Physics Research in The SciDAC Center for Wave – Plasma Interactions

Paul Bonoli on behalf of the SciDAC Center for Simulation of Wave-Plasma Interactions

Meeting of the PSACI Program Advisory Committee
Princeton Plasma Physics Laboratory
June 7-8, 2007

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Outline

- **Results produced over the course of the past year:**
  - Successful comparison of synthetic diagnostic for energetic ion tail detection with experimental measurements in Alcator C-Mod.
  - Quasilinear evolution of multiple nonthermal ion species.
  - Calculation of full admittance matrix needed to couple full-wave solver (TORIC) to 3D electromagnetic antenna code (TOPICA).
  - Time domain simulations of ICRF antenna loop – edge plasma using VORPAL.
  - Scaling of full-wave solvers to 5000-22,500 processor range (AORSA, TORIC, and TORICLH).
  - 3D reconstruction of ICRF wave fields from full toroidal mode spectrum of antenna loops in NSTX and ITER.
  - Implementation of nonthermal ions and electrons in TORIC in preparation for closed loop coupling between TORIC and CQL3D.
  - Scaling of Monte Carlo orbit code to > 1000 processors in preparation for self-consistent coupling of ORBIT RF to full-wave solvers.

- **Plans for concluding phase of project:**

- **Progress to date against original plans:**

Wave propagation and the plasma response are governed by the Maxwell-Boltzmann system of equations

For time harmonic (rapidly oscillating) wave fields **E** with frequency ω, Maxwell's equations reduce to the Helmholtz wave equation:

$$-\nabla\times\nabla\times\mathbf{E}+\frac{\omega^2}{c^2}\left(\mathbf{E}+\frac{i}{\omega\varepsilon_0}\mathbf{J}_p\right)=-i\omega\mu_0\mathbf{J}_{ant}$$

The plasma current ($\mathbf{J}_p$) is a non-local, integral operator (and non-linear) on the rf electric field and conductivity kernel:

$$\mathbf{J}_p(\mathbf{r},t)=\sum_s\int d\mathbf{r}'\int_{-\infty}^{t}dt'\sigma\left(f_{0,s}(E),\mathbf{r},\mathbf{r}',t,t'\right)\cdot\mathbf{E}(\mathbf{r}',t')$$

Wave Solvers (AORSA) (TORIC)

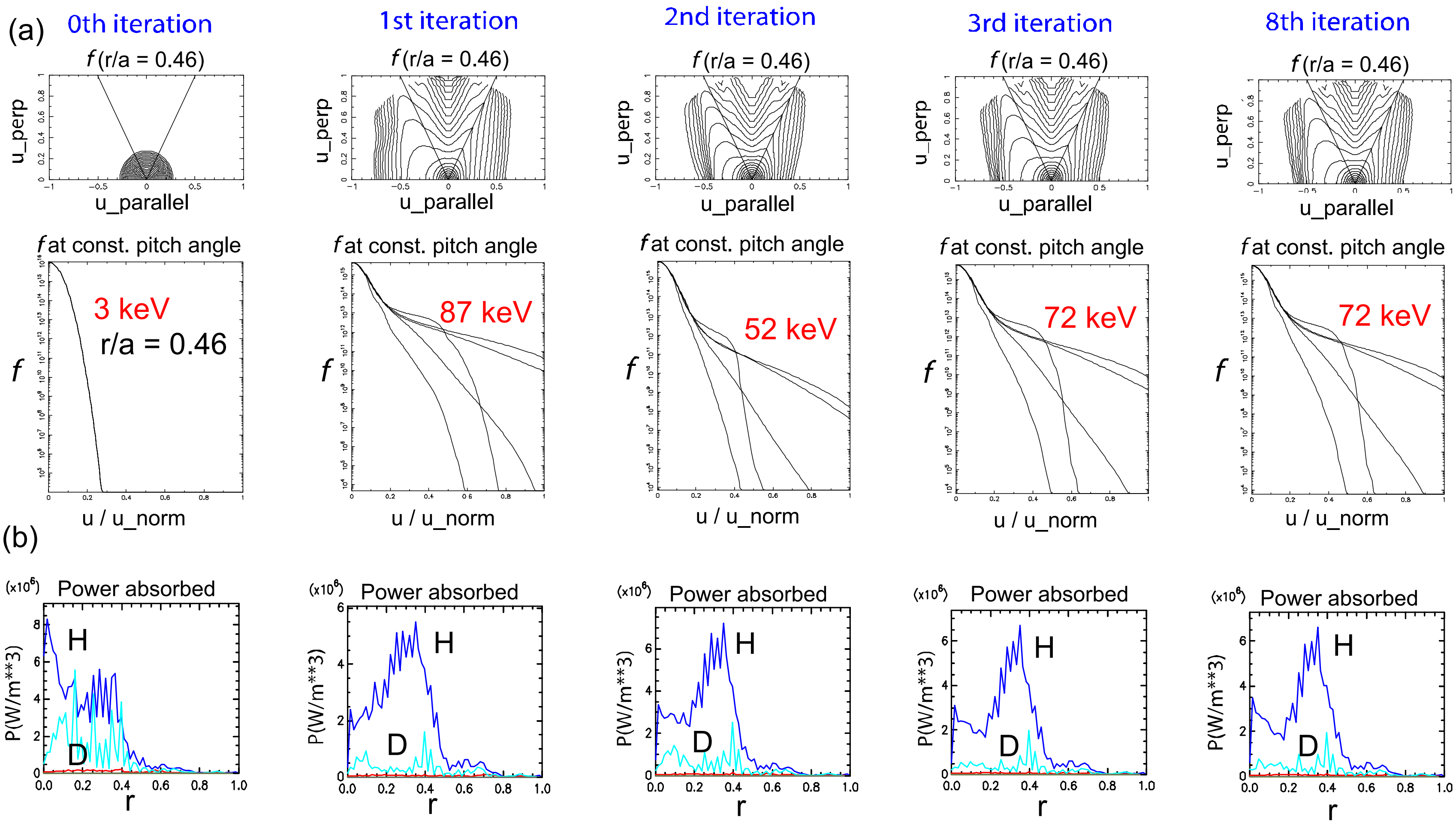
The long time scale response of the plasma distribution function is obtained from the bounce averaged Fokker-Planck equation:

$$\frac{\partial}{\partial t}(\lambda f_0)=\nabla_{\mathbf{u}_0}\cdot\Gamma_{\mathbf{u}_0}+\langle\langle S\rangle\rangle+\langle\langle R\rangle\rangle^{\nearrow 0} \quad \text{where} \quad \nabla_{\mathbf{u}}\cdot\Gamma_{\mathbf{u}}=C(f_0)+Q(\mathbf{E},f_0)$$

Plasma Response (CQL3D)

Need to solve this nonlinear, integral set of equations for wave fields and velocity distribution function self-consistently. This requires an iterative process to attain self-consistency.

Calculation for C-Mod minority H, $N_R = 128$, $N_Z = 128$, [256 processors for 3 hrs on Cray XT3 – ORNL]



P(H) = 0.459 MW = 76 %

P(H) = 0.499 MW = 83%

P(H) = 0.518 MW = 86%

P(H) = 0.526 MW = 87%

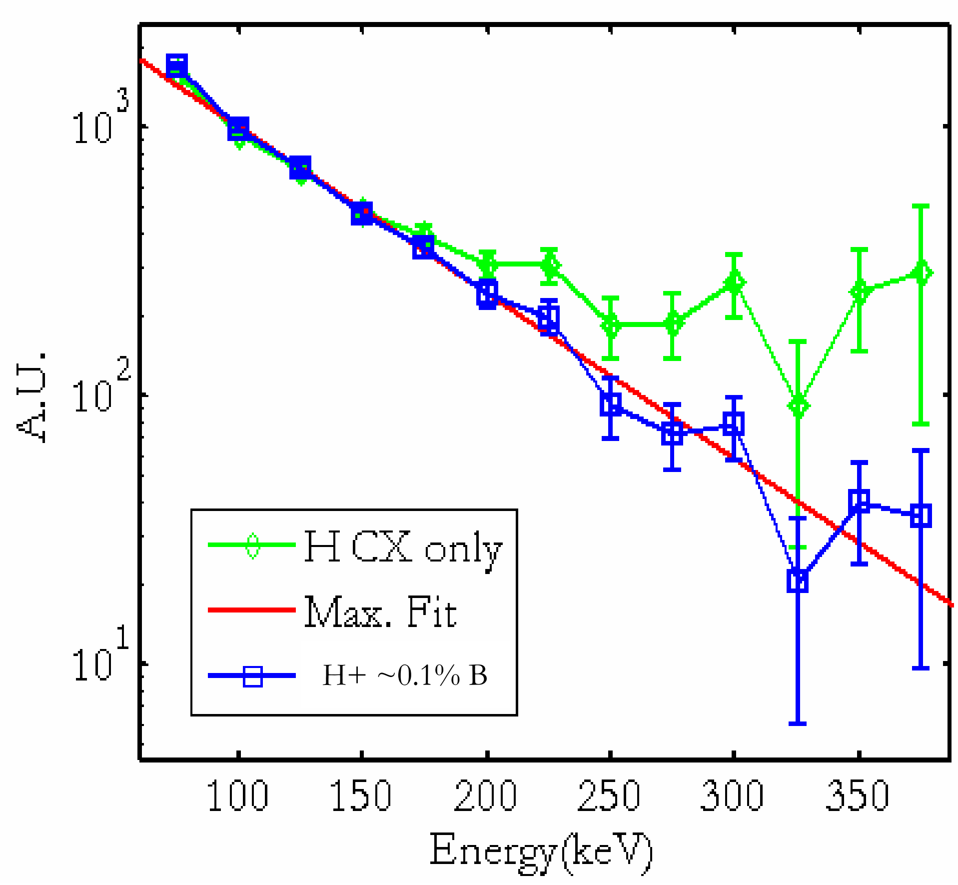
P(H) = 0.522 MW = 87%

Experimental measurements of the energetic ion tail on C-Mod have been made using a compact neutral particle analyzer (CNPA) – V. Tang

