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Book of Abstracts

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MAD - Modelling-Aided-Design of a tokamak magnet system

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Complex, multi-physics modelling undeniably plays a fundamental role in the design of superconducting magnet systems, as that for a tokamak reactor. Although a preliminary estimation and conceptual design can be drafted based on experience and analytical formulations, a higher-level confidence can only be gained by numerical modelling and analyses, that provide insight into design choices, allow a wider exploration of parameters space, and reduce design margins, that often result from over-simplified assumptions. The modelling-aided design of all coil components is discussed, considering as a case study that of the Divertor Tokamak Test (DTT) facility, currently under construction at ENEA. The performance evaluation of the superconducting strands and of the high-current CICCs, as well as the design of the coil winding pack and structures, all rely heavily on electro-magnetic, thermal-hydraulic, and mechanical numerical modeling, as will be shown for example for the DTT Toroidal Field (TF) and Central Solenoid (CS) coil components.

Magnet design - 1 / 25

Machine learning in designing fusion magnets for tokamak-type machines

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In recent decades, a pioneering field of research has been investigating to reproduce the enormous power of the sun nuclear fusion reactions in a relatively small apparatus, i.e. a tokamak. This machine generates a closed magnetic field configuration able to supply and control an ionised plasma. The magnetic system is made by three main components: the Toroidal Field (TF) Coils for the primary confinement, the Poloidal Field (PF) Coils for the plasma vertical stability and the Central Solenoid (CS) which induces a toroidal current on the ionised particles.
Currently, physical-computational models and system codes have been introduced and gradually improved to complete the electromagnetic and the structural assessment of the system components in a more and more efficient way. Further, at this stage, efficient parametric tools are of fundamental importance, since numerous configurations and different approaches are under investigation to theorize and attain nuclear fusion in tokamak devices.
In this paper, the Magnet Design Explorer (MADE) algorithm [1] is exploited as a foundation for developing a machine learning (ML) approach. In detail, first MADE is used to construct the database necessary to train suitable artificial neural networks (ANNs). Second, the supervised learning method is employed to build a model based on the sample data, capable to make reliable predictions with a very good numerical performance. Neural nets properly trained can be the key to access a vast portal of enhanced solutions with a high efficiency in terms of costs and computational time.

[1] L. Giannini et al., The MAgnet Design Explorer algorithm (MADE) for LTS, Hybrid or HTS toroidal and poloidal systems of a tokamak with a view to DEMO, *submitted*.

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Design of the cryogenic loops for the superconducting magnets of the Divertor Tokamak Test

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The Divertor Tokamak Test (DTT) facility is being built at ENEA Frascati (Italy), to address the development of a power exhaust system capable to handle the large heat fluxes expected to be deposited in fusion reactors on the plasma facing components.
DTT will be a compact and flexible fusion experiment relying on low-temperature superconducting magnets for the plasma confinement. The magnets will be cooled to their operating temperature by supercritical He at 4.5 K and ˜0.6 MPa, distributed by at least two cryogenic circuits (one for the AC and one for the DC coils) composed by supply and return cryolines, heat exchangers, control valves and a cold circulator. These circuits need to be designed to handle both the pulsed heat loads deposited in the coils by AC losses and nuclear particles during the operation of the tokamak and the static heat transferred by conduction/radiation from the cryostat to the magnets. To decouple the circuits from the refrigerator, that should operate as much as possible at a constant thermal load, the heat will be transferred to a thermal buffer (a saturated liquid He bath).
The validated thermal-hydraulic code 4C is used here to support the design of the DTT cryogenic system. Different operative phases are simulated, comparing the evolution and peak values of the heat load transferred from the cryogenic circuits to the thermal buffer in different plasma configurations and for different circuit layouts.
To drive the selection of the best layout, suitable figures of merit are identified, such as the number and volume of the buffers and the amplitude of the variation of the power transferred to the refrigerator during the plasma pulses. In case the buffer is not sufficient, some additional mitigation strategies for the smoothing of the power transferred to the refrigerator, involving suitable controls, will be investigated.

Magnet design - 1 / 8

Progress in the conceptual design of the European DEMO magnet feeders

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The magnet feeders are critical systems of fusion reactors since they represent the interface between the in-cryostat components and the external environment. By realising the required electrical, cryogenic and mechanical connections, as well as hosting instrumentation cables, the feeders ensure the safe operation of the superconducting magnets. Therefore, the design and integration study of the magnet feeders is one of the key activities within the conceptual design phase of the European DEMO. Despite several preliminary studies have been performed, a systematic overview of the feeder system is still missing.

In this work, we report recent progress in the design of the magnet feeders, starting from the outline design of the superconducting bus bars and current leads, which connect the room-temperature power supply to the coils at about 4 K. Further design activities have been centred on the integration of the feeder structures within the tokamak building, considering also the positioning of additional critical components, such as the auxiliary cold boxes and the fast discharge units. The process flow diagram of the feeders for the toroidal field coils has been also introduced, with a particular focus on the operation of the cryogenic lines at different temperature and pressure levels.
We believe this work is relevant for advancing the design of the whole European DEMO fusion reactor, representing a solid starting point for future engineering design activities and industrial studies.

