MOMENTUM CONFINEMENT OF ASDEX PLASMAS DURING CO AND COUNTER NEUTRAL BEAM INJECTION

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I. Introduction

Toroidal rotation velocities of ASDEX plasmas of up to $2 \times 10^7 cms^{-1}$ have been measured under a variety of conditions and for both co- and counter neutral beam injection. The velocities were obtained from the Doppler shifts of OVIII 2976 Å and/or C VI 3434 Å excited by charge exchange recombination (CXR). Up to five lines of sight have been used (table I), each of which intersects the axis corresponding to a source in the north-west neutral injection beam line. The main objective has been to compare the global momentum confinement with the energy confinement of ASDEX plasmas for different plasma parameters and heating scenarios.

II. Estimates of Momentum Confinement Time

The experimental global momentum confinement time was estimated from $\tau_\phi = L/\Gamma$ where L is the total toroidal angular momentum of the plasma and Γ the momentum input from the beams. $L \simeq 2\pi R^2 m_p f \int_o^a V_\Phi(r) n_e(r) 2\pi r dr$ where f is the ratio of the average atomic mass to that of a pure hydrogen plasma at the same n_e. With the assumption that only carbon and oxygen impurities, present in roughly equal densities, contribute to Z_{eff}, $f \simeq \frac{1+2g}{1+g} + 0.16\frac{(Z_{eff}-1)}{(1+g)}$.
The ratio $g = n_D/n_H$ was typically rather small ($\simeq 1$) in the $H_o \rightarrow D_+$ plasmas and was estimated to about ± 50 % from neutron measurements. Z_{eff} was obtained from infra-red continuum measurements. Errors in g and Z_{eff} do not affect τ_ϕ too critically and these two quantities were assumed to be independent of radius. The main uncertainty in τ_ϕ arises from that in $V_\phi(r)$.
One problem with measuring V_ϕ with the observed CXR lines is that they are also excited in the plasma edge region even without NI. It has been possible to investigate the importance of edge excited lines, with plasmas heated by the SE beam which is not seen directly by any of the lines of sight in table I. Interference from the edge excited transition together with low signal to noise for the inner channels, due to beam penetration limitations (E_o= 41 keV), give rise to problems in measuring V_ϕ at small radii, particularly for CVI 3434Å. However, at least for $r \geq 14cm$, V_ϕ is believed to be accurate to within a systematic uncertainty $\simeq \pm 10^6 cms^{-1}$ with statistical errors of a similar size. The estimated errors in τ_ϕ are $\approx \pm$ 15 % statistical with a further $\simeq \pm$ 20 % systematic.
Apart from neoclassical theory, which gives estimates of $\tau_\phi \simeq 10^3 \times$ higher than experiment, the only theory which allows a quantitative estimate of τ_ϕ is the gyroviscous theory of Stacey et al. [1]. Here $\tau_{\phi G} \simeq 2R_o^2 B_o \langle Z_{eff}\rangle / \langle T_i \rangle$, where the brackets imply

volume averages. T_i can also be estimated from the CXR diagnostic and the uncertainty in $\tau_{\phi G}$ from experimental sources amounts to $\simeq \pm 25$ %.
An estimate of τ_ϕ can, however, also be obtained from the diffusive transport of particles. In the source free case, with D = const, the particle confinement time is given by $\tau_p^* \ (r) = \frac{a^2}{4D}(1 - \frac{r^2}{a^2})$ [2]. Global dynamical confinement times τ_E^*, τ_ϕ^* and τ_p^* can then be estimated from $\tau_\psi^* = \int_o^a \psi \ \tau_p^* \ (r) r dr / \int_o^a \psi r dr$ with $\psi = n_e T, n_e V_\phi$ and n_e respectively. Assuming parabolic profiles of T, V_ϕ and n_e this yields $\tau_E^* = \tau_\phi^* = \frac{3}{16} a^2/D$ and $\tau_p^* = \frac{1}{6} a^2/D$. For peaked energy and momentum sources these decay times should become close to the stationary confinement times τ_E and τ_ϕ considered in this paper.