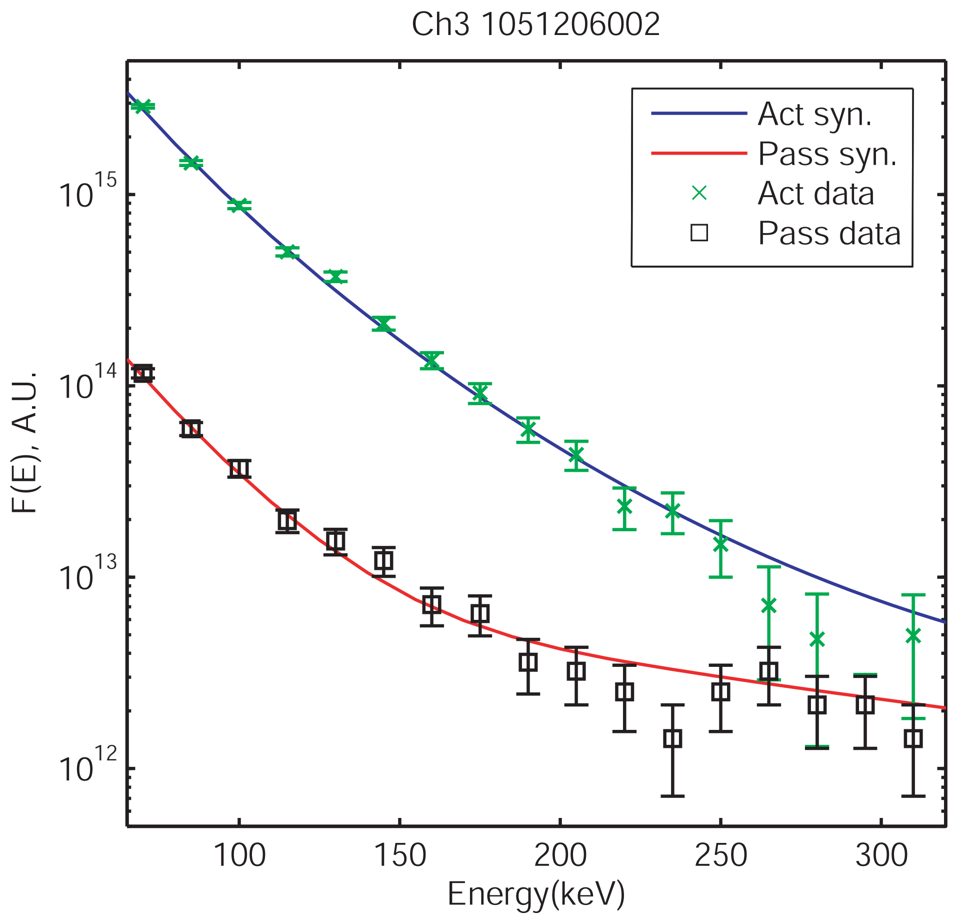
•Using a Maxwellian fit to data gives $T_{ion} \sim 70$ keV.

•Vincent Tang, MIT [PhD Thesis, 2006; also V. Tang, PPCF, 49, 873 (2007)]

•Good agreement between simulation and measurement on T_{ion}



3D (r, $V_\perp$, V//) distribution function from CQL3D – AORSA reproduces CNPA measurements using a synthetic code diagnostic

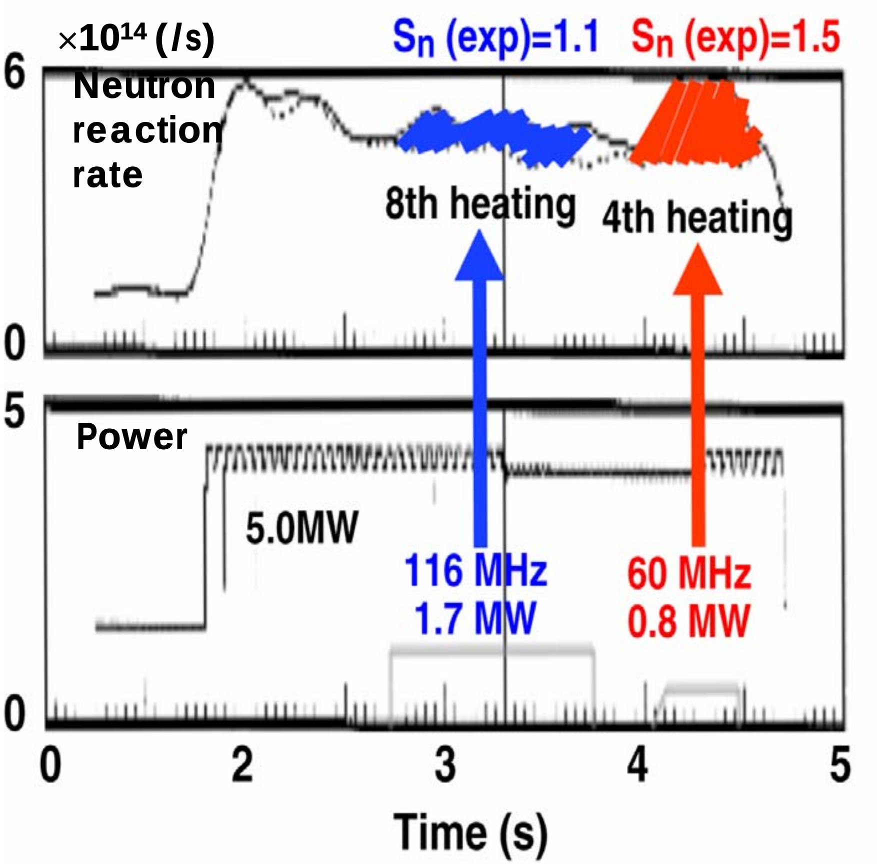


Building this synthetic diagnostic required a close collaboration between theory and experiment (V. Tang and R. Harvey)

V. Tang, PhD Thesis, MIT (2006); also PPCF, 49, 873 (2007).

Simulations of high harmonic fast wave (HHFW) – fast ion beam interaction in DIII-D are still unresolved

- DIII–D high density L-mode



S_n: neutron enhancement factor

Stronger Beam Interactions at $4\Omega_D$ (60 MHz) Than at $8\Omega_D$ (116 MHz) Observed in DIII-D

CQL3D-AORSA predicts increased absorption as frequency was raised.

Monte Carlo ORBIT code (ORBIT-RF) combined with an RF operator (using fields from TORIC solver) does reproduce the experimental trend.

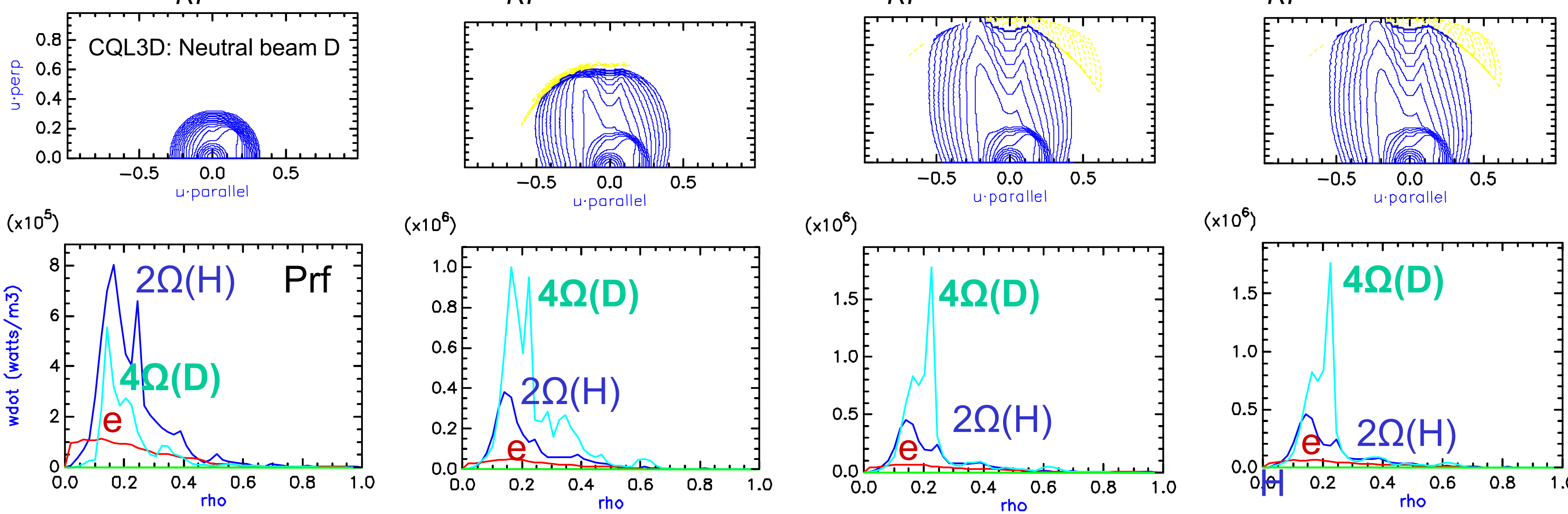
(HHFW) – fast ion beam interaction in DIII-D Physics issues under investigation

- Evolution of multiple nonthermal ion species:
  - **Found to be an important effect, but does not reproduce experimental trend.**
- Inclusion of finite ion drift orbit effects in a closed loop computation between full-wave solver and Monte Carlo code:
  - **Codes not yet coupled self-consistently.**
- Parasitic absorption mechanisms in weak single pass damping regime (e.g. RF sheaths).
- Validity of quasilinear approximation at high ion cyclotron harmonics.
- Perform comparisons with experiment using synthetic diagnostic for neutron enhancement factor (S_N).
- **All of the above issues also apply to NSTX !**

AORSA and CQL3D were iterated to solve for the wave fields and distribution function self-consistently in the DIII-D HHFW – NBI Interaction

f = 60 MHz (4th harmonic D; non-Maxwellian) and 2% minority H (2^{nd} harmonic H, Maxwellian)

0^{th} iteration	1^{st} iteration	5^{th} iteration	6^{th} iteration
P_{RF} = 0	P_{RF} = 1.1 MW	P_{RF} = 1.1 MW	P_{RF} = 1.1 MW



