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Profile of Fast Ions that are Accelerated by HHFW

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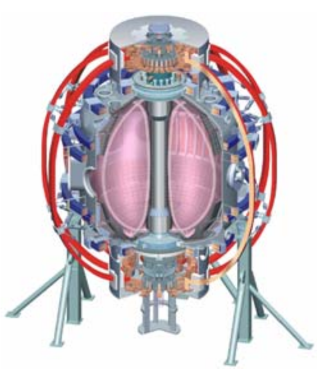

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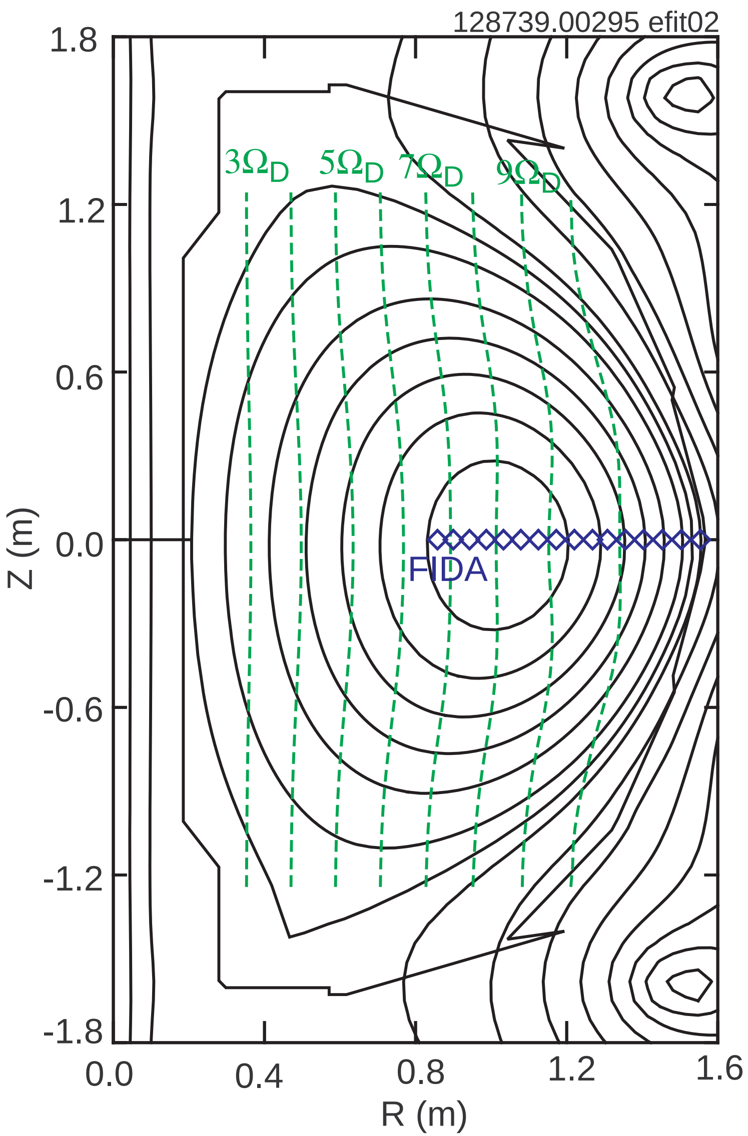
Abstract

The Combined neutral beam injection and 30-MHz high-harmonic fast-wave (HHFW) heating accelerate deuterium fast ions in the National Spherical Torus Experiment (NSTX). With 1.1 MW of HHFW power, the neutron rate is about three times larger than in comparison discharges without RF. A fast-ion tail above the injection energy is observed on an E||B type neutral particle analyzer (NPA), a 4-chord solid state neutral particle analyzer (SSNPA) array and a 16-channel fast-ion D-alpha (FIDA) diagnostic. At some angles, SSNPA can detect neutrals at twice the injection beam energy. The spatial profile of the accelerated fast-ions measured by the FIDA diagnostic is much broader than in conventional tokamaks, presumably due to the multiple resonance layers and large orbits in a spherical tokamak. In addition, Compressional Alfven eigenmode activity is stronger during HHFW, probably due to the bump-on-tail fast-ion velocity distribution which enhances the instability drive. The fast-ion distribution function calculated by the CQL3D Fokker-Planck code is compared with the experimental data.

Motivation



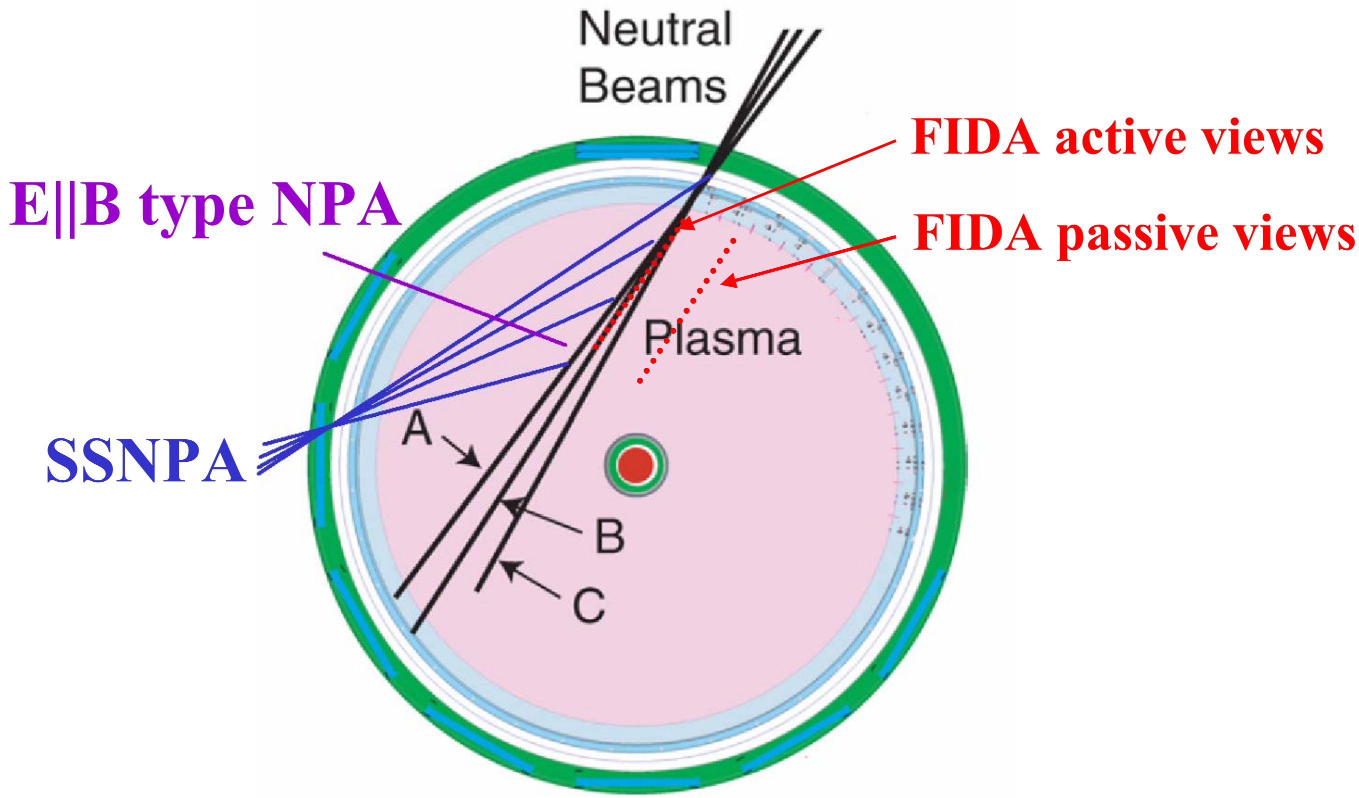
Goal:

Use the new built FIDA and NPA diagnostics to measure the spatial profile of accelerated beam ions by HHFW.

