Conductor Development for a Wide Bore 10 T Nb_3Sn Model Dipole Magnet

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Abstract--**An 87.8 mm bore single aperture 10 T Nb_3Sn model dipole magnet is under development as a next step in the realization of high-field Nb_3Sn dipole magnets. The magnet is a 2 layer cos(θ)-dipole model as an alternative for the proposed NbTi D1 beam separator magnets for the LHC. After completion of the general magnetic and mechanical design, all attention is focused on the manufacturing and cabling of a novel powder-in-tube Nb_3Sn conductor. This Nb_3Sn conductor is characterized by a high non-Cu J_c of 2680 A/mm^2@10 T with an effective filament size of about 20 μm. Cabling should result in a Rutherford type of cable exhibiting a moderate I_c degradation due to the cabling process itself, a low transverse stress sensitivity and a controllable minimum value of R_c. The conductor development program is presented and the results are evaluated. Progress on the actual realization of the coils is briefly described.**

I. INTRODUCTION

After the successful operation of the 11 T Nb_3Sn dipole magnet MSUT [1], the collaborating partners continue their program with the development of a wide bore 10 T Nb_3Sn dipole magnet. This system serves as a model for the beam separator dipole magnets D1 for the LHC [2].

Based on an existing well performing powder-in-tube (PIT) Nb_3Sn cable design [3], the resulting coil cross-section of Fig. 1 as well as the shape of the end-spacers have been optimized using the computer code ROXIE that also takes into account saturation of the iron yoke [4]. Fig. 1 also shows the modest but efficient external support structure to sustain the large Lorentz forces. The elliptical shape of the inner yoke face ensures a flat sextupole component both at low and high field. The resulting design parameters, constraints and operating conditions are summarized in Table I. A brief summary of the actual realization of the coils will be presented.

The most important issue in Nb_3Sn accelerator technology is the development of an optimal performing Rutherford cable. Like in the successful operating dipole magnet MSUT [1], a PIT-Nb_3Sn will be used in this program. The present project, however, aims at the development of an improved cable that exhibits not only an adequate critical current as a function of field and strain but a low filament magnetization ($d_{fil} < 20$ μm) and a controllable minimum resistance between crossing strands as well.

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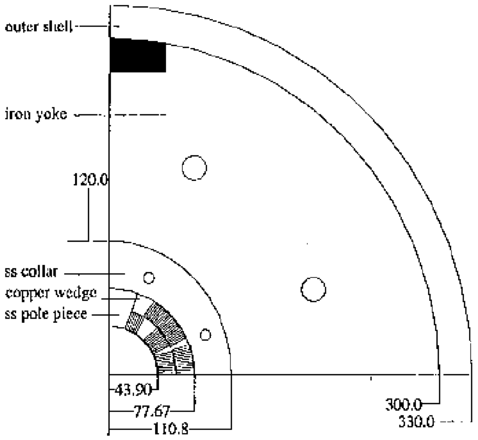

Figure 1. Cross-section of a quadrant of the coils and the mechanical support structure of the proposed 10 T model dipole magnet.

TABLE I
DESIGN PARAMETERS OF THE MODEL MAGNET

nominal dipole field		10	T
peak field pole face @ 20 MPa		10.8	T
operating temperature		4.4	K
nominal current		13	kA
clear bore diameter		87.8	mm
self induction		8	mH/m
magnetic length		0.8	m
norm. multipoles at 16 mm (0.5 < B < 10 T)		$< 10^{-4}$	
required overall J_c strand		601	A/mm^2
allowed J copper		1500	A/mm^2
forces per quadrant	F_x	3.32	MN/m
	F_y	-1.62	MN/m
peak stress midplane @ 10 T		135	MPa
strand diameter		0.9	mm
copper fraction		45-55	%
RRR copper		> 100	
filament diameter		< 20	μm
target cable dimensions		16.40x1.79/1.47	mm
ss core dimensions		12.5x0.025	mm
twist pitch		119.8	mm
cable insulation		folded glass/mica and glass fiber wrap	
insulation thickness		0.14	mm
end spacers		machined bronze-7 or aluminum-bronze	