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Conceptual design and first test results on the high current Nb-Ti/Cu-Ni thermal switches

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High-current superconducting switches can simplify the energy extraction in large magnet systems. For example, they can replace mechanical and vacuum breakers in the conventional electrical circuit of TF coils for fusion magnets, thus mitigate the risk of arcing. Vast majority of current leads to room temperature can be eliminated, and the cryogenic power consumption can be substantially reduced. When used in a chain of HTS accelerator magnets, the quench protection is improved because of much lower energy needed to initiate the fast discharge. Aiming at the experimental study, Nb-Ti wires in a highly resistive Cu-Ni matrix are procured both as a single strand and in a 6-around-1 cabling configuration. An Ayrton–Perry winding, essentially a layer-wound solenoid with reversed currents in neighboring layers, is proposed for this application because of its simplicity and increased distance between the switch terminals, thus reducing the electrical stresses. Multiple parallel strands or 6-around-1 cables can be considered within each individual winding layer, maintaining the full transposition feature. However, the strands in the entire winding are not transposed. Therefore, in order to assess the parameters influencing the current distribution among the strands, an electromagnetic model is developed. The outcome of the modelling is compared with the test results obtained on the first 1 kA/2 Ohm thermally-activated switch made of the two single strands. In addition to the co-wound heater, low inductance of the switch allows to turn it off by applying AC current of low amplitude (˜10 A) and high frequency (˜kHz range), thus triggering the transition into the normal state by coupling loss. Thanks to the model, the current distribution among the strands can also be extracted based on the measured total transport current and produced magnetic fields. The next steps are focused on using the 6-around-1 cables in the switch samples rated up to 10 kA (1 cable per layer in 2 layers) and 30 kA (2 cables per layer in 4 layers).

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FE Analysis of the Winding of a High Curvature Superconducting Dipole Using a Novel Technique

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In collaboration with CERN and CNAO, INFN is developing a demonstrator of a curved dipole as a key element of a superconducting gantry for hadron-therapy cancer treatments. The baseline project includes a cos-theta NbTi 4 T dipole with a radius of curvature of 1.65 m, an aperture of 80 mm and ramp rates up to 0.4 T/s. Considering the inherent difficulty of winding a curved coil, in parallel we are developing an alternative method, which consists of winding the coils on a fully convex shape that is then pushed to the final concave configuration. Since the conductor is a standard Rutherford cable, this winding option involves switching the magnet to a block coil configuration. In this contribution we report the preliminary finite element analysis that we carried out to set up the parameters of this innovative winding system.

Thermal-hydraulic modelling - 1 / 19

Combined thermohydraulic and superconductive issues in FAIR SIS 100 BPL

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Facility for Antiproton and Ion Research (FAIR) is the particle accelerator facility currently being under construction by at GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany. The SIS100 ring accelerator has a circumference of 1,100 meters and can accelerate the ions of all the natural elements in the periodic table to speeds as high as 99% of the speed of light. The SIS 100 accelerator by-pass line (BPL) bypasses warm magnets with cold helium in different thermodynamic states and high current in superconductive Nuclotron-type cables with superconducting strands wrapped around a cooling tube. The BPL characteristic feature, not common in other accelerator cryogenic distribution systems, is the integration of both helium transfer lines and superconducting cable in a single vacuum envelope characterized by a very tight geometry. The paper addresses design, construction and exploitation challenges of the BPL, like impact from fast dump magnets on the line structure, discontinuities in helium and current flows, high magnetic forces and the cables cross-talking. The experience from the BPL elements production and reception tests will be presented.

Thermal-hydraulic modelling - 2 / 14

Toward a better coupling scheme for the co-simulation with 1-d conductor models in thermal contact to the FEM meshes of solid structure

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Since dependable conductor models can be based on 1-D thermal-hydraulic problems, coupled simulation scheme has established itself as a practical approach to evaluate the design of large-scale superconducting magnets. By integrating well-established numerical models around the core of superconducting magnet, i.e. the conductors, such a concept of coupled solution, known as co-simulation technique, has been used in common for most of present platforms, such as SuperMagnet, 4C and TACTICS. Thus, their coupled operations are simply driven by controlling the computational steps of each simulator so as to wait for the update of interface values from the counterpart. Against such a background of the basic architecture, some applications have raised the issue of numerical stability, as identified in terms of implicit solution scheme at the interfaces, and a new approach based on the interface Jacobian was brought to recover the loss of implicit condition in the particular case of hydraulic volumes connected to the conductor model. As an extension of this approach, the interface problem in thermal contact is explored by representing the logical essence of a quench simulation in a CICC, which has emerged as a technical issue of THEA-Cast3M coupling in the TACTICS model. Drawing each numerical step with tangible objects written in FreeFEM++, a partial matrix evaluation is proposed as a core of computational steps on the interface Jacobian. The actual coupling scheme then takes shape in detail as a numerical interface along the conductor model coupled to the 2-D or 3-D model of thermal meshes, intended to be applied to THEA-Cast3M coupling in TACTICS model, as well as to THEA-HEATER coupling in SuperMagnet model.

