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FAST WAVE HEATING AND CURRENT DRIVE IN TOKAMAK PLASMAS WITH NEGATIVE CENTRAL SHEAR*

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Fast waves provide an excellent tool for heating electrons and driving current in the central region of tokamak plasmas. In this paper, we report the use of centrally peaked electron heating and current drive to study transport in plasmas with negative central shear (NCS). Tokamak plasmas with NCS offer the potential of reduced energy transport and improved MHD stability properties, but will require non-inductive current drive to maintain the required current profiles. Fast waves, combined with neutral beam injection, provide the capability to change the central current density evolution and independently vary T_e and T_i for transport studies in these plasmas. Electron heating also reduces the collisional heat exchange between electrons and ions and reduces the power deposition from neutral beams into electrons, thus improving the certainty in the estimate of the electron heating. The first part of this paper analyzes electron and ion heat transport in the L–mode phase of NCS plasmas as the current profile resistively evolves. The second part of the paper discusses the changes that occur in electron as well as ion energy transport in this phase of improved core confinement associated with NCS.

Current drive and heating in L–mode plasmas with NCS

NCS formation. Plasmas with NCS are formed on DIII–D by heating the electrons with neutral beam injection during the current ramp-up phase of the discharge.[1,2] Operating at low density leads to high electron temperature and a long resistive diffusion time, freezing in a hollow current profile. Figure 1 shows time histories for a 1.6 MA discharge with 3.5 MW of neutral beam power injected during the current ramp. In this shot counter fast wave current drive (FWCD) was applied starting at 1.0 sec. The electron temperature immediately increases from 3 to 5.5 keV as the fast waves heat the electrons. There is also a small density rise associated with the rf. At the beginning of the rf injection, $q_{\min} \approx 2.4$ and $q_0 \approx 3.0$ as measured by motional Stark effect spectroscopy.

Current profile modification. Counter current drive in the central region of the plasma enhances and maintains the shear reversal during the current profile relaxation. For comparison, $q_{\min}$ and $q_0 - q_{\min}$ from a similar discharge with co current drive are also shown in Fig. 1. The current density is evolving towards a more peaked profile in both of these discharges as observed in the decreasing value of $q_{\min}$. The difference between the time behaviors of $q_{\min}$ indicates centrally peaked counter

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current drive slows the rate at which the current profile peaks, while co current drive accelerates this process. The difference between the time behaviors of $q_{\min} - q_0$, a quantity related to the degree of central shear reversal, shows counter current drive maintains the negative shear for a longer duration than co.

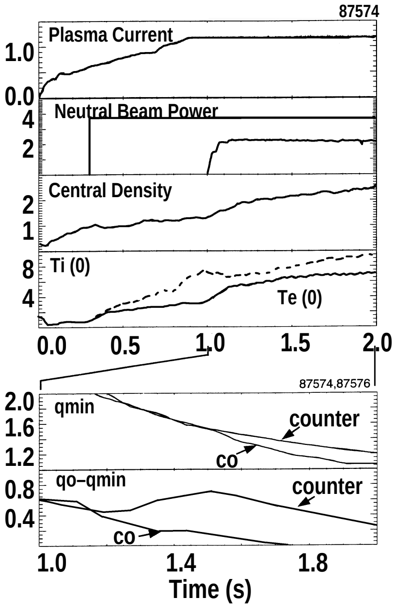

Fig. 1. Time histories for a L-mode NCS plasma with fast wave heating and counter current drive. q_0 and $q_0 - q_{\min}$ are also shown for a shot with similar parameters but co current drive.

q dependence of thermal transport. The scaling of global confinement with plasma current and internal inductance[3] implies that the local thermal transport is related to the poloidal field. Empirical T_e, T_i, density, q, and change in the thermal diffusivities χ_e, χ_i at 1.3 and 1.95 sec. Surprisingly, even though there is a large variation in $q_{\min}$, from 1.8 to 1.0, χ_e drops by less than 15% over this time. Outside the NCS region, χ_i actually increases by 50%. This can be inferred from the profiles of T_e or T_i; T_e changes very little, while the slope of T_i flattens for $0.3 < \rho < 0.8$. The increase in T_i over this region is largely due to an improvement at the plasma edge. The increase in T_i and the corresponding drop in χ_i in the NCS region would appear to be correlated with the dropping q value, allowing the plasma to take on hot ion mode characteristics. The variation of transport at the location of $q_{\min}$ is interesting since the magnetic shear at this point is constant in time and equal to zero. This weak dependence of transport on q over much of the plasma cross section challenges previous explanations of the current scaling of transport.

