

Application of Nb₃Sn Superconductors in High-Field Accelerator Magnets

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Abstract — Last year a record central field of 11 T at first excitation at 4.4 K has been achieved with the experimental LHC model dipole magnet MSUT by utilising a high J_c powder-in-tube Nb₃Sn conductor. This is the first real breakthrough towards fields well above 10 T at 4 K. The clear influence of magnetisation and coupling currents on the field quality, the quench behaviour and the temperature development in the coils has been measured and is discussed. For application in high-field accelerator magnets (10-15 T dipoles, 300-400 T/m quadrupoles) these experimental results clearly reveal the potential, the present limitations and the necessary improvements of Nb₃Sn technology with respect to strand, cable and coil design and manufacturing. A brief review of developments in this field is presented. The focus is on accelerator dipole magnets but the key issues for quadrupole magnets are quite similar

I. INTRODUCTION

The development of accelerator magnets (dipoles and quadrupoles) is focused on high-field strength c.q. high current density, field quality (normalised higher order multipoles $< 10^{-4}$), reliable operation (mechanical and thermal stability) and high quality large scale production. The present practical field limit for NbTi magnets operating at 2 K amounts to about 8.5 T. The relation between design and manufacturing parameters and the quench behaviour (location, ageing and thermal cycling effects, thermal or mechanical limitations) is not well understood yet [1], which impedes large scale production. The amplitude and the time dependent behaviour of the undesired higher order multipoles as well as the ramp rate sensitivity can be described quite well by modelling the interstrand coupling currents and the boundary induced coupling currents [2]. The necessary control of these currents and the consequences for cable stability is still under investigation [3].

To attain a field of 10-15 T presently only Nb₃Sn conductors, operating at 4.4 K, are available in satisfactory quality and quantity. Apart from the general issues concerning high-field accelerator magnets mentioned above, typical Nb₃Sn related difficulties have to be taken into account. All coil manufacturing steps concerning winding, heat treatment at 675 °C, the internal splice, protection heaters, resin impregnation, mechanical support and assembly are strongly related to each other and require a more integrated and careful approach than in the case of NbTi coils.

Manuscript received August 26, 1996.

This work has been supported, in part, by the Netherlands Technology Foundation STW.

The Nb₃Sn dipole magnet program is a collaboration between the University of Twente, STW, NIKHEF Amsterdam and CERN Geneva.

On strand and cable level the key issues comprise the reduction of I_c due to cabling (filament damage), transverse stress sensitivity of J_c , the still existing controversy of a high J_c versus filament size, heat resistant and thermally conductive electrical insulation, control of the interstrand crossing and adjacent resistances R_c and R_a in relation to the thermal and electrical stability and the low normal zone propagation.

To illustrate the present status and the potential of Nb₃Sn accelerator magnets, the experimental results of the successful program to realise a 1 meter 11 T single aperture Nb₃Sn dipole magnet MSUT are discussed. In this program the emphasis has been put on the main challenge, namely to increase the field strength by exploiting the high J_c of the powder-in-tube Nb₃Sn conductor [4] and developing Nb₃Sn dedicated design and manufacturing concepts.

II. MSUT SYSTEM CHARACTERISTICS

Table 1 summarises the most important coil parameters. Note that the inner layer cable is the largest Rutherford cable ever made for accelerator magnets.

In fig. 1 the single pole conductor lay-out in the splice region is depicted schematically. Instead of a ramp splice the inner and outer layer are connected in the pole plane by pre-reacted Nb₃Sn wires which are soldered with SnAg to a 2 mm thick copper plate. This splice configuration eases layer handling and ensures continuity of the mechanical support in the pole plane. As a consequence of this configuration the outer layer conductors in this region experience a 0.15 T higher maximum field than in the normal cross section. Fig. 2 shows the non-copper J_c of the conductors before and after cabling as well as the loadlines for both layers to a maximum central field of 11 T. The significant degradation due to cabling of the outer layer conductors, which reduces the J_c -

TABLE I
MSUT COIL PARAMETERS

	Inner cable	Outer cable	
Dimensions (bare)	1.98/2.47x21.7	1.54/1.82x17.4	mm
Number of strands	33	33	
Strand diameter	1.26	1.00	mm
Twist pitch	147	146	mm
Number of filaments	192	192	
Filament diameter	42	32	µm
Filament twist pitch	30	30	mm
Cu percentage	56	56	%
Insulation thickness	0.14	0.14	mm
Max field in cable	11.3	9.4	T
Max. eq. stress	140	120	MPa

