NSTX-U

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Full gyro-orbit simulations of the interaction between Neutral Beam Ions and High Harmonic Fast Waves in NSTX

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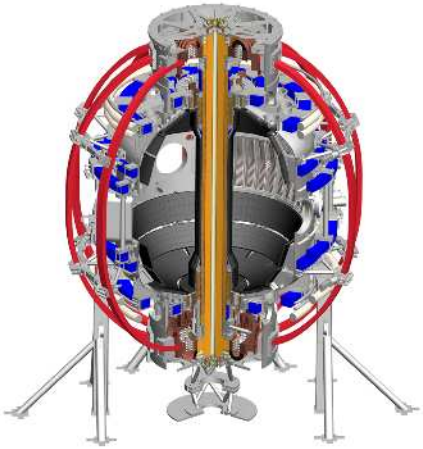

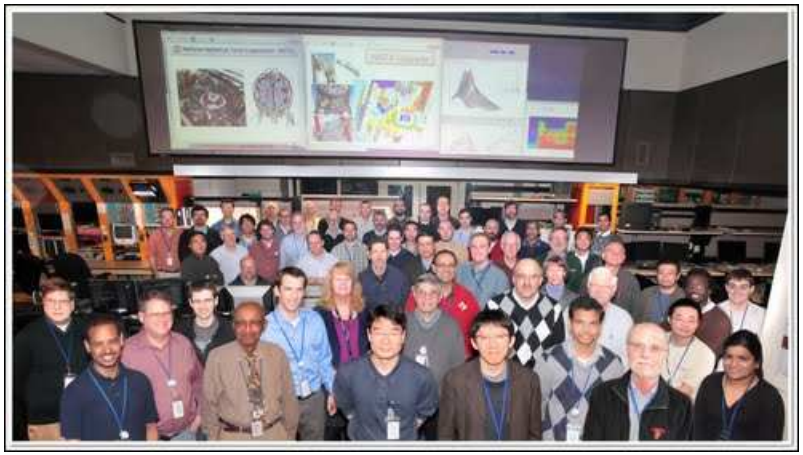

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Question:

How do High Harmonic Fast Waves (HHFW) interact with the fast deuterium ions from the Neutral Beam slowing-down distribution in NSTX? (With a small detour to ITER)

- Adsorption of HHFW power by the ions
- Modifications to the fast-ion distribution

High Harmonic Fast Waves can interact with the Deuterium population in NSTX

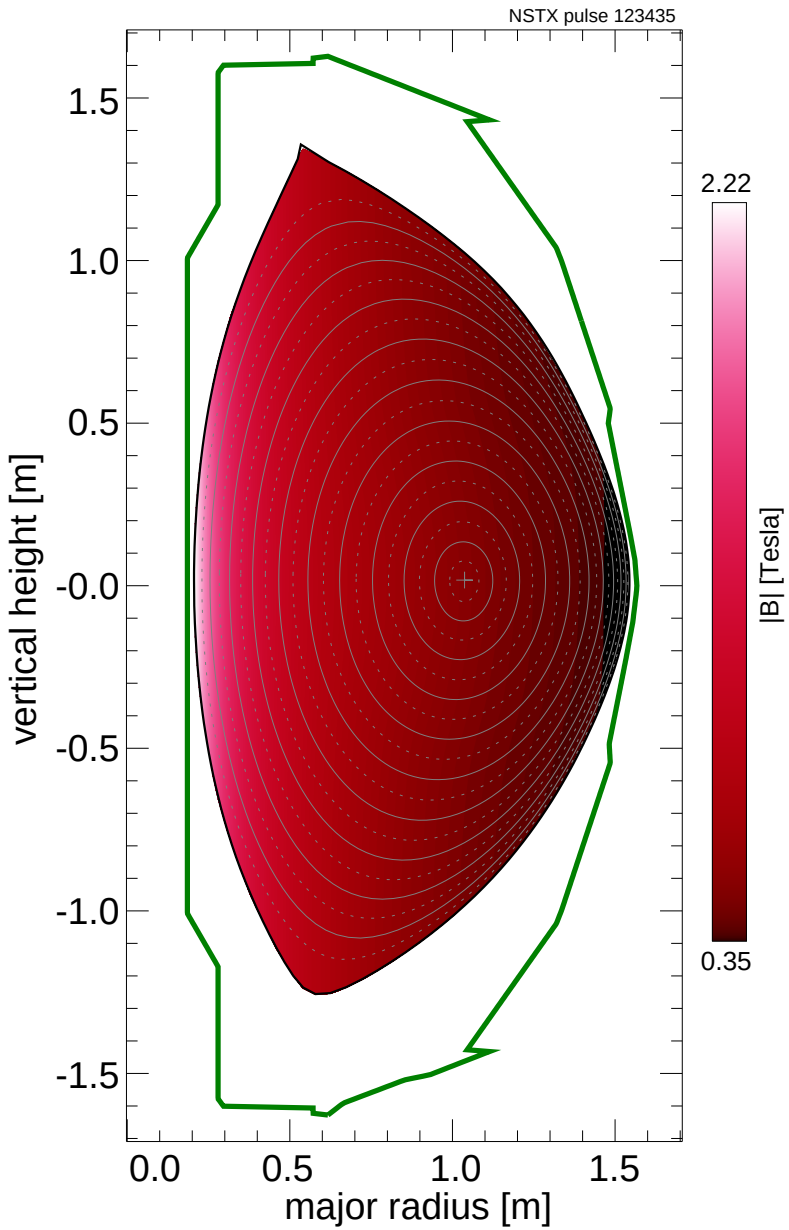
- High Harmonic Fast Waves are used to heat electrons and/or drive current
  - Heating or current drive depends on the antenna phasing
- Waves with a frequency of 30 MHz are launched in NSTX
  - This corresponds to two times the deuterium ion-cyclotron frequency at the HFS and ten times the deuterium ion-cyclotron frequency at the LFS
- The HHFW Deuterium-ion interaction can lead to:
  - a reduced heating and current drive efficiency
  - a strongly modified ion distribution
- We present results from a simulation of HHFW effects on a NBI slowing-down distribution in NSTX using:
  - TORIC: full-wave HHFW code for calculating RF fields
  - TRANSP/NUBEAM: for calculating the neutral beam-ion deposition profile
  - SPIRAL: full-orbit following code to calculate the beam-ion slowing-down distribution and the particle response to the RF fields
- Results:
  - A small amount of HHFW power is adsorbed by the ions
  - The HHFW have a large effect on the fast Deuterium distribution

The toroidal magnetic field varies strongly in the spherical tokamak NSTX

- NSTX parameters:

major radius:	R ~ 1.0 m
minor radius:	a ~ 0.5 m
elongation:	k < 2.7
Magnetic field:	B_T ~ 0.5 T
density:	$n_e(0)$ ~ 2.7 $10^{19} m^{-3}$
temperature:	$T_e(0)$ ~ 1.5 keV

