Alcator C-Mod

Mode Conversion in Three Ion Species ICRF Heating Experiment

Yijun Lin, E. Edlund, P. Ennever, M. Porkolab, J. Wright, S.J. Wukitch and the Alcator C-Mod team

MIT Plasma Science and Fusion Center, Cambridge, MA 02139, USA

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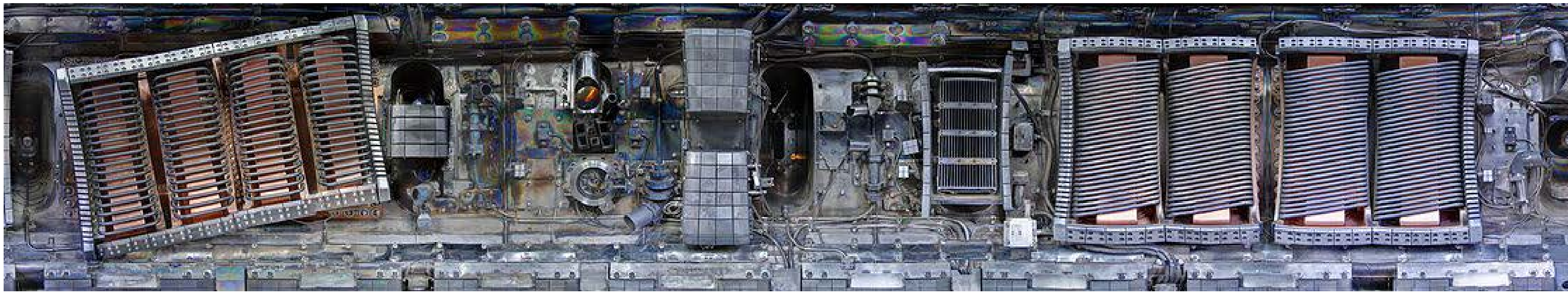
ICRF antennas on Alcator C-Mod

Alcator C-Mod



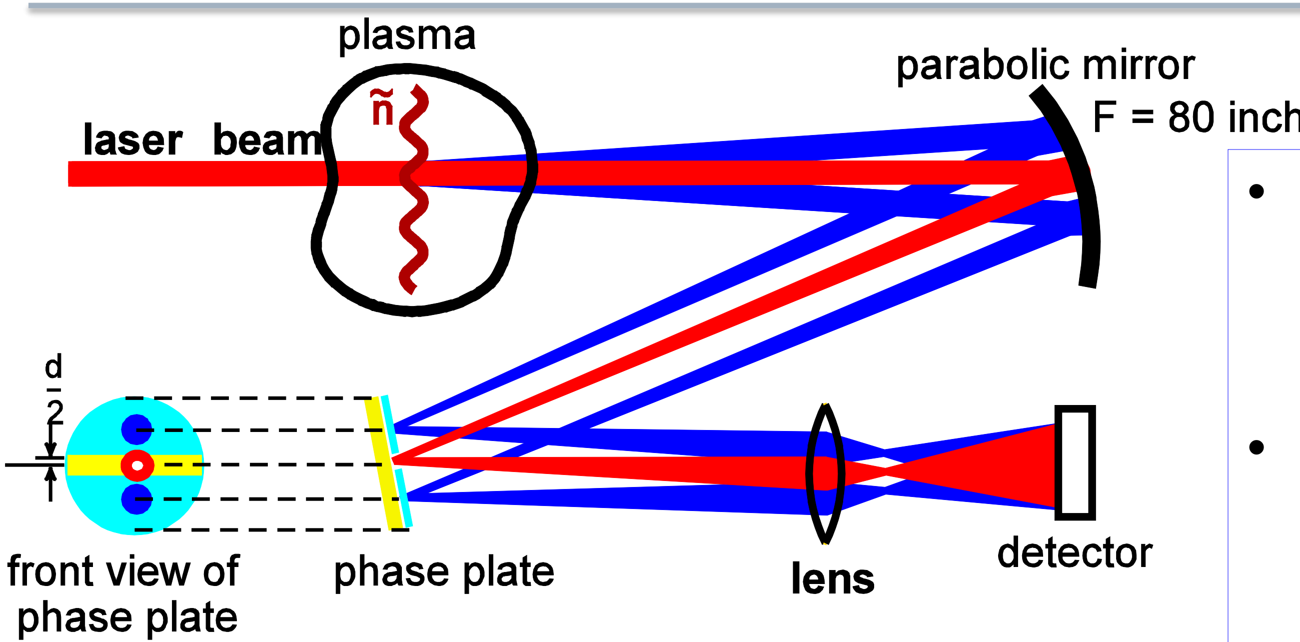
Field-aligned 4-strap antenna at J port (78 MHz)

Two 2-strap antennas at D-port (80.5 MHz) and E-port (80 MHz)

Total RF source power: 4 x 2 MW transmitters.

- D and E antennas are each powered by one transmitter and provide up to 1.8 MW (combined up to ~ 3.6 MW) RF power to plasma.
- J antenna is powered by 2 transmitters and provides up to 3 MW power to plasma.

Phase contrast imaging system (PCI)



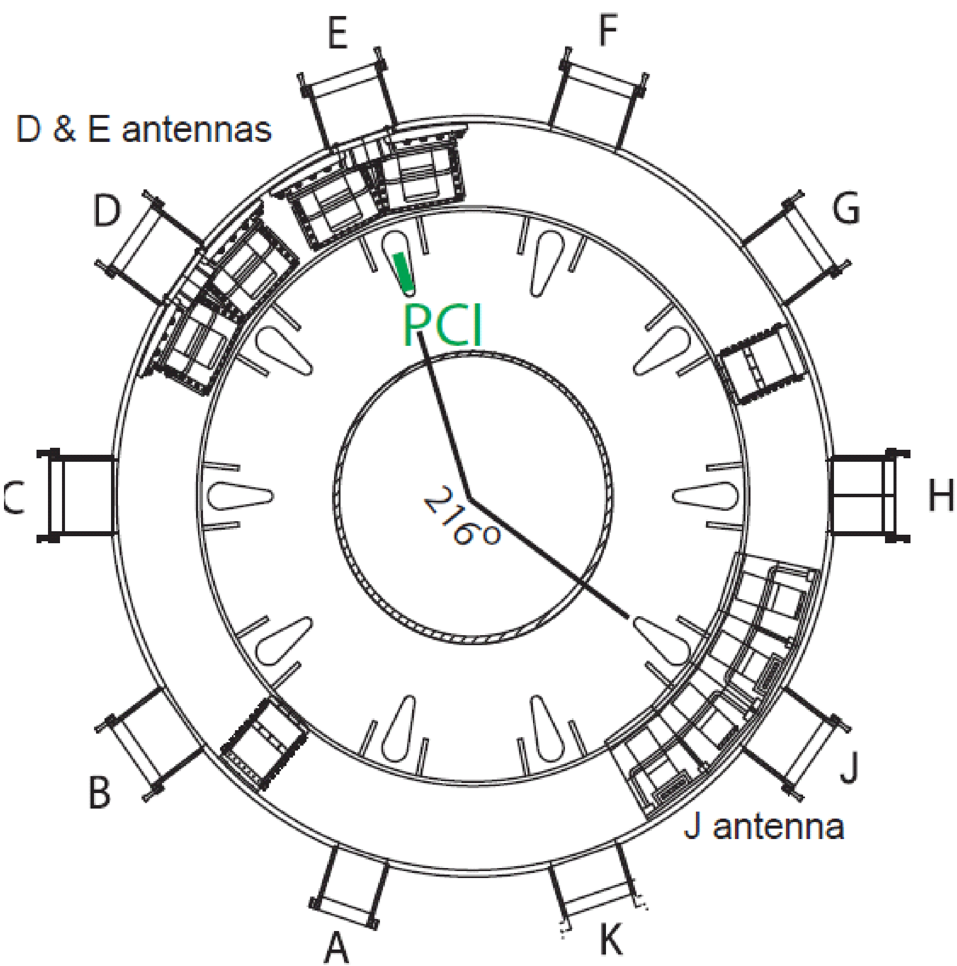
- Plasma density fluctuations introduce phase variations to the laser beam.
- Laser phase variations are converted to intensity variations by a $\lambda/4$ phase plate.

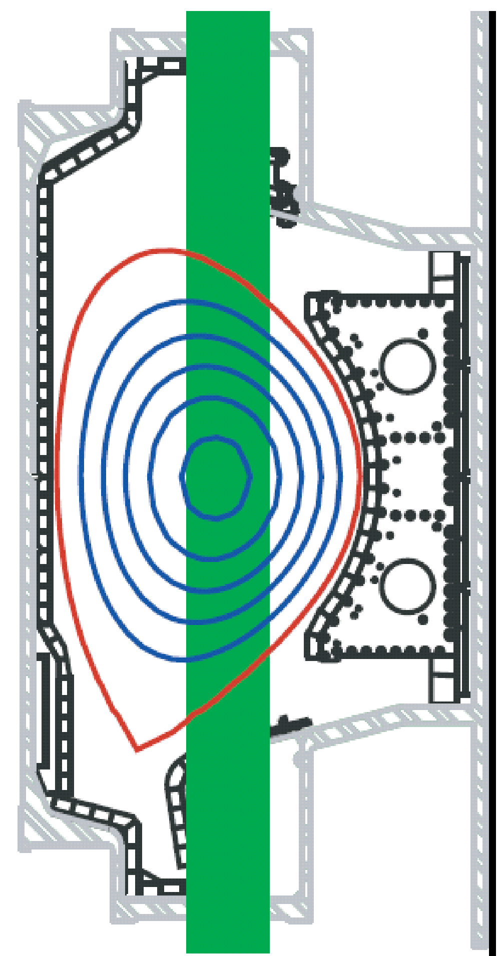
- Acoustic-optical frequency shifter to modulate the laser beam to have a beat-frequency near the RF frequency (heterodyne scheme).
- RF waves can be measured in this setup at the beat frequency.

E. Nelson-Melby et al, PRL 90,155004 (2003).

- The system has recently been upgraded to have higher sensitivity at high frequencies and better calibration.