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Analysis and modelling of the quench experiment on HTS sub-sized cable-in-conduit conductors for fusion applications

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The Central Solenoid (CS) of the EU DEMO is under design within the EUROfusion Consortium. Two different design options are under investigation. One option is based on Low Temperature Superconducting (LTS) Cable-In-Conduit Conductors (CICCs), following an ITER-like design approach. The other option is to employ both High Temperature Superconducting (HTS) and LTS materials to build an hybrid CS.

However, the response of HTS CICCs in typical transients expected in a superconducting coil, such as quench initiation and propagation, is less known with respect to that in LTS CICCs. Therefore, an experimental campaign on the investigation of quench propagation in HTS CICCs was launched by EUROfusion. So far, different CICC concepts designed by the Swiss Plasma Center (SPC) were tested in SULTAN. The conductors were equipped with several voltage taps along the conductor axis as well as temperature sensors on the stainless-steel conduit (jacket) and protruding in the He stream. The quench tests were performed with different mass flow rates and with different values of the transport current and background magnetic field.

In this work, the analysis of the experimental data of the tests performed on two different conductors, i.e., the solder-filled and the BSCCO conductors, is performed first. The analysis is mainly aimed at quantify the normal zone propagation speed and hot spot temperature, using the voltage measurements.

After this analysis, the implementation of the numerical model of the solder-filled and of the BSCCO conductors in the H4C code is described. The free parameters of the model are then calibrated and different tests not used for the calibration are then used for the model validation. The agreement

between the experimental data and the computed results is good both on a global scale, e.g., the total voltage, as well as on a local scale, e.g., local voltages and He and jacket temperatures.

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Thermal-hydraulic modelling - 2 / 20

Modeling and analysis of quench in the 15-kA HTS conductor

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Abstract
High Temperature Superconductors (HTS) are very promising materials to be applied in future fusion magnets. HTS conductors are already considered as a possible option for some components of the superconducting magnet system of the EU DEMO tokamak, which are being designed by the EUROfusion consortium, e.g. for the innermost subcoil of the Central Solenoid coils developed by the EPFL-SPC team. Geometric and thermo-physical characteristics of HTS and LTS conductors differ significantly, e.g. only a few thick macrostrands in HTS conductors vs. ~103 thin strands in LTS conductors, anisotropic thermal conductivity and Jc of HTS tapes vs. isotropic LTS strands, quench propagation velocity in HTS much smaller than in LTS, etc. Thus, it can be expected that numerical simulations of the behavior of HTS conductors may require specific approaches, different from those which are successfully used for LTS conductors, particularly in cases when fast transient processes (such as e.g. quench) are considered. In order to provide data for better understanding of the quench evolution in HTS conductors as well as for testing different numerical approaches and proper tuning of the numerical codes, a series of dedicated HTS 15-kA subsize samples with different geometries were produced and tested at the SULTAN test facility in the Quench Experiment performed within the international collaboration between EUROfusion and China. Our analysis is a part of the work on analysis and interpretation of the results of the Quench Experiment. We simulated selected experimental runs using a few THEA models with different levels of complication. Some uncertain model parameters, such as thermal resistances and copper RRR, were treated parametrically. The goal of the study was selection of the possibly simple model which would properly reproduce the results of the Quench Experiment.

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Thermal-hydraulic modelling - 2 / 15

Finite Element Thermal Thin Shell Approximation for Simulation of Transients in Accelerator Magnets

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Thermal transient responses of superconducting magnets are often simulated with the finite element (FE) method. Accelerator magnet geometries often consist of cables with a high dimensional aspect ratio of metal to insulation. The FE discretization of such geometries requires many mesh elements to resolve thin insulation layers and achieve an accurate solution. This increases computational time, particularly since non-linear material properties are involved.
To improve the computational efficiency for simulations of thermal transients in two dimensions, we propose to use the thermal thin-shell approximation (TSA) [1], which allows collapsing thin electrical or thermal layers into lines for representing the insulation. In this contribution, we present the TSA implementation in the open-source Finite Element Quench Simulation (FiQuS) tool [2], which is developed at CERN as part of the STEAM framework. To achieve this, modifications at the level of construction of geometry and mesh, as well as the FE formulation, are required when compared to classical FE simulations. FiQuS is capable of programmatically generating all components needed for the TSA. The thermal model allows for the Dirichlet (imposed temperature), Neumann (imposed heat flux), and Robin (imposed temperature-dependent heat flux) boundary conditions specified on the winding region with the help of the FiQuS input file.
The TSA is applied to simulate thermal transients in an LHC superconducting magnet including heat generation, thermal diffusion, and quench propagation. The method is verified against a solution obtained with a reference model comprising meshed insulation regions. The results demonstrate the advantages of the TSA, which enables faster simulations while preserving the accuracy of the solution.

