Nonlinear radio-frequency generation of sheared flows*

J.R. Myra and D.A. D'Ippolito

Lodestar Research Corp.

L.A. Berry, E.F. Jaeger, D.B. Batchelor

ORNL

and the RF SciDAC Team

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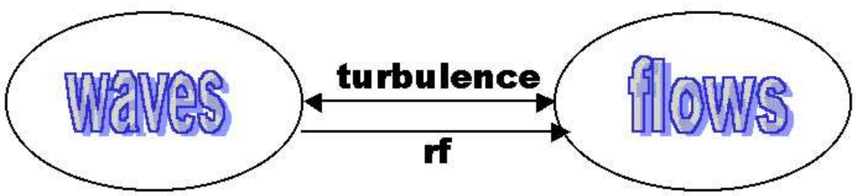
Introduction

RF-driven sheared flows may be important

- **control** turbulence and transport barriers
- investigate fundamental physics of nonlinear waves and flows

RF codes and experiments can help to understand turbulence & transport barrier formation

- rf driven flows are "open loop", easier than "closed loop" turbulence problem



- for rf problem need to understand:
    - how a given wave affects macroscopic responses (flows)
    - macroscopic changes affect instabilities, turbulence
- turbulence: flows modify the waves that create them
    - important but a separate issue

rf allows fundamental nonlinear physics in a controlled context

Experiments suggest that ITB control is possible

direct launch ion Bernstein wave (IBW):

- confinement improvement and/or profile modifications consistent with ITB

PBX-M
B. LeBlanc, et al. Phys. Plasmas **2**, 741 (1995)

FTU
R. Cesario, et al., Phys. Plasmas **8**, 4721 (2001)

Alcator C
J. D. Moody, et al., Phys. Rev. Lett. **60**, 298 (1988)

PLT
M. Ono, et al., Phys. Rev. Lett. **60**, 294 (1988)

JIPPT-II-U
T. Seki, et al., in AIP Conference Proceedings 244 – Charleston (1991)

- direct observation of rf-induced sheared flows

TFTR
J.R. Wilson, et al., Phys. Plasmas **5**, 1721 (1998).
B.P. LeBlanc, et al., Phys. Rev. Lett. **82**, 331 (1999).
C.K. Phillips, et al., Nucl. Fusion **40**, 461 (2000).

Directly launching the IBW can be difficult in practice

- hard to launch wave with $k\rho_i \sim 1$ from macroscopic antenna
- slow $v_g \sim v_{ti} \Rightarrow$ highly nonlinear wave at edge
- more success with high frequency waveguides than antennas

Would really like to launch fast Alfvén wave (macroscopic wavelength mode)

- hardware available on many tokamaks
- antenna coupling is much better understood
- BUT, fast Alfvén wave typically generates negligible flows
    - long wavelength, fluid mode
- mode convert fast Alfvén wave to short wavelength ion Bernstein wave or ion cyclotron wave inside plasma

Previously, it was not known whether flows could be driven by mode-converted waves.

new developments in theory and computation show mode-converted flow drive is possible

mode conversion edge flow drive recently observed

JET
C. Castaldo et al., 19th IAEA, Lyon (2002)

Idea of rf turbulence suppression has been around for a long time

- Craddock & Diamond, PRL (1991)

- Berry et al., PRL (1999)
- Jaeger et al., Phys. Plasmas (2000)
- Myra & D'Ippolito, Phys. Plasmas, (2000)
- Elfimov et al., PRL (2000)

Recent advances in theory and computation

- computation of short wavelength wave fields in real tokamak geometry
  - Jaeger et al., PRL to be published
- 2D nonlocal nonlinear theory
  - post-processes field computations ⇒ flow drive forces

- rf-driven flow calculations similar to turbulence-driven flows but complement the physics regime. ICRF regime is
  - high frequency $\omega > \Omega_i$,
  - short wavelength $k\rho_i \sim 1$ (nonlocal integral equation)
  - fully electromagnetic
  - all species kinetic: Landau, TTMP, and cyclotron resonances
  - weakly nonlinear ⇒ do nonlinear calculations by post-processing

No simulation work so far on the interaction of rf generated flows with turbulence

