The Activities of ENEA on Superconductors Developments

presented by

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Outline

Characterisation of strand, sub-cables, films and bulk samples

- Structural Characterisation (X-rays, Scanning Electron Microscopy)
- Electrical and Magnetic Characterisation

SC Strands and Coated Conductors

- Nb_3Sn
- YBCO
- BiSCCO

Test and characterisation of sub-size conductor solenoids

- ENEA facility
- ASTEX

Participation to ITER testing campaigns

- CSMC,TFMC,PF-FSJS and PFCI
- CDM Measurements

Other activities

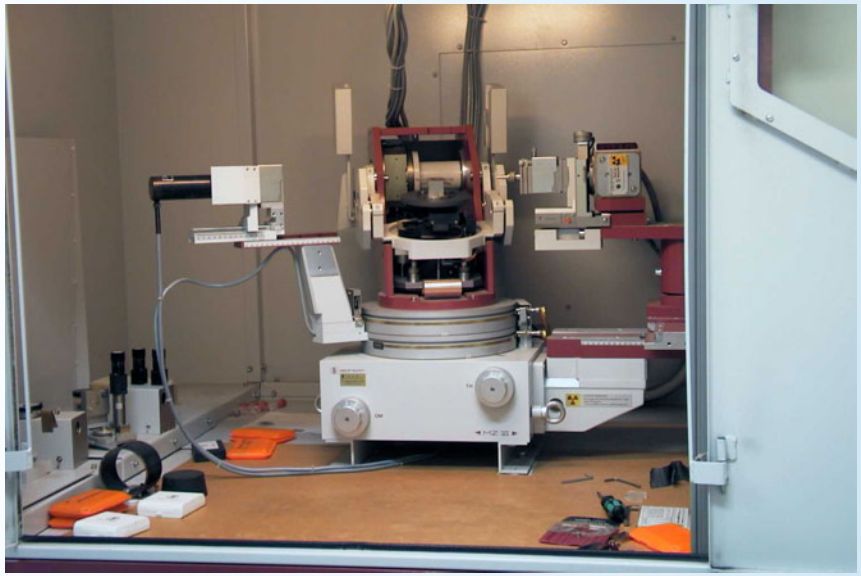
- Code Developing and validation
- Monitoring of industrial activity
- Testing of diodes for LHC SC magnets protection

Characterisation of strand, sub-cables, films and bulk samples

Structural Characterisation

X-rays

In the development of coated conductors, X-ray diffraction are widely used to establish 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 SEIFERT diffractometer at ENEA

In our LAB are available two diffractometers:

- **Rigaku Geigerfex for the θ-2θ scans with Cu-Kα radiation.**
- **Seifert XRD 3003 PTS, equipped with a four circle goniometer, for texture analysis and for residual strain measurements**

Characterisation of strand, sub-cables, films and bulk samples

Scanning Electron Microscopy

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

the characteristics of our SEM LEO1525 are:

- *resolution 1.5nm at 20kV and 2mm working distance or 3.5 nm at 1kV and 2mm working distance;*
- *magnification ranging from 20x up to 500kx*

its equipment:

- *OXFORD INCA Crystal Electron BackScatter Diffraction (EBSD) , to characterise and quantify, crystallographic orientations, grain-to-grain misorientations, texture trends and grain boundary types on a sub-micron scale. EBSD is also a surface sensitive technique (tens of nanometers depth analysis)*
- *Energy Dispersive X-ray Microanalysis (EDX) systems, to establish stoichiometry and elemental composition of superconducting films and buffer layers and to determine the degree of oxidation of the metallic substrate.*

Characterisation of strand, sub-cables, films and bulk samples

Electrical and Magnetic Characterisation

Critical current versus magnetic field:

Ic of low-Tc strands and sub-cables can be measured on coiled samples mounted on standard Ti-Va ITER or stainless steel sample holders, immersed in a magnetic field up to 14.5T with 0.1% uniformity, or up to 16T, restricting the sample holder diameter. The sample can be fed with current up to 3.5kA.

