ICRF-Edge and Surface Interactions

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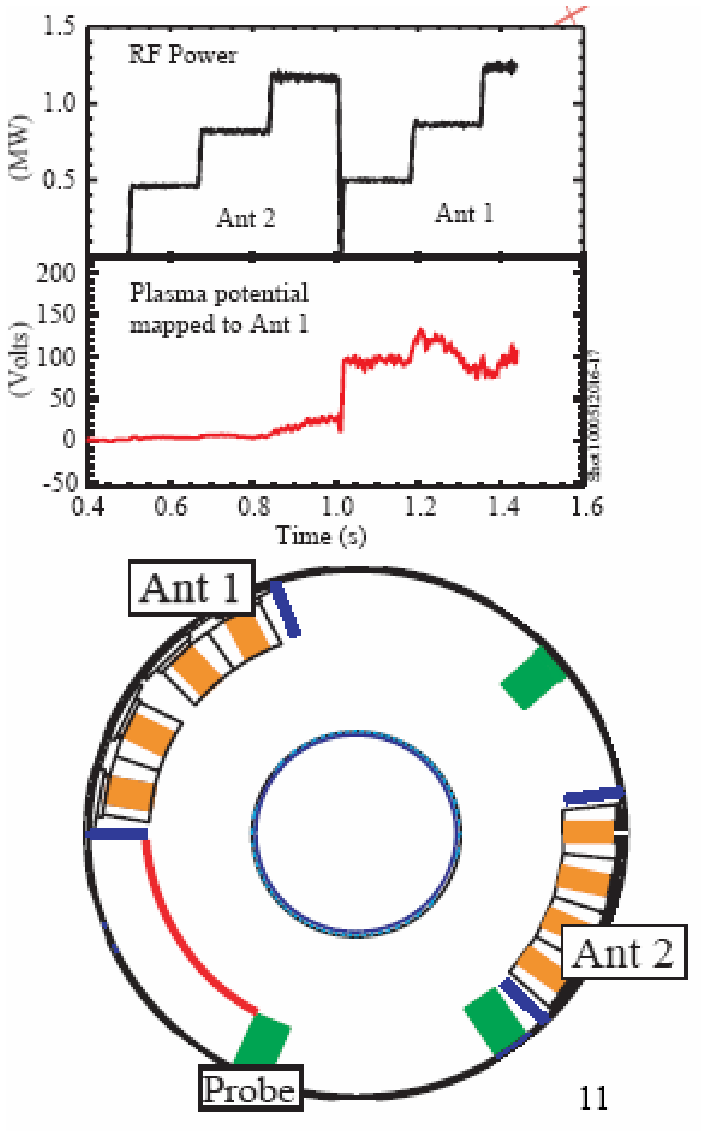
Introduction

- Heating and current drive with ICRF waves works well in many experiments, but unwanted rf-edge interactions remain a problem; these must be controlled for use of ICRF in long-pulse operation (ITER and beyond).
- Coupling MW of power to the edge of a tokamak plasma is a challenging task
  - complicated geometry and wave physics
  - nonlinear interactions, e.g. rf sheaths
- Rf sheaths impact
  - functioning and survivability of antennas, walls, and divertors
  - heating efficiency
  - impurity concentration of edge and core plasma

Physics of rf coupling ⇒ rf sheaths

- ICRF antennas are intended to launch fast waves (FW) with rf $\tilde{E}_{\|} = 0$
- Various mechanisms give parasitic coupling to slow waves (SW) with $\tilde{E}_{\|} \neq 0$
  - magnetic field line not aligned properly with antenna
  - electrostatic coupling / feeder and corner effects
  - wave propagation along field lines in SOL to walls
  - poor single pass absorption ⇒ waves at far wall
  - FW cannot satisfy BC at wall ⇒ local coupling to SW
- $E_{\|}$ accelerates electrons out of plasma; a (large) dc sheath potential develops to preserve ambipolarity

$$\Phi_{dc} \propto \Phi_{rf} = \oint ds\, \tilde{E}_{\|} >> 3T_e \ \text{(Bohm)}$$



