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Fusion Development Facility (FDF) Coil Mechanical and Structural Design*

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***Abstract*—The Fusion Development Facility is intended as an intermediate step between ITER and DEMO. It provides a long term, high fluence test bed for components. ITER provides long pulse operation, but the neutron exposure of the ITER first wall components is well below what will be experienced in DEMO. FDF would be a nuclear machine, requiring remote handling. Coil systems would have to be de-mountable in order to access and change-out blanket modules and other internal components. FDF is a steady state copper machine to satisfy a low initial cost, at the expense of large resistive power losses in the magnets. Active water cooling is required for steady state operation.**

Structural solutions are investigated that allow support of the large centering and separating forces in the TF coils, while providing a capability to disassemble the legs of the TF coils. The TF coil configuration is a picture frame coil made up of straight legs with joints at the corners. Two types of joints are being considered. Sliding joints analogous to those used in C-Mod and MAST are the first joint to be considered. These allow relative motion to occur at the corners of the picture frame.

The second joint concept being considered is a sawtooth compression joint suggested by P.H. Rebut in "Remarks on FDF GA proposal," November 2007. Steady state, low cycle operation, with minimal fatigue considerations allows this type of joint to be considered. Large compressive forces are supplied by an external preload ring.

Analysis of these two concepts addresses the feasibility of the concepts. Other joint concepts such as that developed for the Tokamak Fusion Core Experiment (TFCX) are discussed.

Keywords; fusion magnets, component development facility, high fluence, high heat flux, demountable TF coils

I. Introduction

The Fusion Development Facility is intended as an intermediate step between ITER and DEMO. It provides a long term, high fluence test bed for components. ITER provides long pulse operation, but the neutron exposure of the ITER first wall components is well below what will be experienced in DEMO. FDF would require remote handling. Conventional fixed TF coils must be large to produce acceptable ripple, and access for radial blanket removal. FDF TF Coils are de-mountable in order to access and change-out blanket modules and other internal components with a minimum size of the coil system and thus minimal resistive power consumption. FDF is a copper machine to satisfy a low initial cost. Active water cooling is required for steady state operation.

Structural solutions have been investigated that allow support of the large centering and separating forces in the TF coils, while providing a capability to disassemble the legs of the TF coils. The TF coil configuration is a picture frame coil made up of straight legs with joints at the corners. Two types of joints are being considered. Sliding joints analogous to those used in C-Mod and MAST are the first joint to be considered. These allow relative motion to occur at the corners of the picture frame. Large forces acting on the TF coils produce large strains, that would normally concentrate at a corner in a rectangular coil layout. The sliding joints allow relative motion to relieve these strains. Both the C-Mod and MAST sliding joints are inertially cooled. FDF sliding joints would have to have active cooling added. A scheme to accomplish this, developed for the Steady Burn Experiment (SBX) [1], is discussed in Section VI.

The second joint concept being considered is a sawtooth compression joint suggested by P.H. Rebut [2]. Steady state, low cycle operation, with minimal fatigue considerations allows this type of joint to be considered. Large compressive forces, needed to maintain adequate contact resistance, are supplied by an external preload ring. Radial jacking mechanisms similar to those proposed for FIRE or IGNITOR would be needed. See [3] p 5.1-9 .

The important behavioral issue to resolve for both these joint concepts is the maintenance of adequate electrical conduction through the joint for the full range of in-plane and out-of-plane Lorentz loads and thermal differential motions.

Disassembly and servicing procedures for these two concepts are discussed in a companion paper by John Smith titled "Fusion Development Facility" [4].

