

Preparatory Work to Host the EDIPO Test Facility at CRPP

M. Calvi, M. Bagnasco, P. Bruzzone, F. Cau, R. Herzog, C. Marinucci, B. Stepanov, M. Vogel, R. Wesche

Abstract— CRPP has been selected to host the EDIPO test facility for the quality control tests of the ITER conductors. The new facility will be erected next to the existing SULTAN test facility at CRPP (Villigen) in Switzerland and will share the same cryo-plant. Operation of the two facilities is planned in parallel starting 2009. The new facility is designed to test short length samples built to the same specification as for SULTAN. EFDA procures 17 tons superconducting winding under industrial contract and will be delivered to CRPP in late 2008. The preparatory work at CRPP includes the design and procurement of several items as well as the final assembly and commissioning of the facility. An overview and the progress is reported, with focus on the main components: the vacuum vessel, the superconducting transformer and sample holder unit, the cryogenic cooling loop, the power supply and quench protection system, the HTS current leads and the magnetic screen.

Index Terms—Superconducting Magnet, Test facility.

I. INTRODUCTION

WITHIN the framework of the European Fusion Program a new 12.5 T superconducting dipole magnet [1] has been designed by EFDA in collaboration with several European Associations. CRPP has been selected to host and integrate the magnet into a new test facility, EDIPO. The project priority is to make available a new facility in addition to SULTAN [2] for the quality control of the ITER conductors.

The preparatory work ongoing at CRPP to integrate the dipole is addressed in this paper. An overview of the vacuum vessel design is discussed, from the mechanics to the interface with the cryo-plant and the electrical powering system. The status of the procurement of the 100 kA superconducting transformer, based on the design of the SULTAN transformer [3], is reported and details of the main components are recalled, i.e. the sample holder. The HTS current leads are briefly discussed and the new set of power converters, required to operate the new facility, are presented and their specifications summarized.

II. VACUUM VESSEL

In contrast to the SULTAN coils, which are suspended in the vacuum vessel by long steel ropes supported by a strong steel frame outside the vacuum vessel, the dipole assembly will rest on four feet placed on the bottom of the vacuum vessel, which transfer the magnet weight to the floor of the hall. A flat bottom flange is selected for the vacuum vessel. After considering different options, a 48 mm thick,

1990 mm diameter, stainless steel flat flange was chosen, embedded on about 20 mm thick, liquid concrete layer and bolted to the underlying solid concrete floor.

The cylinder body of the vacuum vessel is made of a 10 mm thick, 1800 mm diameter stainless steel tube bolted to the bottom flange with an O-ring. This solution allows assembling the gravity supports and the thermal screen of the dipole prior to installing the cryostat cylinder. Four round openings, 658 mm diameter, close to the bottom of the cylinder, provide limited access to the feet region for adjustment of the gravity supports, at room temperature.

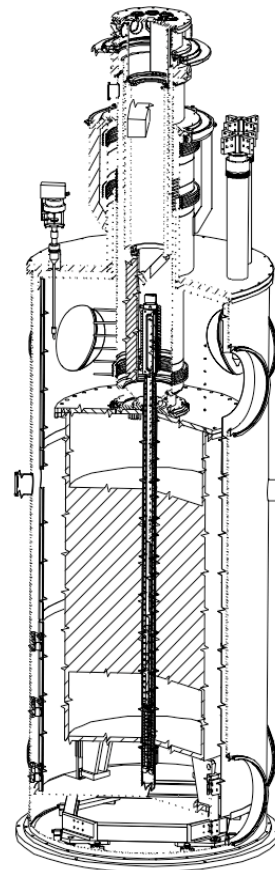


Fig. 1 The 3D technical drawn of the vacuum vessel of the dipole

The four feet, placed at 45 degrees with respect to the field direction, are made of glass epoxy plates. Even in the worst case, when only three feet out of four carry the weight, the test well is vented and there is vacuum in the vessel, the compressive stress is below 20 MPa. Each foot ends with a steel flange, which is bolted to four steel supports welded to the bottom flange of the dipole assembly. These four supports build the actual mechanical interface between the dipole assembly and CRPP vacuum vessel. The thermal screen is fixed at about mid-length of

the non-flanged section (200 mm long), leading to an overall heat conduction loss of less than 15 W from room temperature to the 70 K screen and of less than 2 W to the 5 K cold mass. Finally the lower end of the glass-epoxy feet is rigidly bolted to a steel frame, which is bolted to the flat bottom of the vacuum vessel through adjustable screws to control the perfect verticality of the dipole assembly, and hence of the test well.

