High Current Test Facility for Superconductors at Saclay.

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Abstract — A high DC current (100kA-design) test facility for superconducting material is under realisation. Aluminum stabilised conductor (as for LHC detectors) can be tested including the stabiliser in a 4.75T dipole field of 0.8m length which can be rotated in both cable perpendicular directions. A superconductor transformer creates the high current with a primary current from –200A to +200A. The output power useable is 25kJ so that junctions between cables or conductors can be measured at high current.

Samples, with a cross sections up to 12mm × 30mm, were 0.8m long and were equipped with soldered cables of 0.4m length at both ends. To test different samples without warming the dipole magnet, samples are placed in a separate dewar.

The conception design is described and the first results without external dipole magnetic field are reported.

I. INTRODUCTION

Testing whole large superconducting cable is always a difficulty. Measuring only extracted strands mostly solves this difficulty. But for better understanding of cable capability, experiment must be done on the whole cable. Many laboratories use induced currents produced by transformer in the range of 20kA to 100kA [1]. Power supply and current lead are still used until 30kA (LHC Test station at CERN [2]) or exceptionally more (KFK 50kA power supply), but both laboratories have also developed transformers, respectively 40kA [3] and 70kA [4].

A. Specification

We developed a transformer to test the conductors for the LHC detectors (on the basis of a reduced sample section of 30mm×12mm) and to test the joint technique used inside these detectors. High currents (60kA at 4T) are needed for testing these conductors under real conditions. The most economical way to reach this goal is the use of a transformer. We have fixed the maximal current at 100kA during 5 minutes on a total secondary resistance of 5nΩ. We limited the primary power supply to 200A (I_p) corresponding to the available set-up. In order to test several samples quickly and to have a high performance test station, we thought about duration of each operations: cooling and test have to be done in one day, the mounting or dismounting has to be done in one day too.

B. Magnetic Configurations

a) Compact Configuration

The simplest configuration consists of inducing the current in a secondary loop wound with the sample and placed inside a solenoid [5]. This configuration has many disadvantages:
- the joint is placed in the region of the peak field; the quench will start there,
- the maximum field is located on the cable large face,
- the external field and the primary current are coupled.
- sensor space is limited (secondary current measurement).

b) Separated Solutions

In another solution, the transformer is separated from the external field magnet. External field can be created with a solenoid, a dipole or Helmholtz coils:

The first case concerns the solenoid configuration. The sample is wound inside the solenoid with a helical shape form (a solenoid form with one layer) to obtain the field mostly perpendicular to the current [6]. A second helical shape with its flux in the opposite direction can be used to reduce the sample inductance. The disadvantages of this configuration are:
- the magnetic field is not uniform on a long length; current can occur redistribution.
- samples are wound on very small radius.

The second case concerns the dipole configuration. The sample is placed along the dipole axis and the uniform field prevents current redistribution. The sample can be rotated to shift the position of the maximum field and so measure the cable degradation. The main disadvantage is that high torque can be created. Some configurations cancel the torque:
- the external field direction is fixed perpendicular to the plane containing the sample and the return cable,
- the return cable is placed outside the magnet,
- return cables are symmetrical at both side of the sample,
- the torque can be cancelled by a second pair (opposite side) of sample and return cable: this solution is called the hairpin configuration.

The third case concerns the Helmholtz coil configuration. Large solenoids used as Helmholtz coils [7] give the same kind of solution as the dipole magnet configuration, with higher magnetic fields but higher volume too.

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c) Our choice

Helmholtz coils and dipoles are the best solutions: as operating fields in detector magnets are rather low, we chose an existing HERA prototype dipole [8]. To change more quickly the sample, an insert cryostat is used to keep the dipole cooled and we have just to warm up the sample and the transformer. Available place inside the dipole dewar is too limited to choose the hairpin configuration. To cancel the eventual torque, we choose the solution consisting of placing the return cables at both sides of the sample.

II. DESIGN

A. Mechanical analysis

The sample holder dimensions are limited by the dipole. Force and eventual torque must be contained in a cylinder of Ø=67mm. The instrumentation placed inside the sample holder (Fig.1) reduces sample holder mechanical properties. The "U" form with the cover is designed to constrain the internal forces. The 4 groves transfer the torque to 2 impeller keys fixed on the insert cryostat and then to the dipole. The return cables are glued to the sample holder. The external field and current orientation were chosen to push the sample into the bottom of the "U"; screws holding of the cover are not sufficient to maintain sample forces if field and current orientations are neglected.

