ICRF Minority-Heated Fast-Ion Distributions on the Alcator C-Mod: Experiment and Simulation

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Fast-Ions are Measured and Compared Quantitatively to Simulations for the First Time

- New diagnostic capability to measure fast-ion distributions on Alcator C-Mod (Compact Neutral Particle Analyzer).

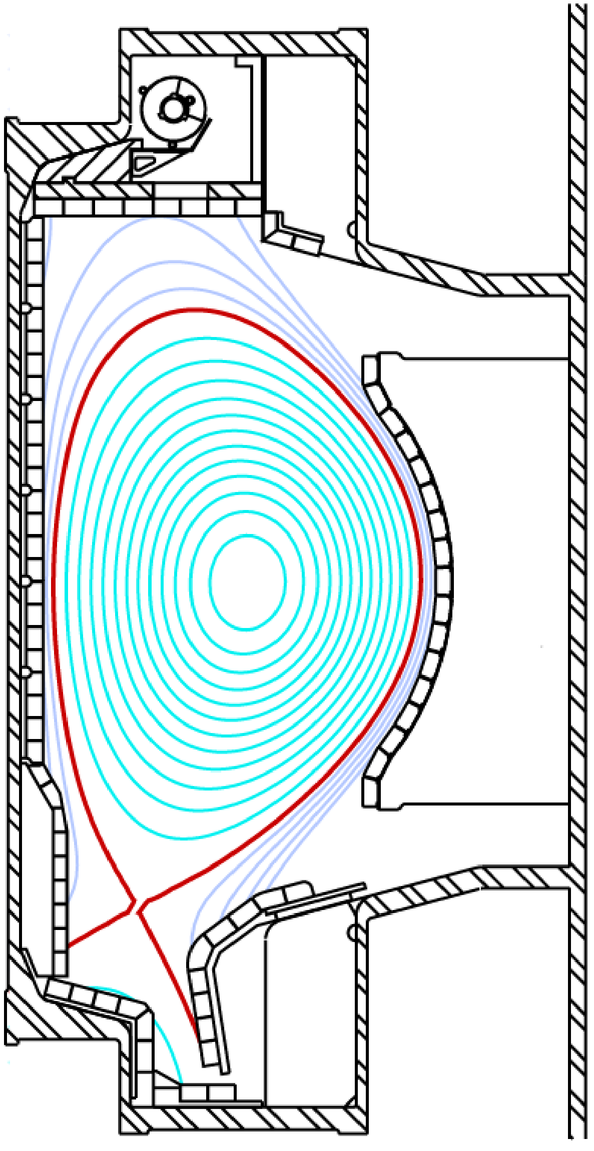
- Fast-ion distributions are simulated using a coupled Full-wave/Fokker Planck model.

- Comparisons between experimental CNPA and a new synthetic diagnostic allow for validation of the simulation models for predicting RF minority heating performances on future tokamaks.

Alcator C-Mod: A Compact, High-density, High-Field Tokamak

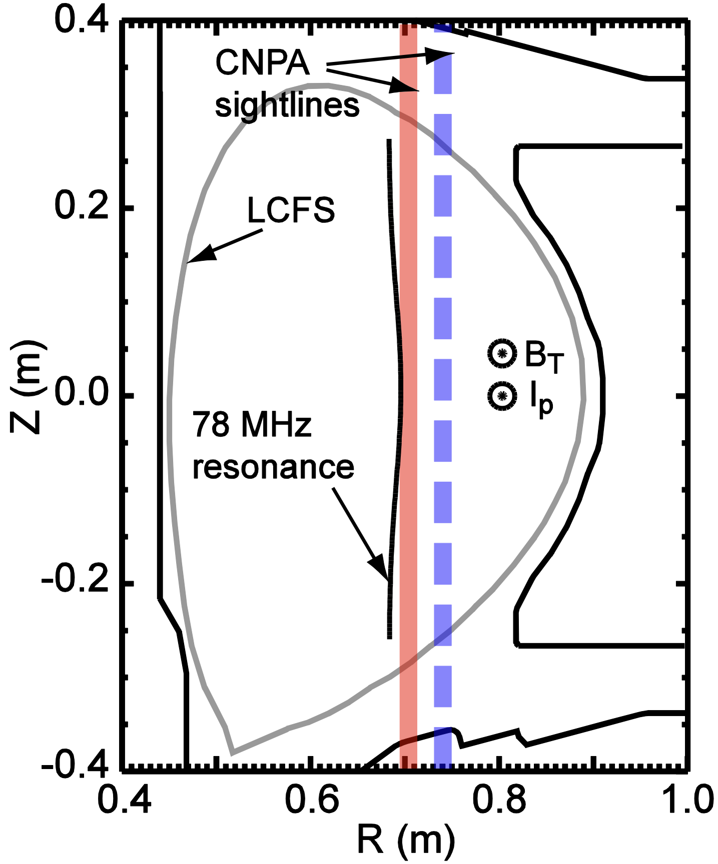
Experimental Parameters

- $R = 0.67$ m
- $a = 0.22$ m
- $B = 5.1 – 5.4$ T
- $I_p = 0.6 – 1.2$ MA
- $T_e \approx T_i = 2\text{-}4$ keV
- RF Power: 2 – 4 MW
- D majority, H-minority (5-8 %)
- $n_e = 1.0\text{-}2.0 \times 10^{20}$ /m^3
- Pulse length: 2 s



CNPA Measures Minority-Heated Fast-Ion Distributions

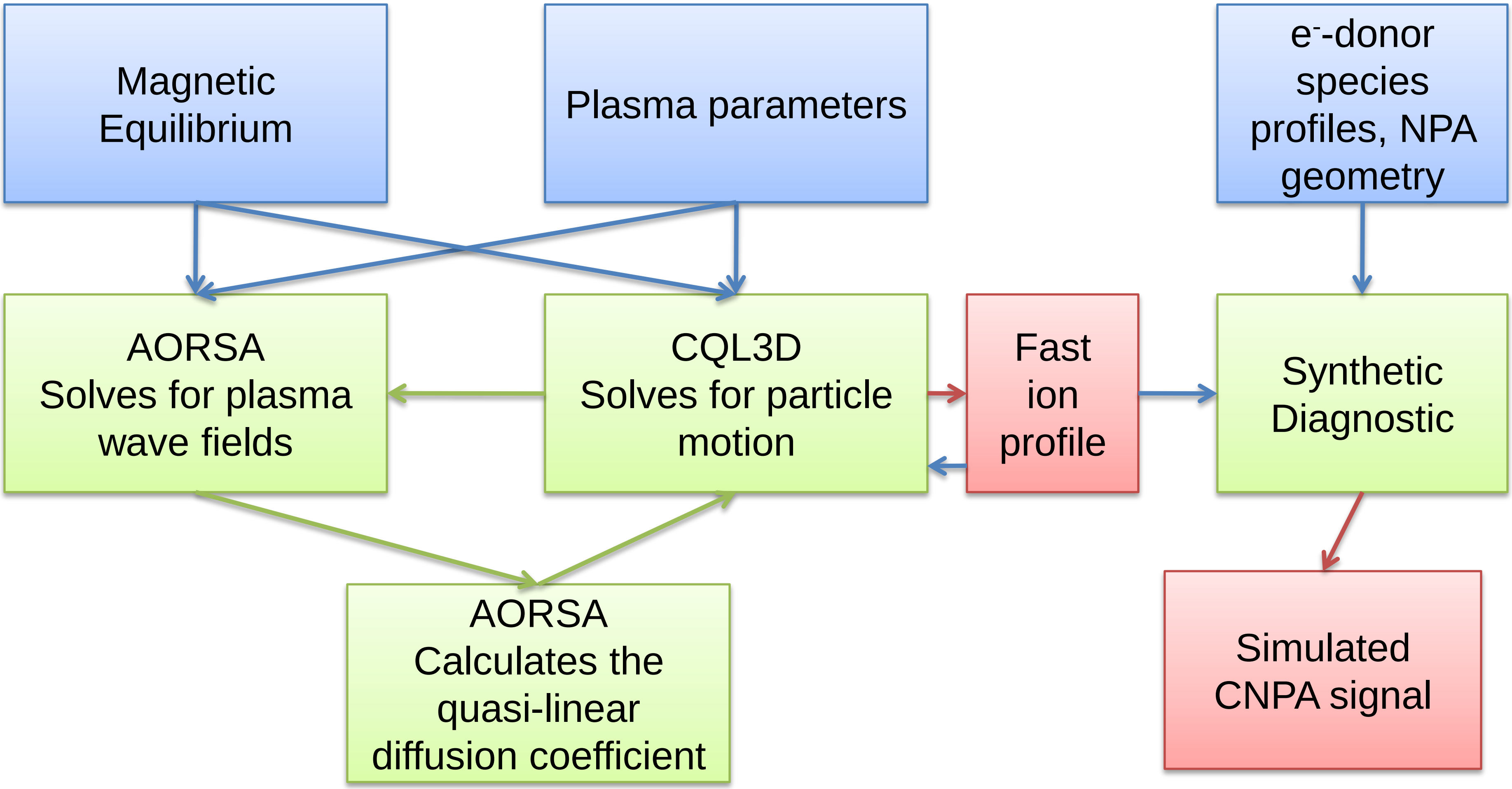
- CNPA = Compact Neutral Particle Analyzer.
- CNPA measures fast-ions that neutralize and escape the plasma.
- Measurements are passive, no neutral beam.
- For our viewing geometry, detected fast-ions neutralize near their banana tips.
- Solid-state Silicon-Diode detectors
- Radial range from ~70 cm to ~78 cm.
- Energy range from ~200 keV to 1.5 MeV.



