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Book of Abstracts

Contents

1D and 2D finite-element approaches to extract the resistivity of the superconductor material from pulsed current measurements on HTS commercial tapes. 1

A-formulation method for full 3D FEM computation of the superconducting magnetization 1

A-formulation method for full 3D FEM computation of the superconducting magnetization. 1

Adaptation of the nuclear safety code CATHARE3 to supercritical helium flow. 2

Adaptation of the nuclear safety code CATHARE3 to supercritical helium flow. 2

An update of dynamic thermal-hydraulic simulations of the JT-60SA Cryogenic system for preparing plasma operation 2

An update of dynamic thermal-hydraulic simulations of the JT-60SA Cryogenic system for preparing plasma operation 3

Analysis of Current Distirbution during Quench in a Pancake coil wound with REBCO Roebel cable 3

Analysis of Current Distirbution during Quench in a Pancake coil wound with REBCO Roebel cable. 4

Analysis of quench in HTS conductors for fusion applications: a novel 1D thermal-hydraulic modeling approach 4

Analysis of quench in HTS conductors for fusion applications: a novel 1D thermal-hydraulic modeling approach. 5

Comparison of quench behaviors on 2G quasi-isotropic strands made by different metal sheaths and fillers at 4.2 K 5

Comparison of quench behaviors on 2G quasi-isotropic strands made by different metal sheaths and fillers at 4.2 K. 5

Design and analysis of HTS subsize-conductors for quench investigations towards future HTS fusion magnets 5

Design and analysis of HTS subsize-conductors for quench investigations towards future HTS fusion magnets. 6

Electro-Mechanical FE modeling of CORC® cable configurations based on bending experiments 6

Electro-Mechanical FE modeling of CORC® cable configurations based on bending experiments. . . . 7

Electro-thermal 1D model of the SIS100 superconducting dipole magnet . . . 7

Electro-thermal 1D model of the SIS100 superconducting dipole magnet. . . . 8

Empowering the 4C code for the thermal-hydraulic analysis of coils for the design of future SC tokamaks: a novel, fully-3D model of the TF coil structures . . . 8

Empowering the 4C code for the thermal-hydraulic analysis of coils for the design of future SC tokamaks: a novel, fully-3D model of the TF coil structures. . . . 8

FEM Modeling Of Multilayer Canted Cosine Theta (CCT) Magnets. . . . 9

Field Quality Analysis in the HTS Dipole Insert-Magnet Feather M2 with the Finite Element Method . . . 9

Field Quality Analysis in the HTS Dipole Insert-Magnet Feather M2 with the Finite Element Method. . . . 9

Fundamental description of Field Induced Josephson junctions and devices built on their base . . . 10

Fundamental description of Field Induced Josephson junctions and devices built on their base. . . . 10

Heat transport in tilted stacks of HTS tapes at temperatures above 20K . . . 10

Heat transport in tilted stacks of HTS tapes at temperatures above 20K . . . 11

Hydraulic characterization of conductor prototypes for fusion magnets . . . 11

Hydraulic characterization of conductor prototypes for fusion magnets . . . 12

LTS magnets electro-mechanical modelling taking into account magnetic iron forces . . . 12

LTS magnets electro-mechanical modelling taking into account magnetic iron forces . . . 13

Modelling of a 50 kA REBCO Conductor with Multi-strand Made by Twisted Stacked Tapes . . . 13

Modelling of a 50 kA REBCO Conductor with Multi-strand Made by Twisted Stacked Tapes. . . . 13

Numerical Investigation of Quench Event in the Innermost Pair of the KSTAR Central Solenoids . . . 13

Numerical Investigation of Quench Event in the Innermost Pair of the KSTAR Central Solenoids. . . . 14

OLYMPE, a multi-physic platform for fusion magnet design . . . 14

OLYMPE, a multi-physic platform for fusion magnet design. . . . 15

On the Mechanical Behavior of a Nb3Sn Superconducting Coil During a Quench: Three-Dimensional Finite Element Analysis of a Quench Heater Protected Quench . . . 15

On the Mechanical Behavior of a Nb3Sn Superconducting Coil During a Quench: Three-Dimensional Finite Element Analysis of a Quench Heater Protected Quench 16

PSpice modeling of the inrush and fault currents in a 21 MVA HTS transformer 16

PSpice modeling of the inrush and fault currents in a 21 MVA HTS transformer. 16

Parametric study and optimization of the cryo-magnetic system for EU DEMO at the pre-conceptual design phase 17

Parametric study and optimization of the cryo-magnetic system for EU DEMO at the pre-conceptual design phase 17

Quench Protection Design of the HL-LHC Hollow Electron Lens System 17

Quench Protection Design of the HL-LHC Hollow Electron Lens System. 18

Quench Thermohydraulic Analysis of Tore Supra/WEST TF Coil and Smooth Quench Occurrence in Tokamak 18

Quench Thermohydraulic Analysis of Tore Supra/WEST TF Coil and Smooth Quench Occurrence in Tokamak. 19

Simulation of a cryogenic capillary tube: thermodynamic behavior subjected to heat load. 19

Simulation of a cryogenic capillary tube: thermodynamic behavior subjected to heat load. 20

Steady-state transverse heat transfer in a single channel CICC 20

Steady-state transverse heat transfer in a single channel CICC 20

Strand-Jacket Thermal Contact Resistance of REBCO Conductor Measured on Dummy Conductors 20

Strand-Jacket Thermal Contact Resistance of REBCO Conductor Measured on Dummy Conductors 21

Study on conditions for successful quench protections of coils wound with coated conductors by short-sample experiments and quench simulations 21

Study on conditions for successful quench protections of coils wound with coated conductors by short-sample experiments and quench simulations. 22

Thermal analysis of AC loss heated Nb3Sn coil samples for the High Luminosity upgrade of the LHC 22

Thermal analysis of AC loss heated Nb3Sn coil samples for the High Luminosity upgrade of the LHC. 23

Towards to Quench Limit Determination of Superconducting Magnet with use of Thermal-Electrical Analogy 23

User Defined Elements in ANSYS for Multiphysics Modeling of Superconducting Magnets 23

User Defined Elements in ANSYS for Multiphysics Modeling of Superconducting Magnets. 24

Workshop wrap-up 24

Session V / 57

1D and 2D finite-element approaches to extract the resistivity of the superconductor material from pulsed current measurements on HTS commercial tapes.