- good problem for the future

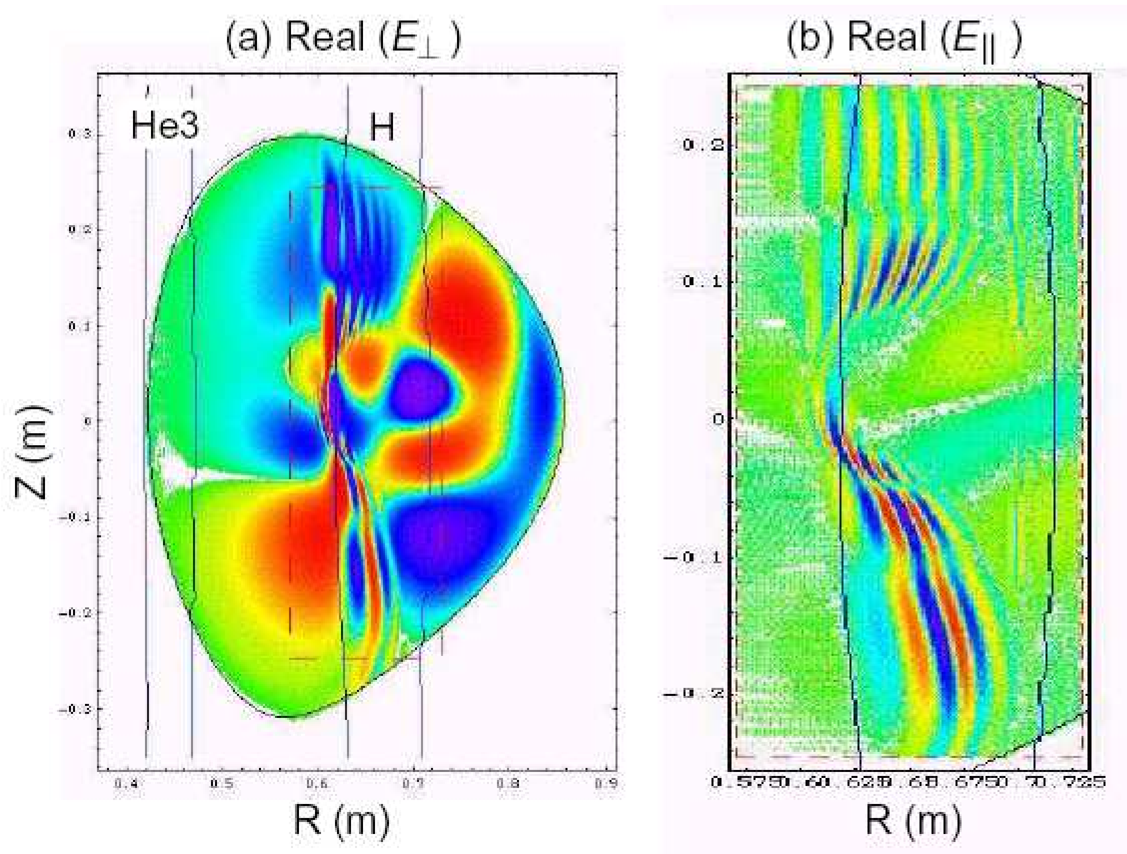
- rf codes can now calculate forces that drive flows and modify other macroscopic quantities
- turbulence codes can calculate transport response

- possibility of comparing controlled experiments with integrated simulations

Results from the rf SciDAC Project

The AORSA code solves an inhomogeneous wave equation with nonlocal integral operator

