Durham University Superconductivity Group

Overview of measurements and experimental facilities

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Rev 1: 6th Feb 2022

CONTENTS / SUMMARY

DUSG
DURHAM UNIVERSITY SUPERCONDUCTIVITY GROUP

High Magnetic Fields

World-class horizontal and 2 x vertical 15 T, 40 mm bore magnets. (+ 9 T PPMS).

15 T horizontal magnet system

This word-class Helmholtz-like split-pair horizontal magnet system has a 40 mm bore and allows field-angle measurements at cryogenic temperatures on non-isotropic (HTS) superconducting conductors

15 T vertical magnet system

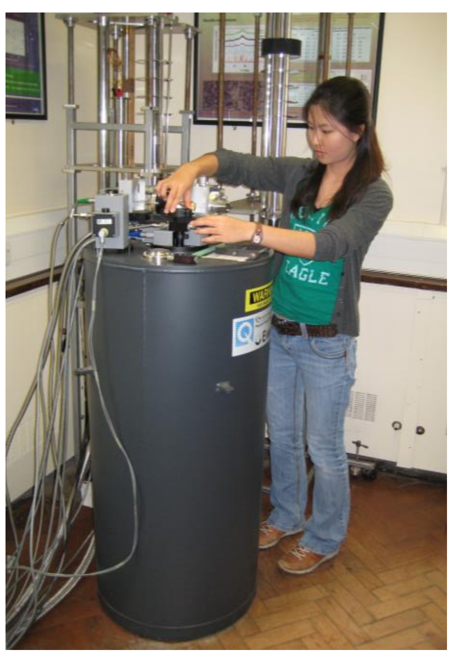
This magnet has a 40 mm bore and allows high-field (15 T) measurements to be performed at cryogenic temperatures.

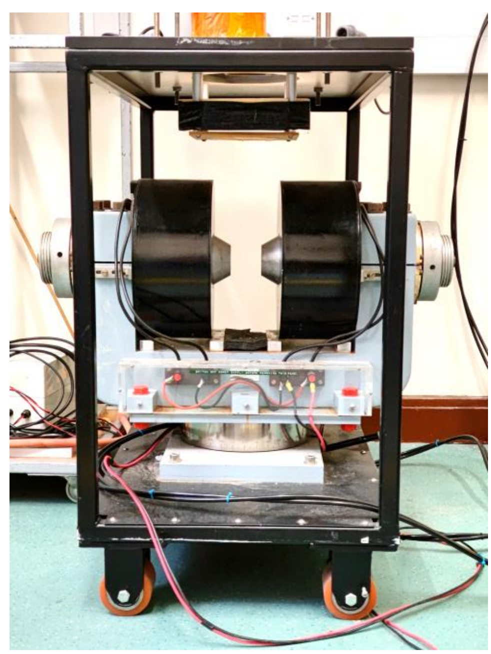
9 T Physical Property Measurement System

The PPMS can perform measurements in fields up to 9 T and at temperatures from ~2 K to 400 K.

2 low-field iron core magnets

These magnets have adjustable bores (by moving the pole pieces) providing 0.7 T in a 40 mm bore and 0.4 T in a 100 mm bore.



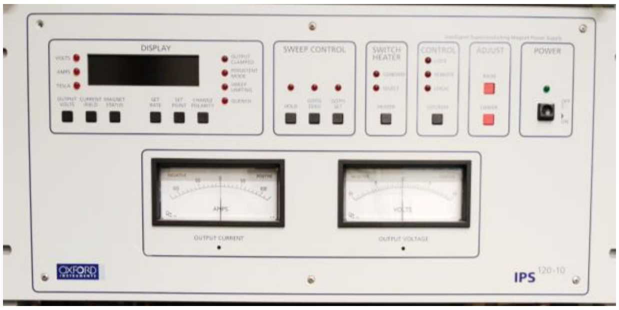


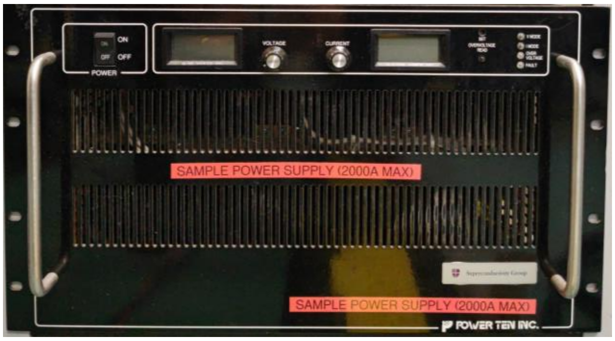
Measurement and Control

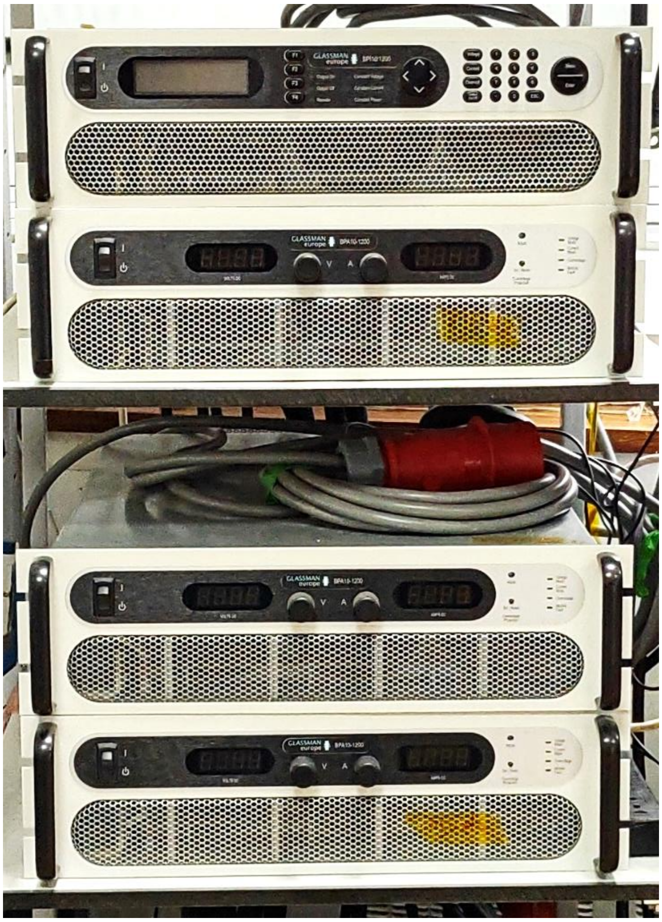
Critical current facilities (< 6 kA, 2 to 400 K, < 15 T) measurements on cables at 1800 A and 10 T

6 kA High current measurements

Durham has four 120 A, three 2 kA and four 1.2 kA power supplies. The supplies can be wired in a master-slave configuration to deliver up to 6 kA (hardware up-grade to 10 kA is simple/commercially available).







Nanovolt measurements

We have more than two dozen high precision Keithley voltmeters that are used in conjunction with nanovolt amplifiers to measure voltages signals close to the fundamental limit of Johnson noise.

