COIL DESIGN FOR HELIAC, A HELICAL AXIS STELLARATOR

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Résumé - On décrit un stellarator à axe hélicoïdal (Héliac) pour le confinement de plasma à Bêta élevé. On présente un projet préliminaire et l'analyse des forces et contraintes.

Abstract - A proposed Helical Axis Stellarator (Heliac) for High-Beta plasma confinement is described. A preliminary design and analysis of loads and stresses is presented.

The helical axis stellarator (Heliac) is a magnetic configuration for plasma confinement which offers the possibility of stable high-beta steady-state operation. The plasma has a bean-shaped cross-section which spirals as it goes around the major circumference. The HX-1, a heliac of 1.5 m major radius, is a proposed embodiment of the configuration.

The overall arrangement of the machine is shown in Fig. 1. It contains toroidal field (TF) coils, as in a tokamak, but the arrangement of these coils is not circularly symmetric. Rather, the centers of the toroidal field coils describe a helix around the poloidal field (PF) core. In the proposed HX-1, the major circumference around the machine contains three periods. The poloidal field core is a circular coil which links the toroidal field coils. There is little or no plasma current, but a small ohmic-heating solenoid is provided for initiation of plasma. Finally, a uniform vertical field is provided by a set of external coils. In HX-1, the vacuum vessel follows a helical path through the bore of the TF coils. In general, the coil system is simpler than that of a tokamak with the possible exception of the interlocking feature of the poloidal field core. In comparison with other stellarators, the heliac configuration can be produced using only circular coils, which are considerably simpler than the helical coils required by most other stellarators.

The interaction of the PF and TF coils in a Heliac produces magnetic surfaces which are bean-shaped and which also have a magnetic well (local minimum in magnetic field magnitude) located within the plasma cross-section. These two features combine to give a predicted limit of 10% to 20% for beta (the ratio of plasma pressure to magnetic pressure). This is substanially larger than the beta limit for present-day tokamaks and stellarators, and would be an important advantage toward a practical reactor.

OVERALL PARAMETERS

The major parameters of the proposed HX-1 machine are given in Table 1. One of the basic assumptions in this design was that the machine would use toroidal field coils which already exist from an earlier machine at the Princeton Plasma Physics Laboratory. Their inside radius is 0.56 m. The average major radius of HX-1 is 1.47 m, and the average toroidal field is 1.1 T. This toroidal field is relatively low compared to existing plasma confinement experiments, but it is associated with the goal of exploring high beta plasma regimes. Four different currents are used in

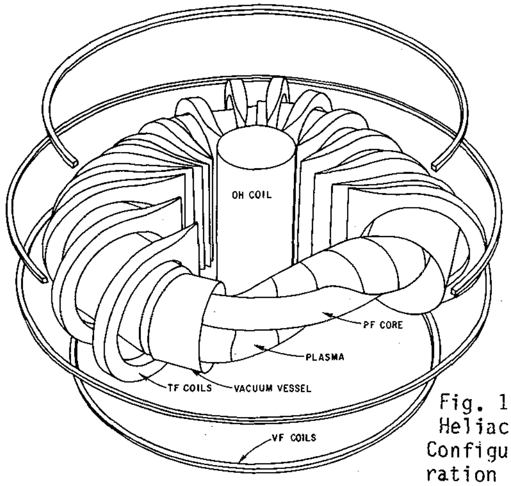

Fig. 1: Heliac Configuration

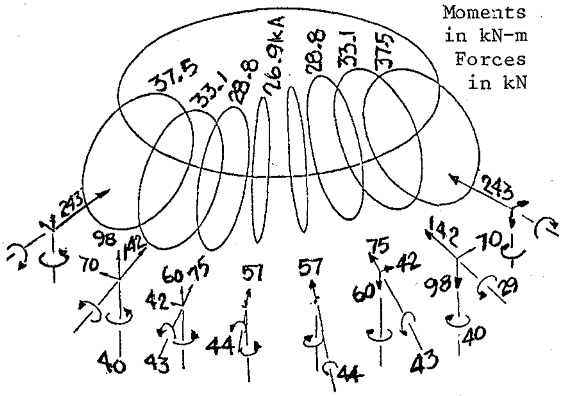

Fig. 3 : Loads on Toroidal Field Coils

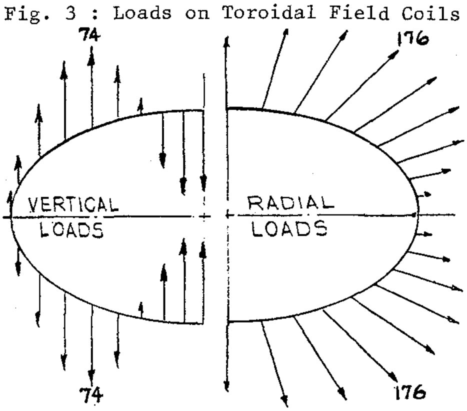

Fig 4: Loads on Poloidal Field Core (kN/m)

