DOPPLER RESONANCE EFFECT ON ROTATIONAL DRIVE BY ION CYCLOTRON MINORITY HEATING

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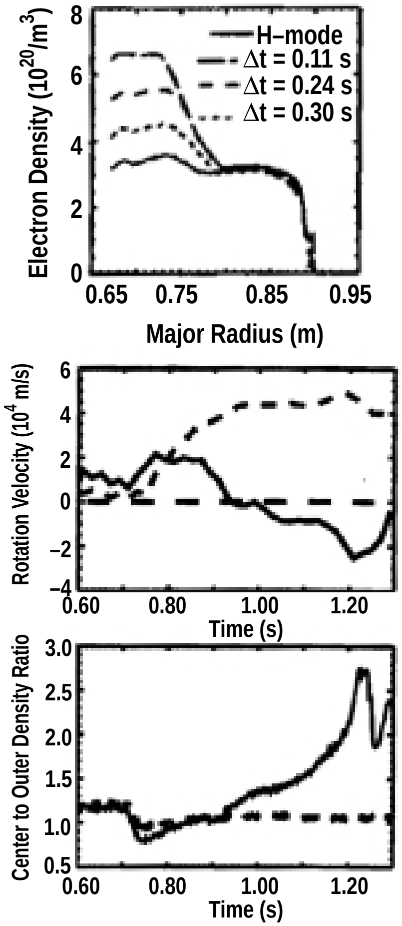
GENERAL ATOMICS

MOTIVATION

- Recently, Alcator C-Mod [J.E.Rice, et al., Nucl.Fusion 39 (1999) 1175], JET [J.-M. Noterdaeme, et al., Conf. on RF Power in Plasmas, Oxnard, 2001] and other tokamaks have reported plasmas with ICRF minority heating can develop an appreciable co-current toroidal rotation with a toroidally symmetric antenna array – how can the ICRF affected toroidal rotation when no direct momentum input is expected?
- A theory by Perkins [F.W.Perkins, et al., Phys. Plasmas, 8 (2001) 2181] predicts co-rotational with ICRF resonance on the low-field side and counter-rotation with the resonance on the high-field side
- The Alcator C-Mod experiment shows co-rotation even with high-field resonance, except when a density ITB is formed, at which time the rotation decreases and might go negative



[C.L. Fiore, et al., Phys. Plasmas 8 (2001) 2023]

FOCUS OF PRESENT STUDY

- How the Doppler resonance: $\omega - \Omega = k_{//} V$ due to a finite $N_{//} = ck_{//}/\omega$ modifies the velocity and spatial distribution of energetic ions produced by ICRH in a driven system; and the effect of this on plasma rotation
- Possible mechanisms that can break the symmetry of the toroidal antenna spectrum
- An explanation of the observed co-rotation with high-field resonance, and the decrease/reversal of co-rotational with the formation of a density ITB

KEY RESULTS

- For lower density and with a flat (H-mode) profile, positive (negative) $N_{//}$ produces co- (counter-) current rotation with high-field side resonance
- A toroidally symmetric antenna array can produce a strongly asymmetric power spectrum [first noted by F.E.Jaeger, et al., Nucl. Fusion 38 (1998) 1, in the context of fast wave current drive]. We found the asymmetry in the presence of an edge density pedestal to favor $N_{//}$ in the co- (positive) direction
- For high density and a profile consistent with an ITB, the plasma rotation for high-field side heating can reverse sign for a fixed positive $N_{//}$

MONTE-CARLO ORBIT-RF CODE

[V.S. Chan, et al., (2001) Submitted to Phys. Plasma]

- Ion trajectories are calculated by solving the Hamiltonian guiding center (drift) equations [9]:

$$\frac{d}{dt}\left\{P_\varsigma, P_\theta\right\} = -\partial_{\varsigma,\theta} H \quad , \qquad \frac{d}{dt}\{\varsigma,\theta\} = \partial_{P_\varsigma, P_\theta} H \quad , \qquad (1)$$

where

$$P_\theta = I\left(\rho_{\|} + \alpha\right) + \Psi \quad , \quad P_\varsigma = g\left(\rho_{\|} + \alpha\right) - \Psi_p \quad , \quad H = \frac{1}{2}\rho_{\|}^2 B^2 + \mu B + \Phi \qquad (2)$$

- The axisymmetric equilibrium field is expressed through its contravariant and covarient forms:

$$B = \nabla\zeta \times \nabla\Psi_p + q\left(\Psi_p\right)\nabla\Psi_p \times \nabla\theta \quad , \quad B = g\left(\Psi_p\right)\nabla\varsigma + I\left(\Psi_p\right)\nabla\theta + \delta\nabla\Psi_p \quad (3)$$

where the poloidal angle, θ is chosen so that

$$d^3x = J d\Psi_p d\theta d\varsigma \quad , \qquad J = (gq + I)/B^2 \qquad (4)$$