III. Results

Momentum confinement results have been obtained for H_o injection into mainly D_+ but also some H_+ plasmas with co- (L-mode) and counter injection. A study of H-mode discharges has also started.
Rotation measurements for a co-injection (L-mode) run at fixed power and different $\bar{n}_e$ are shown in Fig. 1. The rotation velocity falls with increasing $\bar{n}_e$ (as $\simeq \bar{n}_e^{-1/2}$) while the velocity profile is relatively broad ($V_\phi(r)/V_\phi(o) \simeq (1 - r^2/a^2)^{0.9}$) and shows no measurable change over the $\bar{n}_e$ range studied (Fig. 2). T_i also shows a slow decrease with $\bar{n}_e$ so that the ratio of toroidal velocity to deuteron thermal velocity decreases with $\bar{n}_e$ from $\simeq 0.44$ to 0.30 (r = 34 cm). The average ratio of toroidal to oxygen ion thermal velocities is therefore $\simeq 1.0$.
Unlike V_ϕ, τ_ϕ shows no clear $\bar{n}_e$ dependence (Fig. 3), due particularly to n_e profile effects and a strong decrease in Z_{eff} with increasing $\bar{n}_e$ (from $\simeq 4$ to 1.5). The global energy confinement time τ_E likewise shows no marked $\bar{n}_e$ dependence and is larger than τ_ϕ though within the combined error limits. $\tau_{\phi G}$ tends to show a decrease with $\bar{n}_e$, a result of Z_{eff} falling off with $\bar{n}_e$ faster than T_i, but generally the agreement with experiment is better than a factor of 2. The diffusive transport model, with $D = 0.5 m^2 s^{-1}$, gives $\tau_E^* = \tau_\phi^* = 60 ms$, in surprisingly good agreement with experiment.
An extension of the gyroviscous theory was used by Stacey to attempt to explain the decrease in τ_E with input power for TFTR plasmas in terms of increasing viscous dissipation at higher rotation velocities [3]. In this case $\tau_{EG} \sim \tau_{Eo} \ /(1 + \frac{\tau_{Eo} V_\phi^2 f_p}{R^2 \omega})$, where ω is the ion gyrofrequency and f_p a profile factor.
The observed density dependence of V_ϕ for ASDEX plasma in principle provides a way of testing this theory at constant input power because in the ohmic ("reference") phase $V_\phi << V_\phi(NI)$ and $\tau_{EG} \simeq \tau_{Eo}$, which is essentially independent of $\bar{n}_e$ (Fig. 4). However, using experimental values for Z_{eff}, τ_{Eo} and V_ϕ, τ_{EG} is also essentially independent of $\bar{n}_e$, though with a reduction from the ohmic heating case about 2× lower than observed (Fig. 4). This is again due to the strong $\bar{n}_e$ dependence of Z_{eff}, which influences the effective ω.
Significantly different from the co-injection results are those obtained with counter injection. Here the velocities rise to values more than 2× those obtained at the same density with co-injection (Fig. 1) leading to values of τ_ϕ of up to 90 ms, similar in magntiude to τ_E (Fig. 3). In these discharges, the increased energy and momentum confinement is accompanied by improved particle confinement which leads to a steep rise in $\bar{n}_e$ with time. The corresponding impurity accumulation, which occurs for light

as well as heavy impurities, leads to large axial radiation losses and termination of the discharges by major disruption. Gyroviscous theory gives too small a τ_ϕ because Z_{eff} in the counter-NI case is not much larger than in the co-NI case while T_i is approximately the same. The diffusive model gives $\tau_\phi \simeq \tau_E$, as observed.

Co-injection discharges where the density is ramped up with time, as well as pellet injected discharges, (both of which can reach similar densities to the counter-injection cases) attain similar velocities to those in steady state co-discharges, well below the corresponding counter-injection velocities (Fig. 1).

H-mode discharges (single-null) with a high ELM frequency ($\approx 400H_z$) show no significant differences in velocity to corresponding L-mode (double-null) discharges except at the relatively large radius of 35 cm. Here a distinctive increase of $\simeq 2\times$ in V_ϕ is seen which disappears when the discharge goes back into the L-mode. Such an increase in V_ϕ could be interpreted as a decrease in edge momentum diffusivity which accompanies a decrease in edge electron thermal diffusivity and particle diffusion. The lack of significant increase in global τ_ϕ for such discharges is also to be compared with a lack of increase in τ_E compared with the L-mode.

IV. Summary

In the results studied to date τ_ϕ is always about the same size as τ_E. In two scenarios where improved energy confinement is seen relative to the L-mode, improved momentum confinement is also found (and indeed improved particle confinement). There is a global improvement with counter injection but only an edge improvement for the H-mode with high ELM frequency. Gyroviscous theory gives agreement with experiment within about a factor of 2 though systematic differences are apparent. A simple diffusion model also gives satisfactory agreement.

