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Shear, Temperature Gradient and Collisionality Dependences of Particle Pinches in JET

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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives",*
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ABSTRACT.

The peakedness of density profiles in L-modes and in H-modes exhibits remarkably different behaviour. The former scales with overall plasma shear in accordance with Turbulent EquiPartition (TEP) theory ($n_{e0}/\langle n_e\rangle \sim 1.5l_i$), independently of collisionality. On the other hand, peaking in H-modes depends on collisionality, with $n_{e0}/\langle n_e\rangle$ increasing from ~1.2 at $\nu_{eff}= 1$ to $n_{e0}/\langle n_e\rangle$ ~1.6 at the collisionality of the ITER reference H-mode, $\nu_{eff} \approx 0.1$. H-mode density profiles show no shear dependence, except for $\nu_{eff}<0.2$. Evidence for L_{Te}, L_{Ti} or ρ^* dependences has been obtained neither in L nor in H-modes. Carbon density profiles from CXS are always less peaked than electron density profiles.

1. EXPERIMENTAL EVIDENCE

The peakedness of the density profile in source-free MHD-quiescent L-mode plasmas with off-axis Lower Hybrid Current Drive (LHCD) at power levels up to 3.6MW decreases with decreasing peaking of the current profile. For these discharges, which include normal and reversed magnetic shear plasmas (as determined by polarimetry), the relationship can be expressed as $n_{e0}/\langle n_e\rangle \cong 1.6l_i$ where l_i is the normalised internal inductance (fig.1). These experiments, which were previously reported in [1], have been reanalysed with density inversions using the more accurate SVD-I method, which adopts as base functions the topos provided by an biorthogonal decomposition of a sequence of ~50 Thomson scattering profiles [2]. Density profiles remain monotonically peaked at negative shear. The density profiles remain peaked at zero loop voltage and negligible core particle source, as determined using the neutral transport code KN1D [3], confirming investigations in fully current driven discharges in Tore Supra [4] and TCV [5]. The peaking of the temperature profiles and of the current profiles are largely uncorrelated in this dataset, allowing an experimental distinction between their effects on the density profile. No dependence on L_{Te} was found. These discharges have been analysed with respect to microinstabilities with the gyrokinetic code GS2 [6]. The main result is that the sign of the mode frequency is very sensitive to input parameters. We interpret this as an indication that the discharges are in a mixed ITG/TEM regime, where thermodiffu-sion is expected to be weak [7]. Figure 2 shows that the peaking factor is independent of the the-oretically important effective collisionality defined as $\nu_{eff} = \nu^*_{ei}/\omega_{De} \sim 3(m_i/m_e)^{1/2}\varepsilon^{3/2}\nu^*_{ei}/q$ and evaluated at mid-radius, assuming $k_{\theta\rho}= 1/3$. The figure also shows that the carbon density profile from Charge Exchange Spectroscopy (CXS) is significantly less peaked than the electron density profile. We have extended the study to a variety of NBI and ICRH L-modes with a similar results, $n_{e0}/\langle n_e\rangle \approx 1.4l_i$ and no discernible collisionality dependence.

The behaviour of H-modes is in stark contrast to the above, fig.3, with a clear collisionality dependence and no l_i dependence, except for $\nu_{eff}<0.2$. There is also no dependence of peaking on $\langle n_e\rangle$, nor on P_{ICRH}/P_{aux}, P_{nbi}/P_{aux}, L_{Te}, or L_{TI}. Fig.3 is a confirmation of an earlier observation on ASDEX-upgrade [8], with the difference that the collisionalities on JET extend to those expected for the ITER reference H-mode. The peaking is slightly higher (by ~0.1) at ν_{eff}~0.2 in JET than in

[8] when the evaluation of ν_{eff} is based on a flat Z_{eff} derived from visible Bremstrahlung. JET and ASDEX results are however brought into agreement when using the lower and hollow Z_{eff} profiles measured by CXS. The agreement suggests an extrapolation to ITER. Since both β and shear in ITER are within the parameter range of current experiments, such an extrapolation will depend on the scaling with ρ^*. The data in Fig.4 are resolved by ρ^*, showing that for any ν_{eff} interval considered, there is no ρ^* dependence, as expected from theory [9]. In Fig.5 we plot the data in terms of at mid-radius, resolved by $R/L_{Te} = n_e/\nabla ne$ showing that there is also no direct evidence for thermodiffusion. Hence, assuming otherwise similar (sub-ignited) conditions, we expect that the peaking factor on ITER for $\nu_{eff} \approx 0.1$ will be $n_{e0}/<n_e> \approx 1.6+-0.2$, as at JET, corresponding to at mid-radius.

