

Nonlinear radio-frequency generation of sheared flows

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Outline

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Introduction

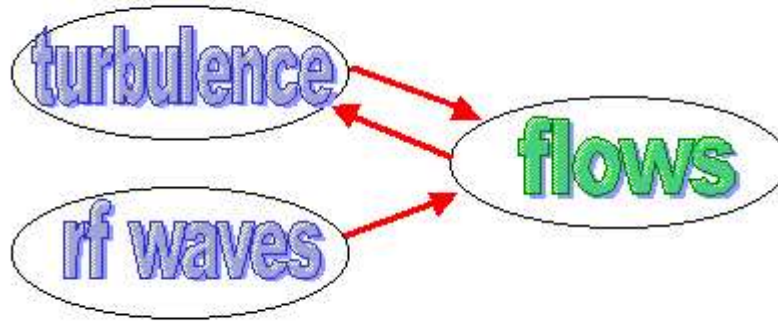
RF-driven sheared flows may be important

- 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
- $n\tau > (n\tau)_{\text{Lawson}}$ 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

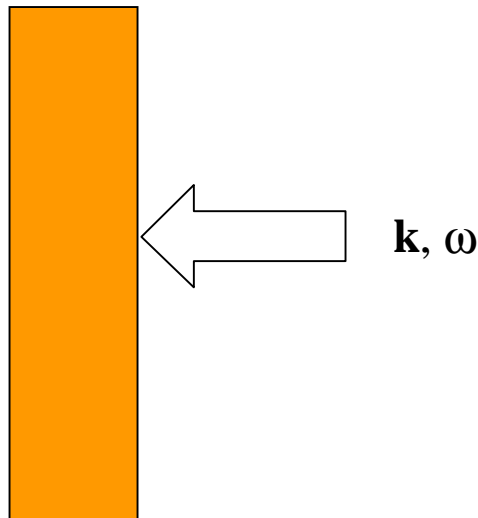
How can nonlinear waves drive flows?

Basic physics of waves, nonlinear forces, momentum transport

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

wave energy = $\omega N_{\mathbf{k}}$

wave momentum = $\mathbf{k} N_{\mathbf{k}}$



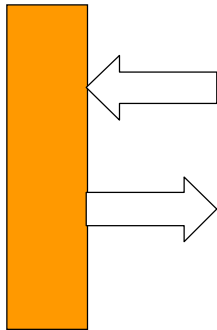
absorbed power $P_{\text{rf}} \Rightarrow$ force on absorbing medium

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

requires slow phase velocity (short wavelength) for good efficiency

Basic physics of waves, nonlinear forces, ...

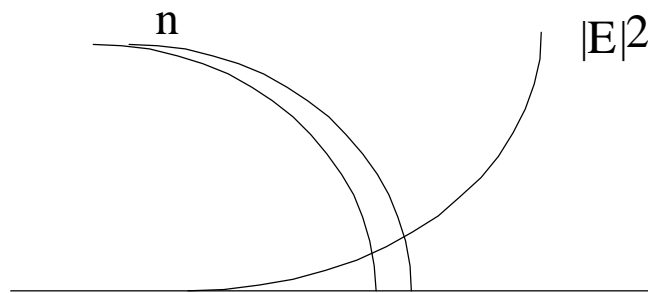
- 1) photon absorption
- 2) photon reflection, reactive ponderomotive forces
- 3) momentum redistribution



reflected power $P_{rf} \Rightarrow$ force on medium

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

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



internal energy \Leftarrow nonlinear stresses Π , (mechanical + field) $\sim \epsilon|E|^2$

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

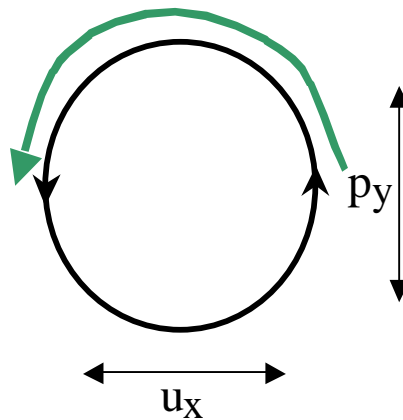
single particle ponderomotive potential $\Psi_p \sim \frac{|E_{\parallel}|^2}{\omega} + \frac{|E_R|^2}{\omega + \Omega} + \frac{|E_L|^2}{\omega - \Omega}$

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 \Rightarrow need dissipation

