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The development of a Superconducting Undulator for the ILC Positron Source

James Rochford
On behalf of the HeLiCal collaboration

Scope

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

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Helical

Helical collaboration

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

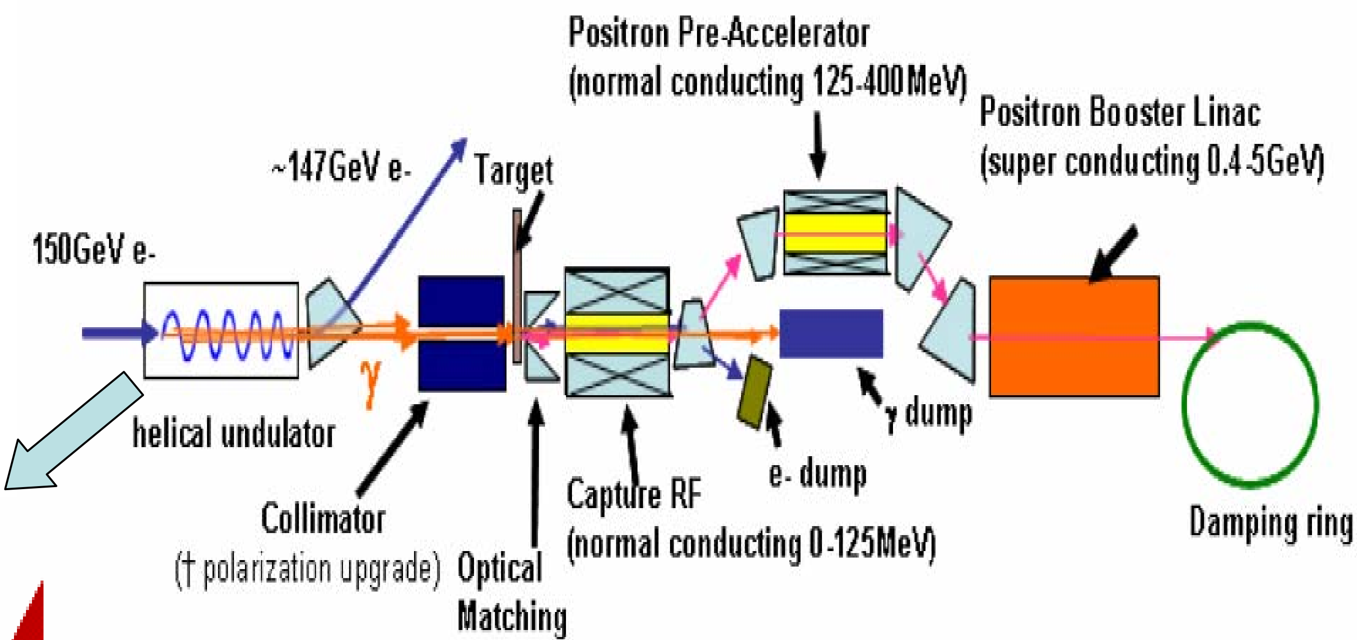
Collaboration members

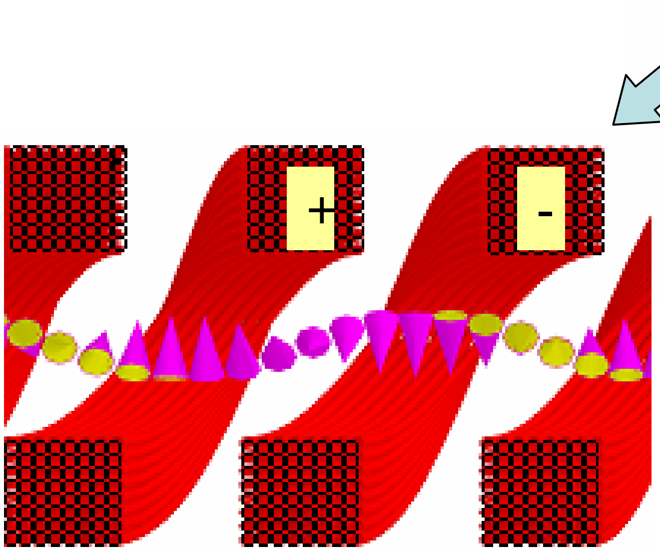
ASTEC:
J.A. Clarke, O.B. Malyshev, D.J. Scott, B. Todd, N Ryder
RAL:
E. Baynham, T. Bradshaw, J. Rochford, A Brummit, G Burton, C Dabinett,S. Carr, A Lintern
University of Liverpool :
I.R. Bailey, J.B. Dainton, P. Cooke, T. Greenshaw, L. Malysheva
DESY :
D.P. Barber
University of Durham :
G.A. Moortgat-Pick
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

ILC

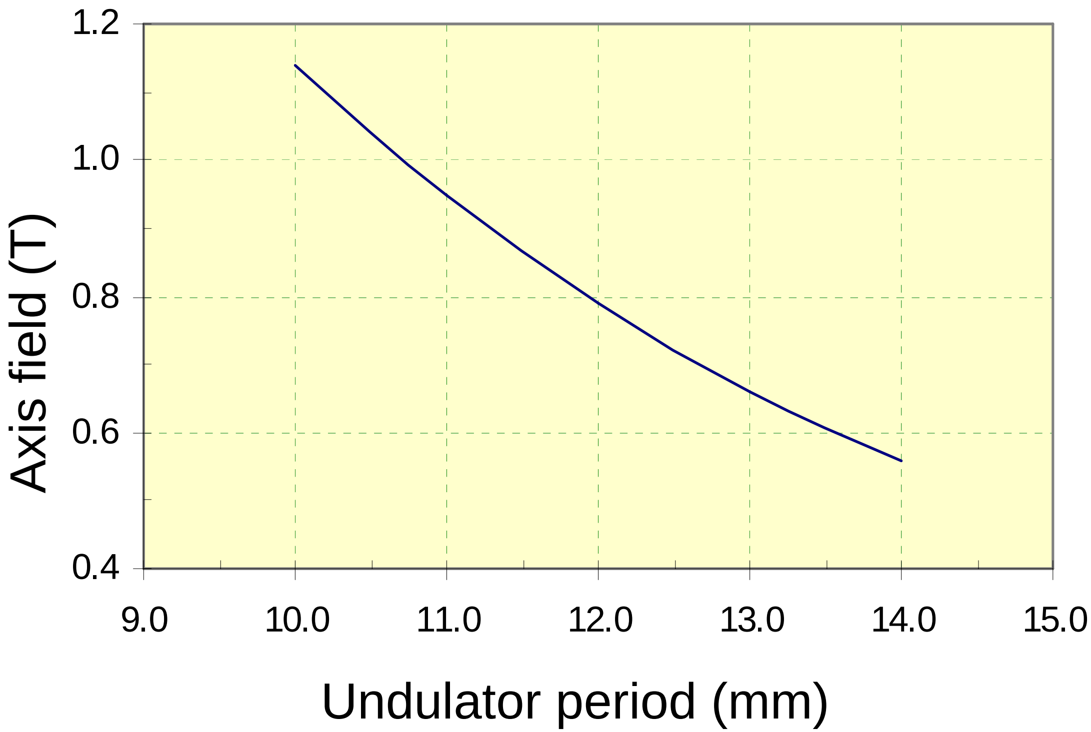




Undulator :

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

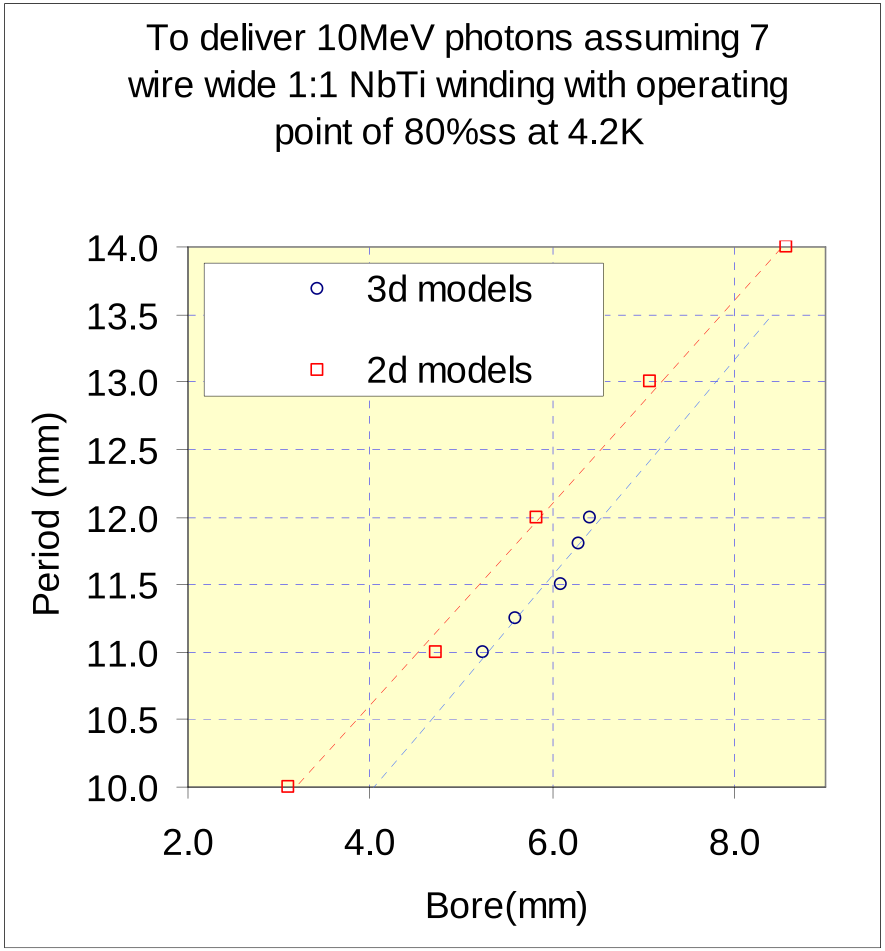
- Magnetic modelling what's achievable with NbTi
- Prototype research and development
- Manufactured specification

