Performance and Degradation Mechanisms of High-Jc Nb3Sn CICC for High-Field Applications

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

Burning plasma Experimental Superconducting Tokamak (BEST) targets compact, high-field operation to advance steady-state deuterium–tritium burning plasma research. In the BEST toroidal-field (TF) high-field region, the conductor is required to sustain a peak field of 13.5 T at an operating current of 55 kA, imposing a challenging coupled electromagnetic–thermal–strain environment on Nb3Sn cable-in-conduit conductors (CICCs). To meet these engineering requirements, we performed a systematic study on several types of high-Jc Nb3Sn strands, focusing on their coupled electromechanical and thermo-electromagnetic responses and the underlying microscopic degradation mechanisms (e.g., local plastic deformation and filament damage induced by cabling). Based on the strand-level findings, two types of cable pattern were developed and fabricated: a short-twist-pitch (STP) cable and a copper-wound-strand (CWS) cable. Short samples underwent full processing and qualification-style testing in the SULTAN facility, including electromagnetic load cycling, overload tests, warm-up/cool-down thermal cycling, and AC loss measurements, to benchmark current-sharing behavior and temperature sensitivity under representative loads. To identify the drivers of irreversible degradation, post-test conductors were analyzed using (i) an image-recognition workflow (Fiji/Matlab) to quantify cross-sectional geometric features such as local void fraction, centroid migration, strand contact, and ellipticity; and (ii) a magnetic-measurement-based inversion method that reconstructs the evolution of non-uniform internal strain distribution from AC magnetic susceptibility–temperature responses. The combined diagnostics reveal that strand migration and the accumulation of tensile strain during electromagnetic cycling dominate the degradation pathway, and they further demonstrate that the CWS configuration provides higher structural stiffness and improved mechanical stability compared with the STP configuration. These results establish an integrated strand–cable–conductor methodology for designing high-performance Nb3Sn CICCs for high-field applications.

Structural Mechanical Performance and Failure Modes of Large-Bore Magnet Systems for Field-Reversed Configuration Fusion Devices

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

The compression coil, serving as a key component in Field-Reversed Configuration (FRC) fusion devices, is subjected to exceptionally transient electromagnetic loads, typically with pulse durations under 10 ms. This results in a rapid and intense electromagnetic impact, imposing significant shock loading on the coil structure. Due to differences in the natural vibration periods of its constituent parts, such short-duration excitation can lead to transient structural decoupling or separation between components. This phenomenon not only induces immediate mechanical impact but also triggers sustained complex vibrations, posing a considerable threat to the structural integrity and long-term operational stability of the magnet. To address this challenge, this paper conducts a comprehensive investigation into the underlying mechanisms of inter-component separation within the magnet assembly under pulsed electromagnetic forces. Furthermore, it proposes targeted magnet design strategies aimed at mitigating or preventing such structural decoupling. The findings are expected to provide a useful reference and support for the engineering development of robust pulsed magnets in fusion applications.

Status and preliminary design of the EU-DEMO Cryogenic System

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The EU-DEMO tokamak, currently under preliminary design within the EUROfusion programme, is foreseen as the fusion power plant demonstrator following ITER. Its primary objective is to demonstrate net electricity production from fusion and to prepare the transition towards commercial fusion power plants. As a baseline, EU-DEMO relies on Low Temperature Superconducting (LTS) magnet technology.

The main cryogenic users identified for the EU-DEMO tokamak are the superconducting magnets cooled by supercritical helium flow at 4.5 K, the high-temperature superconducting (HTS) current leads cooled around 50 K, and the thermal shields actively cooled by helium flow approximately at 90 K to protect the magnets from thermal radiation. At present, no cryogenic requirements are allocated to the fueling and vacuum systems, although this may evolve with the system developments and design maturity.

The EU-DEMO magnet system comprises five Central Solenoid (CS) modules, six Poloidal Field (PF) coils and sixteen Toroidal Field (TF) coils, all surrounded by the thermal shields. Electrical power is supplied using 27 magnet feeders equipped with HTS current lead, with three additional feeders dedicated to the magnet structure cooling.

The cryogenic system consists of a large-scale helium cryogenic plant delivering an equivalent cooling capacity of about 100 kW at 4.5 K, together with a cryogenic distribution system including a segregation box, four auxiliary cold boxes for the magnets, and the associated cryogenic lines connecting the cryogenic plant to the magnet feeders.

This paper presents the current status and preliminary design of the EU-DEMO cryogenic system. The overall architecture and cryogenic user requirements are described. The preliminary design of the cryogenic plant and the main cryogenic distribution components is detailed, with emphasis on integration and safety constraints and design choices derived from the ITER cryogenic system development and related lessons learned.

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Test Results of the 16 T SUCCEX Inner Coil Conductor in the SULTAN Test Facility

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The Superconducting Conductor Experiment (SUCCEX) is a conductor test facility that began initial development at the Korea Institute of Fusion Energy (KFE) in 2012. The official project was launched in 2022, with the facility construction undertaken at the Korea Institute of Energy Technology (KENTECH). SUCCEX aims to evaluate Cable-in-Conduit Conductor (CICC) samples for future fusion magnets, generating magnetic fields exceeding 15 T in a 600 mm bore. The magnet system comprises a high-field inner coil (IC) using advanced high Jc Nb3Sn strands (Jc ~1000 A/mm^2 at 4.2 K, 16 T) and a low-field outer coil (OC) with ITER-grade Nb3Sn strands. The IC design operating condition is 16.2 T at 24.8 kA.

This paper presents the SULTAN test results of the SUCCEX IC conductor performed at the Paul Scherrer Institute (PSI). Since SULTAN provides a background field of 10.85 T, the test current was set to 37.1 kA to achieve equivalent Lorentz force conditions including the conductor's self-field contribution. The 10-day experimental campaign with a single warm-up/cool-down (WUCD) cycle primarily focused on DC performance characterization. The test sequence comprised: (1) initial current sharing temperature (Tcs) and critical current (Ic) measurements, (2) electromagnetic cycling up to 1000 cycles at nominal test conditions (10.85 T, 37.1 kA) with intermediate Tcs measurements at 100, 200, and 500 cycles, followed by Tcs and Ic measurements after 1000 cycles, (3) WUCD cycle and subsequent Tcs and Ic measurements, and (4) tests under partial Lorentz loads (10 T at 37.1 kA and 30 kA) and overload conditions (10.85 T at 44.5 kA and 55.7 kA). The analysis focuses on Tcs evolution, n-values, and effective strain throughout the test campaign. Performance assessment utilized the ITER evaluation procedure with 2D magnetic field integration across the conductor cross-section. The test results provide validation for the SUCCEX IC conductor design.

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Multiphysics analysis of a superconducting transformer for the EDIPO 2 Test Facility

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

The European Dipole Test Facility upgrade (EDIPO 2) is designed to exceed the testing capabilities of the existing SULTAN test facility for superconducting cables. EDIPO 2 will provide a background magnetic field of 15T (compared to 11T at SULTAN), a sample current of 120kA (compared to 100 kA at SULTAN) and a variable sample temperature ranging from 4.5K to 50K. Compared transformers for SULTAN and EDIPO 1 facilities, the new design will be optimized for testing of HTS samples, which have higher overall resistance in the secondary circuit compared to LTS samples. Achieving the 20% higher current requires an updated concept of the superconducting transformer (flux-pump). The transformer consists of two concentric superconducting solenoids, with the primary coil located in the center. This work investigates the magneto-thermo-mechanical response of the primary and secondary coils under testing conditions with a secondary current of up to 120kA by means of Finite-Element Analysis. Key design parameters of the transformer are presented, including coil geometries, conductor parameters, current amplification, temperature hot-spot dissipation and stray- and mutual-inductances. In addition, manufacturing requirements of the primary and secondary coils are derived based on the simulation results.

Comparative evaluation of a resistive and superconducting central solenoid for STEP

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

The Spherical Tokamak for Energy Production (STEP) is the United Kingdom's publicly funded fusion power plant prototype, aiming to deliver 100 MW of electrical power to the grid. STEP's Central Magnet Unit (CMU) consists of the inner limbs of the Toroidal Field (TF) magnets, divertor shaping magnets, and the Central Solenoid (CS). The CS is designed to deliver 9 Vs of flux with a peak field on conductor of 22 T and swings between positive and negative maximum current in 10 s. Its operation is limited to the plasma burn-through and inductive ramp-up stages. The limitations surrounding space present a considerable number of challenges to the performance, cooling and structures of the CS. This paper outlines the various solutions and their risk trade space.

In this work the major requirements, driven by the CS's relationship with the plasma, TF magnets, and the divertor shaping magnets, are presented; these directly impact the choice of location, size, total current, and current per turn. A trade study is put forward between an HTS CS and a resistive CS and the impacts on the overall magnet system and the whole plant. This is followed by a description of the winding pack design and cable choice. Results of the AC losses, cooling, and structural behaviour analyses performed with COMSOL and ANSYS Mechanical are discussed and are followed up by future work.

Preliminary electrical transients and thermal–hydraulic analyses of the toroidal field superconducting magnets of the future European nuclear fusion power plants in case of quench

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The European Fusion Pilot Plant (FPP) is the key intermediate step toward a First-Of-A-Kind (FOAK) fusion power plant for electricity generation. Both concepts are currently under development within the EUROfusion programme.
This paper presents preliminary electrical transient and thermal-hydraulic analyses of the Toroidal Field Coil (TFC) system during a quench event under normal operation of the protection circuits, considering both the designs of the FPP (in the variant of a Volumetric Neutron Source, VNS) and FOAK (in the variant of the demonstration fusion power plant, DEMO) currently under study within EUROfusion.
The toroidal field superconducting magnet system comprises 12 series-connected TFCs in the FPP, operating at 62 kA, and 16 series-connected TFCs in the FOAK, operating at 85.5 kA. The FPP toroidal field magnet system, based on two LTS/HTS technological options (Nb_3Sn and REBCO), being still under discussion. It stores about 4 GJ of magnetic energy and has a discharge time constant of 4 s. The FOAK system, based on Nb_3Sn technology, stores 72 GJ and has a discharge time constant of 22 s. The design limits for terminal-to-terminal and terminal-to-ground voltages are 2.5 kV and 1.25 kV for the FPP, and 6 kV and 3 kV for the FOAK, respectively.
Fast Discharge Units (FDUs) protect the toroidal field circuit by rapidly dissipating the stored magnetic energy during a quench or other anomalous conditions. Electrical transient simulations were performed using MATLAB/Simulink, incorporating the TFC inductance matrix, power cable impedances, stray parameters of the discharge resistors, and temperature-dependent resistance models. The simulations show pronounced voltage peaks during rapid discharge phases, which may impose critical electrical stress on and arcing in the insulation of the TFCs and associated components. As this could lead to destructive failure events, countermeasures are indicated.
A thermal–hydraulic analysis was also conducted for a quench initiated in the first layer of the toroidal field winding pack for both configurations. Two discharge strategies were analysed: pure (isothermal) resistors and temperature-dependent resistors.
The results emphasise the need for a robust quench protection system and accurate coordination of insulation levels to ensure the safe and reliable operation of large superconducting magnet systems. Future work will extend the models to include fault scenarios, supporting further optimisation and safety assessment of the EU DEMO toroidal field magnet design.

Overview of the recent progress of microwave quench detection: theoretical model developments and experimental results.

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

The results of most recent studies and fundamentals of the cooling channel reflectometry (CCR) technique for quench detection will be presented and discussed. Overview of the theoretical studies and numerical simulations based on Multiphysics and RF models will be presented. Results of the experimental studies of gas properties, recently carried out using CCR technique, and the analysis of data observed will be also discussed. The experiments are aimed to demonstrate local gas permittivity variations induced by temperature changes via measurements of the reflected and transmitted microwave signals. In the studies, the reflected and transmitted electromagnetic microwave signals, propagating along the cooling channel under conditions close to the operating regime of high temperature superconducting (HTS) cables, have been analysed. To emulate HTS cable operation the experiments were carried out using specially designed copper channel equipped with RF couplers capable of operating in cryogenic and high-pressure environments. The set up is reproducing the HTS cooling channel and operating conditions of the HTS cable. The channel is pressurised, and it is located inside the cryogenic box filled with liquid Nitrogen. To simulate the heat load occurring during the quench, an external inductive heating element has been designed and implemented. The inductive heating element enables variable power loading and allows the local temperature of the channel wall to be increased by approximately 20K at a selected location. It is shown that monitoring of the amplitude and phase variations of the microwave signals allows local gas temperature fluctuations to be observed and recover the heat-induced hotspots characteristics. A good agreement between the experimental results and theoretical predictions is demonstrated, confirming the validity of the technique. The technique suggested allows to realise non-invasive, noise and radiation resilient diagnostic tool capable of monitoring local variations of the temperature in HTS via its cooling channels.

Performance and microstructural changes in high-energy SiC varistors induced by D-T neutron exposure

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

High-energy SiC Varistors are voltage-dependent resistors with non-linear voltage/current characteristics that offer benefits over conventional energy extraction dumps, namely lower voltage to ground, faster discharge and lower energy deposited in the coil during a quench and discharge. SiC varistors will be used to protect the Toroidal Field Coils of the Divertor Tokamak Test (DTT) facility and have applications in coil and structural protections, with possible installations close to the plasma. It is therefore important to understand the impact of fusion neutron irradiation on the varistor material. To this end, high-energy SiC varistor samples were irradiated with Deuterium-Tritium (DT) neutrons at the Frascati Neutron Generator (FNG) at ENEA, at a range of fluences up to 1 x 10^14 cm-2. This work presents the methodology of the irradiation and the neutron transport simulations (MNCP) used to determine fluences, as well as pre- and post- irradiation characterisation of the varistor samples, including the changes in electrical properties and microstructure.

Development plan of the large-scale HTS SupraFusion Demonstrator Magnet

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

Within the French SupraFusion PEPR (Priority Equipment and Research Program), the SF-DEMO project aims to validate key technologies required for high-field HTS large scale magnets dedicated to future fusion devices. The goal of this demonstrator is to reach 20T and 100 MJ with a fully insulated HTS technlogy. SF-DEMO is conceived as a progressive demonstrator, structured around a comprehensive development plan designed to reduce technical risks from early design phases to the realization of a large-scale REBCO magnet. This paper presents an overview of the global development roadmap of SF-DEMO. It starts with conceptual design studies of the demonstrator, defining the main magnetic, mechanical and thermal requirements and identifying the associated constraints on conductors, coils and protection strategies. Extensive characterization campaigns of REBCO tapes are then described, providing the experimental basis for material selection, modelling and magnet design with improved confidence. Based on these results, the development of a new high-current HTS conductor tailored to the SF-DEMO requirements is presented, together with the associated R&D activities addressing electrical performance, mechanical robustness and manufacturability. Quench detection and protection, which remain critical challenges for HTS magnets, are a central focus of the program. Ongoing R&D on innovative quench detection approaches using Superconducting Quench Detectors (SQD) is introduced, including their implementation and validation on dedicated prototype coils. Finally, the successive technological prototypes planned within SF-DEMO are outlined, with the objective of progressively demonstrating fabrication feasibility, assembly processes and operational robustness on the path toward the final demonstrator magnet. Through this structured development strategy, SF-DEMO aims to provide a robust validation of HTS magnet technologies for fusion and other high-field applications.