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II. CONDUCTOR DEVELOPMENT

A. *Powder-in-tube Nb_3Sn wires and cables.*

As a result of a dedicated development program ShapeMetal Innovation (SMI) [5] has succeeded to reduce the actual filament diameter in a 0.9 mm wire from 40 μm in the traditional 192 filaments lay-out to about 20 μm. After an intermediate step, resulting in a 492 filament wire exhibiting a relatively low $J_{c\,\text{non-Cu}}$ of 1900 A/mm^2@10 T, a 504 filament wire has been manufactured that shows a high $J_{c\,\text{non-Cu}}$ of 2680 A/mm^2@10 T. The optimal properties are obtained after a heat treatment in vacuum at 675 ^{0}C of only 47 hours, which in itself is a great advantage of the powder-in-tube process. It should be emphasized that the investigated PIT conductors contain binary Nb_3Sn without any additions to the Nb tubes or the powder core.

Pilot cables with a typical length of 3-10 meters are manufactured to investigate the validity of the cable design in relation to the actual wire lay-out. Table II summarizes the properties of the investigated wires and the common cable parameters. All cables contain a 12.5x0.025 mm stainless steel foil in between the rows of strands to increase the resistance between crossing strands to an effective value of 20-50 μΩ [6]. This should effectively reduce the generation of coupling currents, which appeared to be a serious source of field errors as measured in the MSUT dipole magnet [1].

B. *Critical current of virgin and extracted strands*

One meter long samples of both virgin wires and extracted strands of the 3 conductor types and cables (Table II) are mounted with a winding tension of 20 N on a TiAlV sample holder. After the heat treatment the sample remains on the same sample holder for the critical current measurements. Because the Nb_3Sn is in a lower compressed state at 4.2 K, critical currents obtained in this way are expected to be about 3 % higher than in the actual coils, which are heat treated on a stainless steel winding post [7]. This mounting procedure however is the present standard for Nb_3Sn conductors since it leads generally to very reproducible results among different samples of the same wire and therefore enables a fair and unambiguous comparison to other types of wire.

TABLE II
LAY-OUT OF THE INVESTIGATED STRANDS AND CABLES

conductor type	1	2	3
number of filaments	192	492	504
manufacturer	ECN	SMI	SMI
diameter (mm)	0.90	0.91	0.90
copper fraction (%)	52	54	52
diam. Nb_3Sn (μm)	28 x 40	10 x 19	12 x 22
reduction process	cold drawn	cold drawn	cold extruded and cold drawn
cable dimensions (mm)	$16.40^{\pm0.01}$ x $1.47^{\pm0.01}/1.79^{\pm0.01}$		
number of strands	35*		
thin edge compaction (%)	84		
twist pitch (mm)	119.8		

*from conductor 3 also a key-stoned and a rectangular cable containing 34 strands have been manufactured and investigated.

TABLE III
CRITICAL CURRENT OF VIRGIN WIRES AND EXTRACTED STRANDS AT 10.8 T

conductor type	1	2	3
required nominal current (A)	372	372	372
virgin wire I_c (A)	609	457	672
extracted strand I_c (A)	560	418	458
I_c degradation (%)	8	9	34*
operational margin (%)	38	11	18

* the two types of cable from conductor 3 containing 34 and 35 strands respectively show the same I_c degradation after cabling.

Table III summarizes the critical currents at a field of 10.8 T, which are obtained by Kramer interpolation using measured values at 10,11,13 and 15 T. Note, that the same critical current is required for the pole face conductors at 10.8 T@ 20 MPa as for the mid-plane conductors at 10 T @ 135 MPa.

The critical currents for the virgin wire of conductor 2 are low compared to a typical PIT conductor like type 1. Improvements on filament and wire lay out resulted in conductor 3, characterized by a high non-copper current density of 2680 A/mm^2 @ 10 T in nicely de-coupled 22 μm filaments. Both SEM microscopy and magnetization measurements confirm this effective filament size [5]. Though the achieved current density exceeds the requirements in this case with about 90 %, the combination of a small filament size, an appropriate copper fraction and a high critical current illustrates the unprecedented potential of PIT-Nb_3Sn conductors for application in high-field accelerator magnets.

Processing these similar wires into a standard cable lay-out (Table II) results in a complete different degradation of the critical current, measured on extracted strands. While the cabling of conductor 1 into highly compacted cables (95 % at the minor edge) for the MSUT dipole magnet resulted in a I_c degradation of 30 % at 10 T, the I_c degradation for this less compacted cable is reduced to an acceptable value of about 8 %. Despite the slight changes in manufacturing process and wire lay-out of conductor 3, the large I_c degradation after cabling was not expected. The low n-value of about 10 points at damage of the filaments.

