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PUBLICATION

FINAL PROTOTYPE SC HELICAL UNDULATOR MEASURED

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Abstract:

This task was focused on increasing the achievable magnetic field levels in short period undulator magnets through the use of the advanced material Nb_3Sn and innovative helical coil designs. The first part of this task was a design study of the undulator using an Nb_3Sn conductor. A comparison was made with an existing Nb-Ti HeLiCal undulator. Following the design stage a ~300 mm prototype of the same nominal design as the HeLiCal undulator was manufactured and tested magnetically.

Delivery Slip

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This task was focused on increasing the achievable magnetic field levels in short period undulator magnets through the use of the advanced material Nb_3Sn and innovative helical coil designs. The first part of this task was a design study of the undulator using an Nb_3Sn conductor. A comparison was made with an existing Nb-Ti HeLiCal undulator. Following the design stage a ~300 mm prototype of the same nominal design as the HeLiCal undulator was manufactured and tested magnetically, which is the first and only milestone of the project.

Nb_3Sn exhibits superconductivity below 18 K; it offers higher performance than the more common Nb-Ti, in that it has a higher critical temperature and can withstand larger magnetic fields and current densities before regaining resistivity. However Nb_3Sn is brittle, and therefore difficult to process, and requires heat treating for several hundred hours. It is also strain sensitive in operation.

Previous work carried out by the HeLiCal collaboration in the UK created Nb-Ti superconducting helical undulators; initially ~300 mm prototypes but later a 4 m cryomodule. The EuCARD undulator used the HeLiCal undulator design as a starting point for the magnetic design.

Three wire types were identified as being suitable for the design: Oxford Superconducting Technology (OST) E2004 and R2006 together with Supercon Internal Tin wire. The low field performance was estimated using a Kramer fit on the manufacturers data and Supercon carried out additional low field testing. After further research and discussion, the Supercon wire was chosen for the final manufacture.

The mechanical design was intended to mirror that of the HeLiCal undulator with some adaptations to allow for the heat treatment required for the manufacturing process. For example the steel bore was not replaced with a copper tube, as had been the case for the HeLiCal. The design included an insulating plasma-sprayed alumina coating on the former with an additional glass fibre epoxy layer in the groove base. After heat treatment the undulator was vacuum impregnated with epoxy resin to provide mechanical support and to act as electrical insulation.

The manufacturing process for the magnets follows the fairly standard wind and react process. Winding trails were carried which highlighted some issues with the winding, splices and vacuum impregnation; these issues were resolved prior to manufacture of the two final undulators.

Testing was carried out at Laboratorio Acceleratori e Superconduttività Applicata (LASA) which is part of Istituto Nazionale di Fisica Nucleare (INFN) and based in Milan, Italy. Coil A was testing in a bath cryostat using liquid helium at 4.2 K. The magnetic field for Coil A was measured at 25 A. However the magnet quenched repeatedly at 28-30A and was found to have a non-linear resistance of 1.375 μΩ at small current which increased with current. Coil B was found to have a room-temperature resistance of 1400 Ω on arrival at LASA and so was not tested.

2. INTRODUCTION

2.1. GOALS

This task was focused on increasing the achievable magnetic field levels in short period undulator magnets through the use of the advanced material Nb_3Sn and innovative helical coil designs. There are several needs for this technology, for example, single pass free electron lasers such as X-FEL or FERMI@ELETTRA could cover a wider wavelength range through field enhancement, or alternatively, operate at significantly lower electron energy. Additionally, short period magnets could be used in the production of positrons for any future lepton collider and increased magnetic field levels will increase the positron yield and also allow for economic savings. The first part of this task was the design study of the undulator using an Nb_3Sn conductor. A comparison was made with existing Nb-Ti HeLiCal undulator. Following the design stage a short prototype ~300 mm was manufactured and tested magnetically; this is the first and only milestone of the project. As this is a direct comparison to the HeLiCal undulator the design and parameters of the EuCARD magnet should be nominally unchanged. Initially it was planned that the results from the first prototype would be used to change the undulator design. Once the on axis field had been found the design could be iterated in order to provide the strongest possible field level resulting in a shorter period length. It was planned that the second optimised EuCARD design would then be prototyped (~500 mm) and characterised; this would be the final and only deliverable of the project. However due to stability issues with the Nb_3Sn wire as discussed in Section 3 the project was re-scoped. The final deliverable was changed to be a ~300 mm undulator of the same nominal design as the HeLiCal undulator.

2.2. NB$_3$SN

Nb_3Sn is a material that exhibits superconductivity when cooled below 18 K. It offers higher performance than the more common Nb-Ti, in that it has a higher critical temperature and can withstand larger magnetic fields and current densities before regaining resistivity. However Nb_3Sn is a brittle material that is difficult to process and is strain sensitive in operation. The brittleness of Nb_3Sn means that wires cannot be made following the extrusion and draw down process used to make Nb-Ti wires. Instead a billet is made up of filaments containing precursors to Nb_3Sn, the billet is then extruded and drawn down to the desired wire size. After that it is wound into the required shape and then finally heat treated in an inert atmosphere for several hundred hours. The heat treatment transforms the precursor material into Nb_3Sn. The heat treatment adds to the difficulty when manufacturing Nb_3Sn, the design and any materials used must be able to withstand the high temperature.

2.3. HELICAL UNDULATOR

Previous work carried out by the HeLiCal collaboration created Nb-Ti superconducting helical undulators. The work ranged from ~300 mm prototypes eventually scaling up to 1.7 m magnets, two of which were positioned back-to- back in a cryostat to create a 4 m cryomodule.

The undulator was wound using 0.4 mm diameter Nb-Ti wire which was insulated with a 25 µm thick enamel coating making it 0.45 mm in total. The enamel also served to bond the wires together allowing a flat ribbon seven wires wide to be fabricated. Winding with a ribbon was preferred over winding with a single wire because it eased wire placement, the ribbons could be stacked directly on top of one another allowing square packing and it saved time because each layer of wires was wound at once.

The final optimised HeLiCal undulator had a winding pack seven wires wide by eight wires high measuring 3.25 mm x 3.7 mm, this gave a packing factor of 62 %. The winding groove was sized based on the final wire diameter this was 3.25 mm wide, the groove was 4.3 mm high which left a nominal 0.6 mm gap. The pitch between two grooves (the period of the undulator) was 11.5 mm; the winding diameter was 6.35 mm. The groove dimensions are shown in Figure 1.

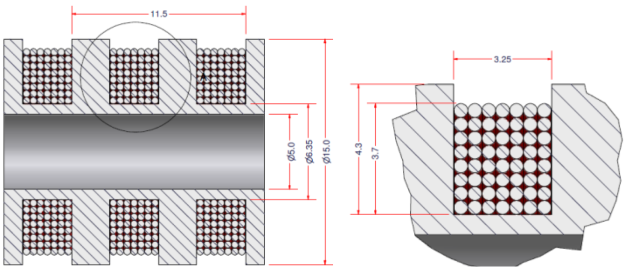

Figure 1: HeLiCal Nb-Ti undulator dimensions(mm)

A significant challenge that the HeLiCal collaboration faced was how to manufacture the iron former used to wind the magnet. The final manufacturing concept is shown schematically in Figure 2. To begin with an oversize iron bar is used, through which the centre hole is gun drilled. The gun drilled hole is straight in relation to itself but may not be concentric with the outer diameter of the bar. So step three is to use the gun drilled hole as a datum about which the outer diameter is turned to its final dimensions, thus ensuring the inner and outer diameters of the former are concentric with one another. In step four some features are machined into the ends to allow other components to be attached to the former. Next a reinforcing rod is inserted into the bore of the former to keep it rigid while the two helical grooves were cut – these grooves go right the way through to the supporting rod. In the final stages the supporting rod is removed and replaced with a copper tube, which is joined to the former by soldering at one end and brazing at the other.

One of the requirements of the copper tube, which served as the beam vacuum vessel, was to have a material with a low resistivity to reduce beam wakefield affects, so it was important that the HeLiCal undulator demonstrated that this could work.

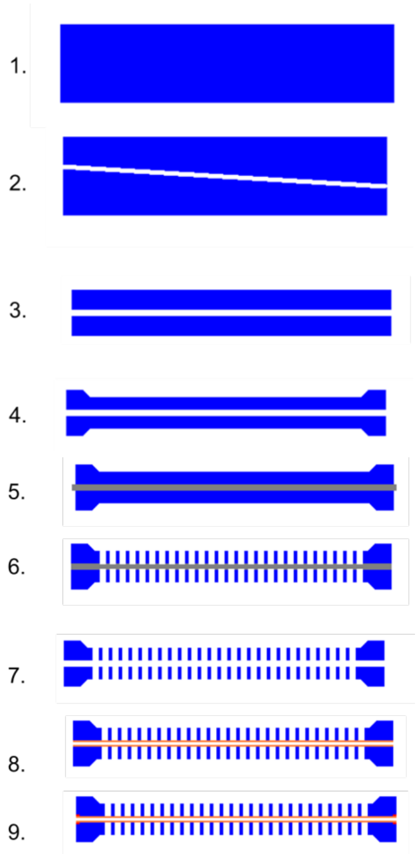

Figure 2: HeLiCal former manufacturing steps

After the undulator was wound it was vacuum impregnated with epoxy resin, the relatively large volumes around the winding pins being prefilled with ballotini glass spheres.

The HeLiCal collaboration reached a milestone during September 2010 when both magnets in the 4 m cryomodule were powered to 215 A individually and then together. When powered with 215 A the field on axis is 0.86 T.

3. MAGNETIC DESIGN

3.1. WIRE SIZE

The EuCARD undulator used the HeLiCal undulator design as a starting point. The wire diameter was chosen based upon which wire size would be best fit into the existing 3.25 mm wide groove. As is shown in Figure 3, including glass fibre insulation the wire that best fits the groove was 0.5 mm diameter bare, 0.65 mm diameter insulated. Based on previous winding experience using a single wire, hexagonal packing of the wires was chosen. This was because it was expected to be very difficult to achieve square packing without the benefit of winding a ribbon and because it also gave a marginally higher packing factor. The winding pack then became seven layers with an alternating five/four wires per layer, this measured 3.25 mm x 4 mm.

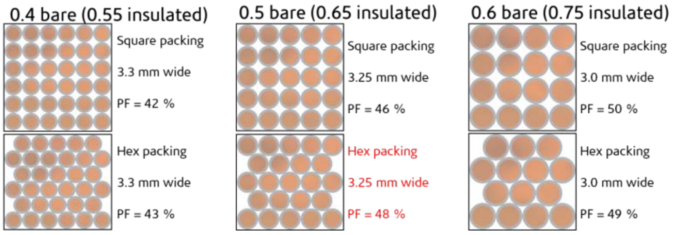

Figure 3: Wire fit schematic

3.2. MARKET SURVEY

The market survey was undertaken once the 0.5 mm wire size had been chosen. During the market survey it was found that several wire manufacturers didn't produce 0.5 mm wire as a standard product. Three wire types were shortlisted, Oxford Superconducting Technology (OST) E2004 and R2006 together with Supercon Internal Tin wire. The manufacturers' provide performance data for their wires when operating in a high field region, generally above 10 T. However the EuCARD undulator would be operating in lower field region (<5 T) so it was necessary to estimate the low field performance of the OST wires using a Kramer fit, as shown in Figure 4. Supercon carried out additional low field testing of their wire which is also shown in Figure 4.

