NSTX

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Comparison of Measurements and Simulations of Fast Ion Profiles during High Harmonic Fast Wave Heating in NSTX

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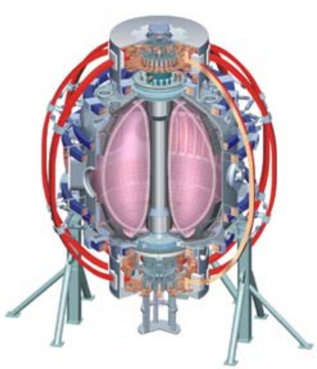

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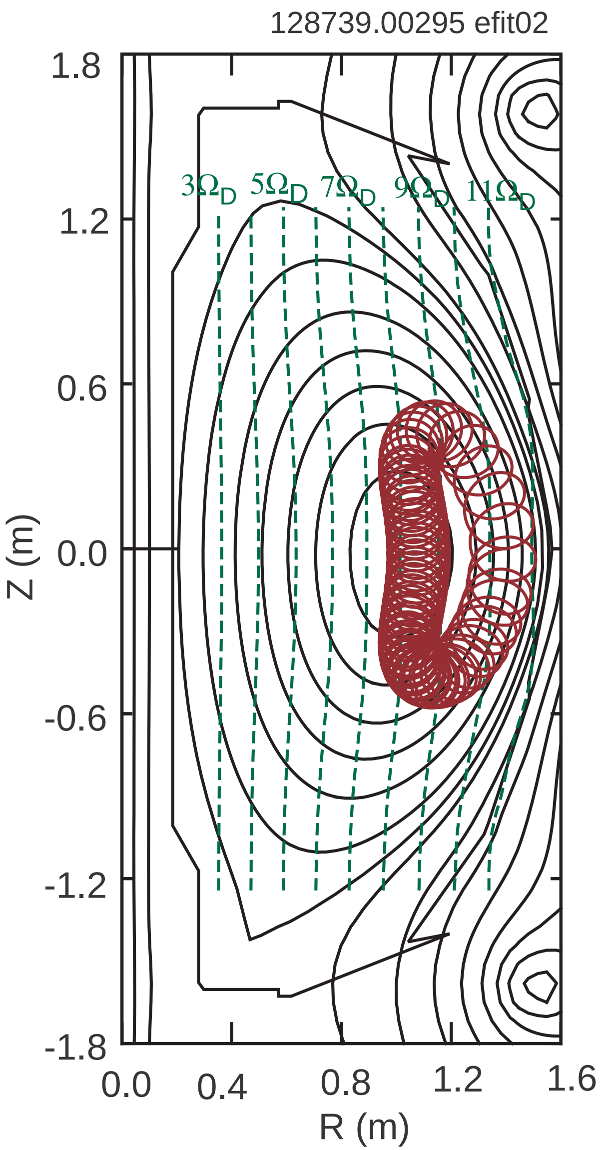
Abstract

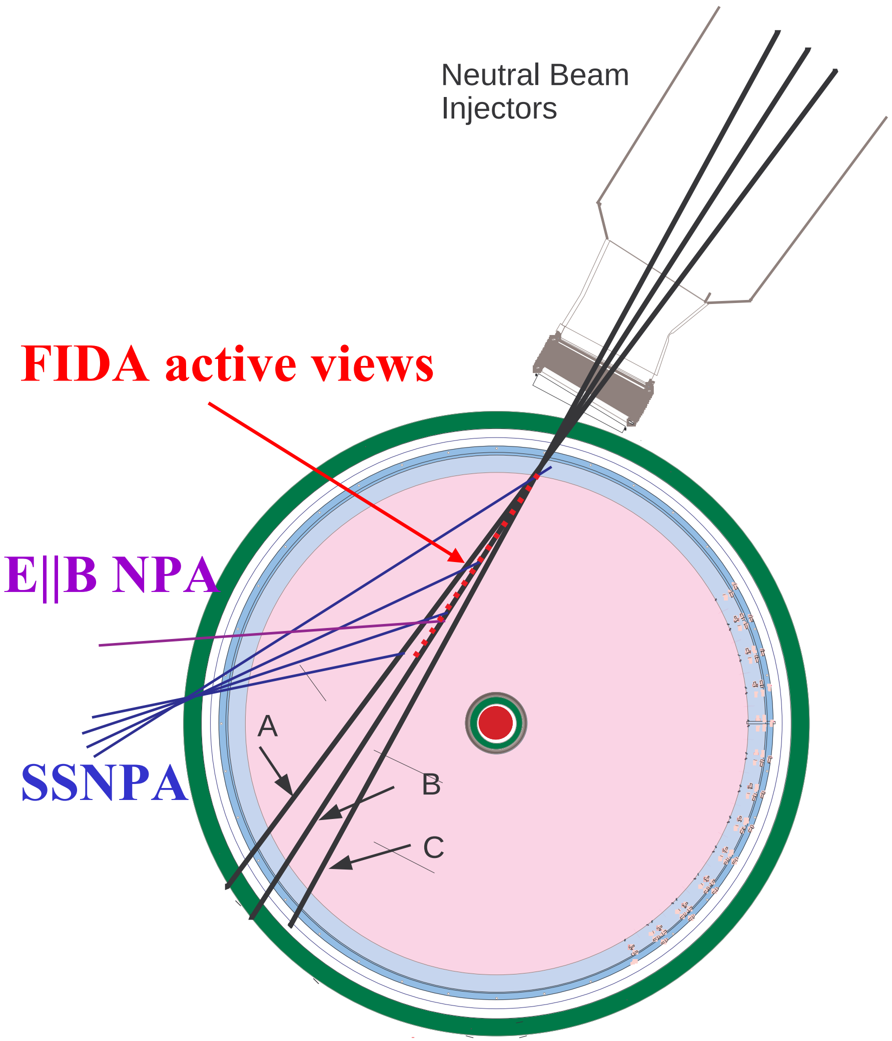
Combined neutral beam injection (NBI) and high harmonic fast wave (HHFW) heating at cyclotron harmonics accelerate deuterium fast ions in the National Spherical Torus Experiment (NSTX). Acceleration of fast ions above the beam injection energy is evident in the data from neutron, E||B type Neutral Particle Analyzer (NPA), Solid State Neutral Particle Analyzer (SSNPA) array and Fast-Ion D-Alpha (FIDA) diagnostics. The fast-ion spatial profiles measured by the FIDA diagnostic show that the acceleration is at four harmonics (7-10) simultaneously and it is much broader than in DIII-D. This is because of the multiple resonance layers and large orbits in NSTX. The measured spatial profile of accelerated fast ions is farther from the magnetic axis and broader than predicted by the CQL3D Fokker-Planck code, for which we conjecture that finite Larmor radius and banana-width can have significant effects on the fast ions in NSTX. To test this hypothesis, simulations with ORBIT-RF code coupled with full wave code AORSA and CQL3D with first order orbit width correction are in progress. (*This work is supported by US DOE Contract DE-AC02-09CH11466.)

Goal: Understand the Interaction between High Harmonic Fast Waves and Fast ions



- **NSTX operates in a novel regime for HHFW heating. (super-Alfvenic fast ions; large Larmor radius; multiple & closely-spaced resonance layers)**
- **The acceleration of fast ions by HHFW in NSTX was observed by neutron and E||B type NPA diagnostics.** [A. Rosenberg et al. POP 11, 2441 (2004)], **but little information was obtained on the spatial profile of the absorption.**
- **FIDA diagnostic measured fast ion profile in 4th and 5th harmonic cyclotron heating on DIII-D and qualitative agreement was obtained between CQL3D simulation and measurements.** [W.W. Heidbrink et al. PPCF 49, 1457 (2007)]
- **FIDA diagnostic became available on NSTX in 2008 and measured fast ion profile during HHFW heating.** [M. Podesta' et al. RSI 78 (2008), D. Liu et al. PPCF submitted]

Radial Profile of Fast Ions during HHFW Heating is Measured by FIDA Diagnostic and compared with Various Predictions



➢**Fast ion diagnostics**

▪**16-channel FIDA diagnostic:** line integrated in velocity space, core-weighted in real space

