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Summary

Spherical Tokamak for Energy Production (STEP) requires high-field magnet designs and has therefore adopted REBCO-based high temperature superconductor (HTS). HTS enables the Toroidal Field (TF) coils to be re-mountable, which unlocks STEP's vertical maintenance approach, however, re-mountable joints, approximately 18 GJ of stored energy, and limited space down the centre of a spherical tokamak, make the TF coils the most challenging. STEP has pursued a passive approach to TF coil quench protection in order to limit coil terminal voltage. Initial results suggest that a solution may rely on tuning internal coil resistance, which requires the development of targeted resistivity 'partially insulating' material, coupled with actively powered heaters to deliver TF system de-energisation without hotspots and mechanical load imbalance. The pre-conceptual inter-coil structure demonstrates acceptable stresses and deflections under steady-state operating conditions and preliminary fault scenarios, and loads are distributed to limit the tensile force on the TF centre rod. Finally, HTS must operate reliably in a high radiation environment and endure high neutron fluences to ensure commercially relevant magnet lifetimes. Initial experiments indicate that instantaneous gamma irradiation of HTS has no negative impact on current carrying capacity. Experimental programmes are underway to cold irradiate HTS to fusion-relevant fluences and to develop a cost-effective method of assuring tape irradiation resistance quality using oxygen ions as an analogue for neutrons.

1. Introduction

To achieve a compact spherical tokamak, STEP has adopted high-field coil designs which make REBCO-based high temperature superconductor (HTS) the most suitable candidate for its principle magnetic confinement systems. HTS conductors have greater thermal capacity than low temperature superconductors (LTS) and the comparatively large margin between operating and current-sharing temperature Tcs opens up the possibility of segmenting coils using resistive joints [1] [2]: re-mountable Toroidal Field (TF) coils are considered by the programme to be a key enabler for STEP's vertical maintenance approach (see accompanying 'unlocking maintenance' paper). However, the tight aspect ratio of a spherical tokamak severely constrains the space available for these magnet systems, particularly down the centre of the reactor, and this, coupled with the need for Re-Mountable Joints (RMJ), makes the TF coils the most challenging.

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This space constraint requires engineering current density in excess of 200 A/mm^2 in the inboard TF winding pack, which pushes at the boundaries of HTS cable technology. Due to the high field (~17 T) in this region, HTS tape in the TF cables is subject to Lorentz loads >1000 kN/m which risks damaging the REBCO layer in the tape given that it is brittle, can only tolerate small tensile strain and is liable to delamination from its structural backing. The TF coil set also has the greatest stored energy (~18 GJ) of the magnetic confinement systems so protecting an HTS TF coil from runaway thermal transients (or 'quenches') is the most significant challenge [3] and has yet to be demonstrated at fusion power plant scale.

The TF coils generate substantial electromagnetic forces (100s MN) which impose very challenging requirements on the tokamak Inter-Coil Structure (ICS), especially on the slender central rod where space for supporting structure is scarce. The central rod also operates in the most challenging environment of the machine because space for neutron shielding is limited, resulting in very high thermal loads (10s kW/m^3) and short inboard magnet lifetimes. This has serious implications for planned maintenance and overall availability of the plant. Replacing the central rod vertically, which requires accurate alignment of a component 20+ m in length, and the re-connecting of cryogenic services and current leads, is a significant remote handling challenge. Realising low resistance terminal joints, routing current leads, winding, impregnating and assembling inboard magnets to the required manufacturing tolerances of the central rod also requires careful consideration.

This paper focuses on progress on the TF quench protection method, which is considered fundamental to the viability of the entire tokamak concept. Feasibility of the accompanying ICS is also discussed. In addition, given how crucial it is that HTS tape operates reliably in a high radiation environment, and endures high neutron fluences, the progress in this area is briefly summarised.

Finally, the PF coil set is the starting point for the spatial integration of the tokamak: the positions of, and the currents within, the PF coils define the shape of the plasma. Compared with the TF coils, all the PF coils (except for the inboard divertor shaping coils) are less space limited allowing for lower engineering current densities (<100 A/mm^2). The TF RMJ also opens up the possibility of positioning the PF coils inside the TF cage, allowing the PF coils to be closer to the plasma, and thus enabling the advanced divertor configurations needed by STEP. These divertor configurations require more PF coils than would be needed in an equivalent conventional tokamak which poses as significant integration challenge. This paper also discusses the approaches and tools developed to effectively manage this integration challenge.

2. Quench Protection of Toroidal Field Coils

2.1. TF System Overview

The primary function of the TF coil set is to confine the plasma by providing the 3.2 T toroidal field at the plasma centre needed by the microwave heating and current drive system. The TF coil system comprises 16 'picture frame' shaped coils approximately 24m in height and 11m in width. Each TF coil is segmented into three parts, as shown on the left of **Error! Reference source not found.**, held together by remotely operable RMJ. The RMJ facilitate the replacement of the central rod which comprises the inboard TF limbs, the inboard divertor shaping coils (or S coils) and the Central Solenoid (CS). The central rod is planned to be replaced as a single line removable unit given the limited lifetimes of its magnet systems and a representation of the central rod being replaced is shown to the right of **Error! Reference source not found.**.