TABLE 1: PARAMETERS OF HX-1

OVERALL MACHINE PARAMETERS	
Average Major Radius (m)	1.4688
Minimum Major Radius, Plasma Axis (m)	1.2025
Maximum Major Radius, Plasma Axis (m)	1.8377
Aspect Ratio	4.96
Average Toroidal Field (Tesla)	1.1286
Number of Field Periods in Major Circumference	3
Pulse length, equiv. square wave (sec)	1.5
Repetition time (sec).	180
TOROIDAL FIELD COILS	
Inside Radius of Coil (meter)	0.56
Outside Radius of Coil (meter)	0.725
Number of Coils	24
Turns per Coil	10
Coil Currents:	
I1, I8, I9, I16, I17, I24, (kA)	37.5
I2, I7, I10, I15, I17, I23, (kA)	33.1
I3, I6, I11, I14, I19, I22, (kA)	28.8
I4, I5, I12, I13, I20, I21 (kA)	26.9
Total NI (Mega-Ampere-Turns)	7.578
Number of Coolant Paths per Coil	2
Peak Temperature (°C)	85.
POLOIDAL FIELD CORE	
Major Radius (meter)	1.46875
Minor Radius: (main body of torus)(m)	0.305
(joint regions only)(m)	0.387
Number of Turns	24
Current (Kilo-Ampere)	37.5
Total NI (Mega-Ampere-Turns)	0.9
Conductor Size	73mm x 16.7 mm
Water hole dimensions	15.9 mm x 6.4 mm
Number of Coolant Paths	2
Peak Temperature (°C)	42.
OHMIC HEATING COILS	
Total Turns:	100
Mean Coil Radius (m)	0.4
Overall Solenoid Length (m)	2.
Current (Kilo-Ampere)	11
System Maximum Volt-Sec	0.2
Copper Size (Square); Hole Dia.	15.2 mm; 6.4 mm
VERTICAL FIELD COILS	
Turns	100
Current (Kilo-Ampere)	3.0
Total NI (Mega-Ampere-Turns)	0.336
Uniform Field (Tesla)	-.0653
Copper Size (Square); Hole Dia.	11.1 mm; 6.0 mm

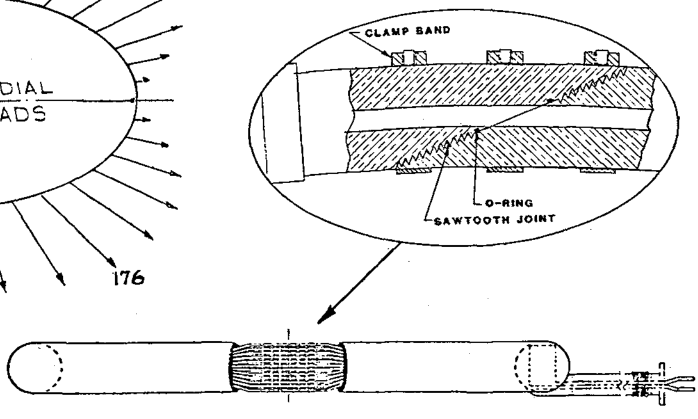

Fig. 2: Details of Poloidal Field Core and Splice Joint

different TF coils so that the plasma sees approximately the same toroidal field despite the fact that the major radius of the center of the plasma changes as the plasma spirals. The maximum current in a toroidal field coil is 37.5 kA. Although the Heliac configuration is capable of steady-state plasma confinement, the HX-1 is designed to operate on a pulsed basis because of thermal limitations of the existing toroidal field coils. These coils are sharply shaved at the nose, a feature not required for Heliac.

Each toroidal field coil is supported at three locations: at a line support (column) all along the nose, and at support pads near the top and bottom of each coil. The column support at the coil nose extends from a lower shelf to an upper shelf, which are connected to each other by diagonal braces in a manner similar to the torque frame of many tokamaks. The ohmic heating solenoid and the vertical field coils are conventional copper coils with the parameters given in Table 1. The primary plasma heating method in HX-1 is neutral beams.

POLOIDAL FIELD CORE DESIGN

The major design requirements of the poloidal field core are that it interlocks the toroidal field coils, and that it must be surrounded by a vacuum-tight stainless steel liner. The interlocking feature requires either a wound-in-place core or a core with a joint in it. Wind-in-place schemes were considered using pre-insulated water-cooled cable-type conductors, but were rejected because of space limitations and the difficulty of fabricating the liner around a wound-in-place core.

