Nonlinear ICRF-plasma Interactions

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When are nonlinear ICRF effects important?

- near the antenna where fields are large

- where the group velocity is slow $P = \mathbf{S} \cdot \mathbf{A} \propto v_g W \propto v_g |E|^2$
  - k is large, e.g. vs. $1/\xi$

- where the temperature is low $\psi_{pond} \sim T$, $eV_{rf} \sim T$

- where the nonlinear effects compete with other effects that are weak
  - flows in a flux surface

- on long time scales
  - transport evolution

Nonlinear ICRF tokamak physics topics

Edge

- **Antenna sheath interactions**
- **Wall/sheath interactions**
- **Parametric decay instability**
- **Ponderomotive forces**
- Arcing, breakdown, out-gassing

Core

- Quasilinear/Fokker Planck evolution: ion tails, electron CD
- Transport-time-scale RF/MHD
- Fast-ion-loss-induced rotation
- **E_r shear, sheared flow**

Goals

- physics insight
- experimental motivation
  - J.-M. Noterdaeme, 1991 (sheaths); Noterdaeme, Van Oost PPCF 1993
  - M. Ono, PoP 1993 (IBW)
- available modeling/analysis tools
- opportunities for new predictive capabilities

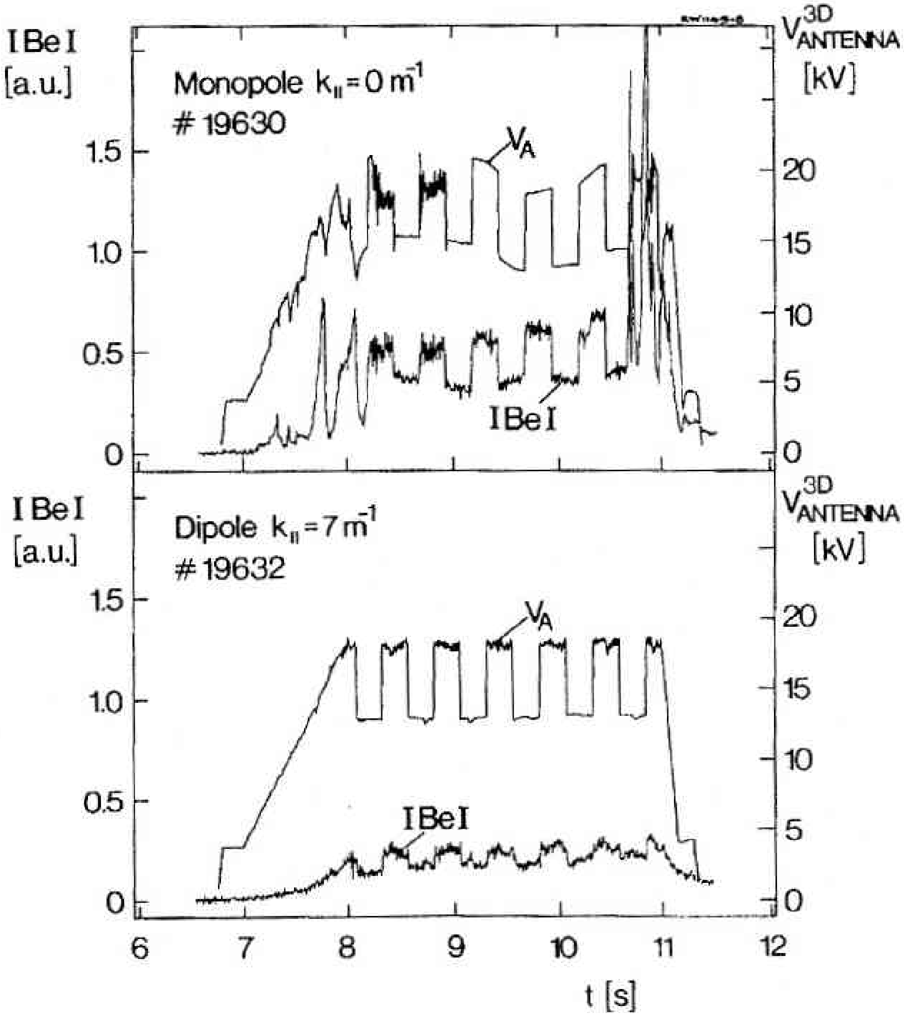
I. FW launch antenna/edge interactions: rf sheaths

II. IBW edge interactions

III. IBW/ICW core interactions: flow drive

IV. Integrated modeling: the new forefront

Edge interactions on ICRF experiments

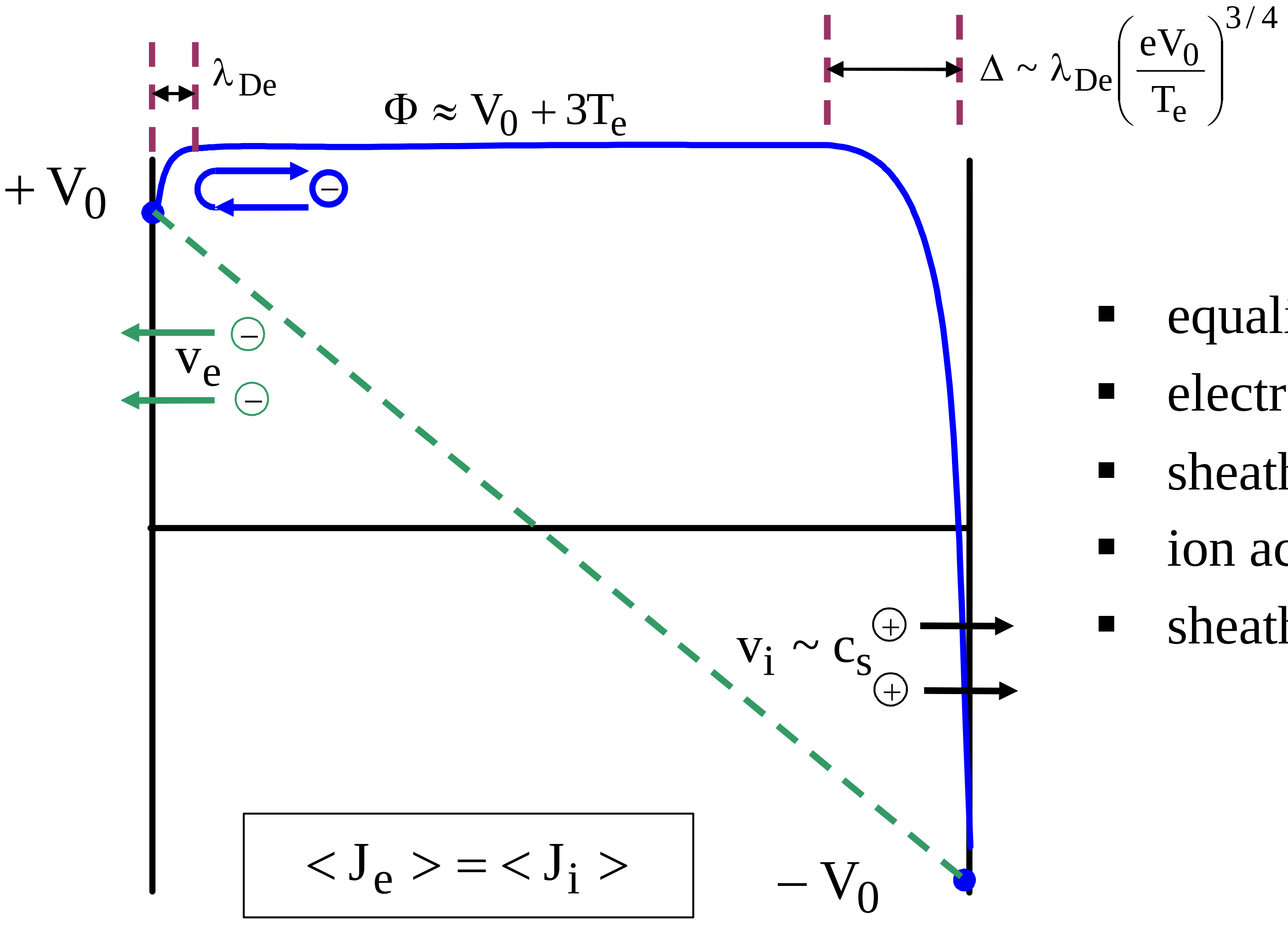


JET, Bures (1991)

- rf specific effects
  - impurities (RF-enhanced sputtering)
  - density rise
  - arcs and antenna damage
  - missing edge power
- implications for long-pulse operation (Tore Supra, LHD)

