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Status of the Next European Dipole (NED) Activity of the Collaborated Accelerator Research in Europe (CARE) Project

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Abstract

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Work supported by the European Community-Research Infrastructure Activity under the FP6 “Structuring the European Research Area” programme (CARE, contract number RII3-CT-2003-506395).

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***Index Terms*—Accelerator magnet, high magnetic field, LHC upgrade, Nb_3Sn superconductor.**

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I. INTRODUCTION

In 2003, the European Union approved, after peer review and amendment, the Collaborated Accelerator Research in Europe (CARE) project of Integrated Activities (IA) submitted by the European Steering Group for Accelerator R&D (ESGARD) within the 6th Framework Program [1]. CARE integrates High-Energy-Physics-related accelerator R&D in Europe and involves more than 100 institutes. It includes three Network Activities (NA): linear colliders, neutrino beams and hadron beams, and four Joint Research Activities (JRA): radio-frequency cavities, photo injector, high intensity pulsed proton injector and high field magnets.

The high-field-magnet JRA, nicknamed Next European Dipole (NED), is aimed at the development of a large-aperture, high-field (up to 15 T conductor peak field) superconducting dipole magnet relying on Nb_3Sn conductors. Such magnet will serve as a technology test bed for LHC luminosity upgrade [2-4]. It can be used also to upgrade an existing superconducting cable test facility at CERN, presently limited to a 10-T background field [5]. The NED activity is also meant to complement the vigorous efforts on Nb_3Sn accelerator magnet technology carried out the in the USA within the framework of the US-LHC Accelerator Research Program (LARP) [6] or as part independently-funded base programs at Lawrence Berkeley National Laboratory [7] and Fermi National Accelerator Laboratory [8].

The NED program is divided up into two phases. The first phase, fully funded through CARE, encompasses three main work packages: Thermal Studies and Quench Protection (TSQP), Conductor Development (CD) and Insulation Development & Implementation (IDI). It also includes a working group on Magnet Design and Optimization (MDO). The Nb_3Sn conductor development will be carried through industrial sub-contracts, with financial contributions from some of the industrial partners and is aimed at a non-copper critical current density of 1500 A/mm^2 at 4.2 K and 5 T. The second phase of the NED program, for which funding is not yet secured, groups together all the tasks related to the detailed design, manufacturing and test of the model magnet.

Seven institutes are presently collaborating to NED: CCLRC/RAL, United Kingdom (IDI and MDO), CEA/DSM/DAPNIA, France (TSQP, CD, IDI and MDO), CERN, International (CD and MDO), CIEMAT, Spain (MDO), INFN/Genova, Italy (CD), INFN/Milano-LASA, Italy (TSQP and CD), Twente University, The Netherlands (CD) and Wroclaw University of Technology, Poland (TSQP).

Let us now review in detail the various work packages and report on their status.

I. Thermal Studies and Quench Protection

The TSQP work package includes two main tasks: heat transfer measurements and quench protection computations.

A. *Heat Transfer Measurements*

A key issue in the operation of superconducting accelerator magnets is the power deposited by beam losses on the magnet coils. This power determines the coil temperature margin and must be evacuated through the conductor insulation and absorbed by the cryogenics system [9-11]. The problem can only get worse for LHC luminosity upgrade and for Nb_3Sn magnet technology, in particular in the case of the conventional “wind, react & impregnate” where the magnet coils are fully potted with epoxy resin [12].

As detailed in Section IV.D, engineers are now developing new insulation based on ceramic materials [13-14]. Ceramic insulation with good wrapping capability and excellent thermal resistance during heat treatment would eliminate complex coil fabrication, lower costs and reduce fabrication time. For magnets cooled by superfluid helium, the thermal resistance created by the conventional electrical insulation of the cables forms the main thermal resistance to He II cooling [15]. Ceramic materials can have porosities much lower than those of conventional electrical insulation, which would reduce even more cooling efficiency with helium. Therefore, the NED activity includes a task to study the thermal behavior of this new ceramic insulation, as well as that of traditional polyimide and impregnated glass fiber back-up solutions.

Heat transfer measurements will be performed in superfluid helium (He II) and in normal helium (He I). The investigations will be focused mainly on two configurations. The first one, called the stack experiment, models the coil configurations reproducing the heat transfer through the insulation under mechanical and geometrical constraints [15-16]. The second one, called the drum experiment, creates a 1-D transverse heat transfer through the insulation [17]. This program should be held in the period 2005 to 2006 with 5 to 10 tests for each configuration.

In order to carry out this program, the NED collaboration is manufacturing a pressurized, He-II, double-bath cryostat (relying on the Claudet-bath principle) at Wroclaw University of Technology. As illustrated in Fig. 1, the double-bath cryostat has a classical design with the heat exchanger and the Joule Thomson valve located outside of the pressurized He II bath [18]. The cryostat is expected to be delivered in the first trimester of 2005 to CEA/Saclay where the facility will be implemented an operated.

