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Studio sulla fattibilità di un sistema magnetico poloidale e toroidale superconduttore per FAST

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STUDIO SULLA FATTIBILITÀ DI UN SISTEMA MAGNETICO POLOIDALE E TOROIDALE SUPERCONDUTTORE PER FAST

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Sommario

Uno degli obiettivi principali della macchina JT-60SA è lo sviluppo di regimi di plasma a confinamento avanzato, necessari per poter dimostrare l'effettiva possibilità di realizzazione di un reattore a fusione "steady state" ovvero capace di rimanere in funzione per un tempo sufficientemente lungo da poter essere considerato stazionario non solo dal punto di vista della fisica dei plasmi ma anche da quello delle tecnologie. A tale scopo è di basilare importanza verificare la possibilità di utilizzare FAST per lo studio delle soluzioni, sia dal punto di vista dei componenti che da quello degli scenari, capaci di garantire lo smaltimento del flusso termico di un plasma quasi ignito in queste condizioni di regime "steady state".
Il sistema magnetico previsto nel progetto attuale di FAST prevede che tutte le bobine (di campo toroidale, esterne di campo poloidale e del solenoide centrale) siano realizzate in rame, con conseguente intrinseca limitazione della durata della scarica. Per realizzare invece una macchina capace di raggiungere regimi "steady state" sarà necessario fornire adeguati sistemi di Current Drive per la corrente di plasma, già previsti in FAST, e realizzare il sistema magnetico con bobine superconduttrici, analogamente a JT-60SA.
L'alto campo magnetico toroidale (circa 13 T) nelle bobine interne e la compattezza del design di FAST rendono il progetto di un sistema magnetico basato su bobine superconduttrici ai limiti della presente tecnologia, con valori prossimi ai limiti ammissibili sia per il campo magnetico (circa 17 T) che per la densità di corrente (circa 15 MA/m^2) nelle bobine. E' stato perciò effettuato uno studio, concettuale e di fattibilità, di un sistema magnetico superconduttore per FAST utilizzando materiali superconduttori e tecnologie di fabbricazione già sviluppati e ragionevoli dal punto di visto economico e tecnico.

A tale scopo sono state effettuate le seguenti attività:

- Progettazione preliminare delle bobine superconduttrici di campo toroidale e poloidale, utilizzando lo spazio disponibile nel design attuale;
- Valutazione del carico neutronico atteso sul magnete nei diversi scenari di plasma;
- Analisi termo-meccaniche preliminari per il sistema superconduttore con i carichi nucleari durante le scariche alle massime prestazioni e con i carichi elettromagnetici e termici attesi nelle peggiori condizioni di fault ipotizzabili;
- Comparazione dei costi e benefici per le soluzioni con le bobine in rame o in superconduttore.

1 Introduction

FAST (Fusion Advanced Studies Torus) is an Italian proposal for a new European satellite tokamak reactor aimed at supporting ITER [1] activities and at anticipating some DEMO [2] relevant physics and technology issues [3]–[5]. It has been conceived as a compact (1.82 m) machine working at high field (up to 8.5 T) and high plasma current (up to 8 MA). Currently, FAST magnetic system is designed with 18 TF (Toroidal Field), 6 CS (Central Solenoid) and 6 PF (Poloidal Field) resistive coils, cooled by helium gas flow at 30 K. ENEA performed a feasibility study to verify whether a superconductive solution for the whole magnetic system would be possible or not, avoiding any major modifications to the machine geometry or scenarios. The reactor compact size along with the high magnetic field values reached during some scenarios, represent a big challenge to deal with, when designing superconducting (SC) coils. All the main aspects that drive the magnet design are presented and discussed along with the main results obtained from different thermo-hydraulic, neutronic and mechanical analyses. The un-resolved issues and the required minor modifications, are pointed out as well.

FAST is a flexible machine both in terms of performance and physics, able to operate in H-mode scenarios as well as in advanced Tokamak regimes. The machine will be capable to access advanced tokamak regimes with long pulse duration compared to the current diffusion time. It will work in a dimensionless parameter close to that of ITER and it is aimed at integrating the study, in Deuterium plasma burning condition, of fast particle physics, plasma operations and wall interactions. In addition, FAST will be able to test technical solutions for the first wall/divertor, which are relevant both for ITER and DEMO, as full-tungsten wall and divertor and advanced divertor liquid-metal devices.

