AC Losses Measurement of the DISCORAP Model Dipole Magnet for the SIS300 Synchrotron at FAIR

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Abstract—Considerable attention has been paid in the last years to the development of fast-cycled superconducting magnets for future accelerators, leading to the design and construction by INFN and GSI of a 3.8-m-long prototype of a 4.5 T, 1 T/s, dipole magnet, for the SIS300 synchrotron of the FAIR facility (Darmstadt, Germany). This ramp-rate is 20-100 times higher than the one used in other superconducting synchrotrons like RHIC or LHC. Being operated at rather large dI/dt, these magnets are subjected to a wide spectrum of ac dissipation, taking place in the superconductor as well as in the metallic components of the mechanical structure, requiring the development of specialized superconducting cables and a careful consideration of the other aspects of the structural design. Between July and September 2012, the dipole magnet prototype has been subjected to a test at LASA laboratory (INFN Milan, Italy), during which it was successfully operated at current ramp rates as high as 0.7 T/s (the power supply limit). In this paper, we describe the V-I apparatus used to assess the dissipations within the magnet during the ac regime, the measurement results, and their comparison with the values expected from the design and on the basis of superconducting cable qualification results.

Index Terms—AC losses, inter-filament coupling, magnetic hysteresis, measurement techniques, superconducting magnet, transverse resistivity.

I. INTRODUCTION

FAST-CYCLED superconducting dipole model for the SIS-300 synchrotron for the new FAIR facility at GSI (Darmstadt, Germany) has been developed, built and tested within the scopes of the INFN NTA_DISCORAP project [1]–[3]. This magnet is designed to operate up to 1 T/s between 1.5 T and 4.5 T.

Manuscript received July 17, 2013; accepted August 28, 2013. Date of publication September 5, 2013; date of current version September 27, 2013. This work was supported in part by INFN and GSI, and in part by the UE through EU-FP7 funded project CRISP ("Cluster of Research Infrastructures for Synergies in Physics") Grant Agreement 283745, WP5 (Accelerators: Fast ramped superconducting magnets).

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Digital Object Identifier 10.1109/TASC.2013.2280733

The construction of the magnet has called for a relevant upgrade of the technology of superconducting Rutherford cables, which incorporates smaller filaments, shorter twist pitch and technical solutions like higher resistivity interfilamentary matrix and a high resistance metallic core, in order to reduce power dissipation in the pulsed regime. Special care was also taken to mitigate the contributions to the dissipations from eddy currents in the metallic components of the cold mass and from the iron yoke hysteresis. During the preliminary test, performed at LASA lab in July–September 2012 the magnet has been operated in cycling conditions up to 0.7 T/s [4], the largest value allowed by the power converter at disposal.

Here we report the losses measured by means of a V-I method. In Section II we revise, on the basis of the electrical properties measured on the superconducting cable, the loss estimate performed during the design; Section III is devoted to the presentation of the experimental apparatus while the analysis of the results is performed in Section IV.

II. REVIEW OF THE LOSS SOURCES

A. Loss Estimate

The expected losses in the magnet during AC operation were thoroughly estimated in [1], [5], [6], where the contributions coming from the conductor (hysteresis, filament coupling and strand coupling), from eddy currents in the metallic components (yoke, collars, locking pins and keys, stainless steel coil protection sheet, beam tube) and from iron yoke hysteresis, were taken into account. The loss value is expressed as the instantaneous power at 1 T/s, for three different values of the magnet central field (1.5 T, 3.0 T, and 4.5 T), and therefore it is larger than zero during the ramp periods only. Both a 2D and a 3D analysis have been performed for all the contributions.

Since the Rutherford cable used for the magnet construction [7] has electrical characteristics which differ significantly from the design values (see Table I), we have modified the expected loss contribution from filament hysteresis and filament transverse coupling accordingly. Filament hysteresis loss scales with I_c and d, filament transverse coupling loss scales as ρ_t^{-1} and l_p^2 . The updated results are shown in Table II: the total values (Grand Total) are 4% to 5% higher than the values foreseen during the magnet design. This rather limited change is the result of a partial compensation between a reduction in hysteretic loss due to smaller filaments, and an increase in the coupling loss between filaments, related to the larger wire twist pitch and lower transverse resistivity.