ICRF antenna drives both local and remote sheaths. Example of latter is C-Mod:

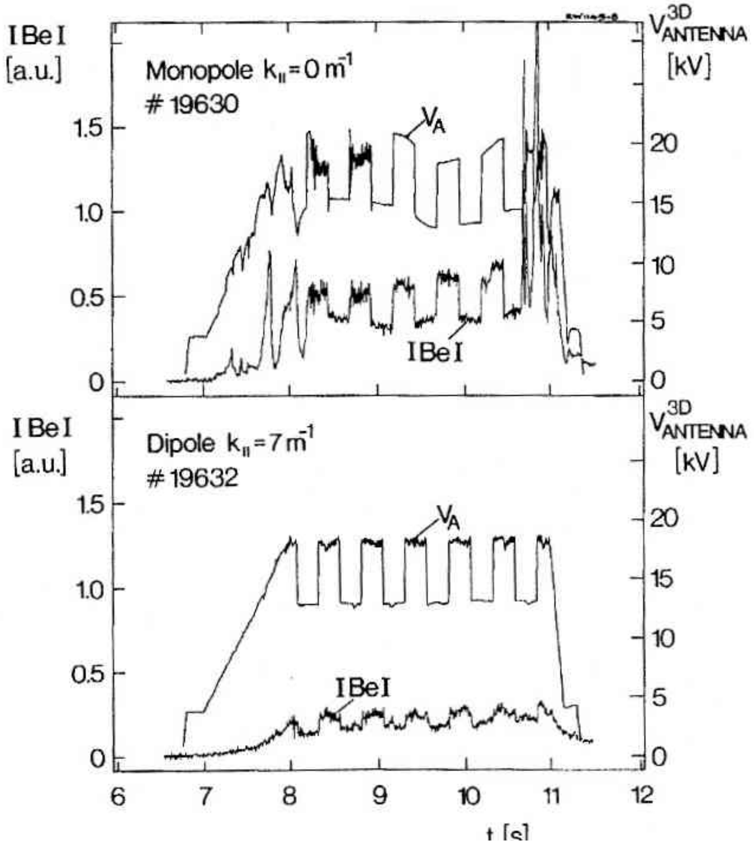
Large plasma potential (100 – 400 V) measured at top of outer divertor on **C-Mod**

- on field lines that map to antenna
- note: driven by antenna but appears at divertor several meters from antenna

The cause of this sheath is still a topic of active research (propagating SW, hot electrons?)

Wukitch IAEA 2006

RF sheath effects in ICRF experiments



JET, Bures et al. (1991)

(phasing dependence ⇒ rf sheath driven)

- rf specific effects
  - impurities (RF-enhanced sputtering)
  - rapid density rise
  - antenna damage (hot spots and arcs)
  - missing rf power
  - convective cells in SOL (increased particle flux to wall)
- implications for long-pulse operation (Tore Supra, LHD, ITER)

