Nonlinear ICRF interactions with the boundary plasma

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with acknowledgements to

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Introduction

- Nonlinear interactions: RF waves + plasma + material surfaces
- Tutorial: emphasis on underlying physical mechanisms
- Scope: emphasis on SOL turbulence, ICRF (ion cyclotron range of freq.)
  - touch on LH
  - touch on nonlinear core interactions
- Referencing
  - incomplete, mainly workers in the area

Motivation

- Plasma heating and current drive with ICRF waves has been successful in many tokamak experiments
- ICRF foreseen to play an important role in ITER: cost effective and flexible
- Unwanted interactions with SOL plasma and material surfaces can be problematic in some regimes
  - enhanced sputtering
  - surface power dissipation
  - material erosion and damage
  - modified edge transport and flows (can be beneficial too)
  - RF wave scattering
- Understand, predict and control

Outline

- Background
- ICRF driven sheaths
- RF-driven convection
- Ponderomotive force
- Scattering of RF by turbulence

Background

(typical tokamak edge/SOL and RF parameter ranges)

Time scales

- turbulence: ~ ω_* ~ < few 100 kHz
- ICRF: ~ Ω_i ~ 10's MHz; LH: ~ GHz

Turbulence is frozen on the RF time scale

$\langle RF \rangle_t$ affects turbulence; "frozen" turbulent structures affect RF propagation

Space scales

- turbulence: $\perp$ ~ 10 ρ_i ~ cm; $\parallel$ ~ global
- ICRF: $\perp$ ~ δ_e, δ_i ~ mm to 10's cm; $\parallel$ ~ cm – m

Turbulence and ICRF space scales can be disparate or comparable

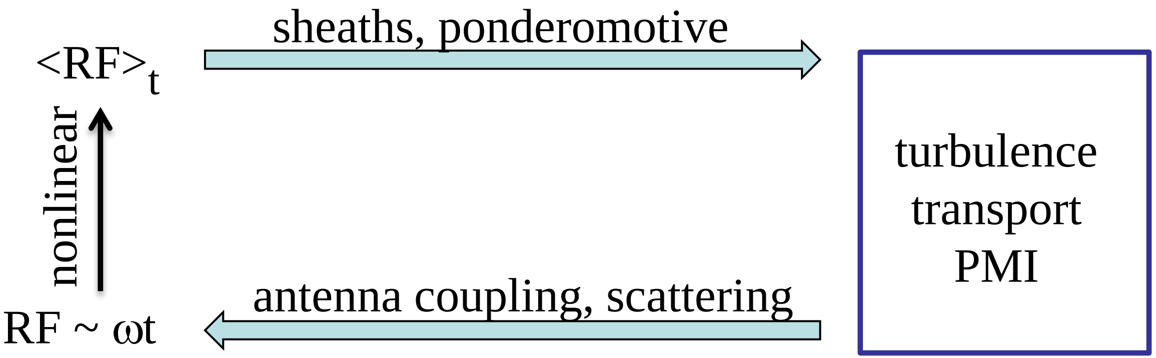
Amplitudes ($\delta\Phi$)

- turbulence: ~ T_e/e ~ 10 V
- ICRF: ~ up to fraction of $V_{antenna}$ ~ 100's of V

ICRF can present a large amplitude perturbation

Interactions between RF, turbulence and transport

- ***Turbulence is frozen on the RF time scale***
- ***Turbulence and ICRF space scales can be disparate or comparable***
- ***ICRF can present a large amplitude perturbation***
  - near the antenna where fields are large
  - where the group velocity is slow $P = \mathbf{S}\cdot\mathbf{A} \propto v_g W \propto v_g |E|^2$ (large k)
  - where the temperature is low $\psi_{pond} > T/e$, $V_{rf} > T/e$



Background: RF waves

What you need to know

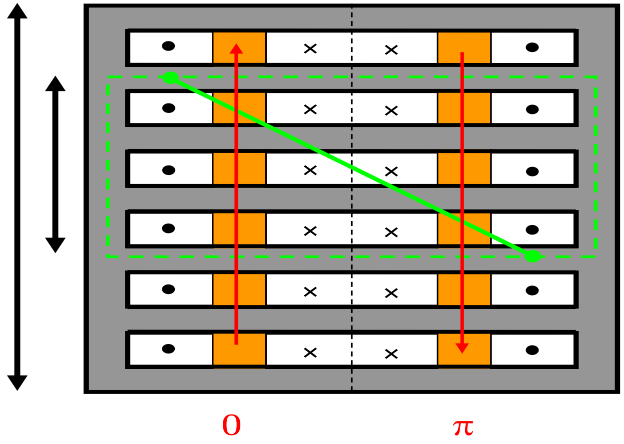
- ICRF (Ion cyclotron range of frequencies) antennas attempt to launch a pure fast wave (FW) = compressional Alfven wave which propagates into the core and is absorbed ☺
  - electromagnetic
  - **E** is ⊥ to B_0 and elliptically polarized; $E_{||}$ is negligible
  - can be evanescent in the SOL with ~ cm scale lengths
  - antenna coupling to FW improves at high antenna n_e
- In practice antennas also excite some power in the slow wave (SW) branch = shear or torsional Alfven wave ☹
  - $\mathbf{E}_\perp$ is very large for a given power ($P \sim v_g |E|^2$)
  - $E_{||}$ is significant
  - can be evanescent (high n_e) or propagating (low n_e)
  - short spatial scales (mm to cm)
- ***SWs excited at the antenna or produced by FW/SW mixing at boundaries are implicated in many nonlinear RF-plasma-surface interactions.***

Outline

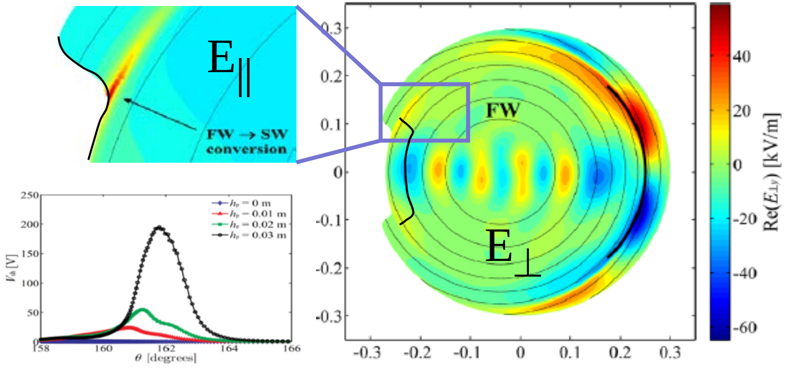
- Background
- **ICRF driven sheaths – fast time scale (RF) physics**
- RF-driven convection
- Ponderomotive force
- Scattering of RF by turbulence

ICRF sheaths form where plasma, RF and material surfaces coexist

- Typically $E_{\|,RF}$ is responsible for enhanced electron losses: an RF sheath builds up to preserve plasma quasi-neutrality …



Kohno PoP 2015



- near field sheaths, on antenna surfaces
- **magnetically connected**: field line
- $E_{\|}$ driven directly $J_{\|,ant}$