References

[1] W.M. Stacey Jr., C.M. Ryn and M.A. Malik, Nucl. Fusion **26**, (1986), 293.

[2] G. Fussmann, Nucl. Fusion **26**, (1986), 983.

[3] W.M. Stacey, to be published.

Channel	radial position (outer minor radius) (cm)	spatial resolution (cm)	angle with toroidal direction
CXR1	42.0	±2.0	4°
CXR2	34.5	±2.0	1°
CXR3	24.0	±2.0	4°
CXR4	14.0	±3.2	10°
CXR5	4.0	±4.0	24°

Table I: Details of lines of sight used for CXR spectroscopy
(The separatrix is at $r = 40$ cms and the limiter typically at $r = 46.0$ cms.)

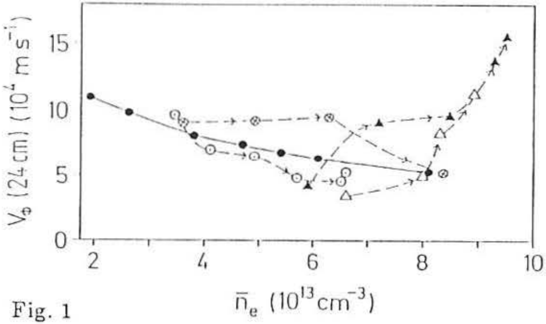

Fig. 1

V_ϕ (24cm) versus $\bar{n}_e$ for counter injection (triangles) and co-injection (circles) with $P_{NI} = 1.3MW, I_p = 380$ kA. The symbols ▲, △ (counter-NI) and ⊙, ⊗ (co-NI) each refer to one discharge, with the arrows indicating the time sequence. The symbols ● each correspond to an average of several measurements taken during the density plateau of a discharge.

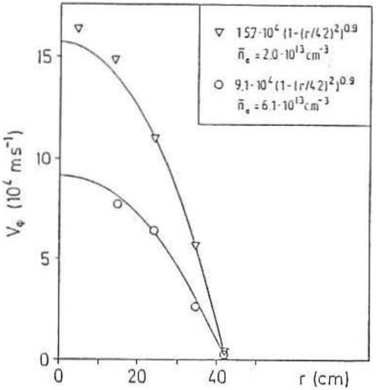

Fig. 2

Radial profile of V_ϕ for two values $\bar{n}_e$ for the density plateau co-injection series shown in Fig. 1.

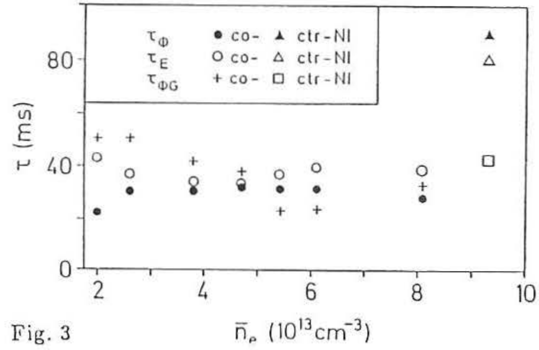

Fig. 3

Comparison of τ_ϕ with τ_E and $\tau_{\phi G}$ as a function of $\bar{n}_E$ for co- and counter injection.

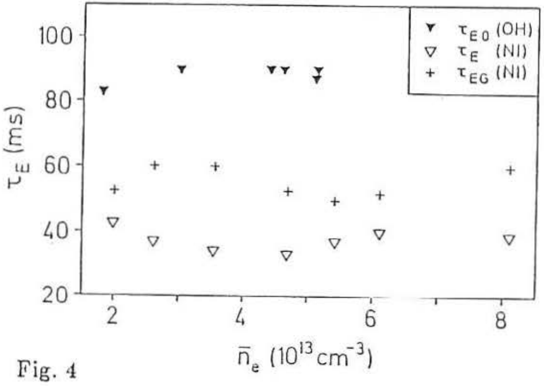

Fig. 4

Test of the velocity dependence of τ_E from gyroviscous theory. τ_{Eo}, τ_E are the experimental confinement times for ohmic and beam heated plasmas respectively and τ_{EG} the values given by gyroviscous theory with experimental V_ϕ, Γ_{Eo} and Z_{eff}.