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Validation test of fusion grade superconductors

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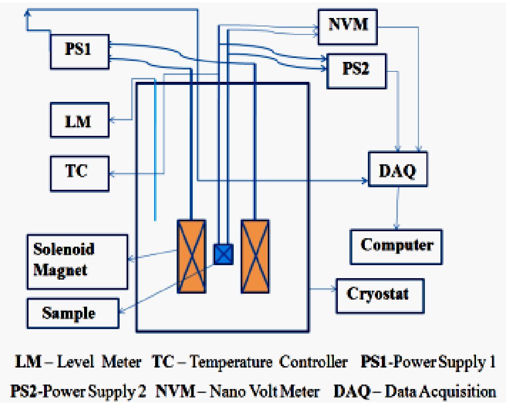
Abstract. The need of high magnetic field for long pulse operation of Tokamaks and future fusion reactors is an essential requirement. The superconducting magnets operating at low temperature, high current and produce high magnetic field for long time can certainly full-fill this requirement. Three types of magnets namely central solenoid, toroidal filed and poloidal filed are used for initiation, confinement and equilibrium of plasma. The presently available basic conductors for these magnets are Nb_3Sn, Nb_3Al, NbTi and MgB_2. The presently operating SST-1 Tokamak has superconducting magnets made up of NbTi as basic conductor. The design and prototype initiative for SST-2 magnets has also begun at IPR. The low temperature and high magnetic field characterization of in-house developed and commercial superconducting strands have also been initiated in the custom made standard test facility at IPR. Encouraging results on testing of Nb_3Sn, NbTi and MgB_2 have been found for suitability of these conductors for magnets and current leads. The basic test set up and test results of fusion grade conductors will be discussed in this presentation.

1. Introduction

The installation and commissioning of critical current(I_C) measurement facility [1] for superconducting (SC) strands with a background field of 12 T at 2.2 K has been completed in MEL lab at IPR. The schematic and real test facility is shown in figure 1.



(a) Schematic of I_C measurement facility

(b) Real Facility

Figure 1. Schematic and real I_C measurement facility

The system includes a high homogeneous superconducting solenoid magnet, Lambda refrigerator, persistent switch, magnet protection circuit, magnet system supports, a low loss magnet housing cryostat, high speed (500 l/s) pumping system and two numbers of 10 V, 200 A power supplies. This facility has been installed for testing of superconductors and fusion grade superconducting strands developed by IPR at high magnetic field and low temperature. The magnet system was cooled up to 4.2 K by liquid helium after ensuring 3.5×10^{-6} mbar of vacuum in outer vacuum chamber (OVC). The temperature of the system was ensured at various stages using Allen Bradley (A/B) resistor thermometers installed on magnet top and lambda refrigerator. The liquid helium level was measured with ILM 200 cryogen level meter. The magnet was charged up to 100 A successfully and current wave form was recorded by cathode ray oscilloscope (CRO). The SC magnet produced magnetic field of 10 T at 100 A. The SC strands samples were prepared and V-I characteristics measured using four probe technique.

The V-I characteristics of SST-1 NbTi strand; MgB_2 strands and Nb_3Sn strands have been studied in this facility and analysed. The principle of V-I measurement, test results of SC strands and analysis of test results have been discussed in different sub-sections of this paper.

2. V-I Measurement Principle

The voltage current characteristics of superconducting (SC) strands have been measure with standard four probe technique as shown in figure 2. Voltage taps, current taps and sample schematic are shown in this figure. The cross-sectional view of MgB_2, NbTi and Nb_3Sn SC strand samples are shown in part A and B of this schematic respectively.