Coupled Codes AORSA and CQL3D are Used to Produce a Self-Consistent Fast-ion Distribution

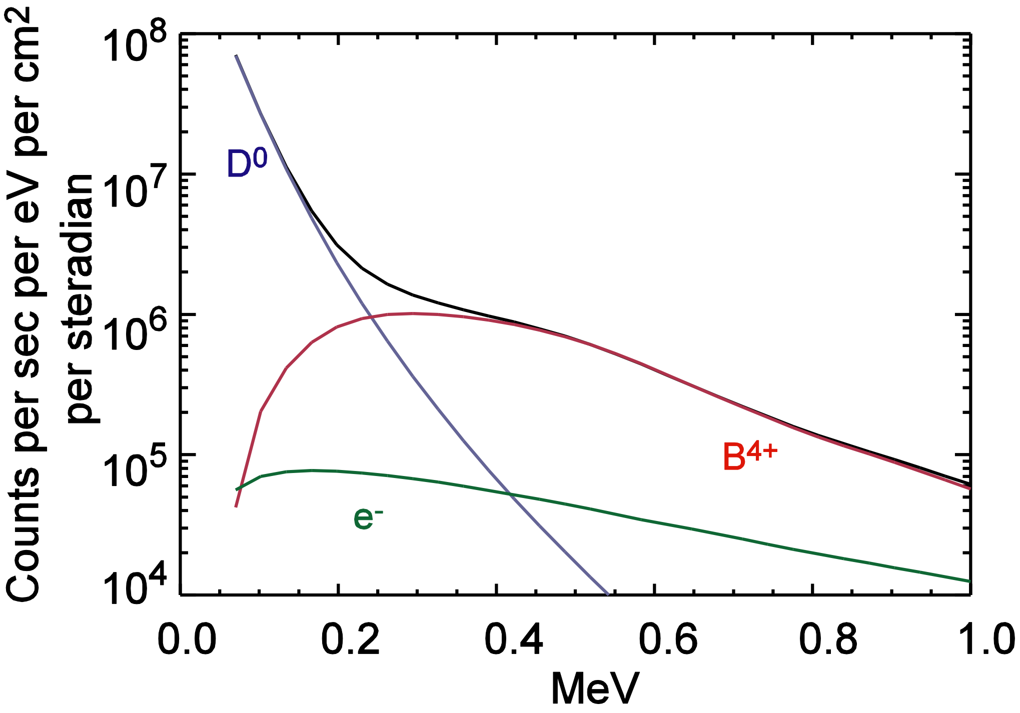
- AORSA (All ORders Spectral Algorithm)
  - Solves for the wave fields given a general distribution function. (e.g. as computed by CQL3D)
  - Does not assume $k_{\perp}\rho_i \ll 1$.
  - Can assume multiple toroidal modes for a fully 3-D solution.
- CQL3D (Collisional Quasi-Linear 3D)
  - Fokker-Planck solver.
  - Averages over a bounce period.
  - Assumes zero banana-width.
  - Assumes zero gyroradius.

Iterating Between AORSA and CQL3D Produces a Self-Consistent Fast-Ion Distribution



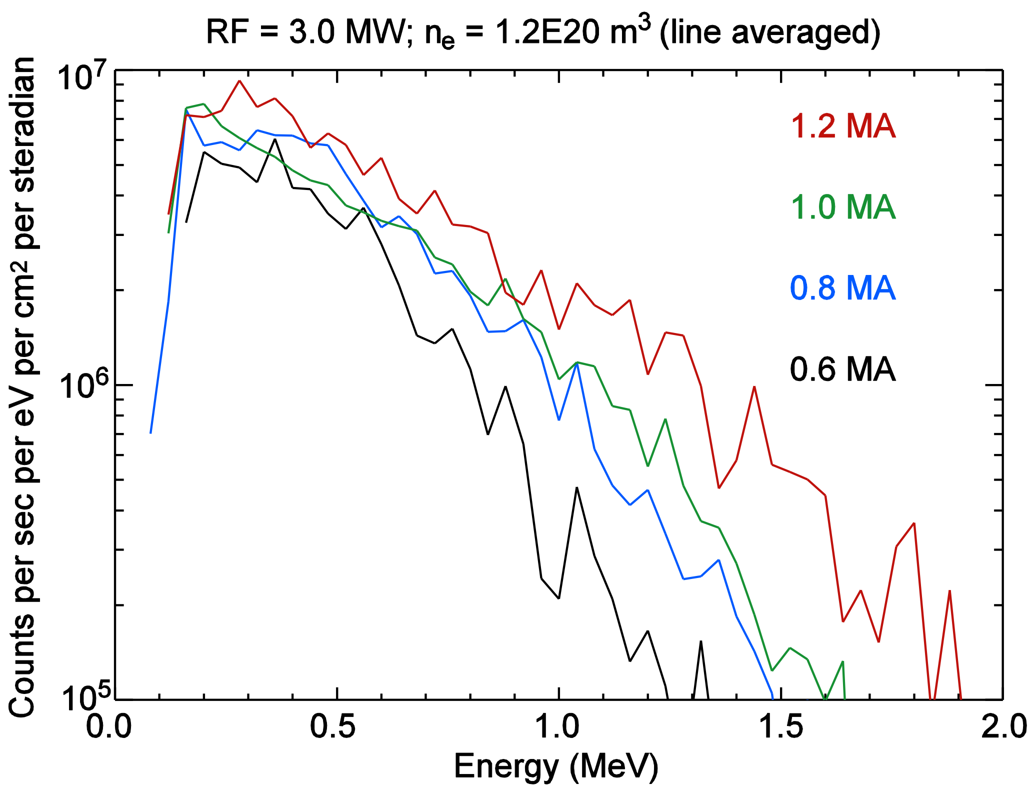
Over the Energy Range of Interest, CX with B^{4+} is Dominant.

- Neutral deuterium is contributed from wall transport and volume recombination (no beams)
- B^{5+} densities are a free parameter constrained by Zeff. Here, we assume that B^{5+} is 2.5% of n_e
- B^{4+} densities are calculated assuming that boron is in coronal equilibrium.