2.2. TF Quench Protection

Protecting large scale HTS magnets from quench is the most significant challenge facing the technology and remains an area of active research and development [4] [5]. However, this challenge is compounded in the STEP TF coil due to three resistive RMJs per turn, the inherent asymmetry of the coil, its tight corners, and the irregular winding pack configuration necessitated by spatial constraints in the central rod.

A quench can occur when the HTS tape locally heats up over its current-sharing temperature Tcs, the temperature at which the tape can no longer carry the full design current in the superconducting layer. The cable used for the TF coil system is designed to operate at 20K and have a Tcs of 40K. The 20K difference provides margin against AC losses, thermal gradients due to nuclear heating, localised ohmic heating in the joints, and degradation of the conductor performance due to radiation. It also allows time for action to be taken in the event of a cooling system failure. Upon heating the TF coil above Tcs, some current begins to flow in the resistive components of the cable, causing it to heat up further. If heat is lost to the cooling system or adjacent coil structure more quickly than it is generated, then the coil will return to thermal equilibrium. If not, thermal runaway (a 'quench'), driven by the TF coil’s 18GJ of stored magnetic energy, will occur as the temperature continues to rise until all the current flows in resistive components, forming a ‘normal zone’. If the magnet is unable to mitigate the normal zone, irreversible damage is likely to occur.

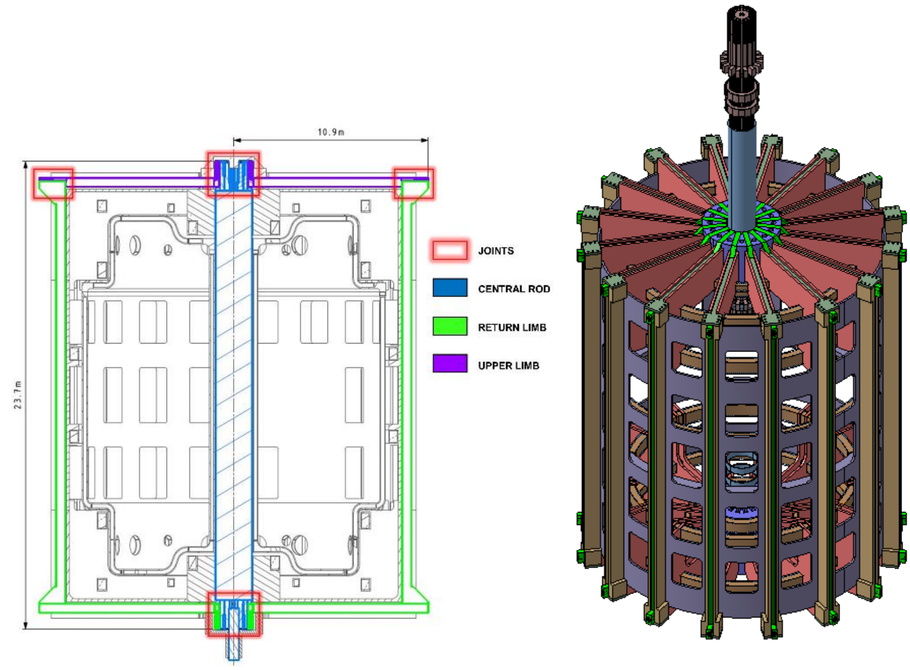

Figure 1: Cross section of the TF cage indicating segmentation of TF coil (left), and representation of the central rod being removed (right).

Quenches propagate slowly in HTS magnets compared to LTS magnets due to energy margins that are orders of magnitude higher. A quench which starts locally is unlikely to propagate quickly enough by passive means to avoid excessive local heating. It is therefore necessary to develop techniques to detect the onset of quenches and manage the stored magnetic energy to protect the TF coil set.

A schematic of the proposed TF cable can be seen in Figure 2. It comprises a stack of HTS tapes assumed to be soldered into a copper channel with an integrated cooling pipe. In a 1D thermal diffusion model cooling is provided by 3.7 g/s of super-critical helium. A quench is initiated by a ~60 J/cm^3 perturbation over the central 6 mm of a 2 m cable. Figure 3 illustrates the rapid temperature rise and slow quench propagation.

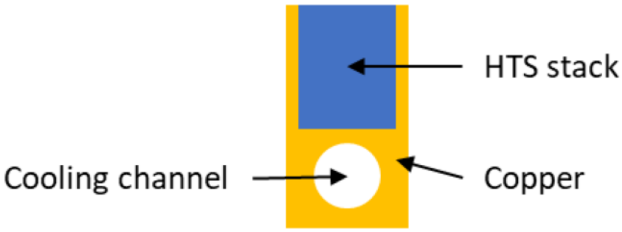

Figure 2: Cross section of a cable comprising a copper channel with a built-in cooling pipe and a simple stack of HTS tapes.

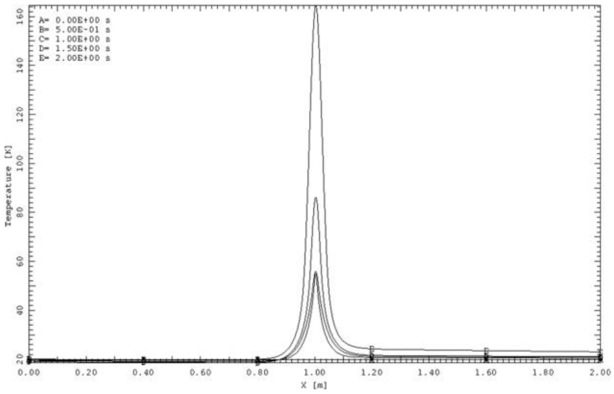

Figure 3: Temperature distribution along a cooled cable at various times after quench initiation.

