Finite Orbit Monte-Carlo Simulation of ICRF Heating Scenarios In DIII-D, NSTX, KSTAR And ITER

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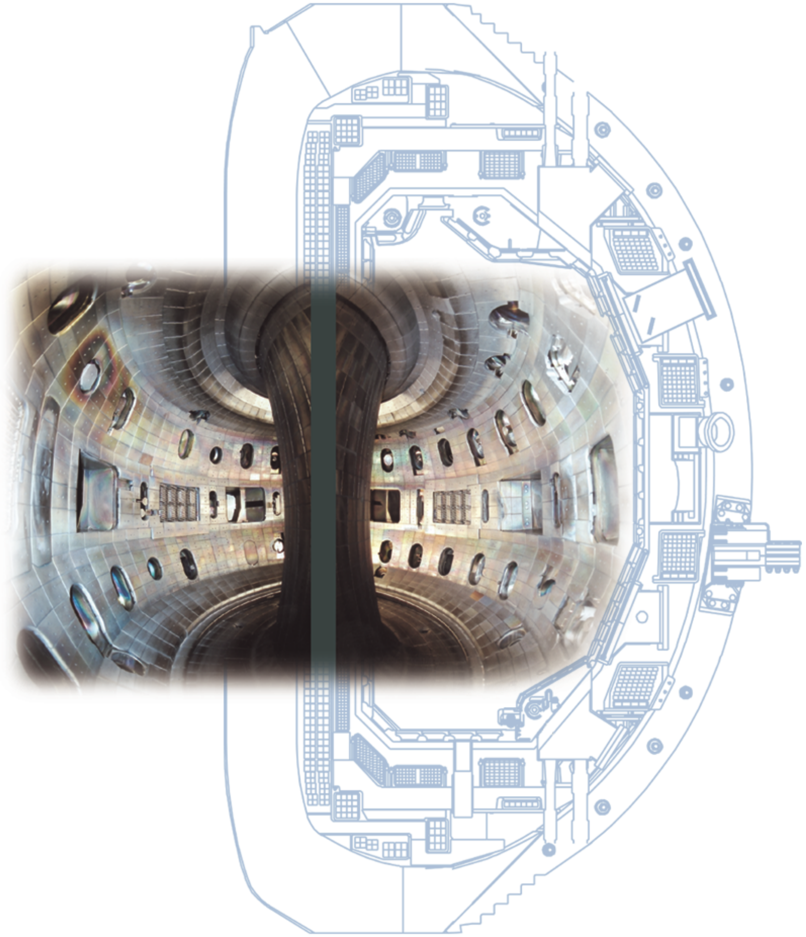

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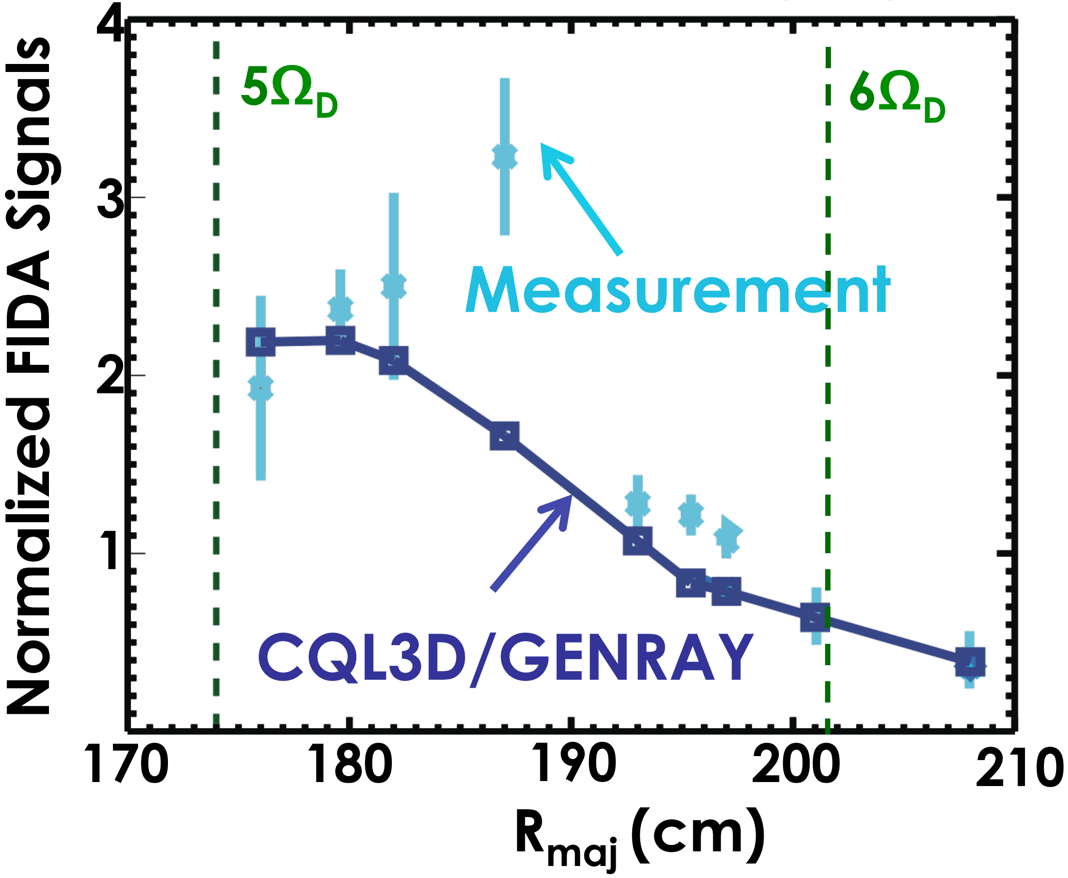
Outline

- With no ICRH, simulation reproduces spectra and spatial profile of measured FIDA signals (NSTX)
- With ICRH, simulation reproduces spectra with slightly enhanced outward radial shifts (NSTX)
- Qualitative agreements are obtained in spectra and spatial profile with ICRH (DIII-D)
- Finite orbit effect may significantly modify fast ion distribution in ITER and KSTAR, depending on applied ICRF power density

Zero-Orbit Simulation Does Not Reproduce Outward Shifts of Measured FIDA Signals In DIII-D

DIII-D ICRF discharge #122993

W.W. Heidbrink PPCF **49** (2007)



- **Qualitative agreements in spectra of FIDA signals and neutron enhancement**
- **Similar discrepancy in NSTX HHFW discharges**
(D. Liu, PPCF **52** (2010))

