NSTX DIII-D NATIONAL FUSION FACILITY SAN DIEGO UCIRVINE COMPX

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Use of Fast-Ion D-Alpha diagnostics for understanding ICRF effects

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18th Topical Conference on Radio Frequency Power in Plasmas
June 23-26, 2009 Gent - Belgium

Ion-cyclotron waves are a promising tool for non-inductive heating and current drive

- Future fusion devices (ITER) will need additional heating from rf waves and neutral beams (NB)
- Physics of ion-cyclotron resonant frequency (ICRF) waves widely studied, including ICRF harmonics
  - Heating, current drive (CD), q-profile control
- Spurious absorption on *fast* (supra-thermal) ions can occur during simultaneous rf and NB injection
  - Decrease in heating, CD efficiency
- **How does fast ion distribution interact with ICRF?**

Approach: measurements & modeling

Outline

- Experimental setup and diagnostics
  - Fast-Ion D-Alpha (FIDA) spectroscopy
  - The NSTX and DIII-D tokamaks
- Experimental results in NSTX and DIII-D
  - Spectral features and spatial profile modifications
- Comparison with codes: discussion
- Summary and conclusions

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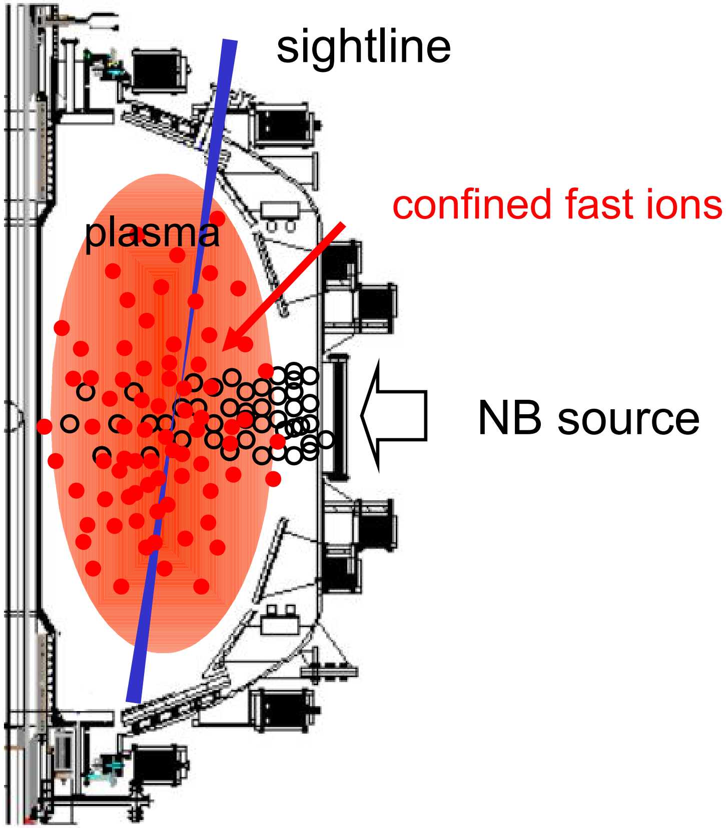
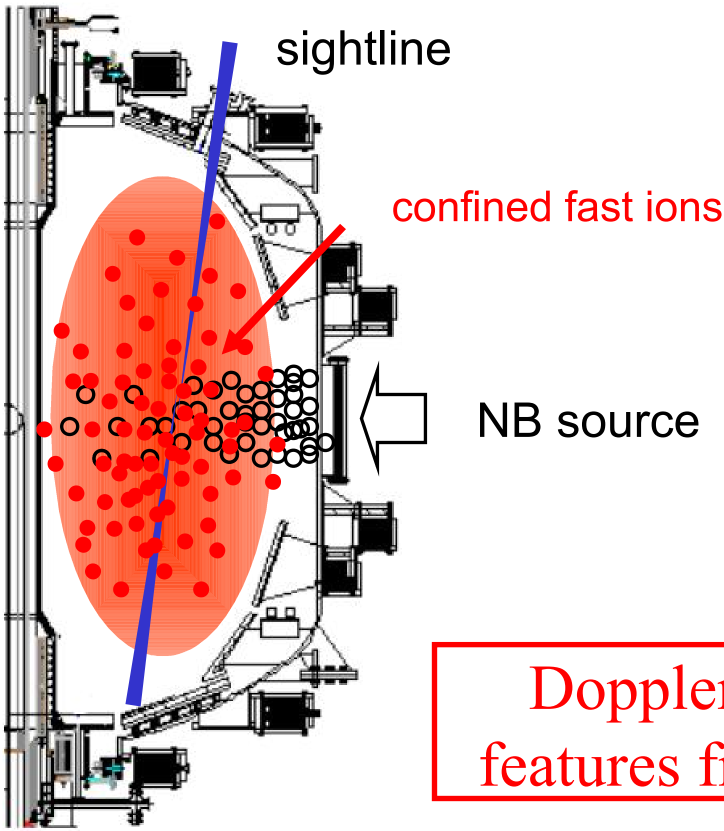
FIDA technique based on active charge-exchange recombination spectroscopy

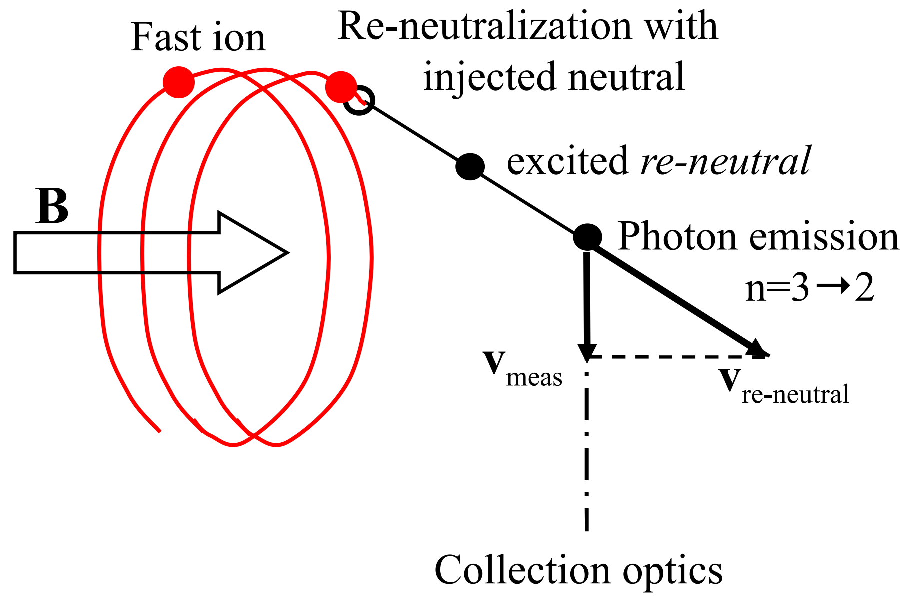
- Fast ion population created by Neutral Beam injection