The temperature rises to ~160 K in 2 s. To prevent the temperature rising above 200 K, it is necessary to discharge the coil in approximately 5 s. This requires a total of 80 kV across the coil set, or 5 kV per TF coil, which is comparable to the terminal voltage of ITER TF coil pairs. However, the TF coils' RMJs operate in a vacuum in a highly constrained space, and in order to maintain coil terminal voltages below a few hundred Volts to avoid Paschen breakdown, the STEP TF coils cannot be discharged quickly enough using traditional methods.

An alternative approach often used for small scale HTS magnets is to omit insulation between turns altogether. During energisation current can flow radially through the magnet structure between the turns. Eventually, in an unjointed coil, the radial resistive voltages produced will force all the current through the superconducting circuit. If part of one turn becomes resistive the resulting electric field drives current radially through the magnet structure and through turns that are still superconducting. This reduces local cable heating and helps spread the normal zone quickly by distributed heating of the coil structure. The potential for self-protection has been demonstrated many times in small magnets [6] [7].

However, STEP's RMJs add resistance exceeding 100 nΩ in series with the superconducting cable in a TF coil. This is higher than the radial resistance of the TF coil stainless steel structure and additional resistance, or 'partial' insulation, must be added between the turns to ensure most the current flows azimuthally. The resistivity of this partial insulation can be tuned such that current transfer between adjacent turns can still occur, the radial resistance is sufficiently high to allow coil energisation despite the resistance of the joints, and the voltage across the coil terminals is kept below that required for Paschen breakdown.

Little Beast Engineering have used their Racoon model to investigate hot spot development in this scenario. An example is seen in Figure 4.

In this example the radial resistivity of the coil is such that the discharge time constant is approximately 26,000s. If current sharing occurs somewhere in the coil but the radial currents do not result in the coil recovering full superconductivity, such a long time-constant means it cannot be de-energised quickly enough to avoid damage. To date, no satisfactory solution has been found that works within the required resistivity constraints and the problem is exacerbated when the whole sixteen coil set is considered.

Furthermore, in a completely passive system there is no guarantee that all the TF coils will de-energise at the same rate and in the same way, which could lead to significant out of balance toroidal forces. The STEP TF coil may require some action to be taken to safely dissipate the stored energy without creating hotspots. The STEP Programme is currently investigating the use of the TF magnet's stored energy to power heaters embedded within the coil structure. A simplified schematic can be seen in Figure 5.

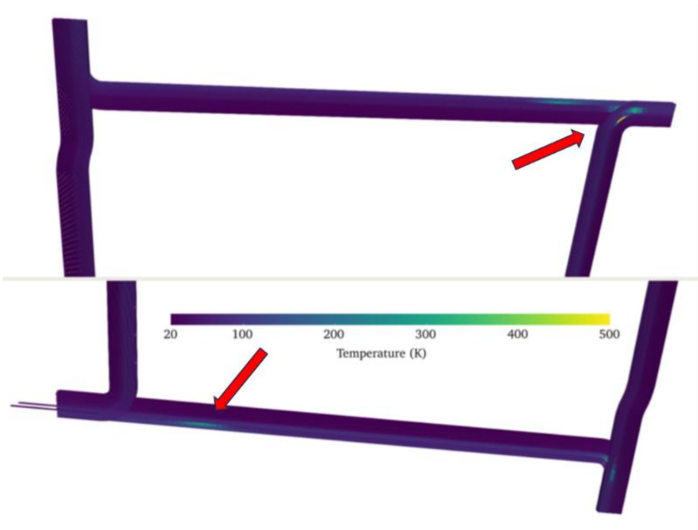

Figure 4: The temperature rises locally to 1000K in 300s, at which point the simulation is terminated.

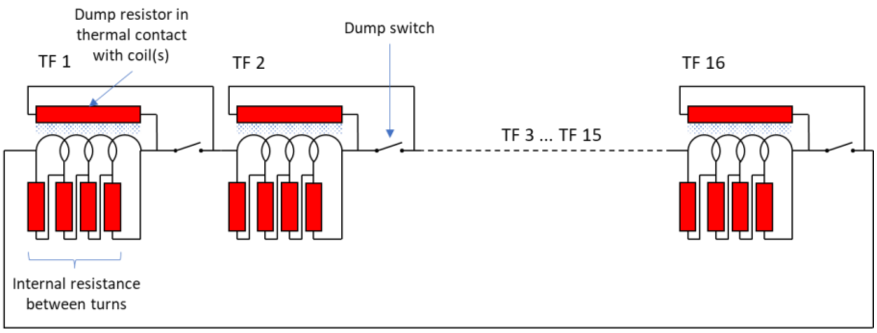

Figure 5: Dump switches are used to transfer stored magnet energy to heaters embedded in the coil structure.

