ICRF-Edge and Surface Interactions

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Introduction

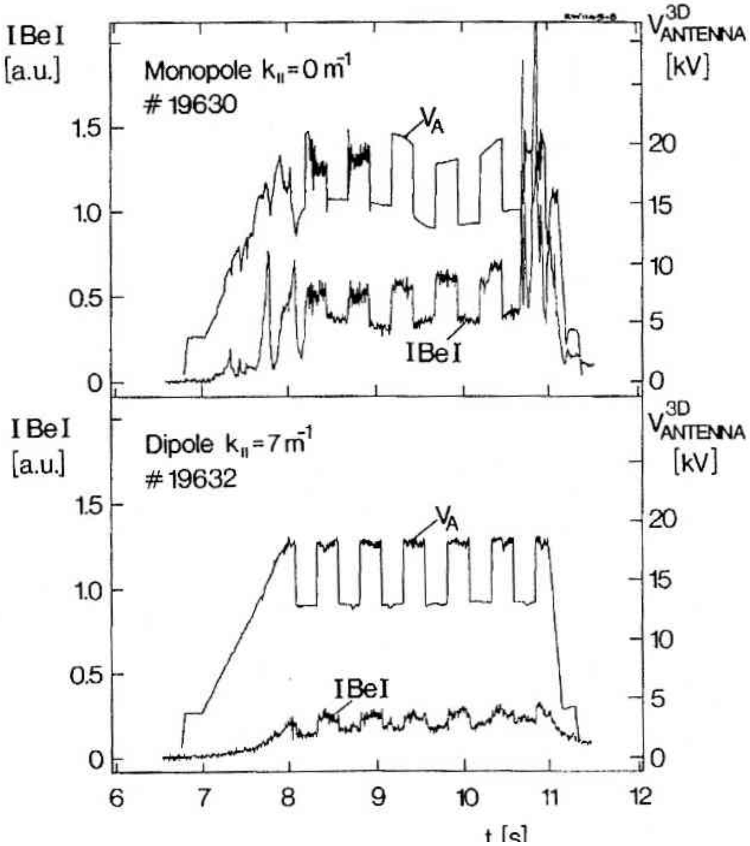
- Heating and current drive with ICRF waves works well in many experiments, but unwanted rf-edge interactions remain a problem; these must be controlled for use of ICRF in long-pulse operation (ITER and beyond).
- Coupling MW of power to the edge of a tokamak plasma is a challenging task
  - complicated 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

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

RF sheath effects in ICRF experiments

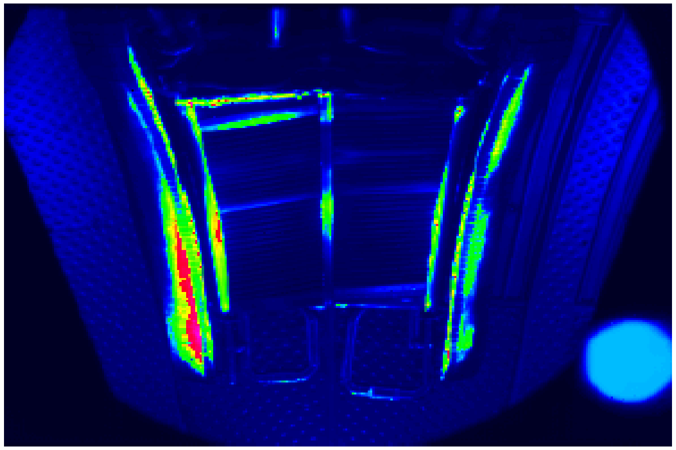


JET, Bures et al. (1991)