FIDA technique based on active charge-exchange recombination spectroscopy

- Fast ion population created by Neutral Beam injection
- FIDA exploits wavelength Doppler shift from cold D-alpha line of photons emitted by re-neutralizing fast ions





Doppler shift allows to distinguish fast ion features from dominant cold D-alpha emission

Post, JFE **1** (1981) McKee, RSI **66** (1995) Heidbrink, PPCF **46** (2004) Podesta', RSI **78** (2008)

Fast ion signal results from convolution in energy, pitch of fast ion distribution and response function

- **Measured fast ion signal**:

  $$s(\lambda) = \iint F * W \, d(v_{||}/v) \, dE$$

  $F(v_{||}/v,E)$: fast-ion distribution

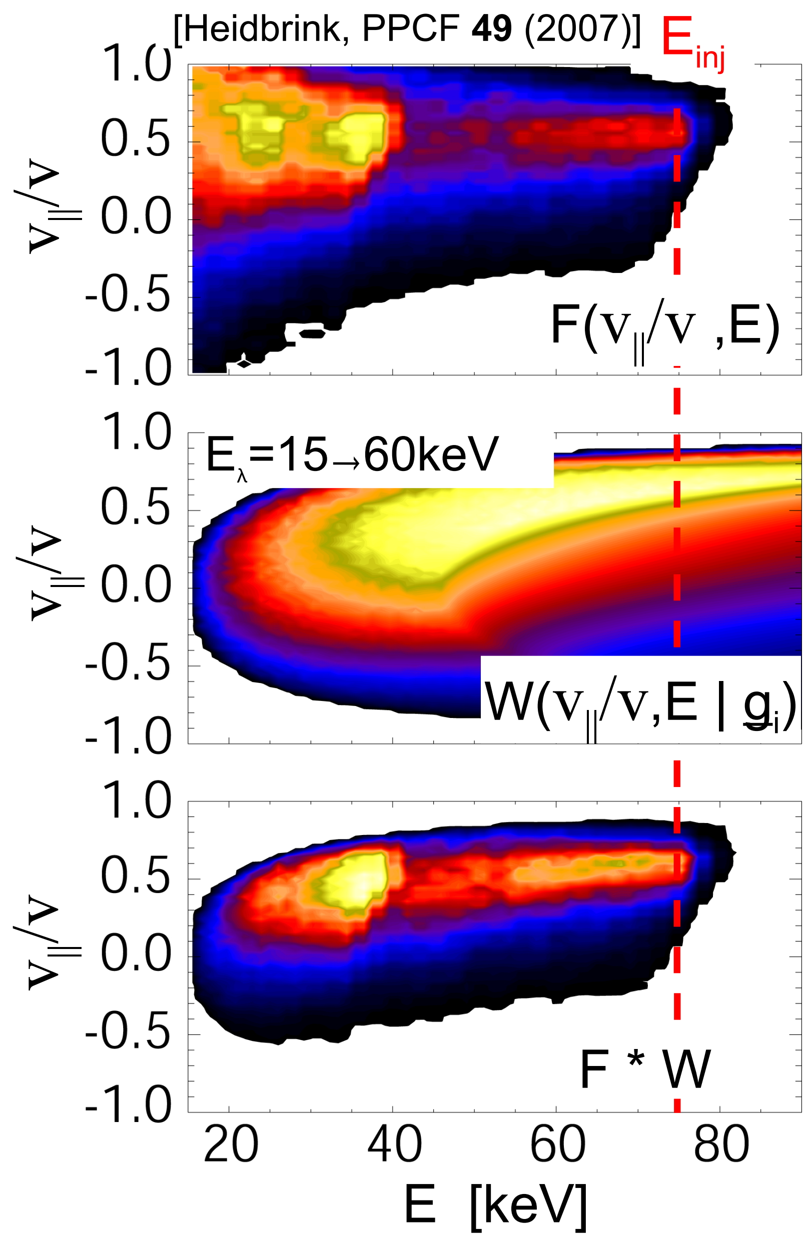
  $W(v_{||}/v,E \mid \underline{g}_i)$: weight function

  $v_{||}/v$: pitch, E : energy, $\underline{g}_i$: geometry & NB

  λ : wavelength from Doppler shift formula

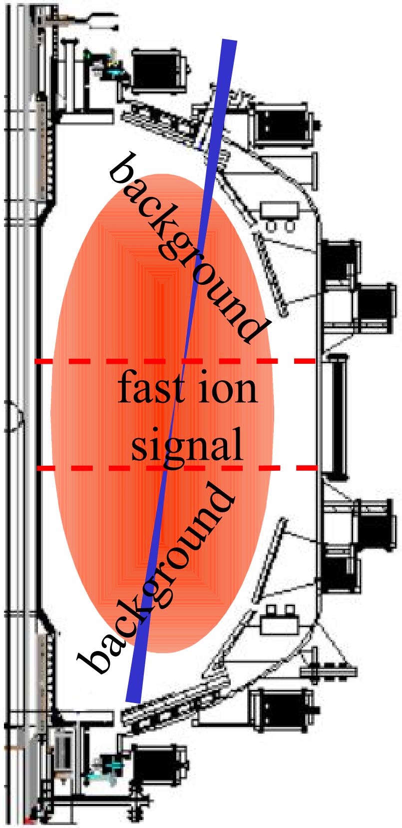
  $E_\lambda=E(\lambda)$: "measured" energy

- **FIDA density,** N_f ($\propto$fast-ion density) obtained by integrating spectrum over energy E_λ and taking into account local neutral density in W
- **Vertical views:** signal weighted toward perpendicular velocities
- **$s_{tot}=s(\lambda) + B(\lambda)$: Background** $B(\lambda)$ is main source of experimental error



Measured signal = fast ion signal + background, but… background > fast ion signal

- Main contributions to background:
  - Bremsstrahlung, impurity emission
  - Light from divertor & plasma facing components
  - Scattered light

