

# Heat treatment optimisation of advanced $\text{Nb}_3\text{Sn}$ strands

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## **IPR REPORT**

The important results from the task are summarised in the extended abstract and summarised in detail in the accompanying report – there was no IPR created in the course of this work .

Pre-existing knowledge is outlined in the publicly available literature – in particular the published reports and articles of those scientists cited in the reference section of this report.

There is no foreground IPR – all techniques used are encompassed within the publicly available state-of-the-art literature.

There is no new business confidential information, business confidential know-how, or trade secrets - the materials used in this report were supplied without any obligations re confidentiality .

Disclosure of the information – this report will be made available through the public-accessible Web in the first instance and thereafter discussed at specialist scientific meetings and published in international scientific journals.

The work in this report has been discussed with the Technology Transfer Unit at Durham University.

Prof. Damian P. Hampshire Durham University

January 31<sup>st</sup> 2009.

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## ABSTRACT

The programme within the framework of this task includes: heat treatment of strands; measurement of the critical current  $I_C$  (and  $n$ -values) at 4.2 K, 10 to 14 T and zero applied strain; determination of the residual resistivity ratio (RRR(20K)); electron microscopy to identify strand layout; magnetic SQUID hysteresis loss measurements; variable strain  $I_C(B, 4.2K, \varepsilon)$  data; scaling parameters derived from  $I_C(B, 4.2K, \varepsilon)$  data taken at 4.2 K alone. The experimental procedures used are all presented in the main text. The data are all presented in the annexes.

Two batches of material have been measured. Microscopy clearly distinguishes the barriers used for each of the two batches – the magnetic SQUID measurements show that the HK004 batch has significantly ( $\sim$  factor 5) higher losses than the HK003 batch over the range  $\pm 3$  T at 4.2 K.

A detailed description of  $I_C(B, 4.2K, \varepsilon)$  data is presented using scaling laws. The RMS values ( $\sim 1$  A) for the difference between the data and the scaling laws show that the data at 4.2 K are accurately described using a 9 free-parameter Durham scaling law. The data can also be described by the ITER scaling law with RMS values of  $\sim 3$  A. Accompanying this report are four spreadsheets that contain tabulations of the  $I_C$  and  $n$ -value data, as well as the scaling-law parameterisation of  $J_c(B, T, \varepsilon)$  for these strands at:

<http://www.dur.ac.uk/superconductivity.durham/publications.html>

MANUFACTURERS REFERENCE NUMBER	DURHAM UNIVERSITY REFERENCE NUMBER	ANNEX A HEAT TREATMENT RECORDS	ANNEX B $I_c$ (B,4.2K) TEST RESULTS	ANNEX C RRR(20K) TEST RESULTS		ANNEX D ELECTRON MICROSCOPY		ANNEX E $Q_{hyst}$ SQUID (MPMS)	ANNEX F VARIABLE STRAIN DATA $I_c$ (B,4.2K, $\epsilon$ )	ANNEX G SCALING PARAMETERS $I_c$ (B,4.2K, $\epsilon$ )
				REACTED	UNREACTED	REACTED	UNREACTED (Not shown)			
NSTT 8305-HK003-A1 SL-NR 9108a	DU 2008/3	1	Strain data Annex F			1	1	1	1	1
NSTT 8305-HK003-A2 SL-NR 9109a	DU 2008/4	1	1							
NSTT 8305-HK003-A1 SL-NR 9108i	DU 2008/5	1	1							
NSTT 8305-HK003-A2 SL-NR 9109i	DU 2008/6	1	Strain data Annex F			1	1	2	1	1
NSTT 8305-HK004-BA SL-NR 9110i	DU 2008/7	1	1			1	1	1	1	1
NSTT 8305-HK004- BBBA SL-NR 9113a	DU 2008/8	1	1			1	1	1	1	1
NSTT 8305-HK003-A2 (01BR8305A01C)	DU 2008/9	1	3		2	1	1	2		

**Table 1: Strand identification codes. The table provides a summary of test results – there are 6 samples measured for contract NoEFDA/06-1524. Also included is sample DU 2008/9 which was measured as part of the benchmarking process.**

# 1 INTRODUCTION

## **Objectives:**

The objectives of this task are to characterise two batches of industrial Nb<sub>3</sub>Sn strand for the optimisation of the ITER heat treatment schedules. In total there were six industrial Nb<sub>3</sub>Sn strands which were supplied for the task and are specified in table 1. The two batches are HK003 and HK004. A range of different measurements were completed. In addition, data for a seventh strand measured as part of a bench-marking exercise are included for comparison.

## **Background:**

In the framework of European Nb<sub>3</sub>Sn strand procurement actions several new strand types have been successfully developed and produced. Due to the different layouts of the strands individual heat treatment schedules are being used. Heat treatment studies are necessary to minimise the duration and reaction temperature without significantly reducing the strand performance. In constructing ITER, it will be an advantage to have one common heat treatment schedule to enable different pancakes to be reacted at the same time.

In Durham, we have significant expertise developing measurements of the critical current of superconducting strands in high magnetic fields. We have already successfully characterised Nb<sub>3</sub>Sn and Nb<sub>3</sub>Al in detail (e.g. contract 03-1126).

This work includes a detailed study of six strands all reacted using a single heat treatment schedule. This work was done in collaboration with CEA Cadarache (contract 06-1521) to reduce the load on test facilities and to minimise the risk of delay in case of facility problems.

## **Scope of the task:**

The programme within the framework of this task includes:

- i) Heat treatment of strands.

- ii) Measurements of the critical current  $I_C$  (and  $n$ -values) at 4.2 K, from 10 T to 14 T and zero applied strain – determined at a criterion of  $10 \mu\text{Vm}^{-1}$ . The samples were mounted on an ITER type sample holder. The  $n$ -values were evaluated in the range of  $10 - 100 \mu\text{Vm}^{-1}$ .
- iii) Determination of the residual resistivity ratio (RRR(20K) ).
- iv) Electron microscopy to identify strand layout.
- v) Measurement of the hysteresis losses using a SQUID.
- vi) Variable-strain  $I_C(B, 4.2K, \varepsilon)$  data taken at 4.2K alone
- vii) Scaling parameters derived from variable-strain  $I_C(B, 4.2K, \varepsilon)$  data.

Given the unavoidable effect of strain<sup>1-3</sup> on Nb<sub>3</sub>Sn strands in large magnets, the strain-dependence of critical current density has a significant impact on the design and final performance of large Cable-in-Conduit Conductors (CICC) like those used in ITER. In the framework of the European Fusion Technology programme, the University of Durham has been involved in several strand characterization tasks (e.g. EFDA contracts 02-662, 03-1126, 05-1296 and 06-1534), and has a lot of experience in sample preparation, testing and evaluation of the results<sup>4</sup>.

The seven samples investigated are described in table 1 (cf abstract). The measurements made on each sample are also tabulated. Variable-strain  $I_C(B, 4.2K, \varepsilon)$  data are presented for four of the samples (annex F) which can be accurately parameterized by the Durham scaling law with 9 free-parameters (RMS ~1 A) and also by the ITER Scaling law (RMS ~ 3 A) as shown in Annex G. Four spreadsheets that contain tabulations of the  $I_C$  and  $n$ -value data, as well as the scaling-law parameterisation of  $I_C(B, T, \varepsilon)$  for these strands are available on the web at :

<http://www.dur.ac.uk/superconductivity.durham/publications.html>

The report is structured as follows: Section 2 outlines the experimental procedure. Section 3 presents the experimental results and analysis. Finally, section 4 presents the summary of the results obtained which are explicitly included in the format of benchmarking datasheets in annexes A-G.

## 2 EXPERIMENTAL PROCEDURE

### 2.1 Strand Identification Codes

In table 1, all strands investigated are labelled both by their DA code and a Durham University code.

### 2.2 Sample Heat-treatment and Preparation

Measurements were performed on chrome-plated Nb<sub>3</sub>Sn strands 0.82 mm in diameter, which were manufactured by EAS (European Advanced Superconductors). All strands were heat-treated in an argon atmosphere in a three-zone furnace, with an additional thermocouple positioned next to the sample in order to monitor the temperature. The details of the heat treatment for each strand were recorded and are shown in Annex A.

### 2.3 Sample Preparation for Critical Current Measurements

#### 2.3.1 $I_C$ measurements

For the  $I_C$ -measurements, each sample was mounted and then reacted on an ITER type sample holder. The chrome plating was removed and the ends of each sample was soldered to the copper ends of the sample holder. The holder (and sample) was then mounted onto the  $I_C$ -probe and voltage taps were attached. Measurements were made in the 15 Tesla vertical-field magnet system at Durham.

#### 2.3.2 $J_C(B, 4.2 \text{ K}, \varepsilon)$ measurements

For the variable strain  $I_C$ -measurement, samples were mounted and reacted on oxidised stainless-steel mandrels. The samples were then etched in hydrochloric acid to remove the chrome plating. Each sample was then transferred to Cu-Be helical springs, to which they were attached by copper plating and soldering. The Cu-Be helical springs had four-turns and a rectangular cross-section<sup>5, 6</sup>. The samples were then mounted onto the  $J_C(B, T, \varepsilon)$  probe, which will be described in section 2.4 .

### 2.4 Using the Durham $J_C(B, T, \varepsilon)$ probe

In this work, the Durham strain probe<sup>5, 7</sup> was used to carry out voltage–current ( $V-I$ ) measurements on the strands as a function of magnetic field ( $B$ ), and applied axial strain ( $\varepsilon_A$ ) at 4.2

K. The spring (and sample) is mounted onto the probe and the strain is applied by twisting the spring via concentric shafts. The inner shaft connects a worm-wheel system at the top of the probe to the top of the spring, and the outer shaft is connected to the bottom of the spring via an outer can. For measurements at 4.2 K, the outer can contains a number of holes to admit liquid helium from the surrounding bath<sup>8</sup>. The detailed description of the experimental apparatus and techniques can be found elsewhere<sup>5, 7, 9, 10</sup>.

The measurements consist of monitoring the voltage across different sections of the sample as the current through it increases. Measurements were made in the 15 Tesla vertical-field magnet system at Durham.

## 3 RESULTS AND ANALYSIS

### 3.1 $I_C$ and $n$ -value test results

This report presents critical current ( $I_C$ ) defined at an electric-field criterion of  $10 \mu\text{Vm}^{-1}$ . Values of  $n$  were obtained over the range of electric field ( $E$ ) from 10 to  $100 \mu\text{Vm}^{-1}$ . The  $I_C$  and  $n$ -index data for the  $\text{Nb}_3\text{Sn}$  strands are provided in Annex B. The first page of annex B is a summary of data taken over the field range from 10 to 14 T. Also provided are benchmarking sheets with measurements taken at 11.5, 12 and 12.5 T and the  $V$ - $I$  (voltage–current) characteristics. The noise in these measurements is a few nanovolts – primarily the Johnson noise from the room-temperature section of the voltage leads. The flat base-line of the  $V$ - $I$  characteristics provide strong evidence that the strand filaments were not damaged during the process of sample preparation. The difference in  $I_C$  values for two different sections of the same sample is less than 0.5%. The maximum difference in the  $n$ -index for different sections is about 1%.

### 3.2 Variable-strain $I_C$ ( $B$ , 4.2 K, Strain) test results

Variable magnetic field, variable-strain  $I_C(B, 4.2\text{K}, \varepsilon)$  measurements have been performed using Durham strain probe<sup>5, 7</sup> at 4.2 K. The procedure described in section 2 was followed. Four samples have been measured. Strain cycling tests were carried out for each strand with the applied axial strain ( $\varepsilon_A$ ) between -1% and 1%. The  $I_C$  as a function of strain was found to be reversible within the range  $-1\% \leq \varepsilon_A \leq 0.5\text{-}0.6\%$ . All these four strands were grossly damaged when the

applied tensile strain was increased from 0.6% to 1%, which was indicated by irreversible  $I_C$  behaviour (not provided here).

We show the variable-strain  $I_C(B, 4.2K, \varepsilon)$  data obtained during the reversible strain cycling process in Annex F. The data are the points in the figures and the solid lines were obtained from the Durham scaling laws characterised by the free-parameters in annex G. The figures of  $I_C(B, \varepsilon)$  are similar for these four strands.

### 3.3 Scaling Law Parameterisations of $I_C(B, 4.2K, \text{Strain})$ test results

#### 3.3.1 Durham Scaling Law parameterization

The  $J_C(B, 4.2K, \varepsilon)$  or  $I_C(B, 4.2K, \varepsilon)$  data at  $10 \mu\text{Vm}^{-1}$  are parameterised using the Durham scaling law<sup>4</sup>, which involves the following relations:

$$J_C(B, T, \varepsilon_1) = A(\varepsilon_1) [T_C^*(\varepsilon_1)(1-t^2)]^2 [B_{C2}^*(T, \varepsilon_1)]^{n-3} b^{p-1} (1-b)^q \quad (1)$$

$$B_{C2}^*(T, \varepsilon_1) = B_{C2}^*(0, \varepsilon_1)(1-t^\nu) \quad (2)$$

$$\left( \frac{A(\varepsilon_1)}{A(0)} \right)^{1/u} = \left( \frac{B_{C2}^*(0, \varepsilon_1)}{B_{C2}^*(0, 0)} \right)^{1/w} = \frac{T_C^*(\varepsilon_1)}{T_C^*(0)} \quad (3)$$

$$\frac{B_{C2}^*(0, \varepsilon_1)}{B_{C2}^*(0, 0)} = 1 + c_2 \varepsilon_1^2 + c_3 \varepsilon_1^3 + c_4 \varepsilon_1^4, \quad (4)$$

$$\varepsilon_1 = \varepsilon_A - \varepsilon_M, \quad (5)$$

where  $J_C$  is the engineering critical current density (the critical current divided by the total cross-sectional-area of the strand),  $\varepsilon_A$  is the applied strain,  $\varepsilon_1$  is the intrinsic strain,  $\varepsilon_M$  is the applied strain at the peak,  $T_C^*$  is the effective critical temperature,  $t = T/T_C^*$  is the reduced temperature,  $B_{C2}^*$  is the effective upper critical field and  $b = B/B_{C2}^*$  is the reduced field.

To date we have found that if comprehensive data are available, a 13 free-parameter fit is best for engineering purposes. However in many cases, there is little loss of accuracy parameterising the

strands if the number of free parameters is reduced to 9 and universal values of  $n = 2.5$ ,  $\nu = 1.5$ ,  $w = 2.2$ ,  $u = 0$  are used<sup>4</sup>. The  $I_C(B, 4.2K, \varepsilon)$  data presented here and obtained only at 4.2 K, for these four Nb<sub>3</sub>Sn strands were parameterised using scaling laws with 9 free-parameters. The RMS difference between the measured  $I_C$  and parameterized values is  $\sim 1$  A. The parameters from the Durham scaling law are given in the tables in Annex G (the four parameters in bold are not varied in the fitting procedure).

### 3.3.2 The official ITER scaling law parameterisation

The  $J_C(B, 4.2K, \varepsilon)$  or  $I_C(B, 4.2K, \varepsilon)$  data in this work has also been parameterised using a scaling law proposed for characterising interlaboratory measurements known as the official ITER scaling law which has 9 free parameters and is of the form:

$$J_C(B, T, \varepsilon_1) = \frac{C}{B} s(\varepsilon_1) (1 - t^{1.52}) (1 - t^2) b^p (1 - b)^q . \quad (6)$$

where  $s(\varepsilon_1)$  is a specified function of strain. This equation follows excellent work that explicitly incorporates the 3-dimensional nature of strain into the scaling law<sup>11-14</sup>. It effectively includes a  $1/\kappa$  term which rather than a  $1/\kappa^2$  term used in the Durham scaling law. The  $1/\kappa^2$  term has been found for example by Dew-Hughes<sup>15</sup> and Kramer<sup>16,17</sup> analytically, found in computational work<sup>18</sup> and in detailed experimental data<sup>9</sup>. Nevertheless we have provided the free parameters obtained using Eqn. (6) in Annex G that best fit the data in annex F. The ITER scaling law gives RMS differences of  $\sim 3$  A between the data and the parameterisation.