2. DISCUSSION

Such strong peaking raises concerns about impurity accumulation in the core. CXS measurements show, that for light impurities, this is not the case. Carbon density profiles are close to flat at any collisionality, resulting, for the lowest collisionalities, in hollow Z_{eff} profiles, Fig.6. This may be due to neoclassical ion temperature gradient screening, as well as to anomalous effects. Simulations using the Weiland model show that an initially flat Z_{eff} profile in H-mode evolves into a hollow one, purely as an effect of anomalous transport. However the issue of heavy impurities will require further investigation.

In Fig.7 we plot the cumulated, normalised number of particles N, versus the poloidal flux for the LHCD L-modes and for H-modes. Normal shear L-modes (black) and low colli-sionality H-modes (red and yellow) are remarkably close to the TEP behaviour expected from purely diffusive transport of trapped electrons in poloidal flux space, i.e $dN/d\Psi$ constant over most of the cross section [9]. Higher collisionality H-modes, reversed shear L-modes and plasmas with strong central electron heating ([10], not in fig.7) depart from TEP.

The density profile resulting from a combination of trapped and passing particle transport was discussed in [9]. We conjecture that a density profile directly reflecting trapped electron transport may also be consistent with a virtual absence of anomalous passing electron transport, consistently with the TEP assumption of conservation of the second invariant (enclosed toroidal flux for passing particles), i.e. passing electrons arriving at any location would do so by collisional detrapping only. The absence of l_i dependence for ν_{eff} in H-modes, as well as the $\nu_{eff}>0.2$ and the independence of peaking in L-modes are puzzling paradoxes, hinting at basic differences in the underlying turbulence. A plausible interpretation may be that L-modes are near the ITG/TEM stability boundary, with little thermodiffusion. Plasmas with density flattening due to central electron heating may be driven well into the TEM domain, experiencing outward thermodiffusion [7], whilst H-modes at $\nu_{eff}>0.2$ are in the ITG domain [8]. H-modes at $\nu_{eff}<0.2$ may be peaked enough to destabilise TEM. If so, $n_{e0}/<n_e>$ in ITER may be reduced by the strong α heating, to below the level observed in JET at $\nu_{eff}\sim 0.1$ [7].

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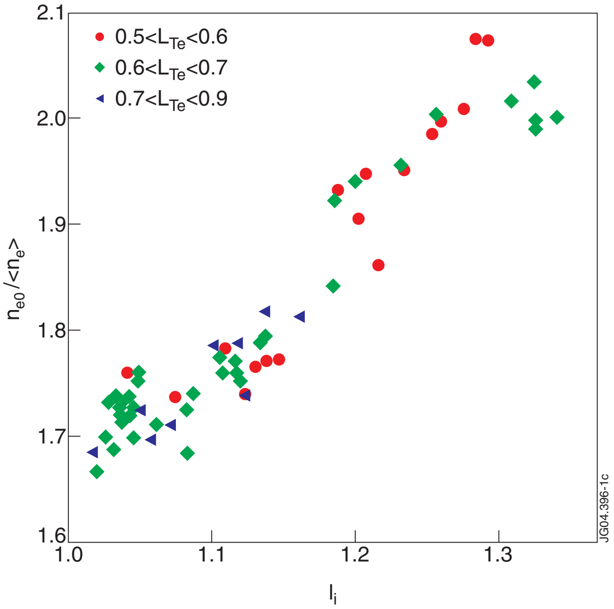

Figure 1: Density peaking in LHCD L-modes versus internal inductance, resolved by electron temperature gradient length.

