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A FUSION DEVELOPMENT FACILITY TO TEST DIVERTOR AND PFC SOLUTIONS FOR DEMO

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GENERAL ATOMICS

DEMO PFC ISSUES

The development and operation of a DEMO fusion reactor represents a large step beyond ITER for the operating conditions Plasma Facing Components (PFCs) are expected to face. The unique operating conditions include:

1. **Heat flux:** While ITER is expected to produce 100 MW of alpha heating power with limited duty cycle, DEMO should produce 4 times this power in a similar volume.
2. **High temperature:** While ITER is limited to operation at ~300°C due to water cooling and safety issues with the beryllium first wall, DEMO will need to operate at high temperature, > 600°C, for efficient generation of electric power.
3. **Neutron fluence:** While ITER's planned neutron fluence is ~0.5 dpa/yr, DEMO's first wall components should experience a neutron fluence of ~20 dpa/yr.

These operating conditions will have a number of consequences for first wall materials facing DEMO's plasmas.

1. **Heat flux control:** While the parallel heat flux in the SOL of DEMO will be significantly larger than ITER the PFCs are only expected to be able to handle a similar steady state poloidally projected heat flux, $\leq 10\ \mathrm{MWm^{-2}}$. This implies that the divertor solution for DEMO must be more aggressive than ITER. Core plasma radiation can be maximized. Double null divertor operation provided two targets. The target heat flux can be spread over a larger area by tilting the target plate with respect to the magnetic field, either in the poloidal plane or by lowering the poloidal field at the target through flux expansion. Another approach is to increase radiative dissipation of the heat flux by raising the divertor and SOL density and/or increasing the impurity fraction (enrichment) in the SOL and divertor.
2. **Erosion and material migration:** The high heat flux along with long pulse duration implies that tons of plasma facing material will be eroded and redeposited. This will produce layers of material of unknown composition and properties throughout the device. Implications of this include:
   a. Finite lifetime. PFC surfaces must be thin enough to conduct the heat to the coolant, yet thick enough to accomodate significant erosion. Can the divertor plasma operating modes be designed to limit erosion of target surfaces to a tolerable level?
   b. Frequent Maintenance. Will the redeposited material build up in such a way to require its frequent removal? Such effects could include plugging pumping ducts and flaking and falling into the plasma causing disruptions. Neutron damage may change the characteristics of the redeposited material requiring more, or less, frequent maintenance.
   c. Surface conditions. What will be the surface conditions of the redeposited material? This can produce varied effects, from physical properties of the PFCs to recombination rates on surfaces which in turn affect tritium permeation throughout the vessel. The neutron fluence could also play a major role in the properties of these layers and the connection between the near-surface region and the bulk of the tile.
3. **Tritium retention:** The tritium fuel cycle, and tritium retention, in DEMO will be very different than in ITER. This difference is primarily due to the high temperature of the PFCs, > 600°C, required for efficient electric power generation. While the high temperature should drive tritium out of the redeposited material, the higher temperature and high neutron flux may allow for greater permeation of tritium throughout the vessel. The concern is both the total amount of tritium tied up in the machine unavailable as fuel, and migration of tritium into the

cooling channels and other areas where it may be difficult to recapture. Uncertainties in modeling this include:

a. Surface conditions. Tritium permeation depends on the diffusion rate through the PFC material, but also on the surface flux of tritium into the PFCs. The atomic recombination rate at the surface, which allows neutral recycling, will likely depend on a number of factors, including the surface material mixture, temperature and the amount of damage to the material surface. A higher surface temperature could actually lead to lower tritium permeation if the surface recombination rate is significantly higher. The details of this process are extremely uncertain.

b. Neutron damage. Neutron damage sites, up to 1-2% for tungsten, will result in greater tritium retention in the bulk material, provided the tritium arriving at the surface can diffuse to the traps, a temperature dependent process. The presence of traps also slows the speed of the diffusion front, reducing permeation from the back of the tile, until steady-state is reached. of the This may also provide more locations for tritium to diffuse through the bulk material. The affects of neutron damage on the tritium fuel cycle are therefore also complex and highly uncertain.

Requirements for DEMO PFC Development

To address the issues outlined above a new experimental facility is needed to develop the expertise required to design a divertor and other PFCs capable of handling DEMO's conditions. There are a number of characteristics such a facility should have.

1. **Net Breeding of tritium:** Achievement of net breeding of tritium before a DEMO can be committed is necessary owing to the very high tritium consumption rates in DEMO. Two primary concerns for adequate tritium breeding are keeping the PFCs thin enough to allow adequate neutron penetration into the breeding blanket, and not retaining significant tritium in the PFCs. A DT facility is needed to test boundary plasma and PFC solutions designed to meet this requirement.

2. **High power density and duty cycle:** The parallel heat flux should reach at least that of ITER, ~0.5 GW/m^2. Further improvements in heat flux control need to be made on the way to DEMO from ITER. Because these issues of divertor heat flux control occur on a relatively short time scale the underlying physics of such control can and should be developed on existing devices. The important aspect that needs to be addressed for DEMO is a high heat flux duty cycle high enough that significant material is eroded and redeposited within a reasonable operational period. ITER's limited duty cycle will only make a start on this problem.