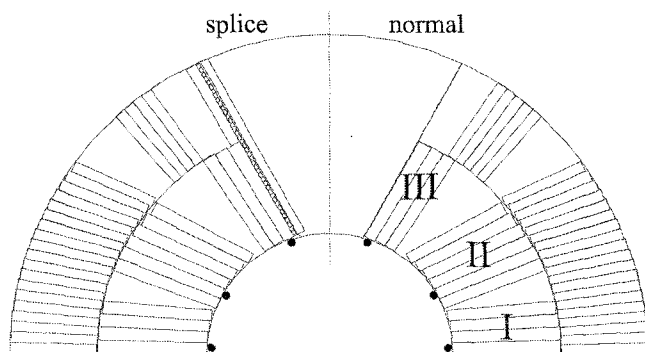


Fig. 1. Conductor lay-out in the splice region of a single pole, which extends to 30 cm of the straight part. Also shown are the 6 thermometer positions and the inner layer block labels. The bore diameter is 50 mm.

margin in the splice region from about 35 % to 10 %, was not expected from earlier experiences with PIT-conductor Rutherford cables [5]. The cabling degradation of the inner layer conductor is less severe, though the initial strand J_c is quite low due to a non-optimised strand lay-out. To exploit the high J_c -potential of Nb_3Sn conductors for a particular application a dedicated optimisation process with respect to strand and cable lay-out seems to be imperative. This is an important observation for the development of optimally performing Nb_3Sn cables. In the MSUT program the optimisation has not been carried out due to time constraints. More details of the electromagnetic and mechanical design of the MSUT magnet are described elsewhere [6], [7], [8].

A. Manufacturing experiences

As important as the design and the conductor performance is the manufacturing of sound Nb_3Sn coils and their me-

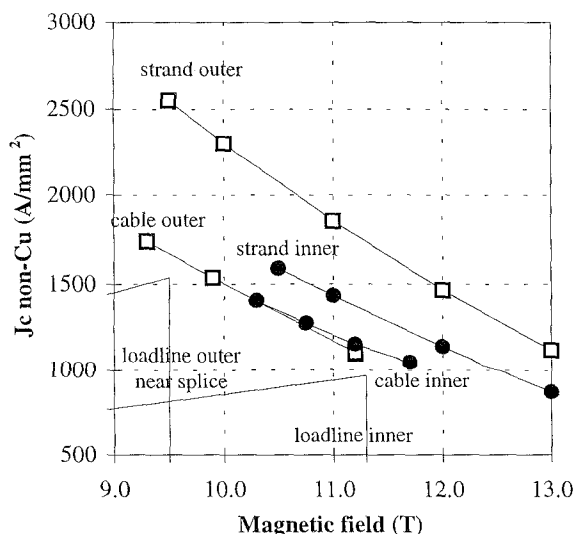


Fig. 2. Measured non-copper critical current density versus magnetic field before (strand) and after cabling (cable) for both layer conductors. Also shown are the loadlines to a maximum central field of 11 T.

chanical support. The only insulation material that appeared to be reliable during winding of the large inner cables was a folded mica/glass sheet wrapped with a glass fibre tape [9]. Even at the beginning and the end of the turns where severe cable deformation occurred during winding and pressing, this insulation system did not suffer from any turn-to-turn shorts.

For controlling the shape and position of such large cables the empirically developed method for coil head support elements is to our opinion still the only way to realise reliable turns [8]. Though perhaps more time consuming, it assures continuous support between the straight section and the coil head, good support in the turns itself and flexibility of the coil head during the heat treatment. Especially this last issue is important because the heat treatment gives rise to complete stress release and a significant axial expansion of the coils. Irrespective what support elements are used, this expansion manifest itself in the heads as large gaps between turns and support elements. This approach especially facilitates gap filling with glass fibres afterwards to ensure complete support.

Shrinking of the warm (225 °C) ring shaped collars around the finished coils was successful though heating of the coils to about 90 °C, at which temperature yielding of the epoxy starts, could not be prevented. This resulted in a reduced prestress after collaring, which could be compensated for by adapting both the collar-yoke and the yoke-outer shell interference. This collaring technique will be more difficult but is still worth developing for longer coils.

