Time-Domain Modeling of Plasmas at RF-Time Scales

SciDAC Project: Center for Simulation of Wave Plasma Interactions
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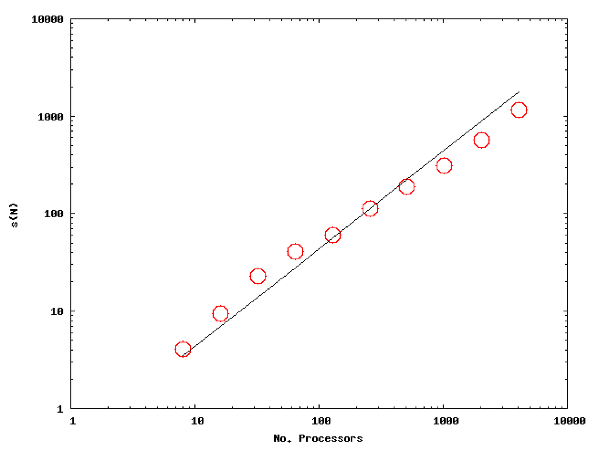
Abstract

Results from tokamak experiments such as PPPL's NSTX indicate that significant anomolous power absorption can occur in the edge of the fusion plasma. Understanding of this phenomenon is a critical issue for analysis of RF heating scenarios on the ITER fusion experiment. Two probable edge absorption candidates, rf sheath losses and parametric decay instability, are both inherently non-linear, and likely to depend significantly on non-axisymmetric geometric detail in the vicinity of the antenna structures. Analysis of these phenomenon is beyond the capabilities of existing axisymmetric freqeuncy-domain linear-solvers used for analysis of RF heating and current drive in core fusion plasma, and so we are augmenting our analysis capability with the time-domain 3-D general-geometry electromagnetic and particle-in-cell simulation framework, Vorpal[1]. This framework is a modern object-oriented software package, which has demonstrated fast scalable operation on clusters of over 1000 cpu's, a necessity for this type of calculation. We have successfully introduced into this framework an implicit plasma solver[2], in order to accurately treat electromagnetic plasma wave characteristics in the wide range of plasma conditions occuring from edge plasma to core plasma, including situations where the plasma frequency is not resolvable at the rf time-scales of interest, and including sharp plasma resonances and cutoff behaviors common in the rf regime. We present benchmarking of this new plasma solver for 1-D, 2-D, and 3-D scenarios. We also discuss implementation plans for non-linear sheath boundary models, non-linear edge-plasma conditions leading to parametric decay, and also tracking of high-energy particles in core-heating scenarios, where issues of finite-banana-width effects and superadiabaticity remain outside the scope of the existing frequency-domain solvers.

Time-domain plasma algorithm is implemented & verified in VORPAL

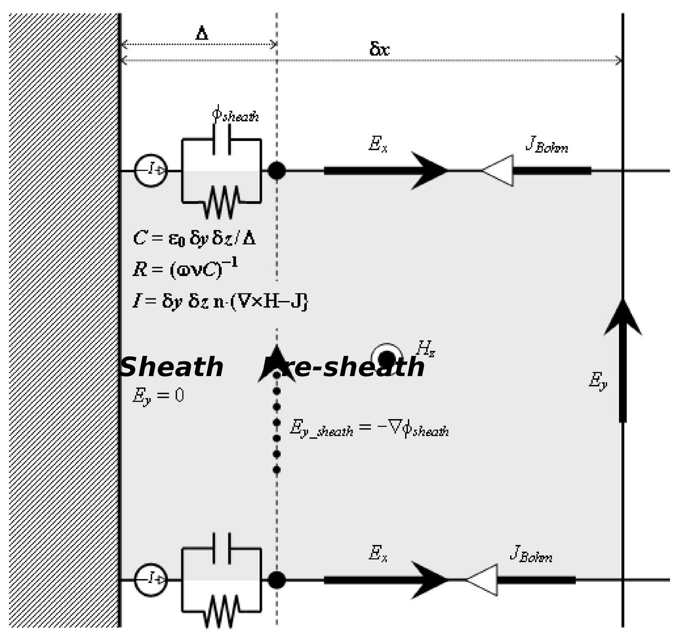
Takes advantage of pre-existing
- Parallel processing communications
- General definable fields
- Boundaries, including cut-cells
- PIC and Delta-F particle dynamics
- Diagnostics and Visualizations



Speedup of VORPAL on the Seaborg supercomputer at NERSC.

