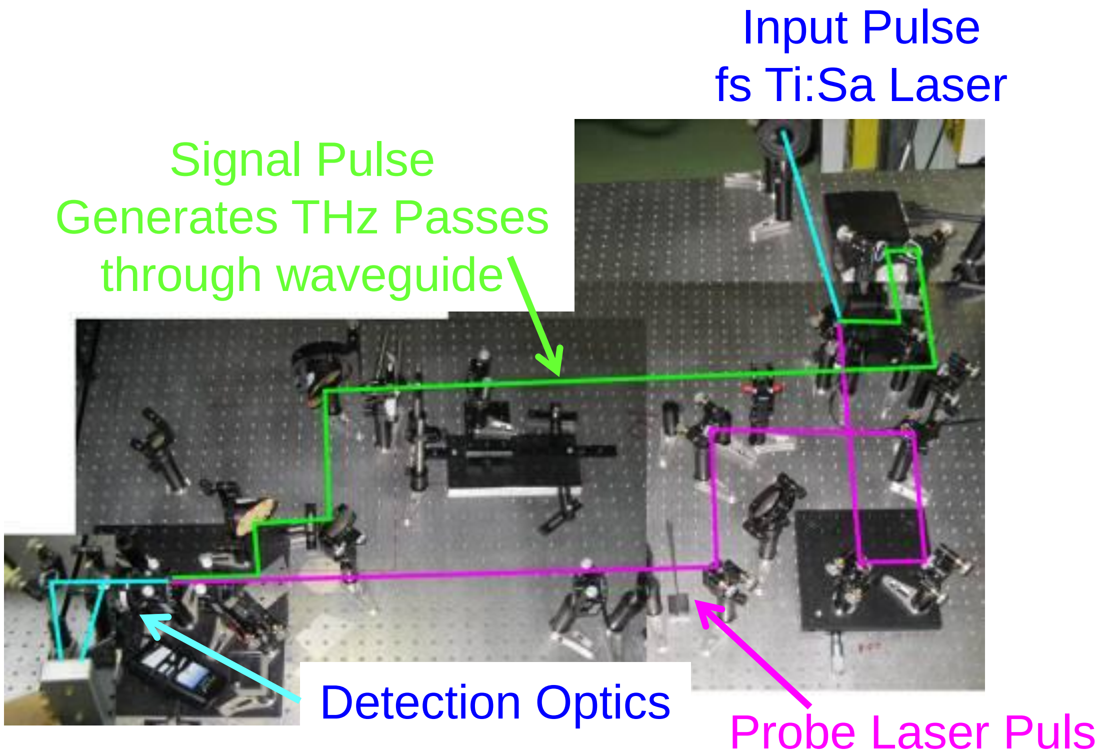


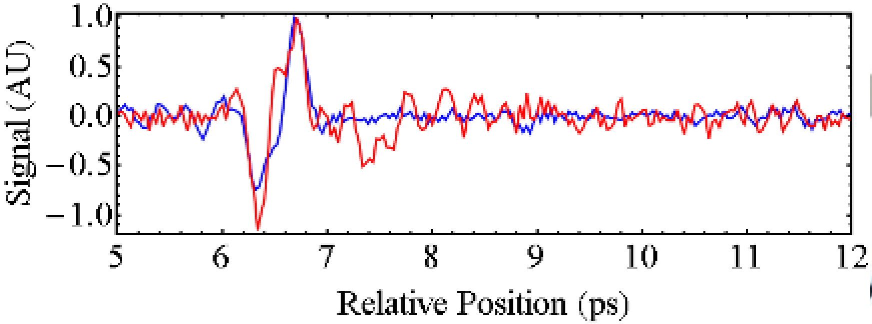
– sub-picosecond time-resolved measurement of the attenuation and dispersion of a THz pulse (generated by optical rectification) through a waveguide

ology

Initial Results

- First stage: get experiment working with simple rectangular and circular waveguides at room temperature
- First results encouraging
- Measure difference signal between two different length waveguides





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Summary

- SCU Helical constructed from NbTi and full spec achieved (0.86T @ 11.5mm)
- Nb_3Sn short prototypes will be constructed soon (1.5T @ 11.5mm?)
- SCU Planar design virually complete (NbTi)
  - 1.4T @ 15mm, 1.8K magnet with 5mm beam aperture
- Winding trials underway
- Turret system procured and will be assembled and performance confirmed soon
- Experiment technique developed to measure directly the electrical properties of warm or cold vacuum vessels
  - Initial results promising

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