Preliminary Design of a Power Quality Compensation System for Reactive Power and Harmonic Mitigation in a FOAK Fusion Power Plant Toroidal Field Power Supply.

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

Ensuring high power quality in fusion power plant grids is essential for the successful integration of future fusion facilities into electrical networks. This paper presents the preliminary design of a power quality compensation system for the Toroidal Field Power Supply (TFPS) of a First-of-A-Kind (FOAK) fusion power plant.

The TFPS under study is based on ITER-like thyristor technology, configured as a 2-quadrant AC/DC 24-pulse converter delivering ±1 kV at a maximum current of 85.5 kA. The power supply is fed by two converter transformers with three-winding configuration D/d/y, rated at 33 kV/0.74 kV with a combined capacity of 2 × 45 MVA. Without compensation, the system exhibits substantial reactive power demand and harmonic distortion, resulting in a degraded power factor and elevated Total Harmonic Distortion (THD), both of which compromise compliance with grid codes and affect system efficiency. Therefore, a reactive power compensation and harmonic filtering (RPC&HF) system is necessary.

A comprehensive MATLAB/Simulink model was developed to replicate the electrical behaviour of both the RPC&HF stage and the superconducting TF coil system, including detailed cable network impedance. The simulation considers 16 TF coils with a total inductance of 19.68 H, and stored energy of 72 GJ. Simulations were conducted over an operational window comprising the ramp-up and flattop phases, to evaluate system performance under realistic operating conditions.

Simulation results demonstrate that the proposed RPC&HF stage significantly enhances power quality metrics. During the flattop phase, reactive power and THD are substantially reduced, while the active power remains quite unaffected, due to the high efficiency of the RPC&HF system. Frequency-domain analysis via FFT confirms effective suppression of low-order harmonics, validating the control scheme's ability to maintain a nearly sinusoidal current waveform at the grid interface.

These results confirm the feasibility and effectiveness of filtering strategies for high-power fusion installations. The proposed architecture not only ensures compliance with some power quality standards applicable to nuclear facilities but also enhances overall system reliability and efficiency, supporting the pathway toward commercially viable fusion energy generation.

Requirements, Architecture, and Key Features of the DTT Cryogenic System

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The Divertor Tokamak Test -DTT- project was developed as a strategic pursuit to test innovative solutions for the divertor, a key component responsible for exhausting the extreme thermal power generated in a tokamak. Its experiments are designed to operate in regimes relevant to ITER and the future fusion power plant, helping bridge the gap between today's research devices and tomorrow's commercial fusion reactors.

At the core of the DTT are superconducting magnets, capable of generating extremely strong magnetic fields while consuming minimal electrical power. The operation of such magnets requires very low temperatures up to around 4.5 K. The magnet system is then protected from radiation of surrounding environment with dedicated thermal shields, actively cooled with pressurized helium flow at 80 K. In addition, a 50 K refrigeration branch is required to cool for high-temperature superconducting (HTS) current leads, which connect the magnets to their power supplies.

In this framework, the DTT cryogenic system was conceived to handle the operation of the different temperature levels and to deal with the variable heat loads, characterized by very high peaks during the Plasma Operation State (POS). This work presents the main thermal loads and cooling requirements of the DTT cryogenic system during the different phases (operational states) of the DTT machine, which form the basis of the conceptual design of the Cryoplant.

Furthermore, customized helium flow distribution has been engineered to optimize the cooling strategy, aiming at rationalizing the total number of cold boxes, control valves, lowering costs and simplifying the cooling management. The helium distribution is organized in 5 main cooling loops, each one characterized by several cryogenic users grouped in parallel, mostly protected by customized non-return valves to prevent backflow in case of quench or pressurization events. The main features of the cooling distribution system are also illustrated thoroughly in this document.

Confirmation of Electromagnetic Loads and Structural Integrity of ITER Thermal Shield Sector Modules under Multi-Physics Loads

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The ITER Thermal Shields (TS) play a critical role in limiting radiative heat loads on superconducting magnets while being subjected to significant Electro-Magnetic (EM), thermal, and seismic loads during normal operation and off-normal events. This paper presents the methodology and scope of a reassessment aimed at confirming electromagnetic loads and structural margins in the Thermal Shields. This activity addresses limitations identified in previous Final Design Review analyses by updating EM load evaluations for plasma disruptions and magnet fast discharges, using the current design configuration and detailed models for panels and manifolds. The EM behavior of pipe-shaped components is represented through ANSYS USER300 wire elements, enabling the assessment of current paths and electrical breakers within the manifold system, while thermal load definitions are refined and the resulting dynamic and static structural responses are reassessed. The analysis scope covers TS panels, manifolds, cooling pipes, supports, bolted and welded joints considering all ITER Category I–IV load combinations in accordance with applicable ASME and ITER design criteria.
A multi-physics and multi-scale finite element strategy is adopted, combining dedicated electromagnetic simulations with detailed thermo-mechanical and dynamic structural models. Sector-based and full 360° models are employed to accurately capture cyclic-symmetric effects as well as inertial responses during seismic and EM events. Thermal analyses incorporate radiative heat transfer and active helium cooling, while structural verification includes elastic strength checks, fatigue and ratcheting assessments, and fracture-mechanics-based fast-fracture failure evaluation to ensure adequate structural integrity margins of the ITER Thermal Shields prior to installation. The proposed workflow provides a robust basis for confirming structural integrity margins of the ITER Thermal Shields prior to installation.

Completion of power supply systems for the DTT in-vessel coils

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

The power supply (PS) systems for the in-vessel coils were delivered to the DTT site. DTT contains three types of in-vessel coils, denoted as Vertical Stabilization (VS), Divertor (DIV) and Not-Axisymmetric (NAS), respectively. Since their requirements are different, three independent PS designs with three different procurement contracts were developed.

Elongated plasmas and alternative configurations, as expected in DTT, are particularly sensitive to vertical instabilities. In DTT, two equatorial coils with an anti-parallel magnetic coupling are inserted into a circuit containing two PSs with a coordinated control and a common branch with additional impedance to limit disruption effects. The PS converters consist of series and parallel IGBT-based H-bridges up to 6 kA and 8 kV. Supercapacitors inserted in the DC-links provide a buffer to guarantee energy for critical transitions. In this configuration, the PSs can produce two high-performance actions at the same time: current flowing in both the coils achieves plasma VS, while an imbalance between coil currents can be used for fast radial control during plasma transients.

DTT aims to study different DIV configurations and technologies, thus requiring a flexible local control of the plasma flux surfaces in this region. Simulations showed a good tradeoff between flexibility and complexity with three in-vessel coils controlled by independent 5-kA IGBT-based PSs. These coils can adjust (and sweep) strike-points, scrape-off layers and possible secondary X-points and can assist in X-point formation and in diverted-limiter transition during ramp-down.

Coils that are not symmetric with respect to the tokamak axis (NAS) are necessary to address two classes of phenomena: error fields (EFs), due to the uncertainties in construction or assembly, and edge-localized modes (ELMs), due to fast localized instabilities. EFs can be corrected by NAS DC currents, while ELMs can be mitigated by NAS AC currents. After a study to identify a suitable likelihood of correction, DTT is equipped with 3 rows of 9 NAS in-vessel coils shaped. The PS system can independently control currents up to 2.5 kA in the 27 coils by H-bridges sharing a common DC-link for each row.

Specific activities were focused on the modeling and simulation of PS equivalent loads and of plasma disruptions. PS design, especially balancing of input power and DC-link capacitance, took into account that equivalent coil impedance can show even an order of magnitude of variation over the frequency bandwidth. Active electrical loads allow the emulation of such behavior with common hardware during tests.

ITER TFC Safety Class Quench Detection: Thermohydraulical Analyses, Quench Occurrence and Detection Criteria

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The Toroidal Field (TF) system of the ITER tokamak comprises 18 Nb3Sn superconducting coils, cooled by forced flow supercritical helium at 4.5 K and carrying a nominal current of 68 kA. The quench induces some very important heat loads in Cable-In-Conduit Conductors (CICC) and structures (stainless steel radial plates and casing). Previous thermohydraulical undetected (by voltage) quench analyses have shown the paramount interest of secondary quench detection (thermohydraulical signals, difference of outlet – inlet helium expulsed mass flow rate at Coil Termination Box -CTB).

The feasibility studies of a Safety Class Quench Detection (SCQD) system (third and last quench detection) based on helium pressure gradient in a venturi located at the CTB is considered. One thermohydraulical model based on SuperMagnet Code, with implementation of the radial plates in the THEA model, permits to validate and confirm the previous thermohydraulical results and response of undetected quench. In particular, a severe quench initiated at the higher field location of the CICC (at 11.8 T, near the thermohydraulical inlet) is studied with rapid quench propagation velocities and more easy to detect. This kind of quench event seems to be the one with higher occurence probability, considering WEST TFC quench feedback analyses. Complementary smooth quench event with initiation at low field region (2 T near the middle of CICC length), are presented. With lower quench propagation velocities and pressure gradient, and thus more difficult to detect, the thermohydraulical analyses of smooth quench confirm that the pressure signals in venturi detection is valid. Preliminary crucial SCQD criteria are here proposed and discussed within a time delay that should be maintained lower than 20 s (after quench initiation). These analyses results confirm the potential criticality of a so called undetected quench, and considering safety issues, can be useful for ITER tokamak magnets safe operation and protection.

Overvoltage protection of the new IGBT motor drive of ASDEX Upgrade's main flywheel generator EZ2

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The Tokamak ASDEX Upgrade at IPP Garching is one of the leading experiments investigating the principles of a future power plant, which will produce energy from thermal fusion of light atomic nuclei. During a ten seconds plasma discharge up to 400 MW of electrical power are required for magnetically confining the plasma and heating it up. Such high pulsed power cannot be taken from the public grid. Therefore, plasma operation relies on three large flywheel generators with a total available energy of 2.8 GJ.
Recently, the old thyristor direct converter of the motor drive of flywheel generator EZ2 has been replaced by a three-level IGBT inverter. The economic implementation available on the market, with 1200 V IGBTs, limits the DC link overvoltage to 2400 V in case of fault events. The old selenium surge arrestor, clamping by an equivalent of 2800 V, had to be replaced by a thyristor crowbar. Thereby appeared new challenges: The reverse freewheeling diodes and DC link capacitors offer a very low impedance path in case of ac overvoltage. In order to clamp the DC link voltage to a level avoiding damage to the IGBTs and capacitors, the crowbar must be designed with very low resistance. While so the sensitive converter will be protected, the rotor of the 50 years old double fed induction motor faces overcurrents up to 10 times the peak nominal current. So as to protect the motor by faults, a series resistor, bypassed by a fast switch in on-state during regular operation, will limit the overcurrent to a predesigned value.
The paper will describe in detail the determination of the crowbar resistor, technological ways and challenges in the implementation of the fast switch as well as the trade-offs in the selection of the series resistor. The practical realization with necessary signal and safety issues will be presented. The results of commissioning and first operational measurement will complete the article.

Benchmarking Quench Analysis Strategies for Next-Generation Stellarator Systems Codes

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

Superconducting coils in fusion magnet systems are susceptible to the quench phenomenon which can cause severe damage if not properly mitigated. Since experimental quench testing is impractical in the pre-conceptual design phase of a fusion power plant, (semi-)analytical approaches and numerical simulations play a crucial role in the quench-safe design of its magnet system. To take all aspects of a fusion power plant into account, such quench analysis methods are embedded into systems codes, requiring a balance between computational efficiency, physical fidelity and usability. These requirements instantly disqualify a full 3D simulation, and in the case of stellarators, also a cross-sectional 2D model is infeasible since its inherently complex 3D coil system cannot be reduced to an axisymmetric model as it is the case for tokamaks. Fortunately, there is a large bouquet of 0D and 1D methods to model and analyze the quench behavior in a coil with adequate accuracy.

This work presents a benchmark study of such 0D and 1D quench analysis methods, evaluating their performance for a potential use in a stellarator systems code. The methods are first validated against quench test measurements from the Wendelstein 7-X stellarator coils. Subsequently, they are employed within an optimization framework to identify quench-safe coil parameters for a stellarator reactor scenario while keeping the coil winding pack as compact as possible in order to obtain the most cost-efficient configuration. The study compares the resulting coil configurations, critical physical parameters such as hot-spot temperature, computational cost and practical aspects such as usability and ease of integration into systems codes.

Finite Element Analyses of Thermal Stresses at Cooling Pipes During Cool Down of Wendelstein 7-X Cryo Vacuum Pumps

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

The Wendelstein 7-X fusion experiment has 10 cryogenic vacuum pumps (CVPs) to enhance the pumping capacity for neutral gas in the in the sub divertor region of the plasma chamber. The pumping surfaces of the CVPs consist of stainless steel tubes that are cooled with helium at 3.9 K and 3.7 bar under steady-state conditions. The tube bundle of each pump is enclosed within an actively cooled stainless steel housing, which protects the pumping surface from both the thermal and the plasma radiation inside the plasma vessel vacuum chamber. This stainless steel tank is cooled using liquid nitrogen at approximately 80 K. All 10 cryopumps are supplied in parallel with helium via the helium cryoplant and with nitrogen via a liquid nitrogen storage tank.

During cooldown from room temperature to operating temperature, both the helium and nitrogen circuits are cooled simultaneously at a ramp rate of approximately 30 K/h. Due to the thermal load on the stainless steel housing, temperature differences of up to 50 K between the inlet and outlet of the nitrogen circuit may occur. While the mixing temperature in the helium circuit can be easily controlled, the cooling of the nitrogen circuit—achieved by injecting liquid nitrogen into a gaseous nitrogen stream—is very limited in its adjustability. Both effects contribute to significant local temperature gradients during cooldown, especially during the transition from gaseous to liquid nitrogen. when the cooling medium undergoes a sudden change in properties: heat transfer between the nitrogen flow and the inner tube wall improves, mass flow increases due to higher density, and the nitrogen temperature remains nearly constant along the saturation curve due to its latent heat of vaporization.

This paper presents the finite element (FE) investigation how the temperature distribution within the cryopump changes due to the rapid temperature drop during the transition from gaseous to liquid nitrogen. Details regarding the FE mesh generation and assumptions made for modeling the transient state are discussed. Calculated temperature profiles between the cooling tubes and adjacent stainless steel plates are presented as a function of time, along with the resulting thermal stresses. The calculations reveal stress peaks of up to 410 MPa. These stresses are treated as secondary stresses in highly localized regions and are acceptable in accordance with AD2000 code.