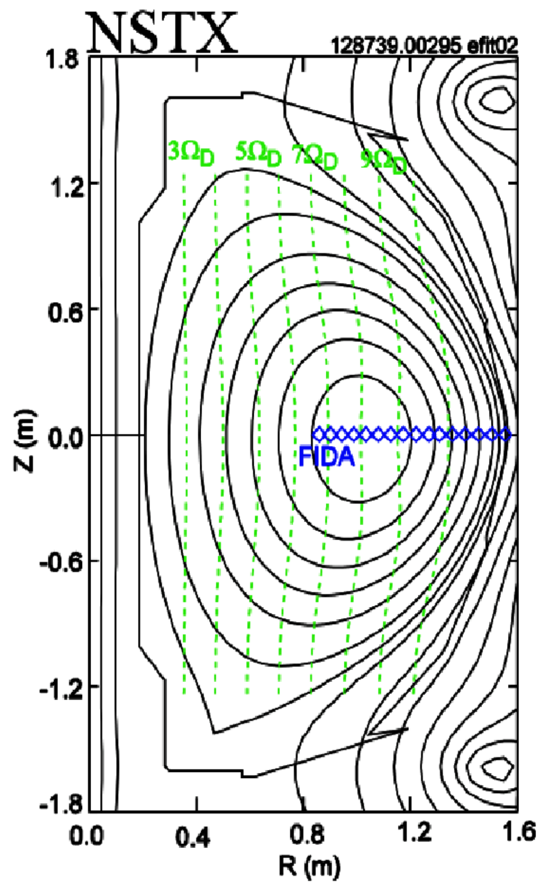


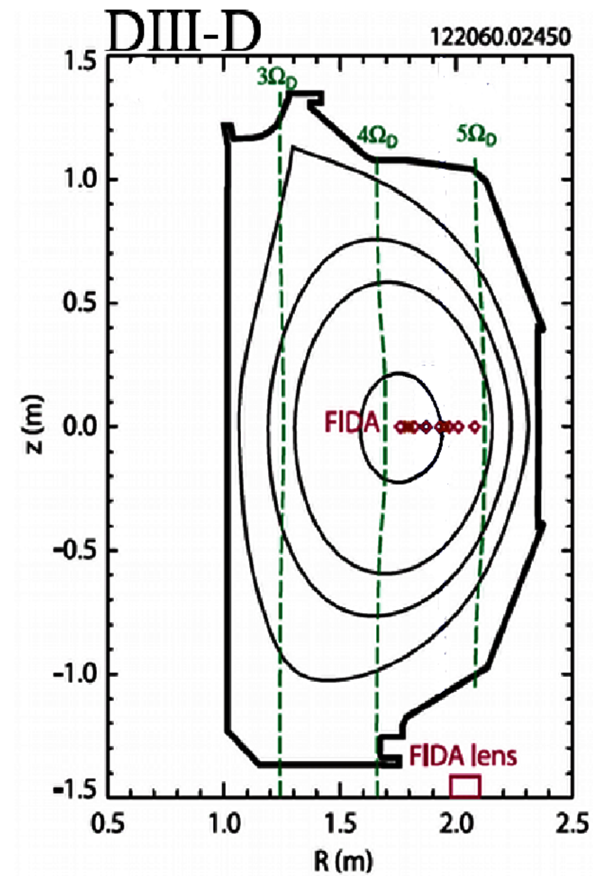
- Two techniques can be used to measure background contribution:
  - ON/OFF modulation of Neutral Beam (DIII-D, NSTX)
    - ✓ Same views for active/background measurements
    - ✗ Temporal resolution reduced; specific NB waveform required
  - *Passive* views, toroidally displaced, missing the neutral beam for background measurement (NSTX)
    - ✓ Temporal resolution not affected
    - ✗ Number of views doubles; toroidal symmetry required

[W.W. Heidbrink, PPCF **46** (2004)] [M. Podesta', RSI **78** (2008)]

NSTX and DIII-D tokamaks
Main parameters for the study presented here

	NSTX	DIII-D
R_0, a [m]	0.8, 0.65	1.7, 0.6
Aspect ratio	~1.3	~3
B_0 [T]	0.55	1.5-1.9
n_0 [10^{19} m^{-3}]	3	2
$T_{e,0}$ [keV]	1	3
ρ_f [cm]	<20	~2
P_{NB} [MW]	1	1
P_{rf} [MW]	~1	~1
f_{rf} [MHz]	30	60
$k_{//}$ [m^{-1}]	7	5





Different regimes for HHFW physics can be explored:

- Large *vs.* small fast ion Larmor radius ⇨ $k_\perp \rho_f$ effects
- Single *vs.* multiple resonances ⇨ absorption profile

Comparison between experiments and rf code CQL3D : approach

- CQL3D calculates fast ion distribution, F_f, resulting from HHFW absorption by fast ions [www.compxco.com/cql3d.html]
  - Bounce-averaged, Fokker-Planck, zero-banana width
- F_f used as input of a FIDA simulation code
  - "Experimental" signal reconstructed for real geometry, NB parameters, plasma profiles (TRANSP), ...
- Simulations validated for no-rf, MHD quiescent discharges
  - "Classical" fast ion dynamics expected
- TRANSP code w/o fast ion acceleration by ICRF used to distinguish between "profile" and "rf" effects during HHFW injection

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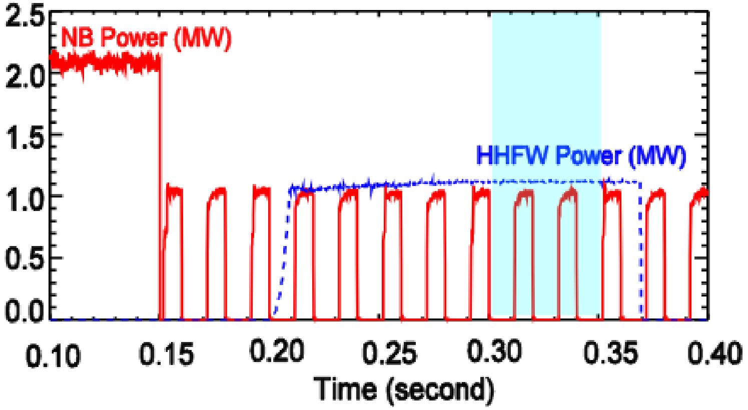
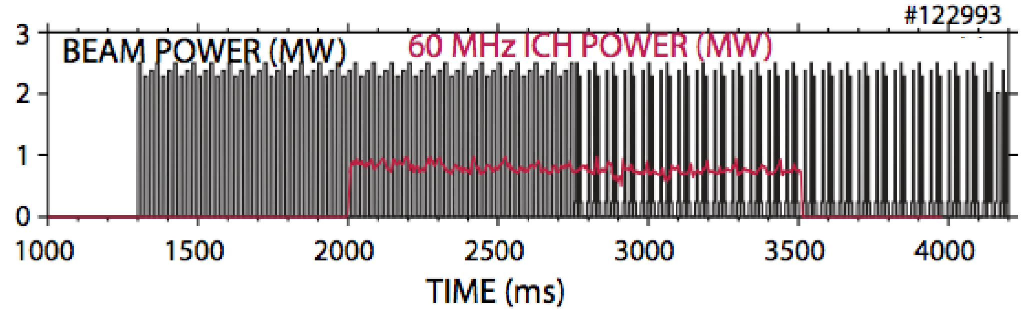
Experimental scenario: NB injection + HHFW heating