Motivation:

- **NSTX is in a novel regime for high harmonic ion cyclotron heating.**
- **Super-Alfvenic fast ions**
- **Very large values of $k_{perp}\rho_{fast}$**
- **Multiple resonance layers**
- **The new built FIDA diagnostic can be used to get some information on the spatial profile of the absorption.**

The Spatial Profile of Fast Ions is Measured by FIDA and NPA Diagnostics

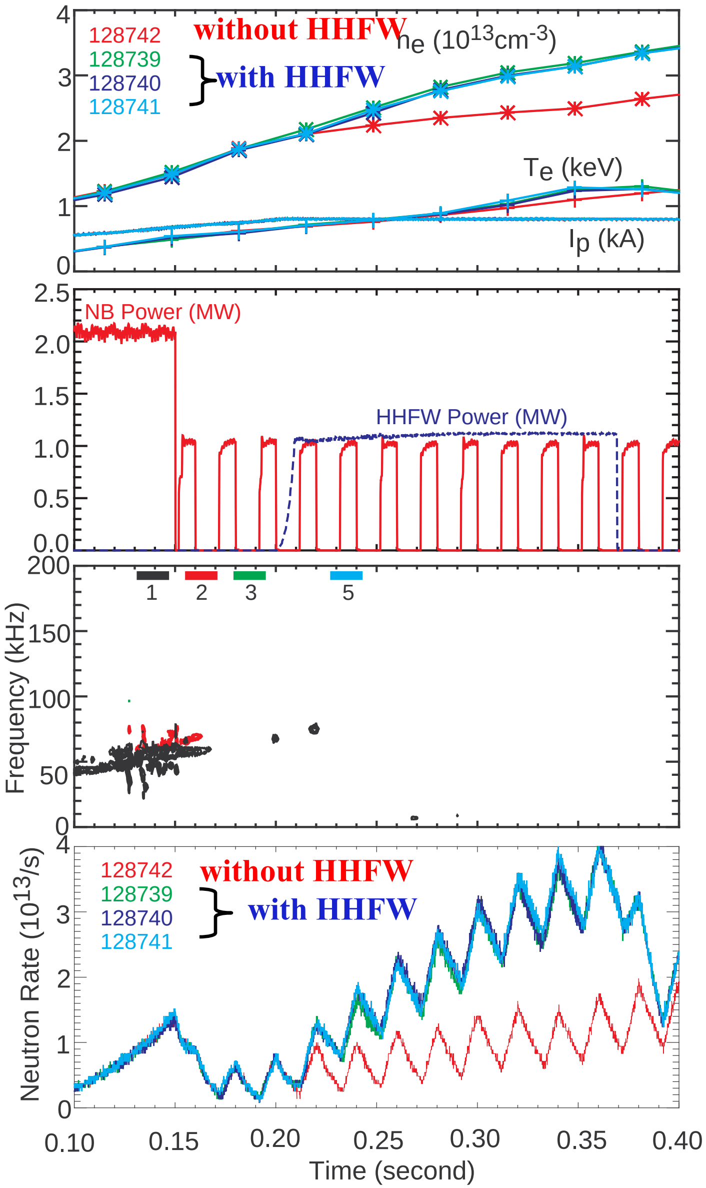


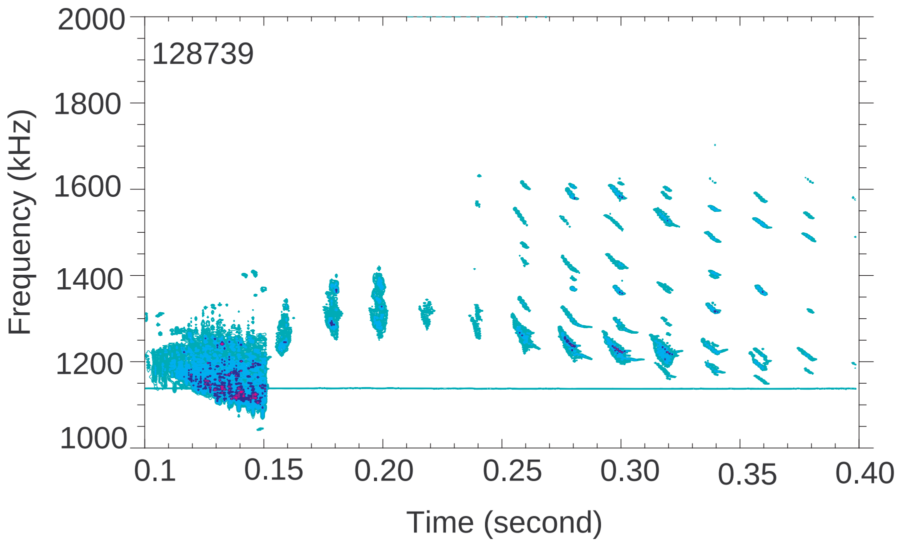
Fast ion diagnostics:

16-channel fast-ion D-alpha (FIDA) diagnostic, E||B type NPA, 4-chord solid state NPA and neutron detectors

