The EuCARD High Field Magnet project

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Abstract— **In the EC FP7 program EuCARD (European Coordination for Accelerator Research & Development) the subject of work-package 7 is High Field Magnets. The aim of the HFM work-package is to develop technologies for magnets in the range 13 T – 20 T for accelerator applications like HL-LHC and HE-LHC. The work-package foresees construction of a 13 T dipole with an aperture of 100 mm, an HTS dipole insert with ΔB = 6 T, an HTS current link and a helical undulator. The work-package has 12 European partners and the funding is shared between the EC and the partners. This contribution describes the aims of the work-package, the status of the work and the structure of the collaboration.**

Index Terms—**superconducting magnet, niobium-tin, high temperature superconductors.**

I. THE EUCARD PROJECT

THE EuCARD project is an Integrating Activity co-funded by the European Commission under the 7th Framework Programme for a duration of four years, starting April 1st, 2009 [1]. It has 37 European partners with as its main goal to upgrade the large European research accelerators by R&D on innovative concepts and techniques. This common venture will strengthen durable collaboration among the partners and will contribute to the development of world-class infrastructures, one of the main features of the European Research Area. EuCARD consists of one management work-package, three communication and networking work-packages, two trans-national access work-packages and five joint research activity work-packages. The development of High Field Magnet technology is the subject of work-package 7 (WP7) of EuCARD.

II. WORK-PACKAGE 7: HFM: SUPERCONDUCTING HIGH FIELD MAGNETS FOR HIGHER LUMINOSITIES AND ENERGIES

The LHC has at present the highest nominal field accelerator magnets in operation. The conductor used is Nb-Ti, which limits the flux density in the magnet bore to 10 T. In order to upgrade the LHC with new larger aperture low-beta insertion quadrupoles, Nb_3Sn conductors will have to be used. This luminosity upgrade, the High Luminosity LHC (HL-LHC) is scheduled in 10 years. After the LHC one of the options is to build in the same tunnel a new proton collider, High Energy LHC (HE-LHC), with 2-3 times the energy of the LHC [2]. For this machine (HE-LHC), dipoles with a flux density of ~20 T will be needed. A possibility is to use a layered coil with an outer coil of 14 T in Nb-Ti and Nb_3Sn conductor and an (6 T) inner coil of HTS. This project is envisaged on a > 20 years time scale. High fields will also be needed for other HEP projects like the neutrino factories and the muon collider. For all these projects, high current density and temperature margin will be needed to get the flux density requirements and to withstand the radiation heating.

Current density and temperature margin are also the limiting parameters for undulators and wigglers with small periods for which Nb_3Sn as conductor is to be tested out.

The EuCARD HFM work-package [3] runs from 1st April 2009 for 4 years with a total budget of 6.4 M€ from which 2.0 M€ will be contributed by the EC. The 12 partner institutes are: CERN (Int), CEA-Saclay (Fr), CNRS-Grenoble (Fr), COLUMBUS (It), BHTS (De), INFN-Milano-LASA (It), KIT (De), Wroclaw University of Technology (Pl), Southampton University (UK), STFC-Daresbury (UK), Tampere Technical University (Fi) and Université de Genève (CH).

The WP7 has one management and five R&D tasks:

1) Coordination and communication.
2) Support studies for the high field dipole model with two sub-tasks: “thermal studies” and “insulation radiation hardness”.
3) High field model: the design construction and test of a dipole magnet with an operational flux density B = 13 T in an aperture with a diameter of 100 mm, made with Nb_3Sn conductor. This magnet is intended to upgrade the cable test station FRESCA at CERN (FRESCA2).
4) Very high field dipole insert: fitting inside the magnet of task 3, which provides the background field, the aim is to approach 20 T. The insert will be made with HTS conductor and have a flux density contribution ΔB = 6 T.
5) High Tc superconducting link: HTS powering links for the LHC.
6) Short period helical superconducting undulator (ILC e^+ source).

III. PREPARATION FOR THE CONDUCTOR OF THE HIGH FIELD MODEL

A targeted development of the Nb_3Sn strand for a project to upgrade the FRESCA magnet started in 2004 with the Next European Dipole project (NED) in the framework of the FP6-CARE endeavour [4]. NED placed two contracts in European industry for the development of Nb_3Sn strand with a diameter of 1.25 mm, a critical current density at 4.2 K, 15 T of 1500 A/mm^2 in the non-copper part and an effective filament diameter of ≤ 50 μm. After six years of development, one of the firms, EAS-Bruker, succeeded in fulfilling the

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requirements with a strand made with ‘Powder In Tube’ technology (PIT) [5]. The Nb_3Sn PIT technology was started at the Energy Research Centre of the Netherlands (ECN) in the 1980’s. Afterwards, this technology was transferred to the firm Shape Metal Innovation (SMI). For the NED contract, EAS-Bruker acquired the necessary technology from SMI and has performed the industrialization step. For the High Field Dipole, in the last two years EAS-Bruker has developed a 1 mm diameter Nb_3Sn PIT strand as a sequel to the NED strand development. This strand has been widely studied and the work has been published (see [6],[7],[8],[9],[10]).