2 to 400 K temperature control

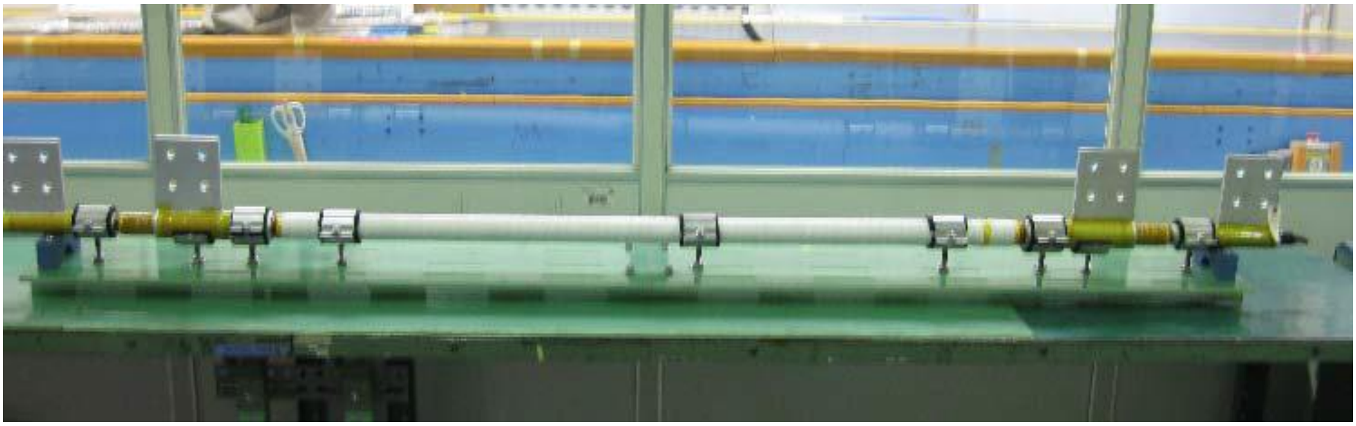
Standard state-of-the-art temperature controllers are used with field calibrated CERNOX thermometers and heaters for temperatures above 4.2 K. Vapour pressure control is used for 4.2 K > T > 1.8 K and 80 K > T > 65 K.

I_c for HTS and LTS Cables

HTS and LTS cables critical current up to 2 kA

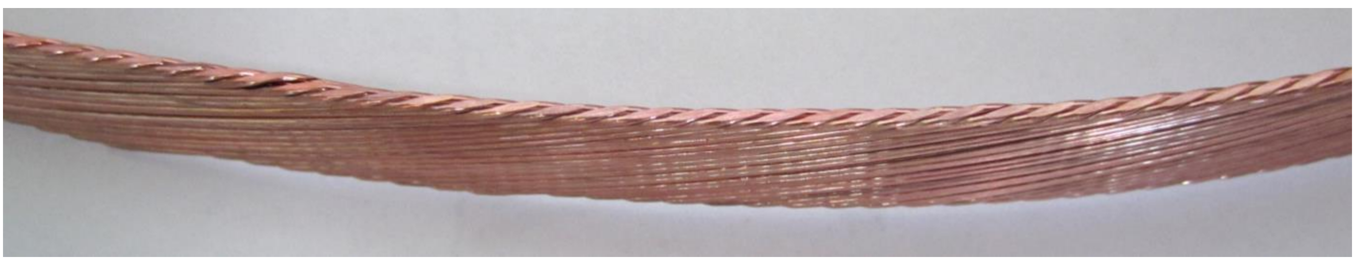
Bi-2223 HTS Cable International Round robin (August 2022)

Durham has been invited to participate in the International round robin critical current measurements on Bi-2223 superconducting cable as part of the Japanese Project of DC Critical Current Test Method Standardisation of Cables. The measurements are anticipated to take place during August of 2022.

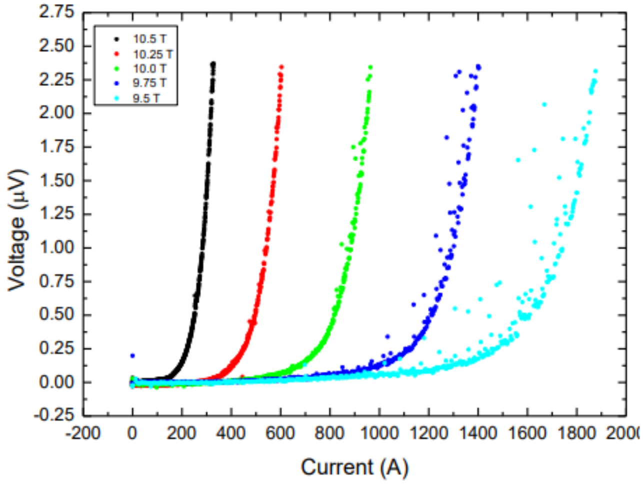


Rutherford cable critical current

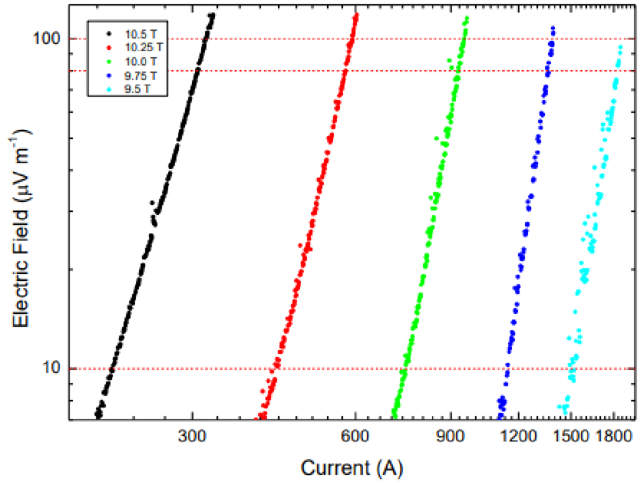
Low to high-field critical current measurements were performed on Nb-Ti Rutherford cable up to 2 kA.



A bespoke, high current, probe was designed and manufactured to measure the Rutherford cable measurements with a high electrical/thermal resistance section hard soldered into the copper sample mount to restrict current shunting and cryogen expense during measurement.



Ref [10]

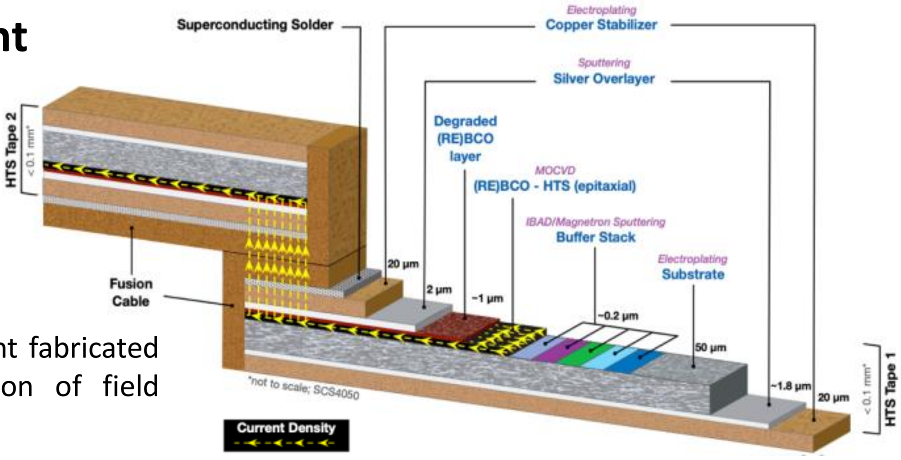


I_c for HTS and LTS Joints

LTS and HTS critical current up to 1 kA in high fields on jointed superconducting samples

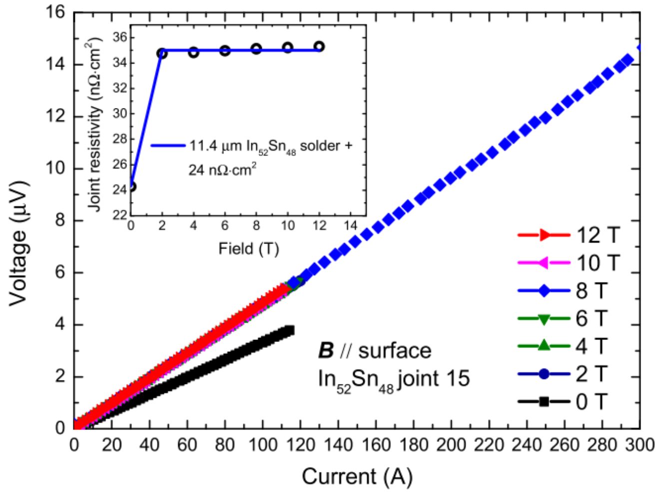
HTS joints critical current

State-of-the art joints between high temperature superconducting REBCO tapes have been fabricated and measured to determine joint resistance.