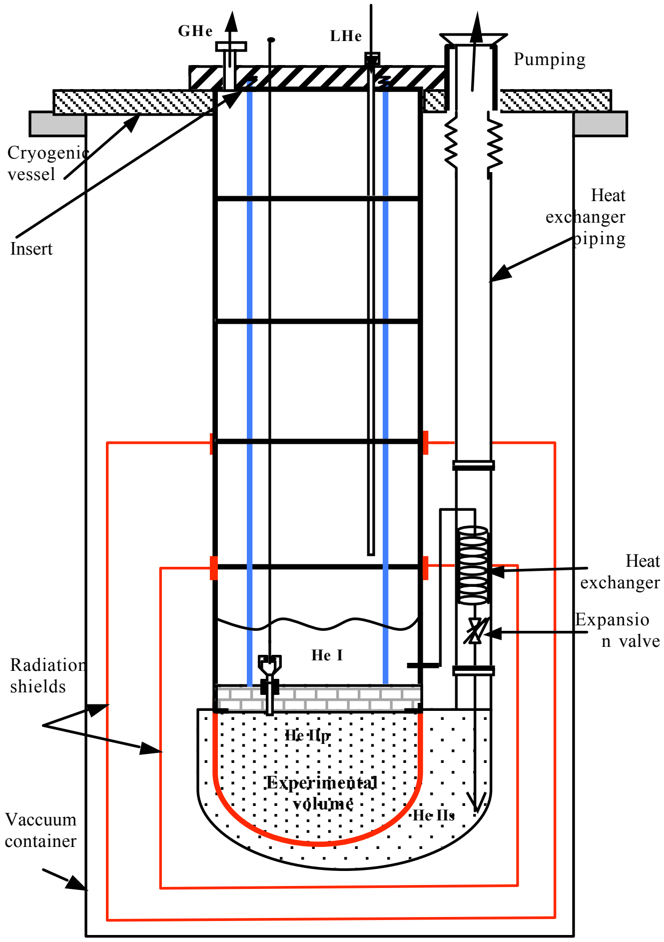

Fig. 1. Schematic of double-bath cryostat for heat-transfer measurements.

A. *Quench Protection Computations*

The main purposes of this task is:

1. to study the transition from the superconducting to the normal state of NED magnet model,
1. to design the protection system of the magnet (dumping resistors, diodes, heaters, etc.),
1. to study the extension of the protection system scheme to longer length of magnets.

The quench study will be performed by INFN/Milano-LASA using mainly the numerical code QLASA [19], cross-checked with analytical calculation. We also consider the possibility of making a comparison with other tools devoted to this purpose, like the QUABER code at CERN [20].

The QLASA code was originally developed for adiabatic multiple solenoids, both in NbTi and Nb_3Sn; it makes assumptions similar to those of the QUENCH code [21] and it can exploit different models for quench velocity calculation. Its modular and flexible structure will allow the implementation of features more suitable to our case, like a geometry and a magnetic field which are not axi-symmetric as for a solenoidal magnet. It will be also necessary to verify the correct implementation of the propagation velocity using experimental data from literature for Nb_3Sn conductors, and consider AC losses in the magnet coils.

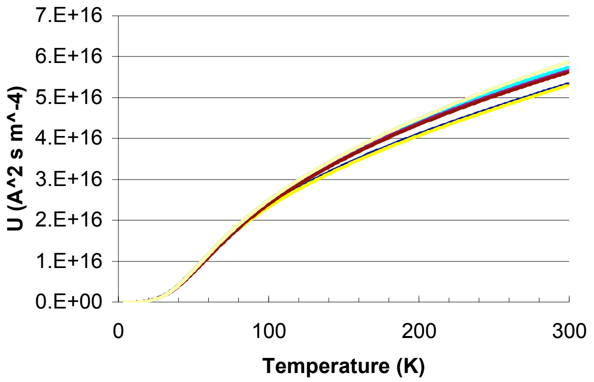

Fig. 2. Comparison of MIITs curve computations relying on different data sources for Cu and G10. The volume fractions of the conductor components are calculated according the NED reference design, *i.e.*: Cu=52%, Nb_3Sn=10%, Ta=4%, Bronze=18%, G10=16%.

In the quench study, a primary role is played by the thermal and electrical properties of materials. Consequently we have compared the properties from a number of material libraries available at LASA [21-28]. The conclusions from this comparison performed between 2 K and 300 K are:

1. for Cu, the sources agree within 25% for all properties,
1. for G10, the differences vary from 50% up to 350% for the specific heat,
1. for Nb_3Sn, Ta, Sn and CuSn only one source was available for each property.

