WP 09-16

A FUSION DEVELOPMENT FACILITY TO TEST HEATING AND CURRENT DRIVE SYSTEMS FOR DEMO

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Submitted to the
DOE ReNeW Process for
Posting on the ReNeW Website

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February 27, 2009

GENERAL ATOMICS

DEMO HEATING AND CURRENT DRIVE ISSUES

The DEMO tokamak fusion reactor requires extremely long pulses to obtain sufficient neutron fluence to meet its goals. This implies that the plasma current must be supported fully noninductively. To reduce the power to manageable levels the bulk of the current should be the neoclassical bootstrap current, but extensive modeling says this is limited to around 80% of the current, and the remaining current must be supported by auxiliary systems. Four main techniques for driving current have been developed: neutral beam current drive (NBCD), lower hybrid current drive (LHCD), fast wave current drive (FWCD), and electron cyclotron current drive (ECCD). These techniques have been explored in the tokamak program, and all have scientific and/or technological issues when extrapolated to DEMO parameters and conditions.

1. **Neutral Beam Current Drive Issues**. Neutral beam injection is the main heating method of most modern tokamaks, but its extension to DEMO is not straightforward.

   a. ***Source Technology***. NBCD requires beams of neutrals with energy in the 1 to 2 MeV range to provide penetration to the plasma core. Development of this negative ion beam source technology is underway for ITER, but its success is far from assured, and the ITER team is studying options for heating and current drive (H&CD) if the technology development stalls. Multi-MeV multi-MW power supplies are also extremely challenging and expensive. Extremely long pulses exacerbate all the problems

   b. ***Activation and Tritium Containment***. Neutral beams cannot have windows or bends separating the neutralizing cell, accelerator, and the ion source from the powerful flux of neutrons from the fusioning plasma. This has three detrimental effects:

      1) The tritium boundary is extended from the plasma vacuum chamber to the source. This can be a major extension of the tritium containment cell.

      2) The neutralizer cell, accelerator, and ion source will be quickly extremely activated, requiring that all service be performed remotely. This is a difficult challenge even for well-developed technologies.

      3) The neutron flux and the activation decay products will make reliable operation of the neutral beam components even more difficult, for example by compromising insulators and creating a background of ionized decay products.

   c. ***Flexibility***. NBCD and neutral beam heating lack flexibility for purposes of plasma physics. Beam heating and current drive are inextricably linked, so central heating will always drive currents that might not be wanted centrally if reversed shear is desired. NBCD can support off-axis current drive, but unless the beams are pivoted (a technically difficult solution) the location of the current drive is fixed.

2. **Lower Hybrid Current Drive Issues**. LHCD is known for its very high current drive efficiency in present-day tokamaks, in which an energetic tail, sometimes in the MeV range, to the electron distribution function is created by waves with $n_{\parallel}$ in the range below 2. This high current drive efficiency, perhaps double that of other techniques, is good, but some physics and technical issues remain. LHCD is not at present a component of ITER, so LHCD techniques may not be developed there.

   a. ***Generation***. Wave sources in the 5 GHz range are not well developed. A 500 kW klystron is under development for KSTAR, but extension to pulse lengths of millions of seconds will not be done for that objective. Low unit power is a cost driver, and combining power from many klystrons is complicated.

b. ***Coupling***. Lower hybrid waves do not propagate in vacuum. The launchers tend to be rather delicate structures that must be recessed behind the adjacent walls to avoid damage by the plasma. This leaves a gap between the launcher and the plasma where the wave is evanescent. The gap may be rather large in a device like DEMO, so means of propagating the waves to the plasma must be developed. Some successful work has been done by puffing gas near the antenna, but the robustness of this solution and the effects on the plasma and the adjacent walls have not been addressed. The PAM launcher technology may help, but this has not been demonstrated, particularly in extremely long pulses.

c. ***Control***. LHCD waves, after coupling to the plasma core, tend to be absorbed where the electron temperature reaches 7 or 8 keV. For a high-pressure pedestal, this may be very close to the plasma edge. In any event, control over the radial location of the current drive is very limited.

d. ***Absorption of Waves by Alpha Particles***. Absorption of waves by alpha particles is theoretically predicted but the models are not validated against experiment.