NSTX



DIII-D



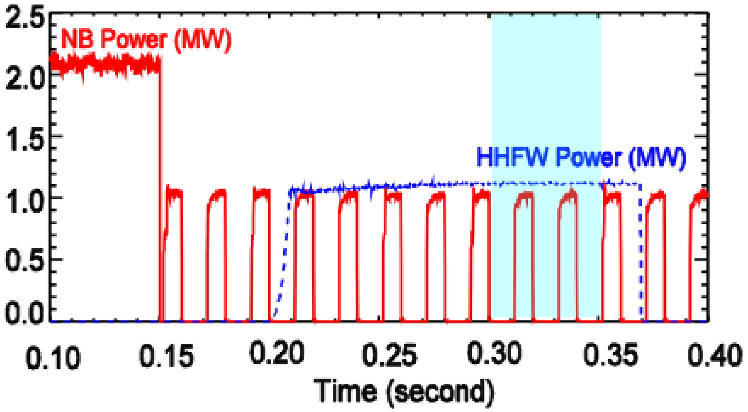
- P_{NB}=1MW, injection energy 65keV (NSTX), ~80keV (DIII-D)
- P_{rf}=0.7-1.1MW
- NB modulation, 50% duty-cycle for FIDA background
- No strong MHD affecting fast ion dynamics

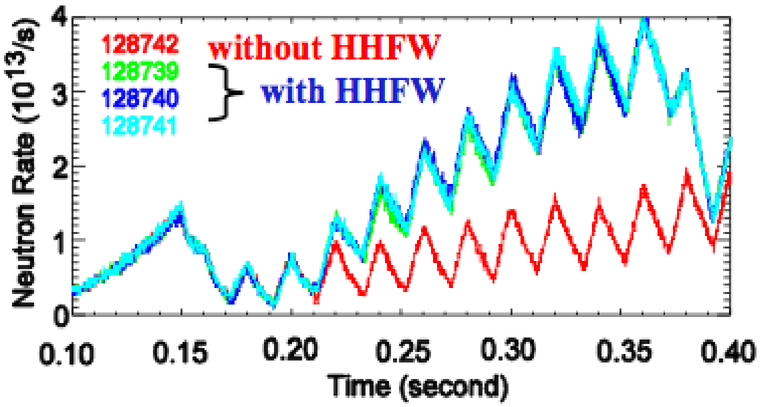
Main References for this work:

[D. Liu *et al.*, PPCF 2009 (submitted)] [W.W. Heidbrink *et al.*, PPCF **49** 2007]

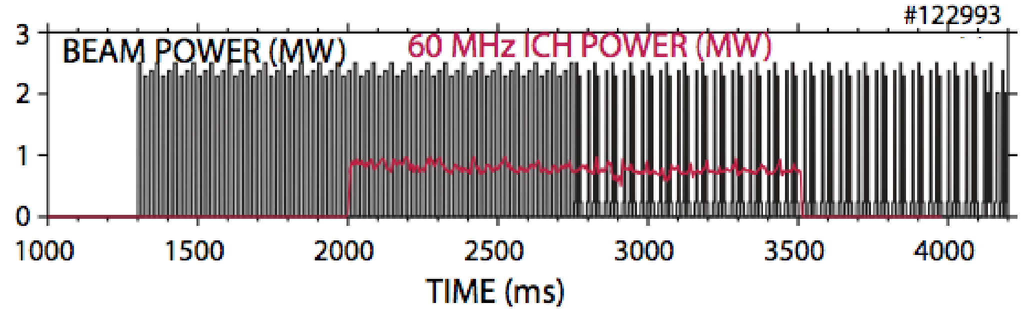
Enhancement x 2-3 in neutron rate during HHFW suggests acceleration of beam ions to high energy