For the evaluation of the MIITs curve these differences are probably not so significant, as it can be appreciated from Fig. 2, while they can be relevant in the case of the quench propagation velocity. As general rule, we have decided to use the data from the Cryocomp library [22] when available (Copper and G10).

A preliminary analysis based on the NED reference design (see Section III.A) is expected in December 2004. The completion of the final parametric study is scheduled for June 2005; this will investigate the impact of the following parameters: wire Cu-to-non-Cu ratio, Cu RRR, magnet length, dumping system, quench heater performance, quench-back inside coils, longitudinal and transverse quench speed.

I. Conductor Development

The CD work package started with a preliminary magnetic design, aimed at deriving meaningful strand and cable specifications. A working group on conductor characterization has been set up to oversee critical current and magnetization measurements. Also, a numerical model describing the deformation of Nb_3Sn wires under transverse load is being developed so as to simulate the cabling effects.

A. Preliminary Magnetic Design

Preliminary magnetic designs for large bore and high field dipole magnet have been studied at CERN [29] in order to define the characteristics of Nb_3Sn strands suitable to reach fields in the 13-to-15-T range. Two types of dipole magnet designs have been considered: a layer design and a slot design [30], for three apertures: 88 mm, 130 mm and 160 mm.

Figure 3(a) presents the conductor and electromagnetic force distribution in a quadrant of a 88-mm-aperture, layer-type design. The 26-mm-wide keystone cables are the same in the 2 layers and consist of 40 Nb_3Sn strands of 1.25 mm diameter and a Cu-to-non-Cu ratio of 1.25. The inner yoke radius is 125 mm and its radial thickness is 350 mm. This design as been chosen as reference. Figure 3(b) presents the conductor and electromagnetic force distribution in a quadrant of a 160-mm-aperture, slot-type design. The 20.8-mm-wide rectangular cables consist of 32 Nb_3Sn strands of 1.25 mm diameter and a copper to non-copper ratio of 1.25. The inner yoke radius is 183 mm and its radial thickness is 640 mm.

The preliminary magnetic designs have studied the impact of various parameters like strand diameter, copper-to-non-copper ratio, cable strand number and cable dimensions. The insulation thickness has been kept constant at 0.2 mm on each side of the cable. The study leads to define a strand of 1.25 mm diameter and a copper to non-copper of 1.25 as the most suitable for the development program.

Table I presents a summary of the performance for two dipole designs. The calculations are based on a critical current density of 1500 A/mm^2 at 15 T and 4.2 K in the non-copper part and a cable degradation of 10 %. It appears that the bore field B_0 stays around 14 T for a quenching field of ~15 T on the conductor. Hence, the magnet should be operated at 1.9 K to reach bore fields higher than 15 T.

TABLE I. Performance Summary for 2 Designs

Bore [mm]	Design Type	B_o[T] /I[kA]	Energy [kJ/m]	Max Pres. [MPa]	$F_x$$^{a)}$ [MN/m]	Outer Diam. [mm]
88	Layer	14.42 /28.7	1810	148	15.8	1004
160	Slot	13.87 /23.7	3959	129	21.48	1734

$^{a)}$ resultant of the horizontal forces for the overall dipole magnet.

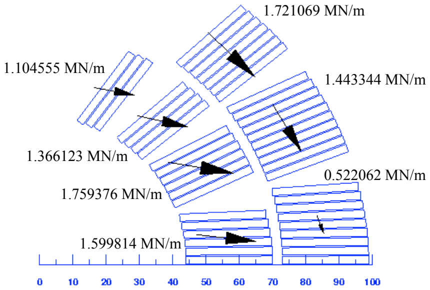

Fig 3(a). Conductors and forces in 88-mm-aperture, layer-type design.

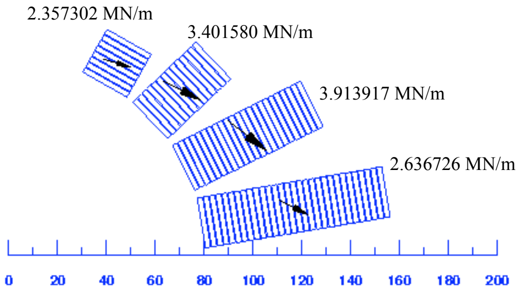

Fig 3(b). Conductors and forces in 160-mm-aperture, slot-type design.

TABLE II. SALIENT STRAND CHARACTERISTICS.