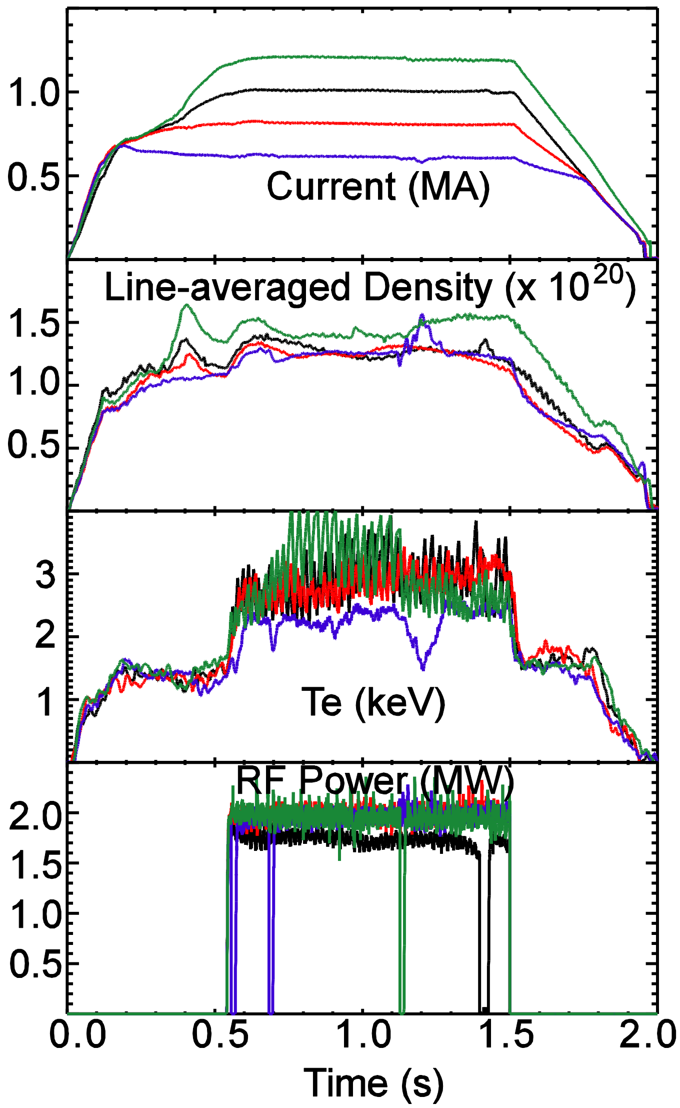


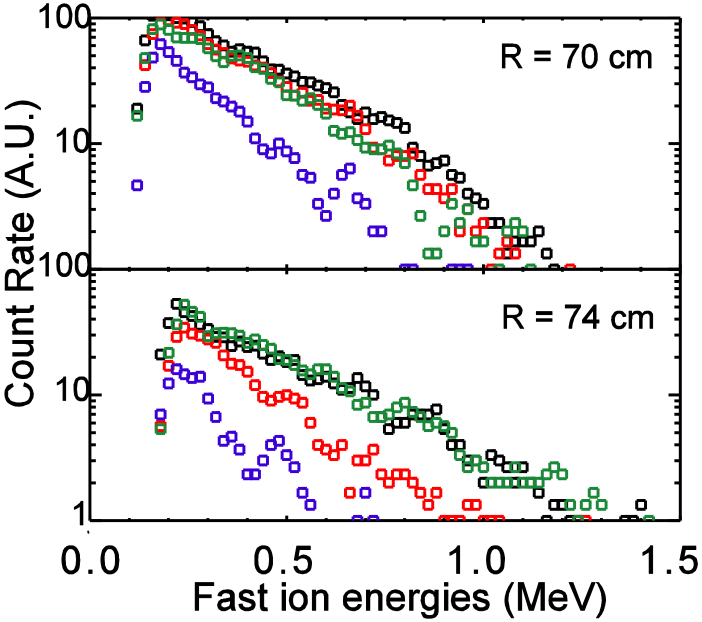
Fast-ion Tails are More Energetic at Higher Plasma Currents

- CNPA signals combined over all shots during a campaign show strong dependence on plasma current.
- Reason for current dependence is unclear. (Could it be a banana orbit effect?)
- The fast-ion trend vs current presents a good test for zero-orbit width simulation models.

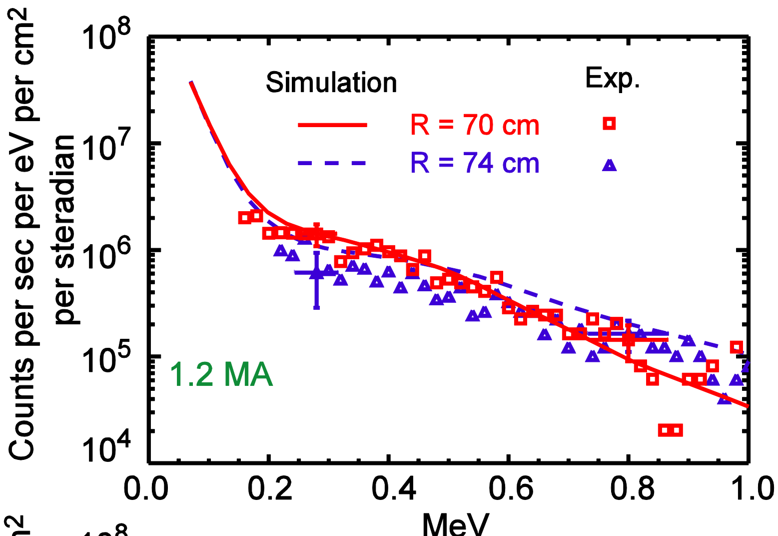


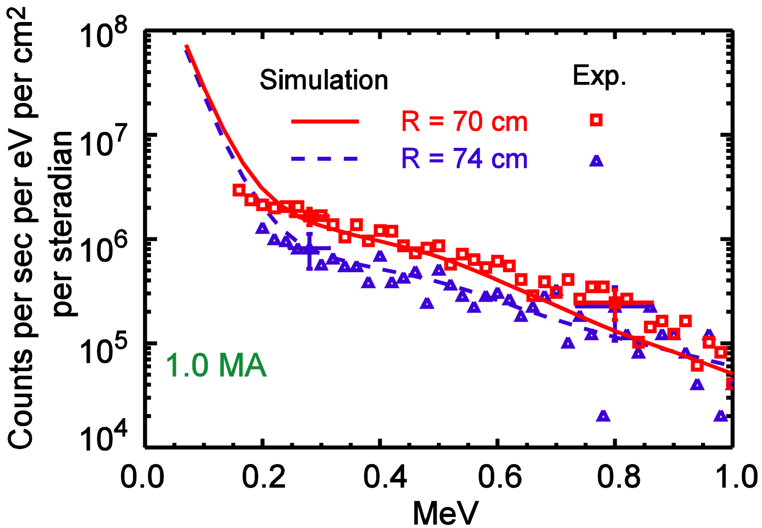
Four Discharges with Varying Currents were Simulated with AORSA-CQL3D

