Modeling of Neutral Beam Ion Absorption of High Harmonic ICRF Waves in the DIII-D Tokamak

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In collaboration with

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Joint Meeting of US-Japan Workshop on Theory-Based Modeling and
Integrated Simulation of Burning Plasmas
and 21COE Workshop on Plasma Theory
Kyoto, Japan, December 15-17, 2003

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The Monte-Carlo Code ORBIT-RF is Developed to Study Energetic Particle-Wave Interaction

Finite orbit effect is important even for moderate energy ions

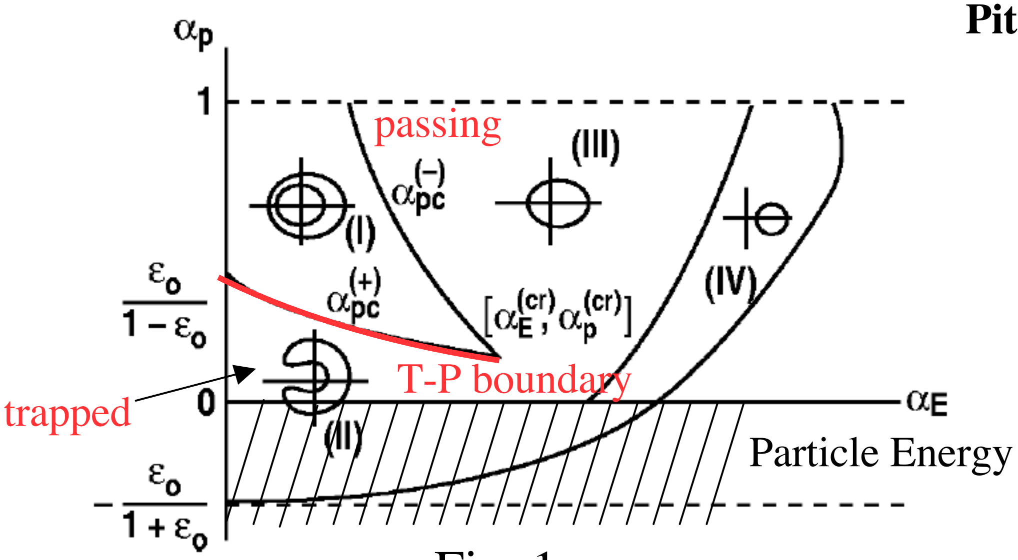
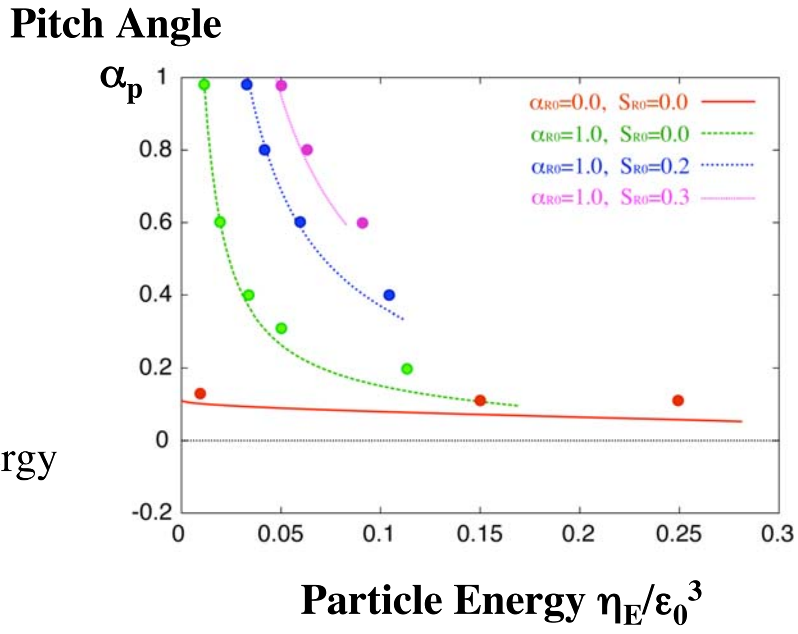


Fig. 1

LINES : Theory
POINTS : ORBIT



$$\eta_{E0} = \frac{8q_0^2(1+S_0)}{R_0^2\Omega_0}K_{*0} \equiv \frac{2\varepsilon_0^3}{3}\alpha_E$$

S. C. Chiu, V. S. Chan, and Y. A. Omelchenko, Phys. Plasmas 9, 877 (2002).

Motivation

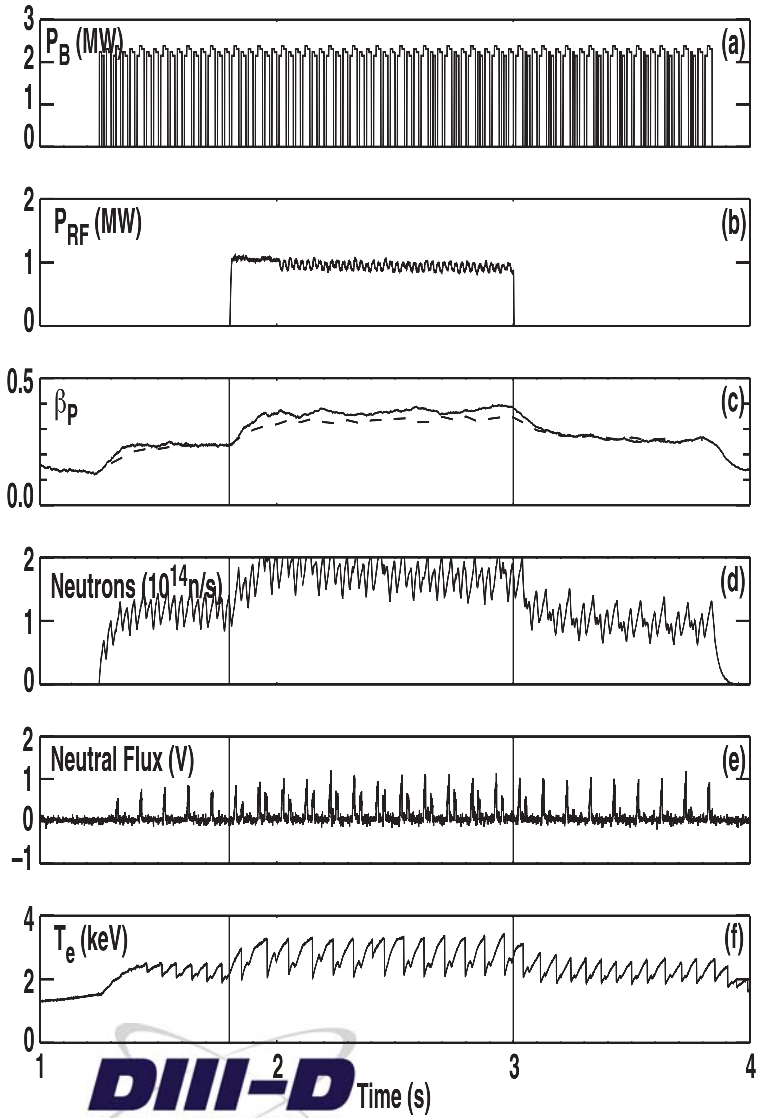
- **The absorption of ion cyclotron resonance frequency (ICRF) waves by neutral beam (NB) ions at high ion cyclotron harmonics has been observed experimentally in DIII-D during fast wave current drive.**

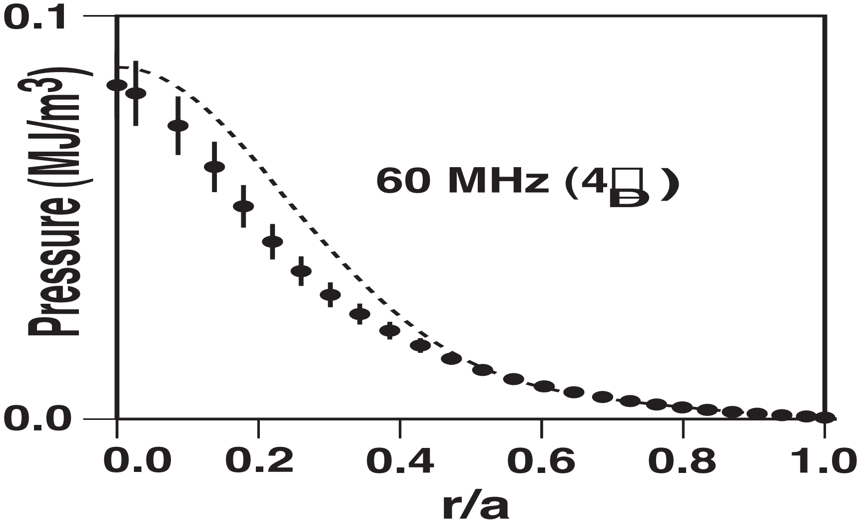
Experimental Observations

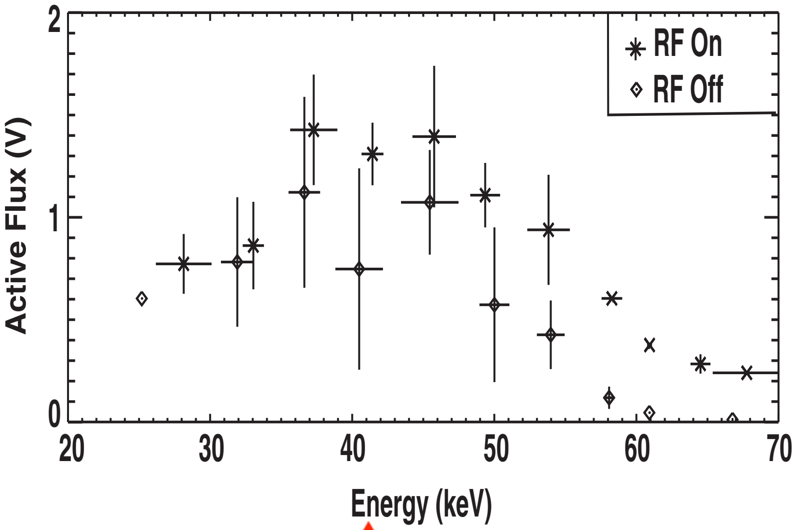
- **Anomalously peaked pressure profile was observed in the central region of plasma with a significant enhancement of the measured neutron rate when RF pulses were applied to NB heated discharges.**
- **Energy spectrum from neutral particles analyzer showed a strong enhancement of the tail energy above the injected beam energy.**

- **To understand this phenomenon of beam-wave interaction theoretically, a Monte-Carlo RF orbit code, ORBIT-RF, has been upgraded to treat steady-state NB injection and ICRF absorption at higher harmonics, and applied under the DIII-D experimental conditions. Questions:**
  - **Fraction of RF power absorbed by the NB fast ions**
  - **Modification of fast ion pressure profile, NBCD and rotation by ICRF**