A single dump switch might have several heaters in parallel in different locations around the TF magnet, but only one is shown for clarity. The aim is to tune a combination of internal coil resistance and actively powered heaters to deliver TF system de-energisation without excessive hotspots and mechanical load imbalance. This approach requires a reliable method of detecting the onset of thermal runaway.

2.3. TF Coil Quench Detection

Various quench detection methods have been proposed, for example:

- Voltage taps
- Fibre optics (Discrete Fibre Bragg Gratings and Continuous based on Rayleigh back-scattering)
- HTS circuits that transition from superconducting to normal earlier than the coil cable
- Ultrasonic waveguides [8]
- RF coolant density measurement

- Coolant mass flow rate, pressure and temperature
- Inductive quench antennas
- Acoustic emission monitoring
- Diffuse-field ultrasonic methods [9] [10]
- Hall sensor arrays

The traditional voltage tap method is unlikely to work in a large HTS coil system: slow normal zone propagation and rapid heating mean damage will be caused before a measurable voltage develops in the electrically noisy reactor environment. Several of the proposed methods require the installation of additional hardware in places where space is at a premium. It's also required that sensors embedded within the coil pack can tolerate high mechanical stress without risk of damage whilst also surviving radiation damage for the life of the coil. The STEP TF coil system will contain around 30 km of cable and quench hot-spots have scale lengths of order 10mm (see Figure 3). Methods with discrete, localised sensors are likely to require too many data channels to be useful. Acoustic emission monitoring and diffuse field ultrasonic methods are likely to be difficult to interpret given the size and complex geometry of the STEP TF magnets. Whilst it's too early to rule out any technique, non-invasive, distributed measurement methods are preferred.

For example, RF coolant density measurement techniques to detect quenches in LTS cables have been developed for ITER in the 1990s [11]. These involved helium density measurements using resonant frequency sensors (660MHz) and super-high frequency (37Ghz) interferometry. Helium density measurement sensitivity was in the range 0.5-2.5 g/m^3 [10]. However, ITER did not adopt the technique due to attenuation losses caused by the nature of the ITER cable cooling channels, whereas STEP cables could adopt a smooth wall cooling channel. Furthermore, the minimum quench energy for HTS coils is higher, so less sensitivity is required. While the use of RF methods in superconducting magnets diagnostics has been minimal, recent experiments with HTS have shown its potential as a robust and inexpensive option for the detection and localisation of quench hot spots [12].

A CFD solver has been coupled to the 1D quench model illustrated in Figure 3. The heating causes a reduction in helium density downstream of the disturbance within the anticipated range of detection. See Figure 6.

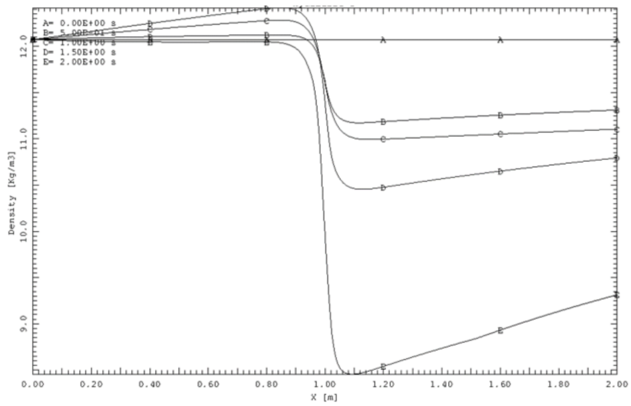

Figure 6: Helium coolant density along the quenching cable at various times.

A proof of principle test programme is underway, starting with a pipe and heater system at room temperature and building up to a full-size cable operating at 20K in background field in the SULTAN test facility, to further investigate this approach.

3. Poloidal Field Coils

The PF coil set consists of seven (P3, P4, P5, P6, P9, S1 & S2) pairs of coils (mirrored around the midplane of the tokamak) and a Central Solenoid (CS), as shown in Figure 7. All Poloidal Field coils are assumed to be HTS using insulated conductors except the CS given the high rate of ramping required during plasma start-up and inductive current drive: STEP has adopted an insulated, resistive design. The resistive CS can tolerate higher neutron fluxes than an HTS coil could and so it also improves the overall lifetime of the central rod. The primary roles of the PF coils are as follows:

- The CS delivers a minimum of 6.2Vs of flux using a unipolar current swing (because resistive heating prevents the coil carrying significant steady-state current), which is predicted to be sufficient to achieve plasma breakdown, burn-through and ramping up the plasma current inductively to ~1-2MA. This provides a suitable target plasma for the non-inductive current ramp-up phase that will use a high-power microwave system [as described in accompanying paper…]. The solenoid current is ramped up just before the start of the pulse and will return to zero at the end of the inductive current drive phase approximately 5s later. During this phase the required magnetic field null for plasma breakdown is achieved using a combination of currents in the outer P3-P9 coils.
- During the remainder of the plasma pulse (non-inductive current ramp, plasma flat-top and current ramp-down) the P3-P9 coil currents are used to achieve the required plasma shape, including divertor formation. Generally, there is sufficient space available for these coils to allow the design current density to be in the typical range for HTS coils.
- The S1 and S2 coils are used to tailor the shape of the inner legs of the divertors. The limited space available for these coils means that the required current density is high, and the space afforded for neutronic heating low, which is challenging.
- For some of the coils, there is also a secondary role of assisting with plasma control through low amplitude field fluctuation.
- Passive vertical stabilisation of the plasma current and active control of plasma instabilities is achieved using separate dedicated coil sets not described in the is paper.

