

The role of plasma rotation in error field scalings

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Introduction

Error-field driven tearing modes can affect the large-scale stability of tokamak plasmas, sometimes leading to current-terminating disruptions. This is a key issue for a “next-step” tokamak as large devices may require correction of error fields to access baseline operating scenarios. COMPASS-D’s role in error field studies is important as it is the smallest machine of suitable geometry to carry out these experiments, thus providing high-leverage data for the scaling laws. It is also equipped with a uniquely adaptable array of toroidal resonant magnetic perturbation (RMP) bars allowing error fields with a wide range of harmonic mixes to be simulated. and new Doppler spectroscopy techniques have been developed to give further insight into COMPASS-D error field physics.

Experiments

The experiments were carried out in Ohmic SND plasmas ($\kappa \sim 1.6$, $q_{95} \sim 3.5$) with static RMP’s of mode numbers $m = 2$, $n = 1$ and $m = 3$, $n = 1$ at toroidal magnetic fields between 0.9 and 1.7 T and line-averaged densities between 2 and $8 \times 10^{19} m^{-3}$. For toroidal field scaling experiments, density and B_ϕ/I_p were kept constant, to minimise variations in q_{cyl} . In the density scaling experiments B_ϕ and I_p were maintained constant. The RMP field was steadily ramped up during discharges and mode penetration was indicated by sudden changes in B_r and v_ϕ , the toroidal impurity velocity (fig. 1).

Measurements

Plasma flow, relative to the error field is a key factor in determining whether and when magnetic islands can form. Impurity ion flows, measured by Doppler spectroscopy, are generally closely coupled to the bulk plasma flow.

B^{3+} has been successfully used in impurity fluid studies on COMPASS-D, COMPASS-C and other tokamaks in the past [1]. In COMPASS-D plasmas, the B^{3+} emission shell is located a few centimetres inside the last closed flux surface of the plasma. However, rotation at the $q = 2$ rational surface, nearer to the core of the plasma is of more interest in error field mode experiments, as $m = 2$, $n = 1$ modes are usually formed. B^{3+} is not ideally suited to diagnosing rotation at this radial location, so an impurity ion with a higher ionisation energy, emitting radiation further inside the plasma would be preferable. Transport simulations indicated that the emission shell of Ar^{13+} in COMPASS-D plasmas is located closer to the $q = 2$ surface than

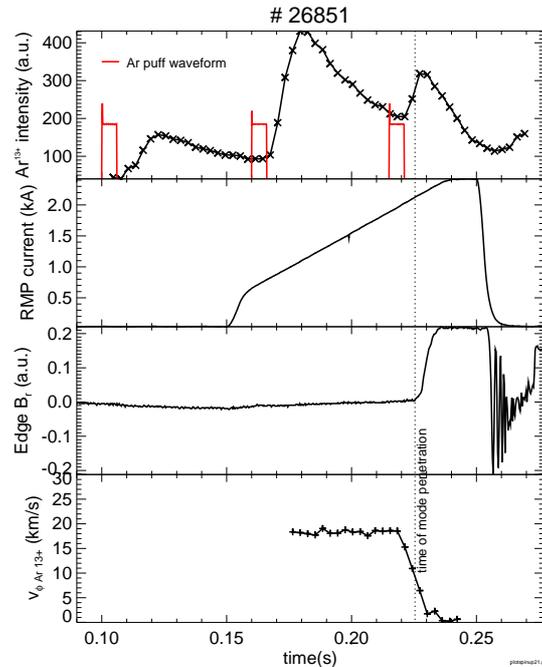


Figure 1: Ar^{13+} intensity, RMP current, edge B_r and $v_{\phi,Ar^{13+}}$ vs. time for shot 26851 (SND plasma, $B_\phi = 1.1$ T, $I_p = 130$ kA, $\bar{n}_e = 2.3 \times 10^{19} m^{-3}$, 2,1 RMP).

that of B^{3+} . A “forbidden” transition of Ar^{13+} ($2s^22p(2P_{1/2} - 2P_{3/2})$) at 441.3 nm, thought to be previously unused in tokamak plasma spectroscopy, was suitable for measurement using the existing visible Doppler spectrometers. Ar^{13+} , an intermediate ionisation state, is short-lived in the plasma as it is lost through ionisation and radial transport processes. A series of small puffs of argon during the discharge was used to maintain a sufficient signal from Ar^{13+} for rotation to be measured.