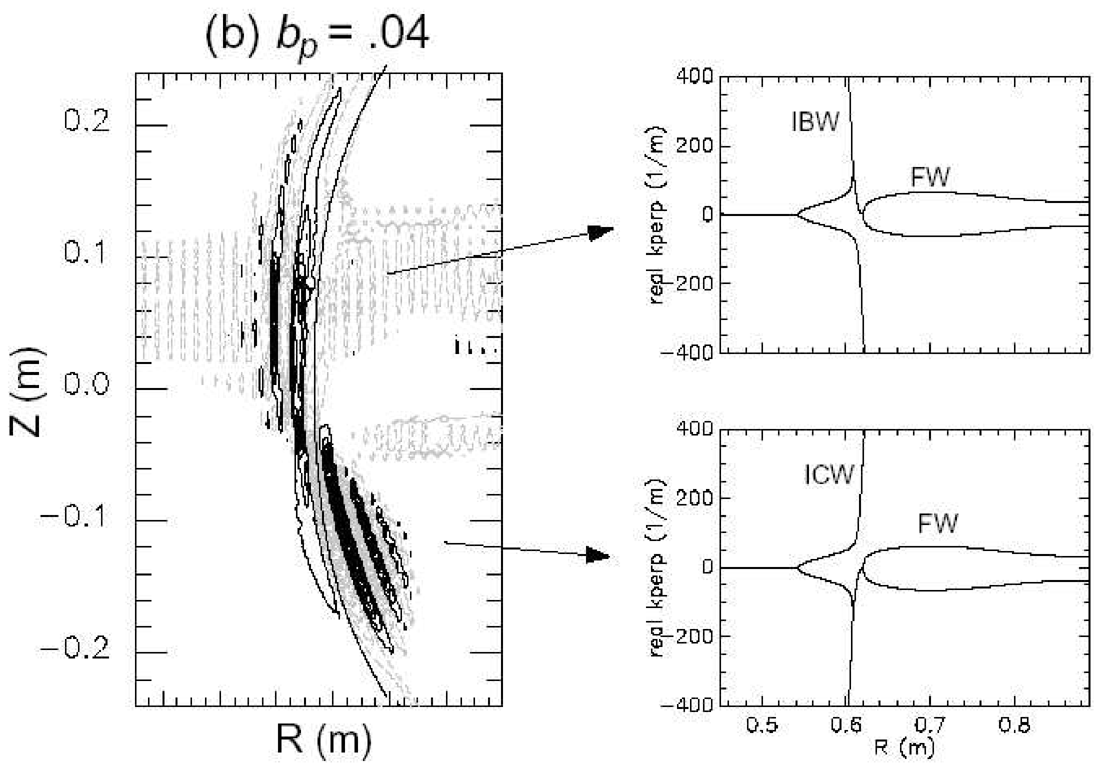
- AORSA and TORIC have been used to simulate mode conversion in a torus



- He3-H-D mode conversion in Alcator C-Mod from AORSA (Jaeger et al., PRL, 2003)
    - o mode conversion (ion-ion hybrid) and ion-cyclotron resonant surfaces
    - o IBW and ICW

Poloidal magnetic field effects control the mode conversion products

- predicted by Perkins (1977) but not able to be seen directly in experiments [Nelson-Melby et al, submitted to PRL] or simulations until 2002