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

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

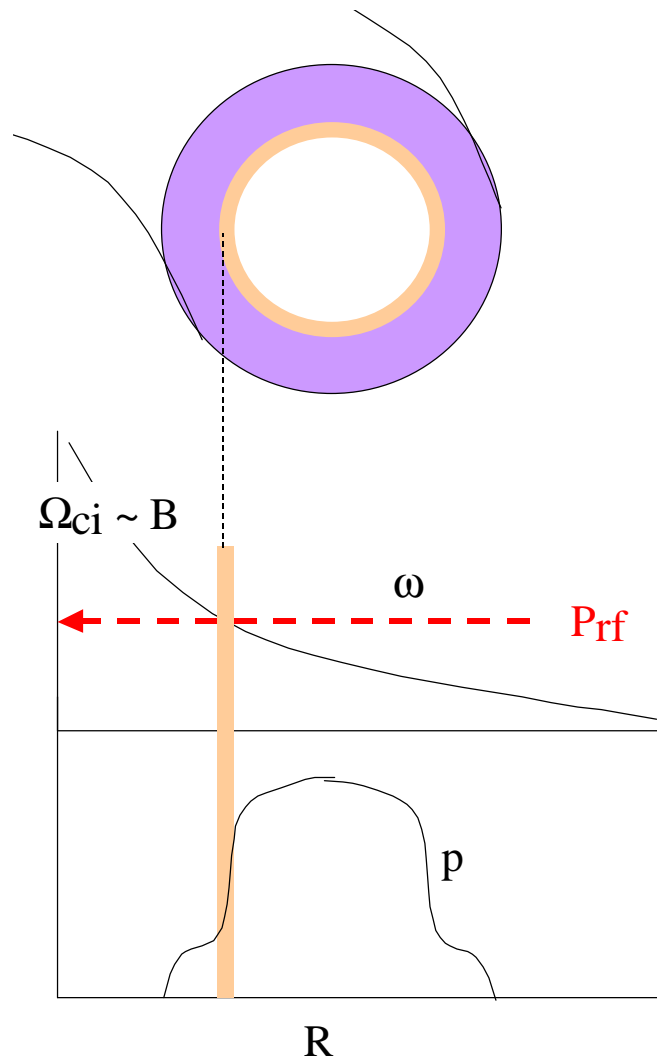
will turn out to be related to absorbed power

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

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

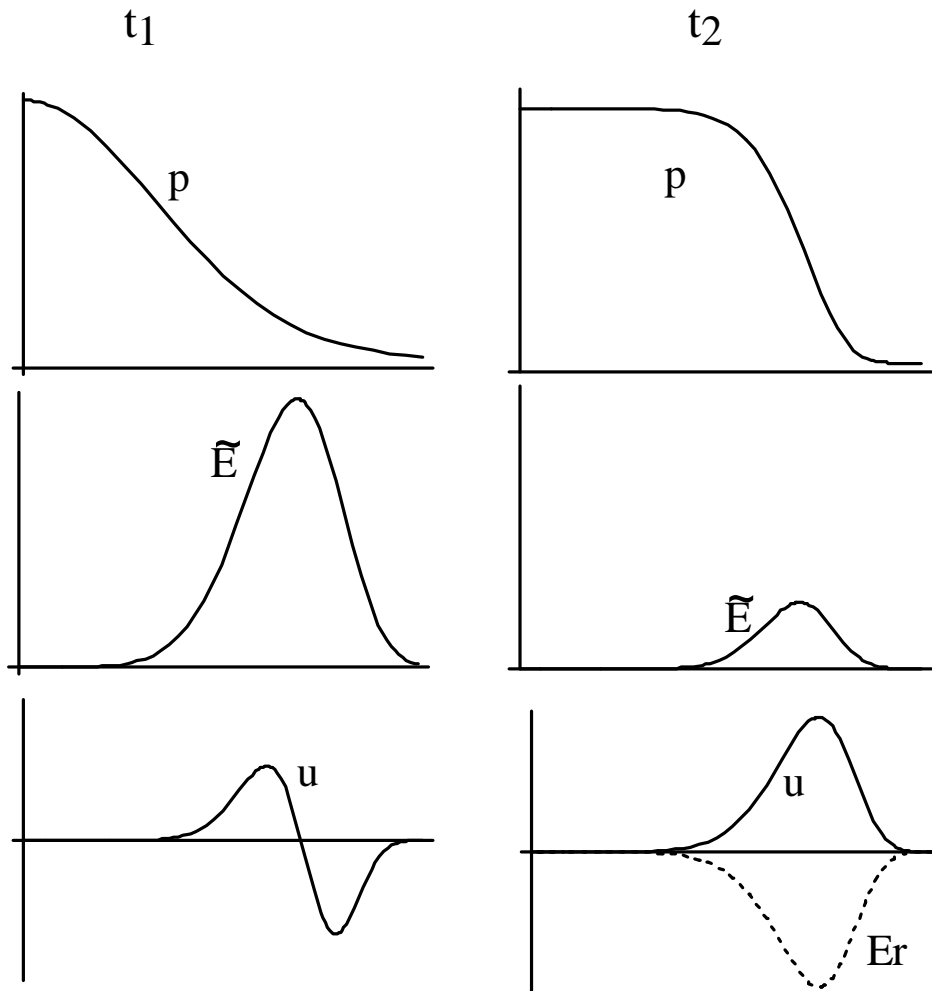
Basic physics: tokamak transport barriers and flows

- 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

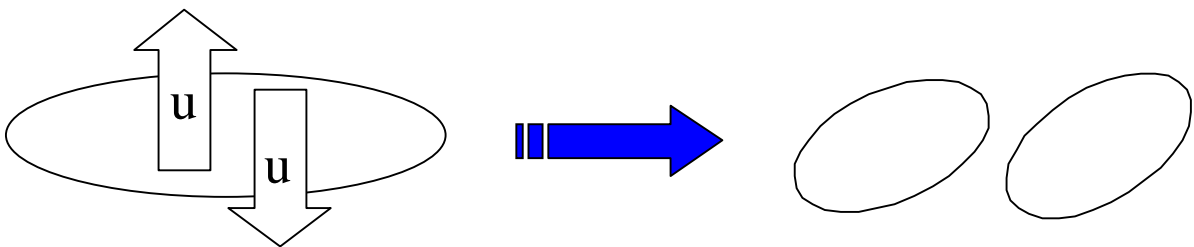


- vary location and P_{rf}
- modify p_e , p_i , \mathbf{u} , J_{\parallel} (nb: many rf mechanisms possible)