VORPAL has demonstrated excellent parallel speedup with pre-existing algorithms. Speed-up with new time-domain plasma algorithm is expected to also be favorable, with computation dominated by point calculations, and field communications based upon pre-existing framework.

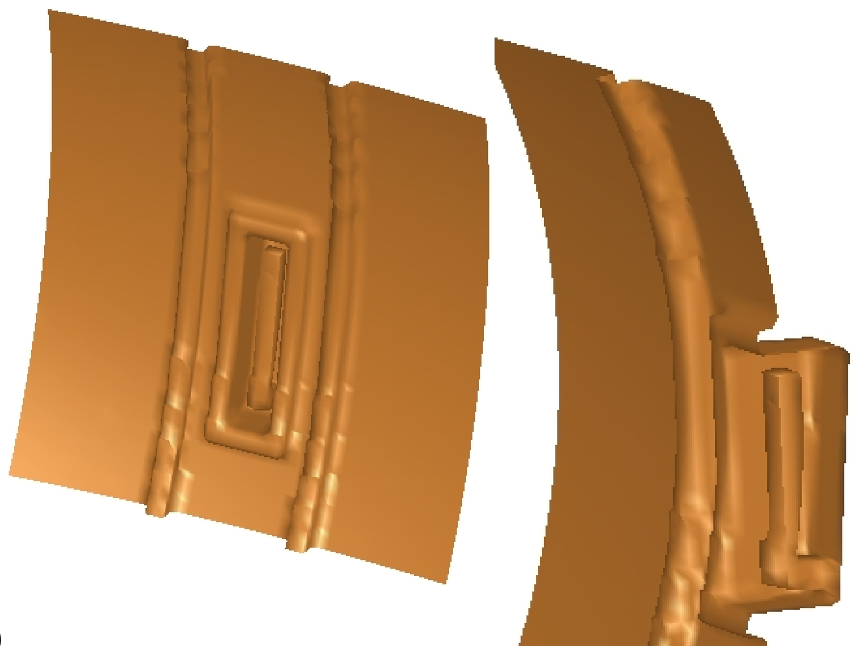
Edge Sheath Model is in Progress



The RF sheath resembles a lossy capacitor, where the capacitance width, Δ, and loss parameter, ν, depend non-linearly on the RF electric field at the edge.[4] The voltage across the capacitance, ϕ_{sheath}, is the sheath potential.

Initial Demonstration with 3-D Edge Geometry

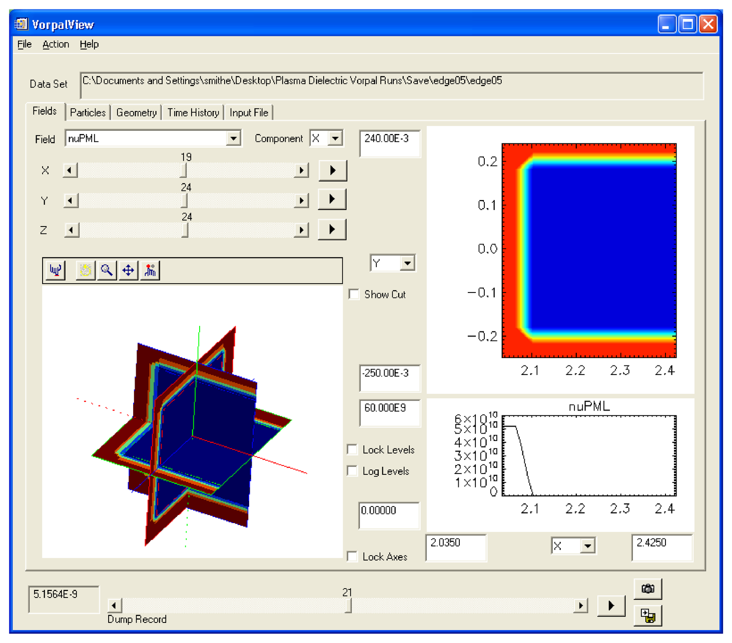
Simplified 3D loop-coupler geometry
- Toroidal Surface
- Coupler box
- Loop
- Limiter on box
- Two more limiters



Loop
- Shorted on bottom
- Open-circuit on top
- Current runs across open circuit

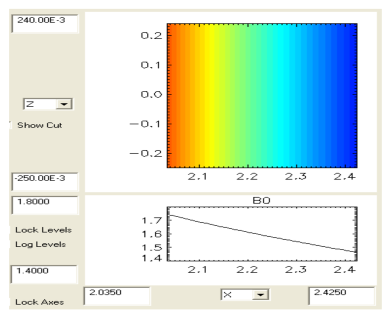
Use Absorber for other Boundaries

- PML (a general purpose absorber) on five of six sides.
- Matched damping
  - E, B, and J
- Prevents reflection

