Nonlinear radio-frequency generation of sheared flows

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Outline

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Introduction

RF-driven sheared flows may be important

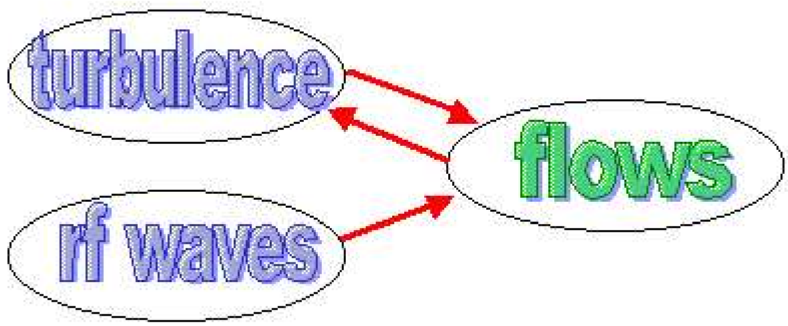
1) investigate fundamental physics of nonlinear waves and flows

2) **control** turbulence and transport in tokamaks

The confinement time τ in a tokamak is set by turbulence

- turbulence is spontaneous
- $n\tau > (n\tau)_{Lawson}$ and transport $\Rightarrow$ size, \$ of fusion
- nonlinear regulation
    - transport “barriers” (local reductions in transport)
    - leading candidate mechanisms involve sheared plasma flows
- $\Rightarrow$ study nonlinear driven flows in a controlled context

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

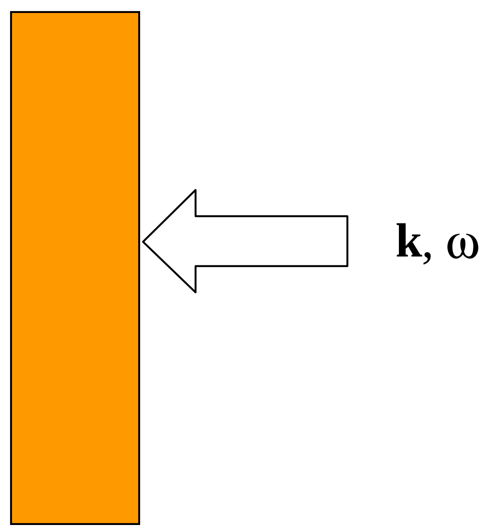
rf allows fundamental nonlinear physics in a controlled context

How can nonlinear waves drive flows?

Basic physics of waves, nonlinear forces, momentum transport

1) photon absorption
2) photon reflection, reactive ponderomotive forces
3) momentum redistribution

wave energy = ωN_k
wave momentum = $\mathbf{k} N_k$



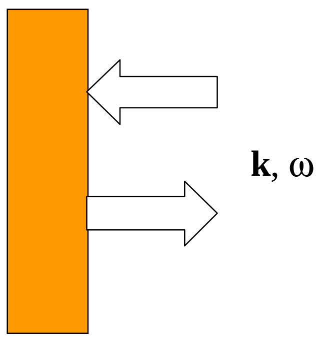
absorbed power $P_{rf} \Rightarrow$ force on absorbing medium

$$\mathbf{F} = \frac{\mathbf{k}}{\omega} P_{rf}$$

requires slow phase velocity (short wavelength) for good efficiency

Basic physics of waves, nonlinear forces, …

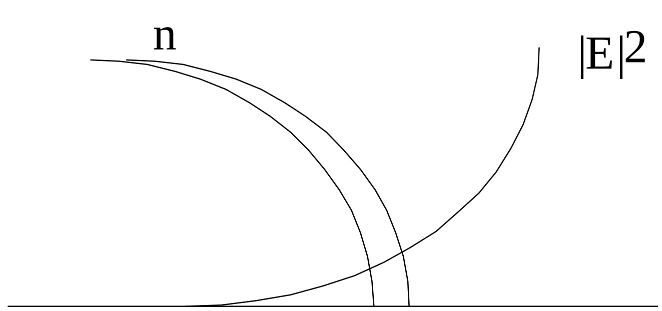
1) photon absorption
2) photon reflection, reactive ponderomotive forces
3) momentum redistribution



reflected power P_{rf} ⇒ force on medium

$$\mathbf{F} = \frac{2\mathbf{k}}{\omega} P_{rf}$$

boundary conditions ⇒ $|E|^2$ rather than circulating power description



internal energy ⇐ nonlinear stresses Π, (mechanical + field) ~ $\varepsilon|E|^2$

$$\mathbf{F} \sim \varepsilon \nabla |E|^2$$

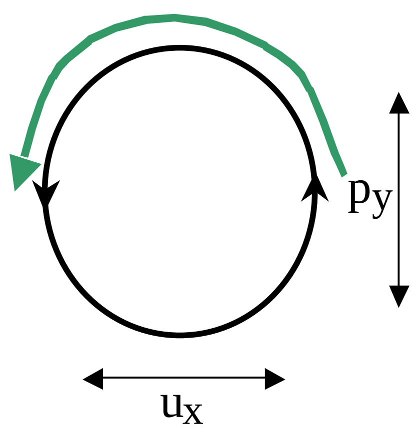
single particle ponderomotive potential $\psi_p \sim \frac{|E_{\parallel}|^2}{\omega} + \frac{|E_R|^2}{\omega+\Omega} + \frac{|E_L|^2}{\omega-\Omega}$

