THE ACTIVITIES OF ENEA ON SC DEVELOPMENTS

G. Celentano[(1)], *A. della Corte*[(1)], *A. Di Zenobio*[(2)], *V. Galluzzi*[(1)], *P. Gislon*[(1)], *A. Mancini*[(1)], *L. Muzzi*[(1)], *A. Rufoloni*[(1)], *S. Turtù*[(1)], *A. Vannozzi*[(3)]
[(1)] EURATOM-ENEA Association, ENEA C.R. Frascati, Via E. Fermi 45, 00044 Frascati (RM), Italy
[(2)] Edison S.p.A., Foro Buonaparte 31, 20121 Milano, Italy
[(3)] INFM-Physics Department, Univ. of Salerno, 84081 Baronissi (SA), Italy

Abstract
ENEA, as an EURATOM Association, is involved since 1968 in the R&D programs for the development of superconducting strands and conductors for the high field magnets of a Fusion reactor. In this frame, the activities range from strand and sub-cable characterization, to sub-size coil performance testing, from industrial cable and joint manufacturing monitoring to the participation to the international campaigns on full-size conductors and model coil characterizations and to the experiments on current distribution in superconducting cables.
On the high critical temperature superconductors development side, ENEA collaborates since 1987 with Italian Universities and Institutions on YBCO and BiSSCO coated conductors, as well as on MgB_2, making use of a large and functional set of facilities for film deposition and characterization. In this paper, an overview of the research activities which are carried out at the Superconductivity Division of ENEA is presented.

1. INTRODUCTION

Since 1968 ENEA Superconductivity Division operates in the field of applied superconductivity research. Main topics of its scientific activity are the development and characterization of superconductor (SC) devices, strands and cables, the design of conductors and magnets for large scale and high field applications, and the experimental study of the stability and operation limits of prototype coils and conductors. Within this frame, the collaboration with Italian industries contributed during these years to develop the know-how for the manufacturing of SC strands and cable and to acquire the ability of manufacture SC magnets.

In the last 15 years the ENEA activities have been mainly devoted to the research and development programme of the International Thermonuclear Experimental Reactor (ITER) project, culminated in the manufacturing and test of the Toroidal Field and Central Solenoid Model Coils.

The study and development of the high Tc materials has taken, since their discovery in 1987, an increasing space in the group activities, the manufacturing of YBCO tape by means of techniques of thin films deposition and its structural and electrical characterization being the main subject. Also in this field, the collaboration with Italian companies, research agencies and Universities led to significant results.

2. CHARACTERIZATION OF STRAND, SUB-CABLES, FILMS AND BULK SAMPLES

2.1 Structural characterization

2.1.1 X-rays

X-ray diffraction (XRD) analyses allow to control samples structural properties and phase compositions. The lattice parameter determination provides stoichiometric and residual stress information, while texture analyses reveal preferred distribution of crystallographic orientations.

In the development of coated conductors, X-ray diffraction are widely used to extabilish the optimum deposition conditions in order to obtain a good epitaxial growth and stoichiometric phases of superconducting films and buffer layers, and to determine deformation and annealing procedures for the enhancement of cube texture in metallic substrates.

The X-ray θ-2θ scans are performed using a Rigaku Geigerfex diffractometer with Cu-Kα radiation. X-ray diffraction measurements for texture analysis are performed on a Seifert XRD 3003 PTS, equipped with a four circle goniometer, suitable for texture and for residual strain measurements (fig. 1).

Fig. 1: the SEIFERT diffractometer with a four circle goniometer.

2.1.2 Scanning Electron Microscopy

A high resolution scanning electron microscope (SEM) is used for morphological and structural characterizations of superconducting thin films (mainly $Y_1Ba_2Cu_3O_{7-x}$) grown on single-crystal ($SrTiO_3$) or metallic (Ni-alloy) substrates (fig. 2).

A field emission gun SEM LEO1525 is used; its resolution is 1.5nm at 20kV and 2mm working distance or 3.5nm at 1kV and 2 mm working distance, magnification ranging from 20x up to 500kx.

The scanning electron microscope is also equipped with OXFORD INCA Crystal Electron BackScatter Diffraction (EBSD) and Energy Dispersive X-ray Microanalysis (EDX) systems.