also ASDEX, PLT, TFR, JFT-2M, TEXTOR, TFTR …

Basic sheath physics

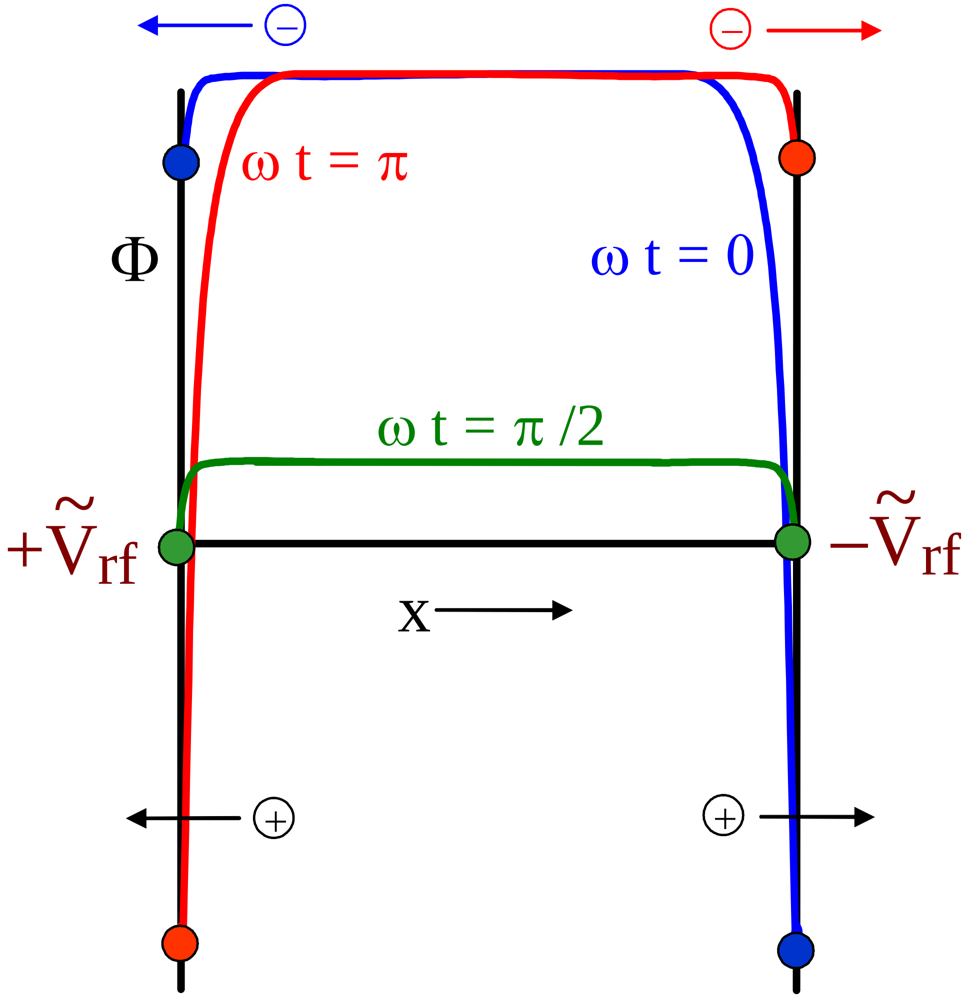


$$\langle J_e \rangle = \langle J_i \rangle$$

- equalize i and e loss rates
- electron confinement
- sheath width Δ
- ion acceleration
- sheath power

Physics of an ICRF sheath

- Butler 1963; Perkins; Chodura; Myra; Lieberman; *ca.* 1990
- Godyak, Hershowitz et al. (probes and plasma processing)



- rectification
- 2nd harmonic
- ions flow out at both ends ⇒
  - $P_{sh} \sim ZeV_{rf}\, n_e\, c_s$
- electrons leave when $V > 0$

  oscillating $J_{\|}$

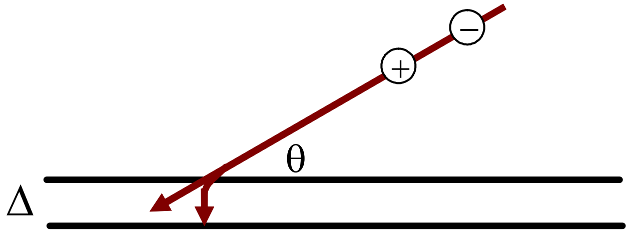
Bessel model

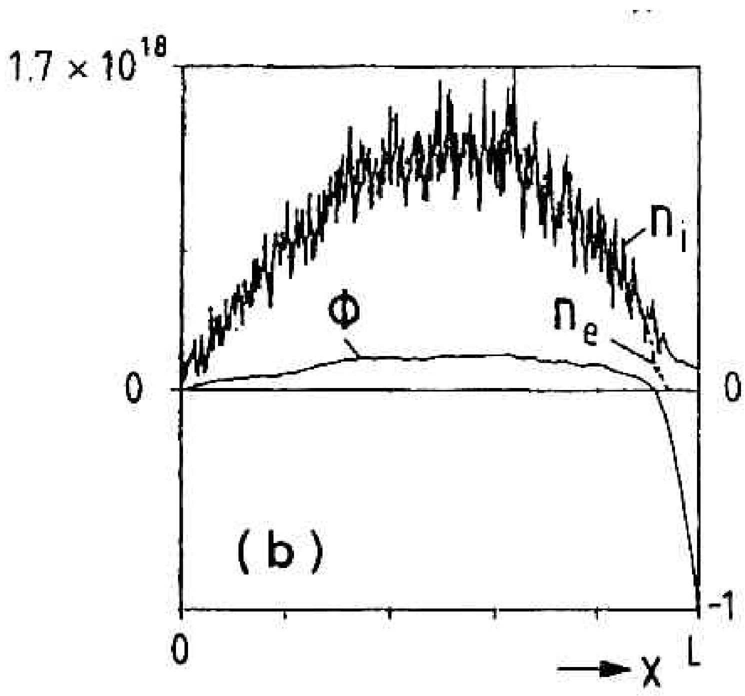
$$\langle J_e \rangle \sim -n_e e v_e \langle \exp(-eV_{rf} \sin \omega t / T_e) \rangle$$

$$\sim -n_e e v_e I_0(eV_{rf} / T_e)$$

Other considerations, sheath simulations

- field line angle
  - ion orbits
- surface physics
  - sputtering





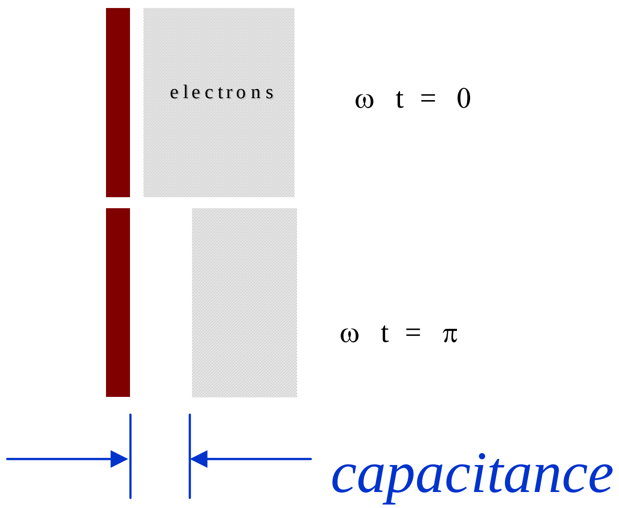
$\langle\Phi\rangle \sim V_{\text{rf sheath}}$

Brambilla, Chodura (1991)

also Perkins, NF (1989)

RF drives sheaths; sheaths modify rf fields

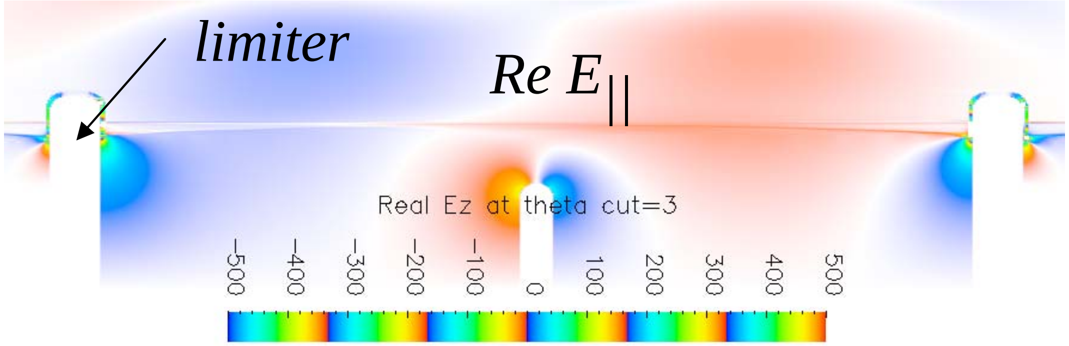
- gap model
    - Lieberman 1988
    - Jaeger 1995



- **n_e(r) competition:**
    - **coupling (evanescence)**
    - **sheath interaction**

e.g. Wukitch 2004

- vacuum gap model in rf codes



Carter, *this meeting*

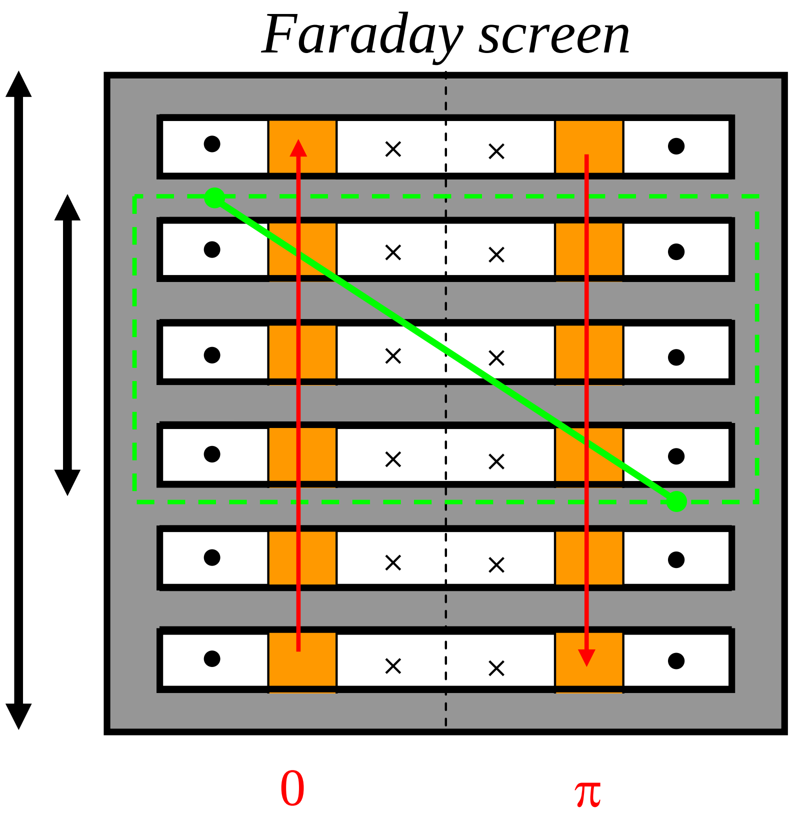
- sheath boundary condition
    - match analytically thin layer