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16

A-formulation method for full 3D FEM computation of the superconducting magnetization

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A-formulation is the basic approach for solving electromagnetic problems using FEM. Utilizing time derivatives of vector potential allows computing of the critical current density distribution in agreement with the critical state model. Previously, such superconductor's representation in 2D delivered results in AC losses estimation for single wires, cables and coils with good agreement with the experiments. Unfortunately, only small part of superconducting device allows a 2D simplification. A correct interpretation for time derivative of the vector potential in 3D space requires to introduce an additional condition for current density distribution inside the superconducting domains. With such modification the modeling procedure based on A-formulation can be extended to 3D problems in superconductors.

Proposed method was used for 3D simulation of superconducting cube, placed in alternating magnetic field. Afterwards, computed current distributions in cube's cross-sections show decent agreement with those obtained by three other numerical methods –H-formulation (FEM), Minimum Electro-Magnetic Entropy Production (MEMEP) and Volume Integral Method (VIM). Experimental testing of our approach continued on modeling the magnetization of BSCCO cylinder and of single and multilayer configurations of ReBCO tapes helicoidally wound on cylindrical former. For all experiments, superconductors were magnetizing in transverse external magnetic field orientation (perpendicular to the main axis of the cylinders). Computed magnetization loops for mentioned cases show good agreement with experiments and confirm the method validity at least for used frequency range – tens of Hertz.

Session III / 51

A-formulation method for full 3D FEM computation of the superconducting magnetization.

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21

Adaptation of the nuclear safety code CATHARE3 to supercritical helium flow.

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Several international projects on nuclear fusion are in progress and comprise cryogenic systems for components such as superconducting magnets or cryopumps. Different thermal-hydraulic codes already exist for sizing and validating these devices, but there is still no qualified scientific calculation tool to perform safety thermal hydraulic analyses encountered in fusion reactors. For this purpose, we started the adaptation of the CATHARE3 system code, the reference thermal-hydraulic tool for safety studies of French Pressurised Water Reactors, developed by CEA, EDF, Framatome, and IRSN, to model supercritical Helium flows. Properties of supercritical Helium are already available in CATHARE3 with the fluid library REFPROP. We implemented suitable correlations for friction factor and heat transfer coefficient to account for high Reynolds numbers and specific hydraulic parameters typical of Helium flow in Cable In Conduit Conductors (CICC) that are used in superconducting magnets.
Several comparisons with the THEA code developed by CryoSoft were performed. We first focused on simple test cases of flow in smooth pipes, in order to identify the origin of the differences between both codes results and to assess the influence of the fluid properties database. Then we started to model a CICC, gradually increasing the complexity of thermal loads: adiabatic conditions, heat deposition relevant to burn and quench scenarios.
Simulations focusing on the behaviour of a safety device were also performed: CATHARE3 results were compared with available experimental data on supercritical Helium discharge through the safety valve of a tank in case of failure of the insulating vacuum.

Session IV / 47

Adaptation of the nuclear safety code CATHARE3 to supercritical helium flow.

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28

An update of dynamic thermal-hydraulic simulations of the JT-60SA Cryogenic system for preparing plasma operation

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The JT-60SA cryogenic system will be operated at cryogenic temperature in 2019 in closed loop, without the cryogenic users (superconducting magnets, current leads, thermal shields). It will be another opportunity to verify the efficiency of the control strategies in order to handle plasma operation planned in 2020. This paper updates the heat load profiles to be extracted by the refrigerator and its thermal buffer. The heat load profiles are calculated through thermal-hydraulic simulations of the magnets and the associated cryo-distribution, also named as supercritical helium loops. This update was performed by taking into account new data from the magnets (measured pressure drops, updated heat loads coming from the plasma), as well as a more accurate thermal model of the magnet. This paper compares the simulation results with those previously obtained with the Vincenta code in 2012. The latter were obtained for the specification of the cryogenic system acceptance tests. The new thermal-hydraulic model is performed by using Simcryogenics, the modeling tool dedicated to refrigeration and cryo-distribution developed by CEA1. The differences between the two simulation results are highlighted and analyzed. These simulations also provide the transient heat load profiles of the magnet cooling loops, highlighting a first smoothing of the thermal loads at the interface with the cryogenic system.

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Session IV / 48

An update of dynamic thermal-hydraulic simulations of the JT-60SA Cryogenic system for preparing plasma operation

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33

Analysis of Current Distirbution during Quench in a Pancake coil wound with REBCO Roebel cable

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Roebel cables assembled with HTS tapes are a promising technology for several AC and DC applications. The continuous transposition of strands, the ability to efficiently redistribute current, combined with the capability of REBCO tapes to operate at high magnetic fields allow Roebel-based devices to carry large transport currents with reduced AC losses. These features make them suitable for application to intense magnetic fields, such as in accelerator and fusion magnets.

This paper presents an electro-thermal 1D model for the analysis of quench initiation and propagation in REBCO Roebel cables. The model is based on a homogenization procedure over the strand cross section, and describes the non-uniform distributed thermal and electrical contacts between strands, thus allowing to compute consistently the heat and current redistribution during quench. The dependence of the critical current density on the magnetic field intensity and angle and on temperature is taken into account. The simulation results are compared with experimental data obtained in quench tests of a 7-turn pancake coil wound with a 2-m long, 15-strand Roebel cable. The experiments were carried out at the University of Southampton (UK) in the frame of the EuCARD-2 European project. The quench decision time, the temperature and electric potential evolution and the current and heat redistribution between strands during the quench event are analysed in this study. Given the reduced dimensionality of this 1D approach, the computational burden is reduced relative to 2D or 3D models, still retaining an accurate description of the main physical phenomena.