▪**E||B type NPA, 4-chord solid state NPA array**

small volume in velocity space, mainly core-weighted in real space

▪**neutron detectors**

volume averaged in real space and velocity space

➢**Codes that predict fast ion distribution**

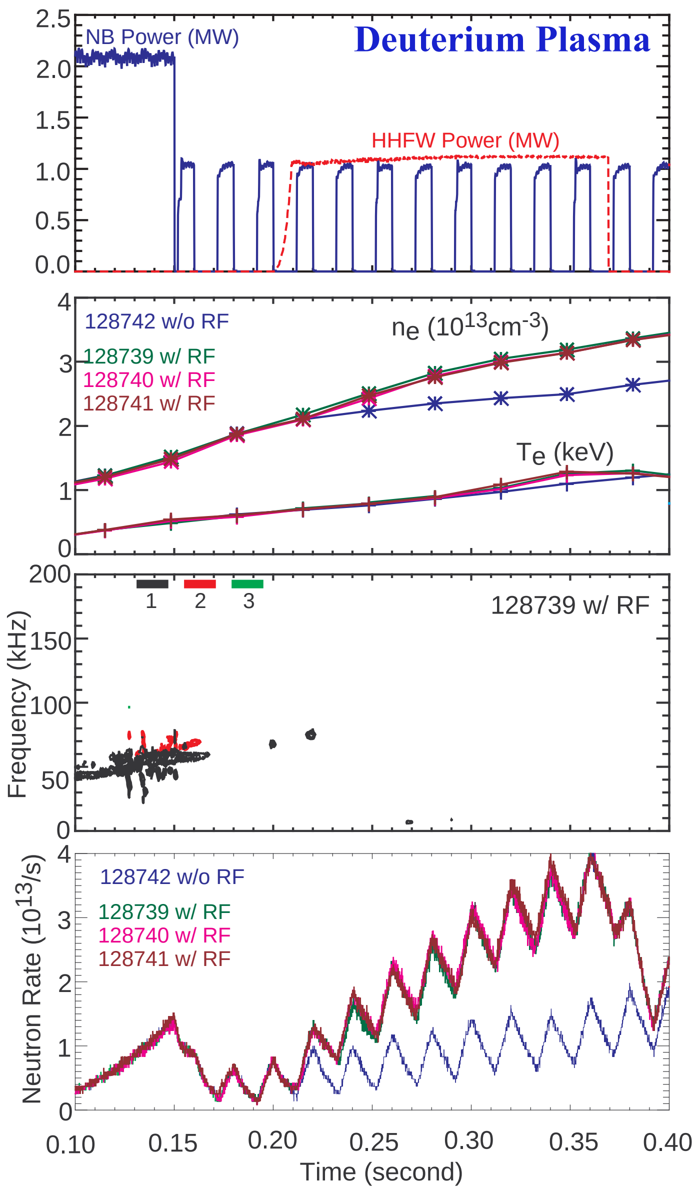
TRANSP: finite Larmor radius and orbit width included, no RF module, used to distinguish the effects of background profiles and RF heating

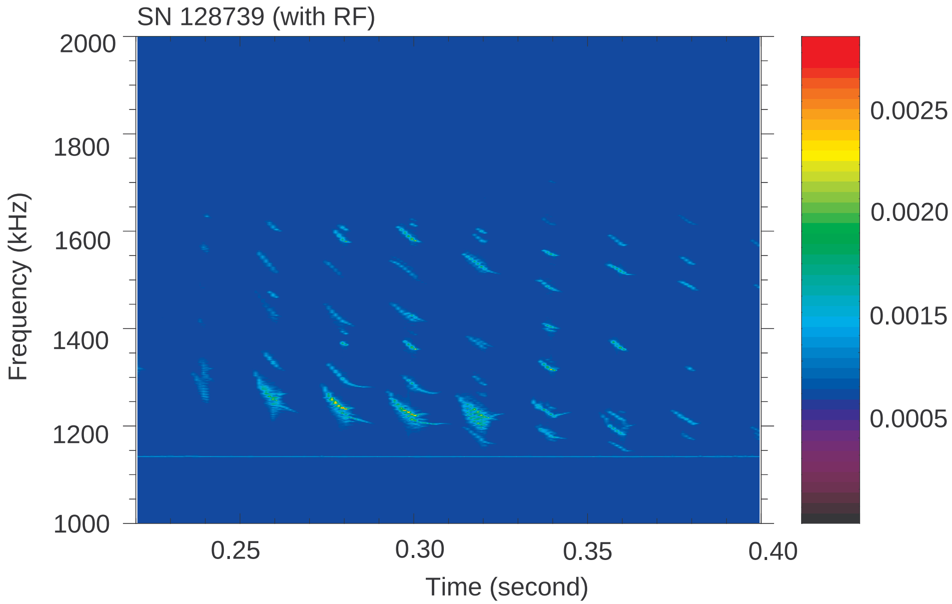
CQL3D/GENRAY: 3D bounce-averaged Fokker-Planck , with RF interaction, zero-banana-width approximation for fast ions in the current version, used to check RF effects

ORBIT-RF/AORSA: finite orbit width effect included, used to check RF effects

Experimental Measurements and Data Analysis

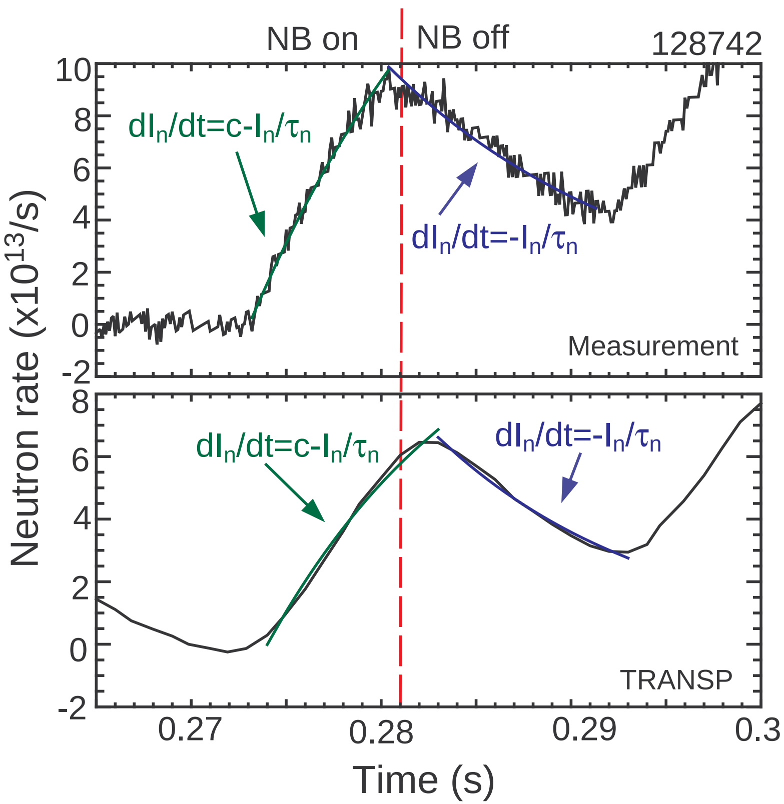
Neutron Rate Increases by a Factor of 2.5 During HHFW Heating





- **Similar plasma profiles in the shots with and without RF except n_e in the no-RF reference shot is lower.**
- **No robust MHD activity thanks to the beam modulation and relatively low injection energy; weak chirping Compressional Alfven Eigenmodes still exists**
- **Neutron rate increase: ×2.5**

Neutron Rise Rate and Decay Time are Estimated and Compared with the TRANSP Simulations



➢**The rise and decay of neutron pulse can be fitted to a simple model.** [W. W. Heidbrink, NF 43,883 (2003)]

▪**Rise depends on the number of confined beam ions**

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

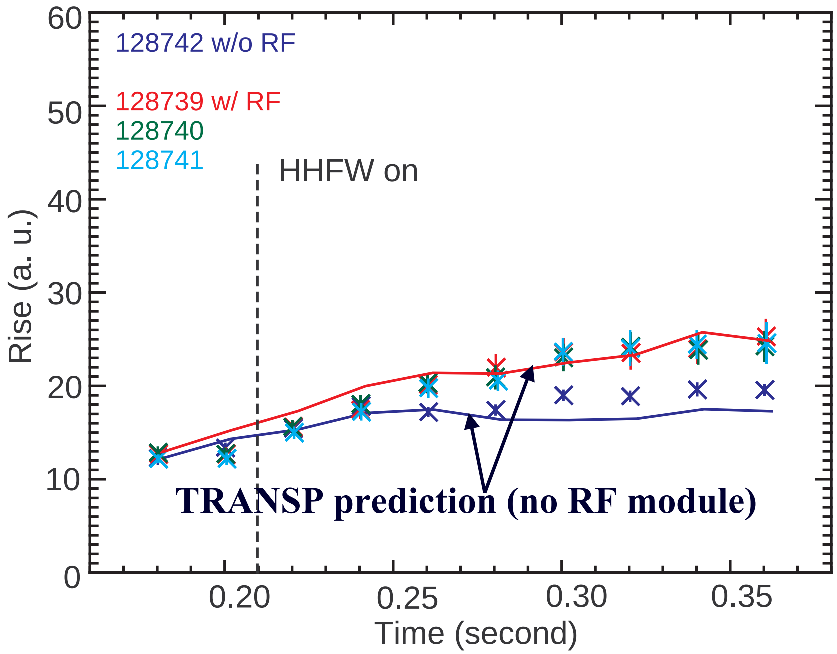
with I_n the neutron emission rate, τ_s neutron decay time and $c \approx N_b n_d \langle \sigma v \rangle$

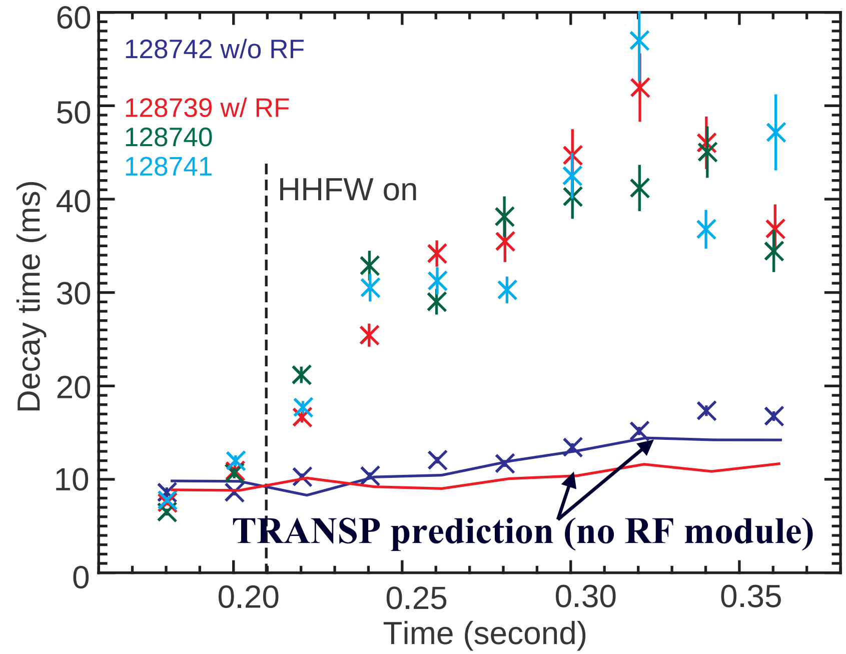
▪ **Decay depends on slowing down & losses** $\frac{dI_n}{dt} = -I_n / \tau_s$

