Ansaldo GIE papers on CICC technology:

A.Bonito Oliva, etc. : "Ansaldo s.c. MHD Magnet Prototype" presented at International Workshop on MHD Superconducting Magnets, Bologna, Italy, 1991

A.Bonito Oliva, etc. : " A MHD superconducting magnet for a linear experimental facility" ; presented at MT-12, Leningrad, URSS, 1991

A.Bonito Oliva, etc. : " Status report on a 0.6 m bore Nb3Sn, "wind and react" CICC solenoid "; presented at ASC-92, Chicago, Illinois, USA

A.Bonito Oliva, etc. :" Development and tests of electric joints and terminations for a CICC Nb3Sn 12 T solenoid"; presented at ASC-92, Chicago, Illinois, USA

P.Bruzzone, etc. : " Test result of full size 40 KA NET-ITER conductor in the FENIX test facility " presented at ASC-92, Chicago, Illinois, USA

A.Bonito Oliva, etc.: " Status of the EURATOM-ENEA 0.6 m, 12 T Nb3Sn magnet: manufacturing experience of the CICC conductor and test results on a model winding:; presented at 17th Symp. on Fus. Technology, Rome, Italy, 1992

A.Bonito Oliva, etc,: "Manifacture and preliminary test of a 12 T "wind and react" coil" ; presented at MT 13, Victoria B.C., Canada, Sept. 93

O.Dormicchi, etc. : "Manufacturing Development for the S.C. MHD Magnet prototype "; presented at MT 13, Victoria B.C., Canada, Sept. 93

TEST RESULT OF FULL SIZE 40 KA NET/ITER CONDUCTOR IN THE FENIX TEST FACILITY

P. Bruzzone[1], N. Mitchell[1], H. Katheder[1], E. Salpietro[1], M.R. Chaplin[2], S.S. Shen[2], D.S. Slack[2], J. Rauch[3], W. Brehm[3], S. Ceresara[4], M. Ricci[5], A. Bonito Oliva[6]

[1]The NET Team, c/o Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, D - 8046 Garching bei München
[2]Lawrence Livermore National Laboratory, P.O. Box 3511, Livermore, California 94550
[3]ASEA Brown Boveri, Oerlikon Works, CH-8050 Zürich
[4]Europa Metalli LMI, Piazzale Luigi Orlando, I-55052 Fornaci di Barga (LU)
[5]ENEA Laboratorio Superconduttività, Via Enrico Fermi, I-(XX)44 Frascati
[6]Ansaldo Componenti, Via Lorenzi 8, I-16152 Genova

Abstract--Three Nb_3Sn cable-in-conduit prototype conductors have been manufactured in the frame of the European conductor development programme for NET. They have been tested in the FENIX test facility beyond their operating conditions (current up to 40 kA, magnetic field up to 13.5 T, supercritical Helium up to 8 K). The testing procedure is described and the test results are discussed. The main object of the test is the measurement of temperature margin under DC operation and the hydraulic pressure drop.

INTRODUCTION

The cable-in-conduit conductor was identified by NET as a possible candidate for the superconducting toroidal and poloidal field coils of a tokamak [1]. Construction of short lengths was started in 1988, accompanied by an extensive testing programme. One of the final elements of these tests (the other being coupling loss [2] to confirm the suitability for the AC conditions experienced in a tokamak) was the operation of a length of full size conductor at its design conditions of ~40 kA current and 12.5 T field. The FENIX facility, whose construction at LLNL began in 1989 was offered for this test [3]. Three conductor samples were delivered in the period ...91 and testing began in December 1991. The samples have ... tested at fields up to 13.5 T. Cycling of the conductor current for 6000 cycles has been used to assess the endurance behaviour.

CONDUCTOR LAYOUTS AND MANUFACTURE

The major parameters of the three prototypes cable-in-conduit conductors are listed in Table I. Those produced by ABB have identical outer dimensions, but different cable structure: one conductor has braided subcables [4] and the other, together with the EM-LMI prototype, has a purely stranded configuration (see Fig. 2).