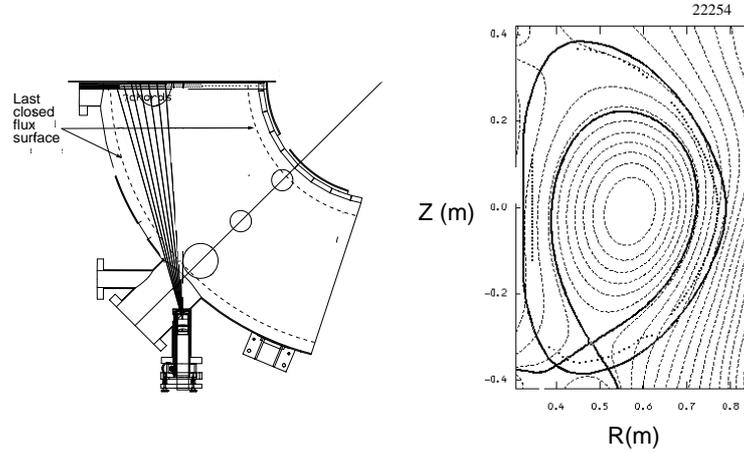


Figure 2: *CELESTE-2 lines of sight through the plasma and poloidal cross-section of a COMPASS-D plasma, from the TOPEOL equilibrium code.*

The CELESTE-2 multichord spectrometer [2], fig. 2, was used for high-resolution Doppler measurements of the Ar^{13+} and B^{3+} lines. The Ar^{13+} spectrum is affected by line blending, making it necessary to discard portions of the spectrum before attempting line fitting. The intensity of the blended lines is observed to increase upon mode-locking and the Ar^{13+} intensity decreases (fig. 1), which makes analysis difficult at this time of the discharge. This may be due to confinement degradation and enhanced radial impurity transport in the presence of a magnetic island. This decrease is seen by all chords, so it cannot be solely due to a change in the position of the emission shell. When the island unlocks and spins up, its width decreases [3] and the Ar^{13+} intensity increases again.

Rotation scaling

Fitzpatrick [4] proposed a model for tearing mode-error field interactions in cylindrical geometry based on hydromagnetic, viscous and resistive effects, characterised by the timescales τ_H , τ_V and τ_R respectively. The threshold island width for mode penetration at $r = r_s$ (r_s is the radius at which the rational surface $q = q_s$ is centred) occurs when the island width reaches a critical value,

$$\frac{W_{pen}}{r_s} \sim \left(\frac{1}{m^2} \omega_0^2 \frac{\tau_H^{7/3} \tau_R^{5/6}}{\tau_V^{7/6}} \right)^{1/4} \quad (1)$$

where ω_0 is the natural rotation frequency (of the island with poloidal mode number m), usually approximated by the electron diamagnetic frequency, ω_{*e} . In the case of an Ohmically-heated tokamak these timescales may be expressed in terms of basic geometric and physics parameters such as R , a , T_e , B_ϕ and q . T_e is estimated by assuming profile constancy and balancing Ohmic heating power against electron energy losses, which introduces τ_E into the relation [4]. The error field at penetration is proportional to W_{pen}^2 , which leads to a generalised scaling relation $\delta B_{pen}/B_\phi \sim B_\phi^{\alpha_B} \eta^{\alpha_n} q^{\alpha_q} R^{\alpha_R} a^{\alpha_a}$.