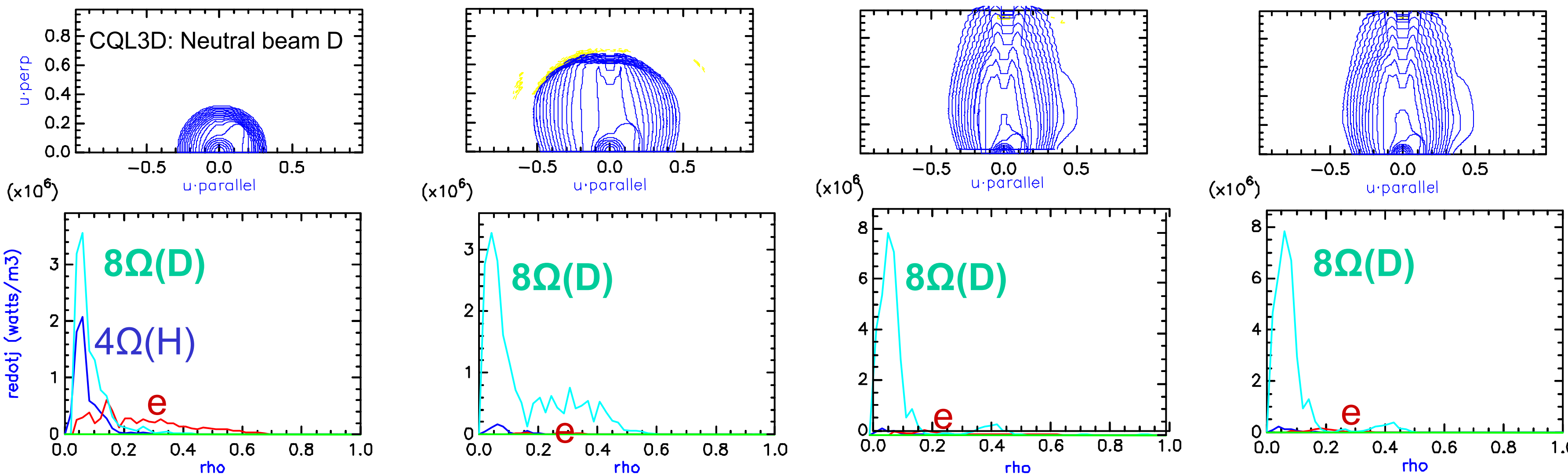
P(D) = 0.29 MW	P(D) = 0.84MW	P(D) = 0.76 MW	P(D) = 0.75 MW
= 23.8 %	= 66.3 %	= 58.2 %	= 57.1%

At 60 MHz, about 57% of the RF power is absorbed by the deuterium

At 116 MHz, about 95% of the power is absorbed by the deuterium beam

f = 116 MHz (8th harmonic D; non-Maxwellian) and 2% minority H (4th harmonic H, Maxwellian)

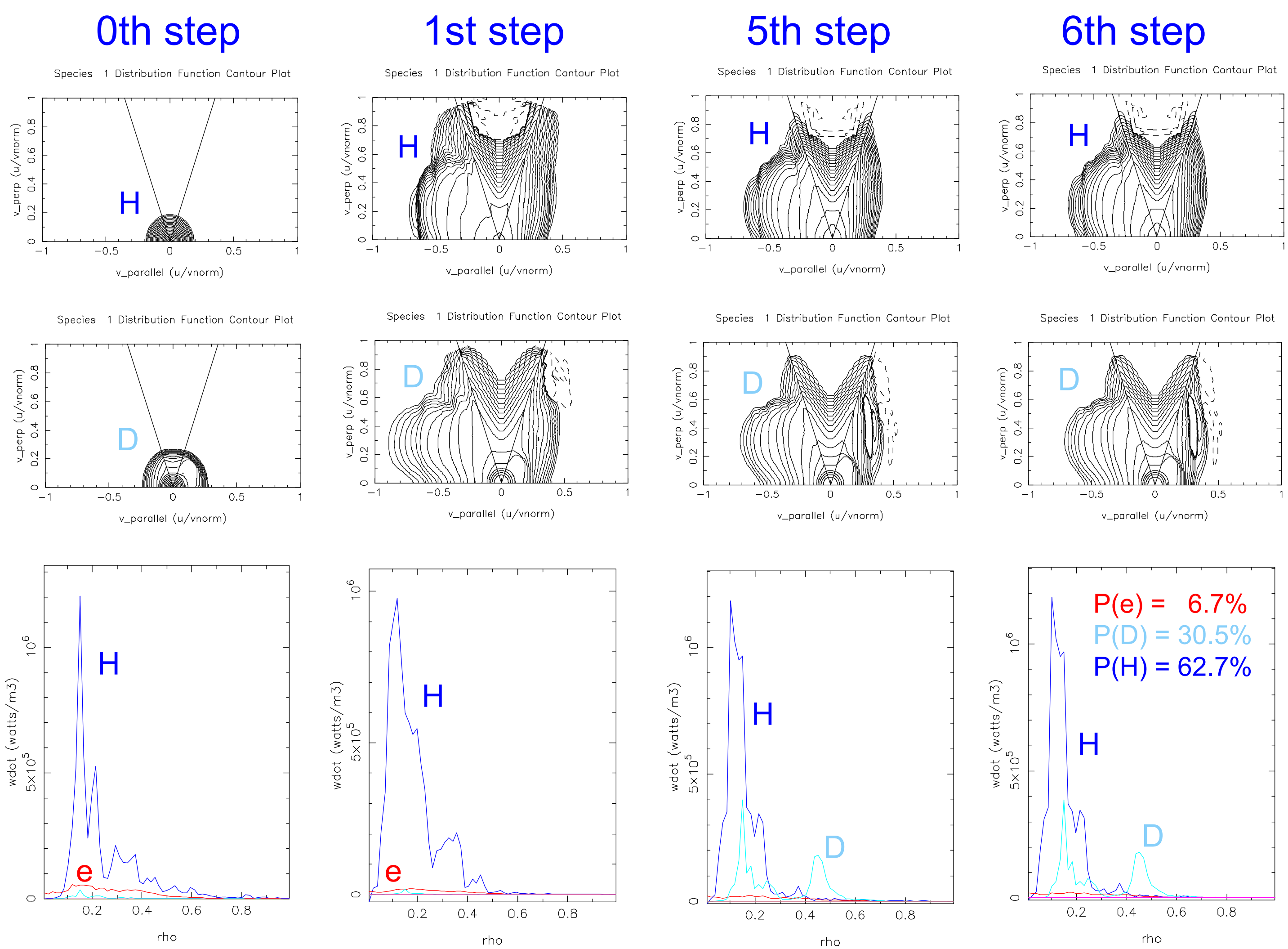
0th iteration	1st iteration	7th iteration	8th iteration
$P_{RF} = 0$	P_{RF} = 1.6 MW	P_{RF} = 1.6 MW	P_{RF} = 1.6 MW



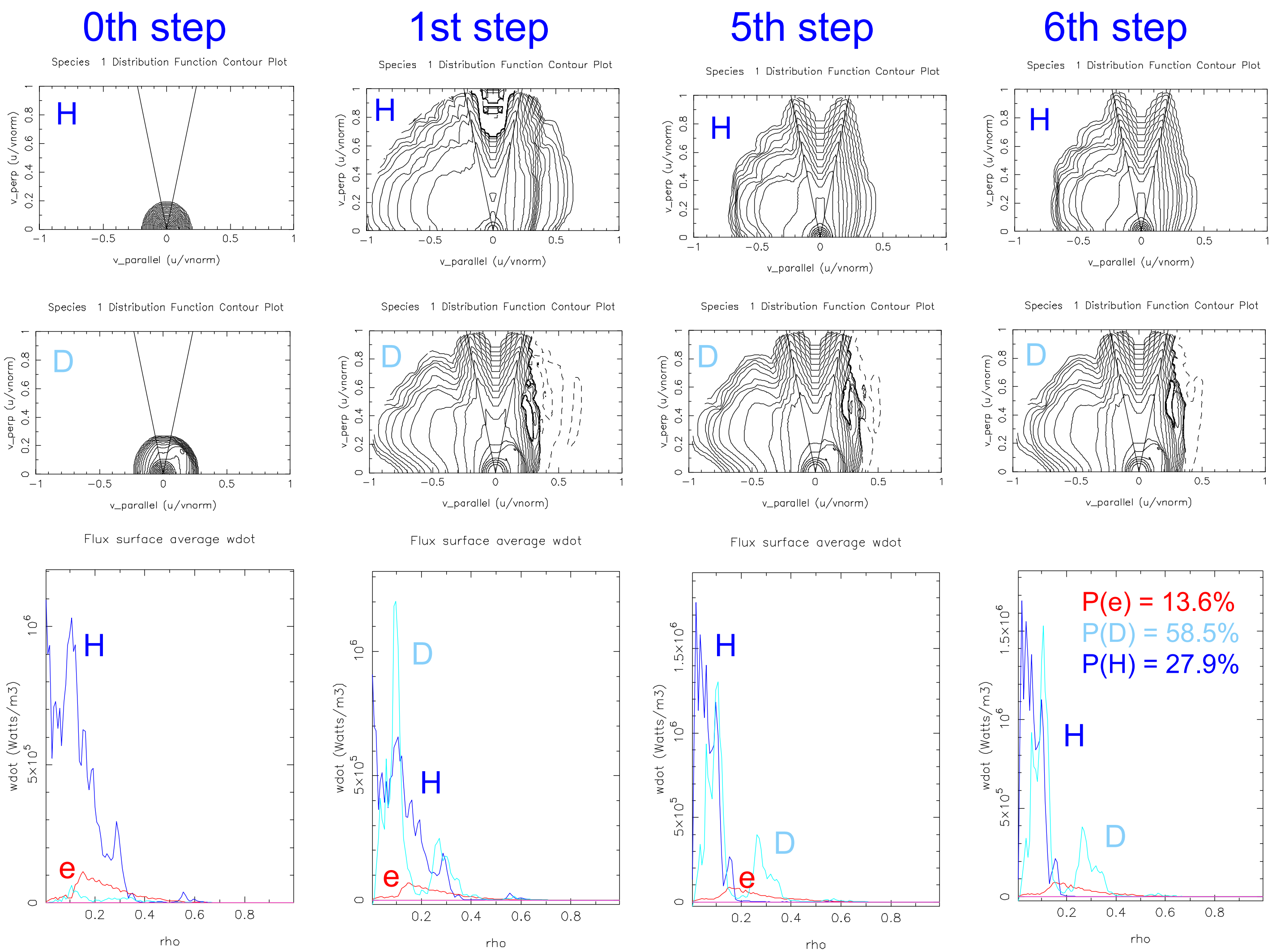
P(D) = .55 MW = 34.5 %	P(D) = 1.54MW = 96.2 %	P(D) = 1.47 MW = 92.3 %	P(D) = 1.50 MW = 94.6 %

This is in disagreement with the experiment which indicates little power absorbed at the 8th harmonic.

Iterative solution for non-Maxwellian H and D in DIII-D at 60 MHz (2% H) shows significant absorption of HHFW on nonthermal background H



Iterative solution for non-Maxwellian H and D in DIII-D at 116 MHz (2% H) also shows significant H absorption – but still does not explain experimental trend.