Fast Ions Move Across Magnetic Flux Surfaces Due to Non-Zero Drift Orbit Width

R. White, The Theory of Toroidally Confined Plasmas

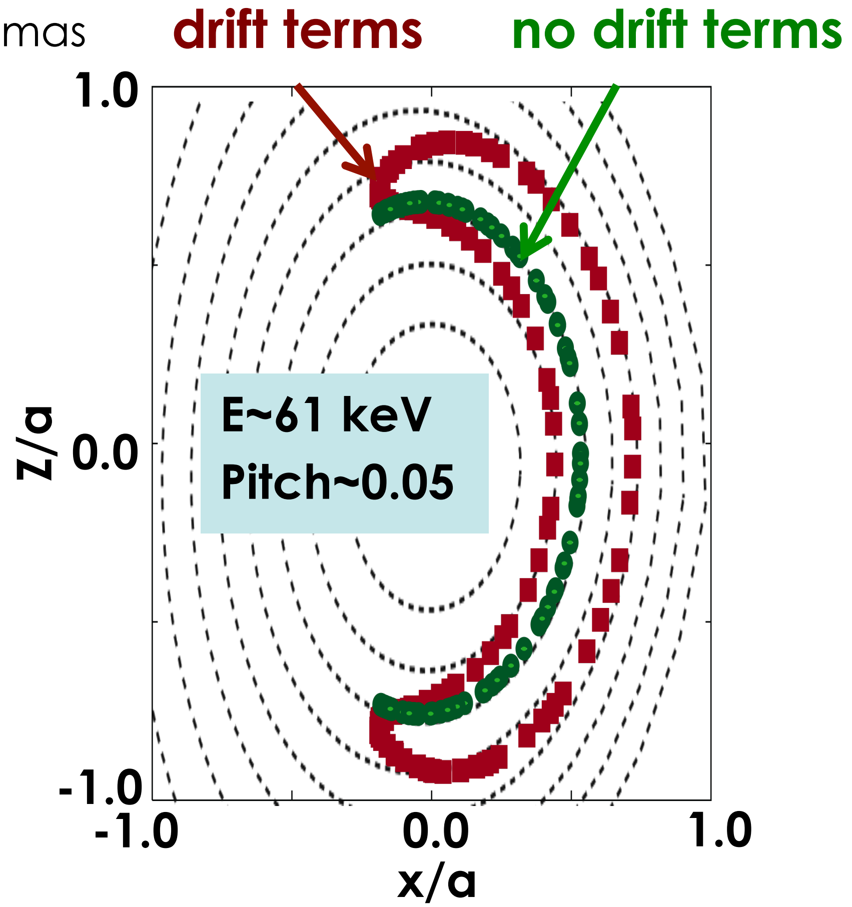
$$\dot{\zeta} = \frac{\rho_{/\!/} B^2}{D}\left(q + \rho_{/\!/} I\right) - \left(\mu + \rho_{/\!/}^2 B\right)\frac{I}{D}\frac{\partial B}{\partial \psi_p}$$

$$\dot{\rho}_{/\!/} = -\frac{\left(1-\rho_{/\!/} g\right)\left(\mu+\rho_{/\!/}^2 B\right)}{D}\frac{\partial B}{\partial \theta} - \frac{\left(q+\rho_{/\!/} I\right)\left(\mu+\rho_{/\!/}^2 B\right)}{D}\frac{\partial B}{\partial \zeta}$$

$$\dot{\theta} = \frac{\rho_{/\!/} B^2}{D}\left(1-\rho_{/\!/} g\right) + \left(\mu+\rho_{/\!/}^2 B\right)\frac{q}{D}\frac{\partial B}{\partial \psi_p}$$

$$\dot{\psi}_p = -\frac{g}{D}\left(\mu+\rho_{/\!/}^2 B\right)\frac{\partial B}{\partial \theta} + \frac{I}{D}\left(\mu+\rho_{/\!/}^2 B\right)\frac{\partial B}{\partial \zeta}$$

🟩 : Drift orbit terms



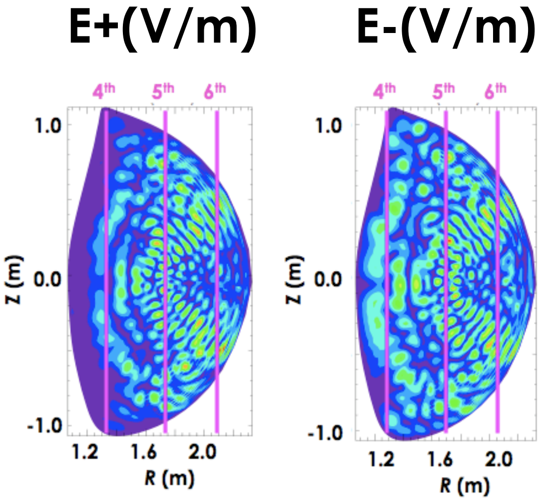
Can non-zero drift orbit resolve this discrepancy ?

For This Purpose, ORBIT-RF Is Coupled With AORSA In A Self-Consistent Way (RF SciDAC)

2-D linear full wave solver

E. F. Jaeger
POP 9
(2002)

AORSA


E+(V/m) E-(V/m)

DIII-D #122993

60 MHz
P_{RF}=1MW
N_{φ}=13

ORBIT-RF

5-D Monte-Carlo fast ion distribution solver

particle distribution

P2f

ICRF and Collision Models Implemented In ORBIT-RF

- **Stochastic quasi-linear perpendicular heating**

$$\langle\Delta\mu\rangle = \frac{1}{4}\frac{\pi q^2 l^2 \Omega^2}{\mu\omega^2 B_0} K|E_+|^2 \times \left[\left|J_{l-1} + e^{2i\theta_k}\frac{E_-}{E_+}J_{l+1}\right|^2 + \mu\left\{2\left(J_{l-1} + e^{2i\theta_k}\frac{E_-}{E_+}J_{l+1}\right)\left(\frac{\partial J_{l-1}}{\partial\mu} + e^{2i\theta_k}\frac{E_-}{E_+}\frac{\partial J_{l+1}}{\partial\mu}\right)\right\}\right] \delta(w_l)$$

S.C. Chiu,POP **7** (2000)

- **Coulomb collisions**

$$\Delta E_n = -2E_0\Delta\tau\left(\frac{m_a}{m_a+m_b}\nu_s - \frac{5}{2}\nu_{//} - E_0\left.\frac{\partial\nu_{//}}{\partial K}\right|_{K=K_0}\right) \pm 2K_0\sqrt{\nu_{//}\Delta\tau}$$

O.A. Shyshkin ,35th EPS(2008)

