Rotation reversal in a 1D turbulence spreading model

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For plasmas without external or boundary momentum sources spontaneous spin up challenges transport theory and our understanding. Without an initial rotation profile or a seed flow the momentum flux due to diffusion and pinch is everywhere equal to zero and no build-up of rotation, neither of net plasma rotation nor of differential plasma rotation, can take place. Specifically the rapid transition from co- to counter-rotation observed in the core region after LH transition on CV [1] and the rotation changes observed in vast detail in Alcator C-Mod [3, 2, 4] and other devices, mainly with edge density (and thus line averaged density) increased in ohmic L-mode plasmas, are unexplained. Rotation reversal is observed when the confinement regime changes from Linear Ohmic Confinement (LOC) to Saturated Ohmic Confinement (SOC). SOC indicates the plasma state where the confinement cannot be further improved by additional fuelling and the profiles are stiff. The rotation reversal is found to take place at a specific radial position in LOC.

The transition from LOC to SOC is coinciding with the disappearance of cold pulse reversal; i.e., for LOC a cold pulse started at the edge results in a temperature increase in the center, while for SOC there is no such reversal. Several ideas to explain such behaviour have been proposed, most based on the concept of nonlocal transport. We suggested an explanation of cold pulse behavior based on the concept of turbulence spreading [5], used in a transport model. This model was able to qualitatively reproduce the cold pulse behaviour observed on JET [6], leading us to the assumption that transport in LOC regime

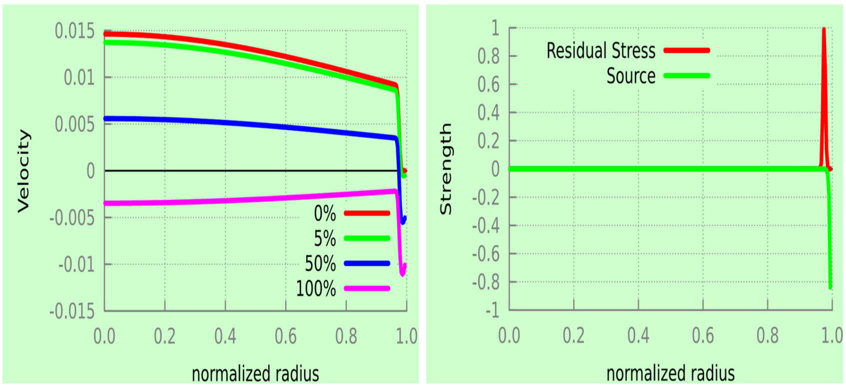

Figure 1: *Rotation due net SOL source in counter direction and residual stress flux (of varying strength) at the edge, due to turbulence intensity gradient. Sources are depicted by the local flux they cause.*

is non-local. Namely, in LOC turbulence is triggered only in the outer, unstable, part of the plasma. The innermost part of the profile, in LOC, is still below marginal stability and provides room for further increase in performance until the SOC is reached. In SOC the pressure profile is marginally unstable everywhere and instability driven turbulence extends over the whole radial domain and the ensuing transport keeps the profile locked to the marginal one. The critical density depends on several parameters, plasma current, toroidal magnetic field, heating, collisionality.

The second ingredient to modelling is the concept of residual stress [7]. It has been suggested that turbulent momentum transport can lead to differential transport of positive and negative momentum fluctuations, thus providing a differential rotation source. The turbulent momentum transport is expressed in the Reynoldsstress (RS). For transport modelling purposes the RS is usually parametrised into diffusion like components proprtional to the gradient of the momentum profile and convective terms proportional to the momentum itself. The residual stress $\mathscr{R}$, as RS as a whole, is a transport term, and as such it exerts a zero net torque on the plasma. It is usually not captured by transport models. However the residual stress can be expressed as nonzero momentum fluxes.

$$RS = n < \tilde{v}_r \tilde{v}_\theta > = -D \nabla V_\theta(r) + V_{convective} V_\theta + \mathscr{R} \quad (1)$$

It should be noted that in situations with finite particle flux the convective component of the momentum flux can play arole, as well as in very non-linear situations, as ELMs the triple correlation between density and the velocity components []. Here we restrict ourselves to situations with zero particle flux.

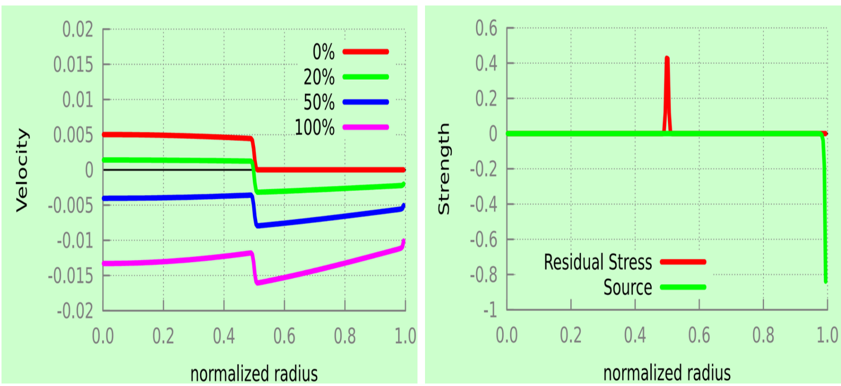

Figure 2: *Rotation due net SOL source (of varying strength) in counter direction and residual stress source in the center of the plasma at the transition from stable to unstable plasma (LOC situation)*