- The magnetic field varies from 2.22 T at the HFS to 0.35 T at the LFS



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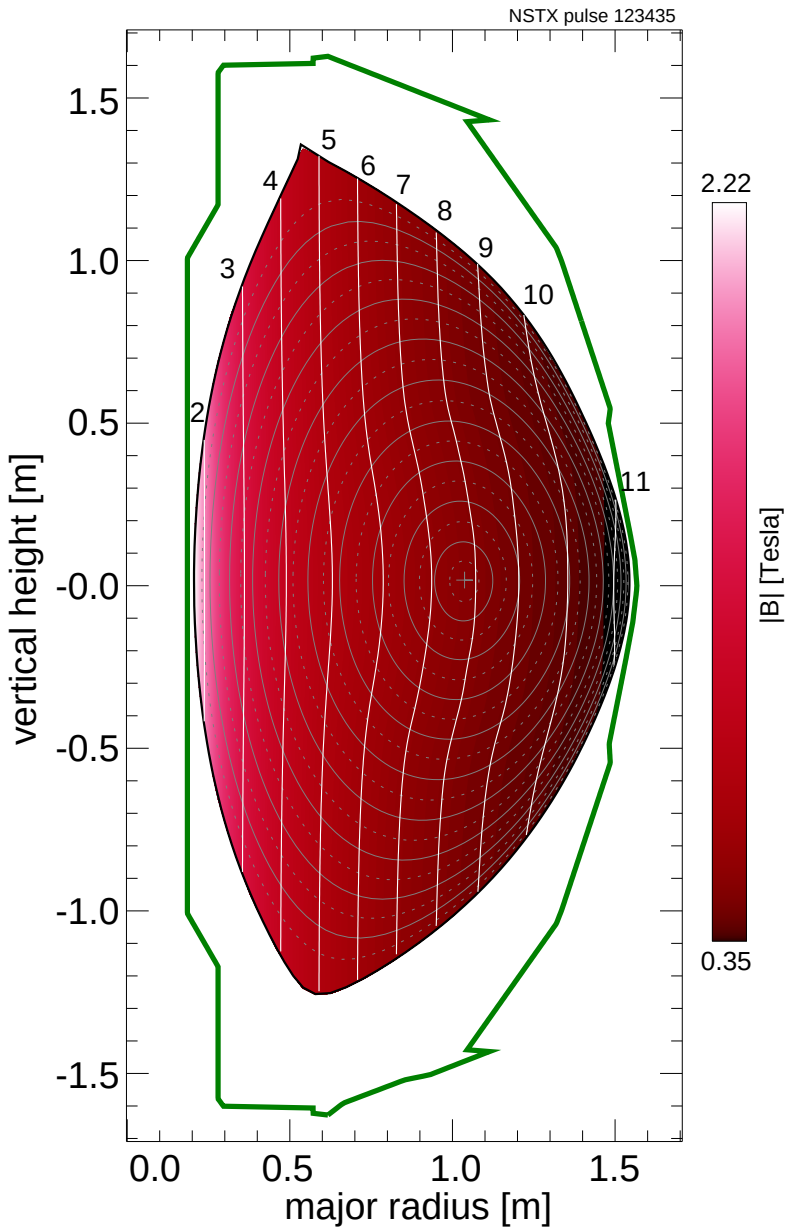
- The magnetic field varies from 2.22 T at the HFS to 0.35 T at the LFS
- When 30 MHz RF waves are injected a large number of Deuterium-cyclotron harmonics are present in the plasma
- Particles can interact strongly with the RF waves at those resonances



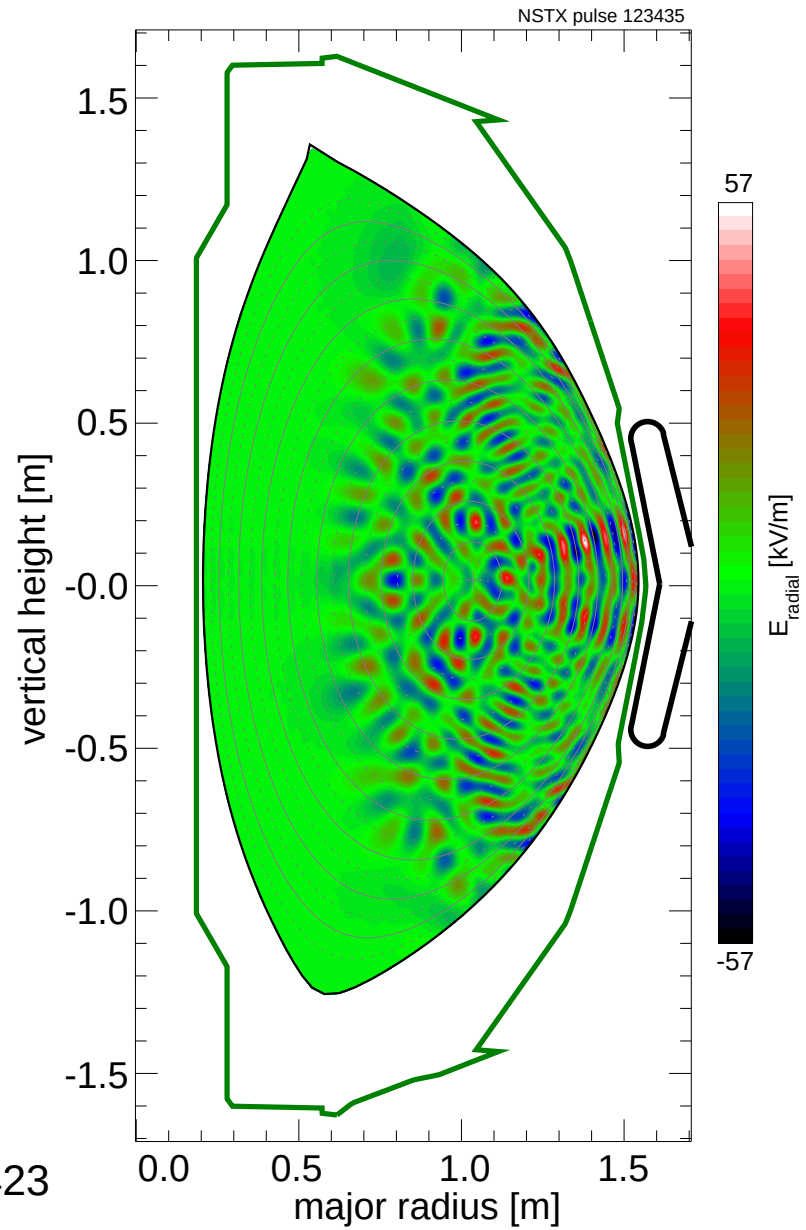
The full-wave code TORIC is used to calculate the HHFW fields in the plasma

- TORIC solves the wave equation:

$$\nabla \times \nabla \times \mathbf{E} = \left(\frac{\omega}{c}\right)^2 \left[\mathbf{E} + \frac{4\pi i}{\omega} (\mathbf{J}_p + \mathbf{J}_a)\right]$$

$\mathbf{E}$ the electrical field
$\mathbf{J}_a$ the prescribed antenna current density
$\mathbf{J}_p(\mathbf{E})$ the plasma current density

- A Fourier ansatz is used in the toroidal and poloidal direction
- The HHFW version of TORIC was used that includes Finite Larmor Radius effects
- A Maxwellian distribution was used in the calculation of the dielectric tensor which is used in the calculation of $\mathbf{J}_p(\mathbf{E})$



M. Brambilla, Plasma Phys. Control. Fusion 44 (2002) 2423

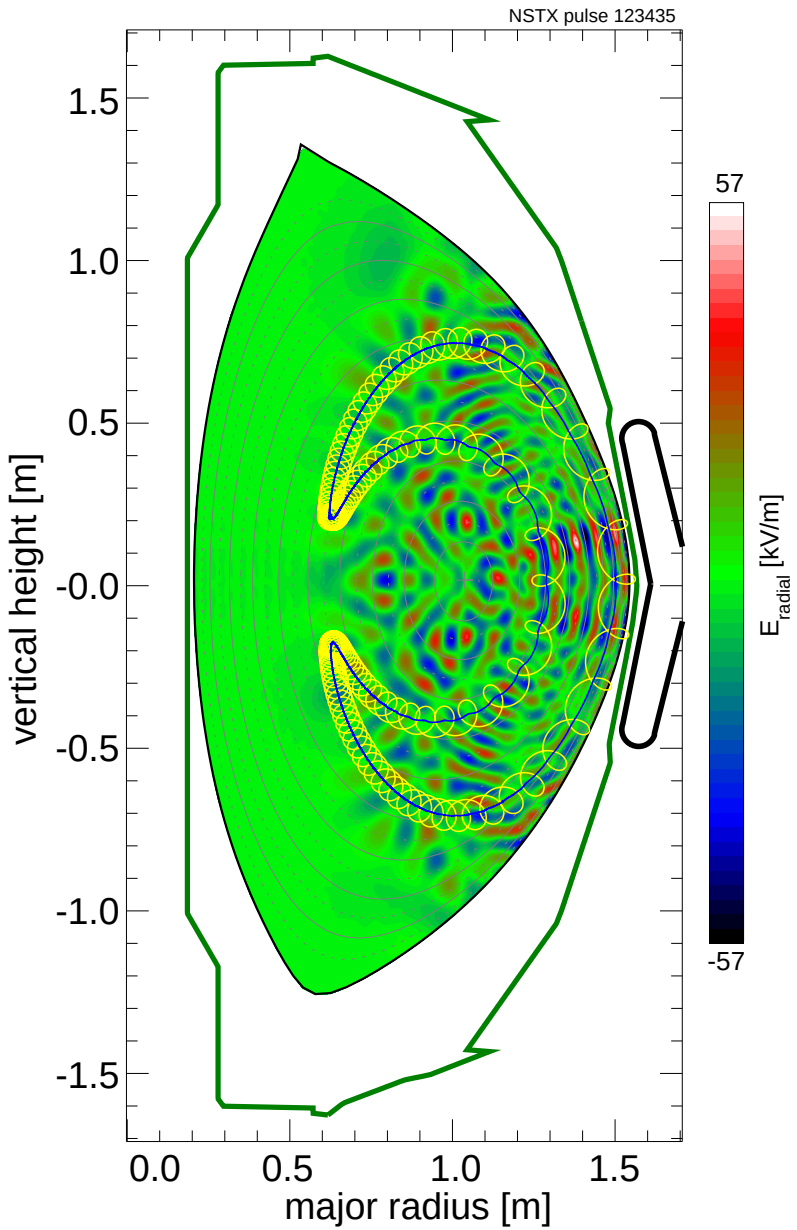
The full-orbit following code SPIRAL is used to calculate fast ion orbits and distributions