Experimental Observations on Neutron Emission Enhancement, Peaked Beam Ion Pressure and Energetic Tails Formation on DIII-D







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ORBIT-RF

Hamiltonian guiding center drift equations are solved to follow the trajectories of test particles in a tokamak geometry under ICRF wave fields and collisions

P_ζ **: toroidal canonical momentum**

P_θ **: poloidal canonical momentum**

ϕ **: electric potential (=0),** H **: Hamiltonian**

$$\frac{d}{dt}P_\zeta = -\partial_\zeta H, \qquad \frac{d}{dt}\zeta = \partial_{P_\zeta} H$$

$$\frac{d}{dt}P_\theta = -\partial_\theta H, \qquad \frac{d}{dt}\theta = \partial_{P_\theta} H$$

$$P_\theta = I\rho_{//} + \psi,\ \ P_\xi = g\rho_{//} - \psi_p,\ \ H = \frac{1}{2}\rho_{//}^2 B^2 + \mu B + \phi,\ \ \rho_{//} = v_{//}/B$$

where ψ_p polidal flux, ψ toroidal flux

θ poloidal angle, ζ toroidal angle

$g(\psi_p)$ poloidal current flowing outside the surface ψ_p

$I(\psi_p)$ toroidal current flowing inside the surface ψ_p

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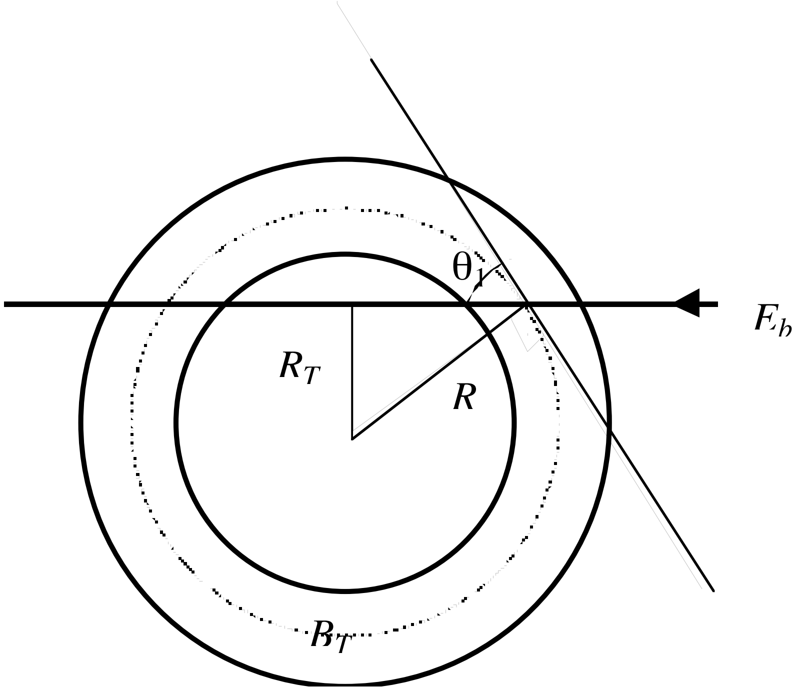
Steady State Slowing-down of NB Injected Fast Ions is Modeled



NB Injection Geometry

- **Injected neutral particles are all ionized by the background plasma at Z=0.**
- **Source rate of fast ions generated by NBI, $S(E_b,\lambda,\psi_p,\theta)$, is calculated with the given NB injection power (P_{NB}), beam ion energy (E_b) and tangential radius (R_T) in phase space.**
- **λ (pitch)=$v_{//}/v=(B_T R_T)/(BR)$**
- **ψ_p poloidal flux**
  θ poloidal angle

Particle Weightings are Adjusted to Model Injection of Constant NB Power

- During 1 slowing down time, E_{tot} is injected : E_{tot} (= P_{NB} *t_s)

- Using $S(E_b,\xi,\psi_p,\theta_p)$, the initial weightings of each test particle (W_k) are calculated to represent the real number of fast ions generated from the NB source: $W_k = S*t/n$

- The injected fast ions will lose their energy and momentum to the background plasma ions and electrons through pitch-angle scattering and drag.

- The thermalized fast ions (<1.5T_i) are replaced in the plasma at the birth energy with a source rate compatible with P_{NB}

- Weightings of replaced fast ions are readjusted to be consistent with constant input power P_{NB}

Absorption of ICRF Wave for High Harmonic is Modeled by Quasilinear RF Operator

$$\Delta\mu_{rf} = \overline{\Delta\mu_{rf}} + R_M\,\overline{\overline{\Delta\mu_{rf}}}$$

$$\overline{\Delta\mu_{rf}} = \frac{\pi q^2 \boxed{l^2\Omega^2}}{m\omega^2 B_0}\left|E_+\right|^2 \boxed{\left[J_{l-1}^2(k_\perp\rho_\perp) + 2\mu J_{l-1}\frac{\partial J_{l-1}}{\partial\mu}\right]}\frac{K}{|\dot{w}_l|}$$

$$\overline{\overline{\Delta\mu_{rf}}}^{\,2} = \frac{2\pi q^2 \boxed{l^2\Omega^2}}{m\omega^2 B_0}\,\mu\left|E_+\right|^2 \boxed{J_{l-1}^2}\frac{K}{|\dot{w}_l|} = 2\,\mu \boxed{\frac{J_{l-1}^2}{\left[J_{l-1}^2 + 2\mu J_{l-1}\dfrac{\partial J_{l-1}}{\partial\mu}\right]}}\,\overline{\Delta\mu_{rf}}$$

$$w_l = \omega - \boxed{l\Omega - k_{//}\rho_{//}\Omega}$$

$$K = \begin{cases} 1 & \sqrt{2}\tau_{uc} \le \tau_c \\ \dfrac{2\pi A_i^2(\zeta)|\dot{w}_l|}{|\ddot{w}_l/2|^{2/3}} & \sqrt{2}\tau_{uc} > \tau_c \end{cases}$$

$$\zeta = -\frac{|\dot{w}_l|^2}{|2\ddot{w}_l^2|^{2/3}},\quad \tau_{uc} = \sqrt{\frac{2\pi}{|\dot{w}_l|}},\quad \tau_c = \frac{2\pi A_i(\zeta)}{|\ddot{w}_l/2|^{1/3}}$$

$$k_\perp = n_\perp\frac{\omega}{c},\quad \rho_\perp = \frac{v_\perp}{\Omega_i} = \frac{\sqrt{2\mu B}}{\Omega_i}$$

$$n_\perp^2 \approx \frac{(S-n_{//}^2)^2 - D^2}{S-n_{//}^2}$$

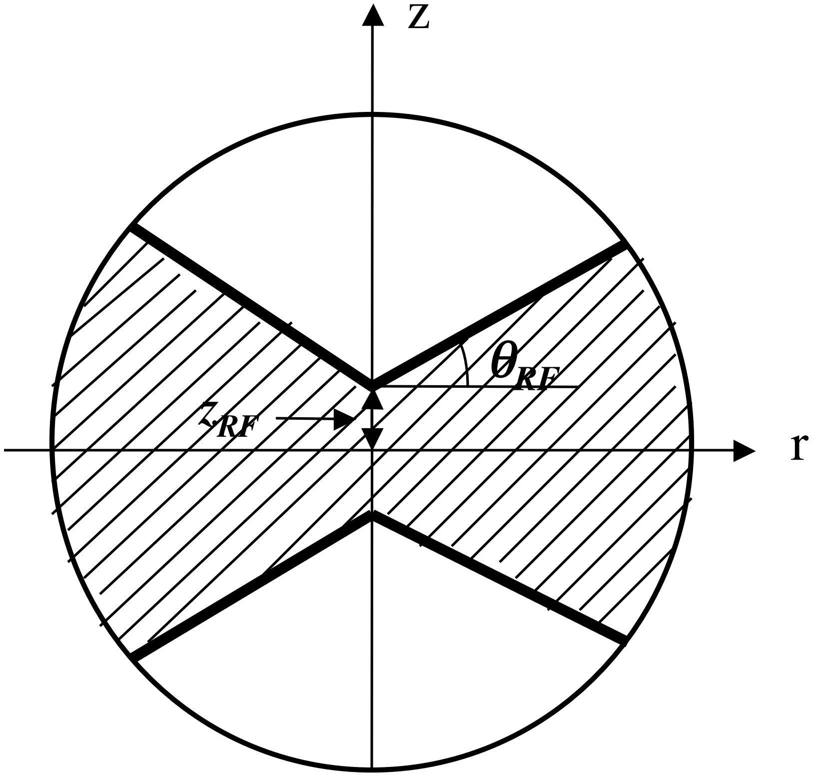
$$S = 1 + \frac{\omega_{pe}^2}{\Omega_e^2} - \sum_i \frac{\omega_{pi}^2}{\omega^2-\Omega_i^2}$$

$$D = \sum_i \frac{\omega_{pi}^2\omega}{\Omega_i(\omega^2-\Omega_i^2)}$$

$$P = -\frac{\omega_{pe}^2}{\omega^2}$$

Simplified Stix Model of $|E_+|$ is Used
(Left-hand polarized component)

Wave cone in (r,z) space



- **Assuming that ICRF waves exist inside the shaded wedge, the interaction of resonant particles with ICRF wave is effective inside shaded wedge bounded by**

$$z = z_{RF} + \tan(\theta_{RF}) \times r$$

- **|E+ (r) | is calculated by**

$$|E_+(r)|^2 = \frac{\Omega_{oi}}{\omega_{pi}^2} \frac{P_{RF}}{dV_{res}} (1 - r^2/a^2)$$

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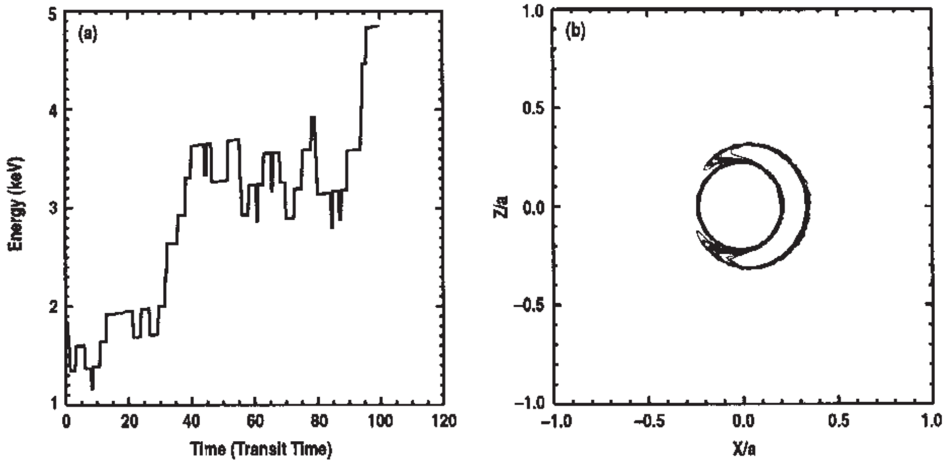
SIMULATION REPRODUCES RF HEATING PHYSICS

