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CONFIGURATIONAL ISSUES AND THE EVOLUTION OF THE MIRROR FUSION TEST FACILITY UPGRADE*

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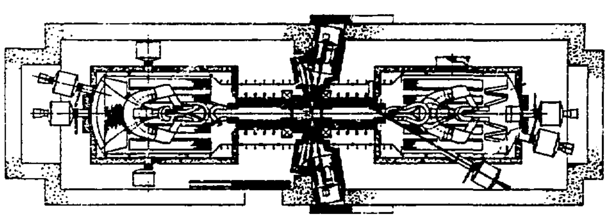
Abstract: Lawrence Livermore National Laboratory (LLNL) and the Fusion Engineering Design Center (FEDC) have been conducting a study concerning the upgrade of the Mirror Fusion Test Facility (MFTF). With MFTF-upgrade, program emphasis will begin to shift away from resolving specific issues toward systems integration of all the subsystems of a tandem mirror reactor. All of the upgrade options considered call for deuterium-tritium (D-T)—burning plasmas and, hence, systems integration in the necessary but difficult nuclear environment of a reactor. The preferred option, MFTF-α+T, has three main objectives: (1) to extend physics performance to Q ∿ 2 in a D-T plasma, (2) to gain experience in tandem mirror systems integration in a nuclear environment, and (3) to provide a unique capability for operating a power-producing section of a fusion reactor at reactor-like parameters. In this paper, the evolution of the MFTF-upgrade configuration to the preferred option is outlined, the important configurational issues for the upgrade are discussed, and a brief description of the selected configuration is presented.

Evolution of the MFTF Upgrade

The Mirror Fusion Test Facility (MFTF) upgrade study has considered a number of alternative concepts.

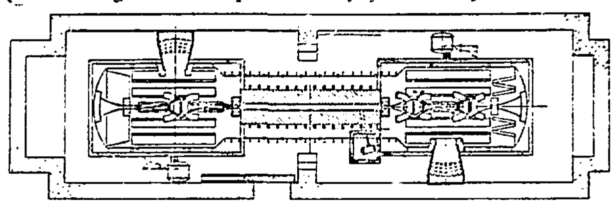
The first alternative concept upgraded the MFTF-B tandem mirror experimental facility by adding a nuclear components test station, thus creating the MFTF-B+T device. This test station is referred to as the D-T axicell. The addition of the D-T axicell involves modification of the central cell of the MFTF-B. The central portion is replaced by a new vacuum vessel, a pair of large-diameter superconducting solenoid coils, a pair of normal conducting choke coils, nuclear shielding with provisions for a blanket test module, and a pair of neutral beamlines with their beam dump assemblies. The coils provide 12-T peaks in the axial magnetic profile to enhance confinement in the D-T axicell. The two beamlines, one using deuterium and the other tritium, act to fuel the machine as well as drive the fusion reaction. The resulting device provides a uniform wall loading of 1.5 MW/m^2 at a radius of 25 cm.



The MFTF-B axicell is reconfigured to leave only a 6-T choke coil, and the central cell solenoid coils are moved axially toward this choke coil. Neutral beams are added to pump the center of the two 6-T coils.

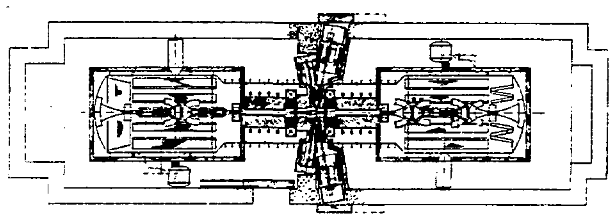
A large cryopanel array located in the end cell is required to continuously pump the high gas load of the D-T axicell beams. Nuclear shielding is provided around the end cell vessels to permit contact maintenance. The device requires modifications to allow steady-state operation and the addition of a tritium processing facility.

The second alternative, called MFTF-α, was aimed at improving the performance of the device from a physics point of view. The objective is to achieve Q ∿ 2 using D-T fuel provided by pellet injection.



The end cell of the MFTF-B is replaced by a Mirror Advanced Reactor Study (MARS) configuration. Bulk central cell heating is provided by ion cyclotron resonance heating (ICRH) and the pulse length is at ∿1000 s. Tritium throughput is much lower than for the B+T design because there are no central cell beamlines and the pulse length is short. The duty cycle could be such that the nuclear shielding requirements are ameliorated.