The residual stress $\mathscr{R}$ can be shown to be connected to symmetry breaking in the experiment, for example due to up down asymmetries in shaped discharges or due to interction with wave fields or, what we will mainly assume here, gradients in the turbulence intensity field [8]. As shown in Figures 1 and 2 the residual stress $\mathscr{R}$ can revert the effect of momentum losses at the SOL and lead, even though not being a source of momentum, to flow reversal at the radial position where the residual stress is localised. Guided by the observations discussed above and the elements of turbulence spreading plus residual stress the following model coupling the evolution of the pressure profile, the turbulence profile and the toroidal momentum is proposed for the pressure p, the turbulence intensity field I and the toroidal velocity V:

$$\partial_t p = -\nabla_r \cdot q_t + \frac{1}{r}\chi_0 \partial_r \left[p3/2\partial_r p\right] + S_h \tag{2}$$

$$\partial_t I = \frac{1}{r}\partial_r \left[r D_r I \partial_r I\right] + \gamma I - \alpha I^3 \tag{3}$$

$$\partial_t V = \frac{1}{r}\partial_r \left[r D_0 \partial_r V + r V_{conv} V + r\beta \partial_r \log I\right] + S(r) \tag{4}$$

$$q_t = I \cdot p \cdot C \tanh(\gamma) \tag{5}$$

where q_t is the turbulent flux, resulting from the correlation between pressure and turbulence field. The residual stress $\mathscr{R}$ is presumed to depend on the turbulence gradient.

Figure 1 shows that a residual stress can counteract an edge source and thus revert the rotation direction implied by the SOL flows. If the $\mathscr{R}$ is located at the edge, no rotation reversa is found in the plasma, but should the $\mathscr{R}$ be localised at midradius, the rotation reversal with a crossover from co- to counter- rotation appears at the localisation of the residual momentumflux.

Full simulations with system (2) to (5) were performed to check the possibility of rotation reversal in situations with transition from stable to unstable profiles. The results are depicted in Fig 3. For different pressure source levels the profile gets supercritical at smaller radial positions, until the discharge is supercritical everywhere.

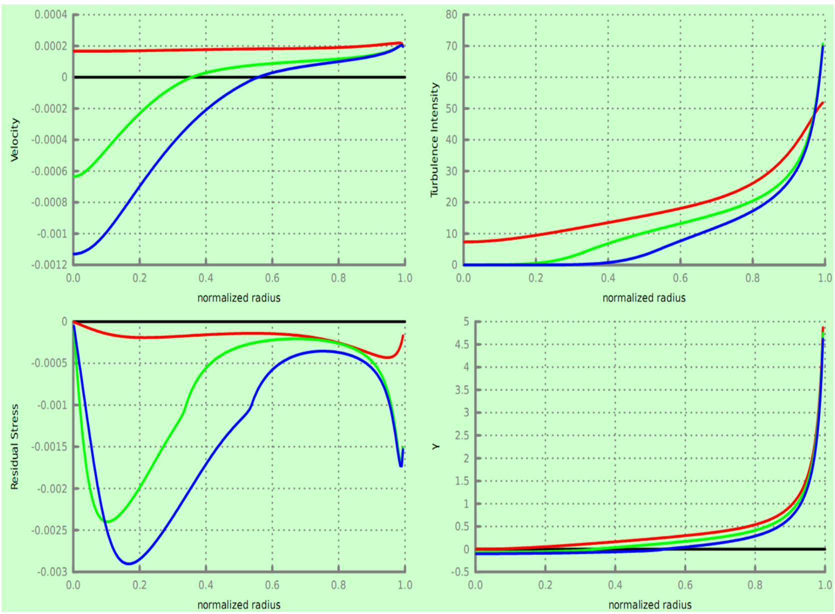

Figure 3: *Simulations for different strength of the pressure source (blue=weak, green= intermediate, red=strong) corresponding to transition from LOC to SOC. Resulting velocity profile, turbulence intensity, instability growth rate, and residual stress (clockwise).*

From this point on the

pressure does not increase further. We identify this as the transition from LOC to SOC. In LOC we observe strong gradients in the turbulence level close to the point where the profile becomes unstable. These turbulence intensity levels in turn drive $\mathscr{R}$ and arrange for a rotation reversal slightly outward from the point where the profile becomes unstable. Thus LOC states show rotation reversal, with the position of the reversal moving inward as SOC is approached and dissapearing completely in the SOC state.

For LOC like cases a strong gradient in the turbulence intensity appears locally at the radius, where the profile becomes unstable. This gradient initiates a localized $\mathscr{R}$, i.e., a localized momentum flux, which is the cause for the rotation reversal. In other situations the transition from unstable to stable profiles have been identified as the location of cold pulse polarity reversal, where the cold pulse actually leads to an increase in temperature (or pressure) as the sub-critical profile is pushed towards the critical profile by the dissipating turbulence created through the cold pulse [6]. Thus cold pulse polarity reversal is expected for LOC situations at the location of transition to an unstable profile, the numerical proof still not available due to the extremme stiffness of the 1D system being solved.

We demonstrated in a simple transport model, including effects of turbulence spreading, how $\mathscr{R}$ can lead to rotation reversal. Specifically, we show how the transition in L-mode (Ohmic) confinement properties is related to the observed rotation reversal.

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