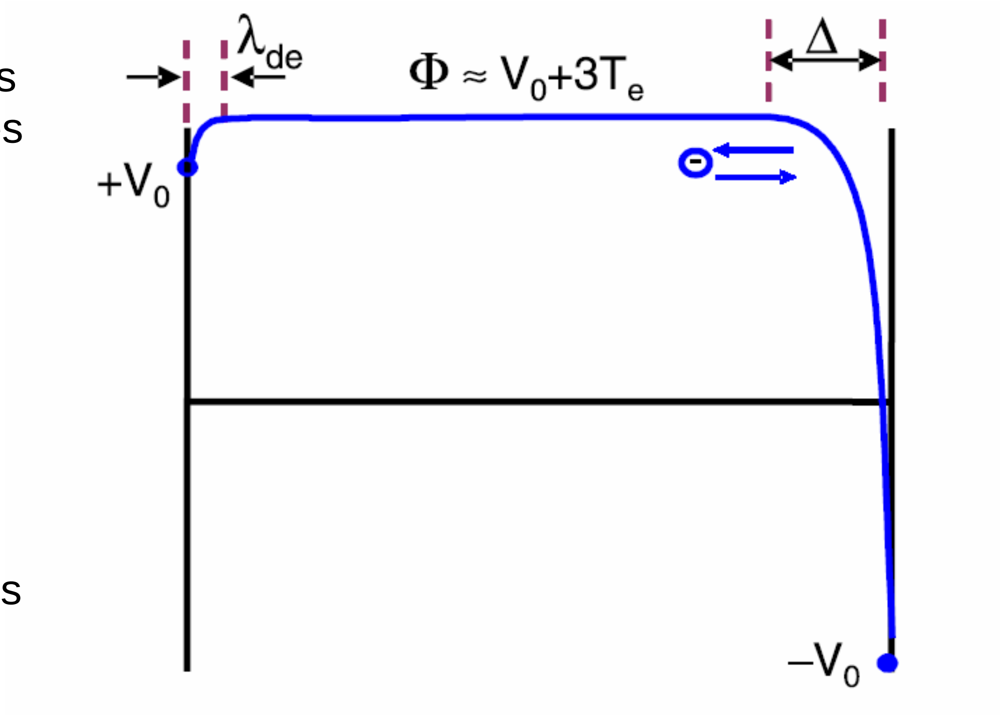
RF sheath rectification $\Rightarrow \Phi_{dc}$

Basic sheath physics. The sheath forms to equalize electron and ion loss rates. The resulting potential enhances electron confinement by forming a **potential barrier for electrons**, i.e. the sheath of width Δ .

The same potential **accelerates ions into the plates** and causes the dissipation of sheath power.

For the **rf-sheath**, the driving voltages $\pm V_0$ at each end oscillate in time and the central potential Φ_{dc} must remain ($\sim 3T_e$) above the maximum voltage at either end.

The rf sheath potential V_0 depends on wave polarization and B field geometry.



For high power ICRF heating, typically $\Phi_{dc} \sim V_0 >> 3T_e$

Outline of posters

- Physical mechanisms for sheath interactions with surfaces:
  - sheath power dissipation
  - sputtering
  - rf convection
  - parallel currents
  - electron heating
- Status of modeling
- Future plans

Sheath power dissipation

Ions are accelerated by the sheath potential and drain energy from the plasma. In the limit $eV_{sh} >> 3T_e$ the rate of power dissipation is given by

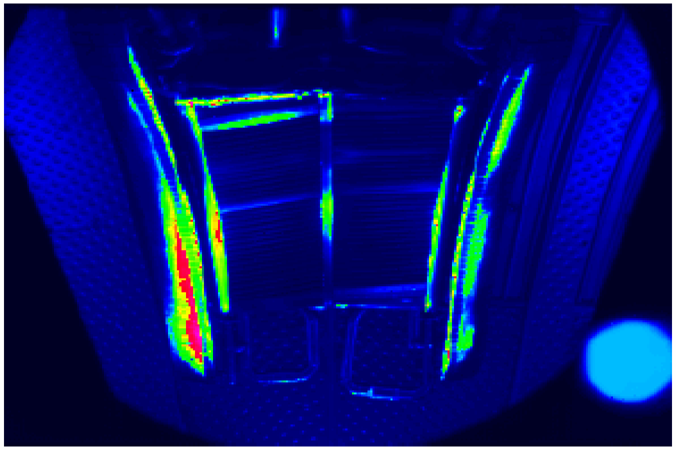
$$P_{sh} \rightarrow C_{sh}\, n_i c_s\, ZeV_{sh} A_{\perp}$$

where C_{sh} is an order unity rectification parameter.