III. EXPERIMENTAL RESULTS

The magnet has been tested for 3 weeks at the model magnet test facility at CERN at a temperature of 4.4 K. For protective and diagnostical purposes the magnet is equipped with meander shaped stainless steel foil quench-protection heaters at the inner and outer layers, many voltage taps at the inner and outer layers, spot heaters and 4 point germanium resistance thermometers at the inner layer bore (see fig. 1). Magnetic field measurements have been performed using rotating pick-up coils [10]. A static pick-up coil set is used for quench localisation [11]. The integrated hysteretic and coupling losses during field cycles are measured electrically [12].

To protect the coils from overheating during this first test run nearly all stored energy is extracted after each quench and dumped into an external resistor.

A. Quench characteristics

At the very first high-field ramp the current was ramped with 2 A/s from 15 kA to the first quench at a current of 18.7 kA, corresponding to a **record central dipole field of 11.03 T**. At intermediate field levels at least up to 10.7 T the ramp could be halted to perform field measurements. Immediately hereafter a second run resulted in a quench at 18.5 kA (10.92 T), about 1.5 % lower than the first quench. After 3 weeks of experimenting a final high current ramp resulted in a quench at 18.4 kA (10.86 T). Fig. 3 shows the measured relation between central field and current.

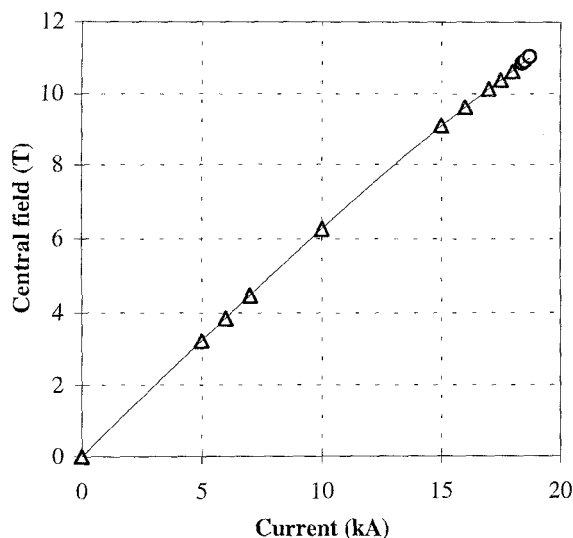


Fig. 3. Measured central field of the Nb₃Sn dipole magnet MSUT as a function of the operating current at 4.4 K. The line is a quadratic fit to the measured points. Open circles indicate the quenches.

All quenches occurred in the outer layer of the same pole in the splice region, where the field-current conditions are most unfavourable (see fig. 2). At maximum field the transverse stress on the wide side of the inner layer amounts to 120-140 MPa, depending on the frictional effects in the mechanical support system. This indicates, that at this stress level the non-permanent J_c reduction of the inner cable is less than 10% (J_c margin in fig. 2), a typical behaviour of a good performing Nb₃Sn Rutherford cable [13]. The slight decrease of the successive quench currents might point to coil damage due to the sudden stress release during the quenches. This issue will be investigated during a second test run.

It is important to note that this quench behaviour without any training effects is characteristic for good performing fully potted magnets. This has also been observed in the first Nb₃Sn LHC dipole magnet, which reached 9.5 T in only a few quenches [14]. This is a remarkable difference with dry NbTi dipole magnets operating at 2 K, that need many training quenches to reach a plateau close to the cable I_c .

B. Losses, field quality and ramp rate sensitivity

Though the main target in the MSUT program was to reach a field strength of 11 T, the field quality is an important operating parameter for accelerator magnets. Presently the demands are, that the higher order normalised multipoles B_n/B_1 (European convention: B_1 = normal dipole) are smaller than 10^{-4} at a bore radius of 10 mm.

At accelerator injection field of about 0.4 T the most significant field errors originate from magnetisation currents, manufacturing tolerances and a non-uniform current distribution due to the soldering connections.

At maximum operating field the magnetisation contribution is negligible and eventually additional distortion due to iron saturation arises.

During ramping of the field, interstrand coupling currents (ISCCs) and boundary induced coupling currents (BICCs)

cause additional field errors. The influence of interfilament coupling currents can be neglected [2].