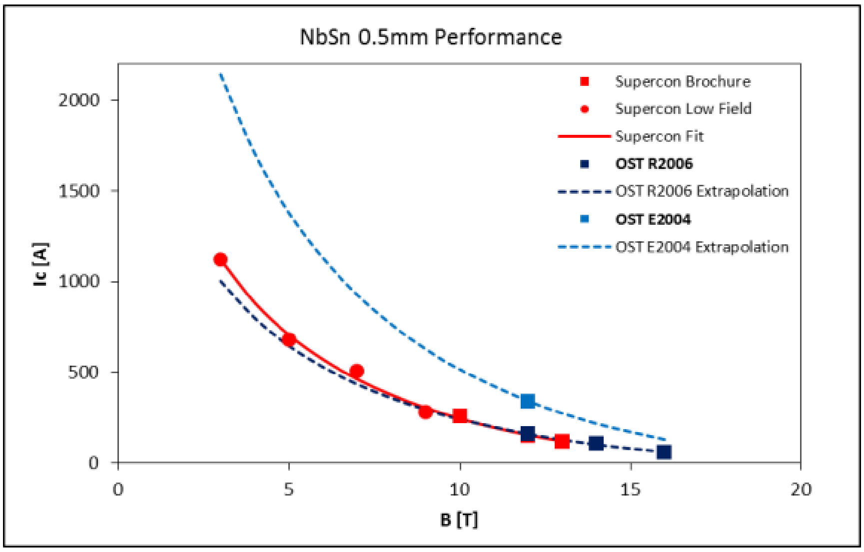

Figure 4: Critical Current vs. Field for available wires

From the available data and predictions the OST E2004 wire was chosen as it appeared to offer the highest performance.

3.3. OST E2004

The magnetic performance of the EuCARD undulator was predicted by using Cobham Technologies Opera3D Finite Element software. This was used to build a 3D model of the conductor and former in order to predict the on axis field. Using a 1 kA current this predicted a field on axis of 1.54 T. Figure 5 shows the load line for the OST E2004 wire at 4.2 K, this shows that at 1 kA the conductor should be at 82 % of the critical current. As shown in Figure 6 the field in the conductor varies from zero to 4.42 T.

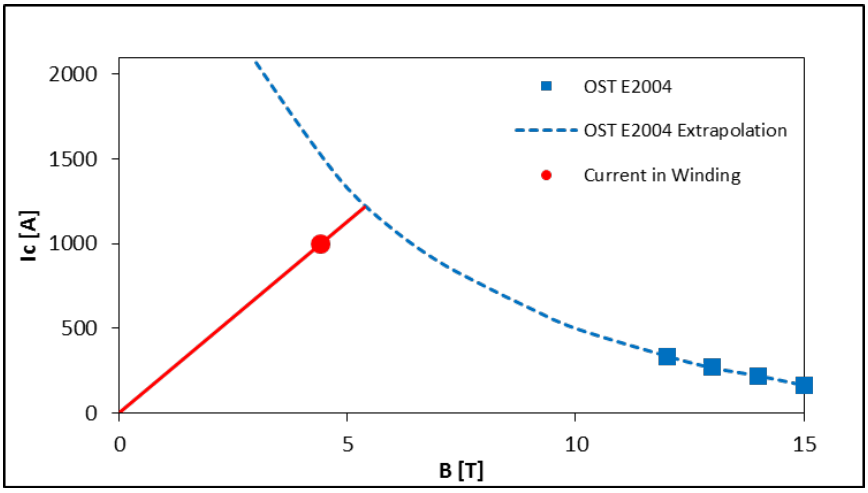

Figure 5: Extrapolated Critical Current vs. Field at 4.2 K for OST E2004

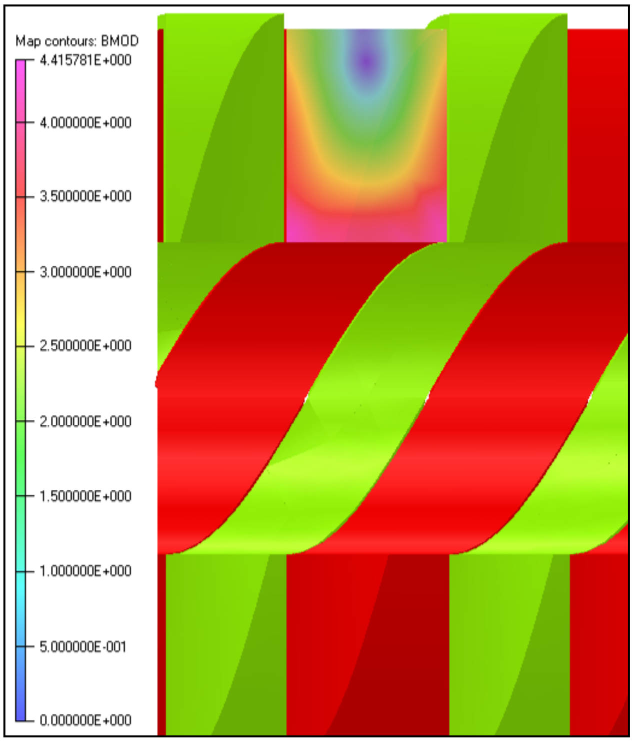

Figure 6: Field in conductor

After discussion with other members of the EuCARD consortium it was highlighted that the Nb_3Sn wire may be unstable at low fields. Karsruhe Institute of Technology – Institute for Technical Physics (KIT-ITEP) were able to characterise the wire using their JUMBO facility. Two heat treatments were tested, one as recommended by OST and one suggested by STFC to give a higher Copper Residual Resistivity Ratio (RRR), these heat treatments are shown in Figure 7.

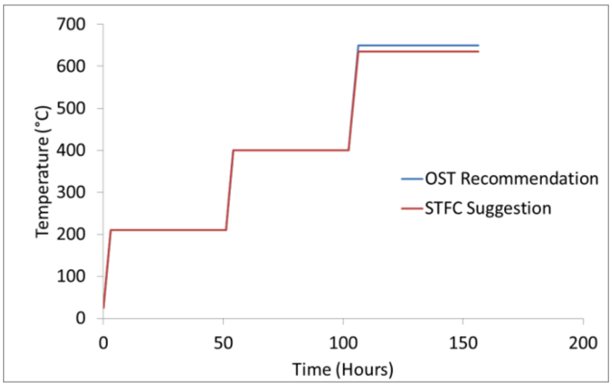

Figure 7: Heat treatments for OST E2004

The characterisation results are shown in Figure 8. These show that for both heat treatments the wire is unstable below 5 T and looked to be unusable for the EuCARD undulator. Although the filament size is unknown it is thought to be large, in the region of 50-100 µm, which it is believed causes flux jumping at low fields leading to the instability.

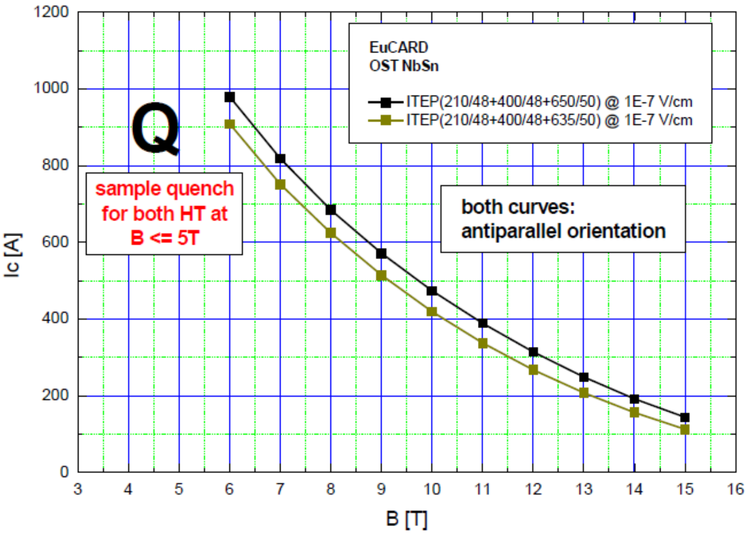

Figure 8: KIT-ITEP Low field Testing of OST E2004

3.4. SUPERCON

The OST E2004 looked unsuitable for the EuCARD undulator. The second choice wire was then reconsidered. In order to find a reasonable operating current for the Supercon wire the load line shown in Figure 9 was used, from this it was found that at 720 A the current in the conductor should be 80 % of the critical current and should provide a suitable margin. As shown in Figure 10 the field on the conductor would vary from 0 T to 3.5 T. This is below the 3 T limit that Supercon had characterised the wire to. In order to show the viability of the Supercon wire it was characterised down to 0 T by CERN, the results of which are shown in Figure 11. The Supercon wire was unstable below 4 T, however it was decided to proceed with the Supercon wire because it appeared to be the best wire available and the instability zone is situated above the load line, although the margin is small.

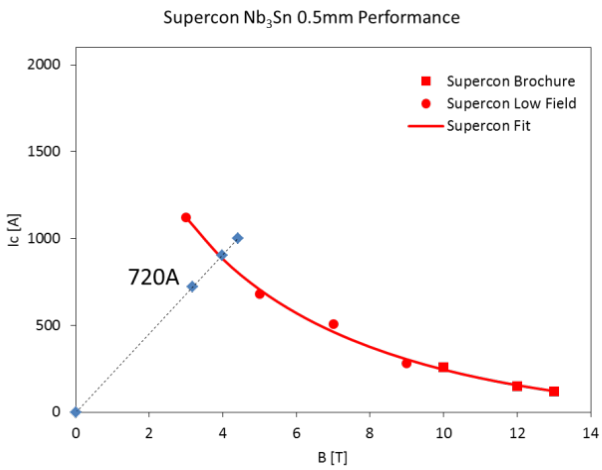

Figure 9: Supercon margin

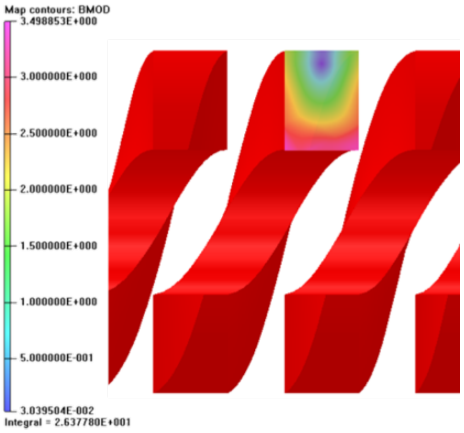

Figure 10: Field on Conductor for Supercon Wire

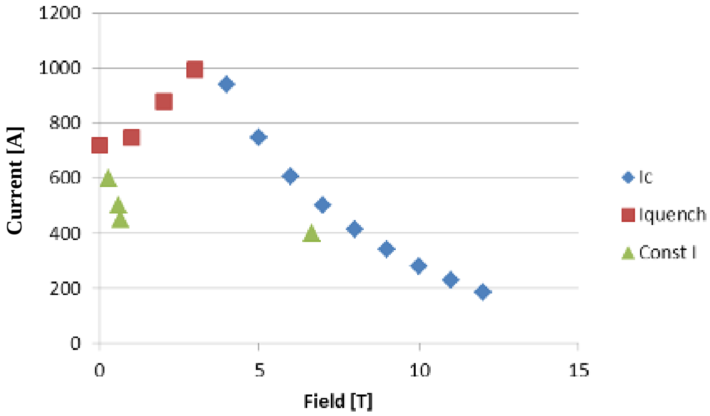

Figure 11: CERN characterisation of Supercon Wire

3.5. IRON BORE

For manufacturing reasons to be discussed in section 4.2, having additional iron in the bore would be beneficial – the affect this would have on the performance of the undulator was therefore modelled. The existing Opera model of the undulator was modified to include a thin walled iron tube in the undulator bore. This is shown as the blue tube in Figure 12, and the green helix is the iron former. The wall thickness was varied to see the influence of the iron on the on axis field. The results of this are shown in Figure 13. Without the iron tube the on axis field would be 1.25 T; as the wall thickness is increased to 3 mm the on-axis field decreases to 1.17 T. It was decided to have a wall thickness between 0.5 mm and 1.0 mm which should give an on-axis field of 1.22 T.