PCI is in front of E antenna but some toroidal angles away from D and J





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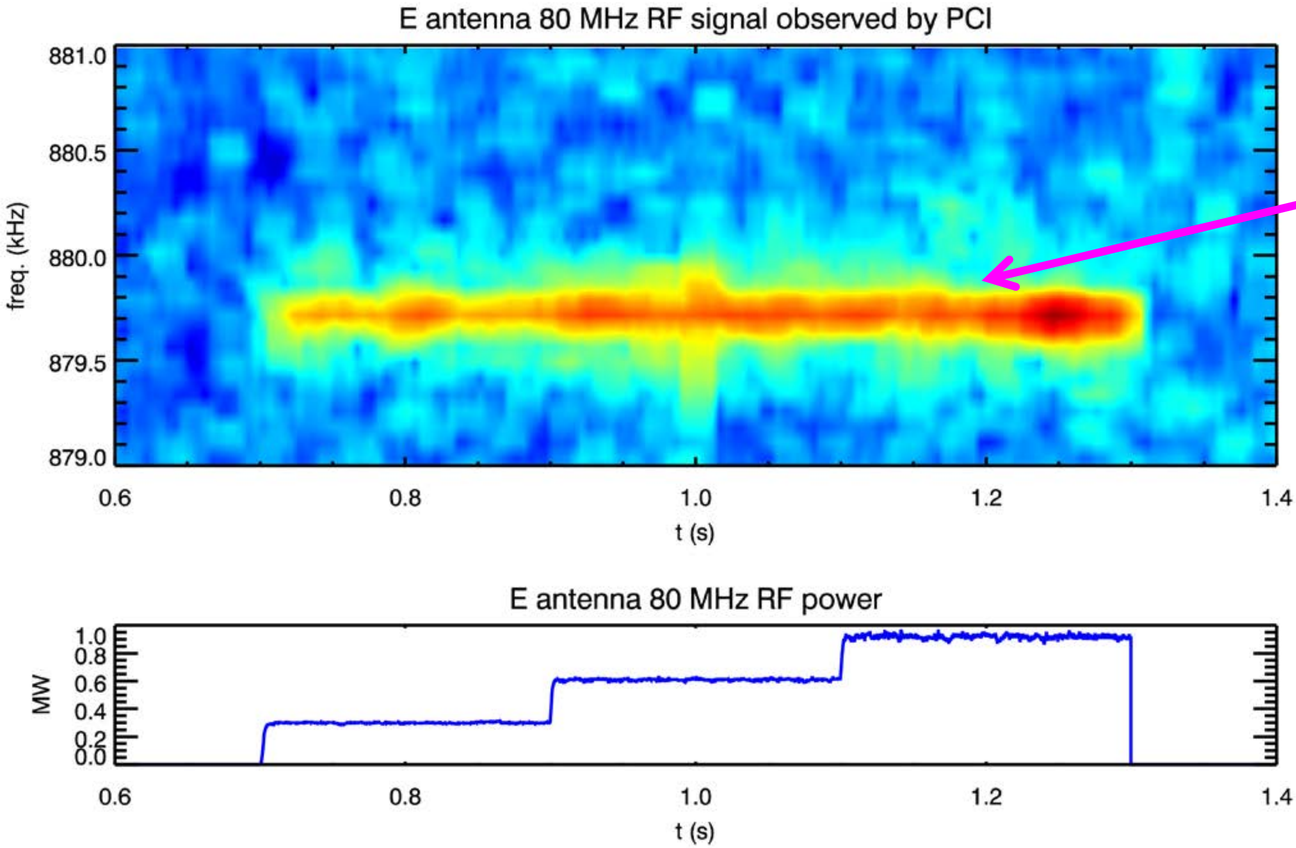
RF signals shown in PCI data



80 MHz RF signal from E antenna, shown in PCI spectra at ~880 kHz after heterodyne modulation

For this typical D(H) minority heating plasma, the PCI signal is mostly from the fast wave.

- **RF wave appears as a coherent signal in the PCI spectra (contour image in *frequency* and *time*);**
- **Signal amplitude is indicative of the wave E field amplitude;**
- **Signal phases from different PCI channels ←→ k_R of the RF waves.**

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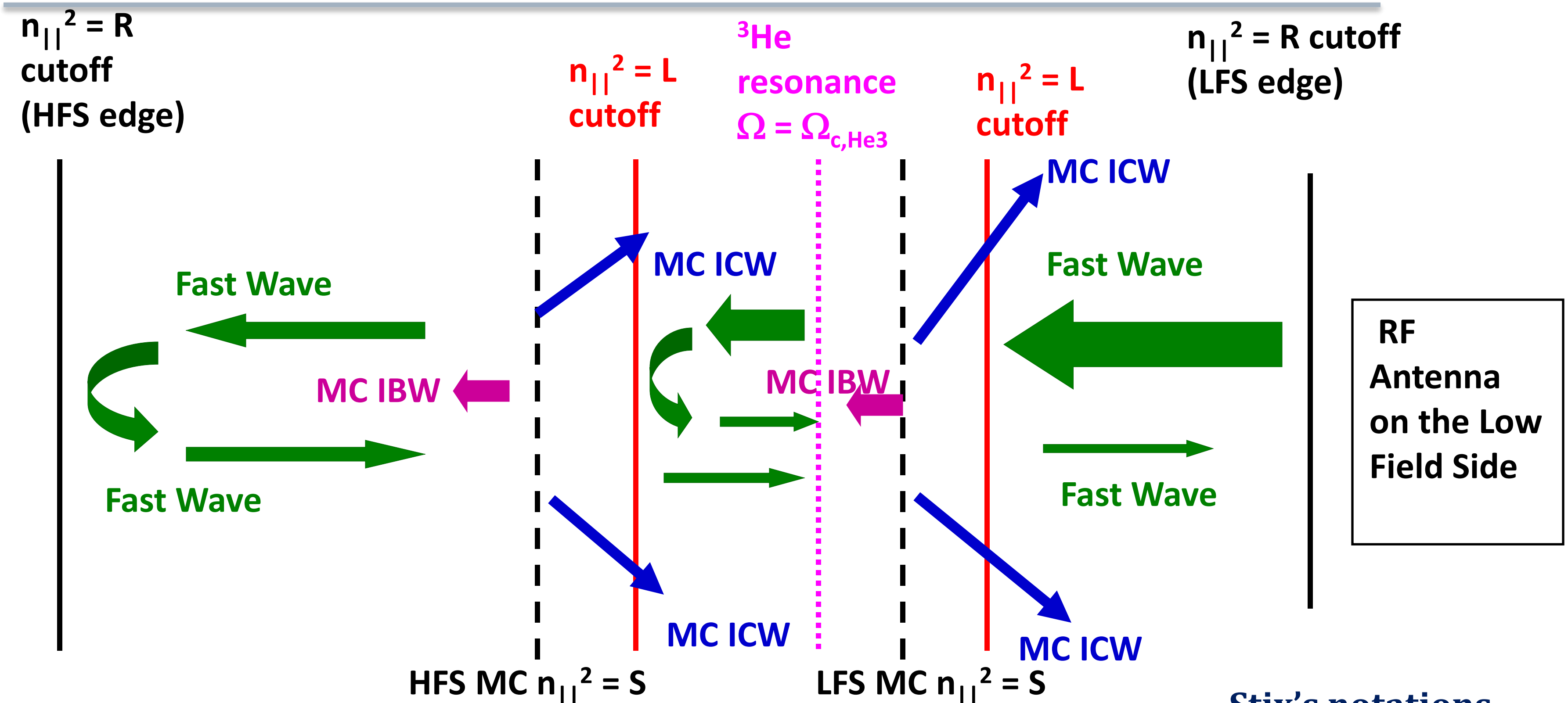
ICRF 3-ion heating scenario

- Majority D and H, e.g., ~50% each
- And small amount of $X[^3He] = n_{3He}/n_e \sim \leq 1\%$
- ➔^{3}He cyclotron resonance in the vicinity of both the D-^{3}He hybrid layer and ^{3}He-H hybrid layer.
- Potentially strong absorption on ^{3}He ions due to favorable wave polarization at the ^{3}He cyclotron resonance.
- This scenario can be used for general plasma heating and also for fast ion generation, e.g., fast ion confinement study on W7-X.
- It is also possibly applicable for ITER D-T plasma heating.

ICRF waves in a 3-ion species plasma



- Two mode conversion (MC) layers exist: on the HFS and the LFS of the ^{3}He IC resonance.
- Mode conversion to the ICW (ion cyclotron wave) is a result of $k_{||}$ up-shift caused by the magnetic shear at where $B_{pol} \neq 0$. MC IBW (ion Bernstein wave) is an electrostatic hot plasma wave.

Stix's notations

$$R = 1 - \sum_j \frac{\omega_{pj}^2}{\omega(\omega + \Omega_j)},$$

$$L = 1 - \sum_j \frac{\omega_{pj}^2}{\omega(\omega - \Omega_j)}$$

$$S = (R + L)/2$$

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Energetic ions are generated in plasmas with low ^{3}He and high RF power

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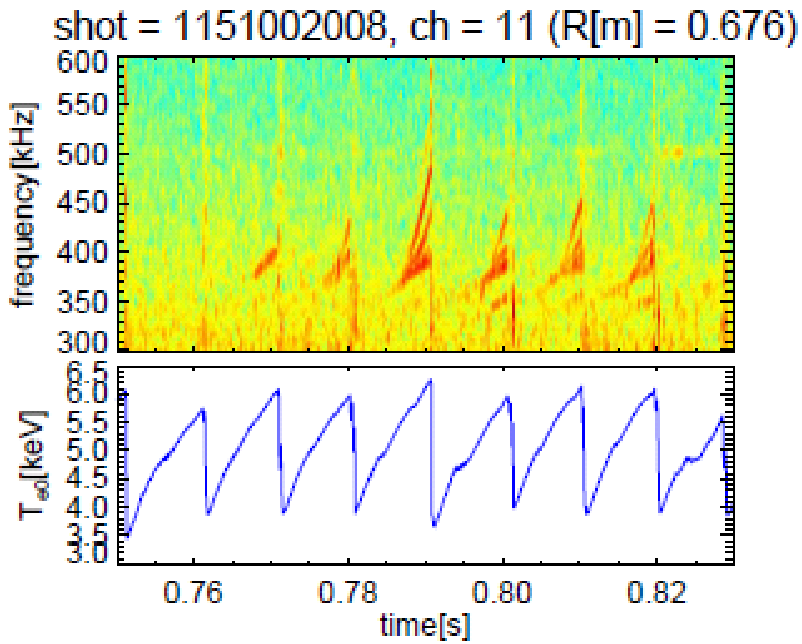