In the US, for the past 10 years the DOE has financed the development of Nb_3Sn strand for High Energy Physics applications. The conductor that is presently used for LARP (LHC Accelerator Research Program), 0.7 mm and 0.8 mm diameter strands made with the Restacked Rod Process (RRP) by OST (Oxford Superconducting Technology), is a result of this development [11], [12]. For the High Field Dipole of EuCARD-WP7, OST is presently developing a 1 mm diameter RRP strand.

IV. PREPARATION FOR THE MAGNET CONSTRUCTION OF THE HIGH FIELD MODEL: SHORT MODEL COIL

The development at LBNL of Nb_3Sn magnets showed that in order to learn the manufacturing of the coils and the handling of the “bladder and key” type support structure, one should start with building small racetrack coils [13]. In 2007, at the end of the NED project, a collaboration among CEA, CERN, STFC-RAL and LNBL was formed for the Short Model Coil (SMC) project. The SMC consists of two double pancake racetrack coils in a bladder-and-key type structure. The conductor is a 1.25 mm diameter strand in a 14 strand cable. The first two coils (SMC1), using an early production (Alstom) Internal Tin conductor, were tested in October 2010 and could be ramped up to 40% of the short sample current only. A second set of coils (SMC3, as SMC2 is a separate CEA project with ceramic insulation), using an early production PIT conductor, profited from the experience gained with the first two coils and was of much better quality (see Fig. 1). The test of this second set was done in June 2011 in the new vertical test station at CERN and the magnet went up to >95% of the short sample current at 4.2 K, corresponding to a field on the coil of 12.5 T. A detailed report of this magnet can be found in [14], [15]. More SMCs will be built to certify the coil building technology with the final cable and insulation scheme for the High Field Model.

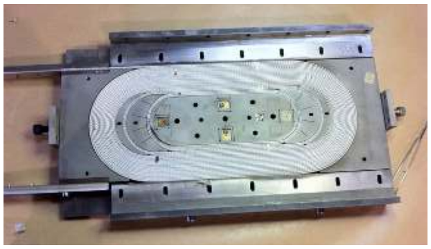

Fig. 1. Short Model coil, second coil set: a reacted double pancake coil inside the reaction mould.

V. HIGH FIELD MODEL

A 13 T magnet with a 100 mm bore is a challenge. When comparing with existing magnets (see Fig. 2) the FRESCA2 magnet is, both on the field and on the aperture axis, at the far end. Two approaches for the coil for high field magnets exist: the classical one, with a cosΘ coil and the innovative one with a block coil. After a study the collaboration decided in June 2010 to take a block coil design with flared ends inspired by the results of HD2 at LBNL [16]. This choice opens the road for future designs at even higher fields. Some of the issues to be solved are: the conductor quality and availability, the maximum field on the coils, the forces and stresses in the coil and the structure, the stored energy and the quench protection and finally the “make-ability” of the magnet.

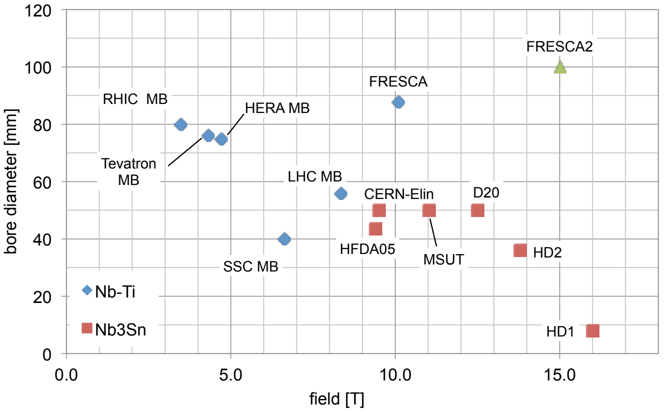

Fig. 2. Field performance and bore diameter for existing dipole magnets. For magnets with Nb-Ti conductor (blue diamonds), that are mostly in working accelerators, the field is the nominal operational field (which is around 80% of maximum achievable field), for the Nb_3Sn development magnets (red squares) the field is the maximum achieved in the magnet bore. For Fresca2 the indicated field is 92% of the short sample field such as to use a similar condition as for the other Nb_3Sn magnets.

