Invited Lecture 1 :

Cryogenic Experiments for the K500 Superconducting Cyclotron

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Introduction:

A K500 Superconducting Cyclotron is in operation in partially commissioned stage at VECC, Kolkata. This is based on the K500 Superconducting Cyclotrons in Michigan State University (MSU) and Texas A&M University (TAMU) in USA. In order to support the construction activities of this Cyclotron in VECC, cryogenic experiments were undertaken and some important experiments have been completed. This experimental work was undertaken as VECC-SINP collaboration programme. This talk will highlight the results of experiments.

The Cyclotron has solenoid coils of copper stabilized Nb-Ti superconducting cable wound on a stainless steel bobbin. The superconducting wire is multi-filamentary composite of diameter 1.29mm, having 500 filaments of NbTi of diameter ~ 40 microns embedded in a copper matrix. The superconducting cable is a wire-in-channel configuration where the wire is soldered within a groove on rectangular copper substrate (2.794mm x 4.978mm) for cryogenic stability. About 35kms length of superconducting cable is used for winding the K-500 magnet coil [1]. As the cable is not long enough, there are five joints in the winding. Joint resistance, being a continuous disturbance is made as low as possible. These are made in-house on the coil-winding machine by brazing copper substrate and soft soldering the lap joint between two superconducting elements of the wire. The lap length of each joint is kept 100mm. Temperature rise in the joint should be low enough to take full advantage of nucleate boiling heat transfer [2] in the bath of liquid helium. The joint must also be strong enough to withstand sufficient hoop stress ~5000psi (34.47 MPa)[3]. The mechanical strength of the joint has been verified up to liquid nitrogen temperature. Joint resistance is an important design issue. Therefore, joint resistances are measured and the procedure for cable jointing is standardized. Test results confirm that they have acceptably low resistance and carry sufficient current.

The superconducting critical current is an important parameter, which determines the performance of any superconducting magnet. In any superconductor, the critical temperature (T_C), the critical magnetic field (H_C) and the critical current density (J_C) mark the limits of the superconducting state. The T_C and H_C are both determined by the chemistry of the superconducting material, whereas the microstructure, and therefore the metallurgical processing of the superconductor affect J_C. Therefore, it is necessary to determine the critical current and thereby the critical current density of the superconducting wire for its electrical characterization. In superconducting composite the transition to the normal state with increasing current occurs gradually. Empirically, the voltage developed is proportional to the nth power of current during the transition to normal state i.e $V \mu I^n$, where n is defined as the quality index of the wire and for ideal superconductor n is infinity [4]. It is believed that the low value of the quality index is caused by the non-uniformity i.e. sausaging effect, in the diameter of the filaments. The n-value is determined from the conductor's V-I plot. The critical current is accepted, as the current at which the voltage developed is equal to 0.1 μvolt/cm. The critical current is measured in different magnetic fields applied perpendicular to the direction of current.

One 1/5th scale of K-500 superconducting main magnet coil has been made in-house and tested to demonstrate its current carrying capability and quench behaviour. The coil is made up of the superconducting cable described above. The magnet coil with supports and current leads is shown in fig 1. Quenching is a term commonly used to describe the process which occurs when any part of a magnet goes from the superconducting to the normal resistive state, specially the rapid irreversible process in which a magnet is driven fully normal. In this process of quench entire stored energy ($1/2LI^2$) of the magnet dissipates as heat. A part of the energy dissipates through dump resistor placed outside the Dewar and connected parallel to the magnet. Quench is detected when the difference in voltage developed across the two halves of the coil is more than a preset value, called threshold voltage for a given interval (validation time). The quench validation time is needed to differentiate between induced voltage spikes or noise and real quenches. The data generated from the experiment is used to freeze design parameters of the quench detection circuit of the K500 Superconducting Cyclotron.