Basic physics of waves, nonlinear forces, …

1) photon absorption
2) photon reflection, reactive ponderomotive forces
3) momentum redistribution

transport of canonical angular momentum p_y by an eddy

$$\mathbf{F}_y = \frac{dp_y}{dt} = \mathbf{u}\cdot\nabla p_y = u_x \frac{\partial}{\partial x} p_y$$



phases important ⇒ need dissipation

related to the off-diagonal terms of the stress tensor (Reynold's Stress)

$$\mathbf{F}_y = \frac{\partial}{\partial x}\Pi_{xy}$$

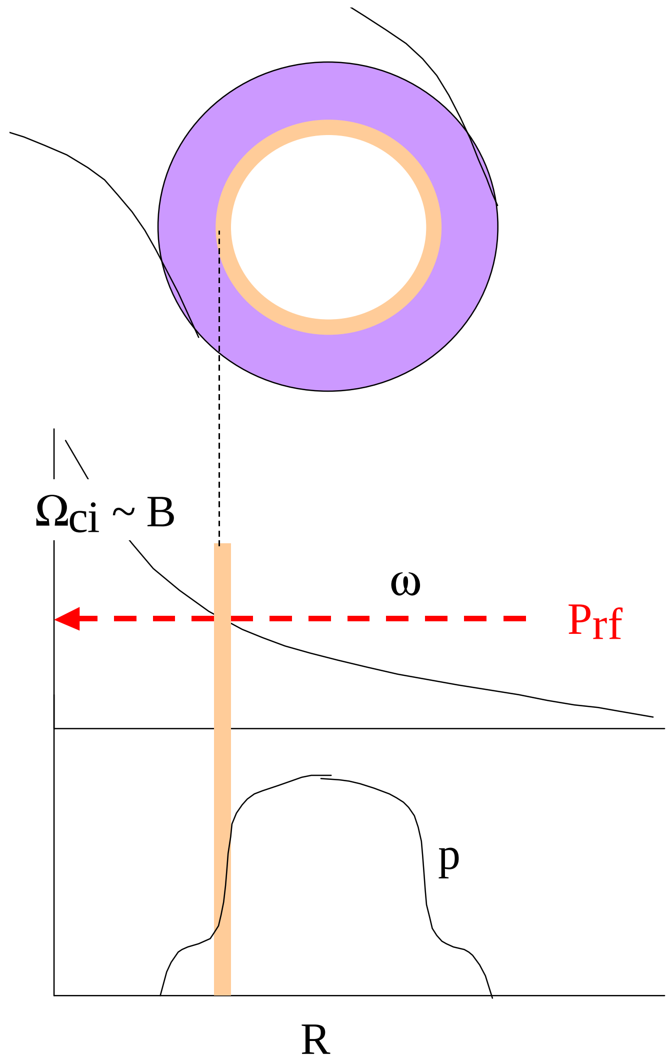
will turn out to be related to absorbed power

$$\mathbf{F} \sim \mathbf{b}\times\nabla P_{rf}$$

plasma flows in a tokamak can be driven by 1) and 3) but not 2)

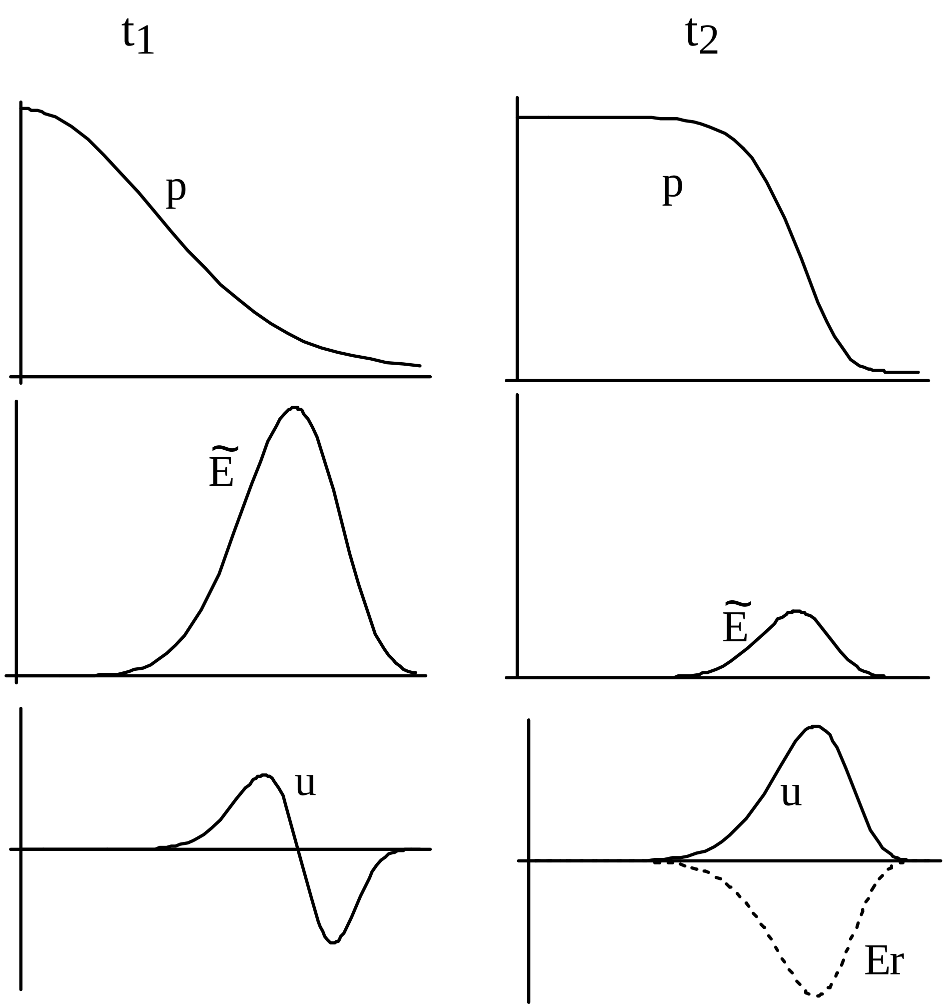
Basic physics: tokamak transport barriers and flows

- spontaneous transport *barriers* have been observed in some cases:
  - local regions of reduced diffusion χ
  - allow locally large gradients in n and T and increase global τ
- transport barrier control (vs. spontaneous formation) is of great interest for Advanced Tokamaks