Table 1. Alcator C-Mod-like parameters for Orbit-RF simulation

Plasma Parameters	Wave Parameters
$T_e = 1.5$ keV	$f_{rf} = 80$ MHz
$T_D = 2$ keV	$k_{\parallel} = 0$
$T_H = 3$ keV	$P_{abs} = 1$–3 MW
$n_e = 3 \times 10^{14}$ cm^{-3}	
$n_H/n_D = 0.05$	
$B_{To} = 47$–58 kg	
$R_{maj} = 67$ cm	
$a = 21$ cm	
$q_{edge} = 4$	



Fast ion energy and orbit with ICRH

20,000 test particles loaded in Maxwellian annulus

Follows fast ion dynamically keeping fast ion contribution to magnetic and frictional torque

Thermalized fast ions "re-injected" to maintain steady-state

Collisions of Beam Ions with Background Electrons and Majority Ions are Accounted For

- **Frequency for slowing-down of fast ions due to Coulomb collisions**

$$\boxed{\nu = 1.6\times 10^{-9} A_f^{-1} T_e(r)^{-3/2} n_e(r) Z_f^2 \Lambda_{ef}(r)\left(1+\left(E_c/E_f\right)^{3/2}\right)}$$

$$E_c = 14.8\times A_f / A_i^{2/3} T_e(r)$$

where A atomic mass number

Λ Coulomb logarithm: $24.0 - \log(\sqrt{n_e(r)}/T_e(r))$

E_f NB injected fast ion energy

E_c critical energy

f stands for the NB injected fast ions

i stands for the background thermal ions

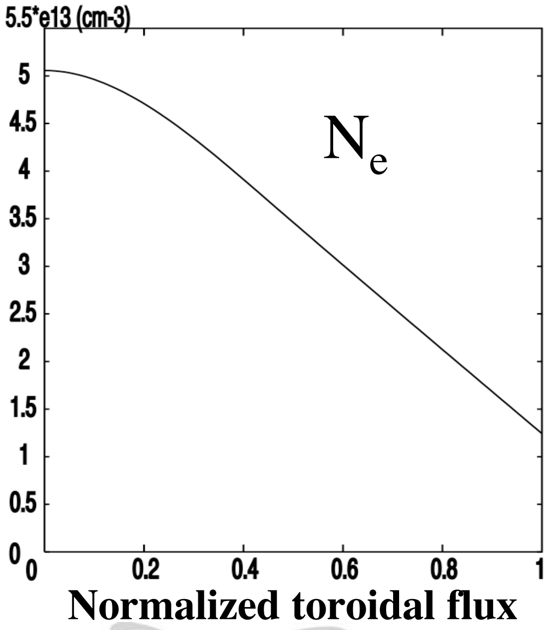
- **Frequency for pitch-angle scattering collisions between fast ions and background ions**

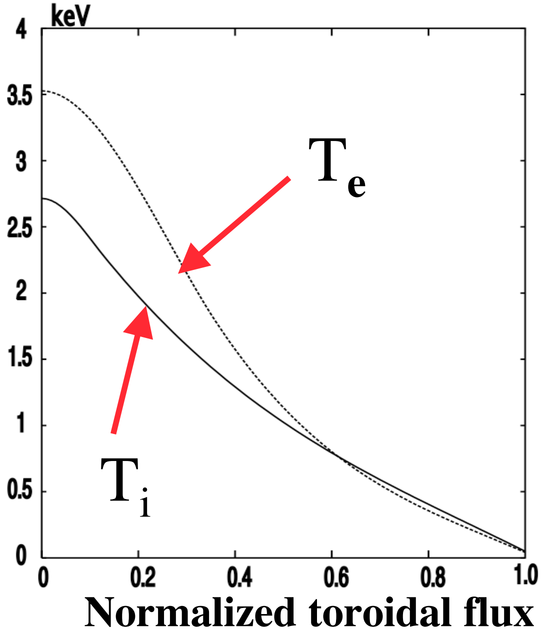
$$\boxed{\nu = 1.8\times 10^{-7} A_f^{-1/2} E_f^{-3/2} n_i Z_i^2 \Lambda_{if}}$$

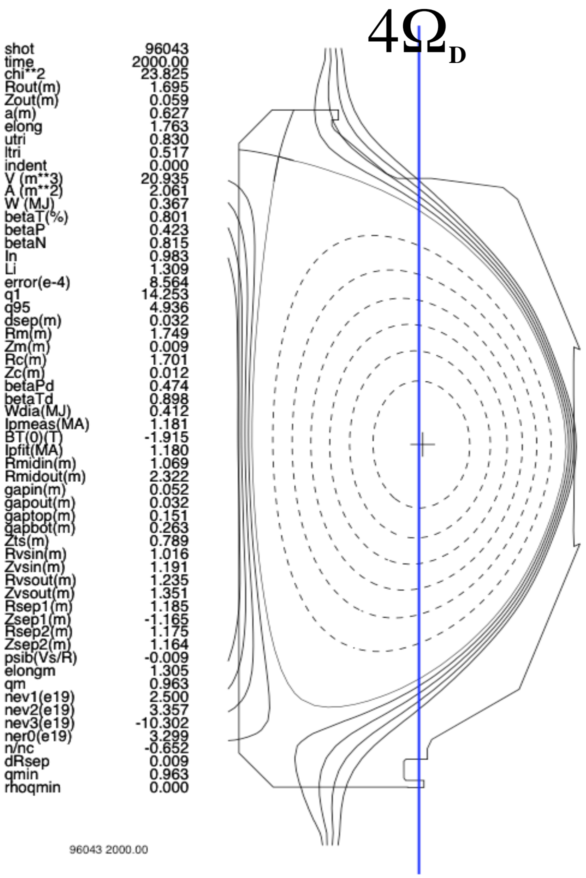
DIII-D Discharge 96043.02000

Plasma parameters		RF heating	NB heating
$T_D(0)$ =2.725keV	$B_t(0)$=1.92T	**P_{RF}=1.1 MW**	**P_{NB}=2.7MW**
$T_H(0)$ =2.0keV	a =62 cm	**f_{RF} = 60.0MHz**	**E_{NB}=80.0keV**
$T_e(0)$ =3.527 keV	R_{maj} =175cm	**$n_{//}$ =5.0($k_{//}$=6.3m^{-1})**	**R_T =115cm**
$n_e(0)$ =0.51($10^{14}cm^{-3}$)	n_H/n_D=0.05	**l = 4th**	

Density and Temperature Profiles







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chi**2             23.825
Rout(m)             1.695
Zout(m)             0.059
a(m)                0.627
elong               1.763
utri                0.830
ltri                0.517
indent              0.000
V (m**3)           20.935
A (m**2)            2.061
W (MJ)              0.367
betaT(%)            0.801
betaP               0.423
betaN               0.815
In                  0.983
Li                  1.309
error(e-4)          8.564
q1                 14.253
q95                 4.936
dsep(m)             0.032
Rm(m)               1.749
Zm(m)               0.009
Rc(m)               1.701
Zc(m)               0.012
betaPd              0.474
betaTd              0.898
Wdia(MJ)            0.412
Ipmeas(MA)          1.181
BT(0)(T)           -1.915
Ipfit(MA)           1.180
Rmidin(m)           1.069
Rmidout(m)          2.322
gapin(m)            0.052
gapout(m)           0.032
gaptop(m)           0.151
gapbot(m)           0.263
Zts(m)              0.789
Rvsin(m)            1.016
Zvsin(m)            1.191
Rvsout(m)           1.235
Zvsout(m)           1.351
Rsep1(m)            1.185
Zsep1(m)           -1.165
Rsep2(m)            1.175
Zsep2(m)            1.164
psib(Vs/R)         -0.009
elongm              1.305
qm                  0.963
nev1(e19)           2.500
nev2(e19)           3.357
nev3(e19)         -10.302
ner0(e19)           3.299
n/nc               -0.652
dRsep               0.009
qmin                0.963
rhoqmin             0.000

           96043 2000.00
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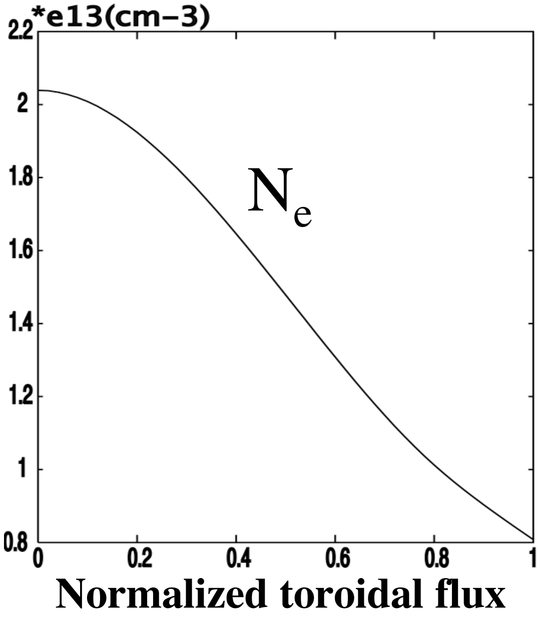
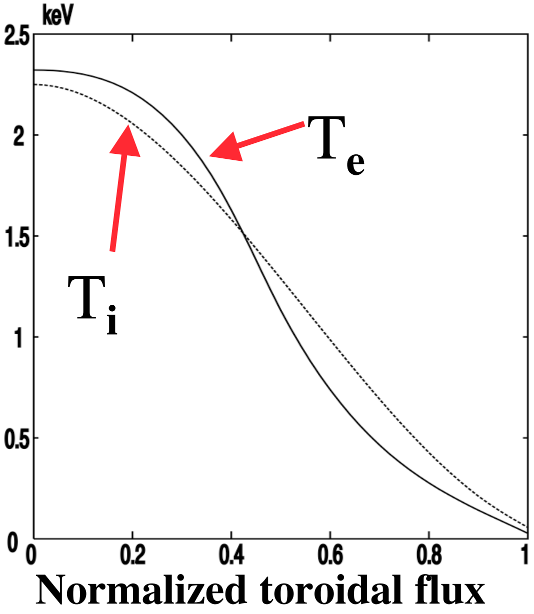
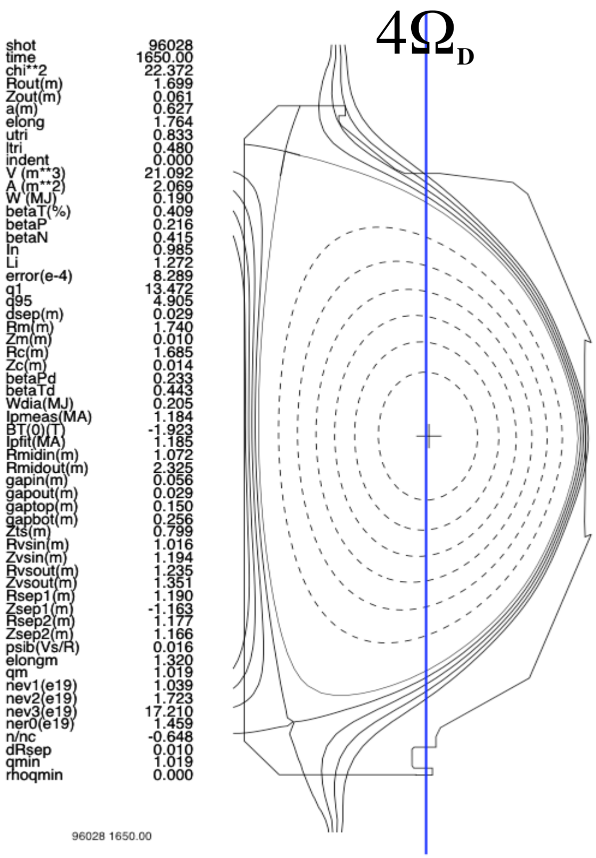
DIII-D Discharge 96028.02650