The basic Nb_3Sn strand was supplied in 1989 by TWCA (internal ...n, jelly roll) for all the prototypes. The critical current density of the several batches delivered to ABB and LMI was very similar [5]. The ...igh field, non-Cu average J_c from all the strand batches used for the conductor manufacture is reported in Fig. 1. The Jc performance was ...ver 20 % higher than the specified value (600 A/mm^2 at 12.5 T, 4.2 ...). The hysteresis losses was, at ~1.5 J/cm^3 non-Cu at ±3 T, much ...rger than allowed in the NET design. The residual resistance ratio (RRR) was low, i.e. about 65, before Cr plating.

The conduit of the prototypes is austenitic stainless steel [6]. For ...e LMI conductor, the JK1 steel was used, extruded as an oversize ...ollow profile (unit length ~4 m). After butt welding the tubing units, ...e cable is pulled through the jacket and a final compaction is ...hieved by rolling. For the prototype manufacture, a maximum ...ngth of 17.5 m was assembled by this way [7]. For the ABB ...ototypes, the jacket consists of two U profiles of 316 LN steel, with ...ntrolled N and C content, delivered in units of 7 m. After butt ...iding the U profiles, the cable is pressed between the two halves ...W laser beam provides the two longitudinal welds of the 5 ...n thick jacket wall [8]. The void fraction is close to 45 % of the ...le space. The average hydraulic diameter is smaller for the LMI ...ductor, consisting of thinner strands. The distribution of the voids ...ore homogeneous in the braided prototype (see Fig. 3). For the same strand diameter, the braided configuration offers a larger wetted perimeter and transversal stiffness [9].

...nuscript received August 24, 1992

TABLE I
MAIN PARAMETERS OF THE PROTOTYPE CONDUCTORS

	ABB Braided	ABB Stranded	EM-LMI
Average strand Jc [A/mm^2 non-Cu] at 12.5 T, 4.2 K, 0.1 µV/cm	769	730	729
Average Cu:non-Cu	1.28	1.23	1.23
Strand diameter [mm]	0.93	0.96	0.78
Number of strands	609	567	864
Total non-Cu cross section [mm2]	181	184	185
Cable space cross section [mm2]	780	780	804
He void fraction [%]	45.6	43.6	44.9
He Area [mm2]	356	340	361
Steel jacket area [mm2]	711	711	724
Jacket material yield 0.2%, [MPa] at 4.2 K, after heat treatment	1100	1100	1000

THE FENIX SAMPLES

The samples prepared for the test in FENIX [10] consist of straight, paired conductor pieces, joined together at one end and connected to the FENIX busbar at the other end. They have been heat treated as individual lengths with their own terminations and have been assembled after the heat treatment. The overall length (including termination) is 4.65 m. From the electrical point of view they are connected in series, but each leg is individually cooled. The feed to the samples is chosen in order to get on each leg an enhancement of the background field by the self field of the other leg. The repulsive force acting on the paired lengths is F = IB = 500 kN/m of conductor (I = 40 kA and B = 12.5 T). This force is reacted by thick steel

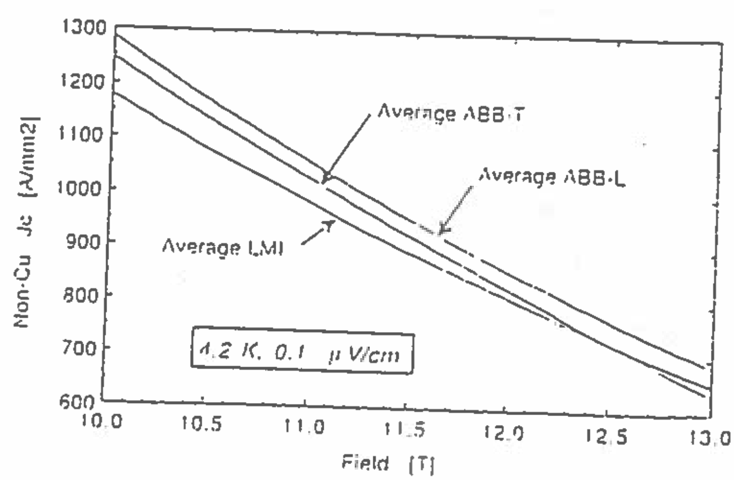

Fig. 1 Average critical current density of all the strand batches delivered by TWCA for the prototype ...