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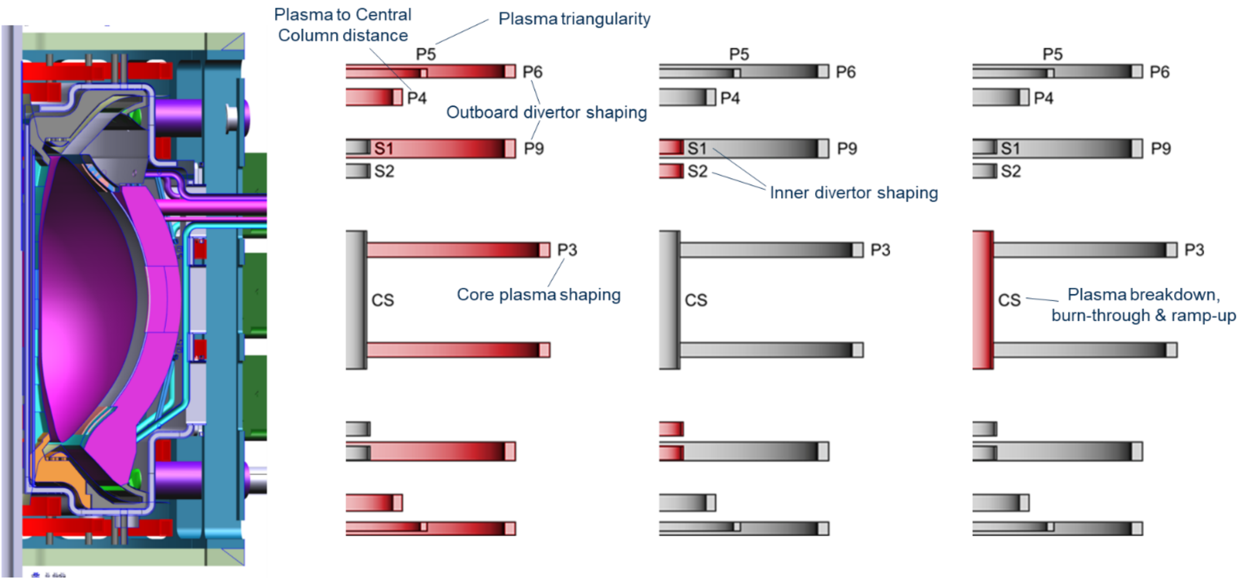

Figure 7: PF coil set and summary of plasma control functions.

The location of the coils, their radii, and the total current carried in them is fundamental to the definition of the plasma design basis. Therefore, the PF coil set configuration is the starting point for the integrated design of the tokamak. Some of the methods and tools for achieving rapid iteration of the STEP concept design are presented below.

3.1. Data-centric Design Process

Three principles form the basis of the PF coil set design process (see Figure 8) to ensure rapid iteration cycles:

1) Centralised Design Data – well defined, consistent and version controlled to enable efficient analysis and collaboration. For example – a schema has been defined for a machine and human readable datafile capturing key coil set parameters which can interface directly with analysis and CAD tools.
2) Knowledge Capture and Reuse – capturing learning through a combination of simple models, design rules and data objects enabling learning to be exploited at earlier stages of the process and minimising the repetition of the evaluation. An example is the capture of local spatial build up from the plasma to each coil to allow spatial integration independent of variation of plasma shape to be used in the definition of the plasma equilibrium.
3) Integrated Design Tools – facilitated by centralised design data with the goal of utilising high degree of automated tools, maximising the value added by engineers by eliminating time consuming pre-processing and data handling tasks. The APECS code presented below is the most important of these tools at this stage of STEP design maturity.