Session V / 58

Analysis of Current Distirbution during Quench in a Pancake coil wound with REBCO Roebel cable.

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7

Analysis of quench in HTS conductors for fusion applications: a novel 1D thermal-hydraulic modeling approach

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Several new conductor designs for fusion applications, based on High Temperature Superconducting (HTS) materials, have been proposed worldwide in the recent past. Most of them are based on the twisted-stacked-tape cable (TSTC) idea: a stack of HTS tapes, whose superconducting layer is made of rare-earth-barium-copper oxides, is twisted, soldered and embedded in a copper tube, constituting a macro-strand. Few macro-strands are then twisted together to make an HTS cable. The cable is inserted in a stainless-steel jacket which provides mechanical support to the cable and confinement for the forced-flow of supercritical helium in the interstitials between the macro-strands.
The interplay among the geometry, material properties and the He flow conditions makes the thermal-hydraulic (TH) modeling of fast transients, e.g., quench, unsuitable with the widely adopted TH codes developed for low temperature superconducting magnets, because of the thermal gradients building up in the macro-strands between the SC stack and the copper tube, and between different macro-strands.
A novel approach is proposed in the present work, which allows modelling each macro-strands, accounting separately for the SC stack and the copper tube. Compressible Euler-like equations describe the He flow in each interstitial fluid region. The dynamic distribution of the transport current between the macro-strands completes the picture.
The model developed is applied to the study of the quench in a conductor made of CroCo macro-strands –a recent design proposal made by the Karlsruhe Institute of Technology and based on the

TSTC idea. A comparison with the modeling approach adopted for quench simulations in LTS conductors is carried out.

Session VII / 68

Analysis of quench in HTS conductors for fusion applications: a novel 1D thermal-hydraulic modeling approach.

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17

Comparison of quench behaviors on 2G quasi-isotropic strands made by different metal sheaths and fillers at 4.2 K

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This paper numerically compares the thermal stability of geometrically symmetrical strands with different kinds of metal sheaths and fillers at 4.2 K, high field environments. The round configuration strands consist of 80 symmetrical stacked second generation 2G wires, metal material filler and sheath. The sheath and filler can be made by different kinds of metals such as copper, aluminum and stainless steel. Owing to the different thermal properties, different metal sheath and filler within the strand will lead to varying thermal stability characteristics like minimum quench energy (MQE) and quench propagation velocity (QPV). So, it is necessary to choose an optimal strand configuration with larger MQE and faster QPV which is most promising for the low temperature and high field magnet applications. 1D model built by THEA code and 3D electro-thermal homogenous model established by Comsol are both adopted to in the simulation.

Session VII / 64

Comparison of quench behaviors on 2G quasi-isotropic strands made by different metal sheaths and fillers at 4.2 K.

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24

Design and analysis of HTS subsize-conductors for quench investigations towards future HTS fusion magnets

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High Temperature Superconductors (HTS) are promising materials for future fusion magnets as they allow operating magnets at higher fields and/or higher temperatures and can offer significantly higher temperature margins compared to state-of-the-art low-temperature-superconductor solutions.
The high critical temperature results on the other hand in drastically different behavior of the superconductor in case of quench, e.g. a slower quench propagation velocity. Additionally, the promising HTS material Rare Earth Barium Copper Oxide (REBCO) is only available as flat tape in long length, and many high-field high-current cable concepts for fusion magnets base on the formation of so-called macro-strands, which are subsequently cabled to the final fusion conductor. Thus, the number and size of strands are additional quantities, which are significantly differing between LTS and HTS.
In this work, the design of HTS sub-size conductors for quench investigations will be presented. The samples are designed for a critical current of approx. 15 kA at operating conditions (T >= 4.5 K, B ~ 12 T) with forced flow supercritical Helium cooling. Such critical currents can be achieved for example by a triplet of HTS CroCo macro-strands. Different designs of such triplets will be discussed and analyzed by modeling with respect to the temperature and voltage evolution in the conductor in case of quench. The total stabilizer cross-section in the conductor, different thermal and electrical resistances between the individual macro-strands, helium and the jacket, and different layouts of the individual macro-strands will be considered. The software THEA will be used to calculate the quench performance of these designs under relevant operating conditions.

Session VII / 67

Design and analysis of HTS subsize-conductors for quench investigations towards future HTS fusion magnets.

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22

Electro-Mechanical FE modeling of CORC® cable configurations based on bending experiments

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Superconducting CORC® cable or wire is composed of helically wound HTS REBCO tapes in multiple layers around a round core. The cable combines isotropic flexibility and high resilience to electromagnetic and thermal loads. The flexibility of the cable is limited by the critical strain value damaging the REBCO layer in the tape. In order to optimize the manufacturing conditions and ultimately the operating performance, the mechanical behavior of CORC® cable must be comprehended for the relevant loads. A set of bending experiments is performed on simplified CORC® cable and wire configurations. Several challenges in bending experiments on simplified CORC® configurations are analyzed experimentally and these influences are accounted for proper comparison with the FEM analysis. Effects like current conduction through the copper core, transverse compressive stresses, friction between tapes and cable core and the effect of lubrication on contact resistance between tapes are studied. FEM analysis on multilayered CORC® cable and wires are carried out to check the influence of various design factors in the overall operational performance of the cable.

Session II / 45

Electro-Mechanical FE modeling of CORC® cable configurations based on bending experiments.

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12

Electro-thermal 1D model of the SIS100 superconducting dipole magnet

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The FAIR Project –a new international Facility for Antiproton and Ion Research is under construction in Darmstadt, Germany. The core machine at FAIR is the SIS100 synchrotron which utilises superconducting magnets in order to guide the heavy ion beam. The bending component of the magnetic field is generated by superferric window-frame dipole magnets symmetrically distributed over the six arc sections of the accelerator ring.
The dipole coils are wound with a LTS low AC loss Nuclotron-type cable. Due to the very thick inter-turn insulation, the coil is characterized by a strong anisotropy of thermal conductivity which enables application of a 1D electro-thermal model. This work presents the latest version of the magnet model used for the simulation of magnet's operating modes at the test facility (including quench). Since currently the series dipole magnets undergo acceptance tests at cryogenic conditions, the simulation results are compared to the available measurements.