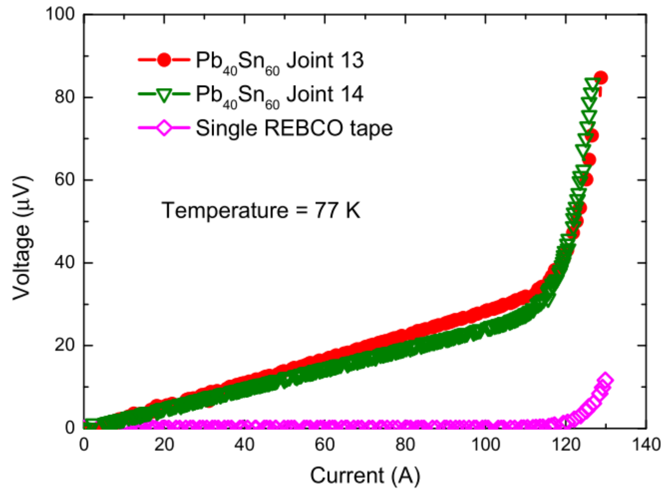


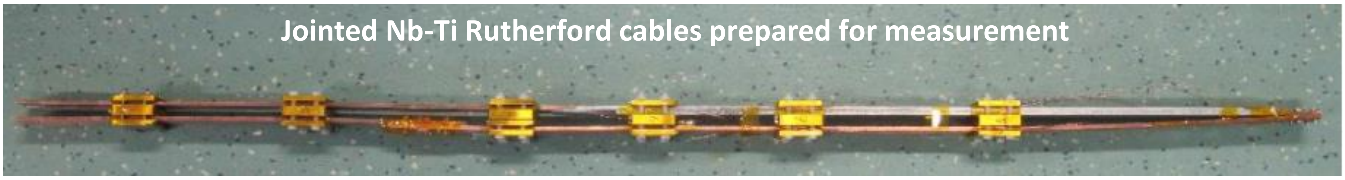
LH Plot: $V - I$ trace at 4.2 K for joint fabricated using $In_{52}Sn_{48}$ solder as a function of field parallel to the tape surface.

RH Plot: $V - I$ trace for two soldered joints and a single REBCO tape.



Ref [8]



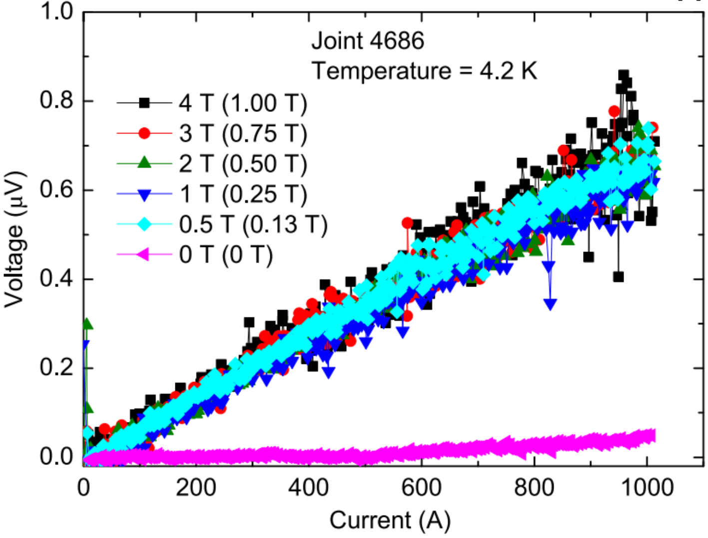


LTS joints critical current

Durham has fabricated joints for low temperature superconducting materials, such as Nb_3Sn and Nb-Ti strands and Nb-Ti Rutherford cables and completed critical current measurements.

V-I data at different magnetic fields for soldered joints formed from Nb_3Sn ITER strands at 4.2 K. The two magnetic field values shown are those at (i) field centre and (i) at the top of the joint approximately 150 mm away. When the solder is normal (i.e. not superconducting), the resistance is 0.7 nΩ.

Ref [7]



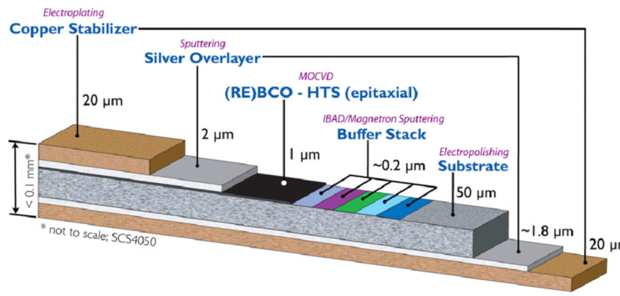
I_c for HTS Tapes

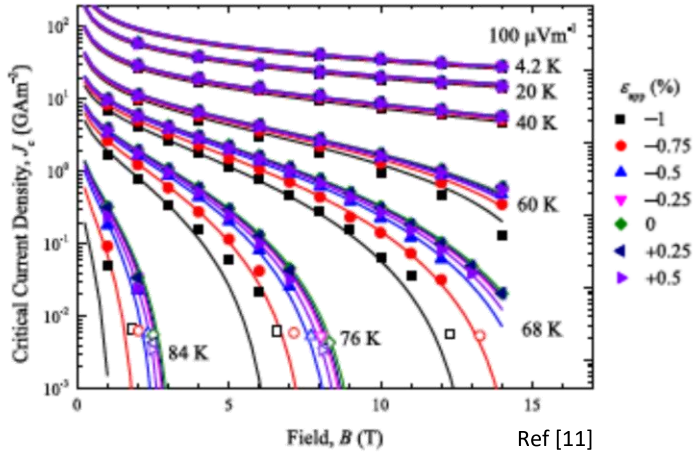
HTS critical current up to 1 kA as a function of field, angle, variable temperature and strain

HTS tape critical current

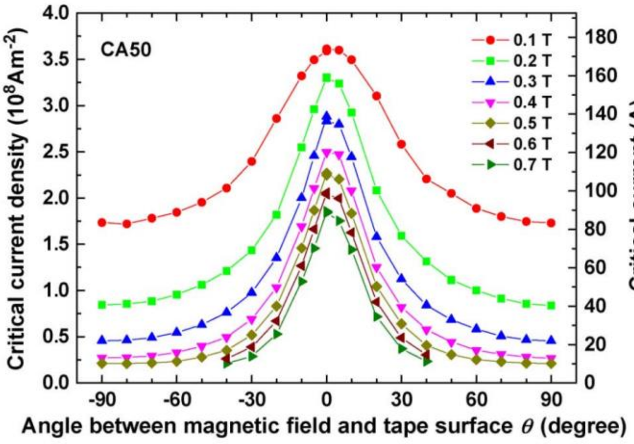
Durham has a wealth of experience in performing critical current measurements on HTS materials as a function of field, field-angle, variable temperature and strain.