➢**Neutron decay time is proportional to fast ion slowing down time.**

➢**Neutron decay reflects the competition between RF acceleration and Coulomb deceleration**

Much Larger Neutron Decay Time during HHFW Heating Indicates that Fast Ions are Accelerated





- **Slight difference in the rise rate in the shots with and without RF heating (NB ramp-up rate dominates); measurements of rise rate agree with the TRANSP predictions**
- **Larger decay time → RF acceleration counteract Coulomb deceleration**

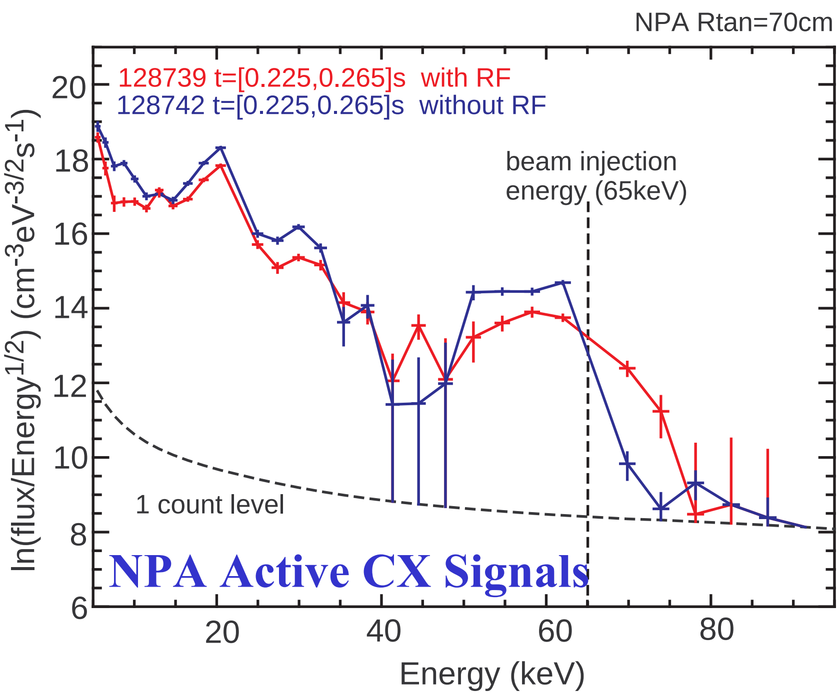
$$\frac{\partial f}{\partial t} = C + Q + S$$

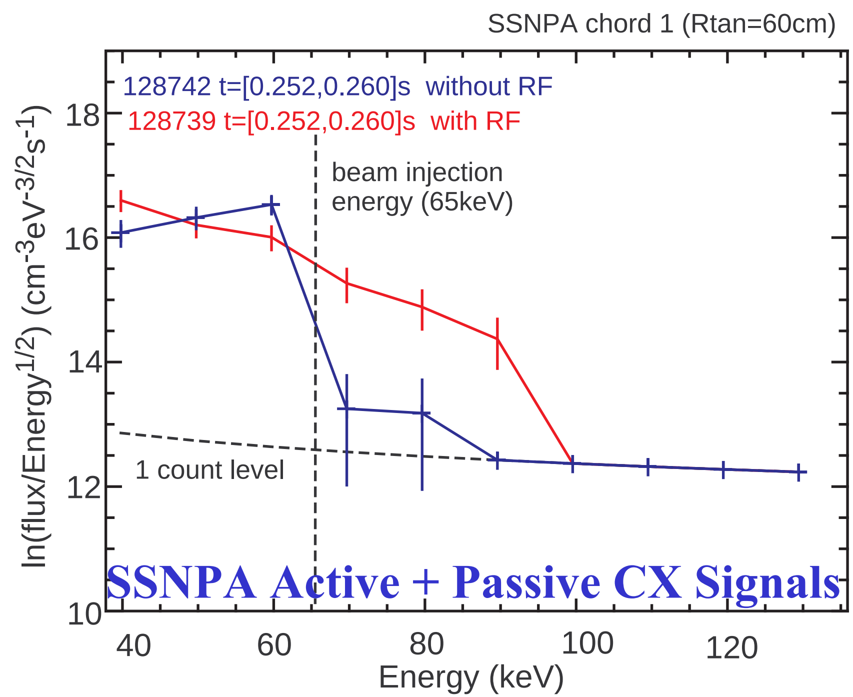
C: Coulomb collision operator, Q: RF acceleration operator, S: sources and sinks

During beam-off period, S≈0

→ $$\frac{<Q>}{<C>} = 1 - \frac{\tau_s}{\tau_{ex,s}} = 0.5 \sim 0.7$$ **for shots 128739-129741**

Fast Ion Tail Observed by the NPA Diagnostics is Mainly from the Passive Charge Exchange Reactions at the Edge





- **NPA active charge exchange (CX) signals are obtained by beam modulation, with the passive CX signals and RF-induced noise subtracted.**
- **Only a small D^+ tail above the beam injection energy on the active CX energy spectra of NPA and SSNPA**
- **D^+ tail extends to ~100 keV on the energy spectra of the total CX signals of SSNPA**

→The observed fast ion is mainly from the passive CX reactions at the edge.

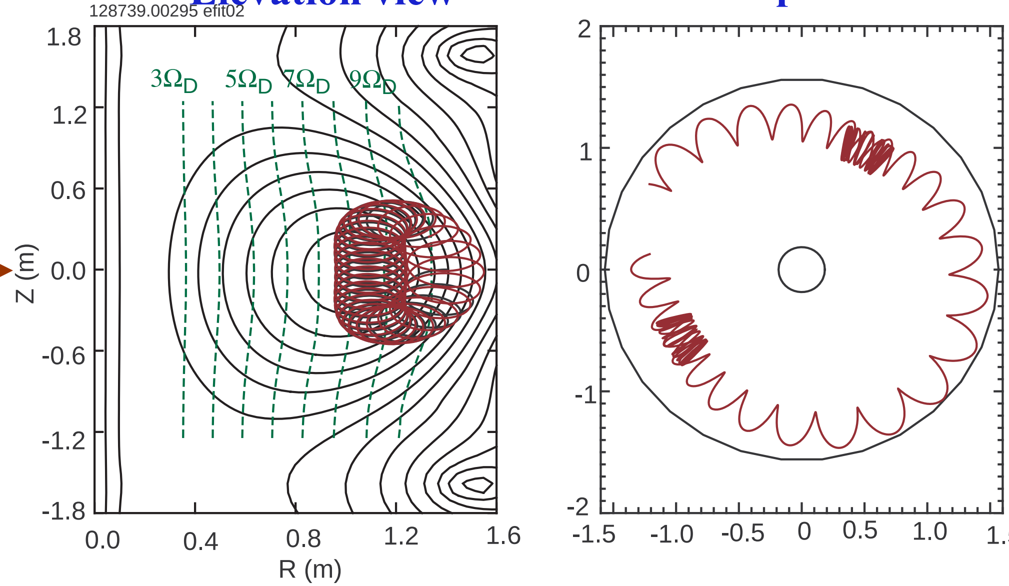
Particle Trajectory Explains Why the NPA and SSNPA Observe Fast Ion Acceleration Only in the Passive CX Signals

(E=100keV, $v_{||}/v$=0.39, R=1.4m)