Strand diameter	1.250 mm
Effective Filament diameter	< 50 μm
Cu to non-Cu volume ratio	1.25 ± 0.10
Filament twist pitch	30 mm
Jc at 15 T, 4.2 K	1500 A/mm^2
Minimum critical current, 4.2 K	1636 A at 12 T 818 A at 15 T
RRR (after full reaction)	> 200
n-value @ 15 T and 4.2 K	> 30

TABLE III. SALIENT CABLE CHARACTERISTICS

Cable width	26 mm
Cable mid-thickness at 50 MPa	2.275mm
Keystone angle	0.22 degrees
Number of strands	40
Critical current at 4.222 K, with field normal to broad face	29440 A at 15 T 58880 A at 12 T
Minimum critical current at 4.2 K of extracted strand	736 A at 15 T 1472 A at 12 T
RRR after reaction	≥ 120
Minimum cable unit length	145 m

B. *Strand and Cable Characteristics*

A call for tender to develop high-performance Nb_3Sn strand and cable in collaboration with European industry has been issued by CERN [31]. The aim of the development program is to produce several hundred meter long cables of accelerator magnet quality, characterized by a high critical current density (1500 A/mm^2 at 15 T and 3000 A/mm^2 at 12 T and 4.2 K) in the non-copper part of the strands and a low magnetization at 2 T. For this purpose, an effective filament diameter less than 50 μm will be targeted. The billet weight should be higher than 50 kg.

Table I summarizes the main characteristics of the strand. Although the final cable dimensions will be decided later on, Table II presents the characteristics for the Rutherford cable that could be used in the reference, 88-mm-bore dipole magnet described in Section III.A. The cable critical currents in the table also assume a cable degradation of 10%.

C. *Working Group on Conductor Characterization*

Industrial development of Nb_3Sn conductors exhibiting such unprecedented properties as those listed in Tables II and III is a major ambition of the NED program and calls for reliable, reproducible and unambiguous methods for the measurement of their electromagnetic properties, such as $I_c(B)$, $M(B)$ and RRR(B=0). For this purpose, representatives of the institutes involved (CEA, CERN, INFN/Genova, INFN-Milano and Twente University) have set up a Working Group on Conductor Characterization (WGCC). The WGCC is charged with the definition and development of standardized and certified procedures to measure the mentioned properties of virgin, deformed and extracted strands and the responsibility for certification of the measured data.

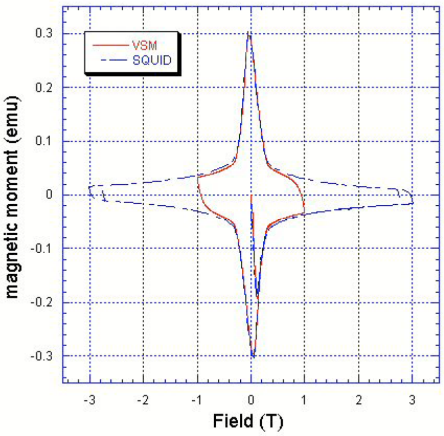

Fig. 4: First magnetization cycle on a 5-mm sample exposed to a transverse field (SQUID measurements are courtesy of C. Ferdeghini, INFM/Genova, while VSM measurements are courtesy of U. Gambardella, INFN/Frascati).

Inspired by the VAMAS program [32] and the successful development of standardized procedures for measuring the critical current of ITER conductors [33], the WGCC has initiated a cross-calibration program between the various test facilities in order to:

1. reveal possible systematic differences of $I_c(B)$ results,
2. get acquainted to preparation and measuring of very high I_c wire samples,
3. bring forward shortcomings or limitations in existing preparation or measuring procedures and agree on a roadmap to improvements,
4. set up procedures for dealing with conflicting results.

As a first step, each laboratory will independently prepare a series of wire samples and measure the $I_c(B)$ and N-value at 4.2 K (10 μV/m criterion) to the extend of their (I,B) capabilities. This first series comprises 2 samples each of: a 1.06 mm LHC NbTi wire, a binary 1.25 mm Nb_3Sn wire, and finally both a virgin and an extracted strand from a Rutherford cable made out of a binary 0.8 mm Nb_3Sn wire. Initially, each laboratory performs heat treatment, sample preparation, measurements and report according to existing procedures. Evaluation of the results of this first round in October 2004 should result in recommendations for adaptations or revisions. After the required revisions, a second round of measurements on different but also highly demanding conductors will start in November and will be evaluated within 3 months. If required, a third iteration will be performed to conclude this cross-calibration program in June 2005.

The aim of the magnetization measurements is to complement the characterization of the electrical transport properties. They will be focused on DC magnetization at low fields (B < 3 T), which can highlight the occurrence of flux jumps. Further information is related to the critical current density and to the filament lay-out. Though different kinds of samples will be analyzed, the basic measurements will be performed on short (5 mm) straight samples in transverse field, with SQUID Magnetometer and Vibrating Sample Magnetometer (VSM). As an illustration, Fig. 4 shows typical $M(B)$ curves measured on a Nb_3Sn multi-filament wire with a collective, Nb/Ta anti-diffusion barrier [34].