Ref [5]

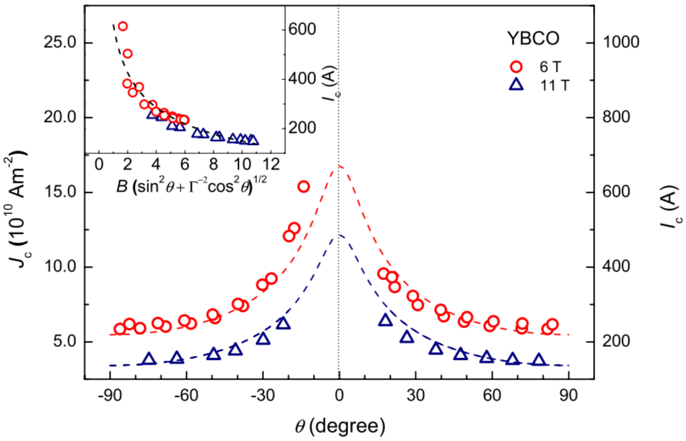




Ref [12]

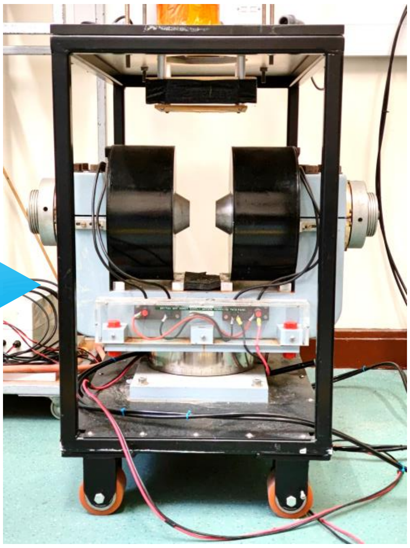


Ref [11]



Critical current density as a function of field-angle (to tape surface) for DI-BSCCO CA50 tape at 77 K and different applied magnetic fields

Transport critical current density of $YBa_2Cu_3O_{7-\delta}$ at 4.2 K versus field-angle (to tape surface) at 6 and 11 T.



Iron core magnet (max field 0.7 T)

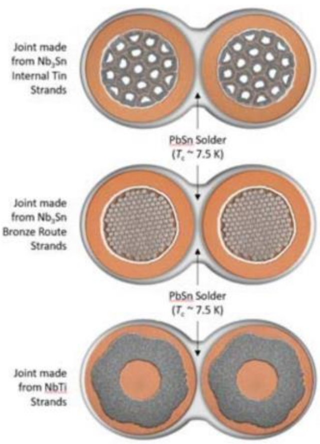
Horizontal magnet (max field 15 T)

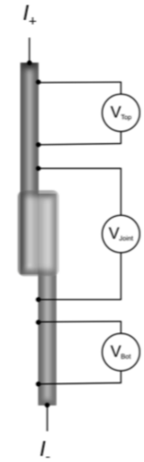
I_c and ρ_n for LTS Strands and Joints

LTS critical current up to 1.2 kA as a function of field and temperature and strand internal resistivity

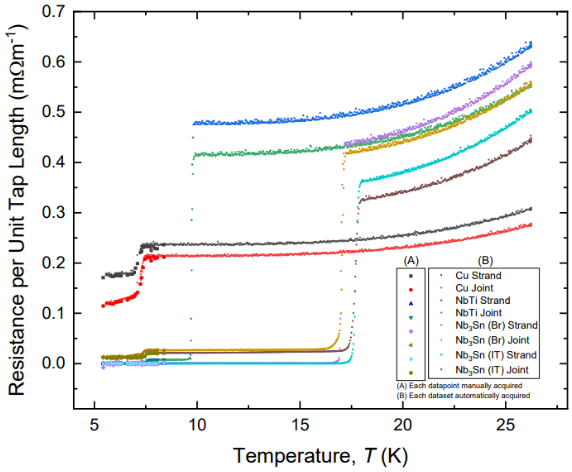
Nb_3Sn and Nb- Ti strand joint internal component resistances

The resistances of soldered joints of Nb_3Sn and Nb-Ti strands were measured as a function of temperature and field to determine the internal bulk and interfacial resistivities to assess optimal cryogenic heat load in practical superconducting fusion joints with these materials [2].



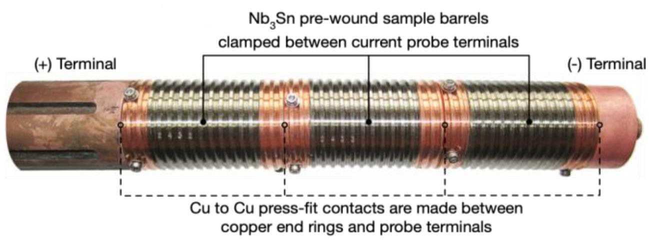


Below 7.5 K the joint solder superconducts and ceases to contribute to joint resistance. At that point the resistance is due to strand architecture

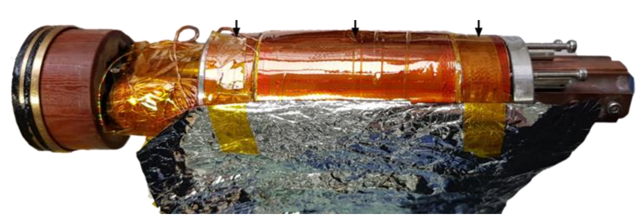


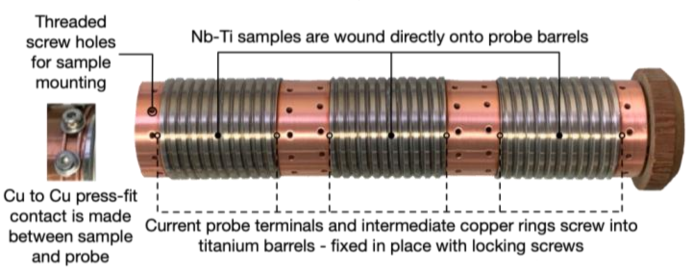
Nb_3Sn and Nb- Ti strand critical current

Durham has completed thousands of critical current measurements on Nb_3Sn and Nb-Ti strands as a QA requirement for inclusion in ITER's toroidal and poloidal field coils.



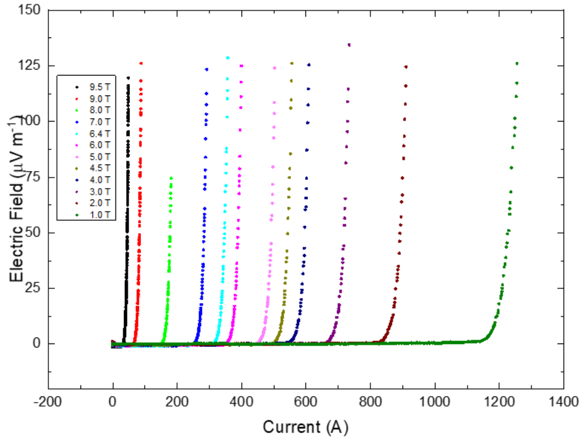
Variable temperature probe





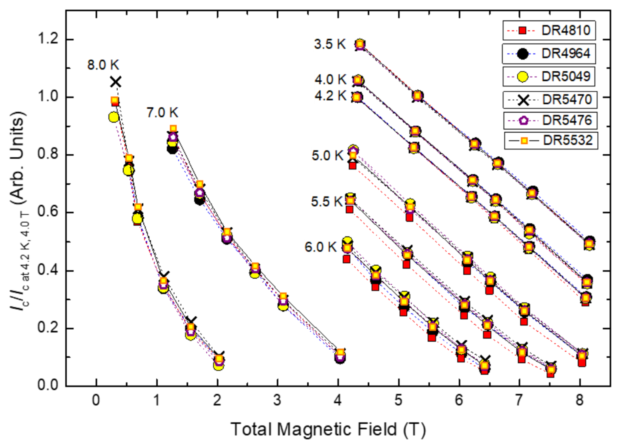
Variable temperature probe with brass temperature cup fitted

High current measurements on Nb_3Sn



Variable temperature measurements on Nb-Ti

Ref [6]