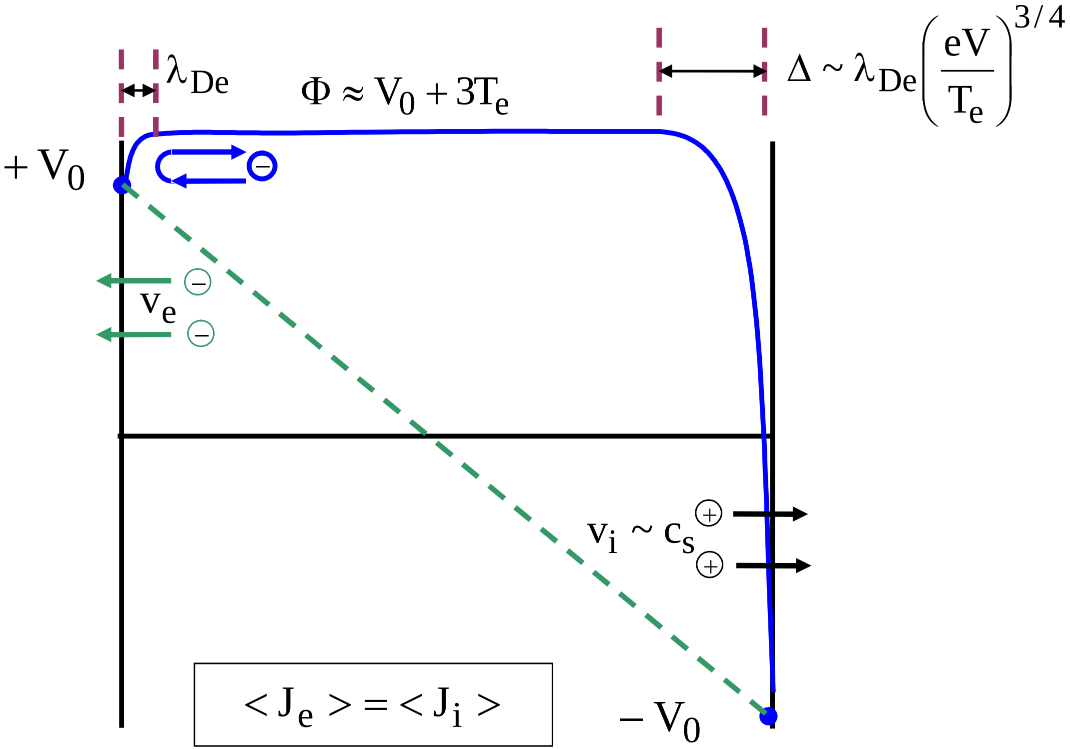
- far field sheaths, on walls, limiters, other hardware,
- **not magnetically connected**
- $E_{\|}$ driven by propagating waves
- FW $\rightarrow$ SW conversion

Basic sheath physics: the biased static sheath

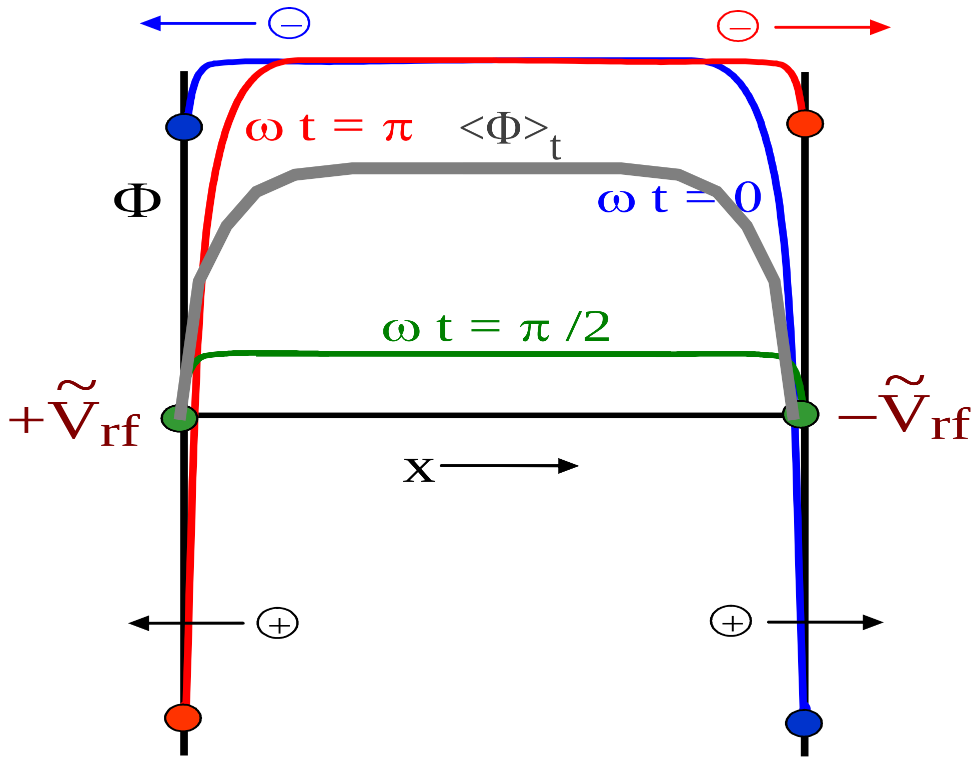
- RF sheaths can typically reach up to 100's V >> $3T_e \Rightarrow$ strong bias

- capacitor plate model
- equalize i and e loss rates
- electron confinement

  $\Phi > \max(V)$ on plates
- sheath width Δ
- ion acceleration
  - sputtering
  - sheath power



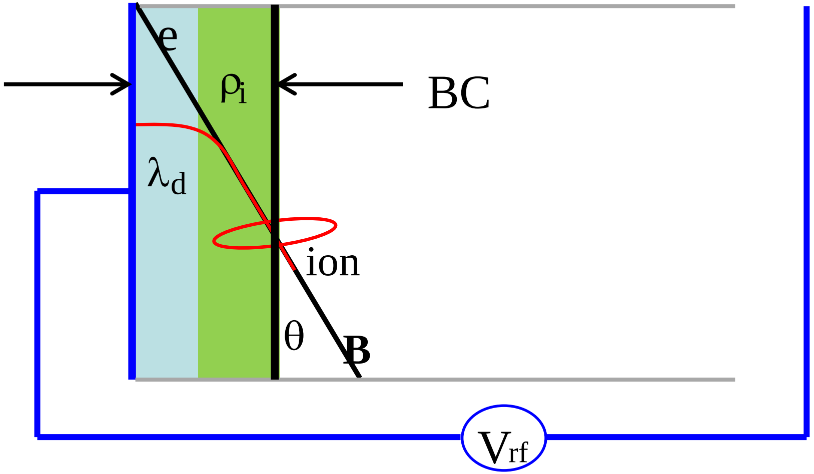
Physics of an RF sheath



Butler; Chodura; Colas; D'Ippolito; Faudot; Gekelman; Godyak; Gunn; Hershowitz; Hosea; Jacquot; Lieberman; Myra; Perkins; Smithe; VanEester

- rectification $\langle\Phi\rangle_t \sim V_{rf}$
  - PMI
  - BC for turbulence
- ions flow out at both ends
  - $P_{sh} \sim ZeV_{rf}\, n_e\, c_s$
- electrons leave when V > 0
- oscillating J_n and V ⇒ sheath impedance ~ V/J_n
  - BC for RF codes