The orientation of crystals down to 150nm can be resolved using the EBSD system and quantitative X-ray analysis can be performed by a microanalysis suite.

EBSD is a very important tool for YBCO-based coated conductors analysis, since crystallographic orientations, grain-to-grain misorientations, texture trends and grain boundary types can be characterized and quantified on a sub-micron scale in the SEM. Moreover, EBSD is a surface sensitive technique with data being acquired from a depth of the order of tens of nanometers; using advanced electron optics and in particular FEGSEM, high spatial resolutions are possible. Thus, EBSD is particularly suitable for the characterization of textured thin films.

In the development of coated conductors EDX is widely used to establish stoichiometry and elemental composition of superconducting films and buffer layers and to determine the degree of oxidation of the metallic substrate.

2.2 Electrical characterization

2.2.1 Critical current versus magnetic field in helium bath

The critical current of low-T_c strands and sub-cables can be measured on coiled samples mounted on standard Ti-Va ITER sample holders, or stainless steel sample holders. Sample holders up to 60mm diameter, allowing to test strands, triplets and 3x3 conductors, are immersed in a magnetic field up to 14.5T strength, 0.1% uniformity [1]. A higher magnetic field, 16T, can be achieved restricting the sample holder diameter to a maximum of 35mm. The sample, in the same helium bath of the background solenoidal magnet, can be fed with currents up to 3.5kA.

In the next months a systematic characterisation activity on upgraded Nb_3Sn strands is going to start.

2.2.2 Critical current versus magnetic field and temperature

A variable temperature insert placed in a 12T, 80mm bore superconducting solenoid is used to perform critical current versus magnetic field measurements at temperatures ranging from 4.5K to 100K. Coiled strands, 1m long, about 1mm diameter for measurements with the external field perpendicular to the strand axis, or 3cm long straight pieces of bulk material or film, for measurements with the external field perpendicular to the film plane, can be tested up to 220A sample current.

Superconducting thin films D.C. transport properties in applied magnetic field at temperatures ranging from 4.2K to 300K are measured using an Oxford Instruments helium gas flow cryostat provided with a 12T superconducting magnet with an internal bore diameter of 6cm.

The measurements can be performed varying the angle between the applied magnetic field and the sample surface normal direction. The bias current is limited to 0.5 ÷ 1.0A, depending on the testing temperature.

Both temperature dependence of the electrical resistivity and *I-V* curves measurements are carried out using the four contact technique. The current inversion technique allows to obtain a voltage stability of about 20nV during the measurements.

2.3 Magnetic characterization

A vibrating sample magnetometer is used to measure magnetisation vs. external applied magnetic fields. External field loops up to $\pm$12T are applied, at temperatures ranging from 4.5K to room temperature; samples are small pieces (<10g, some mm^3 volume) of superconducting low-T_c strands, or of high-T_c bulk and films; the apparatus sensitivity is of the order of 10^{-6}emu.

3. SC STRANDS AND COATED CONDUCTORS

3.1 Advanced Nb_3Sn strands

Within the framework of ITER-related projects, new tasks have been recently launched by the European Fusion Development Agreement (EFDA), for the definition and production on industrial scale of an advanced Nb_3Sn strand, to be used in the manufacturing of the ITER high field CS and TF magnets. This is being done with the aim of stimulating the industrial Nb_3Sn strand production capabilities in Europe, as compared to what has been achieved, within the KSTAR project, by USA (IGC) and Japan (Mitsubishi).

An overall critical transport current of at least 200A (at 12T, 4.2K, 0.1 μV/cm) will be required for the upgraded strand, equivalent to a non-Cu J_c of 800A/mm^2, a Cu : non-Cu ratio of about 1 and a strand diameter of 0.81mm.Target value will be 280A, equivalent to a non-Cu J_c of 1100A/mm^2.

Within this framework, ENEA will be involved in the following activities:

- SAMAN: *the preparation and manufacture of conductor samples required for the final optimization of the ITER conductor*. Single strand samples will be jacketed in a SS tube (fig. 2); cabling and jacketing of sub-size samples (9 to about 100 strands) with different jacket diameters, ready to be tested, will be performed; full-size conductor samples will be manufactured, including jacketing and cabling, as well as joint fabrication.

