Intrinsic rotation generation in DIII-D ELM-free H-mode plasmas

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The turbulent Reynolds stress and edge plasma flows were measured during intrinsic-rotation generation in DIII-D ELM-free H-mode plasmas [1]. In these low-power conditions, a reciprocating multi-tip Langmuir probe can penetrate up to 1 cm inside the separatrix at the outboard midplane. A 1-cm wide rotation layer is observed at the separatrix, also seen in some upper-single-null L-modes [2], which rotates at 40 km/s in the co-current direction, independent of the injected torque [Fig. 1]. The layer forms within < 50 ms after the L-H transition and shows almost no evolution from there on. No feature appears in the C^{6+} impurity rotation measurement by charge-exchange-recombination (CER) spectroscopy [Fig. 1(f)]. However, a dedicated re-analysis of CER data from a similar helium experiment, in which the CER system can measure the main-ion rotation, unambiguously confirms the existence of the layer [Fig. 2].

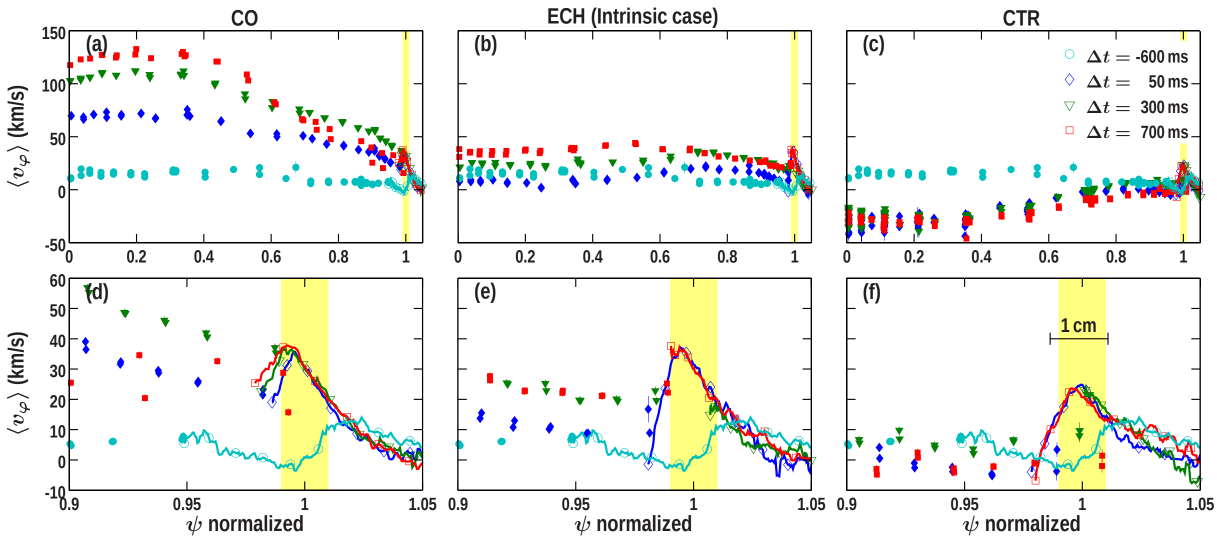

Figure 1: Rotation evolution in early ELM-free H-mode for co-NBI, ECH and counter-NBI heating. A narrow co-current rotation layer forms at the separatrix within 50 ms of the L-H transition in all cases. The bottom row shows an expanded view of the edge region.

The helium data also clearly confirms that a dip in the rotation profile persists at $\psi \sim 0.9$ during the evolution of intrinsic rotation, separating the edge layer from the evolving core region. This observation of a "hole" in the rotation profile rules out a simple picture in which the core rotation evolves according to viscous diffusion starting from a rotating boundary layer.

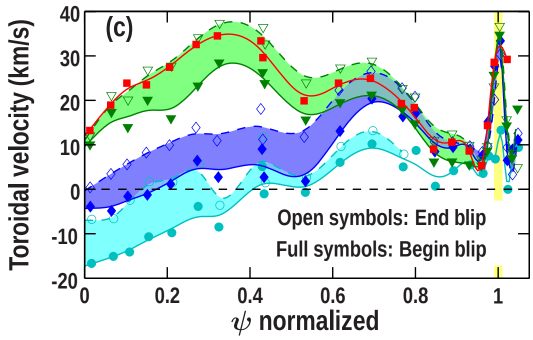

Figure 2: Independent confirmation of the existence of the edge co-rotation layer in helium plasmas. The different profiles (in rising order) are measured in 400-ms intervals, starting at 150 ms before the L-H transition. The bands show the rotation change attributed to the 10-ms co-current beam blips.

A second piece of evidence that the momentum transport must be strongly profile-independent is given by co- and counter-NBI cases in Figs. 1(a) and 1(c), which suggest that the total rotation profile is well described as the simple sum of the intrinsic profile in Fig. 1(b) and a beam driven contribution.