- SPIRAL solves the Lorentz equations:

$$d_t \mathbf{v} = \frac{q}{m}(\mathbf{v} \times \mathbf{B} + \mathbf{E}) \qquad d_t \mathbf{r} = \mathbf{v}$$

- Toroidally symmetric equilibrium fields are used from EFIT
- The 3D TORIC E and B fields are used
- Pitch angle scattering and slowing down are included
- Realistic beam birth profiles are obtained from the TRANSP/NUBEAM codes
  - all three energy components were included

- Because the full gyro orbit is calculated the HHFW-particle interaction is included in the simulations without approximations



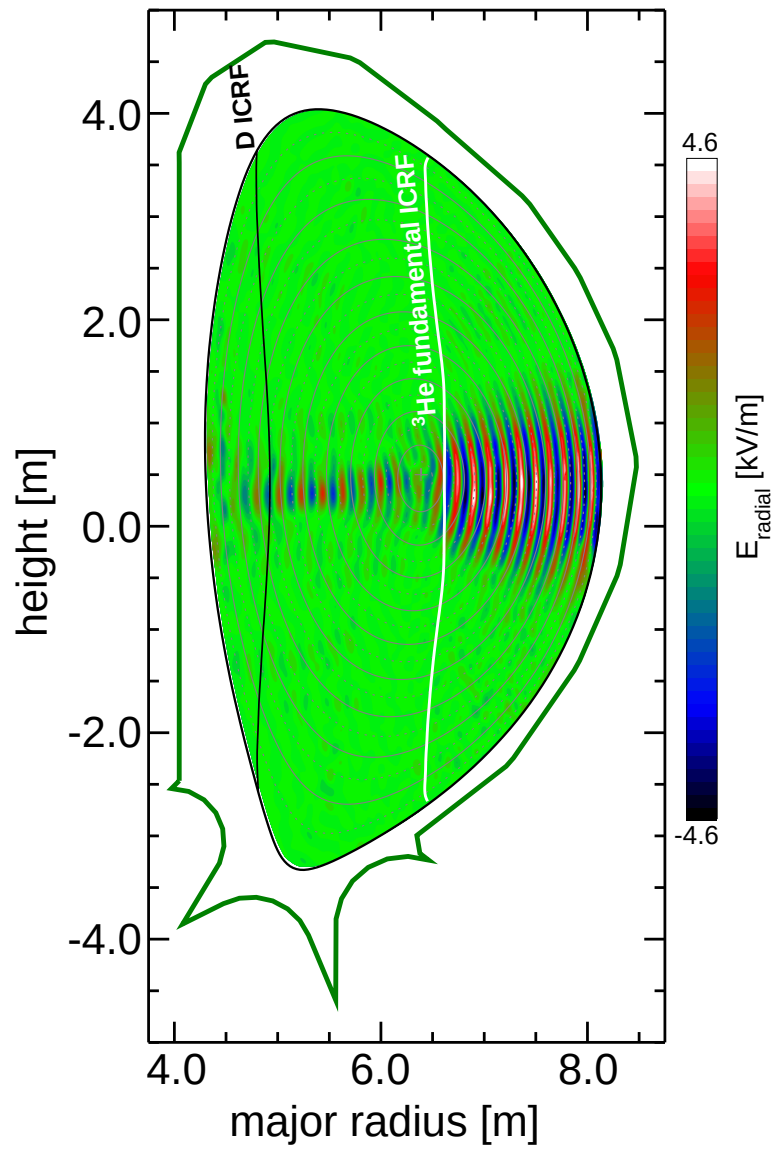
A simple case:
One ICRF resonance in ITER

Before looking at multiple HHFW resonances in NSTX study a more simple case:

A single Ion Cyclotron Resonance layer in ITER

The effects of a single parasitic D-resonance layer on ^{3}He minority ICRF heating in ITER

- ^{3}He minority ICRF heating at 52.5 MHz has been proposed for ITER
- The fundamental D resonance is also present in the plasma
- Deuterium beam ions can interact with this resonance



R.V. Budny et al. Nuclear Fusion 52 (2012) 023023

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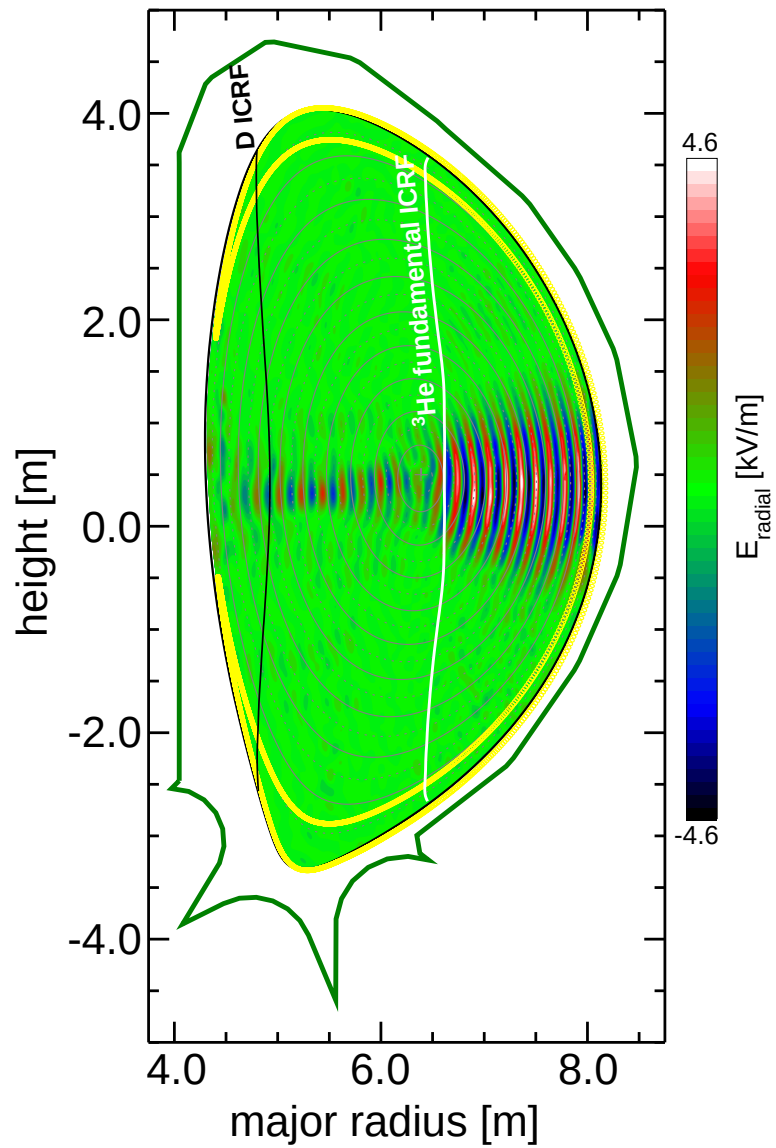