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II. FDF Parameters and Comparison with Other Machines (Table I)

TABLE I. COMPARISON OF COPPER MACHINES

	FDF	DIII-D	SBX	C-Mod
I_p MA	6.7	3.5	3.75	2.3 (3 Design)
R_0 (m)	2.49	1.67	2.0	0.665
B_0	6T	3.4T	6T	9 (8.5 peak to date)
Fusion power	246 MW	~0	30–60 MW	~0
Total plant power MW	507		418	220 to 300
Peak field at TF inner leg	13.5	8.96T		18.58 Tesla
Minor radius, a		0.67		0.021
Elongation	2.31	2.3	2	1.8 (original?)
Aspect ratio		2.5	4.0	
Pulse length	Steady State	~10	Steady state	1 s at 9T 5 s at 5.3T
Number of TF coils	16		10	20
Turns per TF coil			18	6
TF material		AgCu	OFHC Cu	Steel reinforced OFHC
TF coolant	Water		Water (toluene?)	LN_2 inertial
Ave inner leg current density, kA/cm^2	1.6	2.81	2.32 to 2.45	10.5

III. Joint Structural Concepts Considered for FDF

A. *Sliding Finger JointsWith Large Cover Weldment*

The first concept is based on Alcator C-Mod and a scale-up study of C-Mod called the Steady Burn Experiment(SBX). It uses sliding finger joints (Fig. 1) and a large cover structure to support the vertical separating forces. A discussion of the C-Mod finger joints may be found in [5]. The global model for this concept is shown in Fig. 2. The additional height required for the deep cover weldments is evident.

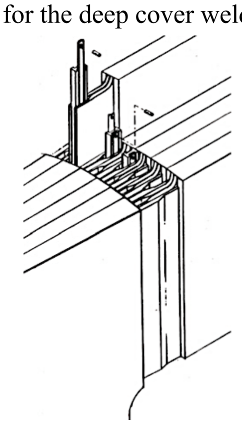

Figure 1. C-Mod sliding TF joint.

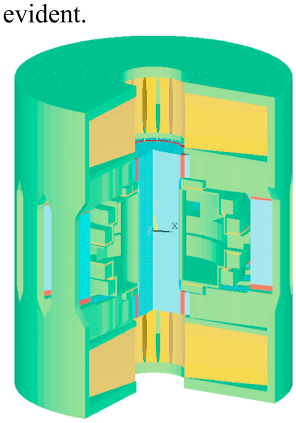

Figure 2. FDF sliding joint concept. Each cover is 3 m high.

B. *Compression Joint with External Ring*

The second concept, uses toothed engagement of the horizontal legs into the central column. An external ring is envisioned to impose a large radial load on the joint to ensure adequate contact. The global model for this concept is shown in Fig. 3, and local modeling of the saw teeth is shown in Fig. 4. The large external rings provide the radial compression required for the sawtooth joints at both the inner and outer legs.

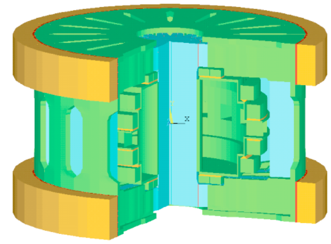

Figure 3. FDF compression joints with ring. The ring is 0.86x2.4 m in this model.

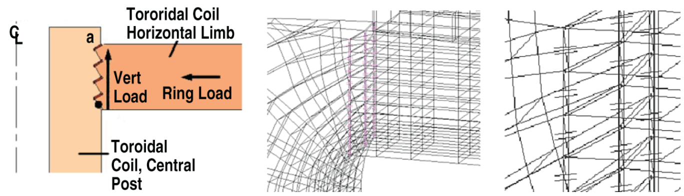

Figure 4. Sawtooth joint and the angled gaps used in the model to represent the sawteeth.

IV. In-Plane Loadings

The sliding joint model with in-plane loads plotted is shown in Fig. 5.

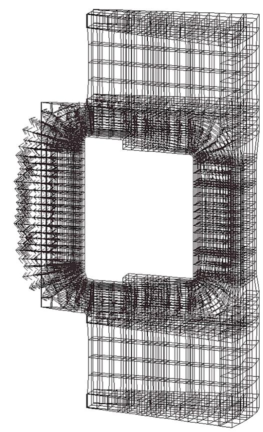

Figure 5. In-plane loading, shown with the sliding joint concept model.