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



- sheared flows break up radially elongated eddies \Rightarrow 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): \Leftarrow 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

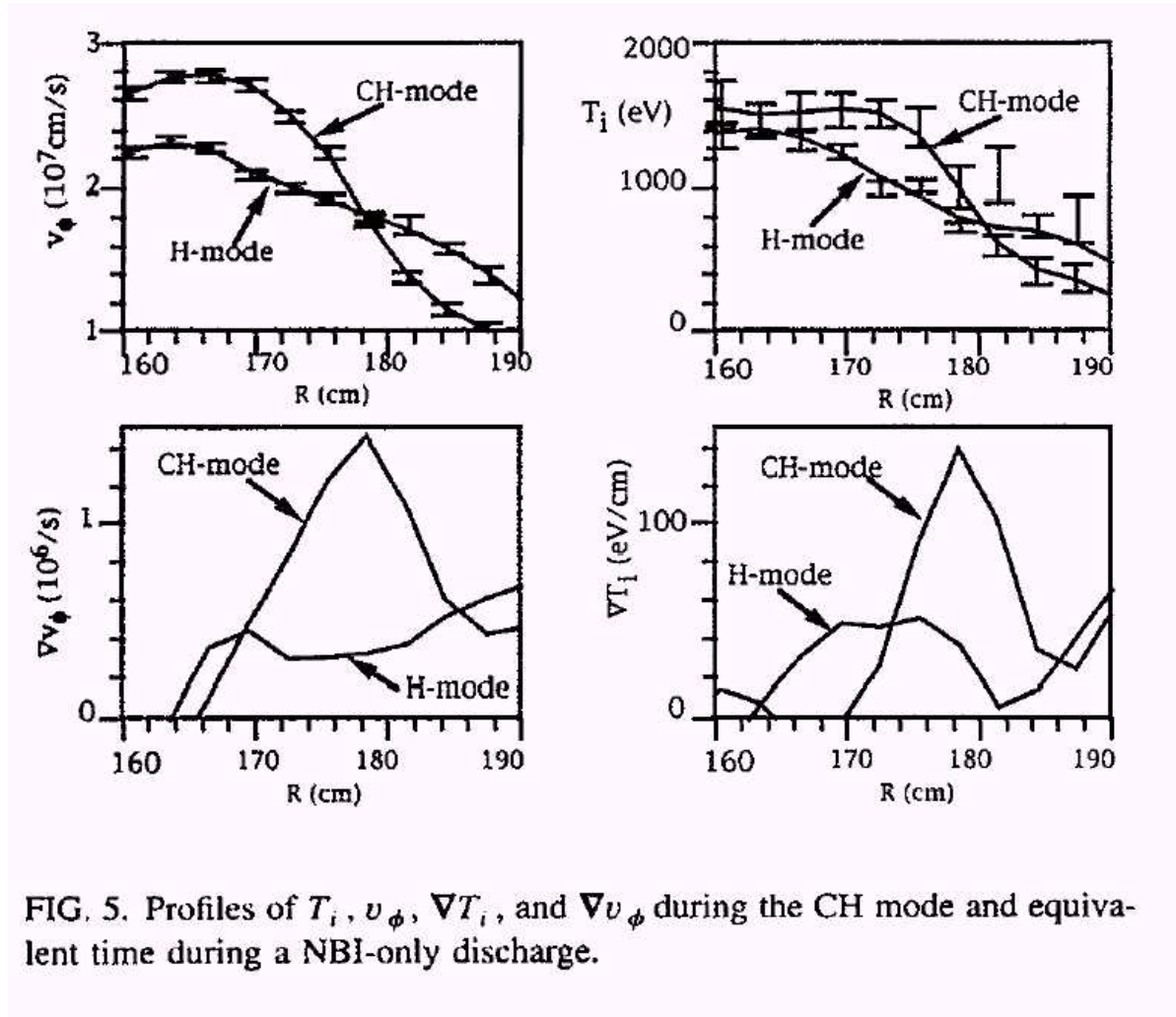
J.R. Wilson, et al., Phys. Plasmas **5**, 1721 (1998).

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)