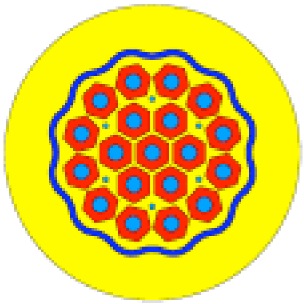

Fig. 5: Example of FE model for mechanical analysis of internal tin wires (Cu is represented in yellow, Ta in blue and Sn in light blue; the wire sub-element, made up of 200 Nb rods arranged in a pure Cu matrix, is represented in red by an average material).

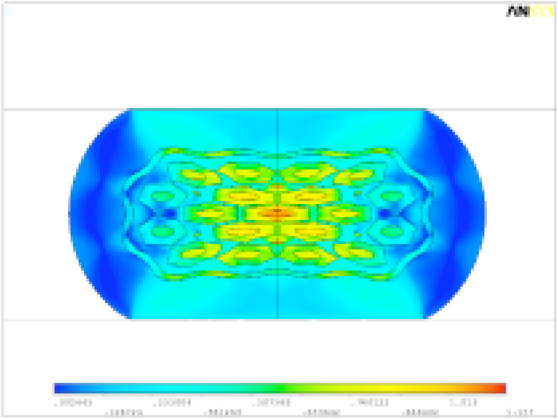

Fig. 6: Von Mises strain due to a diameter reduction of about 40%.

D. *Mechanical FE analysis of Nb_3Sn wires*

Independently on the method chosen to manufacture the Nb_3Sn wires (Internal Tin, Powder-In-Tube, and so on), the wires have to undergo a cabling process to form Rutherford cables. During this operation, the wires are largely and permanently deformed, so that possible damages, as breakages of either filaments or diffusion barriers, may arise.

One way to reduce the risk of damaging the wires during cabling is to optimize their design so as to keep stress and strain within safe limits. The natural approach to this issue is the simulation of the deformation through mechanical Finite Element (FE) analysis. To correctly set up the FE analysis, two aspects have to be deeply investigated: the material properties and the choice of the FE model, which have to be significantly representative of the wires during cabling.

Regarding the material properties, the main difficulty is that we need stress-strain curves for the different phases present in the wires, in the state where they are prior to cabling and for a range extending well beyond the elastic limit. A parallel approach is followed:

1. to find literature data of tensile properties for the metals or alloys constituting the different phases, relative to the level of hardening that the composite wire is supposed to have undergone, based on estimated values of Cu RRR,
2. to experimentally assess, from a wire cross section, the indentation properties of the individual phases at a local scale through nanohardness measurements, thereby allowing the determinations of load-displacement curves.

The mechanical FE model, developed by INFN/Genova, is not of less importance. In Fig. 5., the FE model of a typical, un-reacted, internal tin wire is shown. The simplest deformation which can be applied is an uni-axial compression between two parallel planes. The result is shown in Fig. 6 in terms of Von Mises strain corresponding to a 40% reduction in diameter of the original wire. The maximum strain value, higher than 100%, is in the central tin well, and the tantalum barrier is strained up to 75%; such values demonstrate the importance of optimizing the wire configuration. With this aim, it is important to identify the conditions of the load application which best simulate the wire during cabling. For instance, compressing three adjacent wires would lead for the central one to a different strain map than the one shown in Fig. 6. Finally, we will improve the wire shape keeping, under those conditions, the stress and strain within safe limits

II. Insulation Development And Implementation

A. *Aim of study*

The objective of the Insulation Development Program for NED is to improve insulation techniques in order to improve both industrial manufacture capability and magnet performance. The state of the art insulation processing technology is not sufficiently well developed to enable large-scale production of accelerator magnets by the "wind and react" process [12]. The Rutherford Appleton Laboratory (RAL) is responsible for the development of "conventional," glass or quartz tape, insulation techniques, while CEA is responsible for the development of an "innovative," ceramic-based insulation system [14]. It is intended that a direct comparison of conventional insulation with the innovative system will be performed as part of the program.

The program strings will aim to develop manufacturing techniques through improved durability during cable insulation and coil winding and reliability following heat treatment. Magnet performance improvement will target mechanical, radiation and electrical properties of the magnet matrix. In particular, mechanical strength and radiation resistance will need to be advanced in order to meet the high field (15 T) and high radiation environment foreseen for the LHC luminosity upgrade or for future accelerators. These advances will require new processing techniques, new and improved testing procedures and new materials, *e.g.*, the use of cyanate ester matrices to improve radiation resistance and new fillers to improve mechanical performance at low temperatures.