A. *Vertical Separating Forces*

The sliding joint concept uses large covers to carry the vertical separating force to the outboard structure. In C-Mod the covers are large solid forgings. FDF is significantly larger. The stress in the cover, as modeled is less than 200 MPa. The depth of the cover is 3 m and the flanges are 0.4 m thick. At this stress level, options with plates and welded cover plates could be investigated during conceptual design. It is expected that a weldment could replace the forging. This was also the finding of the SBX study.

As modeled, the upper cover deflects upward 8 mm and the lower cover deflects downward 8 mm. The deflection of the cover and to a lesser extent the thermal and mechanical motions of the TF central column establish the vertical sliding motion that the finger joints must allow while maintaining good electrical contact. C-Mod is a pulsed machine and the contact surfaces which are made out of a copper felt metal must maintain good electrical contact for thousands of "shots". Wear of the felt metal pads is checked when there is a major inspection of the machine. FDF is a steady state machine, and after startup, acceptable electrical resistance must be maintained for a long term static position. C-Mod has qualified felt metal for thousands of sliding motions. FDF will have to consider the contact's ability to maintain good contact after remaining in one position for a substantial time.

The sawtooth concept shares the vertical separating force between the central TF column and the outboard structures. The beam strength of the horizontal legs replaced the bending strength of the large covers used for the sliding joint concept. Reducing the span of the structural component that resists the vertical separating force allows the TF horizontal legs to support the bending stress from the vertical force. Horizontal legs in the sawtooth concept are sized to meet thermal/power limits and structural limits, while the sliding joint concept "wastes" the structural capabilities of the horizontal legs.

B. Centering and Bursting Radial Loads

In both concepts the radial load is carried by hoop stress in the wedged inner legs. In the sawtooth concept, the effective stress, VonMises or Tresca is the sum of the wedge compression and the vertical tension. For the sliding joint, only the wedge compression contributes to the effective stress. As a result, there is a small advantage for the sliding joint concept in terms of inner leg stress, and central column space allocation. This is plotted in Figs. 6 and 7 and quantified in Table 2. In both cases the outboard legs transmit some of their radial loads to the outer shell. The bending that results is shared by the TF outer leg and the shell ligaments between ports.

C. Effect of Ring Load on Sawtooth Joint Gap

The ring radial pressure is intended to close the sawtooth joints and maintain electrical contact. The differential vertical motion of the inner legs vs. the outer legs and outer structure cause a non-parallel displacement of the horizontal legs, and a resultant rotation at the joint. The problem is most severe at the outer joint, where the horizontal leg is thickest and least flexible.

A similar problem was observed on NSTX in which the radial contact pressure at the inner flag joint was overcome by a prying action from the vertical separating force acting on the flag extensions. In FDF, added ring load can close both the inner and outer joint. The ring also was extended in vertical build towards the equatorial plane.

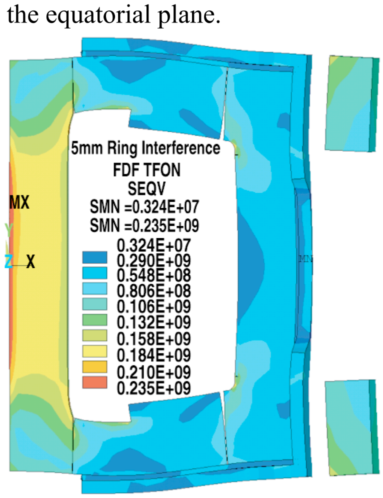

Figure 6. Rebut concept, Von Mises stress – with 0.005 m ring preload, max = 235 MPa.