3. **Fast Wave Current Drive**. Fast wave current drive has moderate efficiency in present-day experiments. Issues include:

   a. ***Generation***. Efficient multi-MW power sources with extremely long pulses in the frequency range 50–100 MHz must be developed.

   b. ***Launcher***. Launchers with high power density and extremely long pulses have not been designed or demonstrated. Launchers are being developed for ITER, but the designs at present are marginal in their power handling. Again, high voltage standoff in the presence of intense activation is a very serious issue. The heat and neutron loads from the plasma are major cooling issues, and disruption forces are a large concern due to the large size of the launcher elements.

   c. ***Coupling***. Like LH waves, the fast wave does not propagate in vacuum. Large outer gaps needed to avoid damage to the first wall make the coupling weak and require large voltages on the launcher elements.

   d. ***Control***. Fast wave current drive tends to be concentrated near the magnetic axis, with little possible control of the location. For reversed shear scenarios this is of limited use.

   e. ***Absorption of Waves by Energetic Particles***. Absorption of waves by energetic particles like alphas is not understood in experiments in present devices.

4. **Electron Cyclotron Current Drive (ECCD)**. Electron cyclotron heating/ECCD (ECH/ECCD) tends to be highly localized to the location where the rays cross the cyclotron resonance, which is useful for controlling the current profile and for MHD control. The current drive has moderate efficiency but it falls off as the minor radius is increased due to trapping effects. The physics of ECH/ECCD is well understood, and application to DEMO does not require operation in new regimes of the dimensionless parameters that characterize the physics. Issues include:

   a. ***Generation***. Gyrotrons have been developed which meet the ITER goal of 1000 s pulses at 170 GHz and 1 MW of power at 55% efficiency. Extension of the pulse length to much longer pulses for DEMO are required. Higher unit power is desirable, and work is proceeding on 2 MW gyrotrons. Stepwise frequency tunability is very desirable for increasing the flexibility of the ECH system. Increasing the robustness of the designs is essential.

   b. ***Launcher***. EC launchers designed for ITER may not be acceptable for the extremely long pulses of DEMO due to the thermal loads and damage to mirror surface conductivity by a high neutron fluence. Development of alternate steering concepts like the "remote steering" would greatly advance the robustness of the ECH launcher, which would become simply a small hole — 5 cm for 2 MW — in the first wall, with dissipation in the walls of the hole being insensitive to the electrical conductivity. Modest advances in transmission line and window technology are desirable.

Many of the plasma diagnostic techniques used in existing tokamaks will not be practical in a DEMO. R&D applied to the design and testing of ITER diagnostics has begun to address these issues, but will not provide the solutions for a DEMO. While plasma physics research may no longer be a major element in DEMO, development of highly reliable diagnostics and sensors capable of providing the inputs needed for plasma and burn control will be required and will be a major challenge.

FDF IS A TEST FACILITY FOR H&CD PHYSICS AND TECHNOLOGY

The H&CD approaches described above can be applied in FDF as a test facility for DEMO. In this use the technologies have two functions: first, to support successful FDF operation, and second, to develop and demonstrate extremely long pulse operation in an intense heat and neutron environment. Success in FDF would go very far in demonstrating a developed technology for DEMO.

Some technologies are more suitable than others for FDF. Negative ion neutral beam injection (NBI) has severe technical problems, negative effects on the facility due to the increased tritium containment zone, and costs. Fast waves require antennas that occupy a large area of the vessel wall, and they drive current at a non-optimum location in the plasma.

LHCD has some attractive features, particularly its current drive efficiency. However, its current drive takes place very near the plasma boundary, as shown in Fig. 1 for a trial FDF equilibrium. This is too close to the boundary to be useful. Lowering the pedestal pressure would help, but that would also affect plasma performance.

