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ALCATOR DCT MAGNETIC SYSTEMS DESIGN

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Abstract - A 2 meter major radius tokamak with 24(150 x 200 cm)10 tesla peak field superconducting coils and an all superconductor PF system is described. All coil systems utilize internally-cooled conductor concepts.

MACHINE DESCRIPTION

The Alcator DCT is a 2 meter major radius, 7 tesla on-axis field machine which follows in the Alcator tradition of a compact high power density, high performance approach, but unlike its predecessor, is dedicated to long pulse issues. The long pulse requirement in a compact machine has dictated the use of superconducting magnets for both the toroidal and poloidal coil systems.

The machine has a relatively large plasma aspect ratio of 5, more typical of reactors than present-day tokamaks. The larger aspect ratio allows this machine to have a very large inductive drive (35 volt-seconds) allowing pulse times of several minutes at densities too high for RF steady-state current drive, which will however, be possible at reduced densities. Steady-state RF power will include 5 MW of ICRF heating and 4 MW of LH current drive. The machine has 24 toroidal field coils, "Dee" shaped to accommodate elongated plasmas (K = 1.6) and to incorporate a single null poloidal divertor. The stored energy in the toroidal field is 550 MJ.

As shown in (Fig. 1), the superconducting coil systems are contained in a common vacuum system as is typical of tokamak reactor designs. Each toroidal coil is in a separate heavy-walled cryostat which serves as both a structural support and cryogenic containment vessel. The central OH coil and individual poloidal field coil packages are contained in individual nonstructural vessels, of special construction to increase their toroidal resistance.

The plasma chamber and access ports utilize a second independent vacuum system, allowing vacuum-break access to the vessel without warm-up of the superconducting magnets. Vertical access is provided between every coil, but horizontal access is only provided at every other coil in order to allow for structure to resist the overturning moments. The cold mass is supported from the central section of the common vacuum chamber, allowing removal of both covers. The central section is in turn supported from the floor by out-board legs, allowing removal of all PF coils if required.
TOROIDAL FIELD MAGNETS

The DCT design requires a 10 tesla peak field at the conductor. The two TF magnet approaches generally considered for fields above 8 T are Nb$_3$Sn at 4.2 K, or NbTi at 1.8 K. Niobium-tin has the disadvantage of requiring stringent quality control to assure undamaged material properties, and 1.8 K NbTi requires a more complex cryogenic system and a "double case" magnet support concept. We have chosen Nb$_3$Sn based on its advantages of a simpler requirement on cryogenic systems and a greater energy margin for stability against disturbances, particularly at higher fields.

We have selected the niobium-tin conductor of the type used in the Westinghouse LCP coil and in the MIT 12 tesla test coil. (Approximately twenty-two tonnes of this conductor have been fabricated by Airco, approximately 40% the total needed for all the DCT coils.) While Alcator DCT will use the bronze-process Nb$_3$Sn conductor used in LCP, we have proposed four improvements: (1) heat treatment after winding, which will relieve the need for several difficult quality control steps during winding; (2) elimination of the substructure support plates which will lead to a more economical construction; (3) use of pool-boiling helium outside the ground wrap to provide a simple technique for removing average heat loads while stagnant helium internal to the conductor provides a high degree of stability; (4) use of a dual cycle heat treatment and an Incoloy 903 sheath, which together dramatically reduce the strain degradation of the material. /1/

The energy margin against the effect of plasma disruptions and other disturbances, is predicted to be about 500 mJ/cm$^3$ of wire for the conductor. This margin has been confirmed on sub-scale conductors utilizing fewer full scale strands, and is consistent with levels predicted by the analytical models. Disruptions are expected to deposit approximately 50 mJ/cm$^3$ and hence the conductor should have a large margin of safety in this regard.