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

TFTR experiment observed poloidal rotation driven by IBW

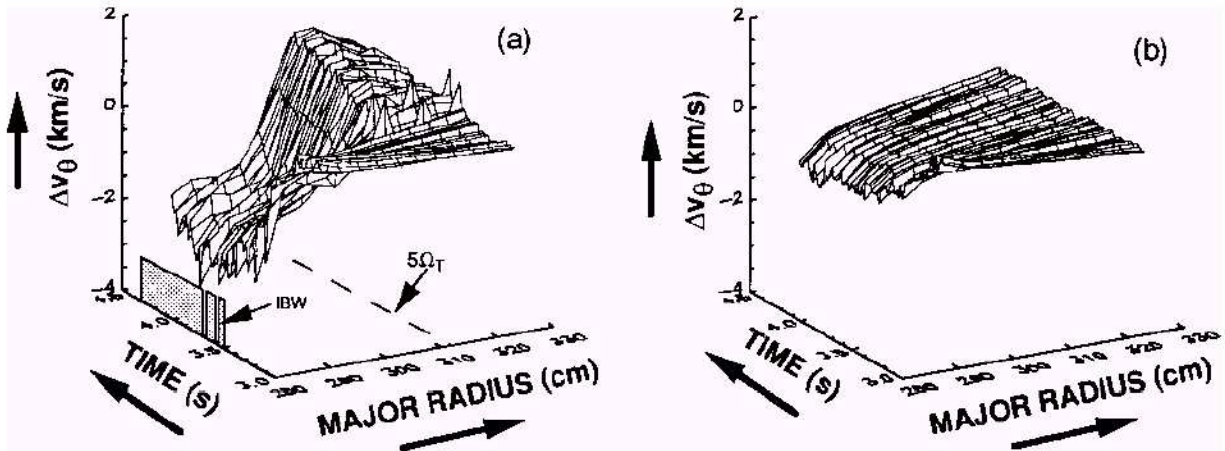


FIG. 9. A change in the poloidal rotation velocity as a function of radius and time. (a) IBW heating, $P=200$ kW, $f=76$ MHz, out-of-phase excitation, (b) no IBW power applied.

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

Experiments show :

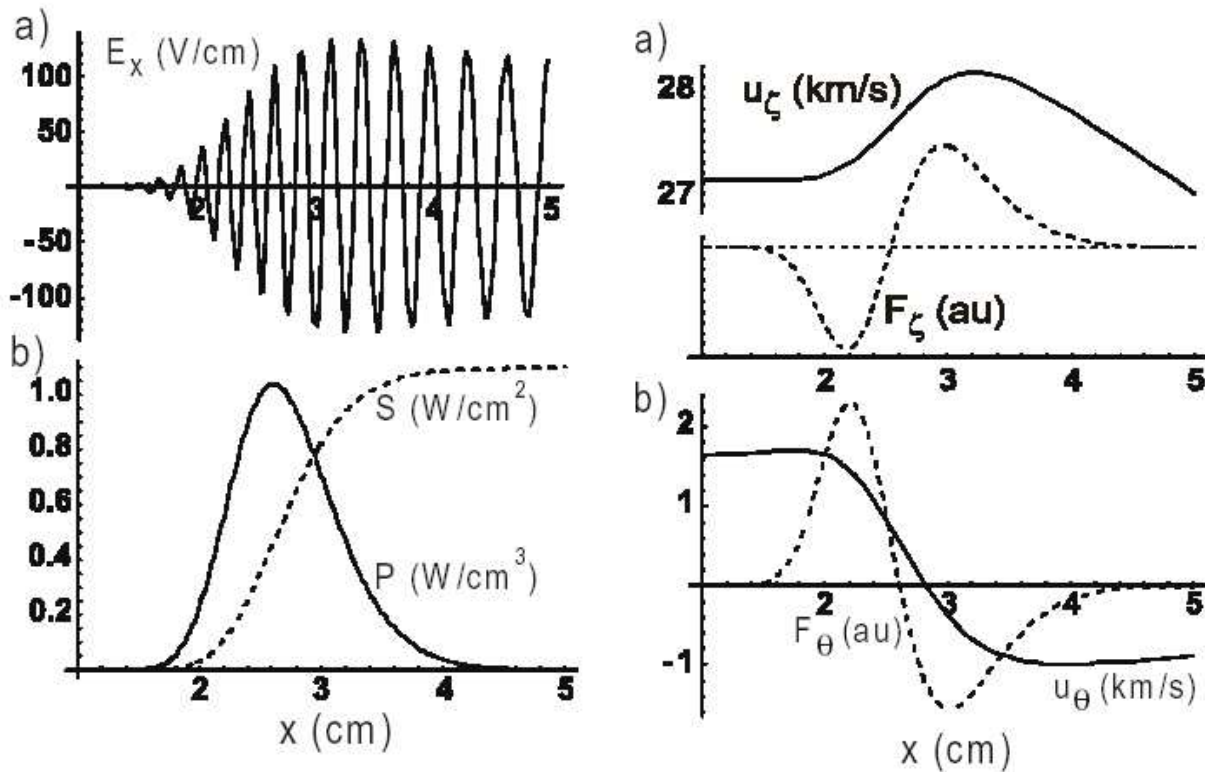
- IBW can drive flows
- IBW can somehow, sometimes, enhance confinement

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

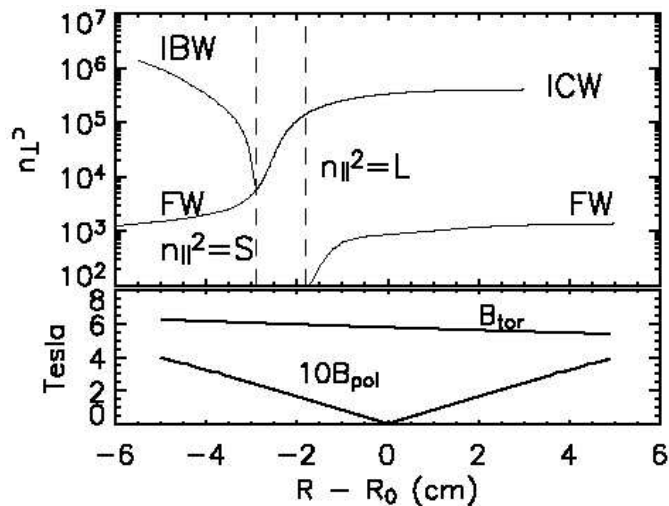
Would really like to launch fast Alfvén wave (macroscopic wavelength mode)

- 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}/ω)
 - 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.