Measurements and Analysis of Neutron Emissions during HHFW Heating

HHFW Enhances Neutron Rate in Quiescent Plasmas

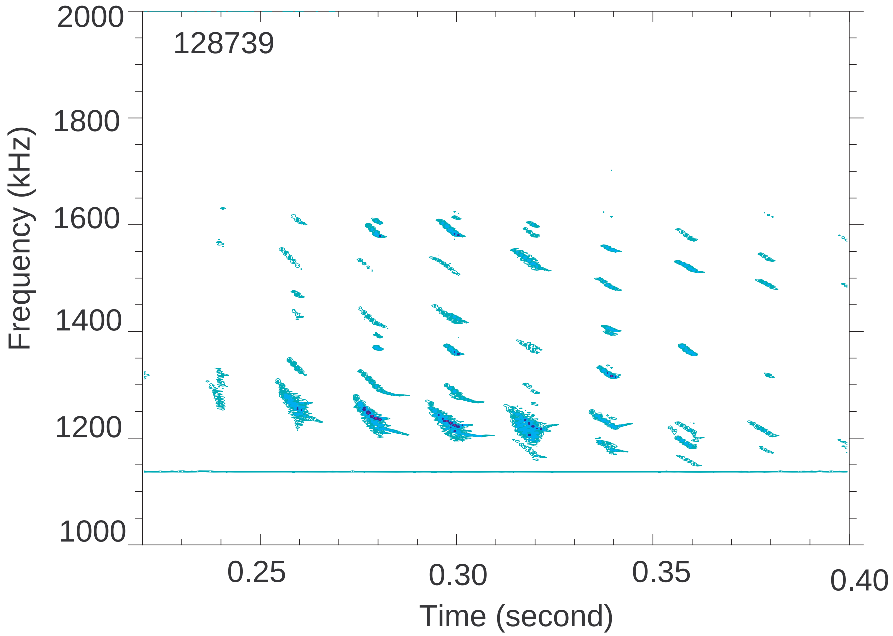




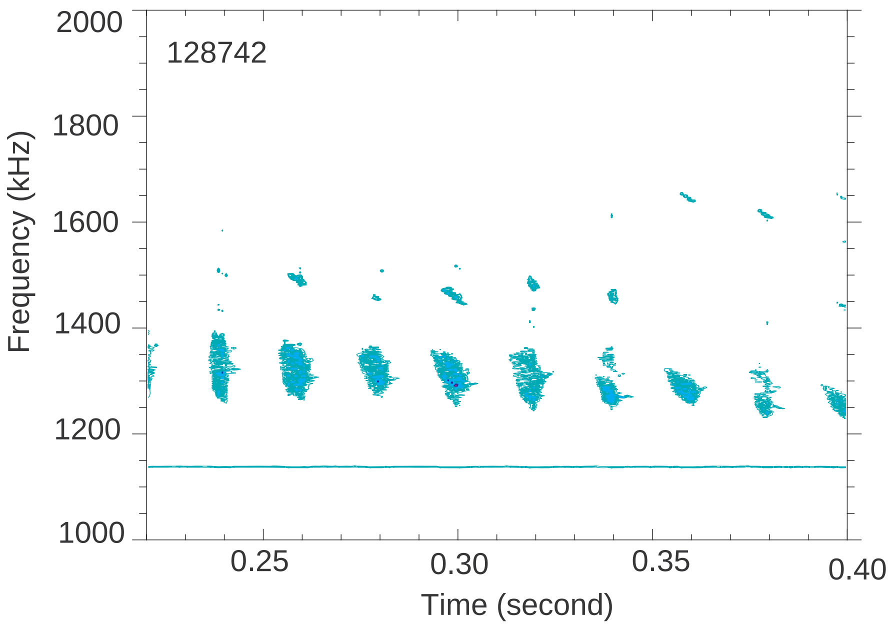
- Deuterium plasmas.
- Similar plasma profiles in the repeated RF shots and the no-RF reference shot except that n_e in the reference shot is lower.
- No low frequency MHD instabilities, but weak chirping CAEs in frequency range of 1100~1800 kHz during RF heating period.
- HHFW enhances neutron rate significantly.

CAEs Behave Differently During RF Heating

With HHFW

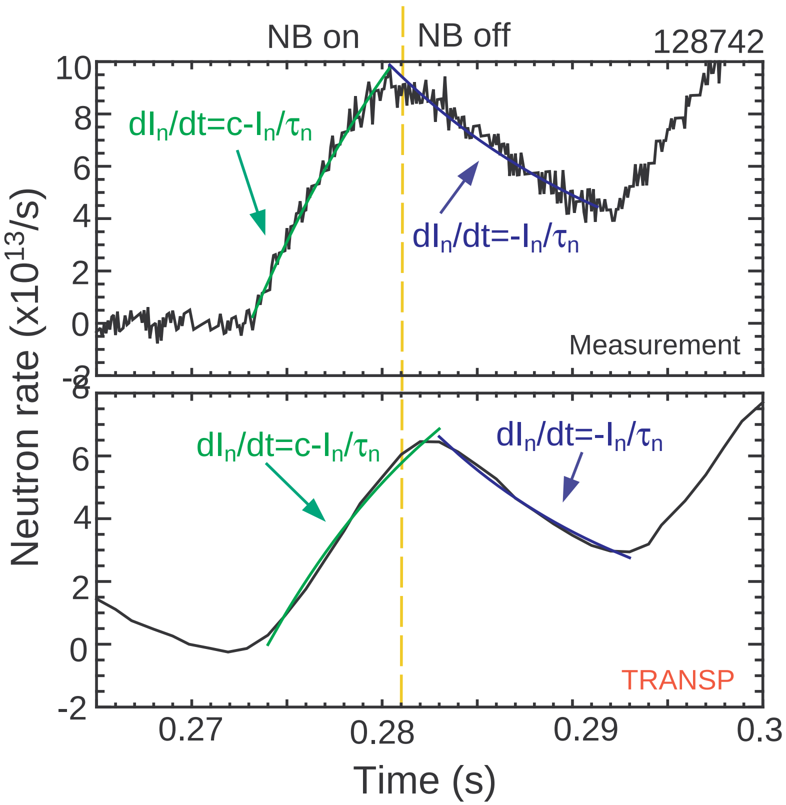


Without HHFW



- **Weak CAEs in RF heating shots and the no-RF reference shot.**
- **CAEs have chirping feature in RF heating shots, but not in the reference shot.**
- **CAE activity is stronger during HHFW, probably due to the bump-on-tail fast-ion velocity distribution which enhances the instability drive**

A simple Model is Used to Derive Rise Rate and Decay Time of Neutron Emissions



See W. W. Heidbrink et al. Nucl. Fusion **43**,*883 (2003)*

During the "beam blip"

$$\frac{dI_n}{dt} = c - I_n / \tau_n$$

where I_n is the neutron emission rate, τ_n is neutron decay time and

$$c \approx \dot{N}_b n_d \langle \sigma v \rangle$$

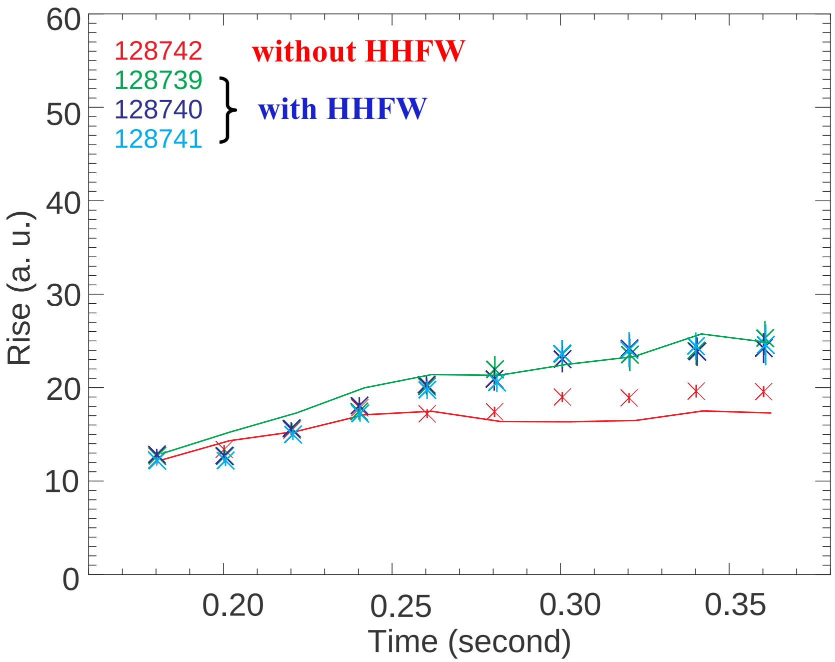
is related with prompt confinement of beam ions.