MONTE-CARLO RF AND COLLISION OPERATORS

- Each time an ion passes through the ion cyclotron resonance layer $[\omega_{rf} - k_{||}v_{||} = \Omega(B)]$ its perpendicular velocity component undergoes a random change, $\Delta v_{\perp}$. This increment can be readily obtained from the quasi-linear equation governing the rf-induced particle diffusion in velocity space [Chiu (1999)]: $(k_{\perp} = 0, E_{\_} = E_{||} = 0)$:

$$\Delta\mu = \Delta\mu_{rf} \pm R\sqrt{2\mu\Delta\mu_{rf}} \quad , \qquad \Delta\mu_{rf} = \frac{1}{2}\frac{e_i^2}{m_i B}\left|E_+\right|^2 \tau_{rf}^2 \quad , \qquad (5)$$

$$\tau_{rf} = \left\{ \begin{array}{ll} \tau_{uc} = \left(2\pi / |\dot{\Omega}|\right)^{1/2} & \text{if } \sqrt{2\tau_{uc}} \pounds \tau_c \\ \tau_c = 2\pi \, \mathrm{Ai}(\varsigma) \Big/ \left|\ddot{\Omega}/2\right|^{1/3}, \quad \varsigma = -\dot{\Omega}^2 \Big/ \left|2\ddot{\Omega}^2\right|^{2/3} & \text{if } \sqrt{2\tau_{uc}} \quad \tau_c \end{array} \right. \qquad (6)$$

- Pitch angle scattering and slowing-down collisions are modeled with simple operators [Boozer, Kuo-Petravic (1981)]:

$$\Delta\lambda = -\nu_{\perp}\Delta t\lambda \pm R\sqrt{(1-\lambda^2)\nu_{\perp}\Delta t} \quad , \qquad \Delta v = -\, \nu_{||}\Delta t v \qquad (7)$$

GENERAL ATOMICS

PHYSICAL QUANTITIES CALCULATED IN SIMULATION

- In our simulation, several key quantities are computed. They include the volume-integrated torque $T(\psi)$

$$T(\psi) = \int_0^{\psi} d\psi' \oint \frac{d\ell \, 2\pi R}{\nabla\psi'} \tau \quad ,$$

which is the sum of a magnetic torque, T_M

$$T_M(\psi) = \frac{e}{c} \int_0^{\psi} d\psi' \, \dot{N}(\psi') \quad ,$$

where $\dot{N}(\psi)$ is the rate of change of the fast ion density inside the volume defined by ψ, and a fricitonal torque, T_c

$$T_c(\psi) = -\frac{e}{c} \sum_{\substack{\text{test} \\ \text{particles}}} \left(\dot{\rho}_{//} g\right)_{\psi} \quad , \qquad \text{where } g = B_{\zeta} R.$$

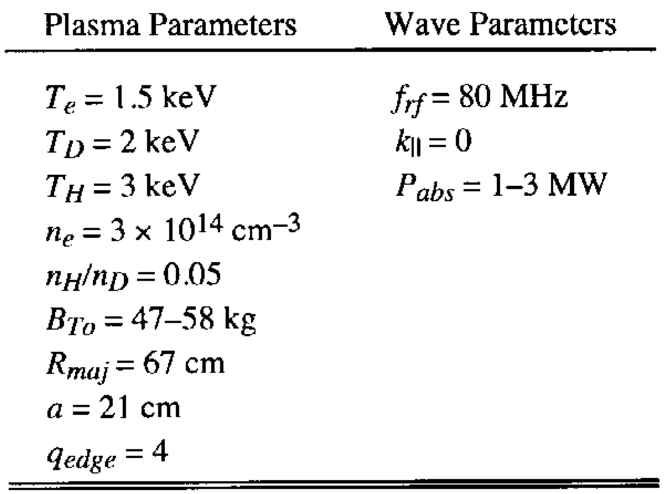
Volume integral of T yields the angular rotation velocity for the bulk ion

$$\Omega(\psi) = \int_0^{\psi_{max}} \frac{d\psi'}{V'} \frac{T(\psi')}{\langle nMR^2 \chi_M (\nabla\psi)^2 \rangle}$$

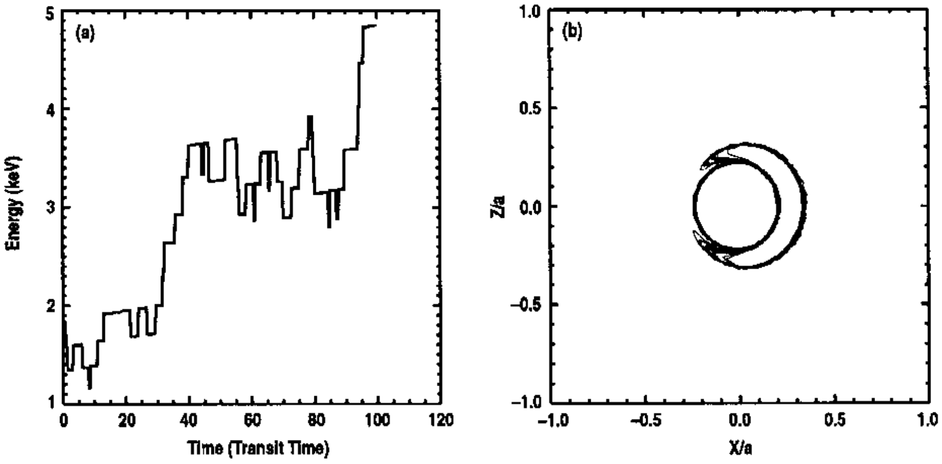
GENERAL ATOMICS

SIMULATION SETUP

Table 1. Alcator C-Mod-like parameters for Orbit-RF simulation



Plasma Parameters	Wave Parameters
$T_e = 1.5$ keV	$f_{rf} = 80$ MHz
$T_D = 2$ keV	$k_\parallel = 0$
$T_H = 3$ keV	$P_{abs} = 1\text{–}3$ MW
$n_e = 3 \times 10^{14}\ \text{cm}^{-3}$	
$n_H/n_D = 0.05$	
$B_{To} = 47\text{–}58$ kg	
$R_{maj} = 67$ cm	
$a = 21$ cm	
$q_{edge} = 4$	