Experimental set-up and procedure

Two experimental set ups are made around one 508 mm bore, 240 litres capacity Dewar and the other 160 mm bore, 8 litres capacity Cryostat from NPL, New Delhi. The joint resistances of the superconducting cable are measured by using both Dewars and RRR and magneto-resistances of the OFHC copper of the superconducting cable are measured by using smaller Dewar. The measurements in smaller Dewar are limited to 100A current through the sample. Also, to minimize the noise pick-up special RF shield is provided around the sample in addition to the use of shielded, twisted, instrumentation cables with appropriate grounding. In addition, these cables are kept of shortest possible length and wrapped with aluminium foil from outside Dewar to the nano-voltmeter. In order to eliminate thermo-electric effect the measurements are repeated for each current level reversing the polarity and results are presented with average values.

The larger Dewar is procured from Oxford Instrument, USA. Its top plate along with central flange with current leads, superconducting magnet coil support, a helium gas recovery port with a pressure relief valve and a rupture disc, and provision for different feed through ports are designed and fabricated to meet our requirements. The central flange is used to mount the sample and to change sample with liquid helium in the Dewar. All ports are designed to minimize heat in-leak and avoid contamination of helium inside the Dewar. A provision is made to initially fill the liquid from the bottom of Dewar and to top up liquid helium from above its free surface subsequently. To minimize the radiation heat flow down the neck of Dewar, five thin and highly polished stainless steel radiation shields are used for each central and top flange plates. The geometry and location of these baffles are optimised for maximum effectiveness. Two vapour cooled current leads of 1500A current rated capacity are used to provide the current to the short sample/1/5th scale SC magnet. The heat capacity of cold helium vapour is used in these counter flow leads to minimize the liquid helium consumption. Each current lead is attached with superconducting bus bar extension made of Nb_3Sn sandwiched between copper strips. Several temperature sensors are mounted inside the Dewar to monitor the temperature during cool down and one level sensor is used to monitor the liquid level. Pre-cooling of the interior liquid helium chamber is performed in a controlled manner to minimize thermal stress. The critical current is measured by passing DC current through a sample and measuring voltage developed along the length of the superconducting cable using standard four-probe method. The samples are made spiral-shaped having outer diameter of 40mm with 7 number of turns and about 50mm long. Figure 2 shows sample with sample holder. Care is also taken to ensure that the sample is adequately supported to resist Lorentz force. Voltage taps are placed sufficiently apart to produce adequate voltage. Voltages are measured with the help of Keithely nano-voltmeters. The sample is placed at the centre of 50mm bore superconducting magnet, which produces field perpendicular to the direction of current in the sample. All necessary arrangements are made to minimize the noise level. The measurements are also performed for decreasing current to get hysteretic effect, if any. Several samples are prepared and tested for critical current and joint resistance measurement.

The $1/5^{th}$ scale SC magnet has winding inner and outer diameters 315mm and 376mm respectively and 195mm axial length. The superconducting cable is wound around a stainless steel bobbin on a coil-winding machine. There are 8 layers of winding having 37.5 turns per layer. The G10 picket fences after each layer provides insulation between layers and passage of helium axially. Turn to turn insulation is provided by mylar with adhesive at both the edges of the conductor. Total length of the conductor is 311 meters. This is an air-core magnet with inductance of 30mH. The total weight of the magnet including the bobbin is about 72 kg. The superconducting cable is wound with the pre-stress of 2000 psi (13.79 MPa) and 2 layers of aluminium banding with a tension of 20,000psi (137.9 MPa) to arrest any mechanical movement during magnet energisation. The quench detection circuit is made in-house and used in $1/5^{th}$ magnet testing. It has a provision to change the threshold voltage from 0 to 200 mV and validation time from 0 to 100 ms. DC contactor is used to isolate the power supply from the superconducting magnet coil during quench, so that the current decays through dump resistor. Two voltmeters are connected to monitor the voltages developed across two halves of the magnet. The current decay through the dump resistor is also measured and recorded. Quench detection circuit triggers voltmeters for data acquisition during quench. The quench is initiated by means of a heater placed close to the magnet coil. The heater also helps lowering liquid helium level faster.

