EFFECT OF PLASMA FLOWS ON TURBULENT TRANSPORT AND MHD STABILITY*

by

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INTRODUCTION: IMPORTANCE OF PLASMA FLOWS

- Plasma flows have important effects on tokamak stability and transport on spatial scales ranging from the gyro-orbit scale to the machine size.
  - In many interesting cases, these flows are self-generated by the plasma.

- For example, a key topic of present-day research is the effect of gyro-radius-scale zonal flows on micro-turbulence-driven transport.

- Somewhat larger scale flows include the changes in sheared $E \times B$ flows observed at the L to H transition, the ERS transition and during the spin-up associated with VH-mode.

- Sheared toroidal flows have been predicted to affect MHD ballooning mode stability [R.L. Miller, et al., Phys. Plasmas 2, 3676 (1995)].

- Toroidal flows with scales of the system size have been shown experimentally to stabilize the resistive wall mode.
GOALS OF PRESENTATION

- Briefly cover some of the previous results on plasma flows and their effects
- Pose a series of questions to motivate later discussion
STABLE OPERATION WELL ABOVE THE NO-WALL $\beta$ LIMIT HAS BEEN DEMONSTRATED IN DIII–D

- Resistive wall mode stabilized by plasma rotation
- Theoretically predicted (Bondeson and Ward, 1994)

A.M. Garofalo et al., APS, 2001
Below a critical rotation value, RWM becomes unstable
HIBP MEASUREMENTS IN JFT2–M SHOW $E \times B$ FLOW CAN CHANGE IN 10 $\mu$s AT THE L TO H TRANSITION

- $E \times B$ flow changes before profiles change
  - $E = -\nabla \phi$

CARBON POLOIDAL ROTATION CHANGE SHOWS CHANGE IN $E \times B$ FLOW PRIOR TO ERS TRANSITION IN TFTR

“This precursor occurs at a time before there are changes in pressure and temperature associated with enhanced confinement” — R.E. Bell

MSE AND SPECTROSCOPY DETERMINE SAME $E_r$ CHANGE AT ERS TRANSITION IN TFTR

- Zero of MSE-determined $E_r$ chosen to match spectroscopic value well after ERS transition

- Rapid change in $v_\theta$ relative to $\nabla p$ shows neoclassical $v_\theta$ is not the whole story

DENSITY FLUCTUATIONS DECREASE AS CONFINEMENT AND $E_r$ SHEAR INCREASE AS H–MODE GOES TO VH–MODE IN DIII–D
ROTATION REVERSES DIRECTION WITH PLASMA CURRENT IN ALCATOR C–MOD H–MODE PLASMA

Core $E_r > 0$ in H–mode

J.E. Rice et al., Nucl. Fusion 41, 277 (2001)
ROTATION AND STORED ENERGY CHANGE TOGETHER IN ICRF AND OHMIC H–MODES IN ALCATOR C–MOD

ICRF and Ohmic H–modes

\[ \Delta W/I_p \text{ (kJ/MA)} \]

\[ \Delta V_{\text{Tor}} \text{ (km/s)} \]

\[ 0 \quad 20 \quad 40 \quad 60 \quad 80 \quad 100 \quad 120 \quad 140 \]

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J.E. Rice et al, Nucl. Fusion 41, 277 (2001)
CORE $E_r > 0$ IN H–MODE AND $E_r < 0$ IN H–MODE + ITB IN ALCATOR C-MOD

![Graph showing various plasma parameters over time](image)

J.E. Rice et al., Nucl. Fusion 41, 277 (2001)
CORE BARRIER FORMS IN ALCATOR C–MOD
WITH OFF-AXIS ICRF BOTH INSIDE AND
OUTSIDE MAGNETIC AXIS

- 70 MHz $P_{ICRF} = 1.5$ MW, $I_p = 0.8$ MA

ZONAL FLOWS SHEAR APART RADIAL TURBULENCE STRUCTURES

- Gyro kinetic code (Gyro), toroidal geometry, shaped plasma

J. Candy, R.E. Waltz, J. Comp. Phys. (submitted)
ENERGETICS OF TURBULENCE/ZONAL FLOW INTERACTION

\[ \nabla n ~ \nabla T_e \]

\[ \nabla \nabla \]

Drift Waves

Reynolds Stress Drive

\[ \frac{d}{dr} \langle \tilde{v}_r \tilde{v}_\theta \rangle \]

Zonal Flow

\[ \frac{\partial \langle v_\theta (r) \rangle}{\partial t} \]

Flow shear decorrelation

Stringer-Windsor drive owing to magnetic field curvature plus poloidal asymmetry

\[ \nabla n \quad \nabla T \]

\[ \nabla n \quad \nabla T \rightarrow \text{Drift Waves} \]

\[ \tilde{P} \quad \text{Poloidal Variation} \]

\[ \frac{\partial}{\partial t} \langle \tilde{P} \sin \theta \rangle \]

\[ B \text{ Field Curvature} \]

\[ \frac{d}{dr} \langle \tilde{v}_r \tilde{v}_\theta \rangle \]

\[ \frac{\partial}{\partial t} \langle \tilde{v}_\theta \rangle \]