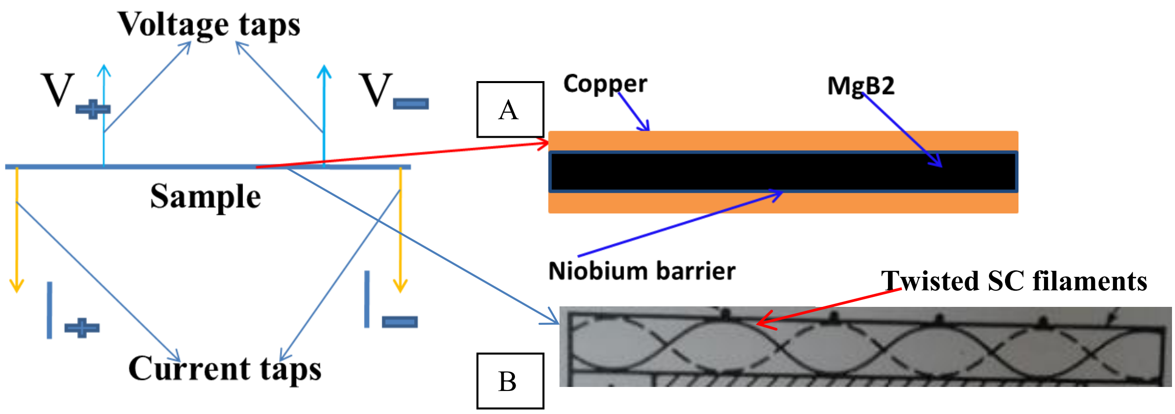


Figure 2. Four probe technique for V-I measurement of SC strands.

3. SST-1 NbTi strand critical current measurement

The SST-1 superconducting NbTi strand [2] sample of length 50 cm was mounted on variable temperature insert (VTI) and current voltage (V-I) characteristics were measured with a dedicated data acquisition system [3] in this test facility. The V-I characteristics were measured with standard four probe technique with voltage measurement criteria of 1 μV/cm .The DC V-I test result of this sample at 2.2 K and 10 T is shown in figure 3. The sample current was measured with direct current transformer (DCCT) and voltage with Keithley™ precision nano voltmeter [4].

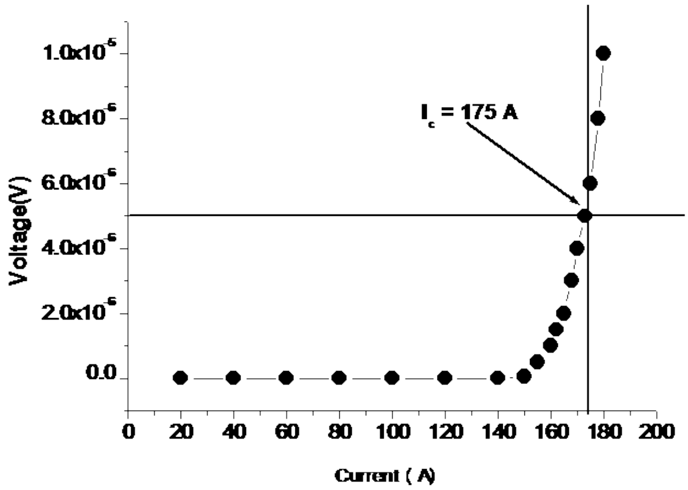


Figure 3. Voltage- Current (V-I) curve of NbTi Strand

4. Analysis of NbTi strand test result

The scaling relation of the critical current(I_C) of a NbTi technical superconductor at magnetic field B and temperature T has been explained by power law [5] and is given by following equation:

$$I_c(T,B) = \frac{C_0}{B} * \left(\frac{B}{B_{C2}}\right)^{\alpha} * \left(1 - \frac{B}{B_{C2}}\right)^{\beta} * \left(1 - \left(\frac{T}{T_{c0}}\right)^{n}\right)^{\gamma} \quad (1)$$

In this equation, C_0 is scaling constant, B_{C2} is upper critical field, T_{C0} is zero field critical temperature, α is low field critical parameter, $\boldsymbol{\beta}$ is high field critical parameter , $\boldsymbol{\gamma}$ is temperature scaling constant and n is constant.