$$\nabla_t \cdot E_t - \frac{\Delta}{\varepsilon_{nn}} \nabla_t^2 D_n = 0$$

$$B_n = 0$$

D’Ippolito, *this meeting*

Phasing and field-line angle dependence

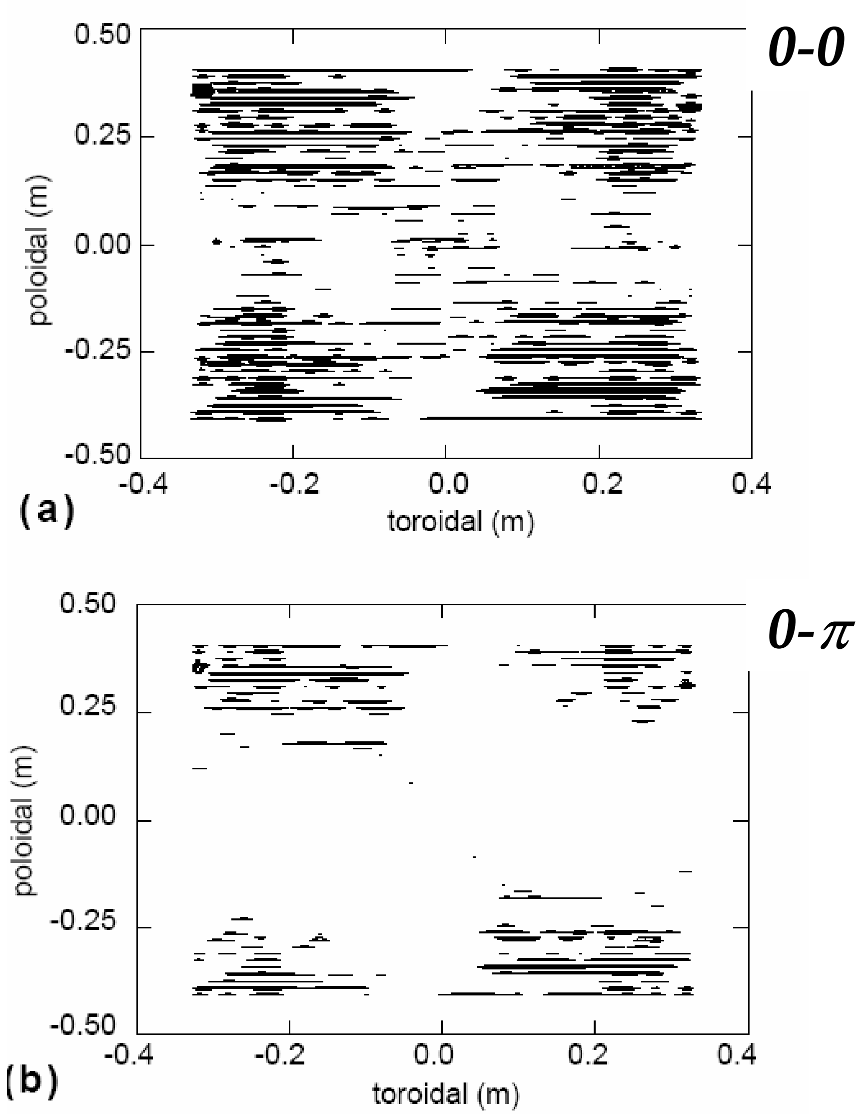


D’Ippolito (1991)
Bures (1991)

- sheaths at contact points
- FS sheath voltage large if:
  - large misalignment of B-field with Faraday Screen and/or
  - large component of B along current strap
  - non-symmetric low $k_{\|}$ phasings
- sheath control easier for heating than CD

Capacitive, corner and feeder effects also drive sheaths

high V points on the screen

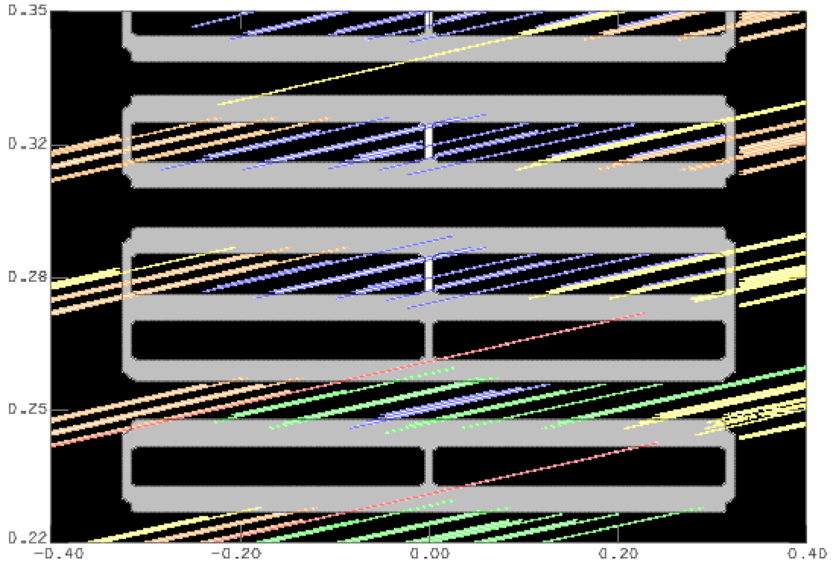


0-0

0-π

Myra (1996)

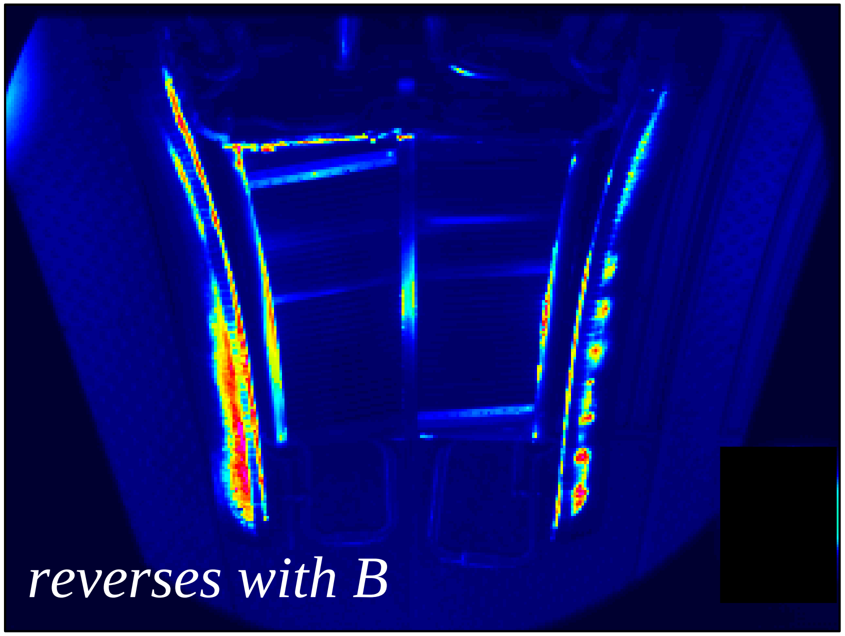
- ARGUS [Y.L. Ho]/ANSAT code vacuum field calculations
- shows $V_{sh} \sim \int ds\, E_{\|}$
- sheath voltage determined by field line connections



TFTR Bay-M (0-0)

RF-induced convection effects have been seen in experiments and modeled

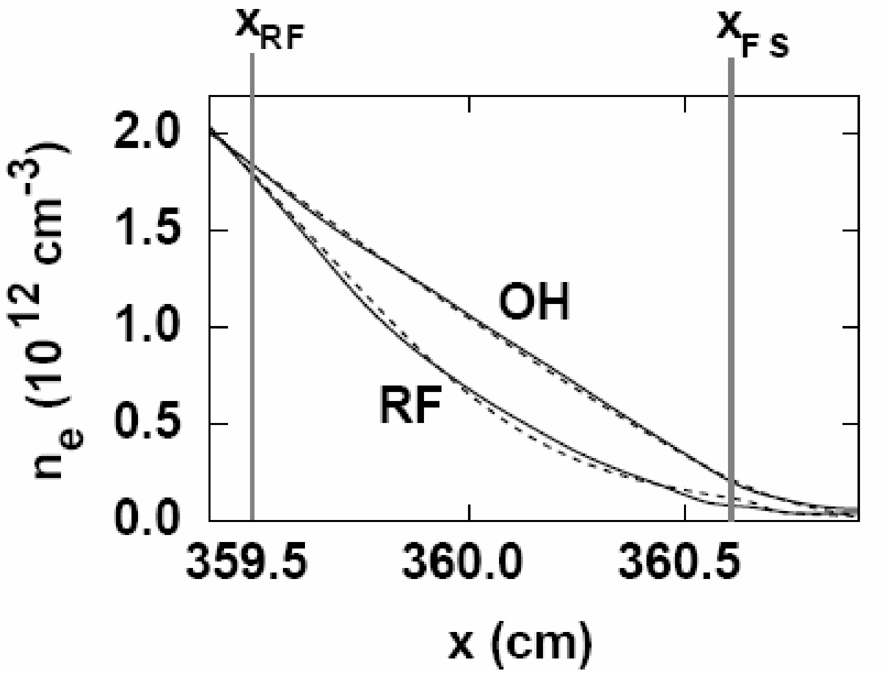
- up/down heat flux asymmetries modify fluxes into antenna
- modified n_e profile (TFTR)



Tore Supra, Colas *this meeting*

also Colas 2003
Faudot *this meeting*
Bécoulet 2002

JET: influence of rf convection on H-mode
D'Ippolito 1993

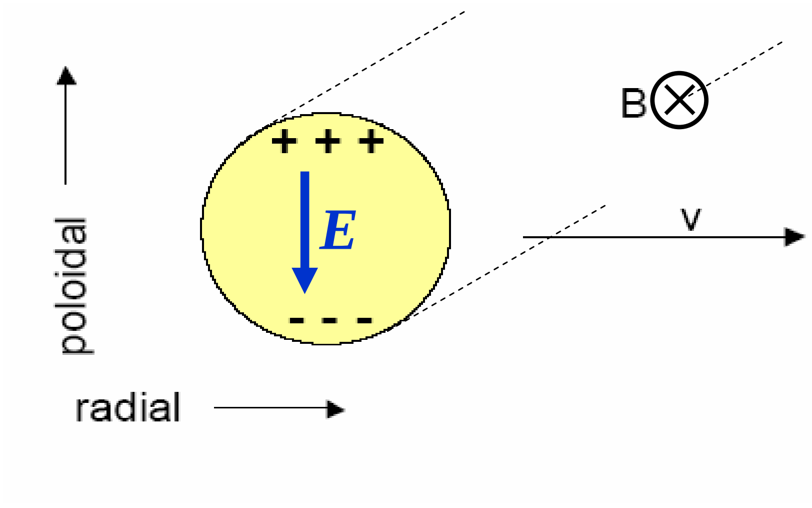


TFTR; D'Ippolito 1998
Wilgen

Time-averaged vorticity (charge-balance) equation

$$\frac{c^2}{4\pi v_a^2}\frac{d}{dt}\nabla_\perp^2\Phi = \nabla_{\|}J_{\|}(\Phi) + \frac{2c}{B}\mathbf{b}\times\kappa\cdot\nabla p$$