A 100 meters long helium gas recovery line is made in-house and is used to recover the boil off helium from the experimental Dewar to the gas bag

Results and Discussions:

Three samples are made from cables selected randomly from three different spools. The critical current is measured for each sample for three different magnetic fields. The critical current is obtained by continuously monitoring the voltage drop across the sample as the current increases. The noise level is about 10nvolt/cm in larger Dewar, which is an order of magnitude lower than the voltage criterion defining the critical current. The V vs I plot of one of the samples under three different magnetic fields is shown in figure 3 for both increasing and decreasing currents. Hysteresis is not observed, indicating the absence of heating or quench during measurement. The quality indices obtained by fitting V-I data to power law ($V\mu I^n$) are more than 40, which indicate the good quality of the superconducting cable without any significant sausaging effect in the filaments. It is observed that the quality index decreases with increase of magnetic field. The critical current density is obtained by taking only NbTi area is shown in Table 1. High critical current density obtained, is related to the number and strength of pinning sites present in the material. The small variation of less than 3% in J_C Vs B, plot for three different samples as shown in figure 4 accounts for either the measurement error and/or small variation in microstructures of material. Ideally all three curves corresponding to different samples should be same. At one instance a sample got quenched and suddenly voltage shot up at 1400 Amp at a background field of 5.5 Tesla. The current was immediately ramped down and sample was observed to have recovered back to superconducting state at around 1000 Amp. It implies the presence of recovery current ~ 1000 Amp, where the cooling exceeds the heat generation. The joint resistance is measured under different magnetic fields to observe the magneto-resistive effect as shown in figure 5. Some non-linearity is observed in lower magnetic fields. Similar observation was reported in reference [4]. Common (Pb-Sn) solder is actually a superconductor having a critical field of 0.3Tesla[2]. So at or near zero magnetic field the solder between the two superconducting wires will also behave like superconductor below a certain current ~200A, which is observed in our measurement. The performance of joint resistance to higher current exhibits no degradation or quenching of sample. So test results indicate that they have acceptably low resistance and carry sufficient current. Table 2 shows joint resistance at 5.5 Tesla for all samples. Residual resistivity ratio of the copper substrate is measured at different magnetic field in the smaller Cryostat and it is shown in figure 6. Low measured value of 120 as against required value of 150 at zero magnetic field is possibly due to cold working on the copper during sample preparation.

The estimated magnetic field of $1/5^{th}$ scale K-500 Superconducting main magnet is about 1 Tesla at 1000 A, which has been energized up to the maximum current of 1476A and kept for 10 minutes without any quench. It shows the magnet is quite stable, without having any training quench even to reach well beyond 800A, operating current of of full scale K-500 magnet. So, the magnet has been quenched forcibly at heater placed close to it and quench occurred only after the liquid helium level partially bared the magnet coil.

Voltage drop across each (+ve and -ve) vapour cooled current lead has been measured by providing the voltage taps at the top and bottom of the leads (which is depicted in figure 7). The measurement is made at different currents with the vent valve closed, so that the boil off helium gas flows only through the current leads. Inductance of the magnet (30mH) has been obtained by measuring the induced voltage across the coil during current ramping. This is close to the calculated value of 26mH. The voltage developed across the top half of the magnet (before the contactor open) is shown in figure 8a for the 800A operating current. Whereas in figure 8b, current decay starts immediately before voltage could develop because threshold voltage was set at very low value. The voltage changes sign suddenly after contactor is opened due to more prominent inductive part. The current decay through the dump resistor is also shown in figure 8a and 8b for 800A and 900A operating currents respectively. It is observed that the current starts flowing through the dump resistor before the dc contactor opens up. It is due to the fact that the dump resistor connected parallel to the magnet has resistance comparable to the magnet coil after quench.