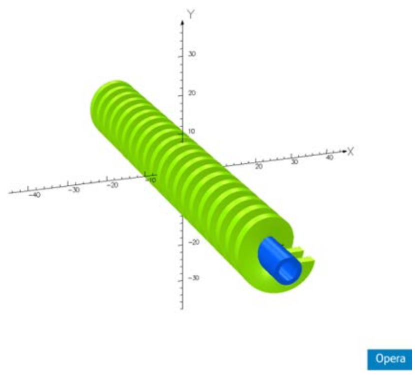

Figure 12: Opera3D model of the iron former

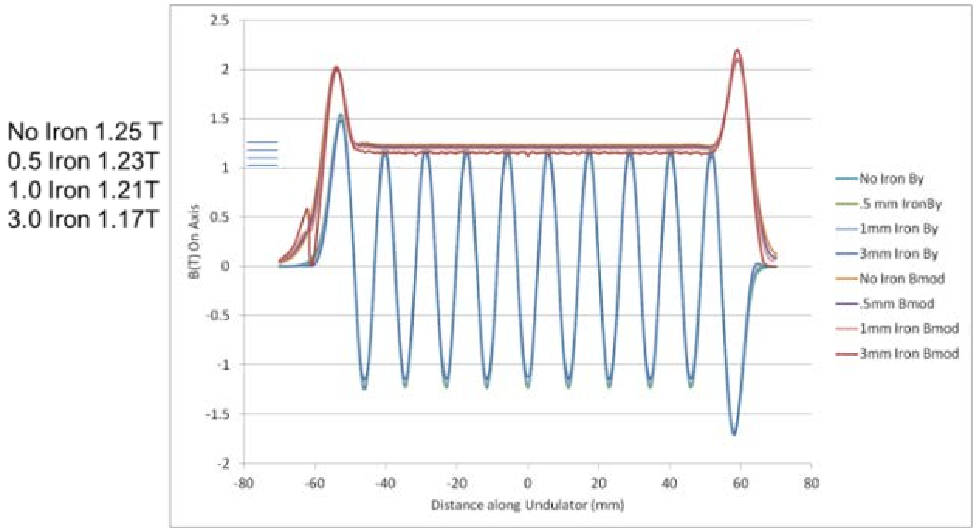

Figure 13: Influence of iron on the on-axis field

4. MECHANICAL DESIGN

As previously discussed the EuCARD undulator took the HeLiCal undulator as a baseline. This meant that rather than having to start the mechanical design anew the EuCARD mechanical design task then became adapting the HeLiCal design to work with the heat treat required for the ‘wind and react’ manufacturing process.

4.1. GROUND PLANE INSULATION

An area of critical importance for a superconducting magnet is the ground plane insulation. The insulation has to be able to withstand high voltages which may occur during a quench. It is also preferable for the coating to be as thin as possible with a uniform thickness. The heat treatment required for the Nb_3Sn wire precludes many coatings that would be used in a Nb-Ti magnet.

A parallel Nb_3Sn project at STFC worked with a company called Zircotec to characterise their plasma sprayed alumina coating.

Bobbin shaped test samples were manufactured from a Titanium alloy. Certain surfaces were then coated, these are shown in black in Figure 14. A single layer of glass fibre was then laid into the groove in the bobbin before a single layer of copper wire was wound onto it. The glass fibre layer is to represent the glass fibre that is usually present on Nb_3Sn wires. After winding, the bobbin was vacuum impregnated with epoxy resin as would be the case with a magnet. It was found that a 50 µm alumina coating broke down between 1 kV and 1.25 kV and a 100 µm coating broke down at 3.5 kV. The 50 µm coating was selected for the EuCARD undulator because, given the expected low inductance of the magnet, voltages of less than 1 kV were expected during a quench.

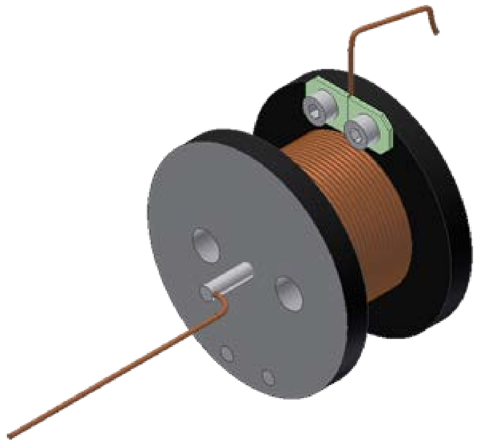

Figure 14: Bobbin sample for ground plane coating

4.2. CHANGE TO FORMER

Although the former design was nominally unchanged from the HeLiCal design, some minor modifications were needed. The HeLiCal undulator incorporated a copper tube, which was joined to the iron former by soldering one end and brazing the other. Neither of these joints would survive the heat treatment schedule, and could pollute the vacuum furnace. In addition the ground plane coating discussed in section 4.1 needs to be applied to a continuous surface. If there was a break between the sides of the groove and the base of the groove, as with the HeLiCal former, then there could be exposed metal in close proximity to the magnet winding creating a potential short circuit path. To counter both of these problems the former manufacturing process was changed to that shown in Figure 15. The manufacturing process is unchanged until step six. When the two helical grooves were cut, the cut doesn't break through into the supporting rod. This leaves a continuous surface for coating and there is no need to insert and then join a copper tube. As mentioned previously the copper bore was used to reduce the wakefield affect. In an undulator that would be used in a beamline, it should be possible to coat the bore of the undulator with copper. However this was felt to be an unnecessary step for a test magnet.

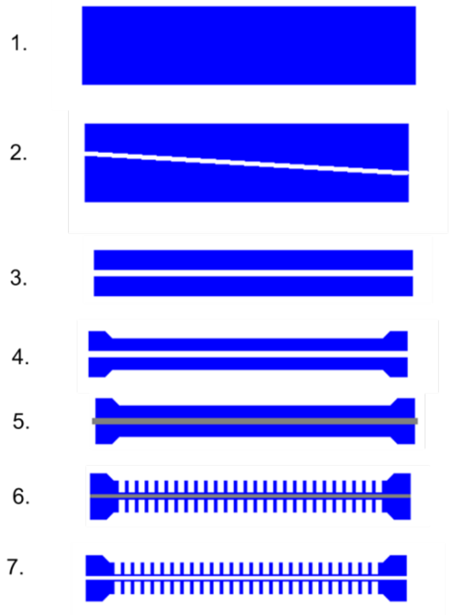

Figure 15: EuCARD former manufacturing steps

The groove width was also widened slightly, as discussed in section 4.1. The ground plane insulation each side of the groove is nominally 50 µm thick so a total additional allowance of 100 µm is needed. During the heat treatment the Nb_3Sn wire expands radially typically between 1 %-4 %, the precise figure for the Supercon wire was unknown so a 2 % expansion was assumed which equates to 50 µm. So in total the winding groove width was increased by 150 µm from 3.25 mm to 3.4 mm. A final change was that a 0.5 mm radius was added to the top of the groove whereas previously this had been a 0.5 mm chamfer, this was to remove any sharp edges that might damage the wire or insulation.

4.3. OTHER CHANGES

Several other minor changes were made to the design. The winding pins were changed to be macor, the machinable glass ceramic that is often used in Nb_3Sn magnets.

After heat treatment the Nb_3Sn wires are very fragile, and cannot be manipulated into position to connect to the current leads. Instead the Nb_3Sn wires need to be spliced to some Nb-Ti wires which can then be connected to the current leads. Figure 16 shows some copper splice pieces that are used to hold the Nb_3Sn wires, after heat treatment the copper is then used to support the Nb-Ti wires and facilitate the splice. In order to isolate the positive and negative wires, pieces of macor were used to provide electrical breaks.

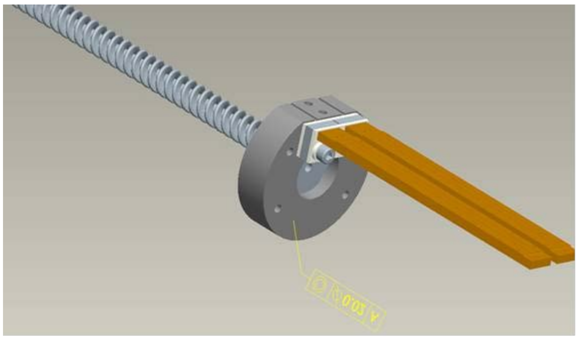

Figure 16: Splice diagram

4.4. VACUUM IMPREGNATION

After heat treatment the undulator needs to be potted; this is to provide mechanical support and to act as electrical insulation. Usually epoxy resin is used. To prevent the resin from cracking on cool down the vacuum impregnation tooling is designed to be a tight fit to avoid resin rich volumes. Where this is impractical, glass fibres or other reinforcement is introduced to displace the resin. Figure 17 shows an illustration of an undulator, there are two regions which have differing requirements in terms of vacuum impregnation; the region around the helix is packed with conductor and glass whereas the region around the pins is very open and requires some type of reinforcement to avoid resin rich volumes. When manufacturing the HeLiCal undulator the volumes around the winding pins were prefilled with Spheriglass® 2024 solid glass spheres, colloquially referred to as *ballotini*, these are small glass spheres 106-212 µm diameter. In order to completely fill the open volumes with ballotini the HeLiCal undulator was placed on a vibrating table. Due to the fragility of a reacted Nb_3Sn wires this was undesirable for the EuCARD undulator. Rather than prefill the volumes with ballotini and then vacuum impregnate with epoxy it was considered whether it would be possible to include a filler material in the epoxy resin and then perform the vacuum impregnation. STFC has had experience creating a filled epoxy for filling large volumes for the ITER Toroidal Field coils.

The epoxy resin chosen was called *Atlas mix* which was used on the end cap toroid magnets in the ATLAS experiment which is part of the Large Hadron Collider at CERN. Atlas mix comprises of 60 parts by weight DGEBF epoxy resin with 40 parts PPGDGE as a flexible resin together with 21 parts DETD is added as the hardener. The filler used was dolomite which is a mineral filler made up of calcium magnesium carbonate. This was added to the resin so that the mixed resin/filler contained 38 % by volume dolomite.

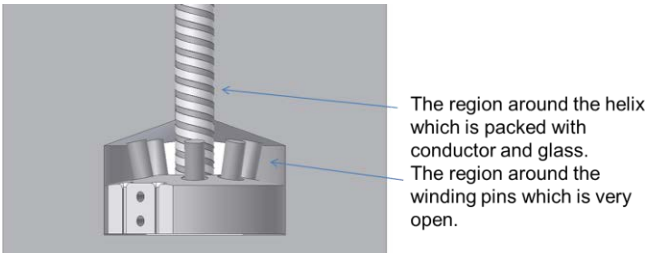

Figure 17: Regions with different vacuum impregnation requirements

There were concerns regarding the use of the resin/filler mix for use in vacuum impregnating the undulator. The mix should work well in the open region around the pins, however it was feared that the high viscosity mix may not be able to penetrate the glass fibre in the helical region.

To test whether the filled resin would work a small experiment was carried out. Figure 18 shows a bobbin specimen that was wound with 7 layers of glass fibre insulated Nb_3Sn wire. This was then vacuum impregnated with the filled resin mix. After impregnation the bobbin was sectioned and examined under a microscope. Figure 19 shows the microscopy of the bobbin. It can be seen that in certain regions surrounding the winding pack the filled resin was able to penetrate. However between the wires was pure resin, where the glass fibre insulation has filtered out the dolomite filler.

