

Cable Design for FAIR SIS 300

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Abstract—GSI, Darmstadt is preparing to build FAIR (Facility for Antiproton and Ion Research) which will include SIS 300, a 300 T·m fast-ramping heavy ion synchrotron. Dipoles for this ring will be 2.9 m long, producing 6 T over a 100 mm coil aperture and ramped at 1 T/s. The cable for these dipoles must have low losses and produce acceptable field distortions during the fast ramp. We plan to achieve this objective by using fine ($\sim 3 \mu\text{m}$) filaments of NbTi in a wire with an interfilamentary matrix of CuMn to reduce proximity coupling and increase the transverse resistivity. The Rutherford cable will have a thin stainless steel core and the wires will be coated with SnAg solder which has been oxidized, using a recipe similar to that developed at CERN, to increase the adjacent strand resistance R_a . Measurements of crossover strand resistance R_c and R_a in cored cable with oxidized SnAg coating will be presented, together with data on critical current, persistent current magnetization and eddy current coupling in a wire with ultra fine filaments and a CuMn matrix in the interfilamentary region of the wire. These data will be used to predict losses and field distortion in the SIS 300 dipole and optimize the final design of cable for FAIR.

Index Terms—AC loss, fast-ramping magnet, fine filament wire, inter-strand resistance, low loss cable.

I. INTRODUCTION

Unlike recently built colliding beam accelerators such as

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RHIC and now LHC, whose dipoles are ramped at rather modest ramp rates (0.042 T/s and 0.007 T/s, respectively) and remain at operating field for hours, the main dipoles for the FAIR SIS 300 synchrotron will be ramped between 1.6 and 6 T, at 1 T/s, with the ramping time constituting 50% of the duty cycle. Minimization of conductor AC losses during such an operating mode is therefore required, to keep refrigeration costs and conductor temperature margin at acceptable levels. The SIS 300 magnets will operate in supercritical helium, with an inlet temperature of 4.4 K and peak magnet temperature of 4.76 K.

The development of a low loss conductor began when it was planned to build the SIS 200 synchrotron [1] with 4 T dipoles. The project requirements were changed, to the present SIS 300 synchrotron, with 6 T dipoles. A Rutherford cable with a central stainless steel core was adopted as the conductor for this design, as well as for the SIS 300 dipole design, although the strand size and number were both increased for the 6 T SIS 300 dipole. The details of such a cable and equations for different types of losses are given in [1]. The conceptual SIS 300 dipole design with design parameters was presented at ASC 2004 [2]. The final magnetic and mechanical design has been completed and will be presented [3]. The SIS 300 cable design parameters from ASC 2004 are presented in Table I.

TABLE I
SIS 300 CONDUCTOR DESIGN PARAMETERS

Wire	
Strand diameter	0.825 mm
Filament diameter	3.5 micrometers
Filament twist pitch	5 mm
Cu/NbTi ratio	1.4
Strand transverse resistivity ρ_{et}	$(4 + 0.9 B) * 10^{-10}$ Ohm m
Strand coating	Sn Ag (Stabrite)
Critical current density J_c	2700 A/mm ² (5 T, 4.2 K)
Critical current density J_c	2130 A/mm ² (6T, 4.2 K)
Rutherford Cable	
Strand number	36
Transposition pitch	100 mm
Width	15.1 mm
Thickness, thin edge	1.362 mm
Thickness, thick edge	1.598 mm
Mid-thickness	1.480 mm
Core:	13 mm wide, 25 micrometers thick, 304 Stainless steel
Crossover resistance R_c	20 milliohms
Adjacent resistance R_a	200 microohms
Insulation:	3 layers polyimide film, 125 micrometers thick, 95 micrometers effective cured thickness in coil azimuthal direction

The calculated conductor loss/cycle per meter of dipole magnet[4], using these parameters, is given in Table II. Hysteresis losses in the iron yoke add 26 J/m to the cycle loss.

TABLE II
Loss per cycle (Joules/m)

Transverse B, crossover R_c	3.2
Transverse B, adjacent R_a	10.7
Parallel B adjacent R_a	0.1
matrix coupling current	15.0
Filament hysteresis	47.9
Total magnet	76.9

These conductor losses depend on the values of the cable crossover resistance R_c and adjacent strand resistance R_a , NbTi filament diameter d_f , and strand transverse resistivity ρ_{ct} , as well as cable geometry, filament twist pitch, and strand transposition pitch. The values of these parameters given in Table I were chosen as achievable goal values, based on past experience. The cable dimensions were chosen to be the same as those of the LHC dipole outer layer cable. The progress in achieving these values as well as possible changes of values, to reduce conductor AC cycling losses, will be described.