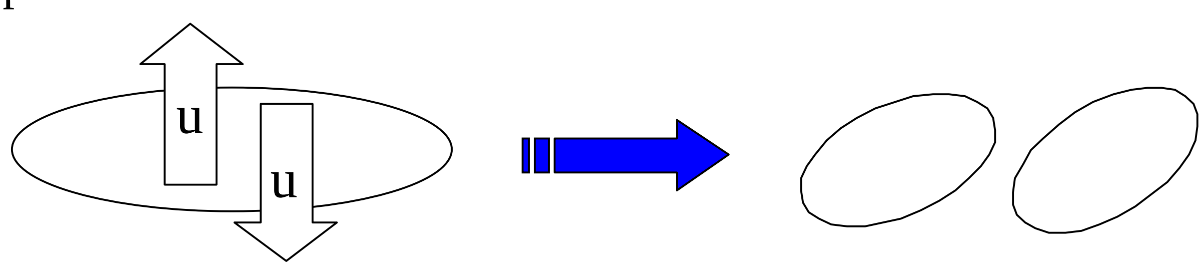


- vary location and P_{rf}
- modify p_e, p_i, $\mathbf{u}$, $J_{\|}$ (nb: many rf mechanisms possible)

One possible paradigm for transport barrier formation: wave-driven sheared flows are the trigger



- sheared flows break up radially elongated eddies ⇒ reduced transport step size



- replace turbulent-driven flows with rf-driven flows

Experiments suggest that ITB control is possible

(ITB = Internal Transport Barrier)

direct launch ion Bernstein wave (IBW): ⇐ short wavelength

- 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).

PBX-M experiment observed core H-mode (CH) with application of IBW power

- peaked profiles
- reduced transport in n, T_i, and L_ϕ (momentum)

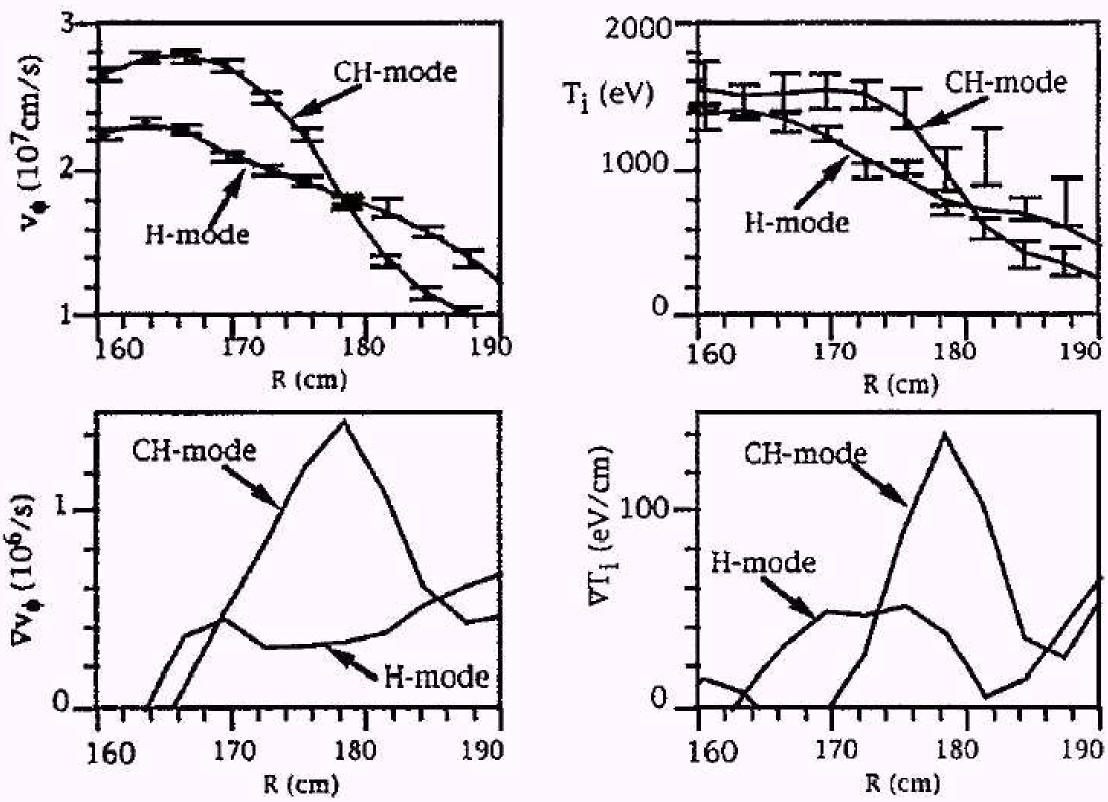


FIG. 5. Profiles of T_i, v_ϕ, ∇T_i, and ∇v_ϕ during the CH mode and equivalent time during a NBI-only discharge.

- B. LeBlanc et al., Phys. Plasmas **2**, 714 (1995)