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

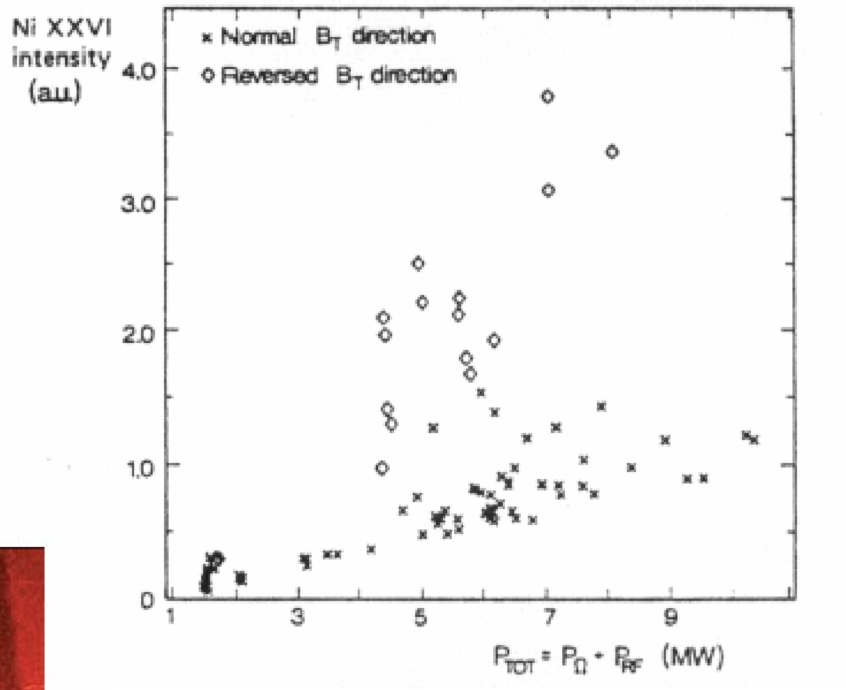
Experimental evidence

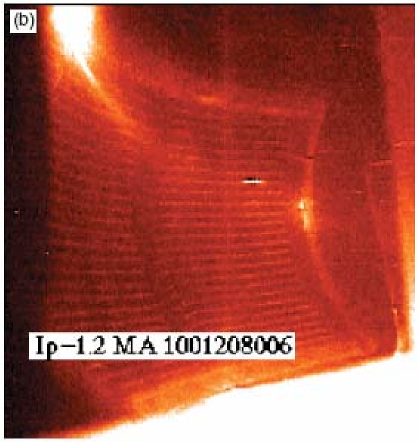
hot spots on **Tore Supra** antenna



(L. Colas, 2005)

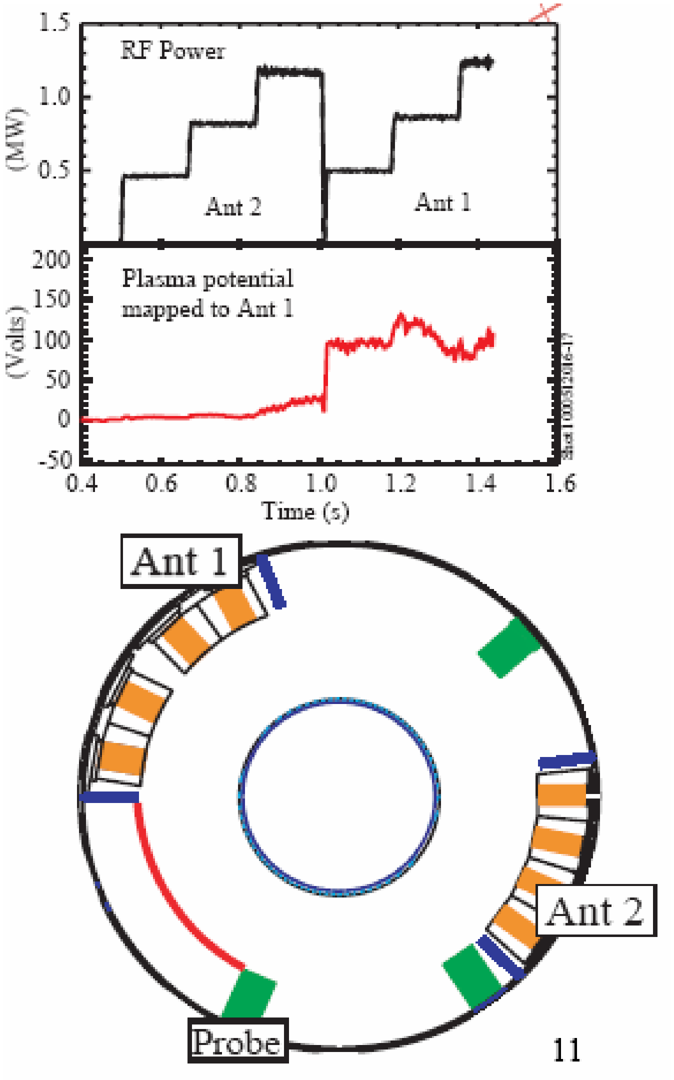
Ni impurity sputtered from **JET** antenna (Bures, NF 1990)