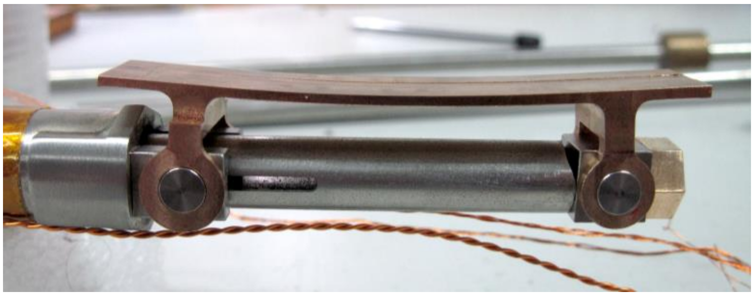


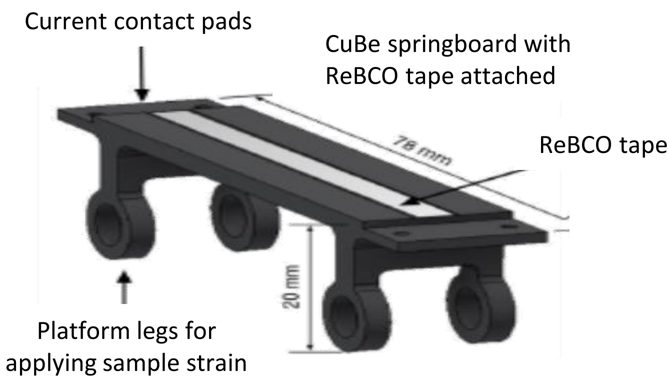
I_c for HTS and LTS Under Strain

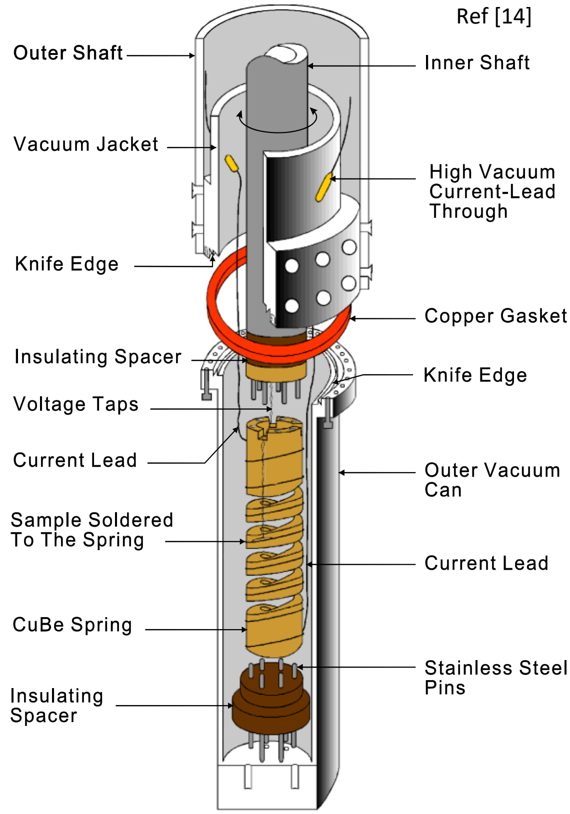
HTS and LTS critical current up to 1 kA in high fields under applied strain

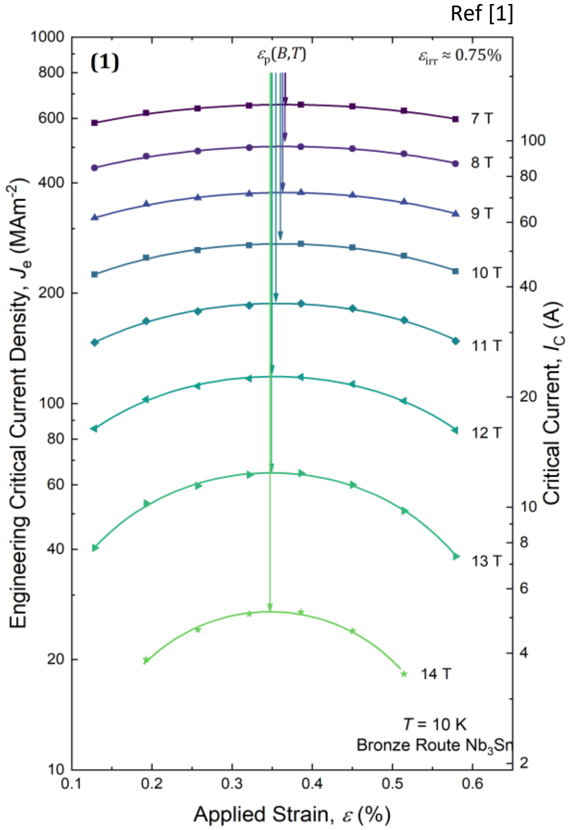
Critical current under applied strain

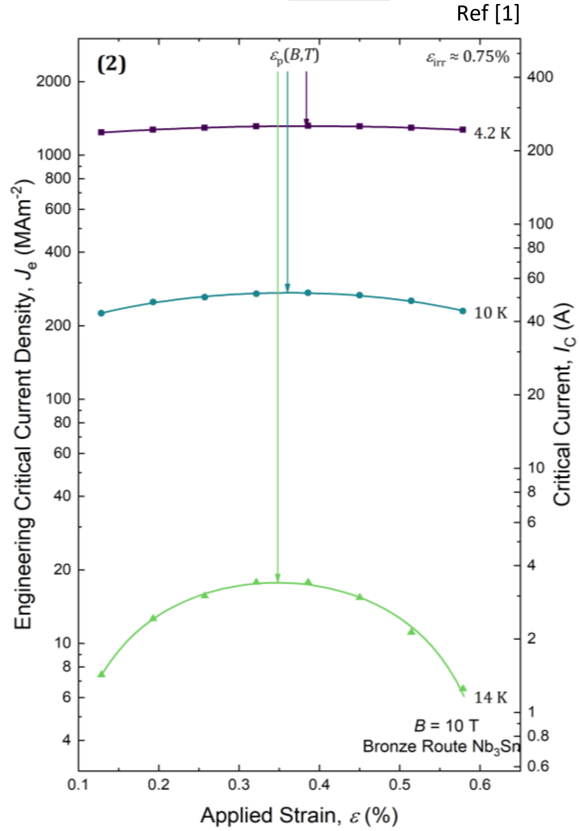
HTS and LTS samples are mounted onto bespoke strain probes. HTS tapes are soldered to a CuBe springboard (see below) and LTS strands to a Walters spring (see figure on right).





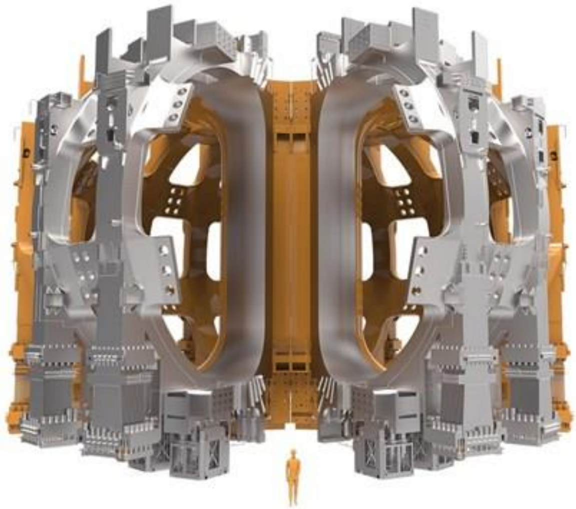


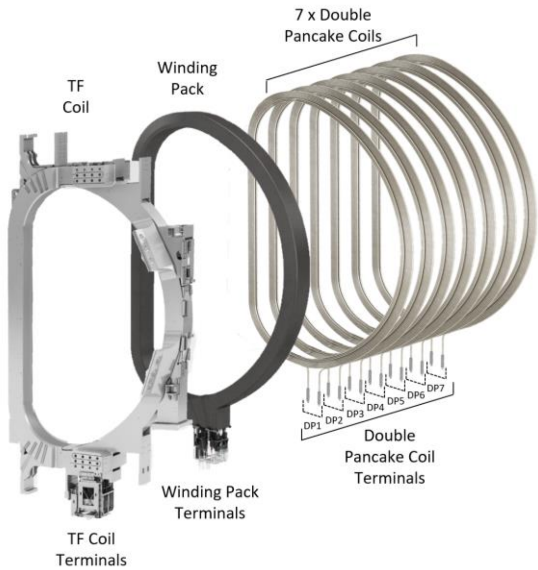




ITER Contract

€1.6M, 5 people for 5 years, 13,000 measurements, on-budget and on-time.