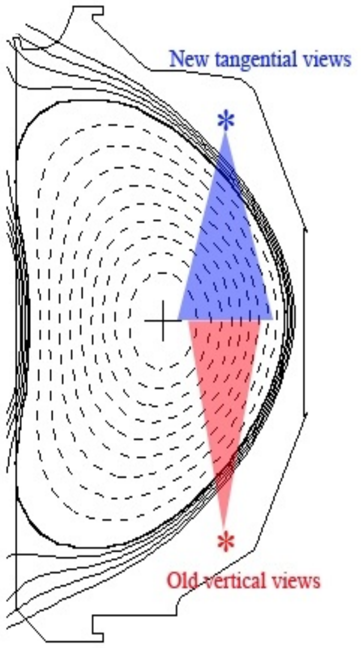
$$\Delta\lambda = -\lambda\gamma_\perp\Delta\tau \pm \sqrt{\left(1-\lambda^2\right)\gamma_\perp\Delta\tau}$$

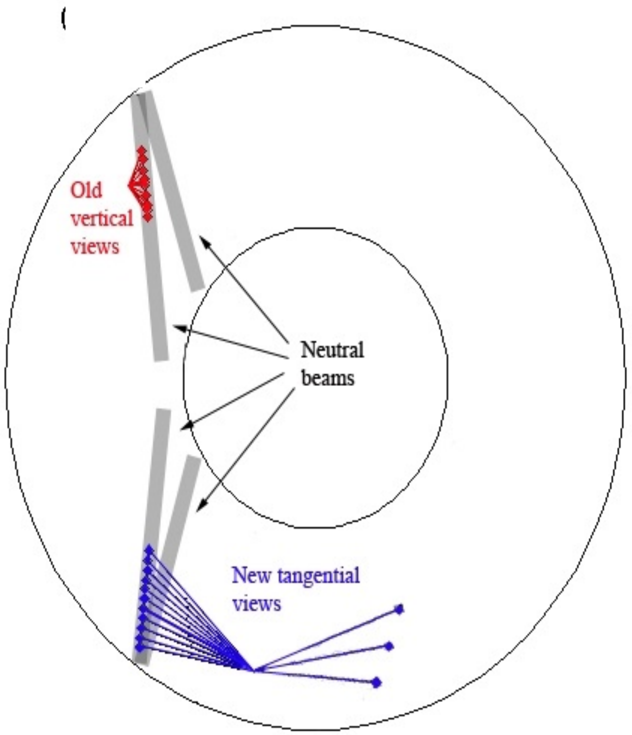
Phys. Vade Mecum, Ed. H. L. Anderson (1981)

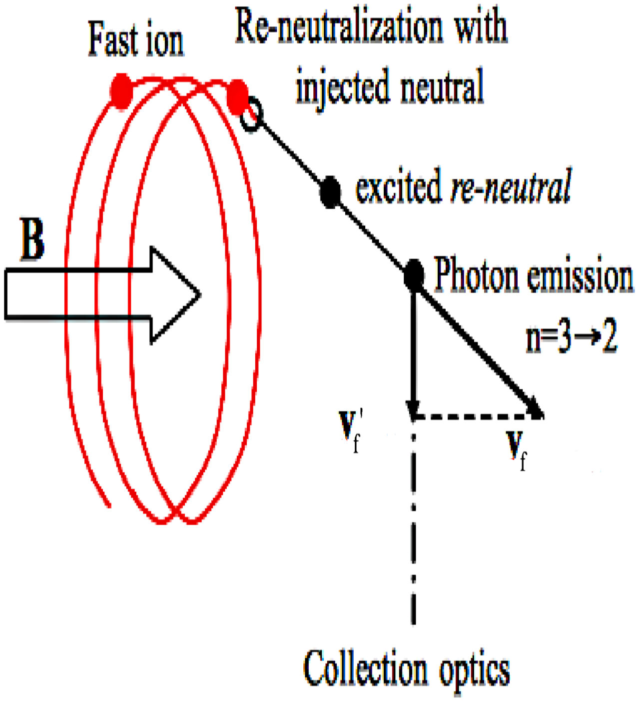
- **A single** $k_{//}=N_{\varphi}/R$ (Upshift of $k_{//}$ ignored)
- $k_\perp$ **from cold plasma dispersion relation**
- $k_\perp=k_x$ ➔ $e^{2i\theta k}=1$
- Axisymmetric equilibrium (no MHD)

FIDA Provides a Comprehensive Tool to Measure Fast Ions Spectra and Spatial Profile

- **DIII-D FIDA spectroscopy**







NSTX : 16 channels
DIII-D: 9 channels

W.W. Heidbrink,
PPCF **46** (2004)

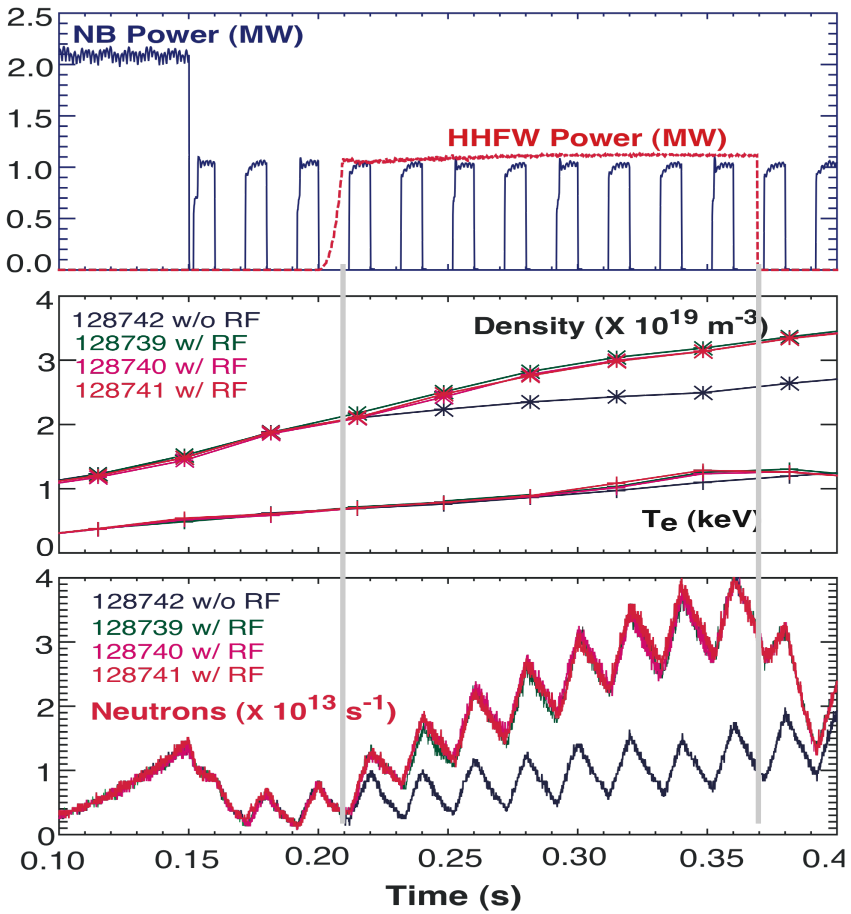
Key Results

- Extensive simulations reasonably reproduce neutron enhancement, spectra and outward radial shifts of measured FIDA signals in DIII-D and NSTX moderate to high harmonic FW heating discharges