- BARBEN: *the investigation of the bending strain effect on strand*. With the aim of assessing the ratio between the strand twist pitch and the current transfer length of jacketed strands, transport critical currents will be measured at 4.2K, 12T on different samples reacted on barrel sample holders with different diameters.

- ASTEST: *the test of advanced Nb_3Sn strands*. The performances of the advanced Nb_3Sn strands coming from European companies will be tested. Different measurements will be performed: strand layout (diameter, thickness of Cr coating, Cu : non-Cu ratio, twist pitch length and orientation), critical transport current and n-value, RRR, and hysteresis losses by magnetization technique. An extended strand characterization of the critical current dependence on magnetic field, temperature, and strain on a wide range of parameters will be performed by other Associations.

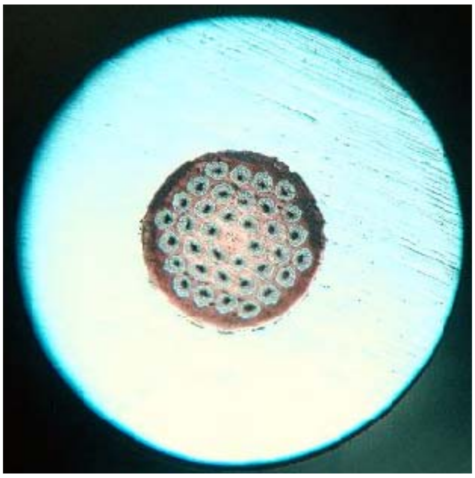

Fig. 2: section of a "jacketed" Nb_3Sn strand inside a stainless steel tube for bending strain testing.

3.2 YBCO Conductors

ENEA is involved in the field of high temperature superconductors (HTS) and a relevant experience in developing high temperature superconducting tapes has been acquired in the last years [2-6].

Due to its good intrinsic transport properties at liquid nitrogen temperature (77K) $YBa_2Cu_3O_{7-\delta}$ (YBCO) was the most studied HTS material, and superconducting tapes were realised using the RABiTS (Rolling Assisted Biaxially Textured Substrate) technique applied on Ni-based substrates. Several binary Ni alloys have been studied such as Ni-Cr, Ni-V, Ni-W [2,3] as well as ternary alloys as Ni-Cr-W, in order to decrease the Ni Curie temperature responsible for magnetic hysteresis losses due to the substrate in AC regimes at 77K, and to improve the Ni mechanical properties. Prior to YBCO deposition, in order to avoid the degradation of transport properties due to Ni diffusion in YBCO film, a buffer layer structure is interposed between the substrate and the superconducting film. Typical structures obtained in the ENEA research framework were NiV-NiO-CeO_2-YBCO (J_C= 0.7MA/cm^2 at 77K and self field), NiV-NiO-CeO_2-YSZ-CeO_2-YBCO (J_C= 0.7MA/cm^2 at 77K self field), NiW-CeO_2-YBCO [4] (J_C=1.2MA/cm^2 at 77K and self field, I_C(77K)=63A, I_C(65K)=130A on 5cm long and 1cm wide samples) (fig. 3).

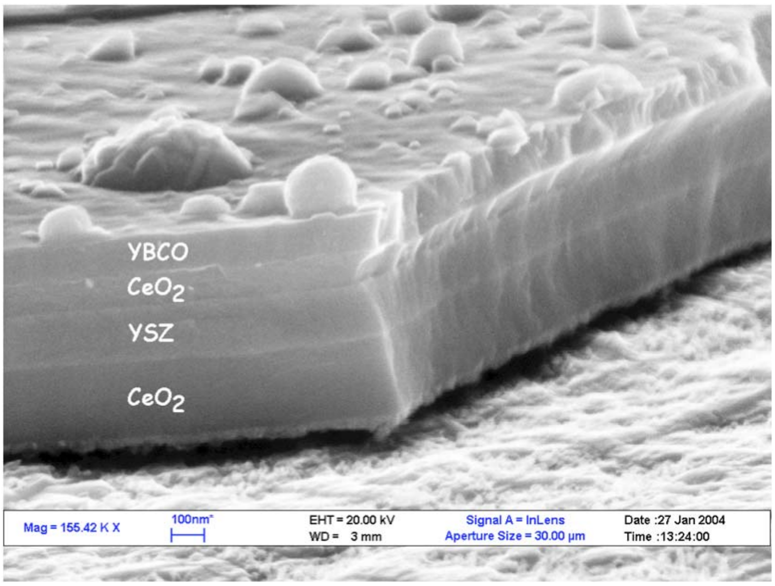

Fig. 3: SEM micrograph of 700 nm thick film cross section. YBCO and different buffer layers can be distinguished.