Sheath boundary conditions for RF simulations



- λ_{de} , Δ ~ << λ_{rf}, L_n, a, R
- collapse the sheath into a boundary condition using a sub-grid sheath model

$$\mathbf{E}_t = \nabla_t (J_n z_s)$$

- replace EM BC $\mathbf{E}_t = 0$ with

Sub-grid sheath model output:

- a relation between the RF electric field and current at the sheath entrance => surface sheath impedance z_s (a *nonlinear* function of RF amplitude)
- the rectified DC voltage $\langle \Phi \rangle_t$ => ***coupling*** to sputtering (PMI), transport and (low frequency) turbulence codes; sheath power dissipation the surface

Sheath BC for turbulence and transport codes

- Use $\langle\Phi\rangle_t$ from the RF simulation directly as a BC, or
- Modify the BC relation between $J_{\|}$ and Φ at the sheath entrance
- Thermal sheath

$$J_{\|,sh} = n_i e c_s \left(1 - e^{e(\Phi_B - \Phi_{sh})/T_e}\right) \qquad \frac{e\Phi_B}{T_e} = \ln\left(\frac{v_{te}}{2\pi^{1/2} c_s}\right) \approx 3$$

- Sheath potential modified by RF

$$J_{\|,sh} = n_i e c_s \left(1 - e^{e(\langle\Phi\rangle_t - \Phi_{sh})/T_e}\right)$$

where $\langle\Phi\rangle_t$ is from RF code

- Complication: $\langle\Phi\rangle_t$ from the RF code depends on $J_{\|}$ which depends on global current flow in the vessel walls (work in progress).

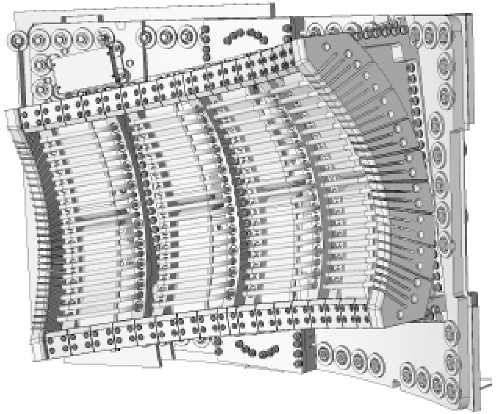
Outline

- Background
- ICRF driven sheaths
- **RF-driven convection – effect of RF sheaths on slow time scale physics**
- Ponderomotive force
- Scattering of RF by turbulence

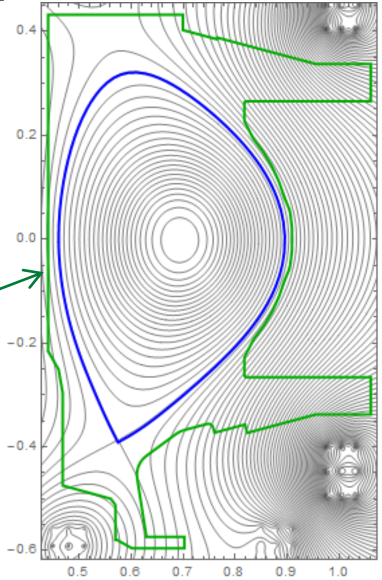
RF-driven E×B convection

- Antenna and wall surfaces are geometrically complicated
- Complex voltage patterns exist on these surface sheaths

CAD model of C-Mod field aligned antenna



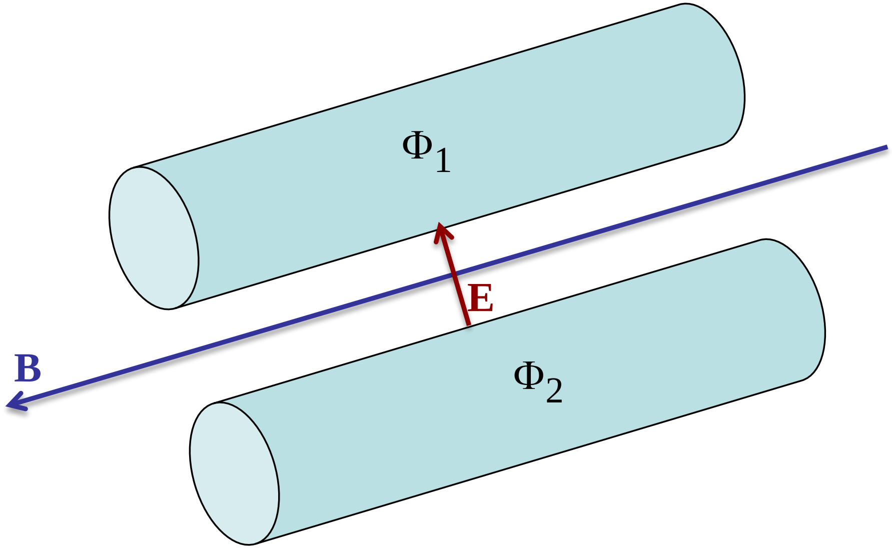
C-Mod vessel wall



- Surface (sheath) potentials spread quickly along field lines
  - Parallel electron conduction

… RF-driven E×B convection

- Flux tubes each charge to ~ independent potentials
- Resulting $\langle E_\perp \rangle_t$ drives convection and influences transport

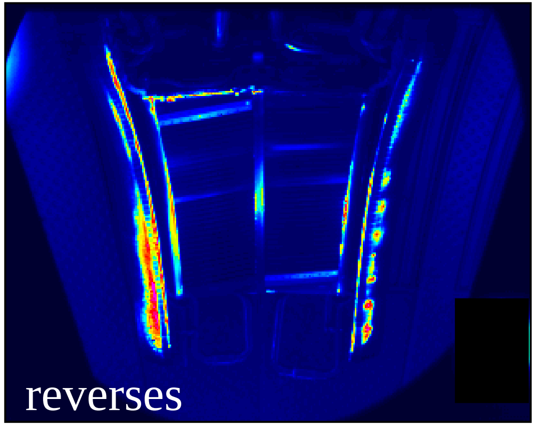


- Simplified 1D picture that in reality is modified by:
  - parallel resistivity & $\langle E_{\|} \rangle_t$ along tube
  - parallel currents
  - cross-field currents

RF-induced convection effects seen and modeled in experiments

Large scale convection:

pattern reversal with **B**

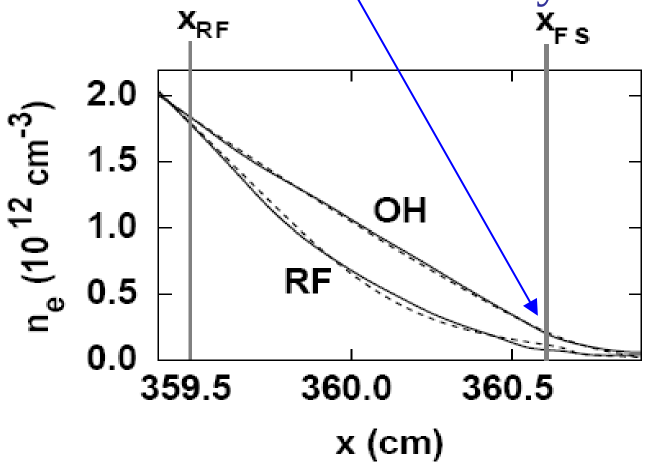


Tore Supra, Colas 2005;