ion polarization   sheaths   curvature



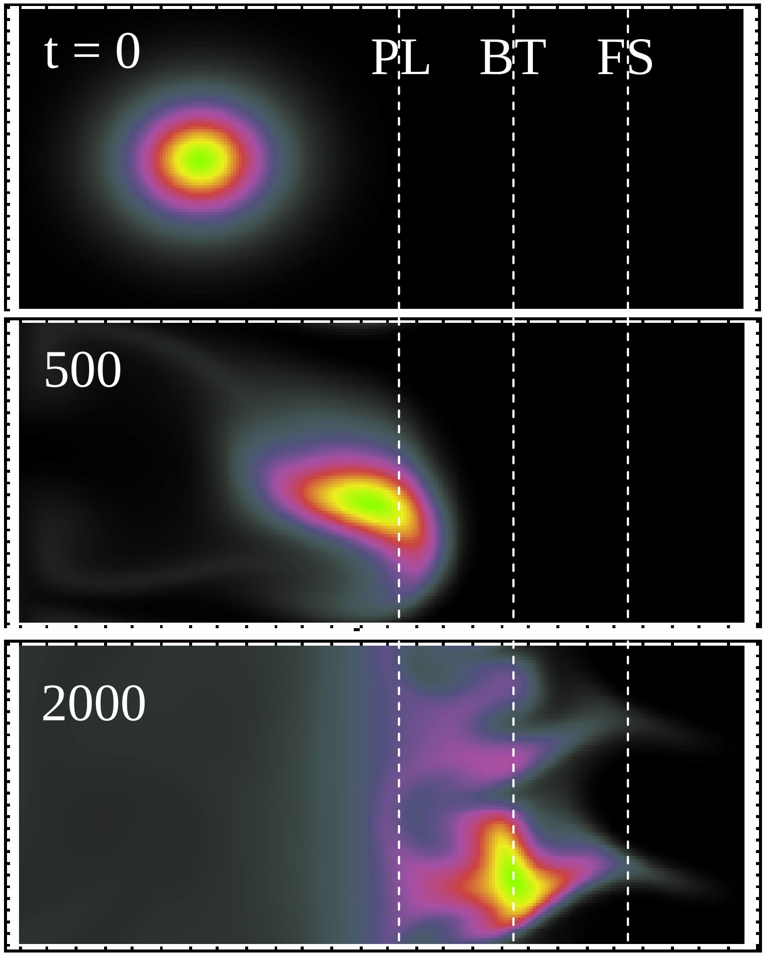
core   *antenna*

Krasheninnikov 2001, D’Ippolito 2002

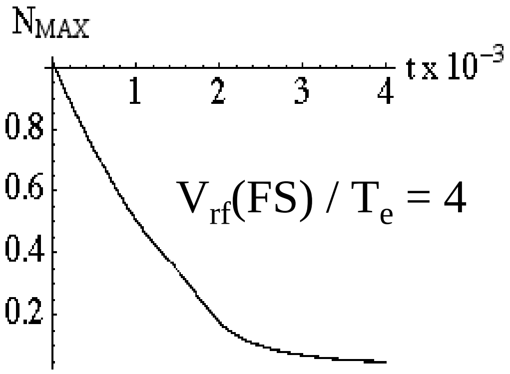
- $J_{\|sh} \sim I_0(eV_{rf}/T_e)$
- $J_{\perp pol}$ couples flux tubes
- curvature ⇒ edge turbulence
- edge instabilities eject “blob” filaments
- blobs convect towards antenna

Blobs from edge turbulence interact with antenna near-field sheaths

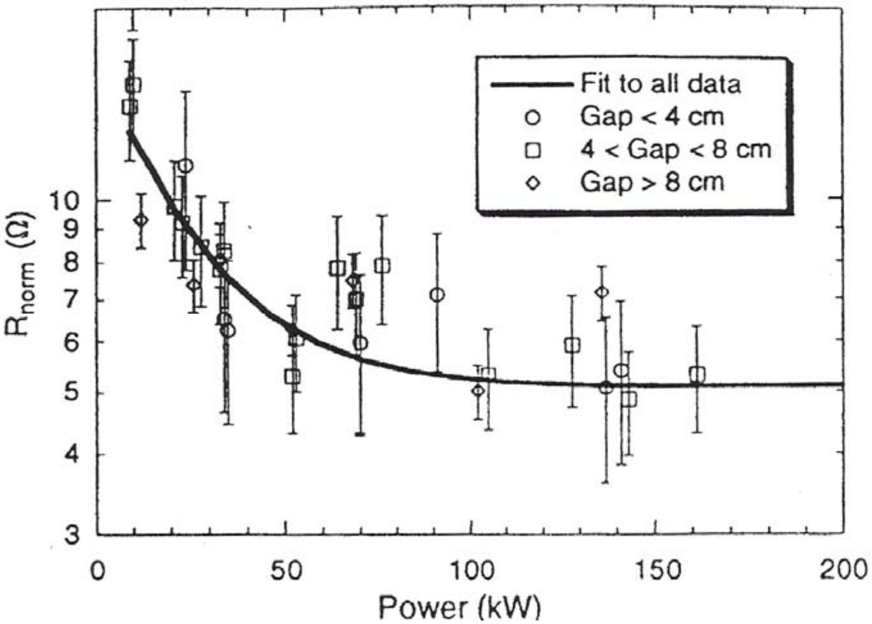
- 2D edge turbulence code with $\langle V_{sheath} \rangle$
- want self-consistent SOL n_e profile for
  - rf coupling
  - impurities, antenna damage, etc.



D'Ippolito, Russell *this meeting*

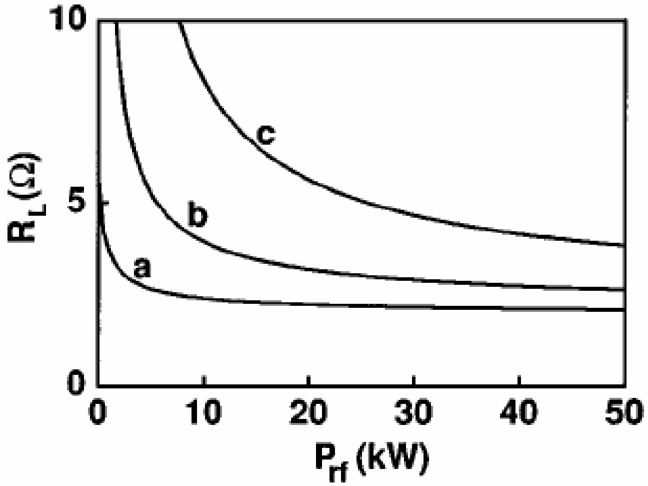


Low-power nonlinear loading is sheath dominated



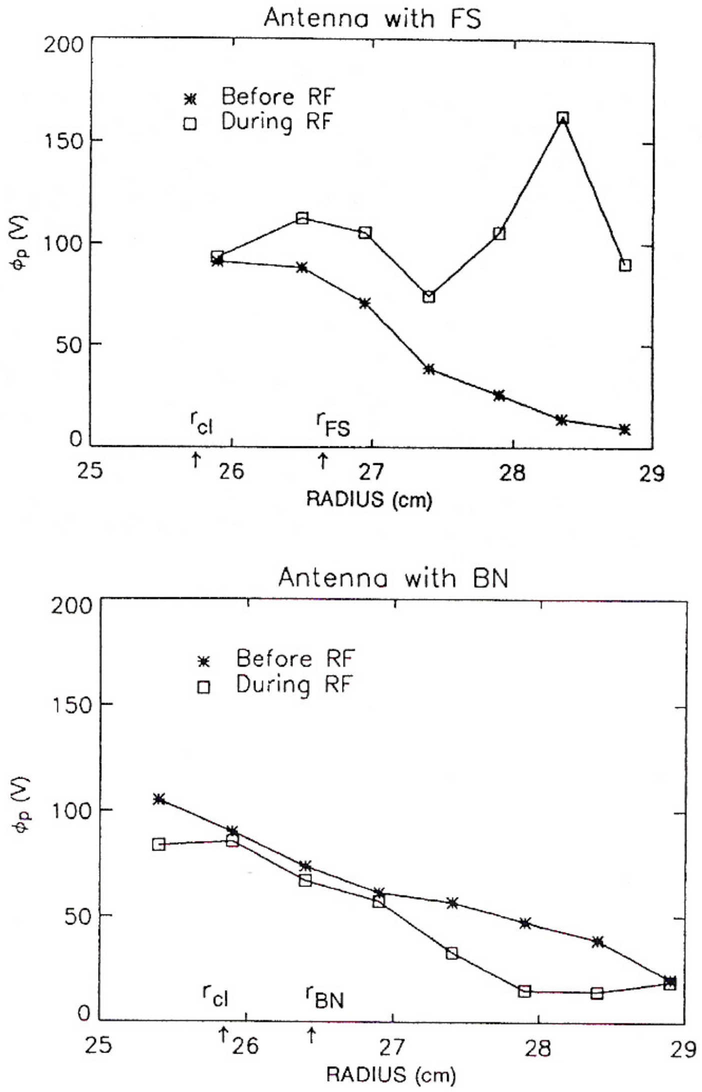
DIII-D Swain, Pinsker 1997

- loading resistance R ~ P/V^2
- linear loading: P ~V^2
  R ~ const
- sheath power dissipation
  $P_{sh} \sim ZeVn_0c_s \Rightarrow R_{sh} \sim 1/V$
- low power
  - ➢ diagnostics & code validation
- high power
  - ➢ small % into small volume