Plasma parameters		RF heating	NB heating
$T_D(0)$ =2.25keV	$B_t(0)$=1.92T	**P_{RF}=0.7 MW**	**P_{NB}=1.2MW**
$T_H(0)$ =2.0keV	a =62 cm	**f_{RF} = 60.0MHz**	**E_{NB}=77.0keV**
$T_e(0)$ =2.32keV	R_{maj} =175cm	**$n_{//}$ =5.0($k_{//}$=6.3m^{-1})**	**R_T =100cm**
$n_e(0)$ =0.21($10^{14}cm^{-3}$)	n_H/n_D=0.05	**l = 4th**	

Density and Temperature Profiles







shot	96028
time	1650.00
chi**2	22.372
Rout(m)	1.699
Zout(m)	0.061
a(m)	0.627
elong	1.764
utri	0.833
ltri	0.480
indent	0.000
V (m**3)	21.092
A (m**2)	2.069
W (MJ)	0.190
betaT(%)	0.409
betaP	0.216
betaN	0.415
In	0.985
Li	1.272
error(e-4)	8.289
q1	13.472
q95	4.905
dsep(m)	0.029
Rm(m)	1.740
Zm(m)	0.010
Rc(m)	1.685
Zc(m)	0.014
betaPd	0.233
betaTd	0.443
Wdia(MJ)	0.205
Ipmeas(MA)	1.184
BT(0)(T)	-1.923
Ipfit(MA)	1.185
Rmidin(m)	1.072
Rmidout(m)	2.325
gapin(m)	0.056
gapout(m)	0.029
gaptop(m)	0.150
gapbot(m)	0.256
Zts(m)	0.799
Rvsin(m)	1.016
Zvsin(m)	1.194
Rvsout(m)	1.235
Zvsout(m)	1.351
Rsep1(m)	1.190
Zsep1(m)	-1.163
Rsep2(m)	1.177
Zsep2(m)	1.166
psib(Vs/R)	0.016
elongm	1.320
qm	1.019
nev1(e19)	1.039
nev2(e19)	1.723
nev3(e19)	17.210
ner0(e19)	1.459
n/nc	-0.648
dRsep	0.010
qmin	1.019
rhoqmin	0.000

96028 1650.00

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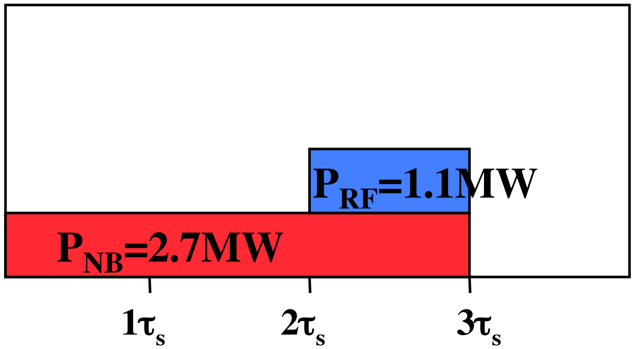
Simulations Conditions

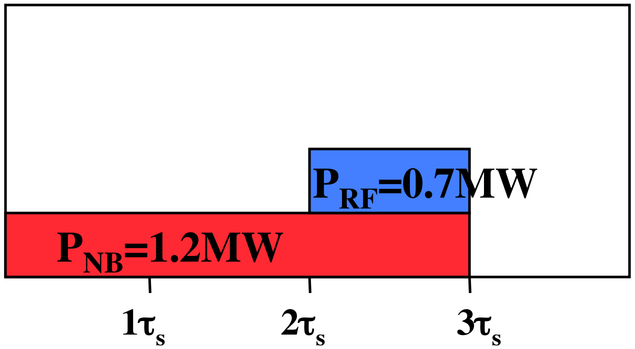
- **Mono-energetic Deutrium beam ions at full energy are injected (half and third energy components are ignored).**
- **Injected input heating powers**

96043.02000



τ_s : slowing down time (340 ms)

96028.02650



τ_s : slowing down time (417 ms)

- **The 4th harmonic cyclotron resonance surface of D beam ion is located approximately at $(R_{res}-R_{maj})/a \cong -0.07$**
- **Simulations are done for 3 slowing down times using 5000 test particles for beam ions using 23 processors on FI at GA(approximately 1.5 hours)**
- **Z_{eff}=2.0 (constant) and (ψ_p, θ) =(100, 50)**

Beam Ion Driven Current is Benchmarked

- **Average Steady State Fast Ion Velocity (<v_f>) on Each Flux Surface**

$$\left\langle v_f(\psi)\right\rangle_{\tau_s} = \frac{\sum_i \left[\int_0^{\tau_s} W_i(\psi)\, v_{//i}(\psi)\, dt\right]}{\sum_i \left[\int_0^{\tau_s} W_i(\psi)\, dt\right]}$$

- **Net NB Ion Driven Current Density**

$$J_{net} = J_f - \frac{J_f}{Z_{eff}} + \frac{J_f}{Z_{eff}}\left\{\varepsilon^{\frac{1}{2}} \times \left(1.55 + \frac{0.85}{Z_{eff}}\right) - \varepsilon \times \left(1.55 + \frac{0.85}{Z_{eff}}\right)\right\}$$

- **The ORBIT-RF simulation result is benchmarked with ONETWO transport code result**

J(r) Computed with ORBIT-RF and ONETWO are in Reasonable Agreement

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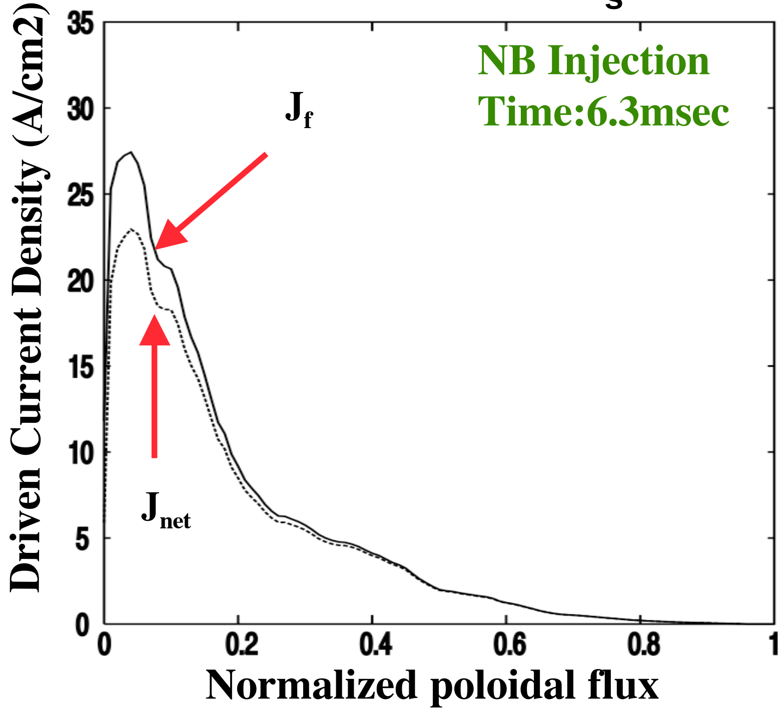
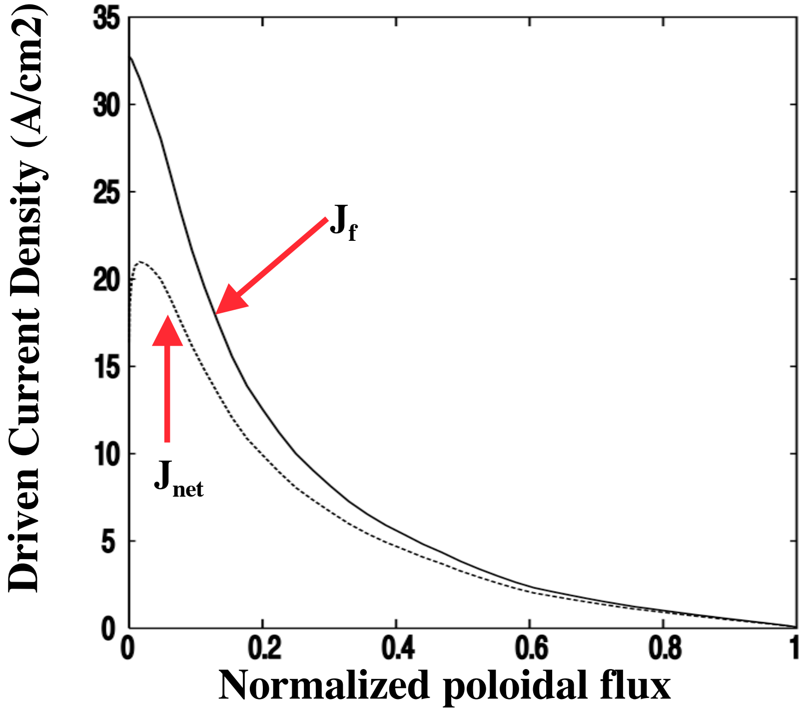
ORBIT-RF Result