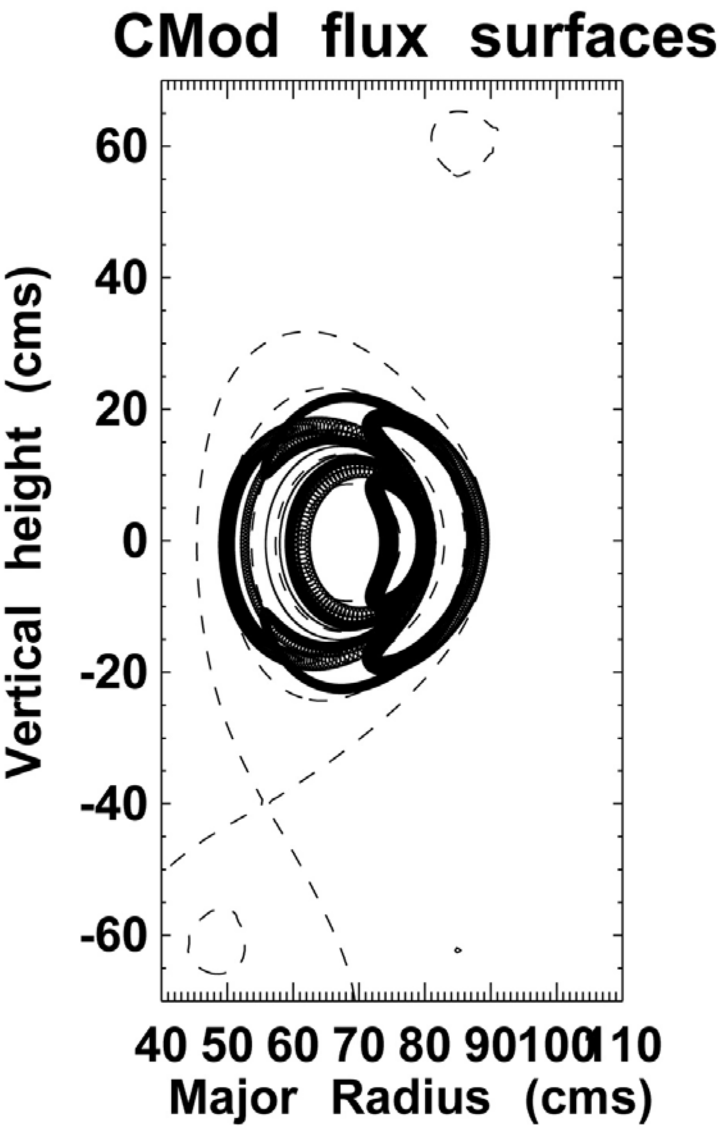
We are investigating finite ion drift orbit effects using two approaches:

- **The diffusion coefficient (D) has been evaluated by a direct orbit integration using electric fields from AORSA:**
  - The "DC" code computes averages of the changes in velocity, pitch angle, and radial position over a complete bounce orbit, to obtain a set of RF induced diffusion coefficients.
  - Diffusion Coefficient calculations done on CRAY XT3 (ORNL) using 256 processors @ 10 min.

- **The Monte Carlo code ORBIT RF has been combined with the TORIC ICRF solver:**
  - Self-consistent iteration not yet carried out.
  - ORBIT RF code ported to JAGUAR where good scaling to > 1000 processor cores has been demonstrated.
  - We are now examining best way to pass statistical distribution from ORBIT RF to TORIC & AORSA to do self-consistent iteration.

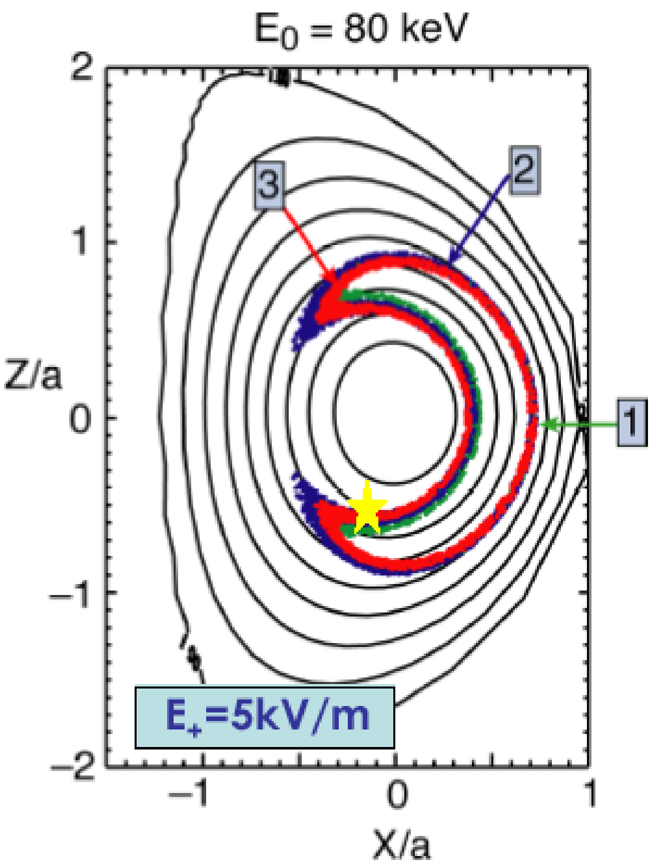
Orbit topology modifies wave-particle resonance

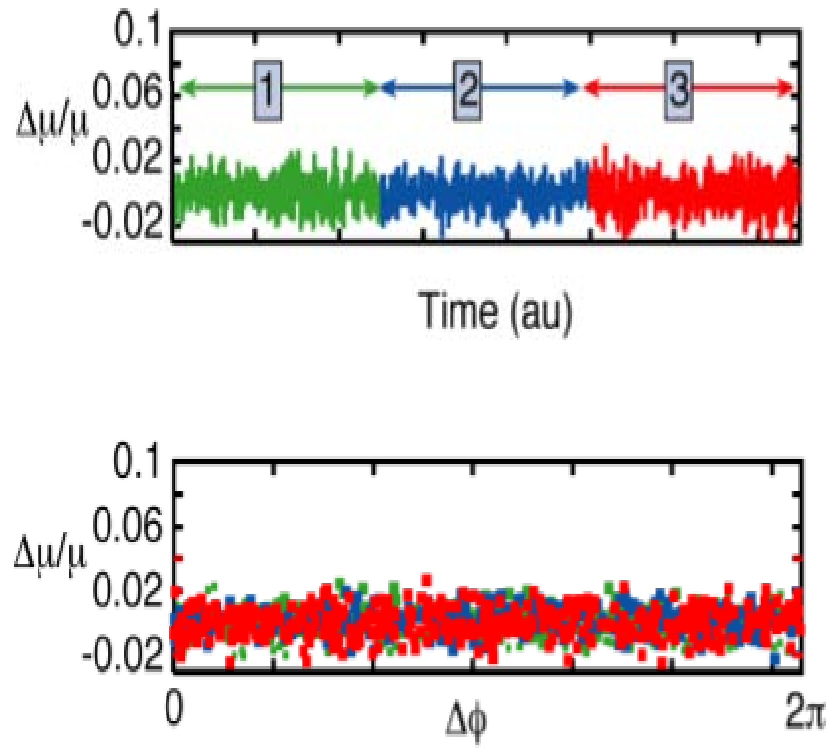
- Shown at right are trajectories for 12 particles in the C-Mod case:
  - 4 equi-spaced || velocities
  - 3 equi-spaced ⊥ velocities
  - 409,600 complete poloidal orbits
- Particle cyclotron resonances and strong quasilinear diffusion occur in roughly vertical planes in zero-orbit width description.
- But orbit topology can move particles away from (or towards) resonances that would be sampled (not sampled) in full-wave solver.



DIII-D HHFW – Beam Ion Interaction:

ORBIT RF has been used with a model RF electric field to show strong phase decorrelation occurs at 4^{th} harmonic of wave-beam interaction $\Rightarrow$ quasilinear description is valid

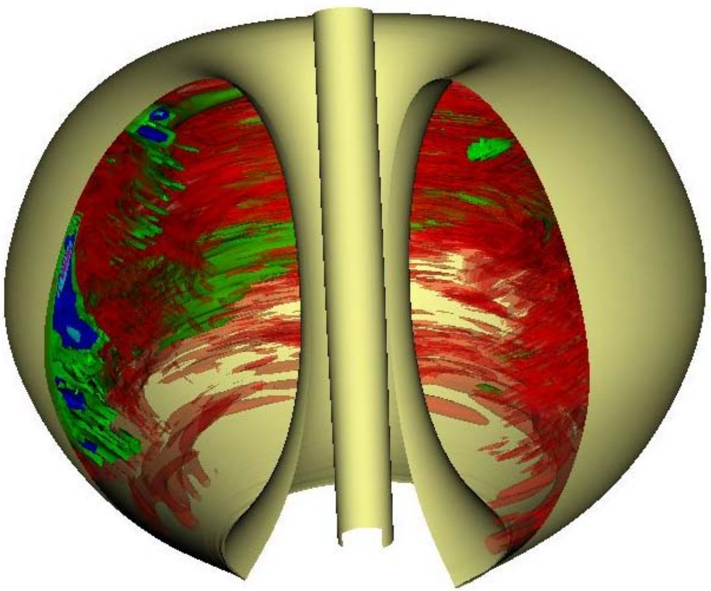




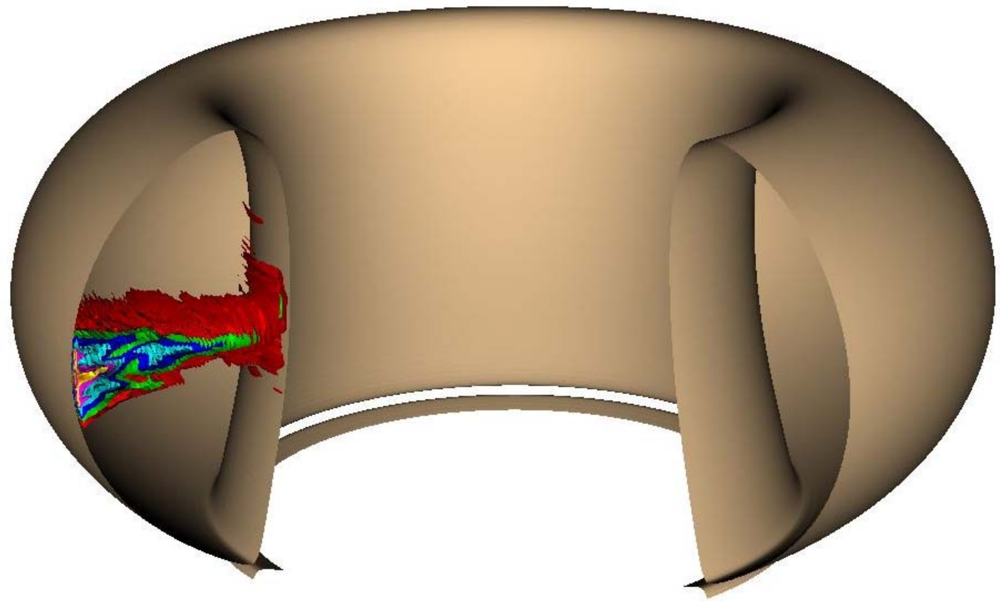
Analysis for 8^{th} harmonic beam interaction is now underway.