Table 1. Parameters used for calculating I_C

Parameters	Value
C_0	31.4
B	10 T
B_{C2}	14.5 T
T_{C0}	9.5 K
α	0.6
$\boldsymbol{\beta}$	1
$\boldsymbol{\gamma}$	2.3
n	1.7
Reference critical current @ 4.2 K,5T	270 A
Calculated critical current @ 2.2 K, 10 T	174.55 A
Measured Critical current @2.2 K, 10 T	175 A

The critical current measurement criteria of 1 μV/cm has been used for the calculation of I_C of SST-1 strand from V-I curve as shown in figure 3. The sample length was 50 cm, the calculated critical voltage and critical current are 50 μV/cm, 175 A. The I_C at 2.2 K and 10 T of this sample is 175 A as shown in figure 3.The critical current of this sample has also been calculated using magnetic field and temperature dependent I_C relation as described at the beginning of this section. The critical parameters which are used for the calculation of I_C are shown in Table 1. The calculated critical current of SST-1 strand of is 174.55 A.

5. MgB_2 strands critical current measurement

The monofilament wire of MgB_2 strand of diameter 0.83 mm with the core occupying 26% of its cross-sectional area was manufactured using the power-in-tube (PIT) method with an oxide dispersion strengthened Monel sheath. The strands parameters are provided in Table 2. A 10 cm long MgB_2 wire sample was heat treated with a 20 °C/min temperature ramp rate up to 650 °C for an hour flat-top in vacuum environment. This wire sample was then cooled in controlled manner with dry protective argon gas purging. The wire sample of length ~70 mm was used to measure V-I characteristics in the test facility. Heat treatment of 36 filament MgB_2 strand was also carried out in similar way at 650 °C for one hour.

Table 2. Monofilament MgB_2 strand parameters

Parameter	Value
Strand diameter	0.83 mm
Barrier	Nb (22 %)
Mono sheath	Monel
Powder material	MgB_2
Boron source	99B
Mg:B	1.05:2
Monel fraction (%)	52
MgB_2 powder percentage	26

The U-bend sample of 36 filament wire of length ~100 mm was used to measure V-I characteristics. The critical current of monofilament and 36 filament MgB_2 strands have been measured in the range of 4.2 K to 25 K in test facility. The V-I characteristics of monofilament and 36 filament strands are shown in figure 4 and figure 5. The critical currents(I_C) of monofilament strand at self-field at 1 A/s ramp rate are 22 A, 12 A, 10.5 A and 9 A at 22.78 K, 24 K, 24.5 and 25.3 K and of 36 filaments at various ramp rates (top right corner of figure 5) are 286 A, 136 A, 13.6 A at 4.2 K, 15.8 K and 25 K temperature.

Table 3. Multi-filament MgB_2 strand parameters

Strand temperature (K)	Value
Strand diameter	0.84 mm
No. of filaments	36
MgB_2 fraction (%)	15
Monel fraction (%)	35
Nb fraction (%)	31
Cu fraction (%)	19

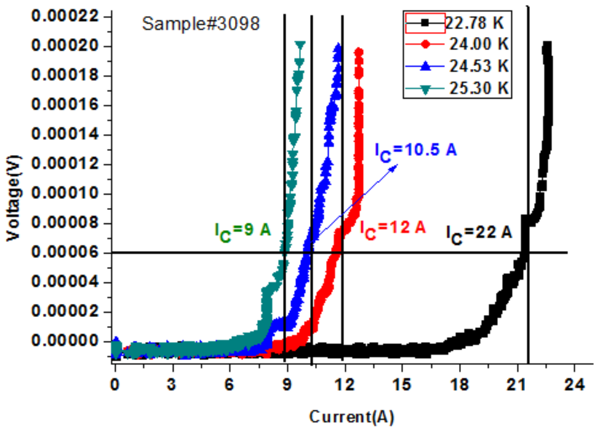


Figure 4. V-I curve of Monofilament MgB_2 strand.

