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Fusion Ignition Research Experiment System Integration

by

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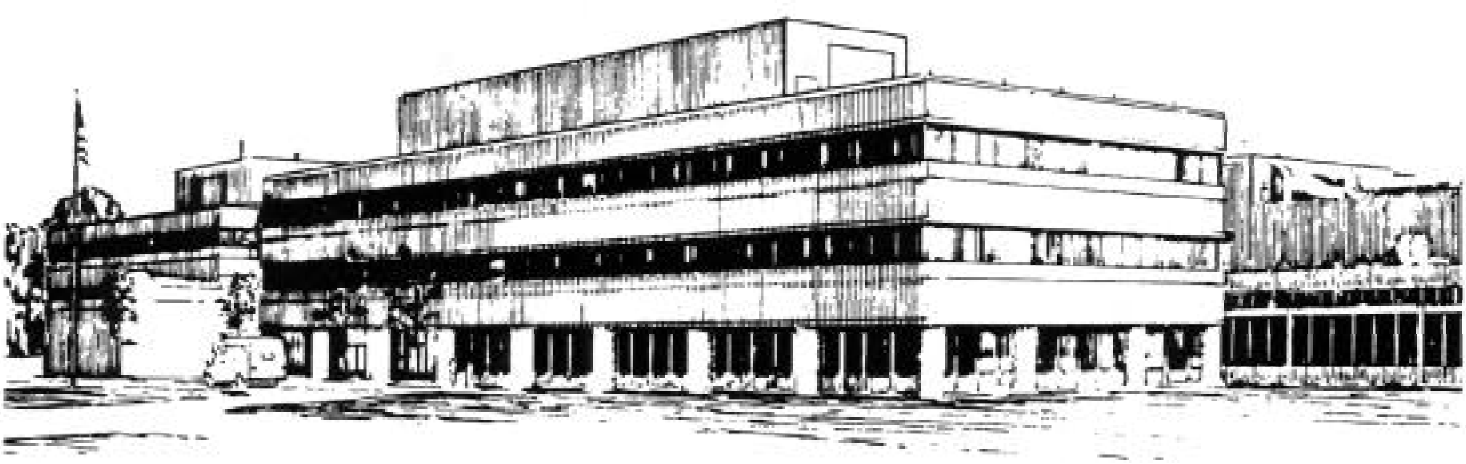

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FUSION IGNITION RESEARCH EXPERIMENT
SYSTEM INTEGRATION *

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Abstract-- This paper describes the current status of the FIRE configuration and the integration of the major subsystem components. FIRE has a major radius of 2 m, a field on axis of 10T, a plasma current of 6.4 MA. It is capable of 18 second pulses when operated with DT and 26 s when operated with DD. The general arrangement consists of sixteen wedged TF coils that surround a free standing central solenoid, a double wall vacuum vessel and internal plasma facing components that are segmented for maintenance through horizontal ports. Large rings located outside the TF coils are used to obtain a load balance between wedging of the intercoil case structure and wedging at the upper/lower inboard corners of the TF coil winding. The magnets are liquid nitrogen cooled and the entire device is surrounded by a thermal enclosure. The double wall vacuum vessel integrates cooling and shielding in a shape that maximizes shielding of ex-vessel components. Within the vacuum vessel, plasma-facing components frame the plasma. First wall tiles are attached directly to inboard and outboard vacuum vessel walls. The divertor is designed for a high triangularity, double-null plasma with a short inner null point-to-wall distance and near vertical outer divertor flux line. The FIRE configuration has been developed to meet the physics objectives and subsystem requirements in an arrangement that allows remote maintenance of in-vessel components and hands-on maintenance of components outside the TF boundary.

The design of the baffle and outboard divertor was revised by integrating the two components into a single module. This was done to increase the baffle heat load capacity by provide coolant to the baffle, a component not actively cooled in the earlier design. The reconfigured baffle-outboard divertor module can be extracted through the horizontal ports in a maintenance scheme that provides for component rotation and a vertical lift.

