# A LOSS MEASUREMENT SYSTEM IN A TEST FACILITY FOR HIGH-CURRENT SUPERCONDUCTING CABLES AND WIRES

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## Abstract

The realisation of a 7 tesla/25 kA test facility for measuring the critical current density and the quench propagation velocity of high-current superconductors has already been reported [1]. The test volume in this set-up is torus-shaped having a diameter of 0.2 m and a cross-section of 5 $cm^2$. The test facility has been equipped with a set of AC coils and pick-up coils in order to perform AC loss measurements. A system of helium gas channels has been included to determine the helium boil-off for calibration and verification purposes. The amplitude of the AC magnetic field is limited to about 0.5 T at 10 Hz. A transport current of up to 25 kA, AC or DC, can be fed to the test conductor by means of a transformer. The facility provides means to perform loss measurements on large conductors at a relatively low cost. In order to test the AC loss measurement system a superconductor manufactured by Vacuumschmelze has been investigated. This NbTi superconductor for TORE SUPRA is a monolith with a mixed matrix, a cross-section of 5.6 × 2.8 $mm^2$ and contains 10164 filaments. The characteristics of the AC loss measurement system as well as preliminary results of the loss measurements on the Vacuumschmelze conductor are reported here.

## Introduction

Over the past few years we have developed in Twente a high-current test facility in which superconductors can be tested up to 7 tesla and 25 kA [1,2]. This facility meets the demand for test equipment in which heavy-duty conductors, such as cables and monoliths, can be tested at high currents and medium background fields at relatively low cost. The samples can be prepared and cooled down in a short length of time compared to large test facilities like SULTAN. The facility used to only accommodate critical current and propagation measurements. These features have now been extended with an AC loss measurement system. In this paper the characteristics of the AC loss measurement system are described. The first results of the loss measurements in the facility on the Vacuumschmelze conductor for TORE SUPRA are also reported.

## Description of the test facility

### The magnet system

The specifications of the DC magnet system have already been reported [1,2]. The AC magnet system consists of an inner and an outer coil, carrying a transport current in opposite directions. Both coils are of the notch type in order to improve the homogeneity of the magnetic field in the test volume. In addition to this, an extra coil is placed in series with the inner and outer AC coil. This extra coil is dimensioned in such a way that the coupling between the DC coil and the AC coil system is minimized. The stray-field in the test volume due to this extra coil does not seriously affect the homogeneity of the applied magnetic field. Fig. 1 shows an overall picture of the magnet system (a) and a more detailed cross-section of the AC coils, the detection coils and the test volume (b). Parts of the DC coils in between which the AC loss measurement system is located are also sketched.

### The loss measurements

The losses in the samples can be obtained using two standard techniques. The first technique, the calorimetric one, determines the helium evaporation due to the heating in the test sample. Therefore the boil-off system of the test volume is separated from that of the cryostat. The second technique, the electrical one, uses voltage taps to measure the voltage drop across the sample and pick-up coils to determine the magnetization of the sample. For this purpose a set of inner and outer pick-up and compensation coils is installed. Using the electrical method, a distinction can be made between the magnetization losses and the transport current losses, which is not possible with the calorimetric method.

When using pick-up coils for determining the losses in a superconductor, the most convenient set-up is the one in which the conditions in the test volume are invariant in the direction of the axis of the coils. In such a set-up the losses can be easily calculated from the voltages arising from the pick-up coils. In this facility however it was not possible to construct such a coil system. Therefore a shape factor, which differs for each sample, has to be determined when using the electrical method. This shape factor can be obtained by calorimetric measurements or by numerical calculations of the magnetization field. Calculations have shown that this factor is almost independent (within a few percent) of the location of the magnetization currents. This justifies the use of such a shape factor.

## Specifications of the facility

### The cooling-down procedure and the helium consumption

The test facility is pre-cooled by liquid nitrogen by means of a heat exchanger. Cooling down from room temperature to 80 K takes about 12 hours. A further 5 hours and 80-100 litres of liquid helium are required to lower the temperature to 4.2 K. Once the test facility has reached this temperature the steady state evaporation is only about 1.2 litres per hour.