- Preliminary results in ITER and KSTAR suggest that non zero orbit effect may also significantly modify fast ion distribution in velocity space, depending on applied ICRF power density

Increased Neutron Rates During HHFW Indicate Strong Absorption of ICRF Waves By Beam Fast Ions

NSTX HHFW discharges
#128739 - #128742



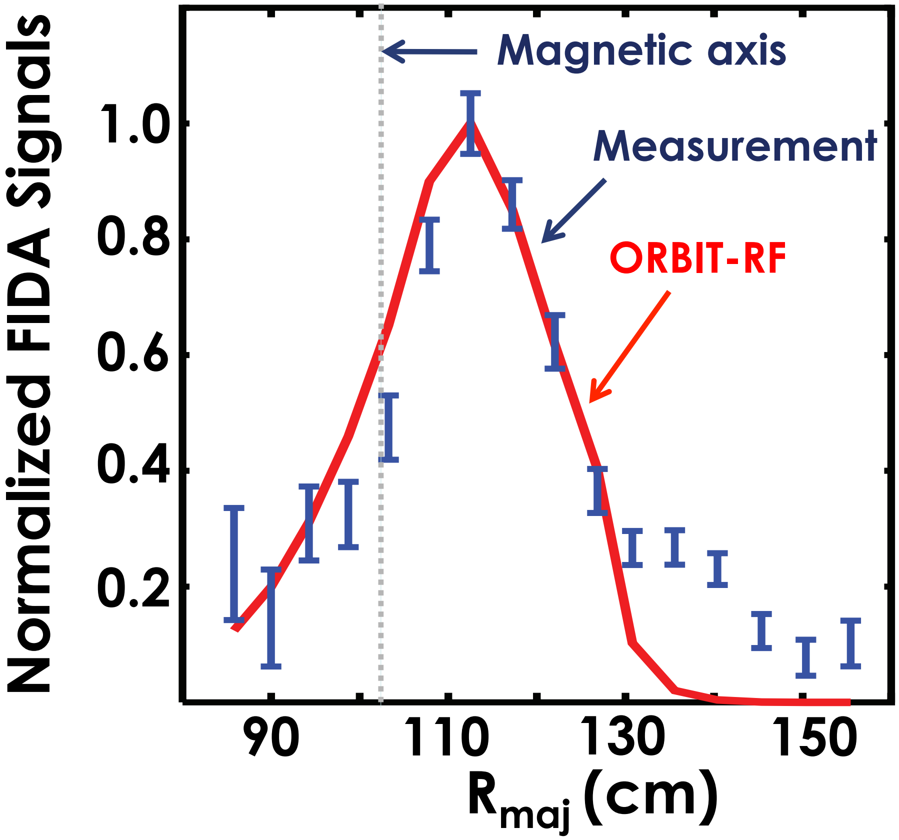
- Beam ion **Deuterium**
- Beam injection energy **65 keV**
- P_{NB} **1 MW**
- Tangency radius **0.59 m**

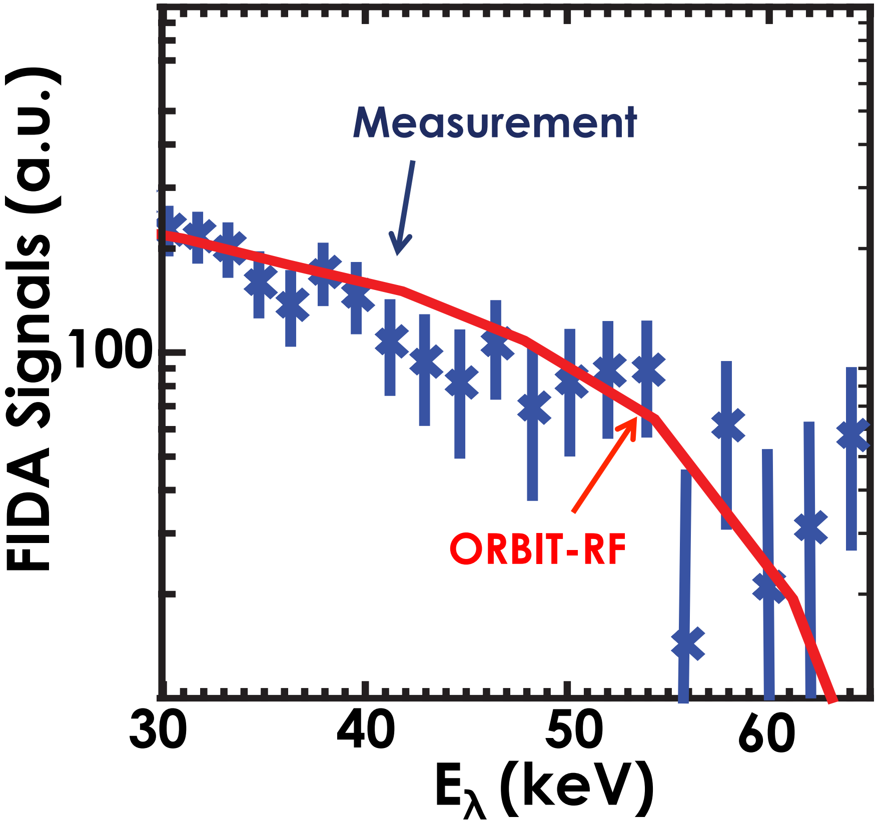
- P_{RF} **1.1 MW**
- ICRF wave frequency **30 MHz**
  3rd to 11th resonance layers (8th resonance layer near the magnetic axis)