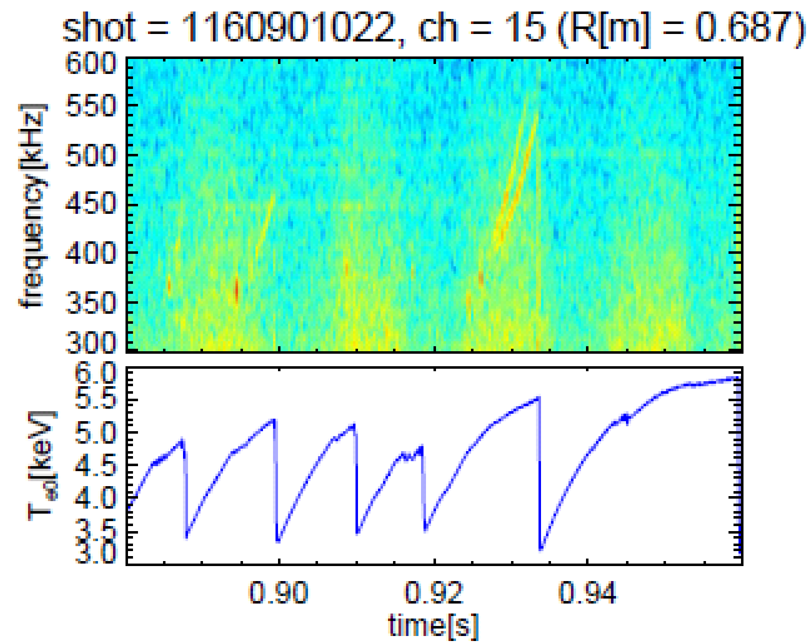

- **AE activities are indicative of the existence of a population of energetic ^{3}He ions near the plasma center.**
- **X[^{3}He] = n_{3He}/n_e ~ 0.6%, P_{ICRF} ~ 4 MW**

(More discussion in Kazakov's and Wright's talks)

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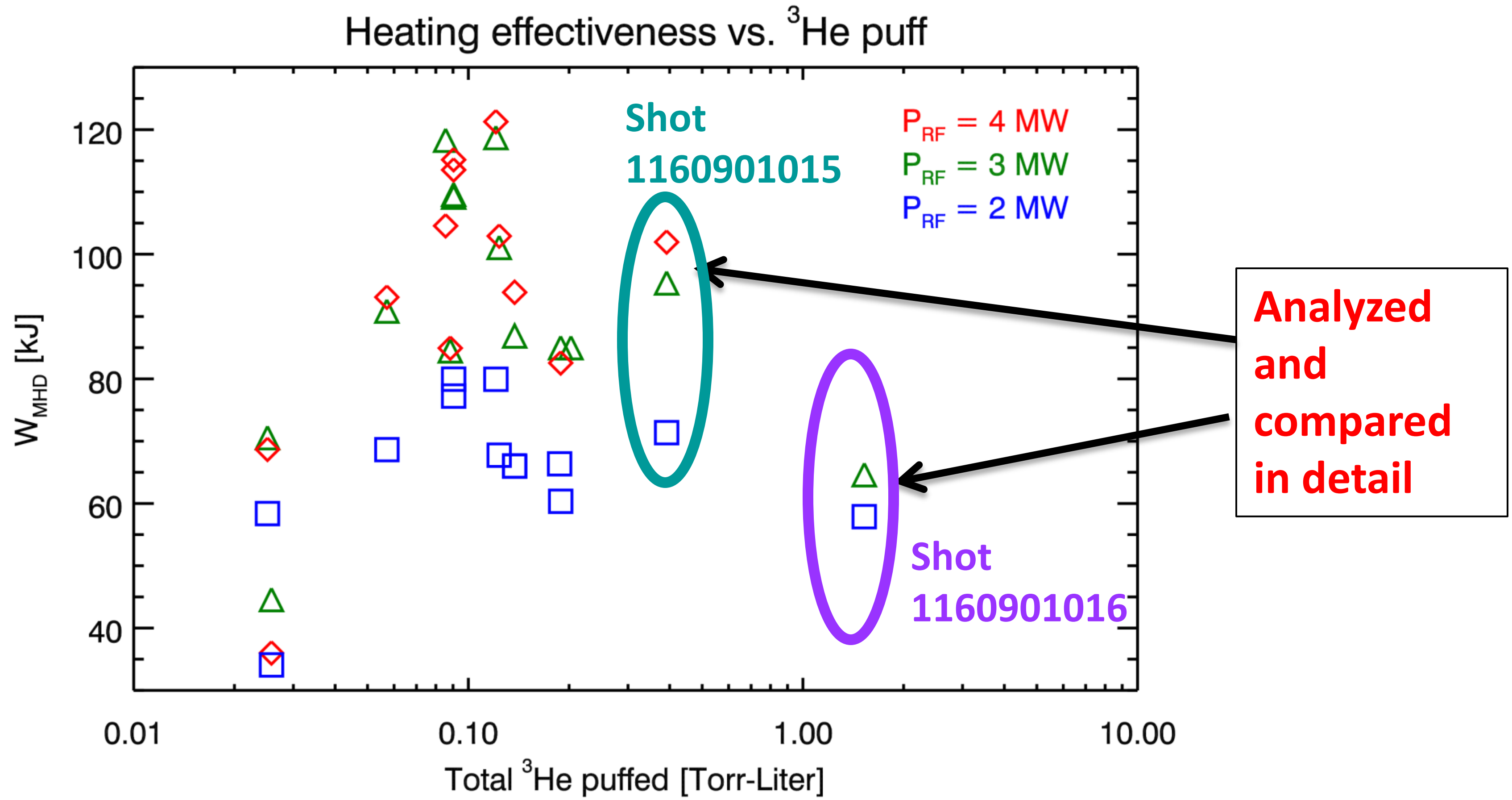
Heating effectiveness strongly depends on the amount of ^{3}He puffed



- **Best effective heating occurs at X[^{3}He] = n_{3He}/n_e ~ 0.5%-1%.**
- **This study focuses on the two plasma shots, 1160901015 (75 ms ^{3}He puff, 0.4 Torr-liter) and 1160901016 (200 ms ^{3}He puff, 1.5 Torr-liter).**
- **In both shots, mode conversion was clearly observed by PCI.**

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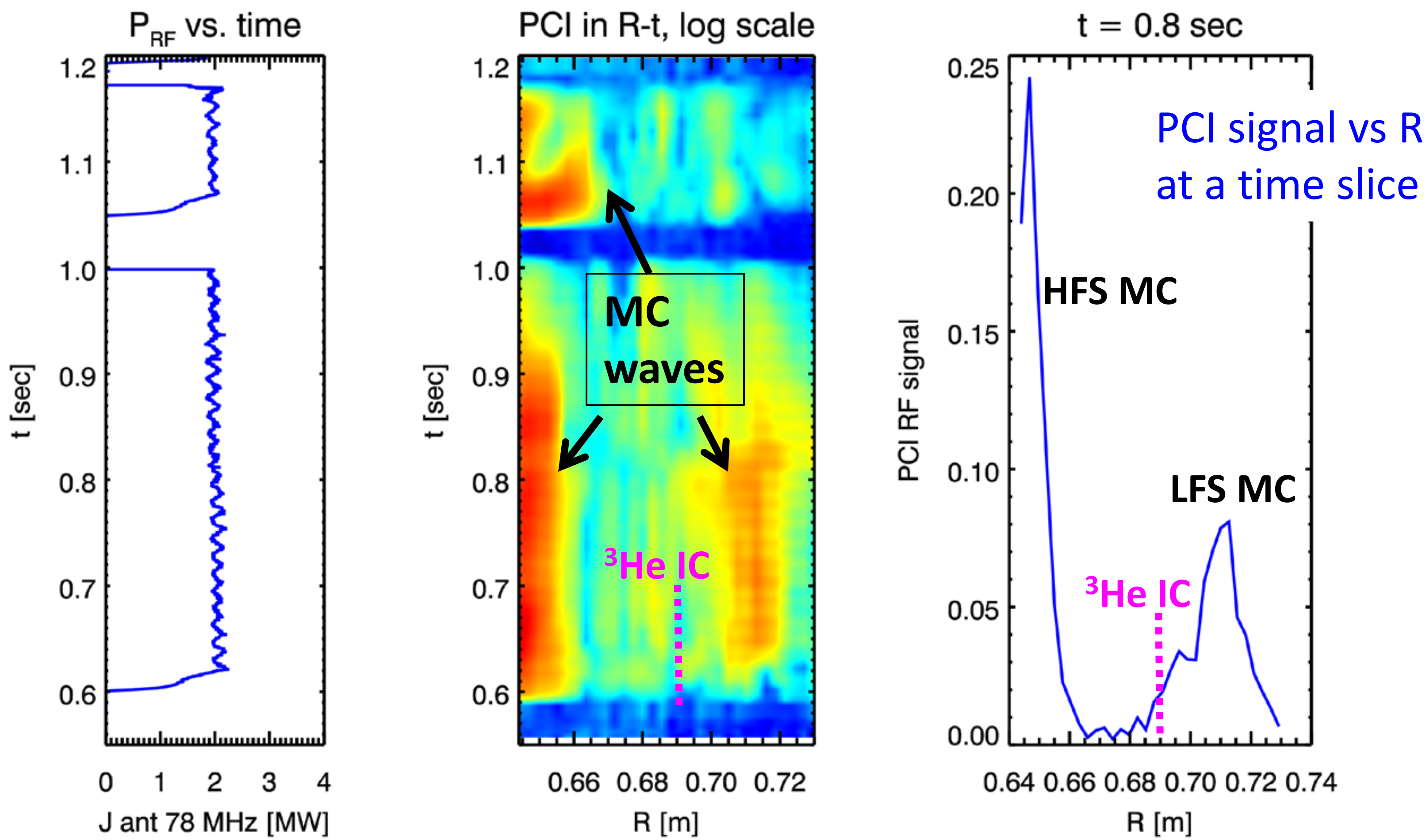
Shot 1160901015 (75 ms ^{3}He puff) - double MC observed in PCI