rf sheath interaction with Faraday screen follows field line on **C-MOD**

(Wukitch, PPCF 2004)



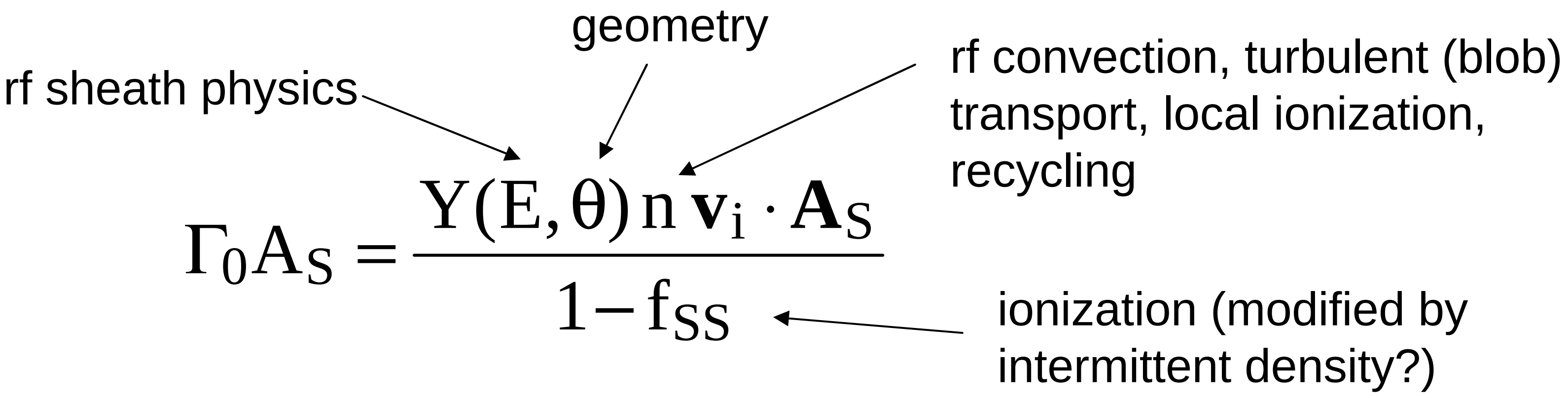
Large plasma potential (100 – 400 V) measured at top of outer divertor on **C-Mod**

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

Wukitch IAEA 2006

Proposed work: integrated effort to solve coupled physics issues

- We have developed many models in the past 25 years which give qualitative agreement with experiments on JET, TFTR, C-Mod, ASDEX-U, Tore Supra, TEXTOR, etc.
- Quantitative predictions of sheath interactions are still not available, partly because of technical issues, partly because of needed input from other areas, e.g. sputtering yield



geometry

rf sheath physics

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

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

ionization (modified by intermittent density?)