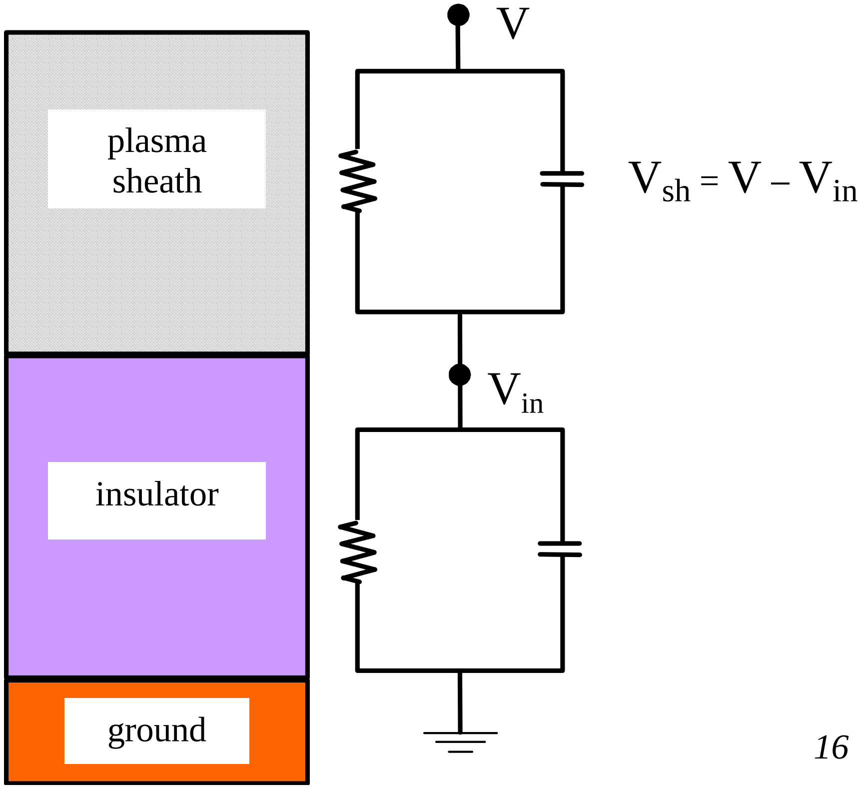
D'Ippolito 1996

Insulating limiters mitigate sheath formation



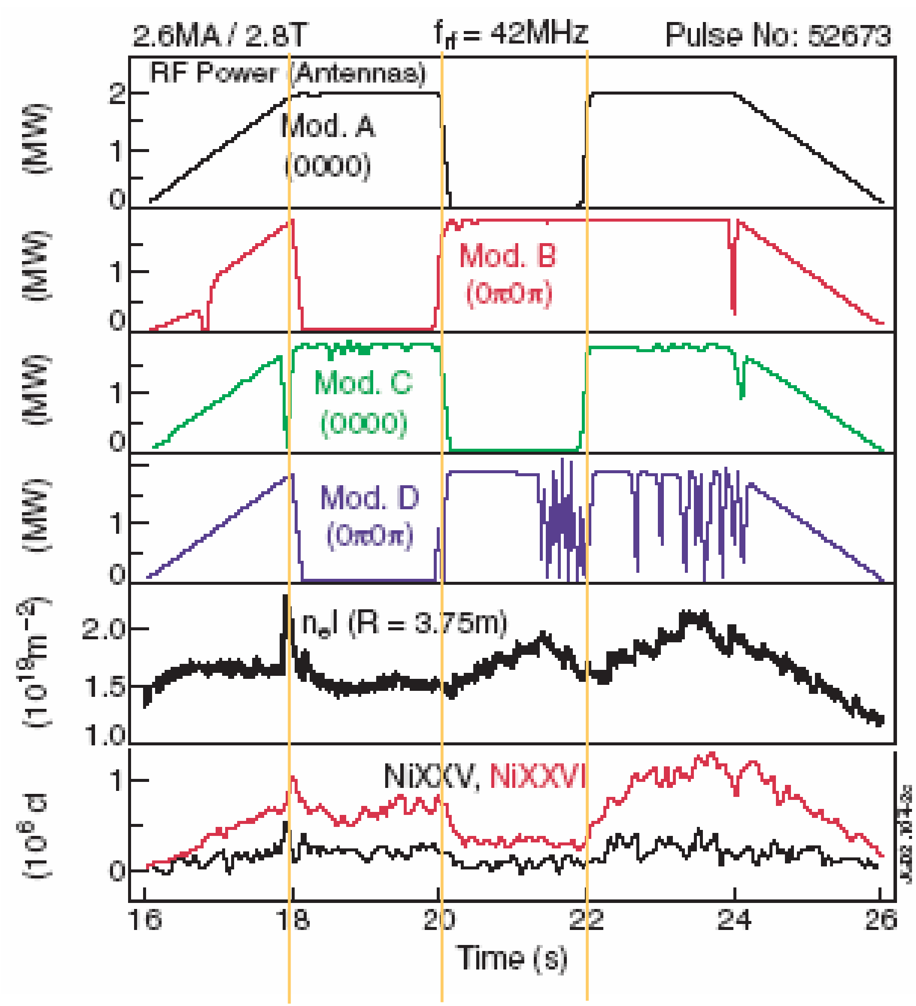
Phaedrus, Sorensen 1996

- Majeski 1994
- sheaths add capacitance and resistance
- high resistance insulator
  - ➢ drop voltage across insulator not plasma
- reactor–compatible materials?

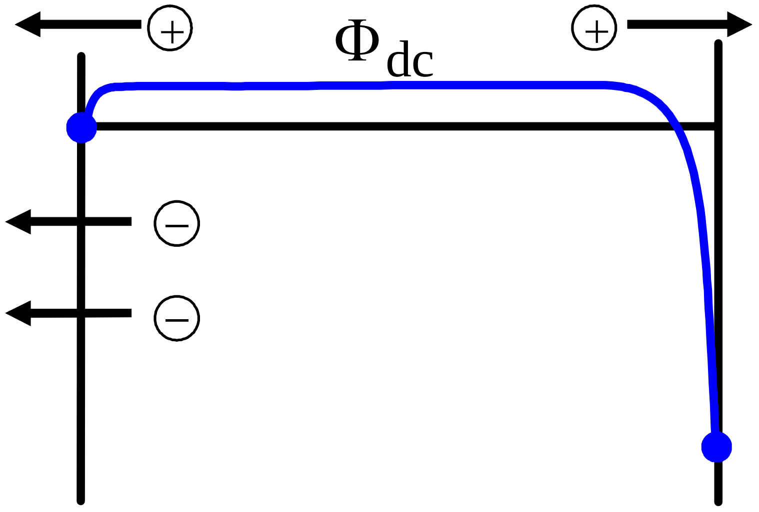


$V_{sh} = V - V_{in}$

Asymmetric sheaths drive parallel currents, and can trigger certain types of arcs

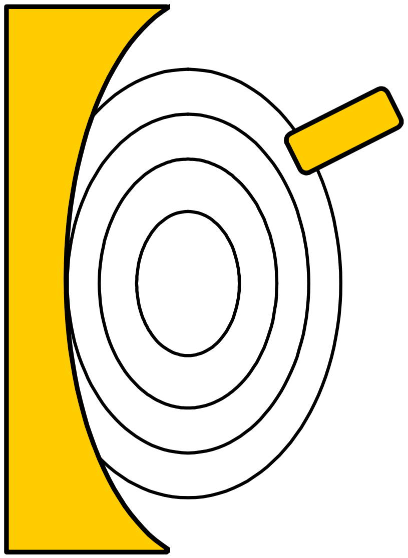


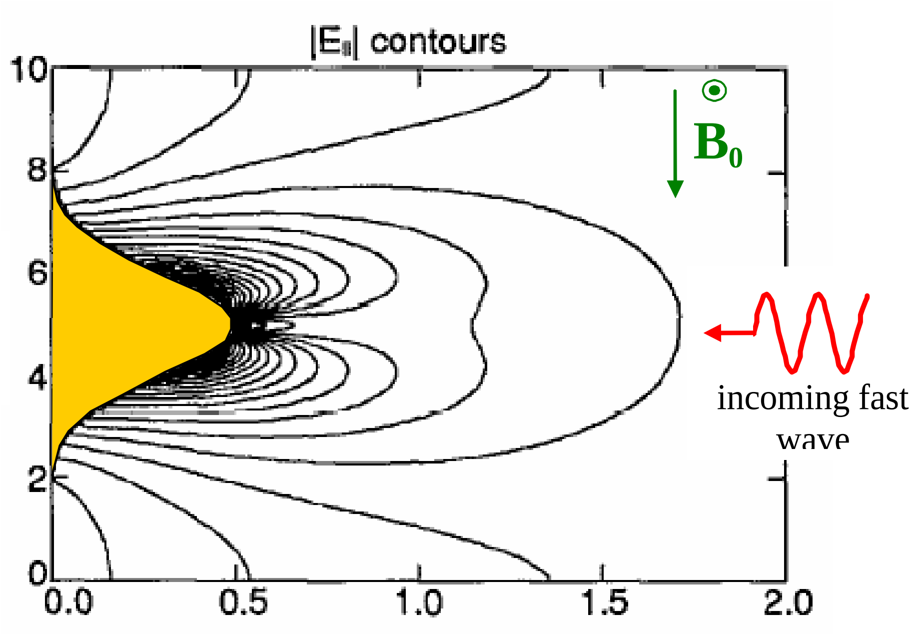
- studied on TEXTOR, Van-Nieuwenhove, Van Oost 1989
- different rectified voltages at each end of field line ⇒ dc $J_{||}$



JET (Heikkinen, Righi,Lamalle, Noterdaeme)   D'Ippolito, NF 2002

Far-field sheaths: dissipation of wave energy in the SOL





Myra, 1994

- JET, DIII-D, ASDEX
- Perkins 1989
- edge rf fields on walls/limiters
  - ➢ poor single pass, or
  - ➢ edge modes [Brambilla, 1991]
- flux surfaces and conduction boundaries not aligned
  - ➢ wave polarization $\Rightarrow E_{||}$
- $\int ds\ E_{||} \Rightarrow$ Vsheath
- edge power loss, Z_{imp}, …
- collisional
- low $k_{||}$ more susceptible
  - ➢ FW less evanescence
  - ➢ coaxial/surface modes