## 3.4 Measurements made using commercial equipment

### 3.4.1 Residual resistivity ratio (RRR(20K) ) measurements (Annex C)

<http://www.qdusa.com/products/ppms.html>

The RRR(20K) measurements were made using the PPMS system supplied by Quantum Design in AC transport mode. The Model P600 AC Transport Measurement System (ACT) supplies four-terminal transport property measurement techniques. Two independent channels are available to measure multiple samples in a single sequence. The RRR(20K) value is defined as the ratio of the resistivity at room temperature divided by the resistivity at 20 K.

### **3.4.2 Microscopy results for strand layout (Annex D)**

[http://www.hitachi-hta.com/media/Hitachi\\_3000\\_LV.pdf](http://www.hitachi-hta.com/media/Hitachi_3000_LV.pdf)

Durham University has more than a dozen electron-microscopes providing a range of analytical techniques. Results can be provided as distribution maps as well as area averaged and spot analysis. Images are provided in various digital formats from about 20 times up to 300 000 times magnification. Annex D provides low magnification images in backscattered electron mode which provides atomic contrast. Although much higher resolution is available, we have used low magnification and simple/fast polishing techniques to provide images of reasonable quality showing strand layout.

The difference in the diffusion barrier for the HK003 and HK004 samples are clear in these micrographs.

### **3.4.3 Magnetic measurements of hysteresis loss (Annex E).**

<http://www.qdusa.com/products/brochures/SQUIDVSM23.pdf>

The magnetic hysteresis measurements were made using a commercial QD MPMS SQUID in fields up to 5 Tesla. The temperature control insert of the MPMS SQUID VSM is a vacuum-insulated chamber into which cold helium is drawn, through a variable flow valve, for purposes of cooling the sample chamber from pumped helium at 1.8 K up to 4.2 K. A finely tuned flow impedance and sophisticated temperature control software allows continuous operation at 4.2 K.

The MPMS SQUID VSM utilizes a 5 Tesla, superconducting, helium-cooled magnet and a hybrid digital/analog magnet controller designed specifically for the SQUID VSM to achieve precise, quiet control of the magnetic field. Data are presented as magnetic moment versus applied magnetic field at 4.2 K.

The analysis of the losses per unit volume of the strand follows from measuring (the integral of the magnetic moment versus applied field)/strand volume. We have calculated losses for the range  $\pm 3$  Tesla for 4 samples (i.e. DU2008/3, DU2008/6 sample A, DU2008/6 sample B and DU2008/7) but have omitted analysis of those samples affected by an instrumentation range change anomaly. Nevertheless it can be seen from all the data (and consistent with the data compromised by the range anomaly) that the HK004 batch have losses that are about a factor 5 higher than HK003.

## 4 SUMMARY

We have reported: detailed heat treatment schedules;  $I_c$  and  $n$ -index; RRR(20K) tests; electron microscopy and SQUID results for seven Nb<sub>3</sub>Sn superconducting strands. We have also provided  $I_c(B, 4.2K, \varepsilon)$  data for four Nb<sub>3</sub>Sn EAS strands. These  $I_c(B, \varepsilon)$  raw data at 4.2 K were accurately parameterized by the Durham scaling law and the ITER scaling law. The RMS values were found to be  $\sim 1$  A for Durham scaling and  $\sim 3$ A for ITER scaling.

Two batches of material have been measured. Microscopy clearly distinguishes the barriers used for each of the two batches – the magnetic SQUID measurements show that the HK004 batch has significantly ( $\sim$  factor 5) higher losses than the HK003 batch over the range  $\pm 3$  T at 4.2 K.

The data for each of the Nb<sub>3</sub>Sn strands are reported in the annexes. Accompanying this report are four spreadsheets that contain tabulations of the  $J_c$  and  $n$ -value data, as well as the scaling-law parameterisation of  $J_c(B, T, \varepsilon)$  for these strands respectively at:

<http://www.dur.ac.uk/superconductivity.durham/publications.html>

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## Appendices for Heat Optimisation of strands

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#### Strand Identification Codes

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ANNEX C – RRR(20K) Test Results .....

ANNEX D – Microscopy strand layout.....

ANNEX E –  $Q_{hys}$  Test Results - SQUID (MPMS) DC Measurement.....

ANNEX F – Variable Strain data  $I_C$  (B, Strain at 4.2 K).....

ANNEX G – Scaling Parameters for  $I_C$  (B, Strain, 4.2 K) .....

MANUFACTURERS REFERENCE NUMBER	DURHAM UNIVERSITY REFERENCE NUMBER	ANNEX A HEAT TREATMENT RECORDS	ANNEX B $I_c$ (B,4.2K) TEST RESULTS	ANNEX C RRR(20K) TEST RESULTS		ANNEX D ELECTRON MICROSCOPY		ANNEX E $Q_{hyst}$ SQUID (MPMS)	ANNEX F VARIABLE STRAIN DATA $I_c$ (B,4.2K, $\epsilon$ )	ANNEX G SCALING PARAMETERS $I_c$ (B,4.2K, $\epsilon$ )
				REACTED	UNREACTED	REACTED	UNREACTED (Not shown)			
NSTT 8305-HK003-A1 SL-NR 9108a	DU 2008/3	1	Strain data Annex F			1	1	1	1	1
NSTT 8305-HK003-A2 SL-NR 9109a	DU 2008/4	1	1							
NSTT 8305-HK003-A1 SL-NR 9108i	DU 2008/5	1	1							
NSTT 8305-HK003-A2 SL-NR 9109i	DU 2008/6	1	Strain data Annex F			1	1	2	1	1
NSTT 8305-HK004-BA SL-NR 9110i	DU 2008/7	1	1			1	1	1	1	1
NSTT 8305-HK004- BBBA SL-NR 9113a	DU 2008/8	1	1			1	1	1	1	1
NSTT 8305-HK003-A2 (01BR8305A01C)	DU 2008/9	1	3		2	1	1	2		

**Table 1: Strand identification codes. The table provides a summary of test results – there are 6 samples measured for contract NoEFDA/06-1524. Also included is sample DU 2008/9 which was measured as part of the benchmarking process.**

## Annex A : Heat Treatment Records

HT Record Sheet ID: Furnace 3 : EAS sample(s) DU2008 /4 /5 /7 /8

DU2008/4 (Ic Holder A)      DU2008/7 (Ic Holder D)

DU2008/5 (Ic Holder B)      DU2008/8 (Ic Holder E)

DA/DU code: Billet: NSTT 8305-HK003-A2 (Ref: SL-NR 9109a): DU2008/4

Billet: NSTT 8305-HK003-A1 (Ref: SL-NR 9108i): DU2008/5

Billet: NSTT 8305-HK004-BA (Ref: SL-NR 9110i): DU2008/7

Billet: NSTT 8305-HK004-BBBA (Ref: SL-NR 9113a): DU2008/8

Contact person(s): Professor Damian Hampshire + Stephen Pragnell

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Tel: 44(0) 191 334 3520

E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

### Summary

Reaction start date (RSD): 20/11/2008

Reaction end date: 11/12/2008

### Eurotherm programmer settings

Segment 1 target 210°C : ramp rate 5°C/hr

Segment 2 dwell 50hrs

Segment 3 target 340°C : ramp rate 5°C/hr

Segment 4 dwell 25hrs

Segment 5 target 450°C : ramp rate 5°C/hr

Segment 6 dwell 25hrs

Segment 7 target 575°C : ramp rate 5°C/hr

Segment 8 dwell 100hrs

Segment 9 target 650°C : ramp rate 5°C/hr

Segment 10 dwell 100hrs

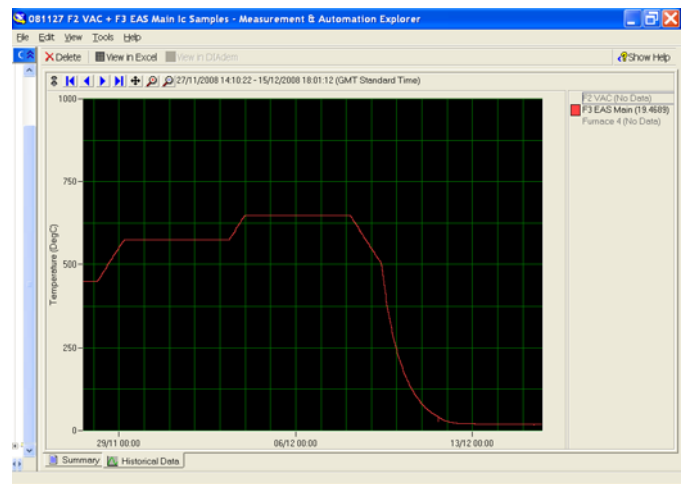
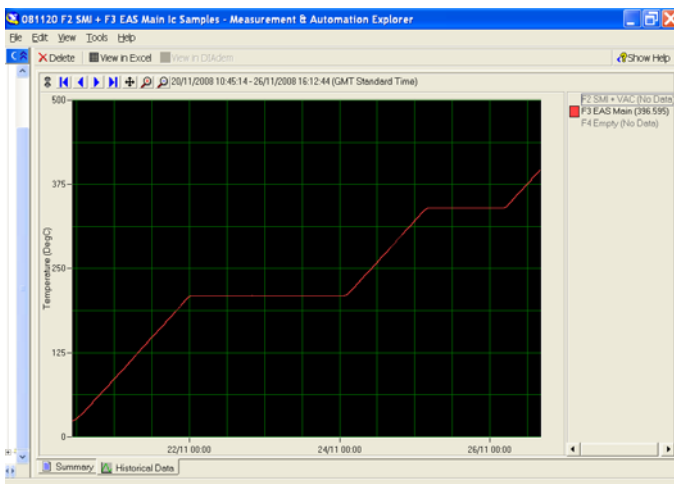
Segment 11 target 500°C : ramp rate 5°C/hr

Segment 12 target 20°C : ramp rate 100°C/hr

Segment 13 end

### Comments

Samples are pre-mounted on ITER design sample holders prior to heat treatment. Furnace temperatures are recorded using NI Measurement & Automation Explorer and monitored at regular intervals by the operator. In this instance the furnace monitoring software was interrupted for one day.



## Annex A : Heat Treatment Records

HT Record Sheet ID: Furnace 2 : EAS sample(s) DU2008 /3  
DU2008/3 (strain mandrel A1)

DA/DU code: Billet: NSTT 8305-HK003-A1 (Ref: SL-NR 9108a): DU2008/3

Contact person(s): Professor Damian Hampshire + Stephen Pragnell

Affiliation: Superconductivity Group, Durham University, UK

Tel: 44(0) 191 334 3520

E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

### Summary

Reaction start date (RSD): 30/07/2008

Reaction end date: 22/08/2008

### Eurotherm programmer settings

Segment 1 target 210°C : ramp rate 5°C/hr

Segment 2 dwell 50hrs

Segment 3 target 340°C : ramp rate 5°C/hr

Segment 4 dwell 25hrs

Segment 5 target 450°C : ramp rate 5°C/hr

Segment 6 dwell 25hrs

Segment 7 target 575°C : ramp rate 5°C/hr

Segment 8 dwell 100hrs

Segment 9 target 650°C : ramp rate 5°C/hr

Segment 10 dwell 100hrs

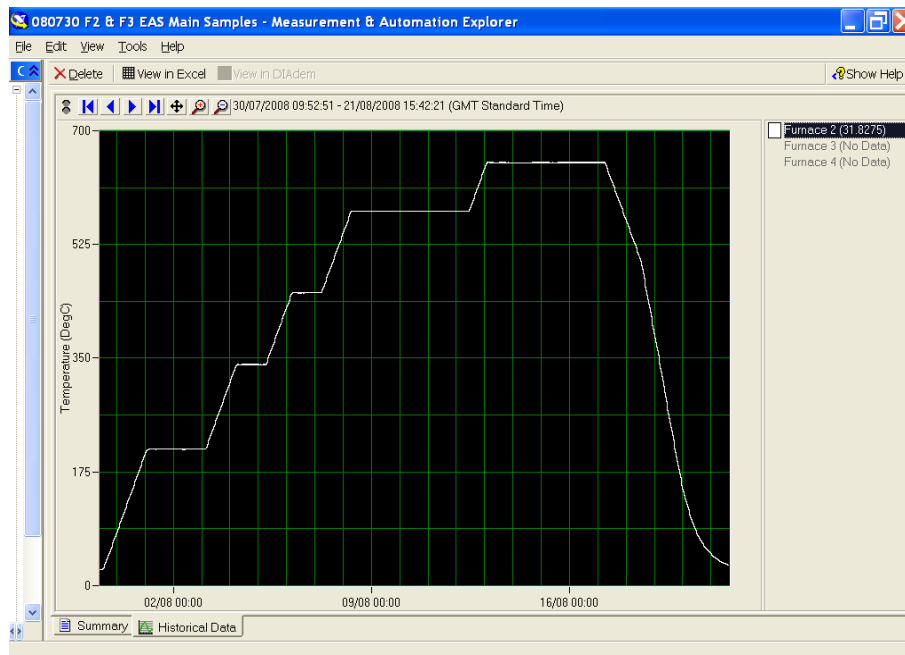
Segment 11 target 500°C : ramp rate 5°C/hr

Segment 12 target 20°C : ramp rate 100°C/hr

Segment 13 end

### Comments

Samples are pre-mounted on mandrels prior to heat treatment. Furnace temperatures are recorded using NI Measurement & Automation Explorer and monitored at regular intervals by the operator.



## Annex A : Heat Treatment Records

HT Record Sheet ID: Furnace 3 : EAS sample(s) DU2008 /6 /7 /8  
DU2008/6 (strain mandrel D1)      DU2008/8 (strain mandrel F1)  
DU2008/7 (strain mandrel E1)

DA/DU code: Billet: NSTT 8305-HK003-A2 (Ref: SL-NR 9109i): DU2008/6  
Billet: NSTT 8305-HK004-BA (Ref: SL-NR 9110i): DU2008/7  
Billet: NSTT 8305-HK004-BBBA (Ref: SL-NR 9113a): DU2008/8

Contact person(s): Professor Damian Hampshire + Stephen Pragnell  
Affiliation: Superconductivity Group, Durham University, UK  
Tel: 44(0) 191 334 3520  
E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

### Summary

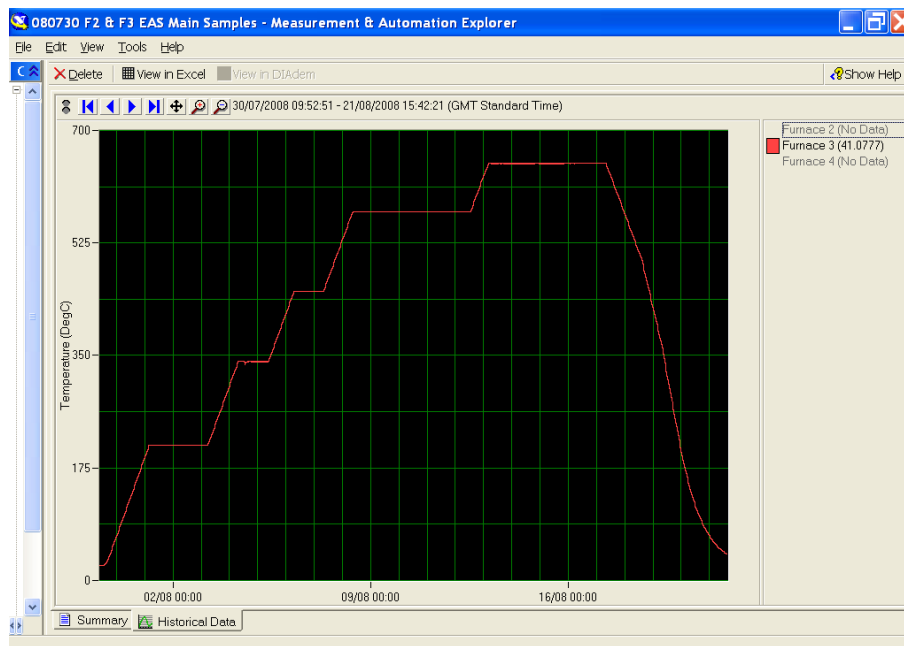
Reaction start date (RSD): 30/07/2008      Reaction end date: 22/08/2008

#### Eurotherm programmer settings

Segment 1 target 210°C : ramp rate 5°C/hr	Segment 7 target 575°C : ramp rate 5°C/hr
Segment 2 dwell 50hrs	Segment 8 dwell 100hrs
Segment 3 target 340°C : ramp rate 5°C/hr	Segment 9 target 650°C : ramp rate 5°C/hr
Segment 4 dwell 25hrs	Segment 10 dwell 100hrs
Segment 5 target 450°C : ramp rate 5°C/hr	Segment 11 target 500°C : ramp rate 5°C/hr
Segment 6 dwell 25hrs	Segment 12 target 20°C : ramp rate 100°C/hr
	Segment 13 end

### Comments

Samples are pre-mounted on mandrels prior to heat treatment. Furnace temperatures are recorded using NI Measurement & Automation Explorer and monitored at regular intervals by the operator.