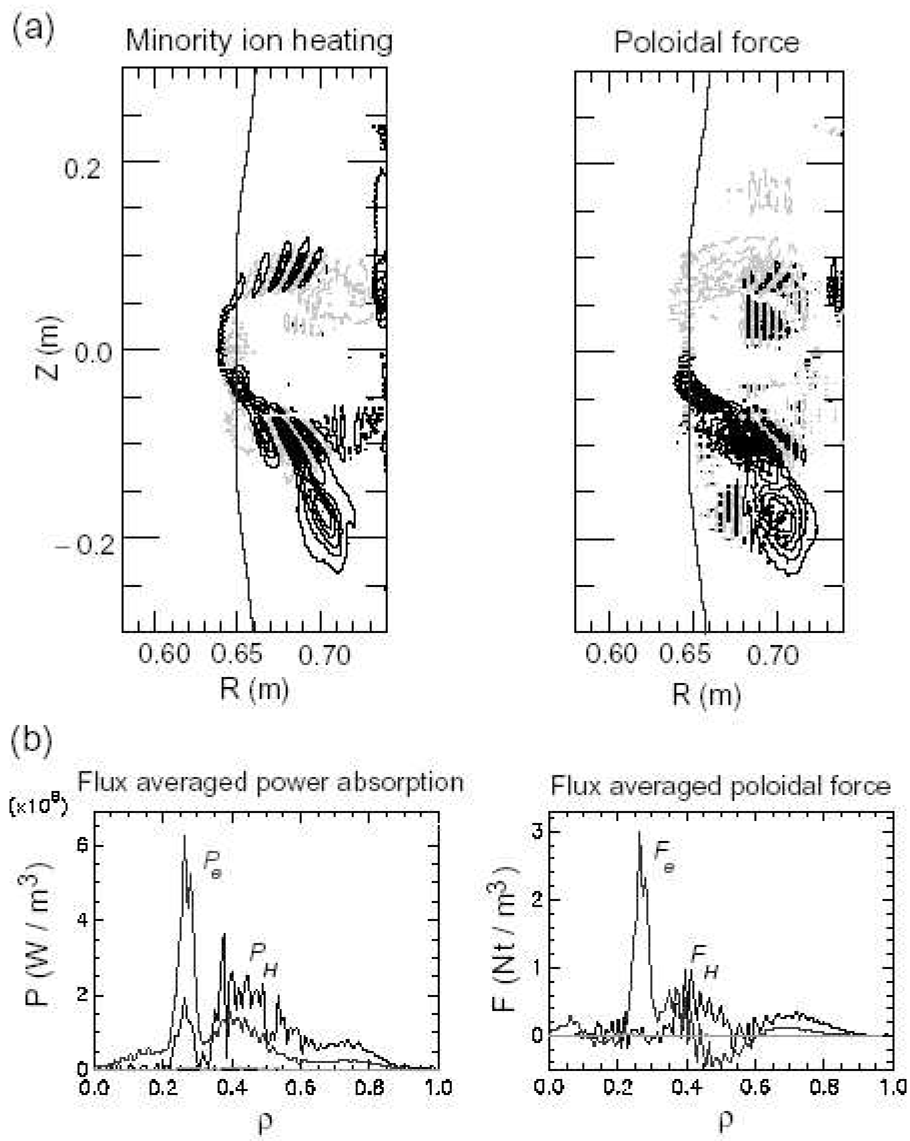


(Jaeger et al., PRL, 2003)

- weak B_θ on axis ⇒ ion Bernstein wave (IBW)
  - o propagates to smaller R
  - o absorption is on electrons
- stronger B_θ off axis ⇒ ion cyclotron wave (ICW)
  - o propagates to larger R (into cyclotron resonance)
  - o absorption is on ions

Minority ion heating and poloidal force

Jaeger et al., PRL, 2003



- net poloidal force follows heating profile
- additional sheared force contribution

Nonlinear calculation of the forces is based on a gyrokinetic formulation

- 2nd order in E, quasilinear average in time (not space)
- energy and momentum moments of gyrokinetic Vlasov equation
- like AORSA: hot plasma, quasi-local theory
    - o $k_\perp \rho \sim 1$, gyrokinetic theory (nonlocal)
    - o $\omega \sim \Omega >> \omega_{drift}$
    - o nonlinear responses retain first order in ρ/L

$$\frac{\partial f}{\partial t} + v_\parallel \nabla_\parallel f - \Omega \frac{\partial f}{\partial \phi} = -\nabla_v \cdot (\mathbf{a} f)$$

$$\mathbf{R} = \mathbf{r} + \frac{1}{\Omega} \mathbf{v} \times \mathbf{b}$$

$$\mathbf{a} = \frac{Ze}{m}\left[I\left(1 - \frac{\mathbf{k}\cdot\mathbf{v}}{\omega}\right) + \frac{\mathbf{kv}}{\omega}\right] \cdot \mathbf{E}_1 = \sum_k \mathbf{a}_k e^{i\mathbf{k}\cdot\mathbf{R} - i\delta_k}$$

$$\delta_k = \frac{1}{\Omega} \mathbf{k} \cdot \mathbf{v} \times \mathbf{b}$$

Energy moment

local power absorption

$$\dot{w} = \frac{m}{4} \sum_{k,k'} \int d^3 v\, f_{k'}\, \mathbf{v} \cdot \mathbf{a}_k^* + cc = \frac{1}{4} \sum_{k,k'} \mathbf{E}_k^* \cdot \overleftrightarrow{W}(\mathbf{k},\mathbf{k}') \cdot \mathbf{E}_{k'}$$