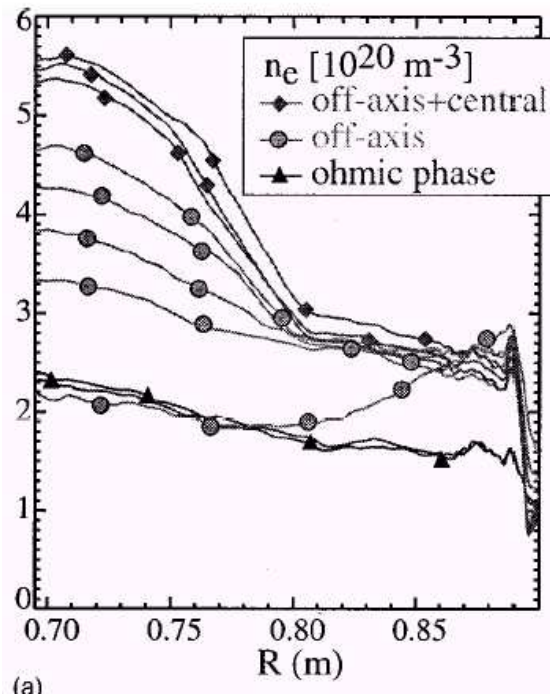
- *experiment*: E. Nelson-Melby et al., PRL (2003): mode conversion \Rightarrow
 - ion Bernstein wave (IBW)
 - ion cyclotron wave (ICW), propagates *into* Ω_i resonance



- *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

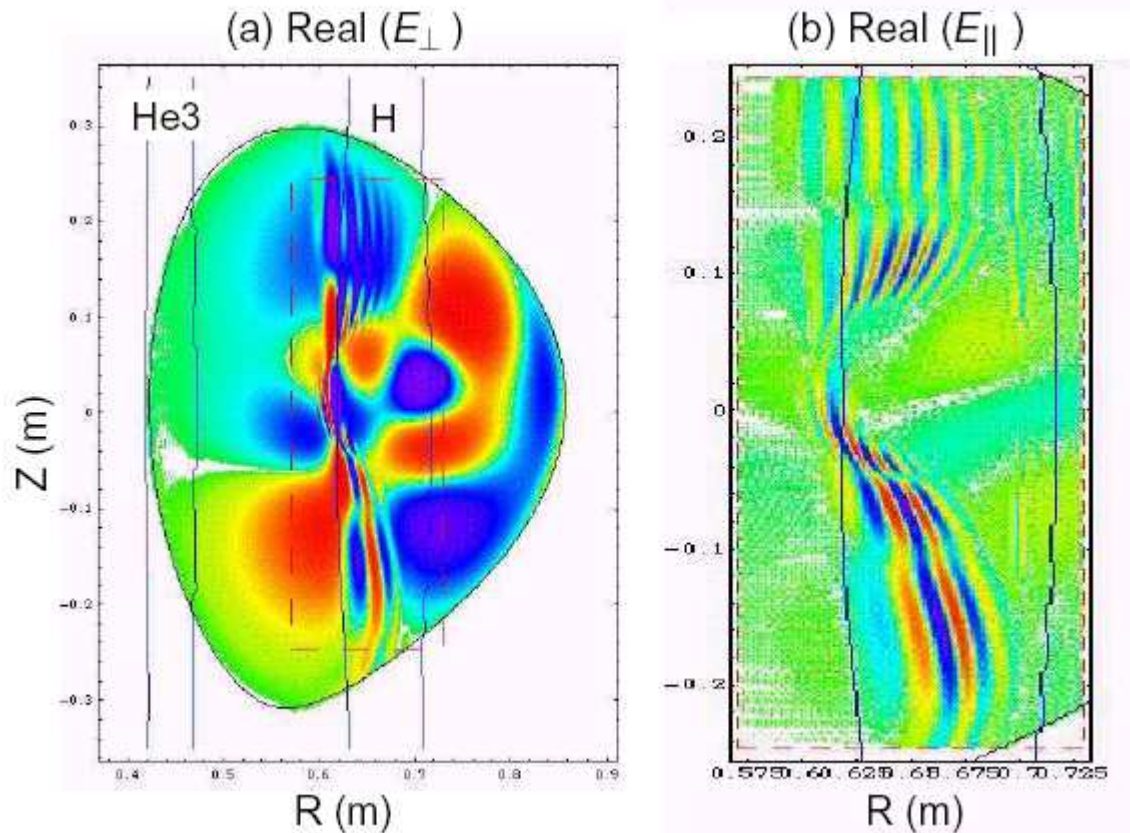
AORSA (Jaeger, Berry, Batchelor, et al.)

- 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 \Rightarrow do nonlinear calculations by post-processing