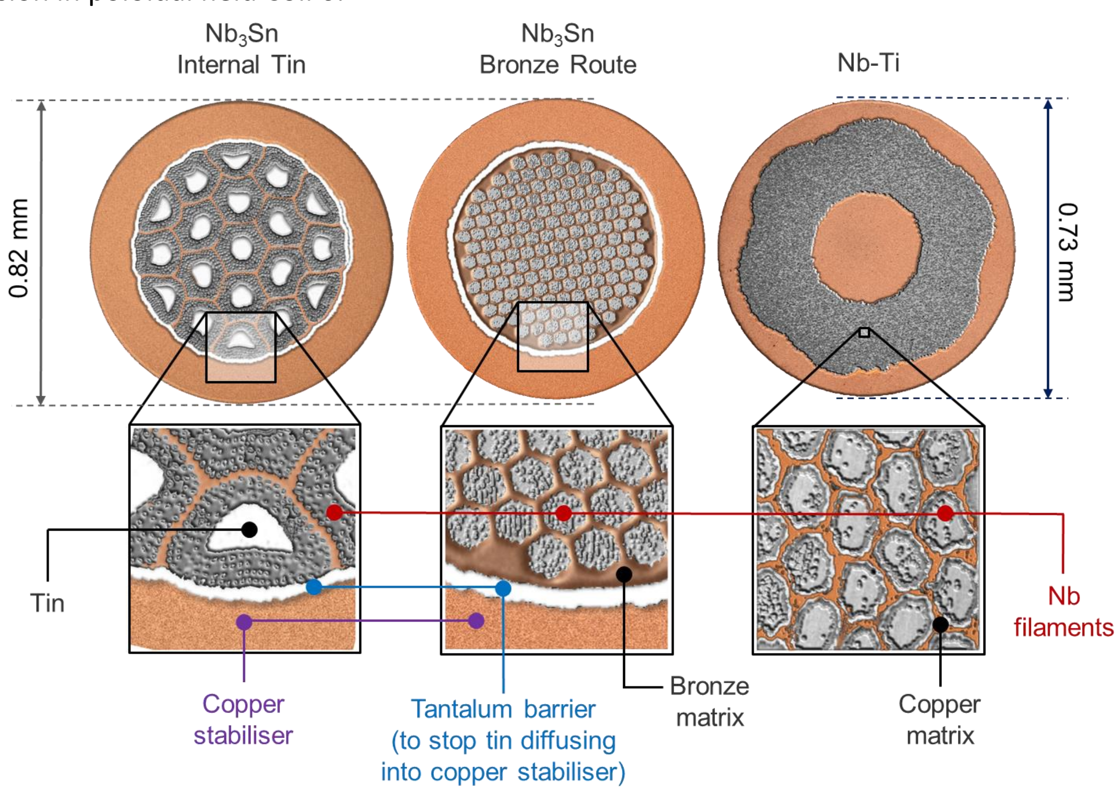


13,000 Measurements for ITER

In early 2011 Durham University signed a **€1.6M** contract with Fusion for Energy (F4E – the Domestic Agency responsible for Europe's contribution to ITER).

We provided seven types of QA measurements: 3 x cryogenic: critical current (and *n*-value), hysteresis loss and residual resistivity ratio and 4 x room temperature: strand diameter, twist pitch, copper to non-copper ratio and plating thickness. Nb_3Sn strands were not included in European ITER magnets if the billet did not pass Durham QA.

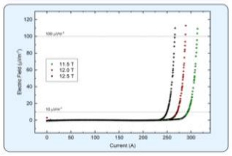
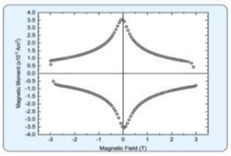
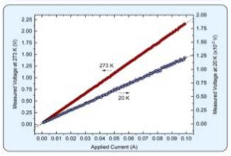
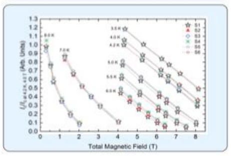
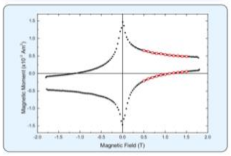
Durham subsequently won contracts to provide 600 Witness sample measurements (used to verify toroidal field coil heat-treatment quality in Italy) and 400 Nb-Ti measurements on strands earmarked for inclusion in poloidal field Coil 6.



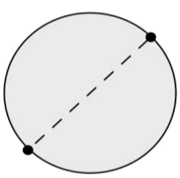
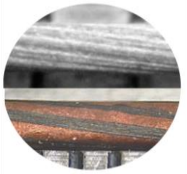
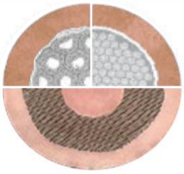
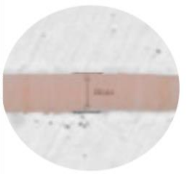
ITER Contract

€1.6M, 5 people for 5 years, 13,000 measurements, on-budget and on-time.

Cryogenic measurements summary for F4E contracts

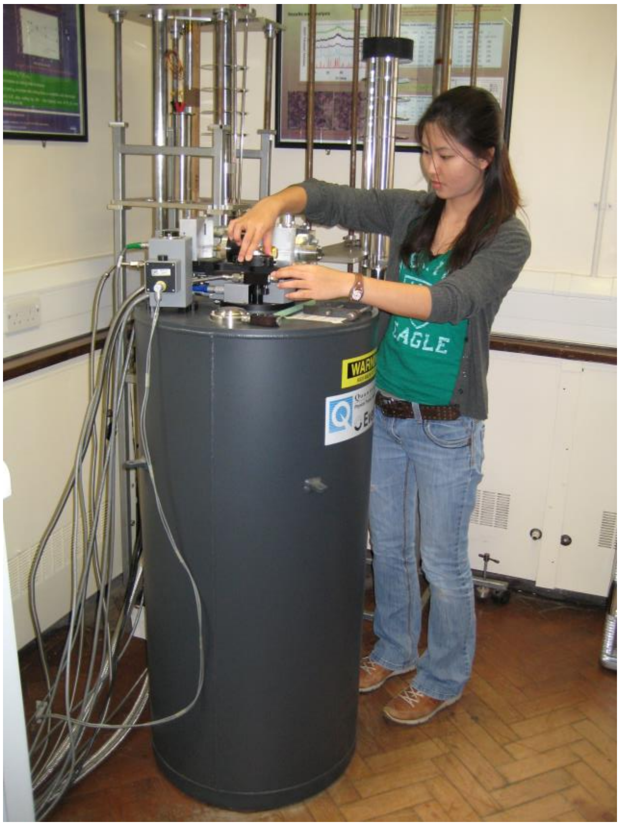
	$I_c(B)$ and n-value	Hysteresis losses	Residual resistivity ratio	$I_c(B,T)$	$I_c(B)$ from magnetisation	
						