## Annex A : Heat Treatment Records

HT Record Sheet ID: Furnace 3: EAS sample(s) DU2008/9  
DU2008/9 (Ic Holder A, B, C)

DA/DU code: Billet: NSTT 8305-HK003-A2 (Ref: 01BR8305A01C) : DU2008/9

Contact person(s): Professor Damian Hampshire + Stephen Pragnell

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### Summary

Reaction start date (RSD): 28/10/2008

Reaction end date: 18/11/2008

#### Eurotherm programmer settings

Segment 1 target 210°C : ramp rate 5°C/hr

Segment 2 dwell 50hrs

Segment 3 target 340°C : ramp rate 5°C/hr

Segment 4 dwell 25hrs

Segment 5 target 450°C : ramp rate 5°C/hr

Segment 6 dwell 25hrs

Segment 7 target 575°C : ramp rate 5°C/hr

Segment 8 dwell 100hrs

Segment 9 target 650°C : ramp rate 5°C/hr

Segment 10 dwell 100hrs

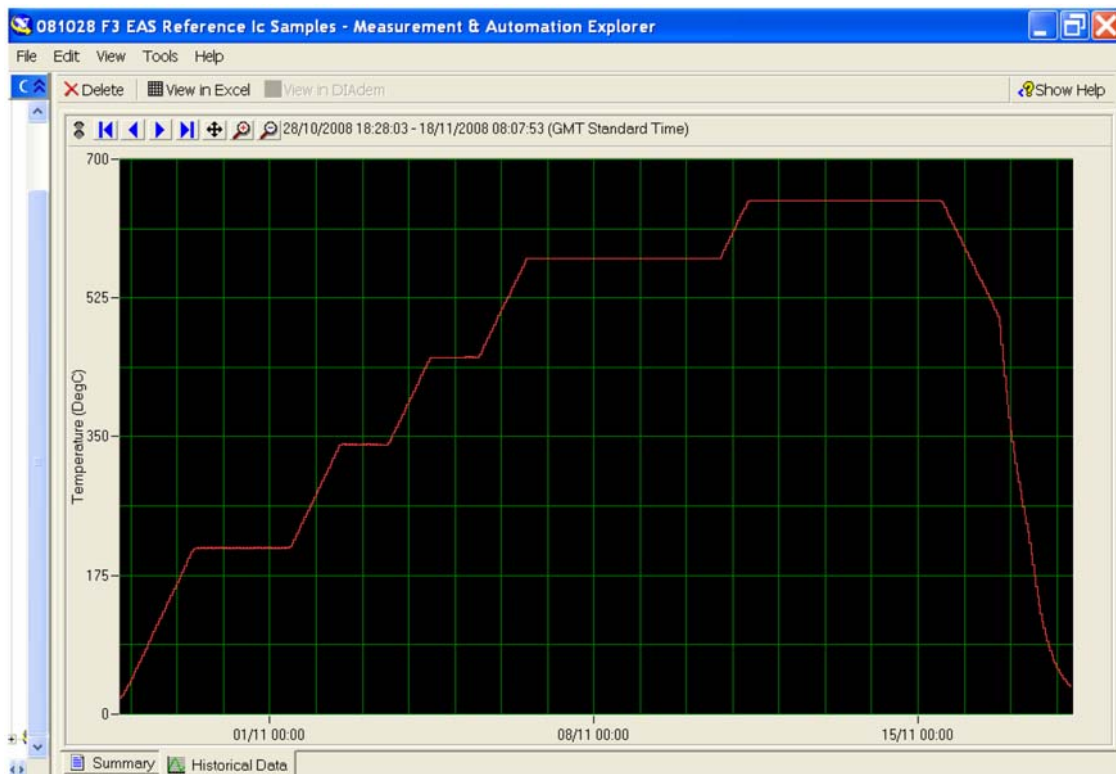
Segment 11 target 500°C : ramp rate 5°C/hr

Segment 12 target 20°C : ramp rate 100°C/hr

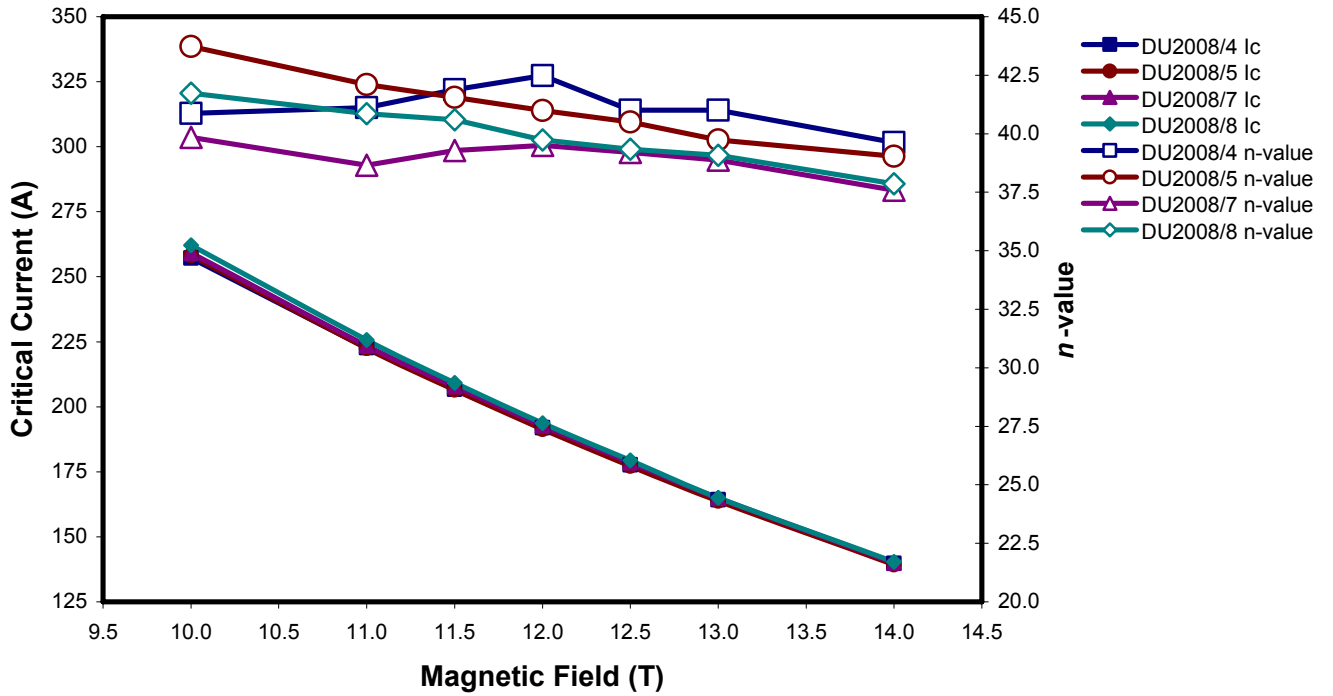
Segment 13 end

### Comments

Samples are pre-mounted on mandrels prior to heat treatment. Furnace temperatures are recorded using NI Measurement & Automation Explorer and monitored at regular intervals by the operator.



**Annex B : Summary of  $I_c$  and  $n$ -value test results**



**Table 2: A summary of the  $I_c$  and  $n$ -value data at 4.2 K as a function of field.**

Annex B : Test Results								
MAGNETIC FIELD (Tesla)	DU2008/4		DU2008/5		DU2008/7		DU2008/8	
	$I_c$	$n$ -value	$I_c$	$n$ -value	$I_c$	$n$ -value	$I_c$	$n$ -value
10.00	257.20	40.87	258.21	43.73	259.17	39.84	262.16	41.73
11.00	222.78	41.12	222.54	42.10	223.47	38.66	225.67	40.85
11.50	206.69	41.88	206.50	41.56	207.80	39.29	209.20	40.59
12.00	191.98	42.48	191.37	40.99	192.72	39.50	193.66	39.73
12.50	177.71	41.01	177.19	40.50	178.56	39.20	179.36	39.34
13.00	164.32	41.00	163.80	39.74	164.84	38.87	165.04	39.08
14.00	139.75	39.62	139.33	39.04	139.97	37.59	140.43	37.86

**Table 3 : A tabulated summary of the  $I_c$  and  $n$ -value data at 4.2 K as a function of field.**

## Annex B : $I_c$ and $n$ -value test results

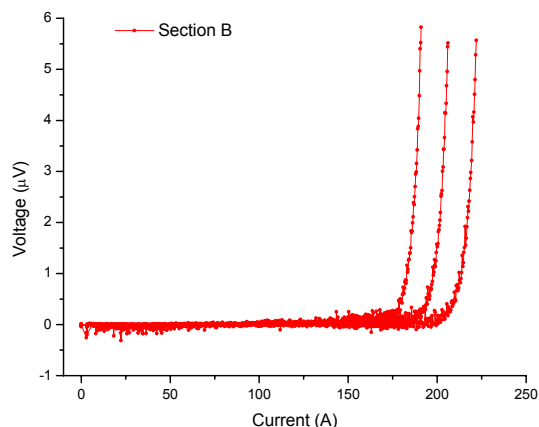
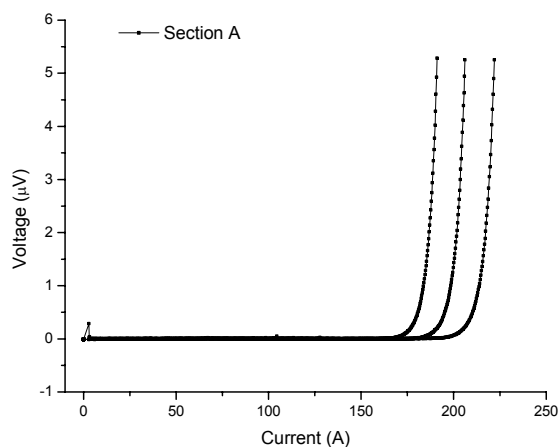
DA code: Billet: NSTT 8305-HK003-A2 (Ref: SL-NR-9109a)  
 Sample ID-code: Furnace 3 : EAS sample(s) DU2008/4 ( $I_c$  Holder/Sample A)  
 Prepared at: Durham University Tested at: Durham University  
 Contact person: Professor Damian Hampshire + Stephen Pragnell  
 Affiliation: Superconductivity Group, Durham University  
 Tel: 44(0) 191 334 3520  
 E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

### Summary

Critical current : 206.7 A at 11.5T, 192.0 A at 12T, 177.7 A at 12.5T  
 Date of cool down: 15/12/2008  
 Date of warm up: 15/12/2008  
 Heat treatment ID: Furnace 3 : EAS sample(s) (DU2008/4)  
Reaction start date: 20/11/2008  
Reaction end date: 11/12/2008

### Top Sample (DU2008/4 : $I_c$ Holder/Sample A)

Time/ Date	$B$ (T)	Temp. (K)	Meas. $I_c$ (A)	$I_{c, \text{Corr}}$ at 4.22 K (A)	Meas. $I_c$ (A) Meas. $n$ -index 27.00/26.84 mm taps		Meas. $n$ -index	Comments
					#1 / 2	#2 / 2		
081215	12.5	4.22	177.70	177.70	178.09 42.37	177.32 39.65	41.01	$I_c$ at $10 \mu\text{Vm}^{-1}$ $n$ ( $10 \mu\text{Vm}^{-1}$ - $100 \mu\text{Vm}^{-1}$ )
081215	12	4.22	191.98	191.98	192.40 42.59	191.55 42.36	42.48	$I_c$ at $10 \mu\text{Vm}^{-1}$ $n$ ( $10 \mu\text{Vm}^{-1}$ - $100 \mu\text{Vm}^{-1}$ )
081215	11.5	4.22	206.69	206.69	207.12 42.10	206.25 41.65	41.88	$I_c$ at $10 \mu\text{Vm}^{-1}$ $n$ ( $10 \mu\text{Vm}^{-1}$ - $100 \mu\text{Vm}^{-1}$ )



## Annex B : $I_c$ and $n$ -value test results

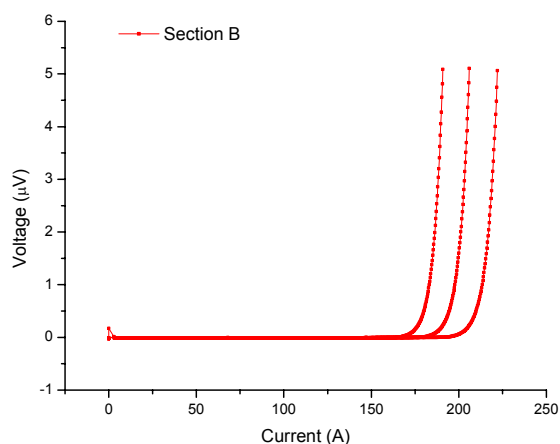
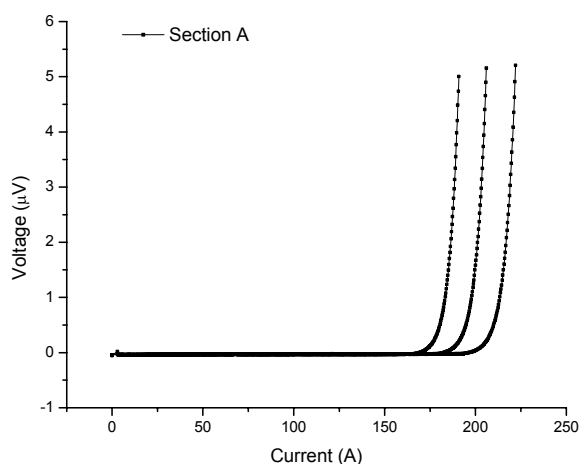
DA code: Billet: NSTT 8305-HK003-A1 (Ref: SL-NR-9108i)  
 Sample ID-code: Furnace 3 : EAS sample(s) DU2008/5 ( $I_c$  Holder/Sample B)  
 Prepared at: Durham University Tested at: Durham University  
 Contact person: Professor Damian Hampshire + Stephen Pragnell  
 Affiliation: Superconductivity Group, Durham University  
 Tel: 44(0) 191 334 3520  
 E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

### Summary

Critical current : 206.5 A at 11.5T, 191.4 A at 12T, 177.2 A at 12.5T  
 Date of cool down: 15/12/2008  
 Date of warm up: 15/12/2008  
 Heat treatment ID: Furnace 3 : EAS sample(s) (DU2008/5)  
Reaction start date: 20/11/2008  
Reaction end date: 11/12/2008

### Bottom Sample (DU2008/5 : $I_c$ Holder/Sample B)

Time/ Date	$B$ (T)	Temp. (K)	Meas. $I_c$ (A)	$I_{c, \text{Corr}}$ at 4.22 K (A)	Meas. $I_c$ (A) Meas. $n$ -index 26.71/25.98 mm taps		Meas. $n$ -index	Comments
					#1 / 2	#2 / 2		
081215	12.5	4.22	177.19	177.19	177.36 40.83	177.01 40.17	40.50	$I_c$ at $10 \mu\text{Vm}^{-1}$ $n$ ( $10 \mu\text{Vm}^{-1}$ - $100 \mu\text{Vm}^{-1}$ )
081215	12	4.22	191.37	191.37	191.49 41.26	191.25 40.72	40.99	$I_c$ at $10 \mu\text{Vm}^{-1}$ $n$ ( $10 \mu\text{Vm}^{-1}$ - $100 \mu\text{Vm}^{-1}$ )
081215	11.5	4.22	206.50	206.50	206.58 41.83	206.42 41.29	41.56	$I_c$ at $10 \mu\text{Vm}^{-1}$ $n$ ( $10 \mu\text{Vm}^{-1}$ - $100 \mu\text{Vm}^{-1}$ )