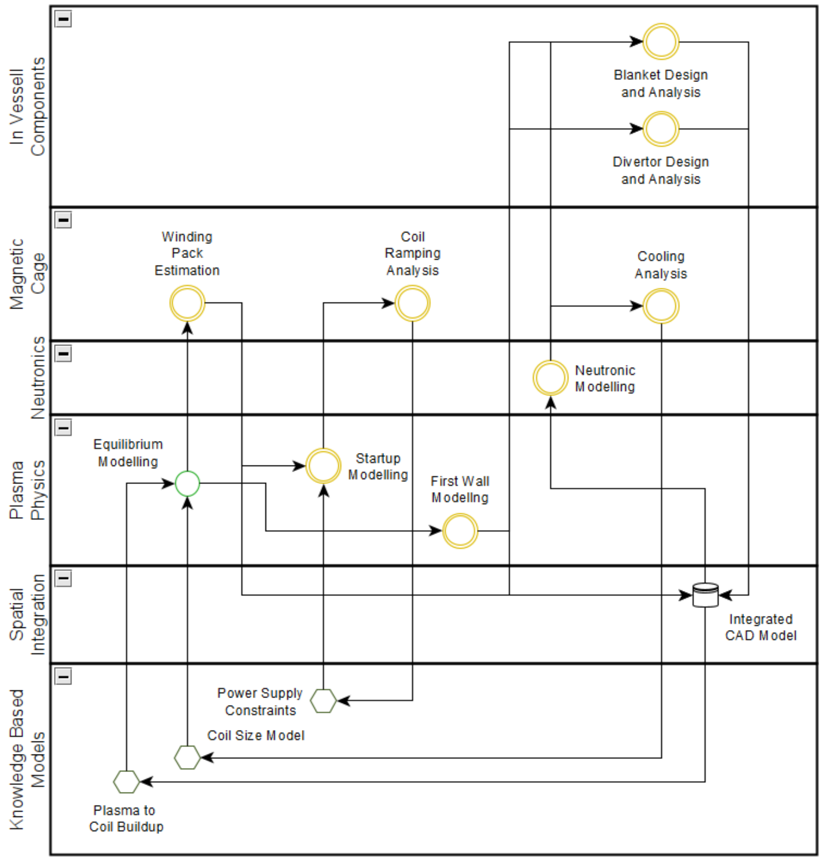

Figure 8: Simplified view of the design process.

3.2. Fast Iteration: APECS Toolbox Development

In the early stages of concept iteration, multiple plasma scenarios and magnet requirements sets were explored. This had to be done at pace with few available tools and no real ability to perform analysis at any reasonable depth. Necessity is the mother of invention, and so emerged the Analytical Python Electromagnetic Coil Simulator (APECS), which uses Biot-Savart equations to calculate the magnetic field of the magnets on STEP. It deals efficiently with magnetostatic calculations in PF (circular, axisymmetric) and TF (picture-frame with straight limbs) magnet systems. The tool also calculates mutual inductances and the resulting voltage response of individual magnets.

Most notably, APECS brought about the "minimum viable winding pack" algorithm – a high level method for quick estimates of the physical size, operating current and peak field of each magnet within a magnet system, given a total current requirement (in MA-turns) and a set of possible, predefined cables. At the time of writing, the greatest limitation of the algorithm is that it only considers the magnetic fields and does not consider stress and strain or perform any optimization on the magnet cable. This has been published and discussed in greater depth in [13].

4. Inter-coil Structure (ICS)

The key functions of the ICS are to maintain the positions of the magnetic coils, to withstand operating loads, and to ensure deflections do not cause clashes with interfacing systems. While initial design iterations focused on a more traditional 'TF led' structure, a 'PF led' approach has been adopted to enable STEP's vertical maintenance strategy: the ICS surrounds the PF coils with all other supports mounted to the PF superstructure.

The ICS is split into five distinct modules, as shown in Figure 9. The structure is assumed to be constructed from 316 LN stainless steel and has been designed to use commercially available plate thicknesses. For maintainability, each module of the structure can be demounted and removed vertically, with sub-assembly masses being limited to 1500t.

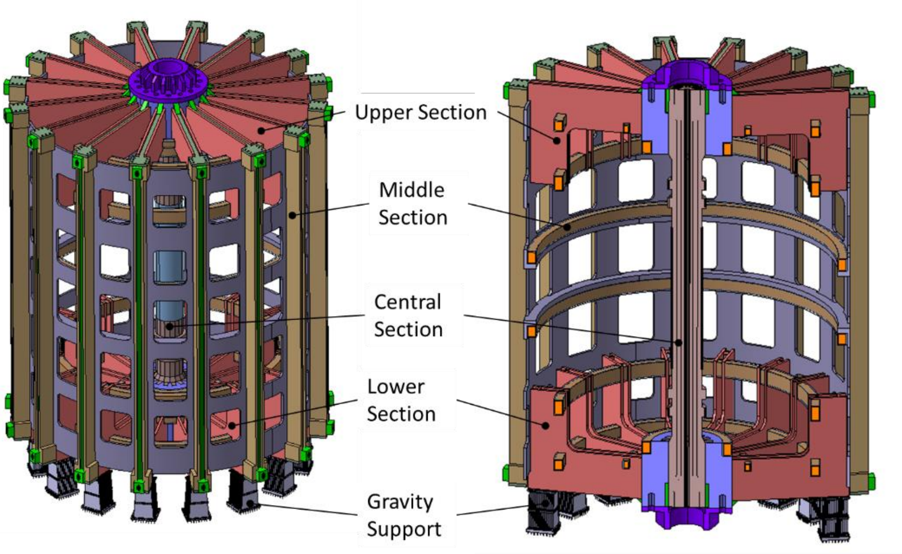

Figure 9: Overview of the ICS.

4.1. Structural Analysis

Preliminary global static structural analysis of the ICS set out to demonstrate acceptable stresses and deflections under steady state flat-top operating conditions. The analysis also served to iterate the design of the ICS with the objective of transferring as much as possible the bursting loads from the horizontal TF limbs through the outer TF legs to limit the tensile loads on the TF centre rod. The flat-top model uses cyclic symmetry to assess a 1/16th segment of the ICS with a coarse mesh and simple, bonded contacts. The loads were applied in time steps, the first load condition applied was thermal, reducing the temperature of the structure to 20 K. The second timestep applied the EM loads, which were calculated using OPERA and applied as a body force density to the coil structure.