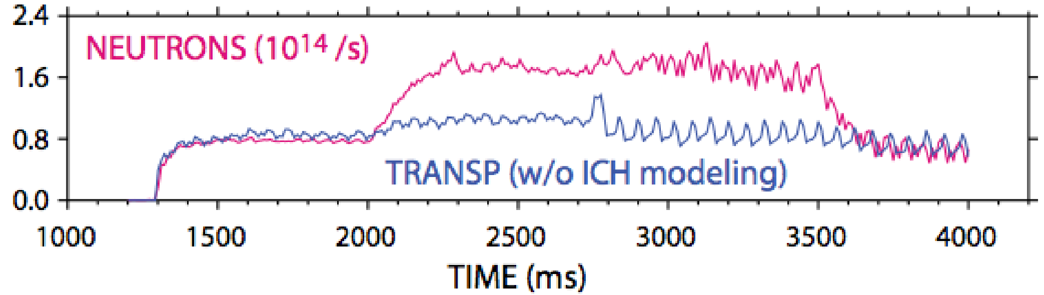
NSTX





DIII-D

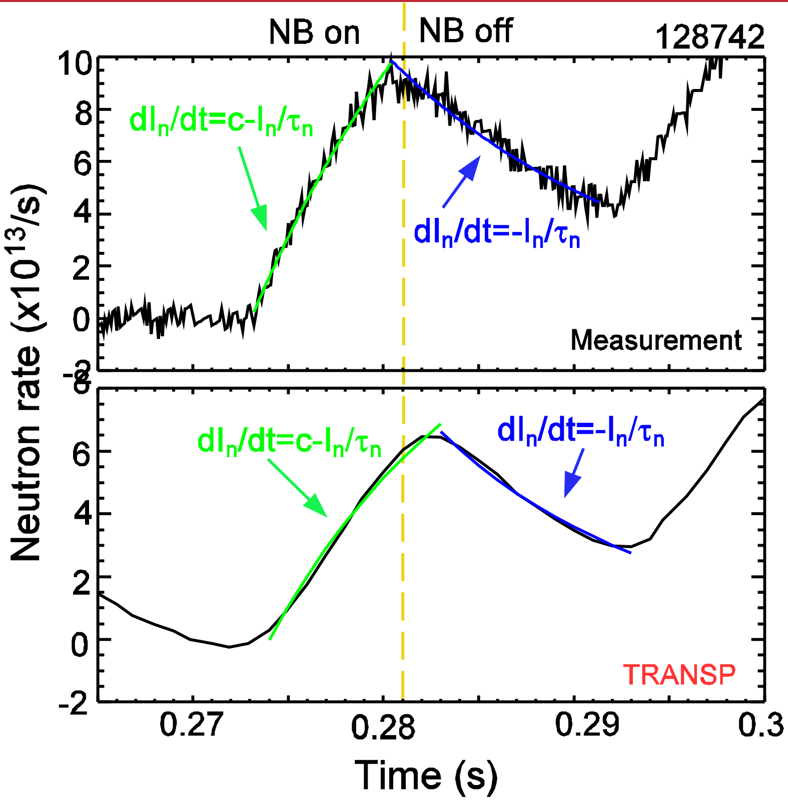


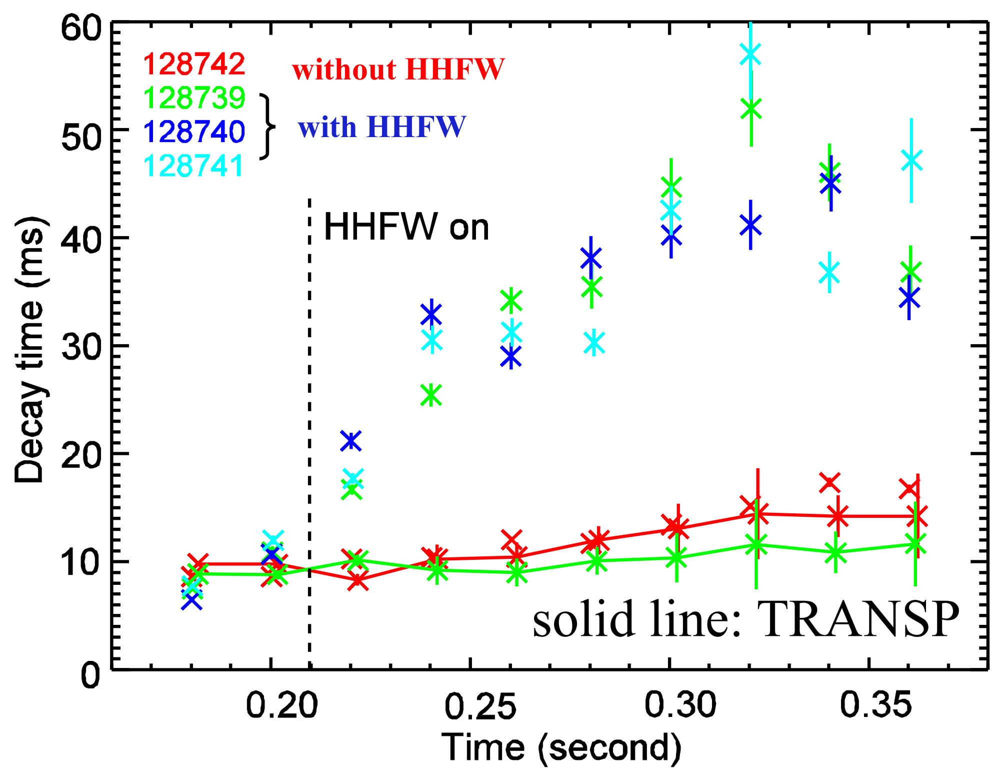


Slight neutron increase from TRANSP without ICRF modeling

"plasma profile" effects do not dominate

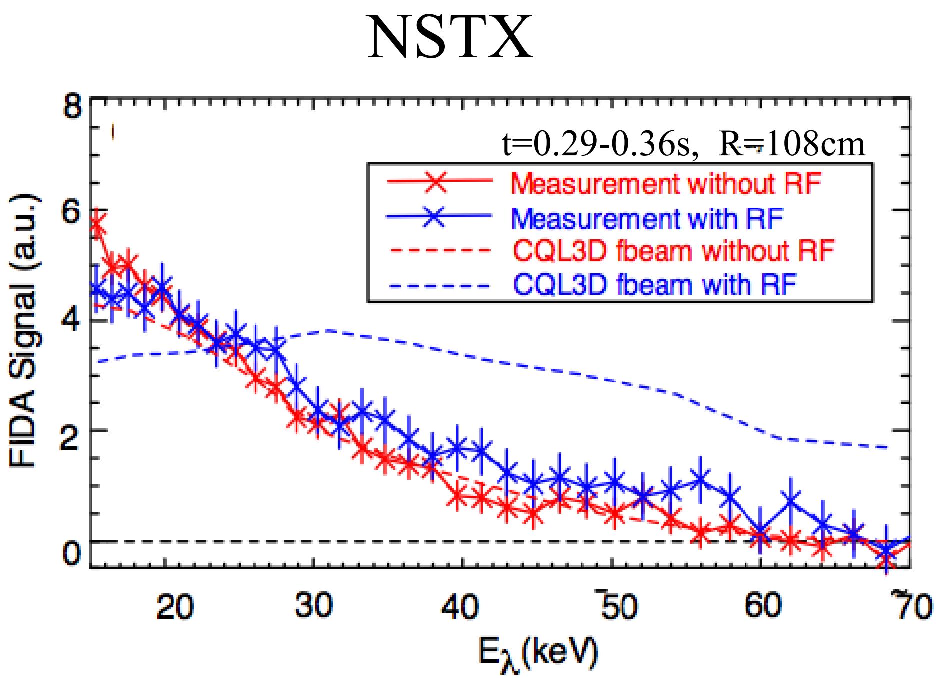
Enhanced high-energy population leads to 3x larger neutron decay time during HHFW (NSTX)

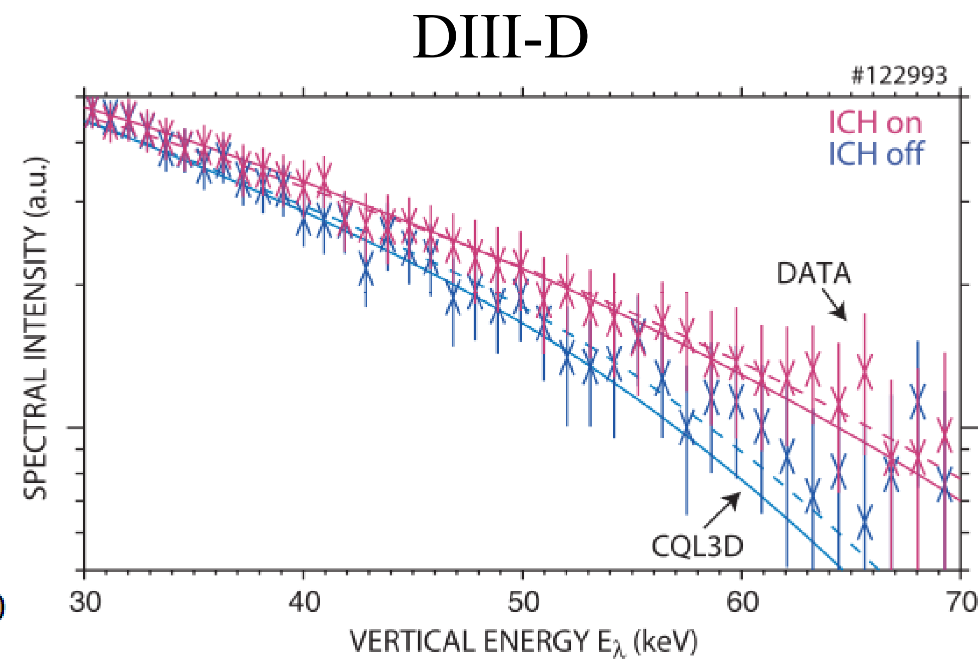




- Rise/decay rates from simple model [W.W. Heidbrink, NF **43** (2003)]
- Larger decay time: rf acceleration counteracts Coulomb deceleration
- No difference seen in rise time (NB ramp-up rate dominates)