- **PCI has 32 channels, covering *0.64 m < R < 0.74 m.***
- **Two peaks are observed at R ~ 0.64 m and R ~ 0.71 m, corresponding to the HFS and LFS MC layer locations. Ion cyclotron resonance is at R = 0.69 m.**

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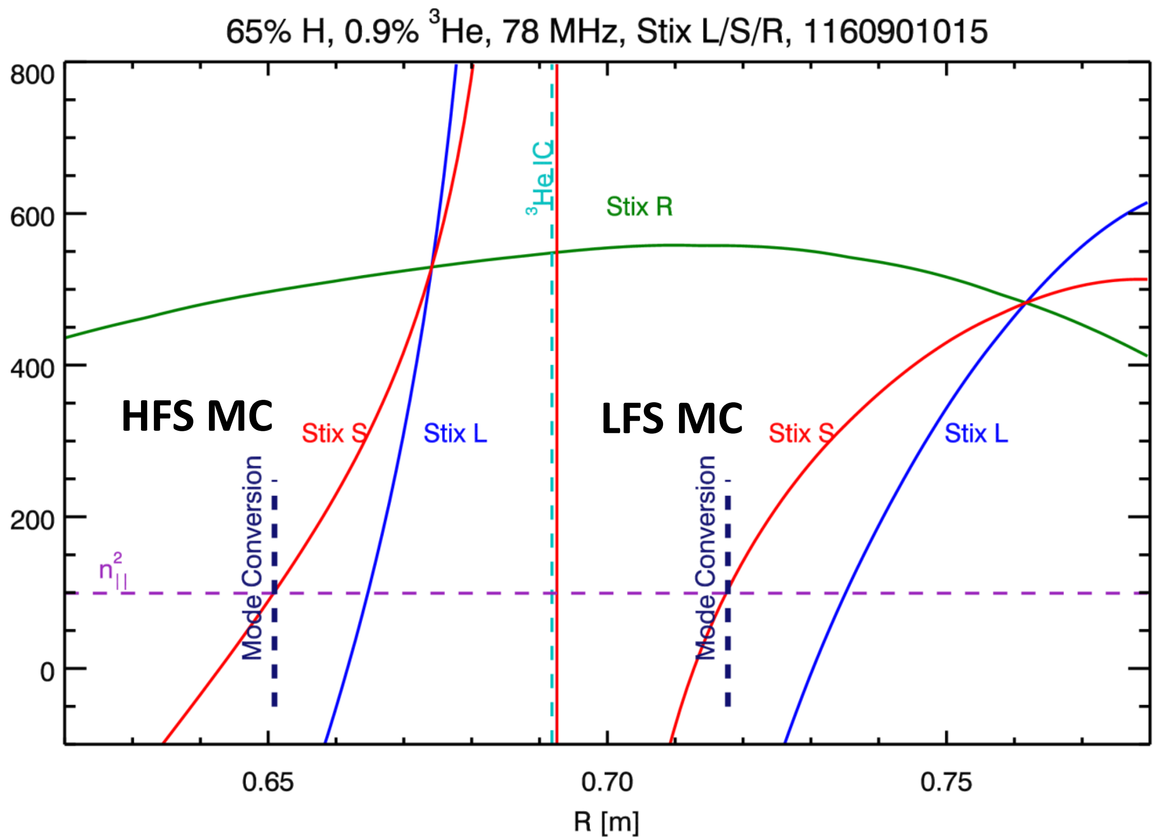
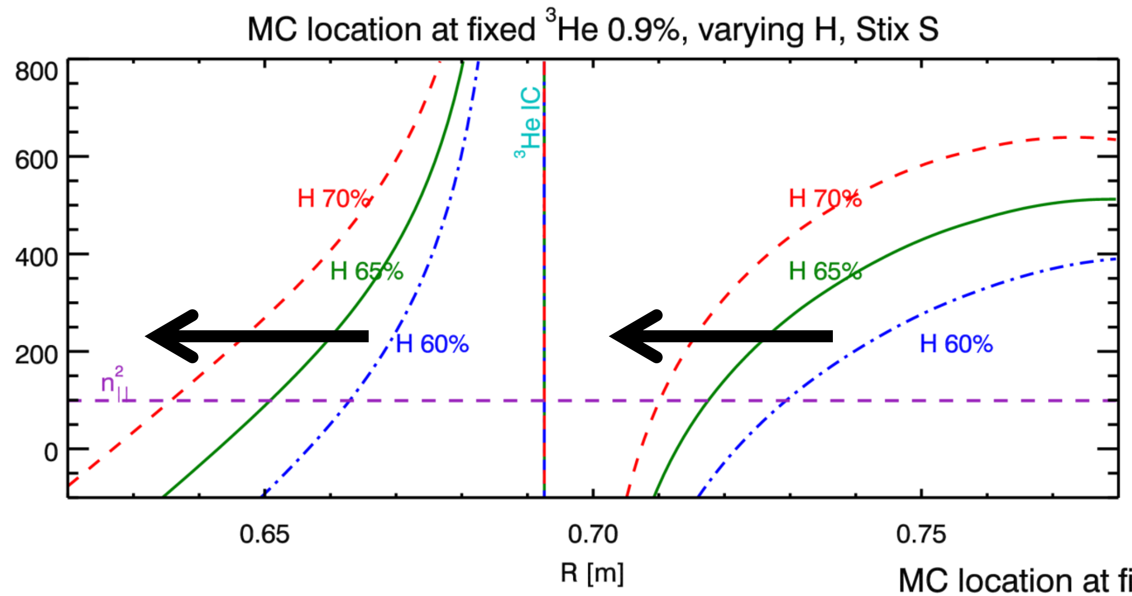
Determine X[^{3}He] and X[H] from the two observed MC locations



- **The location of the two MC locations from PCI can be used to estimate X[H] and X[^{3}He]**
  - Larger X[H] moves both layers to HFS;
  - Larger X[^{3}He] increases the distance between the two layers.
- **X[H] ≈ 65% and X[^{3}He] ≈ 0.9% have the best match.**

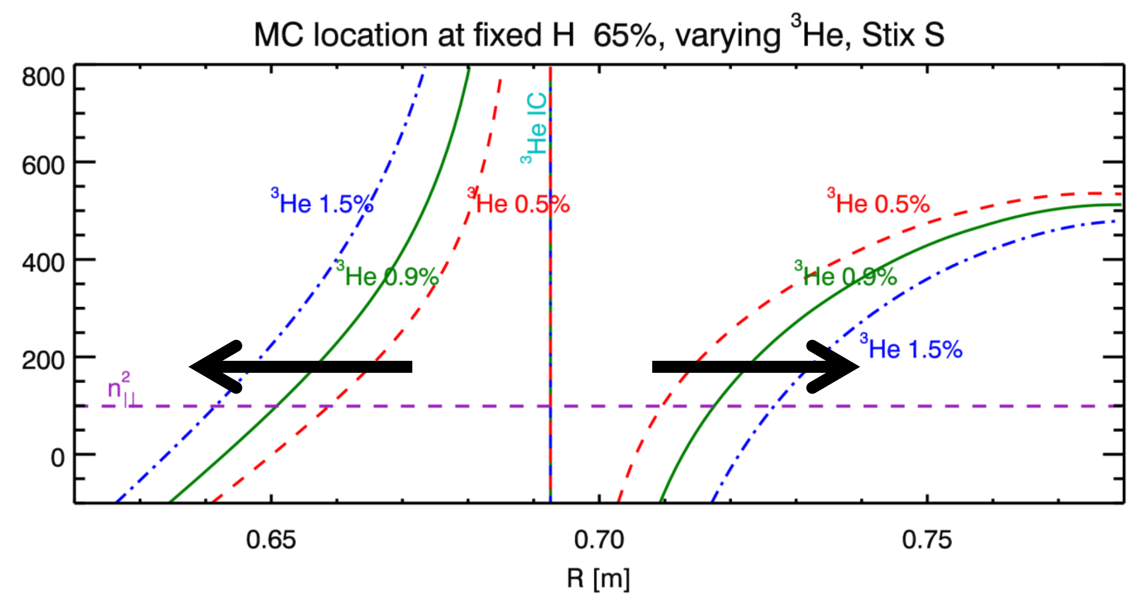
MC locations vs. X[^{3}He] and X[H]



Increasing X[H] moves both MC locations towards higher field side.

Increasing X[^{3}He] moves the two MC locations farther apart.

The distance in-between is approximately proportional to X[^{3}He].