TFTR experiment observed poloidal rotation driven by IBW

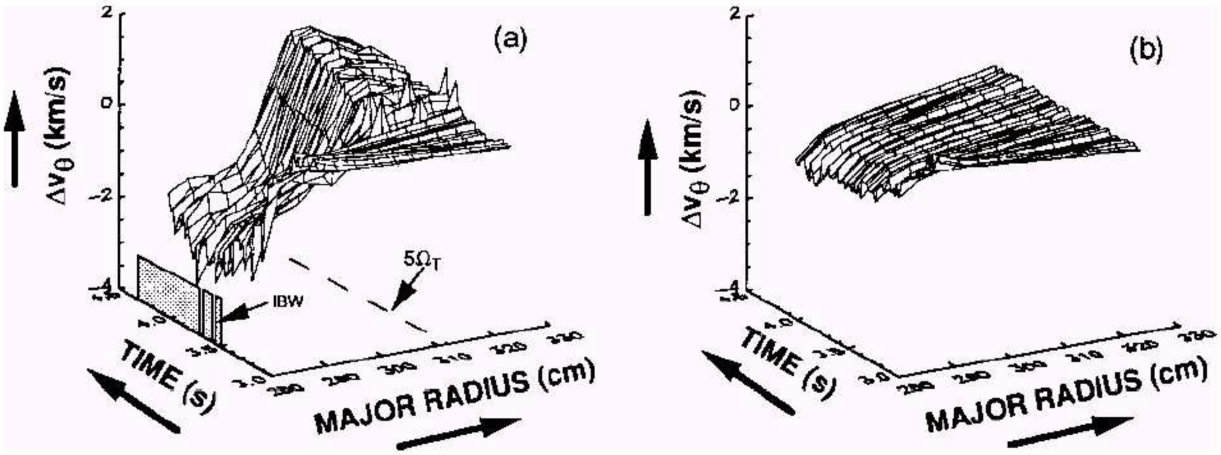


FIG. 9. A change in the poloidal rotation velocity as a function of radius and time. (a) IBW heating, $P = 200$ kW, $f = 76$ MHz, out-of-phase excitation, (b) no IBW power applied.

- J.R. Wilson, et al., Phys. Plasmas **5**, 1721 (1998).

Experiments show :

- IBW can drive flows
- IBW can somehow, sometimes, enhance confinement

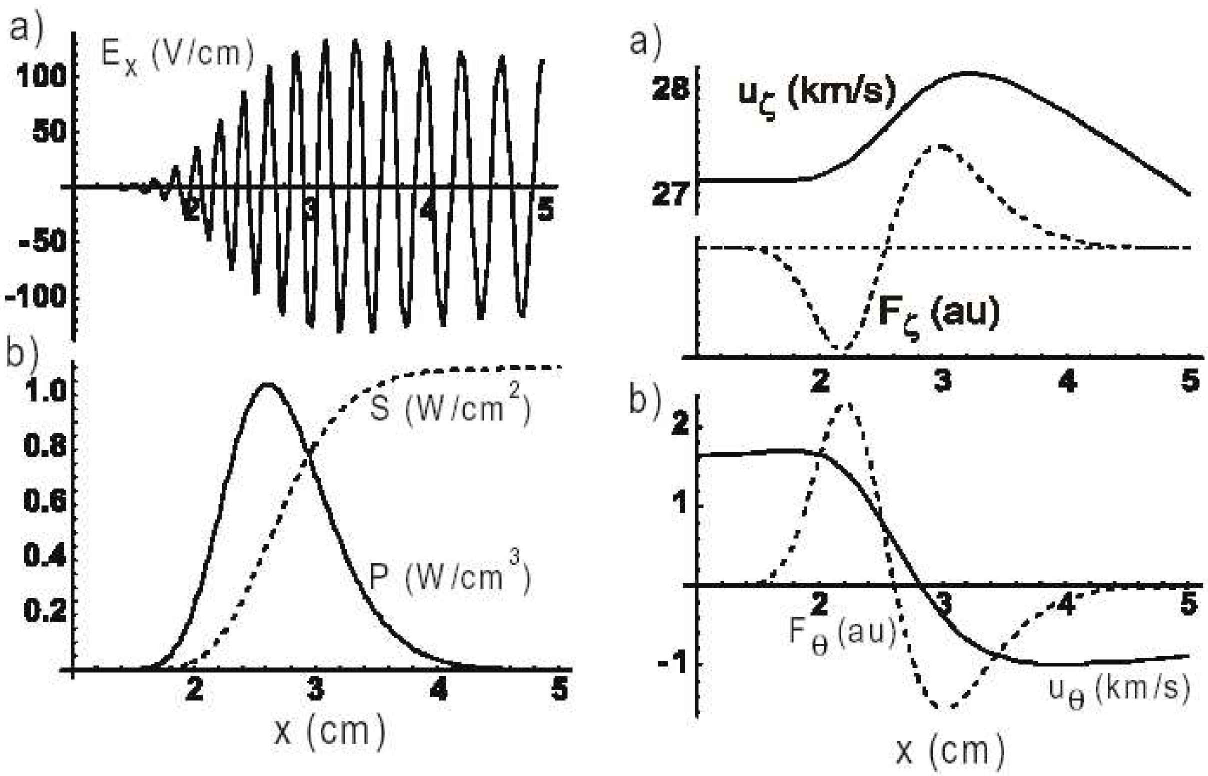
Do rf-generated flows create transport barriers?

need tools

Theory: Idea of turbulence suppression by rf driven flows 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)



1D model for sheared flows generated by IBW absorption
at ion cyclotron resonance layer

ρ_i

photo from Wan. et al. HT-7 tokamak

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, $P_{rf} \sim v_g|E|^2$
- more success with high frequency wave-guides than antennas

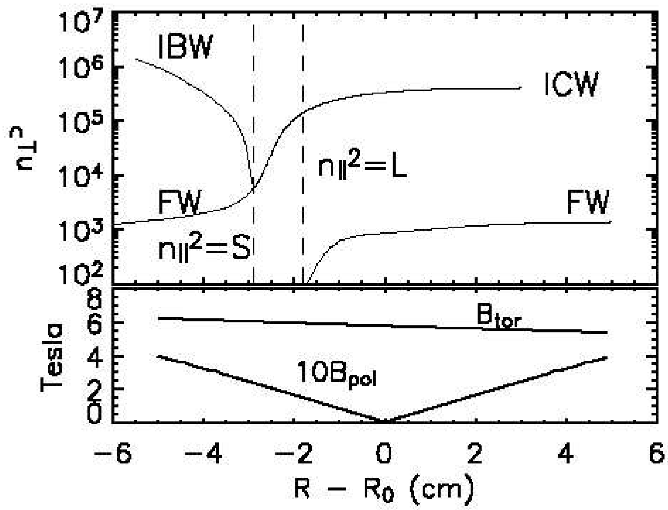
Would really like to launch fast Alfvén wave (macroscopic wavelength mode)

- hardware available on many tokamaks
- antenna coupling is much better understood
- BUT, fast Alfvén wave typically generates negligible flows by these mechanisms
    - long wavelength, fluid mode
    - direct momentum input is small ($\mathbf{k}/\omega$)
    - Reynolds stresses (uu) and magnetic stresses (BB) cancel (Diamond, 1991) $\Rightarrow$ no flow drive

New developments relevant to flow drive

- use short wavelength modes generated in the plasma interior by mode conversion (MC) from the fast Alfvén wave
  - MC: small k $\rightarrow$ large k modes at special resonant surfaces
  - previously thought: MC $\Rightarrow$ IBW
  - IBW propagates *away from the ion cyclotron resonance* Ω_i, and is not useful for flow drive.