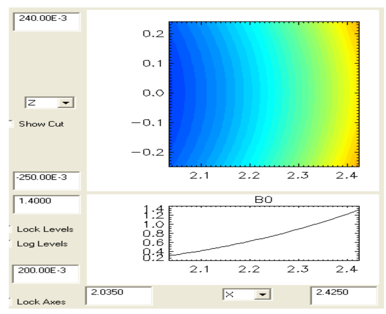


Use Tokamak Edge Plasma Profiles

B toroidal
~1/R

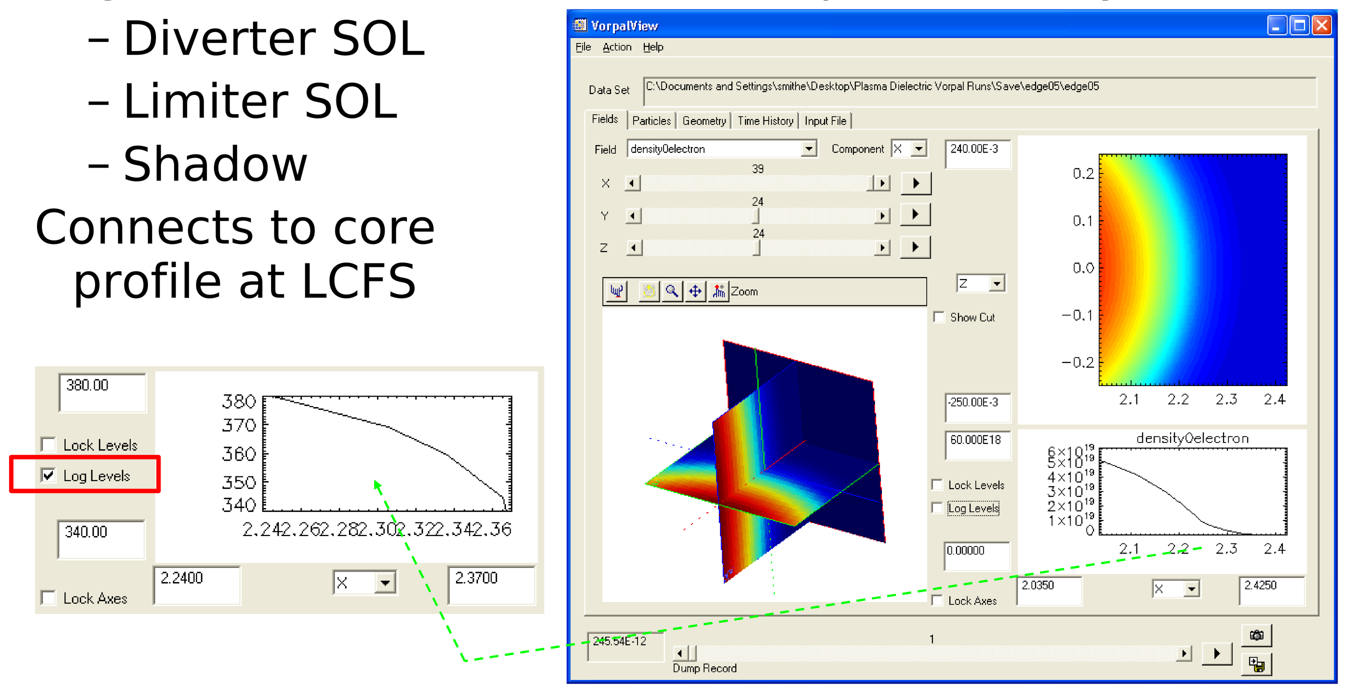


B polodial
~Q(r)