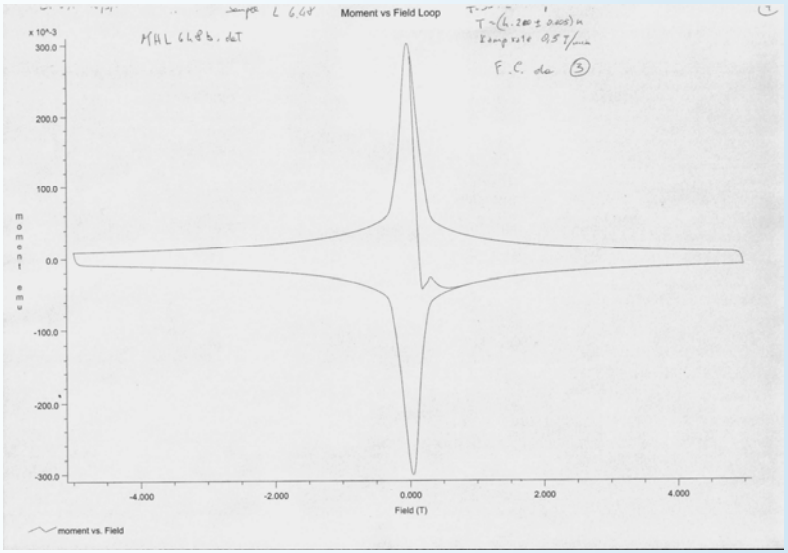
Critical current versus magnetic field and temperature:

Ic(B,T) measurements can be performed in a 12T, 80mm bore Sc solenoid on:
-coiled strands, 1m long, about 1mm diameter with B perpendicular to the strand axis;
-3cm long straight pieces of bulk material or film, with B perpendicular to the film plane with sample current up to 220A.

An Oxford Instruments Helium gas flow cryostat provided with a 12T, 60mm bore solenoid is used to measure D.C. transport properties of thin films at applied B and temperatures ranging from 4.2K to 300K, and varying the angle between B and the sample surface normal direction. The bias current is limited to 0.5÷1.0 A, depending on the testing temperature.

Characterisation of strand, sub-cables, films and bulk samples

Magnetic characterisation: A vibrating sample magnetometer is used to measure magnetisation vs. external applied magnetic fields. External field loops up to ±12T are applied, at temperatures ranging from 4.5K to room temperature; samples are small pieces (<10g, some mm^3 volumes) 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.



magnetisation vs applied B, performed at ENEA by U.Gambardella (INFM) on P.Fabricatore (INFM) Nb_3Sn strand sample.

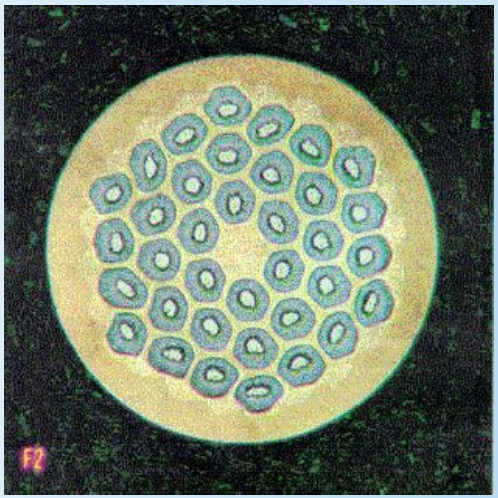
SC Strands and Coated Conductors

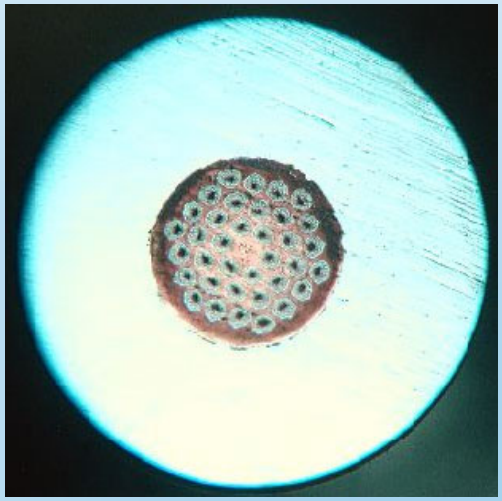
Advanced Nb_3Sn strands

European Fusion Development Agreement (EFDA) recently launched new tasks 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, with the aim to stimulate the industrial Nb_3Sn strand production capabilities in Europe, as compared to what has been achieved by USA (IGC) and Japan (Mitsubishi) in the frame of the KSTAR project.
The requirements of the upgraded strand are:

- an overall critical transport current of at least 200A (at 12T, 4.2K, 0.1 μV/cm), equivalent to a non-Cu J_c of 800 A/mm^2
- a Cu : non-Cu ratio of about 1 and a strand diameter of 0.81 mm

Target value will be 280A, equivalent to a non-Cu J_c of 1100 A/mm^2





SC Strands and Coated Conductors

For the advanced Nb_3Sn strands, ENEA will be involved in the following EFDA contracts:

- **SAMAN**: *the preparation and manufacture of conductor samples required for the final optimisation of the ITER conductor*. Single strand samples will be jacketed in a SS tube; 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 characterisation of the critical current dependence on magnetic field, temperature, and strain on a wide range of parameters will be performed by other Associations.