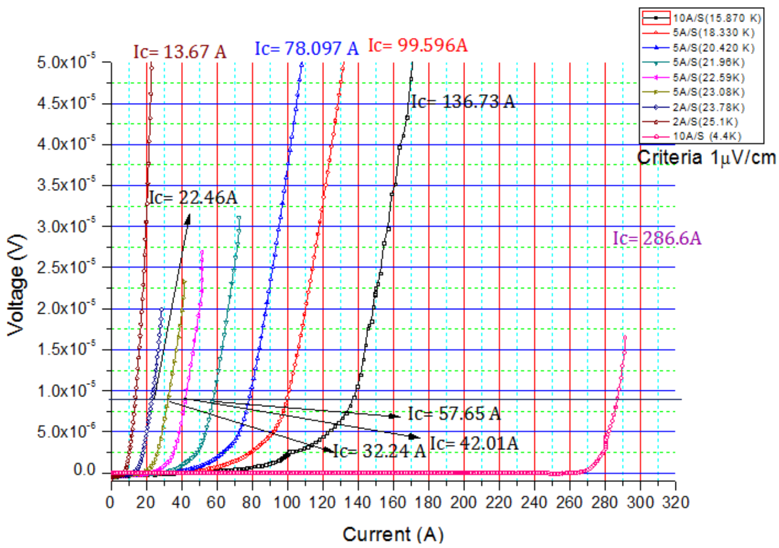


Figure 5. V-I characteristics of 36 filament MgB_2 strand.

6. Analysis of MgB_2 strands test results

V-I characteristics of monofilament MgB_2 strand as shown in figure 4 has been analysed with zero field model [6] and curve shape with Cryo-stability model [7]. The zero applied field model explains the variation of critical current with operating temperature. The Cryo-stability model explains the shape of normalized voltage and current curve of a superconducting strand for various Stekley parameters. The calculated and measured critical current(I_C) using zero field models are shown in figure 6. The resemblance V-I curve shape of this sample with Cryo-stability model for the Stekley parameter of 0.45 is shown in figure 7.

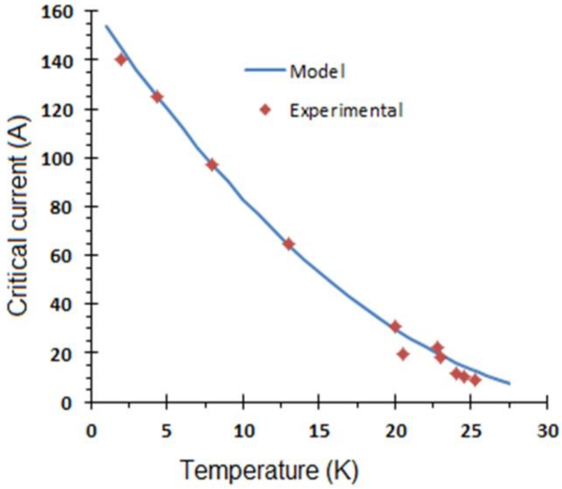


Figure 6. Estimated and experimental Ic -T

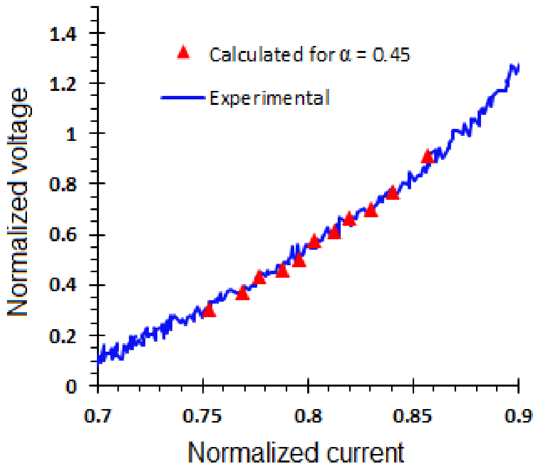


Figure 7. Estimated and experimental V-I curve.

7. Nb_3Sn strands critical current measurement

V-I characteristics of heat treated Nb_3Sn (Luvata) strand has also been measured at 4.2 K at self-field. The diameter of this strand was 0.81 mm and other parameters have been mentioned in Table 4.The length of Nb_3Sn strand was ~500 mm and was wound on TiAlV sample holder. The measured voltage and current curve is shown in figure 8.