Scope of problem

The SOL couples physics in several areas:

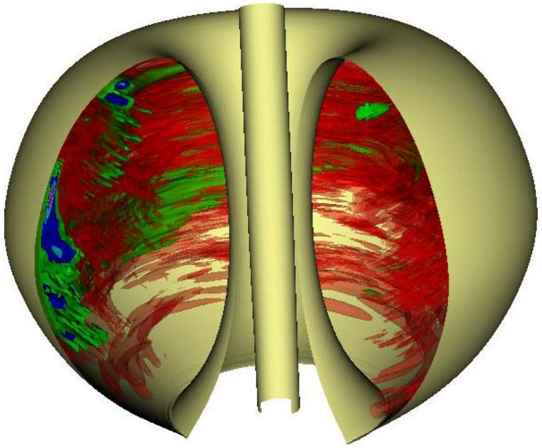
- RF physics (linear wave propagation, nonlinear sheath)
- SOL turbulence (intermittent transport)
- Surface and atomic physics (plasma – wall interactions)

Describe the present status and future directions of the rf area and some remarks about other areas.

Important caveat:

- The rf community (e.g. RF SciDAC project) is developing sophisticated codes for antenna coupling, linear wave propagation and quasilinear heating, nonlinear effects (rf generation of sheared flows) etc.
- There is also a growing effort on modeling sheath effects (analytically and numerically) but this work is not as developed yet.
- Here we are not going to discuss what the rf codes do well, but what they lack!

NSTX



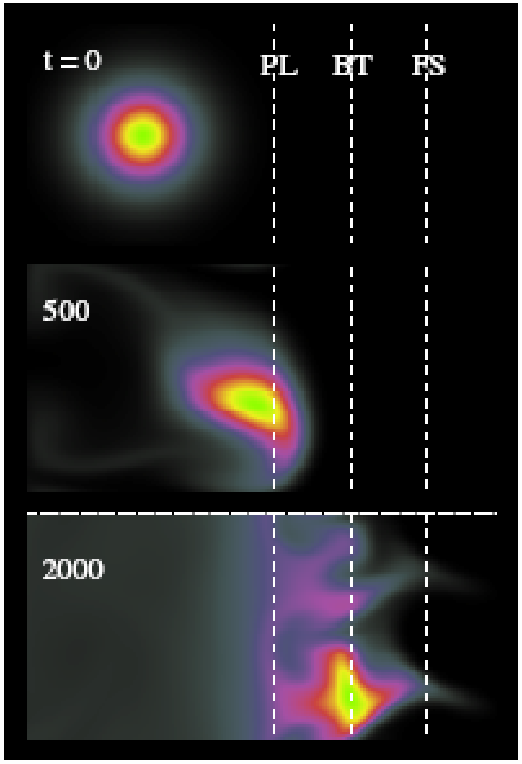
Jaeger, RF Conf. 2007

RF physics for plasma-wall interactions

- spatial distribution of the rf wave energy, rf sheaths and rf-enhanced sputtering energy
  - requires better treatment of SOL plasma and boundary in the wave codes, better treatment of sheaths, and better coupling of turbulence and transport codes
  - new approach: sheath BC for rf codes
- sheath power dissipation
  - local power density ⇒ hot spots
  - integrated over all surfaces ⇒ "missing power", heating efficiency
- interaction between rf waves and turbulence in SOL
  - SW propagation through intermittent (spiky) density field
  - rf effects on SOL turbulence and blobs

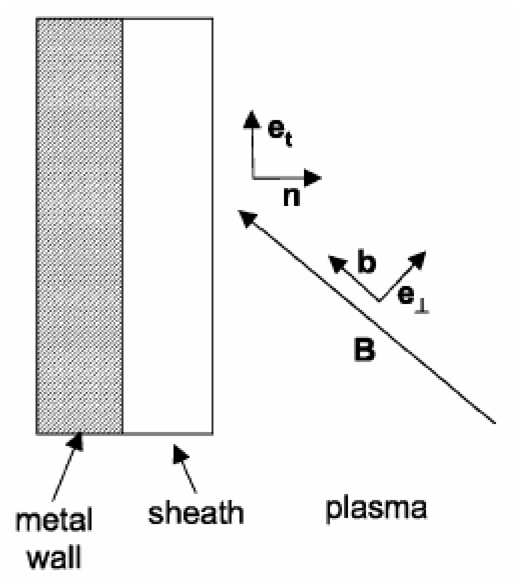
Preliminary modeling of rf + turbulence

- Preliminary work on studying interaction between
  - blobs (Lodestar 2D SOLT code)
  - rf-driven convective cells for a simplified model antenna-sheath pattern