An overview of the total displacement and global Von Mises stress have been included in Figure 10. Given that the ICS is supported by gravity supports, the maximum total displacement (a combination of vertical, radial and toroidal deflections) of 74mm is shown at the crown of the structure on the left of . Total radial and vertical deformation is principally caused by thermal contraction and is similar in magnitude to ITER [ref outstanding]. However, toroidal displacement is approximately twice that of ITER.

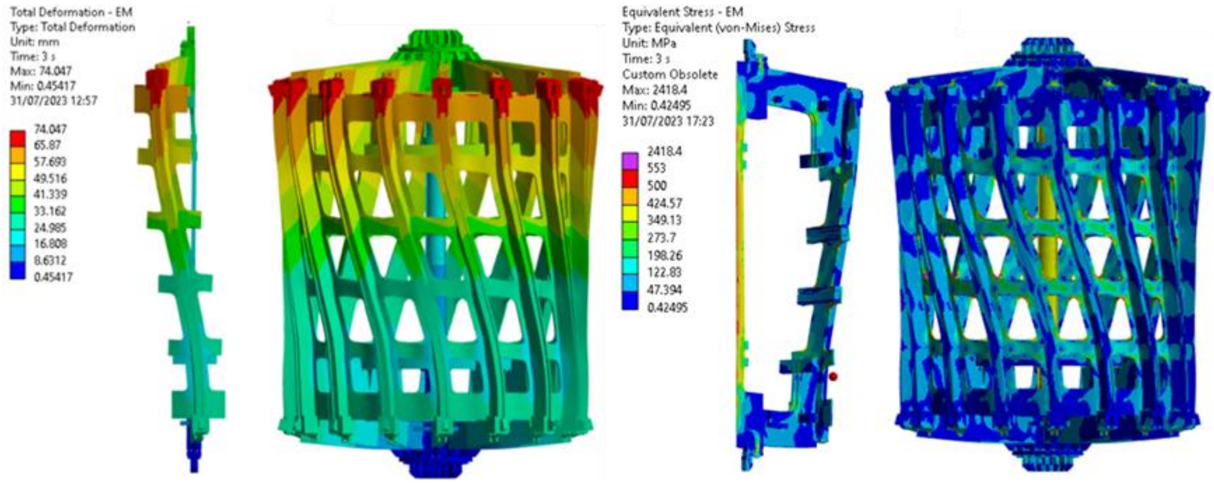

Figure 10: Total deformation plot and Von Mises stress plot under thermal and flat top EM loads.

The maximum Von Mises stress (~550 MPa) occurs at discontinuities in the outboard side of the structure (the point of maximum stress is indicated by the red ball on the right of), these aren't of significant interest in the global model and would require further geometry optimisation and mesh refinement to study further. The analysis has also shown the central rod carries a significant amount of stress. Large loads are transferred through a comparatively slender central rod and the design of the ICS has been iterated to distribute as much load as possible outboard, as shown in Figure 11.

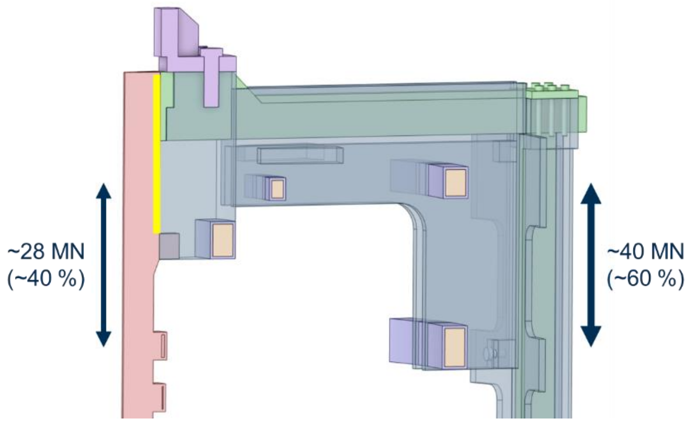

Figure 11: Force distribution through the inter coil structure.

Approximations of the expected bounding fault scenarios were also assessed using a full 16 segment model. The most extreme case assessed was a conservative representation of a TF coil quench with a single TF completely de-energised whilst all others are at full power, resulting in large asymmetric loads. The quench impulse loading has been applied to the model as a static structural load. To limit computational cost, the structure was modelled using bonded contacts throughout.

The stress results shown in Figure 12 indicate the structure would not fail elastically under the applied asymmetric fault load; critical components of the structure are below the 550 MPa material limit. The deflection of the central rod, however, shown to the left of Figure 12, is significant and emphasises the challenge of maintaining clearances with interfacing components tightly packed in the central column of the machine. Note that the central rod mainly comprises of 16 inboard TF limbs and the model optimistically assumes these are all perfectly bonded together: representative connections will affect the stiffness of the central rod structure and therefore the response.

