§10. Progress of the Superconducting Magnet Design for the Helical DEMO Reactor FFHR-d1

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The conceptual design studies of the helical DEMO reactor FFHR-d1 are being intensively conducted [1]. For the magnet system of FFHR-d1, 100-kA class conductors are required to be used at the magnetic field of ~13 T. The total stored energy, including the helical coils and poloidal coils, will reach ~160 GJ. For these coils, three types of conductors are being investigated as summarized in Table 1.

The force-cooled cable-in-conduit (CIC) conductor is supposed to be the primary option for the FFHR magnet [2]. This is regarded as an extension of the ITER technology using low-Tc superconductors (LTS) which has been well developed so far. To reduce the degradation of critical currents due to strains (by cooling after heat treatment, winding process and cyclic loading), Nb_3Al is to be selected for strands in place of Nb_3Sn used for ITER. The specifications of the CIC conductors and the layout of windings are being investigated. Five-parallel winding is considered to be applied to the helical coils in order to limit the cooling path of supercritical helium to be < 500 m so that the pressure drop remains within the acceptable level under nuclear heating of 500 W/m^3 at the innermost layer.

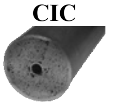
To simplify the complicated structure of windings and layout of the cryogenic plumbing associated with CIC conductors, an indirectly-cooled magnet concept using solid-type LTS conductors seems attractive [3]. To form a 100-kA conductor, multi Rutherford-type cables using Nb_3Al or Nb_3Sn are transposed, heat-treated and imbedded into a jacket. In order to secure good thermal conduction in the coil windings to accept the nuclear heating under the indirect-cooling condition, aluminum-alloy is selected for the jacket. The Friction Stir Welding (FSW) technique has been successfully applied to make the longitudinal seal of the jacket. Scaled-down conductors of 5 kA@12 T class have been successfully tested and the critical current shows good agreement with expectation including the bending strain.

For the both options of LTS conductors, the winding process of the continuous helical coils is being investigated in detail based on the experience of the LHD construction. In case of using CIC conductors, heat treatment for reacting Nb_3Al should be done by installing conductors into a bobbin equipped with a furnace. Then, the conductors are transferred to the reel located on the winding-machine and the bending strain of 0.15% is considered to be applied in this process. The conductors are then extracted from the reel, bent, helically twisted and wound into the helical coil cans. During the winding, the torsional strain of maximum ~0.6% is expected to be applied, which should be accepted for Nb_3Al strands [2].

As an alternative, high-Tc superconductors (HTS) could be a counter option to be considered based on the quickly progressing YBCO coated-conductors technology [4]. Though the HTS has not yet been applied to large-scale magnets, a number of advantages, such as high cryogenic stability and low refrigeration power at elevated temperature operations (>20 K), suggest good potentiality. High mechanical strength of the winding package is also expected due to the strong substrate used for YBCO tapes as well as to the stainless-steel jacket of the conductor. For developing a 100-kA conductor, we commenced a project of 10 kA-class conductor testing, which have shown successful results. Using HTS conductors, it is feasible to propose that the large-diameter continuously-wound helical coils be assembled by joining prefabricated half-pitch conductors on site. Measurement of the joint resistance with 10-kA conductor samples shows that the additional refrigeration power could be <5 MW for 8000 joints along the helical windings. Further reduction of the joint resistance is expected. A 100 kA class conductor will be tested soon.

1) Sagara, A. et al., Fusion Eng. Des. **83** (2008) 1690.
2) Imagawa, S. et al., Plasma Fusion Res. **3** (2008) S1050.
3) Takahata, K. et al., Fusion Eng. Des. **82** (2007) 1487.
4) Yanagi, N. et al., Fusion Sci. Tech. **60** (2011) 648.

Table 1. Three options of conductors for the FFHR-d1 magnet system.

	Features	Requirements	Results and Near-Term Plans
CIC 	**Developed from LHD to ITER** **High cryogenic stability and low cost** **Nb_3Sn strands established** **Nb_3Al strands strain resistant**	**Nb_3Sn cyclic loading** **Nb_3Al mass production** **Winding method** **Cooling path and layout**	**Evaluation of ITER technology** **JT-60SA conductor tests at NIFS** **Nb_3Al strand testing** **1D analysis of nuclear heating**
LTS Solid 	**Reduced strain by react-and-jacket** **Uniform current distribution** **Al-alloy jacket for thermal conduction** **Simple winding structure**	**Cryogenic stability with indirect cooling** **Nuclear heating** **Winding method**	**FSW of Al-alloy jacket established** **5 kA@12 T conductor with expected critical current** **20 kA@12 T conductor test planned**
HTS Solid 	**High cryogenic stability with indirect cooling** **High mechanical strength** **Segmented fabrication plausible** **Wide applications for electrical devices**	**Conductor optimization** **Joint technique and assembling process**	**15 kA@8 T conductor successful** **10 kA joint test carried out** **100 kA@12 T conductor test planned**