W = symmetric bilinear 4th rank tensor operator related to the conductivity (Smithe, 1989)

$$\overleftrightarrow{W}(\mathbf{k},\mathbf{k}' \to \mathbf{k}) = \overleftrightarrow{\sigma}(\mathbf{k})$$

Momentum moment

The order $|E|^2$ terms arise from the Lorentz force

$$\mathbf{F}_L = Zen\mathbf{E} + \frac{1}{c}\mathbf{J}\times\mathbf{B}$$

or using Maxwell's equations

$$\mathbf{F}_L = \frac{1}{16\pi}\left[(\nabla\mathbf{E}^*)\cdot\mathbf{D} - \nabla\cdot(\mathbf{D}\mathbf{E}^*)\right] + \mathrm{cc}$$

where

$$\mathbf{D} = \frac{4\pi i}{\omega}\mathbf{J}$$

and from the nonlinear stress tensor

$$\Pi = \frac{m}{4}\sum_{k,k'}\int d^3v\,(\mathbf{vv} - \langle\mathbf{vv}\rangle)\,f^{(2)}_{k-k'} + \mathrm{cc}$$

Notes:

- Π generalizes Reynolds stress
- requires gyrophase-dependent part of $f^{(2)}$
- gyrophase-average $f^{(2)}$ gives rise to diagonal (CGL type) pressure terms
    - o don't contribute to flow drive
    - o are secular unless heat sink is specified

Then

 …

The ⊥ force from ⊥ field gradients

$$\mathbf{F} = \mathbf{F}_d - \nabla_\perp X_r + \mathbf{b} \times \nabla X_d$$

The $\mathbf{F}_d$ term contains the wave momentum absorption ~ W^H and a reactive term ~ W^A

$$\mathbf{F}_d = \frac{\mathbf{k} + \mathbf{k}'}{4\omega} \mathbf{E}^* \cdot W^H \cdot \mathbf{E} + \frac{i}{4\omega} \nabla(\mathbf{E}^* \mathbf{E}) : W^A$$

The reactive term X_r ~ parallel torques on the plasma,

$$X_r = \frac{m}{8\Omega} \int d^3v\, f_{k'}\, \mathbf{b} \cdot \mathbf{v} \times \mathbf{a}_k^* + cc$$

The term X_d ~ perpendicular dissipation.

$$X_d = \frac{m}{8\Omega} \int d^3v\, f_{k'}\, \mathbf{v}_\perp \cdot \mathbf{a}_{k\perp}^* + cc$$

A more general result is also available

⊥ and || forces from ⊥ and || gradients

Reactive terms reduce to the conventional ponderomotive force

- forces on a fluid element (not a guiding center)
  - for inclusion into macroscopic evolution codes (e.g. transport codes)
  - cold plasma limit of previous result
    - keep reactive terms
    - **u** = fluid velocity
    - add back CGL terms

$$\mathbf{F} = \mathbf{F}_{d2} - \nabla_\perp \left(X_r + \frac{1}{2} nm \left\langle u_\perp^2 \right\rangle \right)$$

$$\mathbf{F}_{d2} = \frac{1}{16\pi} (\nabla \mathbf{E}^*) \cdot \mathbf{D} + cc$$

$$X_r = \frac{nm}{8\Omega} \mathbf{b} \cdot \mathbf{u} \times \mathbf{a}^* + cc$$

  - agrees with standard ponderomotive force
    - ψ_p = ponderomotive potential
    - **M** = ponderomotive magnetization

$$\mathbf{F} = -n \nabla \psi_p + \mathbf{B} \times \nabla \times \mathbf{M}$$

Reactive ponderomotive forces drive no avg. flows

- <…> = flux-surface average
- toroidal rotation is driven by torque $\langle RF_\zeta \rangle$
- poloidal rotation is driven by a combination of $\langle BF_\| \rangle$ and $\langle RF_\zeta \rangle$
- identities

$$\langle \nabla \cdot A \rangle = \frac{1}{\upsilon} \frac{\partial}{\partial \psi} \upsilon \langle R B_\theta A_\psi \rangle$$

$$\langle B \nabla_\| Q \rangle = \frac{1}{\upsilon} \int d\theta \int \frac{d\zeta}{2\pi} \frac{J B_\zeta}{R} \frac{\partial Q}{\partial \zeta} = 0$$