The whole structures were achieved using the Pulsed Laser deposition technique because of its versatility in the use of different materials and easiness in the transfer of the correct stoichiometry from a starting material (target) to the film, fundamental for obtaining optimal transport properties of YBCO films.

Recently, the effect of Ca doping at the grain boundaries of YBCO films on transport properties has also been studied.

The main goal of the ENEA project is to develop a continuous deposition process for long length YBCO based coated conductors fabrication (fig. 4).

Fig, 4: the ENEA plant for continuous deposition of YBCO-based coated conductors.

3.3 BiSCCO Conductors

Bi-2212 has been successfully synthesized by means of electro-deposition and annealing of its precursors on Ag substrates. Ag is the most widely employed material for BSCCO wires and tapes, because of its chemical inertia with the superconductor as well as with its precursors. In order to improve the physical properties of the substrate, without loosing chemical ones, Ag-buffered Ni based tapes have been studied. In order to inhibit the Ni diffusion towards the Ag films during high temperature Bi-2212 synthesis, which destroys superconductivity, an oxide can be introduced as a buffer layer between Ag and Ni tape. In the past two years a collaboration between ENEA and EDISON led to the development of an oxide buffer layer/Ag architecture on NiCr80/20 tape. Both the buffer layer and the Ag film have been deposited by means of electron beam evaporation, allowing deposition on long lengths. At the moment no BSCCO tape has been yet realised over such a substrate.

4. TEST AND CHARACTERISATION OF SUB-SIZE CONDUCTOR SOLENOIDS

4.1 ENEA Facility

The experience gained in the past years on several NbTi and Nb_3Sn inserts (SAFFO, PUFF and S-Ex experiments) [7-9] and the existing and recently updated facility allowed ENEA to be a candidate for present and future testing of sub-sized magnets in ITER-relevant operating conditions.

Goal of the experiments is to study the stability and the quench propagation in coiled conductors cooled by a forced flow of supercritical helium (CICC), to study the limitation due to the current ramp rate and to the current non-uniformity.

Such a well-instrumented sub-size magnets are also perfect candidates for codes validation.

The available facility is composed by: a refrigerator, recently bought by Linde, with 500W power, able to supply helium at 4.5 and 16K; three background magnets, two made of NbTi (with a maximum field of 3T) and one of Nb_3Sn (with a maximum field of 3T); four DC power supplies, 1kA, 5kA, 6kA, and 16kA respectively, plus several smaller ones; an AC power supply, +100A, +10V; a cryogenic and electric facility suitable for large scale experiments; several data acquisition systems.

By now the ENEA facility (fig. 5) is going to be adapted to host ASTEX, an experiment aimed to study the effect of the current non-uniformity on coil performance, in particular on its stability.