Session V / 55

Electro-thermal 1D model of the SIS100 superconducting dipole magnet.

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19

Empowering the 4C code for the thermal-hydraulic analysis of coils for the design of future SC tokamaks: a novel, fully-3D model of the TF coil structures

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The numerical simulation tools are of paramount importance in the ongoing design process of future fusion reactors like, e.g., the Divertor Tokamak Test (DTT) facility or the European demonstrator (EU DEMO). The application of such tools in predictive mode allows to assess the performance of the different sub-systems, giving important feedbacks to the designers.
Concerning the superconducting (SC) magnet system of future tokamaks, i.e. one of the most expensive sub-systems, the 4C code [L. Savoldi, et al., Cryogenics, 2010] for the analysis thermal-hydraulic of transients has recently demonstrated his predictive capabilities [R. Zanino, et al., Supercond. Sci. Technol., 2018] and is being widely applied in the design process of both DTT and EU DEMO.
In order to reduce the cost of the magnets, and thanks to the experience gained in several experiments and to the know-how developed for the massive production of the ITER magnets, the design margins of future tokamaks will be reduced [N. Taylor, et al., Fus. Eng. Des., 2014], demanding for more detailed and reliable simulations.
To tackle this new challenge, a new, fully-3D model of the casing has been developed for the 4C code, to be coupled to the winding pack module. The improved level of detail that is achieved will be demonstrated comparing the results from the new model with those obtained approximating the 3D casing with a set of several 2D cross sections, as done in the current version of the 4C code.
The empowering of the 4C code will open up the perspective opportunity to introduce in the tool new, fully-3D pieces of physics, such as the electro-magnetics and mechanics, to compute the eddy current losses in the steel casing during current ramps or the thermo-mechanic stress during the coil cool-down.

Session VI / 61

Empowering the 4C code for the thermal-hydraulic analysis of coils for the design of future SC tokamaks: a novel, fully-3D model of the TF coil structures.

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Session VI / 63

FEM Modeling Of Multilayer Canted Cosine Theta (CCT) Magnets.

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27

Field Quality Analysis in the HTS Dipole Insert-Magnet Feather M2 with the Finite Element Method

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High temperature superconductors are a promising technology for future particle-physics accelerator magnets. They can help in overcoming the limitations and constraints in today's high-energy particle accelerators by allowing for higher magnetic fields. At the same time, accelerator magnets need to meet stringent requirements in terms of magnetic field quality. Superconductors made of HTS tapes show an inhomogeneous current distribution with respect to filamentary cables based on Nb-Ti or Nb3Sn, which is determined by the larger size and the particular geometry of the filament. Such behavior is detrimental for the magnetic field quality and could be a showstopper in the adoption of the HTS technology. For this reason, the design of future HTS magnets requires an accurate prediction of the electrodynamic phenomena in the conductors for the relevant operational conditions.

We present a 2D magnetoquasistatic simulation of the HTS Dipole Insert-Magnet Feather M2 [1]. The model relies on a formulation based on mixed potentials, implemented with the Finite Element Method. The model is validated for different temperatures against measurements from the magnet in a stand-alone configuration. The code is used to extend the results to the upgraded version of the magnet, which will be operated in a background field of 13.5 Tesla as an insert in the FRESCA2 superconducting dipole.

Acknowledgements

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Session III / 53

Field Quality Analysis in the HTS Dipole Insert-Magnet Feather M2 with the Finite Element Method.

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30

Fundamental description of Field Induced Josephson junctions and devices built on their base

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The placement ferromagnetic strip [1] or ferroelectric strip tuned electrostatically on the top of superconducting strip brings the possibility of obtaining the programmable matter. Such structures can be used for the construction of microelectronics elements. Also they can be used for quantum superconducting circuits. In this work the RCSJ model is used for the simulation of superconducting RAM memory for Rapid Single Quantum Flux electronics [2] . We also present the case of tunable detector for electromagnetic radiation built from the concept of FIJJ (field induced Josephson junction) [1]. Also the case of non-invasive superconducting detector of charge particles is drawn basing on the concept of FIJJ.

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Session VI / 62

Fundamental description of Field Induced Josephson junctions and devices built on their base.

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36

Heat transport in tilted stacks of HTS tapes at temperatures above 20K

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Tilted stacks of HTS tapes show favorable properties in terms of magnetization uniformity [1]. Magnetized stacks can be applied in superconducting rotating machines. In such case they will be subjected to varying magnetic fields and heat generation will occur. Therefore, it is important to understand heat transfer in anisotropic structure of a stack to avoid overheating and optimize the trapped flux density profile.
To analyze the heat transfer an experimental setup is build and a numerical model is developed. A localized heat source is assumed. The thermal behavior of the stacks with different angles of tilt is investigated. Results show that geometry of the stack significantly affects heat transfer. Anisotropy of the structure of the HTS tapes plays crucial role in definition of the thermal behavior of the investigated elements.

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Session I / 39

Heat transport in tilted stacks of HTS tapes at temperatures above 20K

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4

Hydraulic characterization of conductor prototypes for fusion magnets

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Mathematical models used in thermal-hydraulic analyses of superconducting cables, cooled by forced flow supercritical He (SHe), used in fusion technology, are typically 1D, and they require reliable predictive constitutive relations which characterize mass, momentum and energy transfer between different cable components. Momentum transfer is described in terms of friction factor correlations, which can be obtained from the pressure drop measurements.
Forced flow HTS conductors designed for the Winding Demonstrator (WD) or EU DEMO Toroidal Field (TF) and Central Solenoid coils consist of several CroCo or twisted stack monolithic strands, embedded in a stainless steel jacket. Such type of conductors have never been tested for pressure drop yet. On the other hand, Cable-in-Conduit conductors for the DEMO TF coils designed by ENEA have two low-impedance cooling channels, separated from the cable bundle by flat spirals, with the inner/outer diameter of about 5/7 mm, twisted together with the last cabling stage. Experimental pressure drop data for such small spiral ducts are also unavailable yet. Therefore, existing friction factor correlations cannot be validated (or new, ad hoc ones cannot be developed) before their use in predictive analyses supporting the conductor design.