STATUS REPORT ON A 0.6m bore Nb_3Sn, WIND AND REACT, CICC SOLENOID.

A.Bonito-Oliva, A.Della Corte*, S.Parodi, G.Pasotti*,
S.Patrone, R.Penco, R.Renzetti, N.Valle

ANSALDO COMPONENTI Via N.Lorenzi 8 Genova, I-16152 , Italy
* ENEA CRE Frascati, P.O.BOX 65, 00044 Frascati, Italy

Abstract—Ansaldo and ENEA have carried out the design of a Nb3Sn solenoid, 0.6 m bore, wound with a CICC conductor and manufactured with the "wind and react" technique. The solenoid will be tested in the SULTAN facility (PSI,Villigen,CH) where, in operation condition, will be subjected to a magnetic field of 12 T on the inner radius, with a current of 6 kA. An accurate description, including critical energy calculation, quench behaviour and stress analysis are reported in the paper. In order to check the technological aspects of the design, Ansaldo got experience on a 0.6 m bore, 21 turns, model coil.

I. INTRODUCTION

Ansaldo Componenti and ENEA have developed a design of a Nb3Sn "wind and react" solenoid[1-4]. The main parameters of the coil and the cable are reported in Table 1.

Table 1. MAIN CHARACTERISTIC OF THE MAGNET

COOLING	FORCED FLOW SUPERCRITICAL HELIUM (Pin=10 bar, T=4.5K)
OPERATION CURRENT	6000 A
MAX.CONDUCTOR FIELD	12 T
MAX.DUMP VOLTAGE	500 V
COIL PARAMETERS	
INNER DIAMETER	604 mm
EXTERNAL DIAMETER	1020 mm
AXIAL LENGTH	388 mm
WINDING OVERAL CURRENT DENSITY	25.5 A/mm^2
NUMBER OF TURNS	286
NUMBER OF LAYERS	13
NUMBER OF INTERLAYER JOINTS	2
CONDUCTOR PARAMETERS	
STRANDS TYPE	INT. TIN DIFFUSION Nb_3Sn, CHROME PLATED
JACKET MATERIAL	STAINLESS STEEL 316LN MODIFIED
STRANDS DIAMETER	0.78 mm
EXTERNAL JACKET DIMENSIONS	13.8 x 13.8 mm^2
TOTAL CONDUCTOR LENGTH	745 m (in 3 different pieces)

The coil will be tested in the SULTAN test facility (P.S.I.,Villigen,CH) at its nominal current (6KA) and in a total field up to 12T.
Due to the coil characteristics a preliminary development phase was requested in the project.

In Fig. 1 it is reported a conceptual flow chart of the work. It can be seen that, in order to test all the necessary tecnologies, the design, construction and test of a model have been carried out.

At present we are going to start with the costruction of the coil itself.

Manuscript received August 24, 1992

A general overview of the work done is presented in this paper.