Trajectory of particles that can contribute to the NPA passive CX signals

Barely passing particles, spending long time at resonance layers

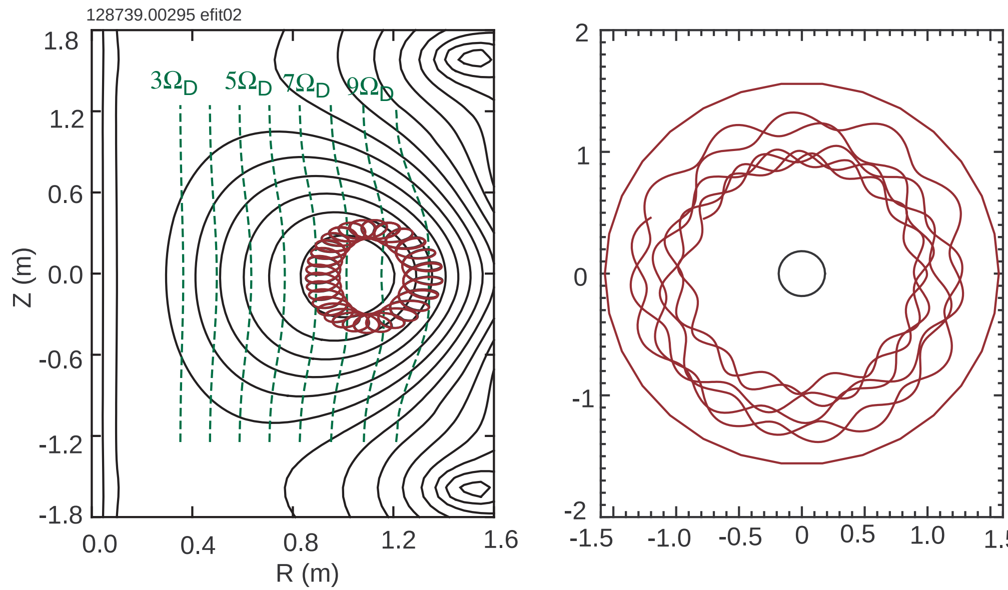
Elevation view **Top view**



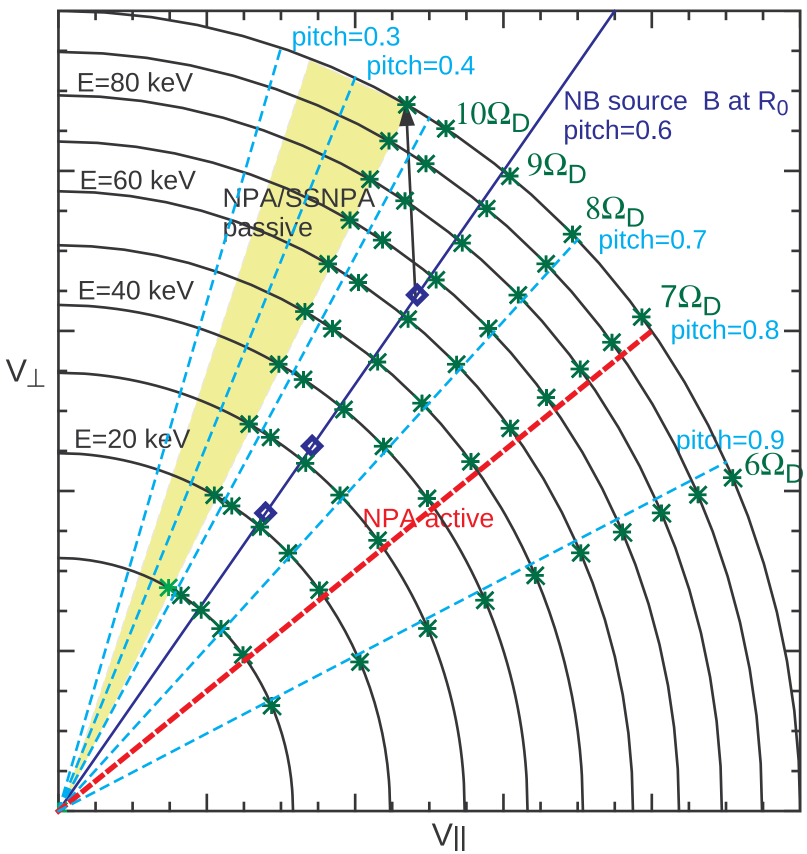
(E=100keV, $v_{||}/v$=0.8, R=0.9m)

Trajectory of particles that can contribute to the NPA active CX signals

Passing particles

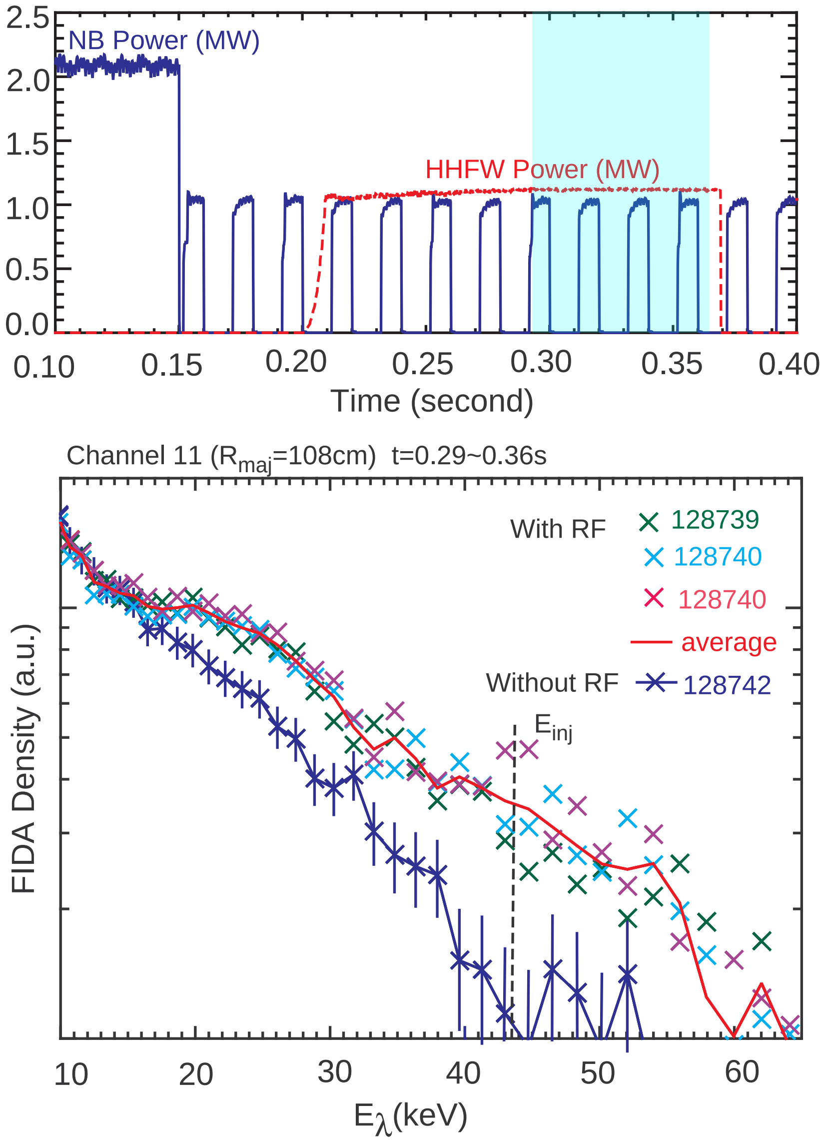


Why can't the NPA Diagnostics Observe Fast Ion Acceleration in the Active CX Signals



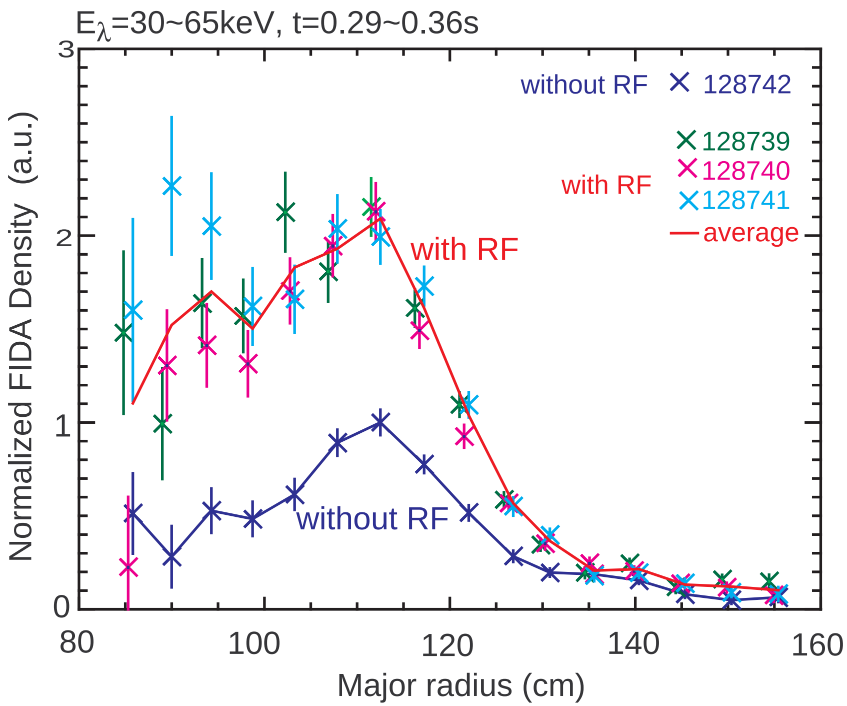
- The injection angle of NB determines the pitch of the produced fast ions, ~0.6
- The detection angle of NPA and SSNPA determines the pitch of fast ions that can be measured. (0.7~0.9 for active CX, ~0.4 for passive CX)
- Fast ions move from the passing particle region to the trapped particle region in velocity space when they gain perpendicular energy during HHFW heating.
- The NPA diagnostics are not in the correct velocity space (i.e. not perpendicular enough) to observe fast ion acceleration in the active CX signals.