The quench propagation, assuming the temperature rise to be less than 20K, is shown in figure 9. The resistivity of copper remains constant up to about 20K and then slowly rises. It is observed that even after quench bottom temperature shows still some liquid or temperature not more than 5-6K, therefore the assumption of coil temperature not more than 20K is quite reasonable. It is also evident from the linear quench propagation curve in figure 9. The slope of the curve gives the quench propagation velocity. This quench propagation velocity depends upon the current at which the magnet coil has been quenched. The quench propagation velocity (7.3 meter/sec) at 800A is calculated by fitting quench propagation curve. This is close to the theoretical adiabatic quench propagation velocity [3]. Indeed, the magnet behaves adiabatically, when inducing the quench by heater after lowering the liquid level. Quench was provoked by supplying 400 mA for a few minutes through the heater. It shows that the magnet coil is quite stable even when the liquid level goes down. Table 3 shows the energy dissipations inside the liquid helium during quench at two different currents and threshold voltages. It is seen that the threshold voltage for quench detection plays the vital role to determine the energy dissipation inside the liquid helium during the quenching of the magnet coil.

Conclusions:

All the major issues on behaviour of the supercoducting cable, cable joints, superconducting magnet on a 1/5th scale model, and quench detection circuit were resolved satisfactorily by this series of experiments. The superconducting cable joints developed in-house have shown to have very low resistance. Same cable jointing technique has been used for the main superconducting magnet of the K500 Superconducting Cyclotron. The superconducting magnet is in operation since the beginning of 2005.

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References:

1. Bhandari, R.K. "*Status of the Calcutta Superconducting Cyclotron Project*" Cyclotron 98, Caen, June 14-19, 1998
2. Wilson, M.N. "*Superconducting magnet*", pp 314-315.
3. Pradhan, J. et.al "*Stresses in Pre-Stress Superconducting Magnet Coil* " Eighteen National Symposiums on Cryogenics December 2001, at NPL, New Delhi.
4. Iwasa, Y. " *Case Studies in Superconducting Magnets*" p 306, p267

Sample number	Spool number	Critical current @ 5.5T (Obtained)	% deviation from the IGC value	Quality index
1	10	1390 A	-2.6	54.8
2	10	1370 A	-1.18	65
3	7	1380 A	+1.84	61

Table 1: Critical currents for different samples.

Serial no.	Joint resistance (nW)	Comments
1	6.0 ±0.1 @ 5.5Tesla	Lap length 80mm, performed on NPL cryostat upto 100A of current
2	5.4 ±0.1 @ 5.5Tesla	Lap length 100mm, performed on NPL cryostat upto 100A of current
3	5.0 ±0.5 @ 5.5Tesla	Lap length 100mm, performed on SMD20 cryostat upto 800A of current
4	7.0 ±0.2 @ 5.5Tesla	Lap length 100mm, performed on SMD20 cryostat upto 800A of current
5	5.7 ±1.2 @ 1.0Tesla	Special joint without brazing with lap length of 100mm, performed on SMD20 cryostat upto 800A of current at lower field value.

Table 2: Joint resistances of different samples.

Current (A)	Total energy (KJ)	Pre trigger dissipation (KJ)	Post trigger dissipation	Total energy Dissipation (KJ)	LHe boil-off (liters) (KJ)	Vthreshold (mV)	% of energy dumped inside LHe
800	9.6	1.30	3.70	5.00	1.9	416	52
900	12.15	0	4.85	4.85	1.85	50	39

Table 3: Energy dissipation due to quench of 1/5th scale superconducting magnet coil

Inner dia (mm)	Outer dia (mm)	Bore dia (mm)	no. of layers	ss thickness (mm)	current (A)	Field (T)	Pre_stress (psi)	Band_stress (psi)	R_stress (psi)
315	375.7	299	8	8	800	0.8 to -0.55	2000	20000	-3460
315	421.23	299	14	8	800	1.3 to -0.9	500	1000	-532
315	421.23	307	14	4	800	1.3 to -0.9	500	1000	-326
200	421.23	192	28	4	800	2.4 to -1.4	500	1000	-556
150	421.23	142	35	4	800	3 to -1.6	500	1000	-725
100	421.23	92	42	4	800	3.7 to -1.7	500	1000	-1010
100	421.23	92	42	4	1500	6.9 to -3.2	500	1000	-854

Table 4: Parametric calculations for 1/5th scale magnet.