QTY~	1900	1100	2600	6	6	5600
Nb3Sn	15 T vertical magnet  At 4.2 K and in fields 11.5, 12.0 and 12.5 T	QD PPMS  At 4.22 K and in a swept field of ±3.0 T	QD PPMS + external eq.  At 273 K and 20 K in zero field	Not required	Not required	Nb3Sn
Nb-Ti	15 T vertical magnet  At 4.2 K and in fields 6.0, 6.4 and 7.0 T	QD PPMS  At 4.22 K and in a swept field of ±1.5 T	QD PPMS + external eq.  At 273 K and 10 K in zero field	Variable temperature I_c probe for 6 samples  At temperatures 3.5, 4.0, 4.2, 5.0, 5.5, 6.0, 7.0 and 8.0 K and in fields 0 to 8.0 T	QD PPMS  Low field I_c to compliment Ic(B,T) data at 4.2 K	Nb-Ti

Room temperature measurements summary for F4E contracts

	Diameter	Twist pitch	Cu-non-Cu ratio	Plating thickness	Plating adhesion	
						
QTY~	1750	1750	1750	1750	330	7300
Nb3Sn	Laser micrometer  80 measurements per sample: 20 circumferential at 4 locations	Acid etching, photography and Photoshop  Twist pitch should be 15 ± 2 mm	SEM and Photoshop  Hitachi SU-70 Field Emission Gun SEM with resolution to 10 nm	Acid etching and mass measurements (chromium) 	Not required	Nb3Sn
Nb-Ti	Laser micrometer  80 measurements per sample: 20 circumferential at 4 locations	Acid etching, photography and Photoshop  Twist pitch should be 15 ± 2 mm	Acid etching and mass measurement  CnC ratio should be 1.55 to 1.75	Couloscope (nickel)  Fisher Instrumentation CM2 with V27 stand using electrolyte F6	Photography  This is a visible check of the adhesion quality	Nb-Ti

ITER QA for Conductor Fabrication

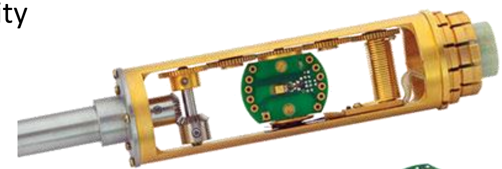
PPMS - Tensile testing - European Reference Laboratory



9 T Physical Property Measurement System

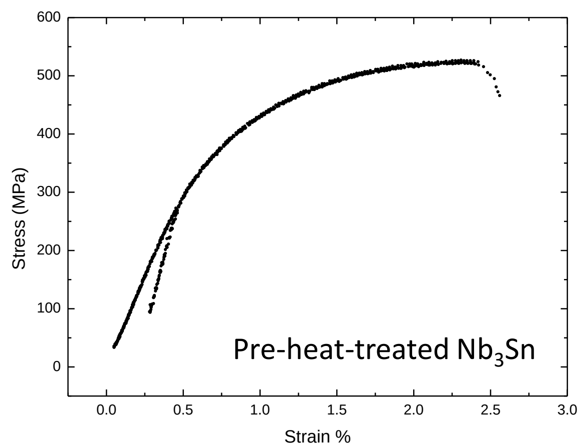
The PPMS can perform measurements (see below) in fields up to 9 T and at temperatures from ~2 K to 400 K.

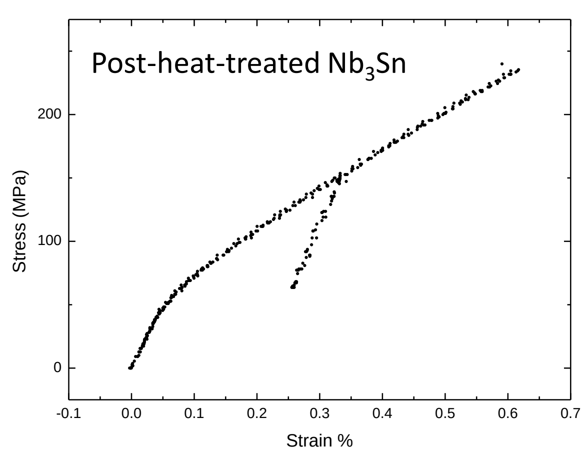
- Ac susceptibility
- Dc extraction
- Ac Transport
- Resistivity
- Heat capacity

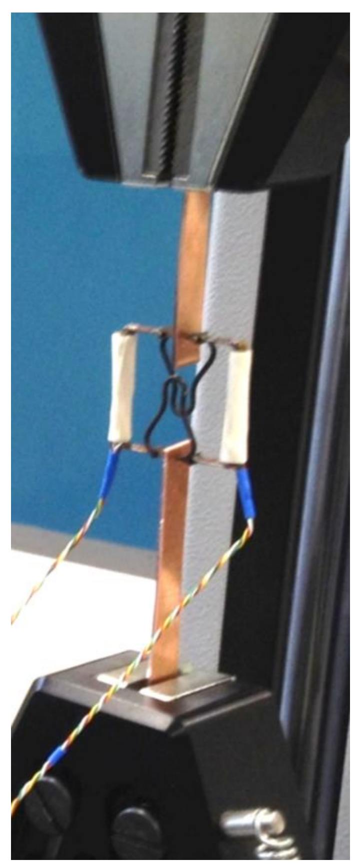


Tensile Stress Testing on Nb_3Sn

Nyilas extensometers were used in conjunction with a Mecmesin single column force tester to conduct room temperature tensile stress tests on pre and post heat-treated Nb_3Sn strand.





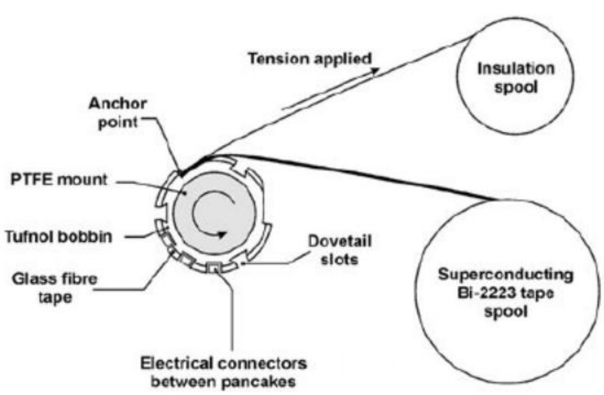


HTS and LTS small magnets
Design, fabrication and performance of HTS and LTS magnet inserts

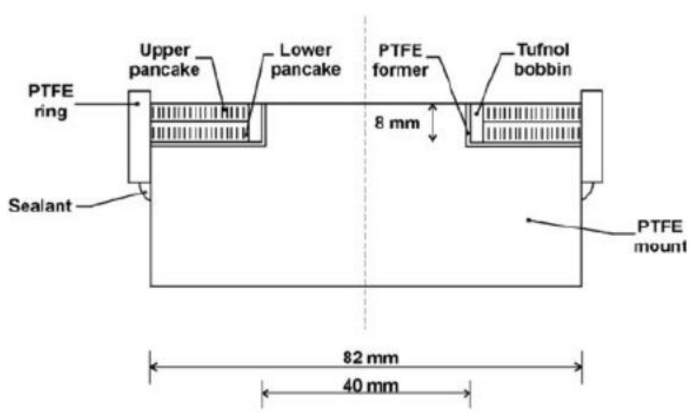
HTS and LTS magnets

i) HTS small magnet producing 1.3 T, 4.2 K with a 40 mm bore (HTS Bi-2223 tape) [13]
ii) LTS small magnet producing an AC field 2T.s^{-1} (0.1 T at 19.7 Hz) [15]
Both magnets were designed, fabricated and tested in Durham.

1.3 T (at 4.2 K) HTS Bi-2223 magnet module with a 40 mm bore [13]



The experimental arrangement for winding the tape and insulation onto the Tufnol bobbin



PTFE components used during the vacuum resin impregnation process.

