Issue: Provide Basis for Tokamak Operation with Dominant Electron Heating

Fusion reactors will operate in the regime with predominantly electron heating, since the main heating power in a high-Q system is the fusion reaction. The fusion of D and T produces 3.5 MeV α-particles, which transfer most of their energy to electrons. In contrast, most experiments at present are heated primarily by neutral beam injection, which heats the ions dominantly. Hence, there are significant uncertainties in extrapolating present-day performance to regimes in which electron heating is dominant. Specific issues include:

• Transport—energy, momentum, and particles---at low rotation and with $T_e \geq T_i$.

Microturbulence: The stability of the various microturbulence modes (ITG, TEM and ETG), a major factor in confinement and performance of fusion plasmas, depends sensitively on the T_e/T_i ratio. In addition, the microturbulence physics depends on collisionality and, more weakly, on beta. In order to investigate effects of T_e/T_i in reactor relevant regimes, sufficient wave power is needed to be able to reach the desired collisionality and beta, with sufficient remaining power to manipulate T_e/T_i.

Pedestal height: H-mode confinement quality is also dependent on the height of the edge pedestal. Experiments indicate that the fast ions injected by neutral beam injection may influence the edge pedestal height. A full range of H-mode operation with dominant electron heating would allow an assessment of any differences anticipated for ITER.

L-H transition and back-transition power: Critical to achieving ITER's goals are accessing and sustaining high confinement regimes during plasma current ramp up, flat top, and ramp down in its H, D, and D-T phases. Experiments have shown that increasing the injected torque raises the L-H transition power, and there have been indications that the L-H transition power is dependent on the partition between ion/electron heat flux in the edge. It is therefore important to fully research these effects using dominant electron heating with negligible torque injection.

Effect on density and impurity profiles without central fueling: Electron heating generated by waves or α-particles supplies heat

without introducing particles, unlike neutral injection. The resulting steady-state density profiles with only edge fueling have not been studied in high performance (high β, low collisionality) plasmas, but they would be expected to differ from those in today's experiments and may strongly affect the technology needed for plasma fueling. Impurity transport would also be affected by the equilibrium density gradient.

<u>Effect on equilibrium electric fields</u>: Dominant wave heating may produce radial and poloidal electric fields that affect confinement and stability. Some evidence for this may be in the effects of wave heating on the density profile.

• Stability

<u>Rotation:</u> Research on intrinsic rotation in electron cyclotron heated plasmas shows that centrally localized ECH produces counter rotation while the edge rotation is in the co-current direction. Some similar effects have been seen with lower hybrid waves. However, the power range in present experiments is quite limited and the plasmas conditions are far from having reactor relevant collisionality and beta, so measurements in the reactor regime are needed. Empirical scaling of the intrinsic rotation shows that beta is a very important parameter, with the edge rotation increasing essentially linearly with beta.

<u>Current Profile:</u> For steady-state scenarios, the ability to direct ECCD with precision at various radii allows optimization of the profiles for stability and current sustainment. For inductive scenarios, this is true to a lesser extent, due to the high efficiency of inductive current drive, but ECCD may be sufficient to avoid tearing/locked modes by changing the stability index Δ'. The stationary inductive current profile obtained with dominant electron heating may also be different than that obtained in present-day tokamaks with dominant co-injected neutral beams.

<u>Susceptibility to locking:</u> Present experience indicates that rotation has a positive effect on the onset of tearing modes at the β values desired for burning plasma scenarios. These modes have a tendency to lock to the wall and grow, leading to disruption. Since this work has been carried out with balanced and co-injected neutral beams, it is not clear whether the observations are due directly to rotation (or sheared rotation) effects or due to the subtle changes in the current profile with the change in the neutral beam geometry.

Sawtooth behavior: It is well-known that fast ions (either from neutral beams or ICRF) can have a substantial impact on the sawtooth behavior. A model describing this effect exists, but detailed comparisons with experiment indicate the agreement with experiment may be fortuitous. Observation of sawteeth with pure electron heating would eliminate many outstanding questions. In addition to the fast ion effects, without rotational shear the tearing modes readily couple to the sawtooth precursors. This makes suppression of the tearing modes by ECCD much harder and may lead to easier triggering of tearing modes by the sawtooth crash.

• **Burn control**: Wave heating may be used in present day experiments to simulate the α-heating of a reacting plasma, where the central heating is adjusted to be a function of the local density and temperature. This allows development and experimental testing of advanced control systems for reacting plasmas.

• **Scenario development:** Dominant electron rather than ion heating is expected to have significant consequences on advanced scenarios. The increased electron β should have the positive benefit of increasing the bootstrap current fraction for a given total β. The lack of rotation, in addition to the effects described above, will challenge the RWM feedback control systems for scenarios that operate above the no-wall β limit.

• **Fueling:** Pellet penetration is strongly reduced as the electron temperature increases. High electron temperature and high density are needed to test pellet penetration in reactor-like conditions.

Initiative: An experimental facility with the capability to deliver large amounts of electron heating power, comparable to NBI power and sufficient to supply most of the power needed to achieve reactor-relevant beta, is urgently needed in the worldwide fusion program to address critical issues for ITER and future burning devices. Without such a facility, significant uncertainties will remain in the performance projections of these devices due to a lack of data in dominant electron-heated regimes. Such a facility would also enable the study of high performance plasmas in dominant electron-heated regimes and the compatibility with with other systems like fueling and plasma control.

Electron cyclotron heating is an excellent choice for this wave heating for many reasons. Its location and profile can be easily controlled by adjusting the toroidal field or the aiming of the wave beam. Unlike

LHCD, it can deliver power without affecting the current profile, but if desired the EC waves can also drive localized currents which are effective for modifying the current profile and controlling MHD instabilities like neoclassical tearing modes. The EC waves do not interact with the discharge boundary and they are not affected or absorbed by α-particles. ECH antennas are simple and robust compared to other wave techniques.

DIII-D offers an excellent facility for having sufficient electron heating power to simulate α-heating in a tokamak with reactor-relevant dimensionless parameters. ECH is already developed at the 6 MW level at DIII-D, and the EC system was used in over 35% of the discharges in the 2008 campaign for a wide variety of applications. Many of the technical issues for ECH have been resolved, an experienced staff for implementation and operation exists, and codes, procedures, and diagnostics for interpretation of EC-related physics is well developed. Raising the ECH power to 12 MW could be economically and relatively quickly done, and this would allow exploring reactor-relevant regimes with $T_e \geq T_i$, with particle and momentum source-free heating.