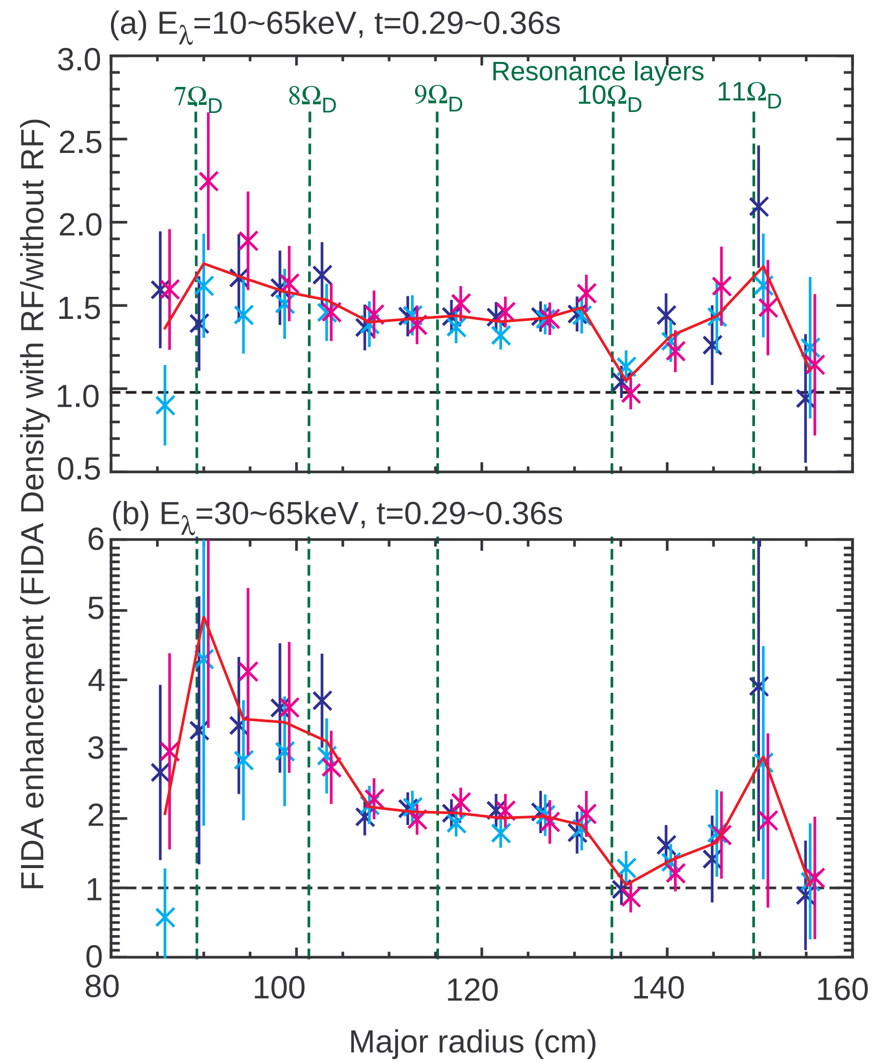
FIDA Energy Spectra Exhibits High-Energy Tails during HHFW Heating



- **Beam modulation is used to remove the background light.**
- **E_λ: determined by the Doppler shift, only perpendicular energy, not the total energy in the NPA diagnostics.**
- **FIDA density (FIDA signal/ local neutral density) increases significantly in E_λ=[20,55] keV during HHFW heating. This suggests fast ions are accelerated.**

The Enhancements of FIDA Density Suggest a Broad Absorption Profile





- A wide region (80-120 cm) of fast ion profile is affected by the HHFW heating, broader than in DIII-D, due to multiple resonance layers and large Larmor radius
- Acceleration is more obvious in high energy: increase 2 times in E_λ=35-65 keV, 1.5 times in E_λ=10-65 keV

Experimental Summary: Acceleration Observed by All Diagnostics

- The averaged neutron rate increases by a factor of 2.5.
- Much longer neutron decay time→ <Q>~ 0.5-0.7<C>
- A fast ion tail is observed in the energy spectra of total CX signals of the SSNPA, but only a small tail observed in the energy spectra of active CX signals
→ due to the localization of NPA diagnostics in phase space
- Acceleration for orbits with turning points near central resonance layers.
- The FIDA energy spectra exhibit a fast ion tail above the beam injection energy.
- FIDA enhancement indicates a very broad absorption profile. (FWHM~30cm, 7-10 harmonics) → due to multiple resonance layers and large Larmor radius
- FIDA enhancement suggest the absorption at high energy range is more obvious. (increase by a factor of 2 in E_λ=35-65 keV and 1.5 in E_λ=10-65 keV)

Comparison with Codes and Discussions

Comparison between Experiments and Simulations : Approach

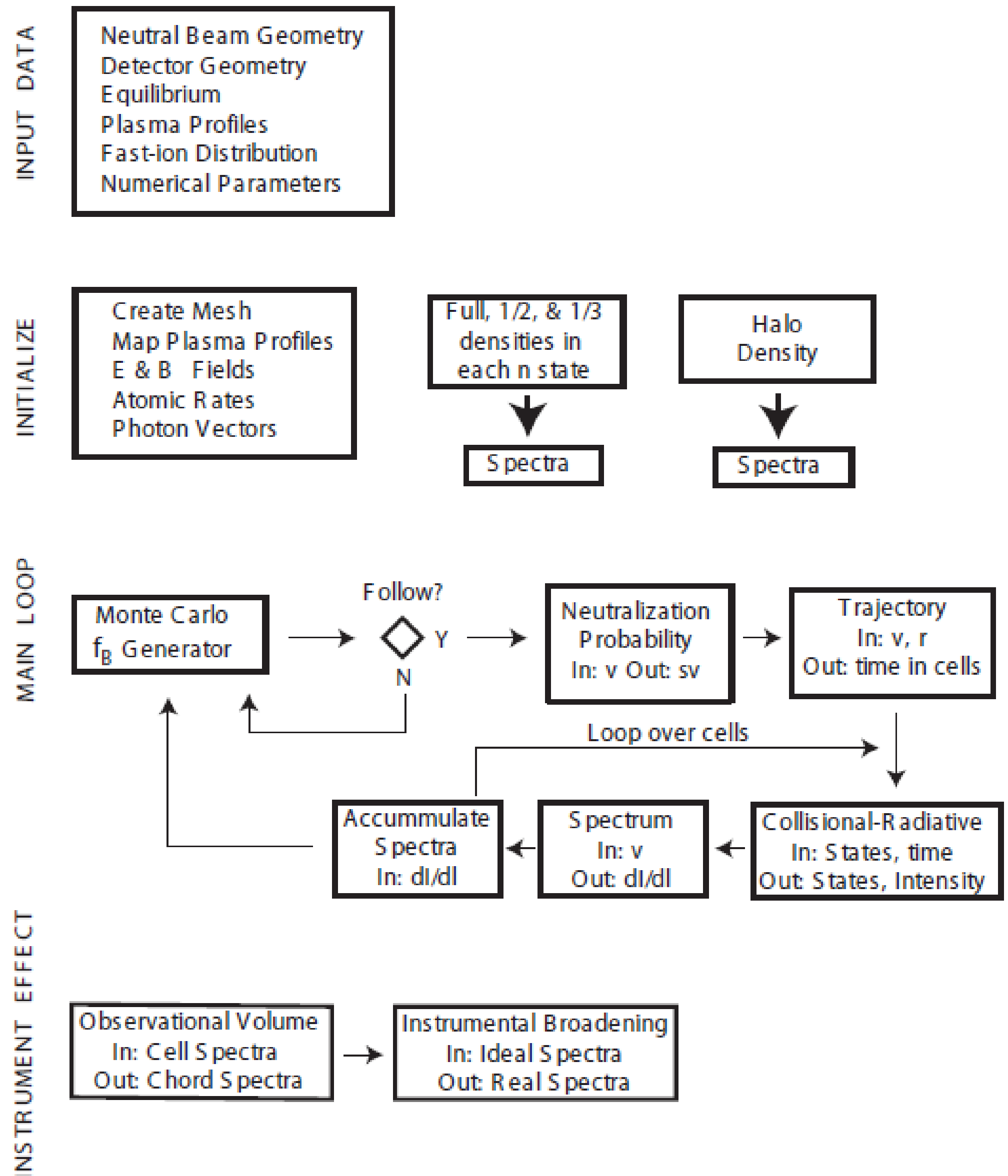
➢**TRANSP, CQL3D, ORBIT-RF… calculate fast ion distribution F_f**

➢**F_f used as input of a forward modeling FIDA simulation code**

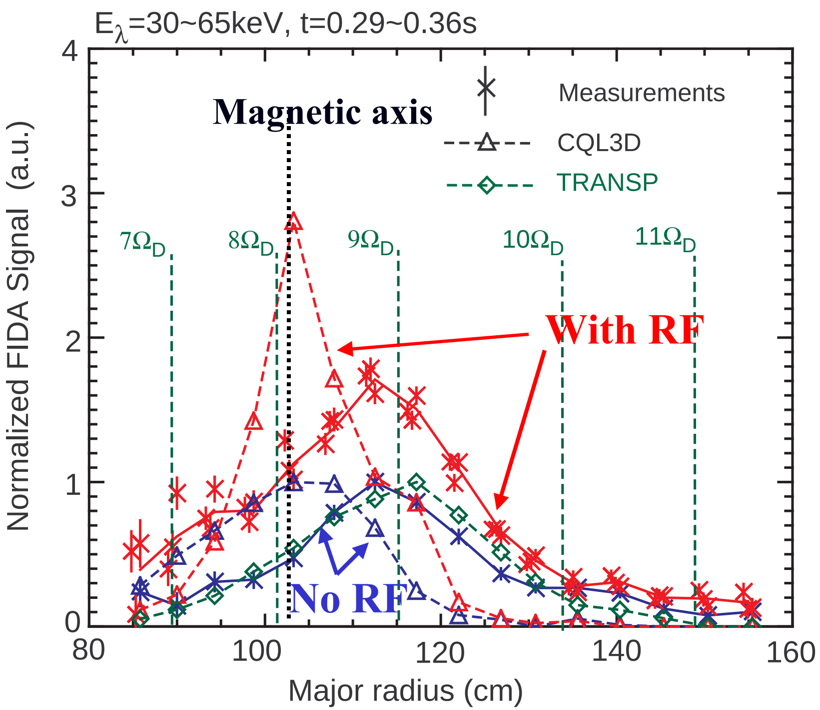
▪**"Predicted" FIDA signal is constructed with real geometry, plasma and equilibrium profiles.**