To fill this gap, several dedicated short samples, namely dummy conductors with the layout similar to the DEMO HTS or WD, conductors and a small spiral-walled pipe, have been prepared and tested for pressure drop using distilled water at different temperatures. The experimental data have been used to develop experimental friction factor correlations for the considered ducts, which will be utilized in future thermal-hydraulic studies of the DEMO coils or WD.

Session I / 42

Hydraulic characterization of conductor prototypes for fusion magnets

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15

LTS magnets electro-mechanical modelling taking into account magnetic iron forces

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Keywords: High field Nb3Sn magnet ; electro-mechanical modelling ; magnetic forces ; reluctance forces ; coupling phenomena ; strongly coupled ; weakly coupled

In this paper, we aim to show mechanical analysis using models of numerous High field Nb3Sn, both Cosine-Theta and block types magnets, namely FRESCA2, Block type demonstrator for FCC, HEPDipo [1], 11 T and MQXF [2].

On these high field magnets, iron is employed for several reasons. Magnetically, the bore field can be increase and it helps in the purpose of shielding. Mechanically, iron helps on the coils pre-load, transferring the mechanical pre-load provided by the aluminium shell, for example.

For considerable Nb3Sn magnets, cable and iron pole are impregnated together. As consequence, the magnetic force applied on the iron can play an important role on the coil stress. The contributions from Lorentz and magnetic forces on coils are investigated.

The influence of the magnetic iron forces on the mechanical structure can be taking into account by using to types of coupling : strong or weak coupling. Weak coupling means that the magnetic and Lorentz forces are applied to the mechanical model but the mechanical strain and displacement doesn't affect these forces. A strong coupling happens when the mutual influence is taken into account. The difference on these methods are investigated.

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Session II / 44

LTS magnets electro-mechanical modelling taking into account magnetic iron forces

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13

Modelling of a 50 kA REBCO Conductor with Multi-strand Made by Twisted Stacked Tapes

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A 50 kA REBCO cable-in-conduit conductor (CICC) based on the Twisted-Stacked-Tape-cable (TSTC) concept is being developed in Swiss Plasma Center (SPC) for DEMO central solenoid. The conductor contains 12 or 13 strands, which is composed of a soldered stack of REBCO tapes encased with copper profile, and a copper core in center.
In this paper, a multi-strand model is implemented in THEA code to model the REBCO CICC with 12 homogeneous superconducting strands. This model includes the isotropic critical current density (Jc) of REBCO tape as well as the inter-strand current sharing and heat transfer. Quench behavior of the conductor is simulated and compared with result by homogeneous 1-D model. The strand-jacket thermal resistance, which was proved an important parameter for quench behavior of such conductor, is measured on triplet dummy. Furthermore, the feasibility of the homogeneous strand assumption is also studied.

Session VII / 66

Modelling of a 50 kA REBCO Conductor with Multi-strand Made by Twisted Stacked Tapes.

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10

Numerical Investigation of Quench Event in the Innermost Pair of the KSTAR Central Solenoids

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In 2011, the KSTAR tokamak underwent a real quench, and it is recorded as the unique event of ramp-down by quench detection in the magnet operations. Whereas many efforts had been made to survey the thermohydraulic data, such a quench-generating scenario has been identified for the first time when a minimalistic (0-D thermal) model assessed the risk of given current profile. On the other hand, any accurate modeling on the practical condition of thermohydraulic states was not established because of limited performance of the latest simulation tools for fusion magnets. Recently, mitigating the trouble of numerical instability, the thermohydraulic simulator is significantly improved owing to our effort to compensate the drawback of the coupled simulator. Thus, a thermohydraulic modeling of the quench event is successfully carried out with acceptable numerical performance. In this presentation, the numerical model is described as the post-event investigation of quench generating scenario. Based on such a simulation work, we discuss actual states of the magnet under the flow driven by the quench, whose detail cannot be known only looking into the experimental data. As a result, some tangible interpretations are presented about the conductor performance.

Session VIII / 70

Numerical Investigation of Quench Event in the Innermost Pair of the KSTAR Central Solenoids.

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18

OLYMPE, a multi-physic platform for fusion magnet design

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Design studies on tokamak superconducting magnets require a first step of pre-dimensioning followed by detailed analyses. Such analyses aim at verifying that the predefined design criteria are met in nominal and in off-normal conditions. These studies involve different physics and thus several specific numerical codes. In order to ease the process of performing these analyses, the development of a multi-physic platform is underway. This platform, called OLYMPE, integrates different solvers in a single interface.
In this paper, the structure of the platform is described, detailing the different links and coupling between the codes. The integration of the pre-dimensioning tool (MADMACS-TF) is presented, as well as the generation of a data model compiling all the information used by the codes for the analyses (geometry, loads, scenario…). Then the automatic generation of inputs for the different codes (electromagnetic, thermic, thermo-hydraulics, cryodistribution) and the post-processing of the results are detailed.

The last part of the paper presents the application of the tool on two projects. The first one is the modeling of the experimental tests performed on the JT-60SA Toroidal Field coils tested in the Cold Test Facility. Parametric studies on some defined parameters are performed to fit the experimental data (e.g. impact on the thermal loads of the winding pack detachment from the casing due to electromagnetic forces, effect of critical current law parameters used for each conductor of a given coil.) The second application focuses on the latest CEA design proposals for EU-DEMO TF magnets, in burn and quench conditions.

Session VI / 60

OLYMPE, a multi-physic platform for fusion magnet design.