***Index Terms* —quench simulation, finite element method, superconducting magnets, thin-shell approximation, FiQuS**

[1] Erik Schnaubelt, Mariusz Wozniak, Sebastian Schöps. Thermal Thin Shell Approximation for 3D Finite Element Quench Simulation of Insulated HTS Coils. 8th International Workshop on Numerical Modelling of High Temperature Superconductors (HTS 2022), Kévin Berger (Université de Lorraine - GREEN), Jun 2022, Nancy, France. ffhal-03791298

[2] FiQuS 2023.1.0. (2023) Finite Element Quench Simulation Tool.
[Online]. Available: cern.ch/fiqus

Thermal-hydraulic modelling - 3 / 30

Numerical analysis of the DTT Toroidal Field conductor samples tested in SULTAN

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In the EU DEMO reactor, currently in its pre-conceptual design phase, power exhaust represents a major challenge, asking for a new, robust design of the divertor. To address this issue, the Divertor Tokamak Test (DTT) facility is being built in Italy. It will be a compact and flexible tokamak, allowing the implementation of several plasma configurations as test bed of DEMO-relevant divertor solutions.
The DTT fully superconducting magnet system will include 18 Nb3Sn Toroidal Field (TF) magnets, cooled by forced-flow supercritical helium at 4.5 K and 0.5 MPa and operated at 42.5 kA in a 11.9 T peak magnetic field.
The TF Cable-In-Conduit Conductors are currently being manufactured and to verify their performance some qualification tests in relevant conditions close to the operating ones were carried out in 2022 in SULTAN (Swiss Plasma Centre, Villigen, Switzerland).
The sample was composed of two conductor sections with a different cabling twist pitch sequence. They underwent 3000 electro-magnetic cycles and two warmup/cooldown cycles, and the DC performance and AC losses were measured before and after the cycles. Minimum Quench Energy (MQE) tests were also carried out.
The 4C code, the state-of-the-art tool for the thermal-hydraulic simulation of transients in superconducting magnets for fusion applications, is being used to support the design verification of the DTT magnet system. In this work, the 4C code is used to model the DC tests carried out on the SULTAN sample. This allows to qualify the Ic scaling parameters obtained from dedicated measurements on the Kiswire Advanced Technology (KAT) strands at E-WASP facility in the ENEA Superconductivity Laboratory of Frascati and used for the numerical analysis of the DTT TF coil performance.
The simulation of the MQE tests is also presented, to support the data interpretation and investigate the stability of the TF conductor.

Acknowledgement
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Thermal-hydraulic modelling - 3 / 5

Improvement of a numerical framework to systematically assess the temperature distribution in complex He II-cooled magnet geometries using open-source software

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In the context of the High Luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN, a numerical framework has been developed to systematically assess the temperature distribution in complex He II-cooled magnet geometries using open-source software. The precise knowledge of the magnet's thermal characteristics and heat extraction performance is essential in determining safe operating margins and validating the thermal design of impregnated accelerator coils.
First, a 1D heat transfer model of a coil section was developed using the Julia programming language. This tool facilitates intensive parametric studies, making use of a phenomenological model for estimation of helium content in the insulation and cable layers.
Secondly, a 2D multi-region solver based on conjugate heat transfer between a composite solid body and stagnant He II has been redeveloped in OpenFOAM, along with the required libraries for material properties. The model can handle complex geometries composed of different materials each with their temperature-dependent properties, and the interface between the solid bodies and the

stagnant He II is mediated by a Kapitza-type interface contact resistance. The strategy of creating a model with only two regions –a composite solid and a He II region –in which the composite solid region can be divided into zones with distinct material properties, has allowed for a reduced usage of baffles and drastically improved the computation time when compared to earlier versions used during the design phase of the magnets [1].
Both tools have been validated with experimental data obtained from laboratory-scale experiments on impregnated coil samples, which are reported and discussed here.
Experimental measurements of impregnated Nb_3Sn coil samples in He II allowed also for the extraction of material properties, especially of composite structures such as the coil's insulation layers where literature data is either unavailable or inadequate.
Recently, a full cross-section of a He II-cooled magnet cold mass exposed to inhomogeneous collision-generated power densities was modelled using the 2D numerical tool [2]. Its potential as a robust, easily adaptable toolkit was demonstrated: it allows for parametric investigation of geometry, temperature, and heat deposition on geometries cooled by stagnant He II in a timely manner and attests to the consolidation work with respect to previous iterations [1] of the model.

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[2] P. Borges de Sousa et al., IEEE Trans. Appl. Supercond. (submitted, presented at ASC 2022)

Electro-magnetic modelling - 1 / 10

Current sharing by copper core in spiral coated conductor cable

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An assembly of coated conductors wound spirally on a copper core such as a CORC® wire is one of the most popular types of high current coated conductor cables. In such a cable, the current sharing by the copper core as well as the current sharing between coated conductors plays a key role for its quench protection. We conducted quench experiments using the simplest configuration, in which one coated conductor was wound spirally on a copper core, in order to clarify the current sharing by the copper core. A sparse spiral winding allowed us to attach voltage taps on the core as well as the coated conductors. We measured the voltages along the coated conductor, those along the core, and those between the coated conductor and the core. From these voltage data, we verified experimentally that the current in the normal-transited coated conductor was shared by the metal core and that this current sharing reduced the hotspot temperature. The numerical modelling of this current sharing is in progress, and the latest results will be presented at the workshop.