One should anticipate for a further cumulative I_c reduction of 10 % resulting from a heat treatment on a stainless steel holder instead of a TiAlV holder, induced damage during coil winding and finally a transverse stress of 135 MPa at 10 T. Taking this into account, the critical current of cable 3 might just be adequate. However, damaged filaments will result in tin diffusion from the core into the copper during the heat treatment. This inevitably reduces the stability.

It should be emphasized, that wires from the same process but with a different lay-out generally show a different behavior during cabling, even in a similar cable lay-out. At this stage it is very speculative to point at one particular manufacturing parameter, cabling parameter or precursor material property that mainly causes this different behavior. These results show however, that there is room for process optimization to obtain a PIT-Nb_3Sn based Rutherford type of cable with optimal properties for application in accelerator magnets.

C. Critical current of transversely loaded Nb_3Sn cables

Not only the cabling process but also the transverse stress experienced by the mid-plane conductors in a dipole magnet affects the cable performance. Since the anticipated maximum transverse stress (perpendicular to the wide side of the cable) for the mid-plane conductors amounts to 135 MPa at full excitation, the influence of such a high stress to the critical current must be known before coil manufacturing. This influence is determined by:

- the type of strand (mechanical state, intrinsic constituent properties),
- the internal lay-out of the strand (Cu-fraction, diffusion barriers, voids after heat treatment, reinforcements),
- the cable lay-out (average width, aspect ratio, key-stone angle, central core, twist pitch),
- damaged regions due to cabling,
- the mechanical properties of the cable insulation and the epoxy resin.

Since the impact of each of these parameters and their interplay is understood only qualitatively, it is highly recommended to determine the stress sensitivity of the critical current experimentally for each specific cable.

To accomplish this, the critical current of U-shaped samples from pilot cables 1 and 3 (Table II) has been investigated using the facility at the University of Twente [8]. This facility enables application of a transverse pressure of 200 MPa over a sample length of 4 cm, in a transverse background field of 11 T for sample currents up to 50 kA.

This set-up exhibits 3 serious disadvantages:

1. Because only 6 cm of the sample is exposed to a transverse field, the current distribution is fully determined by the soldering connection between the sample and the superconducting transformer. This may give rise to a spread in I_c among different strands of 10-15 % (Fig. 3).
2. The field distribution over this 6 cm is highly inhomogeneous, especially at sample currents above 15 kA. Though by a different mechanism, this also leads to a spread in the measured critical currents.
3. The stress is applied over the full cable width but only over a length of 4 cm, which is less than half a twist pitch. As a consequence some strands do not have a sharp bend at one of the cable edges under the pressed surface. Especially the bends are expected to be the most vulnerable regions. Besides, the corners of the pressure block may introduce a local peak stress that exceeds the average stress by 10-20 %.

These experimental limitations make it hard to measure an absolute value of the critical current (Fig. 3). Additionally, the applied stress may be locally 10-20 % higher than the measured average stress. A situation like in Fig. 3 however reproduces very well (after a sample quench) at a constant applied stress and remains qualitatively the same at different stresses. These measurements therefore give valuable qualitative information about the stress sensitivity of the normalized critical current $I_c(\sigma)/I_c(0)$, also because different strands show similar behavior when the stress is varied.

Two cable samples of type 1, of which one is only partially filled with epoxy resin (labeled PI-1 in contrast to the completely filled sample FI-1), and a cable sample of type 3 (FI-3) containing 34 instead of 35 strands are investigated (Table II). Fig. 4 shows the normalized critical current versus the average applied stress at 4.2 K in a background field of 11 T.

The critical current of sample PI-1 not only reduces strongly under pressure, but after complete stress release a permanent degradation remains, which points at severe damage to the Nb_3Sn filaments. This high stress sensitivity and the corresponding permanent degradation can be attributed for the major part to the incomplete penetration of the epoxy resin in the cable. Filling all empty space around every strand with epoxy resin prevents the occurrence of local peak stresses inside the strands [9].

