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Nonlinear multiscale structural analysis of a superconducting coil and support structure for the helical fusion reactor

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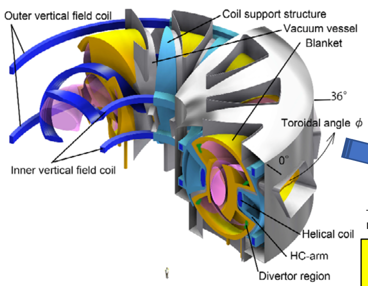
Fusion Engineering Research Project in NIFS

Outline

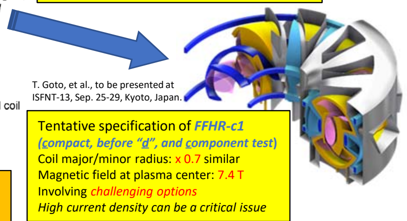
- Conceptual design studies for the LHD-type helical fusion reactor, FFHR, are being conducted in the NIFS.
  - FFHR-d1A is a self-ignition demonstration reactor. This is the basic option.
  - FFHR-c1 is a compact sub-ignition reactor that aims to realize steady electrical self-sufficiency with reduced size and higher magnetic field.
- Since an electromagnetic force is proportional to the square of the magnetic field intensity ratio, the stress on the magnet system can be extremely severe.
- Multiscale FEM analysis was performed to facilitate a detailed investigation of the magnet system in FFHR-c1.

About Helical Fusion Reactor FFHR

A. Sagara, et al., Fusion Eng. Des. 89 (2014).
H. Tamura, et al., Fusion Eng. Des., in press, doi:10.1016/j.fusengdes.2017.03.031.



Specification of *FFHR-d1A (demo oriented)*
Coil major/minor radius: 15.6/3.744 m
Magnetic field at plasma center: 4.7 T
Magnetic energy: 160 GJ
Maximum EM force in the HC;
hoop: 64 MN/m,
overturning: ±8 MN/m.



T. Goto, et al., to be presented at ISFNT-13, Sep. 25-29, Kyoto, Japan.

Tentative specification of *FFHR-c1*
(compact, before "d", and component test)
Coil major/minor radius: x 0.7 similar
Magnetic field at plasma center: 7.4 T
Involving *challenging options*
High current density can be a critical issue

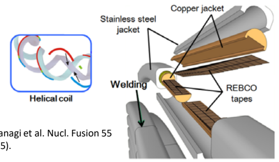
Challenging options can solve key issues in a helical fusion reactor, such as

① Winding method of the huge structure,
② Narrow radial build clearance,
③ High heat flux and neutron irradiation on the divertor, etc.

A. Sagara et al. Nucl. Fusion 57 (2017).

Challenging option #1
Joint-winding

Joint-winding with HTS is feasible for efficient construction of a helical fusion reactor.



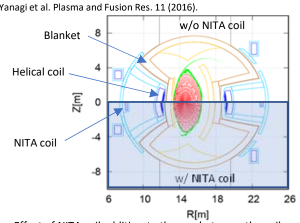
N. Yanagi et al. Nucl. Fusion 55 (2015).

Schematic image of joint-winding of HC.

Challenging option #2
NITA (Newly Installed Twist Adjustment) coil

Additional helical coils with opposite current flow increase distance between the coil and the plasma surface without decreasing the volume of the plasma.

N. Yanagi et al. Plasma and Fusion Res. 11 (2016).

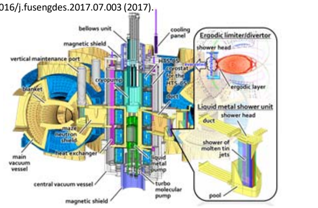


Effect of NITA coil addition to the gap between the coil and plasma.

Challenging option #3
Liquid tin divertor

Divertor with high maintainability, small amount of radioactive wastes, and high permissible heat load is necessary. Consider the flowing liquid metal for the divertor.

J. Miyazawa et al., FED, in press, doi:/10.1016/j.fusengdes.2017.07.003 (2017).

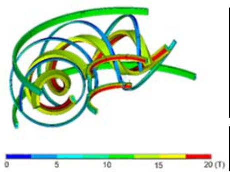


Liquid tin divertor system.

Electromagnetic force on coils

Fundamental design of a coil support structure

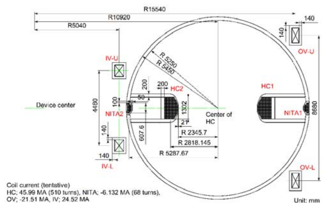
- Current density of the superconductor was assumed to be 47.87 A/mm^2,
- the support structure is made of 200 mm thick stainless steel plates.
- An electromagnetic force and stress analysis were performed to confirm a soundness of the structures.



Magnetic field distribution in the coil.

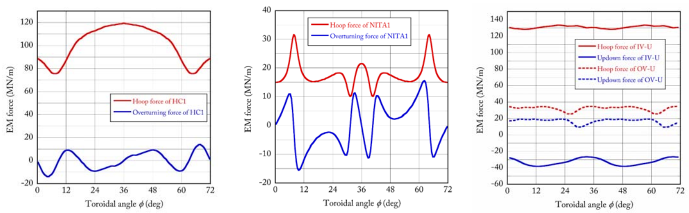
Maximum magnetic field in the coils
HC: 19.3 T
NITA: 10.7 T
IV: 18.4 T
OV: 12.6 T

Total stored magnetic energy: 156 GJ



FFHR-c1: Geometrical position of maget system at toroidal angle 0 degee

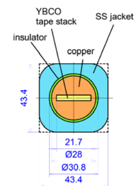
- The maximum magnetic field and EM hoop force on coils increased 1.7 times compare with those of FFHR-d1A.
- Magnitude of EM force in NITA coil was relatively small but rapid change appeared where NITA coil and VFCs were close location.



