Evidence for the Influence of Fast Ions on Toroidal Plasmas Rotation

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Outline

• Introduction

• The role of fast ions in rotation experiments with directed ICRF waves on JET
  - Experimental results
  - Theoretical analysis

• Conclusions
Introduction

• Plasma rotation is a subject of interest for several reasons. For example,
  - turbulence is believed to be suppressed by sheared $E \times B$ flows;
  - rotation can influence the MHD stability, e.g. increase the stabilising effect of a resistive wall.

• In a fusion reactor there will probably not be a strong external momentum source provided by NBI, like in many present day experiments.

• It is consequently relevant to investigate other mechanisms that can give rise to plasma rotation, such as fast ions.
Observations of toroidal co-current rotation in ICRF heated plasmas with little momentum injection $^{1-4}$.

**JET**$^2$


**Alcator C-Mod**$^3$


**Tore Supra**$^4$


$n_i T_i$ (kev 10$^{19}$ m$^{-3}$)
Co-current rotation has been observed in three quite different machines, JET (divertor, moderate densities), Alcator C-Mod (divertor, high densities) and Tore Supra (limiter plasmas, moderate densities).

The proposed explanations for the observed co-current rotation includes:
- Fast particle effects\(^1\)
- Neo-classical effects\(^2\)
- The so called accretion theory\(^3\)

In reality there is probably a combination of effects involved, with fast ions being one of them.

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\(^2\)A.L. Rogister et al., Nuclear Fusion 42, 1444 (2002).
\(^3\)B. Coppi, Nuclear Fusion 42, 1 (2002).
• To demonstrate the effect of ICRF heated fast ions on plasma rotation by comparing plasmas with and without fast ions is difficult since it is virtually impossible two create plasmas with similar background characteristics.

• Solution: compare plasmas with different fast ion characteristics but with broadly similar heating of the background plasma.

• The latter can be achieved by using minority ion heating with directed ICRF waves.

• (Co-I_p propagating waves can create a large number of ions with non-standard orbits in the potato regime. A type of orbit playing an important role for co-current torque in Perkins et al. type theory)

JET experiments with directed ICRF waves

- Absorption of wave momentum from directed ICRF waves could offer a possibility to control, at least to some extent, plasma rotation.
- The momentum carried by the waves is first absorbed by fast resonating ions, and subsequently transferred to the bulk plasma.
- Directed waves can therefore be used to study the effect of fast ions on rotation.
• From basic quantum mechanical equations we obtain for a particle absorbing a wave quantum:
\[ \Delta E = \frac{h \omega}{(2\pi)} \] and \[ \Delta P_\varphi = \frac{R \hbar k_\varphi}{(2\pi)} = \frac{h N_\varphi}{(2\pi)} \]
• Thus the toroidal momentum imparted to the plasma per unit time is given by:
\[ \frac{dP_\varphi}{dt} = \sum (N_\varphi / \omega) P_{ICRF} (N_\varphi). \]
• (The same result is of course also obtained from a combination of Maxwell’s equations and the equation of motion)
• A typical spectrum for the JET four strap antennas with +90° phasing is given below.

\[ \langle N_\phi \rangle = \frac{\sum N_\phi P(N_\phi)}{\sum P(N_\phi)} \]

\[ \Rightarrow \langle N_\phi \rangle \approx 8 \]

\[ dP_\phi \over dt = \langle N_\phi \rangle \omega P_{ICRF} \]

\( N_\phi > 0 \) corresponds to propagation in the toroidal direction of the plasma current.

• Imparted momentum to the plasma:
Overview of two discharges with $+90^\circ$ and $-90^\circ$ phasing and $W_{\text{DIA}}$ for third with 2MW of ICRF power replaced by 2MW of LH power.

$^3$He minority heating in deuterium plasma

$I_p = 2.8\text{MA}$

$B_T = 3.4\text{T}$

$f_{\text{ICRF}} = 37\text{MHz}$

$\Rightarrow$ Cyclotron resonance on high field side ($\sim 20\text{cm}$).
Ion pressure profiles from CX measurements of the ion temperature

- The ion pressure profiles for the +90° and −90° discharge are similar.
- The discharge with LH has a somewhat lower ion pressure than the other two.
Carbon rotation profiles measured with the charge exchange recombination spectroscopy using NBI blips (method described in Noterdaeme et al.\textsuperscript{1})

- The $+90^\circ$ discharge rotates more strongly in the centre than $-90^\circ$, consistent with absorption of wave momentum!
- LH discharge shows the difference is not due to modified heating efficiency

\textsuperscript{1}J.M. Noterdaeme et al, Nuclear Fusion 2003
Back of an envelope calculation assuming carbon impurities

\[ \frac{n_e V_{\text{eff}} m_D R \Delta V_\phi}{\tau_M} \sim \frac{\langle N_\phi \rangle}{\omega} 2P_{\text{ICRF}} \]

- \( V_{\text{eff}} \): effective volume where difference in rotation is seen
  \( \sim 40 \text{ m}^{-3} \).
- \( n_e \sim 3 \cdot 10^{19} \text{ m}^{-3} \)
- Momentum confinement time
  \( \tau_M \sim \tau_E \sim 0.3 \text{s} \)
- \( \langle N_\phi \rangle \sim 8; P_{\text{ICRF}} = 6 \text{MW} \)

\[ \Delta \omega_\phi = \Delta V_\phi / R \sim 3 \text{ krad/s} \]

i.e. the right order of magnitude!
How do the resonating ions transfer the absorbed wave momentum to the bulk plasma?