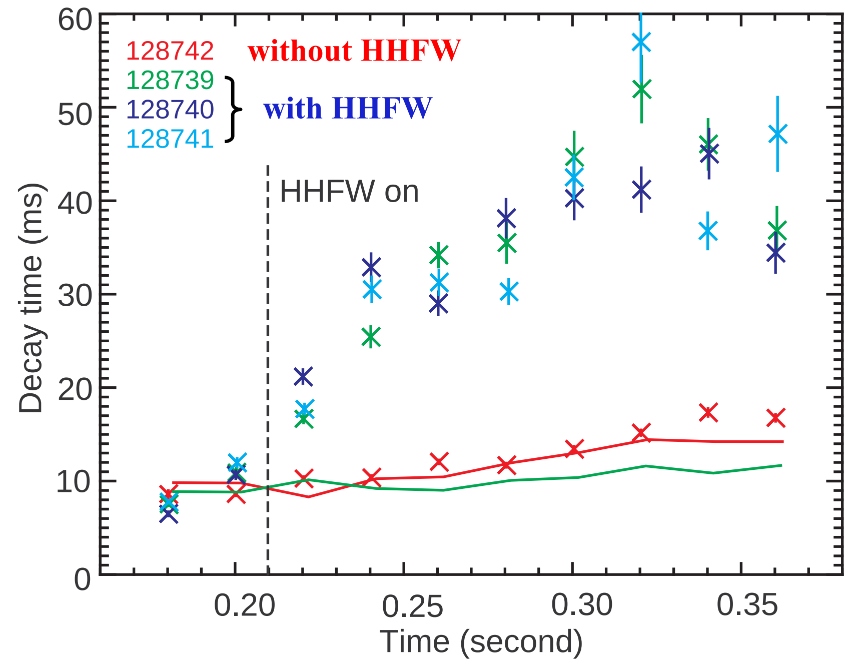
Following the "beam blip", the neutron emission decays approximately exponentially.

$$\frac{dI_n}{dt} = -I_n / \tau_n$$

Through fitting the rise part and decay part of neutron measurements and TRANSP predictions, we can get neutron rise rate c and neutron decay time .

Much Longer Neutron Decay Time during HHFW Heating Suggests Beam Ions are Accelerated





- With and without RF heating, the rise in neutron emission from measurements (discrete points with vertical error bars) agrees well with the TRANSP predictions (solid lines).
- Before RF heating, neutron decay time from measurements agrees well with TRANSP prediction, but during HHFW heating, it is about three times larger than that from TRANSP prediction (without any model for HHFW-induced acceleration). This suggests that fast ions are accelerated by HHFW heating.

Gradual Neutron Decay during HHFW heating Implies RF Operator Q ~ 0.5-0.7 C

The Fokker-Planck equation for the beam ion distribution function f

$$\frac{\partial f}{\partial t} = C + Q + S$$

where *C* represents the collision operator, *Q* represents RF acceleration and *S* represents sources and sinks.

When NB is off, S=0. Neutron decay reflects the competition between Coulomb deceleration and HHFW acceleration.

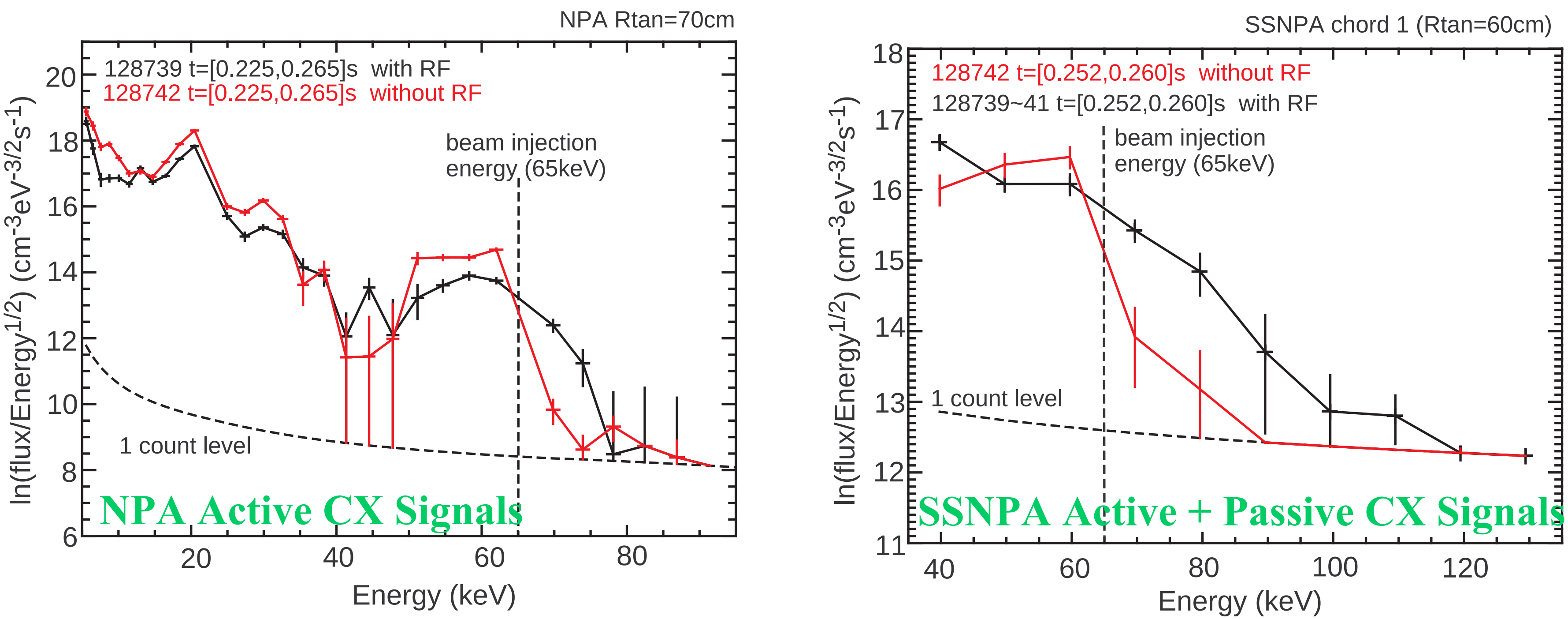
Without RF, $f \propto f_0 e^{-t/\tau_s}$

With RF, $f \propto f_0 e^{-t/\tau_{ex}} = f_0 e^{-(t/\tau_s - t/\tau_{RF})}$

So $$\frac{<Q>}{<C>} = 1 - \frac{\tau_s}{\tau_x} = 0.5 \sim 0.7$$ **for shot 128739**

Measurements and Analysis of Neutral Particle Analyzer Diagnostics

Fast Ion Tails Generated by HHFW are Observed on SSNPA Energy Spectra



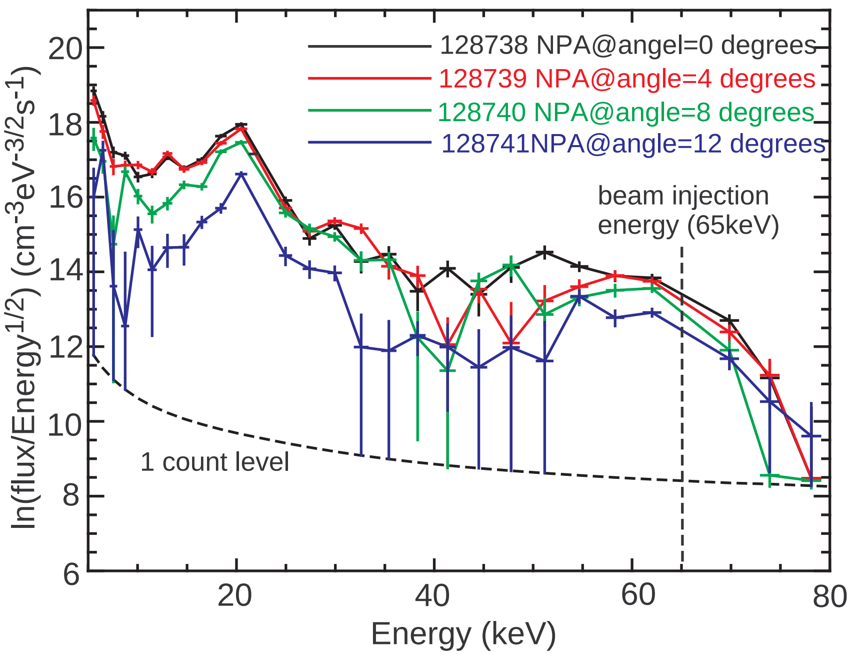
▪RF-induced noise contaminated NPA energy spectra. "Beam modulation" technique is used to obtain active charge exchange (CX) signals of NPA (Passive CX signals and RF-induced noise are subtracted).