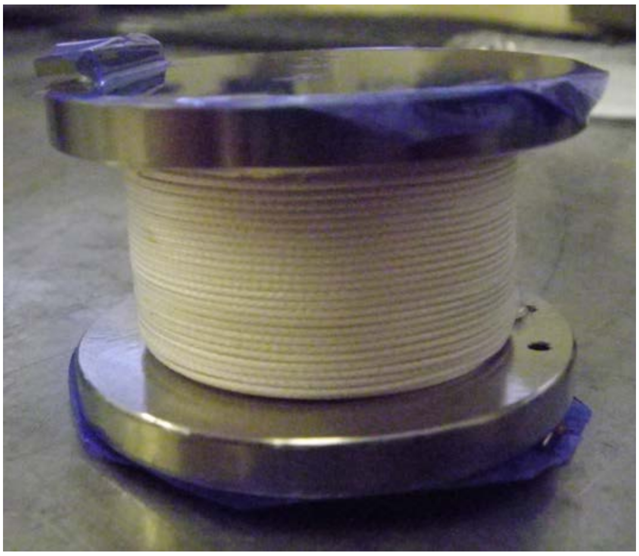

Figure 18: Bobbin test piece for filled resin

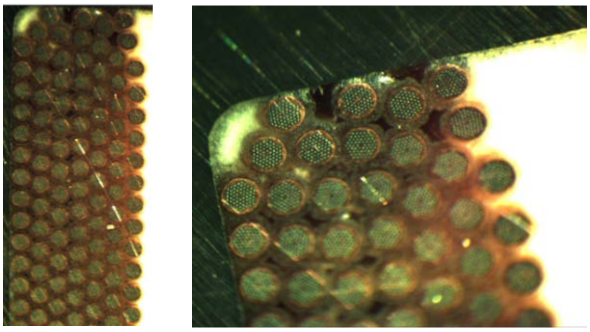

Figure 19: Microscopy of bobbin after vacuum impregnation with filled resin

An earlier winding trial using the OST E2004 wire had produced an undulator which hadn't been vacuum impregnated; after the reasonable success of the small trial it was decided to attempt to vacuum impregnate an undulator using the filled resin mix. The results of which are shown in Figure 20. The filled resin managed to impregnate approximately ½ of the undulator. However the pure resin was able to impregnate 9/10 of the undulator, although the glass fibre insulation had filtered out the dolomite in some regions. This left a filler rich volume at the bottom of the undulator. It would probably be possible to make changes to the filled resin such as optimising the resin:filler ratio and improving resin access in the tool so that using a filled resin would be viable when vacuum impregnating an undulator. However time constraints precluded this future work so it was decided that the EuCARD undulators would be prefilled with ballotini.

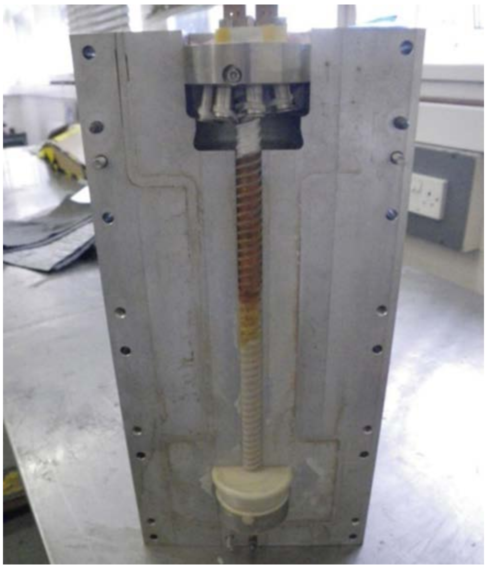

Figure 20: Filled resin trial

5. MANUFACTURING

The manufacturing process for the magnets follows the fairly standard wind and react process as shown in Figure 22. To begin with the undulators were wound using unreacted precursor wire. Once winding was completed the undulators were transferred to stainless steel heat treatment tooling and placed in a vacuum furnace. The magnets were then heat treated using the schedule recommended by Supercon and shown in Figure 21. After heat treatment the low temperature superconducting current leads were attached together with the voltage taps. The final stage of manufacturing was to vacuum impregnate with epoxy resin.

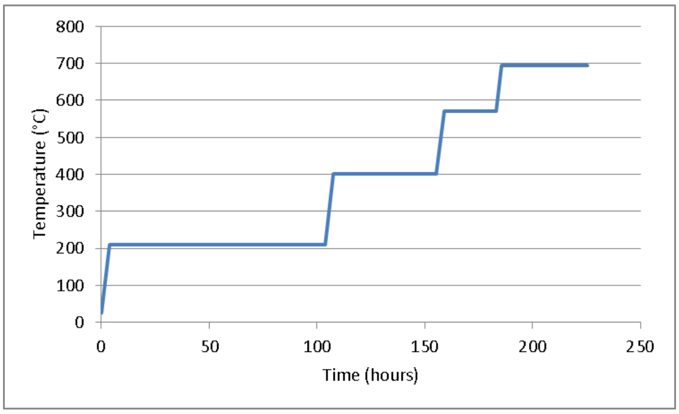

Figure 21: Supercon heat treatment schedule

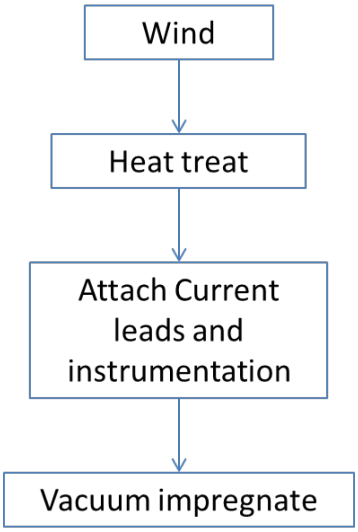

Figure 22: Wind and react process diagram

5.1. WINDING TRIAL

Before manufacture of the first milestone undulator a winding trial was carried out to prove the winding scheme. This used an iron former with a 3.25 mm winding groove. The former had a solid core which meant that this undulator couldn’t be magnetically tested because a Hall probe couldn’t be inserted into the bore. The former was coated with 50 µm alumina by Zircotec which reduced the winding groove width to a nominal 3.15 mm. Stainless steel winding pins were used. The trial wind used the OST E2004 wire and took place in February/March 2012. The winding trial was successful; it proved the winding technique and led to minor changes to the winding machine and splice pieces to be incorporated into later magnets. The wound trial undulator is shown in Figure 23: this undulator was also used in the filled resin impregnation trial as discussed in Section 4.4.

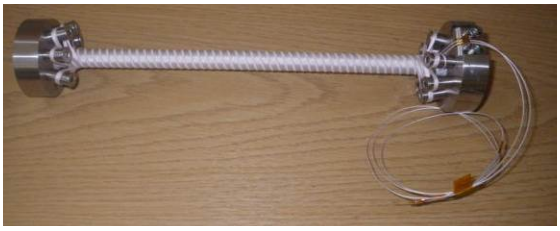

Figure 23: Winding trial undulator

5.2. UNDULATOR 1

The first undulator was wound during October 2012. This used the Supercon Internal Tin wire and was wound onto a former coated with alumina by Zircotec. Prior to winding it was found that there was a problem with the design of the winding flange. The winding flanges are components that are fixed at either end of the former and hold the winding pins (Figure 24). The winding flange at the start end is also used to mount the splice pieces as described in section 4.3, there is a groove cut into the winding flange to locate the wires. It was noticed that the wires had to traverse a sharp 75° corner, rather than a radius transition which would have been safer for the wire. Thin Mica sheet was used to cover the sharp corner and to protect the wire over the transition. It was also found that the macor winding pins were susceptible to damage during installation particularly at their outer edges.

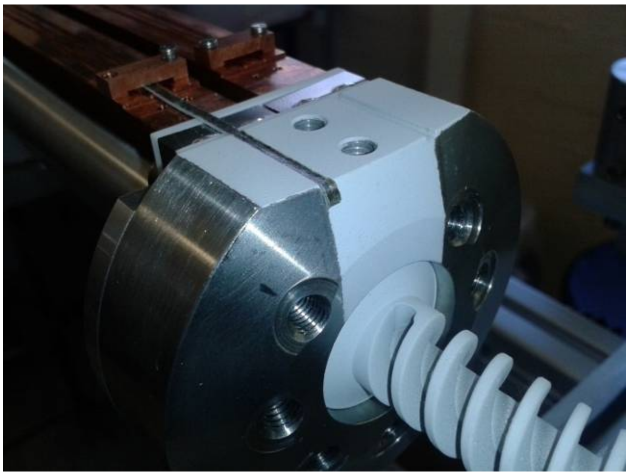

Figure 24: Former and winding flange prior to winding

Once winding started it wasn't possible to place five wires into the base of the groove to make up the first layer. This was surprising because the earlier winding trial which had a narrower groove had shown that this should be possible. The problem was traced to the glass fibre braid insulation on the wire. The braid on the OST wire seemed to be tighter and more robust, whereas the braid on the Supercon wire was looser and more prone to damage. During winding the braid splayed out taking up more room; this meant that there wasn't enough space to get the final fifth wire in position. Figure 25 shows the desired winding scheme on the left and the nominal actual winding scheme on the right – here the first four layers contain four wires and then towards the top of the groove the five, four, five layout is achieved. The wire placement isn't as neat as that shown in the figure. There are several consequences of this.

Firstly there are 30 wires carrying current in a space that was meant to have 32 wires carrying current so the current density is reduced. In addition it is likely to affect the field quality because of the irregular placing of the wires.

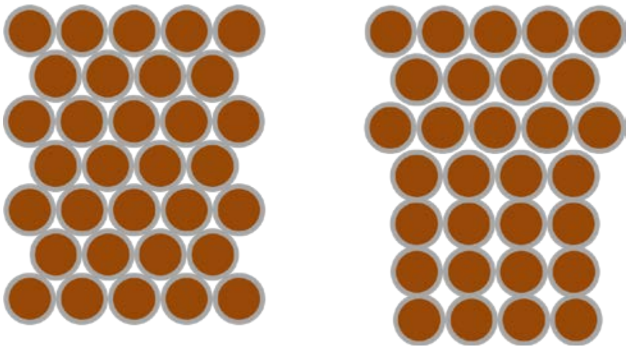

Figure 25: Desired winding scheme (left) and actual winding scheme (right)

After winding the magnet was heat treated following the heat treatment schedule shown in Figure 26.

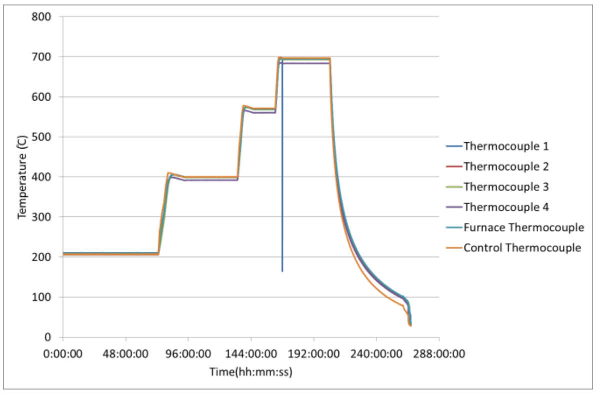

Figure 26: Heat treatment for Coil A

After heat treatment the Nb-Ti current leads were added together with the voltage taps. Figure 27 shows the completed undulator ready for testing.

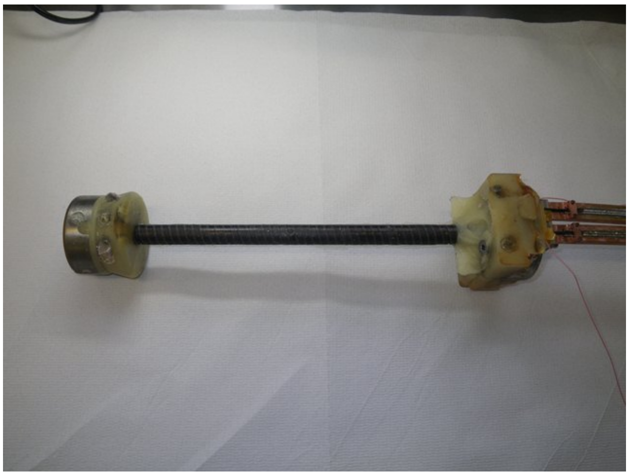

Figure 27: Undulator 1 after vacuum impregnation

5.3. UNDULATOR 2

The second undulator was wound during December 2012. There were several changes made to the design, the most significant being shown in Figure 28, a radius has been added to ease the wire transition.