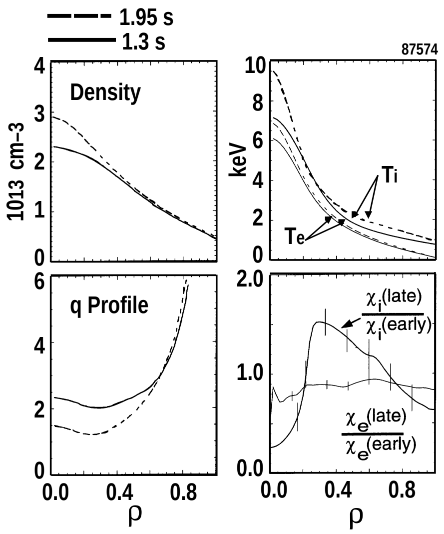

Fig. 2. Profiles at 1.3 sec (dashed) and 1.95 sec (solid) for the shot in Figure 1. The curves are spline fits to the data for T_e, T_i, and density. The q profiles are determined with an equilibrium reconstruction code and data from MSE. χ_e and χ_i are calculated from power balance using the transport code ONETWO.

Transport in NCS plasmas with improved core confinement and fast wave heating

Frequently, a reduction in the core transport is observed in the NCS configuration. A clear reduction in χ_i to neoclassical levels has been reported in neutral beam heated DIII–D plasmas,[4,5] as well as reduction of particle diffusivity for some NCS discharges. A small reduction in χ_e was also inferred from DIII–D NCS discharges, but the uncertainty in the extent of the reduction was large because the direct heating of the electrons with neutral beams was small and significant uncertainty remained in the determination of the ion-electron heat transfer. Use of fast wave heating improves the certainty with which the electron heating is known.

Improved core confinement is found in 1.6 MA DIII–D plasmas when 5 MW of neutral beam injection is applied during the current ramp with low density ($< 1.5 \times 10^{13}\,\mathrm{cm}^{-3}$), and an additional

2.5 MW is applied after flattop. The transition to improved core confinement occurs about 100 msec after the additional neutral beam power is applied and detected most easily in the central density, as illustrated in Fig. 3. Coupling significant rf power to these L–mode plasmas has been difficult; H–mode transitions, triggered by additional rf heating, cause rapid changes in antenna loading which interfere with the transmitter operation. Nonetheless, 1.2 MW of rf power has been applied to this discharge starting before the additional neutral beam (shown in Fig. 3) and lasting through the transition to improved core confinement. This power level was sufficient to cause strong heating and peaking of the electron temperature inside the shear reversal region. Figure 4 shows the kinetic profiles at 1.55 and 1.75 sec, before and after the transition.

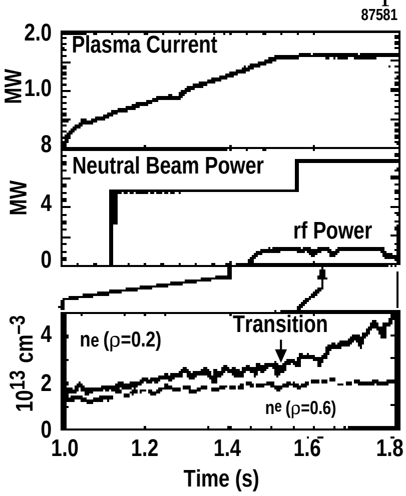

Fig. 3. Time histories for a NCS plasma with fast wave heating and improved core confinement starting at 1.55 sec.

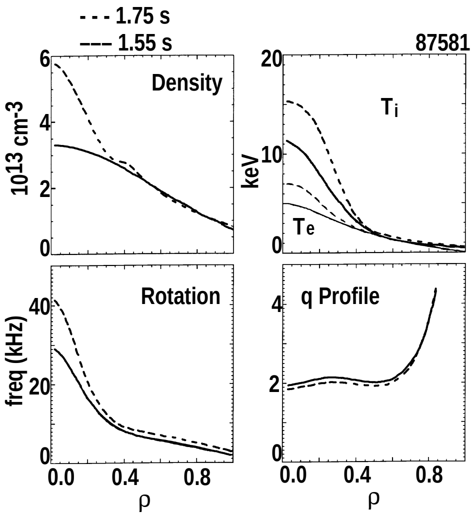

Fig. 4. Profiles before (1550 msec) and after (1750 msec) the transition in Fig. 3.