We found that the measured turbulent Reynolds stress at the edge layer was not consistent with the core spin-up [1]. The turbulent radial and toroidal velocity fluctuations showed weak correlations until 0.5 cm inside the separatrix, which, in addition to a reduction of the fluctuation amplitudes at the peak of the edge co-rotation layer, resulted in a negligible inferred torque (< 0.05 Nm). Further into the core, the correlations increased strongly up to values of $+0.75$, yielding counter-current torques up to -2 Nm. From the evolution of the angular momentum content in the core plasma volume, a co-current torque of $+0.3$ Nm is required in the vicinity of the separatrix [Fig. 3]. An additional mechanism must thus be present that balances the Reynolds stress and provides a net co-current torque of $+0.3$ Nm at the separatrix.

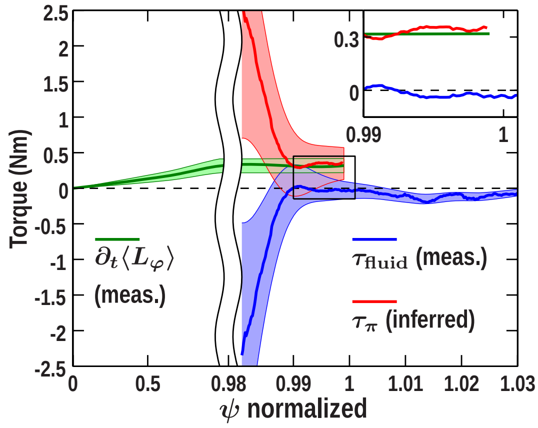

Figure 3: Comparison of the core angular-momentum change with the inferred torque from the measured turbulent Reynolds stress.

We have investigated several candidate mechanisms that could explain the missing torque. When particles move inward across the poloidal magnetic field during the density rise, the ions and electrons feel oppositely directed $\mathbf{\Gamma} \times \mathbf{B}$ torques of up to ∓ 20 Nm. However, since these torques attempt to change the plasma current, they are up against a 500000-fold increased inertia due to the inductance matrix. For such "heavy" particles, 20 Nm is a negligible torque.

In ELM-free H-modes, it is always possible to find a boundary enclosing the plasma that is sufficiently far out that the plasma density on the boundary is essentially zero, yet the experiment shows that the angular momentum contained in the volume clearly increases during intrinsic rotation generation. Thus the missing momentum transport mechanism must either transport momentum along open field lines or must be capable of transporting momentum in vacuum. There are still two mechanisms that can accomplish the latter: Neutrals and Maxwell stress.

To investigate the role of neutrals, a simple model was created that solves the 1D transport equation

$$\langle 1\rangle_\psi^{(0)}\partial_t(n\Omega)+\partial_\psi(n\langle a\rangle_\psi^{(1)})=-n\langle\nu\rangle_\psi^{(0)}\Omega \quad , \tag{1}$$

where $\langle\cdot\rangle_\psi^{(j)}\equiv\langle V'R^2|\nabla\psi|^j(\cdot)\rangle_\psi$ and $\langle a\rangle_\psi^{(1)}\equiv\langle V_\rho\rangle_\psi^{(1)}\Omega-\langle\chi_\varphi\rangle_\psi^{(2)}\partial_\psi\Omega+\langle a_{\mathrm{RS}}\rangle_\psi^{(1)}$, for *ad-hoc* profiles for residual stress $\langle a_{\mathrm{RS}}\rangle_\psi^{(1)}$, pinch $\langle V_\rho\rangle_\psi^{(1)}$, viscosity $\langle\chi_\varphi\rangle_\psi^{(2)}$ and momentum transfer rate to neutrals $\langle\nu\rangle_\psi^{(0)}$. The boundary conditions are $n\langle a\rangle_\psi^{(1)}(\psi=0,1)=0$, since the fluxes must vanish on axis and the point $\psi=1$ is chosen sufficiently far out that $n(\psi=1)=0$. With a negative $\langle a_{\mathrm{RS}}\rangle_\psi^{(1)}$ centered at $\psi=0.75$ and $\langle\nu\rangle_\psi^{(0)}=0$, the rotation profile evolves until the residual stress is balanced by viscous stress: $\langle\chi_\varphi\rangle_\psi^{(2)}\partial_\psi\Omega=\langle a_{\mathrm{RS}}\rangle_\psi^{(1)}$ [Fig. 4(b)]. No net momentum gain or loss occurs. For $\langle\nu\rangle_\psi^{(0)}>0$ rising towards the edge, preferentially oppositely directed momentum is