Other changes have been made to the FIRE design. This includes: the elimination of the center tie rod, reworking the vacuum vessel design to allow active cooling of the inboard wall, developing the TF and PF coil structure details, revising the vertical build of the thermal shield and making changes to the FIRE facility layout.

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Design Configuration and Integration

The isometric view of Figure 1 shows the FIRE experimental device with the insulation enclosure partially cut back to expose the core components. An in-vessel remote maintenance module is also shown attached to one port. Figure 2 highlights in greater detail the major device core components.

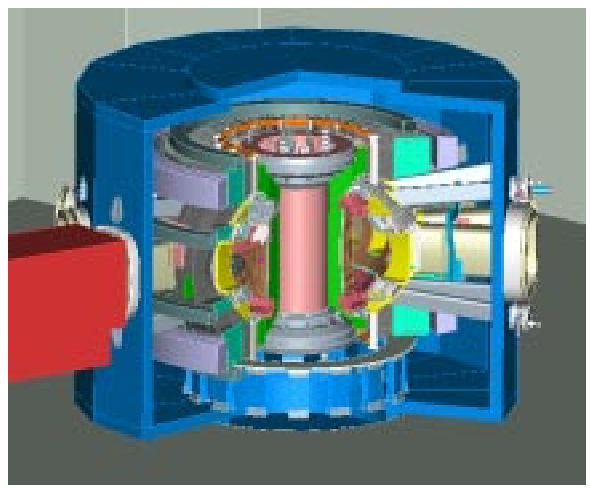

Figure 1. Cross-Sectional View of FIRE Through the Insulation Enclosure

The characteristic features of the FIRE device include:

- Double null, high triangularity gaseous divertors with an outer module that has tungsten plates mounted on actively cooled cooper backing plate.
- A double-walled vacuum vessel with integral shielding.
- Sixteen wedged TF coils that are inertially LN_2 cooled, with a partial coil case. High strength BeCu C17510 is used in the inner legs; OFHC copper is used in the remainder of the coil.

- Compression rings girdle the TF coils to suppress "de-wedging" in the upper and lower inside corners of the coils.
- An active control coil system consisting of a pair of coils is located within the outboard vessel jacket.
- The entire device is in a thermal enclosure similar to the design used for C-Mod (i.e., polyimide foam insulation with fiberglass inner and outer protective/structural skins).