The fast wave power in the central region is the dominant source of electron heating in the power balance, but other terms are also important for accurately evaluating the change in χ_e. The transport analysis indicates that part of the apparent peaking is a result of the change in convective energy loss associated with the improved particle confinement after the transition. The change in the time derivative of the electron energy density and the increased ion-electron heat exchange are also important for evaluating the electron thermal transport. Figure 5 shows χ_e, χ_i, and χ_{mom} before and after the transition, with these effects properly accounted for. χ_i drops by an order of magnitude to neo-classical levels, while χ_e and χ_{mom} decrease by 50%, both remaining well above neoclassical levels. The physical mechanism causing ion thermal transport apparently causes some electron loss mechanism for these channels.

Role of q_{min} in the NCS transition. The phenomenology of the core transport barrier formation might be explained by various aspects of microturbulance theory.First, the negative magnetic shear allows stabilization of both macroscopic MHD modes (*e.g.*, sawteeth) and small scale MHD modes (*e.g.*, ballooning modes) in the plasma core. Then, according to one hypothesis, the microturbulence is stabilized by sheared $\vec{E} \times \vec{B}$ flow. As the pressure and plasma rotation in the plasma core build up, the radial electric field E_r also increases. If sufficient $\vec{E} \times \vec{B}$ shear develops, the rotational shear can stabilize microturbulence and a transport bifurcation can develop.[6,7] One criterion for the bifurcation is that the linear growth rate of the drift waves be offset by a shearing rate $\propto (p/q)(\partial/\partial\rho)(E_r/RB_p)$.[8] This shearing rate is most effective with low q_{min} and large momentum input. Another hypothesis suggests that the increased Shafranov shift associated with high-β_p in the central region of the plasma can lead to drift reversal of the trapped particles in that region, thereby stabilizing drift waves which are responsible for particle and ion heat transport. The Shafranov shift of the central flux surfaces increases with q_{min}; thus, this model would predict that the transition would have a lower power threshold at high q_{min}, a different prediction than for rotational shear stabilization. Furthermore, this would be a potential mechanism for cases without momentum input such as balanced neutral beam injection.

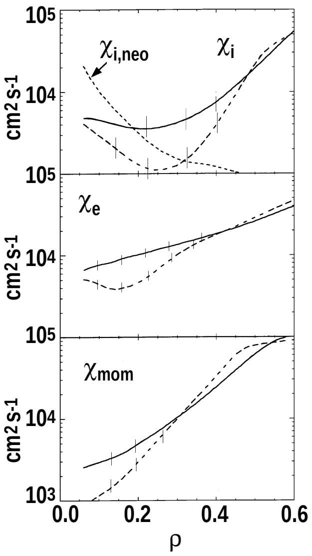

Fig. 5. χ_i, χ_e, and χ_{mom}, before and after the transition in Fig. 3.

NCS transitions at low NBI power, strong rf heating and low q_{min}. Spontaneous transitions to improved core confinement have been observed at lower neutral beam power using 2.2 MW of counter fast wave current drive and heating during the current flattop. Figure 6 shows time histories for the neutral beam power, rf power, and plasma current, and the central electron and ion temperature. At a time 1.95 sec, the T_e and T_i both increase, T_e increasing from 6 to 8 keV. Prior to and during the improved phase, the discharge has NCS, but with q_{min} just above 1. When q_{min} drops below 1 at 2.2 sec, the enhanced confinement mode is lost with the onset of sawteeth. T_e, T_i, and electron density all show reduced transport in the region of shear reversal. As above, the power balance analysis indicates that χ_e drops by less than 50%. The long delay between the turn on of the rf power and the transition in core confinement implies that the q profile is important for the transition; the low value of q_{min} makes the transition easier, thus implicating rotational shear stabilization as the mechanism for reduced transport.

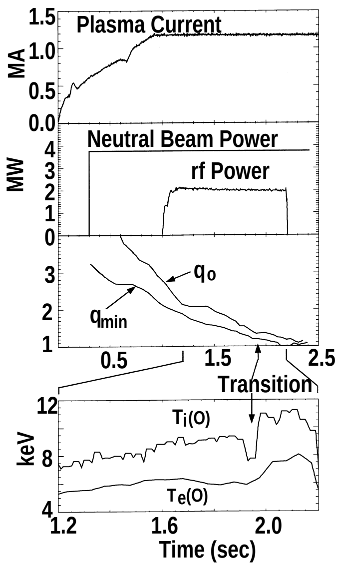

Fig. 6. Improved core confinement in an NCS discharge with a phase transition low q_{min} and substantial rf heating and counter current drive.

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