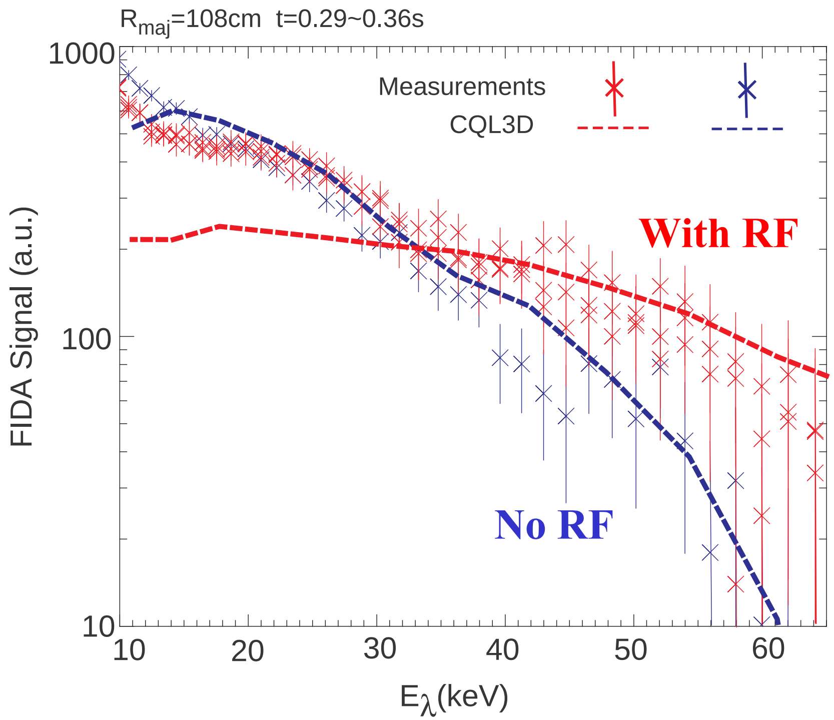
•**FIDA Simulation is validated for no-rf, MHD quiescent discharges.**

*See Heidbrink, PPCF 46 (2004) 1855



The CQL3D Predictions are Qualitatively Consistent with Measurements, but with Large Quantitative Discrepancy





- ➢The radial profile predicted by TRANSP agrees with the measurements in shape for the no-RF case.
- ➢The CQL3D predictions are qualitatively consistent with measurements, but with large quantitative discrepancy.
  - ▪The predicted fast ion tail is similar to the measurements in shape.
  - ▪The predicted radial profiles are closer to the magnetic axis and narrower than the measurements
  - ▪The predicted enhancement of FIDA signals is stronger than the measurements.

What Accounts for the Discrepancies?

- **FIDA data are contaminated by spurious light sources.**

Unlikely, FIDA data are from the cleaner blue-shifted side and look good. The measurements from neutron detectors and NPA diagnostics also confirm that fast ions are accelerated.

- **The FIDA simulation is wrong due to errors in input plasma or equilibrium profiles**

Unlikely, the sensitivity study of FIDA simulation in DIII-D suggests that the input errors could cause ~10 percent difference.

- **Plasma fluctuations cause anomalous fast-ion transport .**

Maybe, need to perform additional experiments to assess

- **MHD instabilities distort distribution function.**

Maybe, weak and chirping CAEs during RF heating although there is no robust MHD instabilities

- **The FIDA simulation misses some physics for spherical torus?**

Possible. Finite Larmor radius effect is included in the FIDA simulation code, which makes TRANSP simulation agree with the FIDA measurements.

- **The FIDA simulation is wrong due to inaccurate fast ion distribution from CQL3D.**

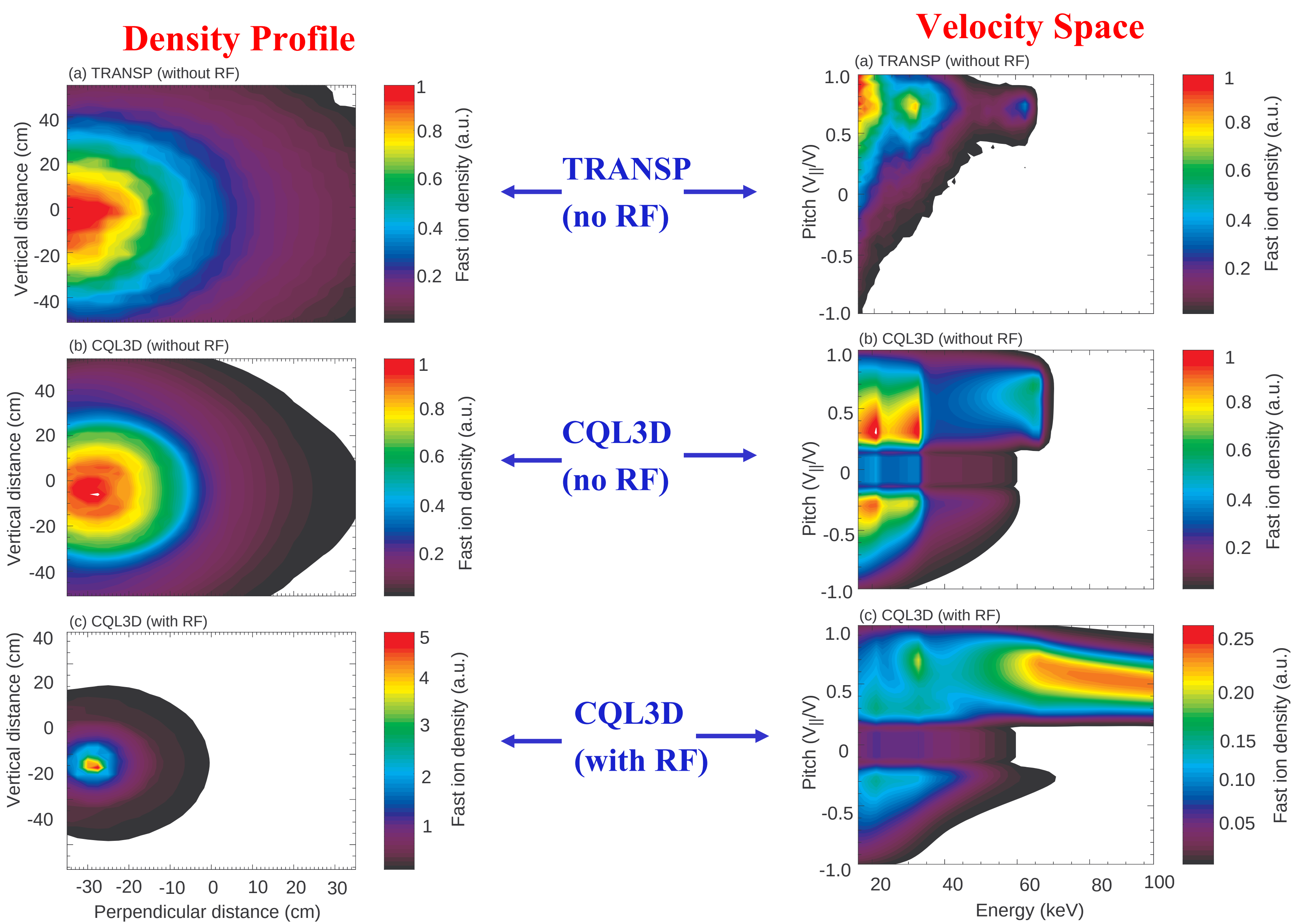
Very likely, (1) The FIDA diagnostic measure a line in the velocity space.

(2) The TRANSP predicted FIDA radial profile is fairly consistent with the measurements, but not for the CQL3D simulations.

(3) The fast ion distributions predicted by TRANSP and CQL3D are quite different in velocity space although they are similar in the density profile.

➔Finite orbit width effect may be important!

Fast Ion Distributions from TRANSP and CQL3D Simulations are Similar in Density Profile, but Quite Different in Velocity Space



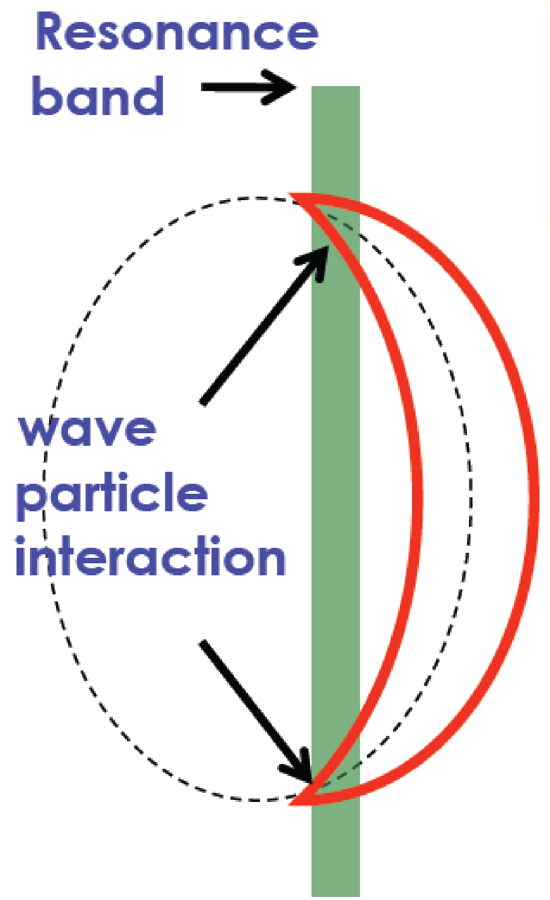
ORBIT-RF/AORSA Simulations Attempt to Resolve the Discrepancies

▪ORBIT-RF code includes the non-zero orbit width effect of fast ions.