Magnetic modelling

Calculated operating point for 7 wire 9 layer Cu:Sc 1:1 NbTi ribbon					
period (mm)	Winding bore (mm)				
	5.25	5.60	6.10	6.30	6.42
12.00	49	58	71	77	80
11.80	55	63	75	80	82
11.50	64	71	80	84	87
11.25	72	80	92	96	99
11.00	80	89	103	108	112

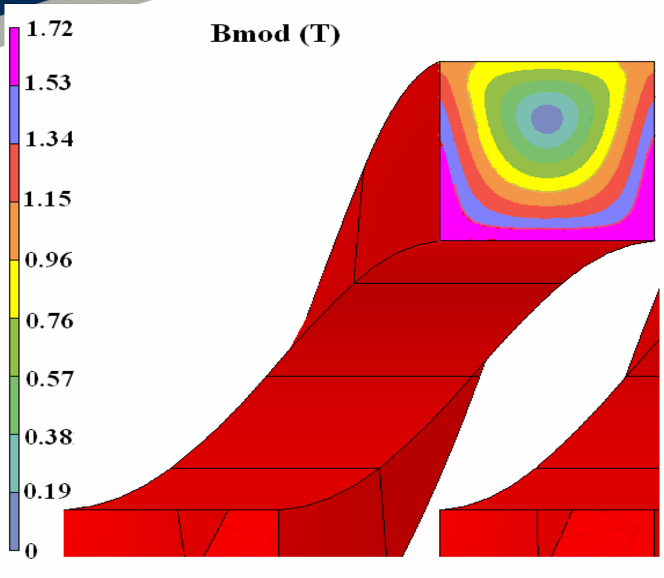
Relationship between period and winding bore in terms of operating point

- 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

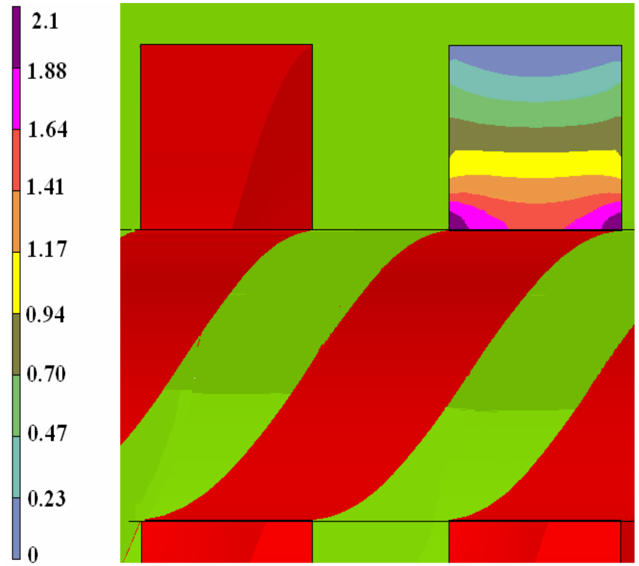


Plots showing realistic bore-period models

Magnetic modelling



The peak conductor field
- No iron present
- bore field 0.8T
- Jrequired= 1000A/mm^2



The peak conductor field
- Full iron poles
- Bore field=0.8T
- Jrequired=400A/mm^2

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

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Magnetic modelling

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

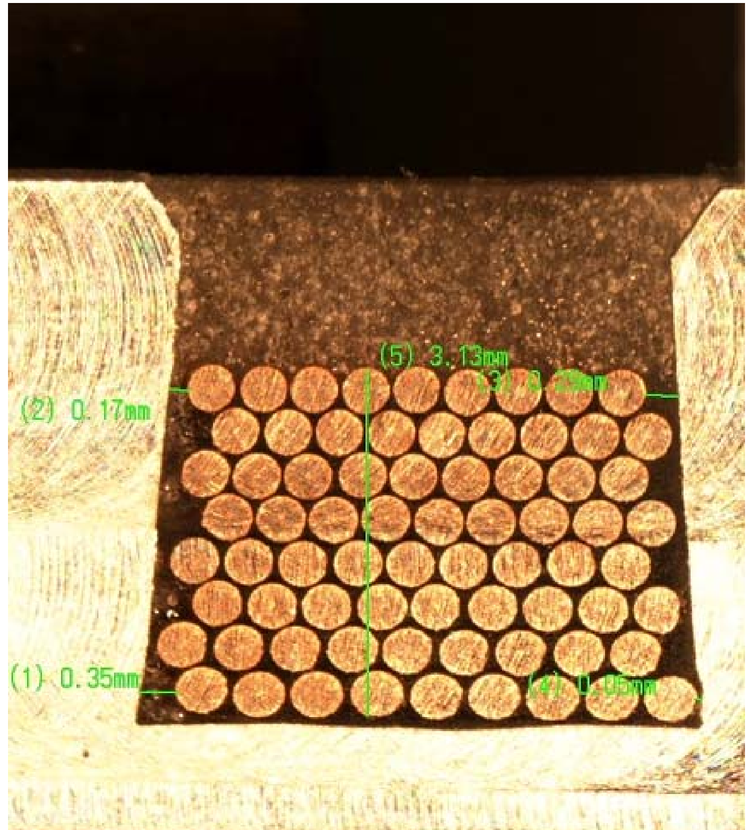
- Employ Quench resistance ~0.5ohm

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

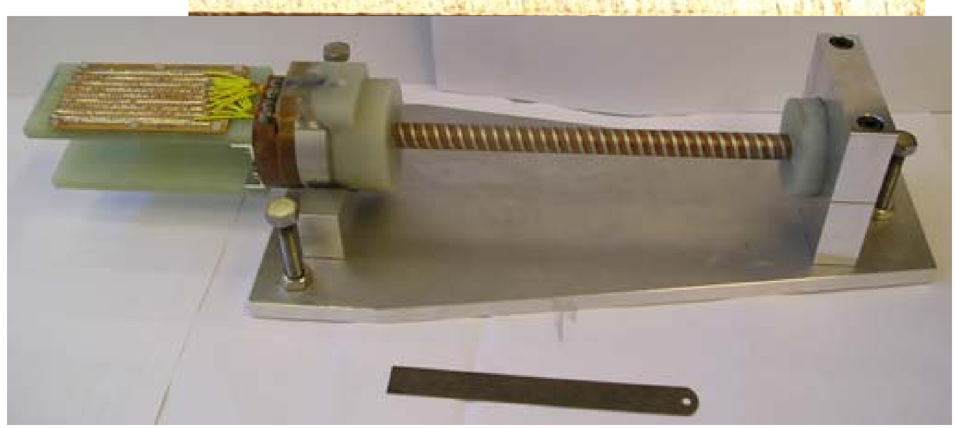
Quench current	A	215	215	300	300
Protection resistance	ohm	0	0.5	0	0.5
Total energy dissipared internally	J	253	21	578	131
Total energy dissipated externally	J	0	232	0	444
Total energy in system	J	253	253	578	576
Maximum temp rise	K	126	54	161	109
Maximum internal voltage	V	86	7	222	47
Time constant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

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

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**
Superconducting 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**

Cu:Sc ~0.8

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Prototype specification

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

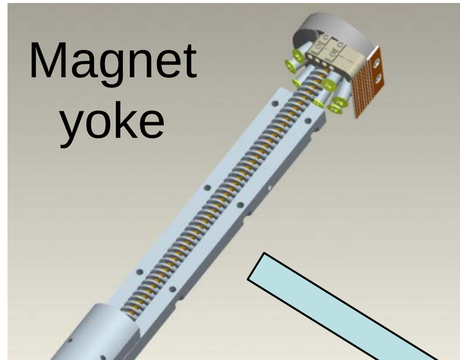
Undulator Period	11.5 mm
Field on Axis	0.86 T
Peak field homogeneity	<1%
Winding bore	6.35mm
Undulator Length	147 m
Nominal current	215A
Critical current	~270A
Manufacturing tolerances	
winding concentricity	+/-20um
winding periodicity	+/-50um
Axial straightness	+/-50um
NbTi wire Cu:Sc ratio	0.9
Winding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