The SC (Super Conducting) coils feasibility study here presented has been centered on one of the hardest scenario among those foreseen during FAST activities, the H-mode reference scenario (7.5 T, 6.5 MA), which main engineering parameters are reported in Table I.

Table I. FAST main parameters

	H-mode reference
I_p (MA)	6.5
q_{95}	3
B_T (T)	7.5
(n20) (m^{-3})	2
$P_{th\ H}$ (MW)	14–18
τ_E (s)	0.4
$t_{discharge}$ (s)	20
$t_{flat\text{-}top}$ (s)	13

2 Activities description and results

2.1 Design of the Toroidal Field SC coils

The Toroidal Field SC coil has been designed utilizing only the room available in the normal conducting design for the inboard straight leg (approximately a trapezium with height of 305 mm and the two sides respectively of 365 mm and 258 mm). Following a complete 3-D electro-magnetic analysis of the whole scenario (with reference currents in all coils and plasma), a maximum field over the winding pack has been defined to be B_{peak} = 14 T, located at the innermost layer of the inboard straight leg at the equatorial plane.

With such a magnetic field value the choice of Nb_3Sn Cable-In-Conduit-Conductors (CICCs) is obliged. We addressed the design towards a Double-Pancake (DP) Winding Pack (WP), wound from a rectangular conductor with an aspect ratio lower than 2, long twist pitch values, low void fraction (VF) and without central channel. These choices, mainly aimed at giving better load support to the Nb_3Sn strands and consequent limited performance degradation, are inspired by many measurement campaigns performed in the last years [6]–[9]. The main coil characteristics are recalled in Table II.

Table II. TF coil design main characteristics

Cond. inner dim. (mm^2)	13 x 21
Jacket thickness (mm)	2.8
# strands (all SC)	360
Strand diam. (mm)	0.81
Cabling pattern	3x3x5x5x6
VF (%)	28.5
I_{op} (kA)	41.2
B_{peak} (T)	14
T_{op} (K)	5.1
ΔT_{margin} (K)	0.9
Turn number	92
Layer number	10
Double Pancake number	3 central + 2 side
Turn insulation thick. (mm)	0.5
Inter-pancake insulation thick. (mm)	1
Coil self-inductance L (mH)	20
Coil magnetic energy (MJ)	17
Central DP conductor length (m)	180
Side DP conductor length (m)	144
Tot. conductor length (18 coils) (km)	15

The nuclear heating (NH) contribution to the operative temperature definition, has been determined using data provided by a MCNP5 code 3-D analysis [10]. This study has been repeated for the superconducting magnets and in particular it has been addressed to investigate if the introduction of a nuclear shield, which is absent in the present design, would be necessary or avoidable. Results refer to $1.2\cdot10^{17}$ n/s (neutron rate corresponding to H-mode reference scenario). The first interesting result is that the different density of materials and position of the superconducting WP, considered as an homogeneous weighted mixture of Nb_3Sn, Cu, He, Stainless Steel (SS) and epoxy resin, that is placed behind 2.5 mm of SS casing with respect to the plasma, cause a considerable reduction in terms of neutron power deposited over the first layer of the magnet (Figure 1). It has then been verified that a 5 cm thick shield, made by 80% SS and 20% water, located behind the vacuum vessel, would permit a further reduction that in turn would give a temperature margin increase of 0.2 K. More efficient shield typologies, as the borated SS mixture adopted for ITER vacuum vessel, could give a further improvement but also have much higher cost.