▪The active CX energy spectra of NPA and SSNPA don't show high energy D^+ tails.

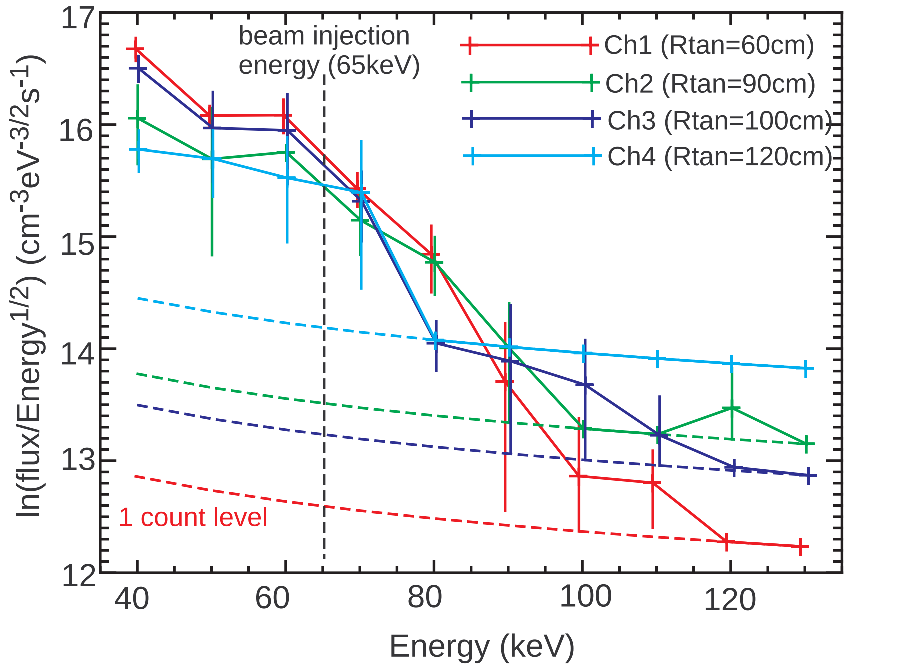
▪D^+ tail extends to ~100 keV on the energy spectra of SSNPA, which is mainly from passive charge exchange reactions.

Acceleration of Fast Ions is Strong in the Perpendicular Direction

NPA Active CX Signals

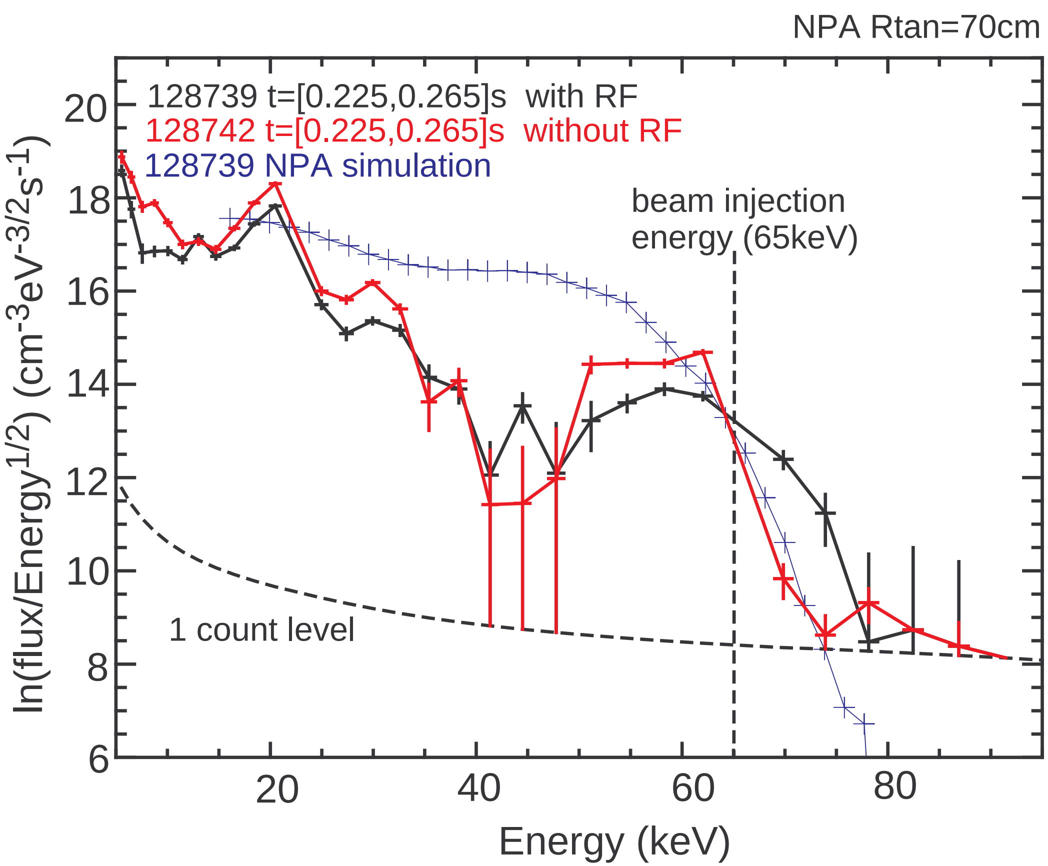


SSNPA Active + Passive CX Signals



- **Little acceleration detected in active CX signals of NPA vertical scan → this portion of phase space weakly affected by RF.**
- **For SSNPA, the acceleration of fast ion tail is strongest in chord 1 and 3 whose pitch at the edge are 0.3 and 0.5.**

Some Discrepancies are Seen between Measured NPA Energy Spectrum and NPA Simulation