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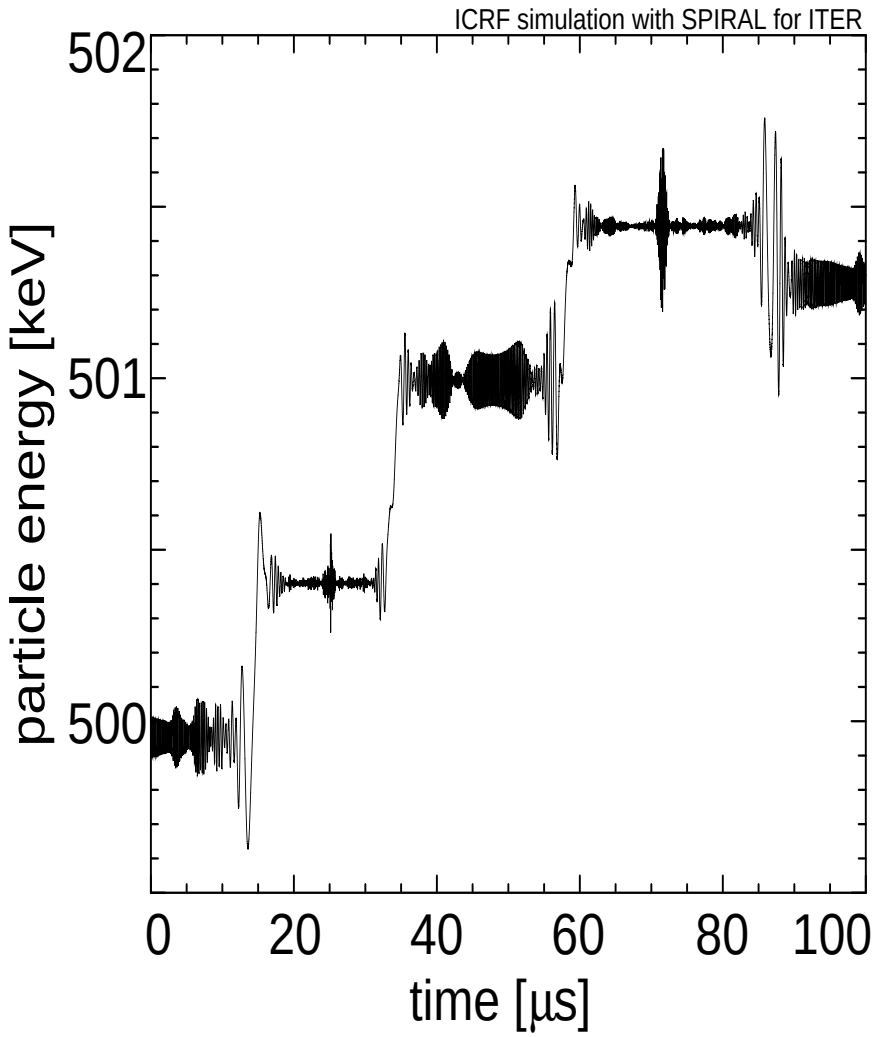

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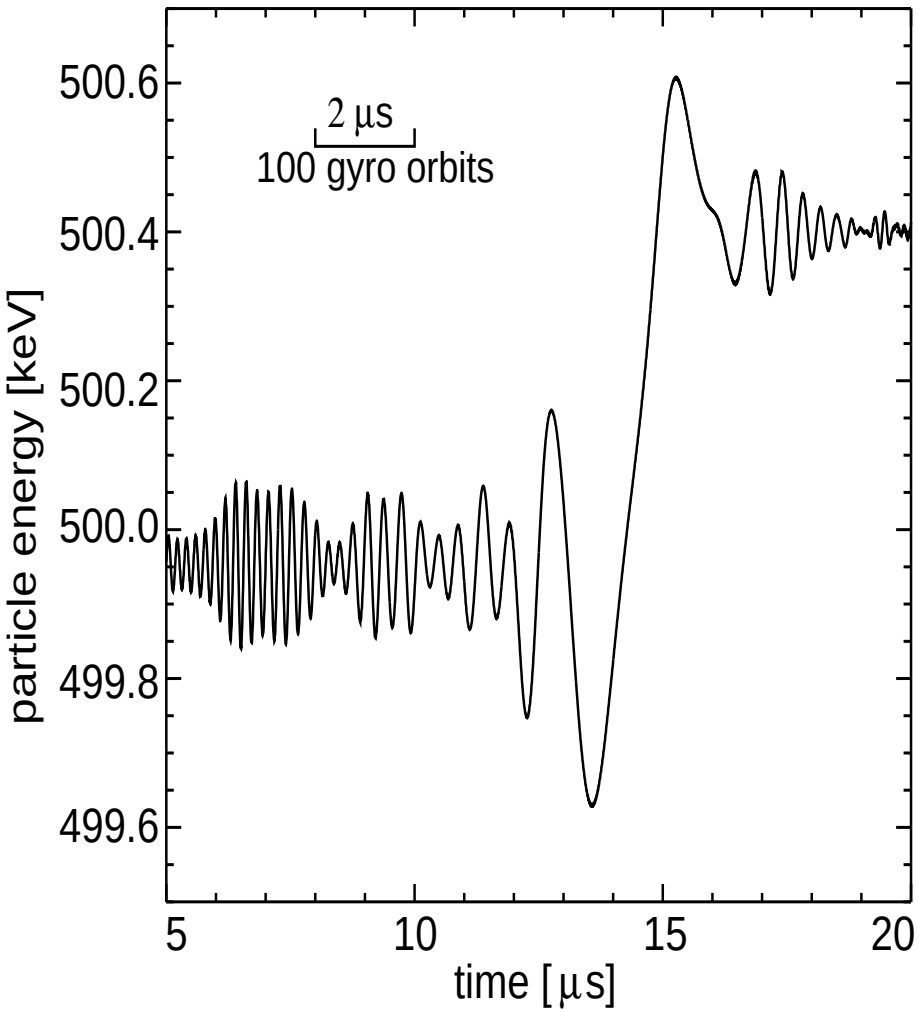

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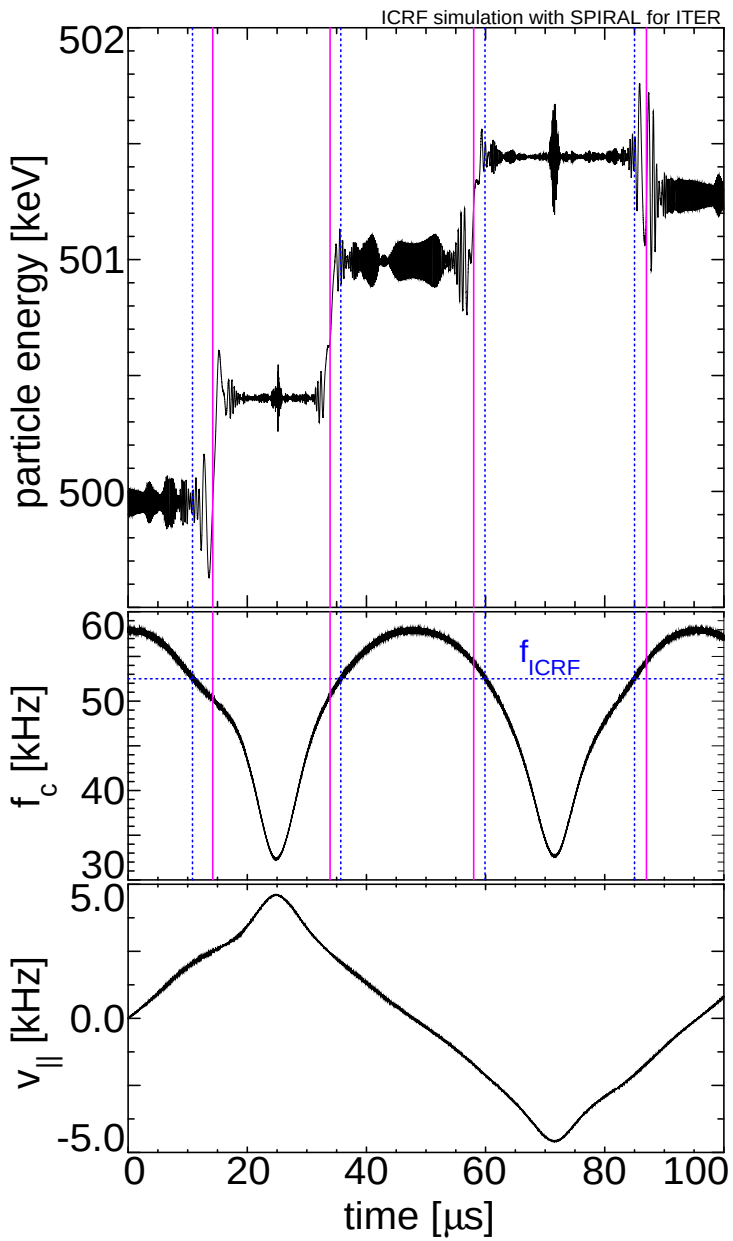
counter going: 52.5 -> 54.0 MHz