- *experiment*: E. Nelson-Melby et al., PRL (2003): mode conversion $\Rightarrow$
  - ion Bernstein wave (IBW)
  - ion cyclotron wave (ICW), propagates into Ω_i resonance

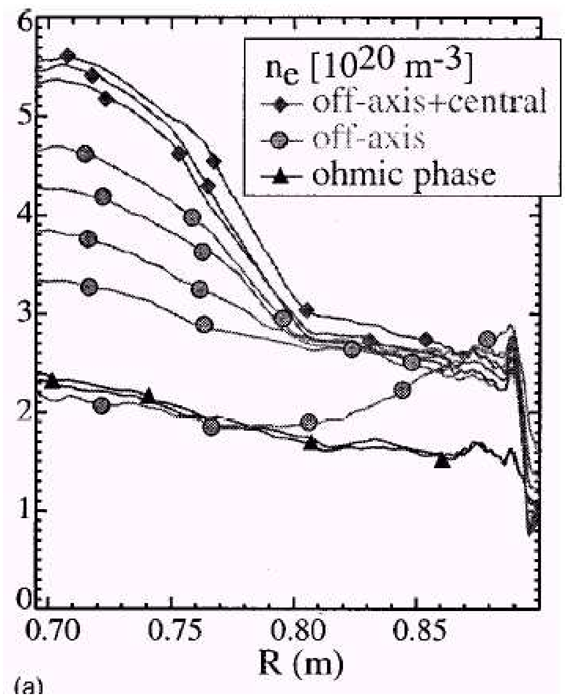


- *computation* of short wavelength wave fields in real tokamak geometry [RF SciDAC: Jaeger, Berry; Bonoli, Wright et al.]
- *theory* [RF SciDAC: Berry, Myra, D'Ippolito et al. (2003)]: *MC flow drive is possible with the ICW*

- mode conversion edge flow drive recently reported on JET, C. Castaldo et al., 19th IAEA, Lyon (2002)

Experiments on C-Mod have shown that the fast wave can trigger transport barriers

- off axis heating
- peaking of density
- barrier in electron thermal transport



- S.J. Wukitch et al., Phys Plasma **9**, 2149 (2002)

also see

- C. Fiore et al., 2003 TTF Meeting, Madison (2003).

Possible mechanisms?

- toroidal spin-up by fast ions (Perkins, Chang, Chan)
- toroidal spin-up by asymmetric edge propagation (Coppi)
- trigger by $p_i(r)$ profile steeping
- rf-driven flows??

Numerical Results from the rf SciDAC Project

2D full wave codes:

TORIC (Bonoli, Wright; Brambilla)

- expands in $k_{\perp}\rho_i$
- finite difference in r for each (m, n) mode
- banded matrix inversion
  - fast and/or capable of very high resolution

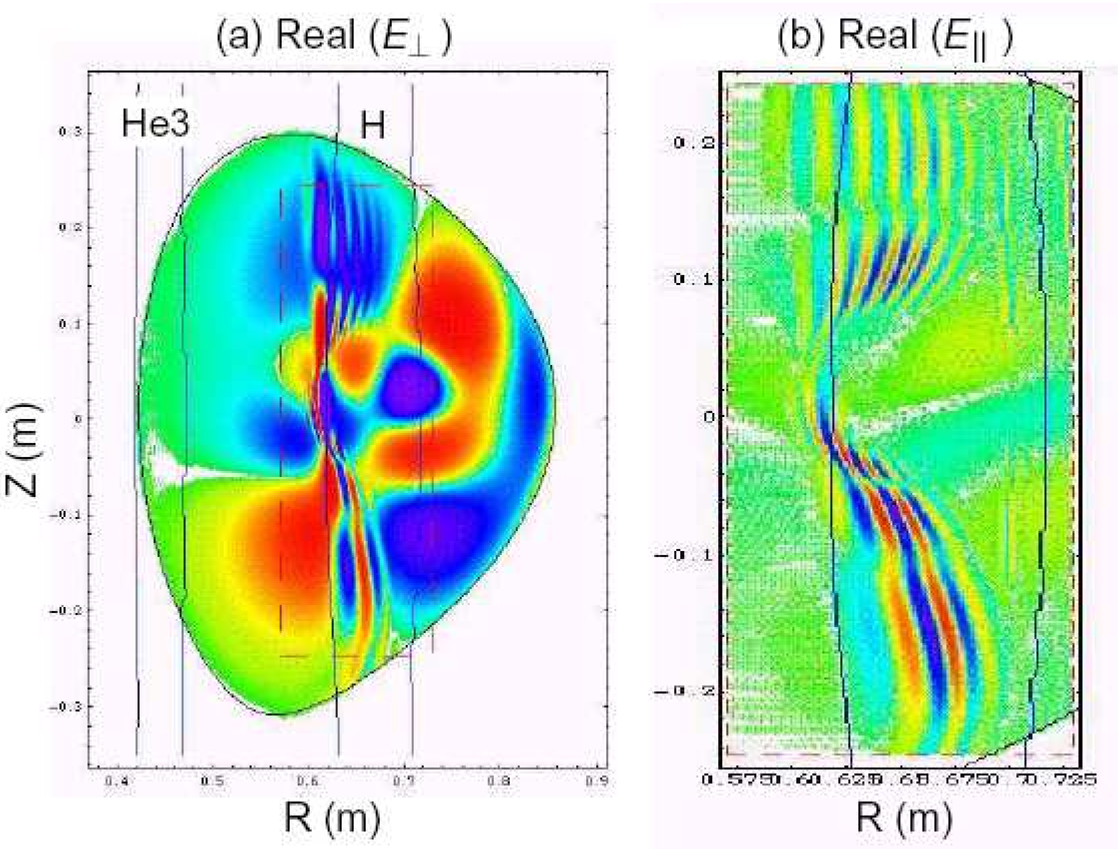
AORSA (Jaeger, Berry, Batchelor, et al.)