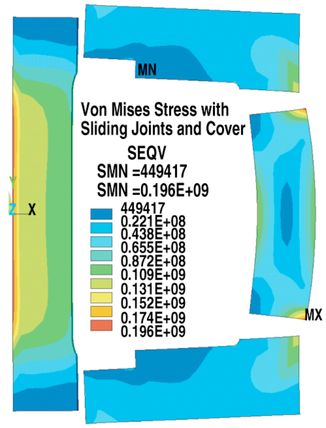

Figure 7. Sliding joints/large cover Von Mises stress max = 0 196 MPa.

TABLE II.	INNER LEG STRESS		
	Wedge Pressure	**Vert. Tension**	**Von Mises Stress**
Sliding joint concept	–213	–30 (ID Poisson effect)	196 MPa
Sawtooth concept	–212	+65 (with ID Poisson effect)	235 MPa

V. OUT OF PLANE RESPONSE

A. Out of Plane Displacement at Sliding Finger Joints

Fig. 8 plot is shown with a full cyclic symmetry expansion. The finger joint regions are modeled with a very compliant material. Differential displacements at the joint which connects the horizontal leg to the vertical leg, should be similar to the 0.35 mm dimension qualified in the C-Mod analysis and operation – but scaled up by the machine size. Or 2.5/6.8 *0.35 = 1.3 mm. At IM the differential displacement is ~1.493–0.491 = 1 mm and at SOF the differential displacement is ~0.828–(–0.499) = 1.33 mm.

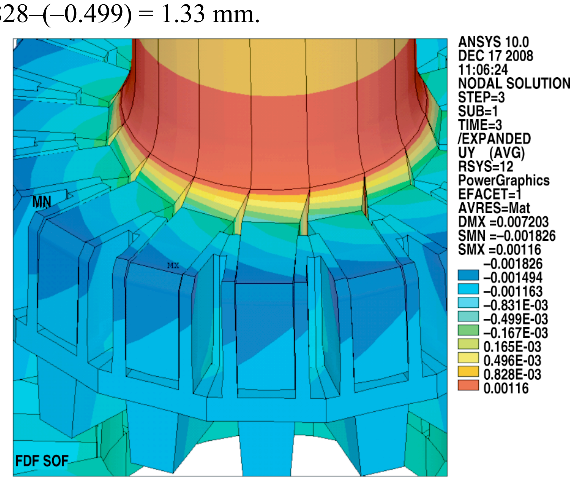

Figure 8. SOF out-of-plane displacements for the sliding joint concept.

B. Out of Plane Displacement at Saw Teeth

Relative OOP motion at the saw teeth results from transverse poisson expansion and the transition from wedged inner leg to un-wedged horizontal leg. So even with no average relative motion, the saw teeth will move a small amount, or about 0.9 mm. This appears as a symmetric displacement – i.e., equal on either side of the horizontal leg. With no ring preload there is slippage and a shift of the horizontal leg with respect to the central column of ~1.5 mm. These effects are shown in Fig. 9.

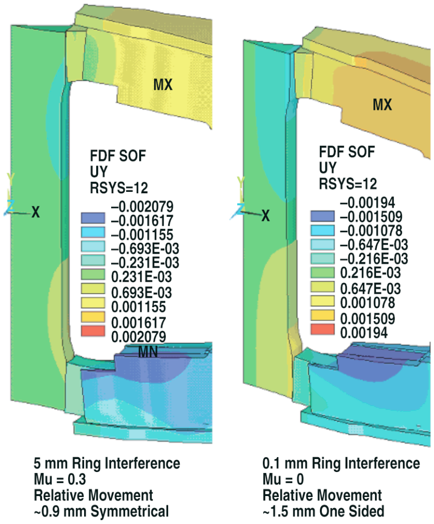

Figure 9. SOF out-of-plane displacements with and without ring preload.

VI. Current Distribution Effects

Currents "hug" the corners of a square picture frame coil, Fig. 10. Lorentz load densities are greatest at the inner corner. The sliding and flexing finger joint must resist these peak loads. Joint thermal behavior is driven by the increased current density in the corner. The sliding joints require active cooling and good contact pressure. A concept to accomplish this is shown in Fig. 11. The sawtooth joint may have poor mechanical contact at teeth at the corner, aggravated by global deformations and currents may have to travel around the region of poor contact, concentrating where there is contact.