SC Strands and Coated Conductors

Coated Conductors: YBCO

In the last years ENEA acquired a relevant experience in developing high temperature SC tapes. Typical structures (substrate+buffer layer+SC film) obtained in the ENEA research framework were:

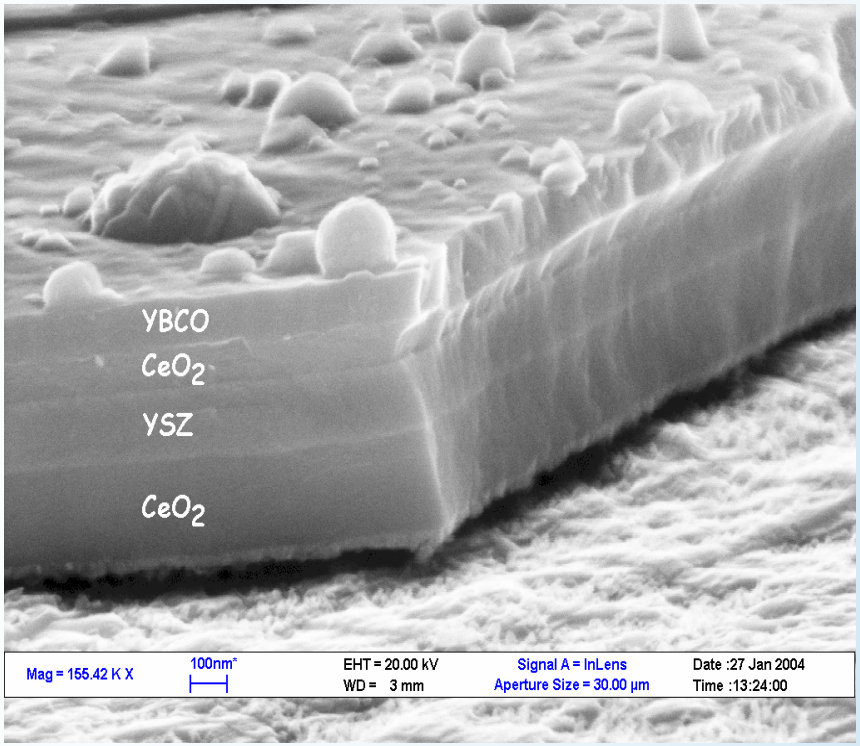
- NiV-NiO-CeO_2-YBCO (J_C= 0.7MA/cm^2 at 77K and self field);
- NiV-NiO-CeO_2-YSZ-CeO_2-YBCO (J_C= 0.7MA/cm^2 at 77K self field);
- NiW-CeO_2-YBCO (J_C=1.2MA/cm^2 at 77K and self field, I_C(77K)=63A, I_C(65K)=130A on 5cm long and 1cm wide samples),

achieved using the Pulsed Laser deposition technique .
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.

SC Strands and Coated Conductors

Coated Conductors: YBCO



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

the ENEA plant for continuous deposition of YBCO-based coated conductors

SC Strands and Coated Conductors

Coated Conductors: BiSCCO

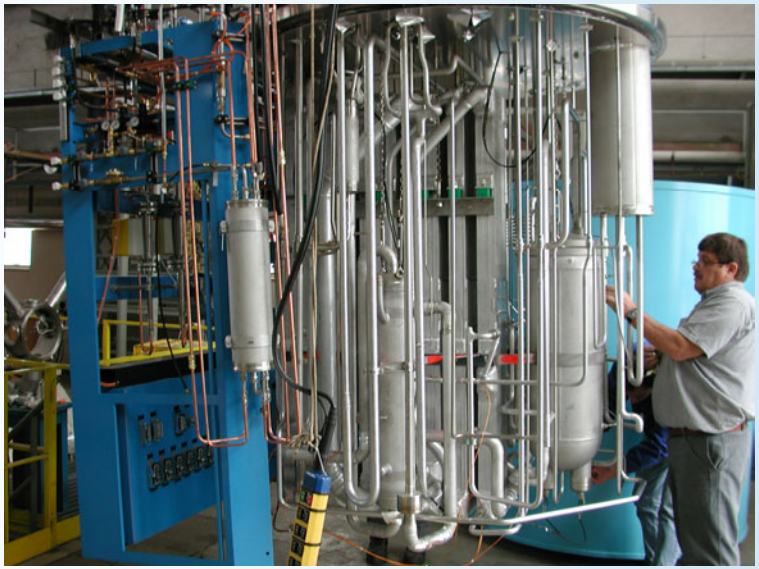
Ag is the most widely employed material for BSCCO wires and tapes, because of its chemical inertia with the superconductor as well as with its precursors. To improve the physical properties of the substrate, without loosing chemical ones, Ag-buffered Ni based tapes have been studied.