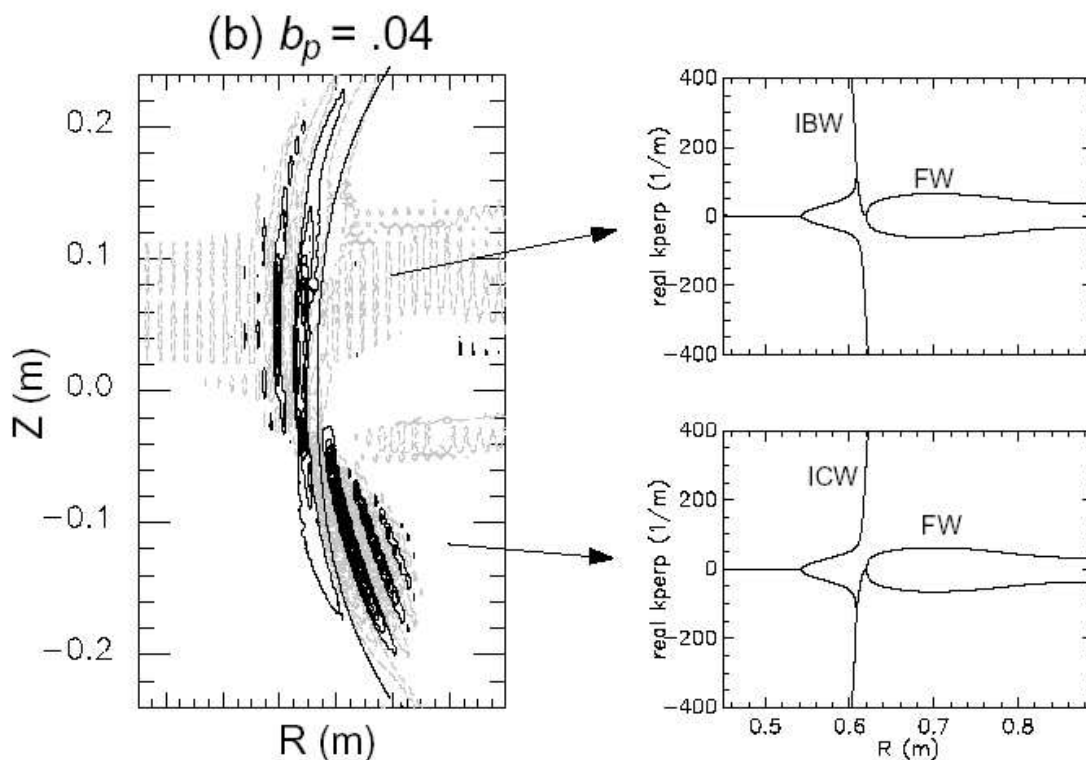
AORSA and TORIC have been used to simulate mode conversion in a torus



- 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

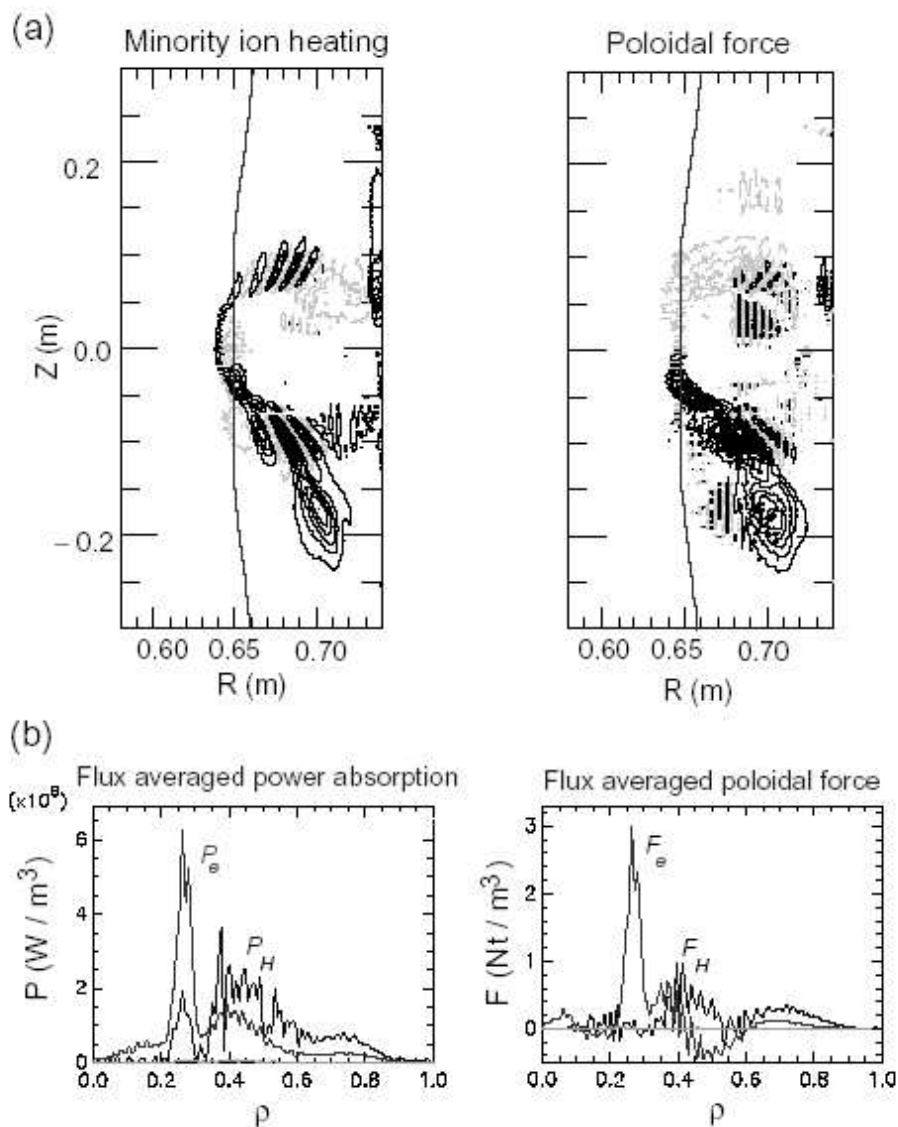
- predicted by Perkins (1977)
then 25 years ...
- seen directly in experiment [E. Nelson-Melby et al., PRL (2003)]
- seen in TORIC and AORSA simulations (2003)