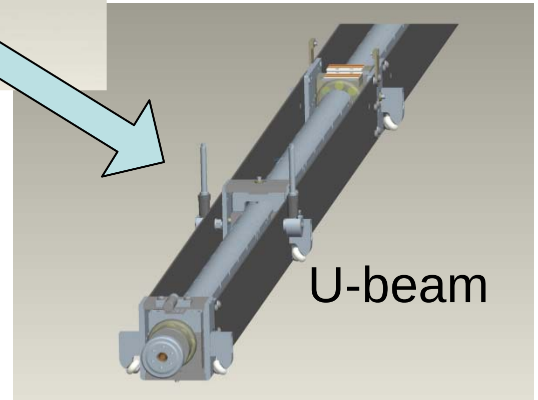
This defines the shortest period undulator we could reliably build as a prototype with a realistic operating margin. The now the baseline for the ILC RDR

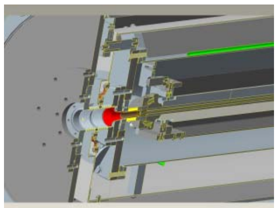
Prototype design

Key features of prototype

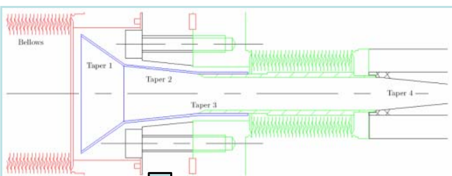
- Magnet rigidity – iron yoke
- Magnet suspension Bessel points in Ubeam
- Alignment between U-beam and He vessel
- Anchored at the midpoint
- Keys allow movement in X and Y
- 4 HTSC current leads
  - independent powering
- Independent beam vacuum