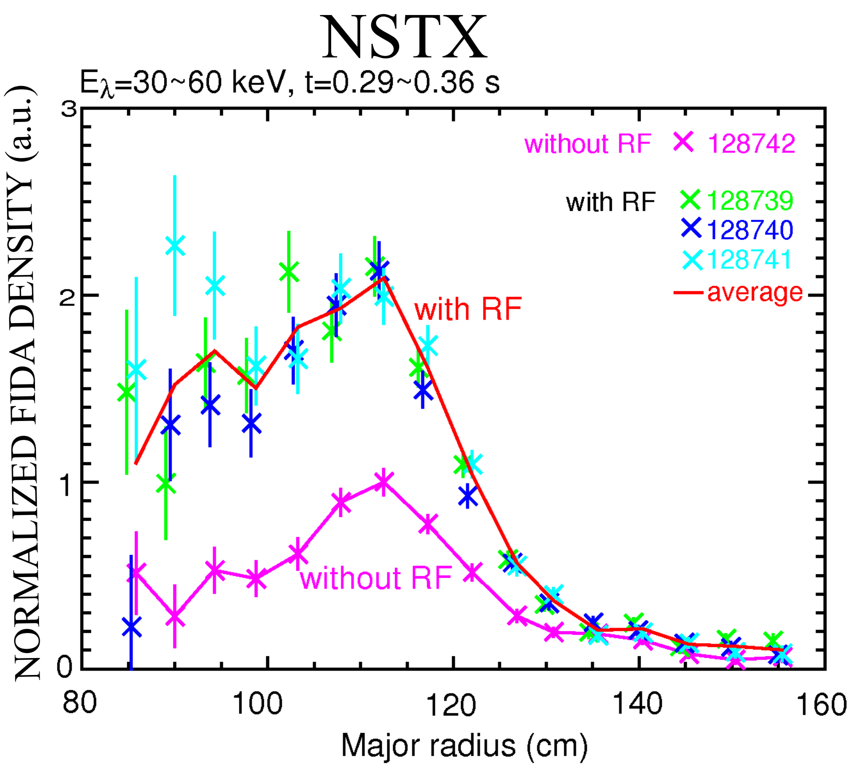
FIDA spectra exhibit enhanced high-energy tails during HHFW injection

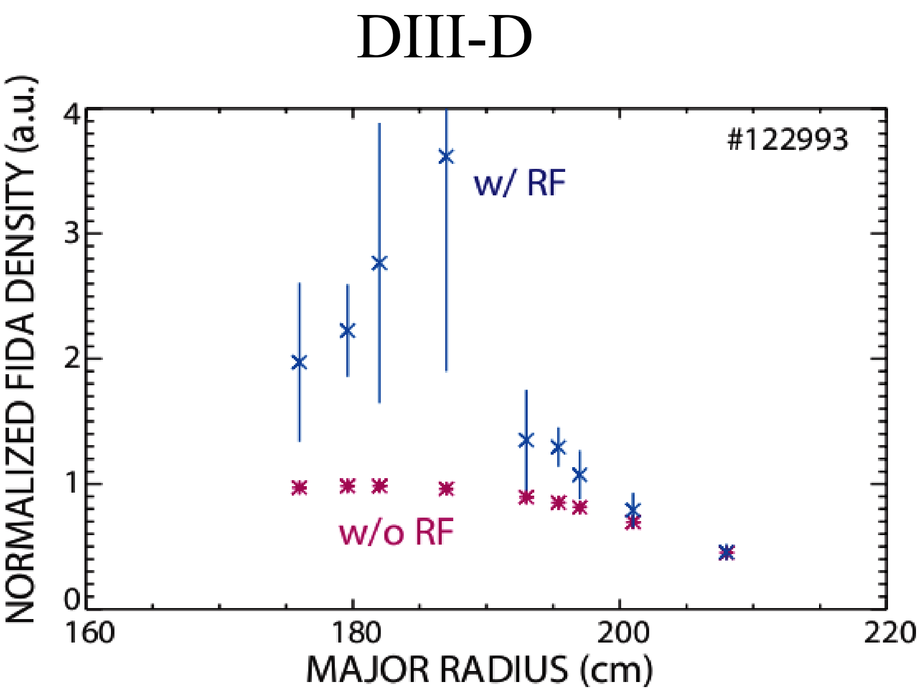




- FIDA signals are weighted toward perpendicular energy
- Higher count rate over broad energy range
- CQL3D predictions and spectral shape
  - NSTX: ✔ no-rf case ✘ rf case (normalized)
  - DIII-D: ✔ no-rf case ✔ rf case

Fast ion profile is modified during HHFW, with clear differences between NSTX and DIII-D