Capability to efficiently compute 3D wave fields will be important for assessing antenna – edge interaction, especially in weak single pass damping regime

NSTX



ITER Scenario 2



**NSTX simulation summed over 81 toroidal modes.
ITER simulation summed over 169 toroidal modes)
[AORSA run on JAGUAR using 2048 processors for 8 hrs]**

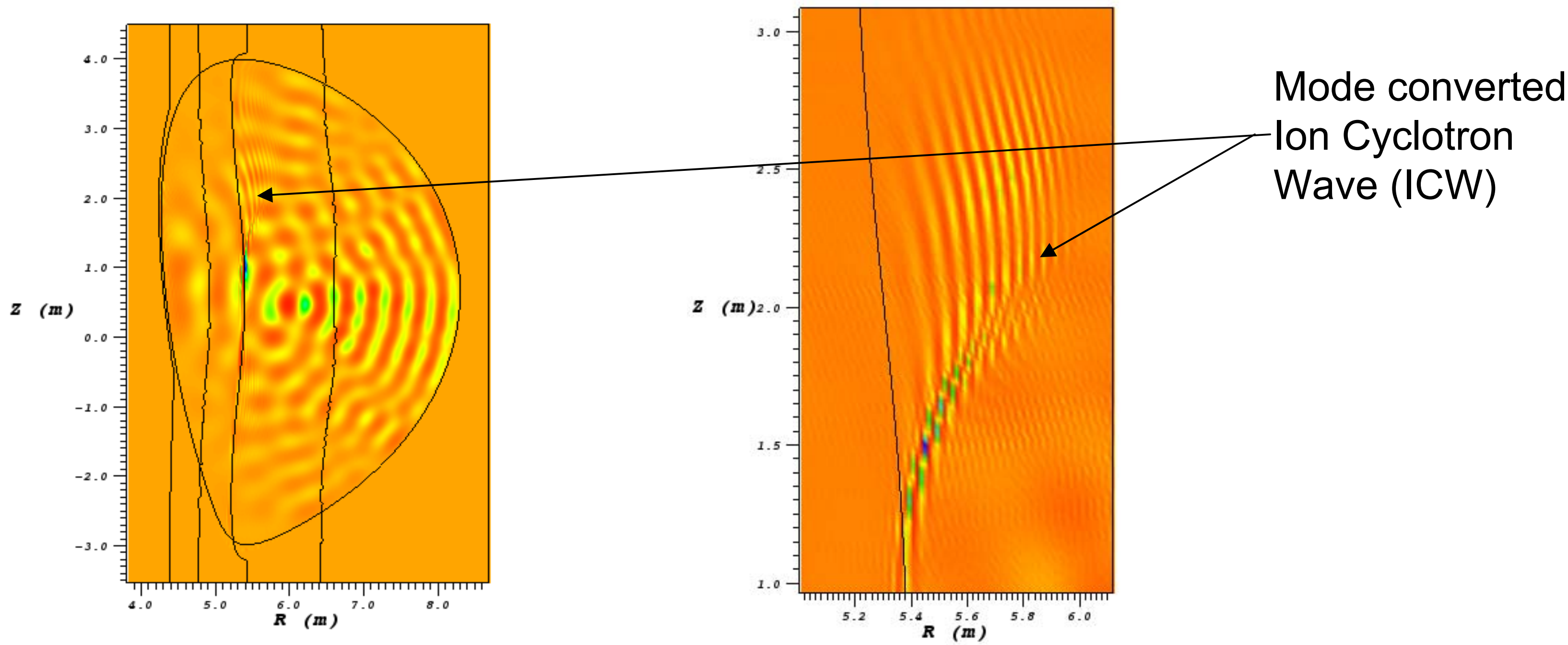
Calculations on the Cray XT3 have allowed the first simulations of mode conversion in ITER

ITER with D:T:HE3 = 20:20:30 with $N_R = N_Z = 350$, f = 53 MHz, n =2.5x10^{19} m^{-3}

(4096 processors for 1.5 hours on the Cray XT-3)

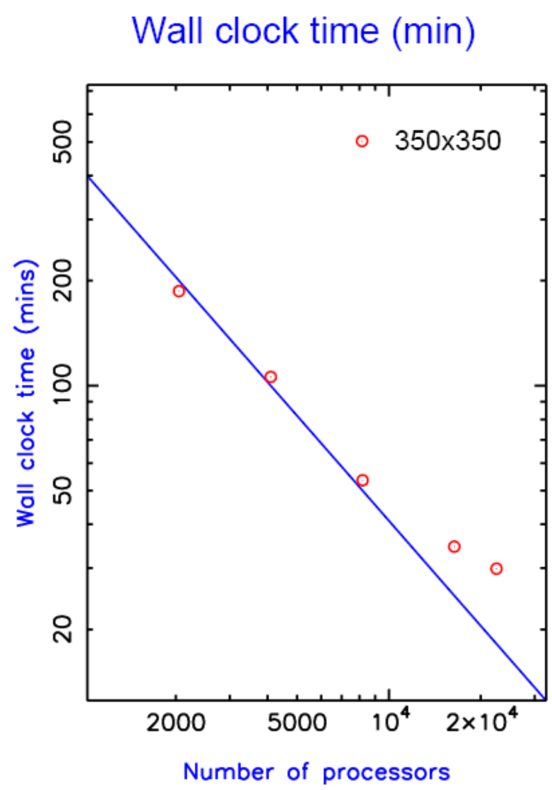
E_perp

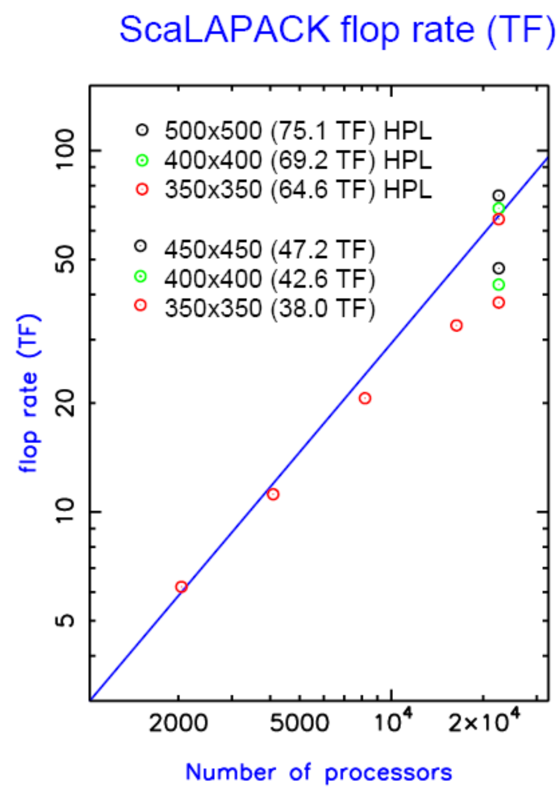
Blowup (E_parallel)



Scaling of Full-wave ICRF solvers to > 20,000 processors demonstrated for ICW Mode Conversion in ITER

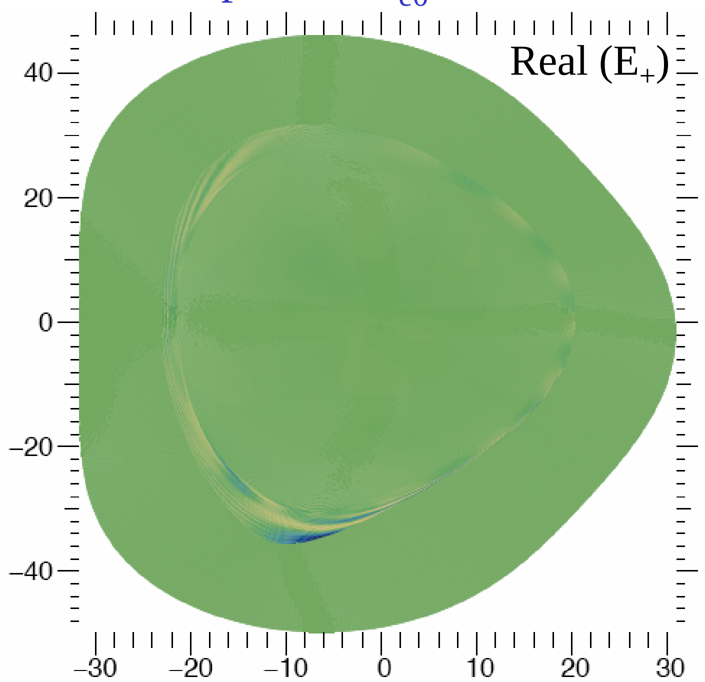
ITER with D:T:HE3 = 20:20:30 with $\boldsymbol{N_R = N_Z = 500}$, f = 53 MHz, n =2.5x10^{19} m^{-3}





Fast wave mode conversion to a kinetic shear Alfvén wave in C-Mod has been simulated with TORIC

H-mode profile: $n_{e0} \sim 3.6e14\ cm^{-3}$



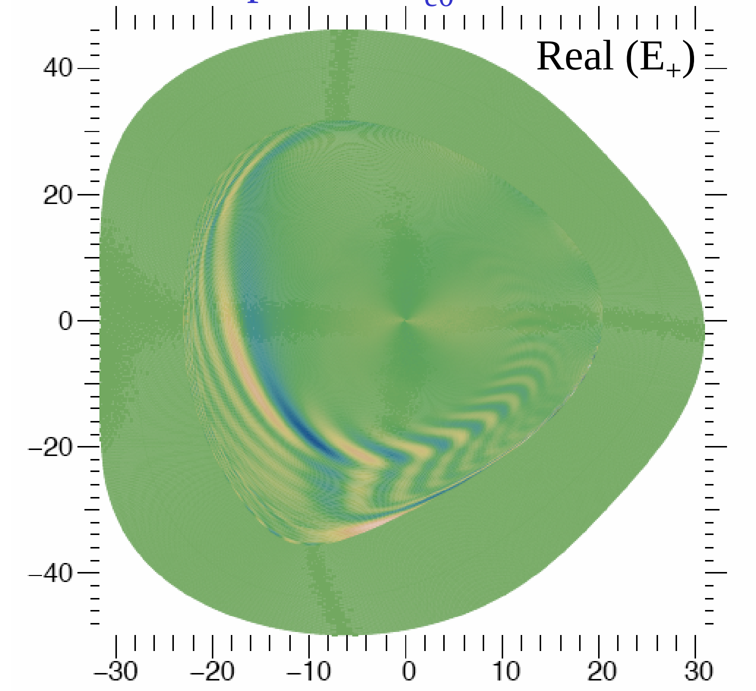
7.48 T

43 MHz

98 % D

2% H

L-mode profile: $n_{e0} \sim 1.3e14\ cm^{-3}$



- May provide trigger for ITB formation via RF-driven shear flow *(Craddock and Diamond PRL 1991)*