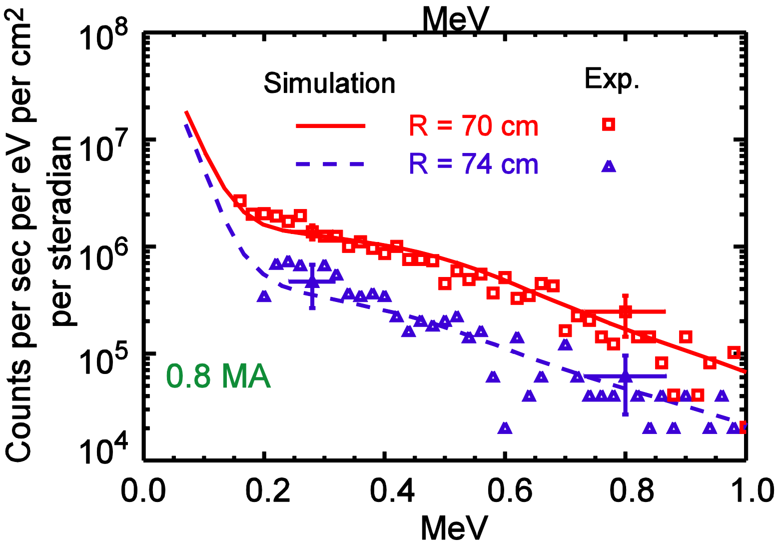


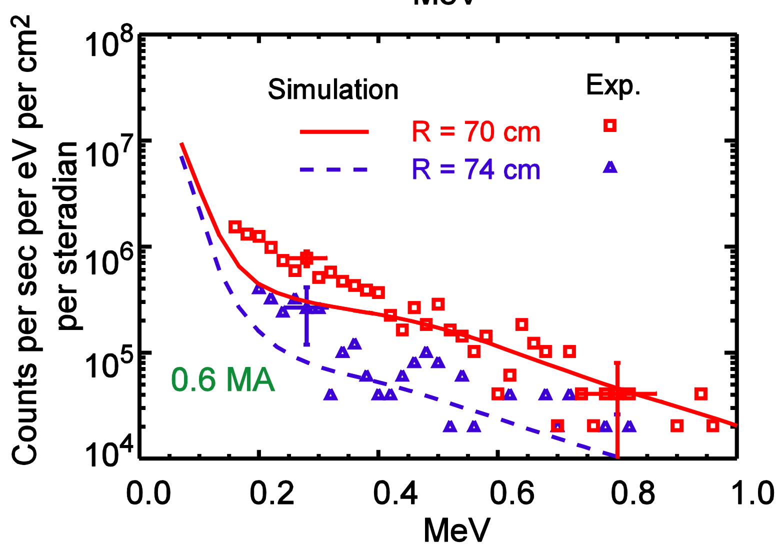


Steady State Simulation Results Show Good Agreement with Experiment



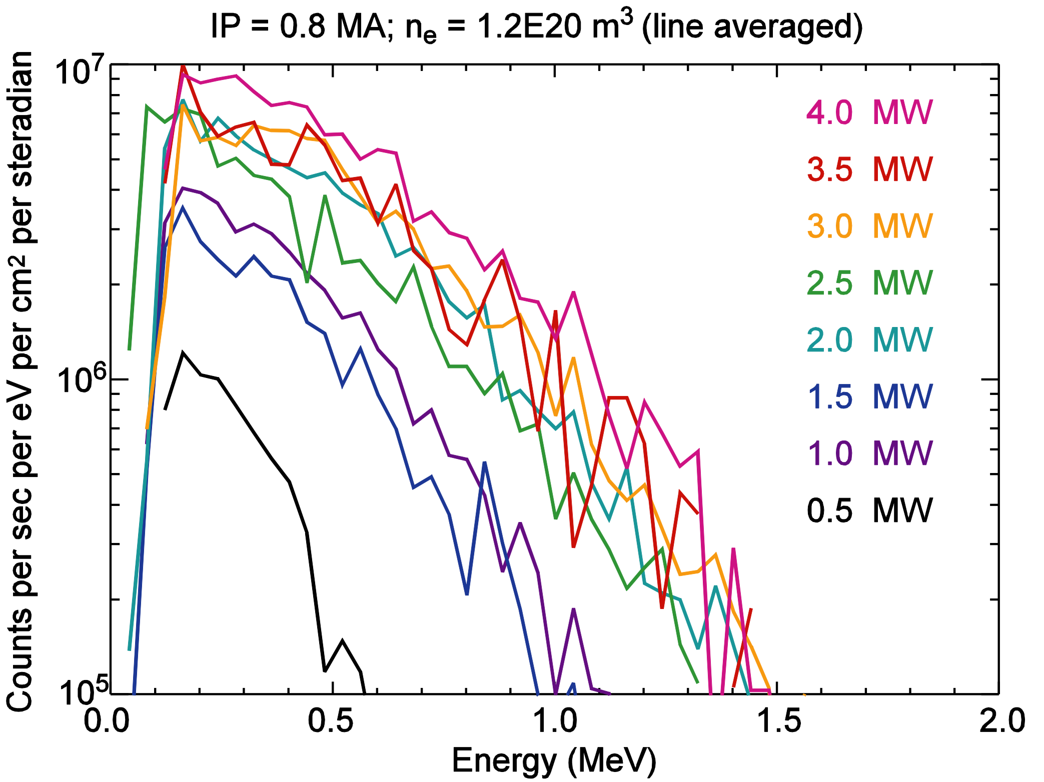




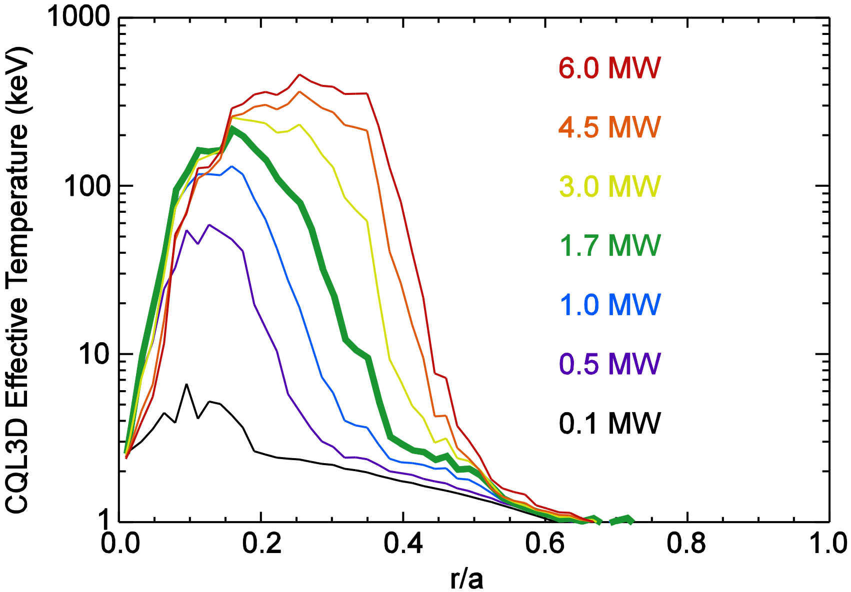


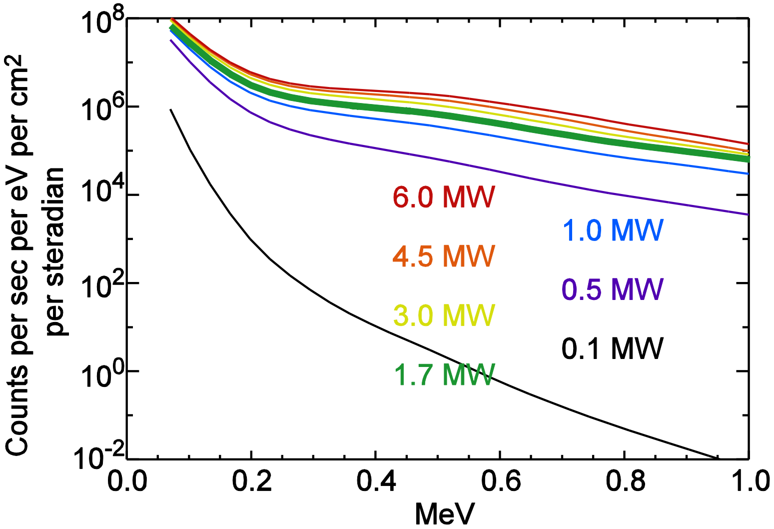
Increasing RF Power Raises the Density of the Fast-Ion Tail, but not the Temperature

- CNPA signals combined over all shots during a campaign show that higher RF Power generates more particles in the fast-ion tail.
- However, there is not a significant increase in the temperature of the fast-ion distribution, as determined by the slope of the distribution.
- This is different from what might be expected from a simple Stix model.