Experimental consequences:

- **reduced core heating efficiency**
- **hot spots**
- **damage to surfaces**

hot spots on **Tore Supra** antenna

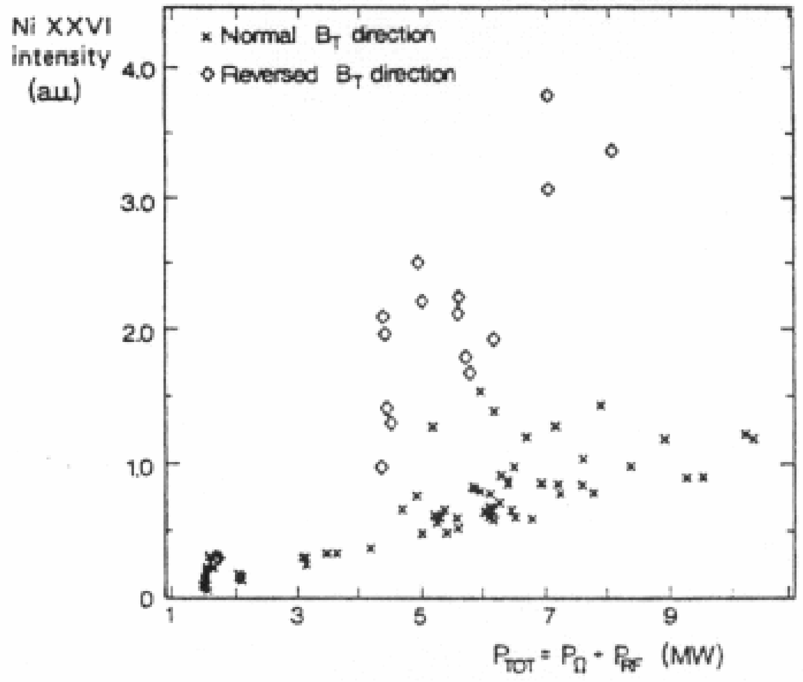


(L. Colas, 2005)

Rf sheaths enhance sputtering from antennas, limiters and walls

Ni impurity sputtered from **JET** antenna (Bures, NF 1990)

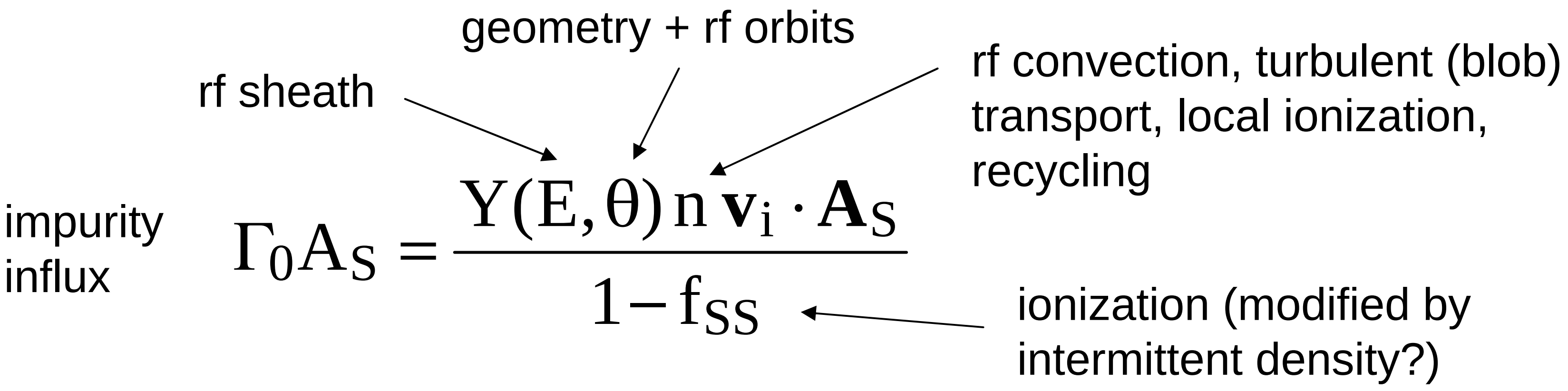
In the limit $eV_{sh} \gg 3T_e$, the **energy of ions hitting material surfaces is much larger than for thermal plasmas**. This increases the sputtering yield and makes a large difference in self-sputtering (**possibility of impurity avalanche**, e.g. Ni as observed in JET A1 antenna.)