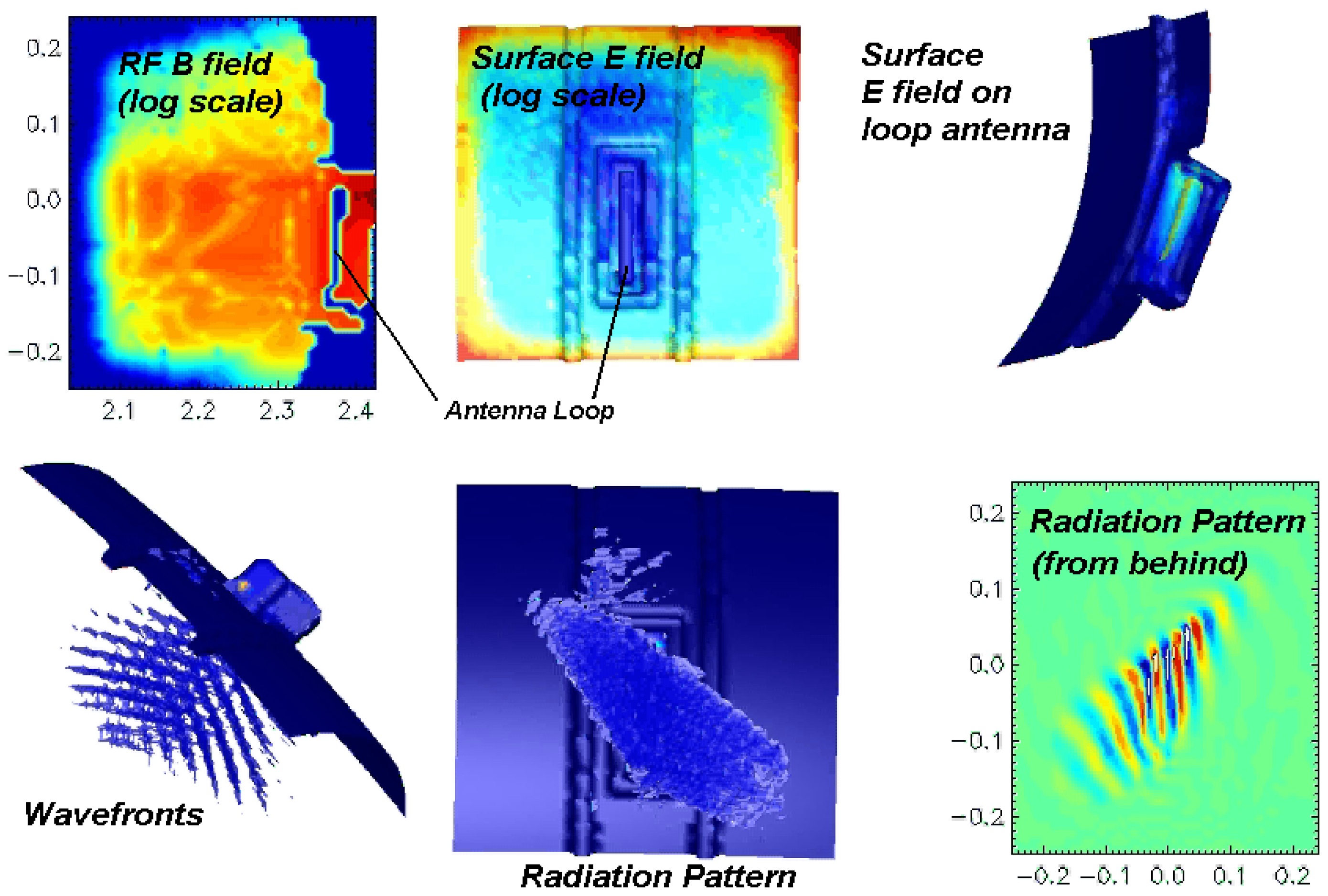


Edge Plasma consists of three exponential layers
- Diverter SOL
- Limiter SOL
- Shadow