Simulation Shows Saturation of Fast-Ion Temperature at High RF Powers

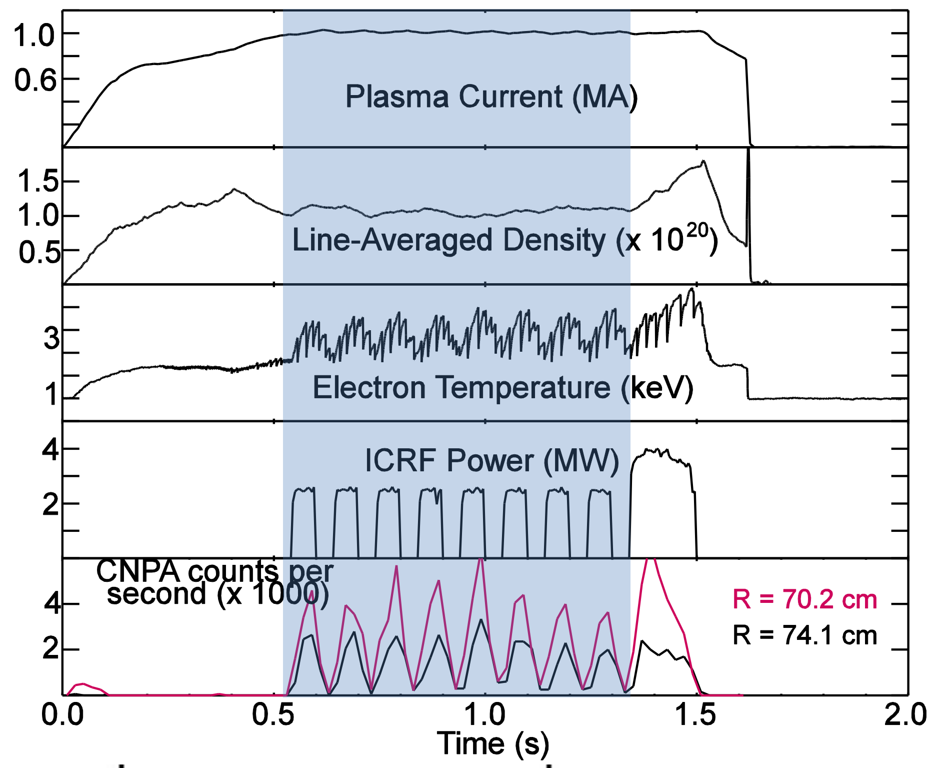


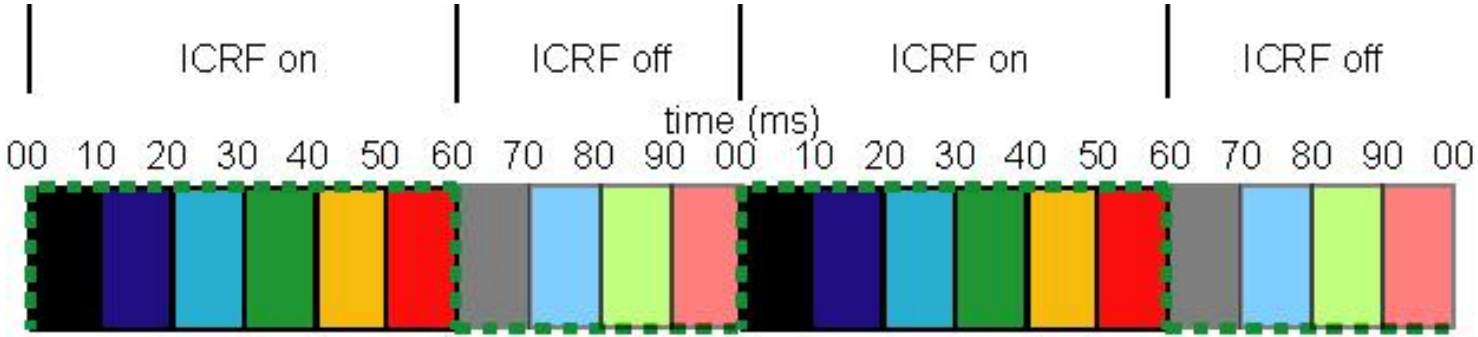


AORSA-CQL3D calculations of the fast ion temperature (left) and the estimated flux to the CNPA (right) as a function of RF power.

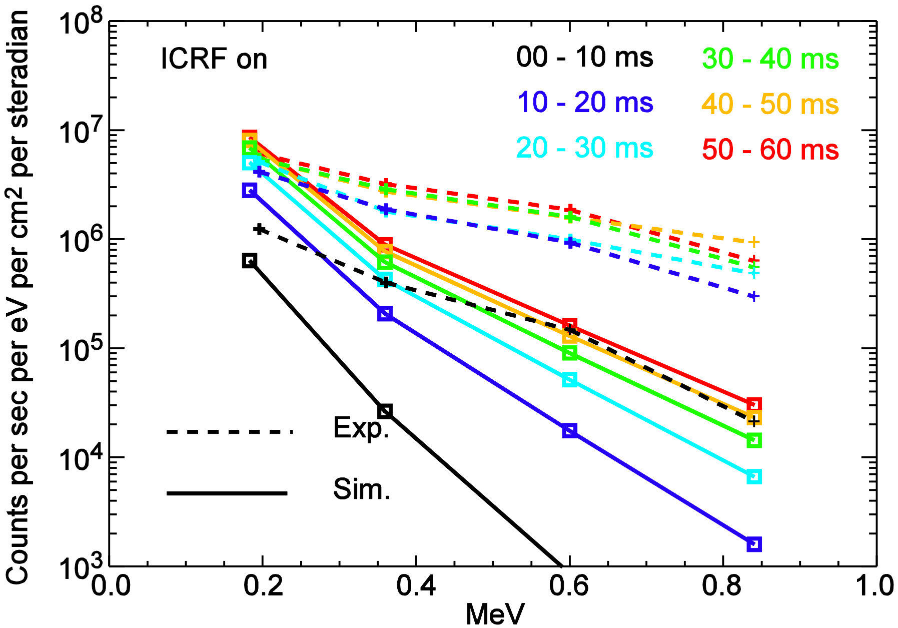
Experiments were Performed to Study the Formation and Decay of the Minority Tail

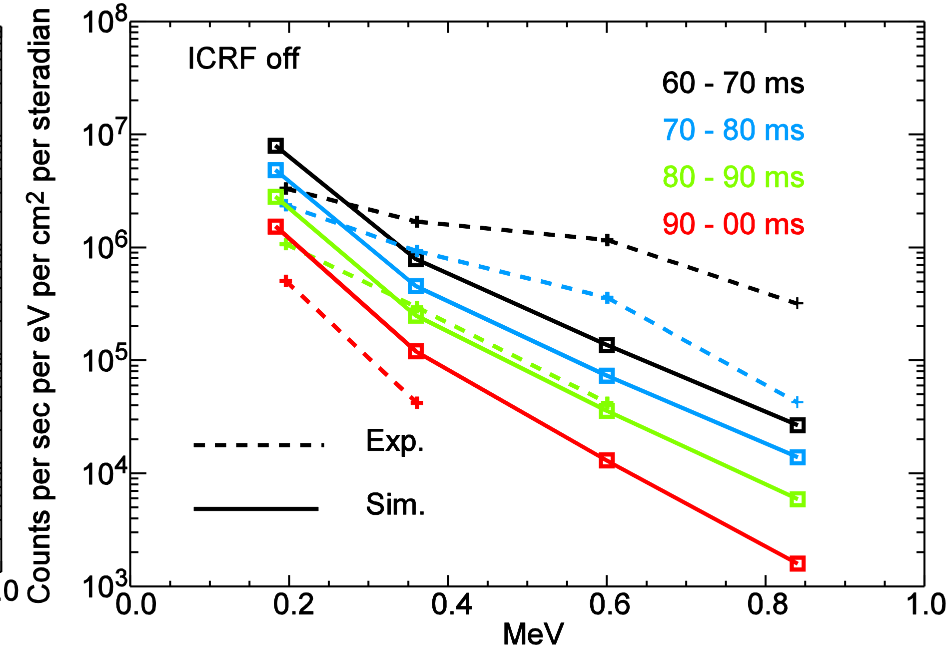
- ICRF is modulated in order to determine the transient behavior of the signal.
- Experimental data are summed over time bins for improved statistics.
- For simulations, CQL3D is evolved for 100 ms, calling AORSA every 1 ms.

