# Progress on the Design of the 15 T Magnet of the EDIPO Test Facility

Xabier Sarasola, Pierluigi Bruzzone, Roberto Guarino, Kamil Sedlak, and Evgeny Solodko

***Abstract*— EDIPO 2 (the upgraded EDIPO test facility) will provide a unique testbed for superconducting cables for fusion magnets, accelerators, and other applications. Compared to the previous magnet assembly, the magnetic field is enhanced from 12.35 T to 15 T, the aperture is enlarged from 90×141 mm$^2$ to 144×144 mm$^2$ and the uniform field length is increased from 680 mm to 1000 mm (assuming a 1% drop of the field along the sample axis). A number of magnet designs have been proposed for EDIPO 2 since the conceptual design activities started in 2017. The design iterations have converged into a flared-end block-coil dipole design with a purely rectangular cross-section (coil windings aligned on the high and the low-field side). The use of a two-stage cable design is considered in order to increase the operating current, reduce the coil inductance and consequently limit the discharge voltage. The magnet structural design keeps the pre-compression applied to the coil winding pack to a minimum and allows a gap to open between the coils and the test well during operation. Progress on the magnet design activities is reported, including the results of magnetic and mechanical analyses, as well as quench protection studies. The procurement of the helium vessel required to contain the liquid helium bath for magnet cooling is also discussed.**

***Index Terms*—High field magnet, test facility, superconducting magnet, $Nb_3Sn$.**

## I. Introduction

The Swiss Plasma Center (SPC) hosts, manages, and operates two test facilities dedicated to testing forced-flow superconductors and insert coils: SULTAN (SUpraLeiter Test ANlage, [1]), and EDIPO (European DIPOle, [2]). Both facilities can provide a high operating current to the samples (up to 100 kA), a variable temperature environment (4.5 to 50 K), and a high background magnetic field in a large rectangular aperture. The background field in SULTAN is generated by a split-solenoid, whereas EDIPO relies on a dipole magnet, which can provide a three times longer uniform field length.

The operation of EDIPO was interrupted in 2016 when the magnet assembly was irreversibly damaged due to an unprotected quench. Since the rest of the test facility (namely, cryoplant, cryostat, magnet power supply, and sample superconducting transformer) remains intact, SPC is preparing to rebuild and upgrade the EDIPO magnet assembly.

EDIPO 2 (the upgraded test facility) aims at providing a testbed with 15 T in a 144×144 mm$^2$ aperture and over a uniform field length of 1000 mm, assuming a 1% drop in the field along the axis of the magnet aperture. The size of the aperture is compatible with SULTAN samples [1] and will enable the test of insert coils with a larger diameter than those tested in FRESCA2 [3]. The high field and large aperture of EDIPO 2 call for a high current density block-coil similar to the one used for accelerator-relevant magnets like FRESCA2, [4].

In this manuscript, we present the status of the EDIPO 2 magnet design and the procurement of the helium vessel which will host the magnet. Section II provides details of the proposed cable design. The main features of the magnet design are described in Section III. The results of the magneto-static and mechanical Finite Element Models (FEMs) are summarized respectively in Sections IV and V, whereas Section VI shows the results of quench protection studies. Section VII reports on the design and manufacturing of the helium vessel.

## II. Cable Design

The design of the EDIPO 2 coils considered until 2020 [5]–[7] was based on a high aspect ratio Rutherford cable made of 44×1.1-mm-diameter $Nb_3Sn$ strands operating at a current of 11.5 kA (purely rectangular coil layout, [7]). This cable design did not make full use of the existing 18 kA power supply, which is undesirable since it increases the coil inductance and the magnet discharge voltage. Increasing the operating current of the Rutherford cable might be possible by increasing the number of strands to an even higher number, but this would result in a rather stiff cable layout and might pose significant challenges during coil winding at the hard bending locations.