Bécoulet 2002

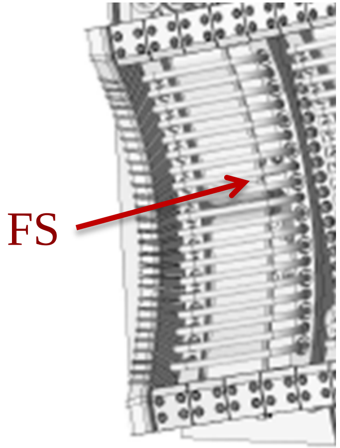
Small scale (FS) convection:

local flattening if $\tau_{eddy} < L_{\|}/c_s$



TFTR; D'Ippolito 1998

Wilgen - reflectometer

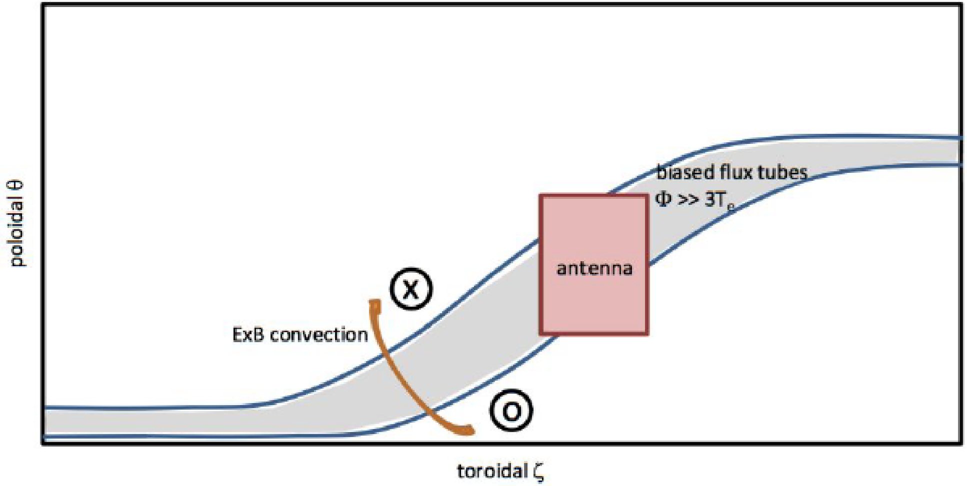


Local density at the antenna is modified by convection

(and possibly ponderomotive effects).

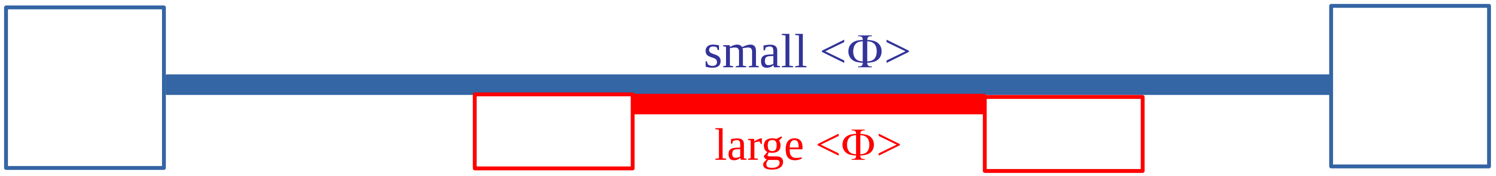
Advanced modeling requires 3D transport codes

- Axisymmetric flows interesting for flow shear and turbulence interaction
- Modeling of RF-driven convective transport will require non-axisymmetric (toroidally varying) BCs; and E×B drifts
- Important to understanding n_e near the antenna and in the SOL
  - ICRF antenna wave coupling improves with higher n_e (good)
  - RF sheath power dissipation and surface heat flux increases with n_e (bad)

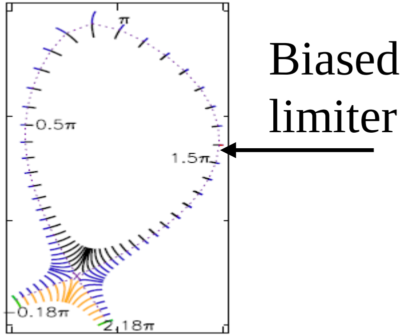


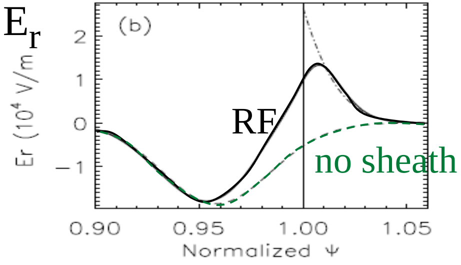
Work planned/underway in RF SciDAC

RF driven <E>$_t$×B flows also interact with turbulence



- Lowest order sheath potentials are constant on a field line ⇒ jump discontinuity, but …
- Plasma will not tolerate arbitrarily large <$E_\perp$> and flow shear
    - Cross-field ion-polarization currents, Kelvin-Helmholtz instabilities, mixing ⇒ effectivwe turbulent ⊥ conductivity
    - May control inward radial penetration of surface potentials [Tamain 2017; Gui 2018]





Gui NF 2018 (BOUT++ transport)

Outline

- Background
- ICRF driven sheaths
- RF-driven convection
- **Ponderomotive force – time averaged force from an RF wave**
- Scattering of RF by turbulence

Single particle ponderomotive potential

[Motz & Watson 1967; Kaufman ,Cary, Hammer, …]

$$\psi_p = \frac{e^2|E_{||}|^2}{4m_j\omega^2} + \frac{e^2|E_L|^2}{4m_j\omega(\omega-\Omega_j)} + \frac{e^2|E_R|^2}{4m_j\omega(\omega+\Omega_j)} = \frac{m_j}{4}|u_j^2| + \frac{m}{4}\,\mathrm{Im}\left(\frac{\Omega}{\omega}\mathbf{b}\cdot\mathbf{u}_j\times\mathbf{u}_j^*\right)$$

electrons

$$\frac{1}{4}m_e\left|\frac{eE_{||}}{m_e\omega}\right|^2$$ ~ jitter kinetic energy

$$\mathbf{f} = -\nabla\psi_p$$

- ψ_p can be significant for the slow wave (SW) polarization: $E_{||}$ and (because it is slow) large $E_\perp$ for a given power density
  - near an ICRF antenna
  - in the core from ICW or IBW or (directly launched or mode converted)

Ponderomotive force density on a fluid element

[Lee & Parks, Catto, D'Ippolito, Smithe, Myra]

- Relevant for coupling for transport and fluid turbulence codes

$$m\frac{\partial \mathbf{\Gamma}}{\partial t}+\nabla\cdot\overline{\overline{\Pi}}=\frac{1}{c}\mathbf{J}\times\mathbf{B}+\mathbf{F}_L, \qquad \mathbf{\Gamma}\equiv\int d^3v\ \mathbf{v}\langle f\rangle_t, \qquad \mathbf{F}_L=\left\langle Zen^{(1)}\mathbf{E}^{(1)}+\frac{1}{c}\mathbf{J}^{(1)}\times\mathbf{B}^{(1)}\right\rangle_t$$

Π_{rf} is important (contains Reynolds stress + …)