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Simulation of current paths and their relaxation within the tapes of monolayer CORC cables

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The Conductor-On-Round-Core (CORC) is a promising design for obtaining cables made of second-generation high-temperature superconducting (HTS) wires. These cables are primarily intended for high-field magnets, but their small size and excellent current-carrying performance make them an attractive solution for AC power applications as well. The AC loss level is an important factor affecting the practical realization of HTS applications. In general, the AC loss of HTS strongly depends on how the current distributes inside the superconductor. In the case of CORC cables, the particular layout of the wires generates differently oriented magnetic fields on the two sides of the superconductor. In turn, this generates a current transfer across the thickness of the superconductor: this ultimately results in a non-trivial zig-zag shaped current pattern, which does not simply follow the direction of the wire. This contribution aims at investigating these current patterns and their influence on the transport AC losses of CORC cables. In particular, we found that the effect is strongly frequency dependent, fully developed at 50 Hz and vanishing in the limit of DC. For this work, we use a full three-dimensional finite-element model, including current components perpendicular to the tape surface. The model is based on the H formulation of Maxwell's equations implemented in the commercial software package COMSOL Multiphysics. The local current and field components are calculated by using curvilinear coordinates and periodic conditions. The anisotropy of the critical current density with respect to the crystal planes of the superconductor is also included.
This work was supported by Germany's Federal Ministry for Economic Affairs and Climate Action –Grant Nr. 03EN4031B.

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Thin Shell Model of a Coated Conductor with a Ferromagnetic Substrate

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Coated conductors with magnetic substrates are thin multilayer structures; their high aspect ratio and nonlinear material properties present significant difficulties for numerical simulation. Using the high width-to-thickness ratio of coated conductors we derive an integral formulation for a new model [1] based on an infinitely thin approximation for the superconducting layer and a quasistatic thin shell approximation for the magnetic substrate. Our model describes electromagnetic response of a coated conductor with a magnetic substrate and is much simpler than the existing models. A single dimensionless parameter characterizes the substrate having a finite magnetic permeability and a finite thickness. An accurate and efficient Chebyshev spectral method is derived for numerical solution. The influence of a magnetic substrate on the superconducting current and AC losses is investigated. In the limiting case our model solution tends to the known analytical solution [2]. As an example, we consider the superconducting dynamo magnetic pump, a perspective device for contactless charging the HTS magnets, and show that with a ferromagnetic substrate of the stator strip the dynamo produces a higher voltage output.
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[2] Y. Mawatari (2008) Physical Review B, 77104505.

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Critical current evaluation of Nb3Sn samples from m(B) curves by SEM image processing in ANSYS APDL using Space Claim import tools

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In the framework of the studies on high field magnets for future accelerators, a specific project called ASTRACT, involving INFN, CNR/SPIN, ENEA and the University of Genoa, is focused on the effect of transverse strain on the critical current of Nb_3Sn wires. The first phase of the project concerns the effects of strain imposed on Nb_3Sn wires before heat treatment and the development of a procedure to compare direct critical current measurements with the values extracted by magnetization cycles. At this purpose we developed a protocol that starts from a SEM image and load it in the Space Claim suite, thanks to a CAD file format. Then the image can be converted in Ansys Neutral File and imported in ANSYS Mechanical APDL. By this way we can perform numerical integration over any bundle surface to calculate the magnetic moment shape factor useful to extract the critical current value from magnetization curves. Furthermore, this technique can lead straightforward to 2D or 3D strand models to realize mechanical or electromagnetic simulations.

Mechanical Modeling - 1 / 24

Experimental and numerical assessment of the electro-mechanical limits of state-of-the-art Nb3Sn accelerator magnets

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The development of accelerator magnets able to produce magnetic fields beyond those attained in the main magnets of the Large Hadron Collider (LHC) requires the use of conductors with enhanced

superconducting properties with respect to the well-known Nb-Ti technology. In the present days, Nb3Sn has become the preferred choice for the windings of such new high-field designs, thanks to its proven large-scale industrial production. Numerous laboratory experiments, which range from tests on single wires up to full cables, have shown that the critical current of Nb3Sn conductors depends on the applied mechanical loads. However, it results very difficult to find a consensus within the magnet community on which is the maximum mechanical stress level that the brittle Nb3Sn superconductor can withstand in a magnet configuration.
Our work tries to fill this gap and reports on the results of an experimental and numerical modelling campaign devoted to understand the electro-mechanical limits of the novel MQXF quadrupoles. These magnets will be the first Nb3Sn units to be installed in a particle accelerator as a part of the High Luminosity upgrade of the LHC. On-going tests carried out in a short magnet model (MQXFS7) have confirmed the correct magnet performance up to compressive stress levels in the coils, at cryogenic temperature, in the order of 160 MPa. These results in magnet configuration are compared here with independent single-wire tests performed in a dedicated experiment at the University of Geneva. The study exploits Finite Element (FE) models reproducing both configurations to provide a complete insight into the physics of the problem. Furthermore, the MQXF FE model has been used as well to optimize the magnet assembly procedure. The refined method eliminates undesired coil stress overshoots during assembly and provides useful guidelines for future high-field designs.