B. *Engineering specifications*

A basic insulation specification for a 15 T dipole has been developed in consultation and is summarized in Table IV [35]. It is not feasible within the scope of the NED activity to explore all the parameter space within this specification. The goal is therefore to select a small range of process variables and materials and subject these to a full range of tests. As we go along, we aim to define and prove standard test specimens with standard tests and develop new testing techniques for important properties such as work of fracture.

TABLE IV. INSULATION SPECIFICATIONS

GENERAL	Design
Insulation thickness per cable	0.2 mm
Winding compatibility: Capable of being applied to the cable and formed into a dipole winding by a semi-automatic winding system	Minimal fraying or abrasion during winding
Conductor bend radius minimum	20 mm
Compatible with Nb3Sn heat treatment cycle	Minimal degradation of basic components
Thermal cycles to low temperature: 300K– 4.2K	10
Running cycles: ramp to max compressive stress	100
For conventional organic insulation scheme and innovative scheme if applicable: ability to be impregnated with a liquid of viscosity 200 mPa.s	200 mPa.s

MECHANICAL1)	Design
Applied conductor winding load	500 N
Compression during heat treatment	20 MPa
Coil re-shaping after heat treatment before impregnation	20 MPa
Compressive stress after completion of coil fabrication – at 300K and 4K.	200 MPa
Shear: Short-beam shear strength at 4K	50 MPa
Tension: Transverse tensile strength of insulation laminate at 4K	25 MPa
Fracture, need to know properties at 300K and 4K, specification to be determined	TBD

1) design stresses are before irradiation.

THERMAL	Design
Transverse thermal contraction (integrated between 300 K and 4K)	0.003 to 0.004
Thermal conductivity at 4.2K	50mW/m/K

ELECTRICAL	Design	Failure
Breakdown voltage inter-turn tested in helium at 300K	1000V 2500V/mm	2000V 5000V/mm

RADIATION	
The failure properties above must be achieved following doses expected during 10 years' running.	
	Range
Dose [36]	50 to 600 Mgy
Fluence >0.1MeV	2.5 to 30x10^{16}cm^{-2}

C. *Test program for conventional insulation*

For magnet manufacture we have identified fiber sizing as a key area for development to improve the viability of industrial Nb_3Sn magnet fabrication. Sizing is applied to glass fibers at the time of fiber manufacture in order to allow industrial fabrication of tape or fabric. Removal of sizing before magnet manufacture to prevent carbonization during Nb_3Sn heat treatment results in substantial degradation of the tape insulating handling properties. Palmitic acid has been used for years at LBNL to act as a lubricant in coil winding [12], As part of the development and test program we propose to study existing sizing chemistry and alternatives, assess and quantify the effect of carbon residue on electrical and mechanical properties. These sizing variants will be subjected to the standard tests.

For magnet performance, material developments which may enhance conductor stability through improved insulation toughness will be studied. This will include radiation hard resin alternatives such as cyanate esters and improved filler materials such as nanoclays and dendritic polymers. The conventional test program will be executed in four phases; development of techniques and tests based on standard specimens; definition of materials parameters to be studied; screening tests to determine the potential of materials; comprehensive tests on selected materials.

D. *Test program for innovative insulation:*

As explained above, the conventional insulation includes vacuum impregnation of glass fibers with an organic material, for instance epoxy, after the heat treatment required to form the Nb_3Sn. This multi-step process is costly and raises the failure risk. As an alternative, CEA/Saclay has been working on an innovative insulation, relying on a pre-impregnated, glass fiber tape, wrapped directly on the un-reacted cable prior to heat treatment, and eliminating the need for a subsequent vacuum impregnation. The feasibility of this insulation has been demonstrated [14]. Developments are now continuing to optimize the mechanical properties of this insulation and to characterize it according to the required specifications [35].

The NED innovative insulation test program will include two phases. The first one will be devoted to tape weaving trials. During the previous development phase, the nature and weaving of the tape have been found to be critical parameters for the final quality of the insulation. The aim is to find an industrial tape better suited to this application. The thickness, the quality and the reliability of the pre-impregnation, will be some of the qualification parameters.

The second phase will concern characterization tests. Mechanical properties have to be checked, beginning with the properties in compression, which are the most constraining ones for the magnets designs under considerations. In parallel, the electrical properties will also be verified.

III. MAGNET DESIGN AND OPTIMIZATION

The aim of this study is to optimize the design of high-field dipole magnets for particle accelerators, taking into account both technical and economical criteria. For the time being, the focus is on Nb_3Sn technology, but the results may also be useful for other brittle superconductors.