TABLE I TARGET AND ACTUAL VALUES OF SOME ELECTRICAL CHARACTERISTICS OF SUPERCONDUCTING CABLE, RELEVANT FOR THE AC LOSS COMPUTATIONS

Quantity	Symbol		Target Value	Actual Value
Filament effective diameter	d	[µm]	3.5	3.0
Transverse resistivity @ 0 T	ρ_t	$[n\Omega m]$	0.4	0.3
Wire twist pitch	l_{D}	[mm]	5.0	6.6
Critical current	\dot{I}_c	[A]	18,540	15,912

TABLE II Computed Values of Loss at Different Field, for a 1 T/s Field Ramp Rate

Loss sources [W]	1.5 T	3.0 T	4.5 T
conductor hysteresis	9.3	6.5	4.8
yoke hysteresis	7.5	7.5	7.5
Total of hysteretic losses, A	16.9	14.0	12.3
conductor: filament coupling	9.1	6.7	5.2
conductor: wire coupling	1.6	1.6	1.6
yoke & pins and keys eddy current	0.9	4.7	2.8
collar & pins and keys eddy current	3.0	3.5	2.5
coil protection sheet & beam tube	6.2	6.2	6.2
Total of eddy current losses, B	20.7	22.7	18.4
Grand Total, A+B	37.6	36.7	30.8

III. EXPERIMENTAL SETUP AND DATA ANALYSIS METHODOLOGY

A. Data Acquisition Hardware

The current flowing through the magnet is measured by a DCCT mod. 15000 SH by HOLEC, whose output is read by a Agilent Voltmeter model 34410. A second model 34410, voltmeter reads the difference of potential across the magnet, taken at the magnet current exits. The readings of the two instruments are synchronized by means of an external clock. The voltmeter integration period, Δt [s], is set at the same value in both instruments; we have performed measurements at 1, 0.2 and 0.02 NPLC's (Number of Power Line Cycles). The choice of the integration time is dictated by the accuracy required to record fast changing current/voltage transients which appeared due to the characteristics of the power supply (see Section III-B).

The clock frequency is set to $1/\Delta t$; in this way the acquisition has no dead time. Special care was taken to verify that the voltmeters perform correctly in this condition.

The measured data are first stored into the voltmeter internal memory, whose capacity is 50,000 readings, equivalent to 1000 s, 200 s, 20 s at 1, 0.2 and 0.02 NPLC's respectively; at the end of a run they are download to a PC through GPIB for subsequent analysis.

B. The Powering Scheme

The current through the magnet is provided by three $10 \text{ kA} \times 6 \text{ V}$ power converters, operated in series [8]. The maximum voltage, 18 V, corresponds to about a 0.7 T/s field ramp rate, keeping into account the parasitic voltage drop along the current leads and the bus-bars. Since these current supplies can only source, but not sink, current, the decreasing branch of the cur-



Fig. 1. Measured current during a test run where the magnet was operated between 3 and 6 kA at a nominal ramp rate of 1 kA/s (${\sim}0.5$ T/s).

rent cycle is achieved by means of a solid-state discharge unit, composed by a series of 24 high current diodes put in parallel with a suitable number of MOSFET's. When the MOSFET's are in the ON state, they behave as a closed switch, carrying all the current with limited voltage drop. When they are opened, the current is diverted through the diodes, whose total forward voltage drop provides approximately -16 V, adsorbing the energy stored in the magnet and allowing about -0.6 T/s.

This system has been implemented to overcome budget limitations which did not allow a two-quadrant power converter. Although it has operated within its design parameters, certain limitations could not be overcome. In particular, the opening and closing of the MOSFET bank in coincidence with the beginning and end of the current ramps, lead to a momentary unbalance of the power converter control feedback, creating current oscillations and overshoots (see Fig. 1).

Despite our considerable concern for their impact on the magnet operation, we discovered that these current oscillations did not affect the magnet stability in pulsed regime. We also feared that they could have spoiled or seriously curtailed the accuracy of the V-I measurements. To mitigate the impact, we performed several loss measurements with short integration times, with the goal to increase the number of experimental points per time lapse so as to record also the subtler details of the V-I curves. The increased time resolution was in competition with the larger noise due to a poorer rejection of the mains AC residual, and to a higher instrumental noise. Comparing the results of measurements performed during identical current cycles but with different integration times, we came to the conclusion that the 1 NPLC integration time allows the best results in terms of experimental accuracy. This may be noticed in Fig. 5 (Section IV), which shows both experimental points at 1 NPLC and at 0.2 NPLC's.