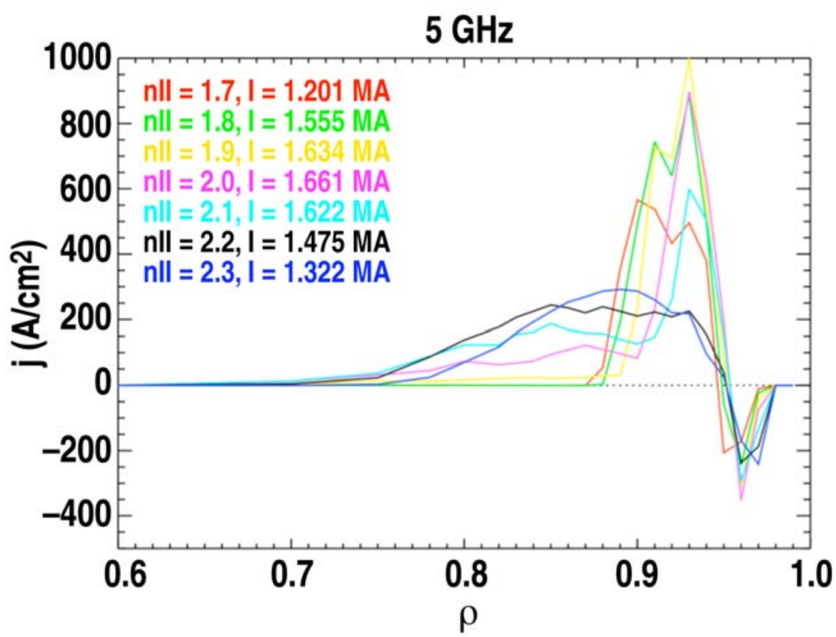

Fig. 1. LHCD current density profile for FDF for 5 GHz and a range of launched $n_{\parallel}$ values. Also shown are the integrated values of total driven current. Calculations were done with the GENRAY ray tracing code and the CQL3D Fokker-Planck code.

Time-dependent modeling has shown that 75 MW of ECCD is sufficient to support the full plasma current, when the bootstrap current is included. While this might be too much power for an economical power reactor, for the mission of FDF it is satisfactory.

Figure 2 shows the final steady-state current profiles for the bootstrap current, ECCD, and residual Ohmic current. Operation at this point will support the full FDF high fluence mission while validating the technology of extremely long pulse ECH. It will also drive the technology development needed for reliable high efficiency gyrotrons at 170 GHz and compatible launchers.

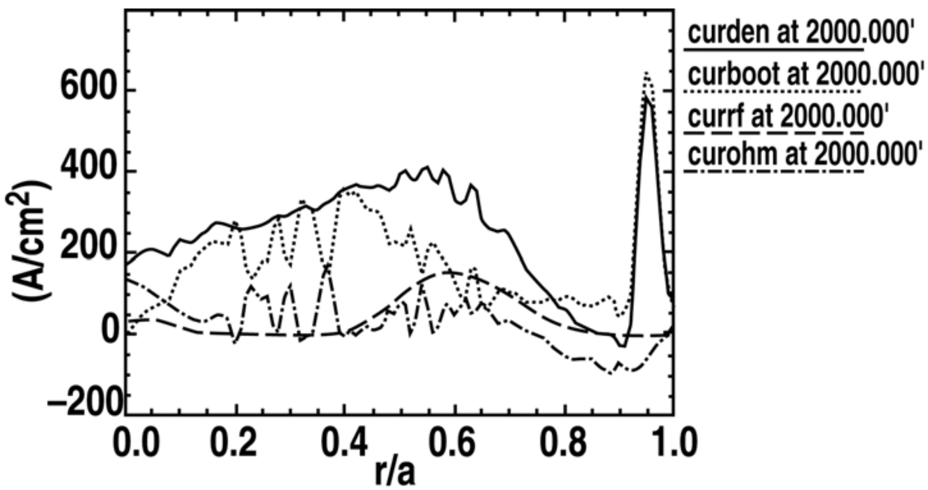

Fig. 2. Radial profiles of total current density, bootstrap current density, ECCD, and residual Ohmic current density, for an FDF equilibrium and 75 MW of EC power at 170 GHz.