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14

On the Mechanical Behavior of a Nb3Sn Superconducting Coil During a Quench: Three-Dimensional Finite Element Analysis of a Quench Heater Protected Quench

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New high-field accelerator magnets based on Nb3Sn are pushing the boundaries of magnet design and quench protection towards new limits. Their large stored energies and current densities result in a very challenging scenario for magnet protection. Furthermore, the strain sensitivity of Nb3Sn cables turns the electro-mechanical limits of the conductor into a parameter of the highest importance. The coupling of the above-mentioned considerations during quench is a case of special interest that adds further complexity to the design and protection of Nb3Sn magnets.

The objective of this paper is to provide a complete three-dimensional analysis of the coil and magnet structure mechanics during a quench event. In a previous publication [1], we presented an innovative approach on how to use a Finite Element Model, coded in ANSYS APDL, for the multiphysics study of quench processes. In this paper, we further expand the work by including the 3D analysis of the magnet mechanics during the quench transient. The results from the thermal-electric model are directly transferred as loads to the magnet's mechanical model, and thus, the coil and structure strain

evolution during quench is obtained. We focus for this time in the analysis of a quench heater protected quench, where dynamic effects are of less importance in contrast to other protection systems. Finally, the results from the simulation are compared to experimental mechanical measurements performed during the quench heater protection tests of MQXFS6 model magnet.

[1] 3D Thermal-Electric Finite Element Model of a Nb3Sn Coil During a Quench, IEEE Transactions on Applied Superconductivity On page(s): 1-8 Print ISSN: 1051-8223 Online ISSN: 1558-2515 Digital Object Identifier: 10.1109/TASC.2019.2897234

Session II / 43

On the Mechanical Behavior of a Nb3Sn Superconducting Coil During a Quench: Three-Dimensional Finite Element Analysis of a Quench Heater Protected Quench

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26

PSpice modeling of the inrush and fault currents in a 21 MVA HTS transformer

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Computer models of superconducting transformers allow for optimal selection and construction, as well as for performing numerical tests, at a time when the performance of laboratory experiments is difficult and would lead to the destruction of the transformer.
The study shows computer models of single-phase transformers with the power of 21 MVA: a conventional one with copper windings and a superconducting one with windings made of 2G HTS tape. The HTS transformer model takes into account the influence of temperature and current on the thermal and electric properties of windings consisting of two kinds of second-generation superconductor tape, differing in the copper stabilizer. Smooth transition of the YBCO superconductor layer to the resistive state is described by means of Rhyner's power law. To consider the non-linear magnetic core of the transformer in the computations a modified Jiles-Atherton model was used.
The proposed models allowed numerical determination of the waveforms and specification of the duration of impulses of the transformer's inrush current, as well as calculation of the heat and temperature increases of the windings during this process. In addition, current, resistance and winding temperature waveforms were determined and compared during operational faults of 21 MVA transformers with copper and superconducting windings.

Session V / 56

PSpice modeling of the inrush and fault currents in a 21 MVA HTS transformer.

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29

Parametric study and optimization of the cryo-magnetic system for EU DEMO at the pre-conceptual design phase

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The EU DEMO magnet system is at the pre-conceptual design phase with mechanical, electromagnetic and thermal-hydraulic analyses of different conductor designs for the Toroidal Field (TF) coils, the Poloidal Field coils and the Central Solenoid magnet. The cryomagnetic system includes the superconducting magnets cooled by forced flow of supercritical helium at about 4.5 K, the cryo-distribution lines and valve boxes, and the cryogenic system with several cold boxes. The present analysis focuses on the cooling capacity of the TF coils with three winding pack options for the cable in conduit conductors (based on 2015 DEMO baseline), featuring pancake or layer winding approaches. Parametric studies on the cold source temperature and on the supercritical helium mass flow rate, are performed on the three conductor designs in order to identify for each one the impact of the cooling conditions onto the temperature margin with respect to the current sharing temperature. In addition, Simcryogenics, a dynamic modelling tool developed by CEA, is used to model supercritical helium loops for cooling different conductor designs. An algorithm has been developed to optimize the cold source temperature and the supercritical helium mass flow, in order to minimize the refrigeration power for each conductor design. At this pre-conceptual design phase, both parametric study and optimization results are analyzed and compared in order to estimate for each TF winding pack design the impact on the refrigeration power. The interest of such quick cross-check analyses is to identify cost effective solutions for the conductor and its cryo-distribution.

Session IV / 49

Parametric study and optimization of the cryo-magnetic system for EU DEMO at the pre-conceptual design phase

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23

Quench Protection Design of the HL-LHC Hollow Electron Lens System

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Hollow electron lens systems are proposed for the depletion of particles in the halo of proton beams of modern high-energy accelerators such as the High-Luminosity upgrade of the LHC. The system allows for actively regulating the diffusion speed of particles as a complement to standard collimation systems already operating in today's particle accelerators. The High-Luminosity upgrade aims at doubling the beam intensity and increasing the peak luminosity of the LHC by an order of magnitude, which translates into a need for an improvement in the beam collimation in order to avoid highly populated beam tails in during fast failures and resulting beam movements. Studies are ongoing to investigate if this can be achieved by the use of a hollow electron lens.

The design of the HL-LHC hollow electron lens system consists of a dozen superconducting magnets, grouped into several electrical circuits, for guidance and confinement of the electron beam. The quench protection strategy and parameters have been studied in order to guarantee safe operation in nominal condition as well as failure scenarios, by maintaining the maximum voltage and peak temperature below safe limits. To this end, we employ electrical, magnetic, and thermal numerical models of superconducting magnets, busbars, and circuits. Depending on the desired accuracy, models with growing fidelity (accuracy, completeness of physics representation) are considered. In this paper, we discuss the quench protection design along with results of an integrated numerical study at both magnet and circuit levels.

Session VIII / 71

Quench Protection Design of the HL-LHC Hollow Electron Lens System.