C. Loss Determination

The total work Q performed by the power supply on the magnet from time t_0 and time t_1 is given by:

$$Q(t_1, t_0) = \int_{t_0}^{t_1} V \cdot I dt \approx \Delta t \sum_{j=1}^n V_j \cdot I_j, \qquad [\mathbf{J}] \qquad (1)$$



Fig. 2. Work performed on the magnet by the power supply, as a function of current, for the current cycle shown in Fig. 1. A quadratic expression (shown in red) has been fitted to the data. The curve has an offset with respect to zero, since the integration [Eq. (1)] begins at an arbitrary instant of the current cycle.



Fig. 3. Work performed on the magnet by the power supply, Q, minus the reversible component $k_1 + k_2 I^2$ (see text), as a function of the magnet current, for the run shown in Fig. 1.

where Δt is the integration time [s], and the summation is extended to all the n V, I measurements performed between t_0 and t_1 [9]. The difference $Q(t + \Delta T) - Q(t)$ gives the energy dissipated in a cycle, where ΔT [s] is the current cycle duration. An example of the experimental values of Q as a function of the current is visible in Fig. 2. The seven current cycles overlap and cannot be distinguished.

At a first approximation, the net stored energy is proportional to I^2 ; in a real situation, iron saturation introduces a dependence of the magnet inductance on the current, and the dissipative effects introduce a hysteresis. To appreciate this, first we fit the experimental data with an expression $k_1 + k_2 I^2$, where k_1 and k_2 are free parameters, which represent an arbitrary constant and the average induction value, respectively. The fitted curve is superimposed to the experimental points in Fig. 2.

The fitted expression is then subtracted from the experimental points, and the resulting values, ΔQ [J], are shown in Fig. 3: in an ideal situation the value of ΔQ would be zero at any time, here the complex structures which appear are related to the magnetization and dissipative effects in the magnet. An analysis of the magnet inductance and of the magnetization will



Fig. 4. Current time derivative of the current profile shown in Fig. 1. The horizontal red lines represent the nominal ramp rate $(0, \pm 1 \text{ kA/s})$.

be presented in a further paper. The time sequence is given by the colors (from red to blue).

The energy dissipated during a full cycle, ΔE [J], is given by the difference of ΔQ between the end and the beginning of the current cycle. From an operational point of view, ΔE is determined with the following procedure. We take the mean of the maximum and minimum current value in cycle, $\langle I \rangle$, then we make the average of ΔQ on a small interval of current around $\langle I \rangle$, for each current cycle. The averages are shown in Fig. 3 as blue (red) circles for the increasing (decreasing) branch of the current ramp. The difference between any two consecutive averages (either on the increasing or decreasing branch) provides an independent measurement of ΔE ; since we have normally more cycles during a run (in the example shown we have seven), the mean $\langle \Delta E \rangle$ of all the ΔE and the corresponding mean r.m.s. are taken as the best estimate for the energy loss per cycle, and its corresponding error. Since the loss have been estimated (Section II) in terms of power during the ramp, we divide the experimental average loss per cycle, $\langle \Delta E \rangle$, by the nominal total (i.e. the sum of the increasing and decreasing branches) ramp duration, $\Delta \tau$ [s], to get the average ramp loss.

D. The Equivalent Ramp Rate

One of the most relevant source of uncertainty comes from the instantaneous ramp rate $I' \equiv dI/dt$ [A/s] during the current cycles, which are quite different from the ideal $0, I'_n, 0, -I'_n, \ldots$ sequence, where I'_n [A/s] is the nominal current ramp rate. In reality I' is different from zero at almost any time (Fig. 4), and its absolute value often exceeds, sometimes largely, I'_n . Therefore, we expect that the losses measured are systematically higher than the value which would be observed with an ideal current cycle.

