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J. N. Doggett

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THE TECHNOLOGY DEVELOPMENT FACILITY (TDF)

J. N. Doggett
Lawrence Livermore National Laboratory, University of California
Livermore, CA 94550

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ABSTRACT

We have been studying small, driven, magnetic-mirror-based fusion reactors for the Technology Development Facility (TDF), that will test fusion reactor materials, components, and subsystems. Magnetic mirror systems are particularly interesting for this application because of their inherent steady-state operation, potentially high neutron wall loading, and relatively small size.

Our design is a tandem mirror device first described by Fowler and Logan /1/, based on the physics of the TMX experiments /2/ at Lawrence Livermore National Laboratory (LLNL). The device produces 20 MW of fusion power with a first-wall, uncollided 14-MeV neutron flux of 1.4 MW/m^2 on an area of approximately 8 m^2 , while consuming approximately 250 MW of electrical power. The work was done by a combined industrial-laboratory-university group.*

1. PHYSICS DESCRIPTION

Calculations indicate that the TDF, consisting of a tandem mirror machine about the size of the TMX, could provide fusion nuclear engineering data. With high-density operation, based on physics already demonstrated in the TMX, this machine would produce 15 MW of DT neutrons in steady-state form from a plasma column 0.10 m in radius and 8 m in length.

To produce copious neutrons in a small device, we use the fact that even small mirror machines have confined dense plasmas at high ion temperatures. Because of the small volume, neutral beams can maintain these plasmas in steady-state form, with modest demands on the plasma confinement time. This was the principle behind the earlier Fusion Engineering Research Facility (FERF) /3/, based on a yin-yang mirror geometry. The tandem mirror version has the advantages of somewhat simpler construction as well as a configuration in the mainstream of tandem-mirror reactor development.

For the TDF base case, 65 MW of 80-keV neutral-beam power (half deuterium, half tritium) is injected into the center cell to sustain a mirror-confined ion density of $6 \times 10^{14} \text{ cm}^{-3}$ at an average energy of 37 keV. In this mode of tandem-mirror operation, known as the Kelley mode, the end cells serve three functions: provide MHD stability, eliminate axial ambipolar electric fields in the center cell, and confine low-energy ions that fill in the loss cone in the center cell. Loss-cone instability in the end cells themselves is "stream-stabilized" by the outflow of low-energy ions from the center cell, which are regulated by the input of gas to the center cell. A brief set of physics parameters is shown numerically in table I and graphically in fig. 1.

*The principal participants are LLNL, TRW, Fusion Engineering Design Center of Oak Ridge National Laboratory, General Dynamics/Convair Division, University of Wisconsin, and Science Applications, Inc.

Table I. TDF Physics Parameters.

Central cell	
Plasma length (m)	8.0
Plasma radius (m)	0.1
Solenoid (T)	4.5
Peak beta	0.4
Hot-ion average energy (keV)	37.0
Hot-ion density (cm^{-3})	6×10^{14}
Beam voltage (kV)	80.0
Incident beam power (MW)	64.8 (1080 A/60 keV)
Trapped beam current (A) atomic	853.0
Injection angle (degrees)	65.0
Pellet gas feed (A) atomic	~ 800.0
Fusion power (MW)	~ 20.0
Neutron wall flux (MW/m^2) at $R = 0.25$ m	1.4
Choke--Transition	
P_{max} choke (T)	15.0
Plasma length (m)	4.75
Plasma density (cm^{-3})	$< 3 \times 10^{12}$
Field at midplane (T)	1.0
Pumping NBI	80 kV, (59.2 A/60 keV) 3.6 MW
Anchors	
Plasma length (m)	3.3
Plasma density (cm^{-3})	$\sim 5 \times 10^{12}$
Field at mirror (T)	3.0
Field at midplane (T)	1.0
Sloshing neutral beams	80 kV, (4.2 A/60 keV) 0.25 W
ECRH	500 kW @ 35 GHz/667 kW @ 60 GHz
Pumping NBI	80 kV, (2.9 A/60 keV) 0.174 MW

2. ENGINEERING

The TDF reactor subsystems were deliberately designed to existing or near-term technology. Table II contains the design parameters; fig. 2 shows the overall system design. At the center of the machine is the central-cell region where virtually all of the neutrons are produced. Here the centerline magnetic field of 4.5 T is produced by three Nb-Ti superconducting magnets spaced to allow the insertion of test modules up to 1 m in axial dimension. The ends of the central cell provide access for the central-cell beams that drive the fusion reactions. The main design considerations in this area are shielding for the solenoid magnets in the area adjacent to the beam ducts and the desire to keep the 15-T resistive choke coil as close to the solenoids for field reinforcement. The choke coil presents a novel design problem for fusion reactors because it must withstand a high radiation load and has a high internal heat load and high magnetic stresses.