### Replacing the sample

From testing conditions (cryostat filled with helium) to the preparation phase (room temperature) takes about one day. Three more days are required to prepare a new test conductor in the sample holder. Therefore the length of time between testing two

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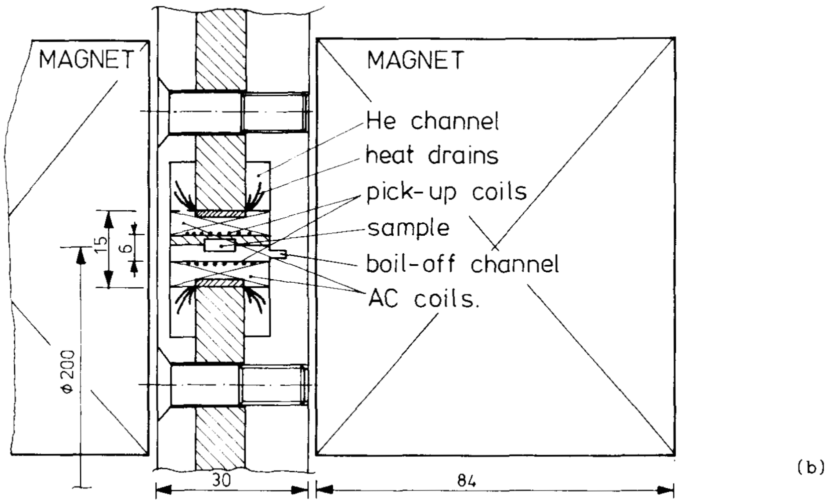

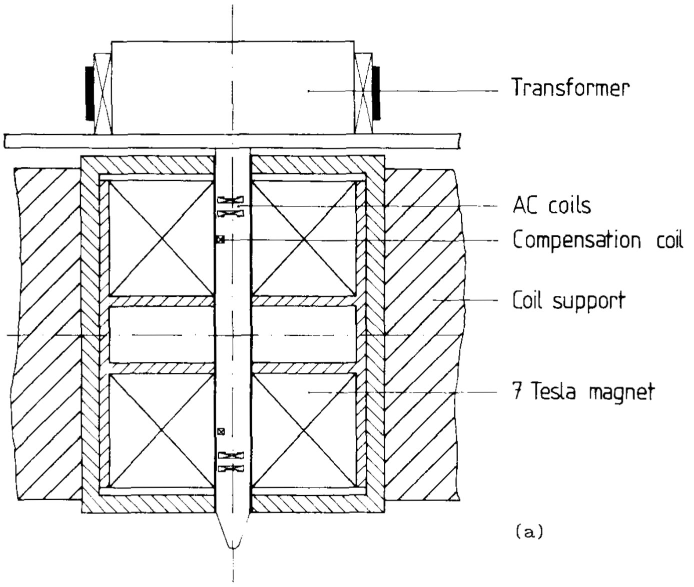

Fig. 1. (a) Overall picture of the magnet system.
(b) Detailed cross-section of the AC loss measurement system, including AC coils, detection coils and sample holder.

conductors is not more than four to five days. This is quite acceptable for test facilities of this size. The high repetition rate in testing samples means running costs are kept low, which was one of the objectives at the development this facility.

## Feasible test conditions

The conditions to which the samples can be subjected are listed in table 1. The DC coils generate a magnetic quadrupole field. The background field points in radial direction at the location of the test conductor. The AC magnetic field is therefore perpendicular to the main field. This however, has little or no effect on the loss behaviour if the main field is large compared to the AC magnetic field. The limitations of the amplitude of the AC magnetic field are determined by the restraints of the available power supply (AMCRON M-600).

The transport current is fed into the test conductor by means of a transformer. In order to maintain a DC transport current one has to compensate for the losses in the joints and in the sample by a small current increase in the primary winding of the transformer. The resistance of the joints however, is very low ($R_{joints} \leq 10^{-9}$ Ω) which results in a time constant $\tau \geq 10^{3}$ s. A superconducting switch is included in the secondary circuit. Using this switch the DC transport current range can be extended to almost twice the value of the maximum amplitude of an AC transport current. In the low frequency range the transport current through the test conductor is measured with a superconducting direct current meter [3]. For higher frequencies a Rogowski coil is used.