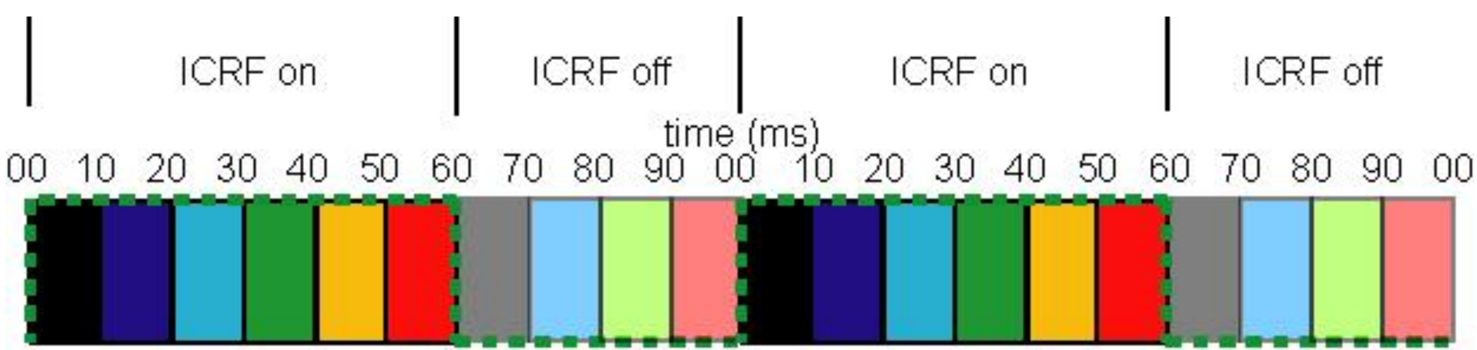




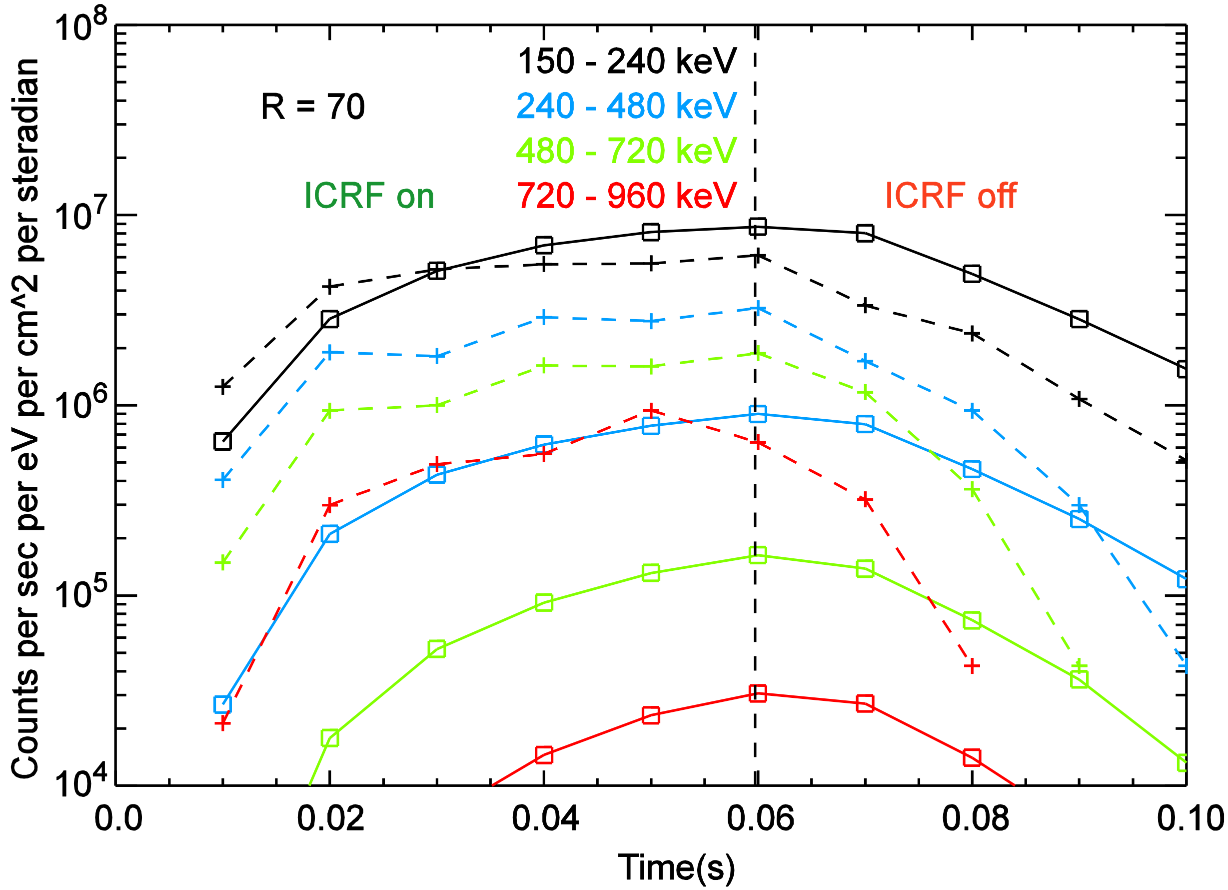
Simulation Takes Much Longer to Reach Steady State than the Experiment



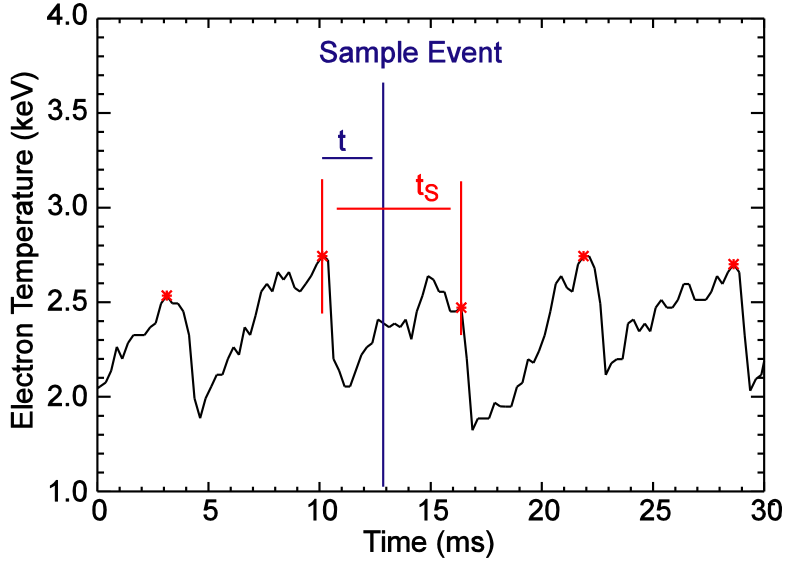


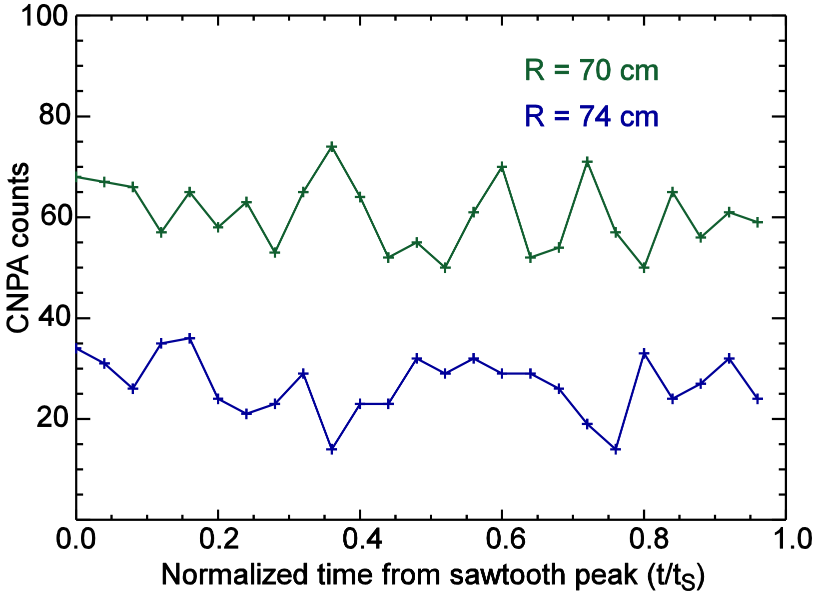


Discrepancy in Time Behavior is More Pronounced at Higher Energies.



Fast-ions in the CNPA View are Unaffected by Plasma Sawteeth





- The fast-ions viewed by the CNPA do not show any significant trend with plasma sawteeth.
- This is likely due to both viewing pitch angles away from the trapped-passing boundaries, and detecting ions too energetic to be affected by sawteeth.