## Annex B : $I_c$ and $n$ -value test results

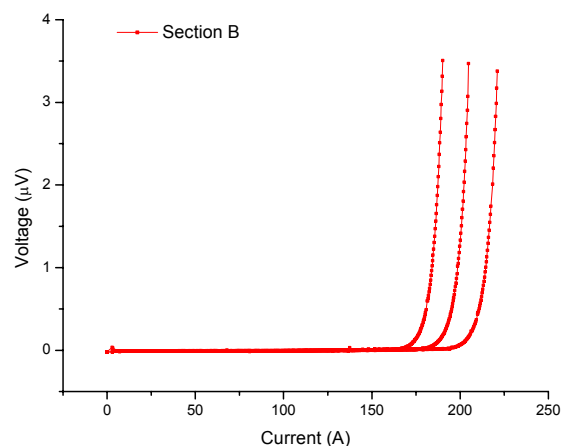
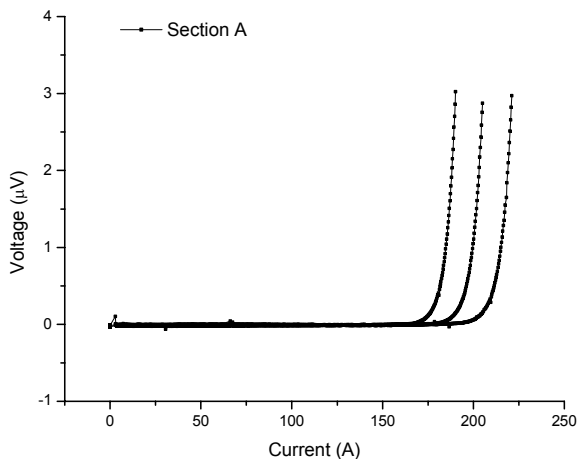
DA code: Billet: NSTT 8305-HK004-BA (Ref: SL-NR-9110i)  
 Sample ID-code: Furnace 3 : EAS sample(s) DU2008/7 ( $I_c$  Holder/Sample D)  
 Prepared at: Durham University Tested at: Durham University  
 Contact person: Professor Damian Hampshire + Stephen Pragnell  
 Affiliation: Superconductivity Group, Durham University  
 Tel: 44(0) 191 334 3520  
 E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

### Summary

Critical current : 207.8 A at 11.5T, 192.7 A at 12T, 178.6 A at 12.5T  
 Date of cool down: 17/12/2008  
 Date of warm up: 17/12/2008  
 Heat treatment ID: Furnace 3 : EAS sample(s) (DU2008/7)  
Reaction start date: 20/11/2008  
Reaction end date: 11/12/2008

### Top Sample (DU2008/7 : $I_c$ Holder/Sample D)

Time/ Date	$B$ (T)	Temp. (K)	Meas. $I_c$ (A)	$I_{c, \text{Corr}}$ at 4.22 K (A)	Meas. $I_c$ (A) Meas. $n$ -index 27.55/28.67 mm taps		Meas. $n$ -index	Comments
					#1 / 2	#2 / 2		
081217	12.5	4.22	178.56	178.56	178.96 39.63	178.16 38.77	39.20	$I_c$ at $10 \mu\text{Vm}^{-1}$ $n$ ( $10 \mu\text{Vm}^{-1}$ - $100 \mu\text{Vm}^{-1}$ )
081217	12	4.22	192.72	192.72	193.07 39.56	192.36 39.44	39.50	$I_c$ at $10 \mu\text{Vm}^{-1}$ $n$ ( $10 \mu\text{Vm}^{-1}$ - $100 \mu\text{Vm}^{-1}$ )
081217	11.5	4.22	207.80	207.80	207.91 39.18	207.69 39.40	39.29	$I_c$ at $10 \mu\text{Vm}^{-1}$ $n$ ( $10 \mu\text{Vm}^{-1}$ - $100 \mu\text{Vm}^{-1}$ )



## Annex B : $I_c$ and $n$ -value test results

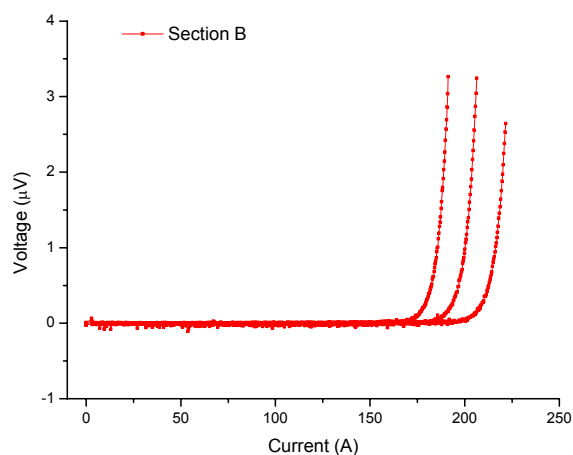
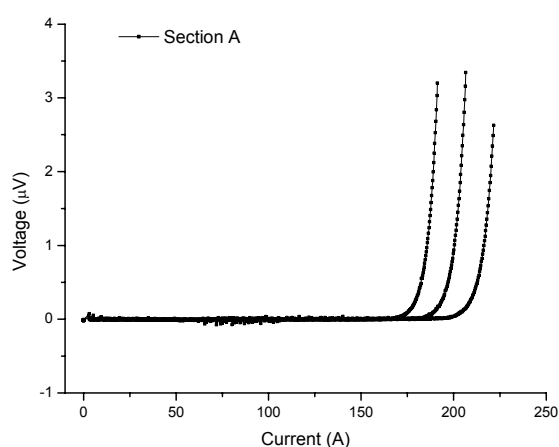
DA code: Billet: NSTT 8305-HK004-BBBA (Ref: SL-NR-9113a)  
 Sample ID-code: Furnace 3 : EAS sample(s) DU2008/8 ( $I_c$  Holder/Sample E)  
 Prepared at: Durham University Tested at: Durham University  
 Contact person: Professor Damian Hampshire + Stephen Pragnell  
 Affiliation: Superconductivity Group, Durham University  
 Tel: 44(0) 191 334 3520  
 E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

### Summary

Critical current : 209.2 A at 11.5T, 193.7 A at 12T, 179.4 A at 12.5T  
 Date of cool down: 17/12/2008  
 Date of warm up: 17/12/2008  
 Heat treatment ID: Furnace 3 : EAS sample(s) (DU2008/8)  
Reaction start date: 20/11/2008  
Reaction end date: 11/12/2008

### Bottom Sample (DU2008/8 : $I_c$ Holder/Sample E)

Time/ Date	$B$ (T)	Temp. (K)	Meas. $I_c$ (A)	$I_{c, \text{Corr}}$ at 4.22 K (A)	Meas. $I_c$ (A) Meas. $n$ -index 25.56/26.40 mm taps		Meas. $n$ -index	Comments
					#1 / 2	#2 / 2		
081217	12.5	4.22	179.36	179.36	179.30 39.42	179.42 39.26	39.34	$I_c$ at $10 \mu\text{Vm}^{-1}$ $n$ ( $10 \mu\text{Vm}^{-1}$ - $100 \mu\text{Vm}^{-1}$ )
081217	12	4.22	193.66	193.66	193.68 40.02	193.64 39.44	39.73	$I_c$ at $10 \mu\text{Vm}^{-1}$ $n$ ( $10 \mu\text{Vm}^{-1}$ - $100 \mu\text{Vm}^{-1}$ )
081217	11.5	4.22	209.20	209.20	209.20 40.76	209.20 40.42	40.59	$I_c$ at $10 \mu\text{Vm}^{-1}$ $n$ ( $10 \mu\text{Vm}^{-1}$ - $100 \mu\text{Vm}^{-1}$ )



## Annex B : $I_c$ and $n$ -value test results

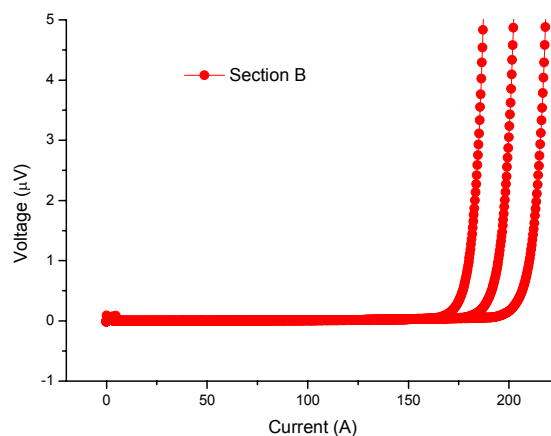
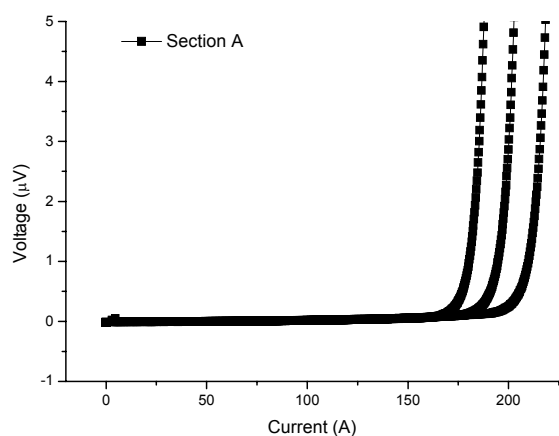
DA code: Billet: NSTT 8305-HK003-A2 (Ref: 01BR8305A01C)  
 Sample ID-code: Furnace 3 : EAS sample(s) DU2008/9 ( $I_c$  Holder/Sample A)  
 Prepared at: Durham University Tested at: Durham University  
 Contact person: Professor Damian Hampshire + Stephen Pragnell  
 Affiliation: Superconductivity Group, Durham University  
 Tel: 44(0) 191 334 3520  
 E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

### Summary:

Critical current : 205.9 A at 11.5T, 188.4 A at 12T, 174.2 A at 12.5T  
 Date of cool down: 26/11/2008  
 Date of warm up: 26/11/2008  
 Heat treatment ID: Furnace 3 : EAS sample(s) (DU2008/9)  
Reaction start date: 28/10/2008  
Reaction end date: 18/11/2008

### Top Sample (DU2008/9 : $I_c$ Holder/Sample A)

Time/ Date	$B$ (T)	Temp. (K)	Meas. $I_c$ (A)	$I_{c\text{ Corr}}$ at 4.22 K (A)	Meas. $I_c$ (A) with 27.6/27.1 mm taps		$n$ -index	Comments
					#1 / 2	#2 / 2		
081126	12.5	4.22	174.2	174.2	174.03	174.30	41	$I_c$ at $10\ \mu\text{Vm}^{-1}$ $n$ ( $10\ \mu\text{Vm}^{-1}$ - $100\ \mu\text{Vm}^{-1}$ )
081126	12	4.22	188.4	188.4	188.33	188.43	41	$I_c$ at $10\ \mu\text{Vm}^{-1}$ $n$ ( $10\ \mu\text{Vm}^{-1}$ - $100\ \mu\text{Vm}^{-1}$ )
081126	11.5	4.22	205.9	205.9	208.30	203.44	42	$I_c$ at $10\ \mu\text{Vm}^{-1}$ $n$ ( $10\ \mu\text{Vm}^{-1}$ - $100\ \mu\text{Vm}^{-1}$ )



## Annex B : $I_c$ and $n$ -value test results

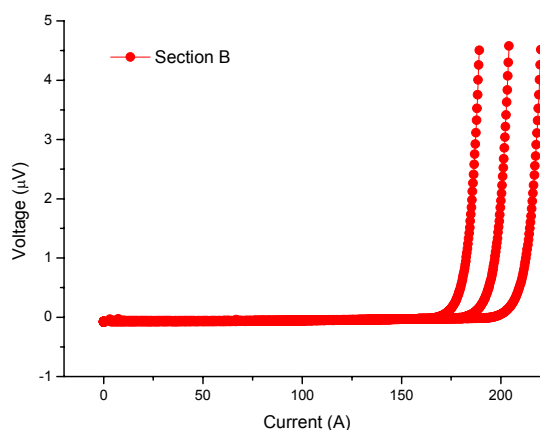
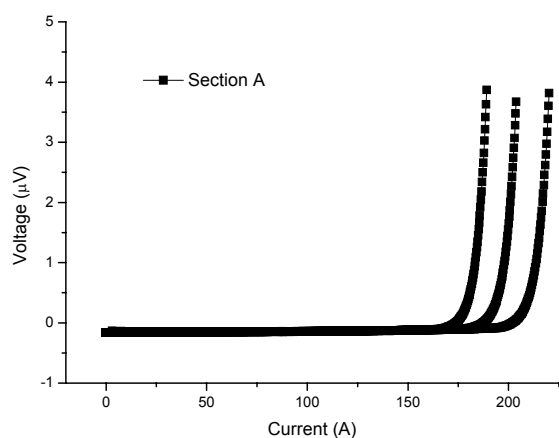
DA code: Billet: NSTT 8305-HK003-A2 (Ref: 01BR8305A01C)  
 Sample ID-code: Furnace 3 : EAS sample(s) DU2008/9 ( $I_c$  Holder/Sample B)  
 Prepared at: Durham University Tested at: Durham University  
 Contact person: Professor Damian Hampshire + Stephen Pragnell  
 Affiliation: Superconductivity Group, Durham University  
 Tel: 44(0) 191 334 3520  
 E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

### Summary:

Critical current : 205.9 A at 11.5T, 190.7 A at 12T, 176.6A at 12.5T  
 Date of cool down: 26/11/2008  
 Date of warm up: 26/11/2008  
 Heat treatment ID: Furnace 3 : EAS sample(s) (DU2008/9)  
Reaction start date: 28/10/2008  
Reaction end date: 18/11/2008

### Middle Sample (DU2008/9 : $I_c$ Holder/Sample B)

Time/ Date	$B$ (T)	Temp. (K)	Meas. $I_c$ (A)	$I_{c \text{ Corr}}$ at 4.22 K (A)	Meas. $I_c$ (A) with 26.6/28.6mm taps		$n$ -index	Comments
					#1 / 2	#2 / 2		
081126	12.5	4.22	176.6	176.6	176.69	176.60	41	$I_c$ at $10 \mu\text{Vm}^{-1}$ $n$ ( $10 \mu\text{Vm}^{-1}$ - $100 \mu\text{Vm}^{-1}$ )
081126	12	4.22	190.7	190.7	190.74	190.60	41	$I_c$ at $10 \mu\text{Vm}^{-1}$ $n$ ( $10 \mu\text{Vm}^{-1}$ - $100 \mu\text{Vm}^{-1}$ )
081126	11.5	4.22	205.9	205.9	205.88	205.91	41	$I_c$ at $10 \mu\text{Vm}^{-1}$ $n$ ( $10 \mu\text{Vm}^{-1}$ - $100 \mu\text{Vm}^{-1}$ )