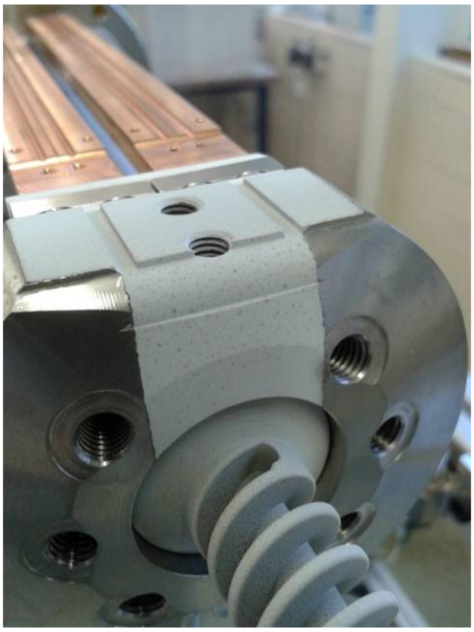

Figure 28: Change to winding flange including radius to ease wire transition

Time constraints meant that it wasn't possible to widen the groove in the former and so the desired winding scheme could not be achieved. The actual winding scheme was near that shown in Figure 25. Figure 29 shows the completed undulator after winding.

Figure 29: Undulator 2 after winding

The heat treatment schedule is shown in Figure 30.

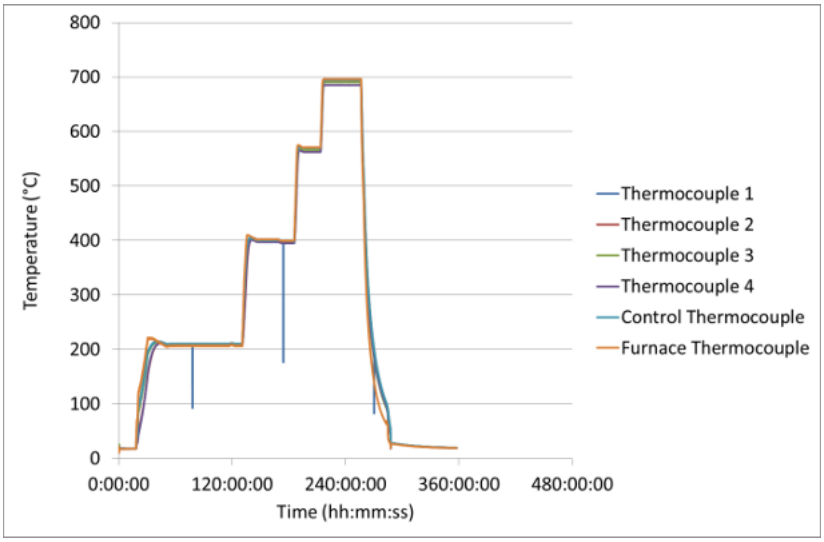

Figure 30: Undulator 2 Heat treatment

After heat treatment the undulator was vacuum impregnated with epoxy resin. A new impregnation mould was used for undulator B, this mould had improved access and made it easier to admit the ballotini. Figure 31 shows the finished undulator 2.

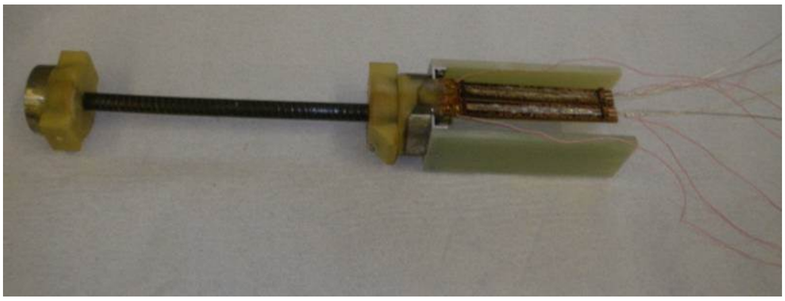

Figure 31: Undulator 2 ready for testing

6. TESTING

6.1. TEST LOCATION

Initially it was planned to test the EuCARD undulator at STFC-RAL. In preparing the test set up it was found that due to the high current of 720 A, if conventional conduction cooled current leads were used there would be a heat load of approximately 30 W per lead. This would lead to unacceptably high helium consumption, thought to be in the region of 80 litres per hour. If vapour cooled current leads could be designed then the helium consumption could be reduced by an order of magnitude. However time constraints meant that it wasn’t possible to design optimised vapour cooled current leads. Another alternative would be to add a 77 K stage to the cryostat and use High Temperature Superconducting leads from the 4 K to the 77 K stage, unfortunately space within the test cryostat precluded this option.

An alternative test location was found at Laboratorio Acceleratori e Superconduttività Applicata (LASA) which is part of Istituto Nazionale di Fisica Nucleare (INFN) and based in Milan, Italy. A schematic of the test set up shown in Figure 34. The undulator was tested in a bath cryostat using liquid helium at 4.2 K. The magnet was suspended from the cryostat top plate. As mentioned previously the Nb_3Sn tails were soldered to Nb-Ti current leads which were then soldered to vapour cooled current leads in the LASA cryostat. Detailed drawings of the set up are shown in Appendix A.

6.2. INSTRUMENTATION

The primary focus of the test was to measure the peak field in the bore of the magnet. In order to do this a Hall probe bonded to a carbon fibre rod was inserted into the bore. The modelled results are shown in Figure 32. This shows how the field varies along the magnet bore in one plane, if the Hall probe were static then it would be likely that the Hall probe would not be aligned perpendicular to the field direction. When testing the HeLiCal undulator a stepper motor was used to drive the Hall probe through the magnet which gave results similar to that shown in Figure 32, from this the peak field could be found, together with the field quality.

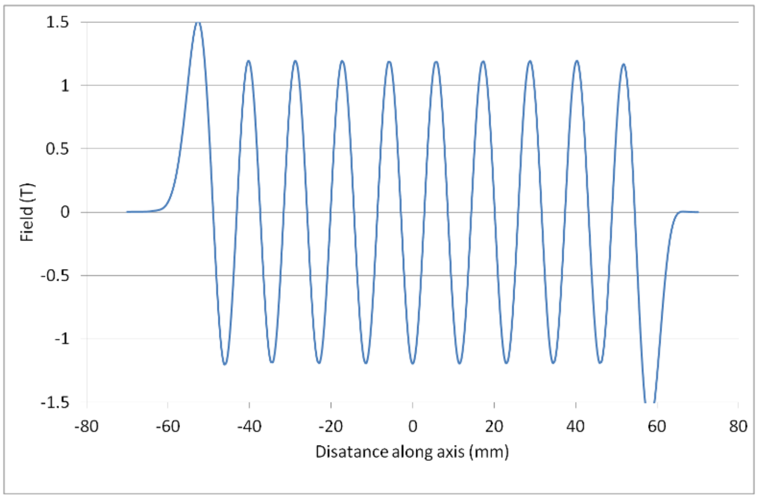

Figure 32: Calculation results for field at various points along magnet bore

As the goal of the EuCARD testing was only to find the peak field a different method was employed. Rather than using a stepper motor to drive the Hall probe through the magnet, the Hall probe position in the bore was fixed and the probe rotated manually to perform a field sweep at one location. The expected results are shown in Figure 33.

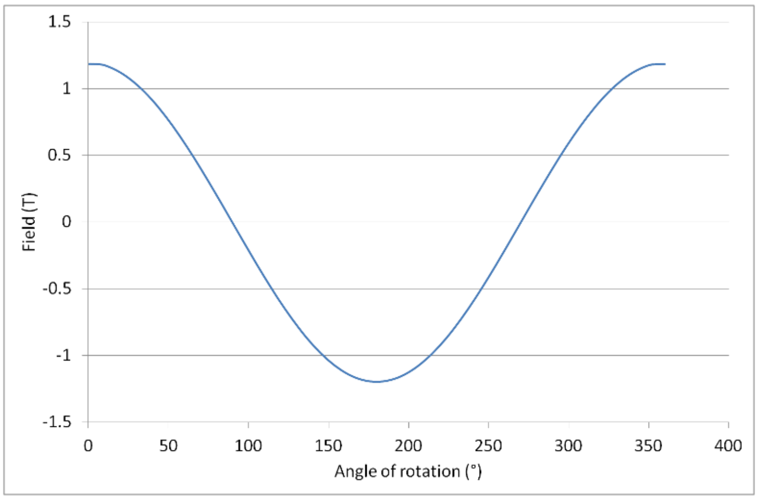

Figure 33: Expected results from rotating Hall probe

The other instrumentation used was voltage taps either side of the splice pieces to detect a quench and turn off the power supply and temperature and helium level monitoring.

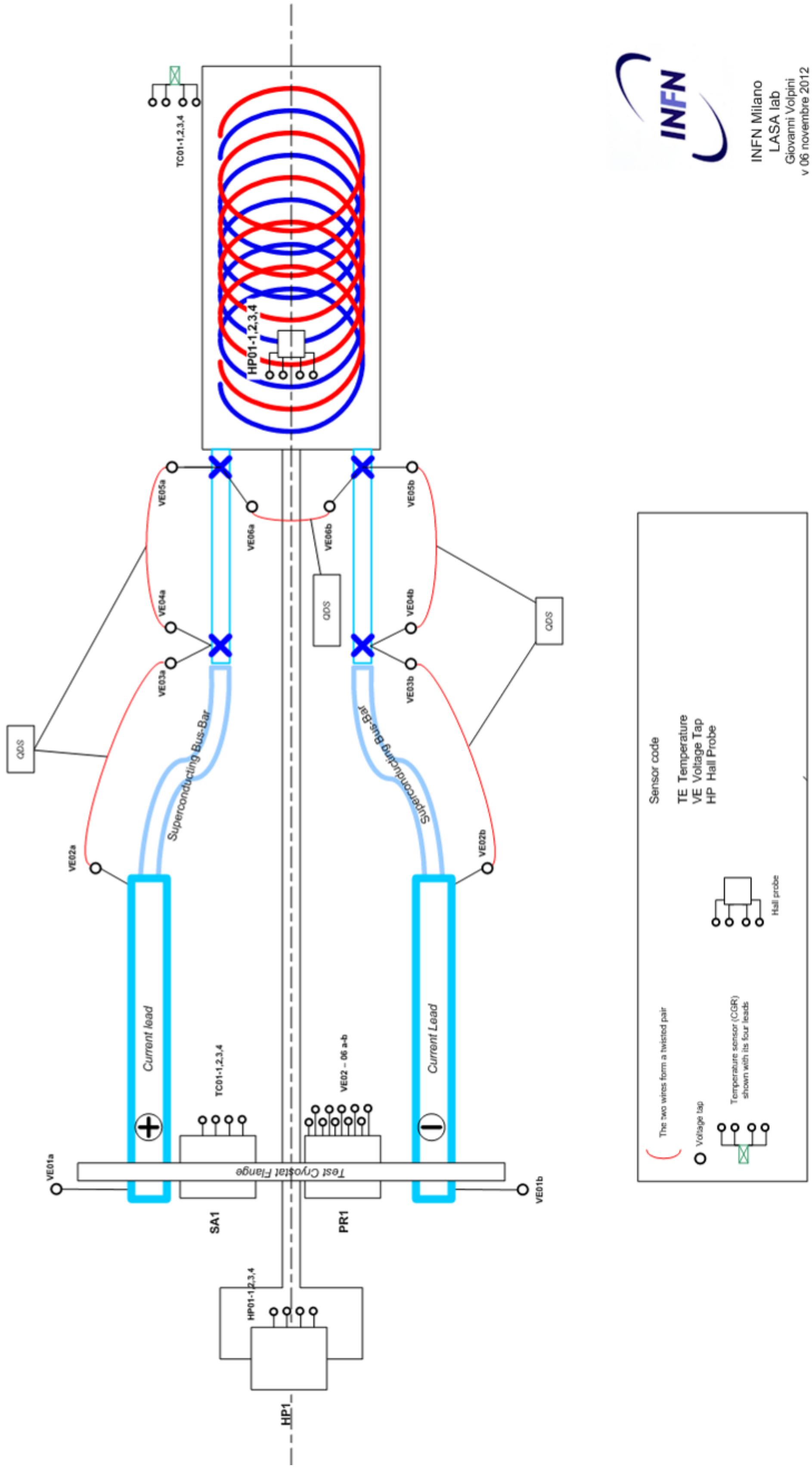

Figure 34 Schematic of the test set up

6.3. RESULTS

The room temperature resistances measured on the coils A and B when they arrived at LASA were 15 Ω and 1400 Ω respectively. Coil B was therefore not tested and the following test results apply to Coil A.