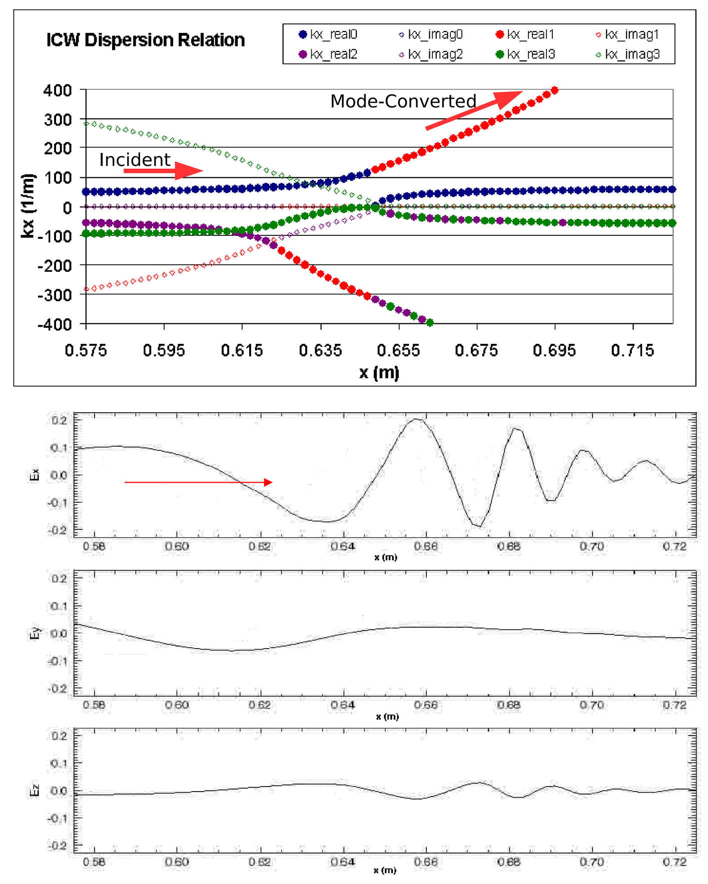
Connects to core profile at LCFS



Simulation Data and Animation



ICW Benchmark

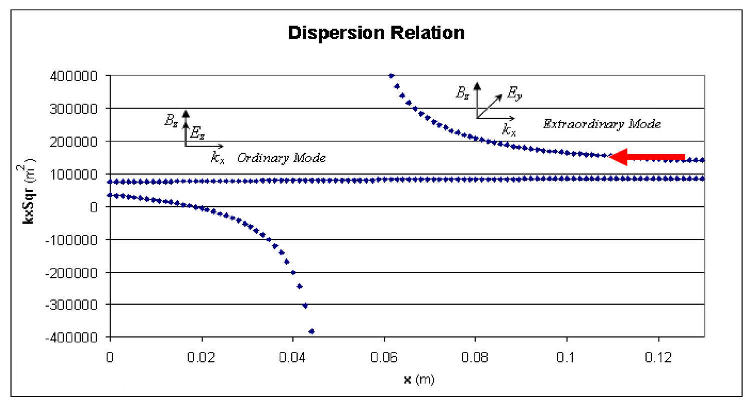


Disperesion relation for ICW caseof Ref. 3. Power is incident from the left, along the +kx fast wave sees a strong mode conversion to the IBW wave

The oblique angle of the field results in all three components being non-zero. *Ez* is dominated by the mode-converted ICW, while *Ey* is dominated by the fast wave, and *Ex* shows both modes.

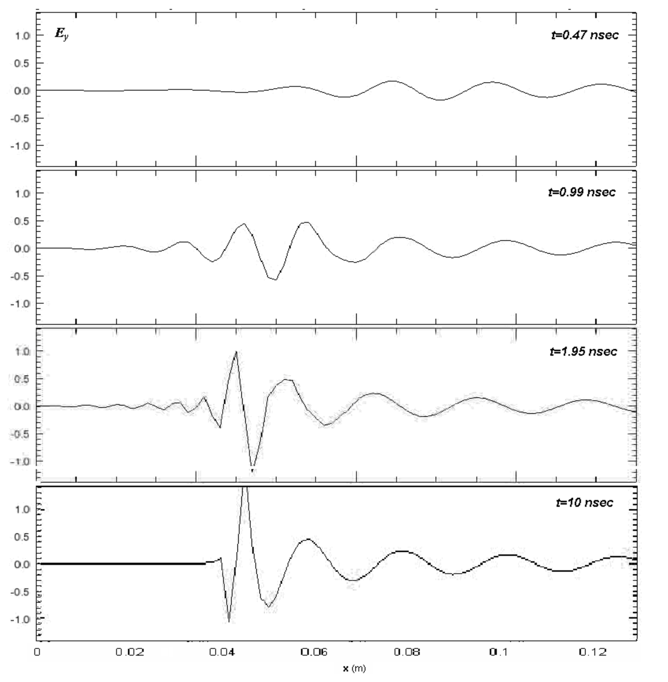
Resonance-Cutoff Benchmark

Dispersion relation for propagation into a resonance-cutoff.



The extraordinary wave enters from the right, and pumps the resonance, with no transmitted power on the resonant branch, due to the cutoff.

Temporal evolution of *Ey* component. In time-domain it takes many rf periods to establish the sharp distinctive field pattern of a resonance.



[1] D. Smithe, Physics of Plasmas, Vol. **14** 056104 (2007).
[2] Chet Nieter and John Cary, Journal of Computational Physics, Vol. **196** (2004).
[3] E. F. Jaeger, L. A. Berry, J. R. Myra, et al., Phys. Rev. Lett. 90, 195001-1 (2003).
[4] D. A. D'Ippolito, J. R. Myra, D. A Russel, and M. D. Carter, LRD-05-104 (2005).

SciDAC '07 Conference

Boston, MA
June 25-28