(D'Ippolito et al., RF Conf. 2005)

Sheath BC (D'Ippolito and Myra PoP 2006, Myra et al., PoP 1994)



normal component of B into wall ⇒ electron losses ⇒ sheath

sheath BC: normal component of D continuous across vacuum sheath-plasma interface implies $\mathbf{E}_t = \nabla_t(\Delta D_n)$

Δ = sheath width, must satisfy Child-Langmuir constraint ⇒ **nonlinear BC**

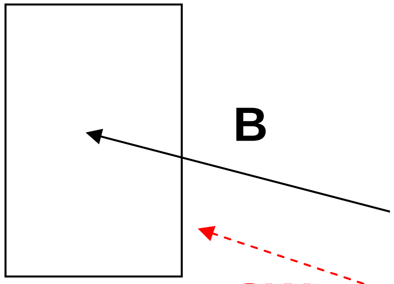
- We have used this BC (with nonlinear solution to CL constraint) to obtain **analytic solutions** for sheath potential in various geometries.
- Can give **local solution** for sheath potential **in rf codes** using nonlinear iteration or rootfinder

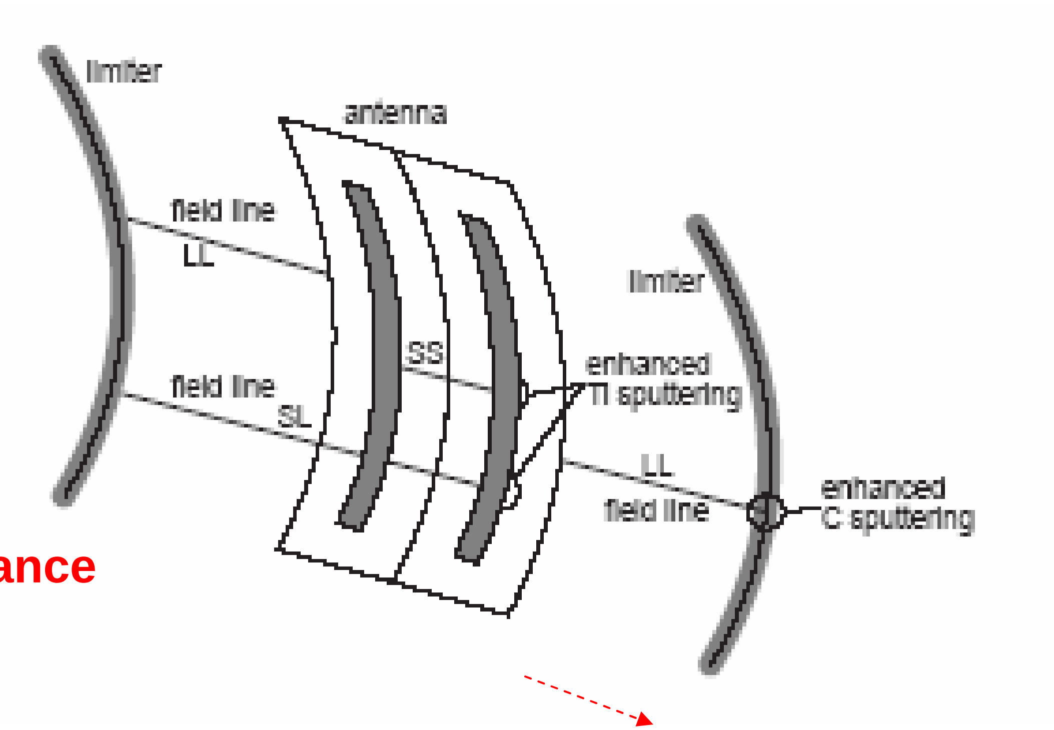
RF sheath topography

far-field

sheaths

(divertor or
distant limiter)