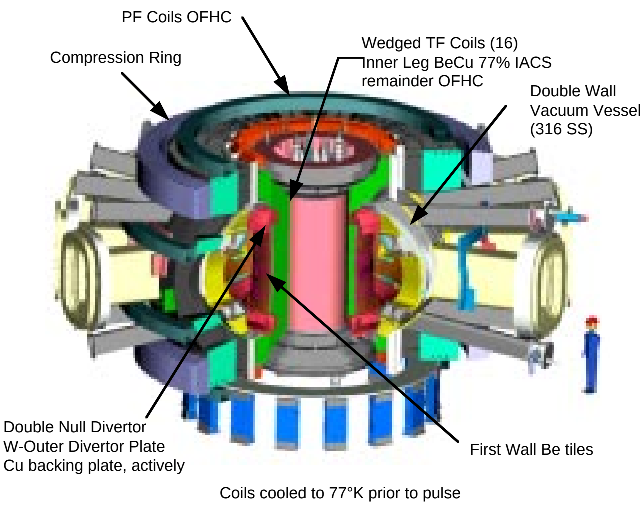

Figure 2. Isometric View Illustrating the Major Core Components

A study was performed to examine the tradeoffs between 12 and 16 toroidal field coils for the FIRE tokamak. The baseline FIRE configuration incorporates a TF geometry that has some of the TF plate windings cut back in the local area of the horizontal ports to provide space for a wider port to improve plasma access (see Figure 3). The tradeoff study was initiated to evaluate the design and cost difference brought about by either increasing the size of the 16 TF coil geometry or reducing the number of coils to improve plasma access, eliminating the need for the local cuts on the winding. The primary advantage of fewer TF coils is that it provides better access for remote maintenance. The primary disadvantage is the higher toroidal field ripple in the plasma. The use of ferromagnetic material for part of the vacuum vessel shielding can reduce the ripple to acceptable values, but can only be optimized for one toroidal field value. In addition, the extra complexity for analysis, plasma startup/control, and diagnostics would be significant. In addition, although fewer, larger ports would make maintenance of the internal components easier and provide a net increase in access area of 20%, it is still possible to maintain the internal components through the smaller ports of 16 TF coil configuration. This study concluded that 16 coil, with local winding cuts, should be retained as the baseline configuration since it meets all requirements with a lower overall cost machine.

In developing the details of the PF solenoid, adding the leads and supporting structure, it was concluded that the marginal benefit of a center tie rod did not warrant the added complexity of its integration with the solenoid service details, so the tie rod was eliminated.

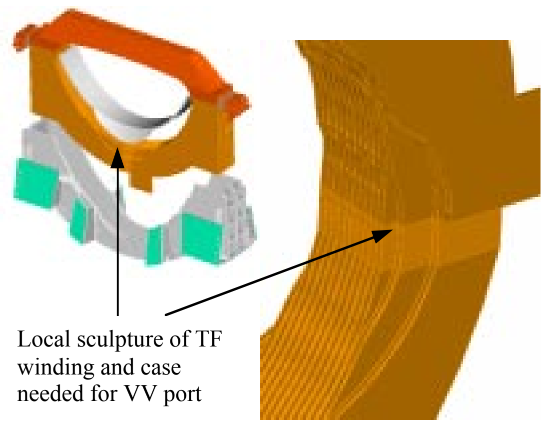

Figure 3. Local TF Winding Cutout

Component Design Updates

The vacuum vessel was reworked to allow active cooling of the inboard wall. Its double wall geometry forms an inner surface that closely follows the contour of the plasma allowing space for the poloidal limiter, outboard passive plates and the divertor components. The vacuum vessel was split into 45° octants from the original design of 90° sectors to reduce the total weight of a TF/VV assembly that will be handled during final assembly.

Figure 4 shows a cask with the in-vessel transporter docked to a 45° vacuum vessel octant and a local blow-up of the divertor module. The boom has a new end-effector design that has been developed specifically for the 800 kg combined divertor/baffle module. The divertor weight and resulting torque was too great for a harmonic drive type pitch joint so a ball screw drive/four bar linkage scheme was adopted. The detailed interface to the divertor has not yet been developed. The Clearance to the port walls is approximately 20 mm all around. Deflection of the boom at full extension and load is about 16 mm assuming 6 mm boom box sections, which could be increase. The boom can reach far enough to handle half

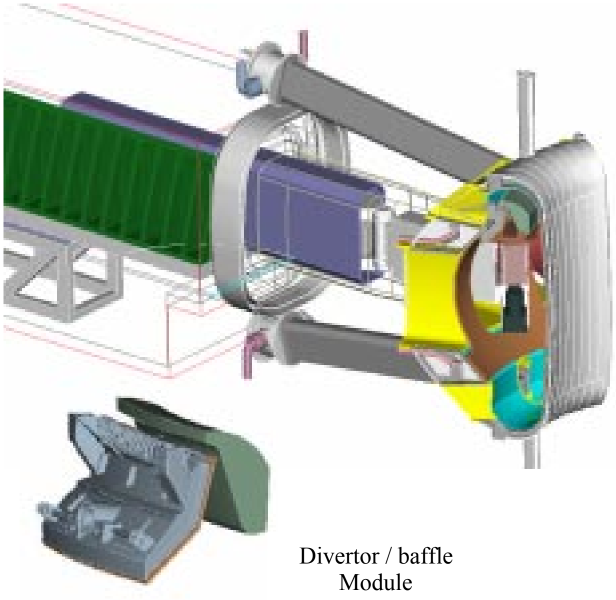

Figure 4. VV / Divertor /RM Details

of the divertors from one port. The cask is 8 meters long, including room to open and close a hinged port-docking door.