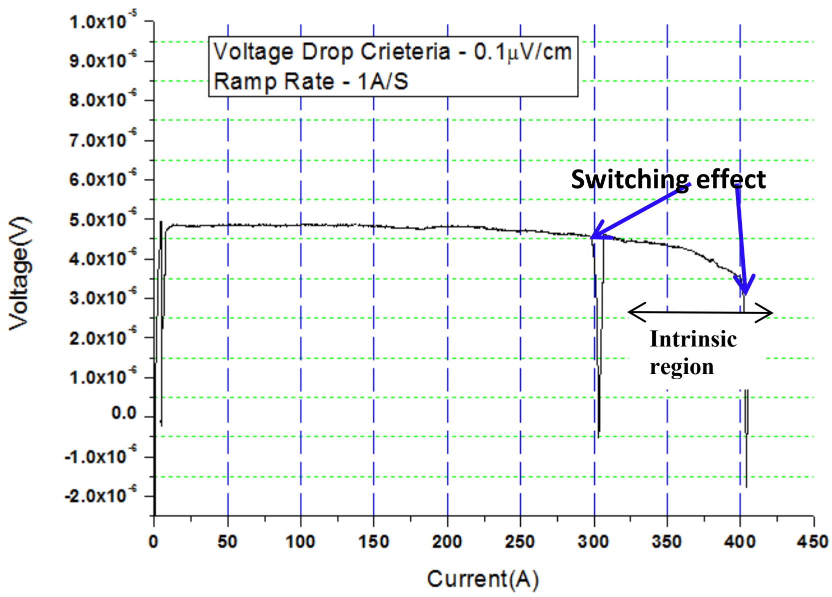


Figure 8. V-I curve of Nb_3Sn strand.

The switching behaviour of voltage has been observed during this measurement and can be seen in this curve. This voltage switching could be due to the poor connection of filaments with stabilizer and non-uniform current injection in the SC filaments. In order to estimate the critical current of this strand with voltage measurement criterion of 0.1μV/cm, positive voltage take-off of 5 μV is required.

Table 4. Parameters of Nb_3Sn Strand

Parameter	Value
Strand diameter	0.81 mm
Cr plating thickness(μm)	2
Filament diameter(μm)	5
No. of filaments	>3000
Filament twist pitch length(mm)	15
Twist direction	Right hand twist
RRR of copper	>100

Even though, the positive voltage takes-off could not be seen for this sample in the range of the operating current of 410 A, from which the exact I_C of this sample could be calculated. The critical current of this strand, could still be predicted from this observed behaviour of the voltage change in the intrinsic region [8]. This negative trend of voltage may continue for some increased amount of current, and then may change its direction towards the positive side of the voltage axis. The predicted critical current of this strand could be greater than 450 A @ 4.2 K, at self-field.

8. Summary and conclusion

The measurements of critical currents of NbTi, MgB_2 and Nb_3Sn strands have been carried out in the test facility at Institute For Plasma Research (IPR), India. The measured critical current of SST-1 NbTi strand at 2.2 K and 10 T is around 175 A. The critical current of SST-1 NbTi strand has also been calculated with empirical formula as described in section 4. The calculated I_C of this sample was 174.55 at 2.2 K @ 10 T. The use of Pinning model and temperature scaling for critical current of NbTi seems to provide a satisfactory match to experimentally measured I_C data. The V-I characteristics of heat treated MgB_2 monofilament and 36 filaments have been measured in temperature range of 4.2 K to 25 K. The critical current of mono filament and multifilament MgB_2 strands at 25 K are 9 A and 13.6 A. The measured critical current of monofilament MgB_2 strand at various temperatures have also been compared with zero field models and found closely matching within the error bar of 5%. The curve shape of voltage-current curve has also been estimated from stability model for Stekley parameter of 0.45 for the mono filament MgB_2 strand. The resemblance of the experimental results of this strand was found between the normalized current of 0.7 to 0.8.The critical current of heat treated Nb_3Sn strand could be greater than 450 A at 4.2 K @ self-field.

9. References

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