Good Agreements Are Obtained in Spatial Profile and Spectra with No ICRF

- **NSTX NB heating discharge #128742**

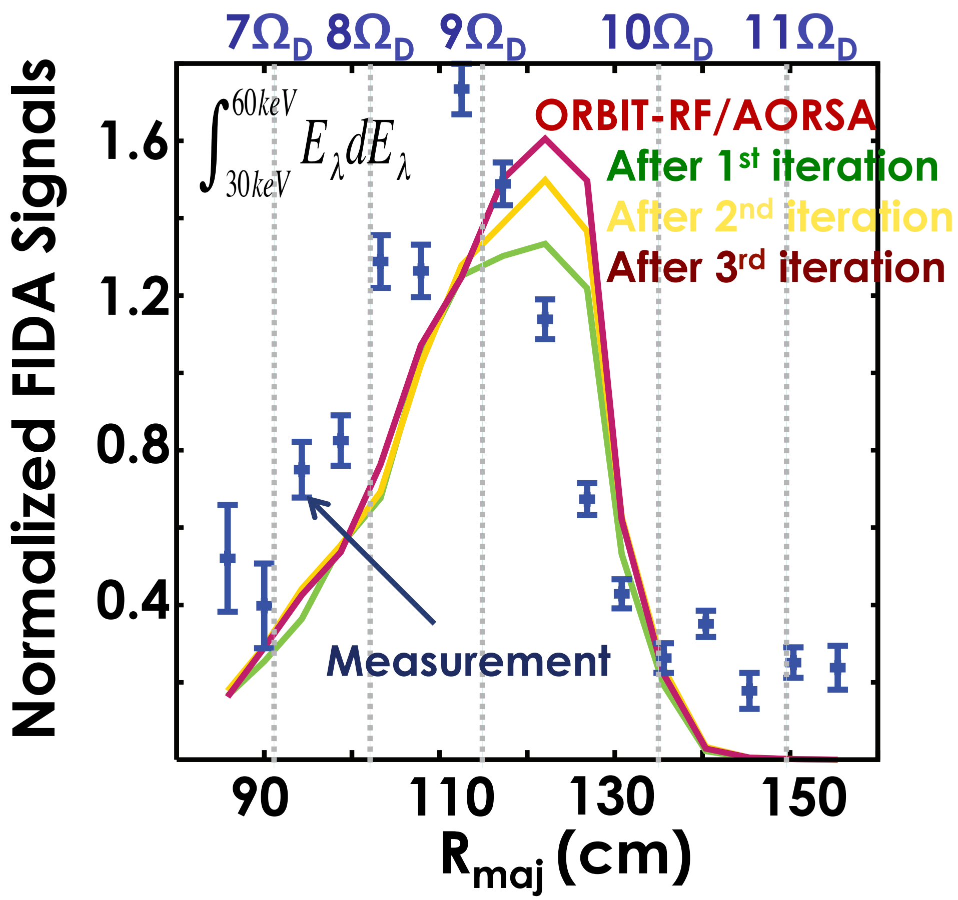
$$\int_{30keV}^{60keV} E_\lambda dE_\lambda$$

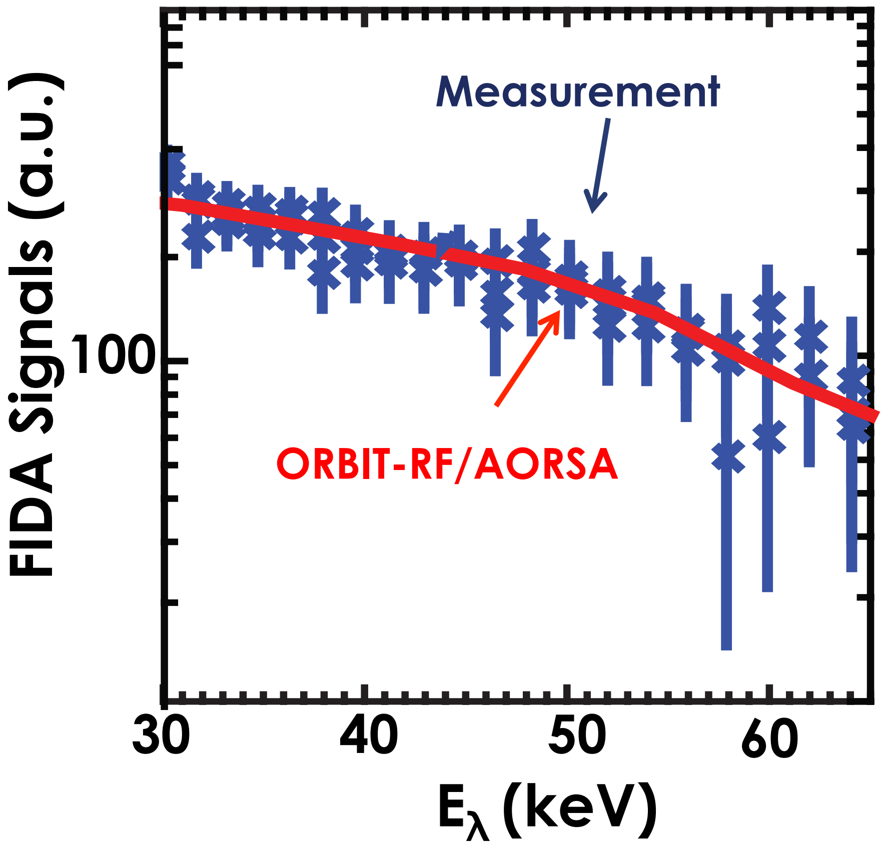




Simulation With ICRH Predicts Slightly Enhanced Outward Shifts

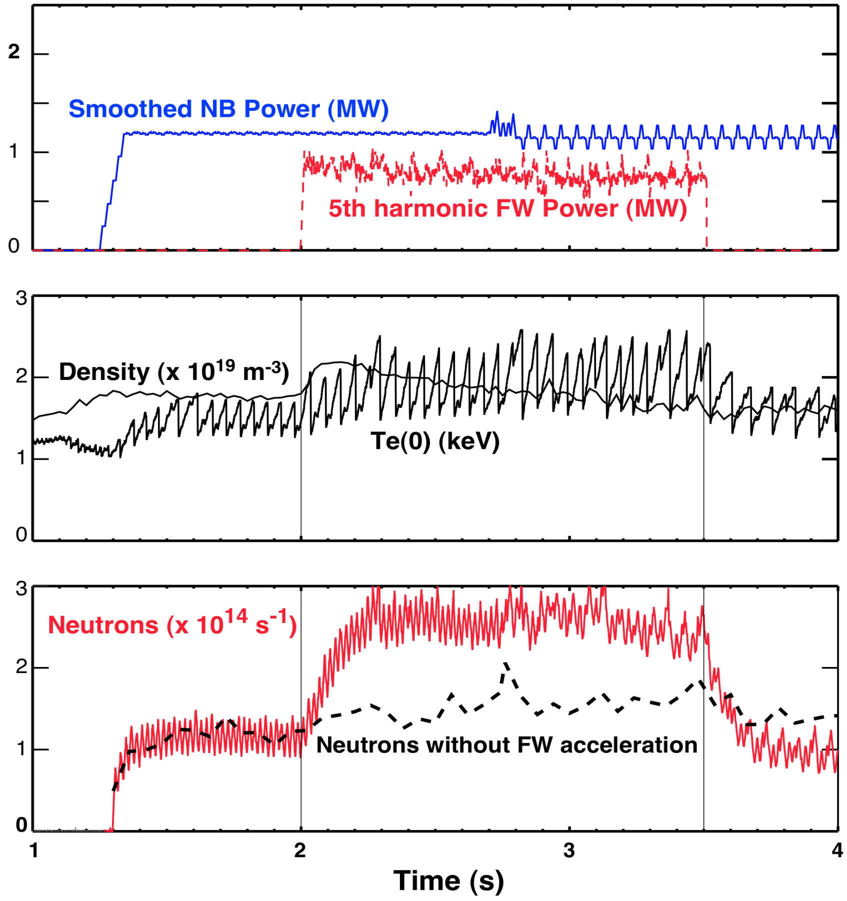
- **NSTX NB+ICRF heating discharge #128739**