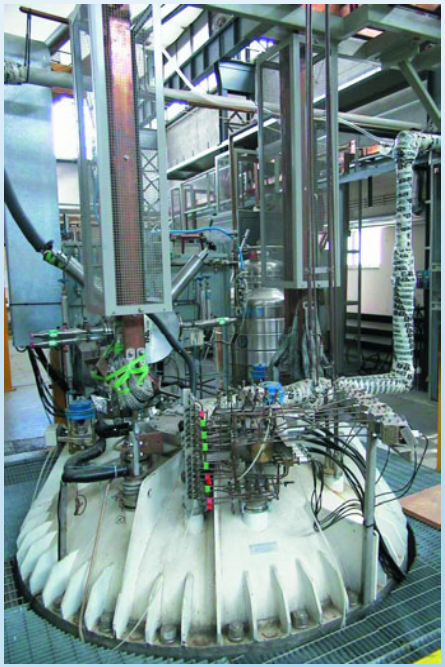
For what concerns BSCCO SC, ENEA activity has been mainly devoted to the study of innovative substrate for BSCCO deposition different from Ag.
In particular, in the past two years a collaboration between ENEA and EDISON led to the development of an oxide buffer layer/Ag architecture on NiCr80/20 tape. Both the buffer layer and the Ag film have been deposited by means of electron beam evaporation, allowing deposition on long lengths.
BSCCO deposition on such substrate is under progress at EDISON.

Test and characterisation of sub-size conductor solenoids

The following devices are available at ENEA for testing sub-size magnets cooled by a forced flow of supercritical helium:

- a refrigerator, recently bought by Linde, with 500W power, able to supply helium at 4.5K, 16K and 77K;
- 2 NbTi background magnets (with a maximum field of 3T) and one of Nb_3Sn (with a maximum field of 3T);
- 4 DC power supplies, 1kA, 5kA, 6kA, and 16kA respectively;
- an AC power supply, +100A, +10V;
- a large scale cryostat;
- several data acquisition systems.





the ENEA facility for testing superconducting solenoid magnets

Test and characterisation of sub-size conductor solenoids

ASTEX (Advanced Stability Experiment)

One NbTi module has been manufactured with the following characteristics:

-Inner diameter Di = 12 cm;
-Outer diameter De = 28.2 cm;
-Height H = 23.8 cm,
-Total number of turns: Ntot = 23turns x 8layers=184 turns
-Conductor length, Lavv = 116 m;
- Iop = 6.0 kA
-Bmax = 4.64 T (self field on the internal radius)

Main goals of the experiment: to study the influence of current distribution on conductor properties, both in stationary and in transient conditions and to use the experimental results for THELMA code validation.

How this will be achieved:

- during conductor cabling one strand of a triplet has been marked;
- after winding, 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.
- a system of external resistors has been realised to feed the magnet with a controlled non-uniformly distributed current.

Test and characterisation of sub-size conductor solenoids

The module if instrumented with:

-16 fast response thermometers;

-15 voltage taps inside the coil + 10 fixed on the SC at both terminations;

-2 flowmeters;

the background Coil characteristics:

-Di = 30.07 cm, De = 50.47 cm, H = 35.5 cm

-Ntot = 287 spire

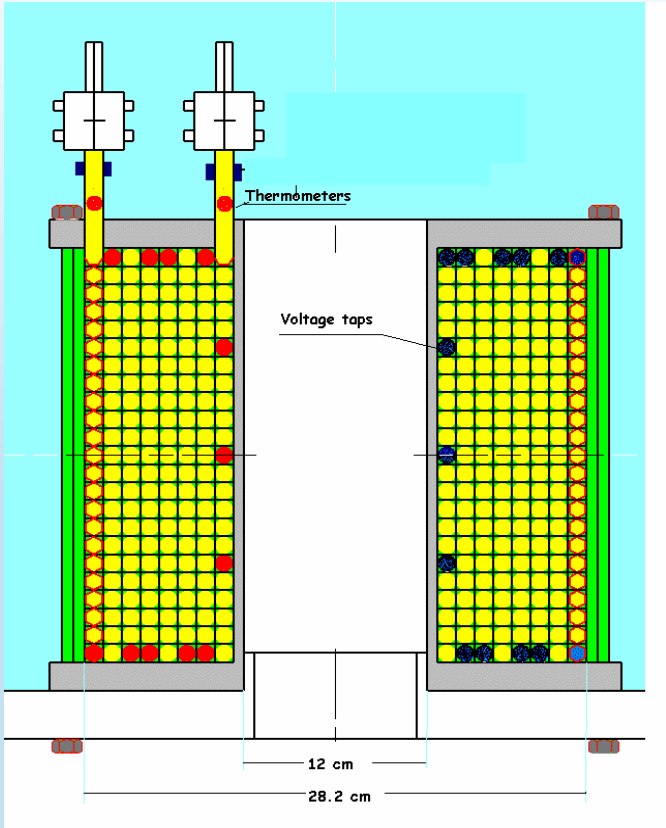
-Iop = 5.0 kA

-Bmax = 2.5 T (on the module)

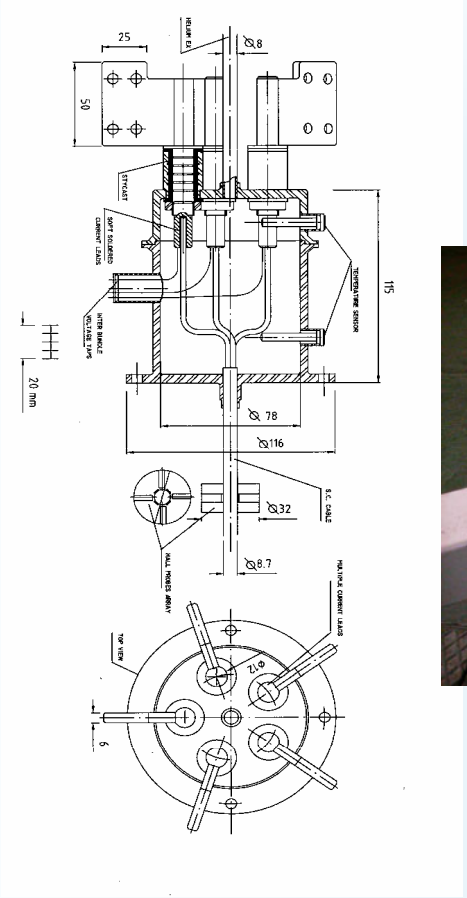
Total field

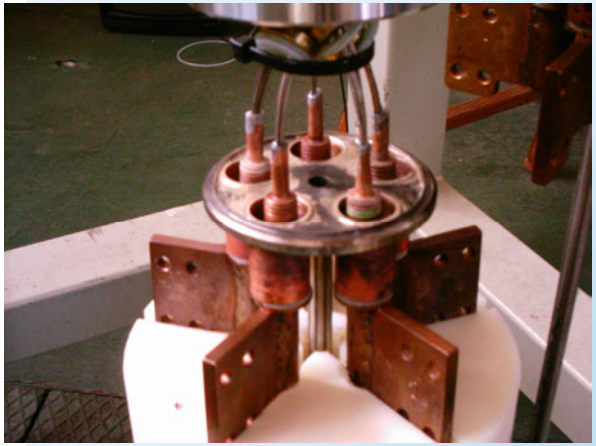
B0 = 6.95 T (on the axis, r = 0, z=0)

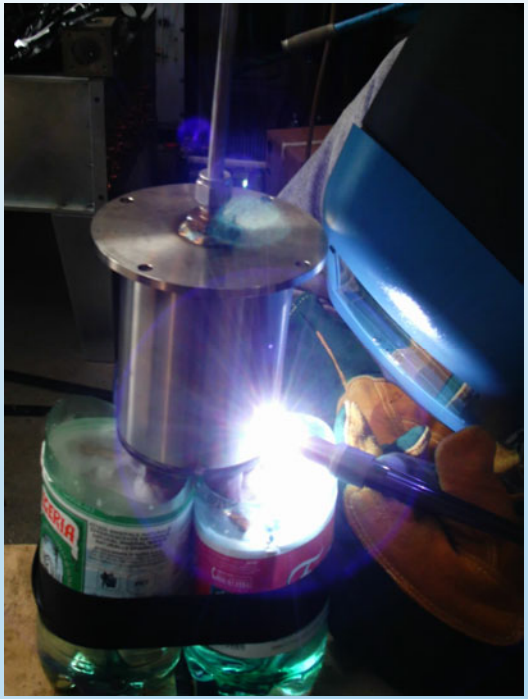
Bmax = 7.16 T (at the module internal radius, z=0)