The selected method uses a pre-fabricated core split into 180° sectors to permit installation within the bore of the vacuum vessel. Each sector will be potted with epoxy inside a 1.5 mm thick stainless steel vacuum liner. The relatively thick liner is permitted because the Heliac does not require current induced in the plasma by the ohmic heating coil. The individual turn halves will be joined by mating sawtooth faced, scarf joints similar to those which have been used successfully in the ASDEX Tokamak for several years now. This type of joint is compact and it carries both coolant and current and transmits tensile loads. The use of such a demountable joint requires that all turns be accessible from the exterior, i.e., a two-layer winding. In order to efficiently fill the circular core with a 12 turn x 2 turn winding bundle, the conductor must be elongated with a racetrack-shaped coolant hole. The joint region causes a bulge in the exterior of the core, but this is acceptable. Details of the core are shown in Fig. 2.

POLOIDAL FIELD CORE MANUFACTURING AND MACHINE ASSEMBLY

The core liner is made of two half-toruses spun of 1.5 mm thick type 305 stainless steel and cut into segments to fit the core halves. The joint regions of the liner are slightly larger. The copper winding is half-hard extruded Alloy CDA-102 copper, with the turn halves being stretch-formed to minimize "keystoning" of the cross-section. All turn-to-turn and layer-to-layer transitions are hydraulically die-formed. The individual conductors are insulated with Mylar tape and fiberglass tape. After the coil turn segments are stacked and positioned, the bundle is insulated with fiberglass tape. This assembly is placed inside the liner and vacuum-pressure impregnated with epoxy of the same formulation use to fabricate the TFTR poloidal field coils. After the epoxy is cured, the joint ends, joint teeth and O-ring grooves are milled in the ends of each core half.During machine assembly, the toroidal field coils and vacuum vessel sectors are assembled into two 180° arcs with a core half rotated into each arc. These are then brought together with the core halves touching but the vacuum vessel halves slightly displaced sideways. This gap in the vacuum vessel provides room for assembly of the splice joint. Finally, the vacuum vessel is closed.

LOAD DEFINITION

The loads on the TF coils are given in Fig. 3 for one of the three periods in the helix. Numerical values are labeled for the larger magnitudes of each load. The toroidal field coils experience radially inward (centering) forces and overturning moments as in a tokamak, but they also experience net vertical loads, net lateral loads, and moments around the vertical axis of the coil. The latter occur because of the oscillation in the locations of the toroidal field coils, and because of the different currents in different toroidal field coils. The loads on the poloidal field core are given in Fig. 4. The vertical loads produce cyclical out-of-place bending, and the radial loads act to bend the core in-plane into a triangular shape. The maximum radial load is 2.4 times as large as the maximum vertical load.

STRESS ANALYSIS:

The stresses in the machine structure and the toroidal field coils are found to be generally low. In the toroidal fields coils the maximum combined hoop and bending stress is 45 MPa (6.5 ksi). In the machine structure the stress levels are less than 70 MPa (10 ksi). The machine structural design is deflection-limited rather the stress-limited. The worst case deflections of points on the TF coils and pedestals are .38 mm (15 mils) to .51 mm (20 mils) if the structure is made of stainless steel.

Stress analysis of the poloidal field core is important mainly because of the teeth used in the demountable joint. These teeth introduce a stress concentration factor of approximately 5 (defined as stress at the root of the teeth divided by average tensile stress in the nearby winding). The stresses in the poloidal field core are primarily bending stresses. In the ASDEX OH coils, the nominal hoop stress away from the joint was 24.8 MPa (3.6 ksi), and fatigue testing to 500,000 cycles was done at 37.2 MPa (5.3 ksi) with no adverse effects. Thus, the design for Heliac must limit stresses in the poloidal field core to values in this range.

Two sets of assumptions strongly influence the stresses calculated in the core: the bonding conditions between the copper and the insulation, and the load support conditions. The assumption used for the bonding was conservative but not completely pessimistic, i.e., partial slippage between turns. Supports were assumed to have the stiffness of the overall machine structure for loads along their length, but no stiffness for loads in other directions or for moments in any direction. In all cases the supports connect to the core from the side away from the plasma.Three different support arrangements were assumed. For the case of the six vertical supports, the peak stress is 76 MPa (11 ksi). For the case of the six radial supports, the peak stress is 51 MPa (7.4 ksi). The lowest peak stress, 26 MPa (3.8 ksi), is obtained with 12 supports, i.e. both sets of supports used in the previous two examples. The splices occupy a large enough angle that some parts of them will probably be in peak stress regions. The tentative conclusion is that a sufficiently low peak stress can be achieved with the 12 support arrangement but probably not with the 6 support arrangement.

RELATED WORK ON HIGH BETA PLASMAS AT PRINCETON

Although the Heliac machine is still in the proposal stage, related work is now being done at Princeton to produce a bean-shaped plasma in an existing tokamak. The PDX (Poloidal Divertor Experiment) is being modified and is renamed PBX (Princeton Beta Experiment). The modification consists of moving and adding coils within the vacuum vessel, without any major disassembly of the machine. First Plasma with the new configuration is expected late this calendar year.

Also, theoretical work is being done on a Helical axis stellarator design which may eliminate the need for a poloidal field core by using noncircular but planar coils.

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