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Ways to reduce your tokamak heating bill: Gaining control of edge transport barriers on Alcator C-Mod

In the tokamak edge, the coupling of particle and energy transport can be loosened under some circumstances, leading to surprisingly enhanced performance. [BI3.00004]

A crucial challenge in magnetic fusion is to obtain high energy confinement in a stationary plasma that is compatible with the engineering requirements of a fusion reactor. The triggering of edge transport barriers at the boundary of confined plasma is a common approach to obtaining high energy confinement, in a regime known as *H-mode*, which extrapolates to high performance in ITER and other burning plasma devices. However, barriers to energy transport can sometimes be self-defeating, since they also provide a strong barrier to particle transport. This can lead to enhanced confinement of impurities in the plasma core, excessive radiated power and deterioration of performance for a given amount of input power.

Ongoing research on the Alcator C-Mod tokamak is exploring techniques for partially decoupling the transport of thermal energy and that of particles and impurities, within the region of the edge transport barrier, or *pedestal*. In H-mode, this is usually accomplished with some variety of edge relaxation mechanism. These occur naturally under certain plasma conditions and promote the flushing of impurity ions from the core. Unfortunately they can have drawbacks. In the case of intermittent edge-localized modes, substantial amounts of pedestal stored energy are released in a very short time, at power density levels which are expected to cause significant damage to materials in ITER. More benign relaxation mechanisms have been found to regulate plasma density and impurity concentration continuously in time, although they can often be obtained only with very specific operational schemes or in a restricted range of parameter space.

C-Mod scientists have experimented with the shape and topology of our magnetic equilibrium in order to optimize overall confinement and understand its relation to pedestal characteristics and edge relaxation type. An exciting example of this shape manipulation can occur when the natural drift direction of ions introduced by magnetic field gradients is directed away from the plasma's X-point, i.e. the null point where the magnetic field is entirely in the toroidal direction. For reasons that are not completely understood, this magnetic configuration leads to a substantial rise in the input power required to access H-mode with an edge pedestal. However, for input power somewhat below this access threshold, a thermal transport barrier forms, yielding H-mode-like edge temperatures and energy confinement, without the presence of a strong particle and impurity barrier. (See accompanying figure.) This improved regime can be sustained steadily without intermittent bursts of edge transport, and demonstrates the potential of suppressing the formation of traditional H-mode. Moreover, exploration of this regime may provide significant new insights into the turbulence stabilization mechanisms that underlie transport barrier formation.

While this operating technique relies on the natural response of the plasma, an additional technique for external pedestal regulation has been explored. Electromagnetic waves in the range of frequencies known as lower hybrid waves were injected into stationary H-mode discharges with a well defined pedestal in both density and temperature. It was discovered that this technique could alter the plasma transport in the edge barrier, relaxing the density gradient and boosting the overall edge temperature. Modeling work is ongoing to understand the character of the lower hybrid wave deposition, and to explain the physics mechanism which is degrading the particle confinement and leaving the energy confinement unchanged or perhaps slightly improved.

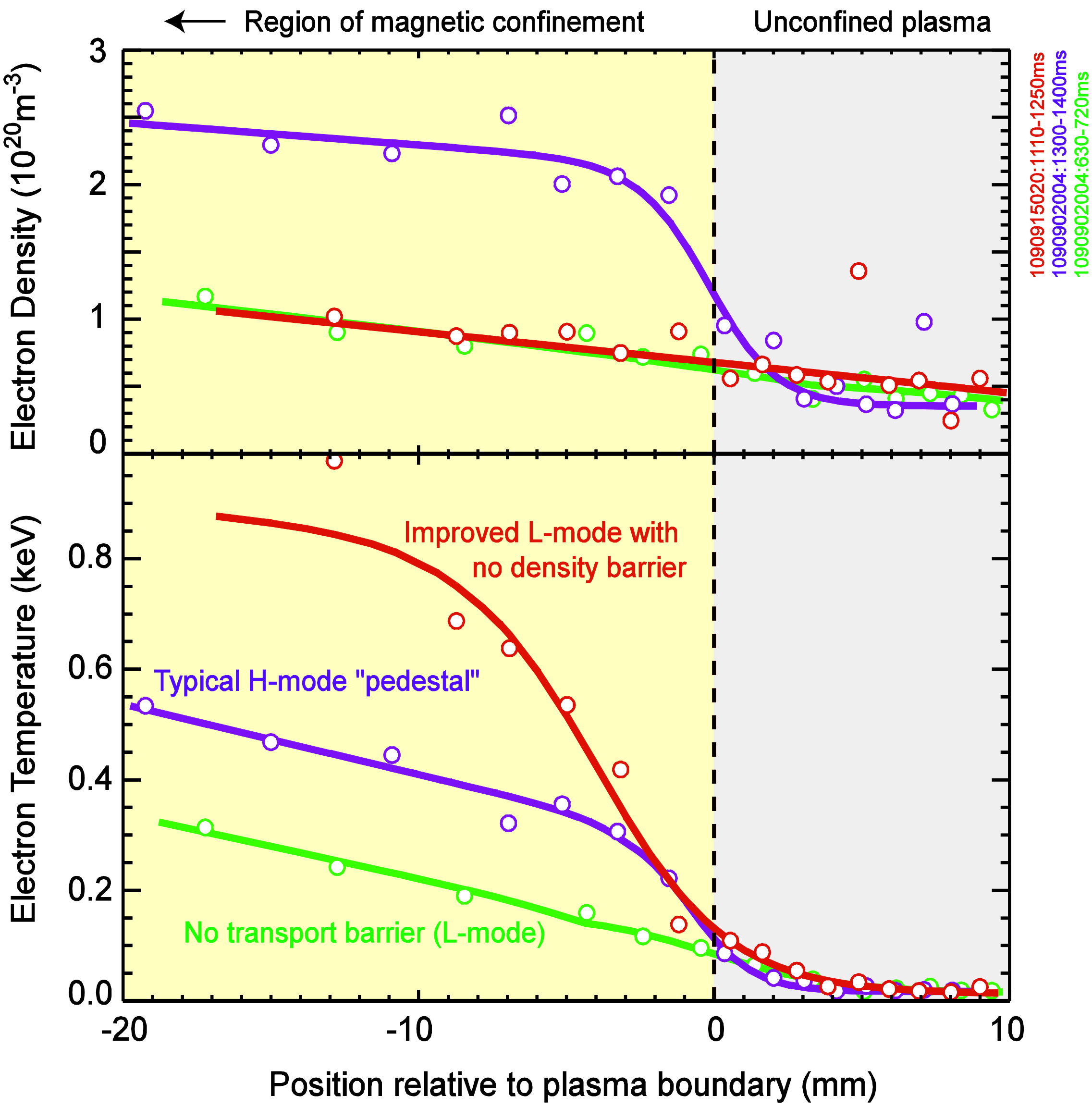

Figure: Density and temperature profiles in a 3cm region near the tokamak boundary are shown. In L-mode (green), the profiles are relatively flat, indicating high transport. In a typical H-mode (purple), transport barriers form, steepening the profiles, and often leading to unwanted impurity confinement. Improved L-modes (red) have excellent energy confinement while keeping particle and impurity transport high, leading to favorable operating conditions.