The thermal screen, made of segmented copper plates surrounding the cold mass and lined with cooling pipes, as well as super-insulation, is installed before lowering the steel cylinder of the vacuum vessel.

The 1800 mm diameter vacuum vessel extends 4370 mm from the bottom flange, i.e. over one meter above the upper flange of the dipole winding. This space is used for the electrical and cryogenic interfaces, as well as for the heat exchanger, current leads and valve access. Four round openings at about 3700 mm height, similar to those placed at the feet, allow access to the upper interface region, e.g. for installation, inspection and repair work.

The feed-throughs for DC and AC current leads, instrumentation wires and the heads of the cryogenic valves are crossing the annular flange at the 4370 mm level. The vacuum vessel extends in the center of the cylinder up to 6100 mm to host the upper part of the retractable transformer unit. A system of bellows and a centering unit allows fine tuning the alignment of the vacuum vessel to the transformer unit and the compensation of the cool-down shrinkage.

No lateral support is foreseen for the dipole winding inside the vacuum vessel. The lateral forces arising from the interaction between the magnetic field of the dipole and the screening iron walls in the SULTAN hall should be very small (see section VIII).

To monitor the displacement of the cold mass from the starting position (due to cool down and energization) four small openings with 160 mm flanges are placed at 90 degrees each at 2702 mm high in the vacuum vessel. At the corresponding location, the surface of the outer cylinder is properly machined to attach a load cell as a displacement sensor.

III. SUPERCONDUCTING TRANSFORMER

To supply current to the sample a superconducting transformer (i.e. flux pump) is used instead of directly feeding the sample with an external power converter. This choice aims to improve the efficiency of cryogenic installations requiring high currents. With this device it is possible to feed high current low inductance superconducting samples at cryogenic conditions with low cryogenic losses and smaller (and cheaper) power converters. The principle is to have low current in the room temperature part of the circuit and high current in the low temperature, low resistance part.

With respect to the SULTAN transformer [3] few improvements have been introduced in the design while the main parameters have been retained. The first change is the increased current in the primary coil from 200A to 300A, to extend the maximum magnetic flux (i.e. time available for measurements). The second concerns the cooling of the primary coil, previously indirectly cooled with a force flow

helium circuit and now in thermal contact with a helium bath at 4.2K. This last change is intended to improve the heat transfer during operation with fast cyclic current loading.

The technical specifications of the NbTi superconducting wire of the primary coil are presented in Table I. The CICC conductor of the secondary, even if very similar to the existing one, has also been changed to avoid segregated copper strands. For this reason the copper to non copper ratio of the superconducting strands has been increased from 2 to 3. This design minimizes the risk of the self-field instabilities observed in NbTi conductors [4]. Moreover coating has been introduced to avoid aging effect on the contact resistance and SnAg coating material has been chosen to guarantee redistribution in case of in-homogeneity of current among strands at the cost of higher coupling losses. Table II and Table III presents the specifications of the strands and of the conductors respectively.

TABLE I PARAMETERS OF THE PRIMARY COIL SC STRAND

Parameter	Value
Bare strand diameter	1.0 ± 0.005 mm
Insulated strand	1.05 ± 0.005 mm
Copper to non copper ratio	1.65
Ic @ 5T and 4.2K	> 650 A (921 A measured)
RRR	> 100 (131 measured)
Filament size	7.6 μm
Twist pitch	11 mm

TABLE II SPECIFICATION FOR THE SC STRAND OF THE CICC

Parameter	Value
Bare strand diameter	0.89 mm
Tin coated strand diameter	0.90 mm
Copper to non copper ratio	3.0
Ic @ 5T and 4.2K	> 450 A
RRR	> 200
Filament size	< 15 μm
Twist pitch	< 12 mm