## Annex B : $I_c$ and $n$ -value test results

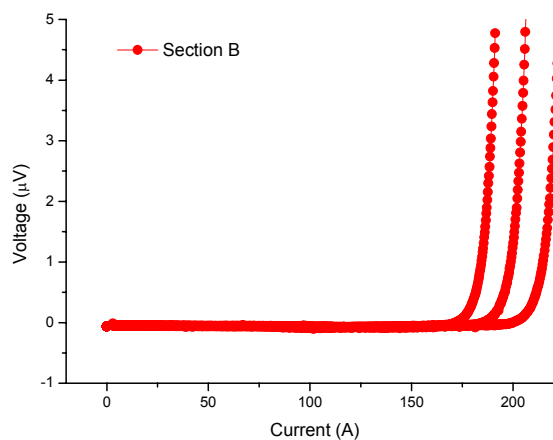
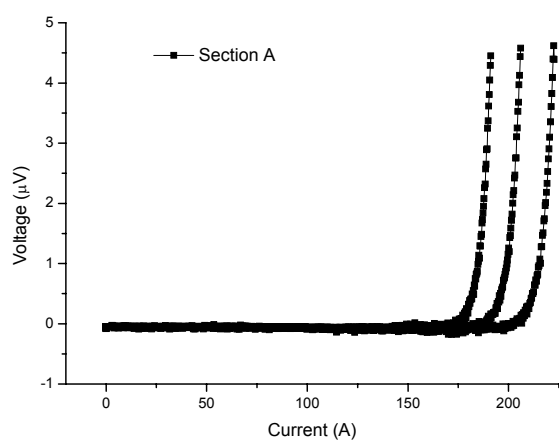
DA code: Billet: NSTT 8305-HK003-A2 (Ref: 01BR8305A01C)  
 Sample ID-code: Furnace 3 : EAS sample(s) DU2008/9 (Ic Holder/Sample C)  
 Prepared at: Durham University Tested at: Durham University  
 Contact person: Professor Damian Hampshire + Stephen Pragnell  
 Affiliation: Superconductivity Group, Durham University  
 Tel: 44(0) 191 334 3520  
 E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

### Summary:

Critical current: 207.7 A at 11.5T, 192.5 A at 12T, 178.4 A at 12.5T  
 Date of cool down: 26/11/2008  
 Date of warm up: 26/11/2008  
 Heat treatment ID: Furnace 3 : EAS sample(s) (DU2008/9)  
Reaction start date: 28/10/2008  
Reaction end date: 18/11/2008

### Bottom Sample (DU2008/9 : Ic Holder/Sample C)

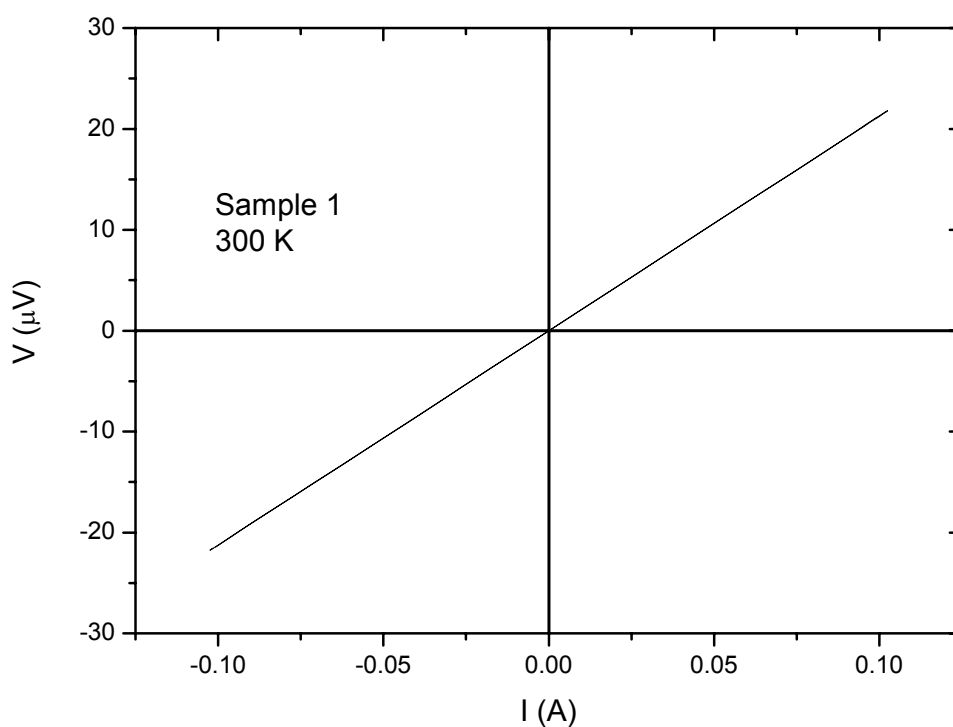
Time/ Date	$B$ (T)	Temp. (K)	Meas. $I_c$ (A)	$I_{c\text{ Corr}}$ at 4.22 K (A)	Meas. $I_c$ (A) with 28.8/25.9 mm taps		$n$ -index	Comments
					#1 / 2	#2 / 2		
081126	12.5	4.22	178.4	178.4	179.23	177.56	41	$I_c$ at $10\ \mu\text{Vm}^{-1}$ $n$ ( $10\ \mu\text{Vm}^{-1}$ - $100\ \mu\text{Vm}^{-1}$ )
081126	12	4.22	192.5	192.5	193.14	191.79	42	$I_c$ at $10\ \mu\text{Vm}^{-1}$ $n$ ( $10\ \mu\text{Vm}^{-1}$ - $100\ \mu\text{Vm}^{-1}$ )
081126	11.5	4.22	207.7	207.7	208.54	206.90	42	$I_c$ at $10\ \mu\text{Vm}^{-1}$ $n$ ( $10\ \mu\text{Vm}^{-1}$ - $100\ \mu\text{Vm}^{-1}$ )



### Annex C : RRR(20K) Test results

DA code: Billet: NSTT 8305-HK003-A2 (Ref: 01BR8305A01C)  
Sample ID-code: Furnace 3 : EAS sample(s) DU2008/9 (Unreacted Sample 1)  
Prepared at: Durham University Tested at: Durham University  
Contact person: Professor Damian Hampshire + Stephen Pragnell  
Affiliation: Superconductivity Group, Durham University  
Tel: 44(0) 191 334 3520  
E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

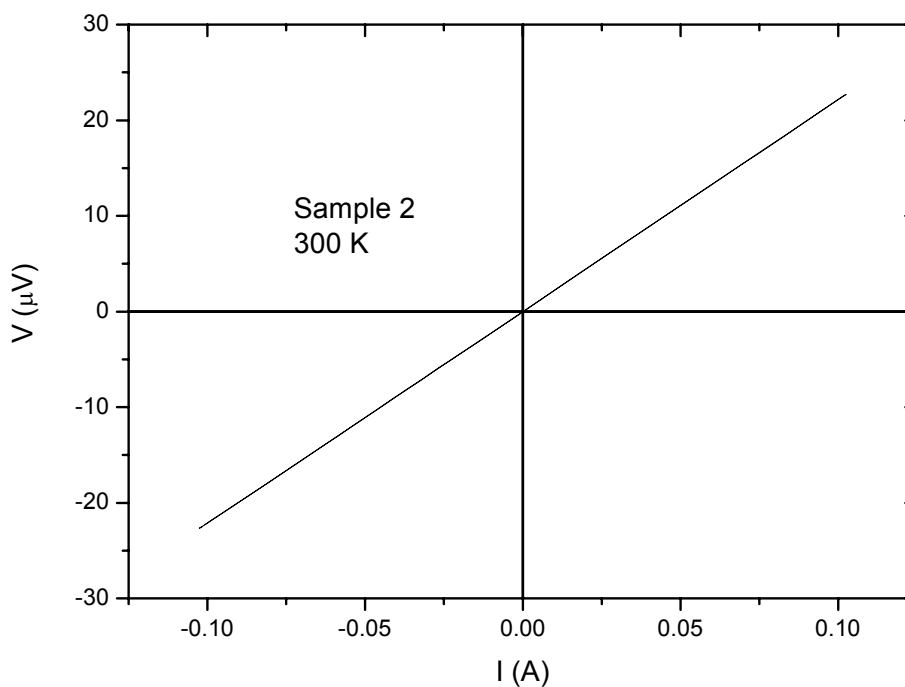
Time/ Date	$I_{\text{at 293 K}}$ (mA- Hz) Gauge: 3.2 mm	$R_{\text{at 300K}}$ ( $\mu\Omega$ )	$I_{\text{at 20 K}}$ (mA-Hz) Gauge: 3.2 mm	$R_{\text{at 20K}}$ ( $\mu\Omega$ )	RRR(20K)	Comments
081126	102-97	228	102-97	2.34	97	



### Annex C : RRR(20K) Test results

DA code: Billet: NSTT 8305-HK003-A2 (Ref: 01BR8305A01C)  
 Sample ID-code: Furnace 3 : EAS sample(s) DU2008/9 (Unreacted sample 2)  
 Prepared at: Durham University Tested at: Durham University  
 Contact person: Professor Damian Hampshire + Stephen Pragnell  
 Affiliation: Superconductivity Group, Durham University  
 Tel: 44(0) 191 334 3520  
 E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

Time/ Date	$I_{at\ 293\ K}$ (mA- Hz) Gauge: 3.2 mm	$R_{at\ 300K}$ ( $\mu\Omega$ )	$I_{at\ 20\ K}$ (mA-Hz) Gauge: 3.2 mm	$R_{at\ 20K}$ ( $\mu\Omega$ )	RRR(20K)	Comments
081126	102-97	219	102-97	2.38	92	



## Annex D : Microscopy

DA code: Billet: NSTT 8305-HK003-A1 (Ref: SL-NR 9108a)

Sample ID-code: Furnace 2: EAS sample(s) DU2008/3 - Reacted Sample (strain mandrel A1)

Reaction start date (RSD): 30/07/2008   Reaction end date: 22/08/2008

Prepared at: Durham University                      Tested at: Durham University

Contact person: Professor Damian Hampshire + Stephen Pragnell

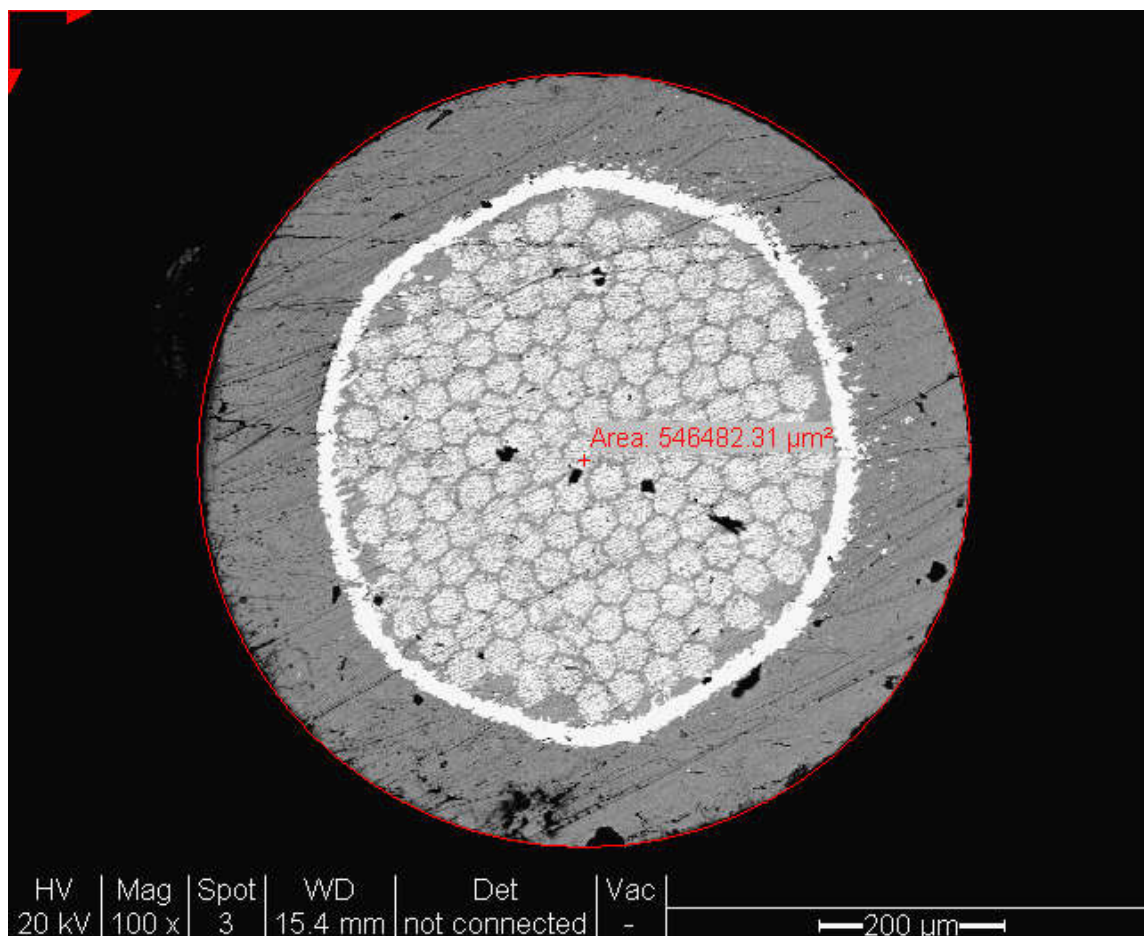
Affiliation: Superconductivity Group, Durham University

Tel: 44(0) 191 334 3520

E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

### Summary

	Value	Date	Method
Diameter (mm)	0.834	081124	BSE – Electron microscopy



## Annex D : Microscopy

DA code: Billet: NSTT 8305-HK003-A2 (Ref: SL-NR 9109i)

Sample ID-code: Furnace 3: EAS sample(s) DU2008/6 - Reacted Sample (strain mandrel D1)

Reaction start date (RSD): 30/07/2008 Reaction end date: 22/08/2008

Prepared at: Durham University Tested at: Durham University

Contact person: Professor Damian Hampshire + Stephen Pragnell

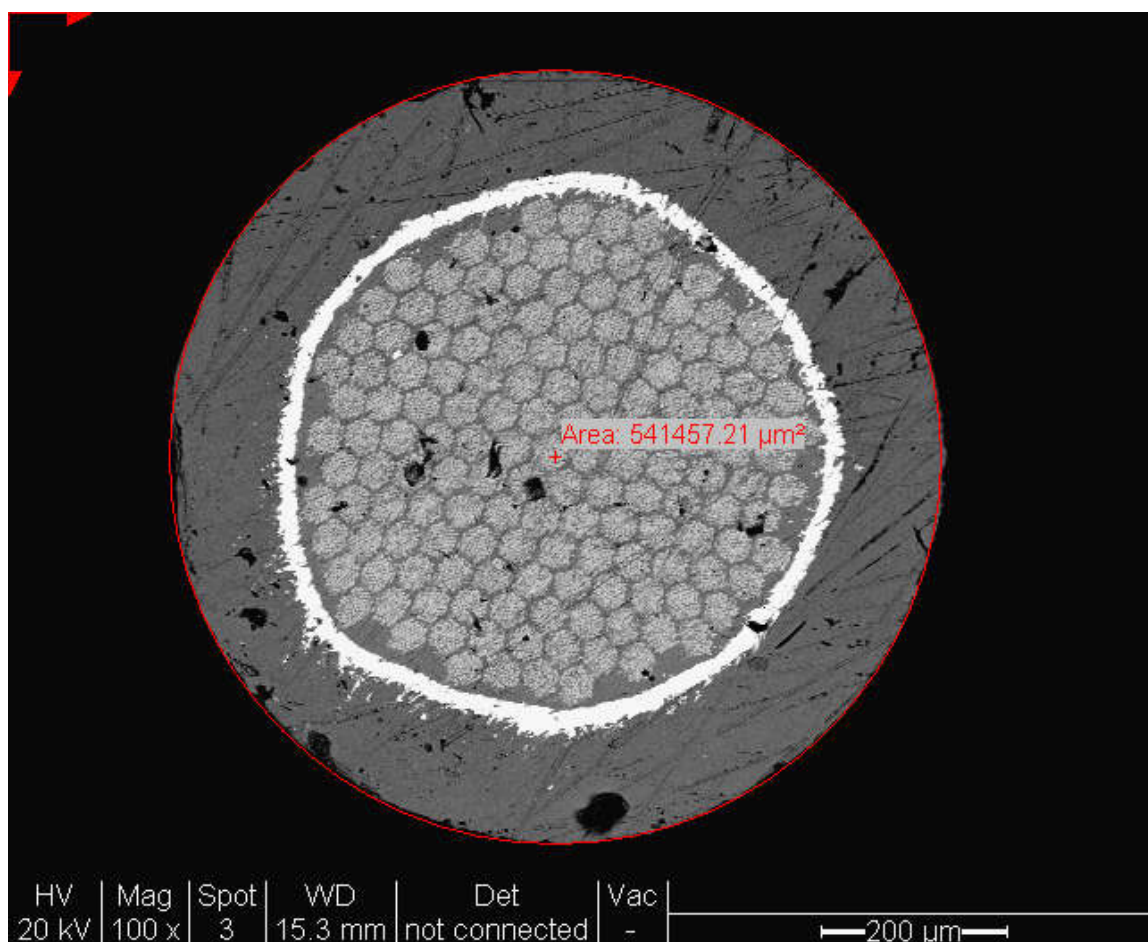
Affiliation: Superconductivity Group, Durham University