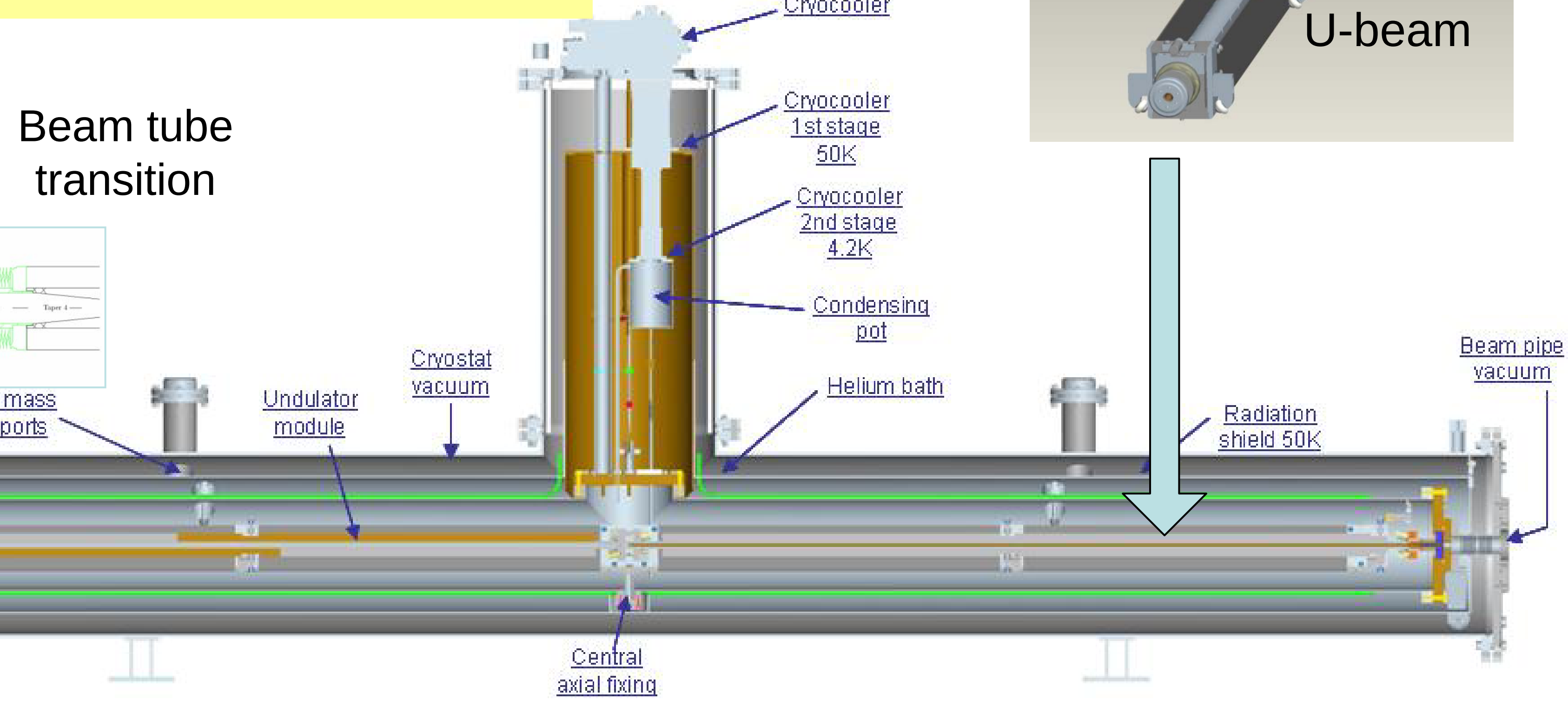




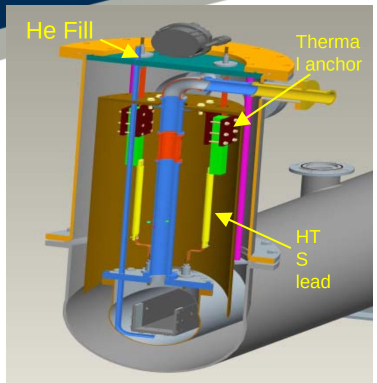


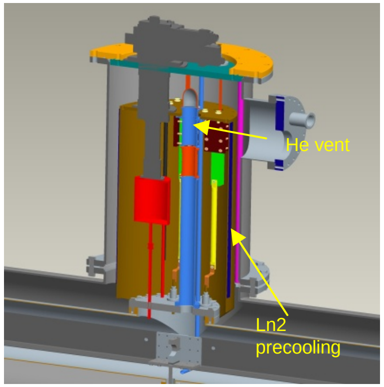
Beam tube transition

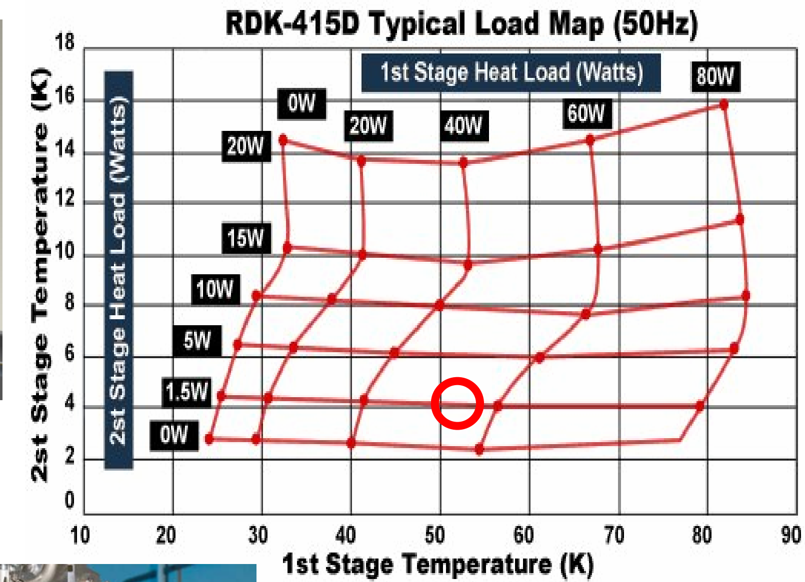




Prototype design







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

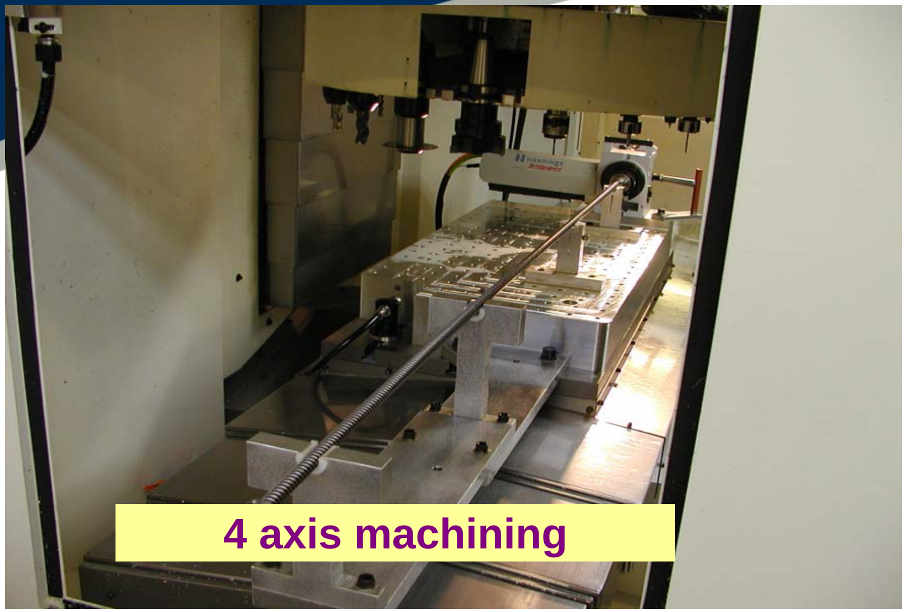
- 50watts 1st stage
- 1 watt 2nd stage

1st stage 55K

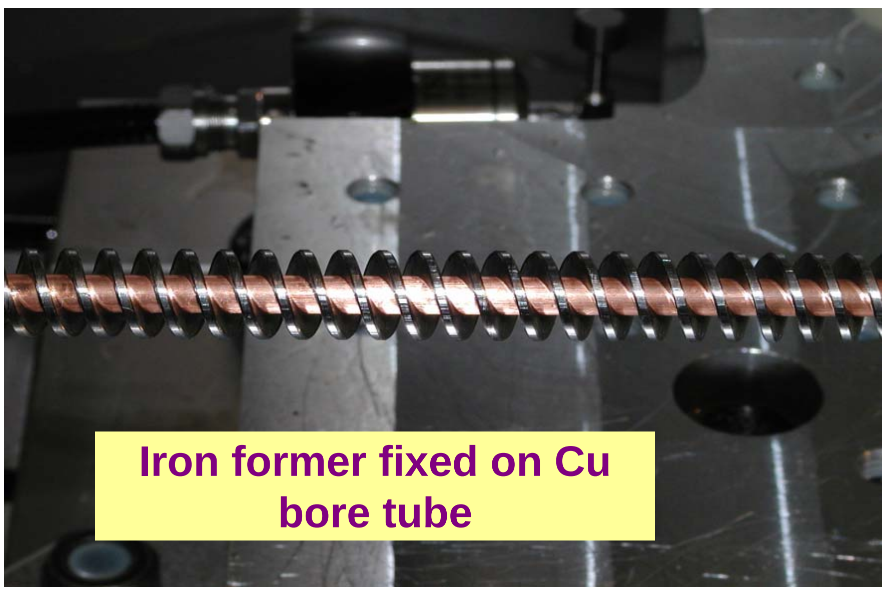
2nd stage 4.5K

0.5W contingency

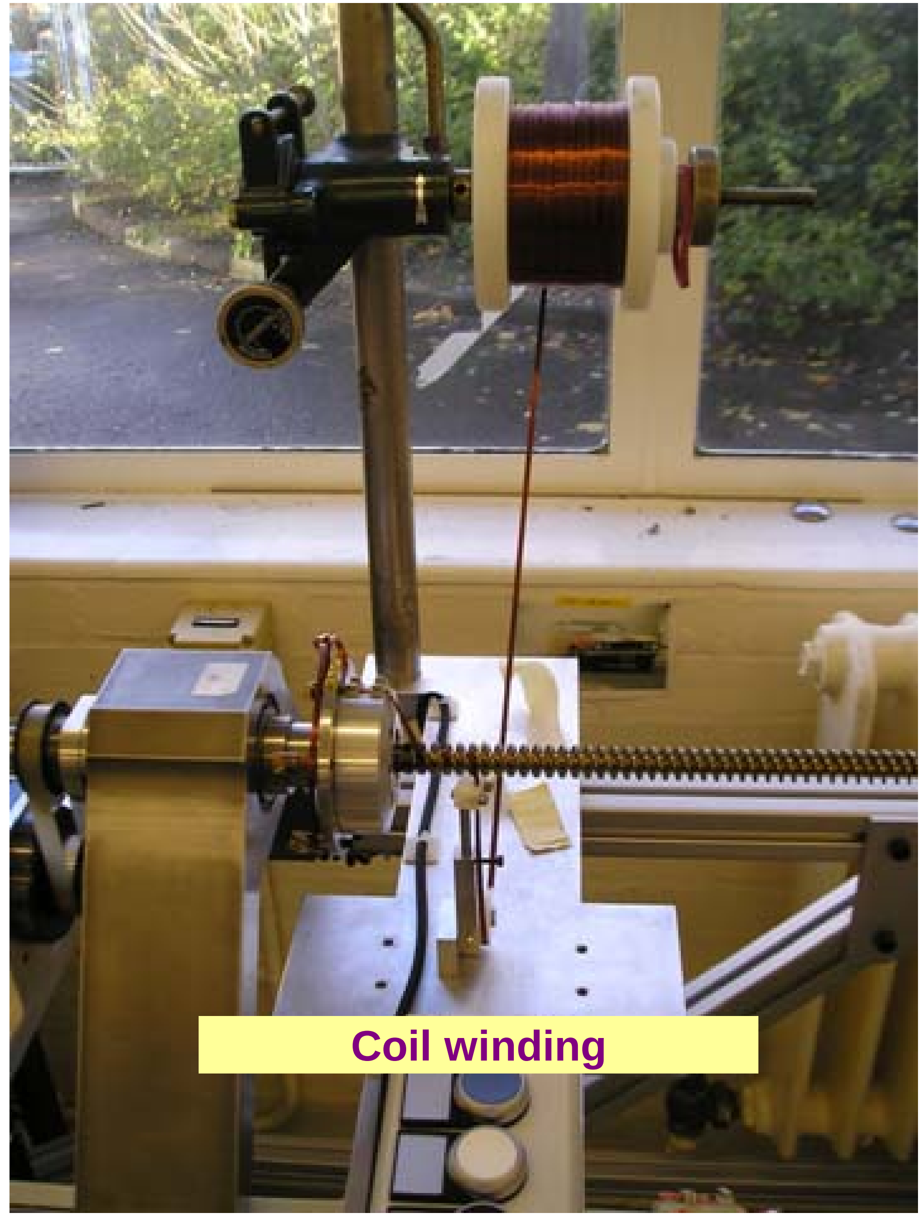
Prototype manufacture



4 axis machining

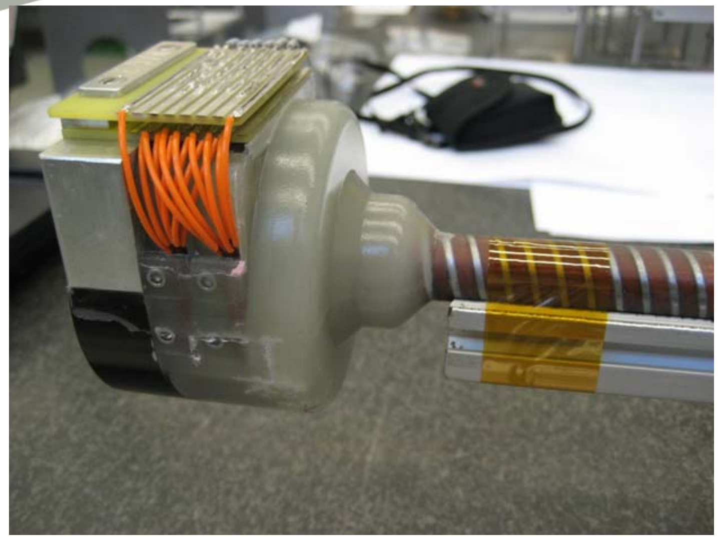


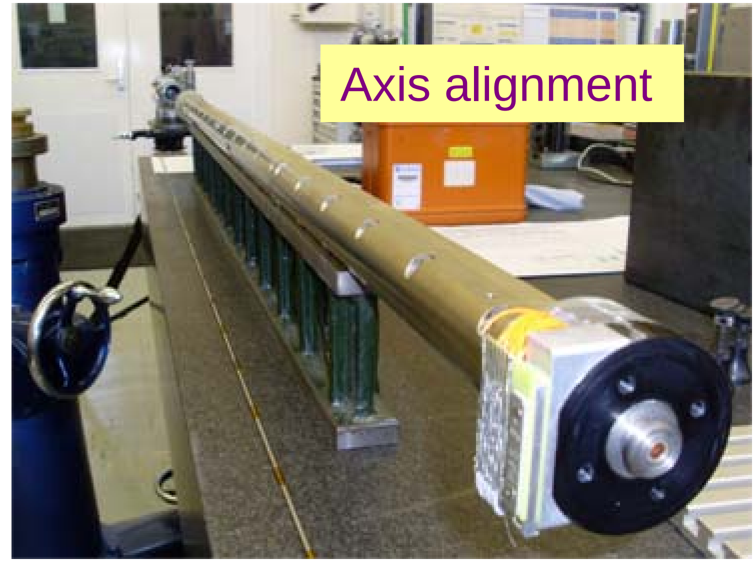
Iron former fixed on Cu bore tube



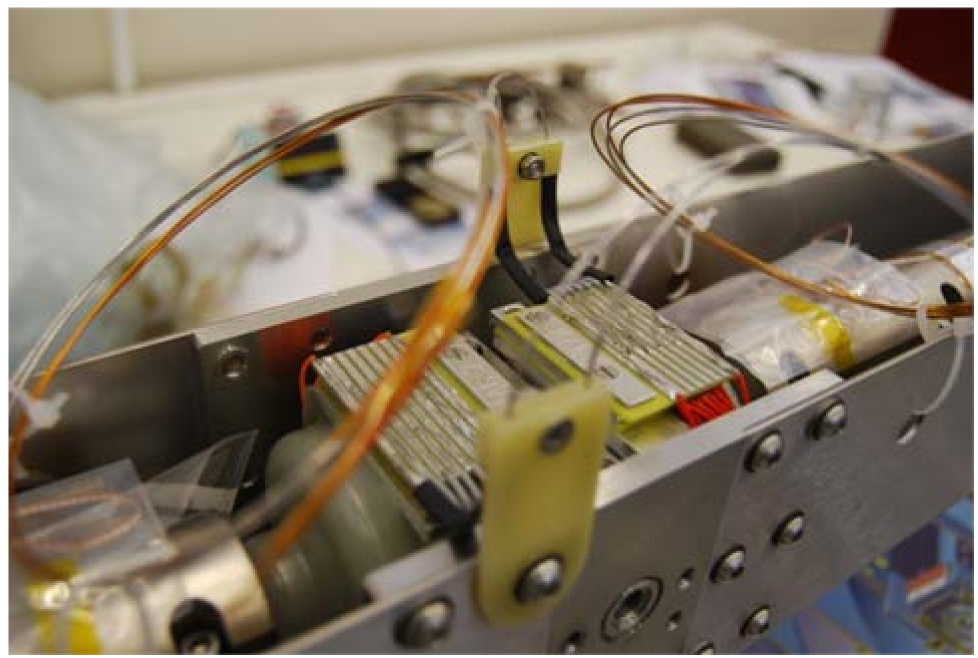