(Jaeger et al., PRL, 2003)

- weak B_{θ} on axis \Rightarrow ion Bernstein wave (IBW)
 - propagates to smaller R
 - absorption is on electrons
- stronger B_{θ} off axis \Rightarrow ion cyclotron wave (ICW)
 - propagates to larger R (into cyclotron resonance)
 - 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

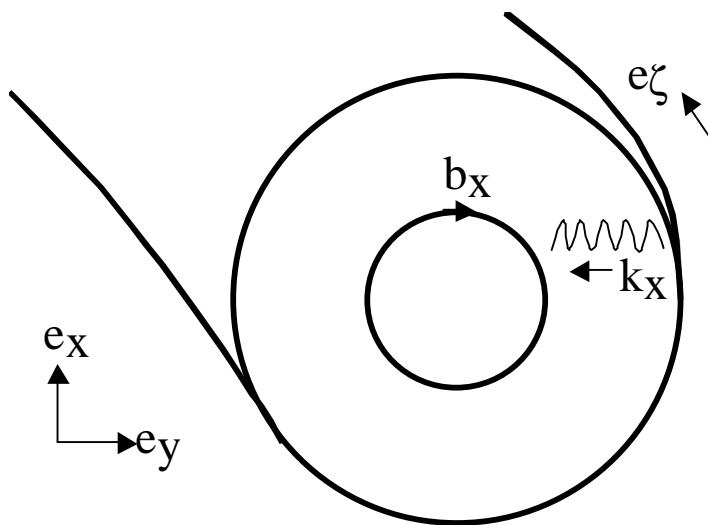
2) photon reflection, reactive ponderomotive forces

3) momentum redistribution

k_{\parallel} 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)

$$k_{\parallel} = \mathbf{k} \cdot \mathbf{b} = k_x b_x + k_y b_y + \frac{n}{R} b_{\zeta}$$



- k_{\parallel} upshift mechanisms:
 - 1) n fixed, R decreases
 - 2) $k_x b_x$ important for off-axis high k modes
- high $k_{\parallel} \Rightarrow$
 - strong i and e absorption $\sim Z(\omega/k_{\parallel}v_e)$, $Z((\omega-\Omega)/k_{\parallel}v_e)$
 - strong $\nabla|E|^2$ and strong F
 - 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
 - $k_{\perp}\rho \sim 1$, gyrokinetic theory (nonlocal)
 - $\omega \sim \Omega \gg \omega_{\text{drift}}$
 - nonlinear responses retain first order in ρ/L for rf fields
 - simple high-freq. gyrokinetics (Lee, Catto, Myra, PF, 1983)

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

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

$$\mathbf{a} = \frac{Ze}{m} \left[\tilde{\mathbf{I}} \left(1 - \frac{\mathbf{k} \cdot \mathbf{v}}{\omega} \right) + \frac{\mathbf{k}\mathbf{v}}{\omega} \right] \cdot \mathbf{E}_1 = \sum_{\mathbf{k}} \mathbf{a}_{\mathbf{k}} e^{i\mathbf{k} \cdot \mathbf{R} - i\delta_{\mathbf{k}}}$$

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

- linear order

$$\frac{df_{\mathbf{k}}}{dt} = \frac{2f_{\text{M}}}{\alpha^2} e^{-i\delta_{\mathbf{k}}} \mathbf{a}_{\mathbf{k}} \cdot \mathbf{v}$$

- nonlinear (2nd) order

$$\frac{df_{\mathbf{k}''}^{(2)}}{dt} = -\nabla_{\mathbf{v}} \cdot \left(\sum_{\mathbf{k}} \mathbf{a}_{\mathbf{k}}^* f_{\mathbf{k}+\mathbf{k}''} e^{i\delta_{\mathbf{k}}} \right)$$

Energy moment

local power absorption

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

use Vlasov to get $\partial f / \partial t$

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

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

$$\vec{W}(\mathbf{k}, \mathbf{k}' \rightarrow \mathbf{k}) = \vec{\sigma}(\mathbf{k})$$

familiar Bessel sums, Z-functions ...

Note

- the local power absorption is *not* $\frac{1}{2} \text{Re } \mathbf{J} \cdot \mathbf{E} = \frac{1}{2} \text{Re } \mathbf{E}_{\mathbf{k}} \sigma(\mathbf{k}) \cdot \mathbf{E}_{\mathbf{k}'}$
 - $\frac{1}{2} \text{Re } \mathbf{J} \cdot \mathbf{E}$ is not positive definite unless
 - only one \mathbf{k} is present OR
 - σ is independent of \mathbf{k} (cold fluid limit)

Momentum moment

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

\mathbf{u} = fluid velocity

nm = mass density

\mathbf{F}_{tran} = transport related forces (friction, viscosity, momentum diffusion)

\mathbf{F} = all explicit $|\mathbf{E}|^2$ terms

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

Contributions arise from **Lorentz force** (fluctuating n , \mathbf{E} , \mathbf{J} , \mathbf{B})

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

and from **nonlinear stress tensor**

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

Using Maxwell's equations

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

where

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

- \mathbf{D} has to be evaluated to first order in ρ_i/L
- \mathbf{J} or \mathbf{D} is readily available in rf codes



Nonlinear stress tensor

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

Notes:

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

$$\begin{aligned} \vec{M} &= \int d\phi (\mathbf{v}\mathbf{v} - \langle \mathbf{v}\mathbf{v} \rangle) \\ &= \frac{1}{4} (\mathbf{v}_\perp \mathbf{v} \times \mathbf{b} + \mathbf{v} \times \mathbf{b} \mathbf{v}_\perp) + (\mathbf{v}_\parallel \mathbf{v} \times \mathbf{b} + \mathbf{v} \times \mathbf{b} \mathbf{v}_\parallel) \end{aligned}$$

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

Then



combine results for Lorentz force and nonlinear stress

some nice cancellations happen

The \perp force from \perp 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** $\sim W^H$ and a **reactive** term $\sim W^A$

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

The reactive term $X_r \sim$ **parallel torques** on the plasma,

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

The term $X_d \sim$ **perpendicular dissipation**.