The third alternative combines the nuclear test station (D-T axicell) of the B+T with the improved physics (new end cell configuration) of the α device to create the MFTF-α+T configuration. The earliest configuration used the existing MFTF-B end cell vessels and a large continuously pumping cryopanel array to handle the high gas load associated with the D-T axicell beamlines.



The LLNL and the Magnetic Fusion Advisory Committee (MFAC) found the third option (MFTF-α+T) most desirable; therefore, it was developed in more detail [1]. The latest configuration has evolved through several iterations to that shown below. It features the same magnetic configuration with two exceptions. The first is a lower coil current density and the second is an improved D-T axicell with respaced central cell solenoid coils. One of the most significant new features is the addition of drift pumping of the ions in the anchor and plug regions [2]. This allows the use of a gridless divertor and, more importantly, pumping of the ions at higher pressure in the two halo scrapers by a set of four turbomolecular pumps. This change eliminated the large cryopanel arrays. An extensive study of the end cell nuclear shielding and vessel requirements resulted in the use of a new, smaller diameter end cell vessel with integral water bulk shielding at reduced total cost. A detailed report of the MFTF-α+T is now in preparation.

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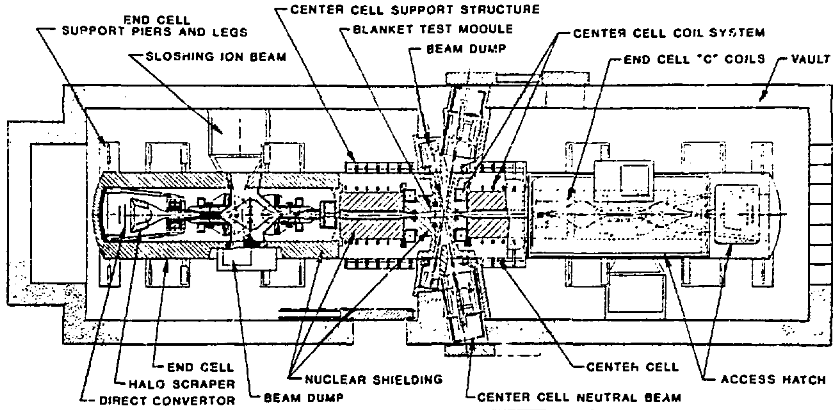
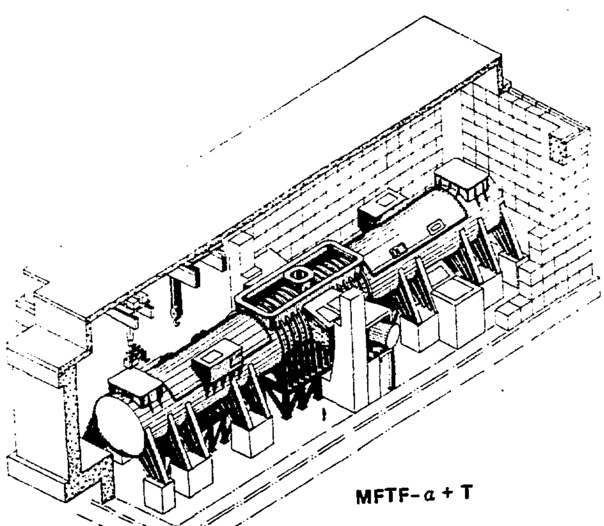


MFTF-α+T: A Testing Workhorse

The test program envisioned for the MFTF-α+T consists of two major goals. The first, high Q, is aimed at demonstrating and increasing the understanding of tandem mirror physics in the reactor environment using all of the device subsystems required of a reactor. The second, high Γ, is the nuclear testing portion of the program. Two liquid and two solid breeder blanket tests will be conducted, followed by testing of two prototype blanket designs for the succeeding machine. Some of the types of tests planned are presented in the following list:

- Subsystem integration and operation
- Plasma characteristics
- Particle control
- Shielding response
- Neutronics testing
- Magnetohydrodynamic (MHD) testing
- Materials compatibility
- Response to off-normal events
- Tritium recovery and reprocessing
- Thermal hydraulic measurements
- Tritium permeation
- Radiation damage testing
- Lifetime performance