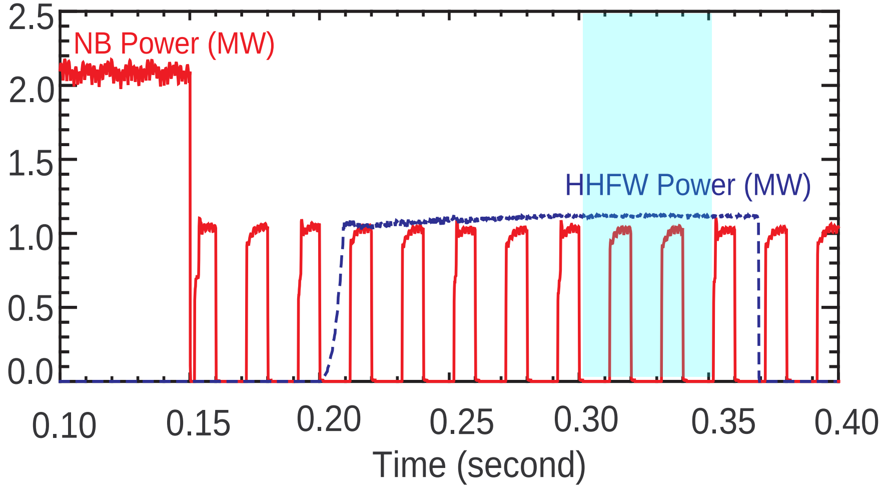


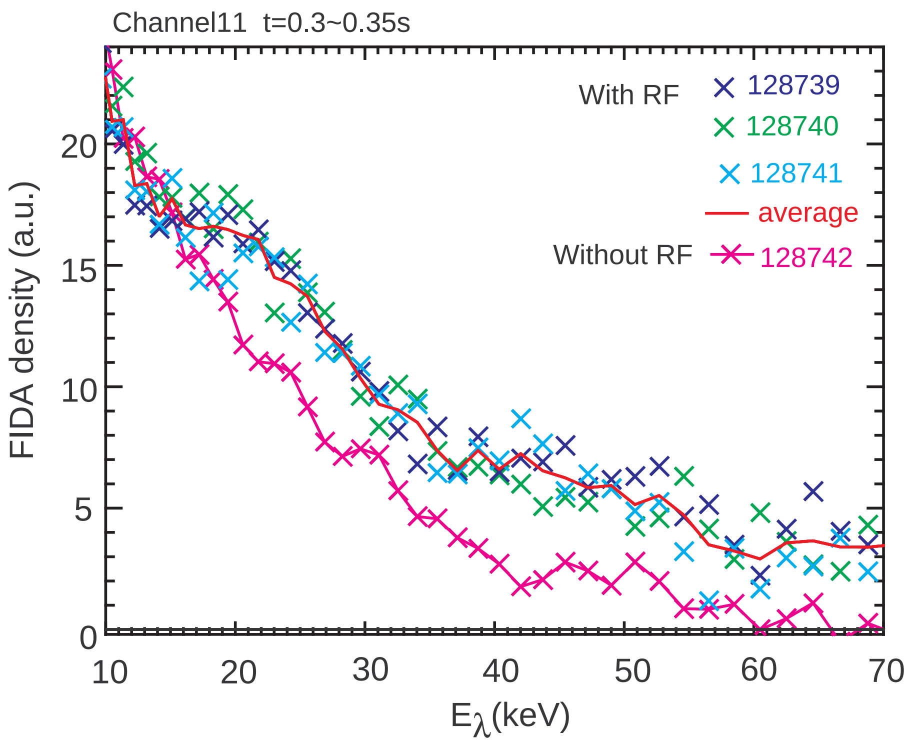
- The magnitude of simulated NPA flux is similar to that in NPA measurements.
- The measurements show that there is depletion of fast ions in the energy region between full and half energy components, but not seen in the NPA simulation results.

→ due to uncertainties in input plasma and equilibrium profiles? Or CAEs?

Measurements and Analysis of Fast-Ion D-Alpha (FIDA) Diagnostic

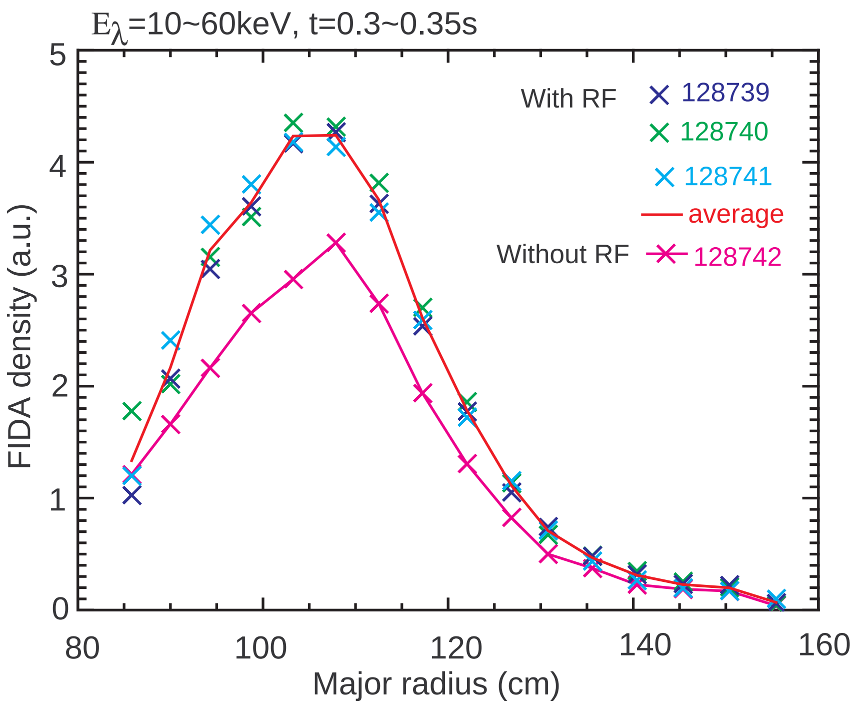
Fast Ion Tails Generated by HHFW are also Observed on FIDA Energy Spectra

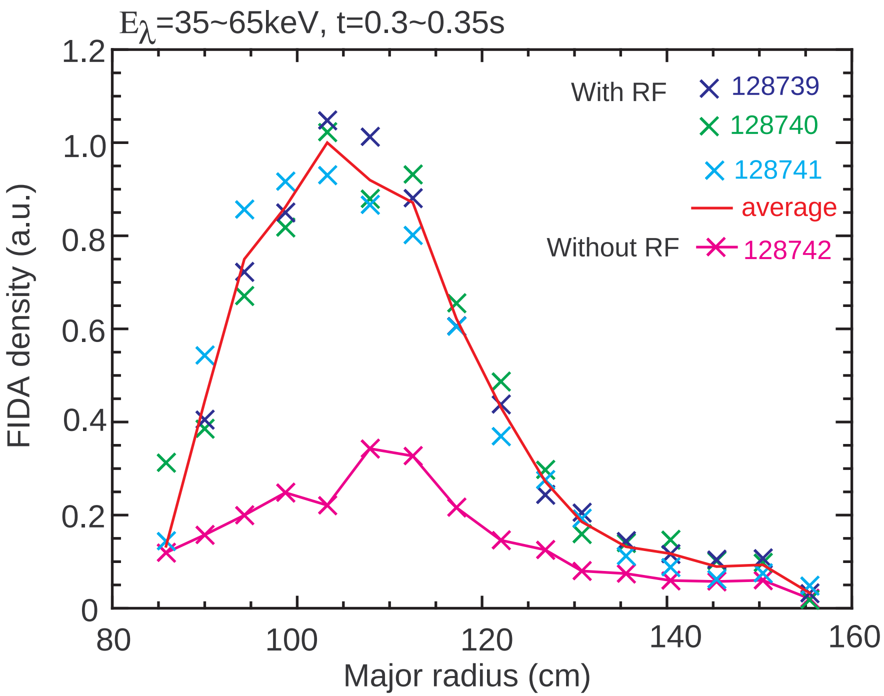




- Neutral beam source B is injected at 65 keV
- "Beam modulation" technique is used to remove the background noise.
- A fast ion tail is clearly seen in FIDA energy spectra during HHFW heating.

