Probable identification of the Coriolis momentum pinch in JET

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Introduction. In view of mounting evidence for non-diffusive momentum transport processes [1,2] and theoretical predictions thereof [3,4], a broad survey of the JET database was undertaken to ascertain the ubiquity of non-diffusive processes, their parameter dependencies and the consistency of theoretical predictions with observations. The database presented here, as well as the analytical approach, builds on previous JET profile databases, constituted for investigating density peaking [5]. This database, 'JETPEAK', contains several hundred steady-state samples used for this study, which provide a comprehensive coverage of the JET operating domain with profile data from CXRS, Thomson scattering (HRTS or LIDAR) and q profiles from EFIT. The data are so far restricted to H-modes and hybrids with NBI power in the range 5-20MW, 0.6<H98<1.4 with operation in deuterium, without additional TF ripple.

Analytical method.

The method is to test whether the normalised gradients follow a dimensionless normalised diffusion-convection equation with a tractable (i.e. limited) number of dependencies, e.g dependencies consistent with the theoretically predicted Coriolis pinch [3,4]. To this effect, we write the local steady state momentum transport equations as:

$$t - l\Gamma_N = -\chi_\phi l \nabla \omega / \omega + lV \qquad (1)$$

Here t is the local torque surface density (N/m) from NBI, $l = m_i n_i R^2 \omega$ is the angular momentum density, ω the toroidal angular velocity, Γ_N is the particle flux associated with the particle source (NBI), χ_ϕ is the radial momentum diffusivity and V is the momentum pinch velocity. Eq.(1) is de-dimensionalised and normalised as:

$$R\frac{\nabla \omega}{\omega} = -\frac{\chi}{\chi_\phi}\left\{\frac{Rt}{\chi l} - \frac{R\Gamma_N}{\chi n_i}\right\} + \frac{RV}{\chi_\phi} \qquad (2)$$

The LHS of eq.(2) is obtained from CXRS measurements, while the term between brackets, the normalized net dimensionless torque t^*-Γ_N^*, is obtained from a combination of measurements and calculations, including the local heat balance. χ is a related transport parameter (preferably χ_i, as hereafter), which is determined from the local power balance. The particle flux term in (2) is a small (~10%) correction to the gross torque from the NBI. The form of eq.(2) lends itself to determining the Prandtl number χ_ϕ/χ_i and the pinch number RV/χ_ϕ, as well as their parameter dependencies, by means of regression techniques.

Experimental scaling

Fig. 1 shows simple fits over the whole database, at two radial positions, aimed at determining only the typical Prandtl and the pinch numbers. The symbols are resolved by the confinement factor H98, showing that the relationship between torque and R/L_ω does not depend on confinement quality.
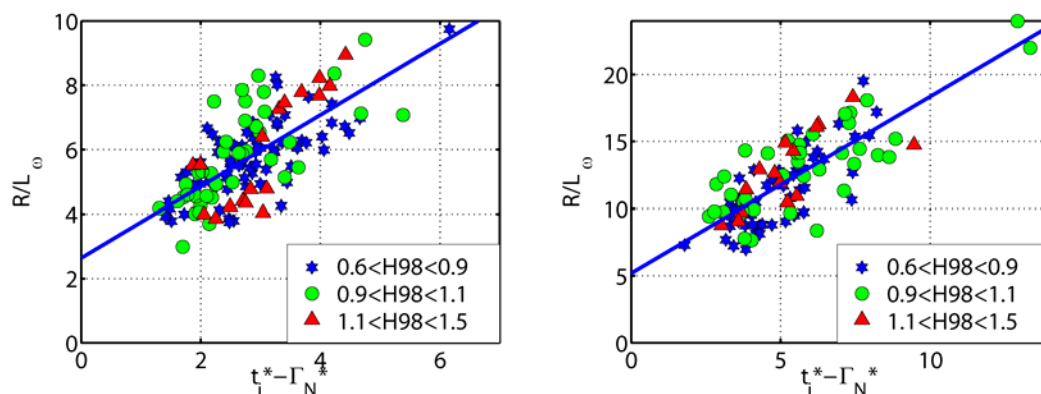