Strong Absorption of ICRF Waves By Beam Fast Ions Is Also Observed In DIII-D

DIII-D 5th harmonic FW experiment #122993



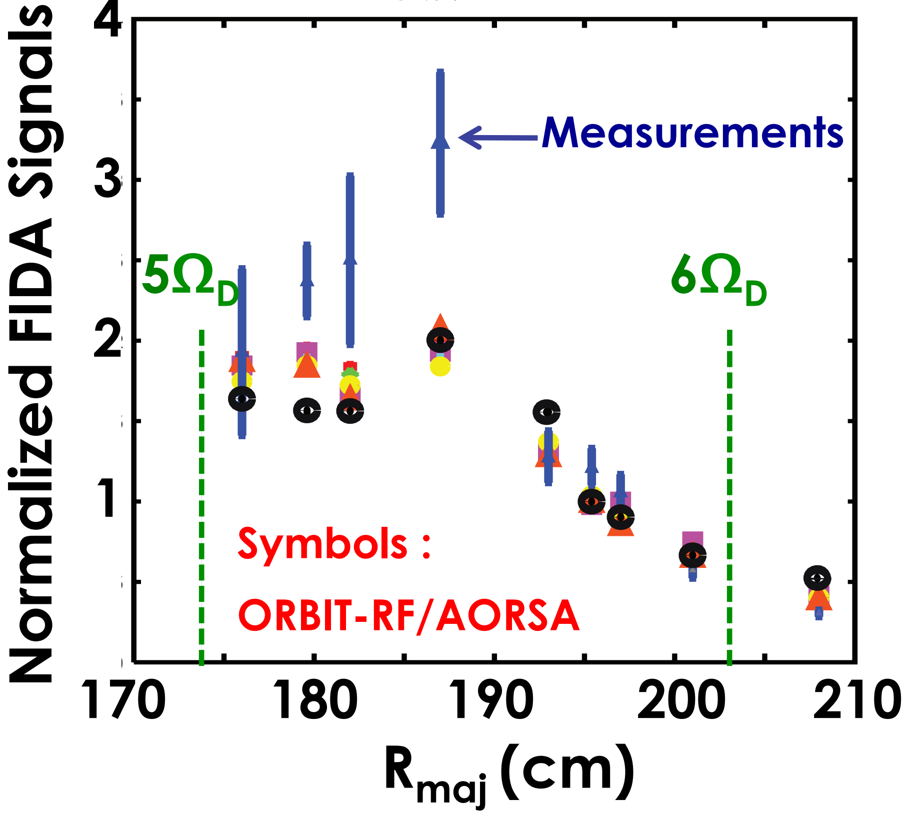
- Beam ion **Deuterium**
- Beam injection energy **80 keV**
- P_{NB} **1 MW**
- Tangency radius **0.59m**

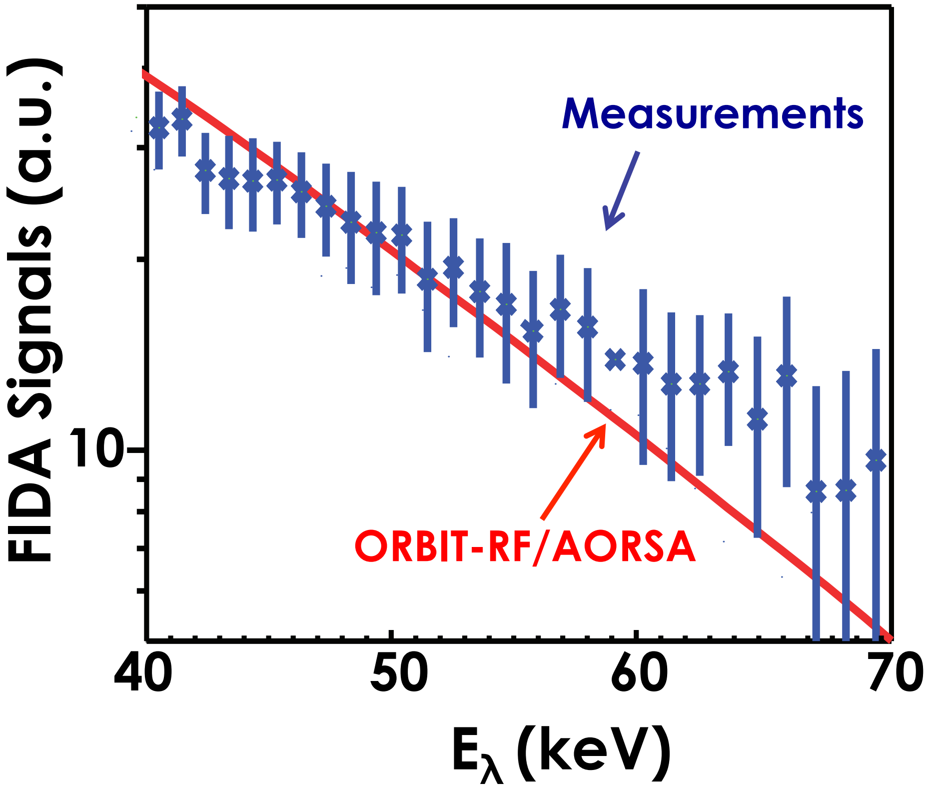
- P_{RF} **1 MW**
- ICRF wave frequency **60MHz**
  4th to 6th resonance layers (5th resonance layer near the magnetic axis)