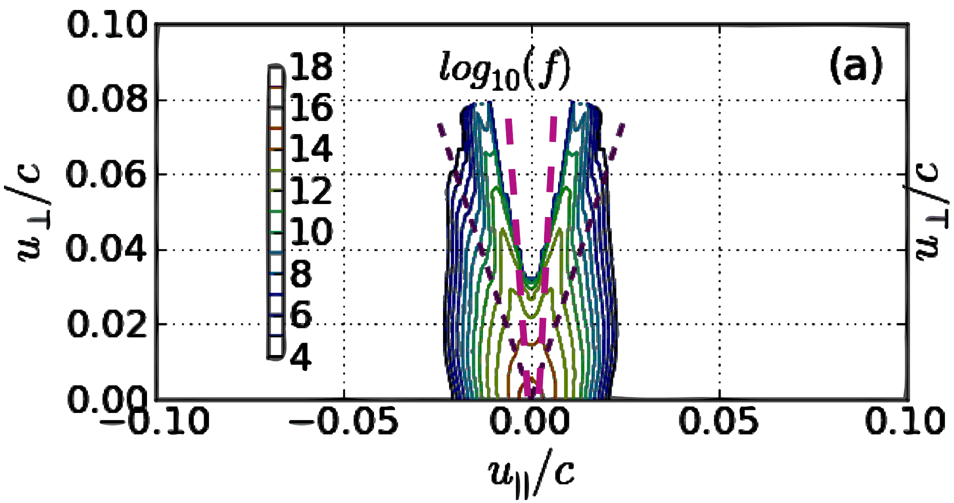
Results Raise Various Questions

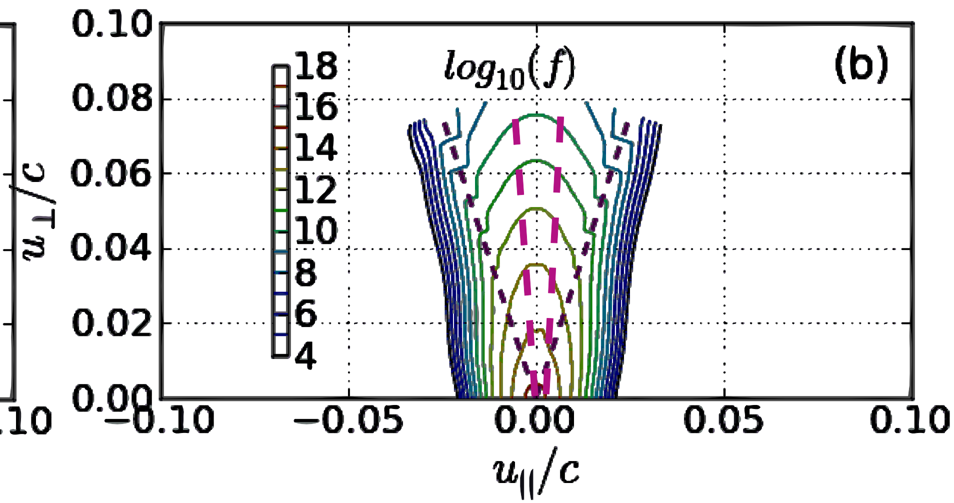
- Why, despite zero-orbit-width assumption in simulations, do the simulation and experiment have good agreement in steady-state over a range of plasma currents?
- What mechanism is responsible for the saturation of tail energy with RF power?
  - Doppler broadening of the resonance layer
- What is the reason for the discrepancies between experiment and the time-dependent simulation both in the rise and the decay?
  - Any explanation for the discrepancy should have minimal effect on the steady-state distribution.

New CQL3D-DC Simulations Show a Different Distribution Function after 4 ms.

- The discrepancy between the time-dependent simulations and the experiment can not be explained by enhanced radial diffusion or improved iteration algorithms.

- Initial results from CQL3D-DC obtained by integrating the Lorentz force on a particle orbit directly from the AORSA calculated fields shows a much faster rise time for deeply trapped particles.





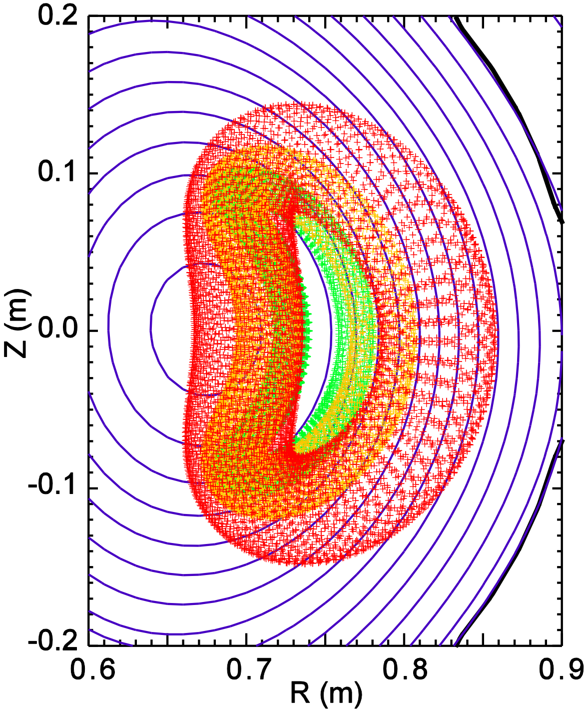
CQL3D-DC (b) shows a distribution function that is more filled in than CQL3D-QL (a) after 4 ms. R.W. Harvey et al. *RF Power in Plasmas*, Newport, RI (2011)

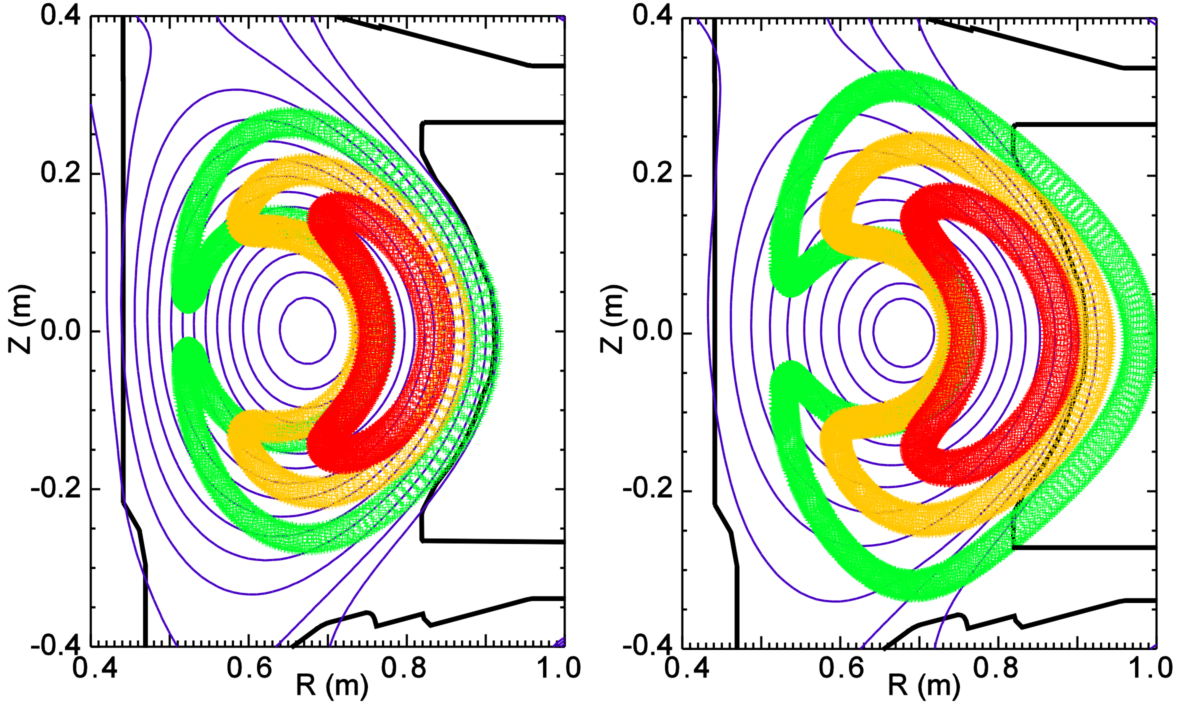
CNPA Measurements have been Used to Challenge Current Simulation Models

- Fast-ions between 200 keV and 1.5 MeV are routinely detected on minority-heated discharges on C-Mod using a Compact Neutral Particle Analyzer.
- Fast-ion distributions are more energetic with increased current but are not significantly more energetic with increased ICRF power.
- Comparisons between experiments and AORSA-CQL3D simulations show good agreement for steady-state (df/dt = 0) discharges.
- Simulations of time-dependent fast-ion distributions show a discrepancy between simulation and experiment.
  – Discrepancy may be resolved by employing a velocity-space diffusion coefficient in CQL3D based on a direct orbit integration of the fast ions using the AORSA full-wave fields.