The outboard divertor and baffle has been combined into a single module to simplify coolant connections to the baffle. This was required to allow active cooling of the baffle in order to meet a higher heat load requirement. As shown in the local figure the baffle detail is currently shown as an envelope that will be updated in further design developments.

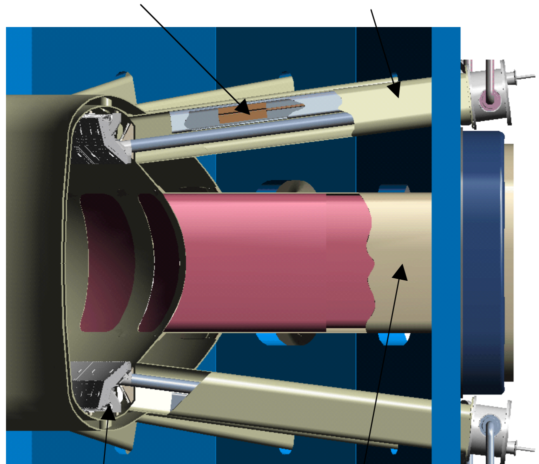

Figure 5. VV Port Details

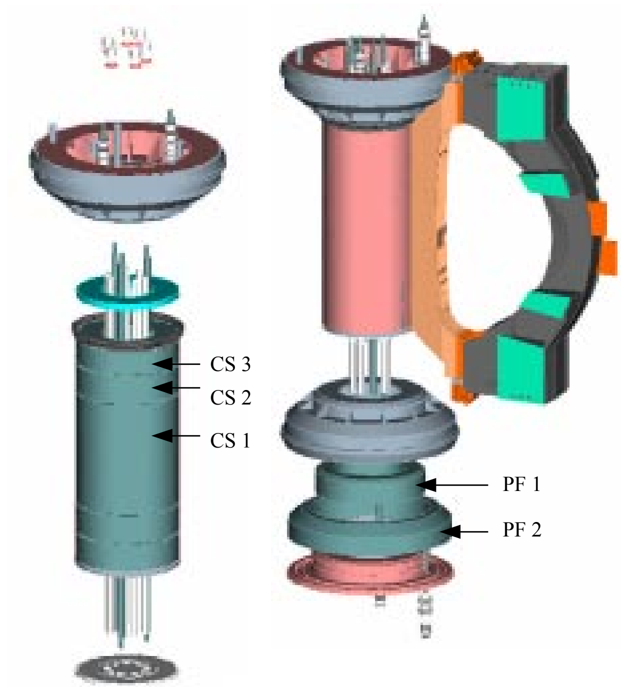

Figure 6. Central Solenoid / TF Interface

The FIRE configuration has sixteen large "straight-in" view ports that are equally distributed along the vacuum vessel mid-plane. Sixteen upper and lower auxiliary ports are provided, angled in a position to allow diagnostic view of the divertor region. Small circular ports are also located at the top and bottom of the vacuum vessel, passing through the region between the TF coil winding.

The horizontal ports provide access to the ancillary systems outside the device. Three ports are assigned to RF heating, and the remaining ports allocated to diagnostics, and in-vessel PFC coolant routings. The angled auxiliary ports, located in the upper and lower vessel regions, accommodate cryopumps, the divertor cooling lines and some diagnostics (see Figure 5).

Support structure and lead details were added to the central solenoid and the space requirements needed for them resulted in the elimination of a large central tie rod system designed in the original baseline configuration. Figure 6 shows the interface between a TF coil, the center solenoid (CS) and divertor shaping coils. A glass epoxy shell with bellows and steel end rings surrounds five CS coils (a center coil and two upper/lower coil sets), forming a containment system for the CS coil LN_2 coolant. The divertor shaping coils (PF1 and PF2) are housed in a stainless steel cast structure that provides coil support and manifolding of the nitrogen coolant. A series of tie rods pass through the upper shaping coil support enclosure and extend through the CS assembly to form a CS/upper divertor coil unit that can be assembled as a single module. The length of the tie rod extends far enough to pass through and provide attachment for the lower divertor coil assembly, as shown in Figure 6.