Mechanical Modeling - 1 / 6

Viscoelastic explanation of the loss of pre-stress in impregnated superconducting magnets

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The SMC (Short Model Coil) program was started at CERN around 2008 to develop the Nb3Sn technology. The small magnet structure allowed relatively cheap and fast test of various superconducting coils. One of the key questions was the relation between the pre-stress and the magnet's performance, to measure which dozens of strain gauges were installed on the coil, axial tie-rods and the external shell. The experimental campaign of strain measurements during all stages of load: room temperature (RT) pre-stress, cool-down, powering, warm-up was analyzed in an extensive report [1]. A repeatable pattern of decreasing strain after the warm-up was observed on the external cylinder for all the tested coils with considerable values from 19 % to 51 %. Such decreased strain was not predicted by any state-of-the art FEM models used by magnet designers.
The SMC program has several successor programs: RMC (Racetrack Model Coil), ERMC (Enhanced Racetrack Model Coil) and RMM (Racetrack Model Magnet) relying on similar design principles and pre-stress with bladders and keys. In the recent tests of the ERMC magnet the decreased strain by 30 % was reported [2]. Similar effect was observed for another Nb3Sn magnet MQXF [3] where strain decrease of 10-19 % measured by strain gauges and 18-25 % by optical fibers were reported for 4 coils.
To understand the effect of decreasing strain on the external shell of impregnated superconducting magnets the visco-elastic material model was applied to the resin used for the impregnation. A conceptual magnet model was developed with the Prony model and solved in Ansys, including the elastic shell and visco-elastic coil. With the two visco-elastic paramters controlling the Prony model: relative relaxation modulus and relaxation time the level of strain decrease was possible to control. The visco-elastic model can describe the effect of loss of pre-stress in a phenomenological way, predicting softening of the elastic constants, an effect analogous to damage and fracture but achieved with much smaller computational cost.

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Mechanical modelling - 2 / 4

Mechanical analysis of the DEMO TF with 2D and 3D models: homogenized and fully detailed –comparison of accuracy

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The most common type of models used to analyzed the design of the toroidal field (TF) coils of tokamaks rely on the homogenized mechanical properties of the winding pack (WP). Such approach simplifies the model and reduces the computational time at the cost of introduced simplifications, the main one being the loss of information on the stress and strain fields inside the WP. In this work a fully detailed 3D model of the DEMO TF coil was developed as well as a homogenized model, and the results of the two models were compared to judge the accuracy/error of the homogenization approach.
The Lorentz forces were computed with a global electromagnetic model, developed in Ansys APDL based on the scalar potential approach (SOLID96+Sourc36 elements). For the detailed model, the circular strands based on the WP#4 TF design by CEA were approximated by finite number of rectangles –due to limitation of the Sourc36 elements. The necessary number of rectangles that approximate the circular strands was found based on a parametric study. Additionally, a method of computing the EM force densities, unavailable directly for Solid96 elements, was proposed allowing easy transfer of the results to the mechanical model.
As the homogenized model does not provide relevant information from the WP, the usual method accepted in the community relies on a detailed 2D model. Such model was developed as well and its results were compared to the fully detailed 3D model to evaluate the error introduced by 2D modeling, especially looking at the stress levels in the conductor's jacket and its insulation.
The computational cost of both the EM and mechanical models was analyzed in details, having a16 CPU workstation as the hardware. Computing times and RAM requirements were analyzed for the Ansys software. Further perspectives of running nonlinear mechanical models with ˜10e6 elements and larger on the state-of-the art workstations were discussed.

Mechanical modelling - 2 / 23

2D Mechanical Representation of Superconducting Magnets: a Comparative Study of Plane Stress and Plane Strain Options.

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When approaching the mechanical design of a superconducting magnet, whenever possible the starting model is a 2D approximation. If rotational symmetry (solenoid-like winding) is present, the 2D representation is unique and contains no approximations. If, on the other hand, a bi-axial system is opted for, the 2D representation is not unique: the main options are plane stress, plane strain, or a combination of the two. If z is the direction normal to the 2D plane, the plane stress option defines a stress state in which no normal or shear stresses perpendicular to the xy plane can occur ($\sigma z = \sigma xz = \sigma yz = 0$). In the plane stress condition, deformation can occur in the thickness of the element, which will become thinner when stretched and thicker when compressed; it is generally used for objects with limited depth (thin objects). In contrast, plane strain refers to the fact that deformation can only occur in plane, which means that no out-of-plane deformation will occur ($\varepsilon z = \varepsilon xz = \varepsilon yz = 0$), while, due to the fixity of longitudinal motion, normal stress will be generated. The plane strain option is generally appropriate for structures of nearly infinite length, relative to their cross section, that exhibit negligible length changes under load. Superconducting magnets, such as racetracks or multipoles, do not fit neatly into any of the above options: they are far from thin but deform longitudinally under load. This work reports a comparative study of plane stress, plane strain and a combination of the two in the specific case study of a dipole magnet.