    -Estimates of RF-driven flow to be derived with the Lodestar-ORNL nonlinear model

-high spatial resolution required to resolve slow mode structure

    -KSAW damps ~ 66% on electrons and ~ 34% on ions

-qualitatively consistent with earlier 1D studies with METS at 8T, 40 MHz

-Possibly detectable on C-Mod with PCI diagnostic

Lower Hybrid Current Drive (LHCD) Simulations in Present Day Devices and ITER

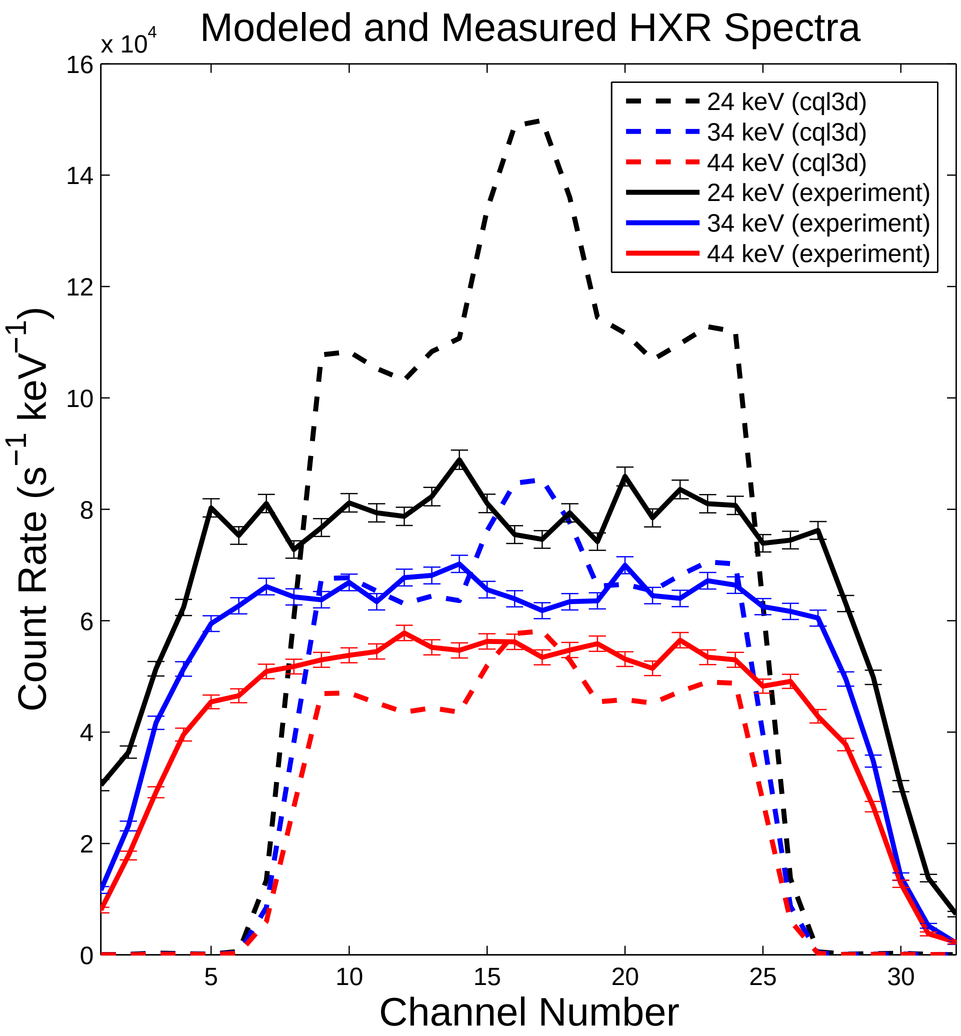
- Combined Fokker Planck – ray tracing models are already run within time dependent simulations (**DELPHINE-CRONOS, TSC – LSC, TRANSP – LSC, TASK**)

- Want to incorporate LH full-wave description with Fokker Planck codes (**diffraction, wave focusing**).

- Full-wave simulations can be done now in mid-size present day devices (even including the full launcher spectrum).

- Full-wave LH simulation for ITER is a petascale problem.

Comparison Between Experimental Hard X-rays and Synthetic Diagnostic (CQL3D) for Shot 1060728104



- **HXR Spectra from Synthetic Code are narrower than measured profiles.**

- **This suggests that radial diffusion effects on fast electrons or diffraction could be important.**

- **Next step is to include a model radial diffusion operator in the CQL3D simulations and couple CQL3D to a full-wave solver.**

Coupled Full-wave – Fokker Planck Simulations of Lower Hybrid Current Drive will soon be Possible

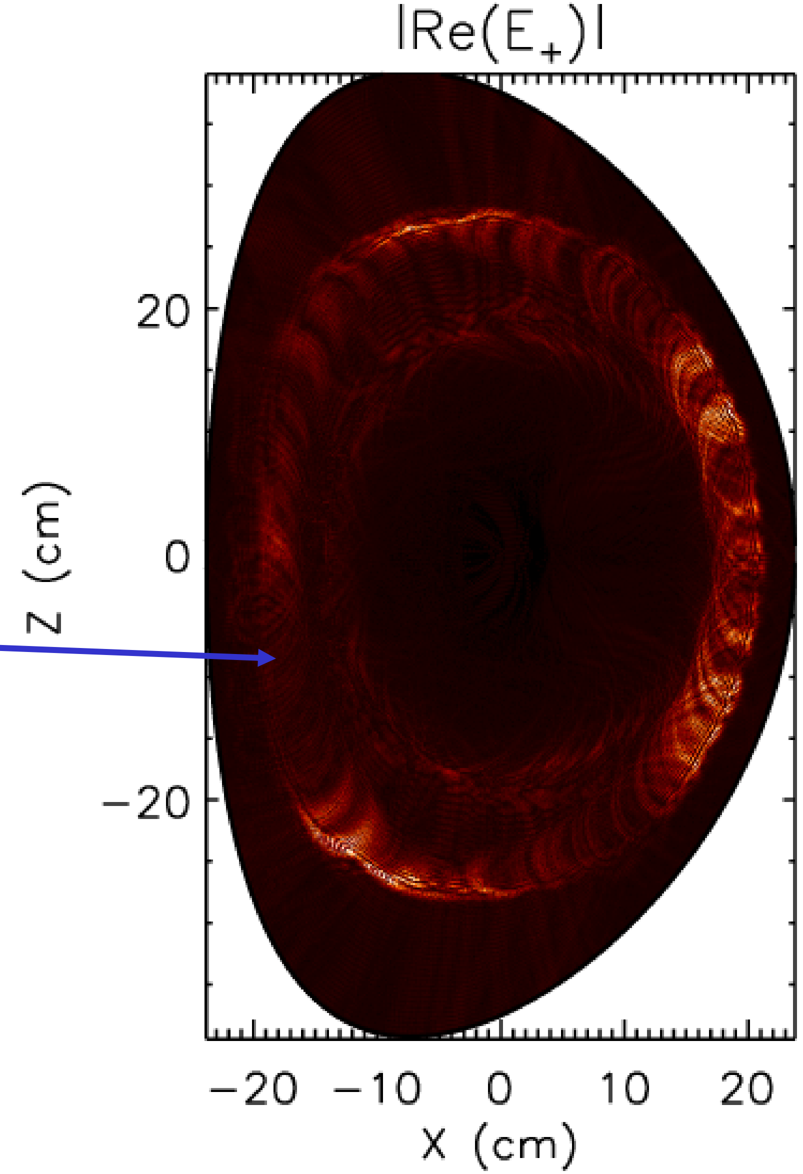
- Electron and ion plasma response in TORIC can now be evaluated using the nonthermal $f_{e,}$ from CQL3D (E. Valeo, C.K. Phillips, J. Wright).

- Final step is to reconstruct D_{QL} from TORIC and pass it to CQL3D.

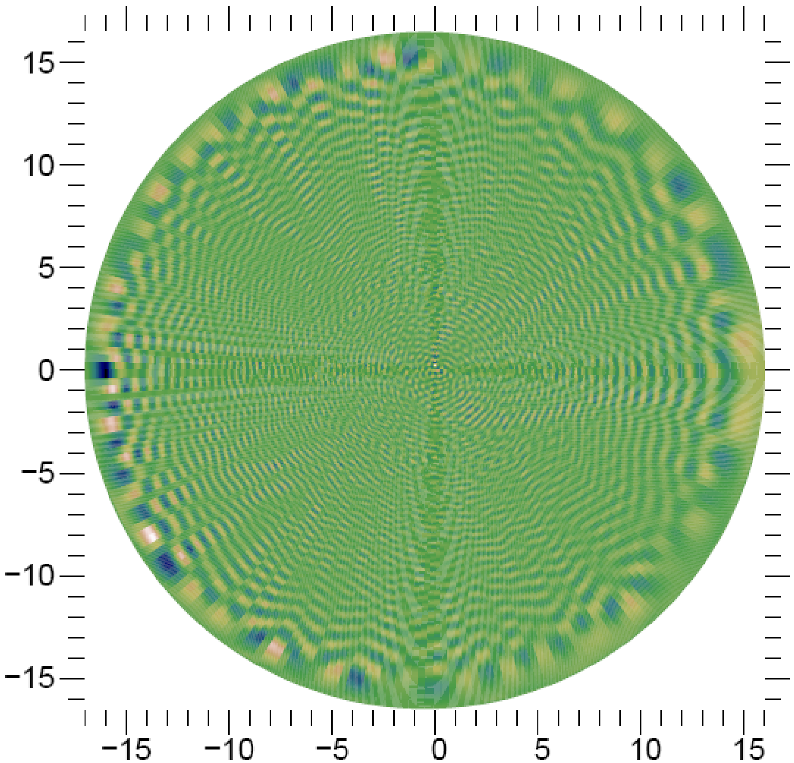
- Full-wave LH Simulation first performed on the MARSHALL cluster at MIT(6 days @ 32 processors) revealed significant spectral broadening due to diffraction.