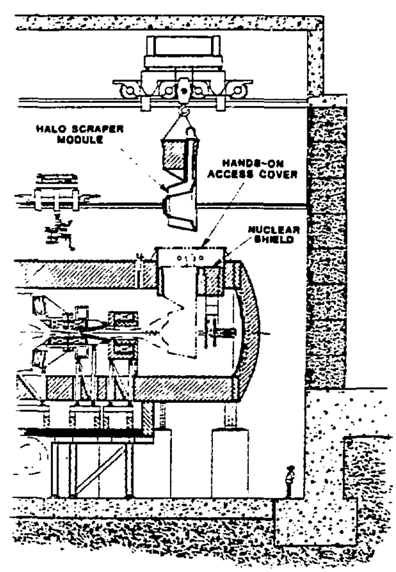
MFTF-α + T

Configurational Issues

Discussions of six critical areas of study are presented below.

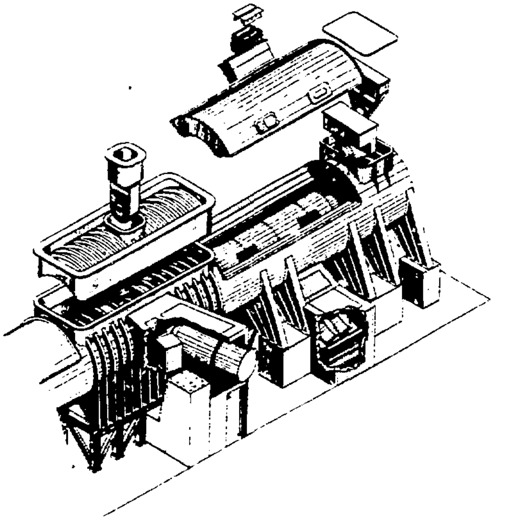
Maintenance in the Nuclear Environment

MFTF-α+T may well be the first reactor designed from the start and, by necessity, to operate in the nuclear environment [3]. The configuration features a modular construction to aid in achieving the 10% availability goal. An example of this is shown below for the modular replacement of the halo scraper. The shielding is internal to the vessel cover to permit hands-on disassembly of the utilities prior to clearing the vault for the remote removal and replacement operations. A secondary bridge is provided for the remote surveillance and manipular system. Large



MODULAR HALO SCRAPER MAINTENANCE

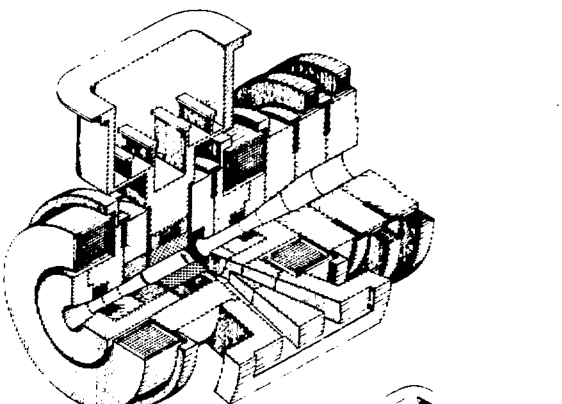
hatches with welded single-convolution seals are provided for access to the lifetime components. This was done to allow any replacements which might prove necessary, as well as to provide for initial assembly and eventual decommissioning. The test module and 12-T normal conducting choke coils are replaced through a dedicated hatch.