B



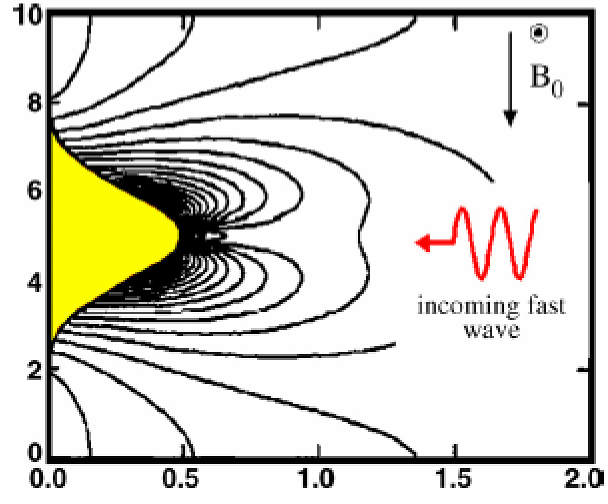
SW
(resonance
cone)

core plasma with **low**
single pass absorption

surface
modes (FW)

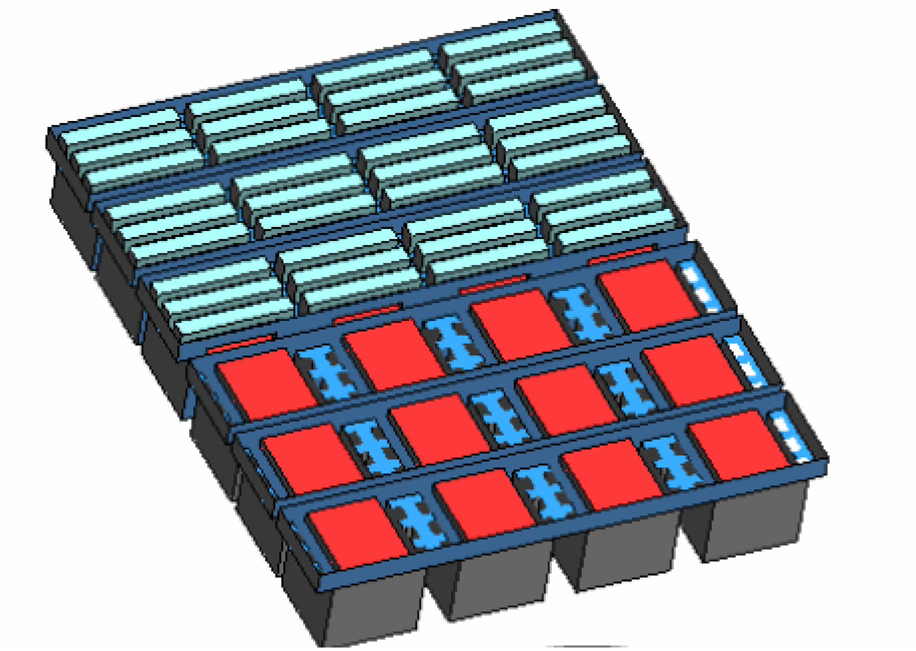
FW + SW

(at far wall)



(Myra et al. PoP 1994)

status: near field (antenna) sheaths



model of 24-strap ITER-like antenna for TOPICA antenna code

(Maggiora et al., 2008)

- **TOPICA calculations** (U of Turin) use detailed antenna geometry, match to plasma impedance
- use vacuum fields and vacuum sheath approximation
- work has begun to implement the sheath BC **(Van Compernolle, 2008)**
- difficult to have plasma at antenna

Recent **analytic antenna sheath calculation** using the sheath BC has derived corrections to the vacuum sheath approximation.