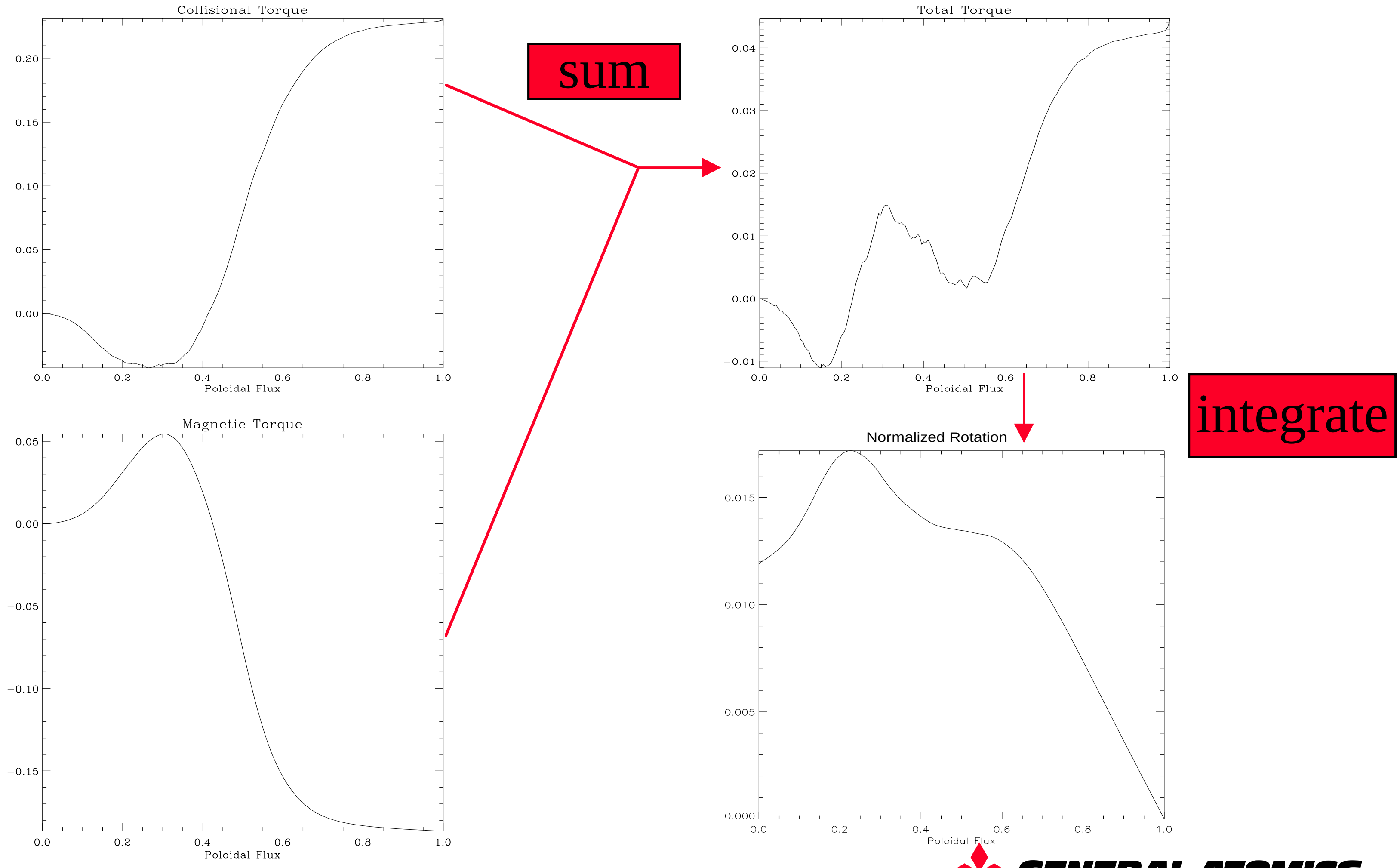


Fast ion energy and orbit with ICRH

- 20,000 test particles loaded in Maxwellian annulus
- Follows fast ion dynamically keeping fast ion contribution to magnetic and frictional torque
- Thermalized fast ions “re-injected” to maintain steady-state

POSITIVE $N_{//}$ PRODUCES CO-CURRENT ROTATION IN FLAT DENSITY PROFILE FOR HIGH-FIELD RESONANCE

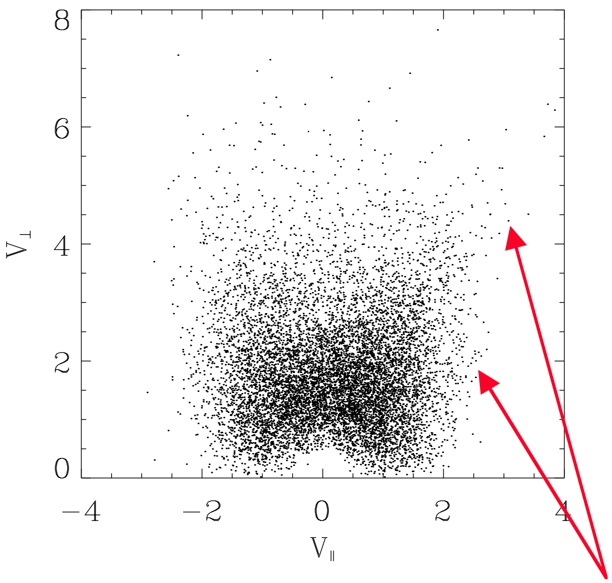
- H–mode-like density profile with $n_c = 3\times10^{14}$ cm^{-3}, $B_T = 4.7$