at the end of 2 τ_s



ONETWO Result



The Time Averaged Profiles

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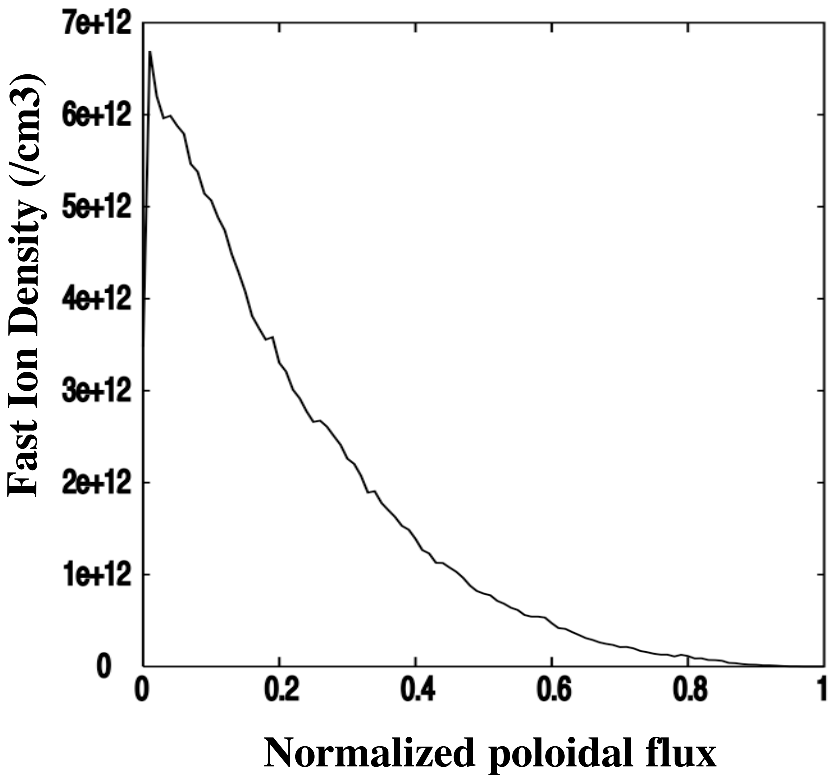
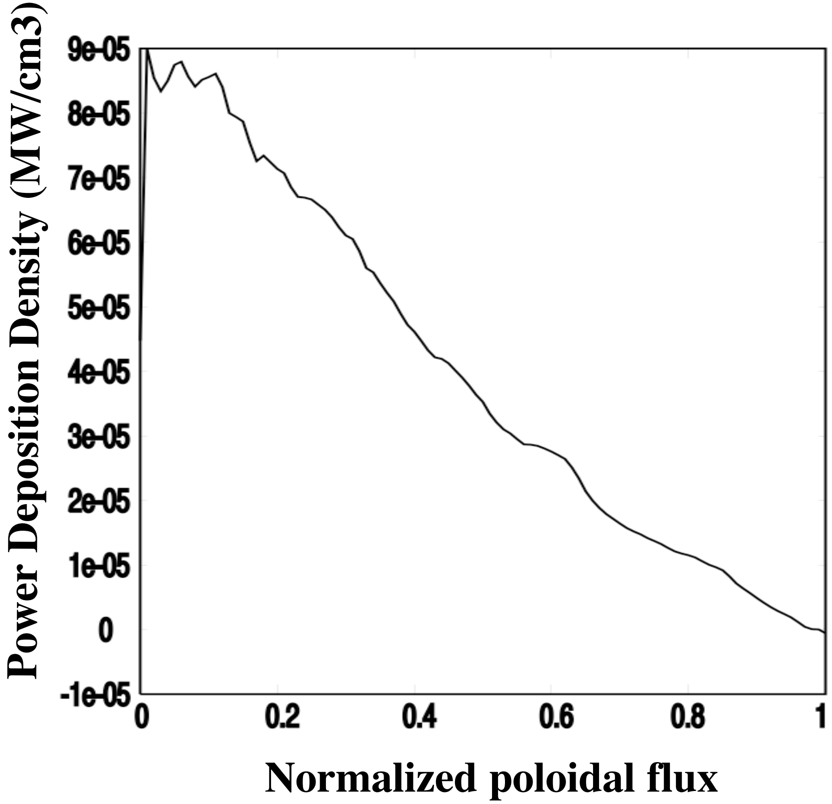
Beam Ion Density Profile



NB Power Deposition profile



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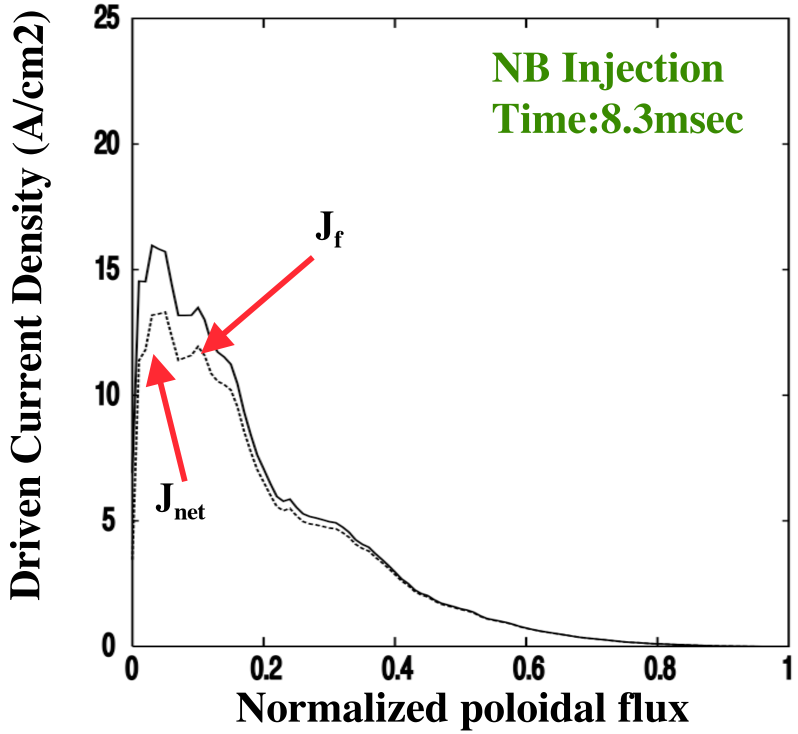
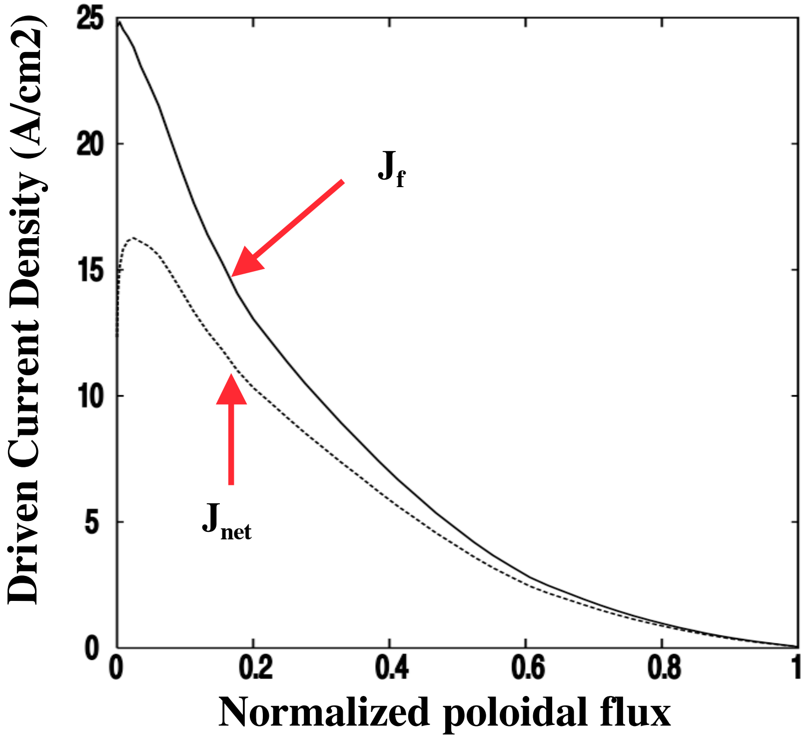
ORBIT-RF Result