(a) Theory	$\omega_0 \equiv \omega_{*e}$		ω_0 explicit		
	α_B	α_n	α_B	α_n	α_ω
τ_E scaling used:					
Neo-Alcator	-0.87	0.58	-1.67	0.58	1.0
Lackner-Gottardi	-1.0	0.21	-1.83	0.43	1.0
ITER89-P	-2.1	0.42	-1.83	0.26	1.0
(b) Fits to experimental results:	without ω		including ω		
B_ϕ scan	-2.83	-	-2.21	-	1.0
n_e scan	-	0.89	-	0.55	1.0

Table 1: Predicted threshold 2,1 error field (B_{pen}/B_ϕ) scalings at constant q and results obtained by regression fits to experimental values from scans of B_ϕ (at constant B_ϕ/I_p , similar n_e) and n_e (at constant B_ϕ, I_p).

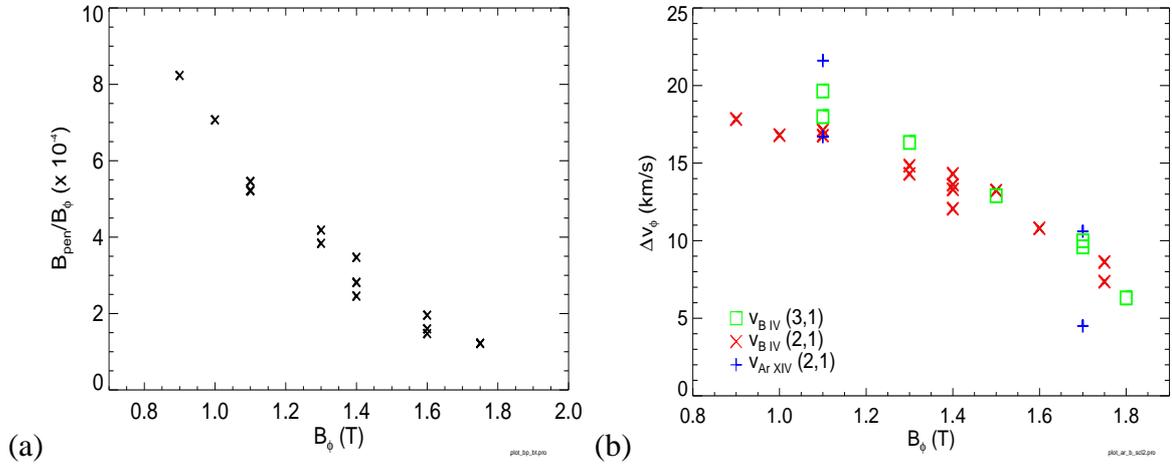


Figure 3: (a) Threshold applied 2,1 RMP field for mode penetration vs. toroidal field at constant $B_\phi/I_p, n_e$. (b) Ar^{13+} and B^{3+} rotation changes at mode penetration with 2,1 and 3,1 applied RMPs as a function of equilibrium toroidal field at constant B_ϕ/I_p .

Table 1(a) shows the power dependences α_B , α_n and α_ω of toroidal field, density and rotation respectively in the generalised scaling relation, derived using several well-known empirical scalings for τ_E . In the first two columns, ω_{*e} ($\sim T_e/B_\phi$) is used to replace ω_0 ; in columns 3-5 the theoretical scaling ($\sim \omega_0$) is retained. Results from fits to COMPASS-D data are similarly presented in table 1(b).

Fig. 3 shows the dependence on toroidal field of Δv , the toroidal rotation change seen between the first applying the RMP and mode penetration. The strong dependence offers a possible explanation for some of the discrepancy between COMPASS-D's observed strong 2,1 penetration threshold scaling with toroidal field ($B_\phi^{-2.8}$ obtained by regression fit) and the behaviour of larger tokamaks (JET: $B_\phi^{-1.2}$, DIII-D: $B_\phi^{-1.0}$)[5] as well as scaling law predictions ($B_\phi^{-0.9 \rightarrow -2.1}$). However, when ω_{*e} is replaced by the measured B^{3+} rotation change between first application of the RMP and mode penetration and a regression fit of $(B_{pen}/B_\phi)/\omega$ to B_ϕ is done, there is a closer agreement between the predicted threshold error field scaling with B_ϕ and the experimental value. This implies that COMPASS-D rotation behaviour does not obey the $\omega_0 = \omega_{*e}$ scaling.