Flow shear decorrelation

Hallatschek and Biskamp, PRL 86, 1223 (2001)
PHYSICAL CHARACTERISTICS OF ZONAL FLOWS:
TESTABLE PREDICTIONS

- Fluctuating poloidal $E_r \times B_T$ flows, $v_\theta(t)$

- Toroidally and poloidally symmetric: $n=0$, $m=0$

- Low frequency ($<<$ ambient $\tilde{n}$, 10 kHz)

- Radially localized ($k_\perp \rho_i \sim 0.1$)

- RMS amplitude predicted to be small, $v_{ZF}/v_{th,i} \leq 1\%$ [T.S. Hahm, et al., PPCF 42, A205 (2002)]

- Geodesic acoustic mode (GAM) frequency $f \approx c_s/2\pi R$ [Hallatschek and Biskamp, Phys. Rev. Lett. 86, 1223 (2001)]
Eddies convect past spatial channels:

\[ v_z(t) = \frac{\Delta z}{\tau(t)} \]

Time delay \( \tau \) between two observation points.

2D TURBULENCE FLOW-FIELD CONSTRUCTED FROM 2D \( \bar{n} \) MEASUREMENTS

Jakubowski, McKee, Fonck APS, 2001
\( \tilde{n} \), AND \( v_\theta \) COHERENCY SPECTRA ARE DISTINCTLY DIFFERENT

- Frequency distributions distinct; frequency range similar

\[ <\tilde{n}_1 \tilde{n}_2>_\theta \]
\[ \Delta z = 1.1 \text{ cm} \]
\[ r/a = .91 \]

\[ <v_{\theta,1}^{}v_{\theta,2}^{}>_{\theta} \]
\[ \Delta z = 1.1 \text{ cm} \]

- Density

- Poloidal velocity

Strong zonal flow feature in \( \tilde{v}_\theta(f) \)

Jakubowski, McKee, Fonck APS, 2001
**Zonal flow feature exhibits expected spatial structure**

$\tilde{\nu}_\theta, ZF$ correlations have long poloidal, short radial length

![Graphs showing correlation of $\tilde{\nu}_\theta$ and $\tilde{n}$ in poloidal and radial directions.](image)

- $\tilde{\nu}_\theta^{\text{pol}} \Rightarrow$ very long wavelength in the poloidal direction
  - Contrasts with $L_{c,\tilde{n}} \approx 3 \text{ cm (poloidal)}$
- In contrast, $\tilde{\nu}_\theta^{\text{rad}} \Rightarrow L_{c,\tilde{\nu}} \approx 3.3 \text{ cm in the radial direction}$
  - Comparable to the $L_{c,\tilde{n}} \approx 2.3 \text{ cm (radial)}$

Jakubowski, McKee, Fonck APS, 2001
ZONAL FLOW MAGNITUDE CONSISTENT WITH PREDICTIONS

\[ \frac{V_{\theta,ZF}}{V_{th,i}} \sim 1\% \]

\[ \Delta z = 1.1 \text{ cm} \]

- \[ \tilde{v}_{th,i} = 150 \text{ km/s} \]
- \[ \tilde{v}_{\theta,ZF}/\tilde{v}_{th,i} \sim 0.005 \]
- Consistent with Hahm

\[ \Rightarrow \frac{V}{V_{th,i}} \sim 0.01 \]

- Broadband \( \tilde{v}_{\text{turb}} \) exists in addition to \( \sim 15 \text{ kHz peak} \)

\[ L_c \tilde{v}_{\text{turb}} \leq 2 \text{ cm} \]

Jakubowski, McKee, Fonck APS, 2001
BICOHERENCE SHOWS $\tilde{n}$ AND $\tilde{v}_\theta$ PHASE COUPLING

- Three-wave interactions with drift waves zonal flows (Diamond '91)
- Zonal flow generation mechanism should be evident in the cross-bispectrum

$$<\tilde{v}_\theta^* (k_z) \tilde{v}_f (k_1) \tilde{v}_\theta (k_2)>$$

zonal flow scale

- We observe a nonzero bicoherency at low frequency

$$<\tilde{v}_\theta^* (f_2 - f_1) \tilde{n} (f_1) \tilde{n} (f_2)>$$

- Peak $\sim 0.3$ at $f_2 - f_1 \approx 15$ kHz $= f_{ZF}$

$\Rightarrow$ Coupling of $\tilde{n}$ to the zonal flow feature

Jakubowski, McKee, Fonck APS, 2001
Recent work by Klaus Hallatschek (PRL 86, 1223 (2001)) simulating turbulence in the edge/core transition region:

— Zonal flows here are Geodesic Acoustic Modes (GAMs)
— Driven by pressure asymmetry on flux surface, rather than by Reynold’s Stress
— couple to pressure perturbations (m/n=1/0) by magnetic field inhomogeneity

Experimental indications

— Nearly coherent zonal flows (radially and temporally)
— f ~ 10 kHz for DIII-D edge parameters

Suggests experimental tests:

— Dependence on ion temperature
— Dependence on plasma shaping/curvature
HEAVY ION BEAM PROBE MEASUREMENTS OF POSSIBLE ZONAL FLOWS

As was pointed out by P. Schoch (APS, 2001), HIBP systems on many devices (TEXT, JIPP TII-U, ISX-B) have long seen fluctuations in the 20 to 50 kHz range which were not understood.