Coil A was cooled down and attempts made to pass a current through it. It was found that the Quench Detection System (QDS) acted repeatedly at around 28-30 A regardless of changes that were made in the ramp rate or QDS settings: the voltage detection threshold was increased to 460 mV, the validation time was increased to 50 ms and the ramp rate varied between 1 A/s and 30 A/s. The voltages measured during six measurements of the quench are shown in Figure 35 it can be seen that the behaviour leading up to and during the quench was consistent.

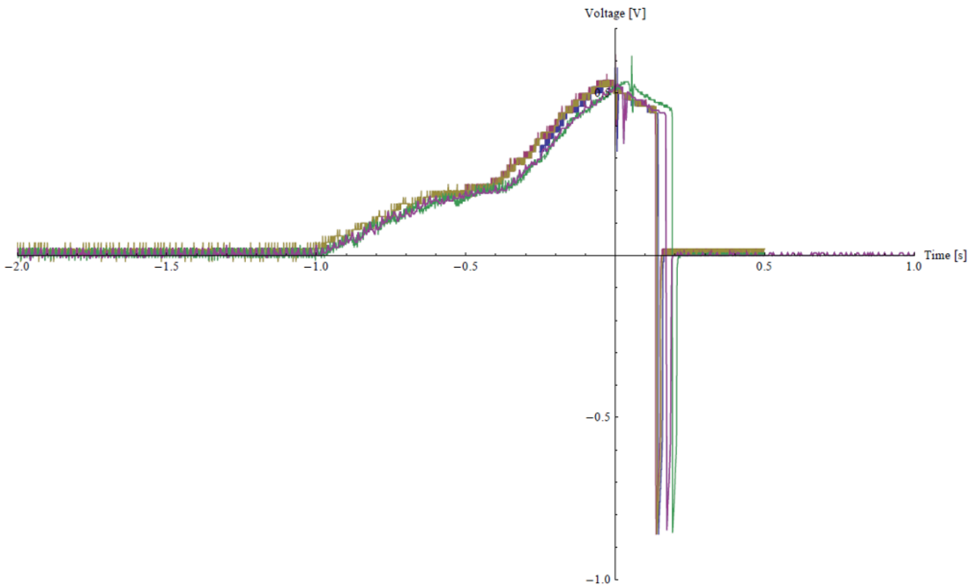

Figure 35: Voltages recorded by the oscilloscope during quench

The magnetic field was measured at 25 A radially and azimuthally, the results of which are shown in Figure 36 and Figure 37 respectively.

The inductance was found to be 2.5-2.8 mH using a 100 mA AC current and measuring the voltages.

A resistance measurement made by means of a 4-wire method showed that the Coil A had a non-linear resistance which varied from 1.375 μΩ at small current and increased with current, as shown in Table 1.

Lastly a rough measurement of the RRR value showed that it was ~ 3.

Further details of the test set-up and results are available in [1].

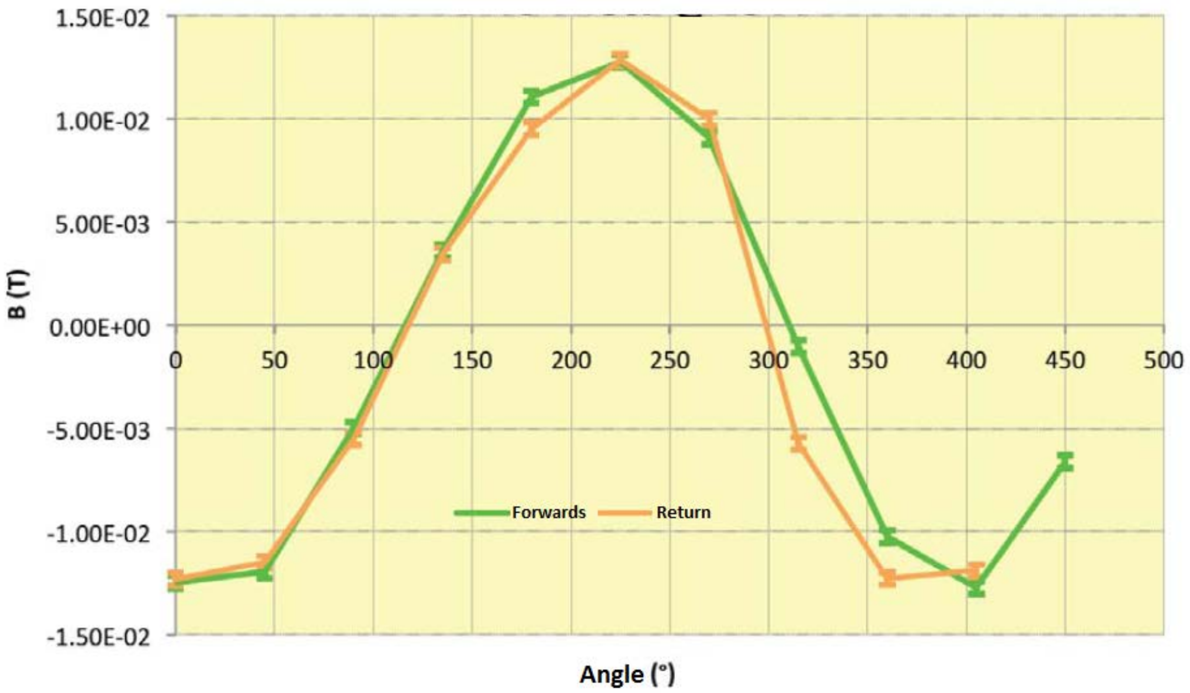

Figure 36: Radial magnetic field measurements at 25A

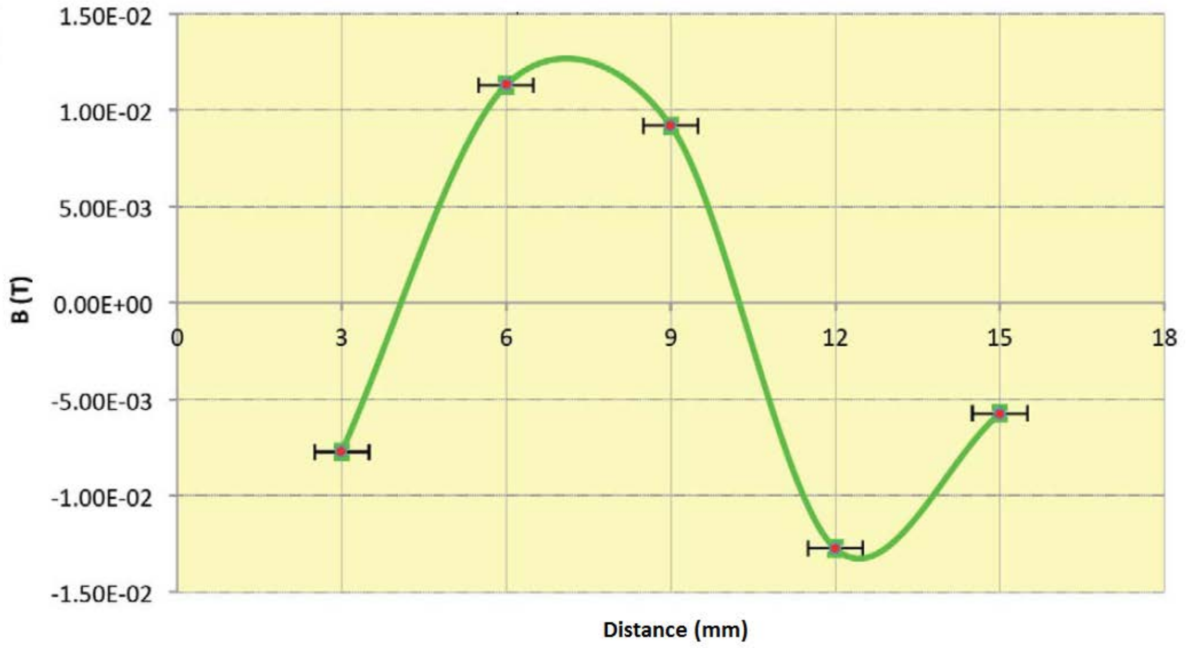

Figure 37: Azimuthal magnetic field measurement at 25A

Table 1: Resistance measurement results

Current	No. Meas	Voltage	Mean RMS	Resistance
A	#	µV		µΩ
0	15	0.74	0.1	
10	22	17.62	0.37	1.76
5	26	8.33	0.2	1.67
15	26	28.99	0.26	1.93
20	26	51.17	0.36	2.56
10	26	17.72	0.3	1.77
0	26	0.81	0.1	

7. DISCUSSION

The first part of this task was a design study of the undulator using an Nb_3Sn conductor. It was found that OST and Supercon manufactured wire that was potentially suitable. The OST wire had a large filament size (50-100 µm) which may have caused flux jumping at low fields leading to instability. As a result the Supercon wire was chosen for the EUCARD undulator.

The final EUCARD undulator was intended to have the same design as the existing HeLiCal undulator; however the design and manufacture of the former and winding had to take into account the heat treatment required for the Nb_3Sn conductor. For example the wire was expected to expand during heat treatment – this meant that the winding grooves had to be widened to allow for this. Due to the fragility of the Nb_3Sn wire, the use of dolomite as an alternative to ballotini as a filler material for vacuum impregnation was considered. This was because in the manufacture of the HeLiCal it had been necessary to use a vibrating table to ensure the ballotini filled all the open volumes completely. However the use of dolomite as an alternative was tested on an early winding trial and tests proved unsuccessful, so ballotini were used in the manufacture of the final magnets (although the shaker table was not required in this instance).

Following the design stage two short prototypes, each ~300 mm long were manufactured and tested magnetically. The manufacturing process for the magnets follows the fairly standard wind and react process: alumina-coated undulators were wound with unreacted precursor wire from Supercon, they were then heat treated in a vacuum furnace following the heat treatment recommended by Supercon, and vacuum impregnated with epoxy resin.

Testing was carried out at Laboratorio Acceleratori e Superconduttività Applicata (LASA) which is part of Istituto Nazionale di Fisica Nucleare (INFN) and based in Milan, Italy. The magnets were both found to be resistive when tested. Coil B was found to have a room-temperature resistance of 1400 Ω on arrival at LASA and so was not tested. Coil A quenched repeatedly at 28-30 A and was found to have a non-linear resistance of 1.375 µΩ at small current which increased with current.

The reasons for the resistance are unclear. It could be as a result of damage to the wire during manufacture or transport, or strain on the wire, particularly on tight corners such as around the macor winding pins. Alternatively the resistance could be indicating that the Nb_3Sn didn't form as intended throughout the whole winding during the heat treatment.