The winding will be constructed from six double pancakes which are 11 layers deep. At 10 tesla peak field, the conductor operating current will be 23 kA, 58% of the critical current at 10 T, 4.2 K, and 32% void fraction. As in the MIT 12 tesla coil /2/, we propose to heat-treat the conductor after winding to eliminate the danger of accidental damage during winding. After heat treating, the turns can be easily separated, reinsulated, and the pancakes then epoxy impregnated. Each double pancake will be epoxy impregnated separately and will consist of a single 150 meter length of conductor. We believe that this ability to epoxy impregnate and fully insulate the winding gives rise to a winding pack of more predictable modulus than a non-impregnated winding, and one with better insulation characteristics.

It is not necessary to circulate helium for stability (local pressure-driven mass flows provide adequate transient heat transfer,/3/) but it is necessary to remove the average heat load over a cycle due to disturbances and heat leakage. While this could be done by low velocity circulation of the supercritical helium, it may be easier to simply provide access for atmospheric pressure 4.2 K helium to the faces of the winding pancakes. The conductance of the thermal path, even through the epoxy-glass ground insulation of the pancakes, would be sufficient to remove the average heat. Each double pancake will therefore be assembled with spacers to provide 1.5 mm gaps to provide supplemental external cooling.

The winding pack will be entirely supported by the heavy wall case which surrounds it. The conductor steel conduit is not expected to carry appreciable in-plane tension load, (although it is capable of carrying significant loads), but must carry the radial compression loads within the winding pack. We have performed mechanical tests on arrays of conductors which have been potted into a support case, and infer from the linear behavior that the average radial pressures of 50 MPa on the lowest field conductors can be readily accommodated. The potting appears to play an important role. Alcator DCT in a single-null divertor configuration experiences a strong non-symmetric out-of-plane load. The method for resisting the overturning moments is to utilize stiff top-to-bottom elements between every other coil, and to use fasteners and keys on all slip surfaces.
Fig. 1 - Elevation view of Alcator DCT.
POLOIDAL FIELD MAGNETS

We have chosen to use superconducting poloidal field coils on the DCT machine to provide the most economic solution for the capability to run long pulses. Were the PF coils to be copper rather than superconducting for example, they would consume more than 100 MW at full excitation. The proposed coil set shown in (Fig. 1), is a hybrid system in that any given coil performs multiple functions, for example, both an inductive drive and an equilibrium function, or both a divertor and a shaping function. This approach is typical of next-step designs, but is a departure from tokamaks in which the inductive drive (OH coils) and equilibrium (EF coils) are independent decoupled systems.

The PF coils will be exposed to field changes of about 3 T/s during the current ramp, and 0.3 T/s during the long flat top. The central solenoid will additionally be exposed to a 30 T/s rate during the initial plasma break-down phase. Disruptions produce about 0.3 T changes in 10 milliseconds as controlled by the vacuum vessel time constant. These field changes, together with control field variations require use of a reasonably finely divided PF conductor to assure stability and a reasonable level of ac loss.

Internally cooled conductors, again in the form of the Westinghouse/Airco conductor are under study as the leading PF conductor choice. That conductor form is sufficiently subdivided and has a large coil manufacturing data base through LCP. While such PF conductors might well utilize Nb3Sn strands, the lower fields typical of the PF coils allow NbTi strands (7.0 tesla central solenoid, 2.0 to 5.0 tesla, EF coils). The internally cooled conductors permit full epoxy impregnation and therefore such superconducting PF coils can share in the large data base for impregnated copper conventional coils. Non-impregnated pool-cooled cable conductors have a very limited mechanical performance data base.

Alcator DCT can use the Westinghouse/Airco sheath in exact form (although made from 316 LN stainless-steel) in order to utilize the existing tube mill without further development. A PF conductor would typically need to have a copper to superconductor ratio of 5 to 1 to give adequate stability under pulse field conditions and hence would necessarily have a lower overall current density than the DCT TF conductors. A sheath of the Westinghouse/Airco dimension could carry a cable capable of carrying 12.5 kA, half that of the TF conductor. We would propose to use two or more such conductors wound-in-hand to build up a suitable total current level of 25 kA to 50 kA.

REFERENCES