THE CO-ROTATION RESULTS FROM THE PRODUCTION OF MORE CO-MOVING FAST IONS THAT AFFECTS THE FRICTIONAL TORQUE ON THE BULK

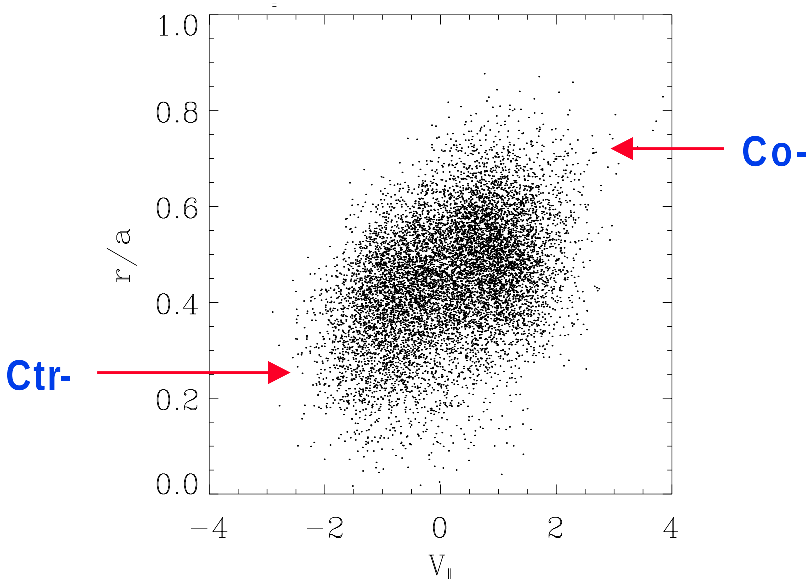
- With positive $N_{//}$ both co-moving passing ions and trapped ions are heated
- The barely trapped ions can easily be detrapped by collisions, scattered inward and outward
- We have found for $N_{//}=0$, high field side resonance leads to counter-rotation, suggesting the difference is due to more co-moving passing ions for finite $N_{//}$