To quantify this effect, we introduce an equivalent current ramp rate, I'_e , defined as follows. We assume first that the power dissipation q depends on I' as:

$$q(I') = q_0 \cdot |I'| + q_1 \cdot I'^2; \qquad [W]$$
(2)

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Fig. 5. Measured losses in tests at 400 A/s nominal current ramp rate. The current interval is shown above the experimental points. Circles represent measurements performed with a 1 NPLC integration time, squares measurements with 0.2 NPLC integration time. Measurements performed with smaller integration time have larger noise.

the total energy dissipated along a cycle, U, is then given by:

$$\Delta U = \int_{0}^{\Delta T} q_0 \cdot |I'| + q_1 \cdot I'^2 dt = q_0 \cdot \int_{0}^{\Delta T} |I'| dt + q_1 \cdot \int_{0}^{\Delta T} I'^2 dt \quad [\mathbf{J}].$$
(3)

The integrals are computed numerically from the experimental data. The equivalent ramp rate I'_e may be found solving the quadratic equation:

$$\Delta U = \Delta \tau \cdot \left(q_0 \cdot I'_e + q_1 \cdot I'^2_e \right), \qquad I'_e > 0. \tag{4}$$

For the current profile shown in Fig. 1, the equivalent ramp rate is 1.064 kA/s. Since the magnet design current is 8,926 A for a central field of 4.5 T, we assume a nominal current transfer ratio of 1,984 A/T.

IV. RESULTS

We performed tests at 0.05 T/s, 0.1 T/s, 0.2 T/s, 0.3 T/s, 0.4 T/s, 0.5 T/s, 0.6 T/s nominal field ramp rate; globally about 450 current cycles were taken and analyzed. As it has been explained in Section III-C each run has provided a measurement of the power loss, with an associated statistical error. For each field ramp rate, runs with different maximum and minimum currents were tried; in Fig. 5 we show the ramp power loss measurements results at 400 A/s. We have chosen this case since we have the largest number (seven) of different current intervals and/or experimental conditions. Although we expect that the ramp loss power changes depending on current interval (see Table II) even when the ramp rate is constant, the experimental error in our measurement covers this effect, since the differences between the different experimental conditions (reported in Fig. 5 near the experimental points) is comparable to the experimental error. Therefore, we report only a single value of measured loss at each ramp rate, determined by taking the weighted average of the single measurements.

The results of all the measurements are shown in Fig. 6. The measured reduced power loss (ramp loss divided by the equivalent ramp rate) is plotted as a function of the equivalent



Fig. 6. Reduced power loss results summary. The blue line represents the best fit (not weighted) of the experimental points, and the blue and red dashed lines the minimum and the maximum expected reduced loss, respectively (from Table II).

ramp rate (Section III-D). The thin blue line is a linear best fit on the experimental points. The two blue and red dashed lines represent the minimum and maximum expected loss, reported in Table II.

The measured losses are within or slightly above the estimated values, a remarkable result, if we consider the number of sources contributing to the loss and the inherent uncertainties. The loss dependence on the ramp rate suggests that the excess is primarily due to an eddy-current-like contribution; it is unclear at this stage whether it comes from the superconductor or from a metallic material of the cold mass.

The loss measured with the calorimetric method gave much smaller results and an analysis is in progress to understand this discrepancy. It could be related to the uncertainty in the subtraction of the large contribution to the evaporation due to heat loading from the current leads and from the cryostat with its ancillary, as well as to the fact that the environmental cryogenic conditions (pressure and temperature) were not truly constant during the measurements.

V. CONCLUSION

Losses in cycling conditions have been measured on the DISCORAP SIS-300 model dipole magnet by means of a V-I method, for field ramp rates from 0.05 T/s to 0.6 T/s.

The loss estimates have been revised on the basis of the measurements performed on the Rutherford cable used for the magnet construction, leading to an increase of about 5%.

The experimental values are in substantial agreement with the expectations, with an excess of about 15% at the highest ramp rate achieved during the test, possibly related to an eddycurrent-like component. More accurate measurements should be performed during the in-depth test at GSI, aiming to determine losses up to, and possibly above, the design ramp rate, along with their dependence on the current. This should allow to clarify whether the excess loss, if any, are related to hysteresis of eddy currents. Current cycles at small current values could provide valuable information concerning the overall magnetization [10].

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