Coil winding

Prototype manufacture





Axis alignment



Following winding

- Potting
- connections to ribbon
- Insertion in Yoke
- Align and clamp in Ubeam

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Prototype manufacture

Magnet straightness

•– Prototype alignment

+/-200um in X

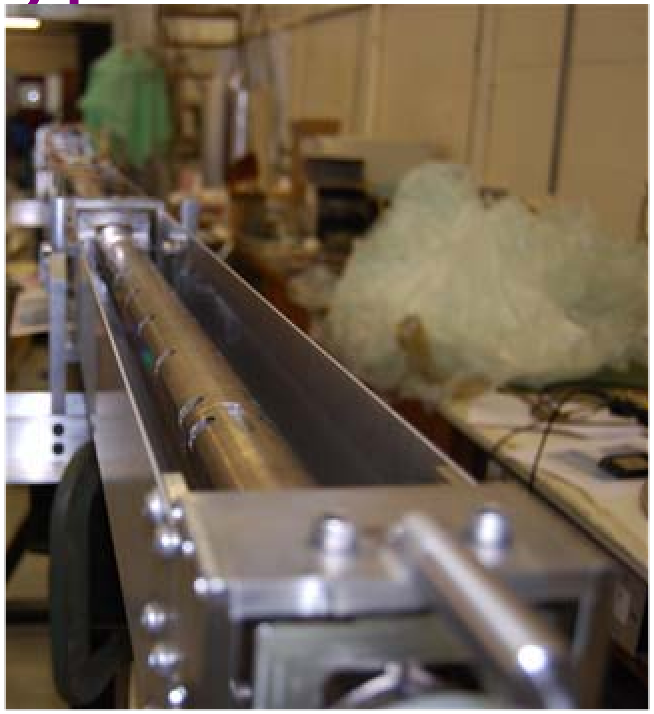
+/-170um in Y

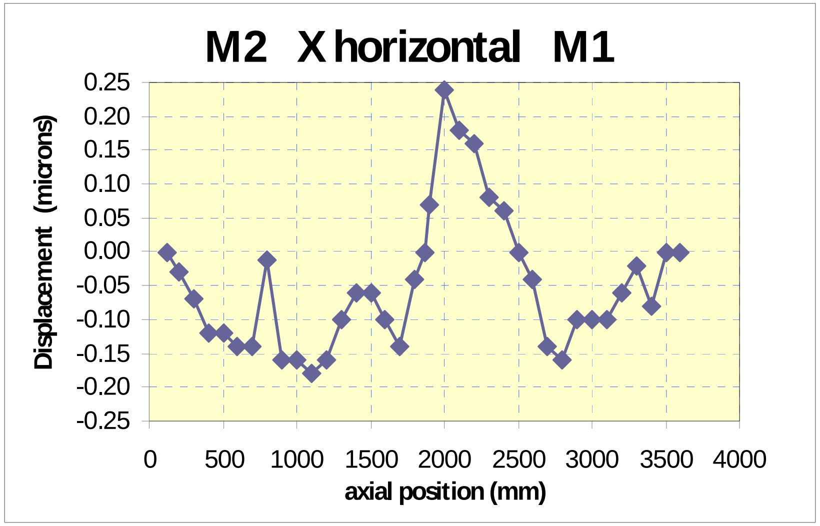
•not adequate to deliver a straightness of +/-50um

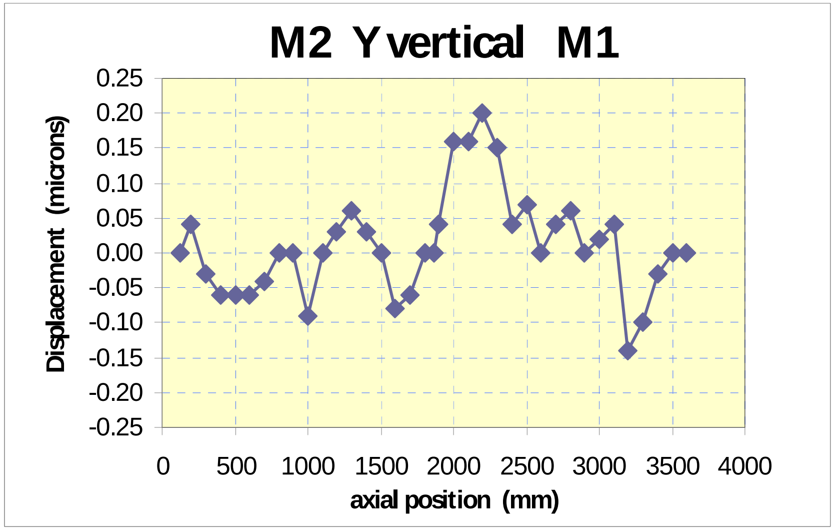
•Developed an active alignment Yoke

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

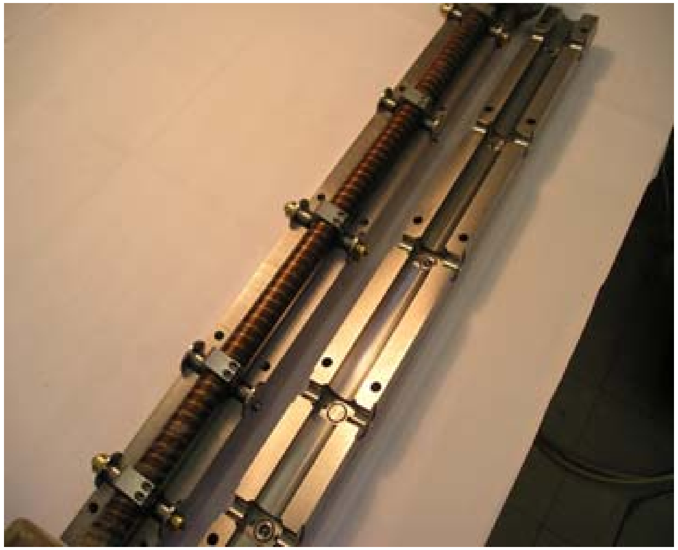
•In principle the prototype can be retrofitted with this system at a later date.