- **Now simulation can be done on CRAY XT3/XT4 JAGUAR at ORNL (1 hour @ 4096 processors).**

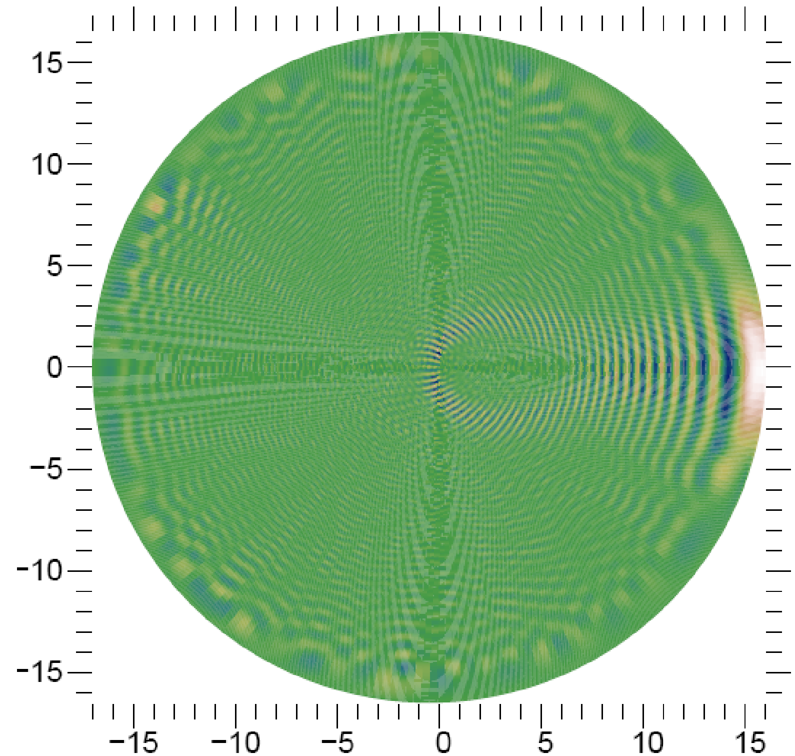
- **Coupled CQL3D – TORIC simulation with 8 iterations requires about 33,000 CPU hours per toroidal mode for C-Mod size device.**



Alcator C: Nonthermal electron distribution can significantly modify LH full-wave fields (TORICLH + SIGMAD)

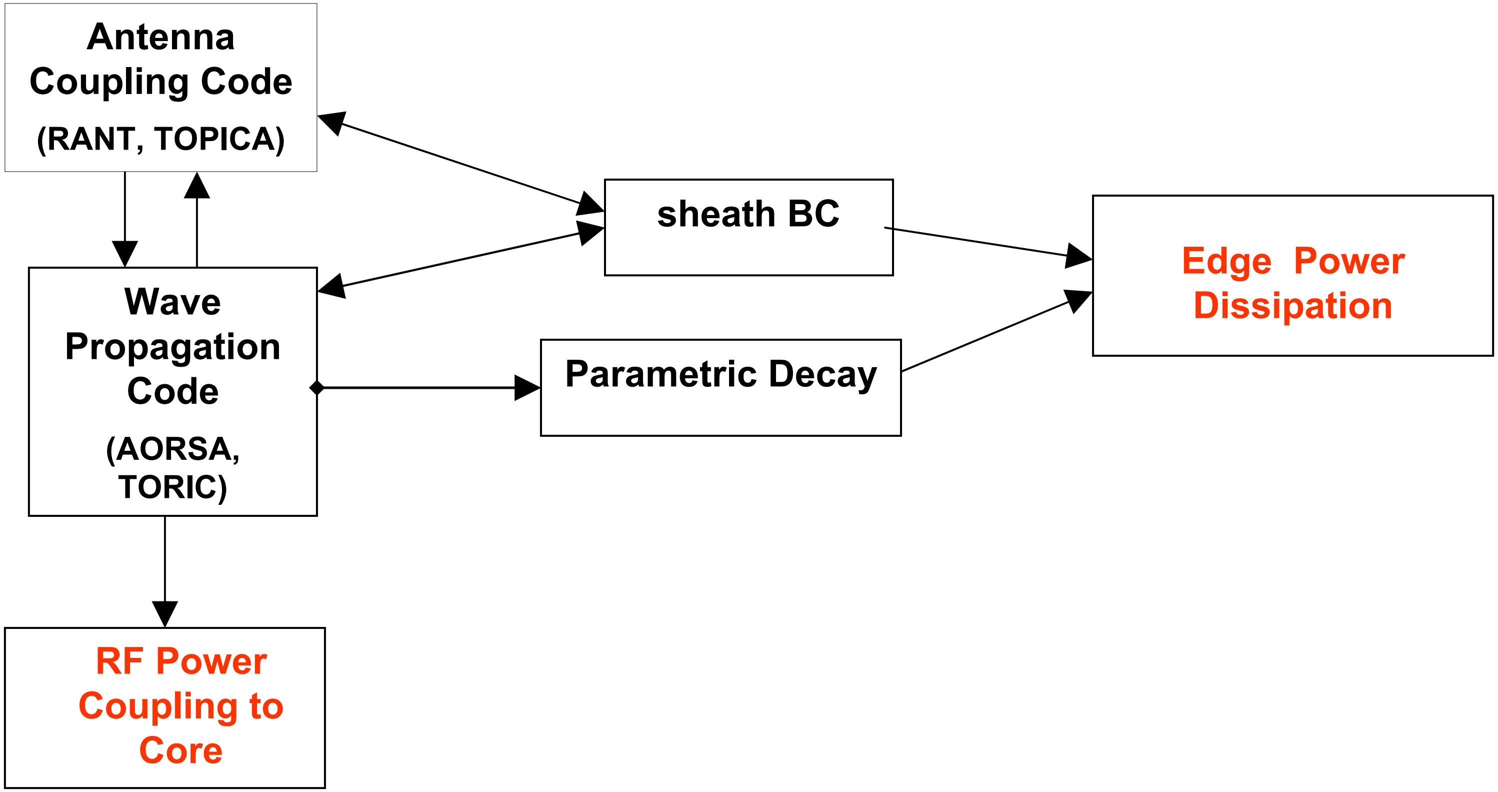


Maxwellian distribution



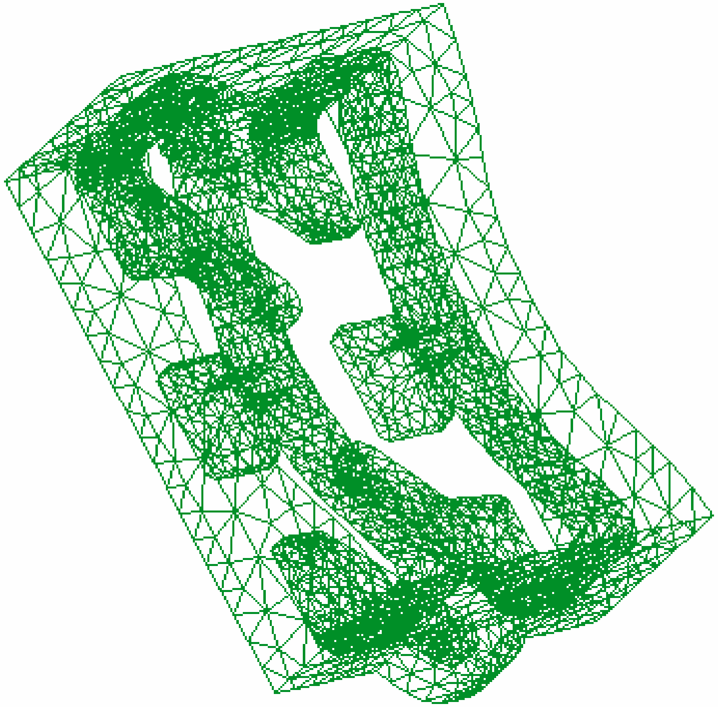
Quasilinear distribution

Integration of linear and nonlinear rf physics in the edge plasma



Linear Coupling of an ICRF Antenna with the Edge Plasma can be Computed by Integrating the TOPICA and TORIC Codes

- **TOPICA:**
  - Fully 3D solid antenna structure model (including FS, box,…)
  - Parallel code has been used to model the ITER ICRF antenna).

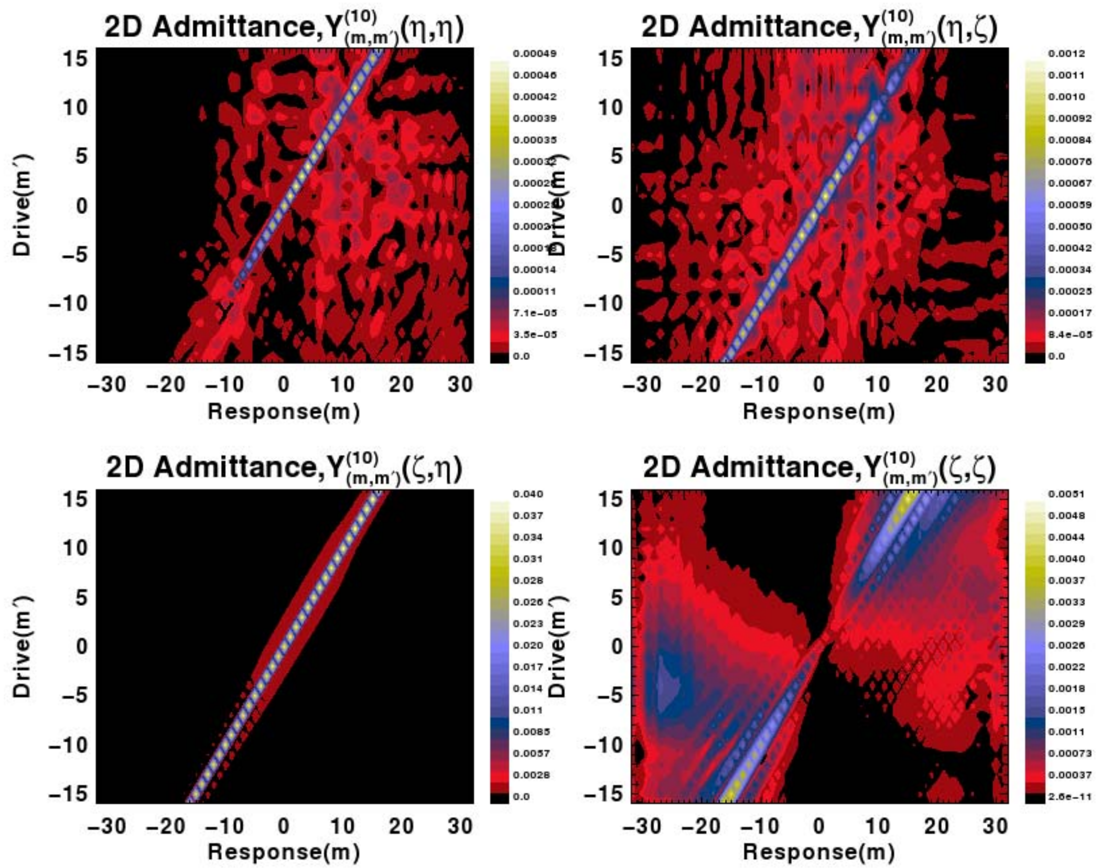


Alcator C-Mod: “E” – antenna

TOPICA is coupled to TORIC through a surface admittance matrix

- Shown is the perpendicular response to a perpendicular drive electric field at the surface.