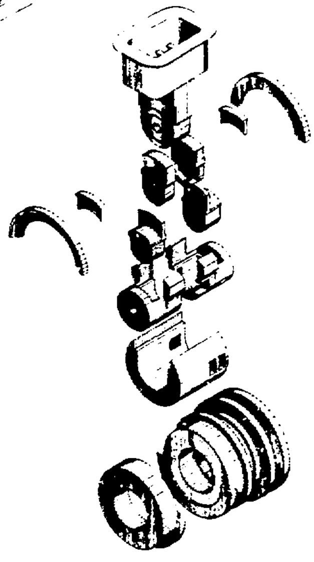


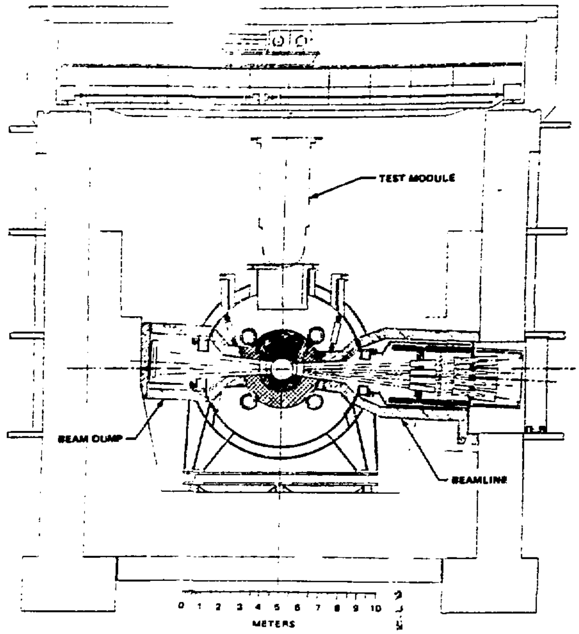
D-T Axicell Magnetic Configuration and Modular Design

A detailed magnetic configuration study resulted in a much improved design [4]. Besides the test volume envelope, the clearance for the beam ducts and their nuclear shielding constrain the design.

The D-T axicell shielding system had to be designed to accommodate choke coil replacement and test module changeouts. The resulting design features a modular set of shield sections which can be remotely removed through the test module access hatch.