I. FW launch antenna/edge interactions: rf sheaths

II. IBW edge interactions

III. IBW/ICW core interactions: flow drive

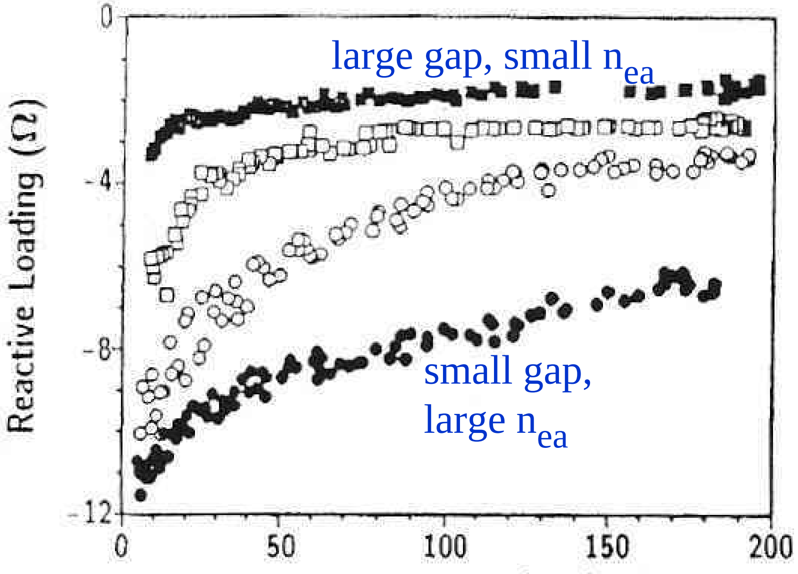
IV. Integrated modeling: the new forefront

The mystery of IBW coupling: mixed success

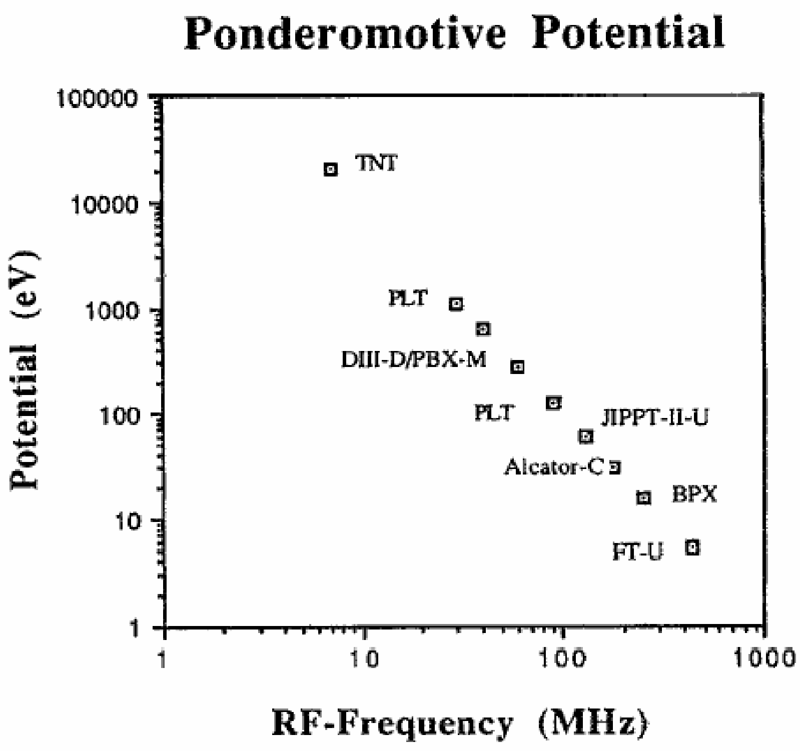
- IBW experiments:
  - PLT, PBX-M, TFTR, Alcator, FTU, DIII-D, JIPPT-II-U, HT-7
- coupling has met with mixed success:
  - generally better on small machines
  - conditioning important
- linear theory well studied [Ono 1993 review]
  - leaves many experiments unexplained
- small $v_g \sim v_i \Rightarrow$ nonlinear effects likely to matter
- IBW physics potentially of interest whenever $E_{||}$ is large
  - large pitch of B (I_p or B ramps, STs)

Ponderomotive expulsion is expected

$$\Psi_{\text{pond}} = \frac{e^2 E_\parallel^2}{4 m_e \omega^2} \sim \frac{1}{2} m_e \tilde{u}_\parallel^2 > T_e$$



DIII-D, Mayberry 1992



Ono 1993

- reactive loading vs. power and position similar => pond. expulsion

LH resonance, EPW, and co-axial modes

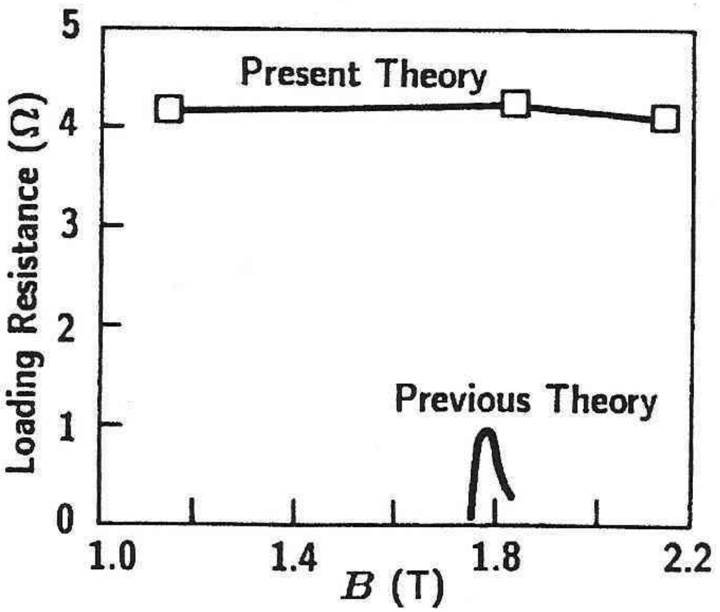
DIII-D, Mayberry, Pinsker 1993

- R_L large, insensitive to ω/Ω_i

also Alcator and others

TFTR, Rogers, Wilson 1998

- $R_L(0) > R_L(\pi)$
- heating efficiency: $\eta(\pi) > \eta(0)$



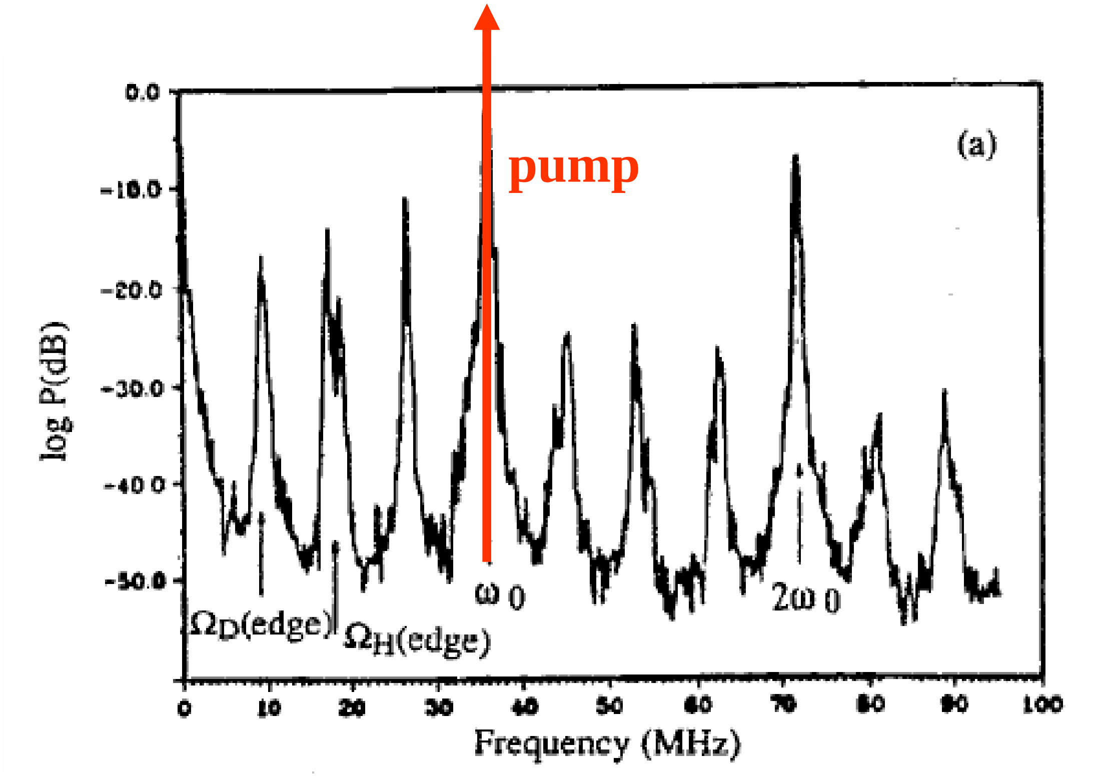
Chiu 1992

- linear theory with cold edge LH resonance absorption

Russell 1998

- 1D nonlinear model
  - ponderomotive profile steepening
  - enhanced wave reflection near LHR
- coaxial mode in halo plasma: [Intrator 2003, Myra 2000]
  - easier at 0-0 phasing and with large plasma-wall distance

Parametric decay instability (PDI) often observed

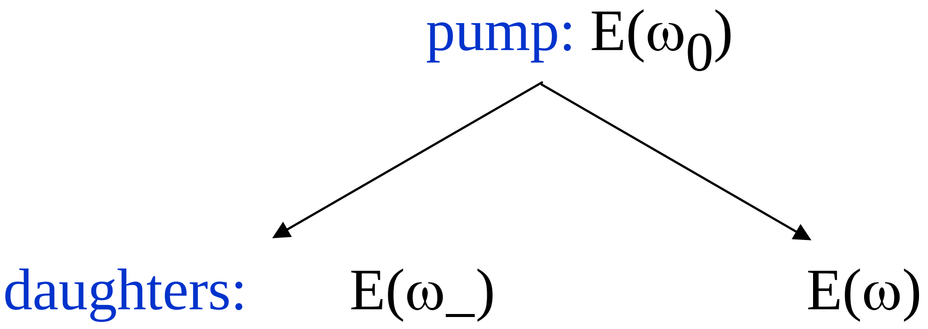


DIII-D, Pinsker 1993

- often correlated with edge ion heating
- difficult to measure the power going into the PDI daughter waves

also Wilson, NSTX (HHFW)
this meeting

Physics of parametric decay



pump: $E(\omega_0)$

daughters: $E(\omega_-)$ $E(\omega)$

$$\boxed{\begin{aligned}\omega_0 &= \omega+\omega_-\\ \mathbf{k}_0 &= \mathbf{k}+\mathbf{k}_-\end{aligned}}$$

$$[\nabla\times\nabla\times\ -\varepsilon\cdot]\,\mathbf{E}(\omega)\propto\underbrace{\mathbf{E}(\omega_0)\mathbf{E}(\omega_-)}_{\text{nonlinear beat current } J(\omega)}$$