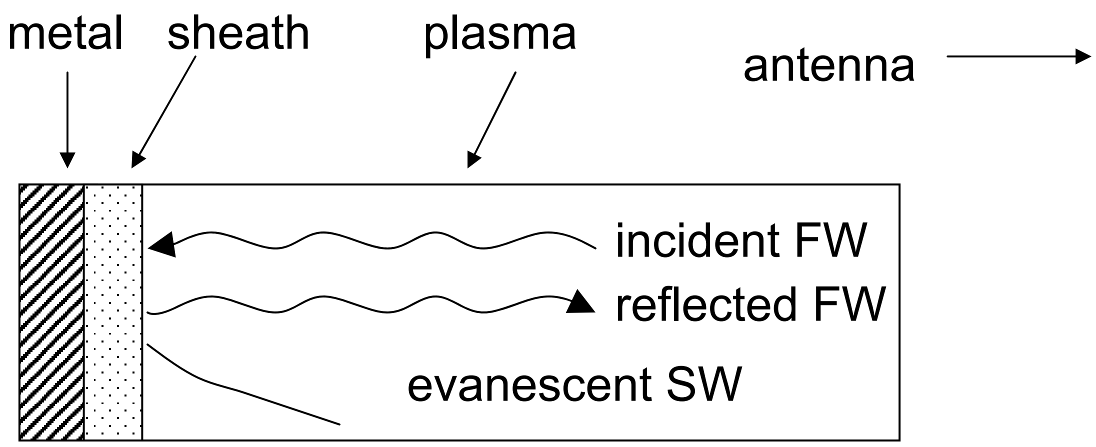
$$\begin{pmatrix} \overleftrightarrow{Y}_{\eta\eta} & \overleftrightarrow{Y}_{\eta\zeta} \\ \overleftrightarrow{Y}_{\zeta\eta} & \overleftrightarrow{Y}_{\zeta\zeta} \end{pmatrix} =$$



Two Approaches are Being Pursued to Study the Nonlinear ICRF antenna – edge Interaction

- Implementation of RF sheath boundary conditions in full-wave solver (spectral solution):
  - Start with linear field response from TORIC-TOPICA
  - Modify metal wall BC in TORIC solver to include sheath dissipation and then iterate with TOPICA.
  - Approach will quantify how much ICRF power is coupled to the plasma.
- Time domain simulations using 3D EM field solver - VORPAL
  - Fully implicit time domain dielectric response module has been implemented for electrons and ions.
  - Can also use PIC-treatment for ion response (fully nonlinear).

Far-field Fast Wave Sheath Solution



Wall is not a flux surface, so the FW couples to the SW to satisfy the BC at the sheath

Posed as a 3-wave coupling problem, the sheath BC gives the following solution:

unit vector normal to sheath

wavevector

$$E_1 = E_0 \frac{\mathbf{s}\cdot\mathbf{g}_2\times\mathbf{g}_0}{\mathbf{s}\cdot\mathbf{g}_1\times\mathbf{g}_2}, \qquad E_2 = E_0 \frac{\mathbf{s}\cdot\mathbf{g}_0\times\mathbf{g}_1}{\mathbf{s}\cdot\mathbf{g}_1\times\mathbf{g}_2}. \qquad \mathbf{g}_j = \hat{\mathbf{e}}_j - i\Delta\left(\mathbf{s}\cdot\boldsymbol{\varepsilon}\cdot\hat{\mathbf{e}}_j\right)\mathbf{k}_j$$

reflected FW   incident FW   SW (slow wave)

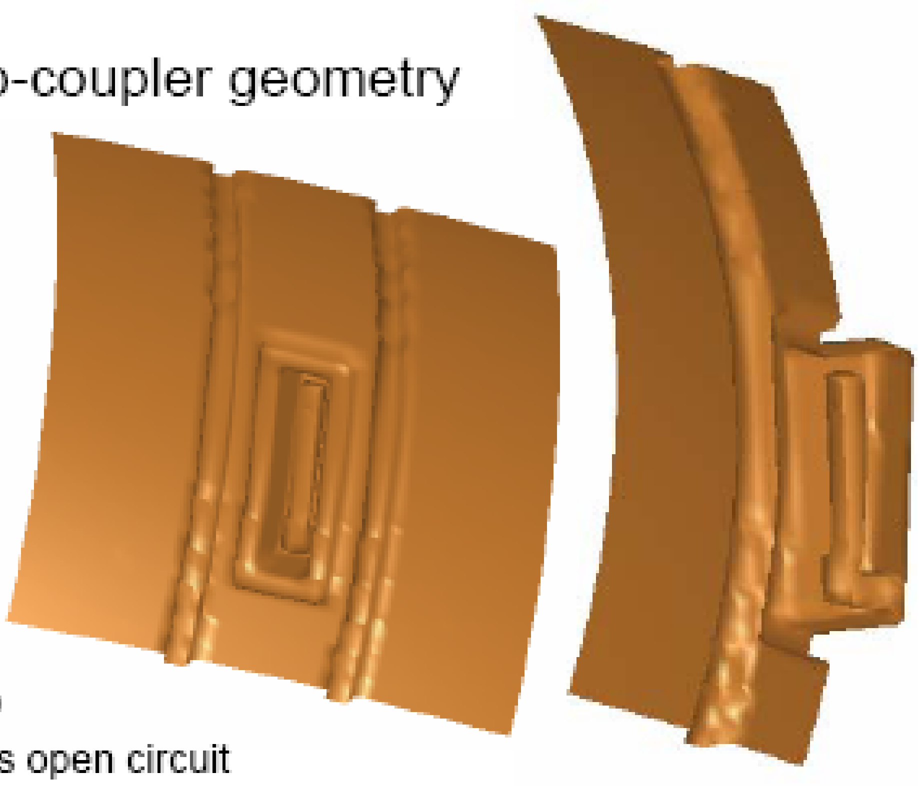
wave polarization   sheath width   plasma dielectric

Use this solution to “post-process” the FW field solution $\Rightarrow$ sheath V and P_{sh}

VORPAL Time Domain Simulation of Antenna Loop

Geometry

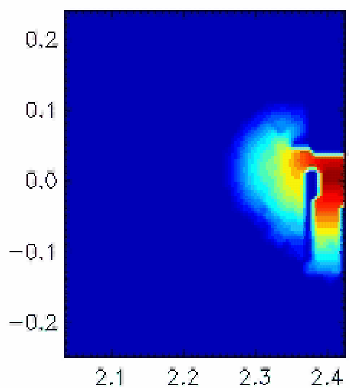
- Cartoon 3D loop-coupler geometry
  - Fully toroidal
  - Coupler box
  - Loop
  - Limiter on box
  - Two more limiters



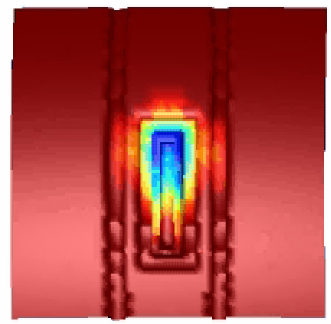
- Loop
  - Shorted on bottom
  - Open-circuit on top
  - Current runs across open circuit

VORPAL Time Domain Simulation of Antenna Loop

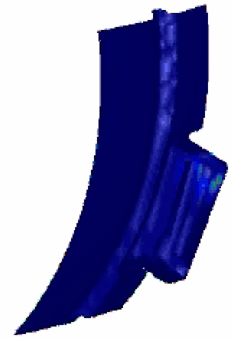
RF B-field

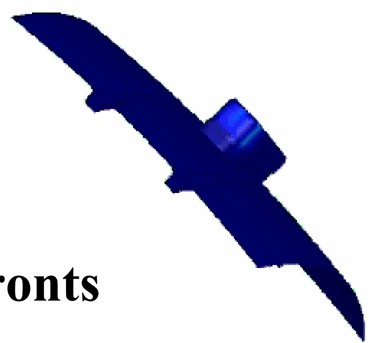


Surface E-field

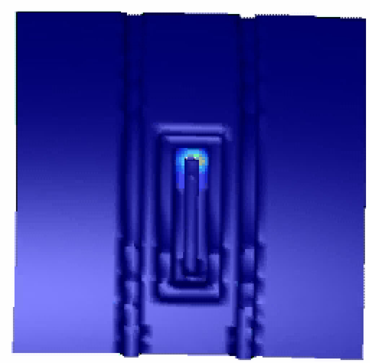


Surface E-field on Loop antenna

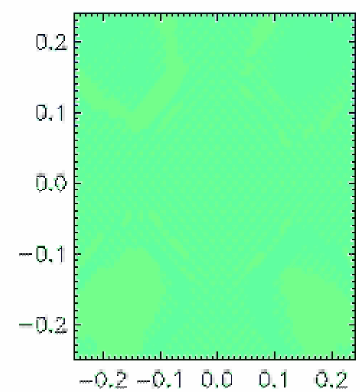




Wavefronts



Radiation Pattern



Radiation from Behind

Summary

- Coupled full-wave Fokker Planck solvers (CQL3D-SIGMAD-AORSA) have been used to simulate minority ICRF, fast wave current drive, and mode conversion current drive in present day tokamaks and in ITER:
  - Full coupling uses self-consistent nonthermal ion distributions and quasilinear diffusion coefficient in differential form.
  - Comparison of synthetic diagnostics (CNPA)with experiment is encouraging.
- Both AORSA and TORIC can simulate ICW/IBW mode conversion in present day tokamaks and in ITER:
  - Comparison of synthetic diagnostics (PCI) with experiment is encouraging.
  - Flow drive has been computed for C-Mod and ITER using AORSA.
- Full-wave LH field simulations have been performed for the first time ever in a mid-size tokamak:
  - Self-consistent coupling to an electron Fokker Planck solver is now underway.

Summary

- Fully self-consistent coupling of our full-wave solvers to a Monte Carlo orbit code (ORBIT RF) is underway:
  - Full coupling will use statistical nonthermal ion distributions and quasilinear diffusion coefficient in differential form
  - We have used the ORBIT RF code to verify the applicability of quasilinear theory in present day ICRF tokamak experiments.
- A self-consistent treatment of the RF antenna – edge plasma is underway:
  - Linear antenna coupling problem is substantially completed using the TORIC – TOPICA suite.
  - Boundary conditions for sheaths will be implemented in our full-wave solver (TORIC)
  - Proof of principle time domain simulations of sheath formation have been done using VORPAL.