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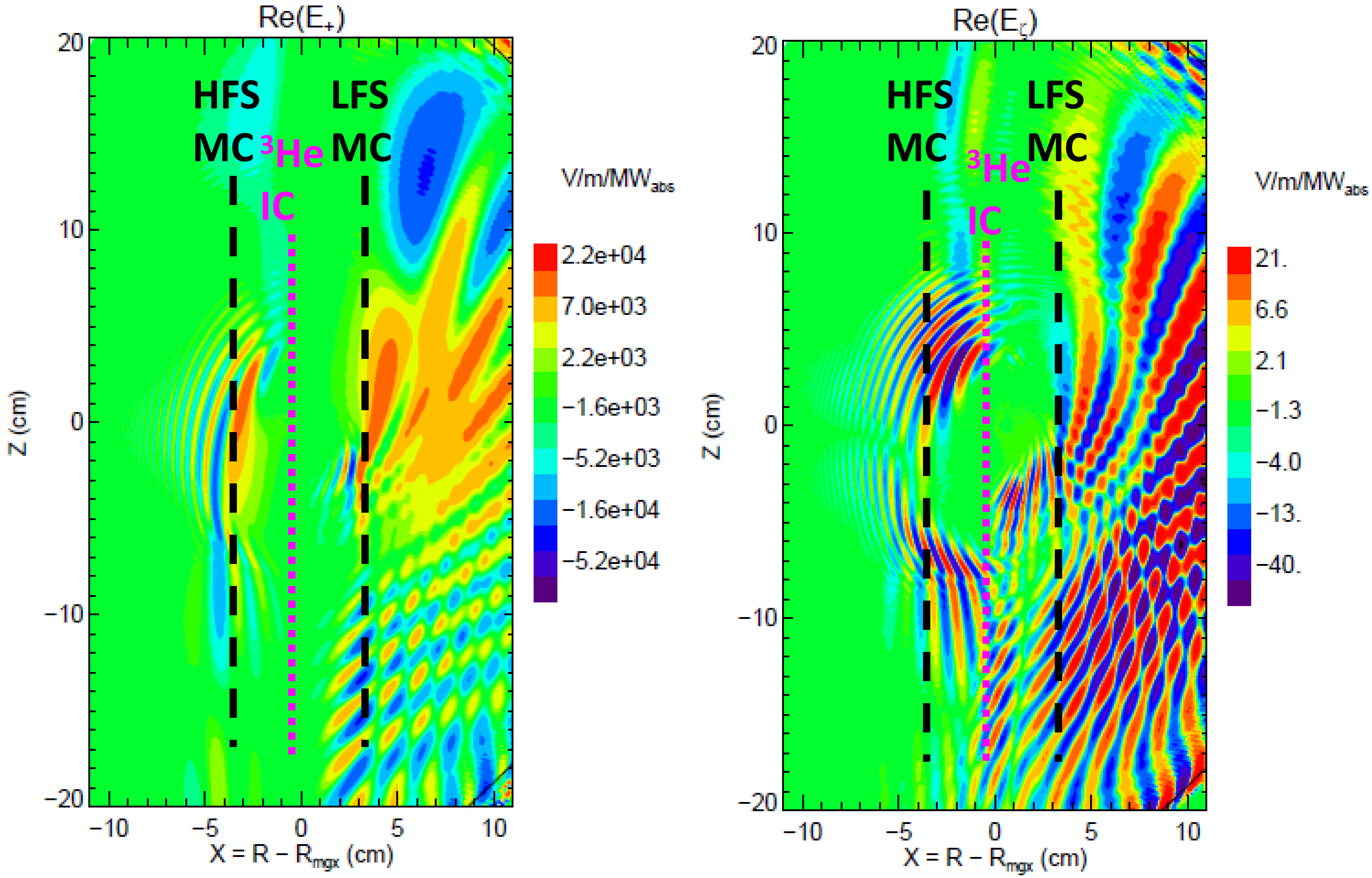
TORIC simulation shows E-field pattern for strong ion absorption

E+ is the electric field that has left-hand polarization, i.e., ion cyclotron motion direction.

Note strong E+ on both sides of IC resonance .



- **TORIC is a 2-D ICRF simulation code. Simulation using X[H] ≈ 65% and X[^{3}He] ≈ 0.9%, RF frequency 78 MHz, and equilibrium of shot 1160901015.**
- **Shown are E fields for the case of toroidal mode n_ϕ = –13. R_{mgx} ≈ 68 cm, the magnetic axis.**

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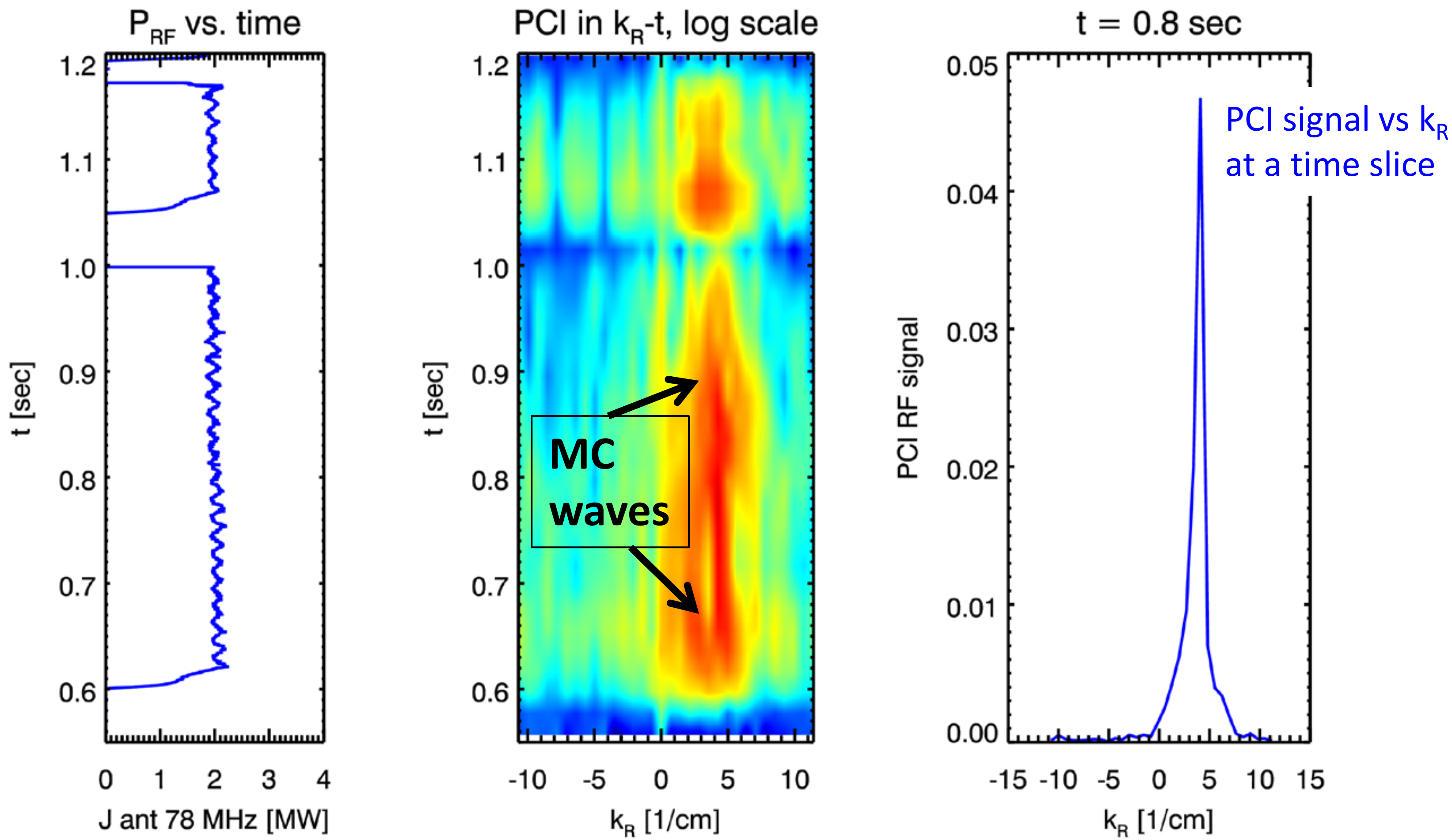
PCI also provides k_R spectrum of the MC waves, in agreement with TORIC



- The observed MC waves have k_R ~ 4 cm^{-1}, corresponding to λ_R ~ 1.6 cm.
- In agreement with the field pattern of the short-wavelength waves shown in the TORIC simulation.

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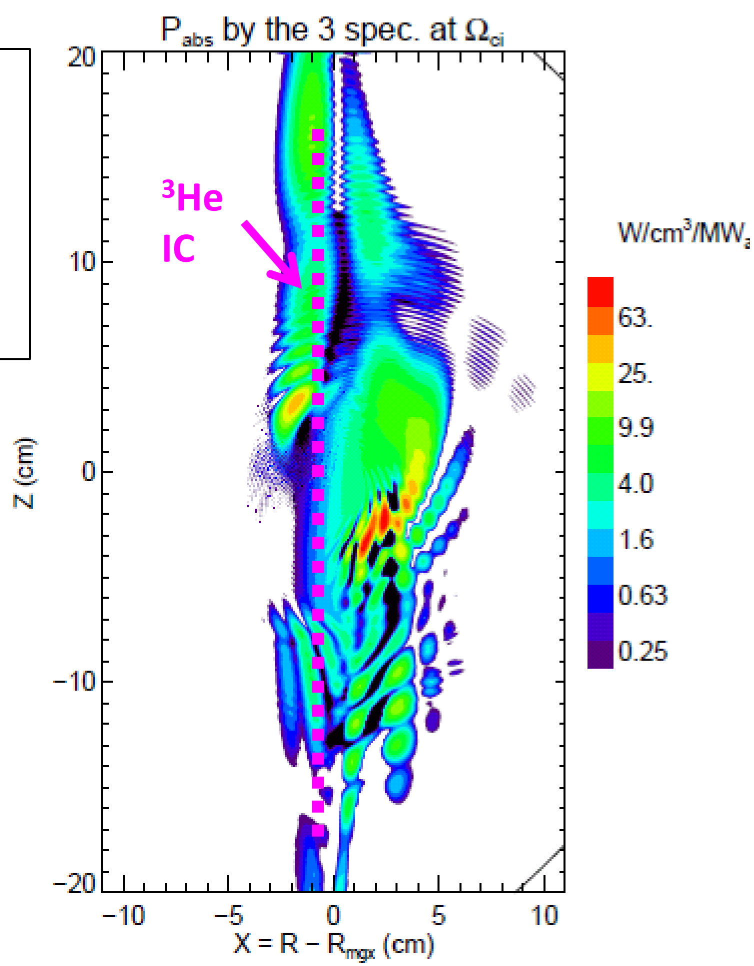
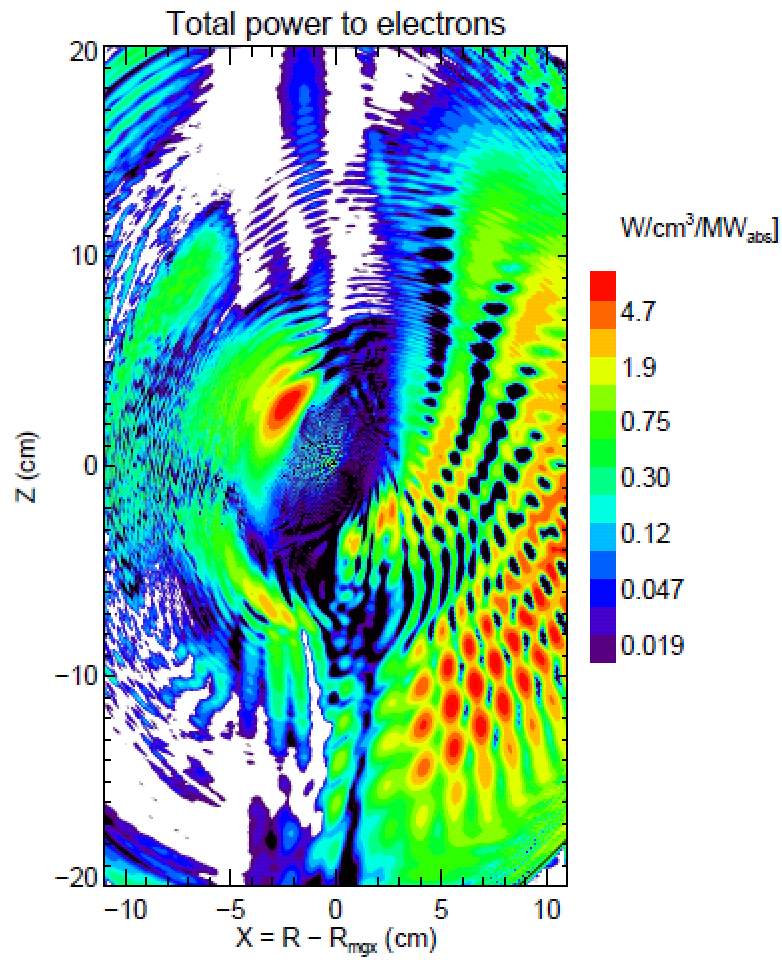
Power deposition to ions and electrons in 2-D from simulation