at the end of 2 τ_s



NB Injection
Time:8.3msec

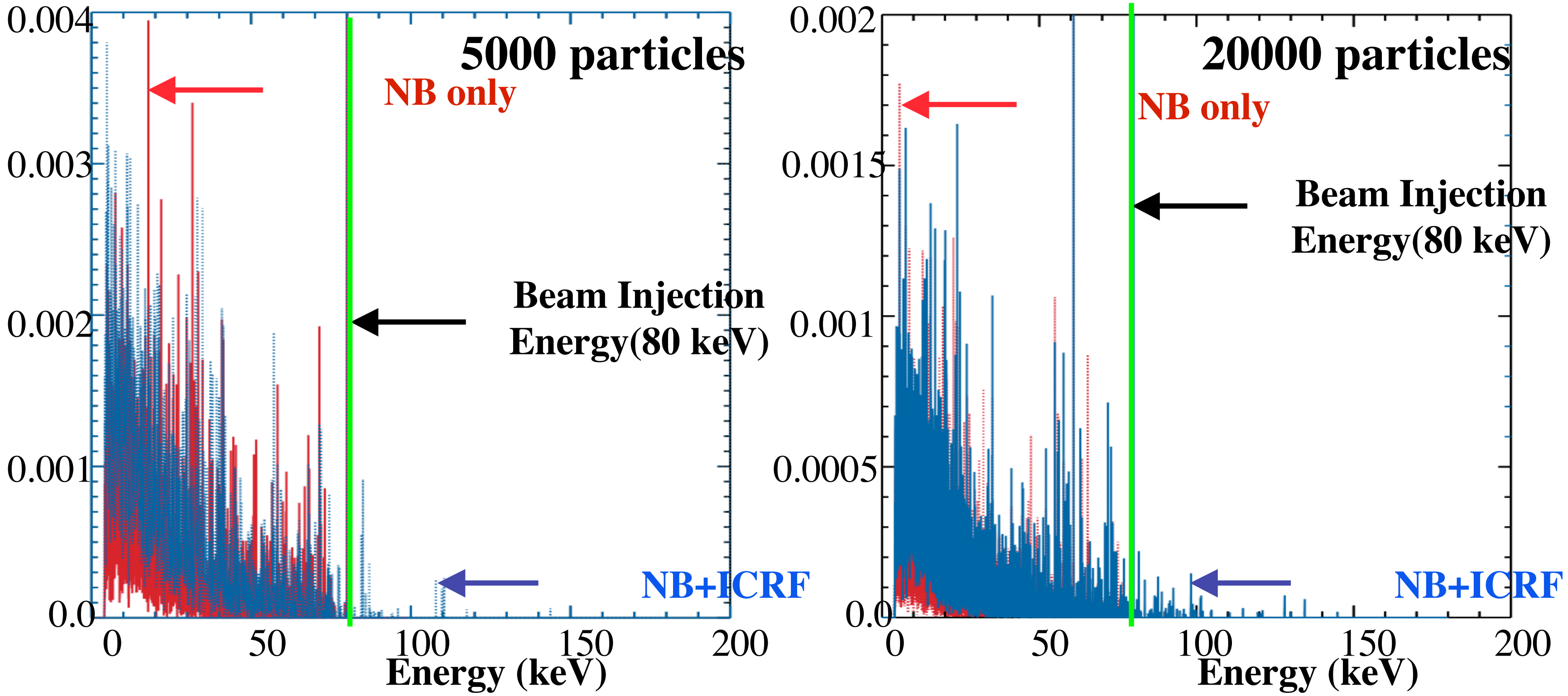
ONETWO Result



Tail Energies Extended Beyond Beam Injected Energy during ICRH

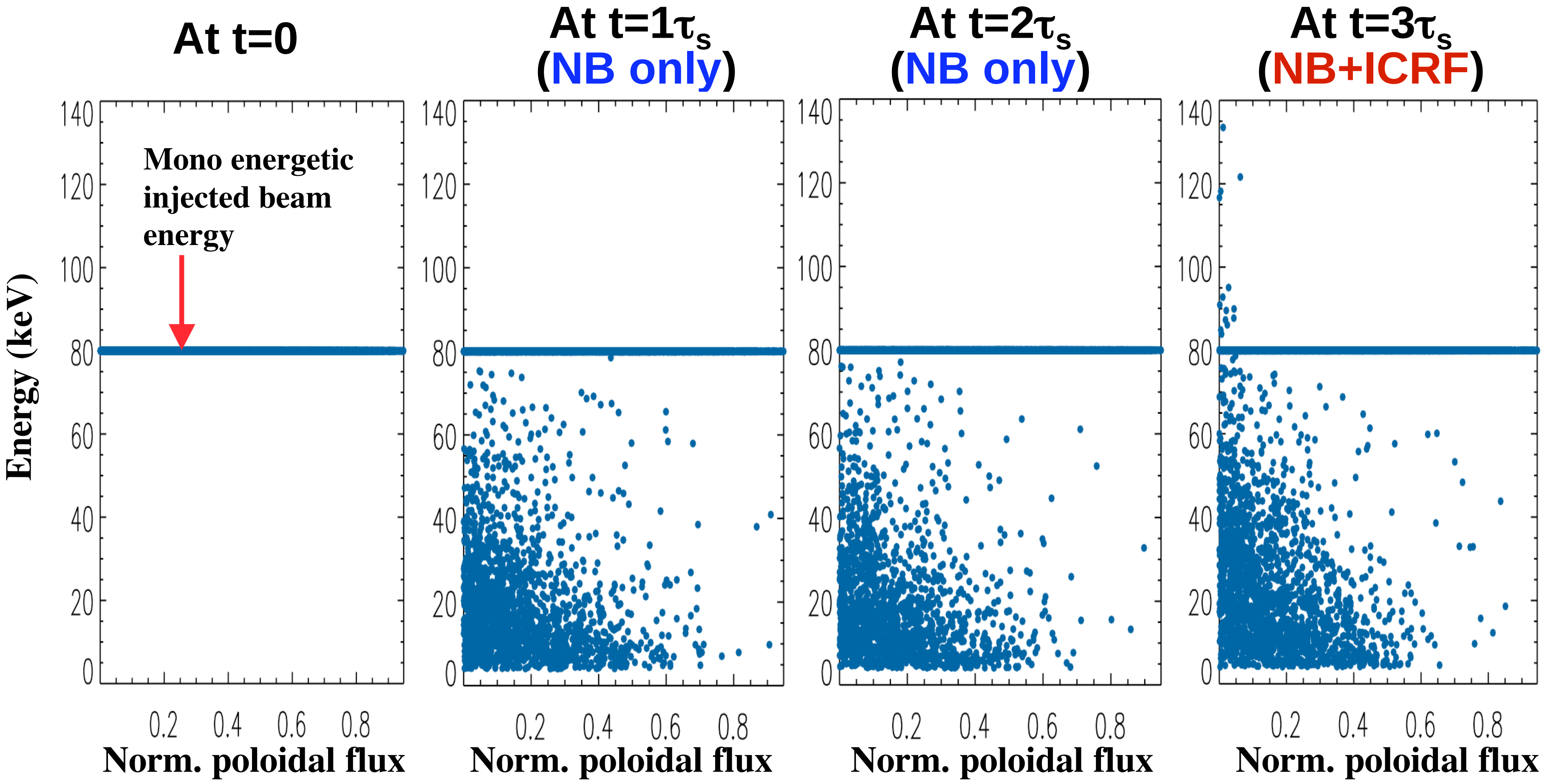
96043.2000

P_{nb}=2.7MW, E_{nb}=80keV, P_{rf}=1.1(MW), $|E_+|_{res}$~2000(V/m)



- **Tail energy enhancement validated with 5000 and 20000 particles with similar qualitative features**

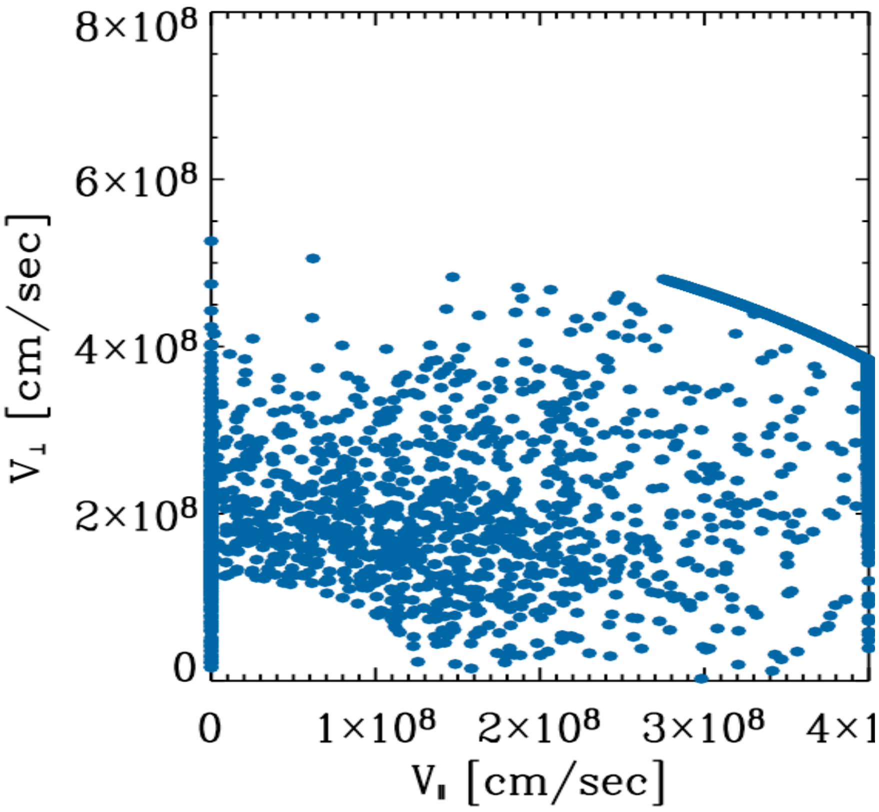
Time Evolution of Spatial Distribution of Energetic D Beam Ions Shows Energetic Tail Peaking On-Axis



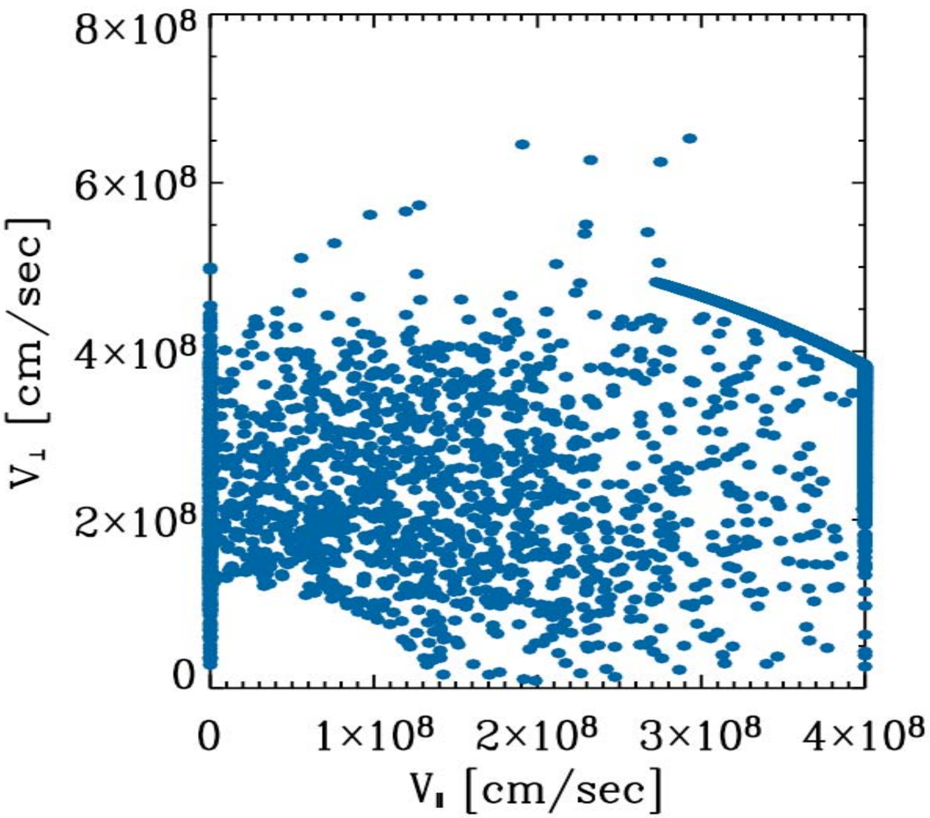
- The peaking can be explained by ICRF interaction with the beam ions

Velocity Space Distributions of Energetic D Beam Ions at $3\tau_s$ Validated the Physics of ICRH

NB only



NB+ICRF



Neutron Enhancement (S_n)

- **Neutron enhancement is calculated using**

$$S_n = \left[\sum_{i=1}^{n} <\sigma v>_i \, w_i\right]^{NB+RF} \Big/ \left[\sum_{i=1}^{n} <\sigma v>_i \, w_i\right]^{NB\_only}$$

- **The ORBIT-RF simulation results are compared with the experimental ones for two DIII-D discharges, 96043.02000 and 96028.02650 with the very different plasma parameters**

Experimental and Theoretical Results for the neutron Enhancement S_n

1998 Experimental and Previous Simulation Results

E_{nb}=73-86keV, P_{nb}<2.7MW

P_{RF} >0.7MW, $n_{//} \approx 5$, f_{RF}=60MHZ,

R0 ≈ 1.7m, a ≈0.6m, B_0=1.9T

R_T=76cm(Right)-115cm(Left)