This makes us consider alternative cable designs based on a flat two-stage layout to increase the superconductor cross-section without increasing the cable aspect ratio even further. Fig. 1 shows a sketch of one of the proposed designs, where the first cable stage is made of 6+1 $Nb_3Sn$ strands, and the second cable stage combines 26 first stages in a flat Rutherford-type layout similar to the cable of the 9 T and 12 T coils of SULTAN

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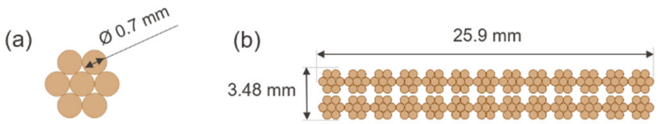


Fig. 1. (a) First cable stage: 6+1 cable layout made of 0.7 mm diameter $Nb_3Sn$ strands; (b) Second cable stage of the design more suitable for a magnet with 4 coils: 26×(6+1) first stages compacted to have the final dimensions of 25.9×3.48 mm².

TABLE I
CABLE DESIGN ALTERNATIVES

| Magnet design | Strand Diam. (mm) | Strand # | Cable Layout | Cable Width (mm) | Cable Thick. (mm) |
|---|---|---|---|---|---|
| Previous baseline | 1.1 | 44 | Rutherford | 26.2 | 1.95 |
| 4-coil design[a] | 0.7 | 182 | 26×(6+1) | 25.9 | 3.48 |
| 6-coil design | 0.7 | 154 | 22×(6+1) | 21.9 | 3.48 |

[a] Fig. 1 shows a sketch of this cable design.

[8]. Table I compares the Rutherford cable considered previously with the proposed two-stage designs: one optimized for a 4-coil magnet design, and the other for a 6-coil magnet design (see Section III). The final compaction of the two-stage cable designs assumes a 20% void fraction.

The considered strands are assumed to have a copper-to-non-copper ratio of 1.0 and a non-copper critical current density ($j_{nc,c}$) following the scaling law specified in [9] and quoted in Eq. (1):

$$j_{nc,c} = \frac{C_0}{B}(1-t^{1.52})^{\alpha}(1-t^2)^{\alpha}b^{0.5}(1-b)^2 \quad (1)$$

where $B$ is the magnetic flux density; $t$ is the normalized temperature, $t = T/T_{c0}$; and $b$ is the normalized field, $b = B/B_{c2}$, being $B_{c2} = B_{c20}(1-t^{1.52})$. $\alpha = 0.96$, $T_{c0} = 16$ K, and $B_{c20} = 28.8$ T are scaling parameters [5]. The magnet designs described in Table II assume a target $C_0 = 255230$ AT/mm², which gives $j_{nc,c} = 3093$ A/mm² at 4.2 K and 12 T (including a 5% degradation due to cabling).

Recently, SPC has procured 20 km of high current density 0.7-mm-diameter $Nb_3Sn$ strand. In 2022, a qualified industry will use the strands to produce ~100 m of the two-stage cable shown in Fig. 1. The resulting cable will be used for winding and bending trials.

## III. Magnet Design

In addition to the operating current, the remaining infrastructure of the existing facility dictates relevant boundaries for the EDIPO 2 magnet design, namely: its maximum outer diameter (1320 mm), length (2500 mm), and weight (20 t).

The two magnet designs considered for EDIPO 2 are illustrated in Fig. 2. In both designs, the magnet is hosted in a helium bath at 4.2 K and the magnetic field is generated by a purely rectangular winding pack with the turns aligned both on the high-field and the low-field sides. In one design, the winding pack is made of 4 double-pancake coils (Fig. 2 a), whereas in the other, it is made of 6 double-pancake coils (Fig. 2 b), which results in a taller and thinner winding pack cross-section.