- For cold-fluid RF plasma responses: using $\overline{\overline{\Pi}}_{rf}=\langle nm\mathbf{uu}\rangle_t$ and $\mathbf{F}_L$

Lee and Parks PF 1983: $\boxed{\mathbf{F}=-n\nabla\psi_p+\mathbf{B}\times\nabla\times\mathbf{M}}$

$$\mathbf{M}=-\frac{iZen}{8\omega c}\mathbf{u}^*\times\mathbf{u}+cc$$

$$\psi_p=\frac{iZe}{8\omega}\mathbf{u}^*\cdot\mathbf{E}+cc=-\frac{1}{32\pi n}\mathbf{E}^*\cdot\overline{\overline{\chi}}\cdot\mathbf{E}+cc$$

M is analogous to diamagnetic force (drift)

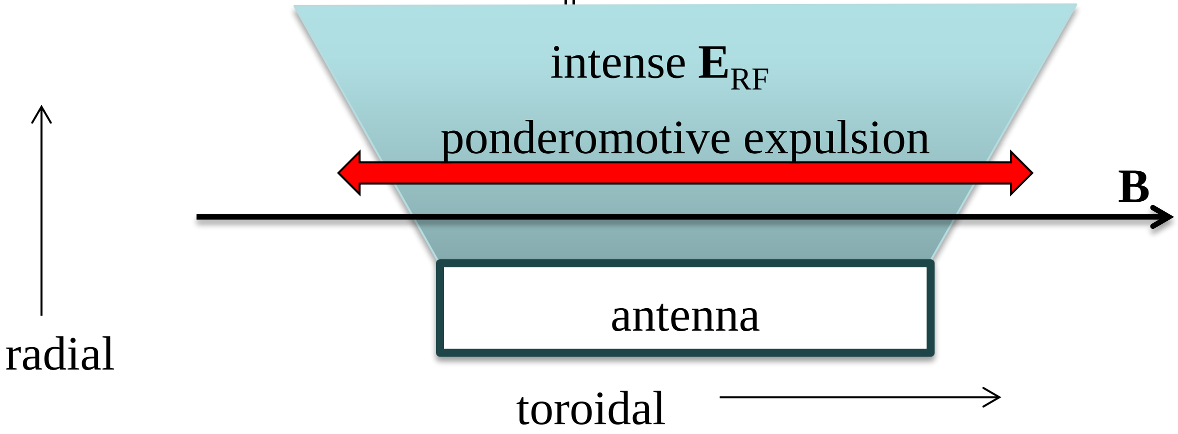
$$-i\omega\mathbf{u}-\Omega\mathbf{u}\times\mathbf{b}=\frac{Ze}{m}\mathbf{E},$$

ψ_p has same structure as $n\times$ single particle force

thermal vs. jitter

Parallel ponderomotive force may contribute to pump-out
(together with RF induced-convection)

- Important when intense $E_{||}$ is present from the RF slow wave



- "pump-out" of density in front of antenna observed
- IBW & LH resonance cones

$$\psi_{pe} = \frac{e^2|E_{||}|^2}{4m_e\omega^2} \qquad n_e = n_{e0}e^{(e\Phi-\psi_{pe})/T_e}$$

$$\psi_{pi} = \frac{e^2|E_L|^2}{4m_i\omega(\omega-\Omega_i)} + \frac{e^2|E_R|^2}{4m_j\omega(\omega+\Omega_i)} \qquad n_i = n_{i0}e^{(-Ze\Phi-\psi_{pi})/T_i}$$

RF SciDAC project: tools for RF ↔ turbulence & transport

A. Dimits – next talk
M. Umansky; S. Shiraiwa (priv. communications)
D. Smithe – ponderomotive, later talk this session

- VSIM/VORPAL [Tech-X] computes EM fields and plasma current **J** near antenna retaining essentially full geometric details.
- RF code Petra-M is also under development for this purpose.
- Ponderomotive force can be expressed as **F(E, J)** and directly post-processed, along with Φ_{sheath}, for passing to turbulence and transport codes
  - pump-out and changes in density profile near antenna ⇒ antenna loading
  - competition with sheath-driven convection and particle sources
  - perpendicular ponderomotive force and drifts

Kinetic RF theory of force on a fluid element

- Conditions for fluid limit of ponderomotive force can be violated (esp. in core)
  - e.g. parallel electron motion: $\pi v_{te}/L_{\|} \sim \omega$; ions for $\omega \approx n\Omega_i$
- Can we drive sheared flows by RF to suppress turbulence?
  - confinement improvement observed in some IBW experiments [198x – 199x]
  - theoretical development of RF driven flows [1990x – 200x]
- Experiments [Lin 2008; 2012] showed flow drive from FW mode conversion to IBW/ICW
- Cold fluid ponderomotive force cannot drive flux-surface averaged flows
  - proof uses $n = n(\psi)$, $\langle \mathrm{Re}_\zeta \cdot \nabla Q \rangle_\psi = 0$, $\langle B\nabla_\| Q \rangle_\psi = 0$, and $\nabla \times \mathbf{M}$ identities

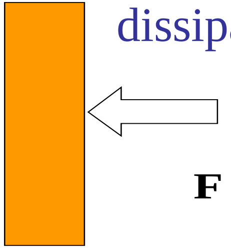
$$\mathbf{F}_{\text{kinetic}} = -\nabla \cdot \left(m \int d^3v \; \mathbf{v}\mathbf{v} f^{(2)} \right) + Zen^{(1)}\mathbf{E}^{(1)} + \frac{1}{c}\mathbf{J}^{(1)} \times \mathbf{B}^{(1)} \Big|_{\text{using RF kinetic moments}}$$

- Flux-surface averaged flows result from dissipative terms in kinetic theory

3 mechanisms for RF-induced wave forces on a plasma

i) photon absorption

dissipative forces

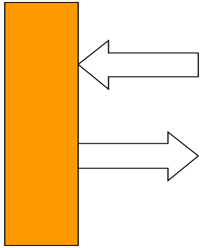


$\mathbf{k}, \omega$

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

ii) photon reflection,

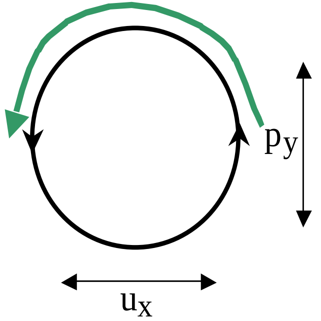
reactive ponderomotive forces



$\mathbf{k}, \omega$

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

iii) momentum redistribution (bipolar flows), Reynold's Stress



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

i) and iii) $\Rightarrow$ flux surface avg. flows

Theory/simulations have not yet quantitatively explained MC flow drive in experiments: possible coupling to turbulent transport?

