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Design and Development of High-Temperature Superconducting Magnet System with Joint-Winding for the Helical Fusion Reactor

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Conceptual design studies of the LHD-type helical fusion reactor, FFHR-d1, are progressing steadfastly. The magnet system consists of a pair of helical coils (major radius 15.6 m) and two pairs of vertical field coils. A 3 GW fusion power generation requires a toroidal magnetic field of 4.7 T and the total stored magnetic energy reaches 160 GJ. A conductor current of 94 kA is needed at the maximum magnetic field of 12 T. We select the high-temperature superconducting (HTS) conductor as a plausible candidate owing to a number of advantages, such as high cryogenic stability and excellent mechanical rigidity. Simple stacking of YBCO tapes is proposed to fabricate a large-current capacity conductor with high mechanical strength. Formation of non-uniform current distribution among HTS tapes having no transposition and twisting is allowed due to the high cryogenic stability. An innovative winding method is proposed by connecting prefabricated half-helical-pitch HTS conductors, which drastically facilitates the in-situ fabrication process compared with a case of constructing a 50-m-diameter winding machine. A bridge-type mechanical lap joint is a viable technique having a staircase-like structure to make face-to-face connection of YBCO surfaces. The joint fabrication should be carried out by an industrial robot. The conductor has internal insulation around the copper jacket. The outer stainless-steel jacket is welded between neighboring conductors to secure mechanical rigidity of windings and to skip the vacuum pressure impregnation process that needs to raise the whole coil temperature to 150 centigrade to fill gaps between windings by epoxy resin. The conductor surface is cooled by gas helium through cooling channels formed on the stainless-steel jacket. A large-scale HTS conductor sample with a 3-m length was fabricated using GdBCO tapes and successfully tested. The maximum current reached 100 kA at 5.3 T and 20 K. A numerical simulation, solving the magnetic field and current density profiles self-consistently among HTS tapes, shows good agreement between the measured and calculated critical currents under a wide range of magnetic fields and temperatures. The joint resistance was evaluated to be 2 nano-ohms, which assures that the Joule heating produced at 7,800 joints in the helical coils be cooled by <5 MW of electricity in the cryoplant.

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