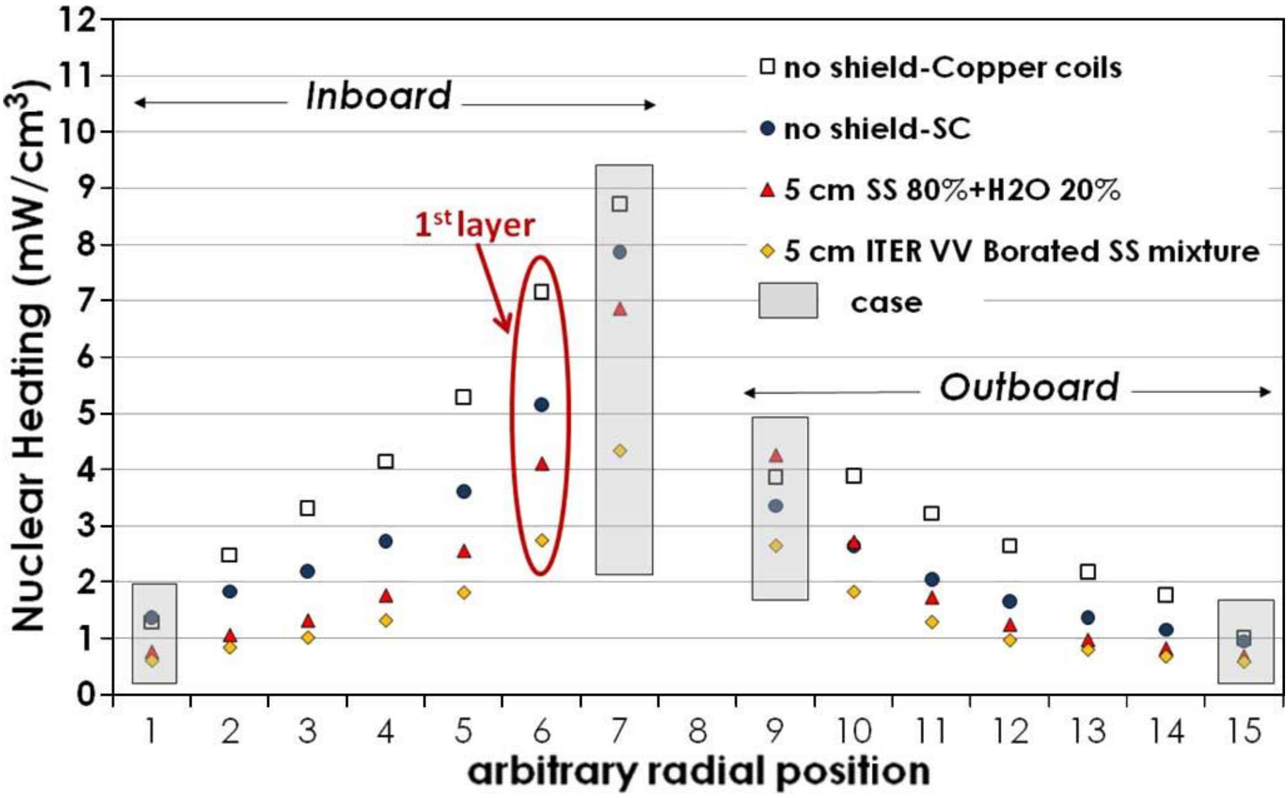

Figure 1. TF NH radial profile used to investigate the effect of the presence of a nuclear shield

As the presence of a nuclear shield would impact the machine geometry, a balance of pros and cons has pushed to consider, at least for this feasibility study, only a solution without any shield, but where the SS casing is actively He cooled by means of ad-hoc designed channels.

With this design, the conductor temperature margin determined with the 1-D Gandalf code using high-J_C Nb_3Sn Internal Tin strand properties, i.e. $J_C(6\text{ K}, 14\text{ T}, \varepsilon_{applied} = -0.45\%) > 450\text{ A/mm}^2$, a mass flow rate of 4 g/s and a pressure drop of 3 bar, is $\Delta T_{margin} = 0.9$ K (Fig. 2). In order to take into account AC losses contribution, as they have been not yet studied, we added 0.2 K to the He inlet temperature (4.4 K). Clearly, this aspect should be deeply investigated before going to the actual design phase.

A mechanical analysis of the stress arising in the Stainless Steel (SS) casing when the TF coils are fully energized, has been performed with the ABAQUS code. The 3-D model consists of a single TF coil, developed under Cyclic Symmetry condition that allows to simulate all the relevant loads to which a coil is subjected as a part of the 18 TF coils system. Since the design is still in a preliminary phase, gravity supports, outer inter-coil structures (OIS), other coils and further reinforcement structures, have not been included in the model. The results show that only in some local areas the Von Mises stress goes above the yield value (indicated by white arrows in Fig. 3).