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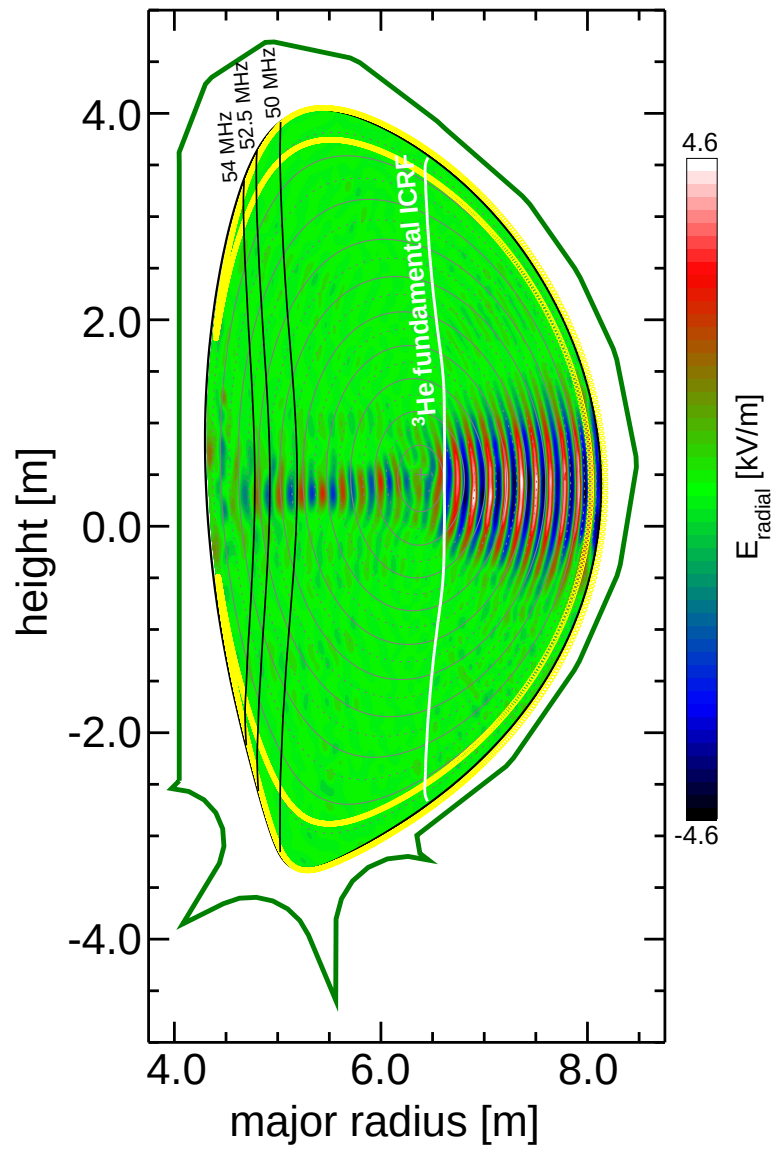
- The ICRF resonances in ITER can have a significant (> 0.4 m) Doppler broadening



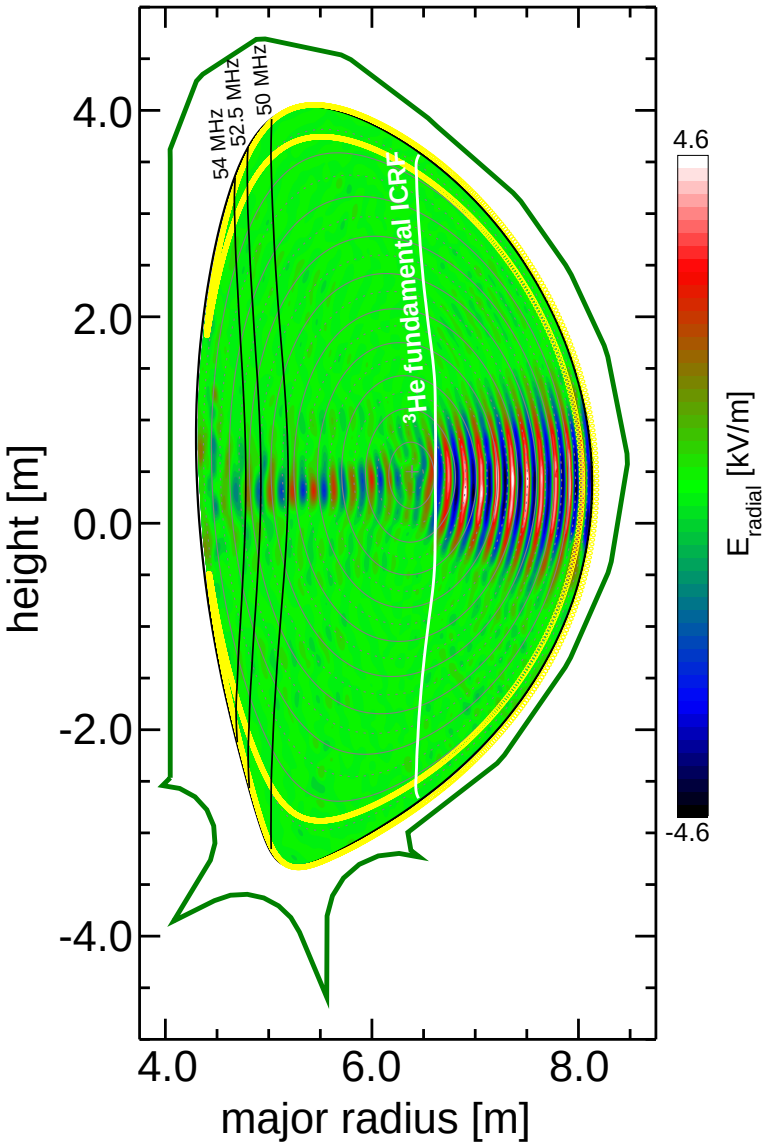
The effects of a single parasitic D-resonance layer on ^{3}He minority ICRF heating in ITER

- The NBI-injected deuterium-beam ions form a slowing-down distribution that can interact with the ICRF wave field
- An ensemble of deuterons drawn from the beam-ion slowing-down distribution was used in SPIRAL to calculate the net energy exchange between the 20 MW ICRF waves and beam ions:

  SPIRAL: 80 KW to the beam ions
  TORIC: 60 KW to the beam ions

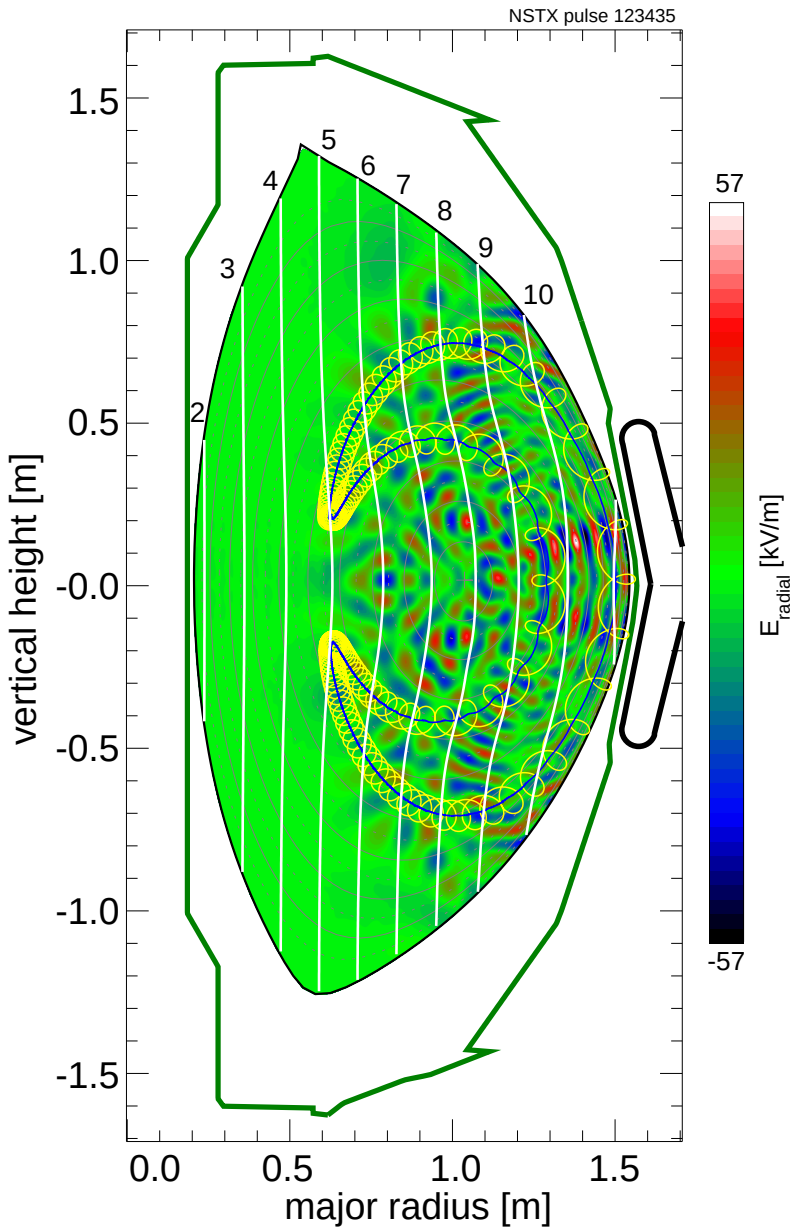
- TORIC and SPIRAL agree well on the adsorbed power: it is small which is good for ITER

- SPIRAL gives sensible results for simple single ICRF resonances. Return to NSTX with its complicated multiple resonances



Significant HHFW-particle interaction occurs when the poloidal drift velocity is low

- Particles intersect a number of resonances on its path through the plasma as shown 20 keV deuteron on a trapped orbit
- Away from the turning points the drift velocity becomes a good fraction of the perpendicular velocity
  - This is a consequence of the low magnetic field



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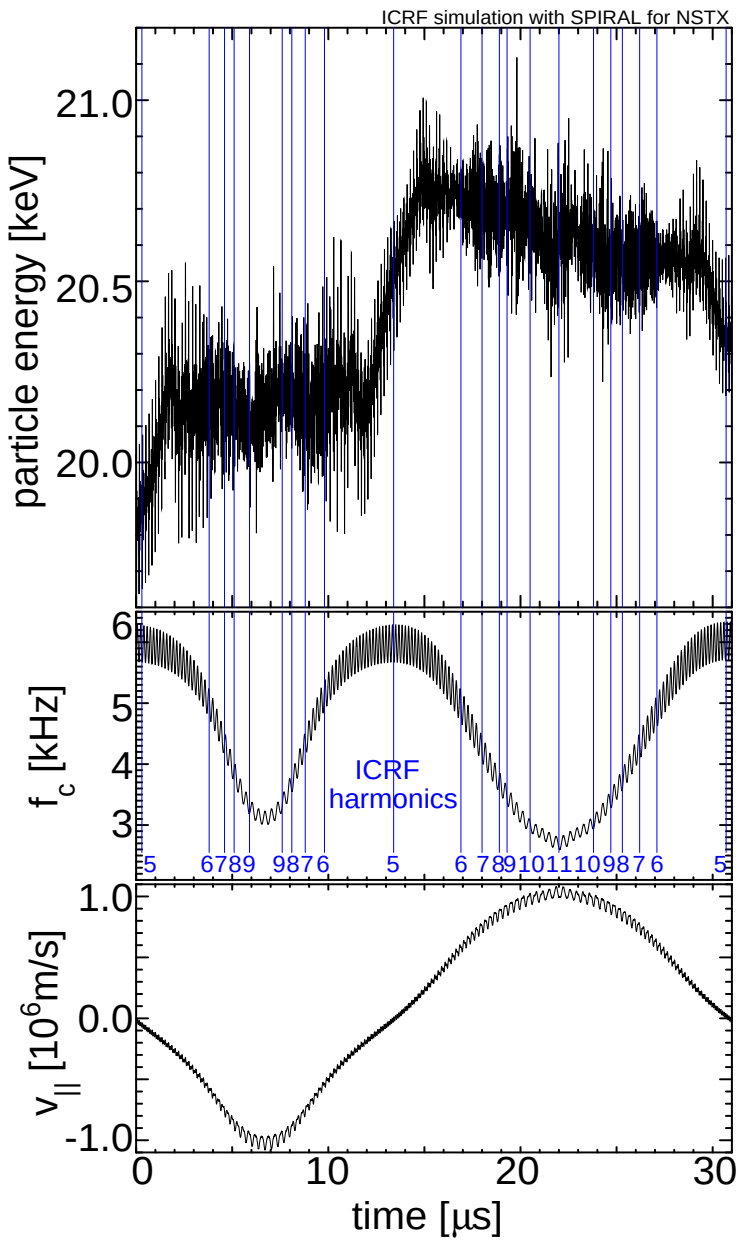
- Away from the turning points the drift velocity becomes a good fraction of the perpendicular velocity
  - This is a consequence of the low magnetic field
- Significant energy exchange occurs only at the lowest resonance where the banana tips are located
- The kicks at the bounce points last for about 3 μs or 18 gyro orbits
- The other resonant layers are passed much faster without any significant energy kicks