Stellarator magnets via laser engraving of wide conductive surfaces

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

In stellarators, steady state operation without plasma current drive is enabled by a complex magnetic field, which requires complex magnet geometries. Traditionally, the inverse problem for the current distribution is solved conformally to the targeted last closed flux surface, discretized into filaments, and spatially optimized. It results in a set of non-identical (within a half-period), geometrically complex magnets, incurring manufacturing challenges that have hindered the widespread adoption of stellarators [1]. Renaissance Fusion proposes a simplified workflow in which the current distribution is solved and optimized on a cylindrical surface and laser engraved onto the conductor itself, shifting current complexity from 3D magnet geometry to 2D surface patterning. To validate this approach, a four-milestone experimental program was established using aluminum and copper/PET laminates as proxies for wide HTS tapes. The first two milestones reproduced the magnetic field configurations of a gyrotron and an MRI magnet, respectively, with field relative uniformity reaching 10^{-5}. The corresponding development and results are reported in [2]. This presentation focuses on the development and results of the third and fourth milestones of this program. The third milestone, completed in October 2025, targets half a period of a classical l = 2, Np = 5 stellarator equilibrium [3], solution reached within 1%. The experimental realization consists of 13 individual coils engraved on a common surface over 171 concentric layers and powered in series, complemented by manually wound external coils reproducing the saddle current loops. An on-axis field of 0.05 T was achieved and characterized by hall-probe scans, yielding a mean relative error of 9% over the solution error. The electromagnetic, mechanical and thermal design, manufacturing considerations, experimental campaign, post-processing, and results are presented. The fourth milestone of the program, currently under development, is a full tabletop stellarator magnet set designed to generate and experimentally verify closed flux surfaces through Electron Beam Mapping. The electromagnetic solution, together with manufacturing considerations aimed at improving engraving control and layer-to-layer alignment tolerances, are discussed in detail, along with the status of the vacuum vessel design, magnet alignment and shimming systems, electron beam mapping mechanism and initial results.

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[2] D. Pereira Botelho et al., “Simplified magnet design and manufacture based on patterning of wide conductors,” arXiv:2409.20143, 2024.

[3] J. Loizu et al., “Equilibrium β-limits in classical stellarators,” J. Plasma Phys., 2017, doi:10.1017/S0022377817000861.

Design and qualification of the ITER In-Vessel Coils' Feedthroughs

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The ITER In-Vessel Coils (IVC) are water-cooled coils, composed by a mineral-insulated copper conductor, enclosed in a stainless-steel jacket (59 mm outer diameter). All IVC are fed by external supplies through feeders and feedthroughs running across the ITER Tokamak ports. The IVC Feedthroughs are used to facilitate the transfer of electrical power and cooling water across the separation boundary of the ITER Vacuum Vessel (VV). On the inner side of this separation boundary is the ultra-high vacuum environment of the VV while on the opposite side is the Tokamak ports' interspace (so-called "air side"). Every IVC is provided with two feedthrough lines (inlet and outlet), for a total of 70 IVC Feedthroughs in the ITER Tokamak.

Each IVC Feedthrough is made of one IVC mineral-insulated conductor, ceramic terminations, electrical insulating collars made of high-temperature polymers and stainless-steel bellows to accommodate the relative deformations between the coils and the VV during operations. The IVC Feedthroughs are designed to withstand operating voltages up to 2.4kVDC and operating temperatures up to 240°C.

The design of the IVC Feedthroughs is now finalized and a dedicated qualification campaign has been carried out with particular focus on the electrical terminations of the mineral-insulated conductor (MgO). The qualification campaign was finally completed with the manufacturing of a full-size prototype of the IVC Feedthrough.

This paper will give an insight into design, prototyping, and qualification tests campaign of the ITER IVC Feedthroughs.

Comparison of Two Nb3Sn DTT PF6 Conductor Designs Tested in SULTAN

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

The DTT magnet system consists of 18 Nb3Sn toroidal field (TF) coils, 8 central solenoid (CS) coils (6 Nb3Sn and 2 high-temperature superconducting coils), and 6 poloidal field (PF) coils which are characterized by a full top-down symmetry. Based on the magnetic field distribution calculated on each PF coil during operations, PF1 and PF6 designs are based on Nb3Sn while PF2, PF3, PF4 and PF5 design are based on NbTi.

This work reports the SULTAN tests of the Nb3Sn PF conductors carried out in August 2025. The SULTAN sample was made of two distinct Nb3Sn CIC sections, namely ‘PF6-A’ and ‘PF6-B’, designed to work in DTT at 28.3 kA - 9.2 T peak field. Both sections were manufactured with ITER like strand wires produced by OST, which will be used in the manufacturing of the DTT PF6 coil. The two sections of the SULTAN sample are identical, except for the cabling twist pitch sequence and the void fraction. In this way, the experimental tests made it possible to investigate whether either of the two designs provides superior performance, particularly with respect to the potential degradation induced by the repetitive electromagnetic loading on Nb3Sn—an aspect of a particular relevance, as the magnets are intended to operate under pulsed conditions.

The PF6 extensive characterization comprised 5000 electro-magnetic (EM) cycles and two warm-up-cool-down (WUCD) steps. In detail, it included: pressure drop measurements as a function of the mass flow rate, AC measurements with a sinusoidal field of 0.3 T amplitude superimposed on a background magnetic field with and without transport current on the virgin conductors, on cyclic loaded conductors and after WUCDs. DC tests in the field range from 7.2 T to 9.5 T, with currents up to 31.1 kA interleaved with EM cycles both before and after WUCDs. AC loss measurements using 0.4 T trapezoidal pulsing superimposed on background magnetic field and minimum quench energy (MQE) tests at 8 T/28.3 kA for different temperature margins.

DC and AC tests analysis verified the designs, as both samples exhibited results well within the expected range. However, the final selection of the optimal design fell on ‘PF6-B’, which proved to be more capable of fully exploiting the performance of the constituent strand.

Designing a Steady-State Cryogenic System for the STEP Prototype Plant

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

The STEP Fusion programme is a programme led by United Kingdom Industrial Fusion Solutions Ltd (UKIFS) to design and build a first-of-a-kind fusion power plant that can demonstrate net electricity generation. The STEP Prototype Plant (SPP) will operate largely as a steady-state machine.

The STEP tokamak machine is a form of magnetic confinement fusion and will use cryogenically cooled high-temperature superconducting (HTS) magnets to contain the plasma. The HTS magnets, alongside the fuel cycle and thermal shielding, require significant cryogenic cooling. The SPP will require a total refrigeration load equivalent to approximately 100 kW at 4.5 K. Producing such refrigeration loads will require significant electrical power: the cryogenic system is a parasitic load that must be minimised.

The STEP cryogenic system will be designed for steady state operation, but as a prototype the machine will experience dynamic operations and transient heat loads. For example, a transient increase in refrigeration load occurs during start-up, when the resistive central solenoid is loaded and then ramped down for plasma breakdown.

The cryogenic system architecture considers isolating the cryogenic users from the steady-state cryogenic plant to minimise disturbances generated by dynamic refrigeration loads. Cryogenic users will be cooled by independent cryogen circuits.

Forced helium flow will be provided in the circuits by cryogenic circulators and heat from the users will be rejected from such circuits to the cryogenic plant via ‘circuit separation’ heat exchangers. Cold circulators and heat exchangers are both sources of inefficiency within the cryogenic system that must be minimised to reduce the cryogenic plants electrical power consumption. Liquid cryogen buffer tanks could be used to provide rapid increases in refrigeration load in response to transient increases in heat load.

This work outlines the benefits of operating a steady-state cryogenic plant and the challenges of managing transient thermal loads and minimising electrical power consumption.

Parametric Study of AC Loss in 50 kA/20 T Stacked Tape Conductor for Future Fusion Central Solenoid

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The calculation of instantaneous AC loss power in superconducting cables is critical for realising magnet stability and cost-effective cryogenic plants, particularly for designs using wide aspect ratio high temperature superconducting tapes. A numerical parametric characterisation of AC loss behaviour has been performed for a 50 kA stacked-tape cable up to 20 T, as expected for next-generation tokamak central solenoid requirements. Instantaneous hysteretic, eddy and coupling loss powers are parameterised from 0 to 20 T, at ramp rates from 0.1-5 T/s, with the field at various angles, and with a range of in-phase currents. The results are tailored to allow easy comparison with other cable designs and are fitted parametrically to allow rough but rapid reconstruction of AC loss power during arbitrary energisation profiles, as required for iterative fusion magnet design tools.

Integration of the new Upper Divertor Coils in the ASDEX Upgrade power supply system and first operational experience

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

During the last maintenance break of ASDEX Upgrade (AUG), a new upper divertor with two concentric coils was integrated into the AUG vessel. These coils had to be integrated into the existing power supply system of AUG.
Both coils are connected in counter-series, and have a common power supply. By using a second power supply, it should be possible to provide a small differential current to a single coil.
For cost reasons, it was decided to use an existing power converter consisting of four converter modules. This converter had to be optimised for the new application, while also remaining as universal as possible so that it can still be used for other applications. The power converter is connected to a crossbar distributor, where two outputs for the new coils were added by rearranging the other connections. For safe operation and to enable a change in the main current direction, disconnectors and earthing switches were integrated into the coil supply lines.
To avoid excessive forces on the coils and their support structure, the current must be strictly limited. The current is measured by open-loop current-sensors, based on Hall Effect sensors, in the supply lines. If the current limit is exceeded, the power supply switches off. During the first operational campaign, the only way to switch off the power supply was through its main circuit breaker, which took up to 100 ms. Consequently, the current-rise rate was reduced by adding extra inductance to the circuit for safe operation. For the next campaign, current limiters (pyro-fuses) were added to enable a faster shutdown. Thus the additional inductance can be reduced, resulting in a higher operational bandwidth.
Until now, the coils have only been operated symmetrically. A so-called “ripping crowbar” was developed for asymmetric operation, which is to be integrated in a later step.
This publication provides a detailed overview of the electrical and mechanical construction of the AUG power supply system extension and its connection to the coils. In addition, the first operational experience with symmetric operation is shown, including a comparison with mock-up tests.

Test facility to determine the contact resistance at cryogenic temperatures of two connected superconducting fusion magnet cables under mechanical tensile load

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

Within the German funded BMBF project demountable, robust and low-resistance contacts for high-current, superconducting conductor concepts for use in stellarator magnets are developed. This allows a new approach regarding the layout of such a fusion device. To perform the detailed characterization of the electric contact resistance between two sections of superconducting cables, a test facility at KIT is adapted for this purpose. The sample are provided by project partners Gauss Fusion, Research Instruments, and ENEA with a clamped internal joint, to be used in a winding pack setup of a coil.

In this work the facility setup will be described and the necessary sensors and interfaces to allow a detailed measurement across the contact parallel with the stress-strain behavior. This will allow the measurement not only at cryogenic temperatures down to 4.2 K but also to apply mechanical tensile loads to investigate the influence of, e.g. hoop stresses during operation on the contact resistance.

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#13220

Design of 100kA HTS cable for fusion magnets

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

ENEA and GFG are collaborating on the design and development of a high-temperature superconducting (HTS) cable for a stellarator power plant. In particular, the cable has been designed by ENEA to transport 100kA of current at 20K and 12T. The concept is based on the twisted stacked tape technology, specifically the “SECAS” type, exploring both sectorial and monolithic core design. To optimize the final cable design, multiple sub-size conductors have been manufactured and tested in liquid nitrogen to compare the main features of the different solutions considered. This work presents the design of HTS cable, along with main test results, emphasizing key findings and their implications for fusion applications.

Upgrade progress of HL-3 power supply system

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

HL-3 is a conventional conductor Tokamak device built in SWIP, which first plasma was obtained in 2020. It obtained 1.6 MA H-mode operation and the ion temperature reached 10.1 keV in 2025. The next goal of HL-3 is to achieve the first DT operation of China in 2027. Now many systems of HL-3, including power supply system, are being upgraded to meet the requirement of high parameter operation.

The existing two 80 MVA motor generator will be replaced by a 300 MVA / 3000 MJ super capacitor energy storage system, and the 140 kA diode-based TF power supply will be upgraded to 190 kA thyristor-based power supply. These upgrades guarantee the power capability of 2.2 T Bt with 7s flat-top.

The central solenoid power supply feeds the CS coil to provide flux-swing and equilibrium component of plasma current and shape control. Its rated parameters are ±240 kA/±750 V, and it is four-quadrant thyristor power supply operated in circulating-current mode. Usually, circulating current reactors are needed in four-quadrant power supply in circulating current mode to limit the current during the circulating current phase, in order to simplify the power supply system, a unique topology and control logic are proposed. The loop of current is controlled in preset routine during circulating current phase, and the amplitude of circulating current is limited in safe region.

IGBT-based power supplies are developed for both poloidal field and vertical stability fast control power supplies. They will increase the control response and improve the power quality of power grid.

Heating system of HL-3 will be upgraded with new NBI, ECRH, LHCD and ICRH systems. Dedicated high voltage power supplies with quick protection and restart function are developed.

Keywords: HL-3, super capacitor, central solenoid, circulating current

Research on the Characteristics of Milliampere-Level Leakage Current Detection Technology in Strong Magnetic Field Environments

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

To address insulation safety concerns arising from the aging of electrical equipment near Tokamak fusion devices and accuracy issues in leakage current detection under high magnetic field environments, an AC/DC milliampere-level leakage current measurement device utilizing a self-excited fluxgate for external magnetic field environments was designed. First, an electromagnetic coupling model of the leakage current sensor based on high-permeability cores was established. The influence of the fusion device's external magnetic field environment on milliampere-level current detection characteristics was systematically analyzed, quantitatively characterizing the relationship between external magnetic field strength and sensor output response. Furthermore, by incorporating magnetic shielding technology and conducting simulation analysis, external magnetic field interference was effectively suppressed, simultaneously enhancing measurement accuracy and linearity. Simulation results demonstrate that the proposed scheme validates the feasibility of online micro-current detection for electrical equipment in fusion devices, offering a technical approach for insulation safety monitoring in strong magnetic field environments.

Dynamic Power Phase-Shift Coordination and Stability Analysis of Fusion Coil Power Supply Based on 3L-DAB

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The third-generation poloidal field (PF) magnetic coil power supply employs a three-phase PWM rectifier cascaded with an H-bridge DC/DC stage. Although it offers significant performance improvements over the second-generation system, the low-frequency (mains, 50/60 Hz) isolation transformer required for this topology is large, and thus becomes the primary bottleneck to further increase power density under very high-current, ultra-high-power conditions. In contrast, the dual active bridge (DAB) converter with high-frequency isolation can operate the transformer at high frequencies, significantly enhancing the system's power density. Therefore, the dual active bridge (DAB) converter with high-frequency isolation is the core development direction for the next generation of high-frequency isolated voltage-source PF power supplies. Among them, the three-level DAB (3L-DAB), with its lower device voltage stress and good modular scalability, better meets the high-voltage, high-power requirements of fusion applications.However, in practical Tokamak operation, the magnetic coil power typically exhibits strong short-term randomness and non-stationary fluctuations. Under these operating conditions, a three-level dual-active-bridge (3L-DAB) employing triple-phase-shift (TPS) modulation will experience frequent, random dynamic switching of its three phase-shift angles during operation. This process is essentially a multi-degree-of-freedom dynamic coordination problem caused by random power disturbances, with the main challenge being the stability control of a multi-parameter coupled nonlinear time-varying system. Without an effective coordination mechanism, random loading of the phase shifts can lead to dynamic instability of the control system, resulting in distorted current waveforms, transient DC flux bias and core saturation, which severely limit the long-pulse steady-state capability of fusion power supplies. To address these issues, this paper shifts the focus from conventional steady-state DAB analysis to dynamic stability under random load disturbances. First, a dynamic model of the system considering random power disturbances is established, revealing the mechanism of the phase-shift angle coupling switching on current stress and bias magnetization evolution. Based on this, an ordered phase-shift scheduling strategy is proposed to address random power fluctuations. This strategy, while ensuring the zero-voltage switching (ZVS) range, enables the coordinated dynamic loading of the three phase-shift variables, effectively suppressing transient waveform chaos and transformer saturation risks. This study provides theoretical foundations and technical support for the development of next-generation, high-power-density, dynamically stable, high-frequency-isolated voltage-source PF magnetic coil power supplies.