- for fixed pump $E(\omega_0)$ and $E(\omega)$, $E(\omega_-)$ small
  - linearly unstable above threshold $|E_0|^2 > \gamma\gamma_-$
- dipole approx: long wave pump
  - linear theory about oscillating equilibrium
  - species dependent jitter in pump field ⇒ coupling

Linear PDI theory (fixed pump) well developed

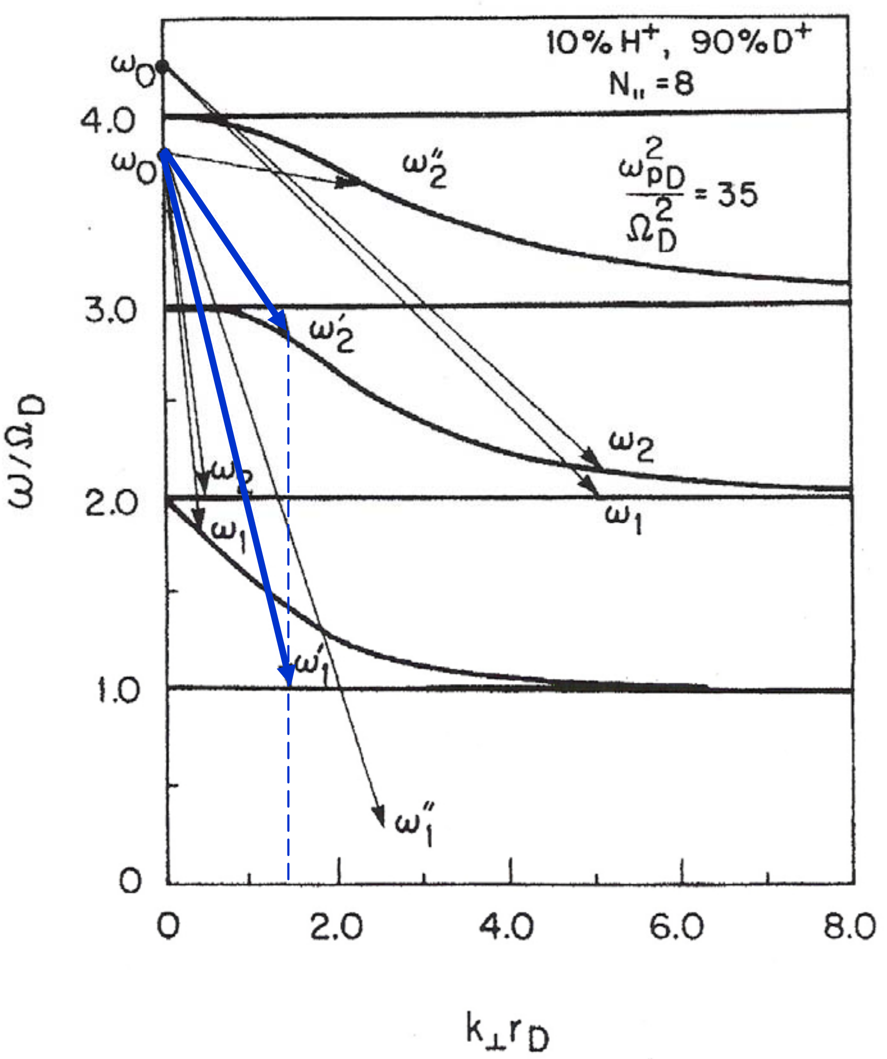
- Porkolab 1990
- Chiu 1988
- convective, inhomogeneous
- Cardinali NF 2002
  - n_e high to reduce PDI
  - n_e low for coupling (P_{refl})

Nonlinear pump depletion?

- kinetic, hot plasma
- time domain
- 2D or 3D spatial

a difficult numerical problem

IBW → IBW + quasi-mode



Porkolab 1990

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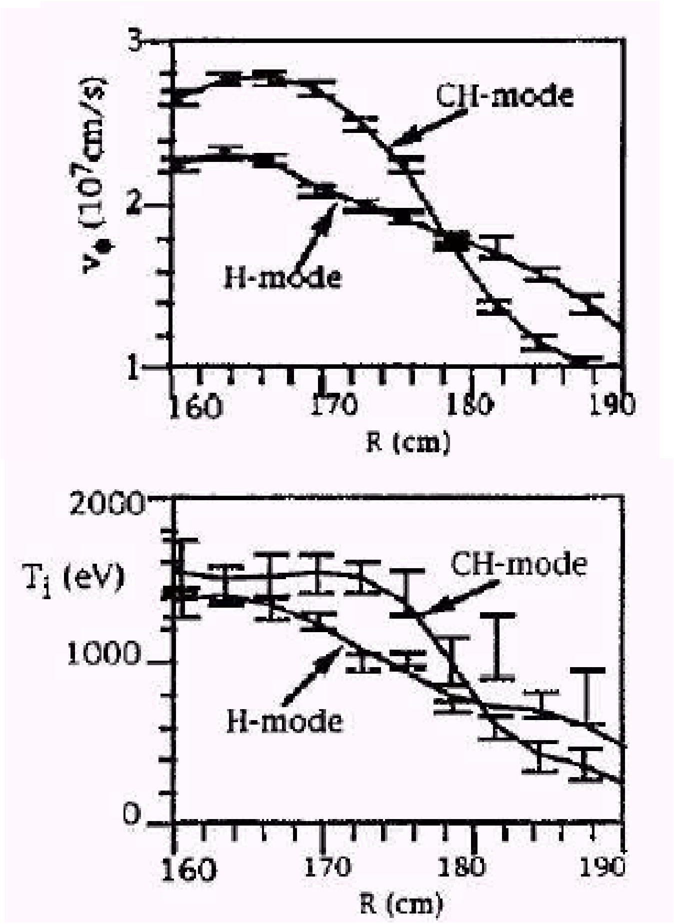
Direct launched IBW can trigger improved confinement



LeBlanc 1995

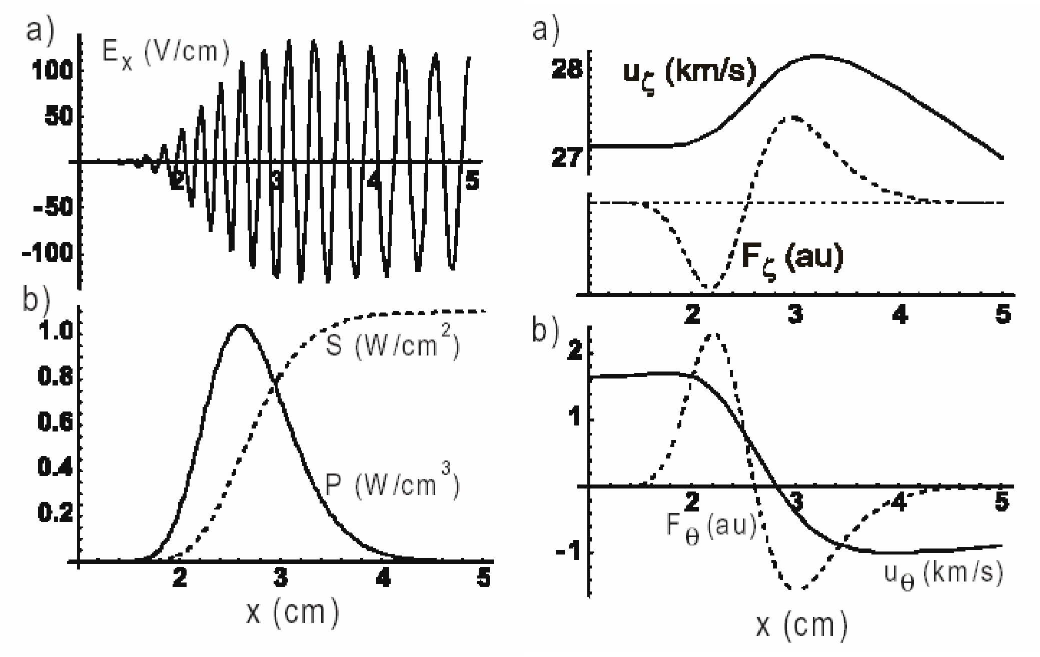
CH-mode PBX-M

- confinement improvement and/or profile modifications consistent with ITB
    - PBX-M [B. LeBlanc, 1995]
    - FTU [Cesario, 2001]
    - Alcator C [Moody, 1988]
    - PLT [Ono, 1998]
    - JIPPT-II-U [Seki, 1991]
    - Thorello [Riccardi 2001]
    - HT-7 [Wan 2003, Zhao]
- IBW-driven sheared flow layer Δv_θ in TFTR [LeBlanc, 1999]

- Collectively, experiments show :
    - IBW can drive flows
    - IBW can somehow, sometimes, enhance confinement

Theory: sheared flows suppress turbulence, calculate rf driven flows

- Craddock & Diamond, PRL 1991
- Ono 1995
- Berry et al., PRL 1999
- Jaeger et al., PoP 2000
- Elfimov et al., PRL 2000
- Myra & D'Ippolito, PoP 2000
- Cardinali, NF 2002
- Weitzner PoP 2000 & *this meeting*



Myra et al. 2000

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

see also:

Ono 1995
Jaeger 2000
Cardinali 2002

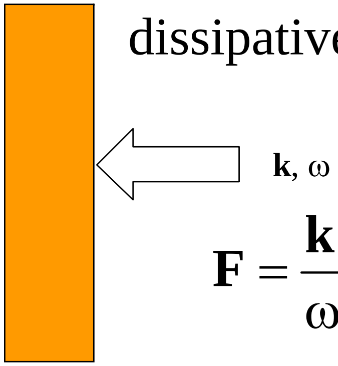
works, but …

Can the mode-converted IBW/ICW be used?