II. LOW LOSS CONDUCTOR DEVELOPMENT

A. Filament Hysteresis Loss

The filament hysteresis loss is proportional to the filament diameter and its critical current density. If the filament diameter is reduced in a strand with an all-copper matrix, the filament spacing (s) to filament diameter (d) ratio (s/d) is kept constant, to avoid filament distortion (sausaging) which decreases the conductor critical current density J_c [5], [6]. As the filament separation decreases, proximity coupling [7] sets in, increasing the effective filament size. The limit for filament size in a strand with an all-copper matrix is therefore limited to about 3.5 μm , before the onset of proximity coupling. The use of a Cu-0.5wt % Mn interfilamentary matrix can suppress proximity coupling down to filament sizes around 1 μm . Cu-0.5wt%Mn is also more resistive than copper at NbTi-based superconducting magnet operating temperatures (~4-6 K), so that its use as the interfilamentary matrix material for a strand allows a reduction of filament diameter and thus hysteresis loss as well as coupling current losses, compared to a strand with an all-copper matrix. Cu-15%Ni could also be used. However, it is more resistive than CuMn, has a lower thermal conductivity, and is also harder. Hence, Cu-0.5wt % Mn interfilamentary matrix wire (with copper outer jacket and inner core) appears as the best choice to reduce hysteresis and coupling current losses.

There was interest in the use of a strand with a CuMn interfilamentary matrix and 2.5 μm filaments in the Superconducting Super Collider (SSC) days, for use in the SSC's High Energy Booster (HEB), which was ramped to 6.67 T at 0.07 T/s. A number of full sized billets of such wire were made, using both single and double stacking techniques. The

concerns were (and still are) critical current density value, filament distortion (leading to a larger effective filament diameter, in terms of AC losses), and long enough strand piece length. A single stacking approach leads to less filament distortion, but requires starting elements that are too small to handle. Some still existing SSC HEB dipole outer layer 0.648 mm diameter wire [8] with 2.6 μm filaments, made by a triple extrusion, double stacking process, was found. This conductor was tested at Twente TU (time and magnetic flux density B dependent magnetization measurements) and BNL (critical current density). The transport critical current density J_{ct} (at 5 T, 4.2 K) was 2511 A/mm², while the critical current density J_{cm} calculated from the measured magnetization, assuming round filaments, was 3088 A/mm², giving a J_{cm}/J_{ct} ratio of 1.23. This can be interpreted as an effective filament distortion, reducing J_{ct} , or as an increase of the effective filament diameter, increasing hysteresis loss, as Fig. 1 shows for this only wire (B944-2) with CuMn interfilamentary matrix, as well as for the other all-copper matrix tested wires. The larger ratio of J_{cm}/J_{ct} can also be associated with greater visible physical distortion of the filament cross sections, although the physical distortion of the filaments at the edge of the filament bundles is not as severe as one might expect, from the J_{cm}/J_{ct} ratio. In general, the single stacked wires of Fig. 1 (3N7 & RHIC) have a higher J_{ct} value than the other (double stacked) wires. The attempt to reduce filament distortion by reducing the number of filament bundles (K201T4 & G201T6), reduced ρ_{ct} .

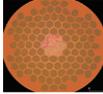
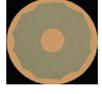
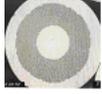
			
Strand dia.	2A212 0.53 mm	3N7 0.42 mm	RHIC 0.64 mm
RRR	-----	-----	198
ρ_{ct} ($10^{-10}\Omega\cdot\text{m}$)	-----	-----	(1.24+ 0.9B)
J_c (5 T, 4.2 K, A/mm ²)	2558	2831	3029
filament dia. (μm)	3.4	3.4	5.71
Ratio J_{cm}/J_{ct}	1.40	0.94	0.92
			
Strand dia.	K201T4 0.67mm	G201T6 0.85mm	B944-2 0.65mm
RRR	173	166	102
ρ_{ct} ($10^{-10}\Omega\cdot\text{m}$)	(0.58+ 0.89B)	(0.82+ 0.46B)	(4.15+ 1.9B)
J_c (5 T, 4.2 K, A/mm ²)	2773	2773	2511
filament dia. (μm)	3.4	4.3	2.6
Ratio J_{cm}/J_{ct}	1.15	1.10	1.23