- all orders in $k_{\perp}\rho_i$; first order in ρ_i/L
- fields represented by Fourier expanding in Cartesian coordinates
- full matrix inversion
  - memory intensive, slower
- nonlinear flow drive module implemented

rf-driven flow calculations complement the physics regime of turbulence-driven flows

- high frequency $\omega > \Omega_i$,
- short wavelength $k_{\perp}\rho_i \sim 1$ (nonlocal integral equation)
- fully electromagnetic
- all species kinetic: Landau, TTMP, and cyclotron resonances
- weakly nonlinear ⇒ do nonlinear calculations by post-processing

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

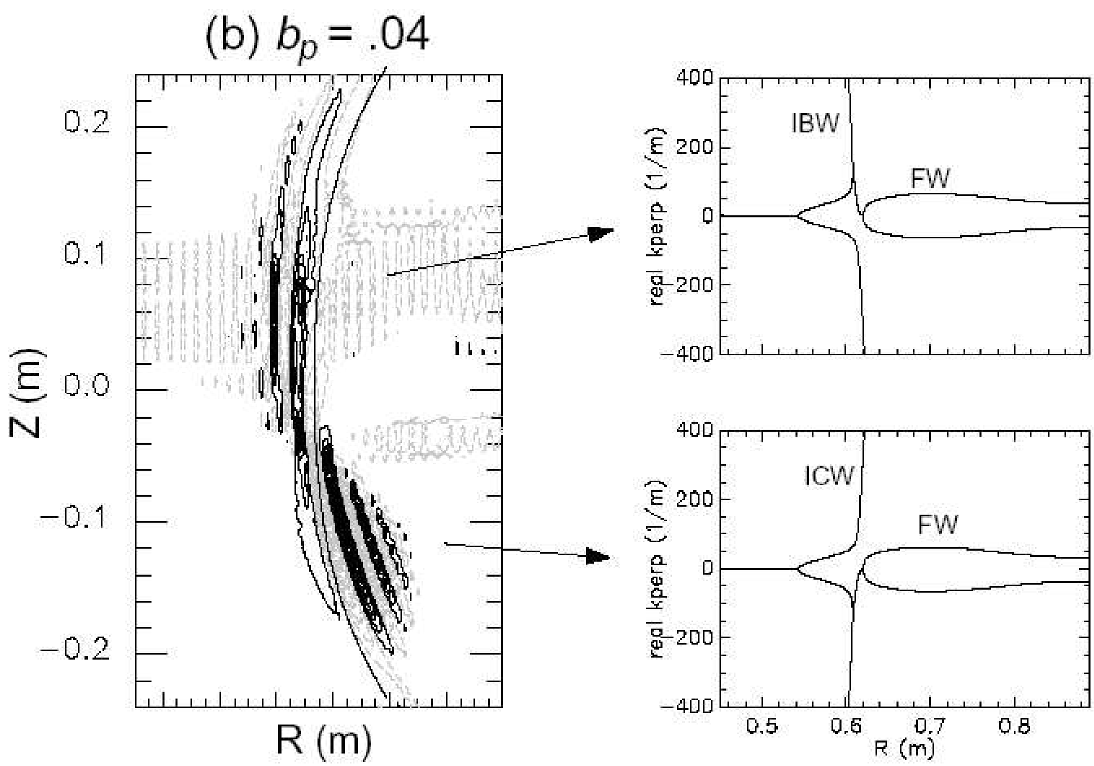


- He3-H-D mode conversion in Alcator C-Mod from AORSA (Jaeger et al., PRL, 2003)
    - mode conversion (ion-ion hybrid) and ion-cyclotron resonant surfaces
    - IBW and ICW

Poloidal magnetic field effects control the mode conversion products

- predicted by Perkins (1977)