I_p=1.2MA, $n_e = 3 \times 10^{13}$ cm^{-3}

- Experimental data showed the enhancement of measured neutron rates of 1 ~ 2
- Previous ray tracing calculations using similar experimental parameters showed higher absorbed power of beam ions (~40%)

Comparison results

96043.02000

$n_{e0} = 0.51 \times 10^{14}$ (cm^{-3})

$|E_+| = 2000$(V/m)

E_{nb} = 80 keV

Prf = 1.1 MW

P_{NB}= 2.7 MW

96028.02650

$n_{e0} = 0.23 \times 10^{14}$ (cm^{-3})

$|E_+| = 800$(V/m)

E_{nb}= 77 keV

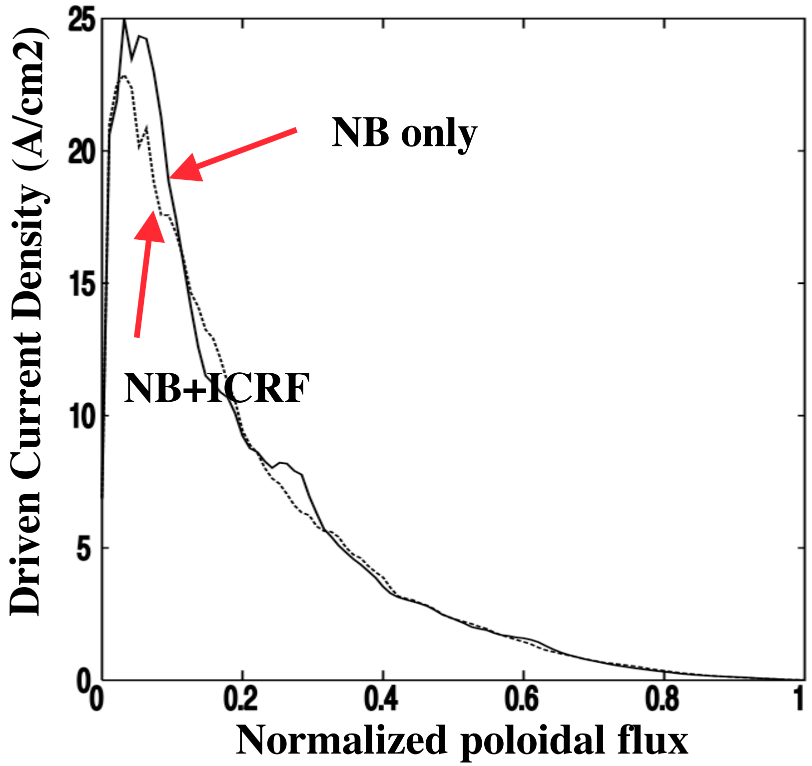
Prf = 0.7 MW

P_{NB}= 1.2 MW

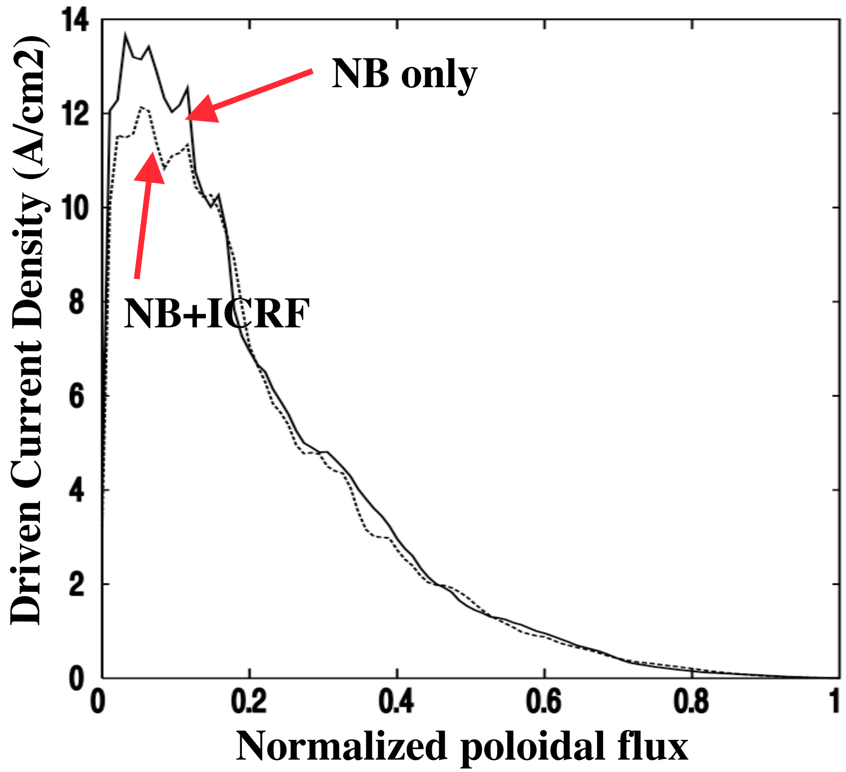
	Exp	Simulations		
	Sn	Sn	E_+(V/m)	P_{ab_RF} (%)
96043	1.36	1.25	2000	12.3
		1.1	1000	6.3
96028	1.1	1.19	800	6.0