- TEXT data indicate these may be geodesic acoustic modes

Retrospective analysis of TEXT results from 1990 show

- $E_r$ fluctuations are consistent with $m=0$ poloidal structure
- Correlation of these $E_r$ fluctuations with density fluctuations is weak
- Frequency is consistent with GAM frequency over a range of radii
- $E_r$ fluctuations seen only for $0.6 \leq r/a \leq 0.95$ in discharges studied
- No $E_r$ significant fluctuations at smaller or larger radii
- Correlation length is short, about the sample volume size
FREQUENCY OF $E_\parallel$ FLUCTUATIONS IN TEXT AGREES WITH GAM FREQUENCY

- Curve is estimate of GAM frequency
- Vertical bars show range of measured $E_\parallel$ frequency
- Horizontal bars show radial spacing of sample locations

P. Schoch, APS 2001
ZONAL FLOW QUESTIONS

- Do the theoretically predicted zonal flows really exist?
  - What criteria do we use to decide that zonal flows have been observed?

- Do detailed zonal flow properties really agree with theory?
  - Why is the geodesic acoustic mode experimentally so obvious compared to the $f \equiv 0$ zonal flow?

- How do we best measure the zonal flow's properties experimentally?
  - Can we distinguish $f \equiv 0$ zonal flows from mean flows?

- What are the relative roles of Reynold's stress and Stringer-Windsor drive in various plasma regions?
POLOIDAL FLOW QUESTIONS

- What physics governs the mean poloidal flows in the plasma?

- What is the role of the physics described by neoclassical theory?
  
  — May need to include collisions with fast ions (W. Houlberg, 2002)

- What additional physics, if any, is needed to understand how the spontaneously generated poloidal rotation arises, for example, at the ERS transition?
  

- How can we best test the neoclassical theory?
IN H-MODE EDGE IN DIII-D, MAIN ION AND CARBON POLOIDAL ROTATION DISAGREE WITH NEOCLASSICAL PREDICTION

- Helium plasma \([I_p = 1 \text{ MA}, B_T = 2T, n_e = (1-4) \times 10^{19} \text{ m}^{-3}]\)

TOROIDAL ROTATION QUESTIONS

- What physics governs the mean toroidal flow in the plasma?

- Does neoclassical theory play any role here?
  - Even in ITB cases where the ion thermal diffusivity is neoclassical, the toroidal angular momentum diffusivity exceeds neoclassical by about a factor of 50.
  - What physics must be added to that in neoclassical theory to understand this?

- How do we understand toroidal flow generation in the core of C-Mod plasmas in the apparent absence of toroidal torque?

- What role do MHD modes play in governing the toroidal plasma rotation?
  - Are MHD modes only important near beta limits?
  - How do we isolate the effects of MHD modes experimentally?
What new tools can we develop to locally reduce turbulence-driven transport by altering plasma flows?

— Present control tools (e.g. NBI) are crude and act over broad regions

— Control is the ultimate demonstration of understanding
Diagnostic Development Issues and Questions

- How can we best use synthetic diagnostics from modeling codes?

- Need to develop improved experimental techniques to measure the zonal flow over wider regions of the plasma
  - Need larger poloidal and radial range
  - Improved signal-to-noise

- Must refine the analysis techniques needed to compute the gyro-orbit cross section effect on poloidal rotation measurements and then verify the calculations experimentally in order to test neoclassical poloidal rotation theory properly

- Improve techniques to measure MHD modes (e.g., resistive wall modes and Alfvén modes) which can affect rotation
FREQUENCY SPECTRUM IN ALFVÉN FREQUENCY RANGE IS EXTREMELY RICH

FIR Scattering Data
107001  k = 1 cm⁻¹

QDB phase
Core localized quasi-coherent modes
Edge modes (EHO)

UCLA

NBI initiation
Time (s)

Frequency (kHz)

0

1.0  2.0  3.0  4.0

-1000 -500 0 500 1000 1500
Reflectometer data indicate the core quasi-coherent modes are localized to $\rho \approx 0.0$–0.4.

Frequency spectrum evolution of fixed frequency reflectrometer data:

- 32 GHz, reflected at $\rho = 0.85$
- 40 GHz, reflected at $\rho = 0.55$
- 50 GHz, reflected at $\rho = 0.3$
CONCLUSION

- Plasma flows have important effects on tokamak stability and transport on spatial scales ranging from the gyro-orbit scale to the machine size
  
  - In many interesting cases, these flows are self-generated by the plasma

- Key open questions include theory and experimental measurements in the areas of
  
  - Zonal flows
  
  - Poloidal and toroidal rotation
  
  - Coupling of rotation and MHD modes