Magnet Design - 3 / 17

Design and analysis of a HTS internally cooled cable for the Muon Collider target magnet

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The Muon Collider is one of the options considered as the next step in High Energy Physics. It bears many challenges, last not least in superconducting magnet technology. The target solenoid is one of them, a channel of approximately 18 m length consisting of co-axial solenoids with a 1.2 m free bore and peak field of 20 T, submitted to large radiation heat load, dose, and damage. We describe here the conceptual design of the solenoid, focusing on the HTS cable design, which is largely inspired by the VIPER concepts developed at MIT. In particular, we show how to address margin and protection, cooling and mechanics specific to the HTS cable selected.

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The role of systems modelling in manufacturing, commissioning and operation of tokamak reactors

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The aim of this contribution is to illustrate the role of computational models during the lifecycle of tokamak systems and components beyond their design phase. At first we discuss the use of high-fidelity modelling during component manufacturing to resolve by simulation, if functional tests are not possible or too costly, the likely impact of non-conformities on in-service performances and lifetime assessment. Then we provide some examples of how the measurements carried out during acceptance tests and/or integrated commissioning are key to calibrate the computational models developed during system design in view of machine operation. The case for computational modelling development is also strengthen by analysing their key use during machine assembly, licensing and operation.

Thermal-hydraulic modelling - 4 / 2

Quantification of the heat flux transferred to supercritical helium flowing in tubes after loss of insulating vacuum

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Cryogenic devices have to be protected against accidental overpressure by installing pressure relief devices such as valves or rupture discs. The sudden loss of the insulating vacuum is often considered as the major accident, with the highest heat fluxes transmitted to the fluid.

Up to now, the design of safety devices was based on the use of experimentally measured standard heat flux values. For supercritical helium, measurements have only been carried out for the tank configuration with natural convection. However, in order to ensure a reliable sizing of pressure relief devices for cryogenic facilities equipped with cryolines, heat flux measurements have also to be performed for forced convection cases.

For this purpose, the HELIOS experimental platform has been previously modified to perform loss of insulating vacuum tests around a pipe with supercritical helium flowing in forced flow. The new HELIOS design was determined using the CATHARE thermal-hydraulic code.

In this work, the results of the two experimental campaigns carried out with HELIOS are presented. During the first campaign, a test section equipped with an electrical heater was installed in HELIOS. It allowed the validation of the new design of the device and the experimental method for estimating the heat flux transmitted to the supercritical fluid. The experimental measurements are also compared with the CATHARE modelling. For the second campaign, the electrical heater has been replaced by a specific test section to achieve an insulating vacuum loss around a pipe in which supercritical helium is flowing. The heat flux received by supercritical helium resulting from vacuum break is estimated from experimental measurement.

Thermal-hydraulic modelling - 4 / 32

A novel 1D - 3D coupled model for the thermal-hydraulic simulation of the gravity support of the Divertor Tokamak Test toroidal field coils

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The Divertor Tokamak Test (DTT) facility is a fully superconducting tokamak currently being built in the ENEA Frascati laboratories (Italy) to study the power exhaust issue in EU DEMO perspective. The massive Toroidal Field (TF) magnets require a robust Gravity Support (GS) to sustain their weight. The GS is a stainless steel column in thermal contact at the bottom to the cryostat base at ambient temperature and at the top to the TF magnet casing at 4.5K. A parasitic static heat load is therefore conducted through it to the TF coil casing and must be carefully evaluated to assess the magnet performance by means of detailed thermal-hydraulic (TH) analyses.

To reduce the parasitic heat load to the magnet, the GS will be actively cooled by Thermal Anchors (TAs), where part of the heat is extracted by helium flowing in pipes suitably attached to or drilled in the GS. While the GS can be easily modelled, from the thermal point of view, as a 1D object, the TA requires a more detailed 3D analysis, exploiting computational-fluid-dynamic (CFD) tools.
In this work the effectiveness of this cooling solution is assessed coupling a 1D thermal model solving the heat conduction in the GS solids with a local 3D CFD TH model of the TA. This minimizes the computational cost, still describing with high fidelity the cooling of the TA.
The novel 1D+3D TH model is based on python programming language and on the commercial CFD software STAR-CCM+, coupled by a Functional Mock-up Interface.

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Thermal-hydraulic modelling - 4 / 29

Development of quench analysis model of spiral coated conductor cables combining one-dimensional heat conduction equations and circuit equation