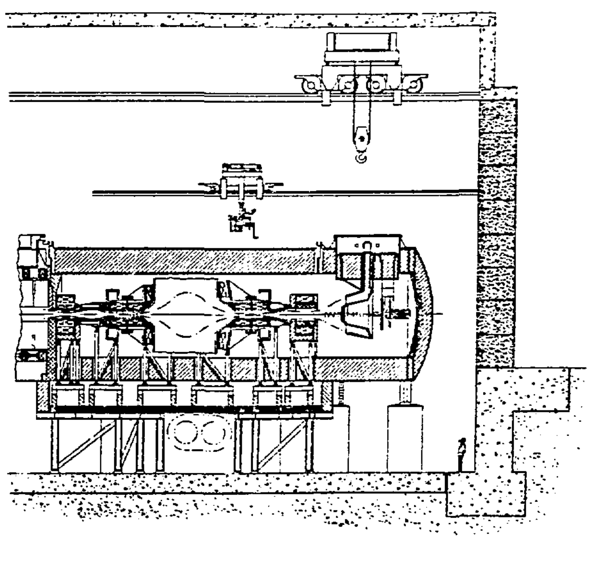


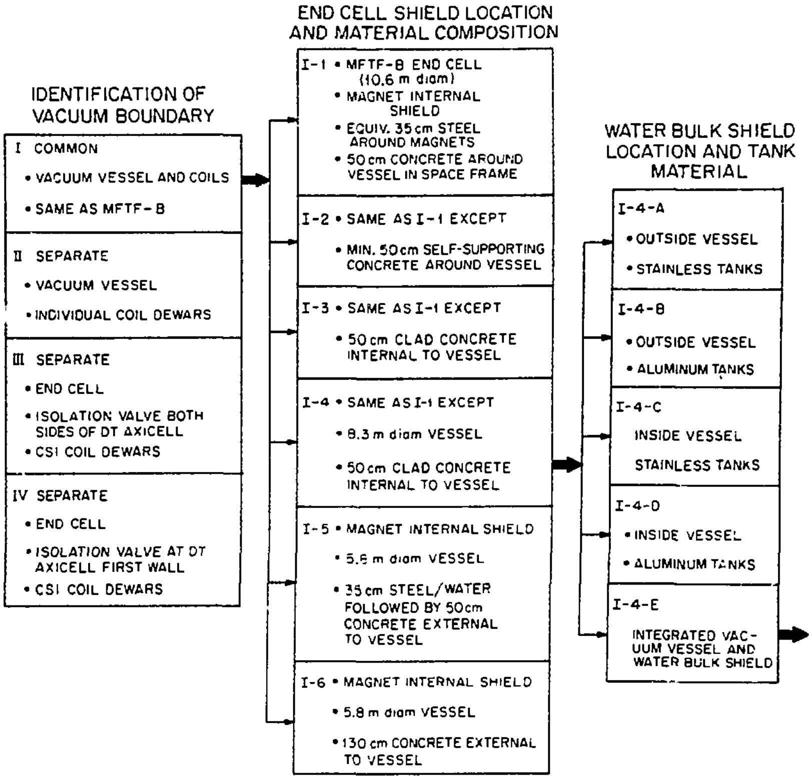




End Cell Vessel and Biological Shielding

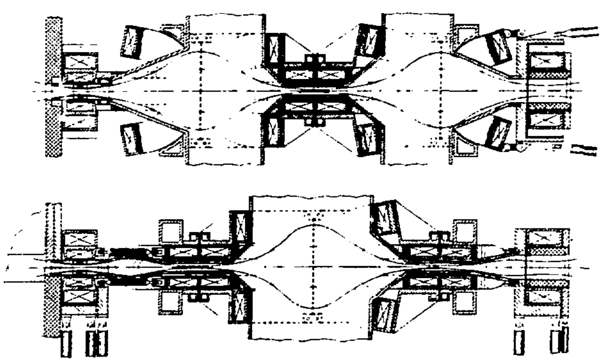
An extensive study was conducted to configure the end cell. The steps involved are shown in the chart. A single boundary was chosen for the vacuum topology; this combines the superconducting magnet set insulating vacuum with that needed for the plasma at the expense of having to warm up the coils to access the plasma chamber. The maintenance and availability study [3] showed that the MFTF-α+T could meet its availability goal of greater than 10% using the less expensive single vacuum boundary configuration. The need for biological shielding to satisfy the design dose rate limit of 0.5 mrem/h, 24 h after shutdown, is a driving force in the end cell configuration. The baseline configuration, which uses a double-walled vacuum vessel with water bulk shielding and layers of B_4C and lead, was selected for its minimum cost [5].



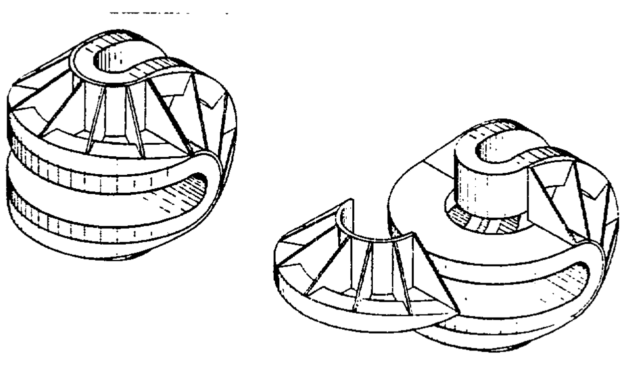


End Cell Magnet Sizing and Structural Design

A trade study was conducted to minimize total and cell system costs [6]. This study considered the size and cost of all end cell subsystems which are affected by changing the coils' internal nuclear shielding thickness. This resulted in a near-minimum cost design. The coil support structure had to be designed to be compatible with the end cell vessel and to allow for remote operations for their replacement should this prove necessary. The coils are supported by liquid-helium-cooled struts attached to cold tables. The tables are in turn supported by sets of roller assemblies similar to those used by the Large Coil Test Facility (LCTF). The rollers permit thermal motion due to cooldown while restraining other motions. The coils are linked together axially and are tied back to the vessel. A set of vessel ports allows the struts to be unpinned from the cold tables prior to lifting of the coil assemblies.



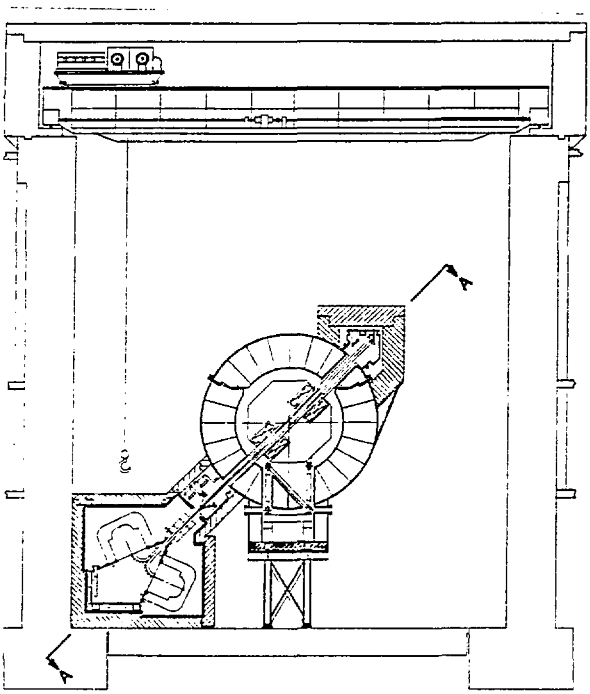
The close proximity of one winding to another proved difficult and limited the design options available for the coil support structure. The selected design uses one coil to support the minor lobe-opening forces of its companion [6]. This is accomplished by the action of four identical collar structures. The companion coil's collars also act to support a large portion of the minor lobe-opening forces. Each coil's major lobe-opening force is resisted by its own case. This concept for supporting the coils should minimize the coil throat structural thickness and, therefore, total end cell system cost. A higher-level structural analysis is planned to establish the requirements for the yin-yang anchor and plug coil sets' structural arrangement. The two transition C coils use the design concept of a conventional pair of strongbacks with tension ties, which is based on the MFTF-B coil design.