In order to design the sample holder, all the charging scenario must be listed. The external field can be parallel or perpendicular to the face of the sample and we have two conditions: the normal one with both return cables with the same current and a fault condition where one return cable is quenched.

In normal condition, the parallel field to the large face of the sample is the worst case for the sample holder but it is the less useful one: the maximum field is placed at the middle of the large face. There is no torque and the forces reach 300kN/m. The stress in the sample holder is around 80MPa, that is half of the elastic limit of the aluminum alloy used. We used aluminum alloys because detector conductors are stabilised with aluminum.

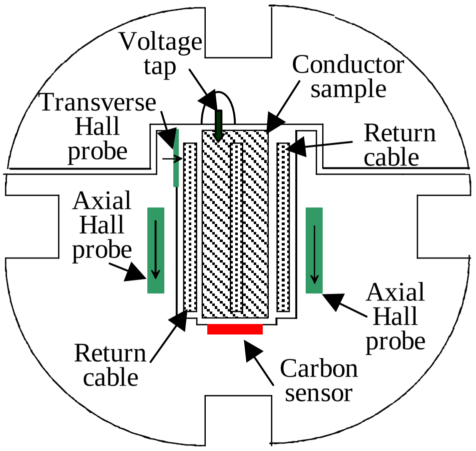

Fig. 1. Cross-section of the sample holder.

In fault scenario condition, the current difference between both return cables is limited to the value of 60kA by time constants. For a field parallel to the sample face, forces are just a little higher than under normal condition. For the perpendicular field orientation, torque occurs and reaches 2000Nm during few seconds.

B. Electrical Conception

A DC transformer should be designed by its active output power; in our case the specification asks for 15kJ plus the energy to reach 100kA. We set the active output power to 25kJ. Optimisation sets the unusable reactive output power (due to secondary inductance) also to 25kJ; so the total transformation energy needed is 50kJ (from I_p = –200A to +200A).

To have a good coupling coefficient (0.95) and to limit the maximum field and stress on superconductors, the secondary coil is located inside the two parts of the primary coil. The transformer dimensions have been optimized to minimise the lengths of the superconducting wire used.

The protection device consists of a dump resistor of 2.5Ω in the primary circuit (<500V). The time constant is ~0.1s or 0.5s if the secondary coil quenches. The secondary coil is not protected directly but the transformer can extract the energy. The maximum temperature reaches 100K. The thermal time constant between the primary and the secondary coil is 5ms. So temperature diffuses between the different circuits. The sole problem concerns the sample. If the sample is not stabilized enough, its temperature can reach more than 350K.

C. Secondary Current Measurement

Different techniques can be used to measure the secondary DC current of the transformer. Table I summarizes these techniques.

TABLE I
CURRENT MEASUREMENT TECHNIQUES

Techniques or methods	Description	Relative Precision
Theoretical	One Hall prob to know the secondary resistance.	10^{-1}
Hall probe	2 Hall probes to compensate the external field.	5.10^{-2}
Pick-up Coils	2 Pick-ups, one to compensate the primary, and an integrator.	10^{-2}
Rogowski coil	Same as pick-up but already calibrated.	10^{-2}
Compensated SC Rogowski coils [9]	A shielding Hall probe measures the zero flux. A complete SC winding performs the integration.	10^{-3}
DCCT	The zero flux is detected by µmetal tore saturation.	10^{-4}
SQUID	The zero flux is measured with flux quantum precision.	10^{-8}

The most precise method (SQUID) appears to be difficult to apply since high current stability and ripple should be in the µA range.

Except for Hall probes, the only absolute measurement is the DCCT (Direct Current Control Transformer); zero current can be measured and a second signal indicating the validity of the measurement. We decided to develop a low cost DCCT (Macc+) in collaboration with Holec (Netherlands).

Two pick-up coils have also been placed to be sure to have measurement at high current because the DCCT could saturate at high field. Pick-up results were calibrated with the DCCT. We also placed 2 Hall probes and 2 flux coils near both return cables to measure the current distribution to evaluate the torque level.