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- Background
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- RF-driven convection
- Ponderomotive force
- **Scattering of RF by turbulence**

RF waves must traverse the turbulent SOL and edge region on their way to the core

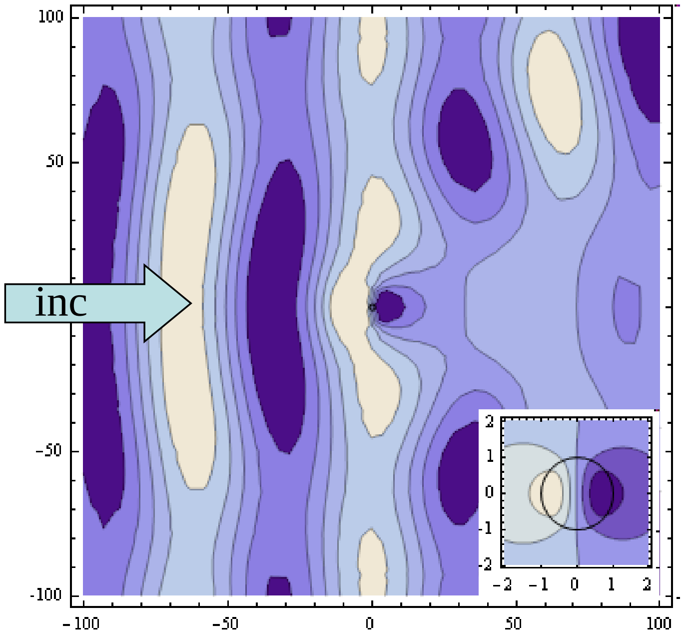
- Potentially important for (ICRF), LH and EC
- RF sees a frozen snapshot of the turbulence
- In the edge: $\delta n/n \ll 1$, background + turbulent wave spectrum [Bonoli; Ram; Hizanidis …]

$$\omega_{scattered} = \omega_{incident} \qquad \mathbf{k}_{scattered} = \mathbf{k}_{incident} + \mathbf{k}_{turbulence}$$

  - refractive effects if $k_{turbulence} \ll k_{rf}$ (short wavelength rf)
  - changes: propagation direction and wavenumber
    - affects absorption location and accessibility (through dispersion relation)
  - ray tracing, wave-kinetic equation, FP equation
- In the SOL: $\delta n/n \sim 1$, blobs [Ram; Myra; Ioannidis; Chellaï; Biswas; Lau]
  - diffraction if $k_{turbulence} \geq k_{rf}$ (comparable/long wavelength rf)

Scattering by a single blob-filament

Re E_z field pattern



$z = 0.1$, $z_b = 2.395$

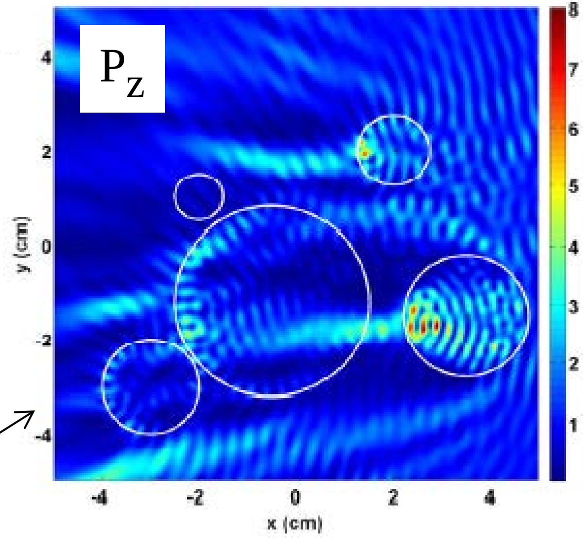
Myra 2010

- SW scattering resonance for $z_b = k_{\perp} r_b \sim 1$
  - SW wavelength fits inside blob-filament
  - approximate "bound state" exists when radiation damping of scattered wave is small (long wavelength in background plasma)
- Bound state condition is also postulated to result in FW $\rightarrow$ SW mode conversion in the SOL
  - may be relevant to observed edge power loss

… Scattering by many blob-filaments

- Extended to multiple filaments and realistic launcher fields and geometry

- Back- and side-scattering of slow LH waves, and changes in the spatial distribution of Poynting flux; and the spectrum



Ioannidis PoP 2017

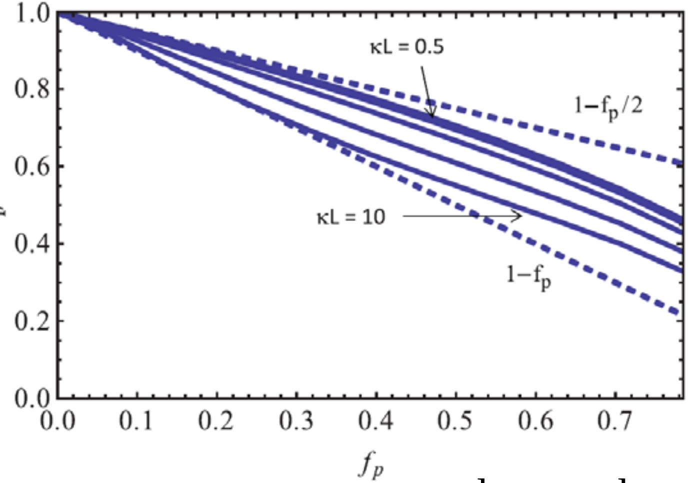
- RF SciDAC project is preparing to exchange high resolution data between turbulence/transport and RF codes: enable predictive calculations

ICRF propagation in an under-dense SOL

- FW that is desired in the core for heating and CD is evanescent in the SOL if $n_e < n_{ec}$ $\Rightarrow$ degraded coupling; antenna is far away from separatrix in ITER

2D blob-lattice model

effective decay rate / background decay rate



$$\text{packing fraction} = \frac{\text{over-dense volume}}{\text{total volume}}$$

- FW decays through tenuous (under-dense) background but could see regions of propagation (high density blob-filaments).
- Result is *not* equivalent to using the average density
  - It *is* similar to using the average decay rate [Myra 2014]

Needed : a predictive characterization of SOL packing fraction

Summary

SW: $E_{\|}$
large $E_{\perp}$
$\langle RF \rangle_t$

sheaths, ponderomotive →

convection, expulsion

RF sheath impedance

nonlinear ↑

RF ~ ωt

← antenna coupling, scattering

SOL-antenna profiles,
refraction, diffraction, k-spectrum
blob-filaments:
scattering & under-dense decay

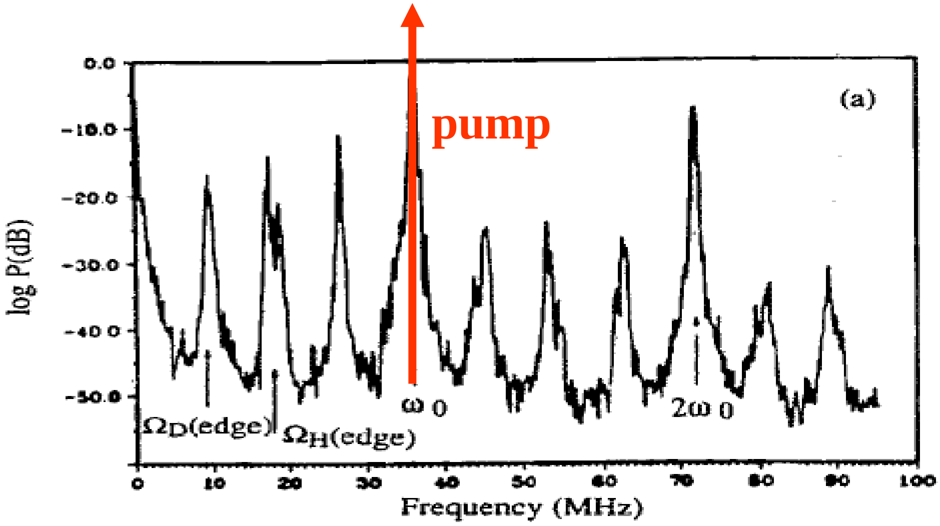
turbulence
RF-sheath-driven flows;
shear suppression , KH?,
ponderomotive flows
(edge, core?)