Tel: 44(0) 191 334 3520

E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

## Summary

	Value	Date	Method
Diameter (mm)	0.830	081124	BSE – Electron microscopy



## Annex D : Microscopy

DA code: Billet: NSTT 8305-HK004-BA (Ref: SL-NR 9110i)

Sample ID-code: Furnace 3: EAS sample(s) DU2008/7 - Reacted Sample (strain mandrel E1)

Reaction start date (RSD): 30/07/2008   Reaction end date: 22/08/2008

Prepared at: Durham University                      Tested at: Durham University

Contact person: Professor Damian Hampshire + Stephen Pragnell

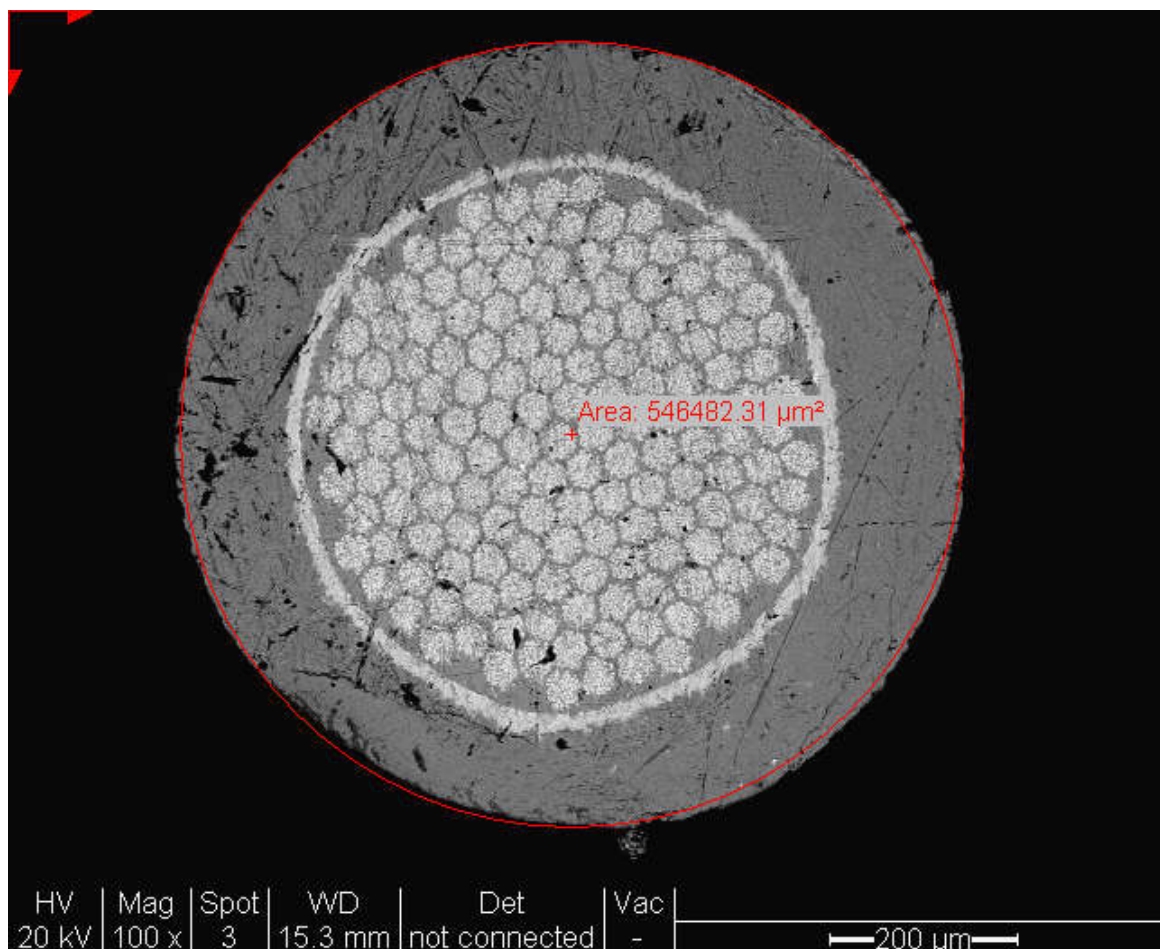
Affiliation: Superconductivity Group, Durham University

Tel: 44(0) 191 334 3520

E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

### Summary

	Value	Date	Method
Diameter (mm)	0.834	081124	BSE – Electron microscopy



## Annex D : Microscopy

DA code: Billet: NSTT 8305-HK004-BBBA (Ref: SL-NR 9113a)  
Sample ID-code: Furnace 3: EAS sample(s) DU2008/8 - Reacted Sample (strain mandrel F1)  
Reaction start date (RSD): 30/07/2008 Reaction end date: 22/08/2008  
Prepared at: Durham University Tested at: Durham University  
Contact person: Professor Damian Hampshire + Stephen Pragnell  
Affiliation: Superconductivity Group, Durham University  
Tel: 44(0) 191 334 3520  
E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

## Summary

	Value	Date	Method
Diameter (mm)	0.830	081124	BSE – Electron microscopy

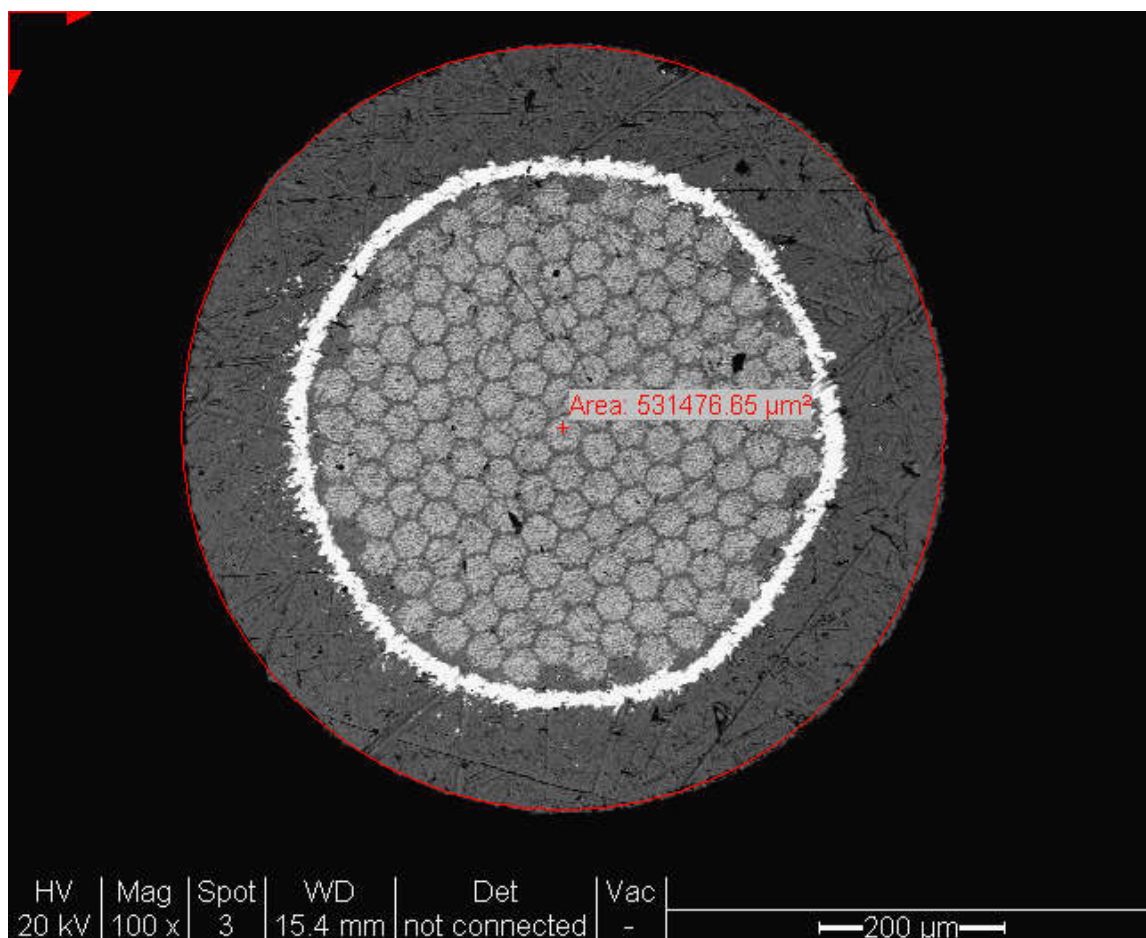


## Annex D : Microscopy

DA code: Billet: NSTT 8305-HK003-A2 (Ref: 01BR8305A01C)  
Sample ID-code: Furnace 3: EAS sample(s) DU2008/9 (Reacted Sample)  
Prepared at: Durham University Tested at: Durham University  
Contact person: Professor Damian Hampshire + Stephen Pragnell  
Affiliation: Superconductivity Group, Durham University  
Tel: 44(0) 191 334 3520  
E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

## Summary

	Value	Date	Method
Diameter (mm)	0.823	081124	BSE – Electron microscopy

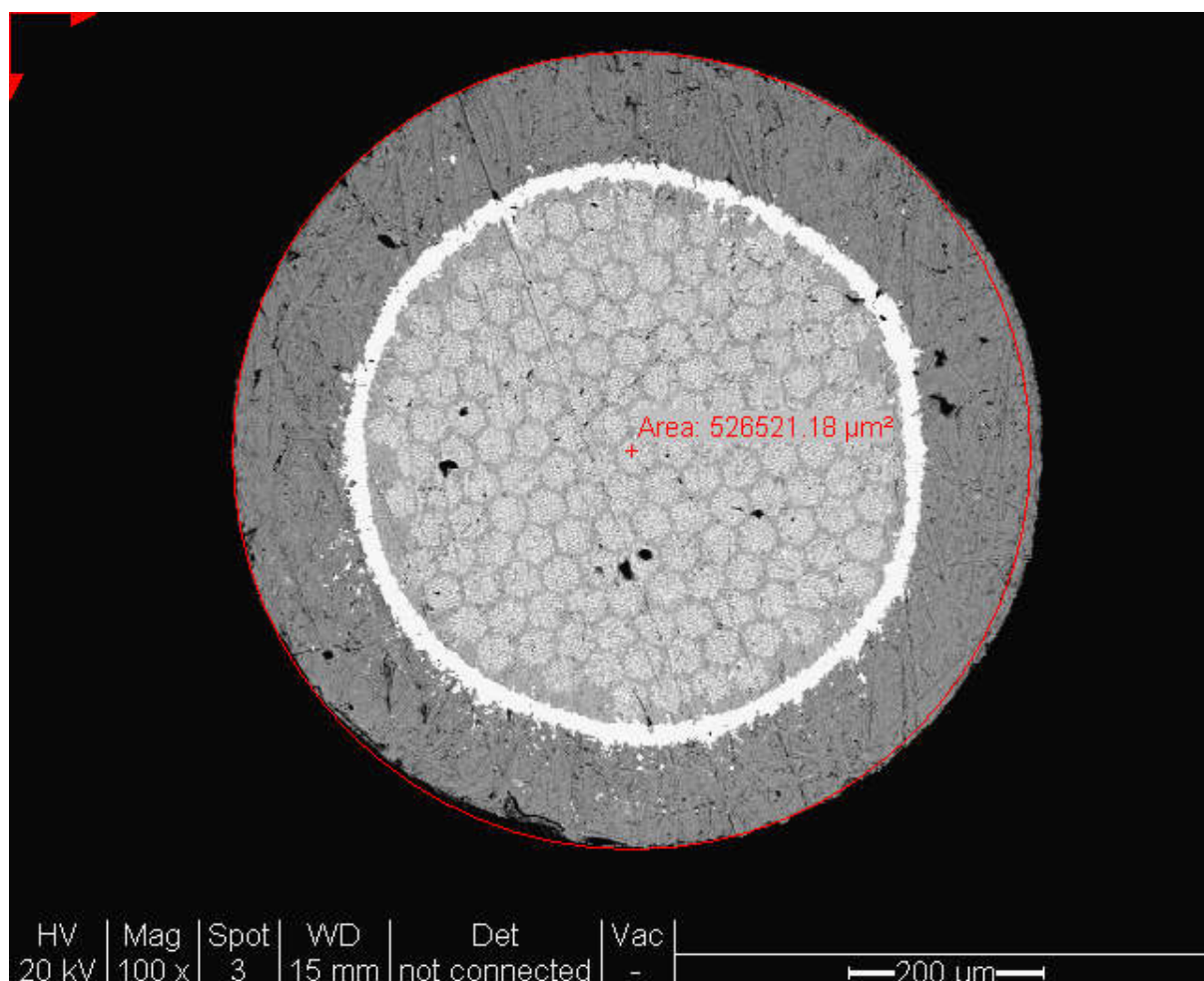


## Annex D : Microscopy

DA code: Billet: NSTT 8305-HK003-A2 (Ref: 01BR8305A01C)  
Sample ID-code: EAS sample(s) DU2008/9 (Unreacted Sample)  
Prepared at: Durham University Tested at: Durham University  
Contact person: Professor Damian Hampshire + Stephen Pragnell  
Affiliation: Superconductivity Group, Durham University  
Tel: 44(0) 191 334 3520  
E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

### Summary

	Value	Date	Method
Diameter (mm)	0.819	081124	BSE – Electron microscopy



## Annex E : $Q_{\text{hys}}$ Test Results

DA code: Billet: NSTT 8305-HK003-A1 (Ref: SL-NR 9108a)

Sample ID-code: Furnace 2 : EAS sample(s) DU2008/3 (strain mandrel A1)

Reaction start date: 30/07/2008

Reaction end date: 22/08/2008

Prepared at: Durham University

Tested at: Durham University

Contact person: Professor Damian Hampshire + Stephen Pagnell

Affiliation: Superconductivity Group, Durham University

Tel: 44(0) 191 334 3520

E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)


### SQUID MPMS DC Measurement

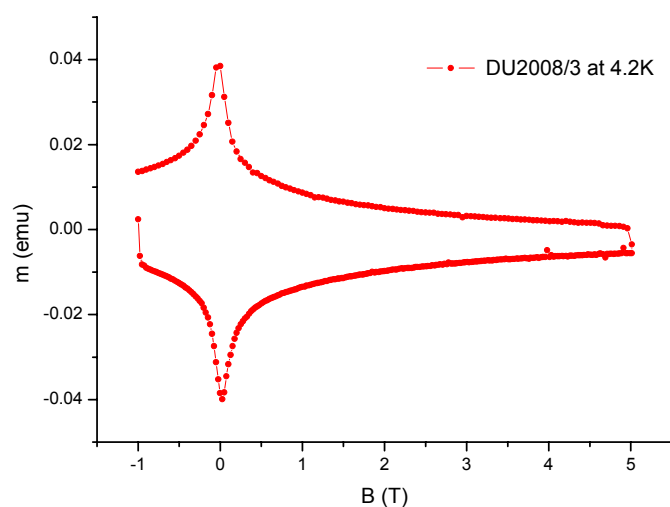
Sample ID: DU2008/3

#### Test Results

Time/ Date	$\pm B$ (T)	Temp. (K)	$Q_{\text{hys}}$ (mJ/cc_st)	Comments
05/12/2008 9:41:33am	0 > -1 -1 > 5 5 < -1	4.2	46	Calculated value depends on estimated value of $J_c$ in low fields

#### Configuration

	Value	
Outer Diameter (micrometer) (mm)	0.825	
Length (mm)	5.57	
Mass (g)	0.02685	