  - $\Rightarrow \langle BF_\| \rangle$ vanishes when $F_\| = \nabla_\|$ (scalar)

$$\langle R\mathbf{e}_\zeta \cdot \nabla \cdot \Pi \rangle = \langle \nabla \cdot \Pi \cdot R\mathbf{e}_\zeta \rangle = \frac{1}{\upsilon} \frac{\partial}{\partial \psi} \upsilon \langle R^2 B_\theta \Pi_{\psi\zeta} \rangle$$

  - $\Rightarrow \langle RF_\zeta \rangle$ vanishes when Π is a diagonal tensor
  - …
- can show that for cold-fluid ponderomotive force

$$\mathbf{F} = -n\nabla\psi_p + \mathbf{B} \times \nabla \times \mathbf{M}$$

$$\langle BF_\| \rangle = 0$$

$$\langle RF_\zeta \rangle = 0$$

Flux-surface-averaged flows are driven by

- direct wave-momentum absorption and
- dissipative stresses

$$\mathbf{F}_{dis} = \mathbf{F}_{d1} + \mathbf{b} \times \nabla X_d$$

$$\mathbf{F}_{d1} = \frac{\mathbf{k} + \mathbf{k}'}{4\omega} \mathbf{E}^* \cdot W^H \cdot \mathbf{E} \sim \frac{\mathbf{k}}{\omega} P_{rf}$$

- $\mathbf{F}_{d1}$ = "photon" momentum absorption term
  - drives net flows
  - electron or ion dissipation
- $\mathbf{b} \times \nabla X_d$ = dissipative stress term
  - drives bipolar sheared flows (no net momentum)
  - significant only for ions

$$X_d = \frac{P_\perp}{2\Omega}$$

    - where $P_\perp$ is the power absorbed into $v_\perp$

Summary: considerable progress has been made on the rf half of the problem

- the short wavelength modes needed for flow drive can now be followed in sophisticated 2D codes
    - fully EM
    - integral equation solve for nonlocal effects $k\rho \sim 1$
    - mode conversion in 2D with poloidal magnetic field effects
    - massively parallel, scaleable computations
    - improved nonlocal nonlinear algorithms have been developed for flow drive
- rf theory has been developed to calculate the forces driving flows
    - nonlinear nonlocal theory
    - includes important 2D effects
    - generalizes Reynolds and magnetic stresses and to $\omega > \Omega_i$, $k\rho \sim 1$
    - theory necessitated and stimulated by new code capabilities
- interesting physics is emerging from these results
    - mode conversion scenarios can generate flows, aren't restricted to direct launch IBW
    - mode conversion in 2D is subtle: ICW replaces IBW in traditional scenarios (Perkins, 1977)

Conclusions

ICRF field computations and the calculations of their nonlinear consequences are at a mature level

- integrated rf and turbulence simulations may now be feasible
    - start with open loop
        - rf code gives forces, flows
        - turbulence simulations give transport reduction

The results of an integrated effort in this area could be

- interesting from a physics perspective and
- important from a practical perspective

rf simulation • turbulence simulation ⇔ experiment

- deeper understanding of interaction of nonlinear forces, flows, and plasma response
- practically for experiments: a flexible knob for external control of ITB’s

Is the effect important for turbulence?

theoretical

$$\text{force} \rightarrow \text{flows} \rightarrow \omega_s > \gamma_{max} \, ?$$

- force calculation is solid
- flows require neoclassical theory
  - o handwave poloidal flows from neoclassical viscosity for TFTR IBW case ⇒ rough agreement with observed flows
  - o better estimates require neoclassical codes (being investigated)
- need γ_{max} from turbulence community

empirical

- several hundreds of kW (< 1 MW) of direct launch IBW have produced ITB effects in experiments (e.g. FTU)
- many MW of fast Alfvén wave can be launched and the mode conversion efficiency can be > 50% in scenarios that are good for flow drive