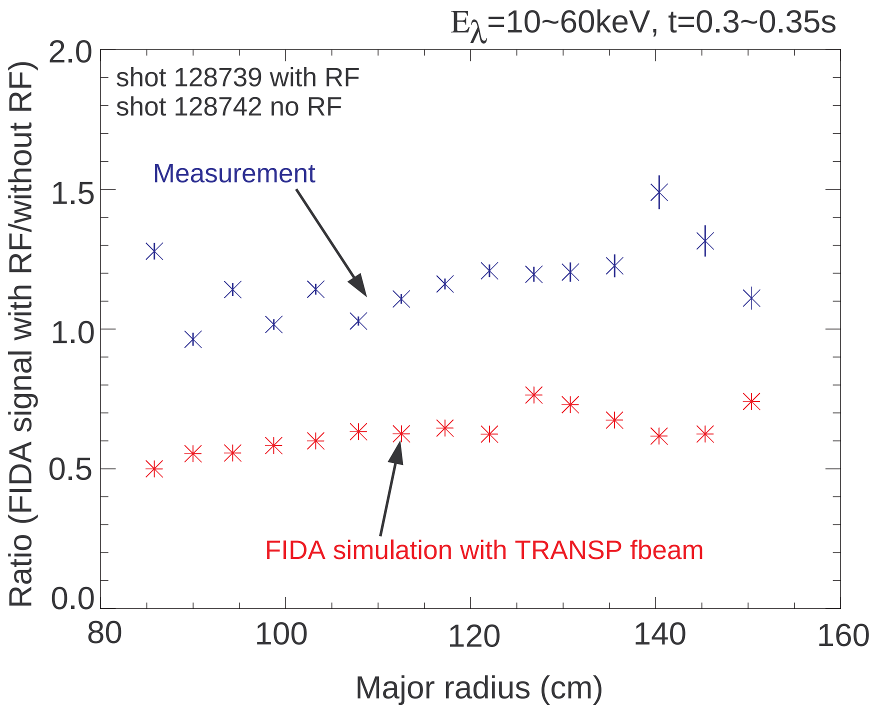
The Acceleration of Fast Ions is Greatest for Energies near or above the Injection Energy

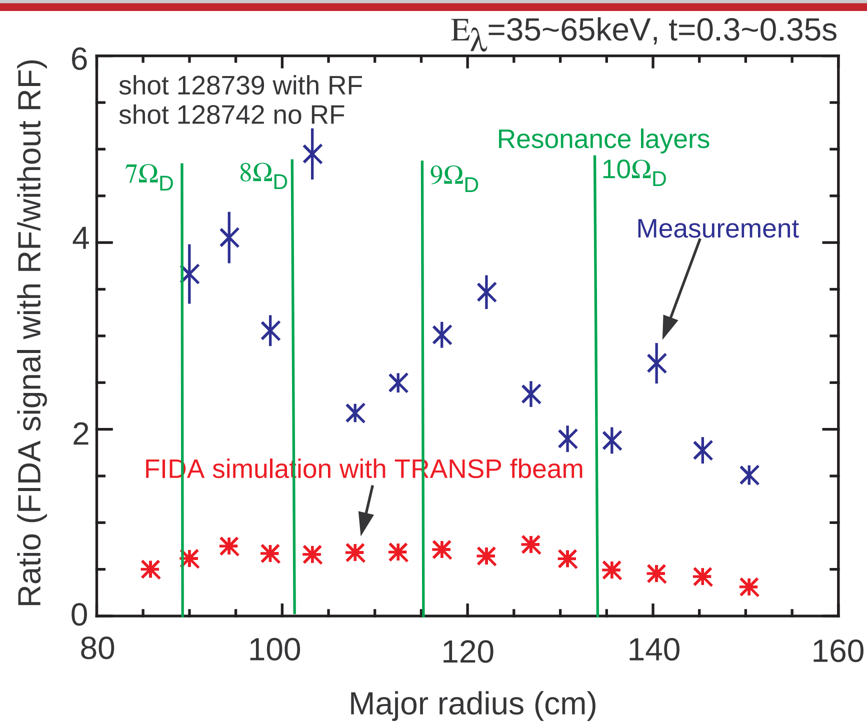




- **The "FIDA density" in the energy range of E_λ=10~60 keV didn't vary much in RF shots compared with the reference shot.**
- **The "FIDA density" in the high energy range E_λ=35~65 keV increased dramatically.**
- **The accelerated tail extended up to 30 cm in FWHM, which is much broader than that in DIII-D.**

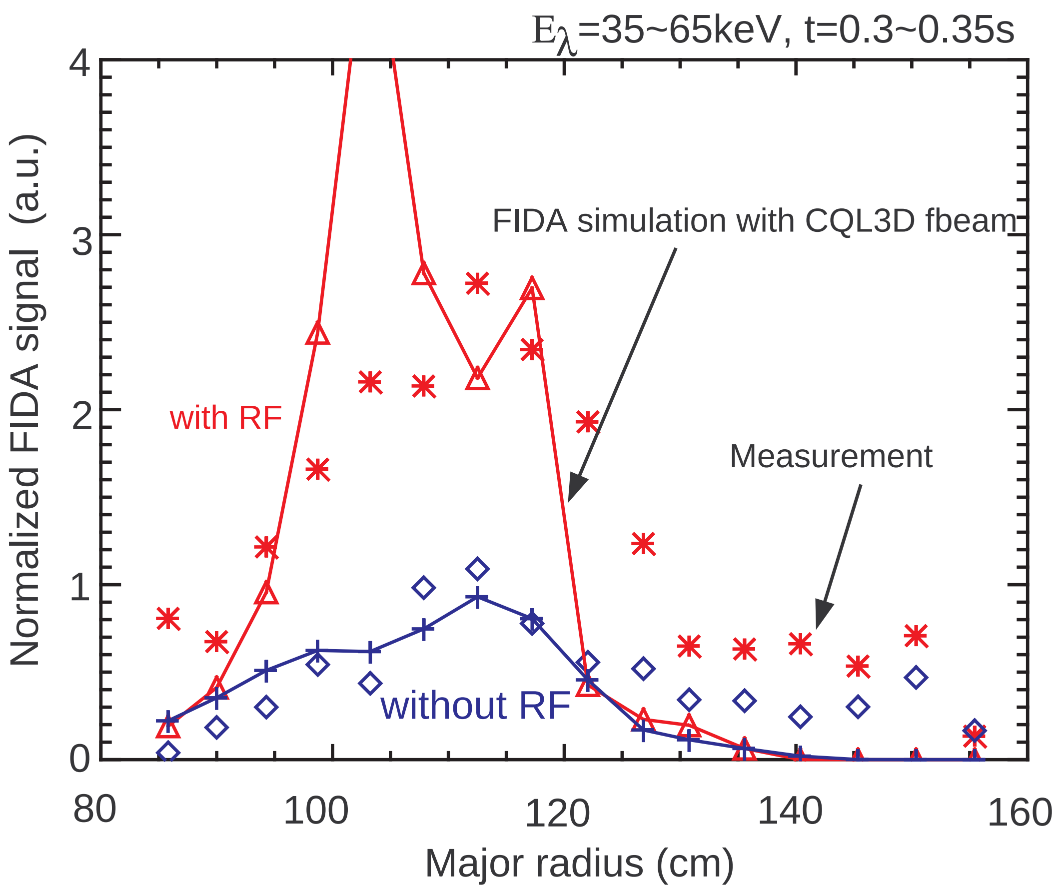
Preliminary FIDA Simulation Results Suggest that Beam Ions are Accelerated by HHFW