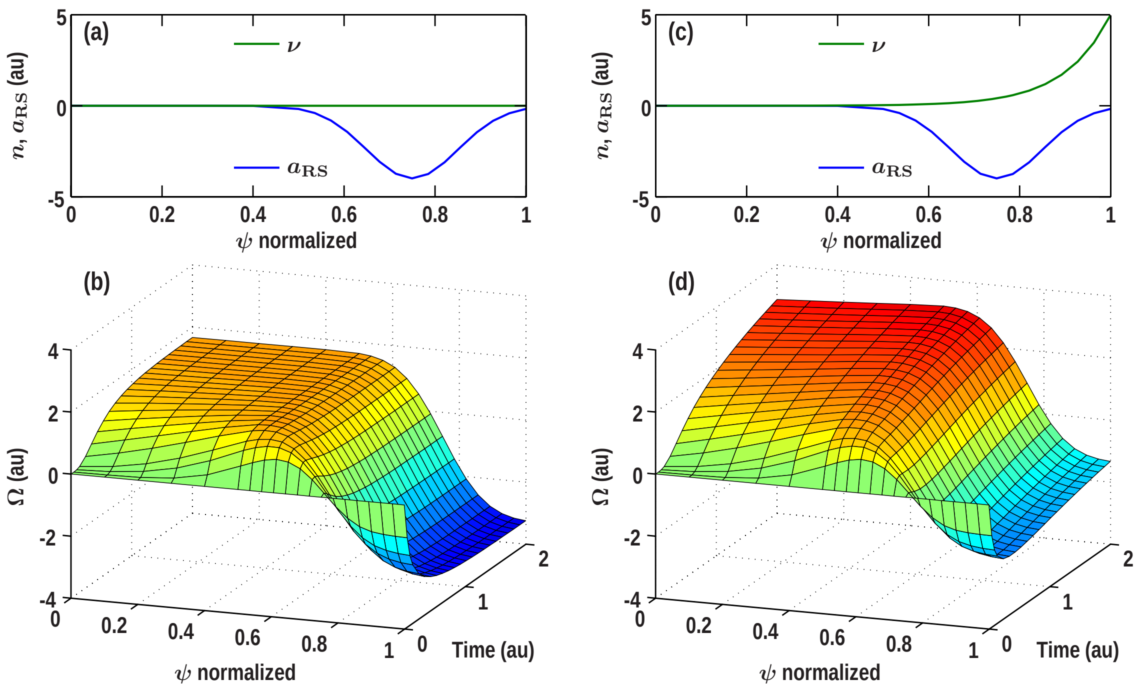

Figure 4: Simple momentum transport model. (a)-(b) A residual stress moves momentum from the edge to the core until balanced by viscosity. (c)-(d) Neutral friction at the edge preferentially removes oppositely directed momentum, leading to a net spin-up of the core.

transferred to neutrals and lost, leading to a net spin-up of the core until the rotation-inversion point has moved sufficiently far out that $\int_0^1 d\psi n\langle v\rangle_\psi^{(0)}\Omega = 0$ [Fig. 4(d)]. The core momentum has changed despite the fact that the residual stress at the boundary was zero, but this scenario requires the existence of a rotation inversion point, which is not seen experimentally [Fig. 1(b)]. Allowing the neutrals to rotate reduces the efficiency of the momentum transfer, requiring an even more pronounced rotation-inversion region. If indeed no rotation-inversion region can be observed experimentally, the idea that neutrals contribute significantly to intrinsic rotation generation in DIII-D could be ruled out. However, it is presently unclear whether the rotation-inversion region could be sufficiently small to be undetectable within the experimental uncertainties. Kinetic calculations of angular momentum transport by a neutral gas in contact with a spinning plasma are under way to clarity this issue.

The second mechanism that can transport momentum in vacuum is Maxwell stress, by observing that the generated torque $\tau_{\mathrm{T}}(\psi) \equiv \oint_{\partial V(\psi)} d^2\sigma R\mu_0^{-1}\langle \tilde{B}_\varphi \tilde{B}_\rho\rangle$ does not depend on the local plasma density. The required correlated magnetic field fluctuations can be generated by current fluctuations elsewhere, in the core or even outside the vessel. At present, no measurements of Maxwell stress are available at DIII-D, but measurements on MAST [3] would result in torques up to 0.03 Nm, which could scale to relevant magnitudes for a device of the size of DIII-D.

Finally, the momentum could go out along open field lines in the form of ions impinging on the divertor plates. Analysis of ion-loss trajectories yields a co-current core spin-up [4] and a co-rotation layer at the separatrix that is qualitatively consistent with our experimental observations [1, 4]. A mechanism that charges up the core plasma negatively after the L-H transition is also required to build up the radial electric field, which cannot be accomplished by an ambipolar transport mechanism. In this picture, momentum transport is generated by kinetic stresses due to strong velocity-space structuring, supported by the extreme gradients of the H-mode pedestal.

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