**Table 1. Test conditions**

| | |
|---|---|
| Maximum background field | 7.0 T |
| Homogeneity of the background field | < 1 % |
| Maximum amplitude of the AC magnetic field for $f \leq 10$ Hz | 0.5 T |
| Homogeneity of the AC magnetic field | < 4 % |
| Maximum transport current (AC or DC) | 25 kA |
| Test volume for loss measurements: | |
| -radius | 0.1 m |
| -cross-section | 10x5 $mm^2$ |

Table 2. Specifications of the TORE SUPRA conductor

| | |
|---|---|
| Manufacturer | Vacuumschmelze |
| Type of the conductor | Monolith |
| Dimensions of the conductor | $2.8 \times 5.6$ mm$^2$ |
| Insulation | None |
| Superconductor | NbTi |
| Matrix material | Cu with CuNi barriers |
| Cu : CuNi : NbTi | 2.20 : 0.33 : 1 |
| Number of filaments | 10164 |
| Filament diameter | 23.5 $\mu$m |
| Twist pitch | 40 mm |
| $B_0$ in the Kim-relation [2] | 0.6 T |
| $J_{c0}$ in the Kim-relation [2] | $1.2\ 10^{10}$ A/m$^2$ |

## Influence of the environment on the loss measurements

Due to the compact construction a heat flow from the environment into the test volume cannot be fully excluded. In order to reduce this heat leakage the test volume is thermally insulated with a Kapton foil.

The pick-up coils also register signals arising from the environment. Magnetization currents in the superconducting coils and in the metal construction parts cause stray-fields which are not cancelled out completely by the compensation coils. This effect is enhanced by the lack of invariance of the set-up in the direction of the axis of the coils.

The behaviour of the loss measurement system was studied under the condition that no sample was present. From these measurements we obtained the dissipation to correct for in the calorimetric measurements and the sensitivity of the electrical method.

## Specifications of the TORE SUPRA conductor

The conductor tested is a monolith designed for TORE SUPRA which was manufactured by Vacuumschmelze. Its specifications are listed in table 2.

## Theoretical considerations

The conductor used in the experiments is a rectangular one. Only a few authors have considered non-round shaped conductors. The difference in shape of a conductor mainly affects the coupling losses. Campbell [4] derived some expressions for the coupling losses in multifilamentary superconductors of various shapes. Adjusting the expression for the rectangular conductor for harmonic functions $B_a(t)$ yields:

$$Q_c = \frac{\pi \hat{B}_a^2\, a\, b}{\mu_0} \, \frac{\omega\tau}{1 + \omega^2\tau^2}, \qquad [\mathrm{J/m}] \quad (1)$$

with:

$$\tau = \frac{\mu_0\, L_p^2\, a^2}{16\, \rho_\perp\, b^2} \qquad [\mathrm{s}] \quad (2)$$

where $L_p$ is the twist pitch, $\hat{B}_a$ is the amplitude and $\omega$ is the angular frequency of the applied magnetic field, $\rho_\perp$ is the effective transverse resistivity and $\tau$ is the time constant of the coupling currents. The direction of the magnetic field is parallel to b.

The effective transverse resistivity depends on the resistivity of the matrix material, the volume ratio of matrix material to superconducting material and on a possible resistive barrier between the matrix and the superconducting filaments. Carr [5] considered two situations: firstly the one in which there is no such resistive barrier, and secondly the one in which there is an insulating layer between the matrix and the filaments. In the case of no resistive barrier present the effective transverse resistivity is given by:

$$\rho_\perp = \rho_{matrix} \frac{1-\lambda}{1+\lambda}. \qquad [\Omega\mathrm{m}] \quad (3)$$

The effect of insulating layers between the matrix and the filaments on the effective transverse resistivity is described by:

$$\rho_\perp = \rho_{matrix} \frac{1+\lambda}{1-\lambda}, \qquad [\Omega\mathrm{m}] \quad (4)$$

where $\lambda$ is the ratio of superconductor to total volume.