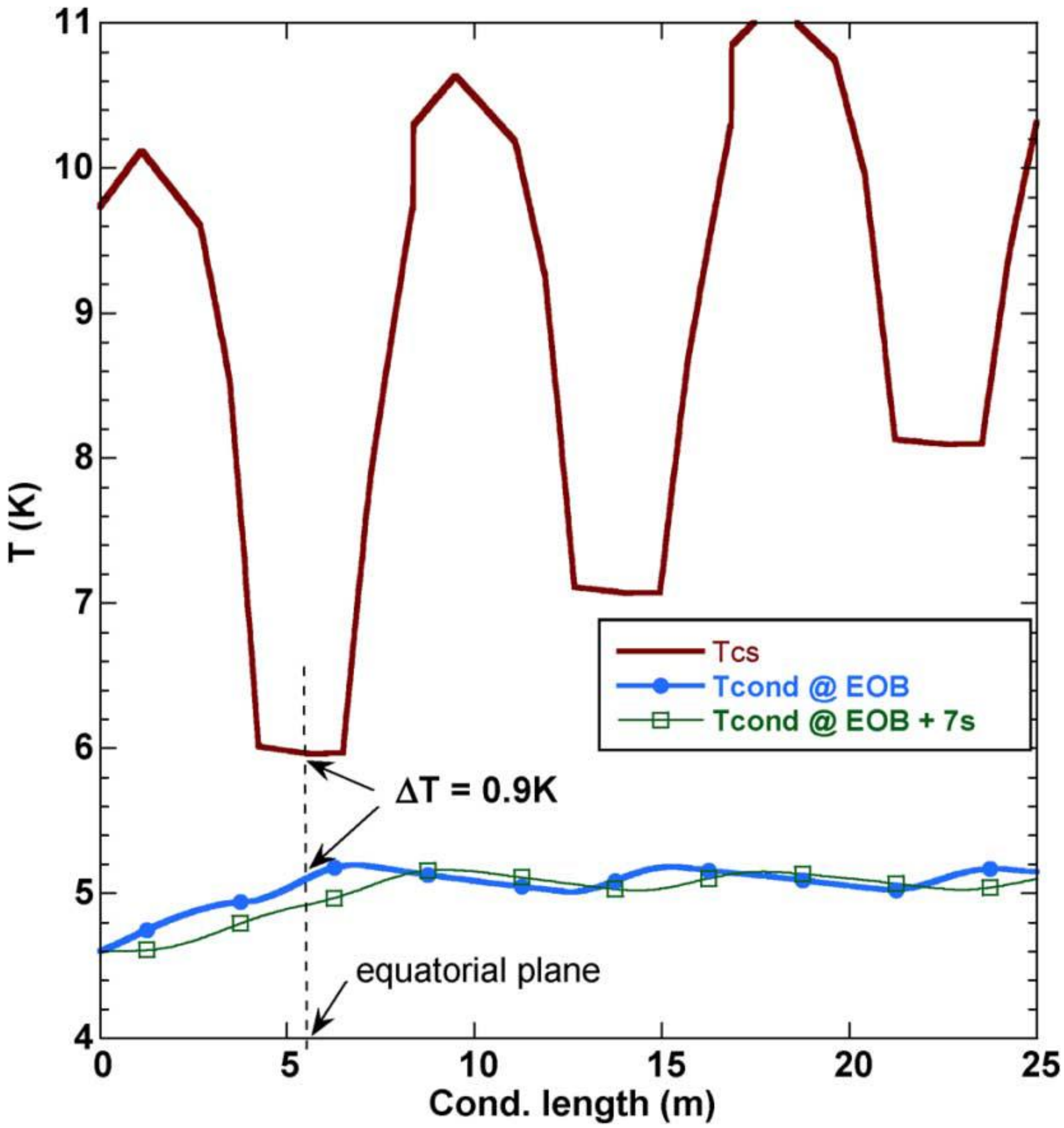

Figure 2. TF conductor temperature analysis with a minimum temperature margin of 0.9 K found at the equatorial plane, innermost layer at the inboard leg

It has to be considered that the absence in the model of OIS causes an higher deformation due to the out-of-plane forces than what would be in the actual coils, reaching a maximum value of 36 mm (Fig. 4). This and other approximations affect negatively the results, that consequently are too conservative.