A Working Group on Magnet Design and Optimization (WGMDO) has been established, made up of representatives from CCLRC, CEA, CERN, and CIEMAT. In a brainstorming session held last May, a number of magnet configurations has been selected as candidates, including classical and novel arrangements such as: layer-type and slot-type cos-θ, window-frame, common coil, motor-type, double-helix, slotted dipole and ellipse-type racetrack. Two of the alternative designs under consideration are illustrated in Fig. 8. The WGMDO will also compare the performance of the calculation tools used in magnet design, and contribute to a European material properties database relevant for these computations.

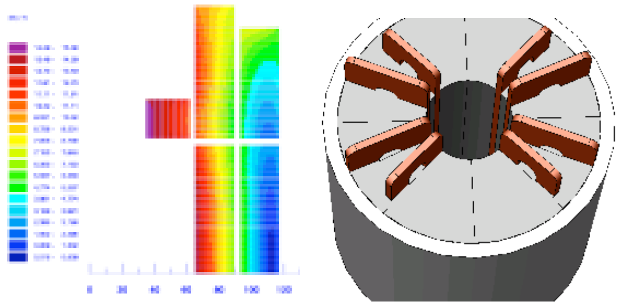

Fig. 8. Two alternative coil arrangements to be optimized and compared:: left, window-frame (proposed by CEA/Saclay), and right, motor-type (proposed by CIEMAT).

TABLE V. SALIENT DESIGN PARAMETERS

Peak field on conductor	15	T
Aperture	88-130-160	mm
Superconductor Jc	3000	A/mm^2 @ 4.2K and 12 T
	1500	A/mm^2 @ 4.2K and 15 T
Cu-to-non-Cu ratio	1÷2	
Operating margin	10÷20	%
Filling factor of cable	87	%
Insulation thickness	0.2	mm per conductor face
Cabling degradation	10	%
X-section multipoles	A few10^{-4}	@ 2*aperture/3
Overall coil length	1.3	m
Peak stress	150	MPa
Max coil deformation	<0.05	mm (due to Lorentz forces)
Peak temperature	300	K (quench)
Peak voltage to ground	1000	V (quench)
Peak inter-turn voltage	100	V (quench)

The present plan calls for each institute to completely study one or two solutions based on the design parameters listed in Table V. The terms of comparison between the different solutions have also been established:

1. magnetics: central and peak fields, nominal current, field quality, tunability, magnetic vs. overall length, margin.
2. mechanics: change of pre-stress during cooling down, peak stress, Lorentz forces.
3. quench: self-inductance, stored magnetic energy, peak voltage and temperature.
4. fabrication: sensitivity to manufacturing tolerance, manufacturability, coil end complexity, minimum bending radius (parallel and perpendicular), superconductor volume efficiency, twin/single aperture and minimum distance, number of splices, cost.

IV. CONCLUSION

The Next European Dipole Activity attempts the integration of high-field accelerator magnet R&D in Europe in preparation for LHC upgrade or a future accelerator. Although not funded through the construction phase, the program is well under way and is triggering the desired synergies.

REFERENCES

[1] http://esgard.lal.in2p3.fr/

[2] J. Strait, M. Lamm, *et al.*, “Towards a new LHC interaction region design for a luminosity upgrade,” *Proc. of 2003 Particle Accelerator Conference*, pp. 42-44, 2003.

[3] A. Devred, “High field accelerator magnets beyond LHC,” *Proc. of 2003 Particle Accelerator Conference*, pp. 146-150, 2003.

[4] A. Devred, D.E. Baynham *et al.*, “High field accelerator magnet R&D in Europe,” *IEEE Trans. Appl. Supercond.*, Vol. 14 No. 2, p. 339, 2004.

[5] D. Leroy, G. Spigo, *et al.*, “Design and manufacture of a large-bore 10-T superconducting dipole for the CERN cable test facility,” *IEEE Trans. Appl. Supercond.*, vol. 10, no. 1, pp. 178-182, March 2000.

[6] A. Devred, S.A. Gourlay and A. Yamamoto, “Future accelerator magnet needs,” to appear in these Proceedings.

[7] A.F. Lietzke, S. Caspi, *et al.*, “Test results of HD1b, an upgraded 16 Tesla Nb$_3$Sn dipole magnet,” to appear in these Proceedings.

[8] A.V. Zlobin, G. Amrosio, *et al.*, “Development of Nb$_3$Sn accelerator magnets at Fermilab,” to appear in these Proceedings.

[9] L. Burnod, D. Leroy, *et al.*, “Thermal modeling of the LHC dipoles functioning in superfluid helium,” *Proc. of 1994 European Particle Accelerator Conference*, pp. 2295-2297, 1994.

[10] G. Ambrosio, F.M. Ametrano, *et al.*, “Stability of a NbSn low-beta quadrupole in the LHC radiation environment,” *Proc. of 1996 European Particle Accelerator Conference*, pp. 2293-2295, 1996.