(D'Ippolito and Myra, PoP 2009)

status: far field sheaths

- unabsorbed FW or surface wave: reaching the far wall and generating SW / sheaths due to B field mismatch with the wall
  - early numerical simulation for model geometry **(Myra et al., PoP 1994)**
  - recent analytic (1D wave scattering) model using the sheath BC to locally solve for sheath potential **(D'Ippolito and Myra, PoP 2008)**
  - 2D wave codes not yet able to treat this problem (lack realistic SOL geometry, sheath BC not implemented)

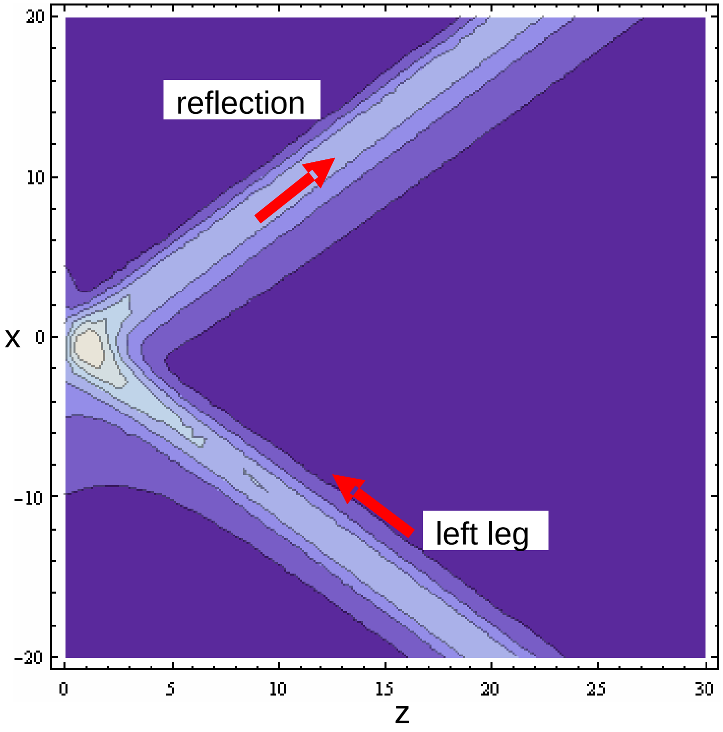
- SW resonance cones: SW launched by antenna in low density SOL and propagates to distant limiters / divertor (e.g. C-Mod?)
  - dispersion relation

$$n_\perp^2 = -\varepsilon_\parallel n_\parallel^2 \quad \text{where} \quad n_\parallel >> 1$$

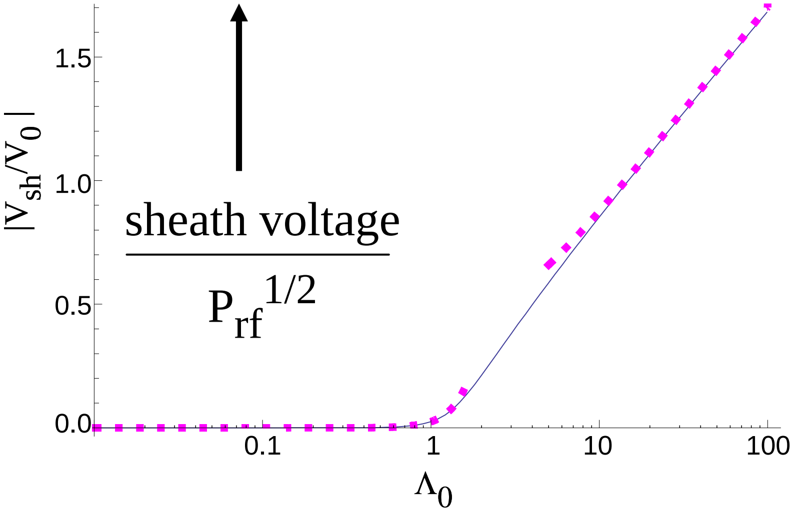
  - recent analytic calculation of SW scattering off sheath (using the sheath BC) calculates the fraction of antenna voltage transferred to distant boundary **(Myra and D'Ippolito, PRL 2008)**

Antenna launches slow-waves which propagate as *resonance cones* to limiter ⇒ enhanced sheaths