Validation of Fast Plasma Decay Electromagnetic Simulations with Wendelstein 7-X Rogowski Coil Measurements Inside and Outside the Plasma Vessel

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The experimental stellarator Wendelstein 7-X (W7-X) has been operating reliably for nearly a decade. During this period, however, a small number of discharges exhibited unexpectedly fast plasma decay. Such “fast” plasma decays are characterised by a high rate of change of the plasma diamagnetic energy and the toroidal plasma current, exceeding the typical values observed at the end of standard W7-X discharges.

Although these events are rare, fast plasma decay may pose challenges for machine operation and safety. In particular, the fast reduction of plasma current can induce eddy currents in various conducting components, causing various electrical and/or mechanical problems. The ability to reliably simulate these events numerically allows assessment of potential risks.

A new simulation model has been developed to analyse the complex electromagnetic interactions between the plasma and the stellarator components. The simulations include both the superconducting coils that generate the static component of magnetic field and the plasma current, modeled with full stellarator complexity. The model enables the calculation of induced eddy currents in conducting machine structures.

As a second step, the simulation results will be validated against measurements from Rogowski coils located on both the inner and outer sides of the plasma vessel. A pair of Rogowski coils positioned at the same toroidal location on the internal and external surfaces of the plasma vessel provides measurements influenced by the vessel’s damping effect and by the local concentration of eddy currents around the corresponding port. This configuration offers a valuable opportunity for comparison, limited only by the number of installed Rogowski coils.

Zero-Voltage Switching (ZVS) Modulation Strategy for a Next-Generation DC-Isolated Fusion Magnet Power Supply Based on a Three-Level DAB Topology

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The currently widely used second- and third-generation fusion magnet power supplies have AC-side power frequency isolation transformers that are extremely large and heavy, and have low power density. In order to effectively increase power density, the future generation of fusion magnet power supplies can consider high-frequency DC isolation solutions based on dual active bridge (DAB) converters. In response to the development needs of higher voltage levels for fusion magnet power supplies, the three-level DAB topology can reduce the voltage stress of a single power device through voltage division to meet the application requirements of high voltage and high power. Moreover, under high-frequency operating conditions, the switching loss of the DAB converter increases significantly. Therefore, realizing bilateral ZVS on the primary and secondary sides of the transformer plays a key role in reducing switching losses and improving system efficiency. Therefore, this article uses a new generation of DC isolated fusion magnet power supply based on three-level DAB (3L-DAB) topology, and uses a collaborative modulation strategy to achieve bilateral ZVS on the primary and secondary sides of the transformer under a certain voltage fluctuation range and wide load conditions, thereby improving the high-frequency operating performance of the system. However, due to the complexity of the 3L-DAB topology, existing research is difficult to achieve bilateral ZVS when the modulation degree of freedom is limited. Therefore, this paper adopts multiple phase-shifting modulation strategies and takes current stress as an important performance indicator. In order to minimize the current stress during modulation, there are two difficulties in the analysis process and the implementation process. First, the increased degree of freedom in multiple phase-shift modulation results in a heavy computational burden and low accuracy in the analytical derivation process. Secondly, in order to achieve multiple phase-shift modulation, if a look-up table is used after the modulation variables are optimized, the modulation performance will not be ideal due to the discrete nature of the look-up table. This article proposes a multiple phase-shifting modulation strategy based on artificial intelligence. This paper uses a hybrid optimization strategy of artificial neural network (ANN) and fuzzy inference system (FIS) to solve the above problems. The proposed method is verified to be effective through simulation and principle experiments. The modulation optimization technology proposed in this article provides a feasible solution for the future development of fusion magnet power supplies in the direction of compactness and high performance.

#13289

The progress of superconducting magnet of next generation of Tokamak

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

The magnet is the key system for fusion reactor. The CRAFT and BEST device are proposed and established for fusion development in China. The magnet system within this project is engineered to operate at higher field than that of ITER. Initially, high Jc Nb3Sn and high-temperature superconducting materials were employed for different magnet, respectively. And also, the new structural steel (SS) materials with enhanced strength were proposed and developed for coil case and the CICC jacket to increase current density. The progress of magnet system is introduced here.

DTT Central Solenoid Winding Pack, Pre-compression system and HTS insert design

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The Central Solenoid (CS) for the “Divertor Tokamak Test” (DTT) facility is made of six stacked Nb3Sn modules, pancake wound, enclosed within a steel pre-compression structure to prevent gaps between the modules during operation. This structure can apply and maintain a preload of 40MN thanks to a wedge system.
An HTS insert is positioned inside the bore of the Nb3Sn modules in the aim to maximize performance and meet the goals of the DTT scientific program. The HTS insert also has its own pre-compression structure with a wedge system similar to that of the LTS pre-compression structure. This structure can apply and maintain a preload of 10MN.
To maintain the coils at the design temperature, a complex system of supercritical helium distribution pipes is required, the design of which proved particularly complex due to the limited space available.
This work presents the technical solutions identified to address the significant technical and engineering challenges involved in designing the DTT central solenoid magnet.

Progress in demountable joint testing for high-current HTS cables

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

High-Temperature Superconductors (HTS) have a planar tape form, and given the superconducting layer is coated with copper, current has to flow through a non-superconducting material to access the superconducting layer. In current leads and joints, it is beneficial to have a low-resistance connection between the superconducting layers of different HTS tapes, which reduces joule heating losses and facilitates continuous operation of high-current HTS cables.

For fusion research, demountable magnets are a sought-after technology. Being able to build a magnet in segments may reduce costs, facilitate the fabrication in-factory, so magnet segments can be more easily built, transported and assembled in the final site. A demountable joint for an HTS fusion magnet needs a fast and reliable assembly process, while ensuring that a low-resistance connection is achieved.

Two sub-size joint concepts for CORC-type and stack HTS cables are undergoing testing at ITEP in KIT, at 77 K and 20 K. With test currents in the kA-range, voltage data has been acquired at different tap positions along the cables and joint, to also grasp the current distribution, and help to estimate different resistive contributions, e.g. from interface and solder layers, pure copper or from Cu-Cu contacts. The purpose is to determine whether the joint concepts are suitable for the requirements of a large-scale demountable HTS fusion magnet (100 kA, 1 nΩ/joint, 20 K, 12T).

For the stack joint concept, tests have been performed at 20 K after the former results at 77 K, obtaining a joint resistance reduction. For the CORC-type joint, tests at 77 K have been performed with straight CORC samples, and the joint resistance determined with the voltage data. From the joint resistance results at 77 K, a full-size joint resistance extrapolation calculation at 20 K suggest, the stack joint may achieve nΩ-range while the CORC-type joint 10 nΩ-range.

Subsequent testing at 20 K at the in-house VATESTA cryostat facility, closer to the critical current of the samples, may allow to confirm whether current stably transfers to the inner HTS tape layers of the CORC-type samples, and a sufficiently low joint resistance is achieved. Additional to direct current feeding by a power supply, a transformer concept to induce the current in a short-circuited CORC-type sample may provide joint resistance data for current up to the 10-kA range.

Experimental studies on the insulation system for the DTT Central Solenoid Winding Pack

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The Central Solenoid (CS) coil for the “Divertor Tokamak Test” (DTT) facility is made of six stacked Nb3Sn modules, enclosed within a steel pre-compression structure. The inter-turn electrical insulation in the Nb3Sn modules is foreseen to be solely based on resin-impregnated glass, with the glass tape applied in-line during winding, before the Nb3Sn reaction heat treatment. This, together with the evidence of particularly high and cyclic mechanical loads expected on the electrical inter-turn insulation during coil operation, represents a serious concern. An experimental campaign has thus been considered fundamental, to validate the inter-turn insulation process, through the fabrication of 5 x 5 turns mock-ups, the application of a representative mechanical compression load in liquid nitrogen environment, up to 670 tons, the application of a inter-turn voltage of 1.5kV and the continuous measurement of the dielectric inter-turn resistance up to 50.000 loading cycles. Two mock-ups have been manufactured with representative CICCs: the former was characterized by an aspect ratio of 1.6 and a steel jacket thickness of 4.9 mm (High-Field Cable In Conduit Conductor); the latter had an aspect ratio of 2.0 and a steel jacket thickness of 2.0 mm (Low-Field CICC). This paper presents the experimental activities carried out on the two mock-ups, from test preparation to data analysis, and the results obtained.

Progress in the ITER Electron Cyclotron H&CD High Voltage Power Supply System: Architecture and Commissioning Progress

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

The Electron Cyclotron Heating and Current Drive (EC H&CD) system is a key heating system of ITER for plasma initiation, heating, and stability control, enabling high performance fusion operation. To power the 1 MW, 170 GHz gyrotrons that form the core of the EC H&CD system, a dedicated high voltage DC power supply (HVPS) architecture is used. Each HVPS set comprises a Main High Voltage Power Supply, two Body and Anode Power Supplies, and the associated auxiliary systems including gyrotron filament and magnetic power supply, dummy load, and medium voltage distribution, forming the complete one set of EC Power Supply for two Gyrotron.

The HVPS must deliver regulated DC power under stringent requirements for voltage accuracy, low ripple, fast dynamic response, and rapid fault energy suppression to ensure reliable gyrotron operation. The Pulse Step Modulation (PSM) topology has been selected as the enabling technology due to its demonstrated reliability, low stored energy, and proven suitability that for meeting Gyrotron demanding performance and protection specifications.

This paper presents an overview of the EC H&CD power supply configuration, describes the overview of topology, and reports on recent progress in HVPS installation, High Voltage safety aspects, and commissioning status. The results highlight the technical maturity of the EC HVPS system and its compliance for integrated commissioning and operation of EC system.

#13317

3D numerical modelling of electric arc faults in nuclear fusion facilities

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The structural and functional integrity of critical fusion reactor components, such as ITER superconducting magnets, requires a rigorous assessment of accidental scenario and their potential consequences. Whereas secondary phenomena, such as quench propagation or the effects of Loss-Of-Coolant Accident (LOCA) have been extensively studied, their triggering mechanism and the resulting direct damage to the conductors remain comparatively less explored.

In particular, high-energy Electric Arc Faults (EAFs) are a significant threat for cryogenic high current, high voltage devices, such as superconducting magnets. The highly localized energy deposition associated with an arc formation can rapidly degrade electrical insulation and perforate conductor jackets, thereby initiating a cascade of failure mechanisms.

In this work a comprehensive multiphysics model is developed to investigate the destructive arcing event that occurred at the CSM test facility in San Diego, USA. By exploring multiple plausible arc configurations, the model reproduces the arc's dynamic behavior and its motion under the influence of Lorentz forces. This approach enables the identification of the different arc evolution modes and clarifies the direction of arc propagation based on both the specific configuration considered and the initial ignition point.

The proposed methodology provides a general framework for assessing EAF scenario in critical fusion reactor components operating under extreme conditions, including high magnetic fields, high currents, and high heat fluxes.

#13332

Extending RMP-Coil Operational Range via Supercapacitor-Based Energy Storage in ASDEX Upgrade

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

Resonant magnetic perturbation (RMP) coils have proven effective in suppressing edge-localized modes (ELMs) in tokamaks such as ASDEX Upgrade. To investigate ELM suppression under advanced plasma shaping scenarios and enable runaway electron (RE) transport studies, magnetic field strengths must increase, requiring RMP coil currents up to three times the original design limit of 1300 A. This cannot be achieved with the existing 16-phase inverter system, BUSSARD, due to limitations in its grid connection. We therefore developed a short-term, high-power energy storage solution using 88 F supercapacitor modules to replace the DC link supply. Concurrently, the converter structure was modified to handle currents up to 4000 A. Initial tests with the supercapacitor array and modified converter demonstrated successful operation at 2800 A. Upon completion of further testing, this system will be scaled to all 16 converter phases, significantly increasing the operational range of RMP coils at ASDEX Upgrade. This will enable both advanced ELM suppression and RE transport studies, directly supporting the broader goals of ITER and future fusion reactors.

#13356

HTS model coils for quench protection of large-scale magnets

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

Fast and reliable quench detection is a key challenge in the development of high-temperature superconducting (HTS) magnets with large stored energy, in the megajoule range and above. Several temperature-based detection methods are under study at EPFL Swiss Plasma Center, including twisted-pair superconducting wires (SQD), shielded thermocouple chains (TCC) and fiber-optics sensing (FOS). All three methods require good thermal coupling to the main winding while remaining electrically insulated, thereby eliminating the need for high-voltage penetrations typically associated with voltage taps in fusion magnets. Their integration into the winding pack and their performance during quench events are studied on multiple samples of increasing size and stored energy.
Initial experimental results have been obtained on a double-pancake winding using a 50 m-long insulated LASSO conductor composed of 15 4 mm-wide ReBCO tapes. The sample was tested up to 0.1 MJ of stored energy at an operating current of 10 kA and initial temperatures between 10 K and 77 K. Robust performance was demonstrated with SQD wires, whose detection signal preceded the response of voltage taps. In contrast, specific manufacturing and integration issues are identified for TCC and FOS, requiring design modifications. These issues will be addressed in a revised version of the quench experiment currently under preparation.
In parallel, a larger sample with approximately 10 MJ of stored energy is being designed in collaboration with industrial partners, with the goal of launching cabling and winding contracts in 2026. This program is ultimately intended to reach 300 MJ of stored energy in order to validate safe quench management of high-current insulated ReBCO coils at a scale relevant for fusion applications.

Advanced high efficiency main high voltage power supply for the STEP Heating and Current Drive system

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

STEP (Spherical Tokamak for Energy Production) is an ambitious program with the goal of designing and building a prototype fusion energy plant (SPP) in West Burton (Nottinghamshire) that can demonstrate the delivery of net electricity to the electrical grid. Its ultimate goal is to pave the way for the commercial viability of fusion technology. To fulfil this target, the STEP programme must strive to minimise the SPP's parasitic loses wherever possible – initially targeting the systems that consume the most power. The Heating and Current Drive (HCD) Power Supplies, whose function is to convert AC grid electrical power to high voltage DC for the large number of high power gyrotrons, represent a significant power consumer. This high-power usage does not stem from poor efficiency on their part - typically they are ≥96% efficient - it is due to the large amount of power that passes through the HCD system.