TABLE III SPECIFICATION OF THE CICC CONDUCTOR

Parameter	Value
Number of SC strands	324
Cable pattern	3x3x3x3x4
External conduit dimension	17.7±0.05 x 25.1±0.05 mm ²
Conduit thickness	1.5±0.01 mm
Conduit material	316L stainless Steel
External corner radius	<4mm
Expected void fraction	~33%
Cabling stages:	Pitch 1 – 45 mm Pitch 2 – 80 mm Pitch 3 – 115 mm Pitch 4 – 175 mm Pitch 5 – 230 mm

The sample holder is electrically and mechanically connected at the bottom of the secondary coil. Its design has not been changed with respect to the SULTAN one. Efforts are made to minimize the thermal voltage generated in wires and connections to improve the absolute accuracy of the signals.

IV. CRYOGENIC COOLING LOOPS

The same conceptual cooling scheme as in SULTAN is used for the dipole. The supercritical, 10.5 bar helium from the cryo-plant is first cooled down by a heat exchanger operating with liquid helium, placed inside the main vacuum vessel. The coolant is then split into a number of parallel circuits (coil 1), each with the same pressure drop, of ~ 2.6 bar. A manifold collects the outlets of the parallel circuits (at about 7.5 bar and 5.6 K) and passes again through the heat exchanger to re-cool to 4.5 K. Then the helium flow into parallel circuits (coil 2) with another pressure drop of about 2.6 bar. The helium collected at about 4-5 bar from the outlets of the second coil expands eventually by a Joule-Thompson valve into the heat exchanger, refilling the liquid helium level. In case of large helium evaporation in the heat exchanger, the liquid helium level can be raised expanding additional helium through a by-pass valve

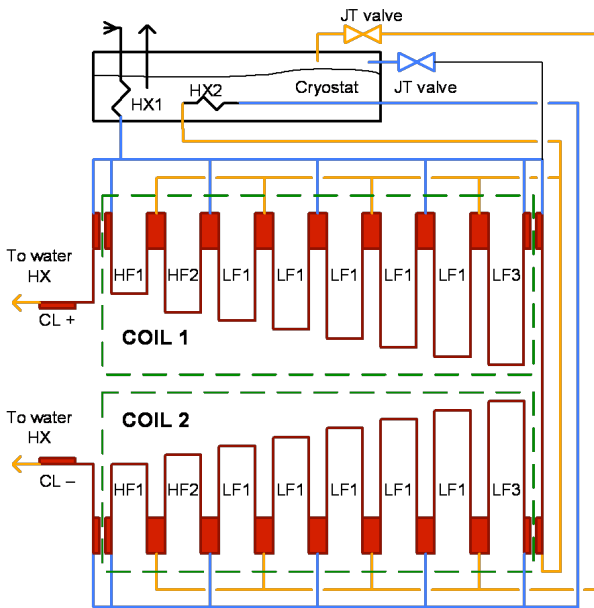


Fig. 2 The schematic of the cryogenic cooling circuit for the dipole.

It is estimated that the overall mass flow rate at 10.5 bar coming from the cryo-plant port for the dipole is about 10 g/s, most of which will flow through the winding pack. At a design pressure drop of 2.5 bar per coil, the mass flow rate per channel will range from 0.8 to 2.0 g/s.

The outer cylinder is cooled in parallel with the two coils. Each of the manifolds is connected to the quench venting line (the existing one for SULTAN) through overpressure valves set at 16 bar, placed outside the vacuum vessel. In case of quench, the helium inventory is fully recovered in the 50 m³, 16 bar container.

The cooling circuit of the AC coils will be supplied from the cold helium inlet manifold. The outlet of the AC coils is recovered as warm helium. The mass flow rate in the AC coils is adjusted according to the operational requirements by a warm valve placed outside the vacuum vessel. The thermal screen of the vacuum vessel is fed by the 80 K helium circuit from the cryo-plant. The actual temperature at the inlet is about 73 K. According to the final design of the HTS current leads, the helium from the screen circuit may be used for the HTS during stand-by operation, while a heat exchanger will be used to decrease the HTS anchor

temperature down to 50K.