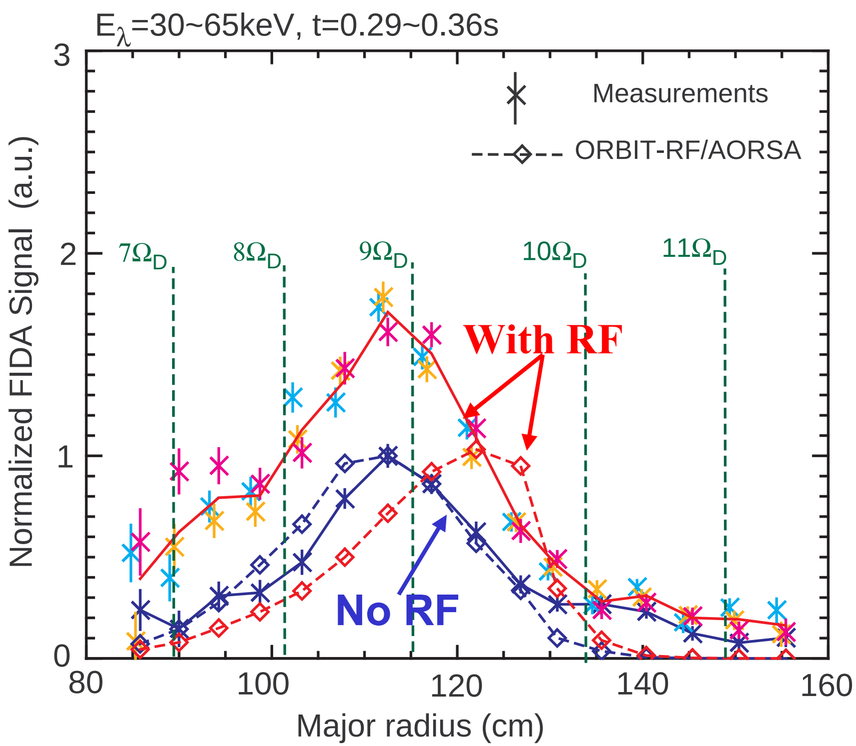
•The resonant interaction between RF wave and fast ions is modeled by stochastic quasi-linear diffusion theory.

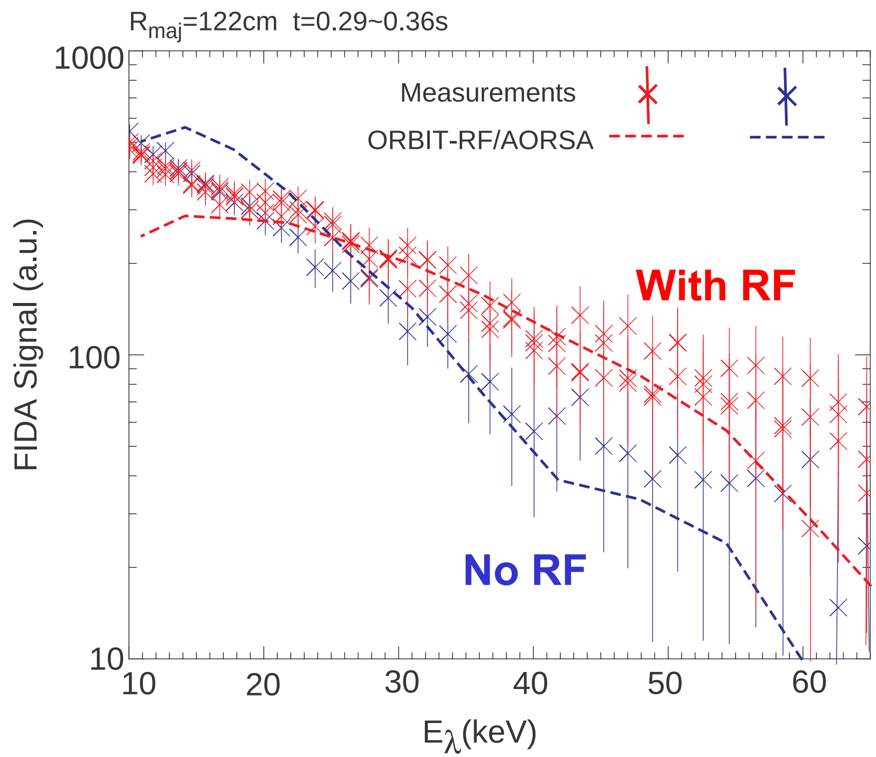
▪ORBIT-RF+AORSA (full wave code) predict fast ion distribution for the calculation of FIDA signals.

*See M. Choi's talk TI3 on Thursday morning in this meeting



Preliminary ORBIT-RF/AORSA Simulations Predict Outward Radial Shift of Fast Ions





- **ORBIT-RF predicts the peak at a larger major radius than observed.**
- **The predicted fast ion tail is similar to the measurements in shape.**
- **The predicted neutron enhancement (1.8) is smaller than the measured neutron enhancement (2.5)**

CQL3D Simulation with First Order Width Correction is in Progress

- **A major inaccuracy in the present zero-orbit width calculation with CQL3D is that while ions hitting the wall are promptly lost (in an approximate manner), leaving few fast ions outside of ~0.3a, clearly there should be fast ions near the plasma edge.**

- **Addition of 1st order orbit effects to CQL3D substantially broadens calculated fast ion profiles giving possible agreement with FIDA measurements.**

Summary and Future Work

➢**Fast ions acceleration due to HHFW heating are observed on all fast ion diagnostics.**

- **The averaged neutron rate is about three times larger**
- **Much longer neutron decay time during HHFW heating→ <Q>~ 0.5-0.7<C>**
- **Fast ion tails above beam injection energy on SSNPA energy spectra; mainly from the passive CX at the edge**
  - **Acceleration for orbits with turning points near central resonance layers.**
- **The NPA diagnostics are not in the correct velocity space (i.e. not perpendicular enough) to observe fast ion acceleration in the active CX signals**
- **Fast ion tail on the FIDA energy spectrum**
- **A very broad absorption profile**
- **FIDA enhancement is stronger at higher energy**

➢**Qualitative agreement between CQL3D simulations and measurements, but there are large quantitative discrepancies.**

- **Effects of finite Larmor radius and banana width my be important for fast ion profiles during HHFW heating in NSTX.**

➢**Comparison with other theoretical predictions (ORBIT-RF and CQL3D with first order orbit width correction) is in progress.**

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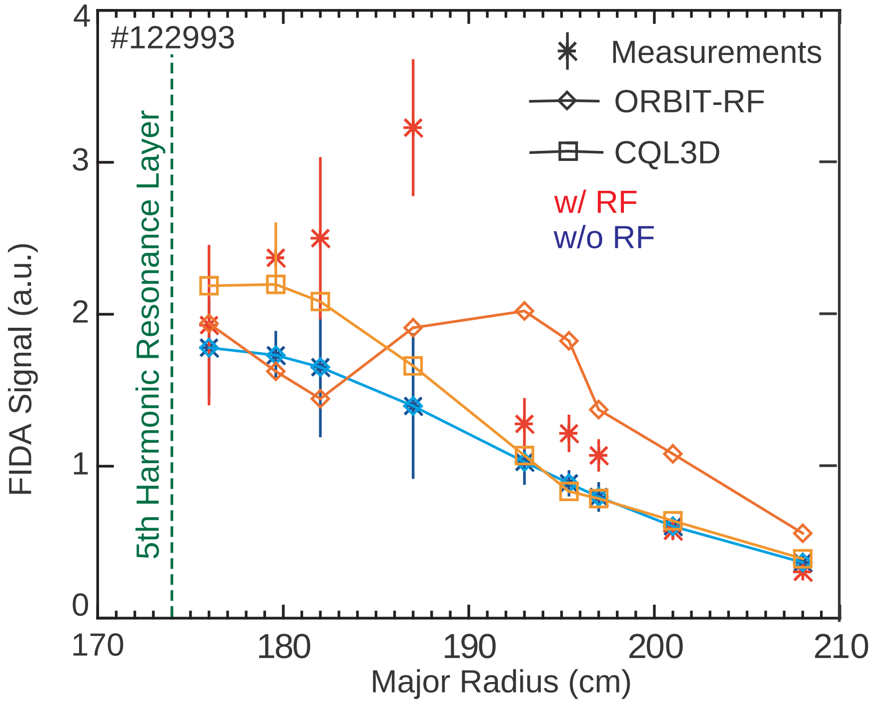
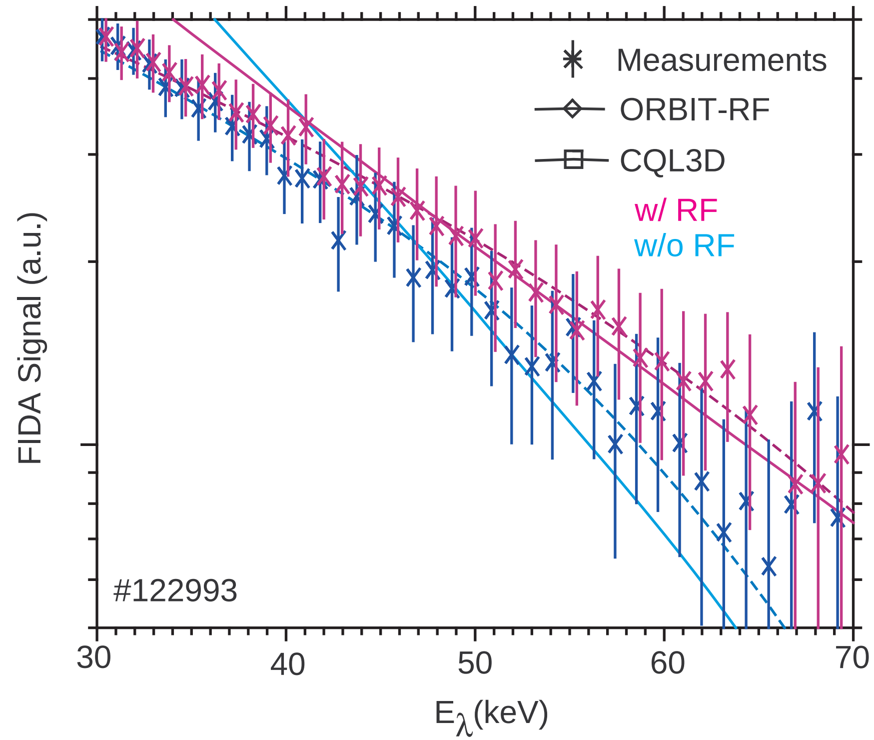
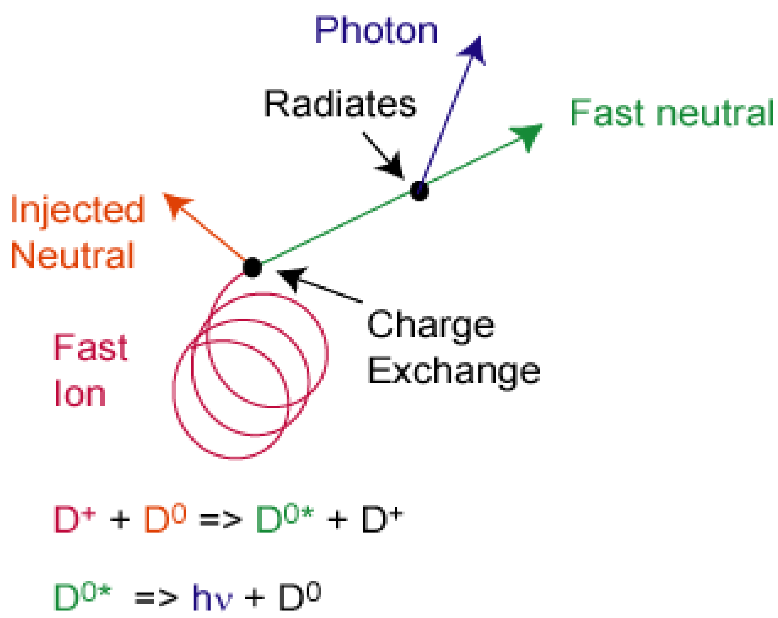
FIDA Comparison in DIII-D ICRF Heating Shows Similar Trend as in NSTX HHFW Heating