Generally the ISCCs are proportional to dB_{\perp}/dt , w , L_p , N and R_c^{-1} , with B_{\perp} the field component perpendicular to the wide side of the cable, w the cable width, L_p the cable twist length, N the number of strands and R_c the resistance between crossing strands. The typical ISCC distribution gives rise to normal odd multipole components. Their characteristic time constant τ_{is} varies from 1-50 seconds. The associated losses are proportional to $(dB_{\perp}/dt)^2$, w^2 , N^2 , R_c^{-1} and L_p .

The BICCs are induced by (steep) gradients or non-uniformities of (dB_{\perp}/dt) and R_c along the cable. This is definitely the case in the coil heads and the internal splice of dipole magnets. The BICC value is proportional to w , R_c^{-1} and a characteristic length L_{bi} . In contrast to ISCC's they run mainly in the filaments over lengths varying from a few times L_p to the whole cable length and are characterised by time constant that varies from 10^2 to 10^5 seconds [2]. Due to their nature BICCs are expected to contribute to all skew and normal multipoles and give rise to a time dependent sinusoidal field pattern with a periodicity equal to L_p [15].

Taking into account the local B_{\perp} for each cable, a global electrical loss measurement during a field cycle B1-B2-B1 at different ramp rates results in an average value of R_c and τ_{is} . Fig. 4 shows the integrated total hysteretic and coupling losses during field cycles between 1.9 and 3.8 T vice versa for both poles. From these measurements an average value $R_c=1.2 \mu\Omega$ and $\tau_{is}=11$ s is calculated. During the heat treatment at 675 °C the uncoated Cu surfaces of the strands are probably sintered together, which results in this very low R_c . The systematic difference between the poles points to a small difference in the average R_c (R_{c1} , R_{c2}).

Due to the low R_c , the internal splice configuration and especially the wide inner cable, both BICCs and ISCCs are the expected sources of relatively large field errors during a field sweep. In fig. 5 the absolute field contribution in the **straight part** of the magnet of the successive multipole terms during a

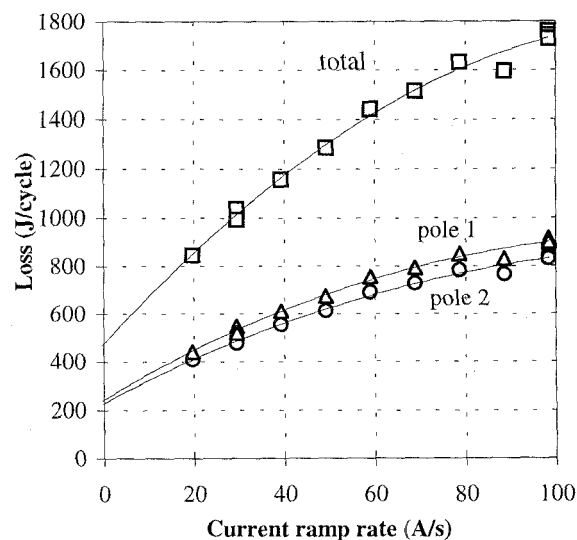


Fig. 4. Measured integrated hysteretic and coupling losses as a function of the current ramp rate during a 1.9-3.8-1.9 T cycle for both poles separately and the total loss.

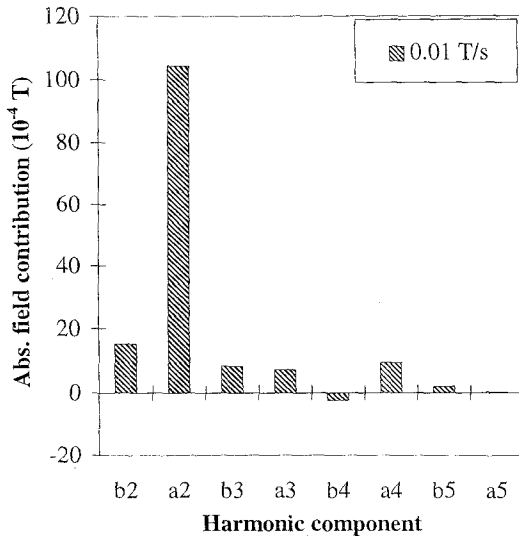


Fig. 5. Absolute field contribution of the higher order multipoles in the straight part during a field sweep from 1.9-5.7 T with 0.01 T/s.

field sweep from 1.9 to 5.7 T with 0.01 T/s are presented. The skew quadrupole field of 10^{-2} T is at least 2 orders higher than the tolerable value of 10^{-4} T and must be attributed to ISCCs proportional to $|1/(R_{c1}) - 1/(R_{c2})|$ and to BICCs. This is also reflected by the relatively large a_4 contribution. The remaining even and skew odd fields must be attributed to the BICCs. With the known cable parameters and the experimentally value of R_c normal odd contributions of 10^{-3} T for b_3 and 10^{-4} T for b_5 can be expected.