STEP's aim is to achieve an overall heating and current drive system efficiency (plug to plasma) of over 60% (currently around 40%). This significant increase will reduce the electrical power draw and the quantity/ scale of the infrastructure required by the HCD system, saving tens of millions in operational and capital expenditure (in GPB). The axis of the system efficiency improvement is an advanced "multi-stage" gyrotron design, but the gain is also enabled by an advanced high voltage power supply.

The advanced high voltage power supply design will harness multiple developments in power converter technology, including high efficiency wide band gap semiconductor devices and modular converter topology. It will also benefit from the "economy of scale" effect of the whole HCD system, which reduces the controllability requirements of the power supply. In addition to achieving an efficiency of ≥98%, the power supply system must meet strict reliability requirements and be as efficient as possible with space – which is particularly constrained in the areas around the tokamak.

This work will justify the need for improving the HCD power supply efficiency, showing that small gains have disproportionately large cost and performance benefits, which will be critical to achieving commercially viable fusion technology.

#13380

Preliminary Design and Simulation of the HTS Poloidal Field Coil Power Supply for the SMART Tokamak

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The SMall Aspect Ratio Tokamak (SMART) is a Spherical Tokamak (ST) operated at the University of Seville to explore flexible plasma shaping and negative triangularity plasmas in an ST [1]. Confinement of the plasma is achieved through a suite of copper coil magnets. The required current profiles are delivered to the coils via a switching power supply [2]. It is planned to substitute one of SMART's in-vessel poloidal field coils with a High Temperature
Superconductor (HTS) coil. The need to preserve the superconductive properties of the coil during plasma discharges within the high-magnetic-field environment of SMART's vacuum vessel imposes unique constraints that motivate the development of a dedicated power supply.

In this contribution, the conceptual design of SMART's HTS coil power supply system is presented. Several state-of-the-art circuit topologies are evaluated against the requirements of the HTS coil. The effects of output current ripple, harmonics, and magnetic coupling with the rest of SMART's coils are analyzed. The procedure for safely extracting the stored energy from the HTS coil following a quench event is defined. DC power losses as well as the AC power losses induced in the HTS tape by varying magnetic fields [3] are evaluated for SMART's operating scenarios. MATLAB/Simulink simulations are carried out to validate the proposed power electronics.

The simulations demonstrate the technical feasibility of the conceptual design, establishing a solid baseline for the future development and integration of the HTS poloidal field coil power supply into SMART.

[1] S. J. Doyle et al. 2021, Fusion Engineering and Design, 171, 112706
[2] M. Agredano-Torres et al. 2021, Fusion Engineering and Design, 168, 112683
[3] Boyang Shen et al. 2020 Superconductor Science and Technology, 33, 033002

Mechanical resilience of the superconducting helical coils in 28 years of LHD operation

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

The performance of the superconducting helical coils of the Large Helical Device (LHD) over 28 years of operation is reviewed, focusing on mechanical resilience inferred from analysis of observed spike-voltage signals in the balance voltage between the pair of helical coils. The helical coils are the world's last-of-a-kind large-scale pool-cooled coils wound by aluminum-stabilized NbTi/Cu composite-type conductor and cooled by liquid helium (subcooled). The electrical insulation and cooling channels are ensured by GFRP spacers. After the completion of construction in 1998, intensive efforts have been made to reliably perform magnet system energizations, as more than 26 temporary normal transitions have been observed from the helical coils, initiated by wire motion. It was later found that the minimum propagation current was ~10% lower than the nominal operating condition, with a current of 13 kA at the magnetic field on the conductor of 7 T, as confirmed in an R&D coil experiment. Pulse-height analysis has been successfully applied to both balance-voltage and acoustic emission (AE) signals to investigate wire (conductor) motions and their changes over decades of operation. The spectrum of the voltage spike signals, measured through a low-pass filter at ~10 Hz, shows an exponential decrease in the voltage with two components during the charging phase but only one during the discharging phase. This observation still requires intensive investigation of its mechanism, and the preliminary results are discussed. The AE signals also respond to the movements of the Poloidal Field (PF) coils. We confirm a gradual decrease in the total intensity of the voltage spike signals and AE signals. This may suggest mechanical stabilization of the windings over the cycles.

Overview and Unique Features of COMPASS-U Tokamak Power Supply System

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

COMPASS Upgrade (COMPASS-U) is a new medium-sized (R = 0.9 m) tokamak currently under construction at the Institute of Plasma Physics in Prague [1], designed to operate at high magnetic field (Bt = 5 T) and high plasma current (Ip = 2 MA), utilizing cryogenically cooled copper coils. Its fully installed and commissioned Power Supply System (PSS), delivering power to the magnetic

coils and auxiliary heating systems, enables pulses with flat-top durations > 1 s at full operating parameters and > 6 s at Bt = 2.5 T, and incorporates several unique safety and efficiency features.

This contribution covers the complete development of the COMPASS-U PSS from design to commissioning. Initial analyses and simulations defined the minimum required parameters of 263 MW and 490 MJ needed to meet all physics requirements. Four custom-built pulse flywheel generators (2 × 108 MVA, 2 × 195 MJ; 2 × 50 MVA, 2 × 50 MJ) serve as a primary source of energy, with a combined starting power of 1.6 MW supplied from the public grid. The 10.4 kV high-voltage switchgear is equipped with pyrobreakers (surge current limiters) to protect the generators under short-circuit conditions. Two 85 MVA 3-winding transformers feed the thyristor-based toroidal field (TF) coils power converter with nominal parameters 200 kA, 780 VDC. Two 53 MVA 3-winding transformers feed a single transistor-based power converter for all poloidal field (PF) and central solenoid (CS) coils. This unique design integrates 12 individual converters (6 × 25 kA, 2 × 30 kA, 4 × 50 kA; 950 VDC) with more than 1000 IGBT transistors into a single power supply with a common distributed capacitor bank and a total apparent power exceeding 390 MVA. This configuration enables energy exchange between individual converters, improving overall efficiency while reducing space and cost requirements. Both TF and PF/CS coils power supplies are protected by crowbar circuits, with the PF/CS power supply incorporating an innovative design feature enabling safe discharge at voltage levels below the Paschen minimum in the event of vacuum loss in the cryostat. The PSS control system achieves a response time < 250 μs to requirements from the Tokamak Control System. Performance of the whole COMPASS-U PSS was verified using the original COMPASS tokamak as a dummy load during acceptance tests to successfully complete the commissioning.

[1] P. Vondracek et al., FED 169 (2021)

#13453

Designing, winding, and testing three-dimensional HTS coils for stellarators

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

Stellarators achieve steady-state plasma confinement using fully external magnetic fields, thereby avoiding current-driven disruptions. Since fusion power scales approximately with the fourth power of magnetic field strength, high-temperature superconducting (HTS) technology offers a compelling route toward higher performance or more compact stellarator devices. The application of Rare Earth–Barium–Copper Oxide (REBCO) tapes to three-dimensional stellarator coils introduces significant electromagnetic and mechanical challenges, including strain sensitivity, anisotropic critical current behavior, and complex force distributions.

To address these issues, we developed a dedicated coil design code, FOCUS-HTS, which incorporates tape strain, electromagnetic forces, and critical current constraints into the optimization framework. In parallel, we established an automated robotic winding system for three-dimensional HTS coils to ensure precise control of winding angles and tape placement. Using this integrated design–manufacturing approach, we successfully fabricated a prototype 3D HTS coil. Preliminary test results demonstrating its performance will be presented.

#13564

Thermal Dilatations-Based Engineering Solutions for High-Field Cryogenic TF Coils in the COMPASS-U Tokamak

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The COMPASS-U tokamak utilizes cryogenically cooled (80 K) copper Toroidal Field (TF) coils to achieve a high magnetic field of 5 T for > 1 s flattop. Differential thermal contraction of structural and coil materials introduces significant structural challenges, which can lead to loss of mechanical preloads leading to structural disintegrity or increased electrical resistance at joints. The current design not only mitigates these effects but also strategically leverages differential thermal contraction to enhance mechanical preloads. To ensure reliable operation of the bolted joint, athermalization with negative coefficient of thermal expansion (CTE) washers made of ALLVAR material is used. These washers expand upon cooling to 80 K, compensating for the differential contraction of the copper and steel bolts. This solution maintains a constant preload, resulting in a measured joint resistance of only 0.07 μΩ and surviving vertical force of 2.5 MN. Additionally, the design implements a passive radial preload by exploiting the CTE mismatch between the copper coil in the stainless-steel support structure and the ceramic rod insert. Upon cooling, the rod housed in the support structure provides a robust radial compression that stabilizes the coils against electromagnetic loads. These engineering solutions have been validated through finite element analysis and some by full-scale mockup testing, confirming that the design is ready for the procurement phase. The implementation of negative CTE materials and passive thermal preloading provides a reliable framework for the next generation of high-field fusion devices.

#13612

Transient Propagation and System-Level Impact of Local Breakdown Events in MV-Class Acceleration Grid DC Power Supply Systems

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

In megavolt-class acceleration grid DC power supply systems for neutral beam injectors (NBI), local breakdown events—such as internal grid flashover, high-voltage platform-to-ground breakdown, or DC transmission line faults—can generate wide-band transient disturbances that propagate throughout the distributed parameter network. Due to the large physical scale and strong electromagnetic coupling of the system, the transient response strongly depends on the breakdown location and may result in significant electrical stress at electrically remote critical nodes.

This work investigates the system-level transient propagation triggered by a single breakdown location. A simulation framework is developed by combining a simplified arc equivalent circuit model with a multi-conductor distributed parameter network. The model incorporates internal parasitic capacitances and inductances of key components, long DC cable characteristics, and electromagnetic coupling between major subsystems.

The influence of local breakdown on critical nodes—including the power supply output terminal, transformer winding terminals on the 1 MV high-voltage platform, and the acceleration grid—is systematically analyzed. Particular attention is given to transient overvoltage amplification, current redistribution, and energy reflection phenomena along the transmission path.

The results demonstrate that wide-band transient waves generated at the breakdown location may lead to non-intuitive stress concentration at electrically remote components. The study provides a quantitative basis for transient severity assessment and coordinated protection design in MV-class NBI power systems relevant to ITER-class fusion facilities.

Electromagnetic Launch Experiment of the enhanced EMPI on J-TEXT Tokamak

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

Major plasma disruption stands as the foremost threat to ITER's safe operation, and impurity injection is the primary measure to mitigate the disruptions. However, massive gas injection (MGI) and shattered pellet injection (SPI) are constrained by gas sonic velocity, resulting in relatively low injection velocities that fail to meet the operational requirements of large-parameter tokamaks such as ITER.

To address this limitation, the J-TEXT team has developed an electromagnetic pellet injector (EMPI) based on the principle of electromagnetic railguns. By delivering a kiloampere-class current to the rails and armature via a pulsed power supply, the armature is accelerated to high velocities under electromagnetic forces, enabling rapid and effective impurity injection.

In this work, a Simulink model for armature-rail velocity analysis and a COMSOL multi-physics field model are established based on the enhanced EMPI. Simulations demonstrate that the enhanced EMPI is capable of accelerating the 9.9 g armature-pellet assembly to over 1000 m/s, while enabling low-speed armature recovery. The EMPI system has been integrated into the J-TEXT tokamak for disruption mitigation experiments. Multiple tests confirm that the pellet injection velocity of the EMPI exceeds the speed of sound, far surpassing that of conventional disruption mitigation systems, which allows impurities to be deposited deeper into the plasma. This work provides an advanced scheme for efficient impurity injection, contributing to the mitigation of plasma disruptions in tokamaks.

#13628

Overview of the french national SF-Cond HTS research project and first activities

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The french national program SupraFusion on HTS and fusion was officially launched in 2025 and will span 6 over years. It is composed of 5 research projects on HTS tapes (SF-Tapes), HTS conductors (SF-Cond), HTS quench detection and protection (SF-Protection), HTS prototype coil (SF-Demo) and the study of HTS magnets-based fusion machines (SF-Plant).
The SF-Cond project, supervised by the CEA-IRFM magnet group, is focused on the study and development of technological bricks around HTS-conductors, going from tape-scale to multi-tape structures carrying current in parallel. The work has been organized in 3 activities: Conductors, superconducting joints and cooling (and associated test facilities).
We will report on the initiation of the activities and progress made, starting with the extensive HTS conductors review that was conducted to define clearly the state of the art in terms of DC performance, AC performance, joints architectures and cooling strategies. In particular, specific analyses of the evolution of key design parameters (engineering current density, amount of Rebco tapes used, critical test conditions) will be illustrated.
We will then detail the first modelling results for multi-staged conductors, emphacizing the importance of good current distribution and adequate quench modelling including contribution of direct or indirect cooling.
Finally we will explain the development and/or upgrades of our two main test facilities, with our first 10kA, 77K self-field tests in CRISTAL and the design of the 77K AC losses Josefa upgrade. The design of our « Helically Wound Rebco Cables » cabling machine will be presented.

#13654

Design of the VNS Toroidal Field coils in Low Temperature Superconductors

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

EUROFusion and its partners are currently focused on the design of a VNS, Volumetric Neutron Source, designed as a compact tokamak that will act as a qualification testbed for in-vessel fusion components, in particular the breeding blanket. The magnetic system relies on 12 Toroidal Field (TF) coils, 6 outer Poloidal Field (PF) coils and a Central Solenoid (CS) stack made of 6 modules. In this work, the authors present the first draft of the design of the TF coils made of Low Temperature Superconductors, in particular based on Nb3Sn Cable-In-Conduit Conductor technology. The main features of this design is presented along with the outcomes of thermal-hydraulic and structural analyses. Finally, a comparison of the more standard approach to the design, Wind&React, with respect to a more innovative React&Wind technique, is also included, discussing main advantages/disadvantages and R&D needs.

Design and Technical Requirements of the Thermal Shield System for the DTT Facility

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The Divertor Tokamak Test (DTT) facility, currently under construction at ENEA Frascati, includes a Thermal Shield System (THS) designed to protect the superconducting magnets from radiative heat loads. The THS comprises the Vacuum Vessel Thermal Shield (VVTS), Port Thermal Shield (PTS), and Cryostat Thermal Shield (CTS), featuring modular helium-cooled panels tailored to their complex geometries. All components are manufactured from AISI 316L stainless steel with restricted content of high-activation impurities.

The VVTS and PTS adopt a double-shell design, consisting of a 2 mm actively cooled bottom plate facing the vacuum vessel/ports and a 2 mm passively cooled top plate facing the magnets, whereas the CTS utilizes a single 3 mm cooled shell equipped with Multi-Layer Insulation (MLI) on the cryostat side.

The THS is anchored to warm components (Vacuum Vessel, Ports, and Cryostat) via gravity supports designed for plasma operation and baking phases (up to 300 K). The supporting system integrates G-10 epoxy components for thermo-electrical insulation and employs slotted holes on the panels to compensate for thermal contraction, securing the assembly against electromagnetic and thermal loads.