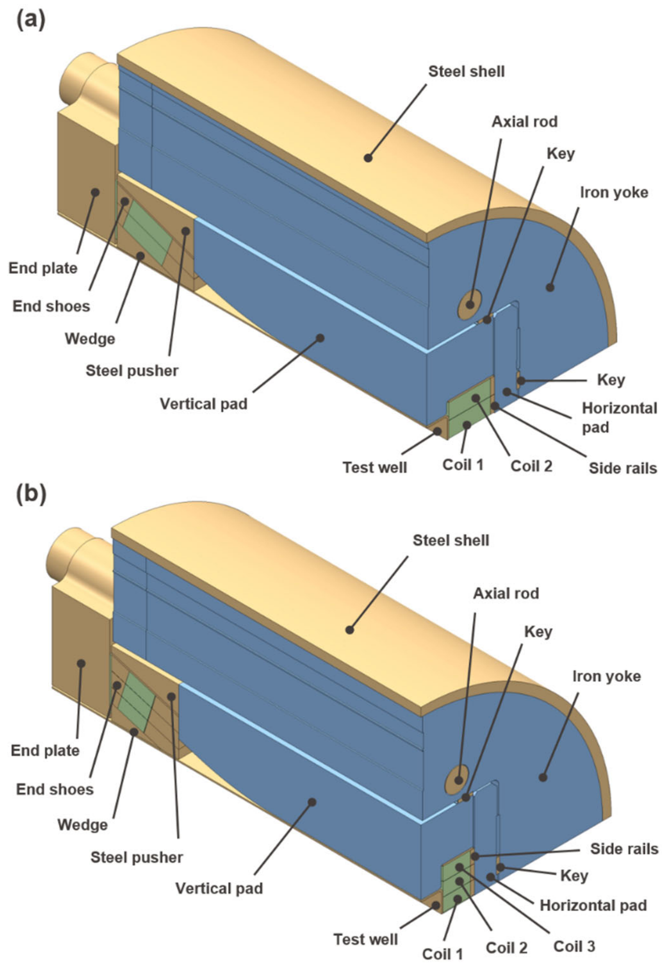


Fig. 2. One octant 3-D geometry of the considered magnet design alternatives: (a) 4-coil design: 2 double-pancake coils per magnet pole. (b) 6-coil design: 3 double-pancake coils per magnet pole.

Other features are similar in both magnet designs. In the ends, the coils flare through the hard-way bend of the cable to reduce the field in the end regions and accommodate the vertical test well where the samples are hosted. The test well is a square pipe separating the cryogenic environment of the sample from the liquid helium bath cooling the magnet. The coils are assembled in a steel shell-based structure with tunable preload by using keys and bladders [10]. Adjustable longitudinal pre-compression can also be provided by an axial support system composed of end-plates and a set of 82-mm-diameter steel rods. The yoke, the vertical pad, and the horizontal pad are made of iron to enhance by ~2 T the magnetic field in the aperture.

## IV. Magneto-static Analysis

The magneto-static analyses are based on 2D and 3D FEM in ANSYS [11] and 2D models in ROXIE [12]. The iron parts are assumed to have the same B-H curve as the low carbon steel used in the former EDIPO magnet [13].

Table II compares the main characteristics of the two designs under consideration. Winding packs with a wide range of height-to-width aspect ratios ($b/a$) have been explored aiming at generating 15 T in the aperture operating at 85% of the magnet load line with respect to the short sample limit ($I_{ss}$). Winding packs with a larger $b/a$ aspect ratio (i.e., the 6-coil design) result in more efficient and better field quality designs. By increasing the operating current closer to the power supply limit, we are able to reduce the magnet self-inductance by more than a factor of 2.5 compared to previous designs [7].

The results of the 3D FEM show that the peak magnetic field in the coil ends is at least 1.85 T lower than in the straight section, and the uniform field length is ~960 mm for both design options.