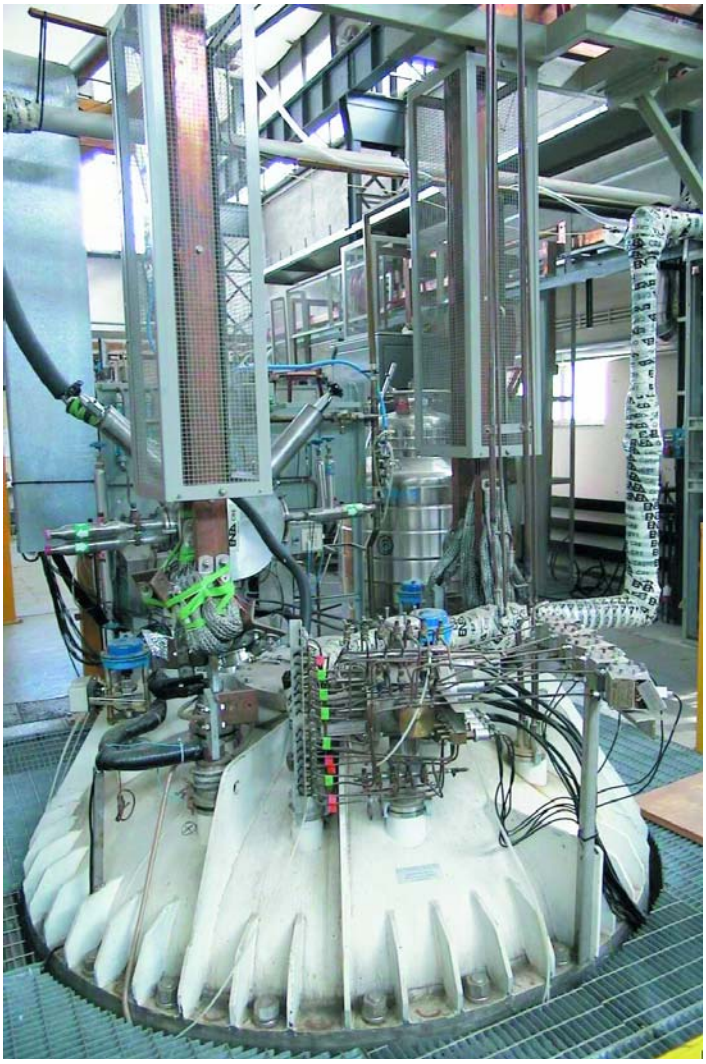

Fig. 5: view of the ENEA facility for testing superconducting solenoid magnets.

4.2 ASTEX (Advanced Stability Experiment)

Inside multifilamentary/multi-stage conductors, current may distribute non-uniformly among different strands or cable sub-elements, both during steady state operation, owing to the different contact resistance of each cable element at the joint, and during current variations, due to the different effective inductance of each sub-element. This has been identified as the main cause leading to premature conductor quench phenomena or to current ramp-rate limitations.

An experiment has been planned by ENEA which is currently in its installation phase, aimed at studying the influence of current distribution on conductor properties, as critical current, AC losses, and stability. To this purpose, a magnet has been coil wound with a sub-size NbTi 36-strands conductor (fig. 6a). The conductor has been opened at both terminations, and subdivided into the four 9-strands last-but-one stages, one of which has been further subdivided into a triplet of strands and the remaining group of 6 strands (fig. 6b). A system of external resistors allows to feed the magnet with a controlled non-uniformly distributed current. The module is fully instrumented, with thermometers, voltage taps, pick-up coils, pressure gauges and helium mass flow meters, in order to characterize its behaviour during both steady state operation and current variations. The module can be fed with a 6kA maximum current, under the effect of a maximum 2.5T background field, for a total maximum peak field of 6T; it will be operated at a temperature of about 5K, with a 10 bar inlet pressure. The hydraulic circuit allows also to reverse the helium flow inside the module with respect to the current supply, in order to study the effect of different initial normal zones on the conductor stability.

Fig. 6: the instrumented ASTEX module and its terminations, at which the cable has been opened and subdivided.

5. PARTICIPATION TO ITER TESTING CAMPAIGNS

ENEA participates with all the other EURATOM associations in the experimental campaigns relevant for the ITER magnet R&D: the Toroidal Field Model Coil (fig. 7), the Central Solenoid Model Coil, the two Central Solenoid Model Coil Inserts in the past and the Poloidal Field Insert in the future.

In collaboration with CEA a NbTi two-legs straight sample has been manufactured and tested in operating conditions relevant for Poloidal Field Magnet, to obtain a complete characterisation of a full-size conductor and a twin box joint [10]. A second sample, PFIS, is going to be tested in the near future.