III. REALISATION

A. *Transformer*

The primary coils were wound with two different wires for superconducting volume optimization (NbTi Ø=0.8mm and Ø=0.6mm) and the secondary is made with two cables (ATLAS BT; 38 NbTi strands of Ø=1.3mm: 25×2.3mm^2) soldered together (Fig.2). TABLE II gives the dimensions of the transformer. Measured magnetic inductances are given in TABLE III. The time constant measured at 4.2K is 1500s, that corresponds to a total secondary resistance of 4nΩ.

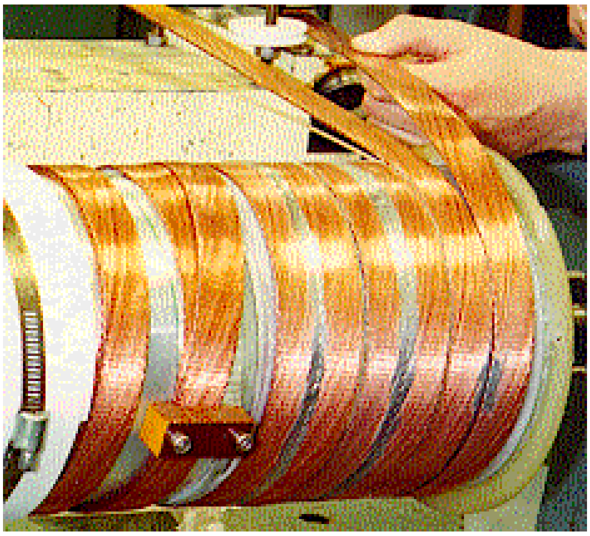

Fig. 2. Winding of the secondary coil. At this stage both cable were cross over to realise a kind of transposition inside the transformer.

TABLE II
GEOMETRICAL DIMENSION OF THE TRANSFORMER

Characteristics	Primary (1st part)	Secondary	Primary (2nd part)
Internal radius (mm)	80.8	87.2	93.1
External radius (mm)	86.2	92.3	99.3
Width (mm)	175	210	175
Number of turns	1 427	6.5	2 143

B. *Instrumentation*

The instrumentation is described in Fig.3. The heater in the secondary circuit is used to cancel the secondary current. Nanovoltmeters measure voltage on 20cm and 30cm.

TABLE III
TRANSFORMER MAGNETIC INDUCTANCE

	L_1 (H)	M (mH)	L_s (µH)
Measured at 300K&50Hz	1.32	2.35	6.2

L_s includes the sample inductance.

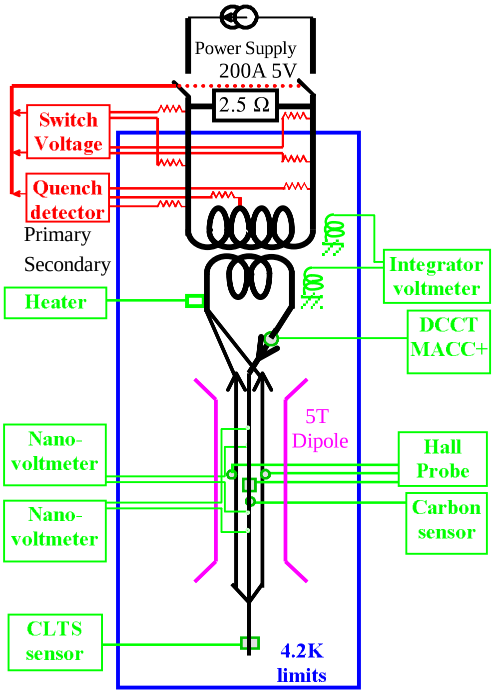

Fig. 3. Electric scheme. The power circuit is drawn in bold. All around in clockwise direction we find: secondary current measurement (pick-up, DCCT, Hall); temperatures (sample for I_c, cooling); nanovoltmeter for I_c; heater to cancel the secondary current; and protection (primary, current leads).

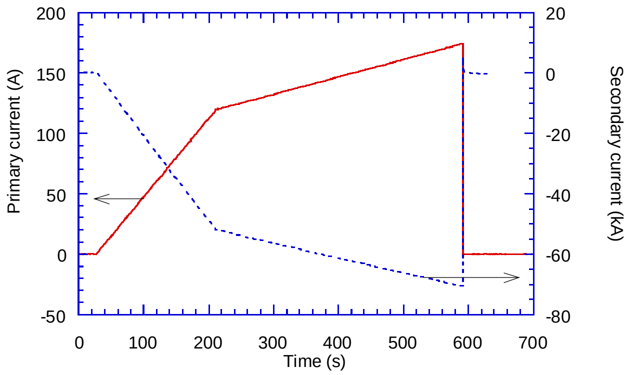

Fig. 4. Variations of currents up to the 70kA secondary quench.