J.R. Myra and D.A. D'Ippolito, Phys. Rev. Lett. 101, 195004 (2008)



resonance cone reflecting off a sheath



$$\Lambda_0 = -\frac{\lambda_{de}\varepsilon_{\parallel}}{a}\left|\frac{\alpha e V_0}{T}\right|^{3/4} \sim n_e^{1/2} P_{rf}^{3/8}$$

sheath voltage shows a threshold in Λ_0

provides a candidate explanation of sheaths on C-Mod observed far from the antenna

status: rf modeling of SOL

- quantitative estimates require a new kind of code for modeling rf wave propagation and sheath formation in the SOL
  - accurate description of SOL geometry (B field, antenna and wall geometry, density profiles, etc.)
  - rf wave solver
  - resolve electron space scales (~c/ω_{pe})
  - nonlinear rf sheath BC

- work has begun at MIT in collaboration with Lodestar to develop such a code as part of the rf SciDAC initiative. (Kohno, Bonoli, Wright, Freidberg, Myra and D'Ippolito, 2009)

Role of turbulence

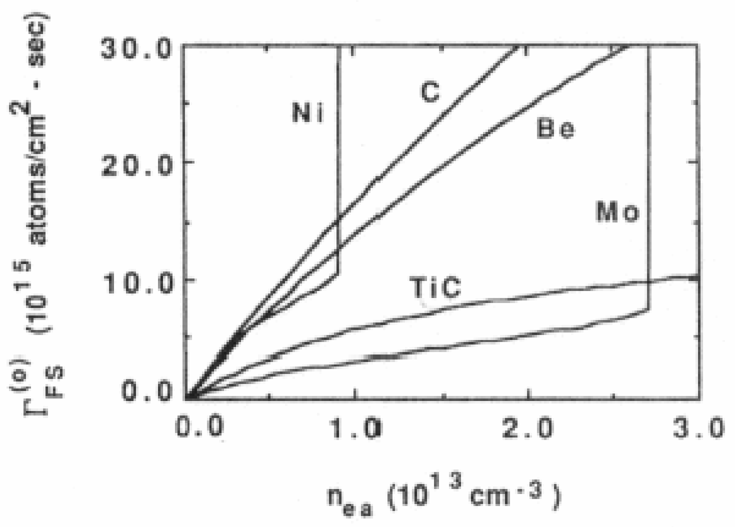
- need quantitative estimates of particle fluxes into antenna and wall
  - n ↑ for good antenna coupling
  - particle flux ↓ to minimize sheath effects
  - far SOL fluxes are not well known: blob transport, particle sources, and rf convection are important
    - e.g. ITER team varies fluxes by 10^2 in antenna sheath assessments ⇒ large sensitivity (failure vs success!)
- 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

Atomic and wall physics

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

calculated impurity influx from JET FS for various materials

(D'Ippolito et al., PPCF 1991)



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

Integrated modeling

- integrated modeling including rf sheath interactions is needed for hardware design (antennas, first wall), scenario development, and interpretation of experimental results. → needed for ITER.
- "grand vision" for long-term research: integrate physics of edge (turbulence, transport, atomic physics), rf (antenna coupling, SOL wave propagation, sheaths), and wall physics (sputtering, recycling).
- this capability would provide
  - self-consistent characterization of SOL plasma
  - antenna loading and heating efficiency
  - sheath effects (power dissipation, sputtering)
  - more accurate estimate of wall lifetime

Available tools for this project

- analytic sheath models **(Lodestar)**
- rf antenna codes
  - 2D **(ORNL)**
  - 3D **(U of Torino, ORNL)**
- rf wave propagation codes
  - frequency domain **(ORNL, MIT)**
  - time domain **(TechX)**
  - need sheath BC or matching to SOL wave code
- SOL rf wave code **(MIT-Lodestar)**
  - under development at MIT
- SOL turbulence codes
  - 2D **(Lodestar)**
  - 3D **(LLNL)**
  - 5D codes under development **(LLNL, NYU)**
- edge plasma transport codes (LLNL)
- sputtering and impurity transport codes