Engineering Workshop

Equipment manufacture

Cryogenic and Magnet Engineering Workshop facilities

We are supported by and have an established working relationship with:

i) *The Physics Department's Engineering Workshop:* Bespoke specialist cryogenic and magnet mechanical equipment has been designed, developed and commissioned over more than 20 years.

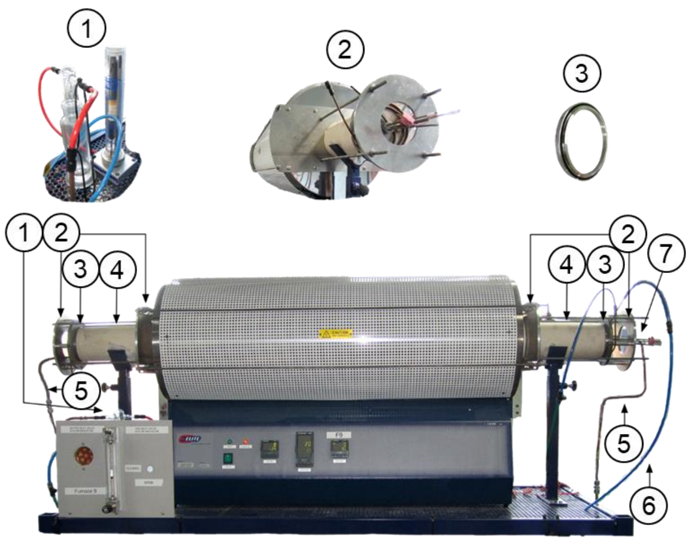
ii) *Many small engineering firms along the Tyne river:* Fast (i.e. time-constrained), mass manufacture of probes and holders were completed by these firms as required for the ITER project.

Heat-treatment furnaces

High purity heat-treatment facilities up to 1150 ℃

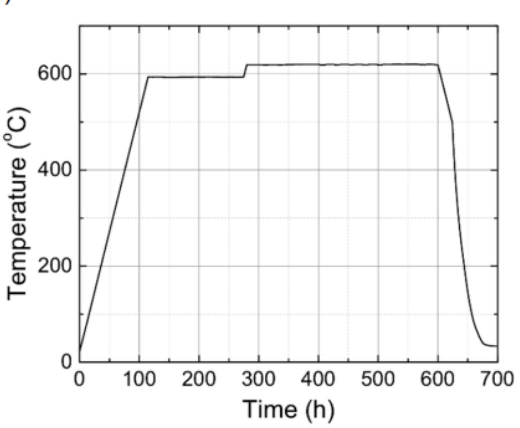
High temperature tube furnaces < 1150 °C

- We have four high temperature furnaces (up to 1150 ℃) used to react 1000s of LTS samples for the ITER project. They include high-homogeneity three-zone tube furnaces capable of extended, programmable, heat-treatments in various gas environments; argon and nitrogen, for example.
- High grade (EA998) alumina tubes with stainless steel double O-ring sealing holders are used to maintain sample space integrity.
- Kanthal tubes with knife-edge seals are used for increased purity environments
- Inline gas filters are used to increased inlet gas purity to six nines

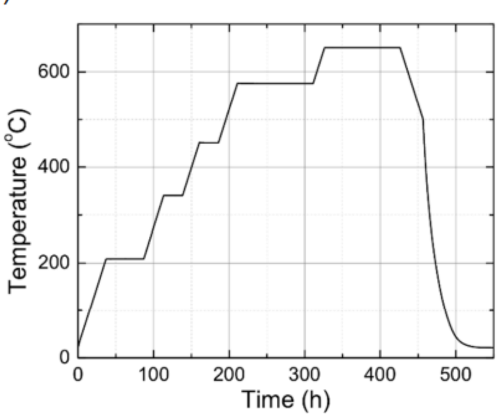


1. Inlet Supelco Superclean gas filter and bubbler
2. Aluminium bracing system for furnace sealing
3. Double o-ring sealing holder (st. stl)
4. Alumina furnace tube (1.5 m long)
5. Copper piping hard soldered to furnace end plates
6. Flexible water pipe for end plate cooling
7. Independent thermocouples and thermocouple sealing port

a)



b)



Nb_3Sn heat-treatment profiles for a) bronze route and b) internal tin strands.

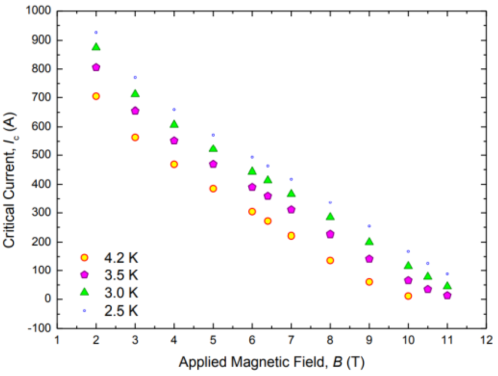
DUSG
DURHAM UNIVERSITY SUPERCONDUCTIVITY GROUP

Commercial High-field Critical Current Measurements

Selected examples of commercial contracts with Durham

OXFORD INSTRUMENTS

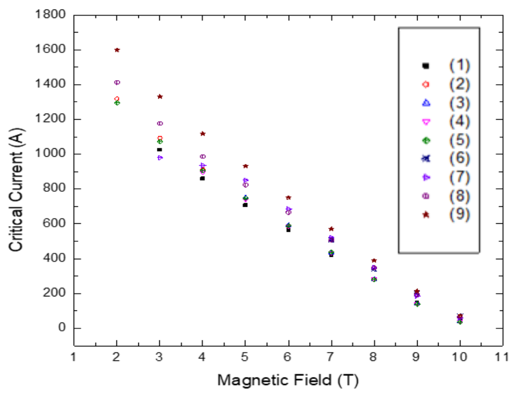
Nb-Ti Samples:
Critical current measurements requested:
- Field range: 2 to 11 T
- Temperature range: 2.5 to 4.2 K
- Maximum current 1000 A



SIEMENS Healthineers

Nb-Ti Samples:
Critical current measurements requested:
- Field range: 2 to 10 T
- Temperature: 4.2 K
- Maximum current 1600 A

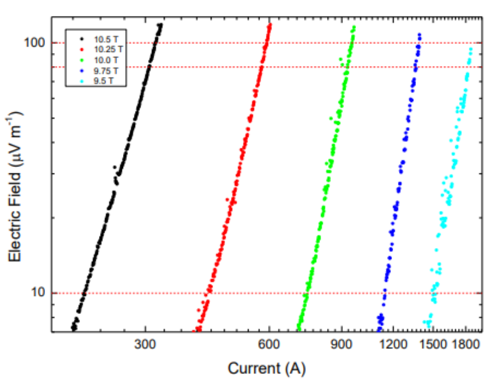
Hysteresis loss
Residual resistivity ratio
Twist pitch
Sample dimensions
Copper to non-copper ratio



Jefferson Lab

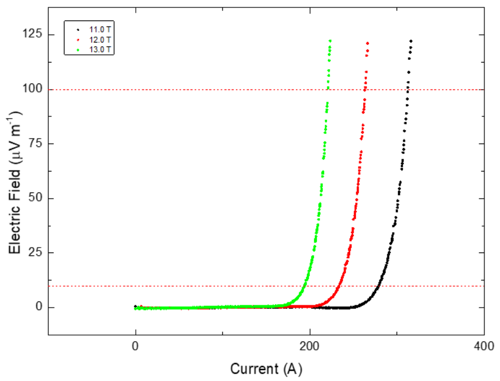
Jointed Cable-in-channel Nb-Ti Rutherford Cables:
Critical current measurements requested:
- Field range: 9.5 to 10.5 T
- Temperature: 4.2 K
- Maximum current 3000 A

Residual resistivity ratio



LUVATA

Nb_3Sn Samples:
Critical current measurements requested:
- Field range: 11 to 13 T
- Temperature: 4.2 K
- Maximum current 300 A



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