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1

Quench Thermohydraulic Analysis of Tore Supra/WEST TF Coil and Smooth Quench Occurrence in Tokamak

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The Toroidal Field (TF) system of the Tore Supra/WEST tokamak comprises 18 NbTi superconducting coils cooled by a superfluid helium bath at 1.8 K and carrying a nominal current of 1255 A. On December 19th 2017, at the end of plasma run #52205, the quench of TFC-09, detected by a secondary thermohydraulic signal, triggered the current Fast Safety Discharge (FSD). The analyses revealed that the quench was induced by highly energetic runaway electrons which, colliding with the outboard plasma facing components, generated a high flux of neutron and gamma. A quench numerical thermohydraulic model has been developed with SUPERMAGNET (CryoSoft) code. The whole TFC-09 circular coil is modelled by THEA as a single large Cable-In-Conduit Conductor (CICC) with 2028 rectangular strands (real monolithic conductors). The external helium relief circuit (cold and warm safety valves, burst disk and magnetic valve with corresponding pressure set) is modelled by FLOWER.
The helium pressure inside the coil, upstream of the cold safety valve, has been used as comparison between measurements and calculations. The simulation results depend on the Minimum Quench Energy (MQE) applied in THEA with small initial heat deposition length (few tens of centimeters) at low field region (external leg). This energy (in the order of few kJ) is compared to the simulated shape and energy of neutron and gamma flux. The expulsed helium mass flow rate (nearly 6 kg/s during 5s) has also been evaluated. This event confirms on one hand the criticity and possible occurence of a so called "smooth quench"caused by small initial heat deposition length at low field region and on the other hand the importance of secondary signals for redundant Quench Detection System (QDS) and safe operation of other Tokamak magnets.

Session VIII / 69

Quench Thermohydraulic Analysis of Tore Supra/WEST TF Coil and Smooth Quench Occurrence in Tokamak.

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37

Simulation of a cryogenic capillary tube: thermodynamic behavior subjected to heat load.

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Pulsating Heat Pipes (PHP) are excellent heat transfer devices, constituting the thermal link between a cold sink and an object to cool. The interest for developing cryogenic pulsating heat pipes to cool superconducting magnets is growing because of their lightness and high thermal performance. A numerical model has been developed using the Navier-Stokes solver from ANSYS Fluent software to evaluate the influence of different parameters affecting the thermodynamic behavior of cryogenic working fluids in the pulsating heat pipes. An existing experiment of a single horizontal capillary tube is reproduced in the simulation where the two-phase operating fluid is computed using the VOF method in a 2D axisymmetric mesh. Different parameters are tested to analyze the liquid-vapor interface and the heat transfer between the wall and the two-phase fluid in order to contribute to a better understanding of the working fluid behavior and to the development of future 2D simulations of pulsating heat pipes.

Session IV / 46

Simulation of a cryogenic capillary tube: thermodynamic behavior subjected to heat load.

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35

Steady-state transverse heat transfer in a single channel CICC

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Current models used for thermal–hydraulic analyses of forced-flow superconducting cables, used in the fusion technology, such as, e.g. Cable-in-Conduit Conductors (CICCs), are typically 1-D. They require reliable predictive expressions for the transverse mass-, momentum- and energy transfer processes between different cable components, in order to reliably simulate the behavior of any superconducting magnet design either in normal operating conditions or during a quench evolution. Only few heat transfer correlations for flow in a CICC bundle have been proposed in the literature, but none of them is widely accepted for predictive purposes. As a result, in thermal-hydraulic studies of conductors designed for the EU-DEMO coils standard heat transfer correlations for flows in smooth tubes are used, which are undoubtedly over-conservative in this case. Systematic measurements of heat transfer coefficients in a CICC bundle should be performed to provide an experimental database for further attempts to develop a predictive correlation. In 2017 we performed first preliminary measurements of the steady-state heat transfer coefficient between a jacket wall and fluid flowing (i) in a smooth tube and (ii) in a CICC bundle of the reference sample (JT60SA TF conductor). Based on these preliminary results, recently we improved the sample instrumentation configuration, and we performed further systematic measurements of the heat transfer coefficient at various values of the water inlet temperature and mass flow rate, to obtain the results in a possibly wide range of Pr and Re numbers. The experimental data are used to develop the experimental heat transfer correlation for the considered CICC.

Session I / 40

Steady-state transverse heat transfer in a single channel CICC

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25

Strand-Jacket Thermal Contact Resistance of REBCO Conductor Measured on Dummy Conductors

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Large amount of steel will be used in the cable-in-conduit conductor (CICC) made of high temperature superconducting (HTS) REBCO tapes for European DEMO central solenoid (CS), to withstand the huge Lorenz force during operation. The maximum cross section of steel in the REBCO conductor is 2588 mm2, which is about 3 times of the total cross section of cable and helium. Consequently, heat capacity of steel will become dominant in the conductor at temperature above 20 K. This means the steel conduit can play an important role for quench protection, which is usually regarded as a critical problem for HTS, by taking the Joule heat from the quenched superconductors, but only if the thermal contact resistance (TCR) between steel conduit and superconducting cable is sufficiently low. Thus, TCR becomes important for a reliable quench simulation and conductor design.
The strand-jacket TCR is measured on dummy conductors with three copper strands, which is made of pure copper instead of the copper profile encasing a soldered stack of REBCO tapes. In the experiment, current is applied to the copper strands and temperature of strands and jacket (steel conduit) is measured. TCR is then calculated by the temperature difference between them or the increasing rate of temperature. Measurement will be done at room temperature and liquid nitrogen temperature. TCR of different kinds of conductor layouts, e.g. keep the void empty or fill with solder or thin copper wires, are measured. Influence of transverse pressure, as in the case of operation in high field, is also studied.