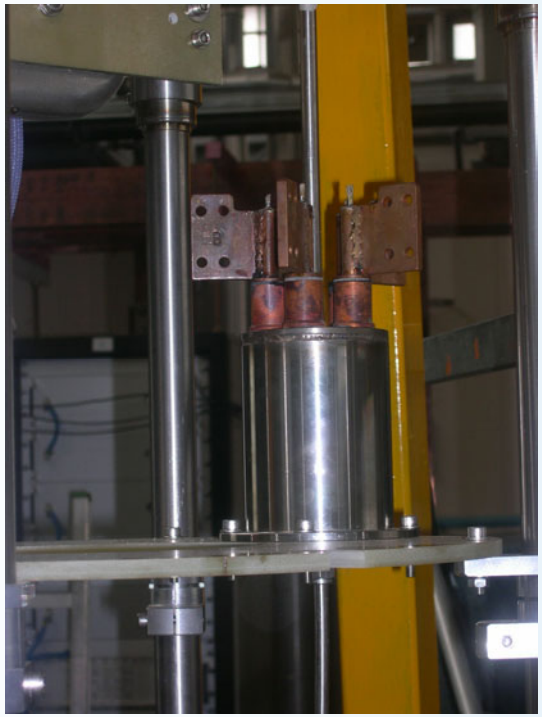
Test and characterisation of sub-size conductor solenoids