The hysteresis losses in the filaments in the case the amplitude of the applied magnetic field exceeds the penetration field $B_p$ of the filaments is given by Pang et al. [6]:

$$Q_h = \frac{2\, N\, \pi\, d_{fil}^2}{3\, \mu_0}\, \hat{B}_a\, B_p, \qquad [\mathrm{J/m}] \quad (5)$$

with

$$B_p = \frac{\mu_0\, J_c . d_{fil}}{\pi} \qquad [\mathrm{T}] \quad (6)$$

where $d_{fil}$ is the filament diameter, $J_c$ the critical current density and N the number of filaments.

## Experimental results

The losses in the conductor under various conditions were measured. Some of the results of the measurements when the conductor was exposed only to a magnetic field (no transport current) are shown in Fig. 2. The applied magnetic field was a sinusoidal AC magnetic field superimposed on a background field. The magnetization losses are plotted against the frequency for different values of the amplitude of the AC magnetic field at a background field of 5 tesla. The losses were obtained using the calorimetric method.

A maximum in the losses per cycle per unit length occurs at a frequency of the applied magnetic field of approximately 15 Hz. Beyond this frequency $f_0$

the losses per cycle decrease due to shielding of the interior of the wire by coupling currents. Using Eq. 2 the effective transverse resistivity of the conductor can be obtained. The effective transverse resistivity of this conductor at a background field of 5 tesla was calculated to be $3.0 \cdot 10^{-9}$ Ωm. Taking into account the more or less insulating sheath of CuNi around the filaments (Eq. 4) and the magneto-resistive behaviour of copper, the calculated value of the effective transverse resistivity fits the measured one fairly well. The measured losses are in agreement with the calculated ones, using Eq. 1 and 5.

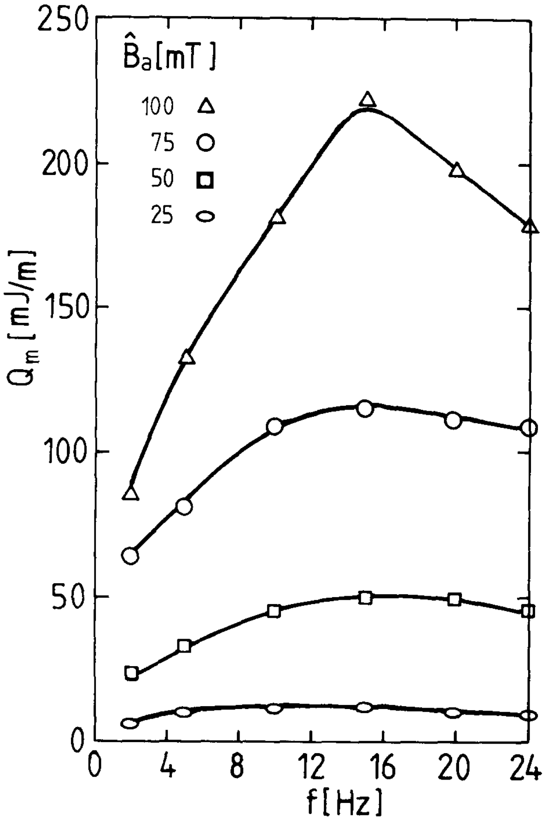

Fig. 2. Magnetization losses as a function of the frequency for various amplitudes of the magnetic field. ( $B_{dc}$ = 5 T, $I_{trans}$ = 0 A ).

## Present status

The measurements on the Vacuumschmelze conductor for TORE SUPRA are still in progress. The tests of the conductor carrying a transport current (AC or DC) are currently carried out. The next step in the development of the facility will be the investigation and evaluation of the electrical method. This evaluation may lead to further improvement of the test facility.

## Conclusions

The AC loss measurement system in the Twente test facility has become operational. Preliminary results of the first loss measurements on a Vacuumschmelze conductor have been presented in this paper. The first tests of the facility have been completed successfully. Loss measurements involving transport currents are still being performed at the time of publication. Research and evaluation of this system for further development and improvement is still going on.

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