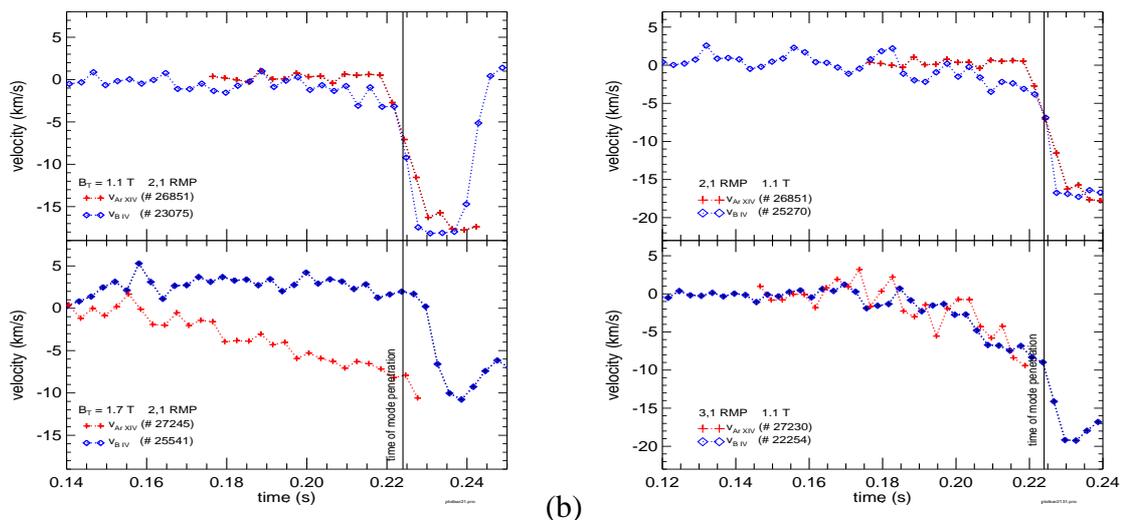


Figure 4: (a) B^{3+} (\diamond) and Ar^{13+} (+) velocity (with velocity before RMP switch-on taken as zero reference for both) vs. time at 1.1 and 1.7 T with ramped 2,1 applied RMP, similar to that of fig. 1. (b) B^{3+} and Ar^{13+} velocities vs. time at 1.1 T with 2,1 and 3,1 RMP's applied.

Dynamic effects

The majority of the rotation change at mode penetration is observed before the growth of the island is indicated by magnetic diagnostics (fig. 1). The difference between the rotation behaviour at 1.1 and 1.7 T with 2,1 RMP's is further illustrated by the Ar^{13+} measurements in fig. 4(a). A rapid change in both B^{3+} (near $q = 3$) and Ar^{13+} (nearer $q = 2$) rotation is seen to accompany penetration at 1.1 T. At 1.7 T the B^{3+} velocity remains steady whilst Ar^{13+} rotation changes relatively slowly as the RMP level is increased in time. Penetration is accompanied by an abrupt change in the B^{3+} rotation. Thus 2,1 RMP's appear to have similar effects on B^{3+} and Ar^{13+} at low toroidal fields, but significantly different ones at high fields.

The helicity of the applied RMP field also affects the rotation prior to penetration. In all cases, even when a 3,1 RMP is applied, the resulting mode has a 2,1 structure. Fig. 4(b) shows that rotation of both Ar^{13+} and B^{3+} is affected much earlier by the 3,1 field as it is ramped up than by the 2,1 field, which may be evidence of 3,1 RMP's coupling to the $q = 2$ surface, slowing the resonant $q = 3$ and also $q = 2$, enabling mode formation from residual 2,1 components.

Conclusion

The strong toroidal field scaling observed in COMPASS-D error field thresholds (compared to larger tokamaks) appears to be associated with changes in rotation behaviour. New Ar^{13+} measurements show significant variation of error field-driven rotation effects with toroidal field. This raises questions for scaling to next step devices, highlighting uncertainties associated with rotation in predictions from empirical scalings. Further studies on COMPASS-D and on larger devices with controlled rotation would improve the understanding.

References

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