- CQL3D predicts the peak at a smaller major radius than observed but ORBIT predicts a larger major radius than observed
- Both CQL3D and ORBIT-RF predict a fast ion tail that is approximately the right size.

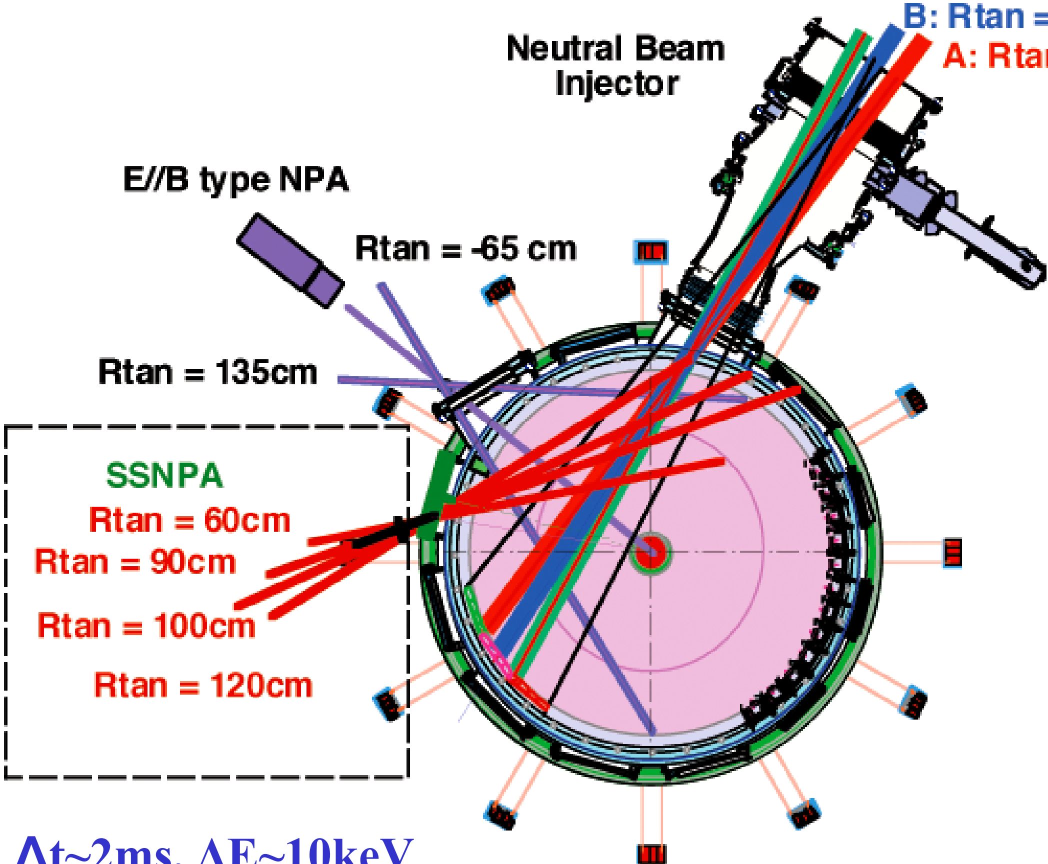
Fast-ion D_α (FIDA) Diagnostic Based on Active Charge-Exchange Recombination Spectroscopy



- ➢**Fast ion population created by neutral beam injection**
- ➢**FIDA exploits large wavelength Doppler shift of photons emitted by re-neutralizing fast ions**
- ▪**Use vertical view to avoid bright interferences**
- ▪**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)

Four NPA Sightlines Intersect the Heating Neutral beams; One Sightline Misses the Neutral Beams



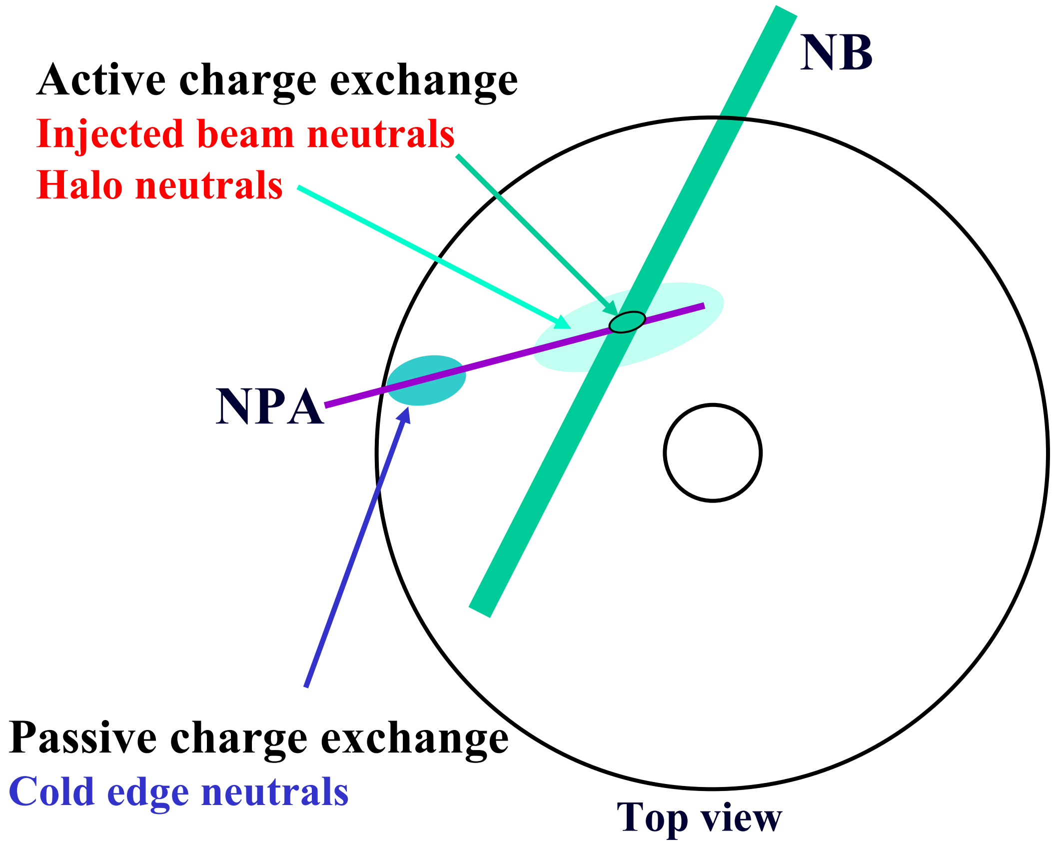
- $D^0 + D^+ \rightarrow D^+ + D^0$
- **E||B type NPA**
  reionize the charge exchange neutrals in the stripping cell, distinguish the particle mass and energy through a parallel electric and magnetic field.
- **SSNPA**
  utilize a silicon photodiode to measure the neural particle energy directly, noise mainly comes from neutron/gamma ray radiation and pulse pile-up

Δt~2ms, ΔE~10keV
Energy range (35~100keV)

*E||B type NPA diagnostic See S. S. Medley et al., Rev. Sci. Instrum 75, 3625 (2004)

*SSNPA diagnostic See K. Shinohara el al . Rev. Sci. Instrum. 75, 3640 (2004), D. Liu et al. Rev. Sci. Instrum. 77, 10F113 (2006)

NPA Diagnostics Measure Fast Ions that Charge Exchange with Three Kinds of Neutrals



NPA signal is mainly from active charge exchange reactions for the sightlines that intersect with the injected neutral beams.

➢**NPA signal is from passive charge exchange reactions for sightlines that miss the neutral beams or during beam off period.**