These experiments point clearly at the significance of a

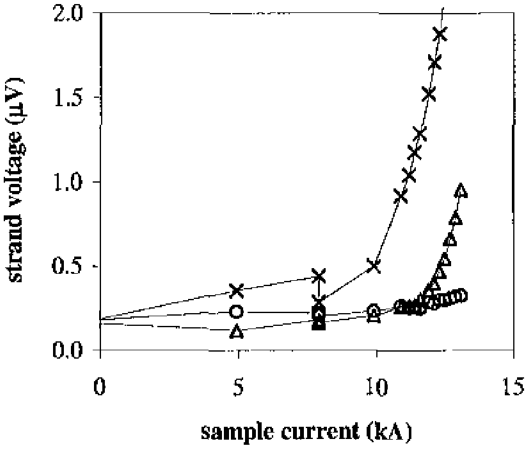

Figure 3. Example of a recorded V-I curve illustrating differences in critical behavior between the strands due to a highly non-uniform current distribution.

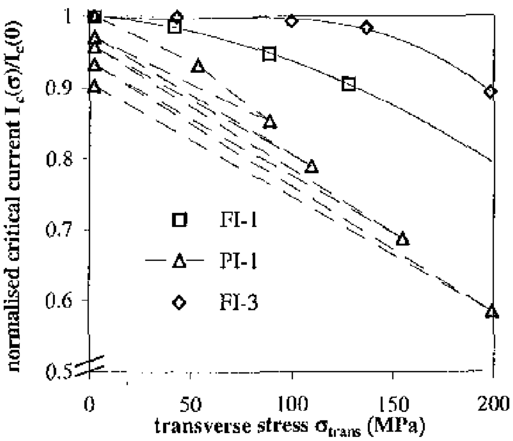

Figure 4. Normalized critical current as a function of the applied transverse stress for 3 PIT-Nb_3Sn Rutherford types of cable. Solid lines represent fits to the experimental data.

well-controlled impregnation process of the coils to guarantee complete resin penetration into the cables.

Though the I_c reduction under pressure of sample FI-1 is still quite high (about 13 % at 150 MPa), no permanent degradation is observed after complete stress release. The measured critical current of the extracted strands allows this non-permanent I_c reduction (Table III).

Despite the large I_c degradation after cabling, sample FI-3 shows only a small I_c reduction of 3 % at 150 MPa. At higher stresses the I_c drops steeper. Also this sample shows no permanent degradation after releasing the stress from 200 to 5 MPa. The different behavior of FI-3 and FI-1 may be due to the lower compaction of FI-3 (34 instead of 35 strands). An additional experiment with the available 35-strand version of FI-3 should clarify this issue.

III. COIL MANUFACTURING

With a dummy NbTi cable a complete inner layer has been wound using machined bronze-7 end-spacers with a calculated shape. Satisfactory shapes of the spacers are obtained after a single winding-rewinding iteration. Without the insertion of glass-fiber or mica sheet it is difficult to prevent electrical shorts between the turns and the end-spacers at all manufacturing stages. The final end-spacers therefore will be covered with a 0.1 mm layer of plasma-sprayed Al_2O_3.

The preparations for the winding of a Nb_3Sn dummy inner layer are nearly completed. This dummy layer will be heat treated, stacked together with a dummy outer layer and finally impregnated.

IV. CONCLUSIONS

A wide bore, 10 T Nb_3Sn model dipole magnet is under development. Much attention has been paid to the development of a good performing Rutherford type of cable, based on a novel PIT-Nb_3Sn conductor. This recently developed PIT wire uniquely combines adequate properties with respect to critical current, filament size and copper fraction for application in accelerator magnets.

The critical current of the wires from the first pilot production in the present lay-out however appear to be sensitive to the cabling process. The properties of the obtained conductor nevertheless meet the specifications for application in the proposed dipole magnet.

Irrespective the type of PIT-Nb_3Sn wire, the investigated fully impregnated Rutherford types of cable with a moderate compaction of about 86 % are not particularly sensitive to transverse strain. Depending on the wire type and cable compaction a critical current reduction between 3 and 13 % at 150 MPa is observed. After stress release no permanent degradation occurs.

The magnetic and mechanical design of the magnet system has been completed. The tooling and components for the actual realization of the magnet system are being manufactured. Winding, heat treatment and resin impregnation of a dummy Nb_3Sn inner layer will start soon.

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