Thus our analysis global interpretation is that no major modifications are needed to the TF design from a mechanical point of view, though a refinement of the model is mandatory and some minor adjustments should be obviously performed.

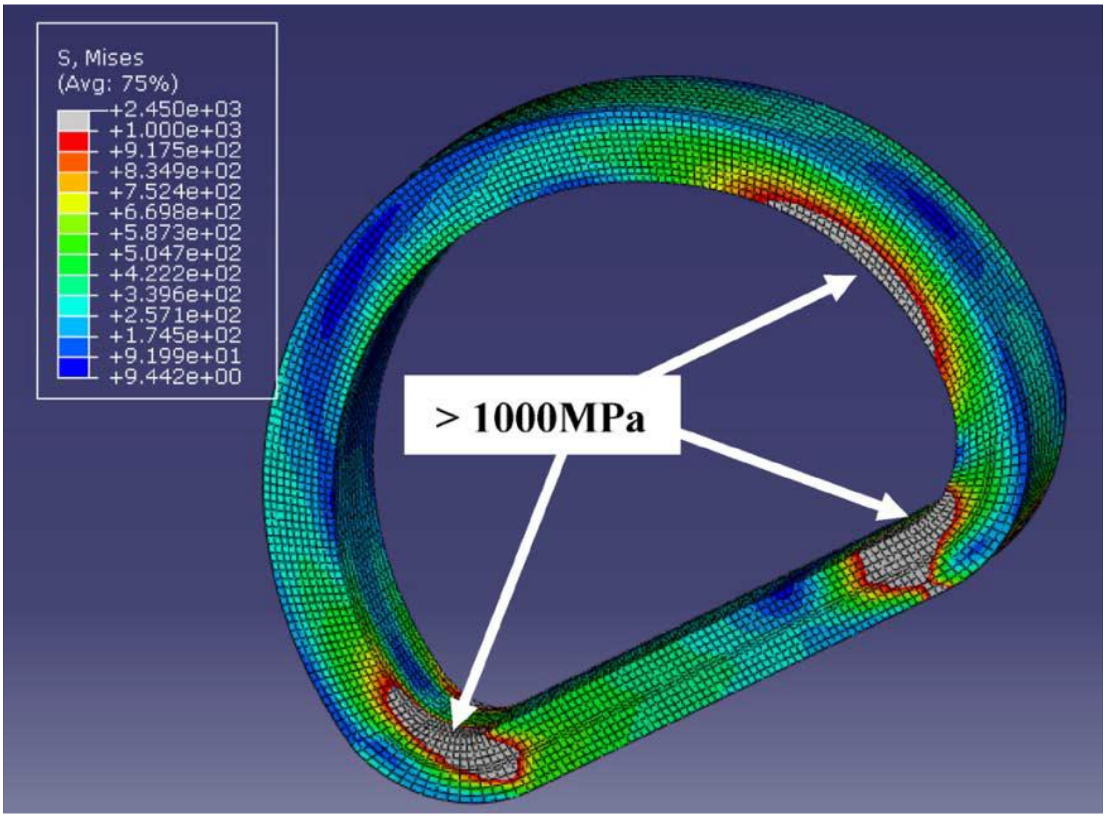

Figure 3. TF 3D ABAQUS analysis with the areas where Von Mises stress is higher than 1000 MPa evidenced