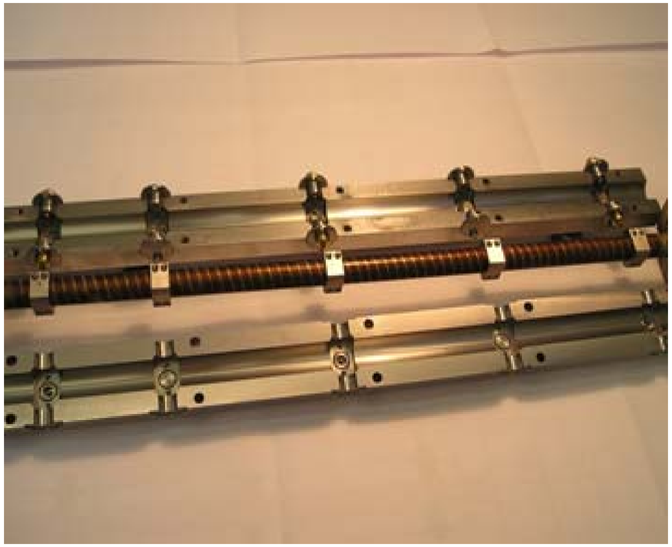


Prototype manufacture

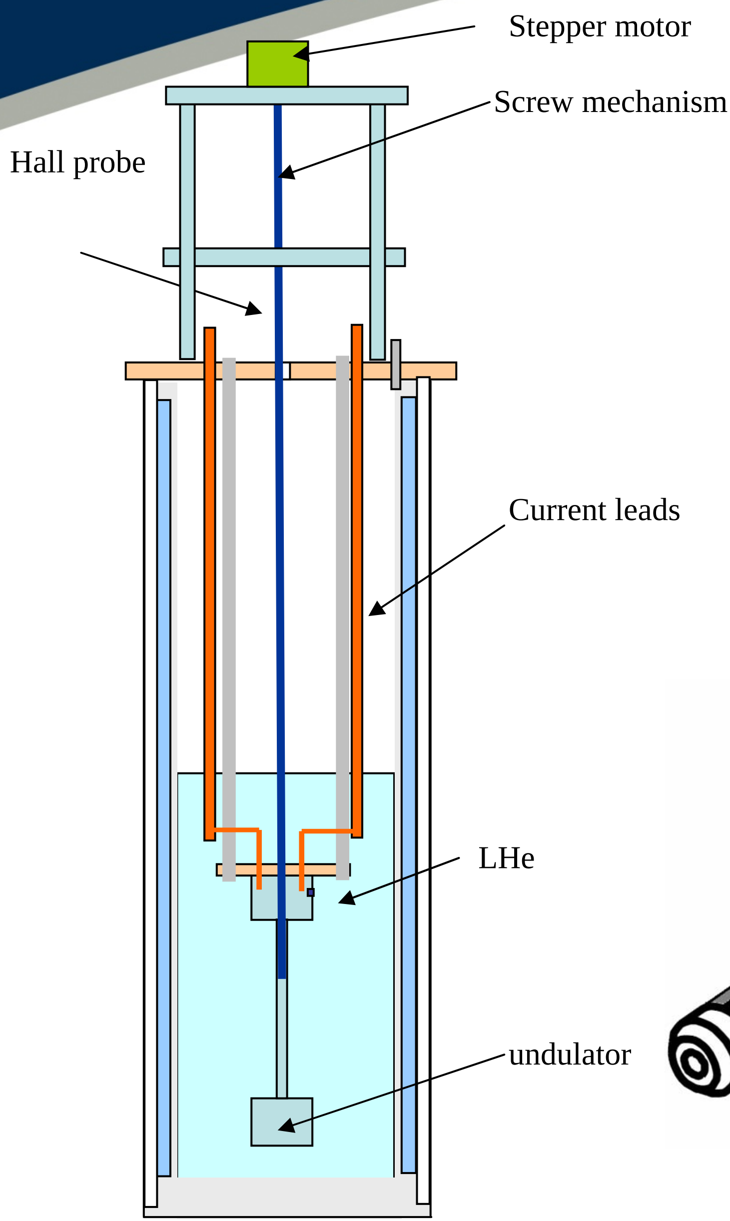


Active alignment system

- 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

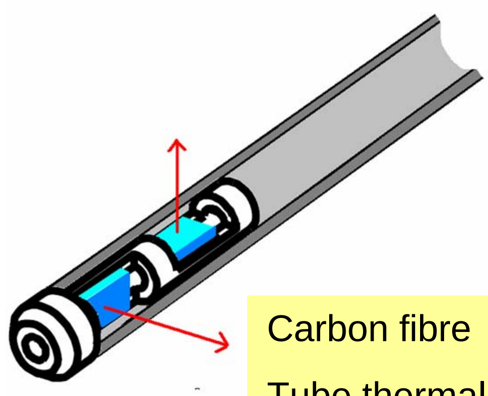


Prototype manufacture



Field maps along the length of the undulator

- Mapping Br along the axis
- At 4 points around the azimuth; 0, 90, 180 & 270 degrees
- At magnet ends more detailed maps at 45^{O} intervals around the azimuth
- Also carried out a Quench study



Carbon fibre

Tube thermal contraction~0

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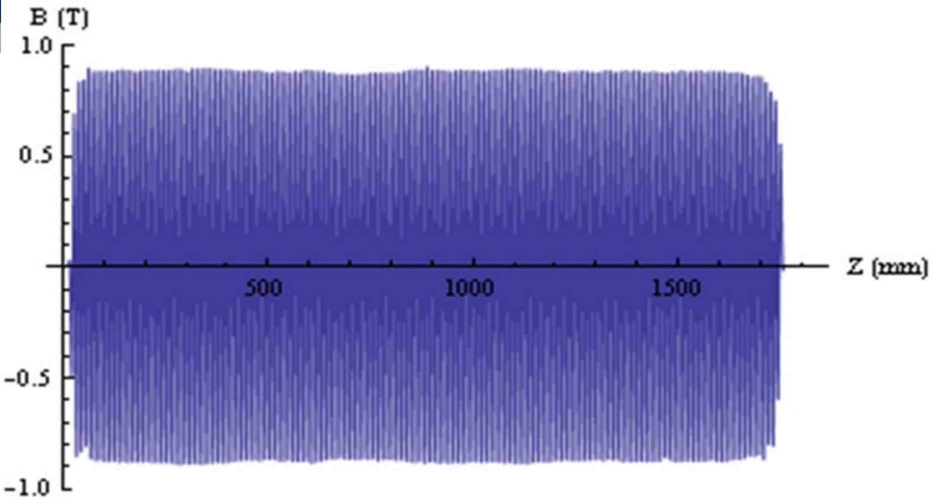
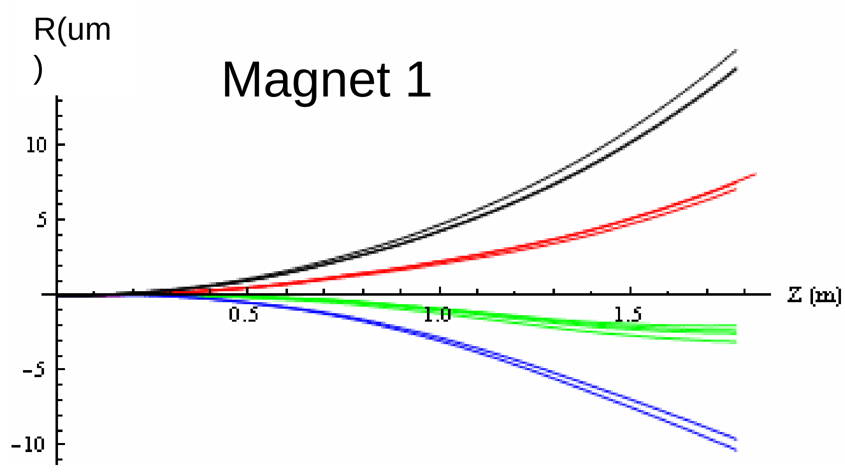
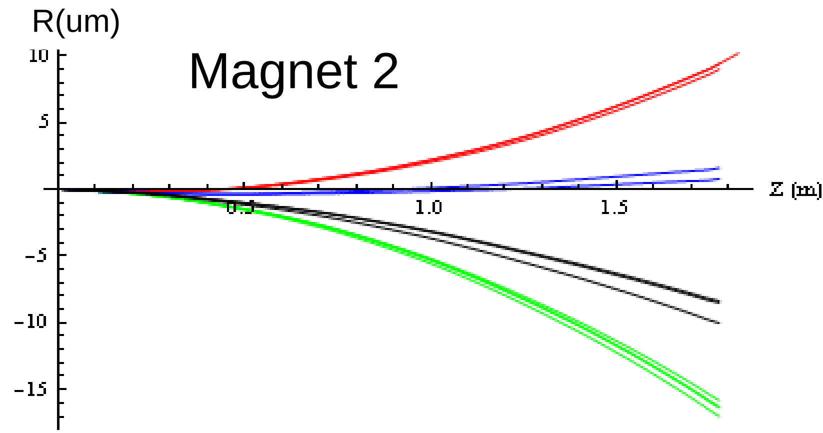
Prototype manufacture







Particle trajectories calculated from measured field data

- Plots show different trajectories calculated from different profiles around azumith 0º,90º,180º, 270º
- Trajectories calculated using SPECTRA
- Trajectories pessimistic limited by hall probe resolution and offset
- These are worst case and easily corrected`