The $j_{nc,c}$ of the selected strand is a primary design driver of a high field magnet like EDIPO 2. Fig. 3 shows the variation of the field in the aperture of the 4-coil design as a function of the strand $j_{nc,c}$ and for a range of operating points (reported as a fraction of $I_{ss}$). The present design targets can be achieved using a strand with $j_{nc,c} \geq 3000$ A/mm$^2$ at 4.2 K and 12 T.

## V. Mechanical Analysis

The mechanical behavior of the magnet assembly has been studied in 2D and 3D using FEMs in ANSYS [11]. The assumed material properties are those specified for the mechanical design of the FCC dipole magnets [6], [9]. The simulations include three loading steps: 1) assembly at room temperature where minimal preload is applied, 2) cool-down to 4.2 K, and 3) powering at the nominal field, which includes the effect of the Lorentz forces in the coils and the reluctance forces in the iron parts. The coil windings are epoxy-impregnated together with the side steel rails and the end shoes (bonded contacts are assumed). Standard frictional contacts with a friction coefficient of 0.2 are assumed elsewhere in the magnet assembly.

The use of minimal pre-load is considered, because it allows to move the coil windings as close as possible to the aperture (the test well does not react a high pre-load), and the magnetic field quality requirements in a test facility are not as stringent as in accelerator magnets (at nominal field a 1.9 mm gap is allowed to open between the coils and the test well in EDIPO 2).

Fig. 4 shows that the stress in the straight section of the coils is always below 132 MPa, and thus no performance degradation of flat $Nb_3Sn$ cables is expected. However, the stress in the coil ends is well above allowable limits. The use of end spacers (Fig. 5) lowers the magnetic field and the mechanical stress in the ends, but in certain locations, the equivalent von Mises stress remains above 200 MPa, which is associated with permanent degradation in impregnated $Nb_3Sn$ Rutherford cables [14]. The stress in other regions of the magnet assembly is within acceptable limits during the three considered loading steps.

## VI. Quench Protection

The protection strategy of the EDIPO 2 magnet relies on an energy extraction system, where the current is discharged through an external resistor upon quench detection. The electromagnetic and thermal transients during an emergency discharge are simulated with the STEAM-LEDET software, [15]. The simulation of two-stage cables was done using sub-cables of an equivalent cross-section. Since the inter-strand coupling losses in two-stage cables are not precisely modeled with STEAM-LEDET, they are neglected in the simulations, thus providing a conservative upper boundary for the hot-spot temperature.

Fig. 6 summarizes the results of the simulated hot-spot temperature as a function of the terminal-to-terminal extraction voltage ($V_{EE}$) for the considered 4-coil, and 6-coil magnet designs. The quench starts locally in the highest field turn, and the simulations assume a quench detection and validation time of 15 ms, and an energy extraction triggering time of 1 ms. The Residual-Resistivity Ratio (RRR) of copper in the strands is assumed to be 100 and the filament twist-pitch, 14 mm. The simulations also consider the case where the inter-filamentary coupling currents (IFCC) are neglected, which gives an upper limit

TABLE II
Parameters of the Considered Magnet Designs Based on a 3D Model

| | 4-coil design | 6-coil design | Units |
|---|---|---|---|
| Cable layout | 26×(6+1) | 22×(6+1) | |
| Total conductor area | 30538 | 25254 | mm$^2$ |
| Operating current, $I_{op}$ $(85\%\times I_{ss})$ | 17.12 | 17.37 | kA |
| B field in the aperture, $B_{center}$ | 15.11 | 15.10 | T |
| Peak B field in the coils, $B_{peak}$ | 16.30 | 15.83 | T |
| Number of turns per pancake, $n_{pan}$ | 37 | 24 | |
| Total number of turns, $n_{total}$ | 296 | 288 | |
| Total ampere-turns, $I_{total}$ | 5.07 | 5.00 | MAt |
| Total magnet stored energy, $E_{total}$ | 13.5 | 12.0 | MJ |
| Magnet self-inductance, $L$ | 92.1 | 79.5 | mH |
| Engineering current density[a], $j_{eng}$ | 165.9 | 198.1 | A/mm$^2$ |
| Copper current density, $j_{Cu}$ | 488.9 | 586.2 | A/mm$^2$ |