Fig. 1. Characteristics of tested wires

The J_{ct} value given in reference 6 for the SSC HEB wire is about 2760 A/mm² (5 T, 4.2 K) but this was for the best

samples, whereas our measured sample ($J_{ct} = 2511 \text{ A/mm}^2$) was from a lot of 130 kg of remaining wire, with an average piece length of 1 km. Commercially available 0.57 mm wire (strand) with a CuMn interfilamentary matrix and about 5 μm filaments has been made by Outokumpu (now called Luvata), with a single stacking process (cross section like RHIC wire of Fig. 1), giving J_{ct} values above 3000 A/mm^2 . GSI is working together with INFN and industry to develop such a wire for the SIS 300 dipole, with the goal of an effective filament size of 2-3 μm and a J_{ct} value around 2700 A/mm^2 . Due to filament size, this will require a double stacking approach and most likely result in some J_c degradation, compared to the single stacked wire.

B Matrix Coupling Current Loss

This is an eddy current loss, due to coupling currents induced in a current loop that includes the superconducting NbTi filaments as well as the strand matrix, plus normal eddy currents that circulate only in the matrix material. The problem has been treated by Turck, Duchateau and Ciazynski [9], [10].

The transverse resistivity ρ_{et} for these coupling currents is given by

$$\rho_{et} = \frac{\dot{B}}{M} \left(\frac{p}{2\pi} \right)^2$$

where \dot{B} is the time rate change of magnetic flux density B, M is the magnetization, and p is the filament twist pitch.

Magnetization loops, taken at different values of B and \dot{B} give the transverse resistivity as well as the magnetoresistance of a strand. Given that the SIS 300 cable must be heat treated to increase its R_a value to the goal value given in Table I and that the magnet coils also undergo a $\sim 190^\circ \text{C}$ cure cycle, to glue the turns of the polyimide tape insulated coil together, the RRR of a strand with an all-copper matrix will be high and the transverse resistivity can be expected to be similar to that of the RHIC wire (See Fig.1). A wire with a CuMn interfilamentary matrix (whose resistivity at 12 K is $2.1 \cdot 10^{-8} \Omega \cdot \text{m}$, versus $0.85 \cdot 10^{-10} \Omega \cdot \text{m}$ for copper with RRR=200) would give a higher value for the strand transverse resistivity and therefore a lower coupling current loss. The transverse resistivity of the SSC wire (B944-2 in Fig. 1) was measured to be $\rho_{et} = (4.15 + 1.9 B) \cdot 10^{-10} \Omega \cdot \text{m}$. The calculated value of ρ_{et} [11] for this wire is $4.70 \cdot 10^{-10} \Omega \cdot \text{m}$, showing fairly good agreement between measurement and calculation for ρ_{et} ($B=0$). This is not true for the magnetoresistivity component of ρ_{et} which must be determined experimentally.

However, this wire was measured, as received, without any heat treatment (which is needed to simulate a coil cure cycle or to increase cable R_a) and has a measured RRR value of 102. The calculated ρ_{et} value, for a RRR value of 200 for this wire, is $2.5 \cdot 10^{-10} \Omega \cdot \text{m}$. Therefore, a more complicated strand design [12], with CuMn surrounding not only individual NbTi filaments, but also surrounding bundles of filaments encased

in copper, will be required, to reach the goal value of $4 \cdot 10^{-10} \Omega \cdot \text{m}$ for ρ_{et} . Such a wire will also need a higher matrix/NbTi ratio (1.6:1), to accommodate enough copper for strand stability.

III. CABLE R_c AND R_a LOSSES

The R_c and R_a goal values of Table 1 were chosen as values that would reduce the R_c and R_a contributions to the total magnet loss to around 10% or less and as values that could be reasonably achieved.

The effectiveness of a central thin stainless steel core inside a Rutherford cable, in reducing the eddy current losses due to cable crossover resistance R_c , has already been shown [13]. In addition, the use of a core allows one to adjust the adjacent strand resistance R_a independently of R_c . The R_c goal value of 20 m Ω can be easily reached with a 200°C heat treatment of several hours [14].

As for R_a , the conventional wisdom has been that one should make R_a high enough to reduce cable eddy current losses to acceptable levels, but not so high that the cable's quench recovery ability through current sharing with adjacent strands of a quenching strand should be adversely affected. GSI has chosen to use Staybrite (Sn95wtAg5wt) solder, the same strand coating as chosen by CERN for the LHC main dipoles, as the strand coating for SIS 300 dipoles. Samples of LHC dipole outer layer cable, but with a 304 SS core, were first heat treated in air for a number of hours and then subjected to R_a measurements [15]. Afterwards, they underwent two simulated coil cure cycles with an R_a measurement after each cycle (see Fig. 2).