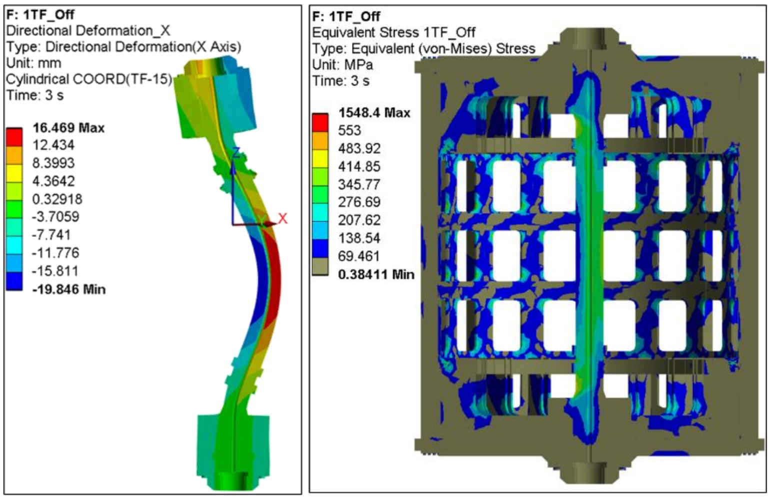

Figure 12: Fault load overview, (left) exaggerated radial deflection of central rod, (right) – stress plot of whole structure (cross-section through the centre of the machine).

5. Technology Development Programme

The successful realisation of the unprecedented scale HTS magnet designs outlined in the previous sections hinges on a robust model validation approach underpinned by an extensive technology development programme, particularly around quench protection. Early stages of this programme have targeted critical technological open questions around re-mountable joint development (see 'unlocking maintenance' paper) and radiation impact on the unavoidable HTS materials proposed to be used for the first time in an active environment. In parallel, a plan to ramp up broader technology development activities, including building industrial capability and human capital skills development, has been formulated and initiated, informed by identified confidence gaps in the concept design.

5.1. Small Coil, Short Cable and Model Coil Test Programmes

The proposed technology development pipeline runs through three distinct areas of focus. Almost in parallel, a small coil test programme will provide essential practical know-how and skill-building in the area of HTS magnet design and manufacture, enabling fast-paced low-cost optioneering and real-world development of novel coil components such as partial insulation and quench heaters, while a short cable test programme will focus on the manufacture, test and optimisation of full-scale short-length cables for each coil type, verifying their performance to the required specification under the expected operating conditions. These full-scale cables will also enable the development and testing of the novel quench detection methodologies previously outlined. Together, these two test programmes then feed into a sub-scale model coil test programme that will provide final validation of the concept for each of the coil sets at representative scale in time to revisit and address any design shortcomings, either through redesign or requirement redefinition.

5.2. Magnet Materials Test Programme

Three high-level needs for magnet materials development were identified early in the programme and work was initiated to address them:

- Quantification of radiation tolerance of HTS REBCO tape.
- Selection / development of radiation-tolerant insulation material.
- Development of targeted resistivity partial insulation material.

The radiation tolerance of available HTS tapes is being considered as a fixed, but so far unknown, quantity around which the machine and its maintenance strategy will need to be designed. In this regard, the Programme is concerned with the effects of the instantaneous flux of irradiation and the lifetime accumulated fluence the HTS tapes can withstand.

STEP has begun a programme [14] to test irradiation resilience of the HTS tapes under consideration for its magnets. Initial experiments have, so far, indicated that instantaneous gamma irradiation of HTS tapes has no negative impact on current carrying capacity at 77 K – an encouraging result [15]. Ion irradiation experiments, by contrast, initially showed an increasing and instantaneous current carrying capacity degradation with increasing flux [16]. Subsequent investigations, however, have suggested that this may be due to sample heating through ion bombardment rather than an intrinsic ion-superfluid interaction [17]. Further experiments are being planned to confirm.

Given the limited availability of fusion-relevant data [18], STEP's experiments have been designed to inform STEP's choice of HTS tape for its magnets and determine a cost-effective method of assuring tape irradiation resistance quality during magnet manufacture. A filtered oxygen ion irradiation experiment [19] seeks to mimic the damage profile of a fusion neutron spectrum using 20 MeV oxygen ions passed through a Steinbach-style energy filter [20]. The programme also includes STEP's High Neutron Fluence Cryogenic Irradiation of Superconductors (Hi-CrIS) experiment with Centrum Výzkumu Řež (CVŘ). Hi-CrIS will irradiate HTS tape samples to fusion-relevant fluences using cadmium-shielded fission spectrum neutrons, while maintaining them at STEP's operating temperature of 20 K. This will provide validation of the oxygen ion irradiation experiment.

The assumed ground insulation material is a radiation-resistant cyanate ester / epoxy blend, as utilised on ITER [21]. By adjusting the proportion of cyanate ester, it is envisaged that the radiation tolerance of the insulation can be raised such that the REBCO tape remains the lifetime-limiting factor. Only if this proves not to be the case will a development programme be undertaken to find a new insulator material.

By contrast, the inter-turn insulation material is a subject of development, in order to achieve a resistivity value that successfully balances the protection of the coil in the event of a quench against charging capability. The latter is an acute issue in the case of large coils incorporating resistive joints, since it has been demonstrated that the coils become not just difficult/slow but in fact impossible to charge if the inter-turn resistance is too low (as in classically envisaged non-insulated coils). Consequently, a degree of resistance is required between turns that nonetheless allows the current to safely bypass a quenching turn, and that facilitates heat dissipation from a hotspot throughout the entire coil. This is found to be beyond what is achievable using metallic 'insulation' necessitating the adoption of some form of novel material.

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