IV. FIRST RESULTS WITHOUT DIPOLE FIELD

A. Critical Currents

With secondary heater powered, we tested the primary critical current. With a single ramp of the primary (0.75A/s) quenches occur at a current of 169A. With 2 ramps of 0.75 and 0.8A/s, we reach the power supply limitation (200A).

Several tests were made to measure the secondary critical current. The maximum current reached is 70kA (Fig.4) but the quenches did not appear in the transformer. The sample critical current is about 80kA at self-field but the soldering at the connections decreases this value.

B. Current Measurement Results

The new shielding torus for the DCCT is working up to 38kA at 4.2K. At this current, the µmetal torus saturated because the secondary conductor getting through is not well enough centered. We deduce that the transformation ratio (from primary current to secondary current) was 460 at 4.2K.

The sensitivity of the pick-up coil with the integrator is 165mV/kA according to the DCCT measurement.

Hall probes give non-symmetrical signals (Fig.5). This effect is more perceptible at low current. Currents are calculated with the hypothesis of uniform current distribution inside the cables and the sample. The position of both return cables symmetrical to the sample nearly cancels the field at the sensor position (Fig.1). Dissymmetry of currents is smaller than field measurements one.

With the 2 flux coils placed also on both return cables, we can not see any difference between both currents (Fig.6). Each flux coil signals are similar to the total current I_S.

The explanation of the non-symmetrical signals on the Hall probes is the non-uniform current distribution inside the sample. The sum of both Hall signals is in agreement with pick-up integrated signal. During the ramp, current distribution is quite uniform because strand inductances are equal. During the step, current distribution changes with a time constant of 100s, so as to minimise the joint resistances that are not perfect as the high resistance value suggest. The solder length is 1.7 time the transposition pitch. Current distribution in the sample will become uniform near the critical current [2].

CONCLUSION

We have tested the transformer without external magnetic field and we reached 70kA corresponding to the sample limitation. A DCCT measured the secondary current at 4.2K up to 38kA with a precision of 10^{-4}.

The dipole and its instrumentation have been mounted and tested. Tests will continue and the integration with the dipole will be realised soon.

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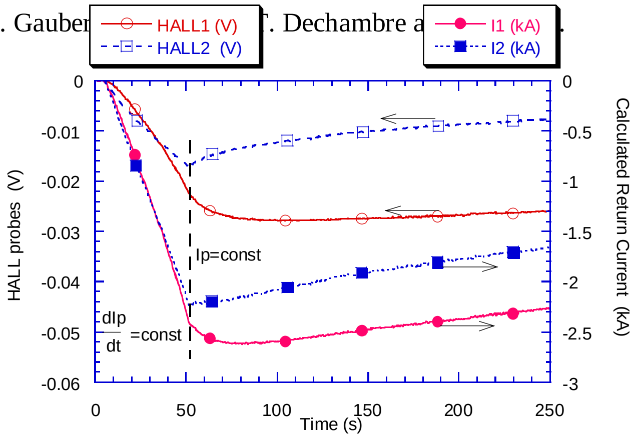

Fig. 5. Hall probe signals.

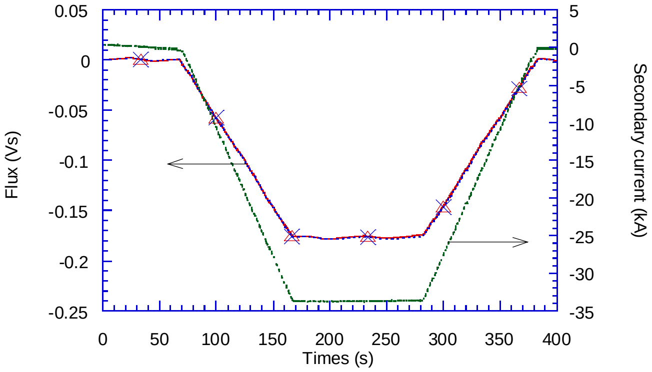

Fig. 6. Return cables flux coils and total current.

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