Prototype manufacture

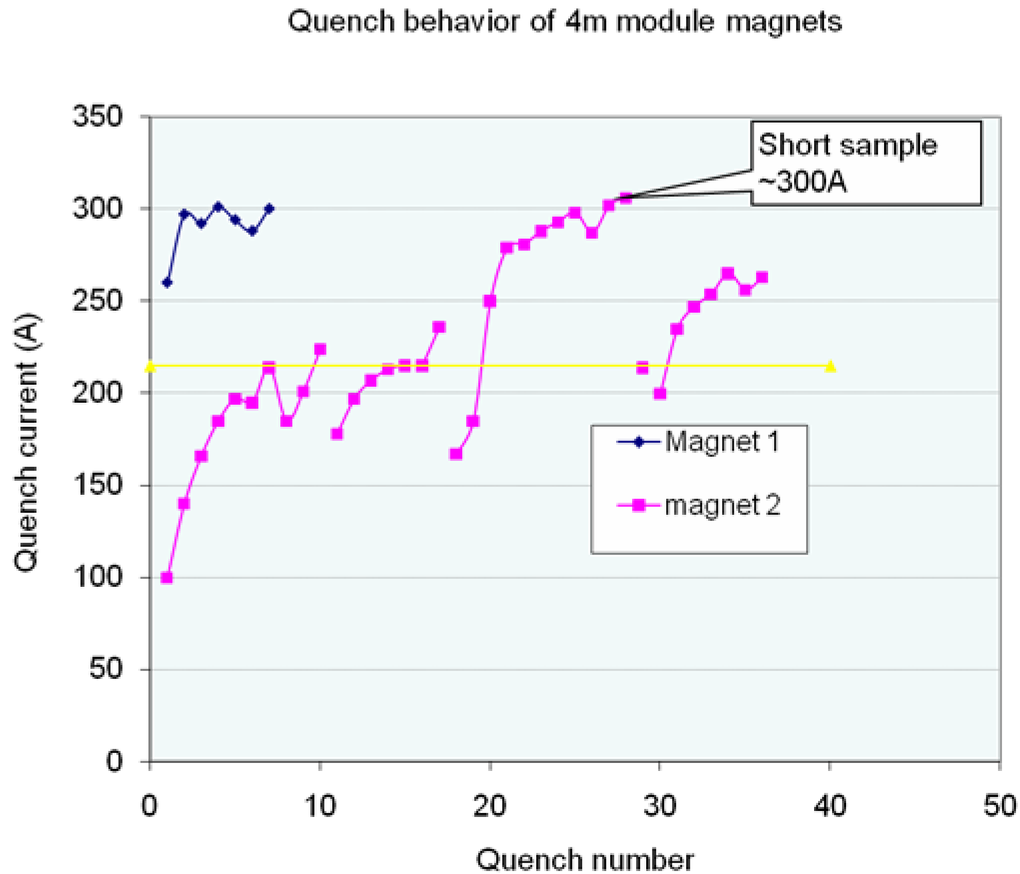
Magnet testing

- Quench testing of both Magnets

- 1st magnet went straight to field

- 2nd magnet repetitive training

- Reasons for this are not understood

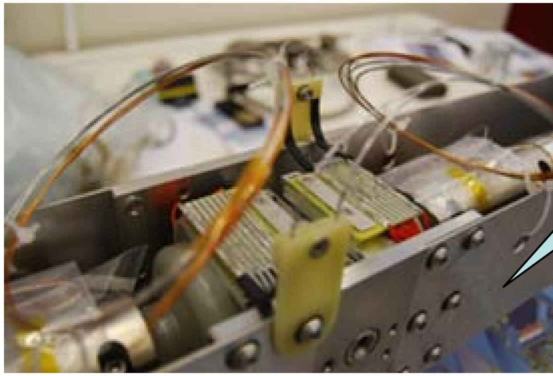


Both magnets can deliver nominal field

with a good margin!