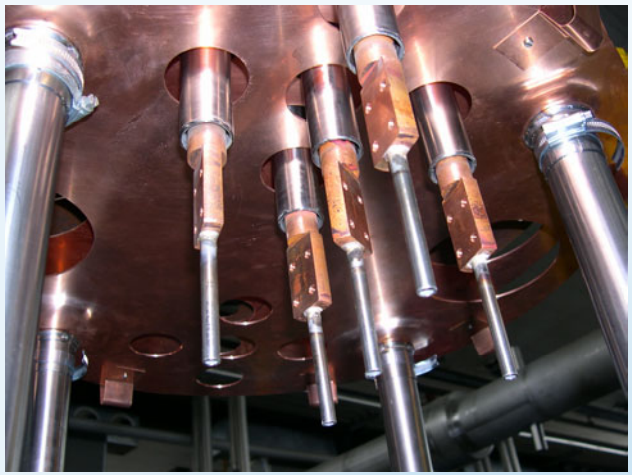


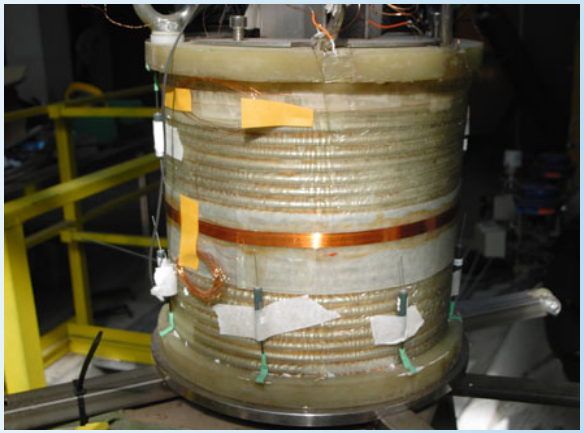




Test and characterisation of sub-size conductor solenoids







Participation to ITER Testing Campaigns

CSMC,TFMC,PF-FSJS and PFCI

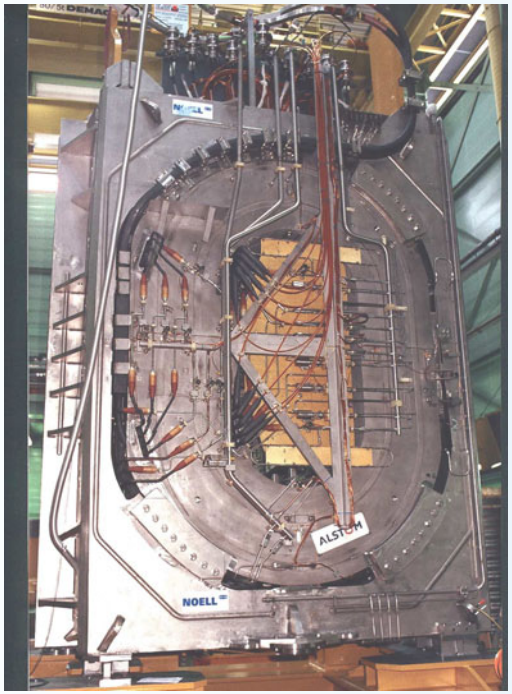
ENEA participates as an EURATOM association in the experimental campaigns relevant for the ITER magnet R&D: the Toroidal Field Model Coil, the Central Solenoid Model Coil, the two Central Solenoid Model Coil Inserts in the past and the Poloidal Field Insert in the future.

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.

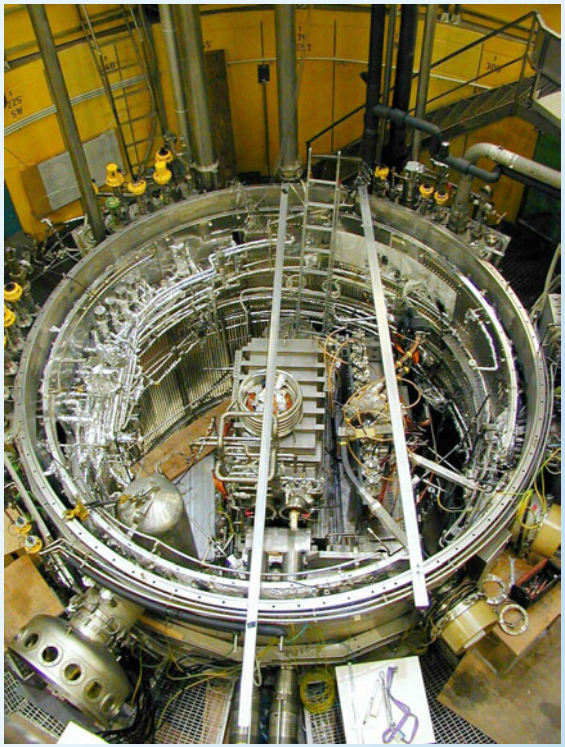
A second sample, PFIS, is going to be tested in the near future.

Participation to ITER Testing Campaigns

CSMC,TFMC,PF-FSJS and PFCI



The ITER TF Model Coil in the Inter-Coil Structure before lifting into the test facility of the Forschungszentrum Karlsruhe



The ITER CS Model Coil at NAKA...

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

Participation to ITER Testing Campaigns

Measurements of Current Distribution in cables

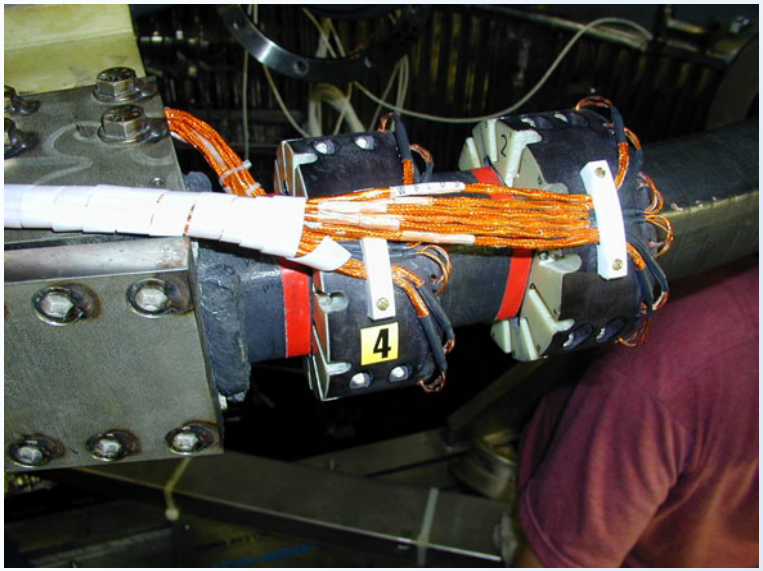
The knowledge of the actual current distribution in the different operating conditions is a relevant information for the optimization of cable and joint layout of CIC ITER-relevant conductors. Unfortunately, it is not possible to obtain a direct measurement of the current flowing in each petal of the 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, 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, and has performed the data analysis, with the aim of reconstructing the current distribution in the six petals of the conductor during operation.