Fig. 1. Magnetic field, plasma potential, and density profiles in TDF.

Table II. TDF Engineering Parameters

Overall machine		Vacuum	
Full-power-run length (hr)	>100	Base pressure (torr)	5×10^{-6}
Availability (% life average)	30	Total pump speed (l/s)	1.3×10^8
Design life (full power yrs)	5.4	Neutral beams	
Test zone		Continuous mode	
First wall radius (m)	0.25	Maximum energy (keV)	80
Neutron wall load (MW/m ²)	1.4	Power	
Area available (m ²)	~8	Central cell (MW)	52
Heat load (W/cm ²)	50	Pumping (MW)	3.8
Fusion power (MW)	20	Sloshing (MW)	0.25
Tritium		RF	
Consumption rate (gm/hr)	0.1	ECRH-type	
Inventory (kg)	~0.3	Frequency (GHz)	35/60
Magnets		Power (MW)	1.2
Superconducting Nb-Ti		Pellet injectors	
Peak conductor field (T)	8	Velocity (m/s)	1500
Peak center field (T)	4.5	Pellet rate (/s)	500
Resistive Cu alloy			
Peak center field (T)	15

Fig. 2. TDF cross section (some components are shown rotated out of plane for clarity).

Beyond the central cell are the transition and anchor regions, which stabilize the central-cell plasma. The fusion power in this region is small, and only minimal shielding is required. The magnets are C-shaped with an Nb-Ti conductor and are housed in an independent vacuum vessel. Three neutral beam systems deliver particles to this area: two are pump beams that enter at shallow angles; the other provides sloshing ions normal to the axis. The relatively complex magnet geometry coupled with rigorous beam geometrical requirements control the design in this area.

Fig. 3. TDF test module replacement detail.

In this case, we limit the plasma power density at the dump to 250 W/cm^2 . This dump, like all those in the TDF, is water-cooled. The plasma startup guns are housed behind movable shielding at the end wall, and they inject a low-energy plasma along the field lines during startup.

The TDF is designed for maximum contact maintenance. Specialized tooling is provided for scheduled maintenance tasks, and general-purpose tooling is used for random failure repair. Therefore, contact operations can be performed in the vault during regular work schedules after a short cooldown with the magnets de-energized and the tritium removed. In this way, all the major connections can be made and broken in a contact mode, but components are removed with remote tooling because of the high flux of gamma rays from unshielded machine ports. Because the components are designed for reliability, most maintenance tasks can be performed in an efficient contact mode, we are confident that the TDF will be a high-availability device with a specified 50% in the last half of its 15-year life.

3. TESTING FACILITIES

The principal testing area is the wall of the central cell in the area between the central cell beam ducts (figs. 2 and 3). There is direct access to two full-diameter test zones between the solenoid magnets, each capable of accommodating a 1-m long test article. Access to the areas inside the coil boundaries are also conveniently available to smaller test specimens. The major test capability offered by TDF is the ability to test full-size prototype blanket modules to qualify them for use in experimental power reactors. With steady-state run lengths of >100 hours, experimental components can be brought to thermal and tritium breeding equilibrium, and energy extraction may be demonstrated.

The neutron flux in the TDF is not high enough for lifetime testing of fusion-reactor, first-wall, structural materials. However, there is ample space and flux to do lifetime tests on insulators and other components that would be exposed to lesser fluence in a power reactor. There is, of course, ample flux for verifying neutronics models used for fusion system design. The machine itself is an excellent engineering test of the integration of a fusion reactor design into a long-life, high-duty-cycle machine. It can provide data on material interactions, interactions between systems, tritium and fuel processing, remote maintenance, and system reliability.

4. PROGRAMMATIC CONTRIBUTION

The Magnetic Fusion Program has a strong need for a device like TDF because (1) it provides a test bed to demonstrate the reliability of technology developed in both the confinement and D&T Programs when integrated into a device operating in the reactor mode; (2) it provides a testing facility for reactor systems, such as magnets, blankets, neutral beams, and tritium breeding, under conditions of high neutron flux, neutron activation, and tritium contamination; and (3) it provides a reactor-level (14-MeV) neutron flux over a large area (several square meters), making practical the in situ testing of a broad range of materials and subassemblies.

A TDF can be built with conservative physics and technology, which should help ensure successful testing and performance. In addition, because it is a relatively modest device, these jobs could be accomplished at a relatively low cost in a timely manner.

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University of California • Livermore, California 94550

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