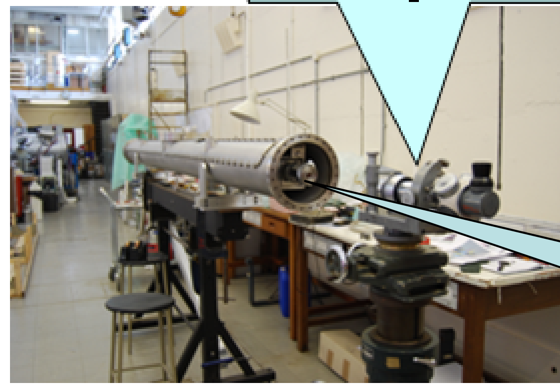
Prototype manufacture

Cold mass integration



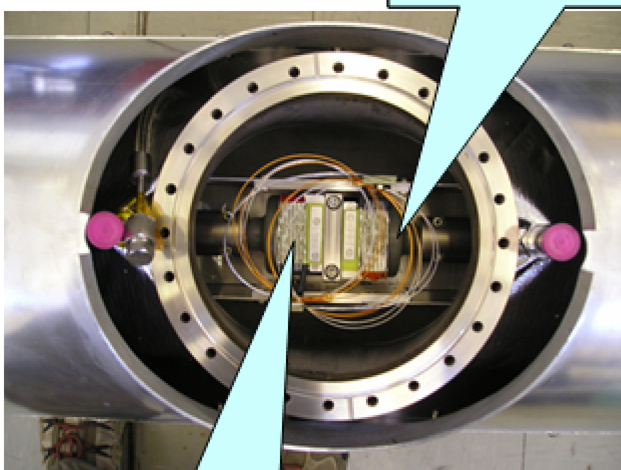
Alignment ~+/-200um

Alignment scope

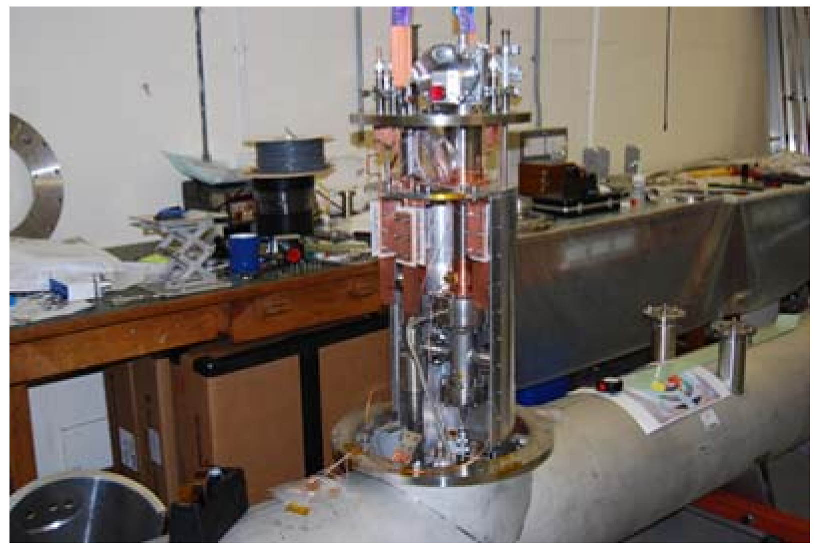


Alignment 0.5mm

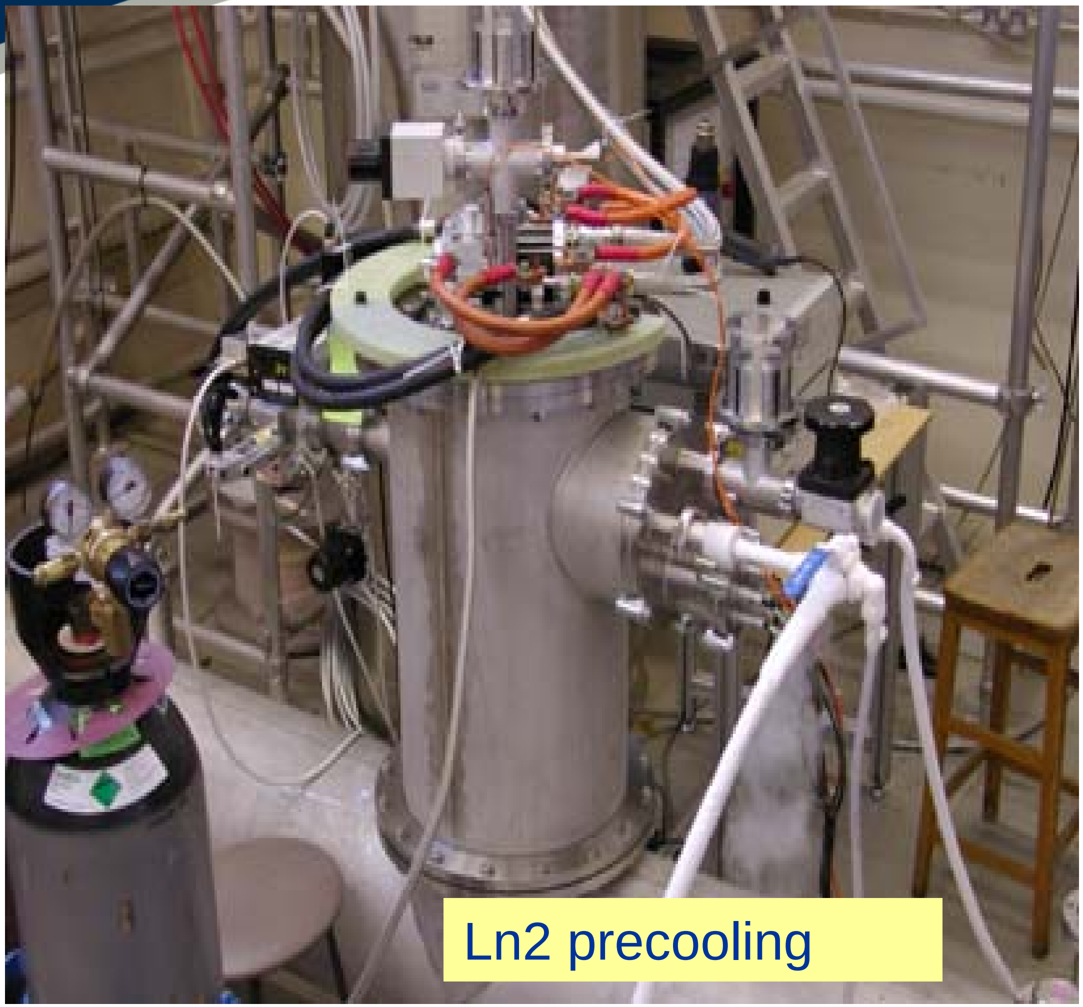
Mag 2 connection



Mag 1 connection



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

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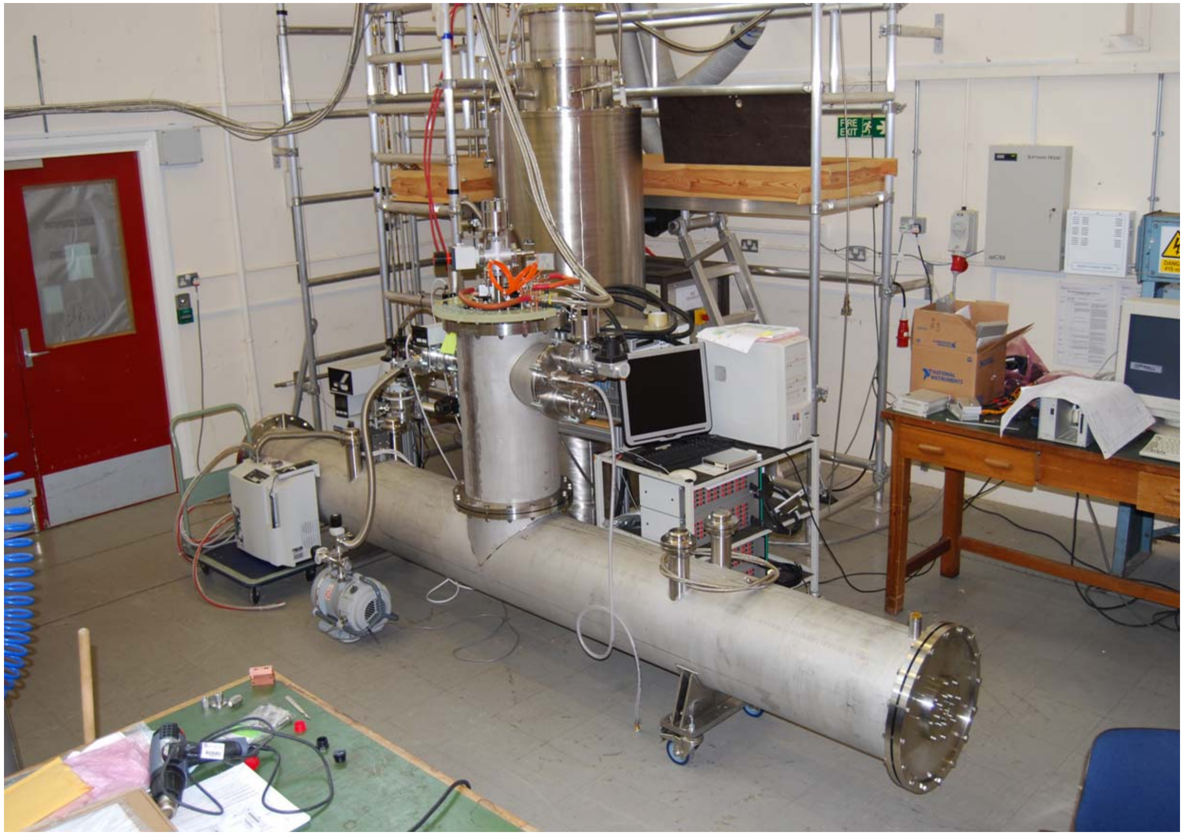
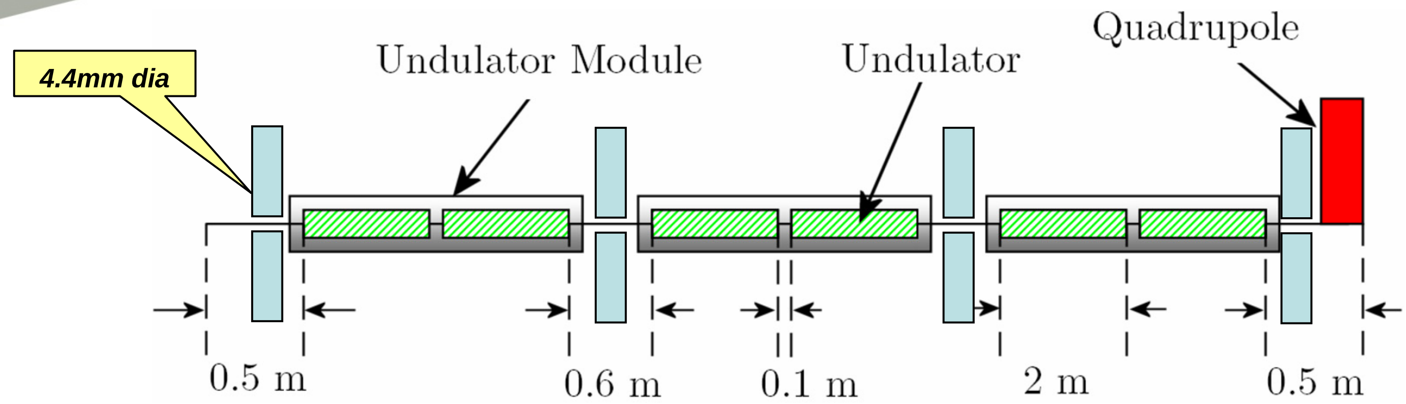
Prototype testing

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



Prototype testing

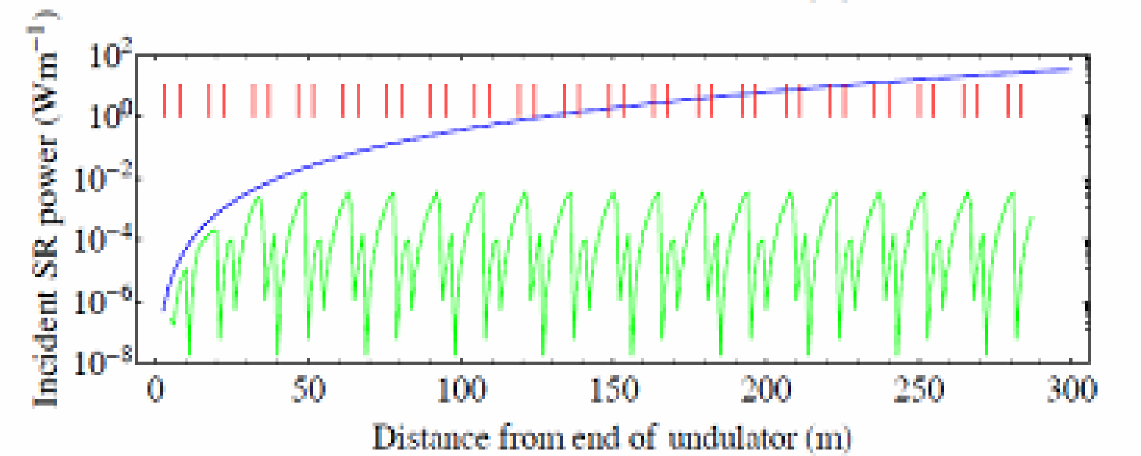


"Beam heating" test planned

- Simulate beam heating effects
- resistors in evacuated bore
- Assess how much beam heating magnets can sustain

Collimation in undulator half-cell.

Synchrotron load per module RDR (W)	
Peak	0.3
Mean	0.1
Wake field heating per module RDR (W)	
Fill pattern 1	
Peak	0.6
mean	0.3
Mean beam load	0.4



Prototype testing

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

Summary

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