Qualitative Agreements Are Obtained in Spectra and Spatial Profile With ICRH

- **DIIID NB+ICRF heating discharge #122993**

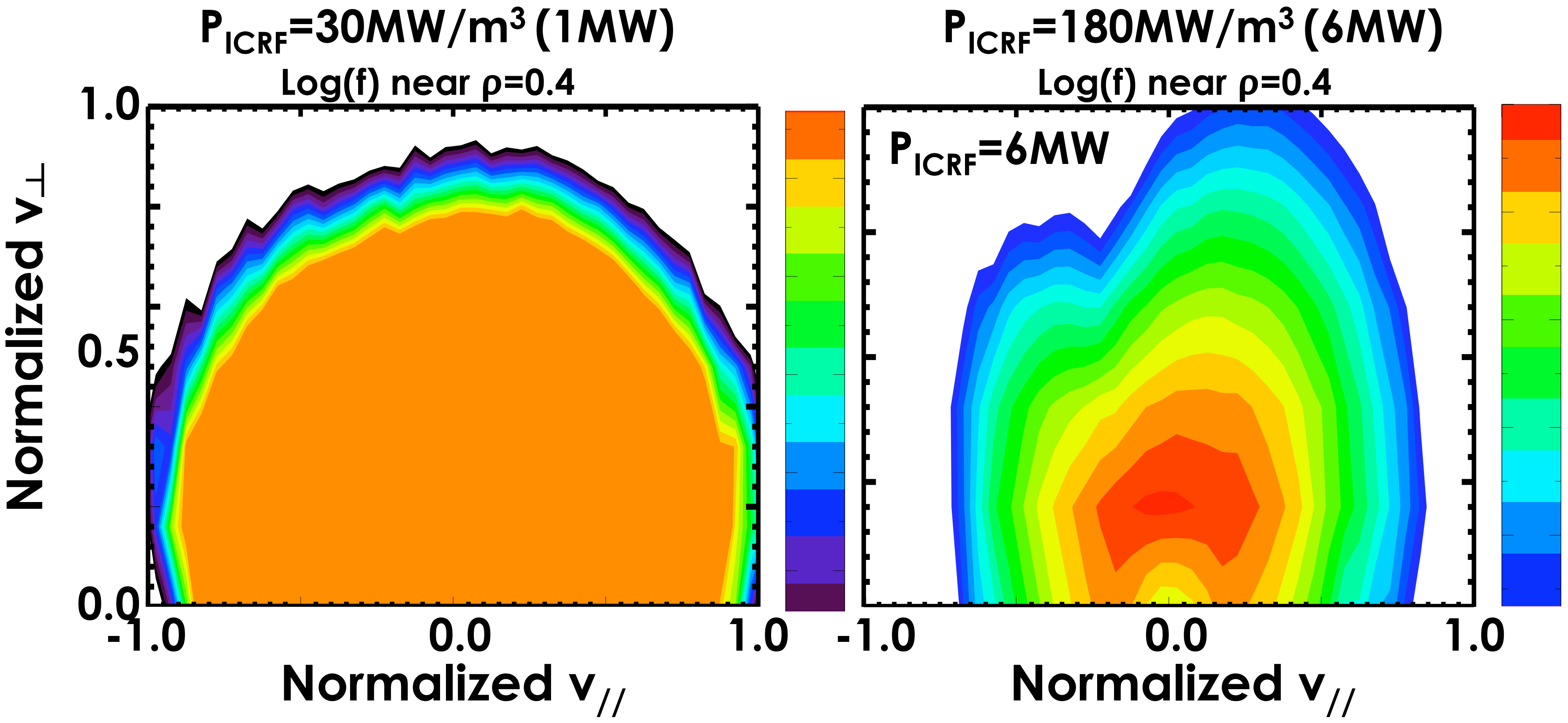
$$\int_{45keV}^{70keV} E_\lambda dE_\lambda$$





KSTAR : Finite Orbit Effect May Significantly Modify Distribution, Depending On ICRF Power Density

- **H (10%) minority fundamental harmonic heating**
- $n_e(0)$ **6.7×10^{13} cm^{-3}**, $T_e(0)$ **2 keV**, $T_D(0)$ **2 keV**, $T_H(0)$ **10 keV** f_{ICRF} **45 MHz** n_φ **19**



P_{ICRF}=30MW/m^3 (1MW)