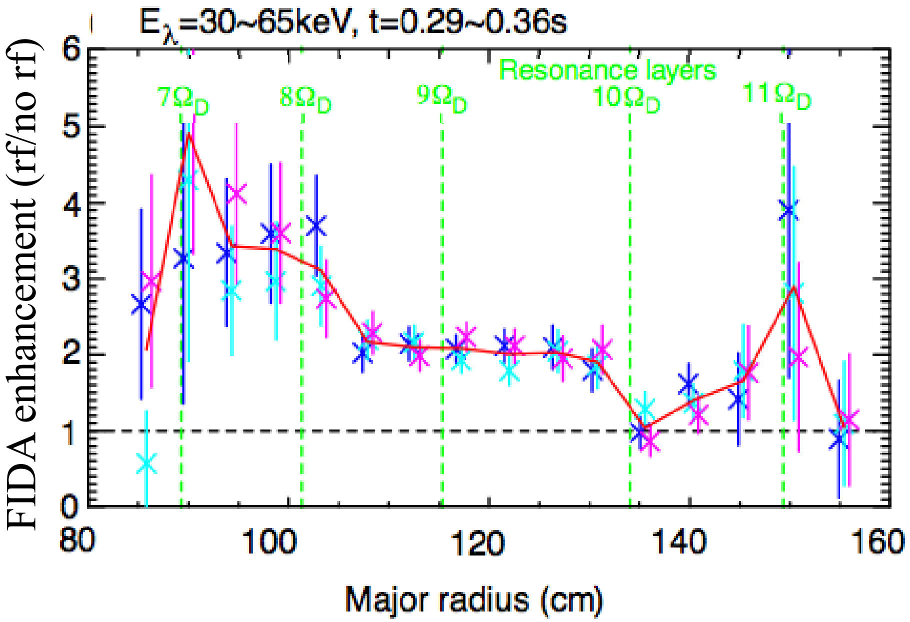




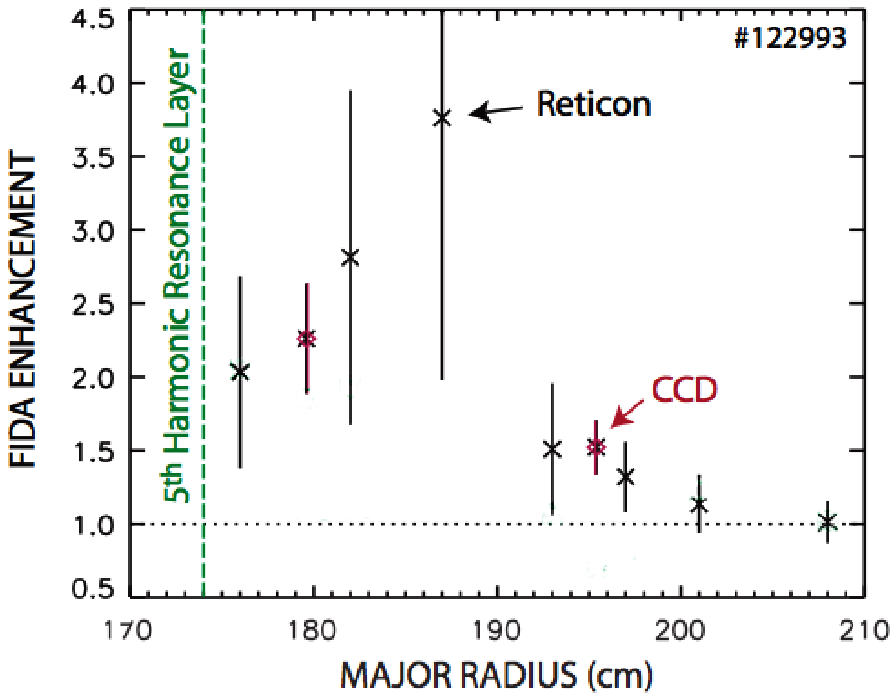
- NSTX: profile broadens over most of minor radius
  - Central region (R=80-120 cm) shows more pronounced effects
- DIII-D: narrower, more peaked profile
  - Narrower region (around R=185 cm) is affected by HHFW

Relative enhancement indicates a much broader absorption profile in NSTX than in DIII-D

NSTX



DIII-D



- Increase by factor ~2 (average) in FIDA profile
- Profile peaking is shifted ~10cm from resonance (DIII-D)
- Multiple resonances in NSTX lead to HHFW absorption over entire minor radius

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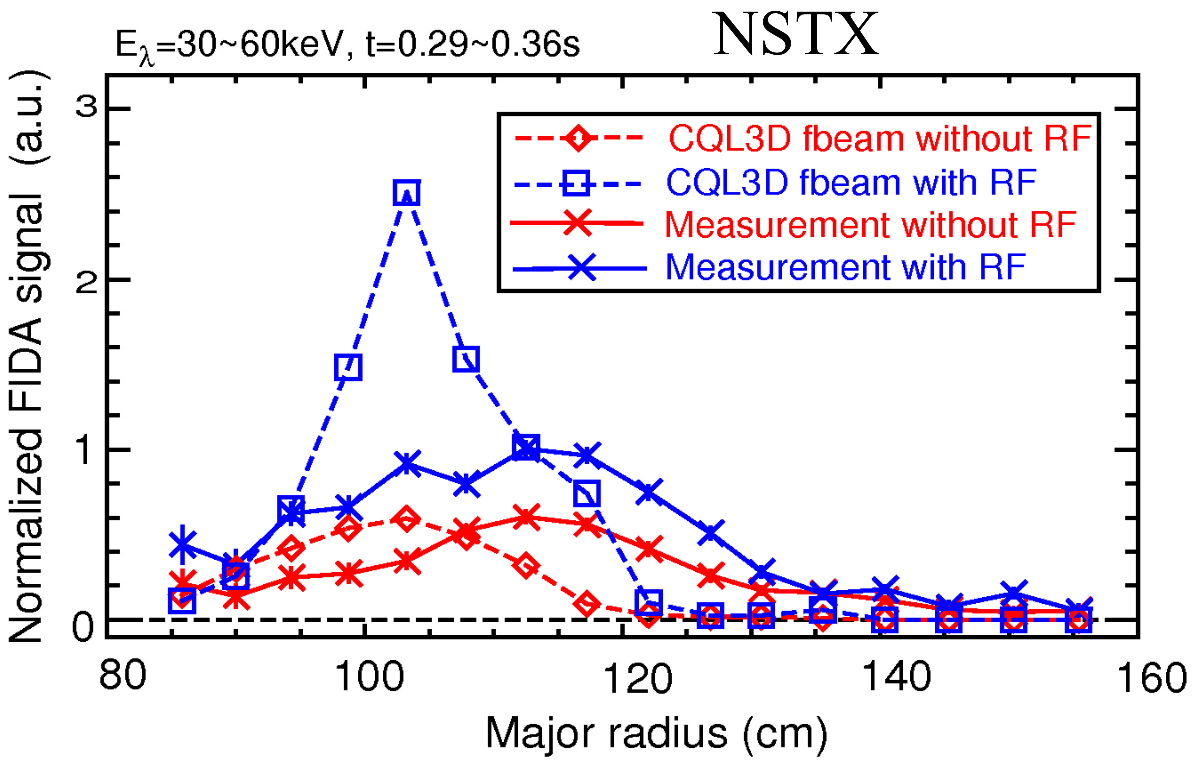
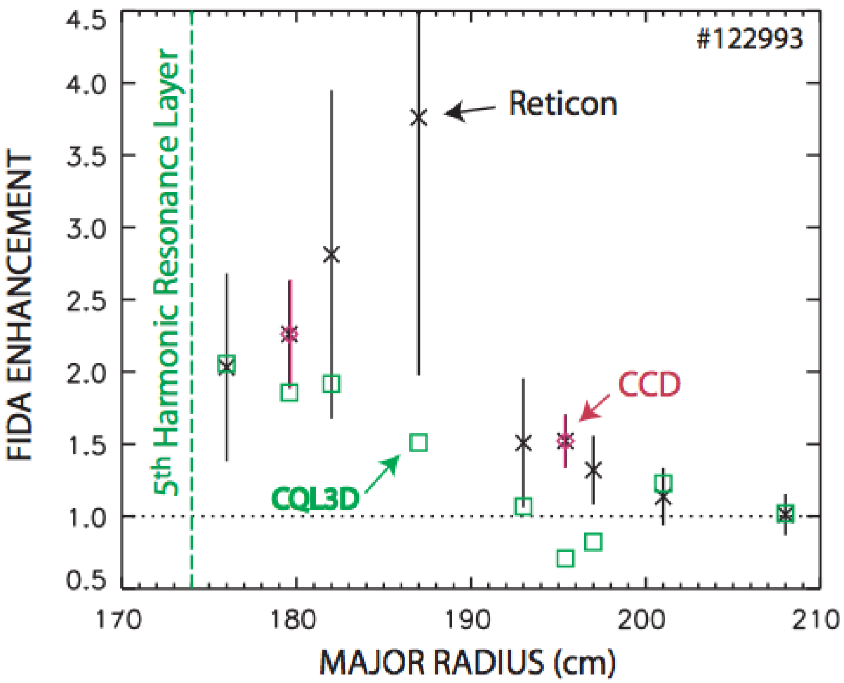
Discrepancy between experiments and codes suggests that some fundamental physics is missing



- Poor agreement for no-rf case, worse for rf-case
- CQL3D simulated profile is narrower, more peaked than in experiments for rf case
- Peak at wrong position for both rf and no-rf case

Effects of multiple *vs.* single resonances not sufficient to explain the discrepancies