The cooling system utilizes fully redundant, continuous seamless pipes (¼" STD) intermittently welded to the panels, operating with gaseous helium at 16 bar and 80 K (inlet conditions). The VVTS architecture follows a 40° toroidal periodicity (9 parallel paths inboard/outboard, shared with Port 5 PTS), while PTS ports 1-4 have dedicated parallel paths and the CTS uses 120° periodicity; all configurations are designed to maximize surface coverage.

Key design aspects address toroidal sectors of the VVTS, redundant parallel cooling paths, surface roughness ≤0.2 μm (VVTS/PTS)/0.8 μm (CTS). A full-scale VVTS prototype will validate welding, distortion management, surface processes, and supports under operational loads.

Factory tests will cover mechanical integrity (gravity supports, pipe omegas), inspections (visual, welds, 3D dimensions), magnetic permeability/roughness/emissivity, pressure cycling, helium leaks, flow verification, and instrumentation (temperature/strain/displacement sensors).

Factory Acceptance Tests of the Power Supply System for the DTT Non-Axisymmetric Coils

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The Divertor Tokamak Test (DTT) facility, currently under construction at ENEA Frascati Research Center in Italy, is a magnetic confinement experiment designed to investigate different divertor configurations for plasma power exhaust management [1]. DTT features several coil systems to control a plasma current of up to 5.5 MA with a magnetic field of 6 T and additional heating power of approximately 45 MW coupled to the plasma [2].
Among the in-vessel coils that will be installed in the machine, the Non-Axisymmetric (NAS) coils play a particularly important role, as they are required to locally correct magnetic field errors and mitigate disruptive plasma edge instabilities (Edge Localized Modes, ELMs) [3].
This work presents the characteristics of the NAS power supply system, commissioned by ENEA to the industrial supplier Equipaggiamenti Elettronici Industriali (EEI). A preliminary study was conducted to optimize the number, layout, currents, turns and energy requirements of the DTT NAS coils [3, 4]. The NAS coils are organized in three rows of nine elements each. The power supply system consists of 27 fully independent power supply units, each capable of delivering 2.5 kA and 400 V according to the DTT facility's design requirements. Each unit is implemented using 5 interleaved IGBT-based H-bridges.
Error fields can be corrected using NAS DC currents, while ELMs can be mitigated by NAS AC currents. To ensure adequate margin, the power supplies can generate full currents up to 10 Hz. In principle, 1500 A are reserved for the DC-component and the remainder for the AC-component. Since ELMs are expected to be mitigated using phase-shifted AC waveforms, each of the three rows of the system is connected to a common DC-link to minimize power exchange with the grid.
The entire system successfully passed all functional tests, including verification of the correct communication between the NAS power supply system and the DTT COntrol, Data Acquisition and Safety system (CODAS). Full-power operational tests were performed using an inductive-resistive dummy load that reproduced the expected coil load with and without the connection cables.
The procurement was delivered to ENEA in December 2025.

References

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Operation results of JT-60SA cryogenic system during plasma operation

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

JT-60SA is a tokamak magnetic confinement device for plasma fusion experiment developed in Japan. This is one of a joint international research and development project involving Japan and Europe. The magnet system with mass of 750 tons is installed to confine plasma. To cool down magnets, the Helium Refrigeration System, which has 9 kW of cooling power at 4 K, has been developed in 2016, and the assembly of JT-60SA was completed in March 2020. The first operation was conducted from October 2020 to March 2021, and the second operation was conducted from May 2023 to December in the same year.
The refrigeration system supplies forced flow of super critical helium to the magnets by using 2 cold circulators. The nominal heat load coming from magnets while TF magnet energization is 3 kW, but transitional pulsed heat will be applied on magnets and magnet structures in case of plasma operation or magnet discharge event. The major feature of the refrigeration system is the use of a 7 m3 buffer tank to mitigate the pulsed heat load generated during plasma operation. However, this control logic has not been tested yet in JT-60SA.
In this presentation, the operational result of the JT-60SA refrigeration system and the result of the pulsed heat mitigation control will be described.
JT-60SA was jointly constructed and is jointly funded and exploited under the Broader Approach Agreement between Japan and EURATOM.

#13769

Active emulation of electrical loads for testing fusion power supplies

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

Nuclear fusion systems are normally first-of-a-kind or bespoke developments with more and more challenging performances. In particular, the power supply currents and voltages can present unconventional behaviors exceeding the limits of available test facilities, making their qualification, maintenance and safety validation challenging.

The emulation of actual electrical loads by active circuits could overcome these limitations and offer a unique and flexible solution for different tests. Especially, it can cover situations that cannot be reproduced by a simple passive load with a constant impedance.

The main application was identified in the tokamak in-vessel coils. A study was carried out on their power supplies under delivery to the DTT facility. The expected operations of these power supplies involve arbitrary waveforms extending over a wide and variable frequency band having variable equivalent inductances and resistances. Electromagnetic simulations showed even an order of magnitude of difference between low and high frequency impedances, making a test at a specific frequency and not including harmonics not meaningful for the performance qualification, which may lead to failures in real cases.

The first adopted solution implemented a combination of passive resistors and inductors (trying to reuse available devices).
A second new approach adopted for active load emulation is based on H-bridges controlled by specific real-time algorithms. The developed hardware and software architecture is modular and can be extended to any current, voltage and frequency band, so that it can mimic a variety of complex scenarios as the real load. For example, the same hardware can emulate the DTT vertical stabilization, radial control and divertor equivalent loads. These cases are particularly interesting as they are characterized by ramps containing several harmonics. The possible physical dimensions, benefits and drawbacks of both the passive and active solutions are considered and evaluated by means of simulations and prototypes, as well as a system simplification that can be obtained by a hybrid approach, where power electronic converters are used to adjust the behavior of some lumped coils. Finally, the benefit of recovery of the energy used for tests is also analyzed.

A versatile load emulator for high powers can be useful for the emulation of coils in complex structure, but also in other fusion electrical loads, such as the gyrotron electrodes (resistive/capacitive loads) and in other fields of research or industry.

Analysis of Operating Characteristics of Switching Mode Power Supplies in Stray Magnetic Field

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

Stray magnetic fields (SMFs) around the ITER tokamak present a reliability challenge to nearby electrical and electronic devices. Switching mode power supplies (SMPS), serving as the power source for the auxiliary systems, are critical to the stable operation of ITER tokamak. Since the SMPS contain magnetic components, they are inherently sensitive to SMF. ITER Organization has conducted tests on the immunity of SMPS against SMF, and the results indicate that the SMPS are highly susceptible to failure in SMF and the influence exhibits distinct directionality. However, the detailed failure process of SMPS under SMF remains unanalyzed. Based on the finite element analysis and circuit simulations, the operating characteristics of several SMPS topologies under SMF were analyzed in this paper. According to the simulation results, the detailed influence process of SMF on SMPS was clarified, and the differences in sensitivity to SMF among several SMPS topologies were analyzed and compared. This study provides insights for designing more robust SMPS for magnetic confinement fusion engineering.

Final design of DTT CS and PF power supplies with unprecedented supercapacitor energy storage

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

The DTT Central Solenoid (CS) and Poloidal Field (PF) coils demand high-power pulses exceeding hundreds of MW on a millisecond scale with peak currents that can exceed 30 kA. Their power supplies (PSs) must follow such pulses while ensuring grid compatibility. Conventional flywheel-based or direct grid-connected systems can face limitations in efficiency, scalability, and response time when dealing with such extreme transient loads and operations.

This paper presents the final design of the innovative CS and PF PS architecture, which employs exceptionally large banks of supercapacitors (SCs) as the primary energy source.

The banks are powered by Active Front-End (AFE) converters to enable bidirectional power flow and energy recovery and to improve overall efficiencies. Grid interaction is thus minimized and actively managed, as SC banks absorb peak loads while drawing only baseline charging currents from the utility grid. During the scenarios, the combined effect of AFEs and SCs mitigates reactive power, harmonics, voltage sags, and frequency deviations that pose essential challenges for the integration of DTT with the national grid.

The effectiveness of the approach is not limited to the DTT case, because such issues are inherent to any magnetic-confinement fusion system and especially to future power plants. The proposed solutions address typical fusion PS challenges and are totally scalable.

For the PF PSs, the DC-links based on SCs are shared by at least two coils to minimize the installed volume, benefiting from the balancing of power flows among the loads during the scenario. Such an innovative use reduces the footprint of the DC storage, together with capital and operational costs, without affecting the required performance or the reliability and stability standards.

The use of voltage-source converters to control the coils scenario can lead to more accurate control with faster dynamics with respect to traditional thyristor-based converters. Moreover, the ripple is lower and is shifted to higher frequencies, resulting in reduced interference with diagnostics.

The design of the CS and PF PS achieves an unprecedented scale, with more than 1.5 GJ of installed storage capacity, comprising thousands of SC modules, far exceeding current industrial implementations in terms of both energy and power capability. These features are expected to be tested also as a grid support in conjunction with the superconducting magnetic energy storage (SMES) available in the coils.

Keywords: Supercapacitors, DTT power supplies, Central Solenoid, Poloidal field, DC-link sharing, Active Front-End (AFE).

Rheological characterization of solid hydrogen extrusion for tokamak pellet injection

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The injection of solid hydrogen isotope pellets into tokamaks is a key point for fuelling and controlling edge localized modes of the plasma in fusion reactor. Large tokamaks, such as JT-60SA, ask for an extrusion volume flow rate of up to 350 mm3/s. To meet these requirements, an experimental testbench has been developed in the DSBT at the CEA Grenoble [1].
Unlike screw extruders [2] [3], this technology works without any moving parts. Gaseous hydrogen is condensed in a cell cooled below its triple point temperature. Once the cell is filled with solid, pressure, acting like a piston is applied upstream forcing the flow through a cylindrical die.

Extrusion instabilities were observed during high velocity extrusion measurements, limiting the flow rate to 170 mm3/s. In order to enable the design of future sources of pellets, current work aims at understanding solid hydrogen flow mechanisms.
The first objective is to determine the viscosity of solid hydrogen using the actual extrusion system as a capillary rheometer. In a second time we will study the source of instabilities.
This paper presents the methodology for determining viscosity by calculating the shear stress and shear rate from experimental measurements of flow velocity and pressure drop. The preliminary results of this campaign provide insight about the solid hydrogen's behaviours in the die.

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#13832

Detailed Magnet Modeling within the DTT Magnetic System

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

Divertor Tokamak Test facility (DTT) is a major European fusion energy research project currently under construction at the ENEA Research Center in Frascati. The facility is designed to investigate viable solutions for managing the extreme thermal and particle fluxes impinging on the divertor region of future fusion power plants.
The DTT magnetic system comprises 18 Toroidal Field Coils (TFC), 6 Poloidal Field Coils (PFC), and a Central Solenoid (CS) formed by seven modules: six identical and independently powered outer modules manufactured with Low Temperature Superconductors (LTS), and one inner module based on High Temperature Superconductors (HTS). All magnets operate at cryogenic temperature (4.5 K), where they are subjected to significant electromagnetic forces combined with high pre-compression levels and cyclic loading conditions up to 25,000 operating cycles.
Given the combined effects of cryogenic temperatures, strong magnetic loads, assembly preloads, and repeated operational cycles, the structural response of the magnet system represents a key design challenge. To accurately capture both global and local mechanical behavior, structural analyses traditionally rely on homogenized models that ensure computational efficiency at the system scale. However, such approaches may limit the accuracy of local stress and strain predictions within the magnet components.
In this context, the present work introduces a detailed strand-by-strand magnet modeling strategy developed in parallel with the global homogenized representation. The two models coexist within a unified multiscale framework: the homogenized model supports global structural assessments, while the detailed model enables high-fidelity local analyses without the need for load interpolation between scales. The proposed methodology enhances predictive capability, improves consistency between scales, and supports the structural design process of the DTT magnets under realistic operating conditions.

#13849

Engineering Feasibility and Structural Assessment of the ASPECT Tokamak with LTS Magnets in the DYT Framework

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

While the Design Your Tokamak (DYT) integrated software framework provides a physics-driven environment for system-level optimization, the technical realization of the Advanced Shaping Pedestal and Edge Control Tokamak (ASPECT)—a proposed successor to ASDEX Upgrade—ultimately depends on the engineering feasibility of its radial build.

This study presents a comprehensive engineering analysis of ASPECT, focusing on the technical challenges associated with employing low-temperature superconductors (LTS) for the magnet system. The design methodology prioritizes verification of a technically realizable radial build by enforcing rigorous mechanical and spatial constraints. A dedicated module in DYT is used to define shielding requirements, accounting for the thicknesses of the first wall, vacuum vessel, thermal shield, and breeding blanket, as well as critical inter-component gaps such as the separatrix-to-wall distance and the spacing between the Toroidal Field (TF) and the Central Solenoid (CS).

Crucial to the machine's inductive capability is the CS sizing module, which determines the solenoid dimensions from the magnetic flux required for plasma current ramp-up and flat-top phases, while ensuring operation within the maximum allowable magnetic flux density.

For the TF coils, the geometry is first optimized to a bending-free D-shape such that in-plane loads are carried primarily by membrane tension, thereby minimizing bending moments in the winding pack (WP). To finalize the TF-coil engineering design, an integrated quench simulation is performed for the cable-in-conduit conductor (CICC). Solving the heat-balance equation yields the required copper fraction and ensures that the peak temperature remains below $T_{max} \leq 250$ K in a worst-case quench scenario. Final structural verification of the TF-coil system is then carried out using a fully automated 2D finite element method (FEM) simulation of the critical inboard TF-coil leg. The model uses high-fidelity discretization, in which the WP is resolved into individual components such as the CICC, G10 insulation, and the TF-coil jacket, enabling a detailed assessment of local stress concentrations.

Physics simulations optimized the initial ASPECT design point at $R_0 = 2.0$ m to match the EU-DEMO dimensionless parameters ρ^*, ν^*, and β_N. However, this engineering study indicates that this design point is challenging for LTS magnets, owing to limited CS flux capability and constrained TF-coil winding-pack space. Meeting the physics targets within allowable engineering limits therefore require increasing the major radius to $R_0 = 2.2$ m.