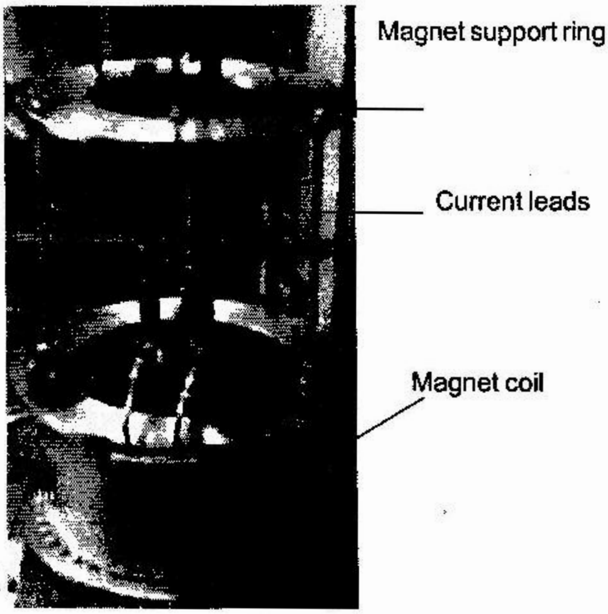


Figure 1: 1/5th scale magnet coil with support

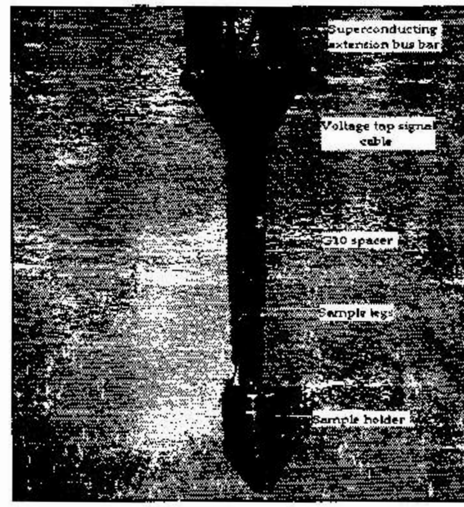
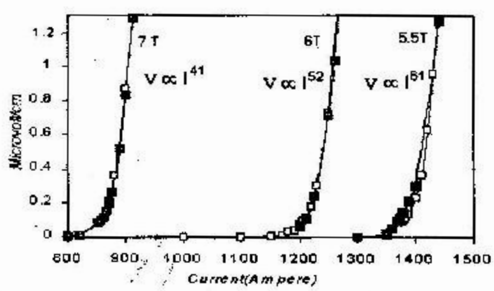