Velocity Distribution



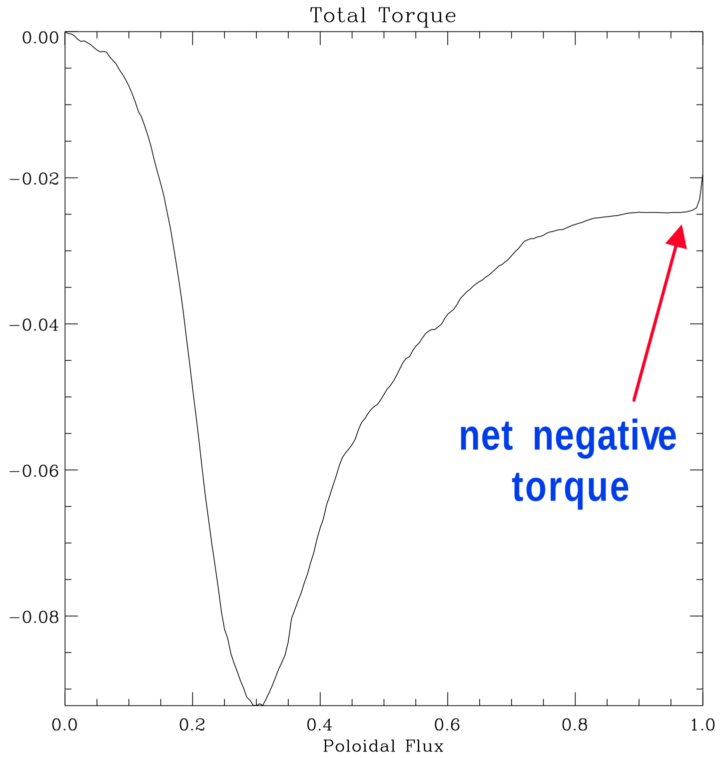
more co-particles

Spatial Distribution

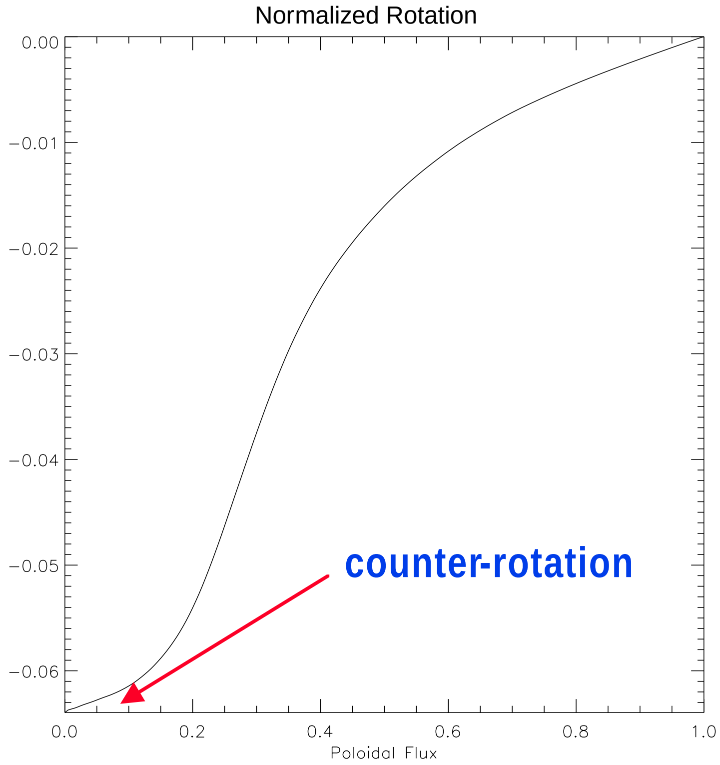


NEGATIVE $N_{//}$ PRODUCES COUNTER-CURRENT ROTATION IN FLAT DENSITY PROFILE FOR HIGH-FIELD RESONANCE

- Consistent with explanation of positive (negative) $N_{//}$ ICRF producing more co- (ctr-) moving passing ions that alter the frictional torque



net negative torque

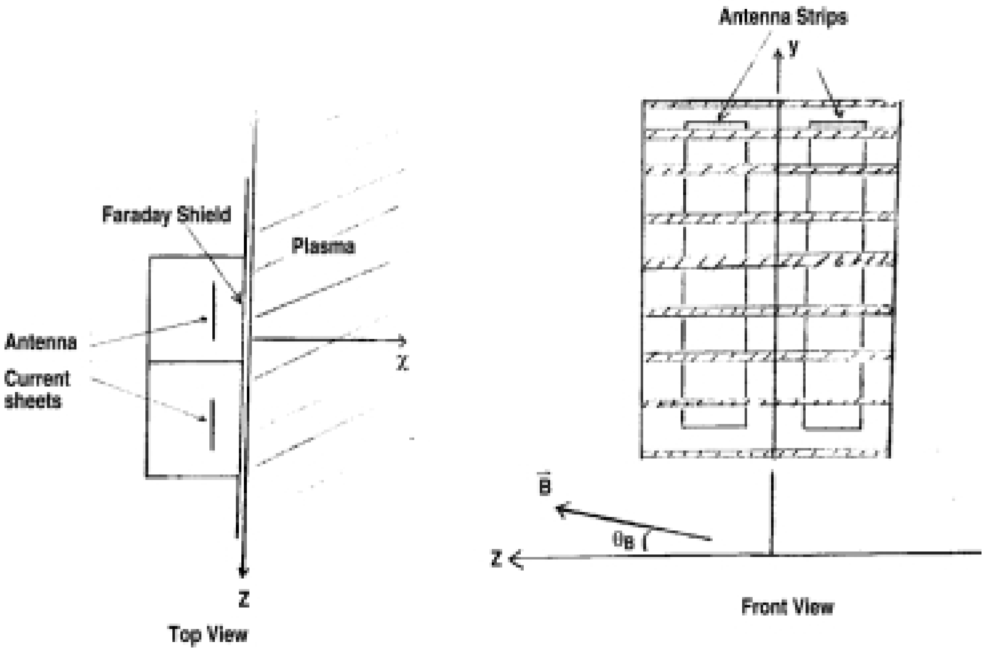


counter-rotation

GENERAL ATOMICS

TOKAMAK ROTATIONAL TRANSFORM CAN LEAD TO ASYMMETRIC POWER SPECTRUM

- **Antenna Model [S.C. Chiu, et al., Nucl. Fusion 30 (1990) 2551]**

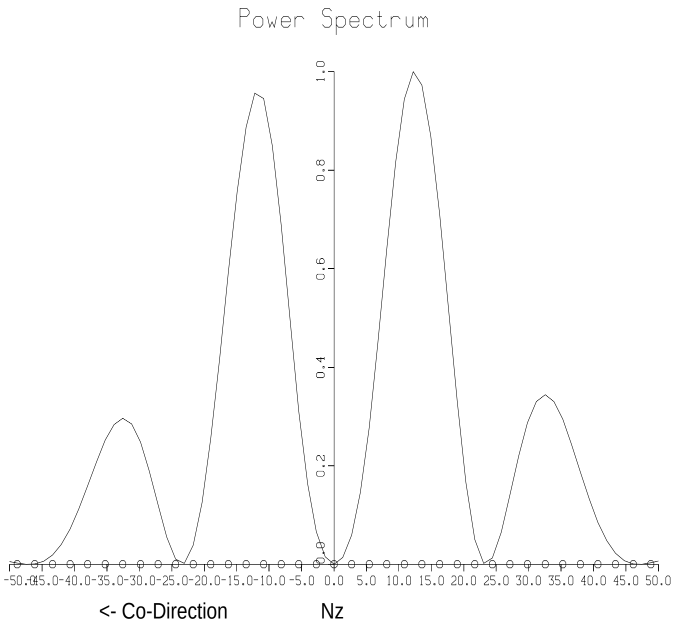


— **With dissipation, the surface impedance is symmetric along B but asymmetric perpendicular to B. This can lead to toroidally asymmetric power spectrum even with symmetric antenna array**