The TF coil case structure, updated since the release of the baseline design, makes an extensive use of castings. Figure 7 highlights the detail of the TF case structure in an exploded view showing the case subassemblies and TF winding. Although shown as a vertical view the coil windings would be lowered into the outer case subassembly in the horizontal position and the inner bore case assembly inserted and welded along the edges.

Figure 8 shows a section view of the FIRE device highlighting the major dimensions of the core components.

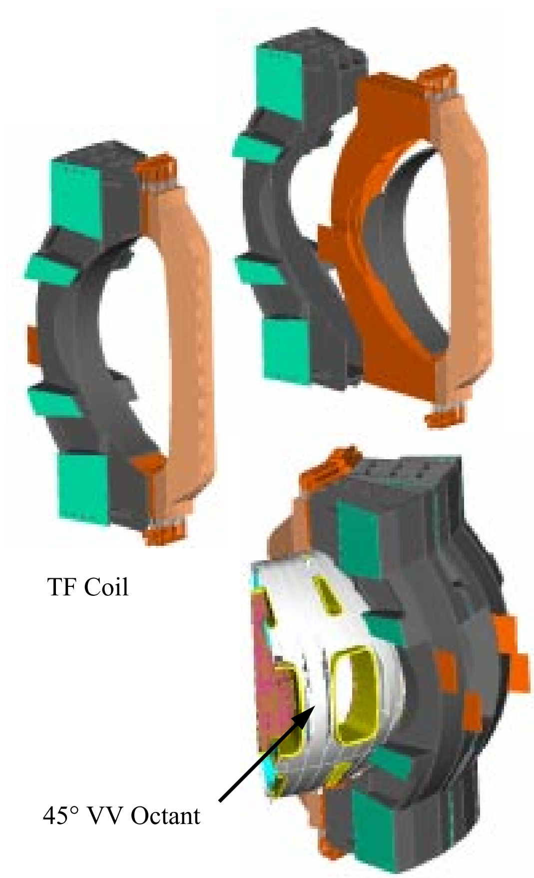

Figure 7. VV / TF Octant Assembly

Machine Assembly

The FIRE device assembly was altered to use a 45° octant as the module size rather than the baseline approach where the device was assembled in four 90-degree sections built up from a four-coil TF assembly and a 90-degree vacuum vessel quadrant. Figure 7 shows a vacuum vessel octant rotated into the bore of a two-coil TF assembly

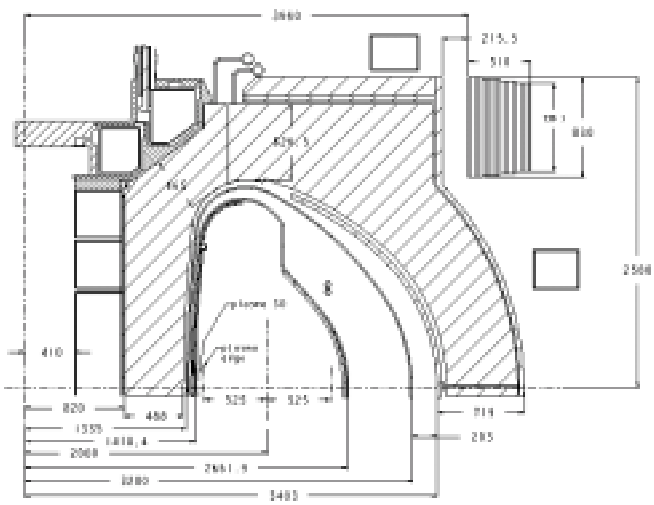

Figure 8. Device Cross Section View

Future Activities

The FIRE design and integration process will continue to refine the overall device configuration and further develop subsystem details. Preliminary discussions on a possible adjustment of the FIRE design point to attain more physics performance are under way. It is expected that any design variation will involve only minor changes and will not increase the overall cost.

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