X[H] = 65%,
X[^{3}He] = 0.9%
$n\phi = -13$
f = 78 MHz
B_{t0} = 7.8 T





- **Power deposition to ^{3}He ions is through the interaction of ^{3}He ions with fast wave and the MC waves at the resonance;**
- **Power to electrons is mostly through MC waves and relatively much weaker.**

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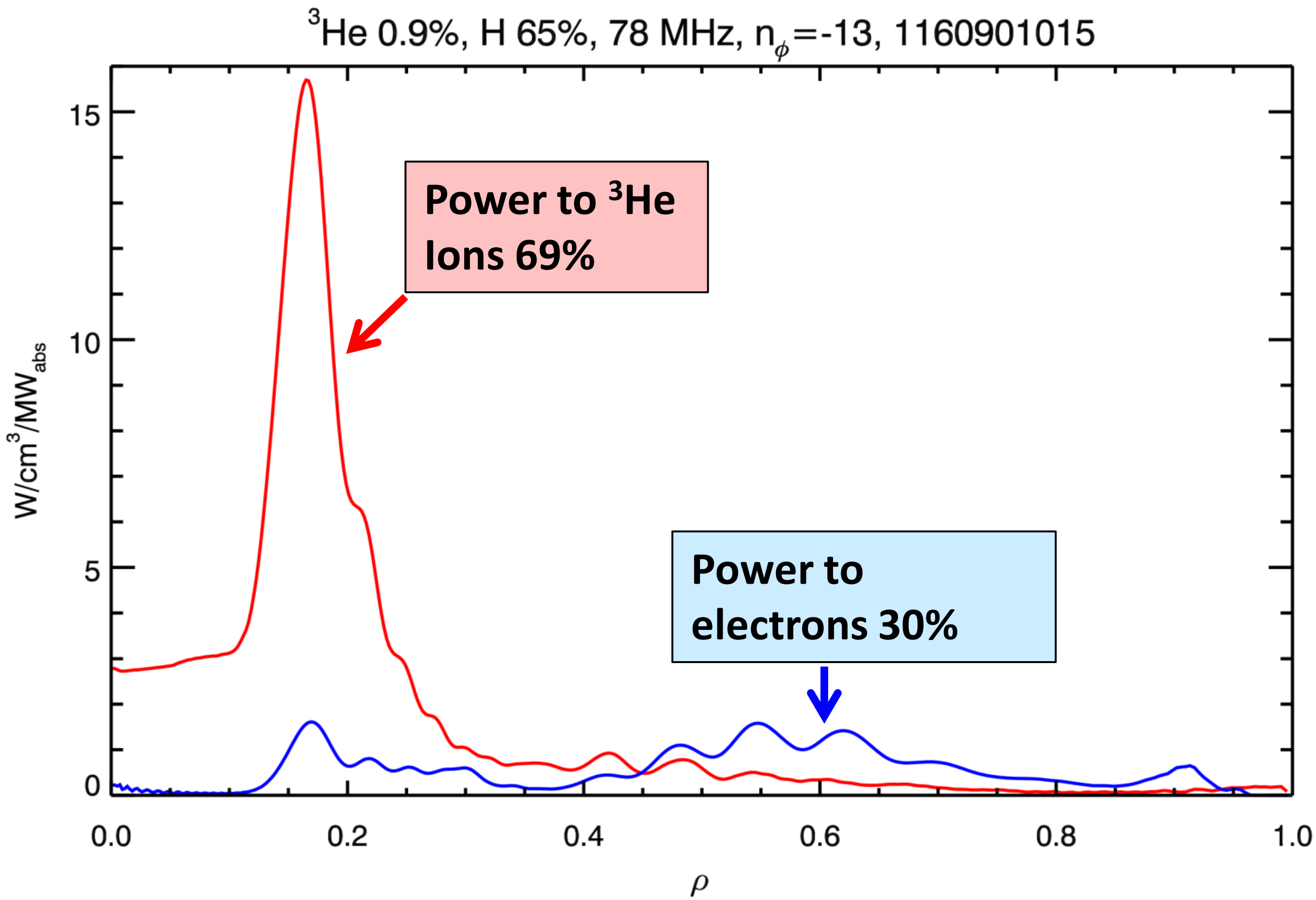
RF power mostly goes to the ^{3}He ions



- For this plasma, most RF power is absorbed by the ^{3}He ions.
- 69% to ^{3}He ions, 30% to electrons, and the rest to D and H ions.
- See Wright - TO4.012 for simulation on how the fast ions are generated.

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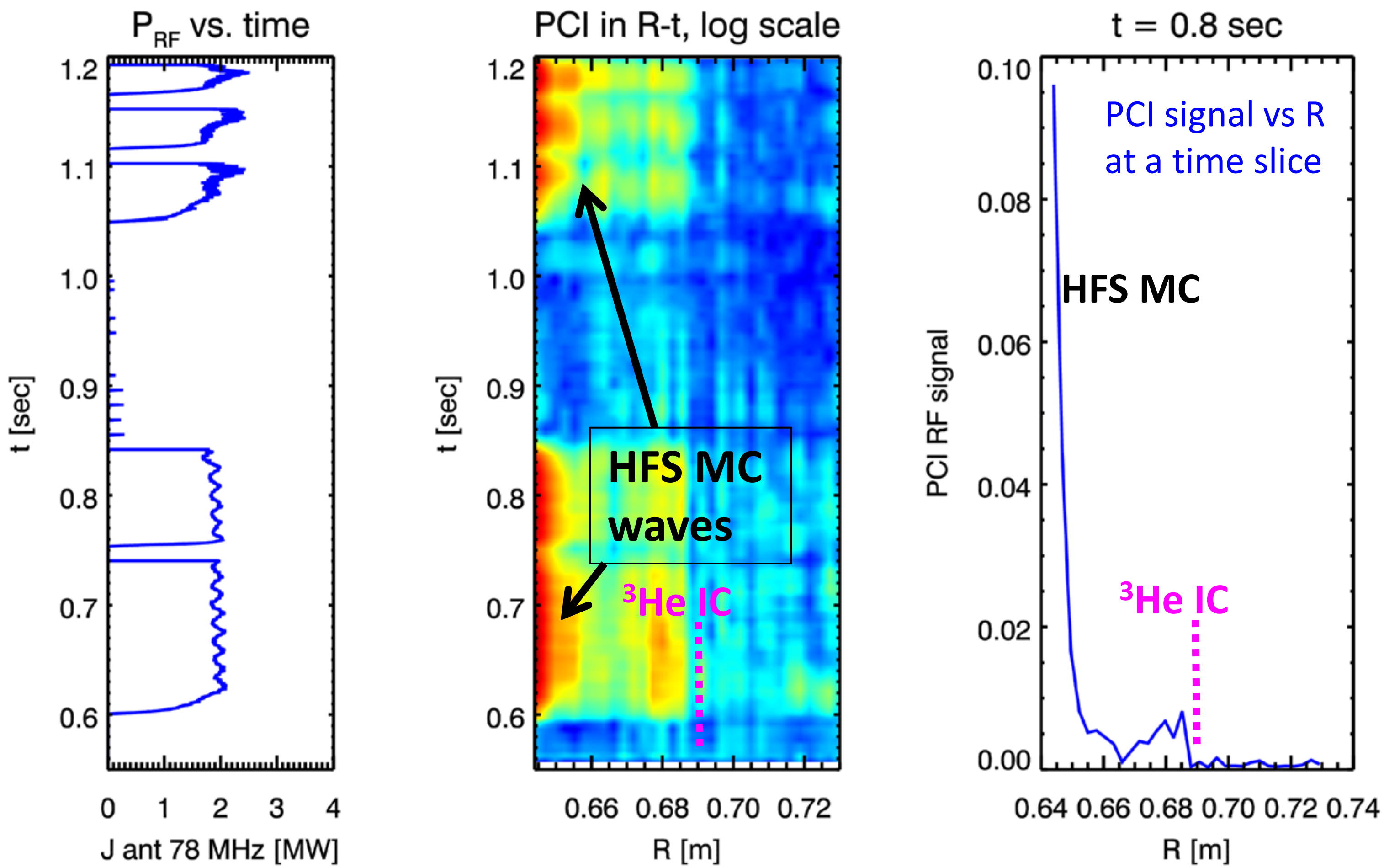
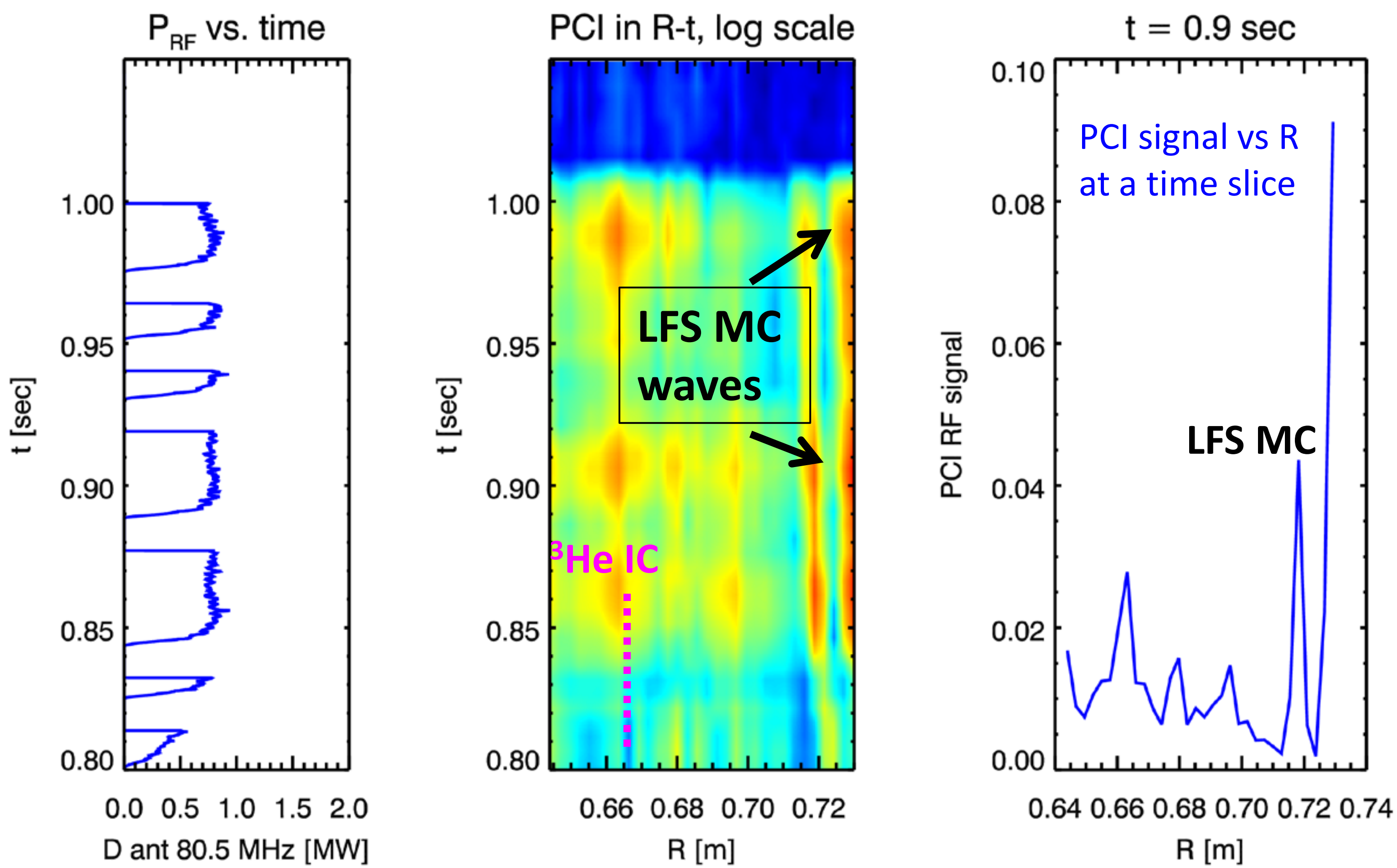
Shot 1160901016 (200 ms ^{3}He) – only HFS MC layer shown in PCI (78 MHz)