transport
sheath BC
convective cells
pump-out

PMI
RF-enhanced sheaths:
- sputtering
- power deposition

Extras

Parametric decay instability (PDI) often observed



DIII-D, Pinsker 1993

- Parametric decay spectra are frequency observed with probes, especially associated with a launched SW (pump); in ICRF and LH regimes
- Difficult to assess fraction of power lost t PDI from point measurements
- PDI thought to be important in explaining loss of LH efficiency at high n_e [Porkolab, …]

Physics of parametric decay

pump: $E(\omega_0)$

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

$$\omega_0 = \omega + \omega_-$$
$$\mathbf{k}_0 = \mathbf{k} + \mathbf{k}_-$$

$$[\nabla \times \nabla \times \; - \varepsilon \cdot]\, \mathbf{E}(\omega) \propto \underbrace{\mathbf{E}(\omega_0)\mathbf{E}(\omega_-)}$$

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 $\Rightarrow$ coupling

Linear PDI theory (fixed pump) well developed

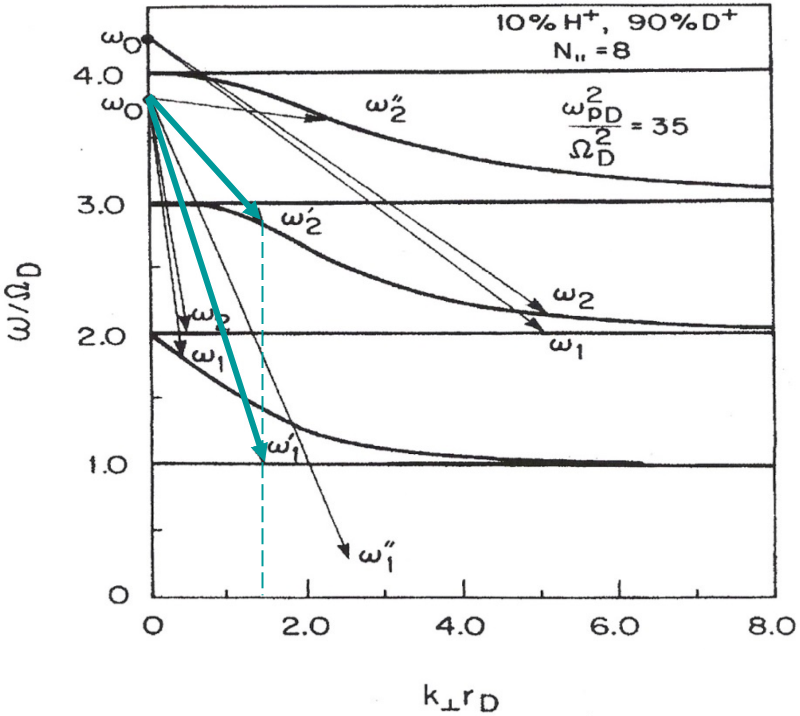
- Porkolab 1990
- Chiu 1988
- convective, inhomogeneous
- Cardinali NF 2002
  - n_e high to reduce PDI
  - n_e low for coupling (P_{refl})

Nonlinear pump depletion?

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

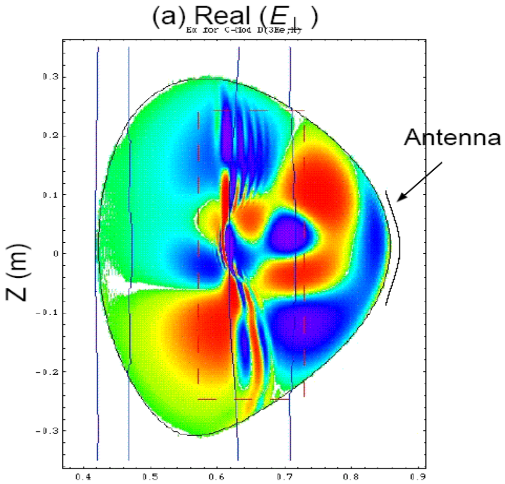
a difficult numerical problem

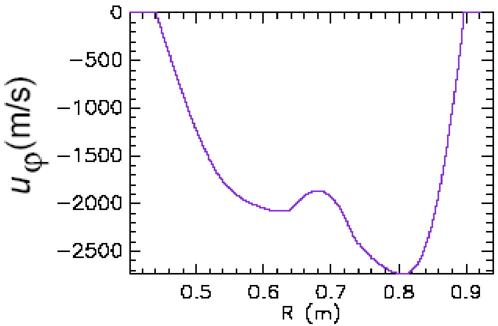
IBW → IBW + quasi-mode



Porkolab 1990

Simulations of sheared flows with AORSA

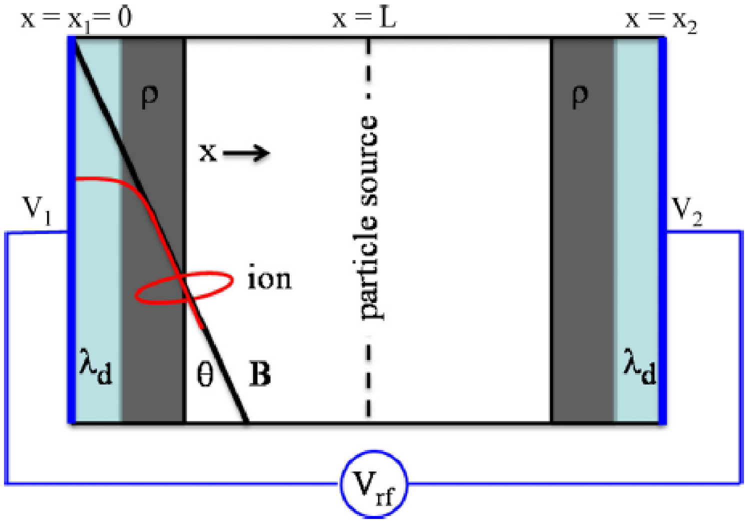




Jaeger, 2003

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

Sub-grid nonlinear RF sheath model



Equations

$$\frac{\partial^2 \Phi}{\partial x^2} = -(n_i - n_e)$$

$$n_e = \exp(\Phi - \Phi_0)$$

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x}(n_i u_x) = 0$$

$$\frac{1}{\Omega}\left(\frac{\partial}{\partial t} + u_x \frac{\partial}{\partial x}\right)\mathbf{u} = \mathbf{v}_E + \mathbf{b} \times \mathbf{u}$$

BCs

$$\Phi(x_1) = V_1 = \frac{V_{pp}}{2}\cos\omega t \equiv \xi \cos\varphi$$

$$\Phi(x_2) = V_2 = -\frac{V_{pp}}{2}\cos\omega t \equiv -\xi \cos\varphi$$

$$J_{x1} - J_{x2} = 0 \qquad J_{x1} = n_{i1}u_{x1} + \mu b_x \exp(V_1 - \Phi_0) - \frac{\partial^2 \Phi_1}{\partial t\ \partial x}$$