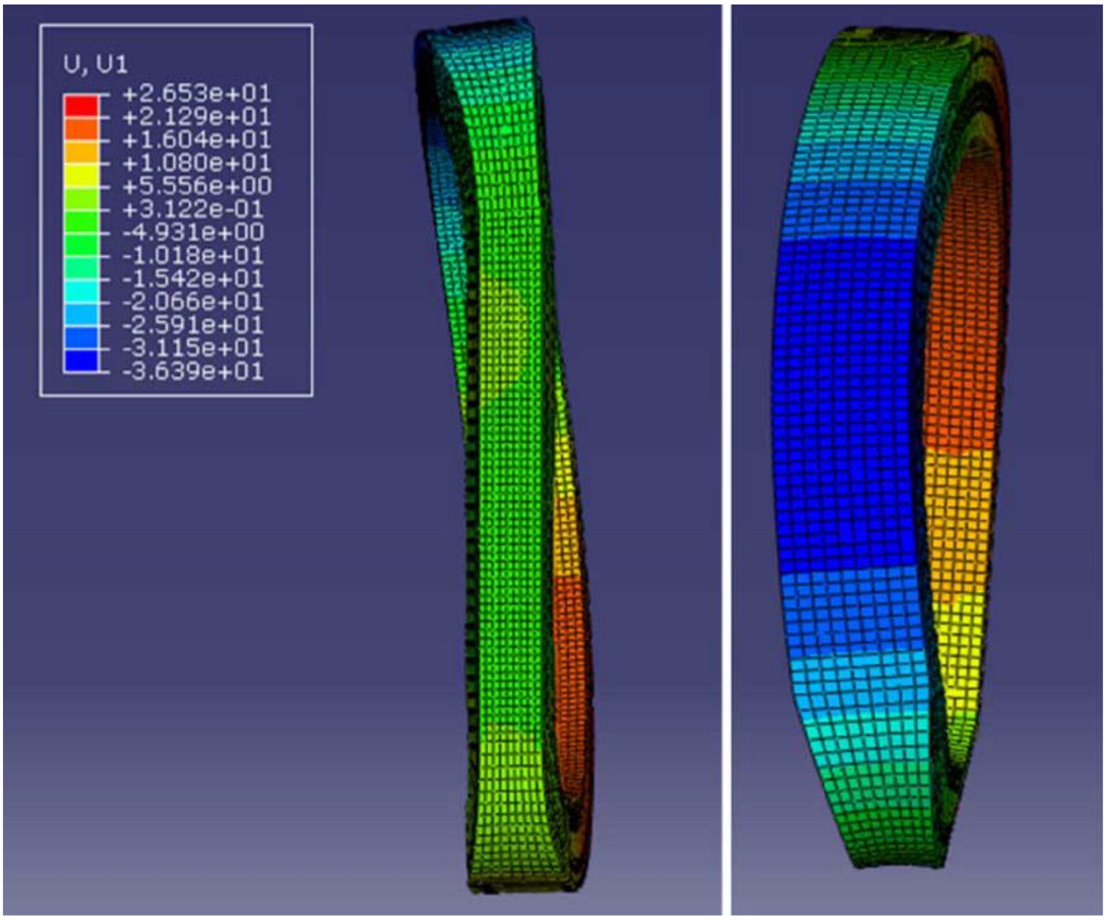

Figure 4. TF 3D ABAQUS analysis with the deformations magnified to be more evident

2.2 Design of the Central Solenoid SC coils

The Central Solenoid is constituted by 6 independently fed modules. The maximum magnetic field is B_{peak} = 17.7 T, located in the central coil pair CS1U and CS1L (Fig. 5), which represents a hard challenge for the SC design and thus should be lowered by minor adjustments in FAST geometry and/or scenario, currently under discussion. In order to investigate the SC feasibility, a design of the 6 modules using high-J_c Internal Tin Nb_3Sn strand performances has been carried out maintaining such stringent operative conditions. Though this wire is not suitable for applications of this kind (too brittle, too large filament size, and so on), it has been chosen because it is the most efficient one, among the present commercial wires. A secondary positive aspect of FAST thus could be that it could boost a further development of superconducting strands, in order to reach the characteristics needed to let such magnets properly operate.