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Spiral coated conductor cables, in which multiple coated conductors are spirally wound around a circular cross-section metal core, such as CORC®-like cables, have advantages such as high mechanical freedom and high current capacity. Such cables are expected to be used in various applications, such as magnets for accelerators and nuclear fusion, and coils for rotating machines and generators. Additionally, even if normal transition occurs in one coated conductor, the current flowing in the coated conductor can be shared with the other coated conductors and the metal core, and thermal diffusion into the metal core is possible. Therefore, the spiral coated conductor cables are considered to have high robustness against quench. Quench analysis models for spiral coated conductor cables are needed to evaluate their quench characteristics.
As results of previous researches, we have confirmed that the temperature gradient in the thickness and width direction of a coated conductor is almost negligible, and that thermal diffusion to adjacent objects such as cores plays an important role in quench and thermal runaway processes. In addition, the purpose of this study is to know the temperature and current distribution among coated conductors and core during quench, and not to know the detailed temperature and current distribution in the coated conductors. Therefore, we propose a quench analysis model that approximates each coated conductor and core in one dimension. We combined one-dimensional heat conduction equations, each of which represents one coated conductor, and circuit equations, in which each coated conductor is represented with a series of non-linear resistance. In the heat conduction and circuit equations, the coated conductors are in partial contact with each other. If these contact points are regarded as nodes, a thermal and electrical network consisting of one-dimensional elements can be constructed. For the metal core, it is considered to be in continuous contact with coated conductors in the innermost layer and is approximated as a one-dimensional line. Then, the thermal conductivity and electrical resistivity are corrected for the length difference caused by the straight shape of the metal core and the spiral shape of the coated conductors. Although the constructed network is represented by one-dimensional heat conduction and circuit equations, it contains a three-dimensional contact structure within the spiral coated conductor cables.

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Electro-magnetic modelling - 3 / 3

Analysis of AC loss reduction potential in round HTS cables

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The Coated Conductor (CC) tapes seem to be prospective for the production of magnets and cables, because of a high upper critical magnetic field as well as temperature, and competitive critical current density in combination with good mechanical properties. On the other hand, the superconducting layer may exhibit high energy dissipation in the external magnetic field because of rather large magnetization currents induced in the commercial tapes currently available in 2-12 mm widths. This could be a limiting factor of the ReBCO tapes application in the transient field or AC regime. It is possible to play with the cable geometry, but a higher impact on reducing the AC losses is expected from the tape filamentation. There are positive experiences in using narrow filaments for low Tc superconductors. But, the CC tape manufacturing technology complicates the dividing of the superconducting layer into narrow filaments. Moreover, the filamentary architecture suitable for AC loss reduction could lead to insufficient electro-thermal stability. In the present study, we analyze the impact of round cable geometry and the filaments coupling effect on the overall AC losses of the cable. The combination of an experimental investigation with FEM modelling and the use of analytical solutions allowed us to formulate relevant conclusions.

Electro-magnetic modelling - 3 / 12

Simulations of electromagnetic responses in superconducting magnets in the time and frequency domains using a physically derived equivalent circuit

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Coherent and accurate modelling in multiple domains of superconducting magnets is challenging as their behavior is usually the result of complex interactions of physical effects on different temporal and spatial scales. However, for example, for the performance analysis of the LHC main dipole circuits, it is important to be consistent across the time- and frequency domains.
A modelling approach is presented that allows consistent time and frequency domain simulations of electromagnetic responses in superconducting magnets. This modelling approach captures the driving physical phenomena in lumped elements within smaller electrical networks. These elements are mutually coupled to the magnet's coil inductances. The coupling parameters are analytically derived using only measured geometric and material properties of the magnets and their components. The specific features of transient responses are thus physically interpretable. As such, the model can reproduce complex transient effects within the magnets'coils, such as inter-filament and inter-strand coupling losses. It can also account for the effect of eddy currents in other metallic components of the magnet, such as the beam-screen located inside the magnets'apertures.
This paper presents the general analytical derivation and practical implementation of the coupled lumped elements, applied to the LHC main dipole magnet model. The model is validated against measurements from Fast Power Abort (FPA) tests of the LHC main dipole magnet circuits. To a good agreement, the model can reproduce frequency-dependent impedance differences of the magnet

apertures, induced by different beam-screen characteristics. In addition, the model can accurately reproduce impedance measurements under various conditions in the low-frequency range.
The model can thus be used in the frequency and time domains to reproduce electromagnetic responses while relying entirely on measured parameters and physically derived components. It can therefore be used to provide insights into frequency-dependent effects in superconducting magnets.

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Electro-magnetic modelling - 3 / 9

Demagnetizing the superconducting part of the magnetic cloak

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The combination of the superconducting and ferromagnetic materials may produce a special kind of magnetic shield, called the magnetic cloak. It offers magnetic shielding while the external magnetic flux lines are not distorted by him. However, because of the presence of the earth's magnetic field, some magnetic flux remains frozen inside the cloak after cooling it down. This phenomenon may be an obstacle for shielding applications sensitive to magnetic interference. The present study is focused on the elimination of the remnant magnetic field inside the cloak. The demagnetization with help of the dynamic magnetic resistance effect is used for this purpose. In our setup, an external magnetic field acts axially on the superconducting part of the cloak. The reduction of the remnant magnetic field requires a proper combination of exposition time and the amplitude of the applied magnetic field. Here is demonstrated the reduction of the remnant magnetic field to a value of 0.142 μT. Unfortunately, a certain number of periods and amplitude of the applied magnetic field should be found experimentally. The numerical model of the demagnetization process is in good qualitative agreement with the experiment, but the computation time is unacceptable high because of the complexity of the FEM model.