- avoid problems associated with direct IBW launch
- at FW mode conversion layer, get both IBW and ICW
  - original theory: Perkins 1977
  - experiment (C-Mod) + simulation (TORIC): Nelson-Melby et al. PRL 2003
  - simulation (AORSA): Jaeger et al. PRL 2003
- renewed experimental interest [C-Mod PCI diagnostic, Lin this meeting]
- stimulated new theoretical work on flow drive
  - handle MC, hot plasmas, general EM theory
  - improved understanding of basic mechanisms

3 mechanisms for RF-induced wave forces on a plasma

i) photon absorption

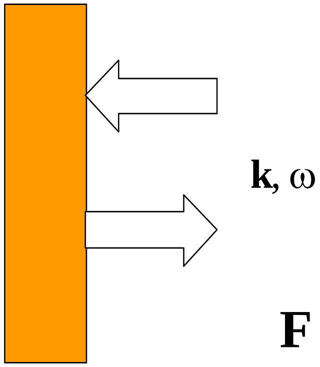


dissipative forces

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

ii) photon reflection,

reactive ponderomotive forces

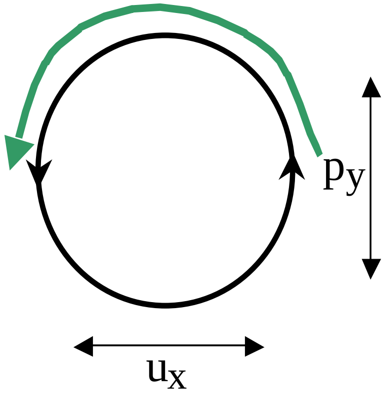


$$\mathbf{F} = \frac{2\mathbf{k}}{\omega} P_{rf}$$

$$\sim \varepsilon\, |\, E\, |^2$$

iii) momentum redistribution

Reynold’s Stress



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

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

cancellation in $\Pi \sim \mathbf{v}\,\mathbf{v} + \mathbf{B}\,\mathbf{B}$

Theory and formalism

- energy and momentum equations, W matrix
- guiding center (Kaufman)
- quiver kinetics (Catto)

Brambilla 1988
Smithe 1989
Jaeger, Berry 2000
Myra, Berry, 2004

energy

$$\dot{w} = \frac{1}{4}\sum_{k,k'} \mathbf{E}_k^* \cdot \overleftrightarrow{W}(\mathbf{k},\mathbf{k}')\cdot \mathbf{E}_{k'} \qquad \overleftrightarrow{W}(\mathbf{k},\mathbf{k}'\to\mathbf{k}) = \overleftrightarrow{\sigma}(\mathbf{k}), \quad \overleftrightarrow{W} \to \mathrm{Re}\ \ \mathbf{J}\cdot\mathbf{E}/2$$

momentum

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

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

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

i) direct absorption

ii) reactive ponderomotive

iii) momentum redistribution

flows

Only dissipative forces cause flux-surface-averaged flows

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

- F_{d1} = direct photon absorption term
  - can drive net flows
  - effective with electron or ion dissipation

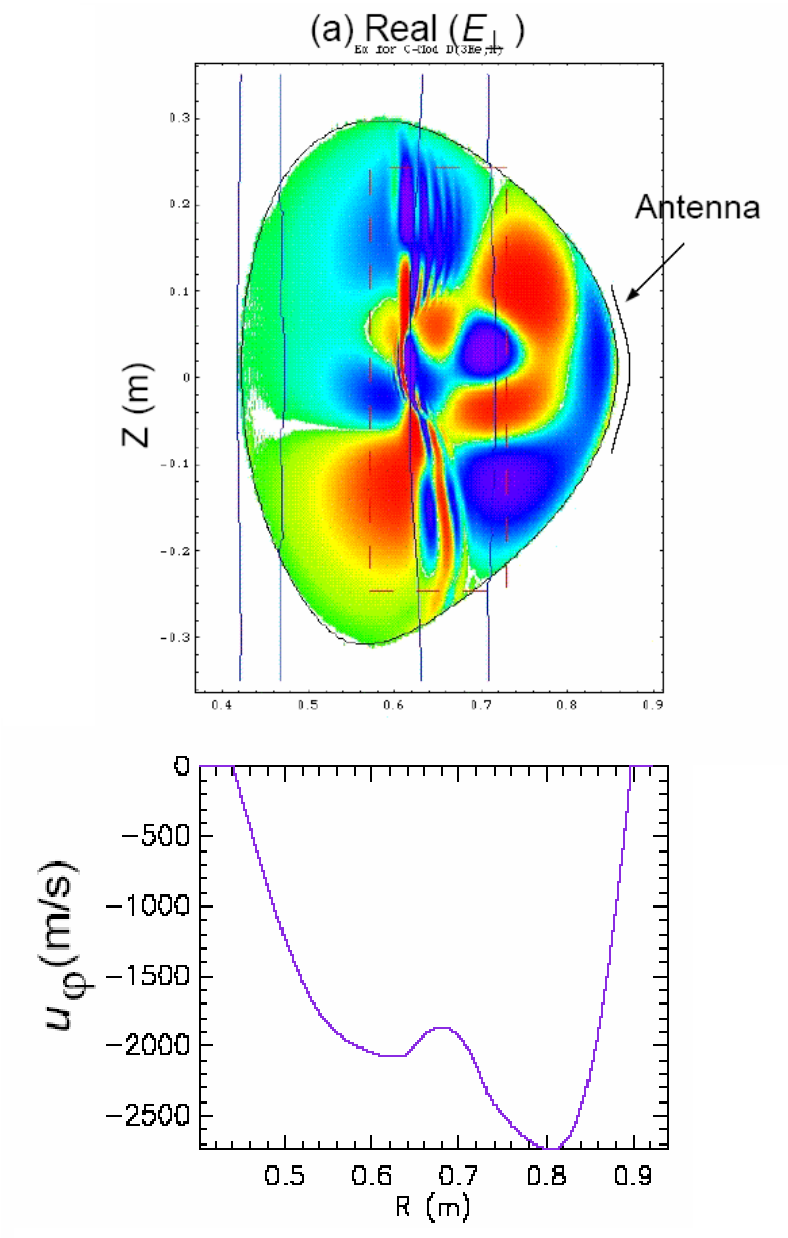
$$\mathbf{F}_{\mathrm{d1}} = \frac{\mathbf{k} + \mathbf{k}'}{4\omega} \mathbf{E}^* \cdot W^H \cdot \mathbf{E} \sim \frac{\mathbf{k}}{\omega} P_{\mathrm{rf}}$$

- X_{d} = dissipative stress term
  - drives bipolar sheared flows (no net flows)
  - significant only for ions

$$X_{\mathrm{d}} = \frac{P_{\perp}}{2\Omega} \sim \frac{n}{2\omega} \mathbf{E}^* \cdot W_n \cdot \mathbf{E}$$

short wavelengths and narrow dissipation layers
$\Rightarrow$ *stronger sheared flows*

Simulations of sheared flows with AORSA



Jaeger, 2003

- C-Mod case
- B_θ controls MC products
- $k_{||}$ upshifts
- ICW propagation into resonance
- flows based on toroidal force balance with $D \sim a^2/\tau_e$
- 1 MW power
  - $\omega_{E\times B} = 1.2 \times 10^4$ /s

Mechanisms for E_r shear by rf

- E_r shear important for turbulence suppression
- ion radial force balance (steady state)

$$\underbrace{\frac{v_\zeta B_\theta - v_\theta B_\zeta}{RB_\theta} \equiv G(\psi)}_{\mathbf{v}\times\mathbf{B}} = -c\left(\underset{E_r}{\frac{\partial\Phi}{\partial\psi}} + \underset{\nabla p}{\frac{1}{Zen}\frac{\partial p_i}{\partial\psi}}\right) + \underset{\mathbf{F}_{ext}}{\frac{c}{Zen_i}\frac{F_{i\psi}}{RB_\theta}}$$

$\mathbf{v} = K(\psi)\mathbf{B} + RG(\psi)\mathbf{e}_\zeta \rightarrow$(poloidal flow) $RG(\mathbf{e}_\zeta - \mathbf{B}/B_\zeta)$

- ➢ nonlinear wave momentum processes drives flows $G(\psi)$
- ➢ $p_i(\psi)$ heating profile
- ➢ radial ponderomotive forces (small)

- measurements (TFTR, LeBlanc) show IBW-driven poloidal flows
- transient or diffusive coupling of flows [e.g. Chan 1999] not yet simulated for flow drive

Future work needed:

- **experiments**:
  - measurements of poloidal and toroidal velocity shear with
  - rf-induced confinement improvement
  - experimental validation of flows in MC scenarios
- **theory**: have rf forces; need rf/neoclassical computations of
  - transient rf-induced poloidal and toroidal flows
  - E_r shear and turbulence suppression

I. FW launch antenna/edge interactions: rf sheaths

II. IBW edge interactions

III. IBW/ICW core interactions: flow drive

IV. Integrated modeling: the new forefront

RF edge physics, antenna interaction, coupling

- incorporation of more edge physics into antenna coupling codes
  - plasma (blob/turbulence) in the antenna region
  - wave scattering from blobs, fluctuations
  - sheath and ponderomotive effects
  - surface physics (sputtering and neutral gas desorption)
- predictive capability for
  - plasma loading with self-consistent density profile ⇒ advance prediction
  - some operational constraints on antenna (local power, damage, arcs?)
  - rf ⇔ edge (turbulence, n_e, T_e, Φ, impurities …)
- low power loading helpful for code validation and experimental diagnosis
- **Tue pm**: B-21 Faudot, B-22 Carter, B-23 D'Ippolito
- **Wed am**: I-19 Colas

More realistic edge conditions for global rf codes

- global full wave codes do not presently treat the edge/SOL well
  - typically all power absorbed in core (even when absorption poor)
- experiments: edge/SOL physics especially important for low $k_{||}$ cases
- need:
  - realistic edge/SOL dissipation
  - BC's to model far-field sheaths (rf SciDAC)
  - collisions, neutrals, PDI
- goal: new predictive capability for lost power

Conclusions

- nonlinear effects are generally important for ICRF at the edge
- nonlinear effects can also be important in the core for IBW/ICW
- a lot of individual pieces of important physics have been established
    - antenna sheaths and their role on impurities, convection, SOL currents …
    - interaction with edge turbulence
    - ponderomotive effects
    - far field sheaths and edge dissipation
    - parametric decay
    - rf effects on plasma flows and E_r
- integrated edge/rf modeling holds out the exciting possibility of a predictive capability that has so far been elusive
- motivation: burning plasma
- means: grand challenge computing resources

the ICRF theory/simulation community is at the threshold of a significant opportunity