Copper contact resistance is a function of the contact pressure. MAST studies [6] show a contact resistance of between 5 and 10 $\mu\Omega$ cm^2 for copper bare metal to metal contact with 3–5 MPa compression. With the larger ring load shown in Fig. 12, the radial pressure at the inner sawtooth joint, is greater than 75 MPa compression, and at the outboard leg saw tooth joint at the plasma side of the corner, the contact pressure is about 20 MPa compression, both should produce adequate joint electrical conductivity.

VII. Other Joint Concepts

Multilams are a commonly used electrical joint. An interesting use of this type of joint was in a variant TFCX concept dating from the early 80s, shown in Fig. 13. The compact size of FDF compared with TFCX favors joint concepts that can support larger current densities.

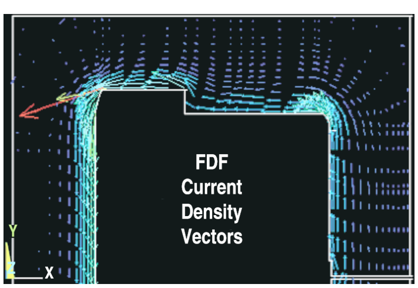

Figure 10. Current density vectors.

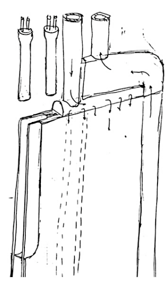

Figure 11. Cooled bladder concept.

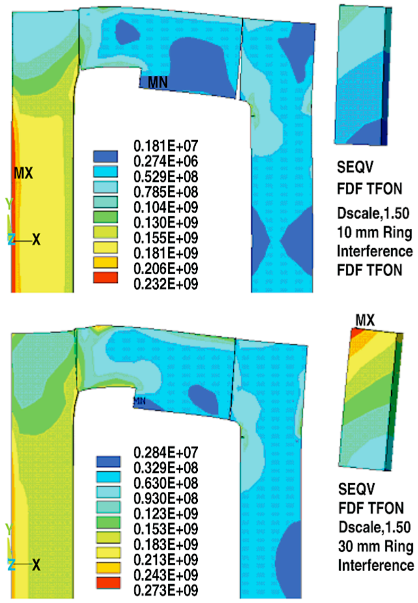

Figure 12. Ring interferences and stresses needed to obtain joint contact.

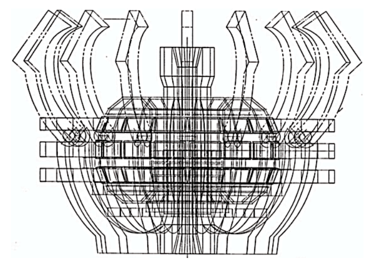

Figure 13. GA TFCX concept.

VIII. Conclusions

Structural analysis has demonstrated the feasibility of two demountable TF concepts. Analyses up to this point highlighted critical features in each of the structural concepts being investigated for FDF. The concept that employs the C-Mod-like sliding joint, initially had relatively large out-of-plane (OOP) differential displacements at the inner TF joints. These were beyond those scaled from qualified C-Mod joints. The vanes, or sidewalls of the TF case structure had not been interconnected at the inner vertex of the wedges. With this connection made, the displacements were then within the finger displacements scaled from C-Mod. A plate weldment cover has been shown to be adequate to resist the vertical separating forces, and limit displacements at the finger joint.

The concept that utilizes a compressed sawtooth joint at the inner and outer TF joints, had differential vertical elastic motions of the inner and outer vertical TF legs that tended to open both the inner and outer sawtooth joints. A modest pressure imposed by a large outer ring was sufficient to close the inner joint. Larger, but feasible radial loads from the ring were required to close the outer joint.

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