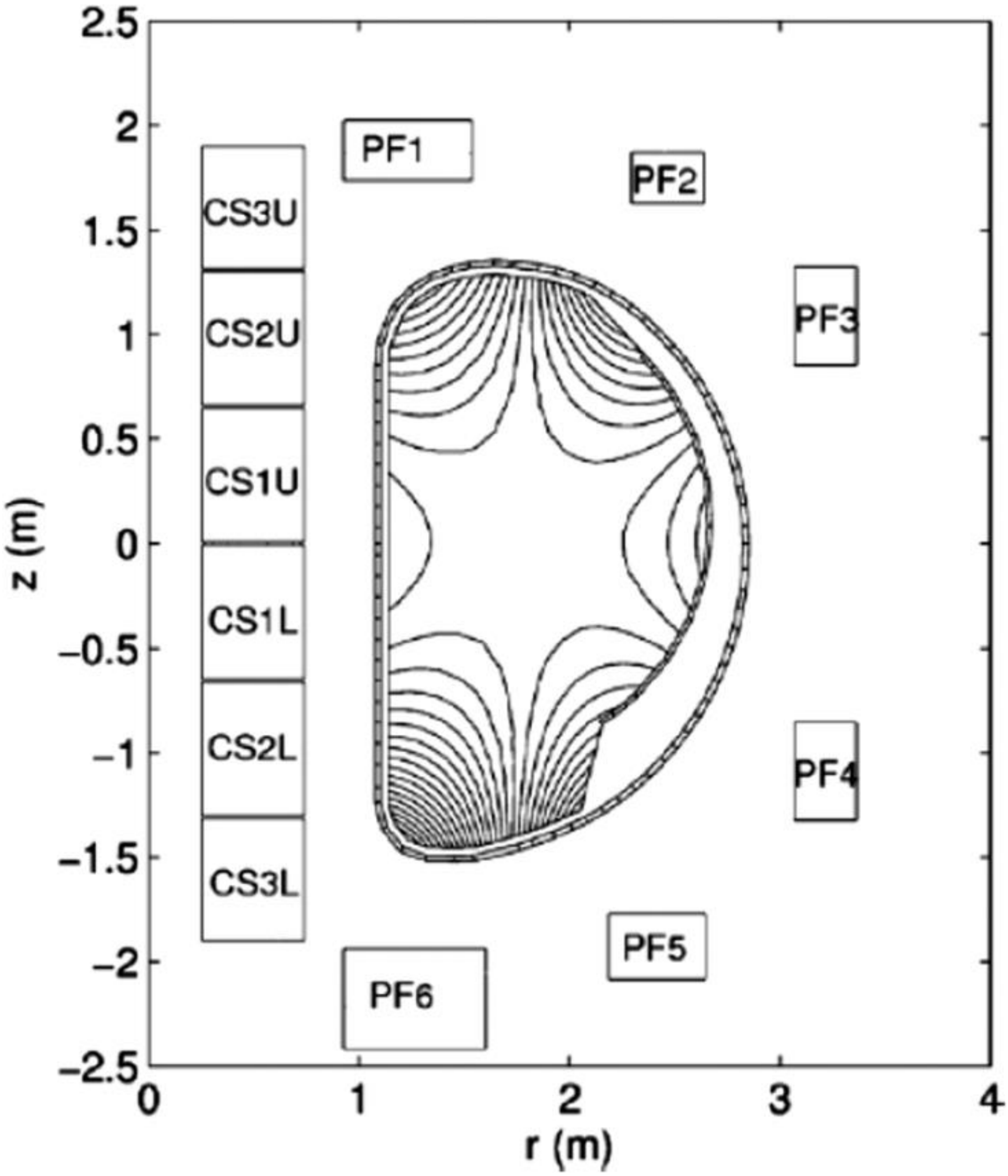

Figure 5. Simplified sketch of the FAST magnetic system (TF coil is not shown)

The six solenoids have been designed identical in size and layout, apart from the Cu/nonCu ratio within the conductors (Table III). The conductor design rationale is similar to that adopted for the TF one, rectangular shape and low VF, and the three different layouts (one for each module pair) are very similar.

Table III. CS coils design main characteristics

	CS1U&L	CS2U&L	CS3U&L
Cond. inner dim. (mm^2)	28 x 35.2	28 x 35.2	28 x 35.2
Jacket thickness (mm)	2.5	2.5	2.5
Strand number	1350	900 SC + 450 Cu	450 SC + 900 Cu
Strand diam. (mm)	0.81	0.81	0.81
Cabling pattern	3x3x5x5x6	(2+1)x3x5x5x6	(1+2)x3x5x5x6
VF (%)	27	27	27
I_{op} (kA)	40.2	40.2	36.2
B_{peak} (T)	17.7	16.4	14.8
T_{op} (K)	4.8	4.8	4.8
ΔT_{margin} (K)	0.6	1.1	1.5
Turn number	210	210	210
Inner bore diam. (m)	0.5	0.5	0.5
Outer diam. (m)	0.74	0.74	0.74