An external committee reviewed the design in January 2011 after which the construction drawings were made and the tooling design started [17]. The main parameters of the dipole can be found in Table I. In Fig. 3 the cross section of the magnet can be seen [18]. The first magnet will be tested at CERN by the end of 2013.

TABLE I DIPOLE PARAMETERS

Parameter	value	Unit
Number of turns per pole	156	-
Aperture diameter	100	mm
Magnet diameter	1030	mm
Magnet yoke length	1600	mm
Strand diameter	1	mm
Number of strands per cable	40	-
Cable dimensions	21.4 x 1.82	mm^2
Number of strands per cable	40	-
Design field	13	T
Design current	10800	A

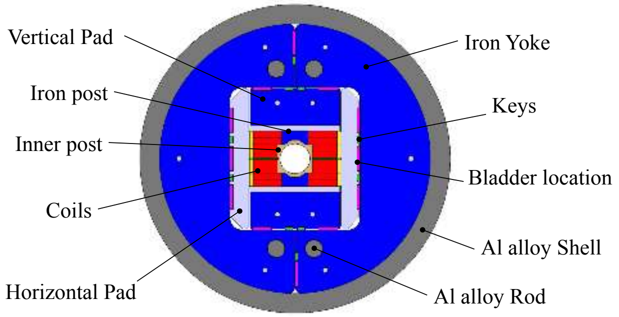

Fig. 3. Dipole cross section

VI. VERY HIGH FIELD DIPOLE INSERT

Dipole magnets in the 20 T range have not yet been successfully built. As a very first attempt to get into the 20 T range in a cost effective way, the idea was to equip the FRESCA2 magnet with an HTS insert. For such an ambitious magnet neither field quality nor available aperture constraints were applied. The development of the insert is planned via three phases, formulated as sub-tasks:

1) conductor development, which implies: specification, characterization and quench modelling;
2) coil manufacturing and development, which implies: design, construction and test of solenoid insert coils;
3) the actual insert: design, construction and test of dipole insert coils.

Initial calculations showed that, in order to get a B = 6 T flux density contribution from the insert, an overall current density of 250 A/mm^2 - 300 A/mm^2 is needed in the coil.

The two main candidate conductors for the insert are Bi-2212 round wire and YBCO tape. Both display a *Jc* that is nearly constant up to well over 20 T. The advantage of Bi-2212 wire is the possibility to make Rutherford cables. The disadvantages are the current density and the very sensitive heat treatment after winding. YBCO has as advantage to be able to provide the current density and is reasonably stress robust but the disadvantage is that it comes in the form of a thin tape for which a high current cable remains difficult. After weighing all the arguments the collaboration decided to use YBCO tape. Double tape will be used, soldered face-to-face through a Cu tape. Two double tapes will be wound in parallel and transposed between the 2 poles to force equal current sharing. The insert [19] will be housed in a 3 mm thick stainless steel tube and will be fixed to the end plates of the FRESCA2 magnet, thus being mechanically independent from the magnet bore. In order to get experience with the conductor several small solenoids consisting of pancake coils, will be manufactured. The aim is to test the conductor manipulations, the splice connections and the quench behaviour [20].

In Table II the main parameters of the insert are listed and in Fig. 4 views of the insert coil can be seen.

Solenoid coils are being built this year. An YBCO double pancake has reached a *Jc* of 1000 A/mm^2 at 18 T. The insert will be tested both in stand-alone mode and in the FRESCA2 magnet in 2014.

TABLE II INSERT PARAMETERS

Parameter	Value	Unit
Number of turns per pole	170	-
YBCO tape width	12	mm
Nominal field contribution	6.1	T
Nominal current	2780	A
Straight section length	274	mm
Overall coil length	700	mm
Coil width	43.8	mm
Aperture width	15	mm
Horizontal force @ 19 T	6.8	MN/m

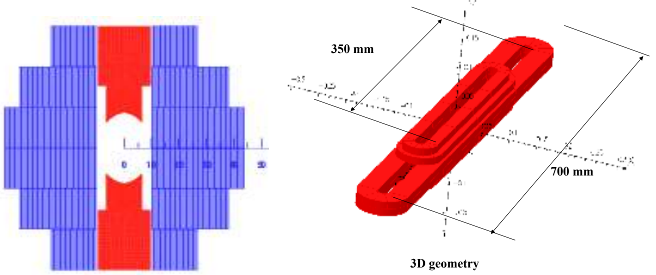

Fig. 4. Left: cross section of the insert coil. Right: 3D layout of the coil.