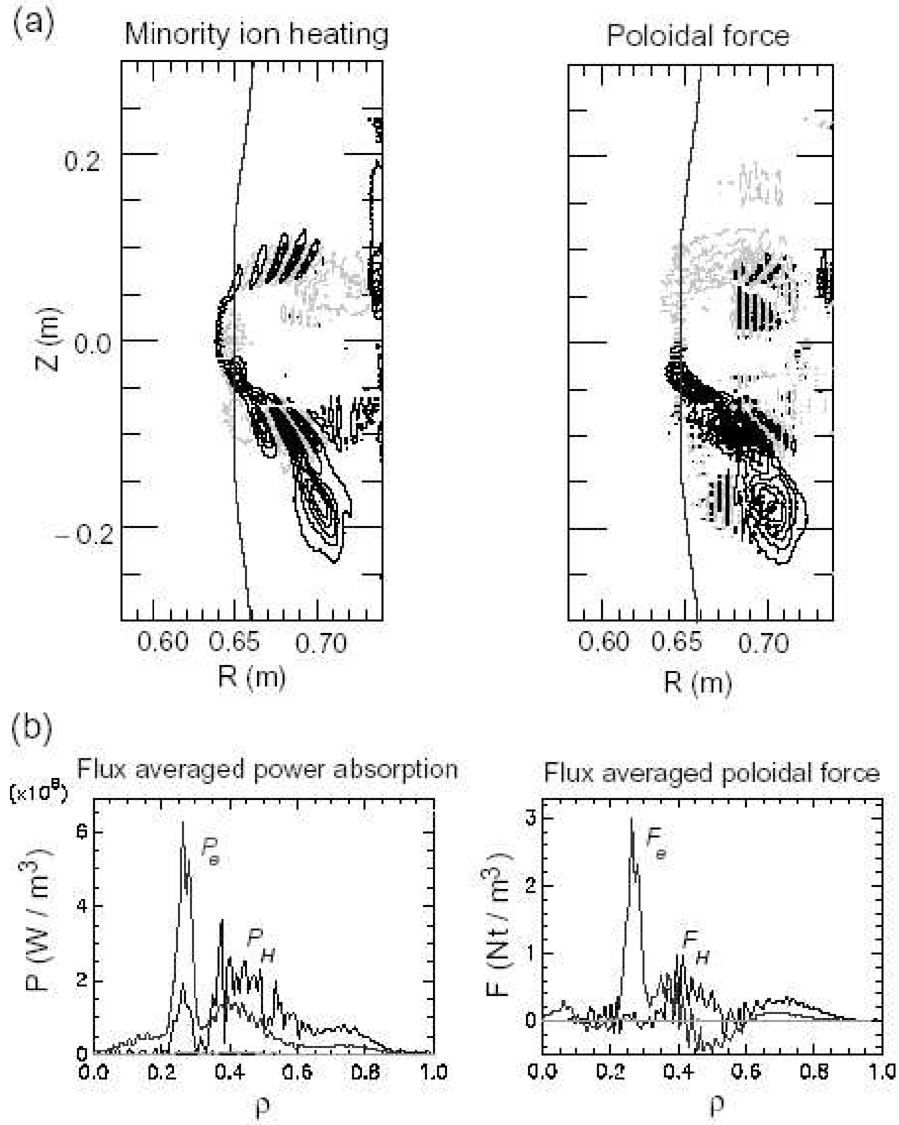
  then 25 years …
- seen directly in experiment [E. Nelson-Melby et al., PRL (2003)]
- seen in TORIC and AORSA simulations (2003)



(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

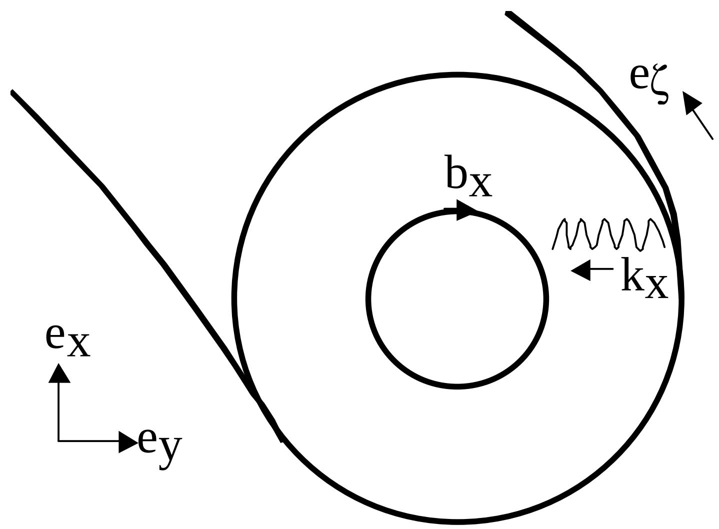
- net poloidal force follows heating profile
- additional sheared force contribution

1) photon absorption
2) photon reflection, reactive ponderomotive forces
3) momentum redistribution

$k_{||}$ upshifts by poloidal magnetic field are critical for:

- MC physics (Perkins 1977, Nelson-Melby 2003, Jaeger 2003)
- propagation of high k modes in general (Ram & Bers, 1991)
- flow drive (Jaeger 2003)

$$k_{||} = \mathbf{k} \cdot \mathbf{b} = k_x b_x + \underbrace{k_y b_y}_{\approx 0} + \frac{n}{R} b_\zeta$$



- $k_{||}$ upshift mechanisms:
  1) n fixed, R decreases
  2) $k_x b_x$ important for off-axis high k modes

- high $k_{||} \Rightarrow$
  - o strong i and e absorption ~ $Z(\omega/k_{||}v_e)$, $Z((\omega-\Omega)/k_{||}v_e)$
  - o strong $\nabla|E|^2$ and strong F
  - o strong flows with strong shear

Theory of RF Flow Drive

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 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 for rf fields
    - o simple high-freq. gyrokinetics (Lee, Catto, Myra, PF, 1983)

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

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

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

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

- linear order

$$\frac{df_k}{dt} = \frac{2f_M}{\alpha^2} e^{-i\delta_k}\mathbf{a}_k\cdot\mathbf{v}$$

- nonlinear (2nd) order

$$\frac{df^{(2)}_{k''}}{dt} = -\nabla_v \cdot \left(\sum_k \mathbf{a}_k^* f_{k+k''} e^{i\delta_k}\right)$$

Energy moment

local power absorption

$$\dot{w} = \frac{\partial}{\partial t}\int d^3v\, \frac{1}{2} m v^2 f^{(2)}.$$

use Vlasov to get ∂f/∂t

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

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

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

familiar Bessel sums, Z-functions …

Note

- the local power absorption is *not* ½Re J·E = ½Re $E_k \sigma(k) \cdot E_{k'}$
    - ½Re J·E is not positive definite unless
        - only one k is present OR
        - σ is independent of k (cold fluid limit)

Momentum moment

$$\frac{\partial}{\partial t}(nm\mathbf{u}) + \nabla\cdot(nm\mathbf{uu}) + \nabla p = \frac{1}{c}\mathbf{J}\times\mathbf{B} + \mathbf{F}_{tran} + \mathbf{F}$$

u = fluid velocity
nm = mass density
$\mathbf{F}_{tran}$ = transport related forces (friction, viscosity, momentum diffusion)
F = all explicit $|E|^2$ terms

$$\mathbf{F} \equiv \mathbf{F}_L - \nabla\cdot\Pi$$

Contributions arise from Lorentz force (fluctuating n, E, J, B)