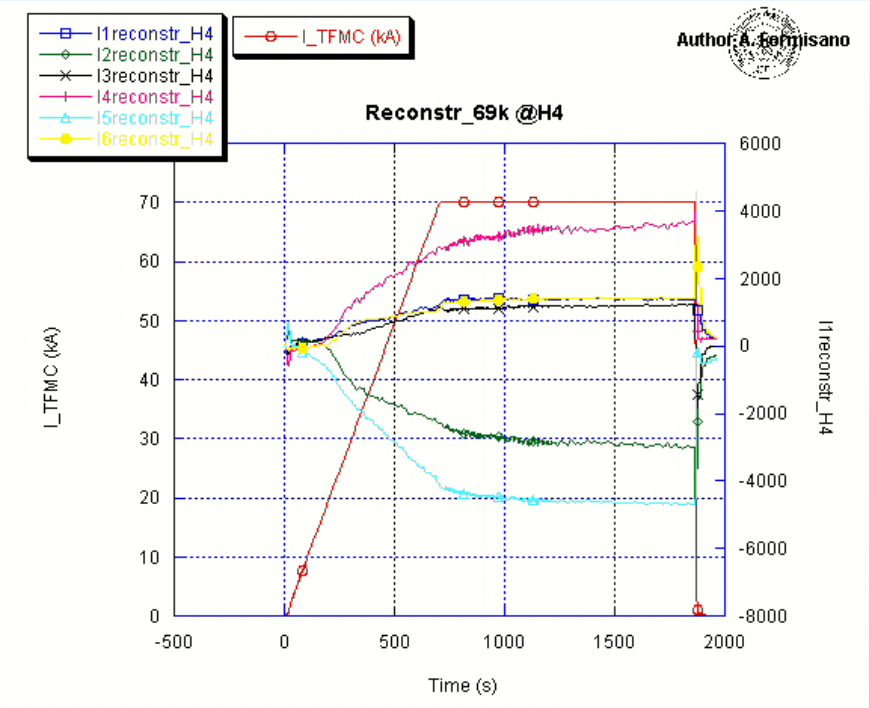
Future collaborations are foreseen for the current distribution measurements on the HT_c current leads short circuit (Bus-Bar III) at FzK, on the PFIS at CRPP, and on the PFCI conductor at JAERI.

Participation to ITER Testing Campaigns

Measurements of Current Distribution in cables



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



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

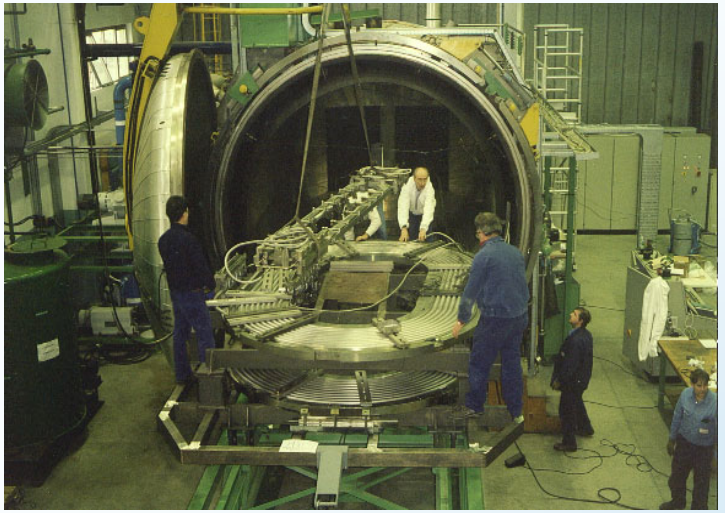
Other Activities

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.

Monitoring of industrial activities: Europa Metalli (EM) and Ansaldo Superconduttori (AS) are the two italian factories which are deeper 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 in the SULTAN facility where it reaches 6T in a bore of 1.3m.
The experience gained allowed EM and AS, first, to manufacture the conductor and coil for a 12T, Nb_3Sn wind and react magnet, and finally, to realise at EM the full size conductor for the TFMC that was wound at AS and successfully test at FzK, Karlsruhe. 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.

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. The direct and reverse characteristics of the diodes at cryogenic temperatures are checked, together with their ability to withstand current pulses up to 14kA.

Other Activities



two TFMC pancakes in the moulds and one full size joint sample in front of the reaction oven at ANSALDO

Cryostat insert with four mounted diode stacks ready for testing at ENEA laboratory

picture of the full-size Cable-in-Conduit Conductor adopted for the ITER magnets.