#13858

From Design to Final Installation Phase of ITER Toroidal Field Gravity Supports

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The ITER superconducting magnet system comprises 18 Toroidal Field (TF) coils, one Central Solenoid (CS), six Poloidal Field (PF) coils, and 18 Correction Coils (CC). These superconducting coils, with a total mass exceeding 10,000 tons, are integrated into a single system to confine and shape plasma and ultimately bolted to the Cryostat Base (CB) through robust yet flexible structures known as TF Gravity Supports.
All magnet deadweight, thermal loads, and the significant electromagnetic loads generated during operation are transferred through the 18 TF Gravity Supports, which are installed on the CB and connected to the TF coils. The successful design, fabrication, assembly, and installation of these components are critical to the performance and reliability of the ITER magnet system.
This paper presents the complete lifecycle of the TF Gravity Supports, including design, fabrication, supplier-side assembly and Testing, and final installation at the ITER site. Lessons learned throughout this process are also discussed, providing valuable feedback for large-scale superconducting magnet support structures in future fusion projects or any on-going Compact Fusion Projects.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

#13869

Electromagnetic and Structural Analysis of the Central Solenoid for the Divertor Tokamak Test Facility

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

DTT is a high-performance Italian research facility focused on the scientific and technological aspects of power and particle exhaust. By testing advanced divertor configurations in in reactor relevant plasma conditions, it aims to provide crucial solutions for the viability of future fusion energy.
The DTT magnetic system integrates 18 TF and 6 PF coils with a Central Solenoid composed of six independent outer modules and a high-temperature superconductor (HTS) inner one.
The CS generates the core magnetic flux essential for both the initiation and the dynamic stabilization of the plasma.
This work focuses on the electromagnetic and structural analysis of the Nb3Sn CS and of the HTS insert, intended to enhance the magnetic flux generation capability of the solenoid, to meet the stringent physics requirements.
The proposed study involves mechanical analyses to evaluate the structural integrity of the conductor steel jacket, of the electrical insulation, and of the pre-compression and support structures, under the combined effects of cooling down, pre-loading conditions, and Lorentz forces. Finite element models (FEM) are employed to simulate the coil and the supporting structures behavior.
Finally, thermal-hydraulic analyses were carried out to investigate the optimal layout and operating conditions for the cooling system of the structural components, during both the cooldown phase and during the operational cycles of the Central Solenoid, including the induced eddy currents effect.

#13874

Impact of hydraulic boundary conditions on CS operation

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

In the framework of EU-DEMO design activities, CEA proposes a hybrid Central Solenoid (CS) design featuring an inner High Temperature Superconductor (HTS) insert surrounded by a winding pack of Low Temperature Superconductor (LTS) conductors. The presence of the inner HTS layers prevents cooling LTS conductors from inner high field side as usually done, and leads to setting a specific hydraulic path with helium inlets and outlets on the external side of the LTS winding pack, with two single pancakes and 15 double pancakes per CS module.

The present study focuses on the impact of hydraulic boundary conditions, and more specifically the pressure whose effect is less predictable than that of temperature, on the operation of the CS LTS side in burn conditions. Considering values of inlet (Pin) and outlet (Pout) pressures of 6 and 4 bar respectively in double pancake conductors (outlet pressure equal to 5 bar in single pancake conductors), a reference case is simulated with the THEA code and provides the temperature margin distribution in all conductors of one CS module.

Due to the pulsed operation, the analysis of CS magnet thermohydraulical behaviour is less straightforward than for a non pulsed magnet such as the Toroidal Field system. For the considered scenario, the minimal temperature margin is reached at end of dwell, after current ramp up from - Imax (Imax for CS maximum current) to + Imax, and the maximum potential gain on temperature margin, namely the increase of helium temperature between inlet and the critical location, is estimated.

Considering the properties of supercritical helium in the area of interest, i.e. pressures from slightly above supercritical value up to about 8 bar, the gain on temperature margin when reducing Pin/Pout is assessed, as well as the margin decrease when increasing Pin/Pout. The impact of higher pressure drop and thus of higher mass flow along the conductor is also checked. Particular attention is also paid to fast current variation phases of the scenario, typically the plasma breakdown, which can become critical for the temperature margin and for which transient thermohydraulical effects may have more impact than pressure at boundaries.

Analysis of the Characteristics of a High-Speed Solenoid Valve under Stray Magnetic Fields

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

As a key fast-response electromagnetic actuator, the high-speed solenoid valve is widely used in fusion devices, especially in vacuum systems, pulsed gas injection systems, and other control units requiring rapid response and stable operation. However, owing to its electromagnetic nature, the solenoid valve is highly sensitive to external magnetic fields. Future large-scale fusion devices such as ITER involve extremely strong stray magnetic fields generated by high-current magnet systems, under which the solenoid valve may suffer from performance degradation, malfunction, or even complete failure, thereby seriously affecting the reliability of related equipment and control systems. In this work, the characteristics of a high-speed solenoid valve under stray magnetic fields are investigated in this paper. A fully coupled dynamic model is established by considering the interactions among the electric circuit, magnetic field, electromagnetic force, and armature motion. Based on the proposed model, the influences of stray magnetic field intensity and direction on electromagnetic force, armature displacement, and dynamic response are analyzed. The results show that the external stray magnetic field significantly changes the magnetic flux distribution in the core and air-gap regions, leading to variations in the force generation process. As the stray magnetic field increases, the valve may exhibit delayed actuation, reduced force margin, and degraded dynamic stability. This work clarifies the interference mechanism of stray magnetic fields on high-speed solenoid valves and provides useful guidance for the performance evaluation and anti-interference design of electromagnetic actuators intended for strong magnetic environments in fusion devices.

Preliminary Design of the CS and PF Power Supplies for the TRUST Tokamak

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

TRUST (Tuscia Research University Small Tokamak) is a small-scale tokamak designed for academic use, currently underway at the University of Tuscia in Viterbo (Italy). The main geometrical parameters of TRUST are a major radius of 0.3 m and an aspect ratio of 2.5. The design includes a set of six poloidal field (PF) coils and six modules for the central solenoid (CS). Considering the short duration of the plasma scenario since the end of the flat-top phase occurs at 0.381 s, the current peaks to obtain the plasma equilibria are particularly demanding, especially for the CS modules, which are in the order of 1 kA for each coil. With these parameters, the required power can reach several hundred kilowatts. For these reasons, TRUST implements a challenging power supply system based on the use of supercapacitors (SCs) as energy storage devices. Due to their ability to deliver particularly high-power peaks in short time intervals, supercapacitors are suitable for these applications, helping to eliminate the peak power required from the grid. This work presents the first sizing of the supercapacitor stage of the TRUST power supply system. The sizing is carried out in two different steps: the first consists of analytically estimating the capacity required for the coils by evaluating the energy demands of the whole scenario and the losses due to the presence of the equivalent series resistance of supercapacitors; the second step consists of validating the entire SC design by simulating the power supply system through the PLECS platform. Once the capacity value has been determined, the number of modules in series and parallel required for the bench is assessed, taking into account not only the energy scenarios but also the maximum allowable peak current of the commercial supercapacitors. Finally, the benefits of adopting a shared supercapacitor bank system among the various coils will be discussed, along with experimental results from a TRUST-like prototype.

Keywords: TRUST power supplies, Supercapacitors, Central solenoid, poloidal field coils.

#13901

Design and Validation of the Upgraded Power Supply for the SMART Tokamak

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The SMall Aspect Ratio Tokamak (SMART) is a spherical tokamak (ST) that offers unique capabilities for studying the potential of negative triangularity in STs. It has been designed, constructed, and is currently being operated by the Plasma Science Fusion Technology Laboratory (PSFT) at the University of Seville [1]. SMART has a total of 21 coils: central solenoid, toroidal field (12 coils), 3 pairs of poloidal field (PF) coils, and 2 independent PF coils, organized into 7 independent circuits and driven by modular power supplies (PS). The construction of PS has been completed for first experimental campaign with switching converter technology based on IGBTs and supercapacitors [2].

This study presents the design and validation process carried out to update the PS for future SMART operational scenarios, as a continuation of the previous work described in [3]. The energy storage systems have been designed using supercapacitors, and the power converter topology, including bus bars and protection systems, has been developed. The safety requirements and the design guide workflow to ensure a structured and consistent implementation will also be presented. The first prototype was developed to validate the proposed control algorithm in the laboratory and to evaluate its performance under scaled nominal operating conditions, as well as fault scenarios.

The experimental results obtained from the prototype show strong agreement with the simulation results, demonstrating a high correlation between the numerical predictions and the experimental measurements. These findings confirm the accuracy of the developed model and further validate the robustness and reliability of the proposed control strategy. The results and conclusions are also presented as part of the roadmap for the next development stage, aimed at upgrading the power supply to its nominal operating values.

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[2] M. Agredano-Torres et al. 2021, Fusion Engineering and Design, 168, 112683
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A highly parallel current source for the toroidal field coil on the QUEST spherical tokamak

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

Fundamental electron cyclotron heating and current-drive (ECH/CD) using 28 GHz radio frequency are planned in the QUEST spherical tokamak. A toroidal magnetic field (TF) of 1 T in the vacuum vessel is a basic requirement to realize such fundamental ECH/CD experiments; thus, a new current source with many power supply modules in parallel has been developed. A single module consists of a lithium-ion capacitor (LIC) and a DC-DC converter. The capacitance of an LIC is 48 F, and the maximum charging voltage is 180 V. 800 A is the maximum current output of the single module. The resistance and inductance of the TF coil are ~0.80 mΩ and ~0.76 mH, respectively. A target of maximum current output is 100 kA in the case that all 125 modules are connected in parallel, where all modules are turned on/off simultaneously. The sum of currents through the central stack of the spherical tokamak is 1.6 MA-turns at an output of 100 kA. The total capacitance of all 125 capacitors in parallel is 6,000 F. The energy of the capacitor bank reaches 97.2 MJ with the charging voltage of 180 V.

The constructed current source comprises of seven blocks. In a single block, 18 sets of LICs and DC-DC converters (17 at the seventh block) are installed. Additionally, two AC-DC converter systems, whose maximum current is 50 A at 180 V, are also stored to charge LICs.

The highly parallel current source is installed on the QUEST TF coil, and the tested output is up to 70 kA using 108 LICs. In the present QUEST operation, the limit of the current is 60 kA, where the pulse width is longer than 2 seconds. The current is ramped up in 1 second and flattened at the target current. In the decay phase, it decreases naturally via parallel flyback diodes. The 1 % overshoot from the target current is observed through measurements using a Rogowski coil, but the following oscillation is suppressed gradually. The new source has been applied to a recent ECH/CD experiment, and it keeps working stably. The results of the test in QUEST indicate that more modules can be installed in parallel if other devices require higher current.

#13933

New developments of prototypes design of de-sublimation cold cell and associated cryostats for ITER disruption mitigation systems

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The development of new high-energy fusion reactors is facing a number of challenges. Within the development of the largest tokamak reactor (i.e., the ITER tokamak), plasma disruption is at risk for tokamak's integrity, as it could damage the main vacuum vessel or the mechanical structure of the reactor. To mitigate this risk, the ITER Organization (IO) developed a disruption mitigation strategy based on the injection of large shattered cryogenic pellets. This strategy intends to define a Disruption Mitigation System (DMS). This system is based on the desublimation of hydrogen, neon or mixture of these gases to grow a large Ø28.5 x 57 mm cylindrical pellet. This pellet is then shot at high speed into a shattering box from which, plume of fragments reaches the plasma. In order to attenuate disruptions anywhere within the main vacuum vessel, pellet injectors are positioned around the reactor, cf. (Giors 2025). The constraints and main characteristics of this system have been discussed for years and proofs of concept were developed through different collaborations between IO, CEA, ORNL and HUN-REN, (Manzagol 2024), (Boujet 2025), (Baylor 2023) and (Zoletnik 2024).

This paper intends to present the latest developments made by the CEA to integrate, industrialize, and increase the reliability of pellet injectors considering ITER constraints. Within this Cryogenics Prototypes framework contract, the CEA has developed a compact cold cell assembly associated with a multi-cell cryostat. These constraints bring new challenges to the design of such a complex system:

• The thermohydraulic management and stability of the flow rate within all cold cells,
• The thermal regulation and stability of the injected gas for desublimation,
• The downscaling and integration of proven designs within a very constrained geometrical environment.

These different objectives should allow the production of high-quality pellets with a high level of repeatability under IO time and geometrical integration constrains, increasing the reliability of the DMS.

This paper presents the methods used to size and design the cold cells and associated cryostat. It is based on the development of two numerical models:

• 1D-1D thermo-hydraulic modelling of the cryostat and cold cells for flow regulation,
• 3D-1D thermo-hydraulic modelling of the cold cell for fine heat transfer modelling and thermal stability of the cold cell.

Results from these models are presented and discussed. Finally, the resulting design and the technologies selected to downscale and integrate the cold cells into the ITER environment are presented and discussed.

Parametric Structural Exploration of High Field Fusion Magnets Using Simplified Electromagnetic and Mechanical Analysis

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

In the pursuit of compact, high-field magnetic confinement devices, the transition toward High-Temperature Superconductors (HTS) has significantly increased the structural demands on coil components. While HTS technology enables operating magnetic fields exceeding 20 T on the conductor, the resulting Lorentz forces become a critical driver of the overall coil architecture. Traditional structural designs, such as wedged D-shaped coils, may no longer be sufficient, necessitating the exploration of alternative configurations during the early pre-conceptual phase. This paper presents a parametric application of CIRCE [1][2], a fast-feedback design toolbox applied to high-field magnet systems.

The code utilizes fully-parametric electromagnetic and mechanical analysis based on simplified 1D and 2D finite elements to enable rapid design iteration. The mechanical trends associated with increased magnetic fields are highlighted. This study places special emphasis on the mitigation of out-of-plane effects, which are often neglected during the preliminary design stage. The close coupling between in-plane and out-of-plane support is underlined, demonstrating the limited efficiency of certain structural concepts. Additionally, we propose standardized post-processing routines that provide common metrics to facilitate direct comparisons between different levels of analysis, confinement devices, and structural configurations.

Finally, the study evaluates the performance gains offered by high-strength steels [3]. This analysis is supported by original experimental data from static and fatigue characterization tests conducted at cryogenic temperatures, supplementing existing bibliographic databases. These material properties, alongside key inputs such as residual stress states, are integrated into the workflow using simplified approaches aligned with standard fatigue and static mechanical design criteria.

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Passive High Temperature Superconductors (HTS) Shielding Concept for Neutral Beam Injection (NBI) in Fusion Devices

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

Neutral Beam Injection (NBI) require low magnetic-field environments along the beamline to preserve ion optics and beam transmission. In high-field fusion devices, the stray magnetic field generated by the tokamak magnets therefore leads to demanding shielding requirements, conventionally addressed by massive ferromagnetic structures. This work investigates an innovative passive magnetic shielding concept based on closed high-temperature superconducting (HTS) tape loops combined with a reduced ferromagnetic shield. The HTS conductors are arranged in an “eye-shaped” configuration around the NBI, where persistent screening currents are passively induced by variations of the external magnetic flux. The concept exploits flux conservation in closed superconducting loops, while accounting for the critical-current limit of the HTS conductor. The resulting superconducting stage strongly reduces and spatially homogenizes the stray field before the residual field reaches the ferromagnetic layer, allowing a substantial reduction of the magnetic material required. The concept is applied to the NBI of the Divertor Tokamak Test facility (DTT), where stray fields can reach 25–10 mT in the NBI region. A shielding architecture composed of a main HTS enclosure and an internal ferromagnetic shell has been analysed. Preliminary electromagnetic calculations predict a reduction of the residual field to the sub-mT range, with values of the order of 0.1 mT in the protected region. Transient models are used to evaluate the induced HTS currents, mutual inductive coupling and the onset of critical-current saturation. Besides reducing shield mass, the proposed approach is intrinsically passive, requires no dedicated power supply for the screening currents, and is modular. The feasibility of the superconducting shielding concept is supported by preliminary laboratory-scale experiments on closed HTS tape loops. These activities provide an initial validation of the underlying shielding mechanism and support its application to the DTT NBI configuration. These characteristics make the concept particularly attractive for long-pulse and high-field fusion facilities. The same design methodology can be scaled to larger NBI systems and stronger magnetic environments, providing a potential shielding solution for next-step devices such as ITER and the Burning Plasma Experimental Superconducting Tokamak (BEST), as well as future fusion power plants.