[11] A.V. Zlobin, G. Ambrosio, *et al.*, “Conceptual design study of Nb$_3$Sn low-beta quadrupoles for 2nd generation of LHC IRs,” *IEEE Trans. Appl. Supercond.*, Vol. 13. No. 2, pp. 1266-1269, 2003.

[12] A. Devred, “Insulation systems for Nb$_3$Sn accelerator magnet coils manufactured by the wind & react technique,” *IEEE Trans. Appl. Supercond.*, Vol. 12 No. 1, pp 1232-1237, 2002.

[13] J.A. Rice, P. E. Fabian and C.S. Hazelton, "Mechanical and electrical properties of wrappable ceramic insulation," *IEEE Trans. Appl. Supercond.*, Vol. 9 No. 2, pp. 220-223, 1999.

[14] A. Puigségur, F. Rondeaux, *et al.*, “Development of an innovative insulation for Nb$_3$Sn wind & react coils,” *Adv. Cryo. Eng. (Materials)* Vol. 50, pp. 266-272, 2003.

[15] C. Meuris, B. Baudouy, *et al.*, “Heat transfer in electrical insulation of LHC cables cooled with superfluid helium,” *Cryogenics,* Vol. 39, pp. 921-931, 1999.

[16] N. Kimura, A. Yamamoto, *et al.*, “Heat transfer characteristics of Rutherford-type superconducting cables in pressurized He II,” *IEEE Trans. Appl. Supercond.*, Vol. 9 No. 2, pp. 1097-1100, 1999.

[17] B. Baudouy, “He II heat transfer through superconducting cables electrical insulation,” *Cryogenics*, Vol. 40, pp. 127-136, 2000.

[18] F. Michel, B. Baudouy and B. Hervieu, private communication, 2004.

[19] L. Rossi, M. Sorbi, “QLASA: a computer code for quench simulation in adiabatic multicoil superconducting windings,” INFN/TC-04/13, July 2004, http://www.lnf.infn.it/sis/preprint/pdf/INFN-TC-04-13.pdf

[20] D. Hagedorn, F. Rodriguez-Mateos, "Modelling of the quenching process in complex superconducting magnet systems," *IEEE Trans. Magn.*, Vol. 28 No.1, pp. 370-373, 1992.

[21] M.N. Wilson, *Superconducting Magnets* (Section. 9.5), Oxford, UK: Clarendon Press, 1983.

[22] Cryocomp Library, © 1995 P. Eckels, available from from Cryodata, Inc., www.cryodata.com

[23] “Bubble Chamber Group – Data Handbook.”

[24] R.P. Reed and A.F. Clark, *Materials at Low Temperatures*, Metals Park, OH: American Society for Metals, 1983.

[25] M.B. Kasen, *et al.*, “Mechanical, electrical and thermal characterization of G-10CR," *Adv. Cryo. Eng.*, Vols. 26 and 32.

[26] “Handbook of Chemistry and Physics”, CRC Press.

[27] *Handbook on Materials for Superconducting Machinery*, Columbus, OH: Metals and Ceramics Information Centre Battelle, p. 979, 1977.

[28] Measurements performed at LASA.

[29] D. Leroy and O. Vincent-Viry, “Preliminary magnetic designs for large bore and high field dipole magnets,” Note AT-MAS 2004-22, CERN, 2004.

[30] A. Patoux, J. Pérot and J.M. Rifflet, “Test of new accelerator superconducting dipoles suitable for high precision Field,” *IEEE Trans. Nucl. Scien.*, Vol. NS-30 No. 4, pp. 3681-3683, 1983.

[31] Technical Specification for the Superconducting Cable for the Next European Dipole (NED), IT-3327/AT/CARE, June 2004.

[32] H. Wada,, C.R. Walters, *et al.*, “VAMAS intercomparison of critical current measurements on Nb$_3$Sn superconductors: a summary report,” *Cryogenics*, V. 34 N. 11, pp. 899-908, 1994.

[33] L.F. Goodrich and A.N. Srivastava, “A simple and repeatable technique for measuring the critical current of Nb$_3$Sn wires,” *Proc. of 7th International Workshop on Critical Currents in Superconductors*, pp. 609-612, 199.

[34] M. Durante, P. Bredy *et al.*, “Development of a Nb$_3$Sn multifilamentary wire for accelerator magnet applications,” *Physica C*, Vol. 354, pp. 449–453, 2001.

[35] S. Canfer, “NED insulation specifications,” CARE-NED-IDI-Document RAL-001, CCLRC, 2004.

[36] N. Mohkov, private communication, 2004, http://supercon.lbl.gov/erice/