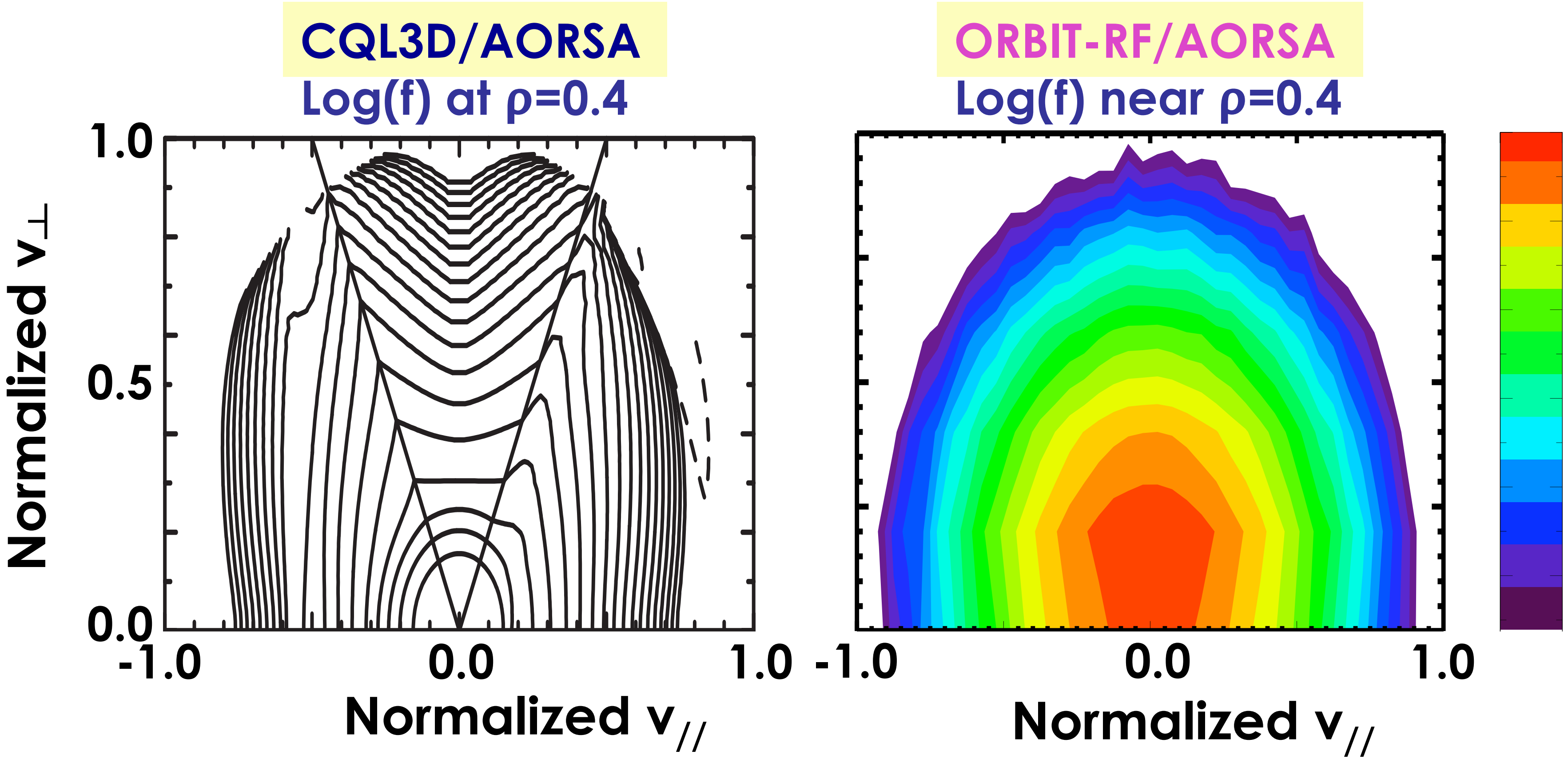
Log(f) near ρ=0.4

P_{ICRF}=180MW/m^3 (6MW)

Log(f) near ρ=0.4

ITER : With P_{ICRF}= 20 MW, Non-Zero Orbit Effect Appears to Average Out Anisotropic Distribution

- **D(10%) minority fundamental harmonic heating scenario**
- $n_e(0)$: **7.3×10^{13} cm^{-3}**, $T_e(0)$: **24 keV**, $T_T(0)$: **25 keV**, $T_D(0)$: **25 keV**
- f_{ICRF}: **40 MHz** P_{ICRF}: **20 MW** n_φ : **-35**



GENERAL ATOMICS

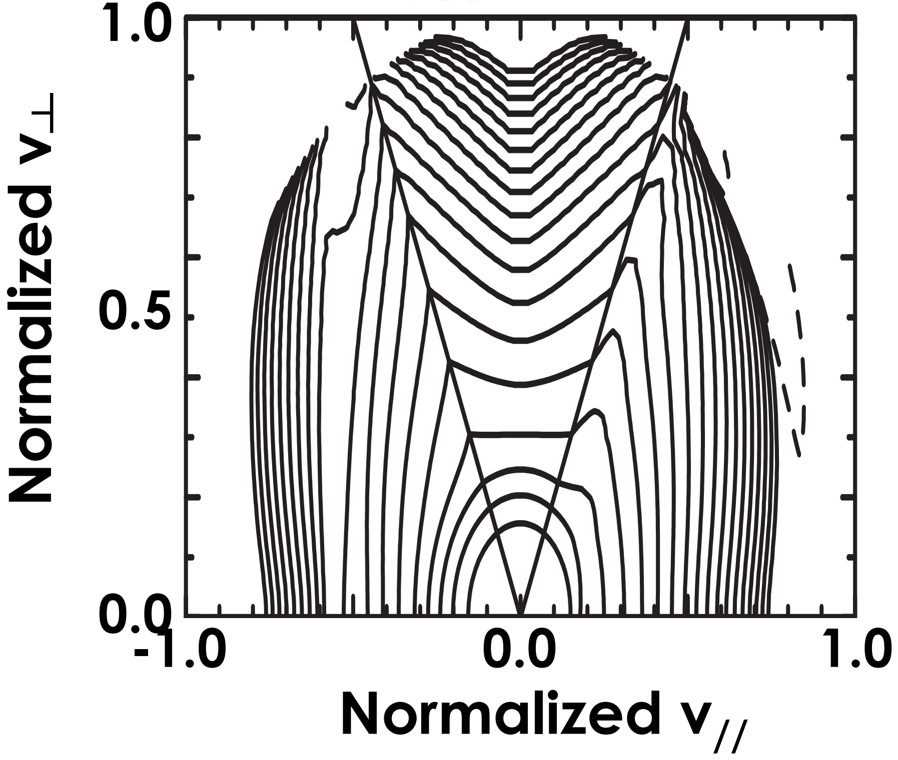
133-09/MC/

ITER : Without Drift Terms, Anisotropic Feature of Fast Ion Distribution Is Recovered

- D(10%) minority fundamental harmonic heating

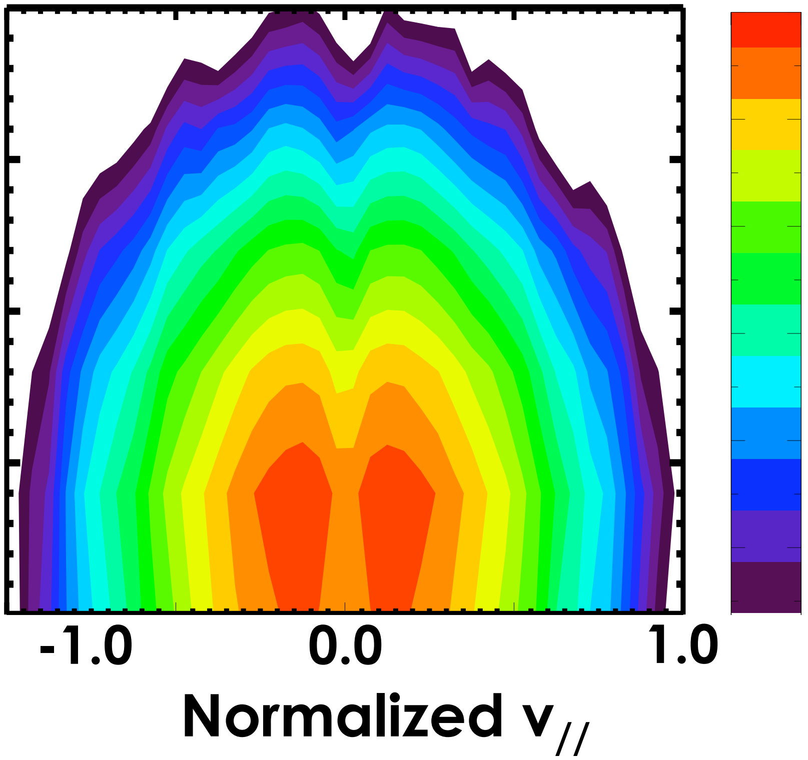
CQL3D/AORSA

Log(f) at $\rho=0.4$



ORBIT-RF/AORSA without drift terms

Log(f) near $\rho=0.4$



Summary

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