Figure 2: Sample with holder



-: Increasing current, X -: Decreasing current

Fig 3. Sample V-I Plot for three different magnetic fields

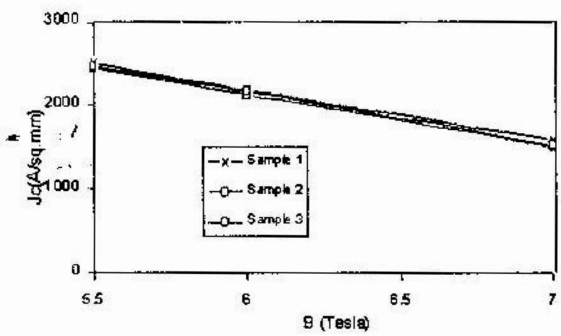


Fig 4. J_c Vs B plot of three different samples

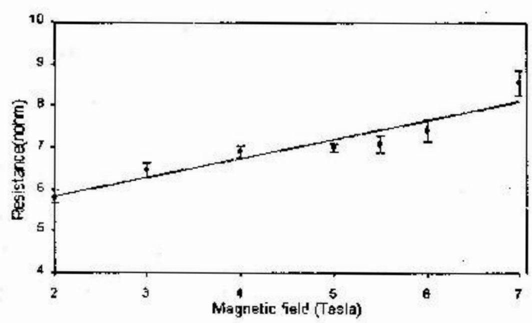


Fig 5. Variation of Joint resistance with applied magnetic field

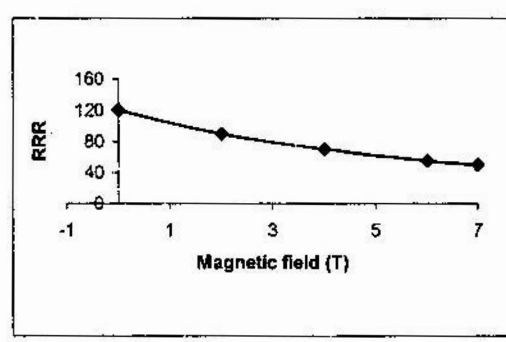


Fig 6: Magneto resistive effect of Copper

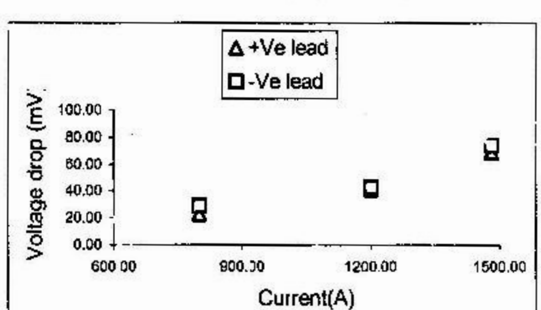


Fig 7: Voltage drop across current leads

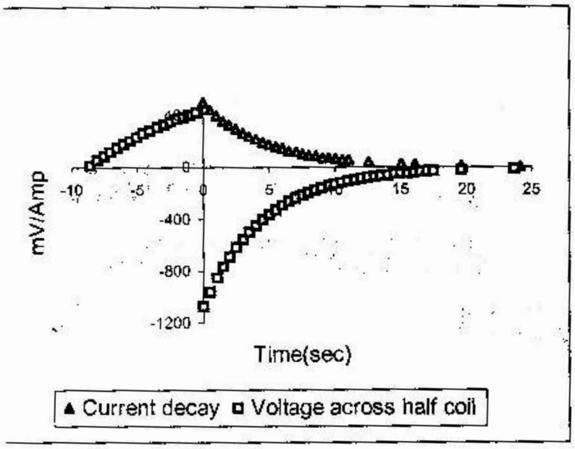


Fig 8a: Quench at 800A

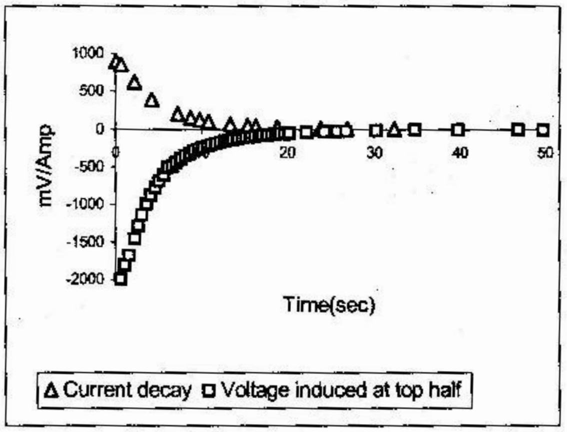


Fig 8b: Quench at 900A

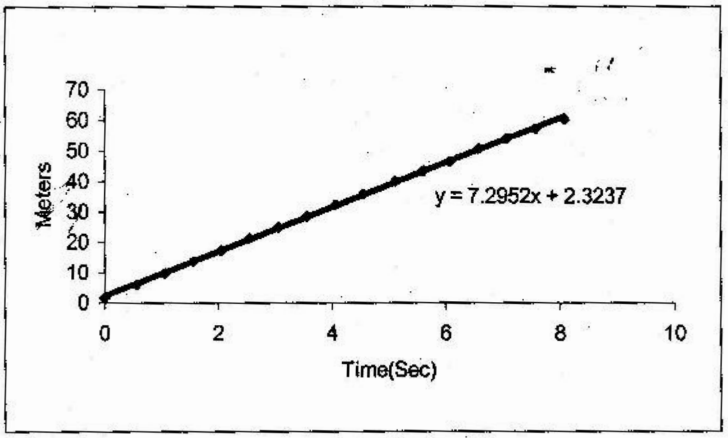


Fig 9: Quench propagation

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