Fig.1 Fits of eq.(2), showing a diffusive component (slope) and a convective component (intercept a zero effective torque) for r/a≈0.45 (left) and r/a≈0.84 (right).
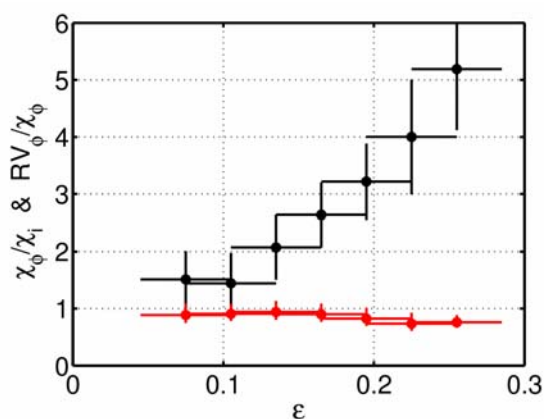

Fig.2. Average pinch number (black) and Prandt number (red) for seven radial intervals.

The regressions in fig.1 are part of a profile, shown in fig.2, constituted of 7 contiguous intervals over which gradients were evaluated. As $\varepsilon^{1/2}=(r/R)^{1/2}$, the trapped particle fraction, is an important physics parameter [4], all profiles were re-sampled, using ε as the radial coordinate. The last closed flux surface is typically at $\varepsilon=0.3$. The figure shows that while the Prandtl number is close to unity, without a significant radial dependence, the pinch number has a clear radial dependence. The vertical bars indicate the 90% confidence intervals for the regressions.

The magnitude of the pinch is consistent with the one obtained in NBI modulation experiments [1]. Toroidal field ripple scan experiments, in the range 0-1%, have also provided corroborating evidence [6]. The ion losses caused by the ripple produce an edge torque in the counter-I_p direction, which can be of similar magnitude as the NBI torque, allowing a scan of the torque without significantly altering other plasma parameters. These experiments were consistent with $P_r \approx 1$ and RV/χ_ϕ rising from near 2 for $\varepsilon \approx 0.1$ to near 8 for $\varepsilon \approx 0.3$ [6].
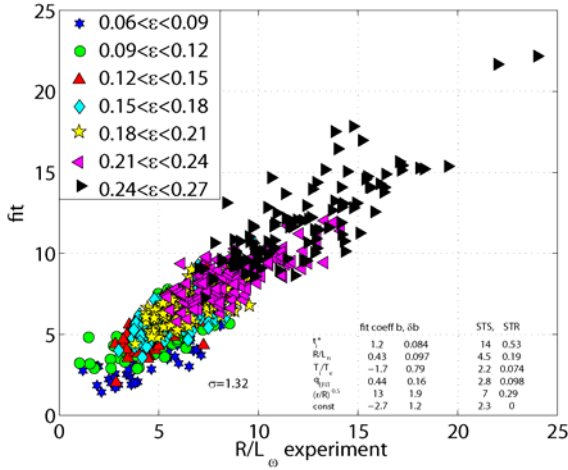

Fig.3 Regression corresponding to eq.(3).
Symbols refer to ε intervals as in fig.2.
STS: statistical significance, STR: relevance.

In order to investigate further parameter dependencies, we tested hundreds of the parameter combinations t_i^*-Γ_N^*, t_{eff}^*-Γ_N^*, R/L_n, R/L_{Ti}, R/L_{Te}, T_i/T_e, ε, q, $s=\varepsilon dq/dr$, ν_{eff}, β, ρ^*. At most 5 parameter dependencies can be simultaneously obtained with satisfactory statistical significance and relevance. Many similar quality fits are obtained with different parameter combinations as a result of correlations in the database. Typically, combinations including t_i^*-Γ_N^*, R/L_n, q, ε, T_i/T_e and R/L_{Ti} or R/L_{Te} provide the best fits. It should be noted that the coefficients for any parameter vary depending on the other parameters of the fit and are not necessarily indicative of the underlying physics dependencies, which may not only be different, but also may not be reducible to simple linear dependencies over the wide JET parameter space. In particular t_i^*-Γ_N^* and R/L_{Ti} are correlated and should not be used together in a fit, as the obtained Prandtl number would be well outside the range seen in fig. 2a and most likely unphysical. In fig.2b, we present the best (in terms of σ) 5 parameter fit:

$$R/L_\omega \approx 1.2(t_i^*\text{-}\Gamma_N^*)+0.43R/L_n+13\varepsilon^{1/2}+0.44q-1.7T_i/T_e-2.7 \qquad (3)$$