V. POWER CONVERTERS

To operate the EDIPO facility, three new power converters are needed. The main parameters of the PCs are summarized in Table IV.

The superconducting dipole coil has to be continuously operated up to 16.5kA and during the charge and discharge phase the current should increase and decrease in a controlled way at rates of ± 20 A/s. To achieve this performance an inquiry for a two quadrant PC has been successfully launched among industries. A twelve-pulse thyristor-based PC was finally chosen which is the most suitable solution if negative voltage is required. Thanks to the DCCT technology used for the current measuring system, stability below 100 ppm is achieved.

For powering the AC coil a four quadrant PC based on IGBT technology will be installed. The design has been based on the PC converter used for the existing AC coil of the SULTAN facility. Only a higher voltage is required because of the higher resistance of the EDIPO AC coil.

For the superconducting transformer, a four quadrant PC will be used as well, also based on IGBT technology. The operation of the transformer requires a dedicated PC control system because not only the current in the PC has to be control but also the current in the sample, which are neither equal nor proportional. This requires two feedback signals proportional to the currents and two regulation loops, acting either in parallel or in series. Moreover, because the demand for testing cables under cyclic load is increasing, the new converter will have a higher voltage to allow higher current rate and reduce the time required by this procedure thus the overall test costs. This higher performance operating mode also demands improvements of the quench detection system of the transformer as it is discussed in section VI.

TABLE IV POWER CONVERTERS PARAMETERS

	Current range	Voltage range
EDIPO	0, 18 kA	-10,+10 V
AC COIL	-500, +500 A	-200, +200 V
TRANSFORMER	-300, +300 A	-40, +40 V

VI. QUENCH PROTECTION

The quench protection system (QPS) must detect a quench in the coil reliably and extract the stored magnetic energy (~ 16 MJ) quickly while not exceeding acceptable voltages in the coil circuit. The EDIPO quench detection electronics will monitor the voltage over each of the 16 conductor segments and trigger the opening of extraction switches to initiate a safety discharge if the resistive voltage exceeds 150 mV for more than 10 ms on any segment. Bridge circuits comparing the voltages of two segments will fully compensate inductive voltages during current ramps. Two sets of extraction switches, which open in less than 50 ms, will separate the power converter from the circuit forcing the coil current to flow across two extraction resistors (see Figure 3). The coil terminal voltage will increase to 2 kV within a few milliseconds and the current will subsequently decay with a time constant of 1 s. Detailed simulations of EDIPO's quench behaviour [5] confirmed

that this choice of parameters will lead to hot-spot temperatures below 160 K and peak pressures not exceeding 22 MPa, which are structurally acceptable values.

The quench detection system will consist of a commercially available, stand-alone data acquisition unit (DAQ), which will be programmed to perform signal digitisation, signal processing and trigger output as well as allow on-line and post-mortem signal analysis. Signal conditioning circuits will protect the DAQ inputs from the 125 V generated by each segment during a safety discharge.

Although at the technical limit, mechanical switches opening in less than 20 ms and coping with voltages of 2 kV are available from a small number of suppliers for currents up to 5 kA. Four or five such switches will operate in parallel to carry the coil current of 16.5 kA. Extraction resistors made of steel plates and able to dissipate the magnet energy without overheating are more common. The resistors and switches will be housed in a dedicated enclosure next to the power converter.

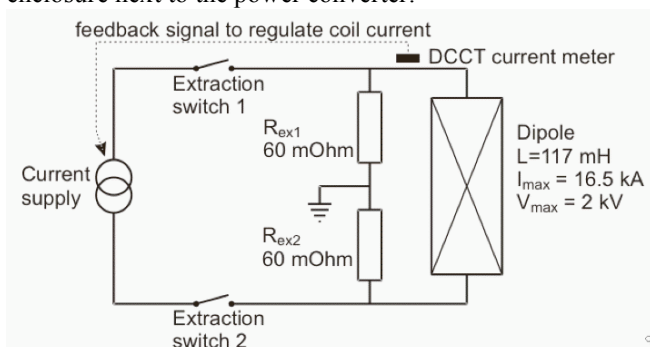


Figure 3 The electrical connections of the dipole with the detail of the quench protection system, the switches and the dump resistor.