- With increase of ^{3}He, the distance between the HFS and LFS MC layers are increased.
- Only the HFS MC at R ~ 0.64 m is observed in the PCI window for J antenna power at 78 MHz and the LFS MC is out of the PCI window.

The LFS MC is observed at 80.5 MHz



- **The LFS MC at R ~ 0.74 m appears in 80.5 MHz D antenna signal, while the HFS MC at this frequency is out of the PCI window.**

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Combined the observation of at 80.5 MHz and 78 MHz → X[H] and X[3He]

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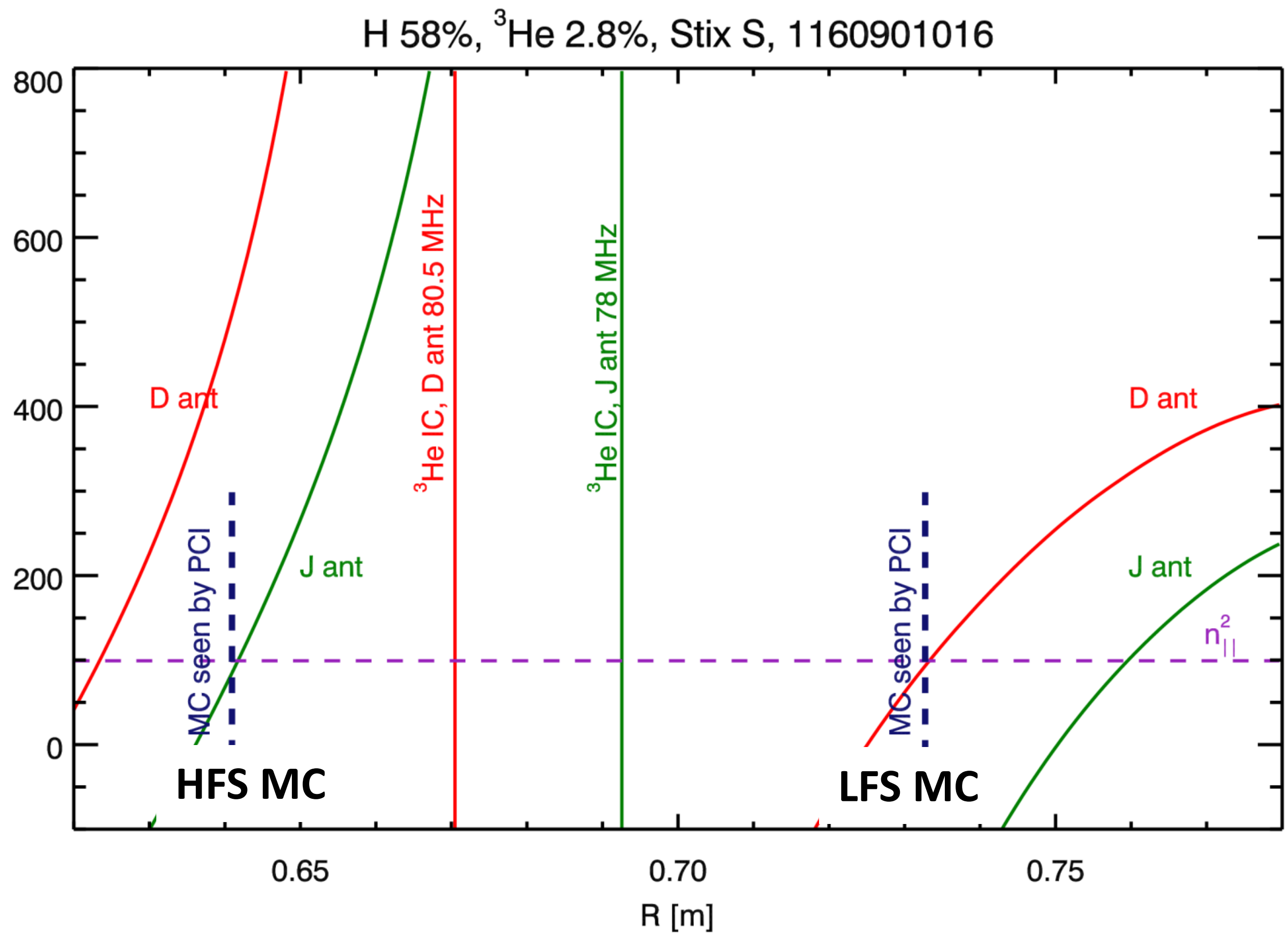

- X[H] ≈ 58% and X[^{3}He] ≈ 2.8% is the best match to the observed MC locations.

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Electric field pattern is not conducive for ion absorption

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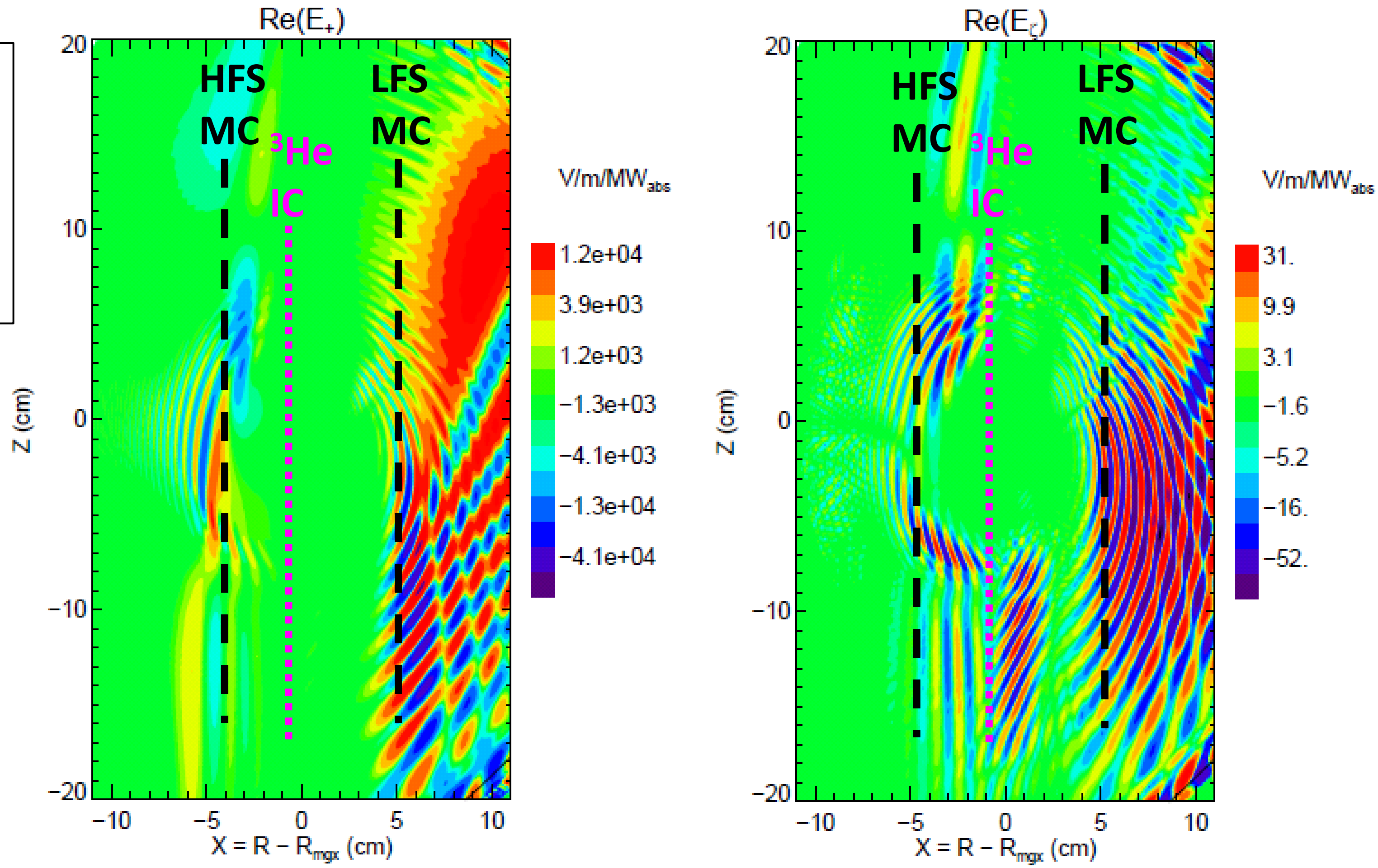
X[H] = 58%,
X[^{3}He] = 2.8%
nϕ = –13
f = 78 MHz
B_{t0} = 7.8 T