To investigate the cause for the resistance, epoxy was removed from one end of coil A by immersion in dichloromethane for some days. This revealed a break in the wire and also two broken macor posts, see Figure 38. The broken wire was located at the post corresponding to the penultimate winding layer (second to top). The post corresponding to the top layer of winding was also fractured.

Figure38: Showing broken wire and fractured macor winding post after removal of epoxy resin

The epoxy was also removed from Coil B, which was not tested and so was not cooled to cryogenic temperatures. No such damage was observed in Coil B. As Coil B has not seen low temperatures it is believed that this indicates that the break in Coil A occurred during cooling.

8. CONCLUSION

The break in coil A and the fractured macor winding posts indicate that significant tensile force was present in the windings. This could have arisen because of dimensional change on heat treatment and from contraction on cooling. It is known that other types of Nb_3Sn wire retract on reaction and it would seem that this is a likely cause of the failure.

Future coils of this type need to be engineered to allow for this dimensional change to reduce stress in the wire to a minimum.

ANNEX: GLOSSARY

Acronym	Definition
INFN	Istituto Nazionale di Fisica Nucleare
KIT-ITEP	Karsruhe Institute of Technology – Institute for Technical Physics
LASA	Laboratorio Acceleratori e Superconduttività Applicata
OST	Oxford Superconducting Technology
QDS	Quench Detection System
RRR	Residual Resistivity Ratio

REFERENCES

[1] Volpini et al, *Undulator Test at LASA result summary*, INFN, March28, 2013

ACKNOWLEDGEMENTS

The authors are extremely grateful to the High Field Magnet Work Package team for all of their helpful comments and remarks. We are particularly grateful to Frank Hornung and colleagues at KIT ITEP for the OST wire characterisation, to Luc Oberli, Bernardo Bordini and colleagues at CERN for the Supercon wire testing and specific advice on low field instability of Nb_3Sn, and to Giovanni Volpini and colleagues at LASA for testing the two prototype magnets. Finally we would like to thank Gijs de Rijk and François Kircher for their excellent management of the Work Package and for their strong support and encouragement.

APPENDIX A

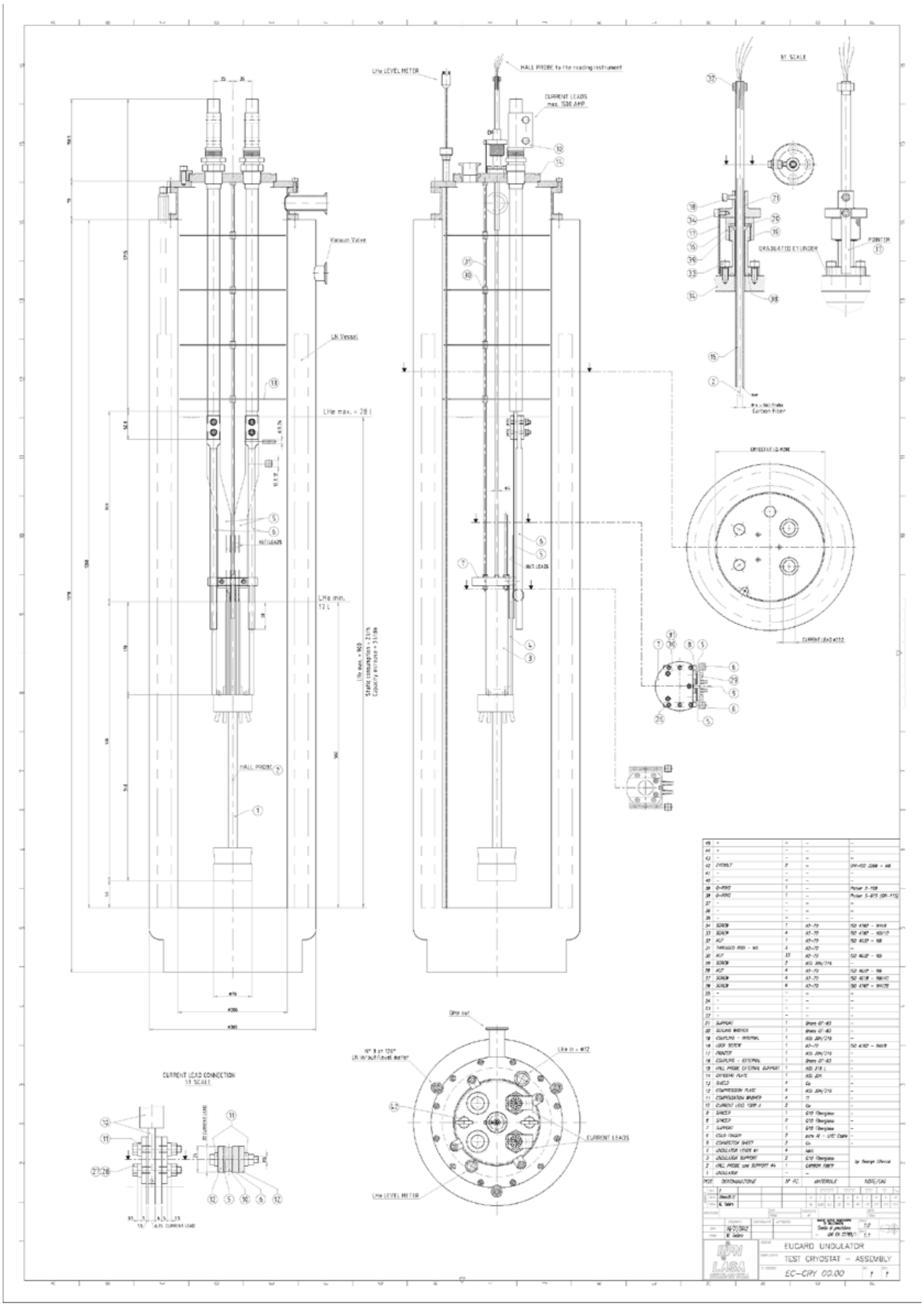

Figure 39 Test cryostat assembly drawing

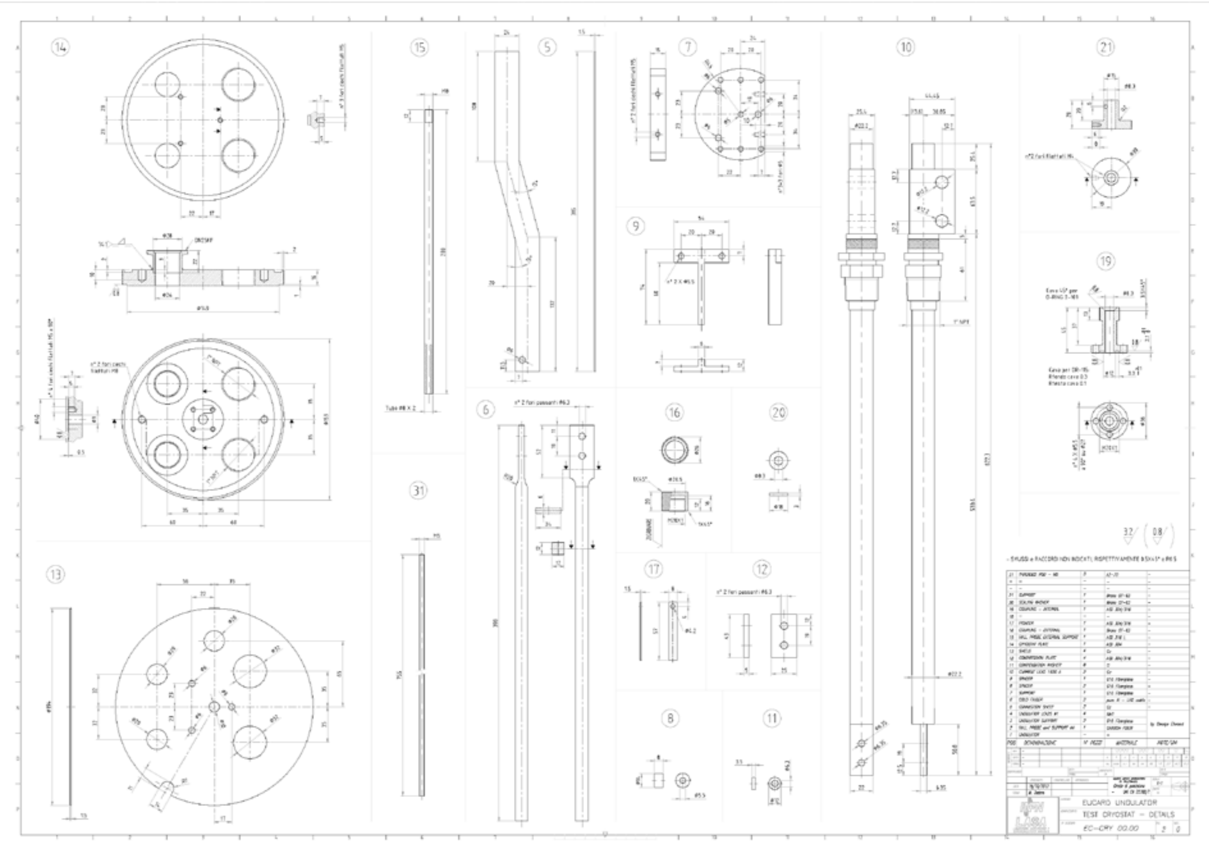

Figure 40 Test cryostat details drawing

APPENDIX B

Current Leads for EuCARD Undulator

George Ellwood 26/06/2012

Initial work based on Copper conduction cooled current leads. The optimum ratio of length to area is given by equation (1).

$$\left[\frac{IL}{A}\right]_{opt} = \int_{T_C}^{T_H} \frac{k(T)dT}{\sqrt{s\int_{T_C}^{T_H} k(T)\rho(T)dT}} \quad (1)$$

This depends on the materials resistivity and thermal conductivity and the temperature range. Once IL/A has been calculated for a material and temperature range, it can then be divided by the operating current to give the optimum L/A ratio. In this case Copper with an RRR of 10 has been chosen because it seems to be typical of what has been used previously and should be available commercially. The thermal conductivity and resistivity values are shown in Figure 43 and Figure 44 respectively. Using this data IL/A = 4.04E6 A/m. With the operating current of 720 A this gives the L/A ratio of 5622.4 m/m^2. This has been evaluated using MATLAB and gives a heat loss of 28.128 W during operation at 720 A. The length of the current leads is constrained by the space available in the cryostat, previous current leads used in this cryostat were 350 mm long, so using the same length the cross sectional area would be 62.25 mm^2.

A simple model has been created in ANSYS to find out how the heat loss in various scenarios and the temperature profile along the lead. Figure 45 shows the model, this is a 3D model with an area of 62.25 mm^2 and a length of 350 mm, the top surface is constrained to be 300 K and the bottom surface is constrained to be 4 K. There are 100 elements between the 300 K and 4 K stage.

To begin with the ANSYS model is run at the operating current of 720 A to cross check the result against MATLAB. This is done by selecting the 4 nodes that make up the area at the bottom of the lead and then checking the reaction solution. This gives a value of 28.219 W which is in very good agreement with the predicted value from MATLAB. To ensure that the area of 62.25 mm^2 is indeed the optimum cross sectional area for the current leads the ANSYS Design Optimisation tool was run. In order to use this tool the area was set as a Design Variable between 10 mm^2 and 200 mm^2 and the heat leak was set as the objective to minimise. Of the various optimisation strategies available from ANSYS the Design Variable Sweep was chosen with 10 sweeps per Design Variable, so 10 variations were performed in this case. The results are shown in Figure 41. This shows that the minimum heat leak is at or near an area of 62.25 mm^2. The optimiser was rerun, this time with the area Design Variable to be set to be between 60 mm^2 and 70 mm^2 as shown in Figure 42. This showed that the optimum area was actually 62.222 mm^2.