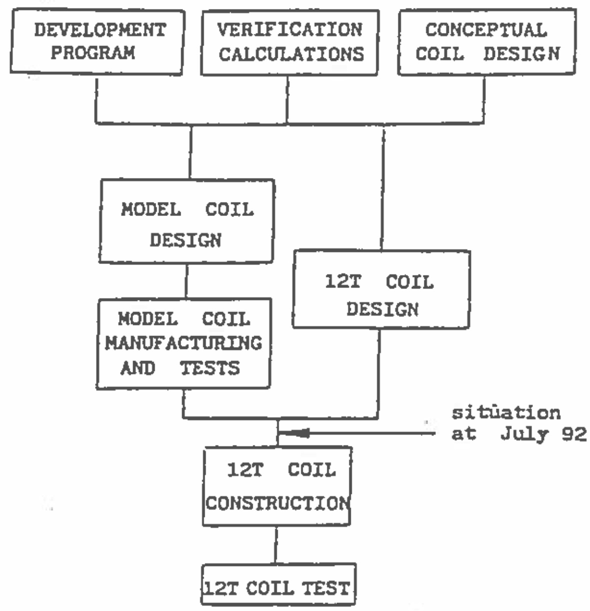

Fig.1 Flow chart of the project program

II. DEVELOPMENT PHASE

In the development phase we concentrate our work mainly on the following aspects:
- interlayer electrical joints and coil terminations development
- choice of insulation type
- optimization of the bonding between the jacket and the impregnation resin
- development of a technology allowing the removal of the coil mandrel after the impregnation.

A. Joints development

As the coil will be tested in an external magnetic field, the electric joints will be subjected to a field higher than 7 T.
Several intermediate dummy models have been manufactured and analized during this phase; at the end, we have developed two different designs for the interlayer joints and coil terminations. In order to test the designs two shorter superconducting models of the coil terminations and interlayer joints have been manufactered and tested. The results were very satisfactory. Extrapolating the experimental data we expect on the final coil an interlayer joint resistance less than $1.8.*10^{-9}$ Ohm (at B=10 T) and a termination resistance less than $2.*10^{-9}$ Ohm (at B=8 T). For more detailed information about this phase see ref.[3].

B.Cable-insulation bonding

The design request was a shear strength higher than 80 MPa at T = 77 K. In order to get this value, different techniques were explored. Several tests at room temperature and 77 K were performed at Ansaldo. The results obtained with the final technology were:

σ = 52 MPa at 300 K

σ = 88 MPa at 77 K

C.Insulation choice

Since the coil has to be subjected to a reaction heat treatment (175 h at 210 °C, 96 h at 340 °C and 200h at 650 °C) after the winding, the insulation must be able to support high temperatures.

After a preliminary analysis we decided to use the R type fiber-glass. The main problem encountered in using this kind of insulation was the burning of glass tape finish during the heat treatment. A special technology was developed by Ansaldo in order to desize the tape after the winding. In order to test this technology an array of 10 x 10 straight insulated conductors was manufactured. The array was desized, heat treated and impregnated. Then, the insulation between adjacent conductors was tested up to 5 KV c.c. applying an external pressure of .22 Kg/mm^2 on the array in order to simulate the magnetic pressure. An insulation resistance higher than 2 Gohm was found between the conductors.

D.Mandrel Removing

Due to the heat treatment process, there are no possibilities to use the usual paints to avoid the gluing between coil and mandrel during the potting by epoxy. We tested several techniques in order to reduce this bonding. At last we found a solution that guarantees a bonding strength between winding and mandrel, after impregnation, less than 5 g/mm2.

III.COIL DESIGN

In Fig.2 it is represented the half of the Sultan facility where the coil will be mounted.

The coil is composed of 13 layers with 22 turns for layer. It will be wound with 3 single lengths of cable respectively 236 m, 227 m and 261 m long. Two interlayer joints will be then present in the coil. They will be placed outside the winding: in fig.3 it is shown the position of joints and terminations in the coil. In order to support them a stainless steel flange 20mm thick have been foreseen for both coil sides.

The thickness of insulation for each turn will be 0.72 mm; between the layers an extra thickness of insulation of 0.28 mm will be used. The thickness of the ground insulation will be 3 mm.

Since quench propagation measurements will be carried out on the coil, 12 voltage taps will be mounted on the first layer turns. The voltage taps consist of 0.05 mm thick stainless steel strips welded on the jacket.

The coil cooling scheme is subdivided in 3 parallel circuits. The input and output of the helium will be in correspondence of the coil terminations and interlayer joints. All the joints and termination will be cooled in series with the coil.