VII. HIGH TC SUPERCONDUCTING LINK

At the start of EuCARD the aims of the task were listed as:

1) studies on thermal, electrical and mechanical performance of HTS conductors;
2) design and test of electrical contacts: HTS-HTS and HTS-Cu;
3) design and assembly of a 20 m long HTS multi-conductor 600A link as prototype for the LHC in IP7.

The 600A link was seen as an option for the LHC upgrade to cope with the limited temperature margin of the existing Nb-Ti link. Meanwhile, the LHC running conditions have shown that electronics inside the tunnel or in cavities near the tunnel are sensitive to radiation induced single event upsets. This has made the development of superconducting links a priority item in the effort to move power converters and feed-through boxes out of the way. The task is thus ahead of schedule and has become part of more general CERN efforts for HTS link development.

Fig. 5. Left: cable with 25 channels of twisted pairs for 600 A. Right: short test piece of YBCO tape twisted pair cable.

There are three candidate conductors for the EuCARD link: YBCO tape, MgB$_2$ wire and tape, and Bi-2223 tape. For the tape based design an example can be found in Fig. 5 for a 25 channel cable of twisted pair YBCO tape [21]. Cables have been designed, assembled and tested in short lengths at liquid helium temperature, at CERN, and in a variable temperature range, at Southampton University. A 20 m prototype will be tested in a CERN test station. In parallel HTS and MgB_2 conductors are being assessed for usage in 6 kA and 13 kA links.

VIII. SHORT PERIOD HELICAL UNDULATOR

The aim of the short period helical undulator task is to reach bore flux densities beyond the 1.15 T flux density achieved with Nb-Ti conductor and to have a larger temperature margin in short period undulators (11.5 mm winding period on a 6.35 mm bore). The primary challenges are:

1) the Nb_3Sn insulation system which has to be compatible with the heat treatment at 650°C;
2) the insulation has to be sufficiently thin to achieve high overall current density in the winding groove;
3) the strand stability at high current density and low field.

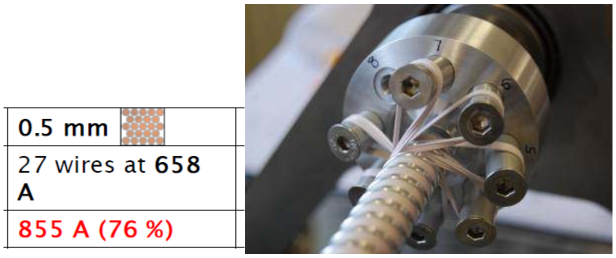

Fig. 6. Left: winding layout in the undulator groove. Right: short test winding for a helical undulator.

Winding tests with a wire of 0.5 mm diameter have shown to be feasible. In Fig. 6 a test model of a helical winding can be seen. The initially selected RRP strand showed instabilities during characterisation measurements below 5 T and thus lower current density strand are being studied. The stability and the current density of commercially available strands will be a trade-off determining whether the switch of Nb-Ti to Nb_3Sn will be worthwhile from the point of view of the field.

IX. SUPPORT STUDIES

Thermal and radiation resistance issues apply to all magnet constructions and have therefore been addressed in a separate task "Support Studies".

A. Radiation resistance certification for radiation resistant coil insulation and impregnation.

Future machines like HL-LHC, the neutrino factory and the muon collider will be subject to very high radiation doses. For the radiation resistance studies the scaled fluencies and resulting dose of 50 MGy from one of the HL-LHC models was taken as benchmark value [23].

Four insulation materials (glass fibre-impregnation composites) were selected and they will be irradiated with a 6 MeV electron beam at 77 K to a dose of 50 MGy to select the best radiation resistant materials. After that, outside the scope of EuCARD, these materials will have to be certified for the specific particle fluencies of the application for which they will be used.

B. Thermal models and design.

The impregnated coils and the bladder and key structure of Nb_3Sn magnets show a different thermal behaviour than magnets with Nb-Ti coils with collar-based structures. Several models are being made to describe the heat flow at 4.2 K and 1.9 K in the FRESCA2 magnet. In a 2D model, where helium is treated as a special case of heat conduction, the temperature profile in the magnet under steady state losses (as e.g. during ramping the magnet) has been calculated. A similar 2D model was used to simulate the cool-down of the magnet. To limit the maximum temperature differences in the structure and coil to 20 K a 3-day cool-down scenario is favoured. Presently a 2D model with HeII and a 3D model are under development. The outcome of the thermal modelling is used for the design of the FRESCA2 magnet [22], [24].

The heat conduction properties of various insulation materials (selected by the radiation resistance task) are being measured in the 1.9 K - 4.2 K temperature range.

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