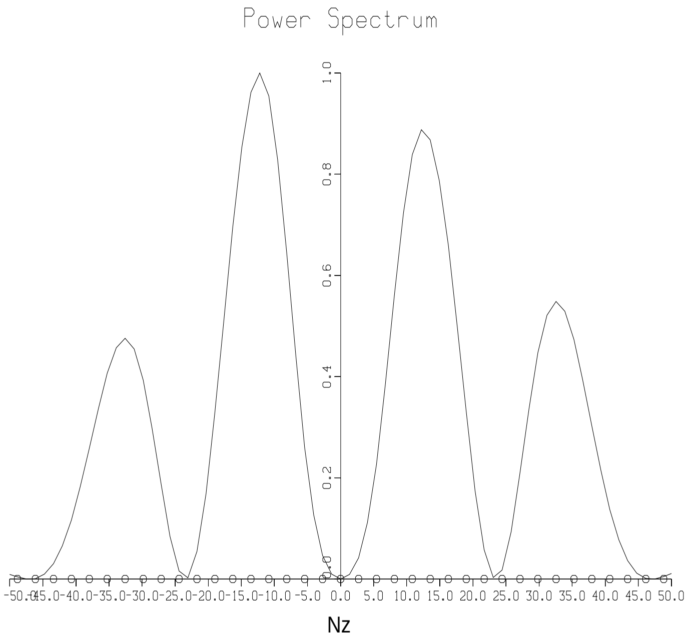
GENERAL ATOMICS

THE POWER SPECTRUM IS SYMMETRIC FOR LOW PEDESTAL DENSITY

- Edge density = $1 \leftarrow 10^{13}$ cm^{-3}



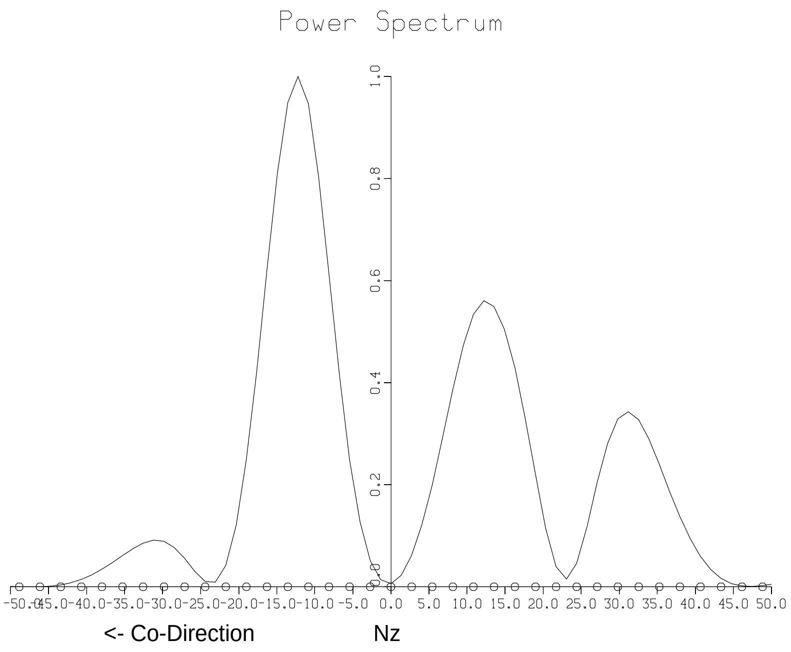
Central density = $4 \leftarrow 10^{14}$ cm^{-3}



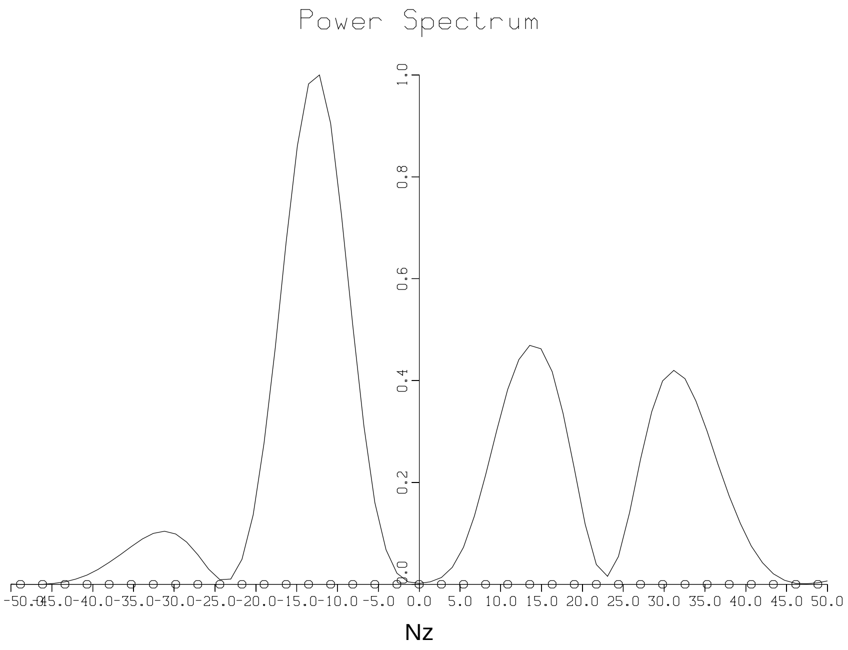
Central density = $8 \leftarrow 10^{14}$ cm^{-3}