EXTRA SLIDES

Particle Orbits in C-Mod

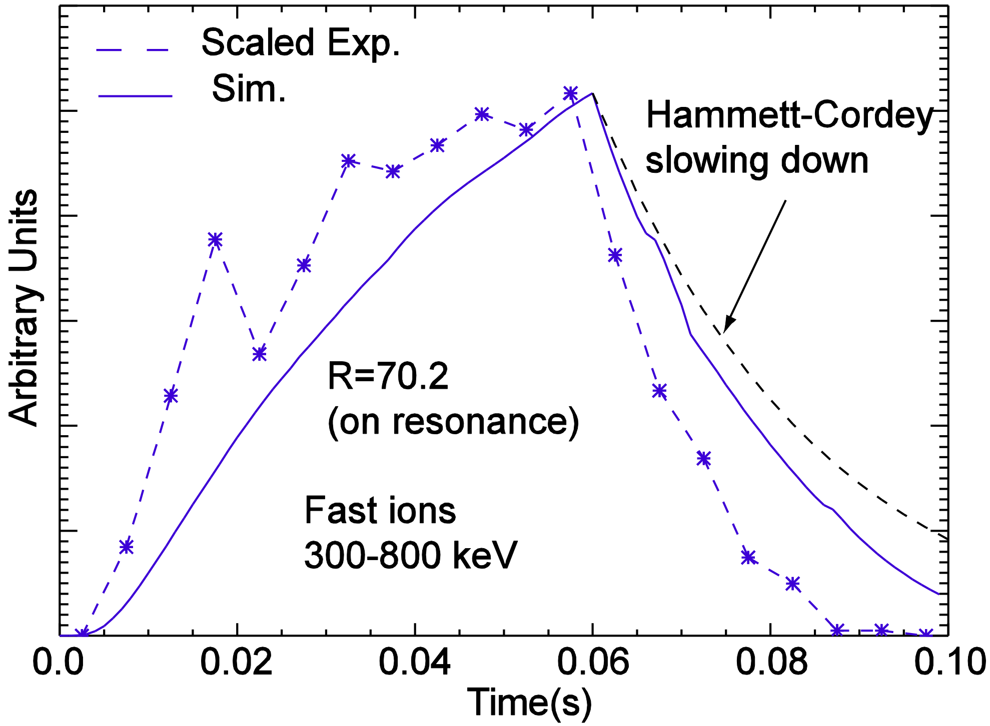




300 keV, 1 MeV and 3 MeV orbits in a 1 MA plasma

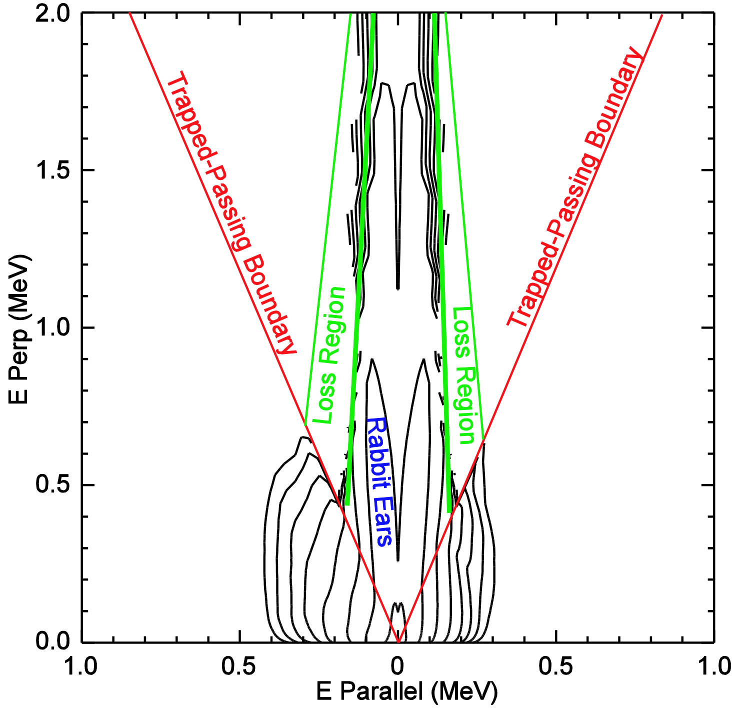
1 MeV ions with different pitch angles in a 1 MA plasma (left) and a 600 kA plasma (right)

Scaled Simulation Results Show Discrepancies in Both Rise and Decay



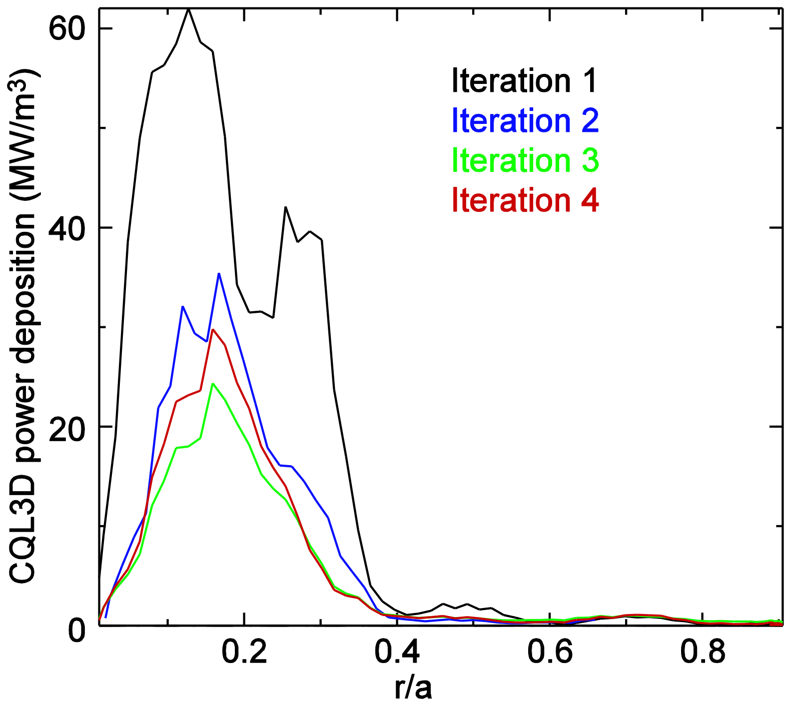
The Hammet Cordey slowing down assumes: $df/dt = -f/\tau_H$ where:
$1/\tau_H = 2/\tau_s(2/3 * E/T_{eff} - 1)$. τ_s is the classical electron slowing down time.

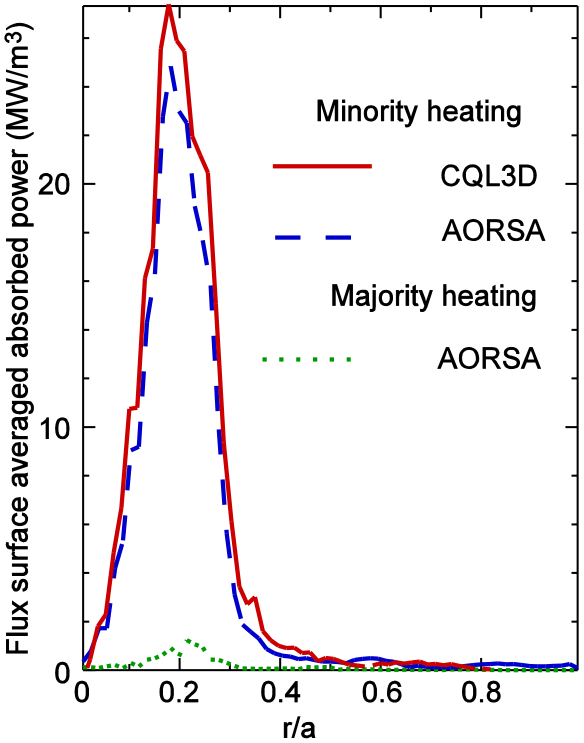
Fast-Ion Distribution is Highly Anisotropic



AORSA-CQL3D simulated midplane distribution at r/a = 0.3 shows a highly anisotropic fast ion distribution

CQL3D and AORSA Converge After 3-4 Iterations.





Convergence between successive runs of CQL3D occurs after 3-4 iterations. After which the absorbed power is seen to vary by ~10% between iterations.

Convergence between AORSA and CQL3D can be determined by comparing the absorbed power calculated by each code.