Beam Ion Driven Current seems slightly reduced due to ICRF wave absorption

96043.02000



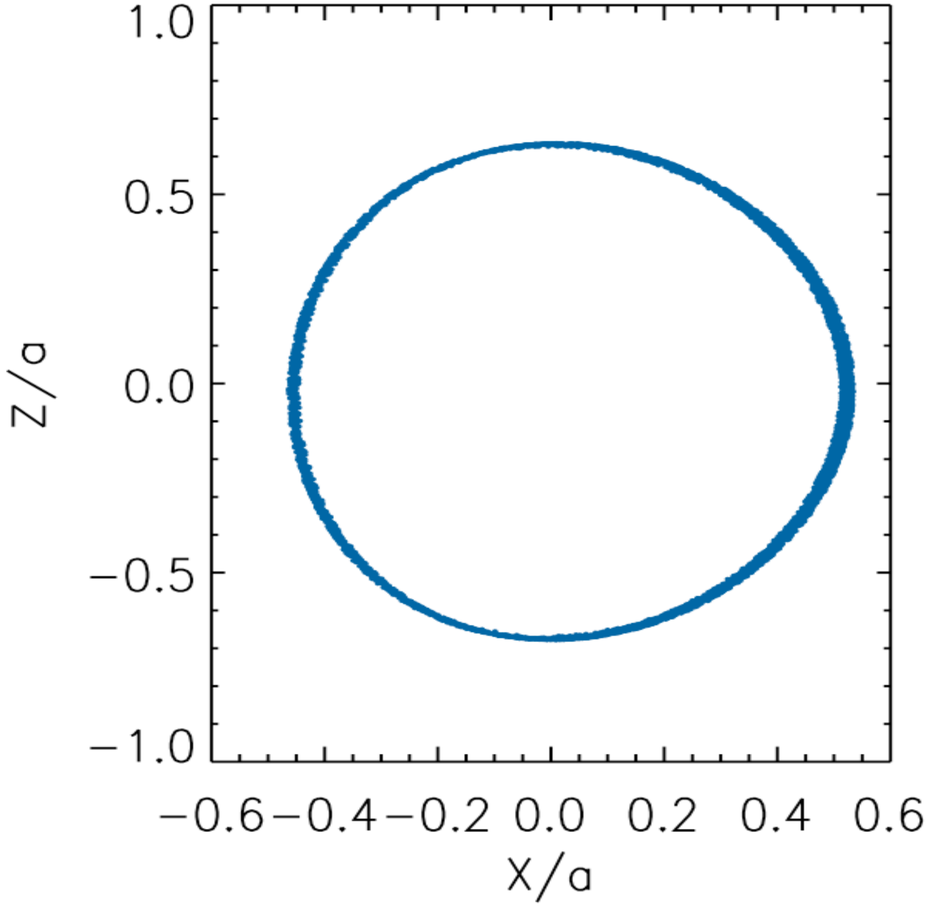
96028.02650



Reduction of Beam Current Possibly due to Trapping

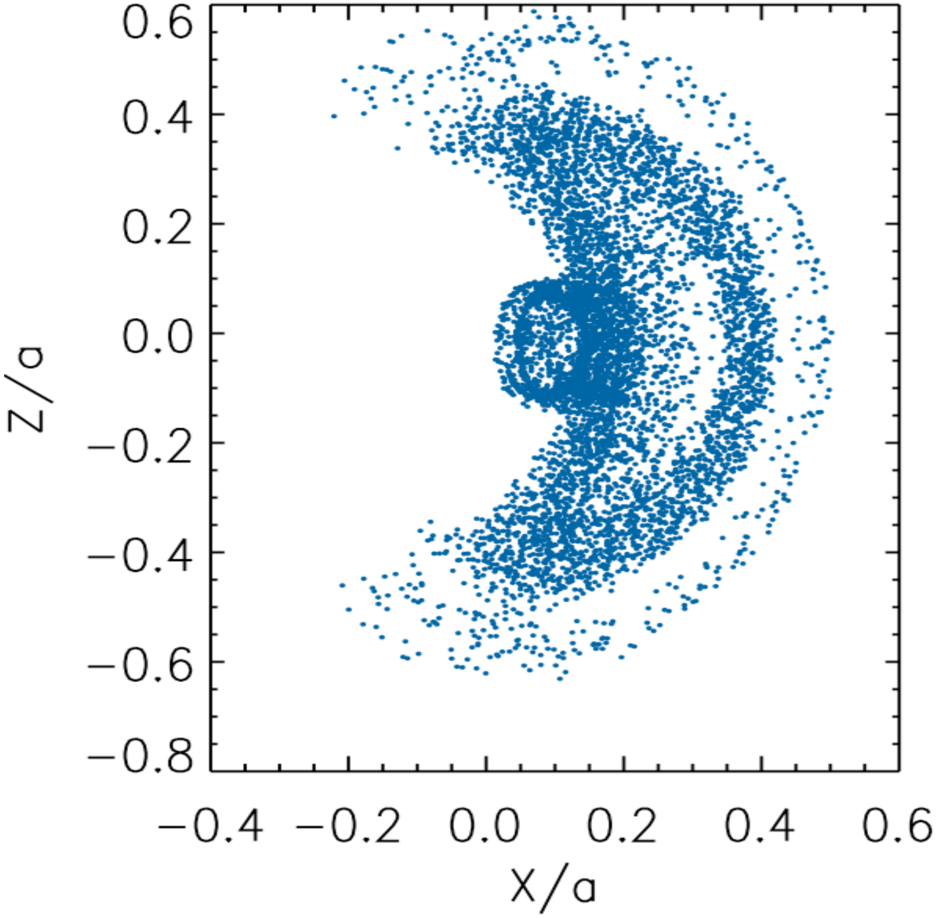
NB only

Non-Resonant Beam ion

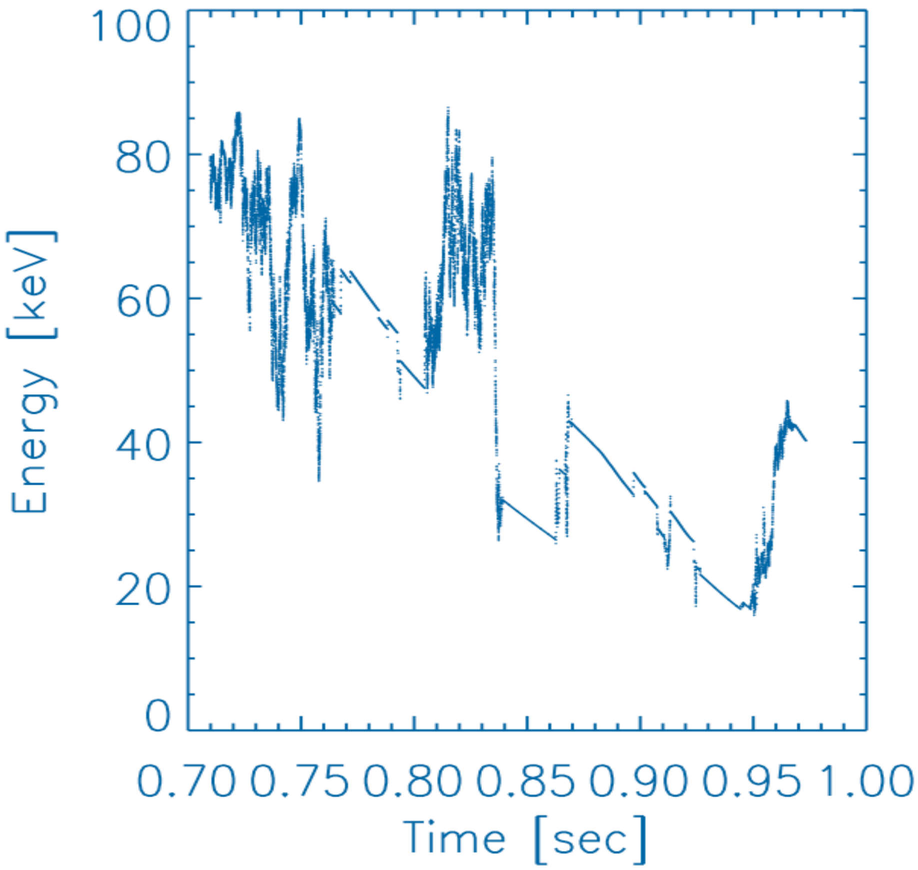


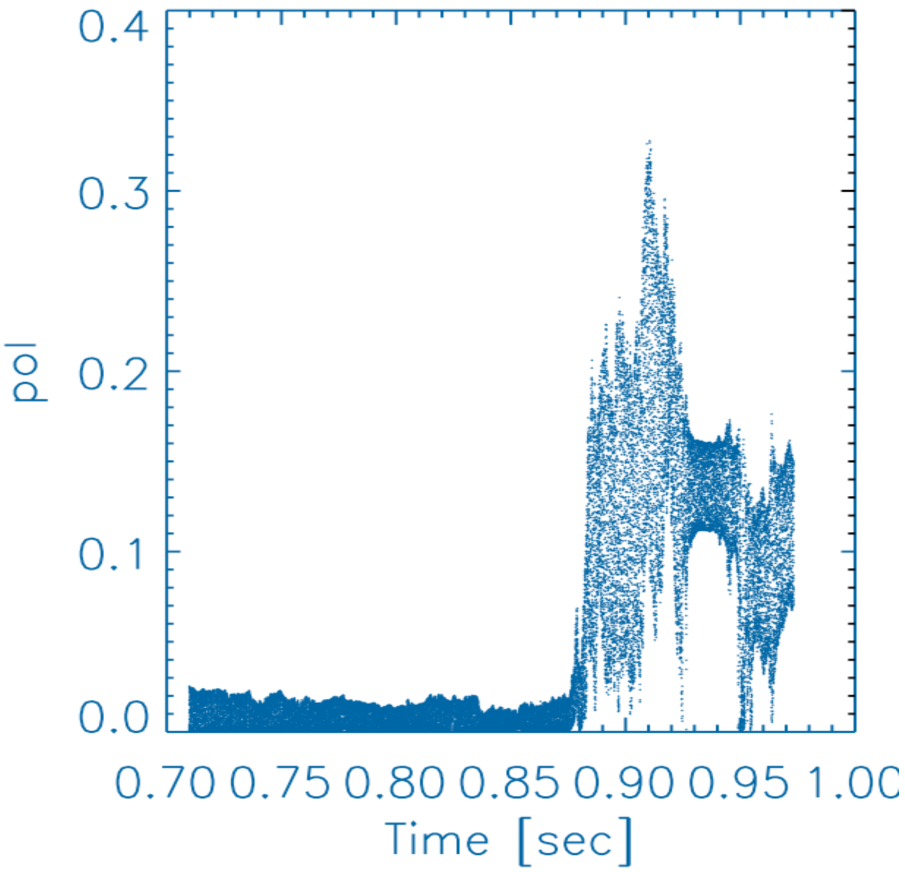
NB + ICRF

Resonant Beam ion

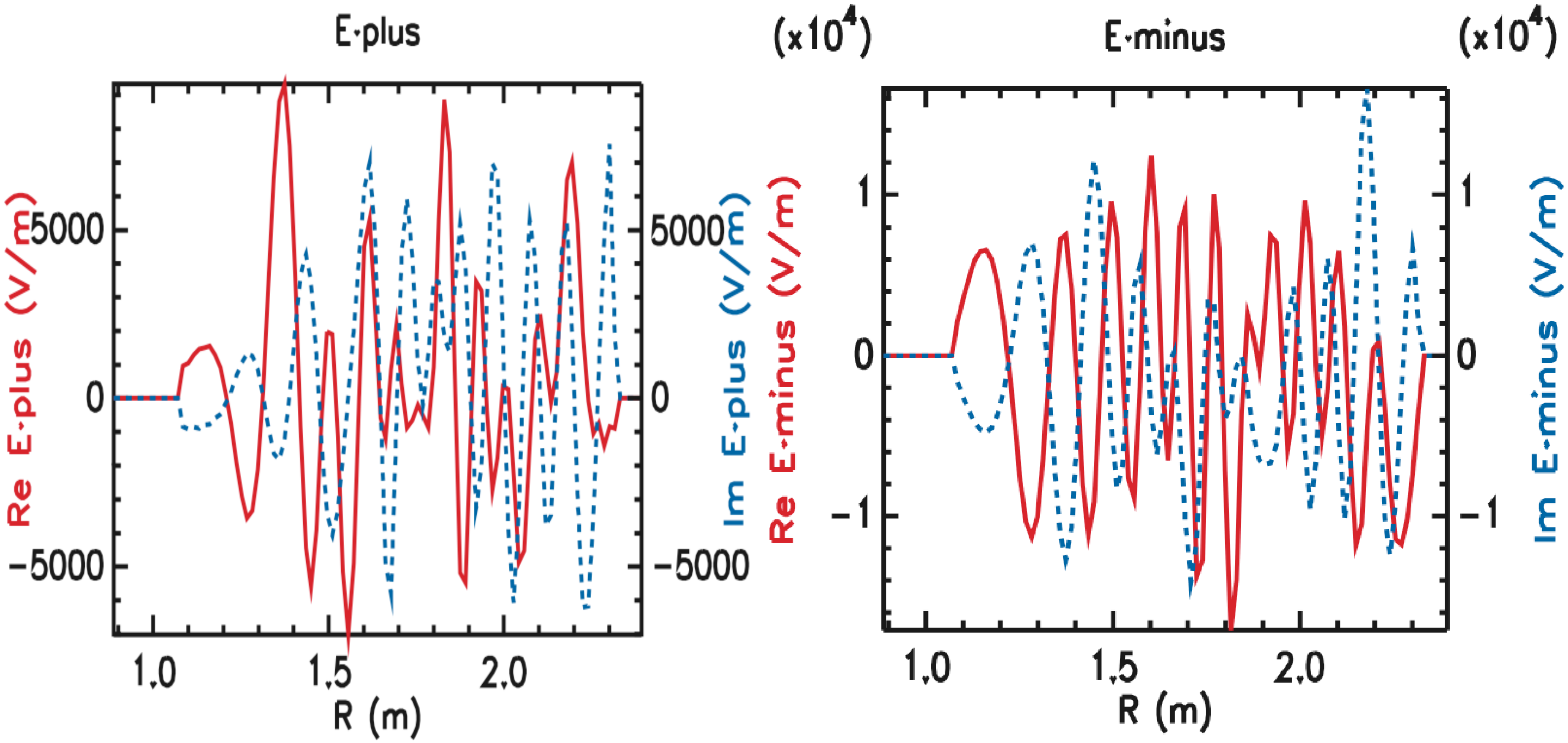


Trajectories of Resonant Beam Ion





E_+ and E_- using AORSA2D at ORNL (by F.Jaeger) for 96043.02000



Summary and Discussion

- The experimentally observed interaction between beam ions and ICRF waves at 4th harmonic during RF pulses of NB heated plasma is reproduced in the ORBIT-RF simulations within reasonable agreement using estimated magnitude of $|E_+|$ based on a simple model .

  - The tail energies of beam ions are extended above the injected beam energy and is peaked on-axis

  - The calculated neutron enhancement using quasilinear high harmonic RF operator is in qualitative agreement with experimental results

- There is some sensitivity of the results to the magnitude of $|E_+|$, hence a more accurate wave model is required for quantitative comparisons and predicition.

Application of ORBIT-RF to ITER/BPX

Important RF issues for ITER

- High harmonic ICRF absorption by energetic particles e.g. NB, alphas - damping on energetic particles with large $k_\perp\rho$ (Choi, RF Conf. 2003)
- MHD stabilization of energetic tails generated by ICRF (Chan, APS 2002)
- Non-inductively driven FWCD
- Plasma rotation and momentum transport of ICRF produced energetic tails (Chan, Phys. Plasmas 2002)
- Synergism of NBI and ICRF heating

Improvements to ORBIT-RF Required

- Coupling of ORBIT-RF to a full-wave code and iterative full-wave calculation with non-Maxwellian fast ions
- Adding modules for energetic ion losses due to charge exchange and orbit loss-cones
- Self-consistent radial electric field effect on particle drift motion
- Multiple-resonant layer wave heating in a large device
- Coupling to a full-antenna spectrum