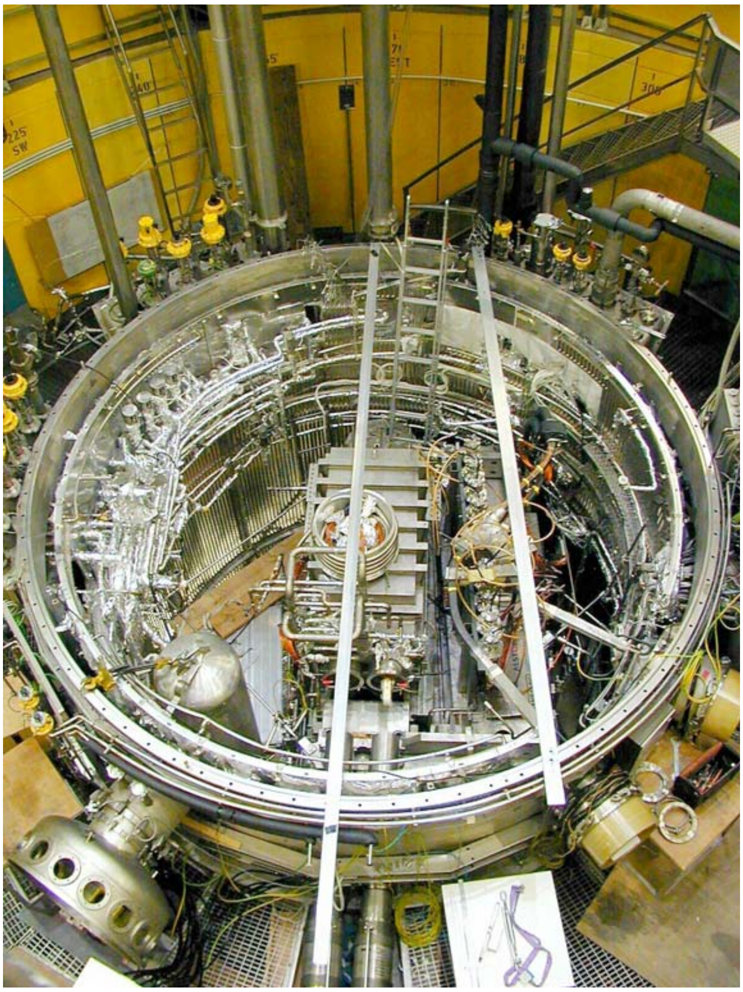

Fig. 7: the TOSKA facility in FzK (Forschung Zentrum Karslruhe), hosting the TFMC and the background LCT coil.

5.1 Measurements on Current Distribution in cables

The knowledge of the actual current distribution in the different operating conditions is a relevant information for the optimization of cable and joint layout of CIC ITER-relevant conductors. Unfortunately, it is not possible to obtain a direct measurement of the current flowing in each petal of the cable; it is therefore necessary to adopt indirect current evaluation by means of magnetic field measurements in regions adjacent to the cable surface. Within this framework, several experiments on full-size magnets and cables have been equipped with Hall sensors' heads, placed around the conductor. ENEA, in collaboration with CREATE, has designed and realized a Data Acquisition System (DAQ) for the Hall Probes Measuring Heads installed at FzK on the TFMC bus-bar during the phase-II test campaign (fig. 8), and has performed the data analysis, with the aim of reconstructing the current distribution in the six petals of the conductor during operation (fig. 9) [11,12]. Future collaborations are foreseen for the current distribution measurements on the HT_c current leads short circuit (Bus-Bar III) at FzK, on the PFIS at CRPP, and on the PFCI conductor at JAERI.

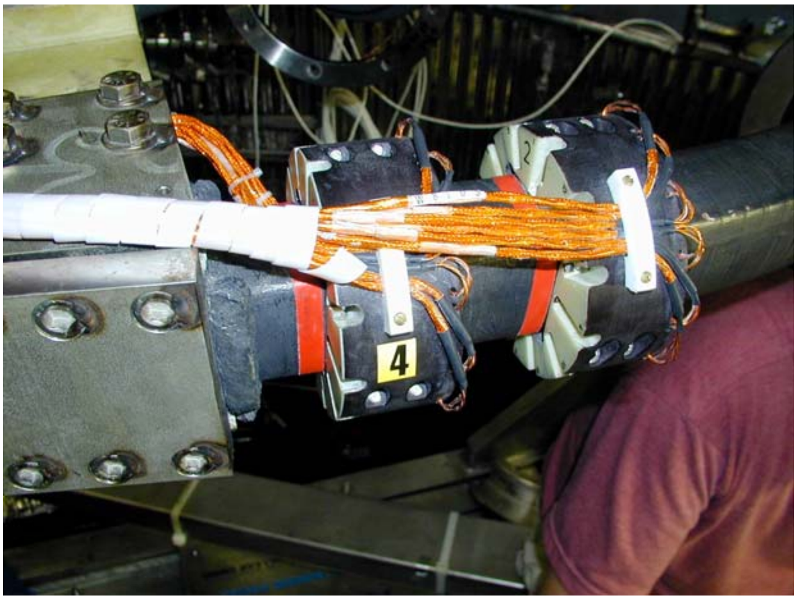

Fig. 8: Hall probes measuring heads installed around the NbTi TFMC BusBar, for the tests performed in the FzK.