- **Clear short wavelength MC waves appear at both HFS and LFS MC layers.**
- **IC resonance is quite far away from the region with large E+ field. The Doppler broadening of the resonance (~ ±1 cm for thermal ions) would be insufficient for strong ion absorption.**

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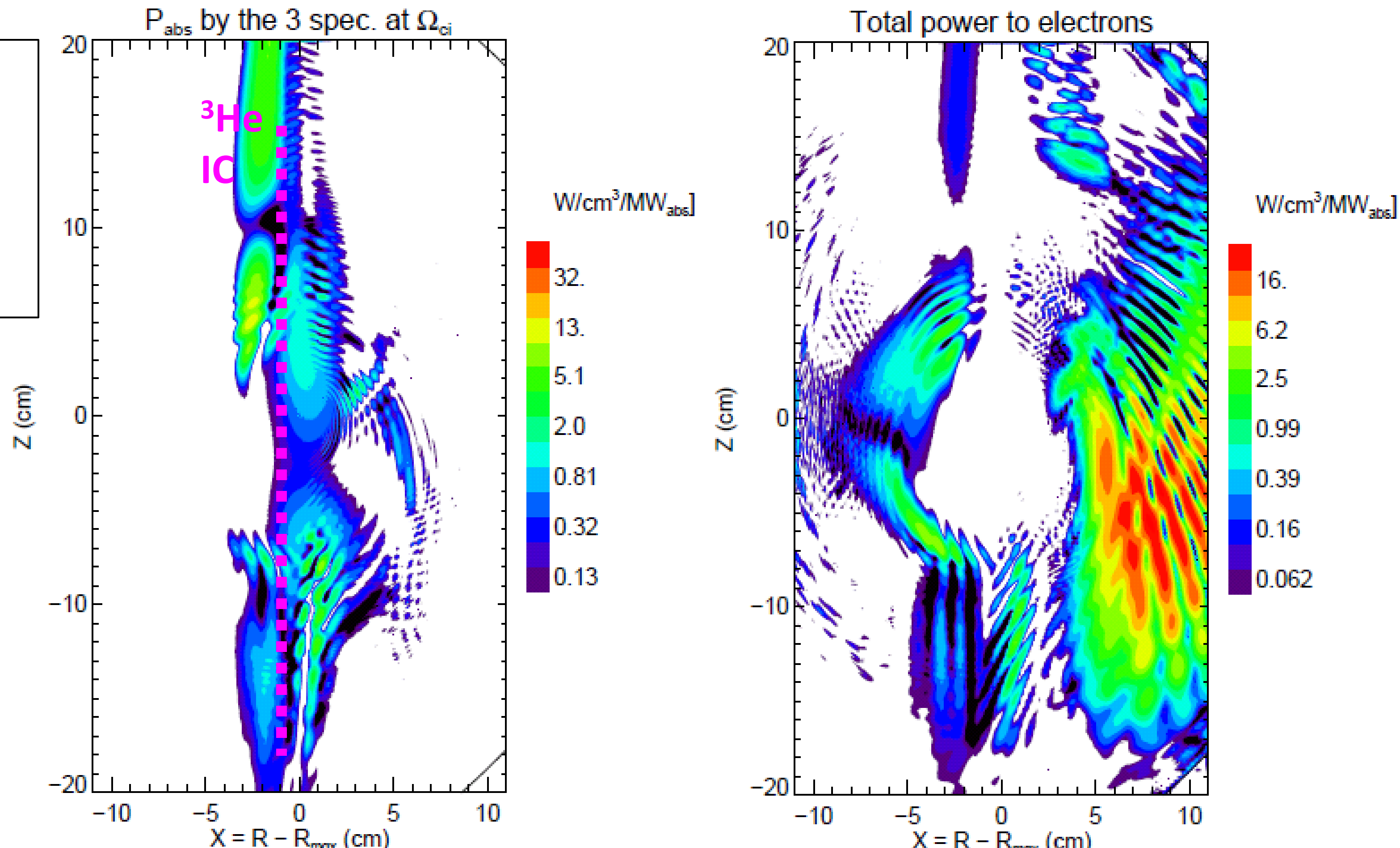
Power deposition to ions is weaker than to electrons

X[H] = 58%,
X[^{3}He] = 2.8%
nϕ = –13
f = 78 MHz
B_{t0} = 7.8 T



- **Power deposition to ^{3}He ions is much weaker than in shot 1160901015;**
- **Power to electrons is through MC waves and it is much broader and stronger than that in shot 1160901015.**

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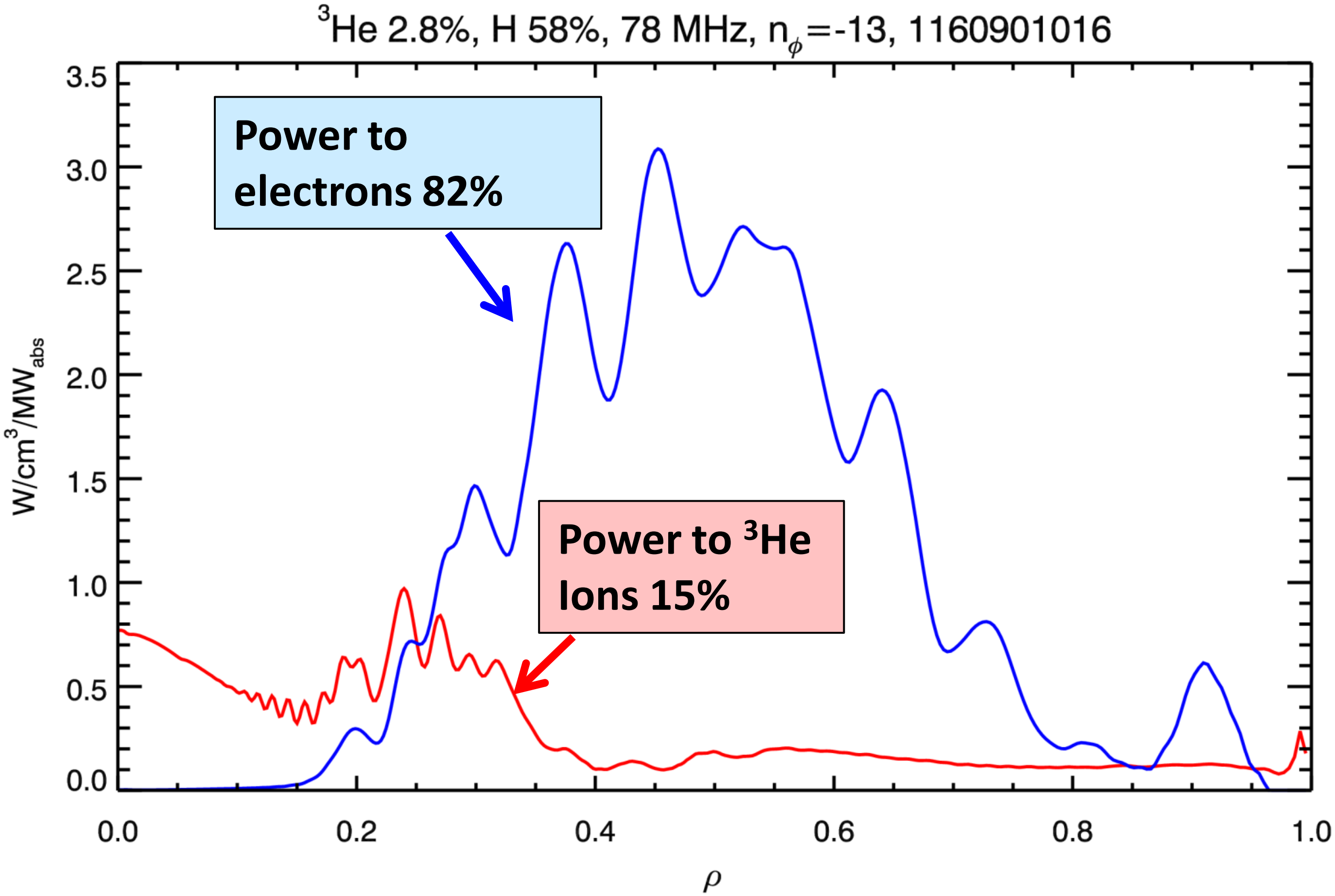
Most RF power goes to electrons via mode conversion electron heating



- 15% power to ^{3}He ions, 82% power electrons and the rest to D and H ions.
- Power to electrons is off-axis and broad.
- Heating effectiveness (increment in stored energy vs. P_{RF}) is low.

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Summary

- RF waves have been measured by PCI in the 3-ion species ICRF heating experiment;
- Double mode-conversion has been confirmed, and the PCI measurement is used to infer the species concentrations;
- TORIC simulation shows that for the low ^{3}He scenario (X[^{3}He] <1%), most RF power is deposited to ions and such power deposition can generate energetic ions at high RF power.
- At higher level of X[^{3}He], most RF power is deposited to electrons via mode conversion, and heating effectiveness is significantly reduced.

More on 3-ion ICRF heating experiment on C-Mod and JET:
Yevgen Kazakov – Invited talk NI3.005, Wednesday morning
John Wright – ITER session TO4.012, Thursday morning