3. **High temperature:** A temperature of ≥600°C for in-vessel is needed to address the unique conditions DEMO will face compared to ITER. At 600°C the tritium trapped in redeposited layers begins to become small enough to be tolerable for the fuel cycle. This is also probably a lower limit needed for efficient electricity generation in DEMO. Ideally the temperature should be controllable in order to experimentally determine the optimal operational temperature for tritium control due to both retention and permeation.

4. **Neutron production:** Material integrity becomes an issue above a neutron fluence on the order of 20 dpa. These effects include not only the bulk material, but also the redeposited material with consequences for the tritium fuel cycle. A fluence of 20 dpa should be achievable in a reasonable operational period, 1-2 years.

5. **Flexibility:**. An experimental facility is needed to develop and test options. This facility should be able to replace PFCs and change material choices. The facility should be flexible enough to install and test different divertor geometries and configurations.

FDF, an Approach to Develop and Test PFC Components for a DEMO Environment

FDF is a facility and program to address the issues outlined above. FDF will be an experimental device designed for development and testing of concepts for use in DEMO. To accomplish these goals FDF design includes the following features.

1. **Compact design**, R ~ 2.5 m, a ~ 0.7 m, employing advanced tokamak features, high beta and confinement to achieve reactor relevant conditions.
2. **Helium or liquid metal cooling**, for hot wall operation and avoiding risk of water coolant accidents
3. **Steady state**, ~ 2 weeks of non-inductive operation.
4. **Flexible configuration.** The upper sections of the normal conducting copper TF coils can be removed for access to the entire vessel, allowing for easy access to change out PFCs.
5. **High density:** The operating density in FDF will be about 3 times that of ITER, allowing the more compact divertor in FDF to have similar neutral retention capabilities as the longer slot divertor in ITER. Higher density also promotes detached divertor operation to reduce erosion.

The characteristics of an FDF facility will allow for a broad and flexible research program on reactor relevant PFCs. Features of this program can include:

1. **PFC material changes:** A number of different materials can be tested during the FDF facility program.
    a. Carbon target plate and PFCs might be used in the early stage, Carbon is a forgiving material to tolerate disruptions, ELMs and periods of divertor attachment while optimizing FDF performance and operation for both the core and divertor plasmas.
    b. Open access to the vessel will allow for relatively frequent changes and tests of PFC material solutions. Particularly a design for PFCs separable from the blankets would afford increased research opportunities..
    c. Later changes to PFC materials and blankets can test all relevant DEMO materials choices, suggestions have been various tungsten alloys, boron infiltrated tungsten, silicon carbide, and other ideas that will arise.
2. **PFC design tests:** A number of PFC design concepts can be tested in FDF. These could include, but are not limited to; swirl tubes and hypervapatrons for heat flux removal and brazing or clamping techniques for the PFC to the heat sink material.
3. **Heat flux solutions:** The detachable toroidal field coils will allow access to the entire vessel for installation of different divertor hardware solutions. These can include:
    a. A toroidally continuous divertor target manufactured and assembled outside the vessel to high tolerance. This would allow for the kind of precision alignment of surfaces (done in DIII-D) that eliminates edge effects and allows practically unlimited use of flux expansion.
    b. Installation of novel divertor concepts to spread the heat flux and decouple the core and divertor plasmas such as the Super-X divertor configuration.
4. **Tritium fuel cycle:** A number of physical processes can affect the tritium fuel cycle. Many of these can be tested in a FDF facility.
    a. Changes to cooling techniques and/or coolant flow rates will allow for testing of the temperature dependence of tritium retention.
    b. Changes to material choices may affect tritium retention and permeation.
    c. Cleaning techniques, such as oxygen bake for carbon, can be tested.

FDF will employ a staged approach for its program plan. The stages of operation are currently envisioned as follows:

1. **1st phase:** Initial run period of ~5 years, ~12 dpa, to optimize the advanced tokamak aspects for high power density. This phase might use carbon as a PFC because of its forgiving nature during this period. . It would be advantageous to be able to try at least a couple different PFC arrangements in front of the first main blanket.
2. **Maintenance period:** A 2 year period for maintenance and change out of PFCs and and installation of the second main blanket. A number of options can be explored based on what is learned in the first operation period. The PFC material is likely to be high Z, perhaps tungsten or other possibilities.
3. **2nd operation phase:** Currently envisioned to be about 5 years, providing ~25 dpa for material testing. The best nearer term options can be explored during this phase. It would be advantageous to be able to try at least a couple different PFC arrangements in front of the second main blanket.
4. **Maintenance period:** This second maintenance period will be used to install the third and most advanced blanket, first wall and divertor materials and components.
5. **3rd operation phase:** A 5 year run period with optimized parameters to achieve a neutron fluence of ~ 40 dpa. Again, it would be advantageous to be able to try at least a couple different PFC arrangements in front of the third main blanket.