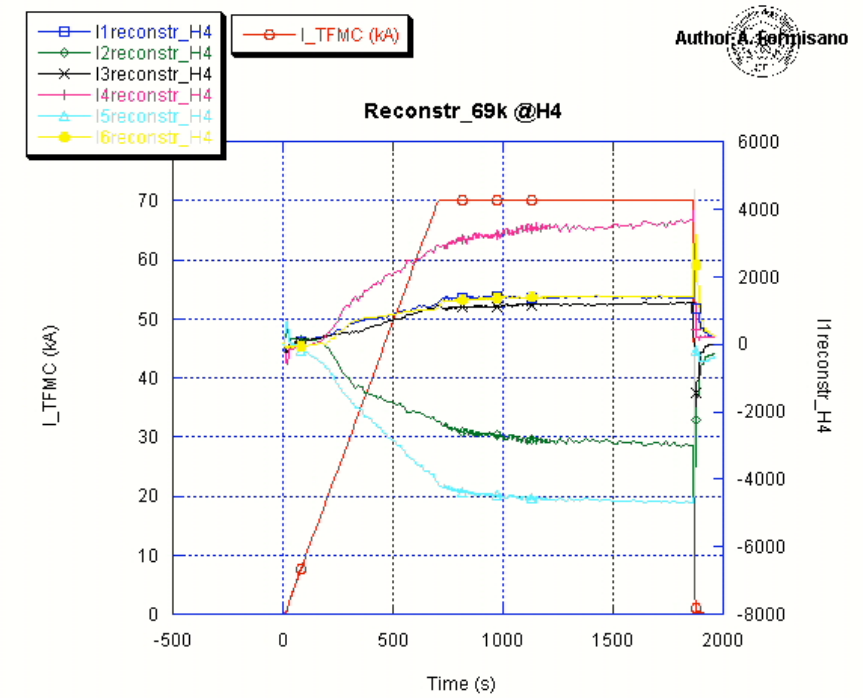

Fig. 9: example of the currents flowing in each of the 6 cable petals, as reconstructed from the Hall Probe signals, during a 69kA test in the TFMC.

6. CODES DEVELOPING AND VALIDATION

ENEA co-ordinates the activities of the group (Bologna, Turin, Udine, and Padova Universities) devoted to the development of a fully-integrated code (thermo-fluid-dynamical + electric + mechanical performances of a magnet realised by jointed superconducting CIC conductors), THELMA. ENEA is now collaborating in the code validation by providing data from different experiments of interest and analysing the results.

7. MONITORING OF INDUSTRIAL ACTIVITIES

Europa Metalli (EM) and Ansaldo Superconduttori (AS) are the two Italian factories which have been more deeply involved with ENEA in the manufacturing of strands, cables and conductors. In fact, under the ENEA monitoring, EM started in 1978 the construction of the NbTi conductor for the first large coil completely designed and wound in Italy by AS in 1980 and installed as one of the background magnets in the SULTAN facility where it reaches 6T in a bore of 1.3m.

The experience gained allowed EM and AS, first of all, to manufacture the conductor and coil for a 12T, Nb_3Sn wind and react magnet, and then to realize at EM the full size conductor for the TFMC that was wound at AS and successfully test at FzK, Karlsruhe (fig. 10) [13].

During year 2003, the collaboration with EM and AS was mainly devoted to the manufacturing of the PF (Poloidal Field) full size conductor samples to be tested in the SULTAN and NAKA facilities.

Fig. 10: picture of a section of the full-size Cable-in-Conduit Conductor adopted for the ITER magnets. External jacket dimensions are about 50 mm x 50 mm.

8. TESTING OF DIODES FOR LHC SUPERCONDUCTING MAGNETS PROTECTION

ENEA superconductivity laboratories host the OCEM activity for cryogenic and electrical testing of the diodes used by CERN to protect the dipole and quadrupole magnets of LHC (fig. 11). The direct and reverse characteristics of the diodes at cryogenic temperatures are checked, together with their ability to withstand current pulses up to 14kA [14].

Fig. 11 : Cryostat insert with four mounted diode stacks ready for testing at ENEA laboratory.

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