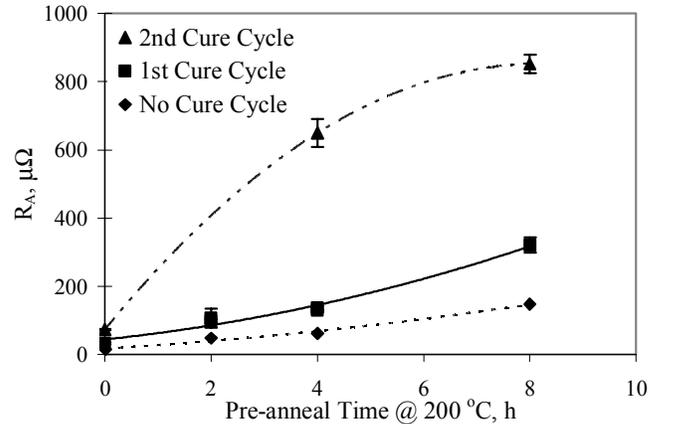


Fig. 2 R_a for samples pre-annealed for different durations at 200°C in air (lower curve) and subsequently subjected to simulated coil cure cycles (upper 2 curves)

One can see that an approximately 6 hour heat treatment and one subsequent cure cycle is enough to get an R_a value of 200 $\mu\Omega$. However, the inner coil of the two layer SIS 300 dipole will be subjected to two cure cycles since it will be

built without an interlayer splice. This means that the cable heat treatment time will need to be optimized to achieve the lowest cable R_a loss for the magnet.

IV. CABLE R_a EFFECT ON MINIMUM QUENCH ENERGY

Minimum Quench Energy (MQE) measurements of Rutherford cables have been made before [16]. An MQE experiment (in liquid helium at 4.3 K) was undertaken at CERN to measure the effect of cable R_a value on the MQE of a cored LHC dipole outer layer cable [17], to determine what the maximum value of R_a could be, before cable stability is affected. Low ($\sim 1\mu\Omega$), medium (0.6-0.7 m Ω), and high (8-9 m Ω) R_a samples (using CERN arbitrary nomenclature for the R_a values) were prepared. Initial results are shown for the medium and high R_a samples (see Fig. 3), for 100 μ sec pulses from a heater in the center of the cable and near the thin edge of the cable.

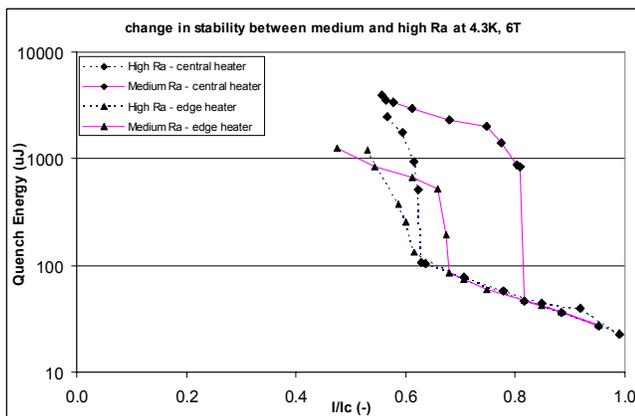


Fig. 3 Quench energy (μ J) versus fraction of critical current I/I_c for medium and high R_a cable samples at 4.3 K, 6 T

One can see that the “knee” of the curve (indicating the onset of current sharing of the quenching strand with adjacent strands) is at about $I/I_c=0.81$ for the medium R_a sample, but only 0.61 for the high R_a sample. Therefore, the medium R_a cable does appear to be more stable, in terms of MQE. Whether this is an electrical effect (R_a value) or thermal effect (heat transfer value between strands) is not yet known. All one can say is that if one heat treats the cable such that the R_a values reaches the above given values, the medium R_a cable has a higher quench energy than the high R_a cable. An estimation was made of I/I_c for the SIS 300 dipole at 6 T (6.42 T max field and maximum conductor temperature 4.76 K), assuming the cable parameters of Table I and uniform distribution of transport current among the strands, with the result $I/I_c=0.75$.

V. CONCLUSION

The progress in achieving fine filament, low loss Rutherford cable superconductor for SIS 300 ring dipoles has been

described. Goal values for filament diameter d_f , transverse resistivity ρ_{et} , cable resistances R_a and R_c have either been achieved in the past, or look achievable, based on tests and calculations. The critical current density J_c goal in long lengths of fine filament strands with CuMn interfilamentary matrix still needs to be demonstrated. Initial test results show that conductor stability (MQE) is decreased as R_a is increased.

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