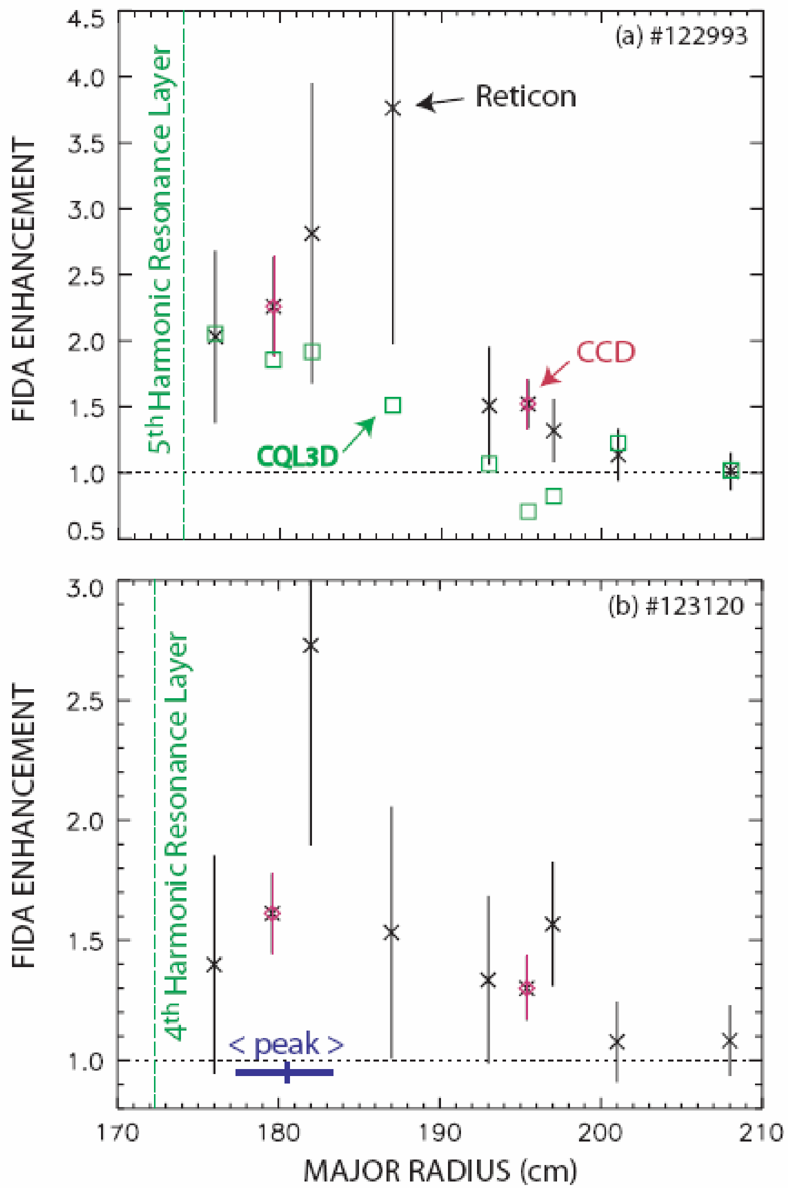
- The FIDA simulation uses fast ion distribution predicted by TRANSP, which doesn't include a model for HHFW-induced acceleration.
- The FIDA simulation predicts less signals in the shot with RF than the ones without RF. It is because N_e and T_e are higher in the RF heating shots.
- The acceleration of fast ions by HHFW heating is clearly seen especially in the high energy range E_λ=35~65 keV.
- The peak locations in fast ion spatial profile (with E_λ=35~65 keV) seems to be correlated with the resonance layers.

Preliminary CQL3D Simulation Results Predicts Acceleration Similar to Experiment



- **The FIDA simulation uses fast ion distribution predicted by CQL3D code, which includes a model for HHFW-induced acceleration.**
- **The enhancement of simulated FIDA signals is in good agreement with the measurements.**
- **The measured FIDA profile is broader than that in FIDA simulation and it is likely due to the zero-banana width approximation in CQL3D.**

Profiles of Fast Ions Accelerated by ICH at DIII-D



The HHFW of the accelerated fast ion spatial profile is about 10 cm.

The peak of the FIDA profile is at larger major Radius than the resonance layer.

- **For the 5th harmonic case, the profile peaks ~10 cm farther out than the resonance layer.**
- **For similar 4th harmonic cases, the profile peak is ~ 8 cm beyond the resonance layer.**
- **Errors are smaller for dedicated (CCD) diagnostic than for Reticon channels.**

**See Heidbrink Plasma Phys. Control. Fusion 49 (2007) 1457–1475*

Summary and Future Work

- Neutron rate is significantly enhanced by HHFW heating
- A fast ion tail above the injection energy is clearly observed on SSNPA and FIDA diagnostics during HHFW heating.
- The acceleration of fast ions is strong in the perpendicular direction.
- The acceleration of fast ions is greatest near or above the injection energy
- The spatial profile of high energy ions is much broader than in conventional Tokamaks.

- Simulate the NPA, SSNPA, FIDA spectra with fast ion distribution calculated from CQL3D Fokker-Planck code and compare with experimental measurements. (in progress)
- Want to compare with other theoretical predictions too
- Understand whether the chirping CAEs affect the interaction between HHFW and fast ions.

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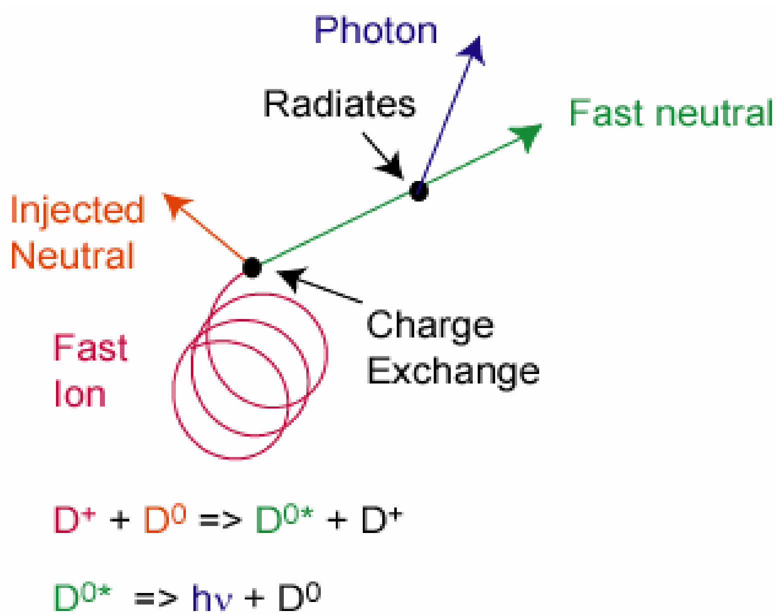
Fast-ion D_α (FIDA) Diagnostic



- A type of Charge Exchange Recombination Spectroscopy
- Use vertical view to avoid bright interferences
- Exploit large Doppler shift (measure wings of line)
- Background subtraction usually dominates uncertainty
- Achieved resolution: ~ 5 cm, ~ 10 keV, 10 ms.

See Heidbrink, PPCF 46 (2004) 1855; Luo, RSI (2006), Podesta Rev. Sci. Instrum. **79, 10E521 (2008);*