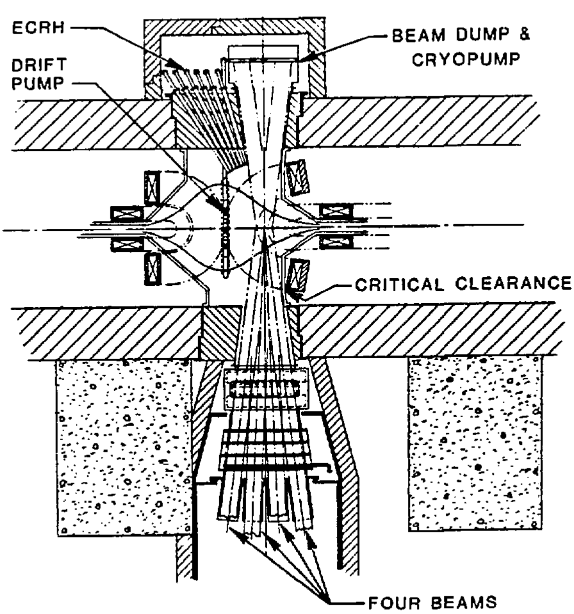


Anchor & Plug Coil Set Support Structure

End Cell Sloshing Beamline Integration

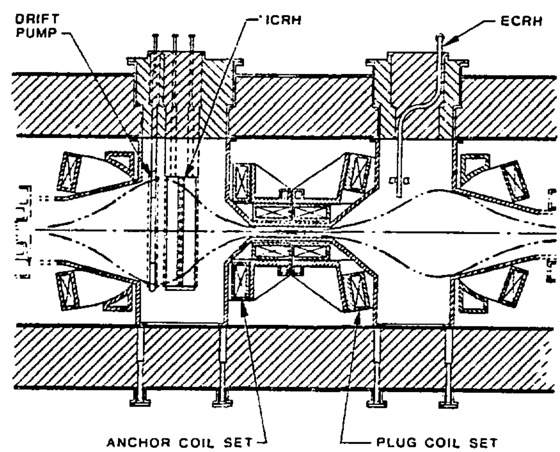
The design of the sloshing beam directly affects the total end cell system cost. The divergence and virtual source location values selected are related to the plasma size and coil throat size. The larger the divergence, the larger the plasma target size required, and the larger the coil size and resulting total system cost. The source design affects the number of them required, and the clear area required for passage of the beams proves a constraint on the magnet support structure. Many different designs and iterations were studied in arriving at the current configuration. Further study of this critical issue is planned.





End Cell Radio Frequency Heating and Drift Pumping Subsystem Requirements

Integration of the two drift pump coil sets in the anchor and plug regions proved to be straightforward for the current design. However, previous designs had much larger coils which required removal with large sections of the internal nuclear shield into which they were mounted. The ICRH arrays in the anchors are also removed radially with a section of the adjacent shielding. The ICRH antenna design is critical because it must project clear of the inner surface of the nuclear shield to avoid interference. This can result in a critical condition for the coil throat dimension. The electron cyclotron resonance heating (ECRH) systems at the two plug locations are mounted in their shield plugs. The six antennas located in the area of the sloshing beam are placed into six tubes in the shield plug. These tubes are between the two drift pump coils. These subsystems are relatively easy to integrate into the system.



Conclusion

The current configuration was selected after study of a wide range of options and after review by a number of organizations. The design results from a wide range of cost-minimizing trade studies of the critical issues. The design will satisfy the program objectives, extending the physics performance and providing a unique capability to test nuclear components in a reactor environment for the whole fusion community.

References

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