A. Transformer quench protection

Because the transformer shall be operated at fast ramp rates and quick ramp-rate changes, its quench detection system requires sophisticated signal processing to reliably distinguish between expected transitory voltages and the ones created by a genuine quench. Technically a similar detection system to the one for the magnet will be used, programmed with the advanced algorithm. In case of a quench the coil current of up to 300 A is switched to an extraction resistor which dissipates the maximum stored energy of 120 kJ.

VII. HTS CURRENT LEADS

Superconducting magnets cooled by 4.5 K super-critical helium require a connection to the power supply located at room temperature. With respect to conventional current lead the cryogenic power needed to cool an HTS current lead is about 4 times lower. The dipole current lead will consist of an HTS part and a conventional copper part operated in the range of 4.5 to 65-80 K and 65-80 K to room temperature, respectively. The HTS part will be conduction cooled from the 4.5 K level and the copper part will be actively cooled with helium gas. This concept was already successfully applied in the European 70 kA HTS current lead demonstrator [7]. Also for this leads the design has been done using Bi-2223 tape as a favorite material.

VIII. MAGNETIC SCREEN

Since EDIPO will be placed close to the existing

SULTAN facility, it was necessary to assess the magnetic forces acting between EDIPO and the two large existing iron screens (0.6 m thick, 3.5 m high and 3.2 m deep) located on both sides of SULTAN. The strong lateral forces between the EDIPO winding at nominal current and the screen located between the two facilities require a compensating screen on EDIPO's side facing away from SULTAN.

A series of finite element analyses have been carried out to calculate the forces and find the location and suitable dimensions of the additional screen. EDIPO's winding pack was modeled as a single racetrack turn with a current of 6.12 MA; the iron yoke was made of the low carbon steel MAGNETIL BC 5.8™, while the iron of the existing screens was used also for the new one.

A new screen with the same dimensions as the old ones, placed at the same distance from the dipole axis as the screen between the facilities, results in lateral forces on the dipole smaller than 100 N with either EDIPO or SULTAN powered. The vertical force on the dipole at full current, however, reaches 4 kN because its centre is not at the same height as the one of the screens. The 70 kN magnetic loads on the screens must be borne by a strong support structure. The simulations also showed that a displacement of the dipole from the symmetry plane by only 50 mm leads to a lateral force of 9 kN. Precise alignment is therefore essential. Halving the thickness of the new screen relative to the existing ones, on the other hand, results in a lateral force of only 120 N, which can be easily compensated by moving the new screen a few mm towards the dipole. Substantial gains in available space, weight reduction and cost savings are thus possible.

IX. CONCLUSION

The design, planning and procurement of the components for the EDIPO test facility is progressing according to schedule, permitting the installation of the EDIPO dipole soon after its foreseen completion date in the second half of 2008. The designs of the various sub-systems follow closely the ones for the existing SULTAN systems – using updated technologies where appropriate – thus allowing realistic schedule and cost planning. The CRPP superconductivity group is excited about and will be ready for the commissioning and operation of the EDIPO test facility.

REFERENCES

- [1] A.Portone et al. "Design and optimization of the 12.5 T EFDA dipole magnet", CRYOGENICS, Vol 45, pp.494-506, 2006.
- [2] B.Blau et al. "First performance tests of the 12 T split coil test facility SULTAN III", IEEE.
- [3] G.Pastor et al, "Design, fabrication and testing of 100kA superconducting transformer for the SULTAN test facility",
- [4] R.Wesche et al. "DC performance, AC loss and transient field stability of five medium size NbTi cable-in-conduit conductors with parametric variations", CRYOGENICS 45 pp.755-779, 2005.
- [5] C.Marinucci et al, "Quench analysis of EDIPO superconducting dipole magnet", this conference.
- [6] L.Bottura, C.Rosso and M.Breschi, "A general model for thermal hydrolic and electrical analysis of superconducting cables". Cryogenics 2000; 40:617.
- [7] R.Heller, G.Friesinger, A.M.Fuchs and R.Wesche, "Development of High Temperature Superconducting Current Leads for 70kA", IEEE Trans. On Appl. Superconductivity, Vol. 12, No.1, March 2002.