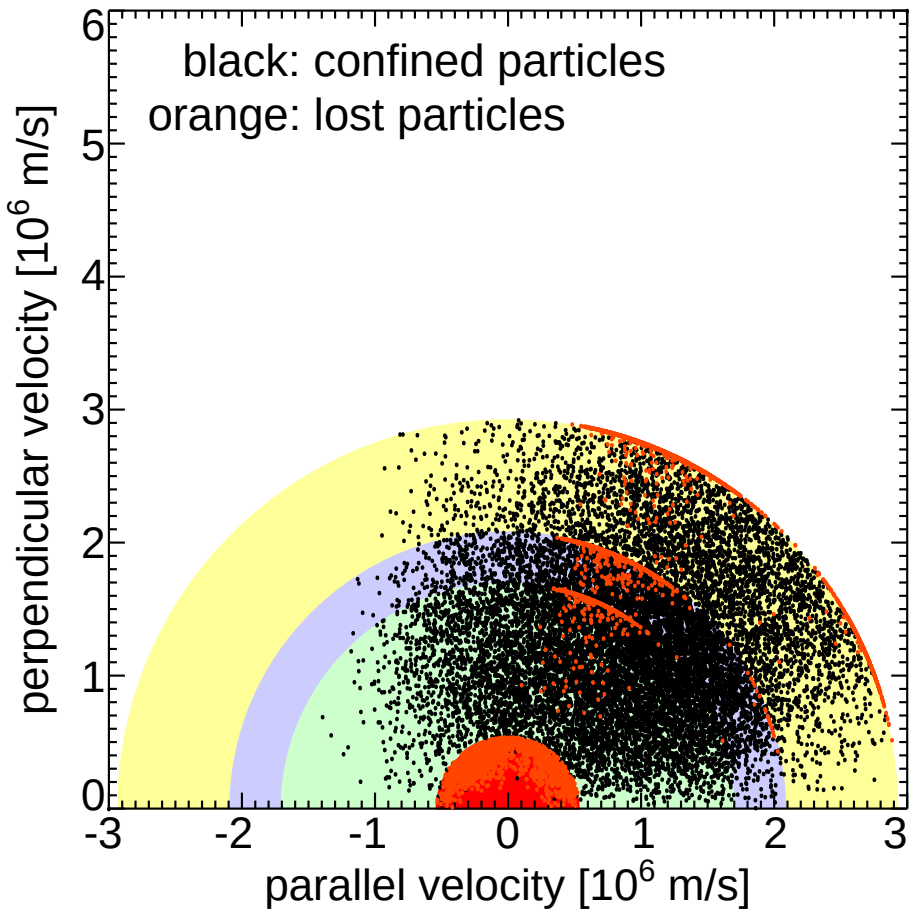
- How does HHFW interact with an ensemble of fast ions from a slowing down distribution?



A slowing-down distribution was calculated with SPIRAL from the NBI birth profile

- Initial beam birth profile from TRANSP/NUBEAM code
- All three beam energy components were included
- Particles were loaded uniformly between 0 and 50 ms and followed until 50 ms
- Slowing-down and 3D pitch-angle scattering were included

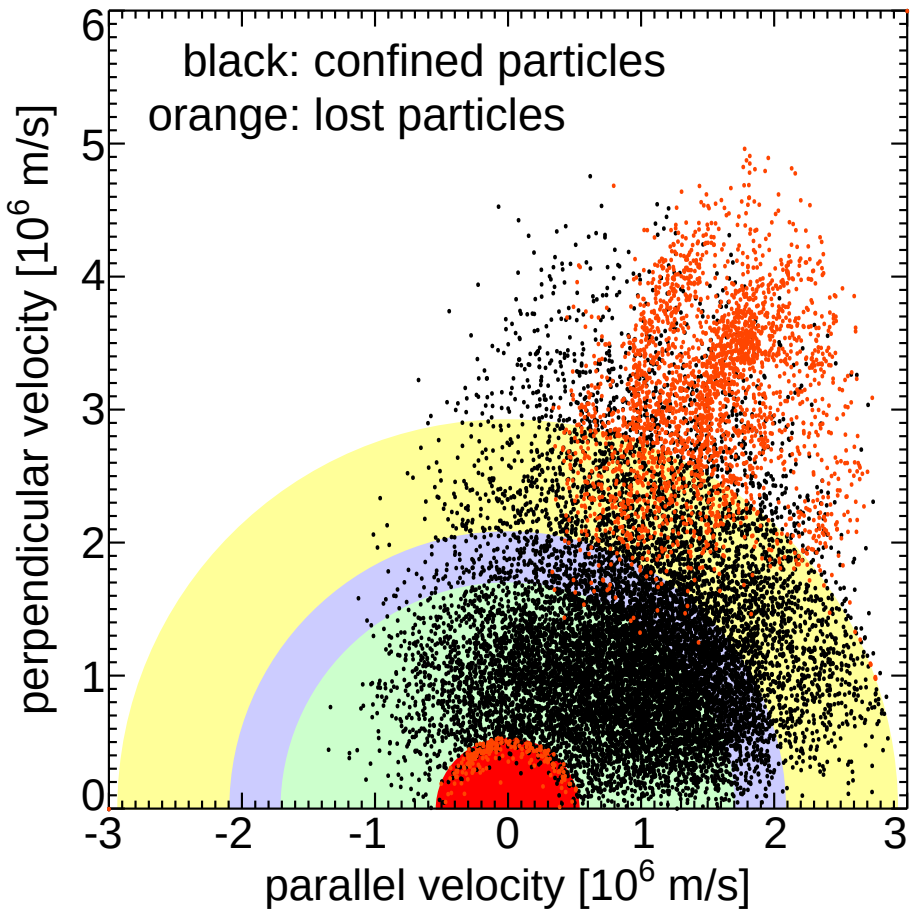
- 20000 particles were followed:
  - 11.3% thermalized
  - 12.7% lost to wall
  - 76.0% in slowing-down distribution



yellow: full energy
blue: half energy
green: third energy
red: thermal plasma

HHFW is effective in accelerating fast ions thereby inducing increased fast-ion losses

- At 50 ms the 1 MW HHFW power from TORIC were included
- Particles gain perpendicular energy
- Fast ions are lost quickly:
  13% of the fast ions is lost in 1 ms
- The HHFW power adsorbed by the fast ions is small:
  21 kW couples to the fast ions



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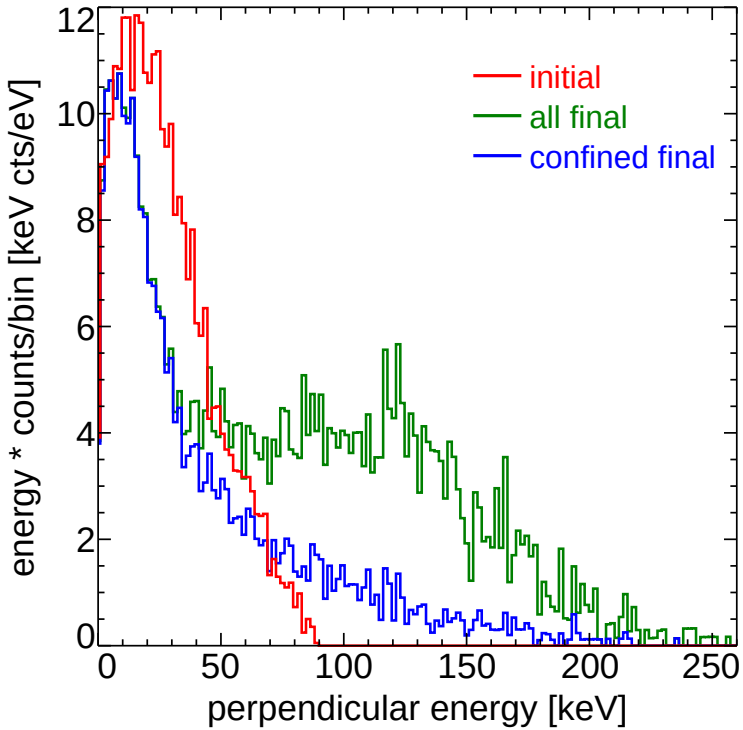
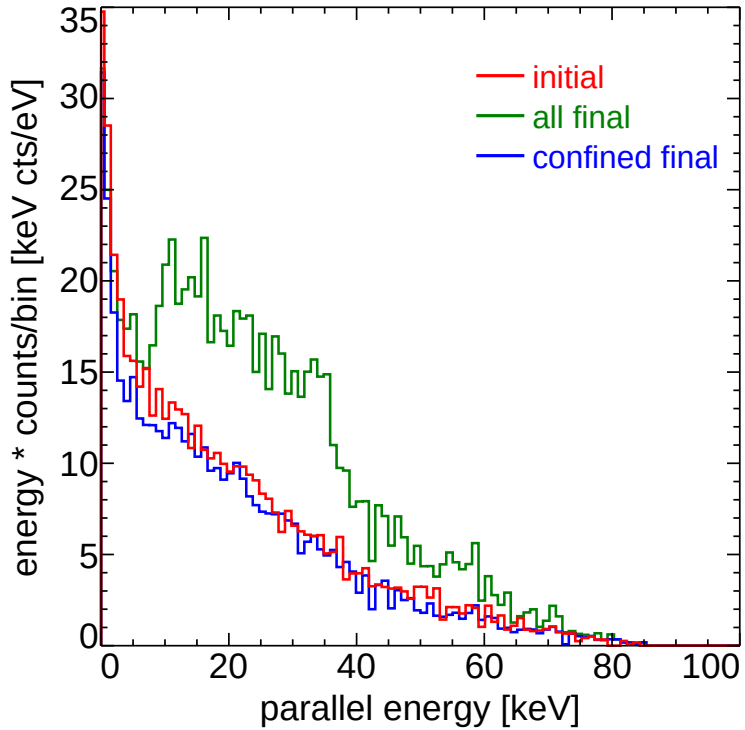