The high B_{peak} value, and thus low ΔT_{margin}, of CS1 conductor requires a future modification of this coil design. A first improvement, that does not impact the machine geometry, could be made by introducing in the coil design a conductor grading, thus increasing the strand number in the innermost layers and decreasing them in the more external ones, as they are subject to lower magnetic field. This could probably permit the use of more suitable strands, than the one here adopted for the study. A particular attention will have to be paid to the AC losses analysis, not yet performed, and their impact on the strand choice, as the coils are here subject to large magnetic field variation during the scenario, in the order of 1–2 Tesla/s.

2.3 Design of the Poloidal Field SC coils

The relatively low maximum magnetic field in all the 6 PF coils suggests the use of NbTi CICCs. Though for this kind of cables the EM load does not cause high degradation of performance, as it happens for Nb_3Sn strands, also for these coils we have designed all the conductors with a rectangular shape: this solution permits a higher packing factor, with respect to the round shape, and it has been shown not to degrade the single strand performance [11], [12]. The VF has been set around 32–33% and the conductors for PF coils number 3 to 6 have been designed identical, though the B_{peak} values are slightly different in the four magnets, in order to speed up and help a possible future production (Table IV).

Table IV. PF coils design main characteristics

	PFC1	PFC2	PFC3-4-5-6
Cond. inner dim. (mm^2)	28.5 x 31.5	20.8 x 26	18 x 18
Jacket thickness (mm)	3.5	4	4
Strand number	678	288	72 SC + 36 Cu
Cabling pattern	3x3x3x4x6	3x4x4x6	(2+1)x3x3x4
VF (%)	33.7	32	33.5
I_{op} (kA)	45.3	23.1	30.6-24-20.8-25.5
B_{peak} (T)	6.2	5.1	2.6-3.3-2.9-2
T_{op} (K)	4.8	4.8	4.8
ΔT_{margin} (K)	1.1	1.5	1.4-1.4-1.8-2
Turn number	160	120	80-120-42-42
Inner bore diameter (m)	1.85	4.59	6.14-6.14-4.37-1.85

The operative temperature for each PF conductor has been fixed to 4.8 K and has not been yet verified with a global analysis, that will be carried out in the next future along with a conductor and coil design optimization. Thus, also the reported temperature margins have to be read just as reasonable indicative values. Regarding the NbTi strand performances adopted for calculations, we used those of a commercial wire candidate for the JT-60SA TF coils, characterized in ENEA laboratories in the past [12].
Each of the new 6 poloidal coils, when designed with superconductors, occupies much less room than that currently utilized for the resistive magnets, as it is expected when SC cables work at relatively low B values. This is not valid for PFC1 and PFC2, that operate at higher B_{peak} values.

3 Conclusion

A superconducting design of the whole magnetic system of FAST has been carried out. Many issues are still to be assessed and some of them represent not-negligible difficulties, but the global feasibility has been proven. A preliminary cost-benefits study indicates that the construction costs of the two solutions, SC vs. resistive, are comparable when including all the involved components (magnets, cryogenic plant, power supplies, and so on) and that the operation budget is favorable to the SC one, considering that also resistive coils should be cooled at cryogenic temperature (GHe @ 30 K). The conductors here proposed for TF and CS

coils, though surely subject to a re-design after future analyses, are challenging and innovative and would represent an interesting step for the advance of applied superconductor technology, as both present conductor design knowledge and single strands characteristics should be object of further studies to completely fulfill present FAST requests. It is worth noting that the reference scenario, considered for the present study, is one of the most challenging one: almost all the other scenarios foreseen during FAST activities could be more easily performed.
If a decision will be taken in the direction of adopting the superconductor technology, a deeper and more detailed study has clearly to be carried out, in order to define the conceptual design and the possible minor adjustments that would be required, but the global machine mission will not be affected.

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5 Acronyms

SC	Super Conducting
TF	Toroidal Field
PF	Poloidal Field
CS	Central Solenoid
DP	Double Pancake
WP	Winding Pack
VF	Void Fraction
CICC	Cable-In-Conduit-Conductor
NH	Nuclear Heating
SS	Stainless Steel