- Fast ions transfer torque to the background plasma via two mechanisms:
  - collisions
  - radial currents

- For the collisions it is important to note that the velocity on the inner leg of a trapped ion orbit is counter current, and co-current on the outer leg.

- In order to preserve quasi-neutrality, a fast ion current must be compensated for be a radial current in the thermal bulk plasma i.e. \( j_{th,r} = -j_{fast,r} \Rightarrow j_{th,r} \times B \) torque on the thermal bulk plasma.
Fast ion transport for asymmetric $N_\phi$ spectra

Toroidal angular momentum for a particle:

$$P_\phi = mRv_\phi - Ze \psi$$

At the turning point of a trapped particle we have,

$$P_\phi = -Ze \psi_{t.p.}$$

Absorption of wave power leads to\(^1\)

$$\Delta P_\phi = \frac{N_\phi}{\omega} \Delta E$$

$$\Delta \Lambda = \frac{n \omega_{co} - \Lambda \omega}{\omega E} \Delta E$$

$$\Lambda = \frac{\mu B_0}{E}$$

- Absorption of wave power with $N_\phi > 0$/$N_\phi < 0$ leads to inward/outward drift of trapped ion turning points.

- Turning points will approach the cyclotron resonance

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\(^1\)See e.g. L.-G. Eriksson and P. Helander, Physics of plasmas 1, 308 (1994)
Illustration for a $^3$He ion accelerated from 100 to 850 keV

Outward fast ion current $\Rightarrow$ counter current torque

Eventual de-trapping into co-passing orbit in the potato regime\textsuperscript{1}. Co-current torque from inward fast ion current and collisions with fast passing ions

Gamma-ray measurements, interactions between fast $^3$He ions and C and Be impurities 

(V. Kiptily)

Consistent with large trapped ion fraction

Consistent with large fraction of co-passing ions
Numerical simulations

• In order to investigate in more detail if the experimental results are consistent with theory, we have done calculations with the SELFO code\(^1\).
• The SELFO code calculates the ICRF power deposition and the distribution function the resonating ions self consistently.
• Full wave code LION for power deposition; Monte Carlo code FIDO for distribution function.
• Finite orbit width effects and wave induced transport are taken into account in SELFO.

Normalised measured and simulated gamma-ray emission for the vertical lines of sights as a function of the major radius where they cross the mid-plane.

Simulation shows: trapped ions spend much time near their turning points ⇒ asymmetric emission around R=3m.

Simulation shows: the more symmetric emission around R=3m is due to ions on co-passing orbits in the potato regime.
Simulation Monte Carlo particles in an orbit classification diagram\textsuperscript{1}; $E > 500$ keV

- $I$, standard passing
- VII, trapped
- VI, non-standard co-passing
- VIII, non-standard co-passing LFS

Clearly co-passing orbits in the potato regime dominates for $+90^\circ$ phasing.

\textsuperscript{1}L.-G. Eriksson and F. Porcelli, PPCF, \textbf{43}, R145 (2001)
Simulated rotation profiles

- The torque from the resonating fast ions to the thermal bulk calculated by SELFO has been used in a momentum diffusion equation of the type:

\[
\frac{n_i m_i}{m_i} \frac{\partial V_\varphi}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[ r n_i m_i D \frac{\partial V_\varphi}{\partial r} \right] + t(r)
\]

- \( t(r) \) is the flux surface averaged torque

\[
D = \frac{a^2}{\alpha_M \tau_M}
\]

- \( \alpha_M \) is in principle profile dependent and should have a value to ensure the correct momentum confinement.

- \( \tau_M \sim \tau_E \)

I should be of the order 5.
The around 5 krad/s difference in central rotation is in good agreement with the experimental value.

- Thus, differences in rotation are well understood in terms of fast ion theory (but underlying co-current rotation is not explained).

- Note co-passing orbits in the potato regime are also important for symmetric wave spectra\(^1\)-\(^3\).

\(^1\)F.W. Perkins, R.B. White, P.T. Bonoli and V.S. Chan, Phys. Plasmas, 2001
Conclusions

- The influence of fast ions on toroidal plasma rotation has been observed in JET experiments with directed ICRF waves.
- The differences between discharges with co- and counter current propagating waves can be well understood in terms of the influence of the waves on the fast resonating ions, and their transfer of absorbed wave momentum to the thermal plasma.
- Co-current passing ions in the potato regime are found to be important for a central co-current torque.
- Directed waves could in principle be used to control, at least to some extent, the rotation profile.
• Difference between deuterium and carbon rotation frequencies\(^1\).

\(^1\)D. Testa et al., Physics of Plasmas 9 244 (2002).