[a]Engineering current density based on the insulated winding pack

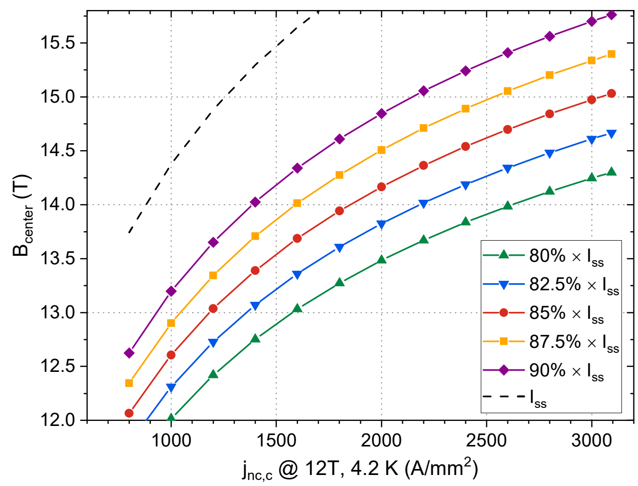


Fig. 3. Magnetic field generated in the center of the aperture as a function of the strand non-copper critical current density ($j_{nc,c}$) at 12 T and 4.2 K. The geometry of the magnet corresponds to the 4-coil magnet design and the results are based on a 2D model. Operation at five different ratios with respect to the short sample limit ($I_{ss}$) is considered.

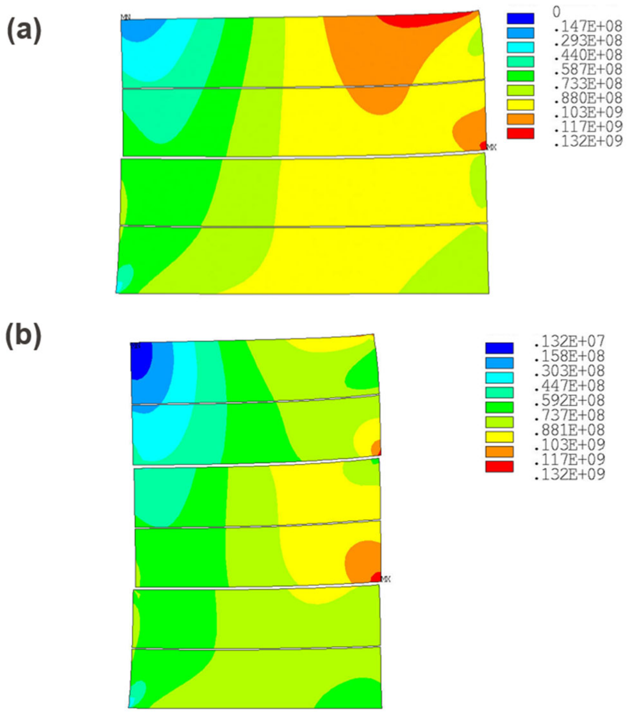


Fig. 4. Distribution of the von Mises stress in Pa in the straight section of coil windings at nominal field: (a) 4-coil design, (b) 6-coil design.