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

and from nonlinear stress tensor

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

Using Maxwell's equations

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

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

- D has to be evaluated to first order in ρ_i/L ☹
- J or D is readily available in rf codes

Nonlinear stress tensor

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

Notes:

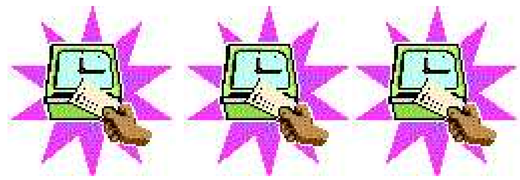
- Π generalizes Reynolds stress
- appears to requires gyrophase-dependent part of $f^{(2)}$
- gyrophase-average $f^{(2)}$ gives rise to diagonal (CGL type) pressure terms
  - o don't contribute to flow drive
  - o are secular unless heat sink is specified

$$\overleftrightarrow{M} = \int d\phi\left(\mathbf{vv}-\left\langle\mathbf{vv}\right\rangle\right)$$

$$= \frac{1}{4}\left(\mathbf{v}_\perp\,\mathbf{v}\times\mathbf{b} + \mathbf{v}\times\mathbf{b}\ \mathbf{v}_\perp\right) + \left(\mathbf{v}_\parallel\,\mathbf{v}\times\mathbf{b} + \mathbf{v}\times\mathbf{b}\ \mathbf{v}_\parallel\right)$$

- parts integrate in ϕ
- use Vlasov
- parts integrate in ∇_v
- gives Π in terms of $\mathbf{a}_k\mathbf{E}_{k'}$
  - o don't need $f^{(2)}$ explicitly ☺

Then

 …

combine results for Lorentz force and nonlinear stress

some nice cancellations happen

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

  - 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

1) photon (direct wave-momentum) absorption
2) ~~photon reflection, reactive ponderomotive forces~~
3) momentum redistribution (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 $v_\perp$

Miscellaneous

Are rf-driven flows important for turbulence?

theoretical

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

- force calculation is solid
- flows require neoclassical theory
  - handwave poloidal flows from neoclassical viscosity for TFTR IBW case ⇒ rough agreement with observed flows
  - 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

Computational issues

- suppose E is to be evaluated using N modes

$$\mathbf{E} = \sum_{k} \mathbf{E}_k e^{i\mathbf{k}\cdot\mathbf{r}}$$

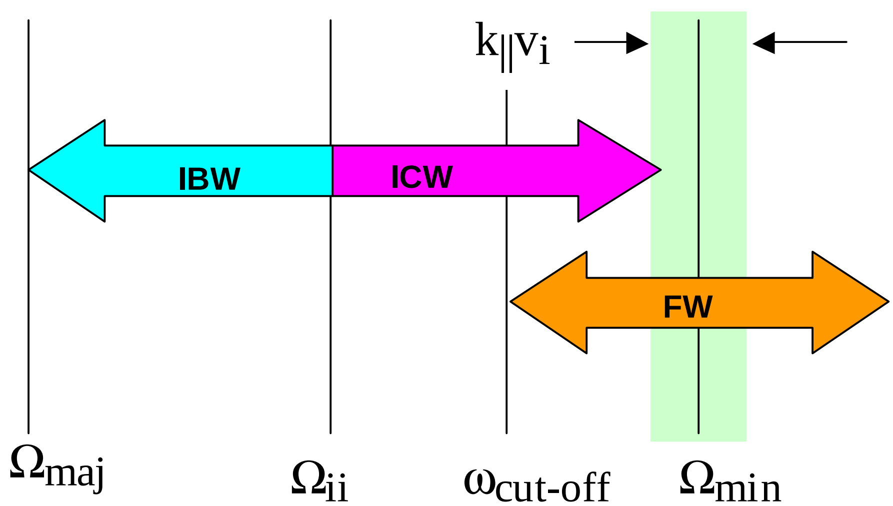
- wave equation solution requires an N×N matrix inversion
  - computational work is $O(N^2 \ln N)$
- now post-process solution to evaluate power absorption and flows

$$\dot{w}(\mathbf{r}) = \frac{1}{4} \sum_{k,k'} \mathbf{E}_k^* \cdot \overleftrightarrow{W}(\mathbf{k},\mathbf{k}';\mathbf{r}) \cdot \mathbf{E}_{k'}$$

  - N^2 terms in double sum at N grid points
  - computational work is $O(N^3)$
- post-processing takes longer than main code for field solve!
- extensive work in the rf SciDAC project has mitigated this problem (Ed D’Azevedo)
  - domain decomposition takes advantage of the fact that the fields at widely separated points are not coupled (use local Fourier decompositions and patch results together)
  - sub-sample W(**k**,**k′**) and take advantage of smoothness

RF driven flows: MC- ICW vs. minority tail ions

- minority tail ions absorb and transport momentum of wave
    - Perkins, Chan,
    - Chang
    - can drive toroidal rotation due to finite orbit effects, preferential absorption, preferential loss, …
- power into MC products vs. tail ions depends on minority fraction
    - reduced minority fraction moves Ω_{ii} and $\omega_{cut\text{-}off}$ into cyclotron resonance layer
    - fast wave resonantly interacts with fast ions $v \sim v_a >> v_i$



light μ/Z minority case

- future work: unified calculation of these two mechanisms using Monte-Carlo code

Summary & Conclusions

Considerable progress has been made on the rf part 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, 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, Nelson-Melby 2003)

flow drive results could not have happened without rf SciDAC: simulations, theory, algorithms all critical

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

- ready to integrate with neoclassical codes to get flows from forces
- open loop integrated rf and turbulence simulations may now be feasible
    - rf code ⇒ gives forces
    - neoclassical code ⇒ flows
    - turbulence simulations ⇒ transport reduction

(rf • neoclassical • turbulence) simulations ⇔ experiment

The results of an integrated effort in this area could be

interesting from a physics perspective

- deeper understanding of interaction of nonlinear forces, flows, and plasma response

important from a practical perspective

- give experiments a flexible knob for control of transport barriers