The results of static field measurements are presented in fig. 6. At low field of 0.4 T the b_3 of $5 \cdot 10^{-3}$ is caused by filament magnetisation, due to the 40 μ m filament diameter and the extremely high J_c at low fields. For this conductor saturation of the filaments occurs at 1.2-1.5 T. The large normal and skew quadrupoles might point to a combination of a small misalignment of the coils, asymmetry in the permanent

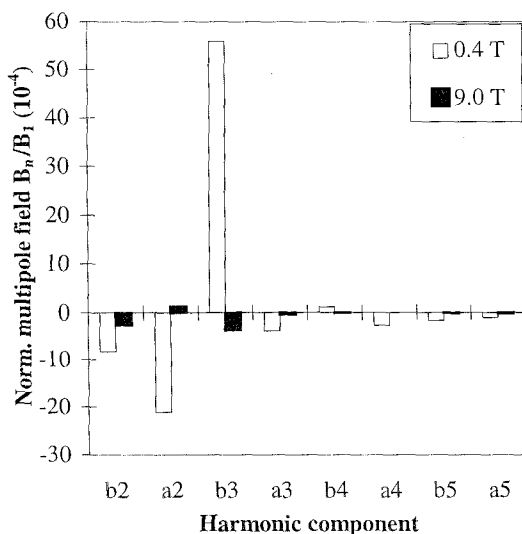


Fig. 6. Normalised multipoles $b_n (=B_n/B_1)$ at low field (0.4 T) and high-field (9T) in the straight part.

vertical gap between the yoke halves or a non-uniform current distribution due to the soldering connections.

The ramp rate sensitivity of the quench current has been measured in 2 arrangements. In the standard arrangement (labelled WP=without precycle) the current is ramped from zero till the quench. In the second arrangement (labelled P=precycled) the current is ramped to an intermediate level of 8-11 kA at a moderate speed. After decay of the ISCC's and the BICC's in about 10 minutes the current is ramped down to 2 kA and immediately ramped up to the quench with the desired ramp rate. In this arrangement the BICC's generated in the down ramp are partially compensated in the upramp due to their long relaxation time. As a result the quench current with P is expected to be higher than with WP, depending on the amplitude of the BICC's. In fig. 7 these results are presented and show a severe reduction of the quench current at higher ramp rates. Especially at low ramp rates between 5 and 50 A/s mainly the BICC's are responsible for the reduced quench current. At high ramp rates the temperature rise due to both magnetisation and coupling losses becomes the dominant source of reduction, which would lead both curves to coincide.

At high ramps rates large voltage spikes (~ 80 mV) across the poles at discrete current levels are observed without quenching the magnet. This confirms the expectation that due to the large BICCs strands become saturated and current redistribution occurs, which in fact illustrates at the same time the high stability margin of the conductors.

C. Temperature development

During all field sweep events the temperature development in the inner layer conductor blocks have been recorded. After a second test run at the end of this year more detailed and clarifying results will become available. As an illustration fig. 8 shows the temperatures during a field sweep from the virgin state to the quench at a ramp rate of 0.13 T/s. Due to the large magnetisation losses a large temperature rise at low

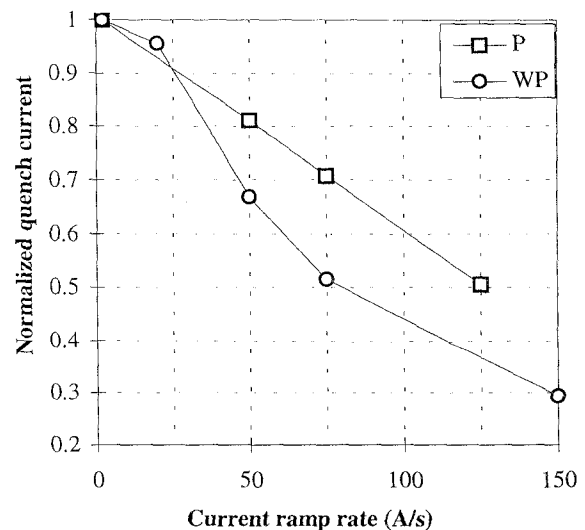


Fig. 7. Normalised quench current $I_q(dI/dt)/I_q(0)$ as a function of the current ramp rate with (P) and without precycle (WP).