The first RHS term is the diffusive term, which has a statistical relevance STR of 0.53 (meaning the variation of this term 'explains' 53% of the variation of R/L_ω). The following terms may be interpreted as providing the dependencies of the pinch number. We doubt that this approach would allow identifying possible residual stress terms.

Gyrokinetic simulations.

A representative subset of 420 samples the JETPEAK database was used as input for a series of linear gyrokinetic calculations using GKW [7] for $k\rho=0.15$ & 0.45 assuming a circular geometry and two kinetic species (D and e$^-$). The pinch and Prandtl numbers are somewhat

larger for kρ=0.45 than for 0.15. In fig.4 we see that the predicted pinch number profile (on the basis of the average for kρ=0.15 & 0.45) is similar to the experimental one, although the theoretical pinch is only ~2/3 of the observed one. Fig.5 shows a fair agreement of theoretically expected and observed R/L_ω, except for magnitude. Collisional and non-collisional calculations mostly produce similar results.
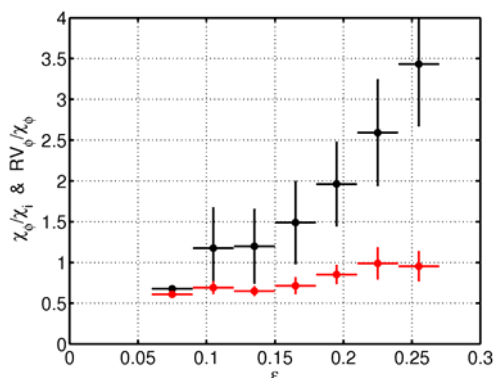

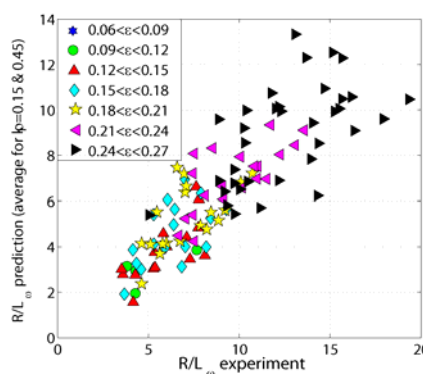Fig.4 Average and std (bars) of Prandt (red) and pinch numbers (black) from GKW.

Fig.5 Sample-by-sample comparison of experimental and modeled R/L_ω.

The theoretical data can be fitted in much the same way as the experimental data, subjecting them to the same correlation issues, as the parameter domain is approximately the same. The best 5 parameter fit for the theoretical pinch is obtained as:

$$RV/\chi_\phi \approx 0.44R/L_n+7.7\varepsilon^{1/2}+0.39q-0.1R/L_{Te}-0.15s-4.3 \qquad (4)$$

The first three of these parameters match three of those representing the pinch in eq.(3), with similar coefficients, further supporting the thesis that the observed pinch may have its origin in the Coriolis drift.

Conclusions

The database analysis shows that the momentum pinch is ubiquitous. Pinch numbers are low in the core plasma and rise strongly to near 5 at r/a≈0.8. Fair agreement is obtained with simple linear GKW calculations, although the theoretical pinch falls somewhat short of the observed one. The main parameter dependencies (R/L_n, ε, q) are consistent with experimental trends, although correlations, errors and non-linearities prevent a definite determination of coefficients. This fair agreement supports the identification of the Coriolis pinch as the likely explanation for the observations. The finding suggests that even a torque applied only at the edge, as e.g. in ITER, may produce a moderately peaked angular velocity profile.

References

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