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

A more general result is also available

\perp and \parallel forces from \perp and \parallel 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
 - \mathbf{u} = fluid velocity
 - add back CGL terms



- agrees with standard ponderomotive force
 - ψ_p = ponderomotive potential
 - \mathbf{M} = ponderomotive magnetization

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

Reactive ponderomotive forces drive no avg. flows

- $\langle \dots \rangle =$ flux-surface average
- **toroidal** rotation is driven by torque $\langle \mathbf{R} \mathbf{F}_\zeta \rangle$
- **poloidal** rotation is driven by a combination of $\langle \mathbf{B} \mathbf{F}_\parallel \rangle$ and $\langle \mathbf{R} \mathbf{F}_\zeta \rangle$
- identities

$$\langle \nabla \cdot \mathbf{A} \rangle = \frac{1}{v} \frac{\partial}{\partial \psi} v \langle \mathbf{R} \mathbf{B}_\theta \mathbf{A}_\psi \rangle$$

$$\langle \mathbf{B} \nabla_\parallel \mathbf{Q} \rangle = \frac{1}{v} \int d\theta \int \frac{d\zeta}{2\pi} \frac{\mathbf{J} \mathbf{B}_\zeta}{R} \frac{\partial \mathbf{Q}}{\partial \zeta} = 0$$

- $\Rightarrow \langle \mathbf{B} \mathbf{F}_\parallel \rangle$ vanishes when $\mathbf{F}_\parallel = \nabla_\parallel$ (scalar)

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

- $\Rightarrow \langle \mathbf{R} \mathbf{F}_\zeta \rangle$ vanishes when $\mathbf{\Pi}$ is a diagonal tensor
- ...

- can show that for cold-fluid ponderomotive force

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

$$\langle \mathbf{B} \mathbf{F}_\parallel \rangle = 0$$

$$\langle \mathbf{R} \mathbf{F}_\zeta \rangle = 0$$

Flux-surface-averaged flows are driven by

- 1) photon (direct wave-momentum) absorption
- 2) ~~photon reflection, reactive ponderomotive forces~~
- 3) momentum redistribution (dissipative stresses)

$$\mathbf{F}_{\text{dis}} = \mathbf{F}_{\text{d1}} + \mathbf{b} \times \nabla X_{\text{d}}$$

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

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

$$X_{\text{d}} = \frac{P_{\perp}}{2\Omega}$$

- where P_{\perp} is the power absorbed into v_{\perp}

Miscellaneous

Are rf-driven flows important for turbulence?

theoretical

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

- force calculation is solid
- flows require neoclassical theory
 - handwave poloidal flows from neoclassical viscosity for TFTR IBW case \Rightarrow 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 \mathbf{E} is to be evaluated using N modes

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

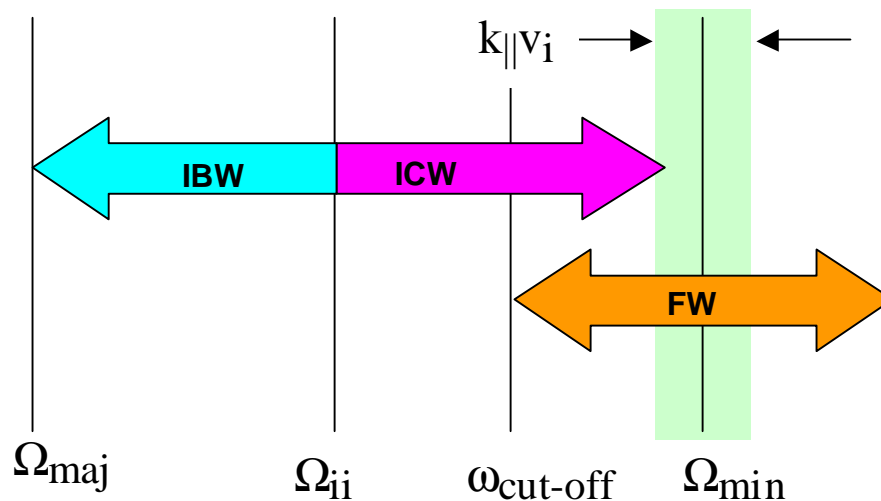
- wave equation solution requires an $N \times N$ matrix inversion
 - computational work is $O(N^2 \ln N)$
- now post-process solution to evaluate power absorption and flows

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

- 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 $W(\mathbf{k}, \mathbf{k}')$ 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 $\omega_{\text{cut-off}}$ into cyclotron resonance layer
 - fast wave resonantly interacts with fast ions $v \sim v_a \gg v_i$



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 \Rightarrow gives forces
 - neoclassical code \Rightarrow flows
 - turbulence simulations \Rightarrow transport reduction

(rf • neoclassical • turbulence) simulations \Leftrightarrow 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