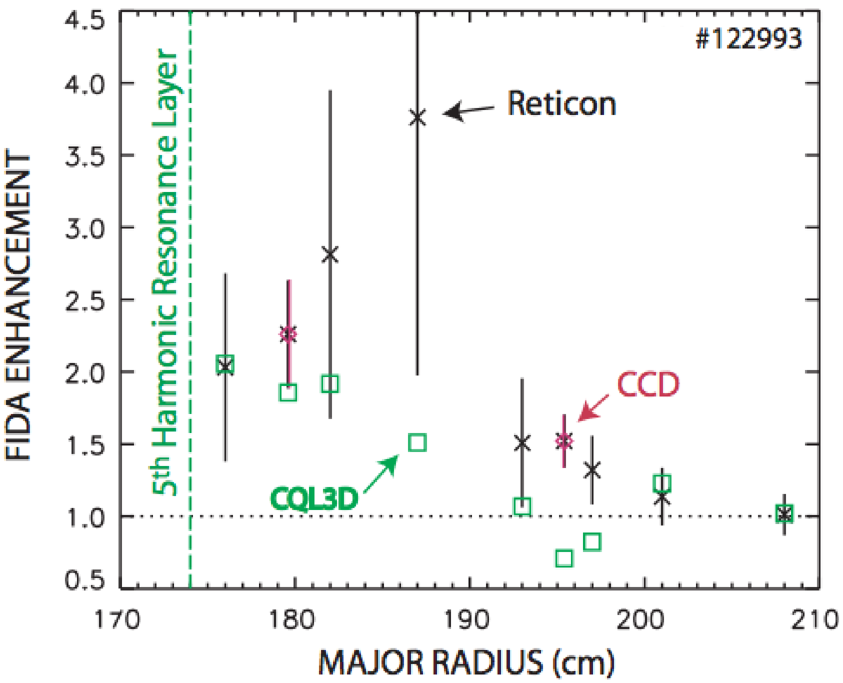
DIII-D



- Simulation works for P_{rf}=0
- Simulated profile peaks at wrong position during rf
- CQL3D predicts smaller enhancement

Analysis of DIII-D case reveals that finite banana width may play a major role to explain discrepancy

DIII-D



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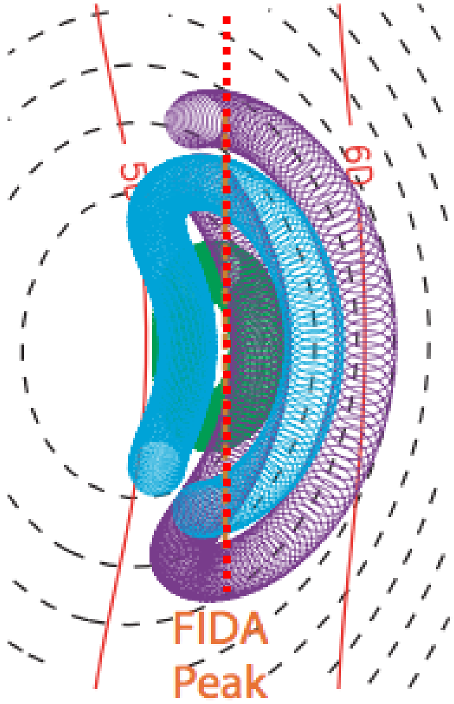
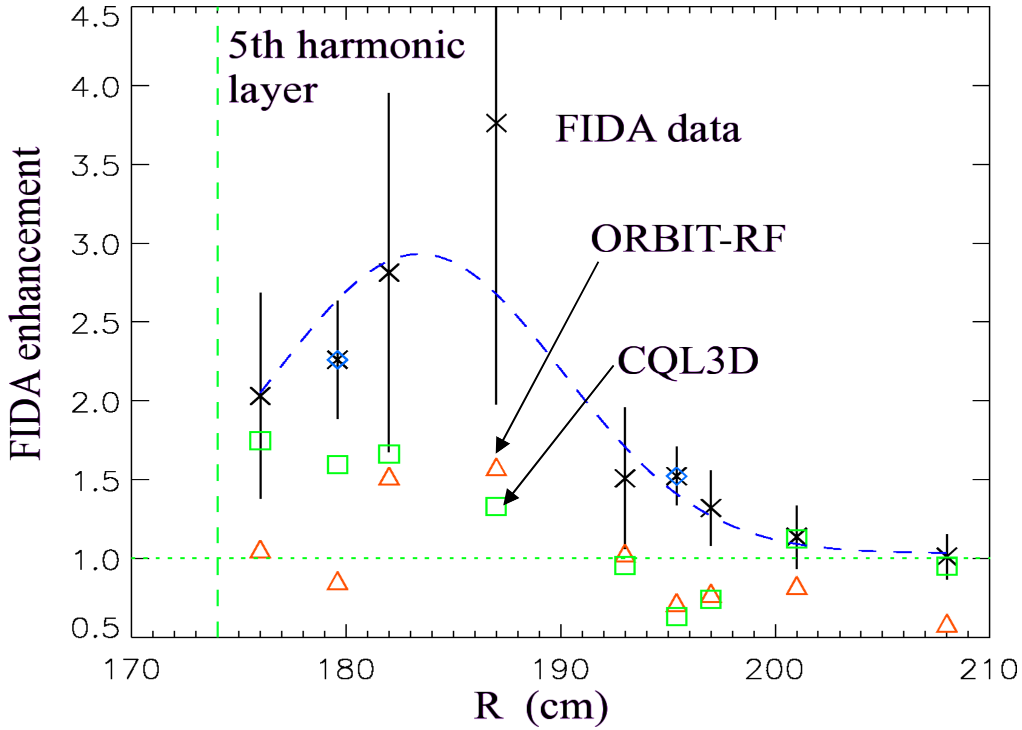


- CQL3D assumes zero-banana width
- Banana orbits likely responsible for observed outward shift
- Effect more evident on DIII-D

Preliminary results with full-orbit code ORBIT-RF show better agreement with experimental data



- ORBIT-RF: finite banana width effects included
- Correct position of peak recovered
- Quantitative disagreement likely due to input fast ion distribution

[M. Choi, PoP **16** (2009)]

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Summary and Conclusions

- FIDA spectroscopy is a powerful tool for understanding ICRF effects in magnetically confined plasmas
  - FIDA can provide time, space and energy resolved measurements of confined fast ion population
- Fast ion acceleration by HHFW during NB injection successfully characterized on NSTX and DIII-D tokamaks:
  - High-energy tails observed in fast ion spectra
  - Modification of fast ion profile
  - Synergetic effect of multiple resonances (NSTX) *vs.* single resonance (DIII-D): broader absorption profile
- Modeling can account for most of the observed features
  - Need correct treatment of fast ion orbits: finite-banana width
  - Future work: extend ORBIT-RF simulation to NSTX

[D. Liu *et al.*, PPCF 2009 (submitted)]   [W.W. Heidbrink *et al.*, PPCF **49** 2007]

Work supported by the US DOE under SC-G903402, DE-FC02-04ER54698, DE-AC02-76CH03073, DE-FG03-99ER54541