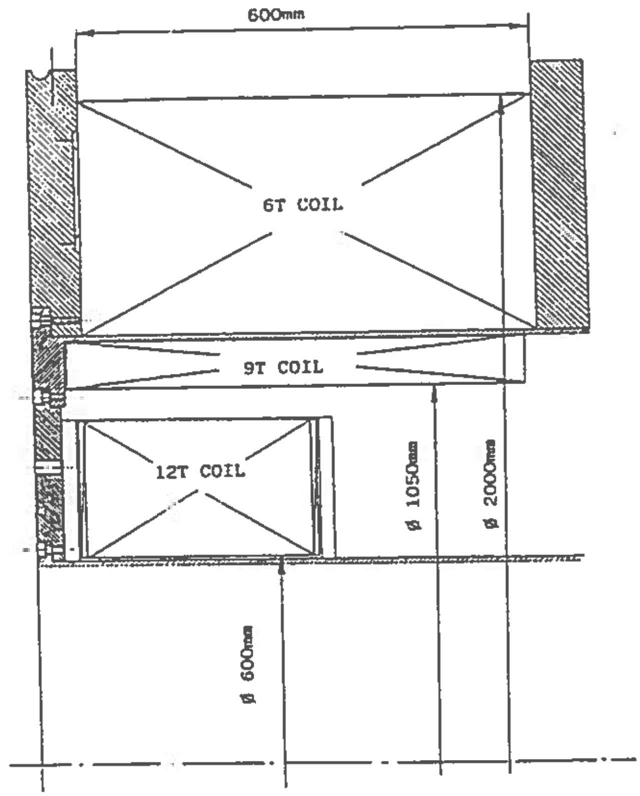

Fig.2 Sultan facility coils configuration.

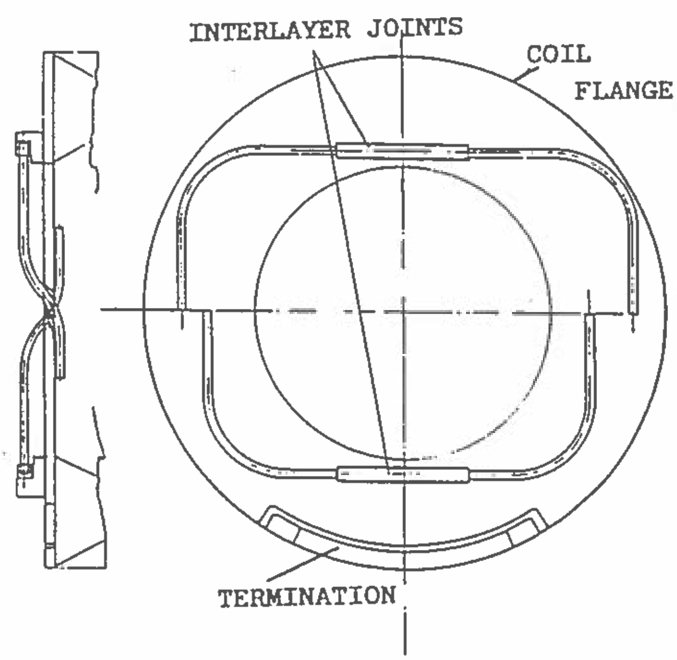

Fig.3 Coil interlayer joints and terminations configuration schematic view.

IV. VERIFICATION CALCULATION

A verification analysis of the final design has been carried out. In particular we have analyzed the problem of the quench evolution in the coil and the mechanical behaviour of the winding.

A. Quench evolution analysis:

The quench evolution has been analyzed using a modified version of the Arp's code[5].
The modification regards:
- possibility to consider the existence in the cable of two types of copper strands with different RRRs.
- possibility to take into account the heat capacity of the jacket.

In particular in our version it is possible to define a diffusion time of the heat in the jacket. From theoretical calculations it comes out a diffusion time of 0.1 sec.; in our calculations a conservative value of 0.5 sec. was used. We considered a single hydraulic circuit corresponding to the five internal layers of the coil. A uniform field of 12 T was considered.
We fixed a maximum pressure of 30 bar at the ends of the circuit; in the real situation two 16 bar safety valves are present.

For the pessimistic case of an istantaneus transition of the 5 layers we obtained a max. temperature of 35 K and a max. pressure of 226 bar.