EM force at each coil cross section of HC (left), NITA coil (middle), and VFC coils (right) against the toroidal angle.

Multiscale structural analysis

Multi-scale stress analysis is appropriate for assessing the mechanical behavior of the magnet system because the components of the superconducting cable/tape, superconductor, and coil support structure have scale orders of mm, cm, and greater than 10 m, respectively, and the superconductor has an identical cross-section throughout its longitudinal direction.



Cross section of the gas-cooled HTS conductor perpendicular to the winding.

Homogenization analysis

- Equivalent physical properties of the unit cell model were obtained using the relationship between the applied 6 kinds of unidirectional strain and the averaged stress.
- Young's modulus/Poisson's ratio:
  YBCO tape; 160 GPa / 0.3,
  stainless steel; 200 GPa / 0.3,
  copper; 120 GPa / 0.3,
  insulator; based on those used for the ITER coils, ex. 20 /12 GPa for woven / layer direction, respectively.

Results

- The longitudinal rigidity was similar to that calculated using the rule of mixtures, while the transverse rigidity appeared to depend not only on properties of the material but also on the outline shape.
- The equivalent physical properties were used to describe the properties of the finite elements at the coil winding.

Obtained homogenized property of Gas-cooled HTS	
E_x (GPa)	79.6
E_y (GPa)	79.4
E_z (GPa)	156.1
G_{xy} (GPa)	44.6
G_{yz} (GPa)	43.9
G_{xz} (GPa)	44.0
ν_{xy}	0.394
ν_{yz}	0.149
ν_{xz}	0.150

Whole structural analysis model

- A support structure assumed to be made of SS316LN; Young's modulus 208 GPa, Poisson's ratio 0.3.
- EM force and the homogenized property of the conductor was assigned to the coil element.
- *Nonlinear contact element* was adopted between the coil and the coil case section of the support structure.

Result

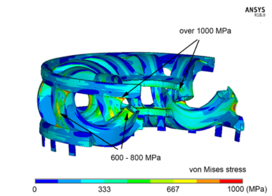
- The maximum von Mises stress in the coil support exceeded 1000 MPa in its peak.
- Spatial stress was 600 to 800 MPa.
- Gap of 6 mm appeared at the bottom of HC.
- The maximum deformation of 26.4 mm appeared in OVFC near the outer port section.
- Normal strain along the coil winding, evaluation criteria of a superconductor exceeded 0.3%.
- Shear stress in the coil are 75 MPa in maximum

Localization

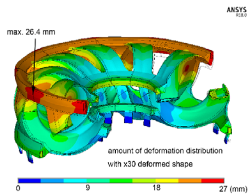
- Local stress distribution in the conductor was calculated by applying the strain of an element volume from the whole-structure analysis to the unit cell model used in the homogenization analysis.
- We focused on the region of maximum axial and in-plane stress, since those are the critical issues for the components in the conductor.

Result

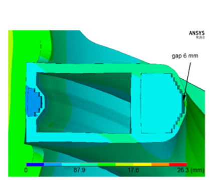
- Localization by the maximum axial stress along the coil winding: The stress level exceeded 300 MPa can be over an yielding stress of a copper. Elastic-plastic model may be needed for more precise evaluation.
- Maximum shear stress of ±75 MPa appeared in NITA / HC. The SS section of the conductor mainly shares this stress and the YBCO, copper, and insulation can be in allowable stress level.



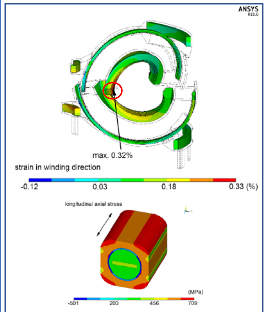
Von Mises stress distribution in the coils support structure.



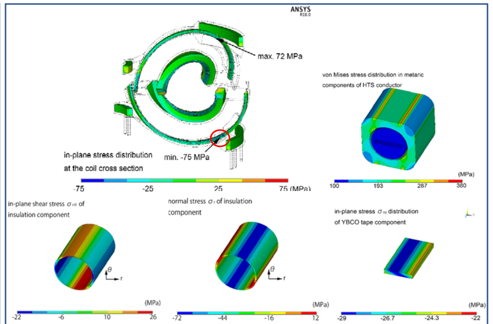
Deformation of the coil support structure.



Movement of the helical coil.



Local stress calculation using the maximum strain in winding direction of the coil.



Local stress calculation using the maximum shear strain in the cross section of coil winding.

Summary

- Structural analyses for FFHR-c1 was performed using a multiscale analytical method.
- Due to a high magnetic field on the coil, HTC would be chosen for a superconductor.
- Multi-scale structural analysis is useful in assessing the superconductors at the development phase of design since it can easily exchange a equivalent physical property of the coil element.
- Although there exists a severe stress level region in the support structure, it could be overcome by design modification such as a basic thickness and fillet addition to stress concentrated region.
- Precise mechanical behaviors of component materials in the conductor will be evaluated considering a contact and a slide among the components.