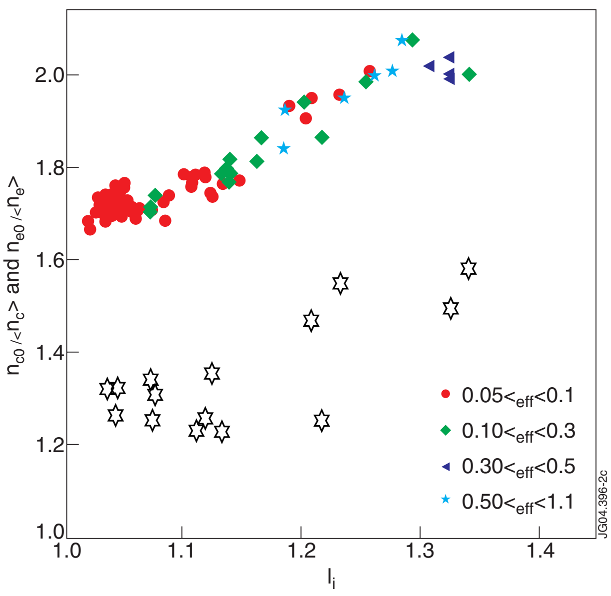

Figure 2: Same resolved by effective collisionality at r/a=0.5. In black, peaking factor of carbon impurities.

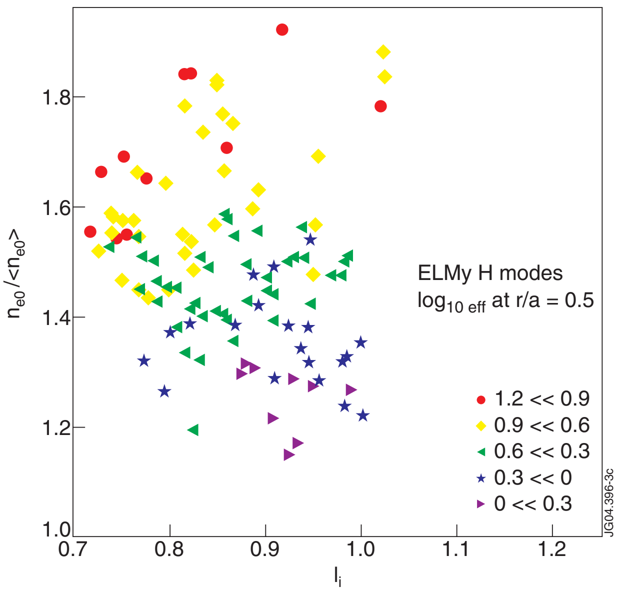

Figure 3: Peaking factor in H-mode versus v_{eff}. Symbols refer to classes if internal inductance.

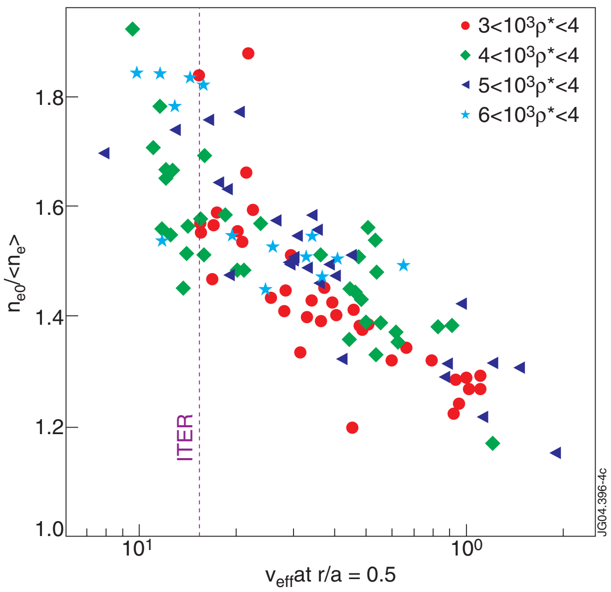

Figure 4: Same, resolved by normalised Larmor radius ρ.*

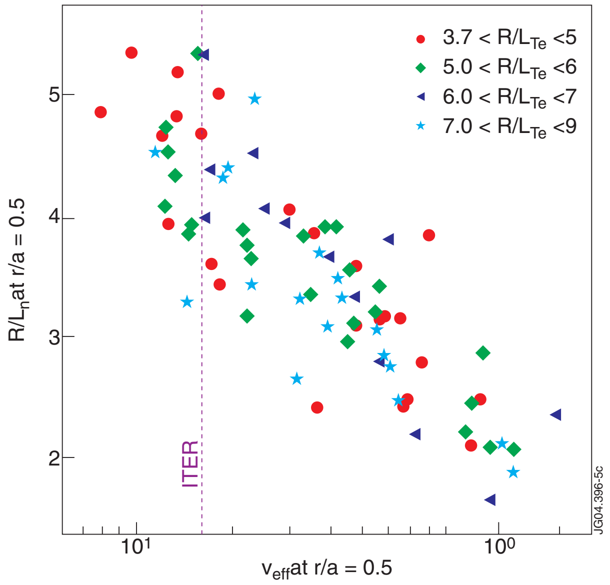

Figure 5: Normalised density gradient at r/a=0.5, resolved by temperature gradient (H-mode).