#14005

Preliminary investigations for electrical modelling of supercapacitor performance in the presence of external magnetic fields and under critical operating conditions

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

Supercapacitors (SC) are an energy storage technology that is finding application in various fusion power systems, such as the DTT (Divertor Tokamak Test) and TRUST (Tuscia Research University Small Tokamak) projects. Banks of many SC cells, thanks to their high-power density, would allow the rapid and efficient supply of very high-power energy pulses to power superconducting magnets. Operating in environments with high currents and stray magnetic fields, low-capacity customised supercapacitors (SCs) have been shown in previous research to be affected by magnetohydrodynamic (MHD) phenomena and Lorentz forces, which alter ion transport within the cell between its components, affecting its electrical performance.

This work addresses this issue by proposing an experimental study on commercial high-capacity SC cells with manufacturer-defined geometry, subjected to charge and discharge cycles in the current range between 100 and 140 A, in the presence of an applied external magnetic field. The aim is to verify how the same MHD and Lorentz effects also manifest themselves in high-capacity configurations, typical of industrial applications. The methodological originality lies in the possibility of comparing the analysis and characterisation with and without a magnetic field. Using an equivalent SC electrical model, the electrical parameters (such as non-linear capacitance and equivalent series resistance (ESR) and equivalent parallel resistance (EPR)) are obtained as a function of the magnetic field intensity. To this end, the experimental apparatus positions the cylindrical cell in the centre between two split coils aligned vertically on the same axis. These coils, based on the supply current and the distance between them, will generate a magnetic field with an intensity of up to 100 mT passing through the cell. To ensure the accuracy of the measurements and isolate the magnetic effects from the thermal ones, the tests are performed according to a specific thermal routine: the cell is initially brought to an equilibrium temperature through repeated cycles, and only once it has thermally stabilised, is the magnetic field applied.

The results of this research represent a possible contribution to the understanding and analysis of magneto-electric interactions in electrochemical storage systems, such as SCs, subjected to the intense magnetic fields characteristic of nuclear fusion, allowing accurate prediction of the behavior of SC banks in real fusion operating scenarios. Understanding the interaction between magnetic fields and ionic dynamics at the electrode-electrolyte interface is essential for the design and optimization of superconducting coil power supply systems, including for future tokamak reactors.

Multiscale Electromagnetic–Structural Workflow for the Optimisation and Verification of DEMO Feeder Busbar Clamping System

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The design of magnet feeders for future fusion power plants requires the simultaneous consideration of strong electromagnetic loads, complex structural layouts, and stringent displacement constraints. In this work, a two-stage modelling and optimisation workflow was developed to support the structural design and verification of the DEMO Toroidal Field (TF) coil feeders.

In the first stage, a preliminary structural design of the feeder busbars and their clamping system was carried out using a simplified beam-based representation. Electromagnetic loads were computed through a dedicated ANSYS APDL model of a 45° tokamak sector with periodic boundary conditions, allowing the reconstruction of the full background magnetic field. The contributions of both background and self-generated magnetic fields were evaluated and mapped onto the busbar centrelines. A parametric optimisation procedure was then implemented to determine an efficient distribution of clamps along the feeders. The workflow combines a design-of-experiments exploration of baseline clamp spacing with an automated routine that introduces additional local supports only where required to satisfy a transverse deflection criterion of 5 mm. The resulting configurations provide a constructible clamping layout while minimising the total number of supports.

In the second stage, the optimised beam-based solution was used as the starting point for a higher-fidelity structural assessment. An automated procedure was developed to identify the most critical spans between clamps and generate detailed solid finite-element sub-models of the busbar–clamp assemblies. Electromagnetic analyses were repeated at the solid-model level to recompute Lorentz forces, accounting for both background magnetic fields produced by the tokamak magnets and the busbar self-field. The loads were transferred directly to the structural model through a consistent mesh, avoiding interpolation errors. The structural simulations include realistic contact conditions between busbars and clamps, while boundary conditions are derived from the global beam model to ensure multiscale consistency.

The results confirm the effectiveness of the optimised clamping layouts and provide detailed insight into local stress distributions and busbar–clamp interactions that cannot be captured using simplified beam models alone. The proposed workflow represents a robust methodology for the progressive design and verification of DEMO feeder systems and provides a solid basis for future design refinements.

#14040

Thermal – hydraulic and quench analysis of conductors for the EU-DEMO LAR central solenoid

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

As Europe moves from ITER toward commercial fusion energy, the EU-DEMO (Demonstration Fusion Power Plant) remains a critical milestone. Within the EUROfusion Consortium, the WPMAG team is currently evaluating the conceptual designs for the plant's superconducting magnets, including the Toroidal (TF), Poloidal (PF), and Central Solenoid (CS) coils.

Following the release of the new Low Aspect Ratio (LAR) baseline by the DEMO Central Team, the EPFL-SPC group has engineered a compliant design for the hybrid CS winding pack and conductors. This study evaluates the thermal-hydraulic performance of these proposed conductors under both nominal and quench conditions. Using numerical simulations with the THEA code by CryoSoft, taking into account heat loads from AC losses, we determined for each conductor: the minimum temperature margins during normal operation and the maximum hot spot temperatures during a quench event. These findings offer vital insights for the continued optimization and development of EU-DEMO superconducting conductors.

Studies on the MEST system decoupling from the electrical grid

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

Active and reactive power request from the ac grid is a critical issue to be addressed for feeding superconducting magnets in future large fusion reactors. A proposal to reduce the reactive power absorption and the active power peaks is to feed the superconducting magnets with the Magnetic Energy Storage and Transfer (MEST) system. The MEST is based on an additional superconducting coil to store energy and a switching section with a capacitor to transfer the energy to the reactor magnets. The MEST system decouples grid power absorption from actual energy utilization. In fact, the storage coil is slowly charged beforehand and its stored energy can be transferred rapidly when needed, to supply the magnets for the complete duration of a shot. This leaves the electrical grid only the duty to provide the average active power needed for the load and to compensate for circuit losses, thereby avoiding grid active power peaks and reducing reactive power demand seen with conventional power supplies.
However, as the magnets have a significant impact on the reactor cost, the additional superconducting coil of the MEST system must be carefully designed, minimizing the stored energy. A possible approach is based on partial decoupling from the grid, where only part of the maximum energy of the reactor magnets is provided by the storage coil, while the remainder is provided directly by the grid through the power supply. This reduction comes at the cost of increased power supply ratings and higher grid power demand.
In this paper, a suitable control strategy for the partial energy storage approach is presented, and a study of storage coil designs is conducted to assess the impact on key system aspects, such as storage coil size, power supply requirements and grid power demand, providing guidance on optimal balance for the MEST system implementation in future fusion reactors.

Evaluation of Residual Stresses in Central Solenoid Layers Induced by the Manufacturing Process

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

The structural assessment of the Central Solenoid (CS) jackets is commonly performed assuming a stress-free curved configuration, where stresses arise solely from external operational loads. However, CS layers are produced through a manufacturing process whose final stage involves bending an initially straight conductor to a prescribed radius. This forming operation inevitably introduces residual stresses within the component, which subsequently superimpose on those generated during service conditions.

This work presents a methodology to evaluate the residual stresses induced by the manufacturing process in CS layers. Two independent approaches are considered: a numerical method based on finite element analysis and an analytical formulation describing the stress state resulting from the bending process. The comparison between the two approaches shows very good agreement. The methodology is then applied to jackets characterized by different cross-sectional geometries and bending radii, and the resulting stress distributions are presented and discussed.

#14068

Results from ITER PS commissioning and future development

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

The ITER ECPS (Ex-Vessel Coil Power Supply System) is a large-scale and complex electrical network designed to deliver controlled DC power to the superconducting magnets for plasma initiation, shaping, and stability control. It comprises two stages for SRO (Start of Research Operation).
The stage-1 ECPS includes three RPC&HF (Reactive Power Compensation and Harmonic Filtering) systems totaling 750 Mvar, thirty-two MCPCs (Main Coil Power Converters) implemented as Thyristor-based LCCs (Line Commutated Converters) rated up to 68 kA DC, and approximately 10 km of DC busbars interconnecting around 120 high-power DC switches.
The ECPS systematic operation and protection functions, such as reactive power open-loop control, converter four-quadrant and sequential control, controlled discharge, and fast discharge, should be comprehensively verified during Component Commissioning prior to Integrated Commissioning with the Magnets. Stage-1 Component Commissioning is currently ongoing with significant progress. Component Commissioning and SAT (Site Acceptance Test) of the RPC&HF systems supplied by CN DA (Domestic Agency) have been successfully completed in November 2024. In addition, Component Commissioning of stage-1 MCPC supplied by both CN DA and KO DA is in progress, with low-voltage tests expected to be completed by May 2026, followed by light-load tests and high-voltage tests. Moreover, Component Commissioning of the DC Switches & Busbars supplied by RF DA started in March 2026 with the low-voltage tests.
The stage-2 ECPS will include twelve additional MCPCs and three additional RPC systems. To support future development and introduce new technologies in ITER power supplies, the stage-2 MCPCs are currently under preliminary design, including four IGBT-based VSCs (Voltage Source Converters) for plasma vertical stability dynamic control. In addition, the conceptual design of three stage-2 RPC systems is planned to start in October 2026, with STATCOM technology under consideration.
Key words: ITER; ECPS; RPC&HF; MCPC; LCC; VSC; DC Switches & Busbars; Commissioning; STATCOM

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

Versatile Distributed Control Platform for the SMART Tokamak Upcoming Power Supplies

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Oral

Abstract

The SMall Aspect Ratio Tokamak (SMART) is a spherical tokamak (ST) developed by the Plasma Science and Fusion Technology (PSFT) group at the University of Seville, Spain. It is the first of its kind as it has been designed to study negative triangularity (NT) plasmas in STs. At the time of publication, SMART comprises 21 copper coils, distributed in seven circuits, that operate in a pulsed regime to induce the required magnetic fields inside the vacuum vessel [1]. This set-up is planned to evolve to accommodate the scheduled phases of the project. Consequently, the power supplies (PS) are bound to adapt accordingly. To meet these evolving requirements, modular and multilevel converter topologies stand as promising candidates, consistent with proposals already made for SMART [2] and other tokamaks [3]. However, traditional centralized control architectures limit the inherent scalability and flexibility that such topologies can offer [4].

This work presents a distributed control platform designed from the ground up for the operation of highpower modular and multilevel converters. Built upon low-cost, off-the-shelf microcontroller units (MCUs), the hardware architecture follows the Power Electronics Building Block (PEBB) [5] philosophy, with modular signal conditioning and communication modules. A non-blocking, micro-service software architecture facilitates the real-time control of the sub-modules (SMs) comprising the converter. Furthermore, to guarantee precise distributed modulation, an efficient synchronization mechanism and a lightweight custom communication protocol have been developed to meet real-time targets like those of SMART.

Detailed insights into the various hardware and software aspects of the platform are presented. Finally, to showcase its viability, the proposed platform is successfully deployed to control a small-scale mock-up of a candidate modular topology for the SMART PS.

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Long-term energy projections for fusion magnets supplied by flux pumps

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

Superconductors (SC) are becoming the base for magnetic-confinement fusion devices. The power supplies (PSs) for the tokamak toroidal field coils and for the stellarator main coils are simply required to produce a constant current with low ripple and low losses. Low ripple allows accurate implementation of the desired physics and limits stress and AC losses in the SCs.
The energy demands can be critical for the economic viability of fusion systems, especially in the perspective of delivering net energy to the electrical grid. Conventional PS schemes introduce significant losses, from resistive busbars to current leads, and subsequent operational costs (OPEX), that could jeopardize the feasibility of future reactors.
Alternative approaches, based on the concepts classified in literature as flux pumps (FPs), can induce current in the SCs without direct electrical contact (contactless) or with a limited contact current. By exploiting the cioil inductance and the unique properties of SCs, especially of HTSs, the current flows in an ideal SC circuit with a minimal contribution of external power to compensate the internal losses. This compensation is the source of a small ripple that can be minimized by proper design and control algorithms.
There are different classes and variants of FPs, with respective advantages and disadvantages, also based on the specific application. In any case, FPs enable a lossless persistent or quasi-persistent current mode after the first ramp-up. This perfectly comply with DC or slow operations, such as the toroidal coils of tokamaks or stellarator magnets, independently of the coil SC technology (LTS or HTS).
This study presents a comparative analysis of traditional PSs versus FP-based systems. Since different FP topologies could be adopted, the analysis moves from general aspects to propose guidelines for practical implementation. Using advanced modeling and simulation tools, the potential energy savings were quantified for fusion applications. The integration of FPs projected over the timeline of fusion plants could drastically reduce cumulative energy consumption from tens or hundreds of GWh to less than ten MWh.
The benefits of the new approach are not limited to economic savings but include the reduction of system complexity and footprint, as well as ripple minimization. The advantages are expected to be enhanced by the present trends of SC coils, such as high-temperature, long charge time, self-protection and jointless assembly.
The impact of the presented technologies is potentially disruptive for the engineering and commercial exploitation of magnetic-confinement fusion.

#14219

Lawson Machine 26 – Pulsed Power Supply Development

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Topics

F. Magnets, Cryogenics and Electrical Systems

Communication type

Poster

Abstract

Lawson Machine 26 (LM26) is a large-scale magnetized target fusion (MTF) machine built to demonstrate that compressional heating of a spherical tokamak plasma can achieve fusion conditions. A coaxial helicity injector forms a magnetized plasma inside a hollow lithium cylinder, which is inside a composite vacuum vessel. A surrounding 36-turn theta-pinch coil generates a strong magnetic field to symmetrically compress the liner and the deuterium plasma it contains in less than 4 milliseconds. The compression of the liner occurs without damaging any major structures, allowing the device to be rapidly restored for the next plasma compressions.

LM26 builds on the pulsed power and plasma formation systems developed for General Fusion's Plasma Injector 3 (PI3), which operated from 2017–2024 and executed over 10,000 plasma shots. The plasma formation system employs a Marshall gun injector, conducting center shaft, and coaxial return geometry to generate and sustain toroidal field via center-shaft current. A 25 kV formation pulse produces up to 3 MA gun current, yielding >500 kA plasma current and ~150 mWb poloidal flux. The inherited pulsed power system stores 5 MJ and drives up to 1 MA toroidal field current with 30 MJ pulsed power platform for millisecond-timescale plasma compression.

This presentation describes the design, integration, and commissioning of the LM26 pulsed power architecture, including in-house development of plasma and semiconductor switching systems, repurposing of a US Navy railgun power supply for compression energy, and implementation of a power-crowbar transformer system for toroidal field sustainment.