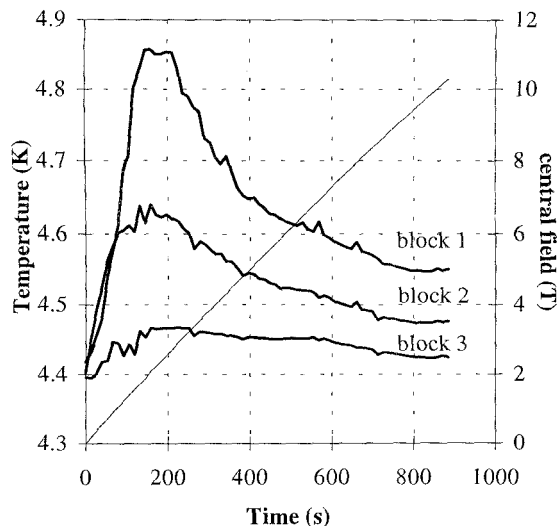


Fig. 8. Measured temperature development in the inner layer blocks (see fig. 2) during a field sweep from 0-10.5 T at a speed of 0.013 T/s (20 A/s).

fields occurs. At the end of the ramp the magnetisation contribution is negligible and only the coupling losses determine the local temperatures. Taking into account the modelled loss power, the surface heat transfer to the helium ($q=3 \cdot (\Delta T)^{2.5}$ W/cm²) and the heat conductivity of the impregnated glass/mica-glass insulation ($\lambda=10 \cdot T$ mWm⁻¹K⁻¹) a temperature in block 1 of 4.52 K is calculated, which agrees very well with these measurements. These unique in-situ experiments show the reliability of the thermometer lay-out and are a valuable tool in the study of the thermal behaviour and stability at cable level.

IV. CONCLUSIONS FROM THE MSUT PROGRAM

The obtained record field of 11 T at 4.4 K at first excitation with the dipole magnet MSUT illustrates the potential of Nb₃Sn conductors in general and powder-in-tube conductors in particular. It is the first real breakthrough towards fields well above 10 T. This result proves that the developed design and manufacturing concepts provide reliable and good performing coils. Though the manufacturing of a Nb₃Sn magnet remains a tedious process which demands total commitment, this program has shown that the technology for reliable Nb₃Sn coil production has evolved to a mature level.

For the highly efficient 2 layer cos(θ)-design the maximum reachable field strength amounts to about 15 T. This limit is imposed by manufacturing abilities (a further increase of the size of the inner cable impedes production of sound coils) and by the maximum allowable transverse coil stress of about 200 MPa.

A high J_c of the strand in itself is no guarantee for a good cable performance but greatly improves stability. Severe I_c degradation due to filament damage during cabling has been observed in this program. Despite this initial reduction the MSUT cables did not show enhanced stress sensitivity during magnet operation, which confirms the mechanical stability of the PIT-conductor. For each particular Nb₃Sn application the first development step must be an optimisation of the strand

and cable lay-out with respect to the specific operating conditions.

The clear influence of the large magnetisation and coupling currents on the field quality, the losses and the associated temperature development in the coils and finally the ramp rate sensitivity of the quench current are caused respectively by the large filament diameter, the cable dimensions and the low interstrand resistance R_c . Reduction of the coupling currents by increasing R_c is imperative. This can be achieved by insertion of a resistive core between the rows of strands while keeping R_a low in order to maintain sufficient thermal and electrical stability. These demands exclude coating of the individual strands with a resistive layer. Further development towards smaller filaments while maintaining a high $J_c(B, T)$ is necessary to reduce the magnetisation effects on the field quality.

Just because the MSUT magnet exhibits large ISCCs and BICCs it may serve as a perfect object to study in-situ the characteristic properties of the BICCs, which still cause problems in high-field accelerator magnets.