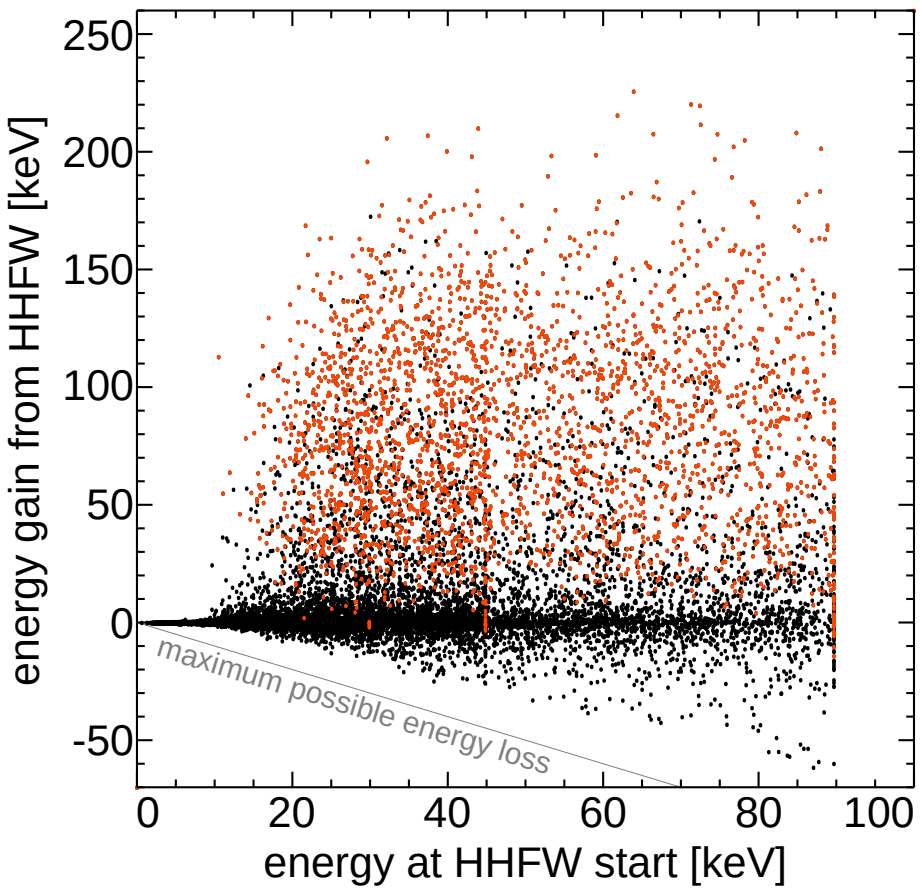


- A perpendicular high-energy tail is created and high-energy ions are lost
- The parallel energy distribution is hardly changed
- Most high-energy ions are lost from the plasma in NSTX

(Simulation: for 1 ms of 1 MW of HHFW working on NBI slowing-down distribution)

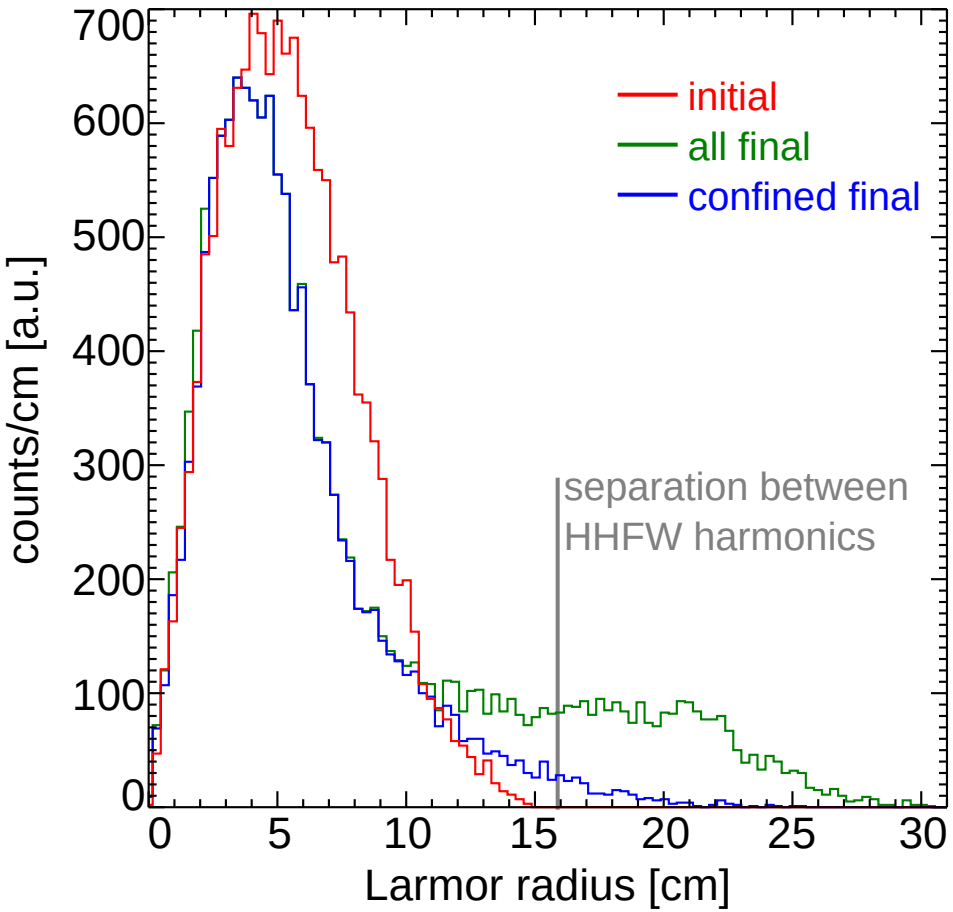
The energetic particles in the slowing-down distribution are accelerated by the HHFW

- The coupling between the HHFW fields and the ions is more efficient for the high energy particles in the slowing down distribution
- Thermal deuterons (below 10 keV) exchange a minimal amount of energy with the HHFW
- Slowing-down and pitch angle scattering become dominant at low particle energies



The Larmor radii of fast ions increase to values larger than typical resonance layer separation

- HHFW increases the fast-ion Larmor radius
- In the high-energy tail the Larmor radius becomes larger than the typical resonance layer separation
- The fast ion can interact with two resonance layers on one gyro orbit



- A study is being performed at PPPL on the effects of such overlaps on fast-ion dynamics (Work by Josh Burby)

Conclusion, Summary, and Outlook

- The combination of the full wave TORIC code and the full orbit-following SPIRAL code forms an excellent tool to study wave-particle interactions
  - A single ICRF resonance in ITER:
    - Particle obtained kicks in energy when passing through the resonance
    - The resonances were Doppler shifted due to the toroidal particle motion
    - Good agreement between TORIC and SPIRAL on the adsorbed power by the beam ions
  - Multiple HHFW resonances in NSTX:
    - A small amount of HHFW power (~2%) is absorbed by the beam ions
    - The beam-ion slowing down distribution is strongly affected:
      - Large numbers of fast ions are lost
      - A high-energy tail (up to 250 keV) is generated
      - Larmor radii become larger than the separation between the HHFW resonance layers

Work in progress:

- Include non-Maxwellian distributions in TORIC for the calculation of the dielectric tensor (work done by Nicola Bertelli)
- Compare simulation results with fast-ion diagnostic measurements (FIDA: confined fast ions, SFLIP and NPA: lost fast ions)
- Study the synergy between Alfvén Eigenmodes and HHFW/ICRF