THE POWER SPECTRUM IS ASYMMETRIC FOR HIGH PEDESTAL DENSITY

- **Edge density = $1 \leftrightarrow 10^{14}$ cm^{-3}**



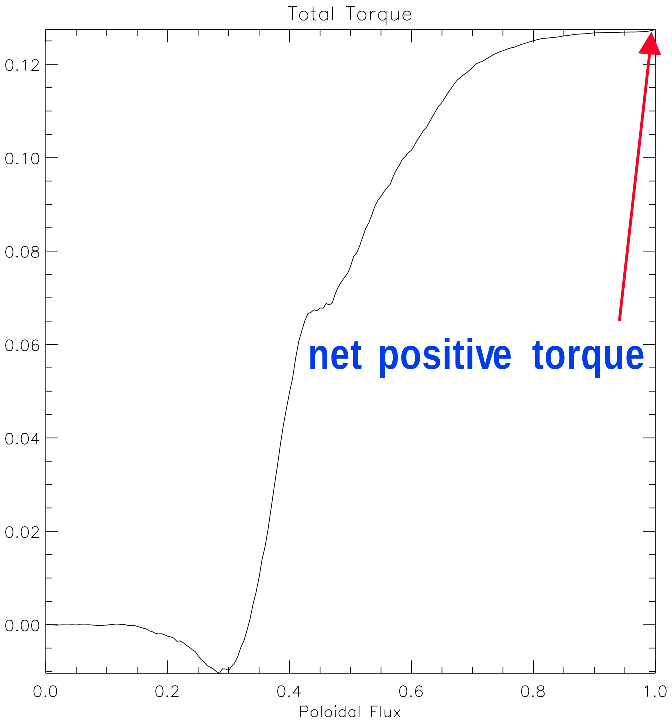
Central density = $4 \leftrightarrow 10^{14}$ cm^{-3}



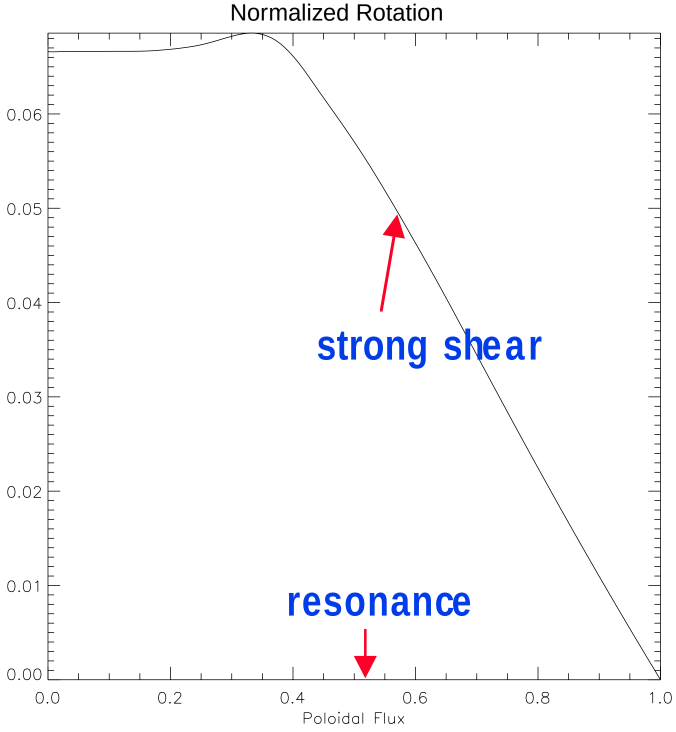
Central density = $8 \leftrightarrow 10^{14}$ cm^{-3}