## Annex E : $Q_{\text{hys}}$ Test Results


DA code: Billet: NSTT 8305-HK003-A2 (Ref: SL-NR 9109i)  
 Sample ID-code: Furnace 3 : EAS sample(s) DU2008/6 (strain mandrel D1) Sample A  
Reaction start date: 30/07/2008      Reaction end date: 22/08/2008  
 Prepared at: Durham University      Tested at: Durham University  
 Contact person: Professor Damian Hampshire + Stephen Pragnell  
 Affiliation: Superconductivity Group, Durham University  
 Tel: 44(0) 191 334 3520  
 E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

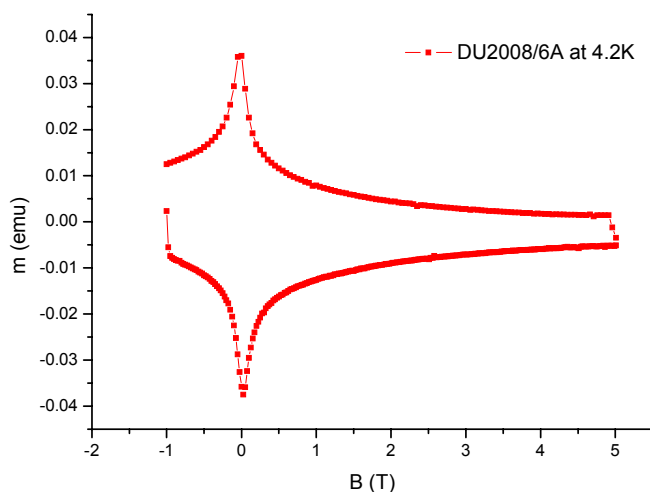
**Summary:**      **SQUID MPMS DC Measurement**      Sample ID: DU2008/6A

### Test Results (Sample A)

Time/ Date	$\pm B$ (T)	Temp. (K)	$Q_{\text{hys}}$ (mJ/cc_st)	Comments
05/12/2008 3:09:37pm	0 > -1 -1 > 5 5 < -1	4.2	43	Calculated value depends on estimated value of $J_c$ in low fields

### Configuration (Sample A)

	Value	
Outer Diameter (micrometer) (mm)	0.824	
Length (mm)	5.59	
Mass (g)	0.02697	



## Annex E : $Q_{hys}$ Test Results


DA code: Billet: NSTT 8305-HK003-A2 (Ref: SL-NR 9109i)  
 Sample ID-code: Furnace 3 : EAS samples DU2008/6 (strain mandrel D1) Sample B  
Reaction start date: 30/07/2008      Reaction end date: 22/08/2008  
 Prepared at: Durham University      Tested at: Durham University  
 Contact person: Professor Damian Hampshire + Stephen Pragnell  
 Affiliation: Superconductivity Group, Durham University  
 Tel: 44(0) 191 334 3520  
 E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)

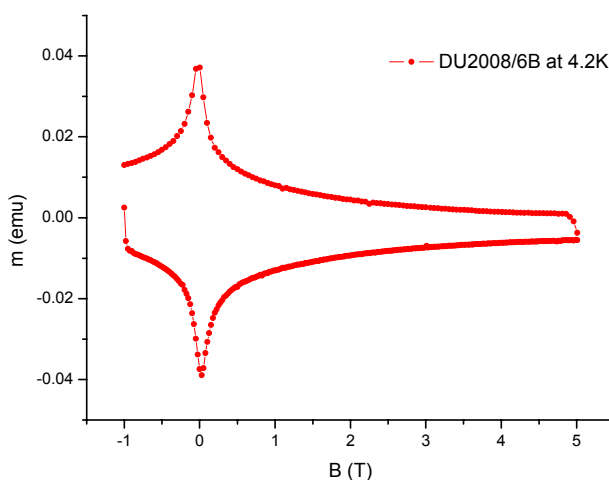
**Summary:**      **SQUID MPMS DC Measurement**      Sample ID: DU2008/6B

### Test Results (Sample B)

Time/ Date	$\pm B$ (T)	Temp. (K)	$Q_{hys}$ (mJ/cc_st)	Comments
08/12/2008 10:13:15am	0 > -1 -1 > 5 5 < -1	4.2	44	Calculated value depends on estimated value of $J_c$ in low fields

### Configuration (Sample B)

		Value	
Outer Diameter (micrometer)	(mm)	0.824	
Length	(mm)	5.63	
Mass	(g)	0.02717	



## Annex E : $Q_{hys}$ Test Results

DA code: Billet: NSTT 8305-HK004-BA (Ref: SL-NR 9110i)  
 Sample ID-code: Furnace 3 : EAS sample(s) DU2008/7 (strain mandrel E1)  
Reaction start date: 30/07/2008      Reaction end date: 22/08/2008  
 Prepared at: Durham University      Tested at: Durham University  
 Contact person: Professor Damian Hampshire + Stephen Pragnell  
 Affiliation: Superconductivity Group, Durham University  
 Tel: 44(0) 191 334 3520  
 E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)


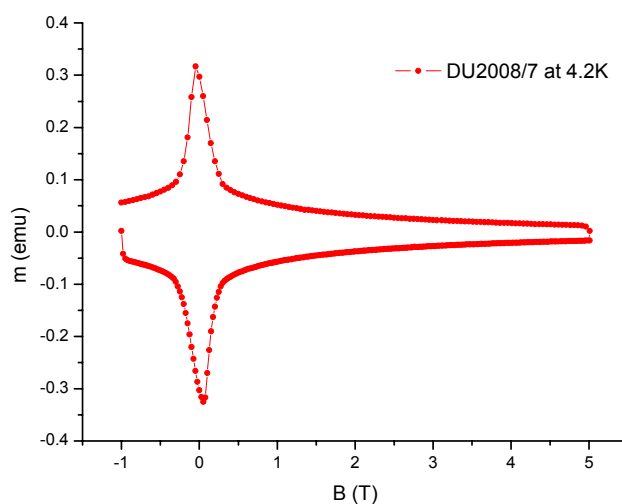
**Summary:**      **SQUID MPMS DC Measurement**      Sample ID: DU2008/7

### Test Results

Time/ Date	$\pm B$ (T)	Temp. (K)	$Q_{hys}$ (mJ/cc_st)	Comments
08/12/2008 2:57:25pm	0 > -1 -1 > 5 5 < -1	4.2	248	Calculated value depends on estimated value of $J_c$ in low fields

### Configuration

		Value
Outer Diameter (micrometer)	(mm)	0.823
Length	(mm)	5.58
Mass	(g)	0.02560

## Annex E : $Q_{\text{hys}}$ Test Results

DA code: Billet: NSTT 8305-HK004-BBBA (Ref: SL-NR 9113a)

Sample ID-code: Furnace 3 : EAS sample(s) DU2008/8 (strain mandrel F1)

Reaction start date: 30/07/2008

Reaction end date: 22/08/2008

Prepared at: Durham University

Tested at: Durham University

Contact person: Professor Damian Hampshire + Stephen Pragnell

Affiliation: Superconductivity Group, Durham University

Tel: 44(0) 191 334 3520

E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)


**Summary:** **SQUID MPMS DC Measurement**

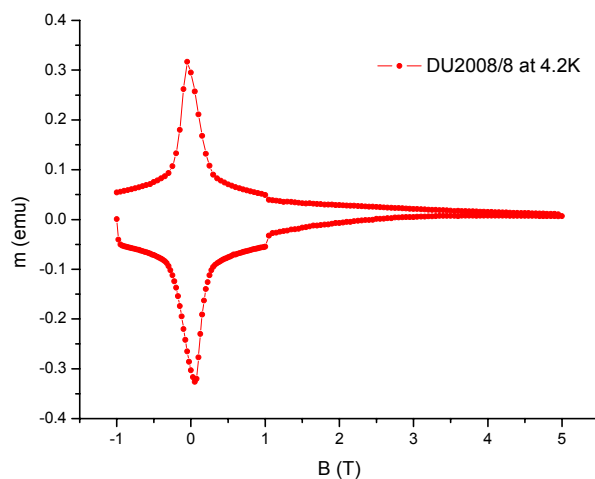
Sample ID: DU2008/8

### Test Results

Time/ Date	$\pm B$ (T)	Temp. (K)	$Q_{\text{hys}}$ (mJ/cc_st)	Comments
16/12/2008 9:45:06am	0 > -1 -1 > 5 5 < -1	4.2	See comments	Instrumentation jump with range change

### Configuration

	Value	
Outer Diameter (micrometer) (mm)	0.825	
Length (mm)	5.66	
Mass (g)	0.02598	



## Annex E : $Q_{\text{hys}}$ Test Results

DA code: Billet: NSTT 8305-HK003-A2 (Ref: 01BR8305A01C)

Sample ID-code: Furnace 3 : EAS samples DU2008/9 (Sample A)

Reaction start date: 28/10/2008

Reaction end date: 18/11/2008

Prepared at: Durham University

Tested at: Durham University

Contact person: Professor Damian Hampshire + Stephen Pragnell

Affiliation: Superconductivity Group, Durham University

Tel: 44(0) 191 334 3520

E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)


**Summary: SQUID MPMS DC Measurement**

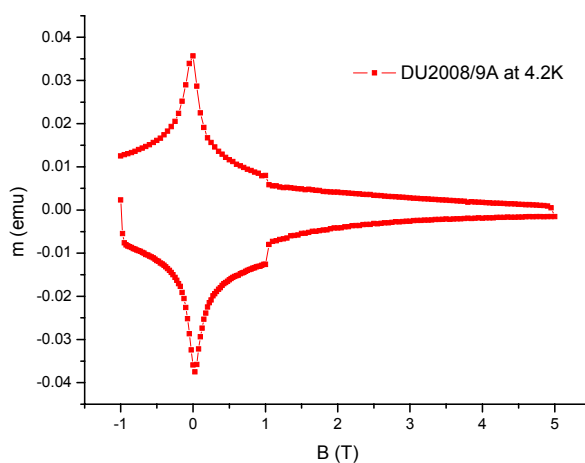
Sample ID: DU2008/9A

### Test Results (Sample A)

Time/ Date	$\pm B$ (T)	Temp. (K)	$Q_{\text{hys}}$ (mJ/cc_st)	Comments
16/12/2008 6:02:32pm	0 > -1 -1 > 5 5 < -1	4.2	See comments	Instrumentation jump with range change

### Configuration (Sample A)

	Value	
Outer Diameter (micrometer) (mm)	0.824	
Length (mm)	5.44	
Mass (g)	0.02633	



## Annex E : $Q_{hys}$ Test Results

DA code: Billet: NSTT 8305-HK003-A2 (Ref: 01BR8305A01C)

Sample ID-code: Furnace 3 : EAS sample(s) DU2008/9 (Sample B)

Reaction start date: 28/10/2008

Reaction end date: 18/11/2008

Prepared at: Durham University

Tested at: Durham University

Contact person: Professor Damian Hampshire + Stephen Pragnell

Affiliation: Superconductivity Group, Durham University

Tel: 44(0) 191 334 3520

E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)


**Summary: SQUID MPMS DC Measurement**

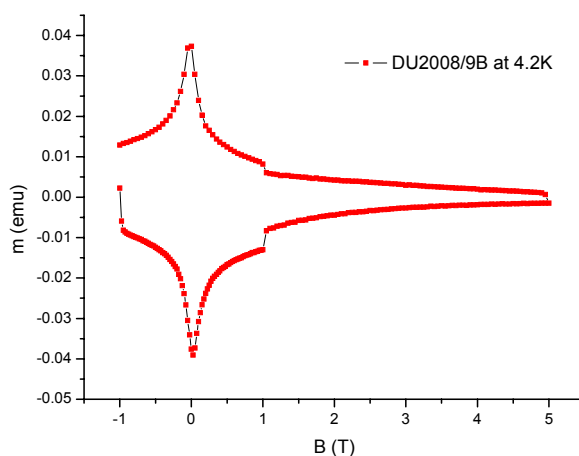
Sample ID: DU2008/9B

### Test Results (Sample B)

Time/ Date	$\pm B$ (T)	Temp. (K)	$Q_{hys}$ (mJ/cc_st)	Comments
23/12/2008 10:48:24am	0 > -1 -1 > 5 5 < -1	4.2	See comments	Instrumentation jump with range change

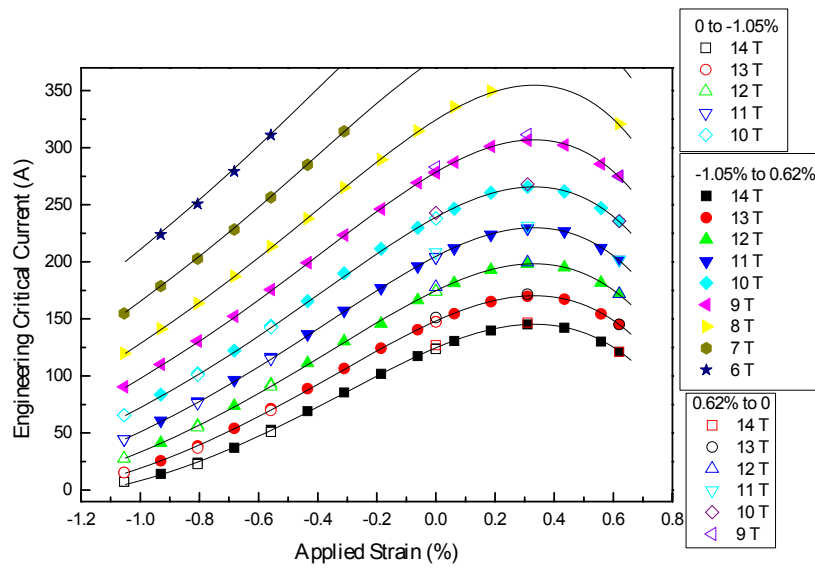
### Configuration (Sample B)

	Value	
Outer Diameter (micrometer)	(mm) 0.824	
Length	(mm) 5.48	
Mass	(g) 0.02654	

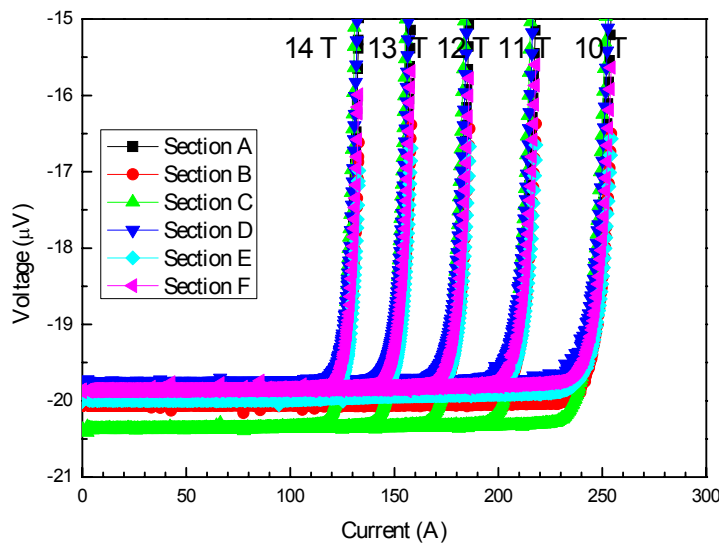


## Annex F: $I_c$ (B, 4.22 K, Strain) Test Results

DA code: NSTT 8305-HK003-A1 (Ref: SL-NR 9108a)  
 Sample ID-code: EAS sample DU2008/3 (strain mandrel A1 : spring R5)  
 Prepared at: Durham University Tested at: Durham University  
 Contact person: Professor Damian Hampshire + Stephen Pragnell  
 Affiliation: Superconductivity Group, Durham University  
 Tel: 44(0) 191 334 3520  
 E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)



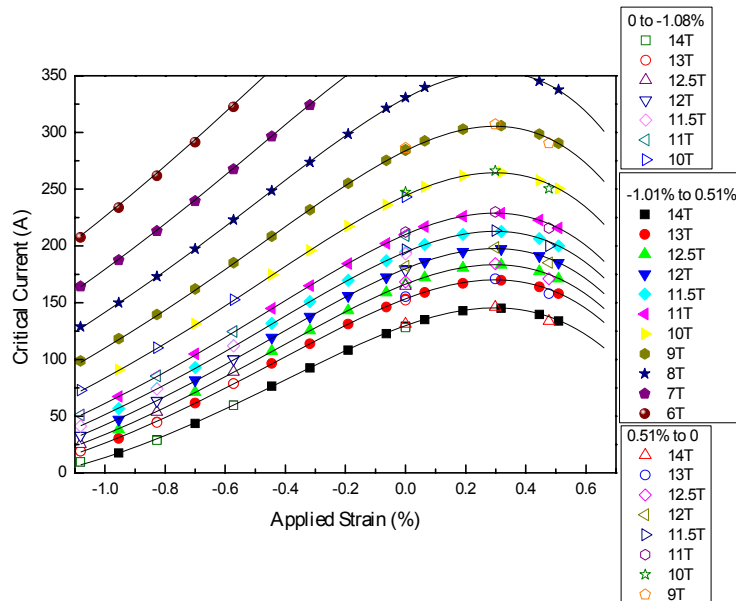
**Fig. F1.** Critical current of EAS strand (DU2008/3) as a function of applied strain at 4.2 K, in magnetic fields from 6 to 14 T. The solid lines are provided from the 9 free-parameter Durham scaling law using parameters in Table I.