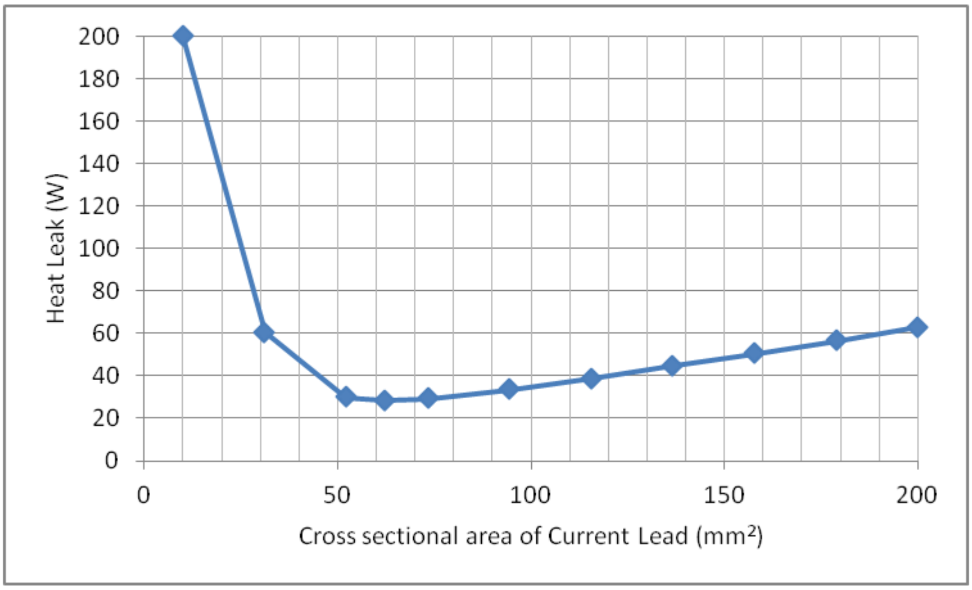

Figure 41: Heat Leak vs. Area for current leads 350mm long operating at 720A between 4k and 300k

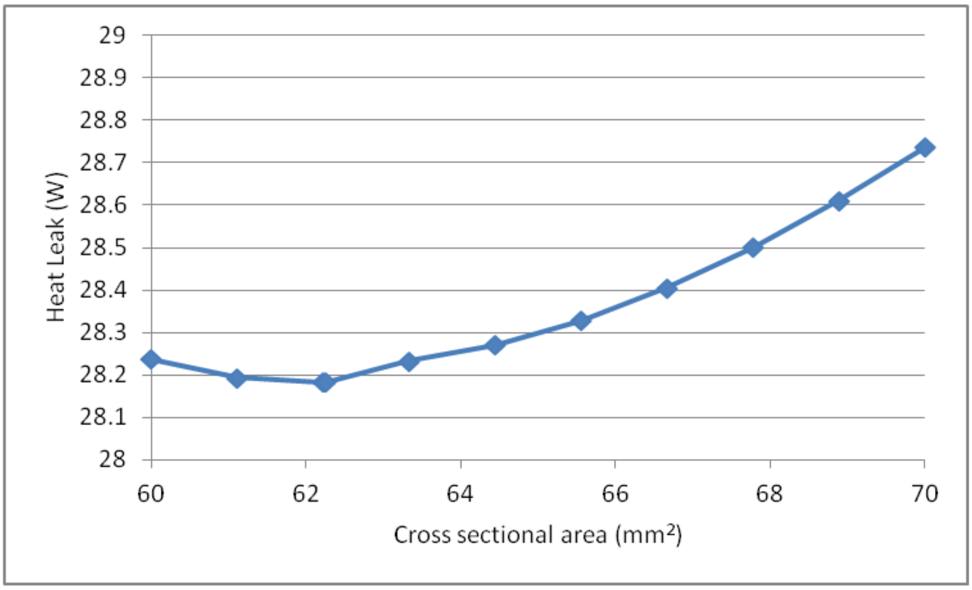

Figure 42: Detailed look at heat leak vs. area in region of interest

The model was then run to calculate the heat load and the temperature profile of the current leads in three scenarios, 0 A, 720 A and 1000 A, these are when there's no current, operating current and maximum expected over current respectively. The heat loss is shown in Table 2 and the temperature profiles are shown in Figure 46.

The heat losses by using conduction cooled Copper current leads are very large. They would equate to a helium consumption of ~39 l/hour when operating at 720 A.

Table 2: Heat loss for different currents

Current (A)	Heat loss (W)
0	18.925
720	28.219
1000	50.461

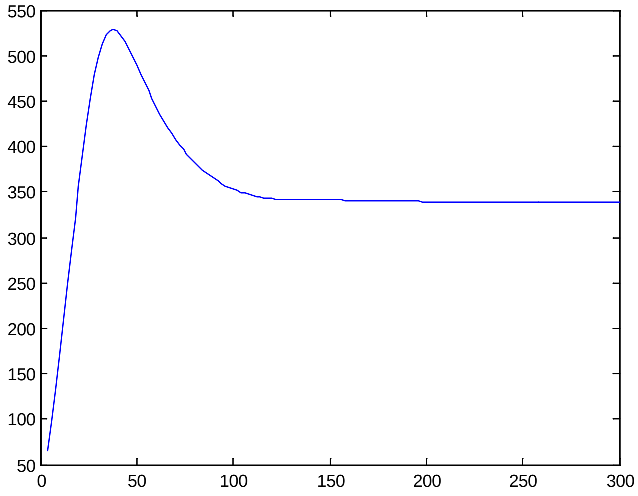

Figure 43: Copper RRR=10 Thermal Conductivity against temperature

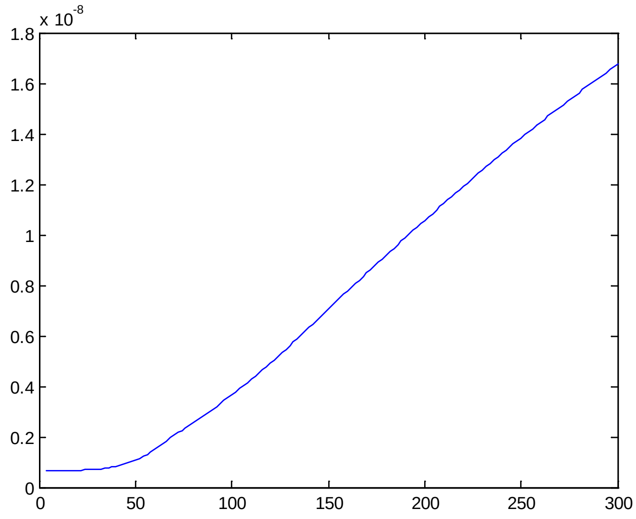

Figure 44: Copper RRR=10 Resistivity against temperature

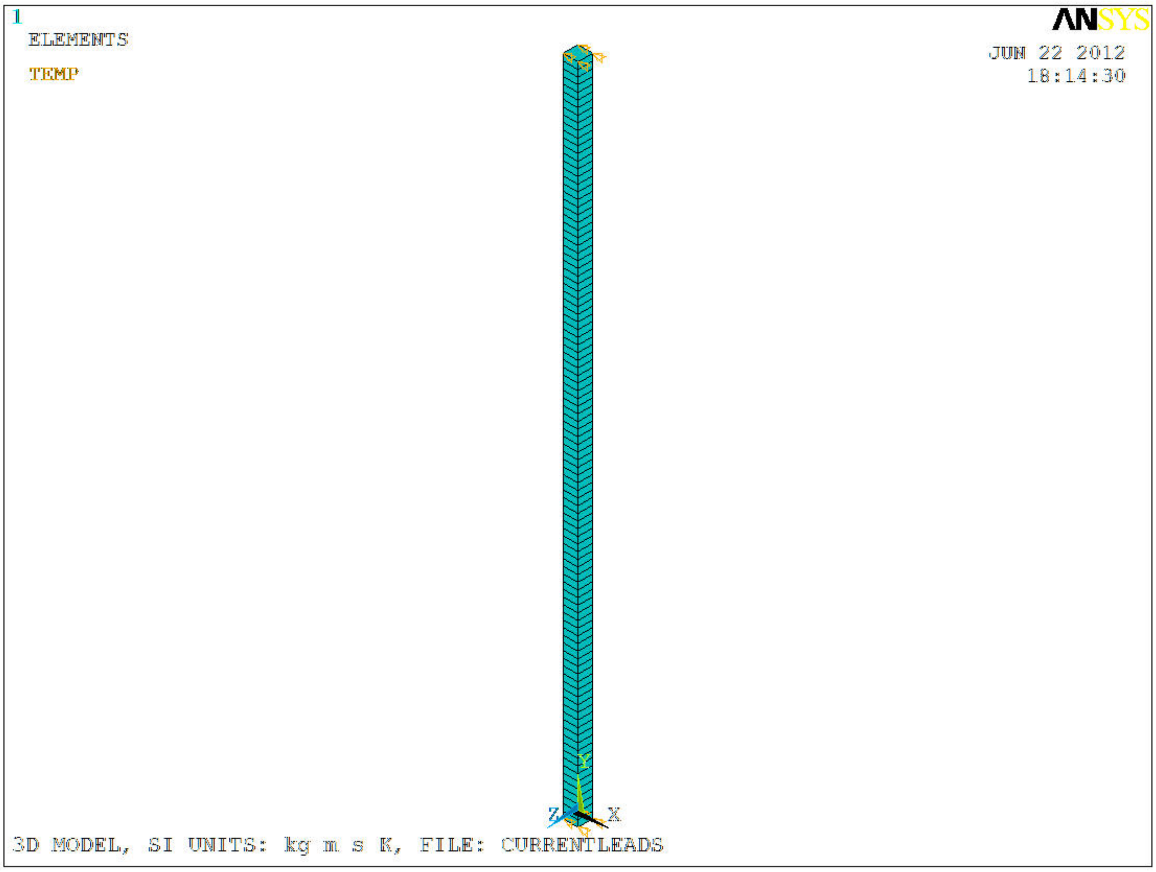

Figure 45: Simple ANSYS model of the current leads

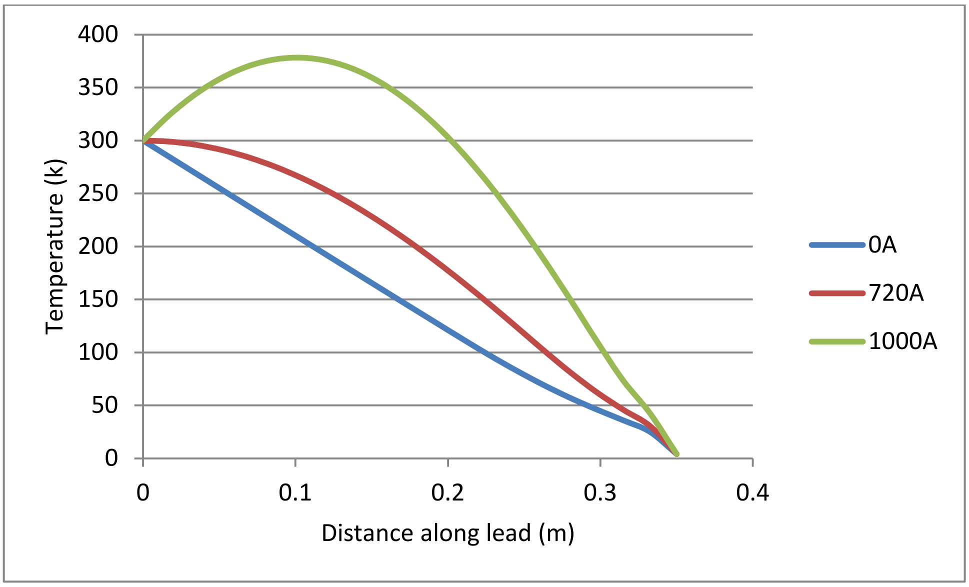

Figure 46: Temperature vs. distance for 0 A, 720 A and 1000 A