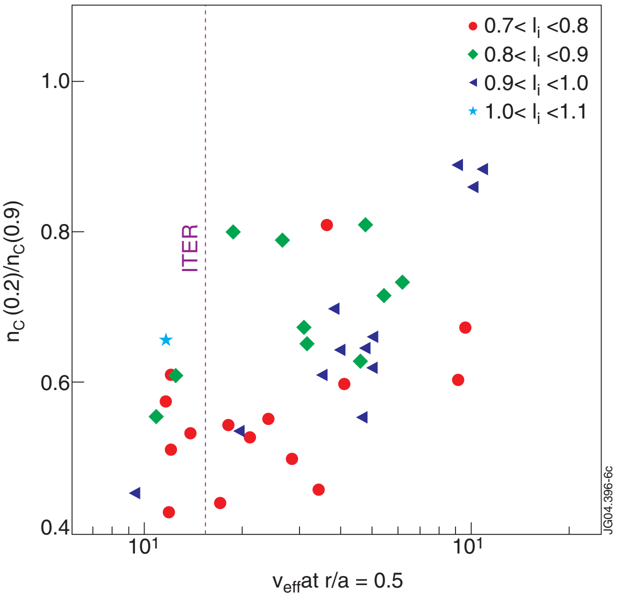

Figure 6: Ratio of carbon concentrations near the edge and in the plasma core (H-mode).

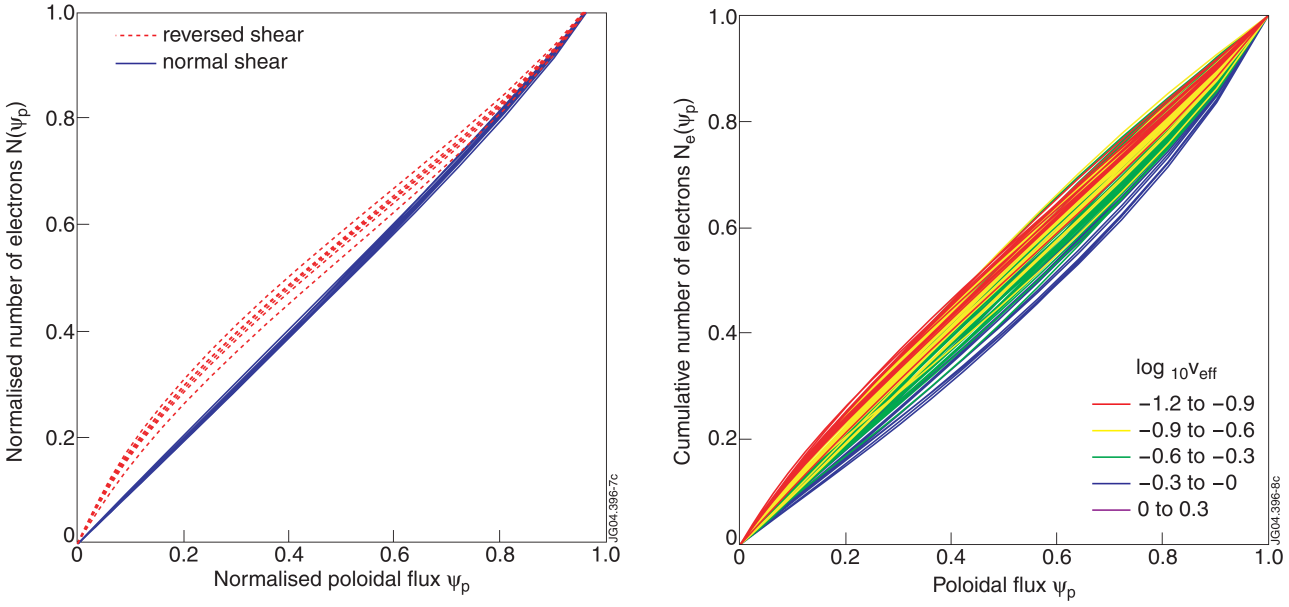

Figure 7: Comparison of density profiles with TEP. left: LHCD L-modes. right: H-modes.