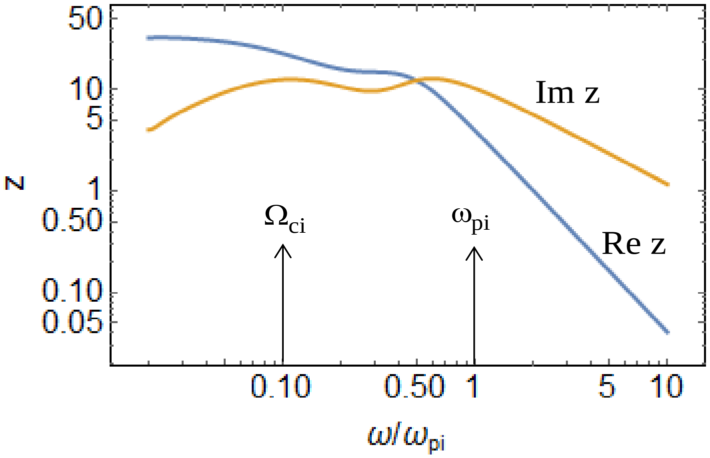
Input Vpp

Output Jx

$\Rightarrow z_{sh}$

… Sheath BC for RF codes

- z_s from a fluid model has been tabulated/fit in a 4D parameter space
  - normalized density, magnetic field, magnetic field angle, RF voltage



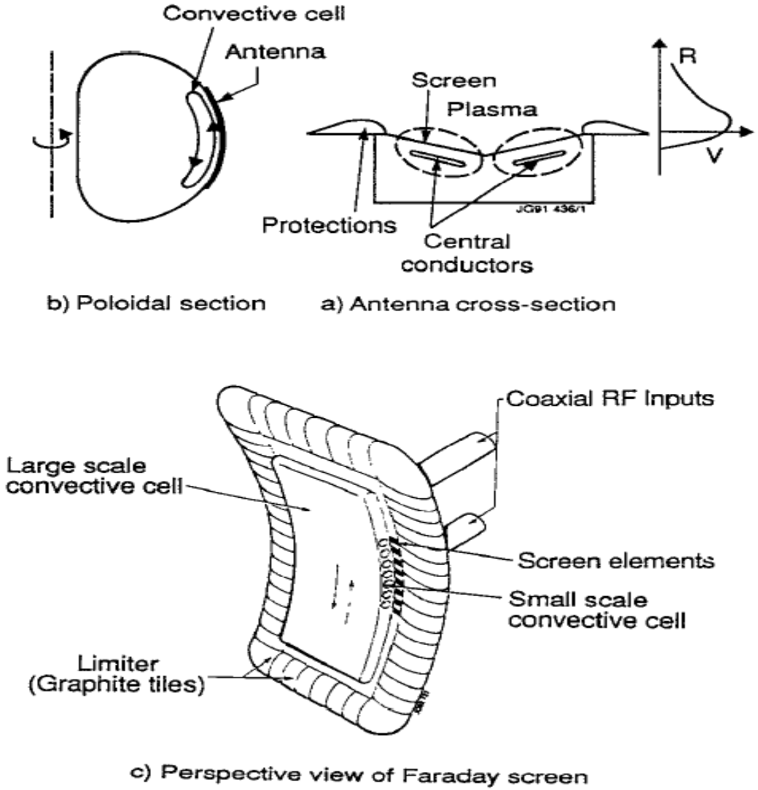
Typical variation of z_s

- real at low frequency
- imaginary at high frequency
- structure at ion cyclotron and plasma frequencies

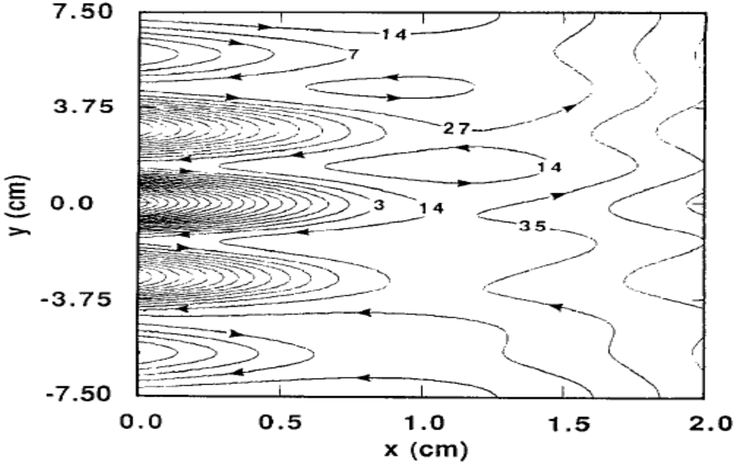
nonlinear dependence on RF amplitude requires iterative RF solves

- sheath resistance, Re z_s, $\Rightarrow$ RF power dissipation in the sheath (surface heating)

ICRF convective cells modeled in JET



local flattening when $\tau_{eddy} < L_{\|}/c_s$

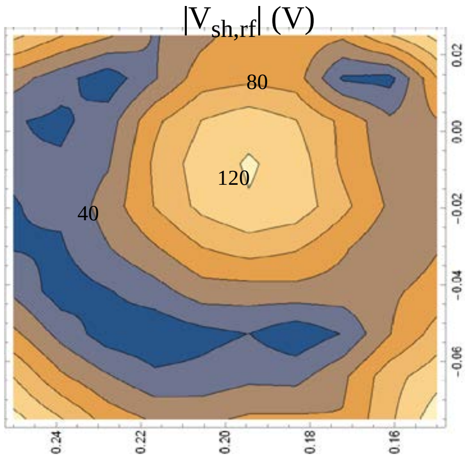


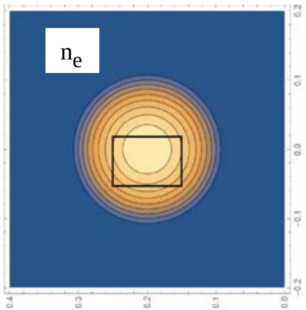
FS separatrix

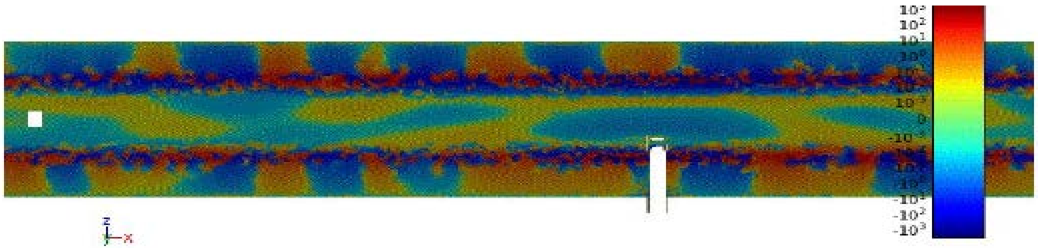
D'Ippolito PoP 1993

LAPD simulation and verification

- A new MFEM-based RF code Petra-M [Shiraiwa] has been employed to model sheaths in a proposed LAPD verification experiment
- FW are launched from an antenna; propagate down the column and are incident on a plate angled at 45 deg. to **B** and the column axis
- FW → SW polarization conversion occurs at the plate generating RF sheaths







Wright, Shiraiwa, Myra