Session I / 41

Strand-Jacket Thermal Contact Resistance of REBCO Conductor Measured on Dummy Conductors

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31

Study on conditions for successful quench protections of coils wound with coated conductors by short-sample experiments and quench simulations

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Many coils wound with coated conductors burned, and there are arguments that the quench / thermal runaway of coated-conductor coil is peculiar and that its quench protection is difficult. Indeed, the non-uniform critical current of a coated conductor or its poor mechanical property on various aspects causes quench / thermal runaway. However, it should be noted that some coated-conductor

coils were operated at currents that were more than their local critical currents and, then, thermally ran away. Quench over the critical current is quite natural in coils wound with low Tc superconductors (LTSs). Furthermore, the amount of stabilizer was rather small in early-stage coated conductors than in LTSs. We might expect too much the stability of coated-conductor coils, because of their high critical temperatures. One of the most important issues is to determine the conditions at which a coil can be protected after quench / thermal runaway.
We are studying these conditions for successful quench protections by experiments using short pieces of coated conductor, which simulate the quench and protection processes of coils wound with coated conductors. Our focus is on the feasibility of quench protection rather than the cause of quench / thermal runaway or quench propagation. Fast turnaround experiments enable us to acquire well-organized set of experimental data. The experimental results were compared with the results of numerical quench simulations. They agreed with each other reasonably by using the heat pulse initiating quench and the coefficient of thermal conductivity between the sample and the sample holder as fitting parameters.

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Session VII / 65

Study on conditions for successful quench protections of coils wound with coated conductors by short-sample experiments and quench simulations.

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11

Thermal analysis of AC loss heated Nb3Sn coil samples for the High Luminosity upgrade of the LHC

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The High Luminosity upgrade of the Large Hadron Collider (LHC) foresees the installation of Nb3Sn based dipoles (11T Dipole) and quadrupoles (MQXF) at select points of the accelerator. In contrast to the presently used NbTi non-impregnated coils, the fully impregnated Nb3Sn coils will have a significantly different heat extraction performance in response to deposited loads. The precise knowledge of its thermal characteristics is essential in determining safe operating margins of the magnets.
With this in mind, measurements on coil-samples of these two varieties of magnets have been carried out using an experimental setup at the CERN Central Cryogenics Laboratory. The heat is generated via AC losses induced by a superconducting coil external to the samples, with the temperature measured in situ.
A numerical model has been developed using open-source software OpenFOAM, to simulate the heat flow in the combined superfluid-solid system of the experiment. The main aim is validate the robustness of the numerical solver, in particular across the domain of the heat loads used in the experiments and in future, to extend its application to models of the full magnet. Steady-state and transient behaviour of the system has been studied and is presented here. Parametrisation studies

have been used to analyse the sensitivity of the thin insulation geometries of the samples on the thermal path of the system. As an addendum, effect of presence of helium within porous parts of the solid regions is modeled to determine possible contributions to the transient thermal behaviour of the samples.

Session V / 54

Thermal analysis of AC loss heated Nb3Sn coil samples for the High Luminosity upgrade of the LHC.

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Session VIII / 73

Towards to Quench Limit Determination of Superconducting Magnet with use of Thermal-Electrical Analogy

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The superconducting magnets are an essential part of large particle accelerators. The superconductors used in winding the coils of these magnets are characterized by the critical surface determined by three parameters: the critical temperature (Tc), the critical current density (Jc) and the critical magnetic field (Bc). The energy deposited in the superconductors by the particles lost from the beam or coming from the experiment collision debris may heat up the conductor in the magnet coil and provoke the magnet to quench. The modern design of the superconducting accelerator magnets requires the thermal optimization at cryogenic conditions in terms of heat transfer from magnet coils to heat reservoir. The main challenge of the accelerators operating with the superconducting magnets is their protection against the energy deposits to the coils from the particles lost from the beam and determination of the energy limits at which beam should be dump from the accelerators in order to avoid the magnets quench.

The thermo-electrical analogy was used to develop a model of the superconducting magnets which has been used to study the thermal behavior of magnet and to determine the limits of quench of the magnets for expected beam loss profiles. The developed Network Model was used for thermal analysis of LHC Nb-Ti magnets and for optimization of Nb3Sn quadrupole magnets developed for use in the LHC luminosity upgrade. The analysis focuses on the heat transfer from the superconductor to the heat exchanger through a multilayer structure of magnet made of solid elements and channels occupied by the normal fluid or the superfluid helium. The results of the simulation by means of the Network Model were validated with measurements. A different sources of heat were implemented (magnet quench heaters, Inner Heating Apparatus) in different configurations. All simulations showed a very good agreemnt with measurements and with expected accuracy. The sources of discrepancy between the results of the simulations and measurements were related to the thermal properties of materials used in simulatiions. The developed model was successfully implemented to study of the thermal behavior of the newly developed enhanced insulation and newly designed Nb3Sn magnets. The future development of the model is foreseen by the design of a dedicated module which will introduce the energy deposits compatibile with the LHC beam pattern as well as module to study the transient mode.

9

User Defined Elements in ANSYS for Multiphysics Modeling of Superconducting Magnets

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The commercial finite element software ANSYS is widely used for mechanical, thermal, and magnetic modeling of superconducting magnets. This software includes the capability for users to create their own element type by writing the code which defines the element's properties and method by which the finite element matrices are generated. After compiling a custom ANSYS executable, all other aspects of the software (such as geometry generation, meshing, solving, and post-processing) are compatible with the user element. We report on the development of 2D and 3D user defined elements which extend the capability of ANSYS to now include the effects of interfilament coupling currents (IFCC), quench, and multivariable dependent material properties. Use of these elements with the ANSYS Multi-field solver is shown capable of simulating strongly coupled transient electromagnetic, thermal, and circuit behavior for superconducting magnets. A first benchmarking study is presented which shows close agreement between the new ANSYS elements and a COMSOL Multiphysics implementation developed at CERN for dump resistor and CLIQ based magnet protection of a Nb3Sn block dipole. Following this, the ANSYS elements are shown reproducing strong quench back behavior observed during the test of a Nb3Sn superconducting undulator prototype at Lawrence Berkeley National Laboratory. The agreement with other codes and to test data is a first demonstration ANSYS can simulate IFCC induced quench back behavior required for accurate modeling of many superconducting magnets.

Session VI / 59

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Wrap-up session / 72

Workshop wrap-up