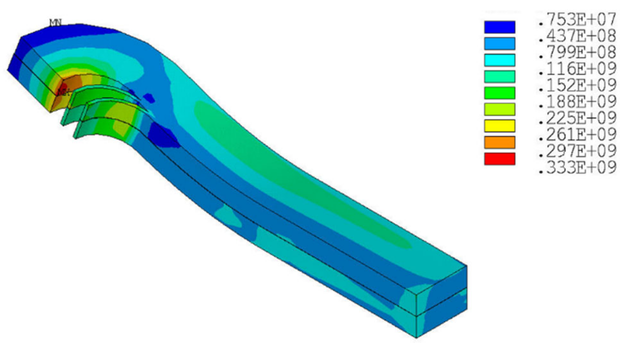


Fig. 5. 4-coil magnet design with 2×30-mm end spacers: distribution of the von Mises stress in Pa in the coil windings at nominal field. The stress in certain locations of the coil ends is above allowable values.

for the simulated hot-spot temperature. The results shown in Fig. 6 demonstrate that the EDIPO 2 magnet can be reliably protected ($T_{hot\,spot} \leq 250$ K) with an energy extraction system for $V_{EE} \geq 1.25$ kV. The selected dump resistance is 71.5 mΩ (4-coil design) and 70.7 mΩ (6-coil design) for $V_{EE} = 1.25$ kV. The voltage to ground ($V_g$) can be halved if symmetric grounding is used, i.e., $V_g = 0.5 \times V_{EE}$.

## VII. Helium Vessel

Until the accident in 2016, the dipole at the core of the EDIPO test facility was based on a cable-in-conduit design [13] cooled by a forced flow of supercritical helium at 4.5 K. However, the EDIPO 2 magnet will be bath-cooled at 4.2 K and a helium vessel has been constructed in 2021 to host the magnet. The vessel is made of three main parts: a thick flat base to hold

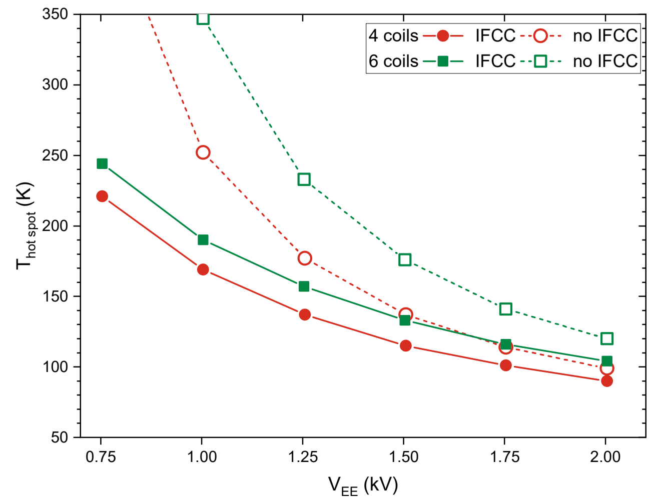


Fig. 6. Simulated adiabatic hot-spot temperature as a function of the terminal-to-terminal extraction voltage ($V_{EE}$). The solid lines refer to the cases including the contribution of the inter-filamentary coupling currents (IFCC), whereas the dashed lines (no IFCC) show the upper boundary obtained by neglecting the inter-filamentary coupling currents.

the weight of the magnet, a cylindrical body, and a torispherical lid. The vessel has been designed to operate at a pressure of 1 bar and withstand an accident pressure of 3 bar according to the relevant industrial standards.

The pressure relief system follows a staged pressure protection concept and considers both a loss of vacuum and an unprotected quench as worst-case accidents. Details on the pressure relief system are reported elsewhere, [16].

## VIII. Conclusion

The considered EDIPO 2 magnet designs are based on a flared-end block coil design (similar to accelerator magnets), but they include innovative features, such as the use of a two-stage flat cable layout, and a mechanical structure providing minimal pre-compression to the coils. The proposed designs satisfy the requirements to generate a background field of 15 T in a large aperture and over a ~1000-mm uniform field length, and it can be protected based on an energy extraction system. However, based on the 3D mechanical analysis presented in Section V, the use of minimal pre-compression seems to be related to the presence of high stress in the coil ends, and the considered end spacers cannot lower the stress below acceptable levels. Increasing the space between turns in the ends as well as providing additional axial pre-compression are among the strategies under consideration to lower the stress in that region.

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