V. Nb₃Sn ACCELERATOR MAGNET DEVELOPMENTS

Presently only one other Nb₃Sn accelerator dipole model magnet is being realised, the 13 T, 4 layer cos(θ) single aperture magnet D20 at LBNL, utilising internal-tin conductors [16]. Characteristic design points different from the MSUT magnet are the small cables (easy to wind, low operating current, higher self-induction), no internal splices, a novel outer shell technique, glass fibre insulation and an optimised coil head lay-out with accurately machined coil head support elements and end pieces. Its completion and first cool-down is expected autumn this year.

To obtain field levels above 15 T new design concepts have to be developed to overcome the excessive cable dimensions and internal stresses and possibly cooling limitations. Though less efficient and probably more difficult to produce and protect, several twin-bore block designs are proposed that are compliant to these severe demands. They show promising perspectives, provided that the expected problems with respect to structural materials and magnet protection can be solved. An interesting aspect of these designs is the parallel-to-the-wide-side orientation of the field lines, thus relaxing the R_c and R_a demands [17],[18].

A 300 T/m, 2 layer 70 mm bore Nb₃Sn LHC quadrupole has been designed by the INFN/CERN collaboration, based on an internal-tin conductor [19]. Recently this quad-dedicated experimental rectangular Rutherford cable showed a non-Cu J_c of 1490 A/mm² @11 T, 4.2 K, 5 MPa and a non-permanent I_c degradation of only 7 % at 200 MPa transverse stress.

Irrespective of the magnet design a further increase in J_c is necessary to attain 15 T. The developments for various types of conductors in the last years are very promising, as illustrated by the enhancement of both the B_{c2} and $J_c > 15$ T with the ternary (NbTa)₃Sn conductors.

For the internal-tin and bronze type conductors there still exists a certain trade-off between J_c and filament size [20], [21]. The powder-in-tube technology seems to be very promising with respect to this point. Experimental PIT

Nb₃Sn strands with 10 μm filaments exhibiting a J_c of 2200 A/mm² @ 10 T, 4.2 K have already been produced [22].

A much better understanding of cabling degradation with respect to the conductor type, strand and cable lay-out and cabling process parameters is required to profit optimally from the high J_c of Nb₃Sn. So far no general guidelines for a specific conductor type nor cable design exist. At present a modest reduction of 5-10 % is found to be acceptable [23].

Also the transverse stress sensitivity of the I_c of Nb₃Sn Rutherford cables still cannot be predicted from general principles. Despite the many experimental results from different kind of cables (size, number of strands, compaction, keystone or rectangular) using different types of conductor, no convincing correlation between the ruling parameters and the permanent and non-permanent I_c reduction has been found yet [24]. Nevertheless a non-permanent I_c reduction of 4-6 % at 100 MPa and 7-10 % at 200 MPa is accepted as good, provided that it is accompanied by a negligible permanent reduction. There is no predictable relation between the transverse stress sensitivity of bare wires and fully impregnated cables because of the incomparable stress distribution. Many experiments at the University of Twente test facility have learned, that the most insensitive cabled types seem to be the bronze and the PIT conductors. Internal-tin cables have shown both excellent behaviour as well as large degradation. A detailed and systematic study on this issue is being carried out at in co-operation with LBNL in which an important correlation between the initial degradation after cabling and the stress sensitivity of internal-tin cables has been found [24].

Without any measures the heat treatment will result in a very low interstrand resistance R_c , resulting in large ISCCs and BICCs and hence large time dependent field errors. Insertion of a resistive metal core between the rows of strands enables independent control of R_c and R_a [25], [26]. However, core insertion also affects the thermal, mechanical and electrical stability. For NbTi cables this issue is being investigated, but so far no experiences with Nb₃Sn cables have been reported.

In the coming three years the existing MSUT collaboration will continue to develop and build an 88 mm wide bore 10 T Nb₃Sn model LHC separation magnet, according to the design and manufacturing concepts developed for the MSUT magnet. To arrive at the required field quality, both reduction of the filament size while maintaining a high J_c and control of R_c and R_a will be pursued in this program. When this next-step R&D project is successful it becomes feasible to incorporate a few Nb₃Sn separator dipole magnets in the LHC insertion region.

ACKNOWLEDGMENT

The authors would like to thank gratefully R. Perin, D. Leroy, P. Sievers, L. Walckiers, A. Siemko, L. Bottura A. Verweij and all members of the model-magnet test facility at CERN for their contribution to the MSUT program.

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