B. Stress analysis

Stress analysis of 12 T CICC coil have been performed for both the normal operation and the quench phase.

The FE ANSYS code rev. 4.3 has been used for the calculations.

1- Normal Operation

The finite Element Model consists of a cross section of the winding with the support flanges and the ground insulation. In this model the whole winding is considered with equivalent elastic properties obtained from the mixture law. The total axial Lorentz force acting on the magnet is 1.1 MN while the total radial force is 6.45 MN/rad. The results are the following:
- maximum Von Mises stress: 127 MPa on the medium plane of the internal surface of the coil
- maximum radial stress: 3.2 MPa in the middle of the cross section
- maximum hoop stress: 117 MPa on the medium plane of the internal surface
- maximum shear stress of the ground insulation: 8.1 MPa
- maximum radial displacement: 0.36 mm on the medium plane of the coil
- maximum axial displacement: 0.18 mm

2- Quench phase

The load condition studied is due to maximum pressure reached during the quench inside the jacket: 226 bar.

Two different positions of the conductors in the winding have been analyzed:
- in contact with the s.s. flange
- on the external surface of the coil

The results are the following:
- Maximum Tresca stress on the steel jacket: 670 MPa (on the external conductors of the model)
- Maximum Tresca stress on the steel jacket: 265 MPa (on the internal conductors of the model)
- Maximum shear stress of the turn insulation: 16 MPa.

The peak stress in the jacket is less than the yield stress (1000 MPa) and the insulation can easily support the shear stress.

V. MODEL COIL MANUFACTURING AND TESTS

In order to test the designs concepts we manufactured a model coil with the actual Nb_3Sn cable.

The model coil has the same inner diameter of the real coil but it has only 3 layers of 7 turns each. All the other design paremeters (insulation thickness, etc.) are the same as the real coil. In the model winding both an interlayer joint and an electric termination are present.

We used the same winding line and manufacturing methods that will be used for the final coil.

In fig.4 it is shown the coil during the winding and in fig.5 the finished model coil.

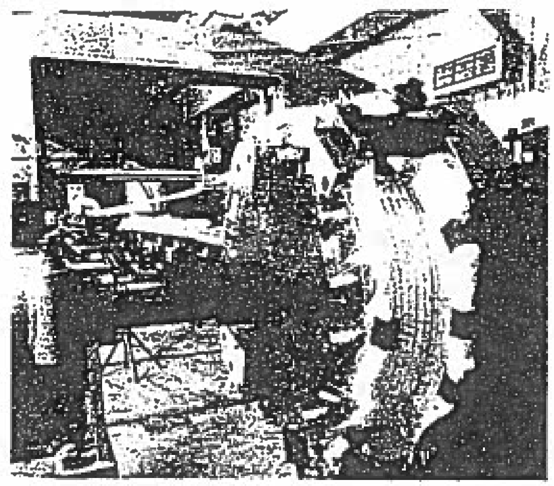

Fig.4

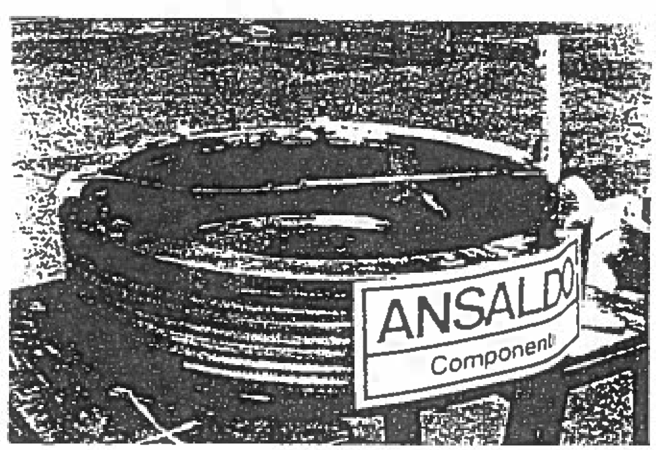

Fig.5