ROTATION REMAINS IN CO-DIRECTION WITH LOWER B_T AND FLAT DENSITY PROFILE

- $n_c = 4 \leftrightarrow 10^{14}\ \mathrm{cm}^{-3}$, $B_T = 4.5$ T



net positive torque



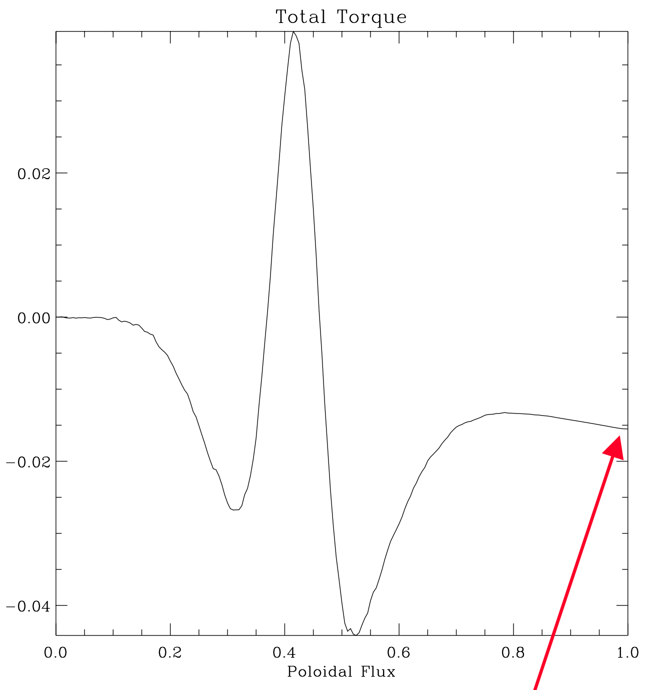
strong shear

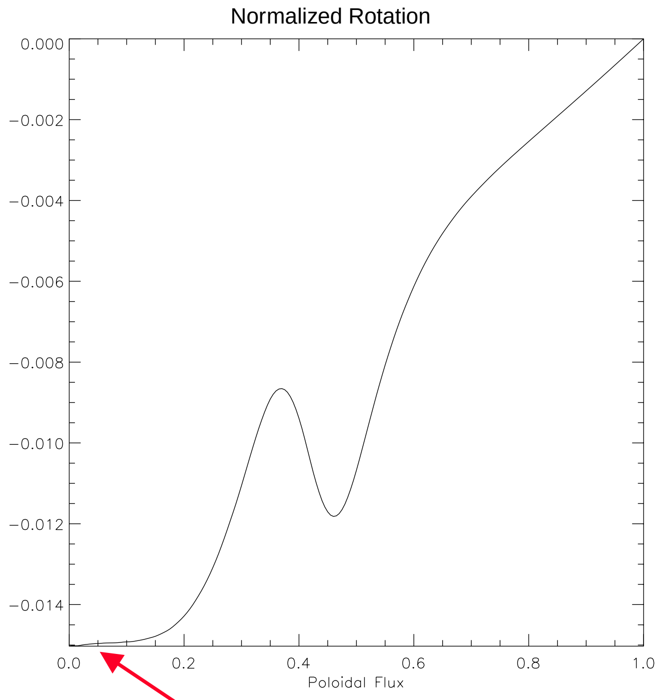
resonance

GENERAL ATOMICS

ROTATION CHANGES TO COUNTER-DIRECTION WITH PEAKED DENSITY PROFILE TYPICAL OF INTERNAL TRANSPORT BARRIER

- $n_c = 8 \leftrightarrow 10^{14}$ cm^{-3}, parabolic squared profile, $B_T = 4.5$ T



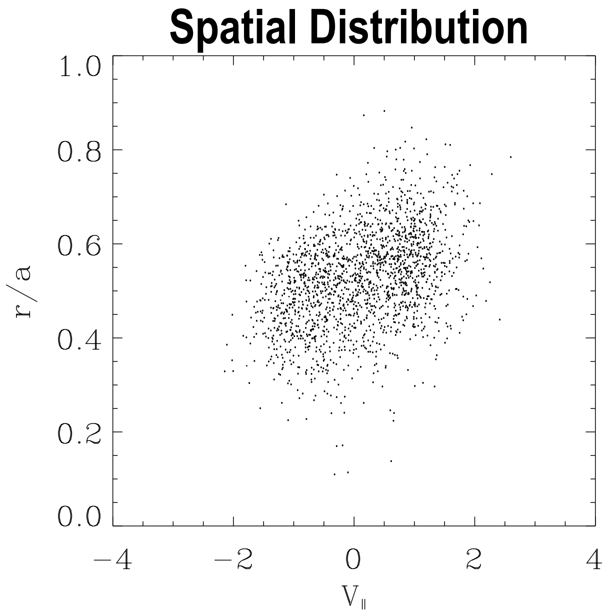


net negative torque

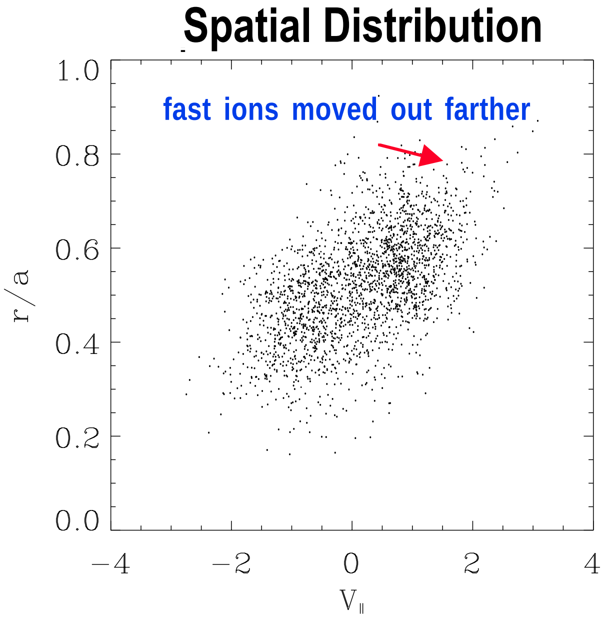
counter-rotation

THE FAST IONS ARE DRIVEN PREFERENTIALLY OUTWARD FOR A PEAKED DENSITY PROFILE

- A larger outward radial current results in a negative net torque



Fast ion spatial distribution for flat density profile



Fast ion spatial distribution for peaked density profile

SUMMARY OF MECHANISMS AT WORK

- A high edge density pedestal leads to an asymmetric power spectrum that favors positive (co-directional) $N_{//}$
- A positive $N_{//}$ ICRF wave acting on a flat density profile produces a co-rotation
  - —More co-rotating fast ions are generated
- Rotational shear possibly produces an ITB and a peaked density profile
- The high central density and a peaked profile cause the positive $N_{//}$ wave to drive a counter-rotation
  - —A larger outward radial current leads to a negative net torque

COMMENTS

- The ORBIT-RF code at present has not included parallel momentum change in the rf stochastic diffusion
  - —A treatment of traveling fast waves on plasma rotation can be found in Perkins, et al., (2001) to be published in Phys. Plasmas
- The antenna calculation is based on a simple two-strap antenna model
  - —More realistic modeling of the Alcator C-Mod antenna and edge profiles is needed to check the power spectrum asymmetry
- A simple model is used for the wave field in the ORBIT-RF code hence the spatial and velocity distribution for the fast ions should only be considered as qualitative
  - —Coupling of the ORBIT-RF code with a full-wave code is being planned