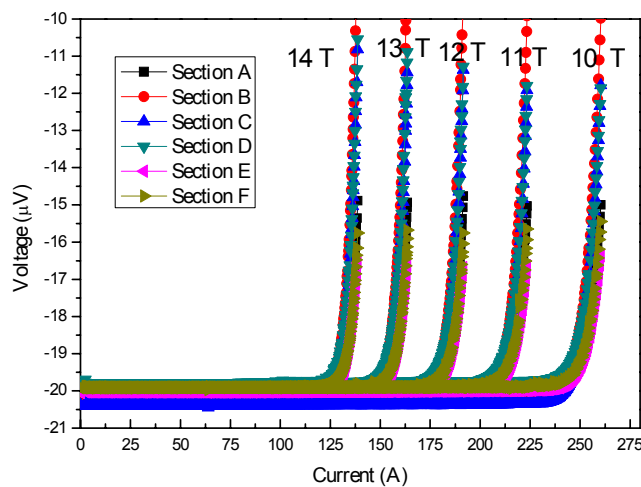
**Fig. F2.** The raw  $V-I$  traces of EAS strand (DU2008/3) for the six sections (A to F) with zero applied strain at 4.2 K in magnetic fields from 10 to 14 T.

### Annex F: $I_c$ (B, 4.22 K, Strain) Test Results

DA code: NSTT 8305-HK003-A2 (Ref: SL-NR 9109i)  
 Sample ID-code: EAS sample DU2008/6 (strain mandrel D1 : spring R6)  
 Prepared at: Durham University Tested at: Durham University  
 Contact person: Professor Damian Hampshire + Stephen Pragnell  
 Affiliation: Superconductivity Group, Durham University  
 Tel: 44(0) 191 334 3520  
 E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)



**Fig. F3.** Critical current of EAS strand (DU2008/6) as a function of applied strain at 4.2 K, in magnetic fields from 6 to 14 T. The solid lines are provided from the 9 free-parameter Durham scaling law using parameters in Table II.



**Fig. F4.** The raw  $V-I$  traces of EAS strand (DU2008/6) for the six sections (A to F) with zero applied strain at 4.2 K in magnetic fields from 10 to 14 T.

## Annex F: $I_c$ (B, 4.22 K, Strain) Test Results

DA code: NSTT 8305-HK004-BA (Ref: SL-NR 9110i)

Sample ID-code: EAS sample DU2008/7 (strain mandrel E1 : spring R7)

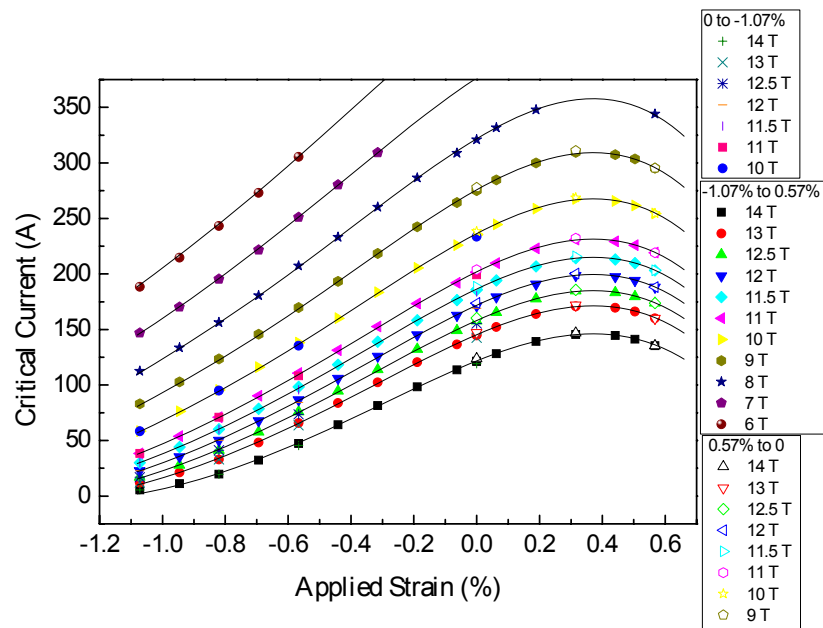
Prepared at: Durham University Tested at: Durham University

Contact person: Professor Damian Hampshire + Stephen Pragnell

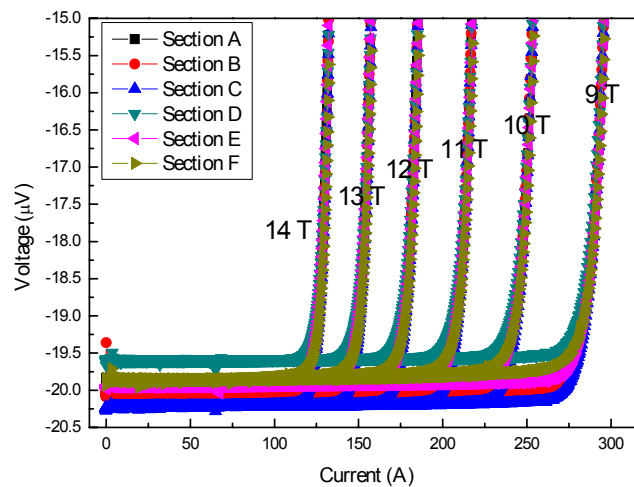
Affiliation: Superconductivity Group, Durham University

Tel: 44(0) 191 334 3520

E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)



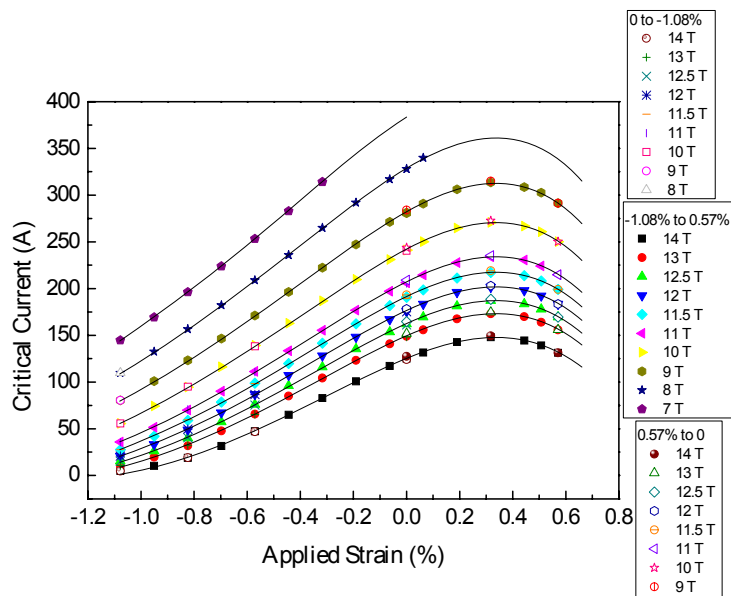
**Fig. F5.** Critical current of EAS strand (DU2008/7) as a function of applied strain at 4.2 K, in magnetic fields from 6 to 14 T. The solid lines are provided from the 9 free-parameter Durham scaling law using parameters in Table III.



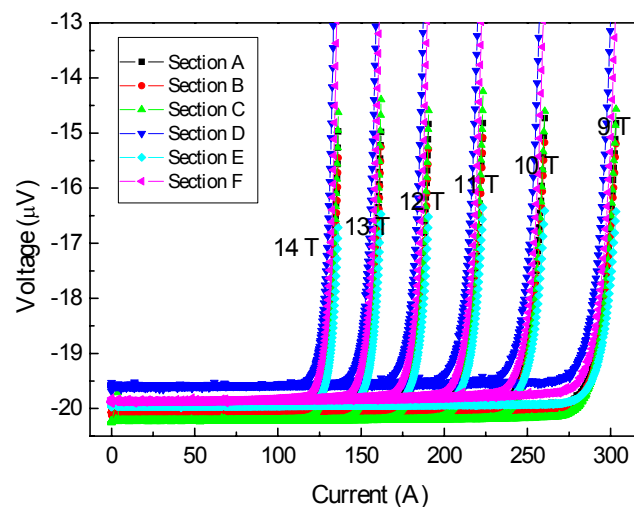
**Fig. F6.** The raw  $V-I$  traces of EAS strand (DU2008/7) for the six sections (A to F) with zero applied strain at 4.2 K in magnetic fields from 9 to 14 T.

## Annex F: $I_c$ (B, 4.22 K, Strain) Test Results

DA code: NSTT 8305-HK004-BBBA (Ref: SL-NR 9113a)  
 Sample ID-code: EAS sample DU2008/8 (strain mandrel F1 : spring R8)  
 Prepared at: Durham University Tested at: Durham University  
 Contact person: Professor Damian Hampshire + Stephen Pragnell  
 Affiliation: Superconductivity Group, Durham University  
 Tel: 44(0) 191 334 3520  
 E-mail: [d.p.hampshire@durham.ac.uk](mailto:d.p.hampshire@durham.ac.uk)



**Fig. F7.** Critical current of EAS strand (DU2008/8) as a function of applied strain at 4.2 K, in magnetic fields from 7 to 14 T. The solid lines are provided from the 9 free-parameter Durham scaling law using parameters in Table IV.



**Fig. F8.** The raw  $V-I$  traces of EAS strand (DU2008/8) for the six sections (A to F) with zero applied strain at 4.2 K in magnetic fields from 9 to 14 T.

### Annex G: Durham Scaling Parameters for $I_c$ (B, 4.22 K, Strain)

$p$	$q$	$n$	$\nu$	$w$	$u$	$\varepsilon_M$ (%)
0.4921	1.457	<b>2.500</b>	<b>1.500</b>	<b>2.200</b>	<b>0</b>	0.3320
$A(0)$ ( $\text{Am}^{-2}\text{T}^{3-n}\text{K}^{-2}$ )	$T_c^*(0)$ (K)	$B_{c_2}^*(0,0)$ (T)	$c_2$	$c_3$	$c_4$	
$1.502 \times 10^7$	16.00	29.57	-0.5524	-0.3770	-0.0872	

**Table I:** Durham scaling law parameters for the DU2008-3 strand derived from variable strain and variable field 4.2 K data using 9 free-parameters. The four parameters in bold were not varied in the fitting procedure. (RMS ~ 1.2 A)

$p$	$q$	$n$	$\nu$	$w$	$u$	$\varepsilon_M$ (%)
0.4450	1.333	<b>2.500</b>	<b>1.500</b>	<b>2.200</b>	<b>0</b>	0.2976
$A(0)$ ( $\text{Am}^{-2}\text{T}^{3-n}\text{K}^{-2}$ )	$T_c^*(0)$ (K)	$B_{c_2}^*(0,0)$ (T)	$c_2$	$c_3$	$c_4$	
$1.37 \times 10^7$	16.00	28.98	-0.5030	-0.3250	-0.0721	

**Table II:** Durham scaling law parameters for the DU2008-6 strand derived from variable strain and variable field 4.2 K data using 9 free-parameters. The four parameters in bold were not varied in the fitting procedure. (RMS ~ 0.9 A)

$p$	$q$	$n$	$\nu$	$w$	$u$	$\varepsilon_M$ (%)
0.4939	1.477	<b>2.500</b>	<b>1.500</b>	<b>2.200</b>	<b>0</b>	0.3707
$A(0)$ ( $\text{Am}^{-2}\text{T}^{3-n}\text{K}^{-2}$ )	$T_c^*(0)$ (K)	$B_{c_2}^*(0,0)$ (T)	$c_2$	$c_3$	$c_4$	
$1.525 \times 10^7$	16.00	29.67	-0.5250	-0.3406	-0.0748	

**Table III:** Durham scaling law parameters for the DU2008-7 strand derived from variable strain and variable field 4.2 K data using 9 free-parameters. The four parameters in bold were not varied in the fitting procedure. (RMS ~ 1.1 A)

$p$	$q$	$n$	$\nu$	$w$	$u$	$\varepsilon_M$ (%)
0.5158	1.505	<b>2.500</b>	<b>1.500</b>	<b>2.200</b>	<b>0</b>	0.3377
$A(0)$ ( $\text{Am}^{-2}\text{T}^{3-n}\text{K}^{-2}$ )	$T_c^*(0)$ (K)	$B_{c_2}^*(0,0)$ (T)	$c_2$	$c_3$	$c_4$	
$1.577 \times 10^7$	16.08	29.66	-0.5628	-0.3792	-0.0867	

**Table IV:** Durham scaling law parameters for the DU2008-8 strand derived from variable strain and variable field 4.2 K data using 9 free-parameters. The four parameters in bold were not varied in the fitting procedure. (RMS ~ 0.9 A)

**The ITER Official Scaling Parameters for  $I_c$  ( $B$ , 4.22 K, Strain)**

$p$	$q$	$C$	$C_{a1}$	$C_{a2}$
0.3062	1.247	$1.539 \times 10^{10}$	32.6967	-3.5014
$\varepsilon_{0,a}$ (%)	$\varepsilon_M$ (%)	$B_{C20max}^*$ (0,0) (T)	$T_{C0max}^*$ (0) (K)	
0.1202	0.2882	31.00	16.07	

**Table V:** The official ITER scaling parameters for the DU2008-3 strand derived from variable strain and variable field 4.2 K data using 9 free-parameters. (RMS ~ 3.5 A)

$p$	$q$	$C$	$C_{a1}$	$C_{a2}$
0.2743	1.220	$1.433 \times 10^{10}$	28.0000	-7.8682
$\varepsilon_{0,a}$ (%)	$\varepsilon_M$ (%)	$B_{C20max}^*$ (0,0) (T)	$T_{C0max}^*$ (0) (K)	
0.1306	0.2478	31.00	16.77	

**Table VI:** The official ITER scaling parameters for the DU2008-6 strand derived from variable strain and variable field 4.2 K data using 9 free-parameters. (RMS ~ 2.9 A)

$p$	$q$	$C$	$C_{a1}$	$C_{a2}$
0.2658	1.264	$1.419 \times 10^{10}$	26.2213	-10.7539
$\varepsilon_{0,a}$ (%)	$\varepsilon_M$ (%)	$B_{C20max}^*$ (0,0) (T)	$T_{C0max}^*$ (0) (K)	
0.0994	0.3076	31.00	18.00	

**Table VII:** The official ITER scaling parameters for the DU2008-7 strand derived from variable strain and variable field 4.2 K data using 9 free-parameters. (RMS ~ 3.5 A)

$p$	$q$	$C$	$C_{a1}$	$C_{a2}$
0.2702	1.263	$1.449 \times 10^{10}$	30.6424	-7.0640
$\varepsilon_{0,a}$ (%)	$\varepsilon_M$ (%)	$B_{C20max}^*$ (0,0) (T)	$T_{C0max}^*$ (0) (K)	
0.1077	0.2895	31.00	18.00	

**Table VIII:** The official ITER scaling parameters for the DU2008-8 strand derived from variable strain and variable field 4.2 K data using 9 free-parameters. (RMS ~ 3.6 A)