In this figure: normal B ⇒ weaker sheath potential

reverse B ⇒ stronger sheath potential

Sputtering yield is sensitive to many factors



geometry + rf orbits

rf sheath

rf convection, turbulent (blob) transport, local ionization, recycling

impurity influx

$$\Gamma_0 A_S = \frac{Y(E,\theta)\, n\, \mathbf{v}_i \cdot \mathbf{A}_S}{1 - f_{SS}}$$

ionization (modified by intermittent density?)

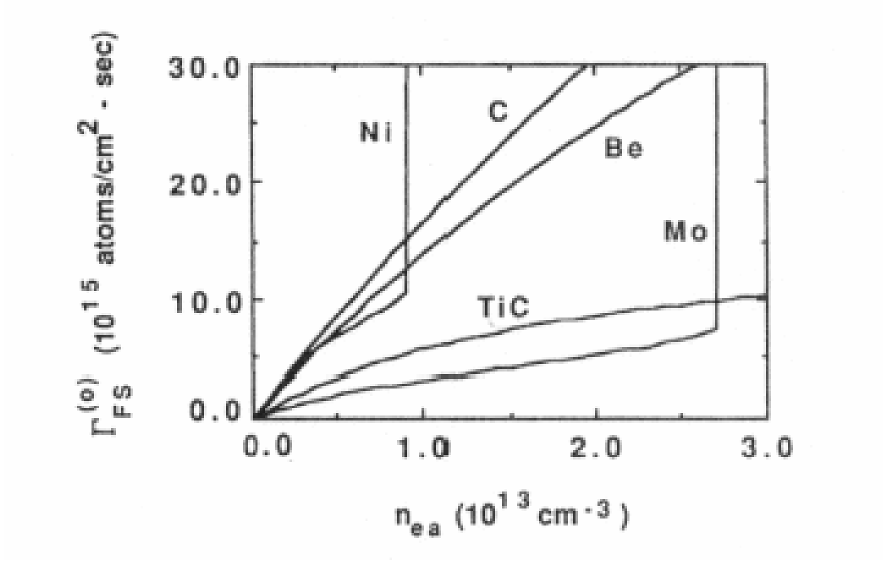
- **sputtering yield is enhanced by rf sheaths and by presence of light impurities** (Bures NF 1990, D'Ippolito PPCF 1991, Wukitch PSI 2008, Bobkov IAEA 2008 & NF 2010)
- **self-sputtering of high-Z material can be important for ions accelerated in high voltage rf sheaths** (Bures NF 1990, D'Ippolito PPCF 1991)
- **typical erosion rate is high at location of rf sheath** (Wukitch PSI 2008)

Self-sputtering for high-Z materials

- self-sputtering of high-Z materials is enhanced by a large rf sheath potential

calculated impurity influx from JET A1 FS for various materials

(D'Ippolito et al., PPCF 1991)



- for fixed average density, intermittency (blobs) can reduce or enhance the self-sputtering yield of high-Z impurities **(D'Ippolito and Myra, PoP 2008)**

rf-driven convection

Integrating the current conservation equation, $\nabla\cdot \mathbf{J} = 0$, along field lines gives the vorticity equation for the dc potential

$$\frac{c^2}{B^2} n m_i \frac{d}{dt} \nabla_\perp^2 \Phi = \frac{J_\|}{L_\|}\Bigg|_{-L_\|/2}^{+L_\|/2} \equiv \frac{J(\Phi - \Phi_0)}{L_\|}$$

where $J(\Phi\text{-}\Phi_0)$ is the sheath current-voltage relation specifying the net current flowing out of the system and Φ_0 is the rectified potential (1D model). $\Phi >> \Phi_0 \Rightarrow$ 2D sheath model with perpendicular currents

2D model implies [D'Ippolito, PoP 1993; D'Ippolito NF 2002]

(1) dc **ExB convection** driven by the spatial variation of Φ

(2) also **perpendicular currents** due to ion polarization drift

rf convection and sheath-induced currents

Experiments indicating rf sheath-driven convection:

- needed to account for density profile and loading in JET ICRF H-modes (D'Ippolito PoP 1993)
- measured directly with reflectometers on TFTR [D'Ippolito NF 1998]
- explains heat-flux asymmetry on Tore Supra [Colas, 2005]
- perpendicular currents may explain mixed-phasing antenna experiments on JET [D'Ippolito NF 2002] and sheath-driven currents getting past insulating limiters on C-Mod [Wukitch PSI 2008]

Asymmetric sheaths (e.g. different areas or different voltages) at the two ends of a field line will drive **parallel currents**. Throughput current can be estimated as

$$\langle I_{\text{thro}} \rangle = I_s \frac{I_0(\xi_1) - I_0(\xi_2)}{I_0(\xi_1) + I_0(\xi_2)}$$

$I_s = A n_e e c_s$ = ion sat. current

$\xi = eV_{rf}T_e$

Currents flowing from antenna to limiter observed on TEXTOR [Van Nieuwenhove, PPCF 1992]

Other effects related to rf sheaths

- Sheath-induced parallel current can sustain arcing when

$$I_s \equiv n e c_s A_\perp > I_{min}$$

where I_{min} = min. current to sustain an arc (~1 – 10 A). Important factors include secondary electron emission, hot electrons, surface roughness and thermal conductivity.

- ICRF can produce hot electrons
  - Fermi acceleration by moving sheaths [Lieberman and Godyak, 1998]

- Hot electrons stream along magnetic field to boundary

  ⇒ stronger sheath potential

  e.g. may account for difference in sheath potentials in L / H mode on C-Mod [Wukitch PSI 2008]

Status of modeling

- Most previous work (and present ITER antenna design studies) use the **vacuum sheath approximation**

$$V_{rf} = \oint ds\, E_{||}$$

where $E_{||}$ is the vacuum rf field component || B and the integral extends between sheath contact points with boundary

- We are now exploring a different approach [D'Ippolito, PoP 2006; Myra PoP 1994] using a "**sheath BC**" at the sheath-plasma interface in the rf full-wave and antenna codes.

$$\mathrm{BC:} \quad \mathbf{E}_t = \nabla_t (\Delta \mathbf{D}_n)\,, \qquad V_{rf} = |D_n \Delta|$$

  - sheath is treated as a thin vacuum layer with a finite capacitance
  - Maxwell eqs imply continuity of E_t and D_n (t = tangential, n = normal)
  - Self-consistent sheath width Δ is determined by nonlinear Child-Langmuir Law

Progress and future plans for rf modeling

- Several analytic calculations have been carried out in various sheath geometries to explore the physical content of this BC. [D'Ippolito, Myra, 2006 - 2010]

- Work is in progress to develop an rf wave propagation and sheath code for the SOL ("rfSOL") with realistic geometry and sheath BC (H. Kohno et al., MIT-Lodestar collaboration).

- Experiments are planned on the LAPD linear plasma device to test the sheath physics in rfSOL code against experimental data.

Coupling to edge turbulence, atomic and wall physics…

- need quantitative estimates of particle fluxes into antenna and wall to calculate sheath interactions
  - n_e ↑ gives **better antenna coupling**
  - particle flux to antenna ↓ to **minimize sheath effects**
  - **far SOL fluxes are intermittent and not well known**: blob transport, particle sources (recycling and ionization), and rf convection are important
    - e.g. ITER team **varies fluxes by 10^2** in antenna sheath assessments ⇒ large sensitivity!

- code integration needed to study trade-off between good coupling and acceptable sheath effects in ITER
- need to calculate intermittent fluxes as well as time-averaged ones
  - note that $\langle f(Q)\rangle \neq f(\langle Q\rangle)$ for any nonlinear f, e.g. Q = ionization

Summary

- rf sheath effects are important for understanding the ICRF heating efficiency, impurity concentration, and survivability of antennas, limiters and wall.
- many aspects of sheath interactions have been studied, both theoretically and experimentally
- a new generation of codes is being developed for calculating self-consistent sheath formation (rf SciDAC project)
- quantitative modeling will require integration of rf codes with SOL turbulence and transport, atomic physics, wall physics codes.