Simulation Study of Energetic Ion Distribution during Combined NBI and ICRF Heating in LHD

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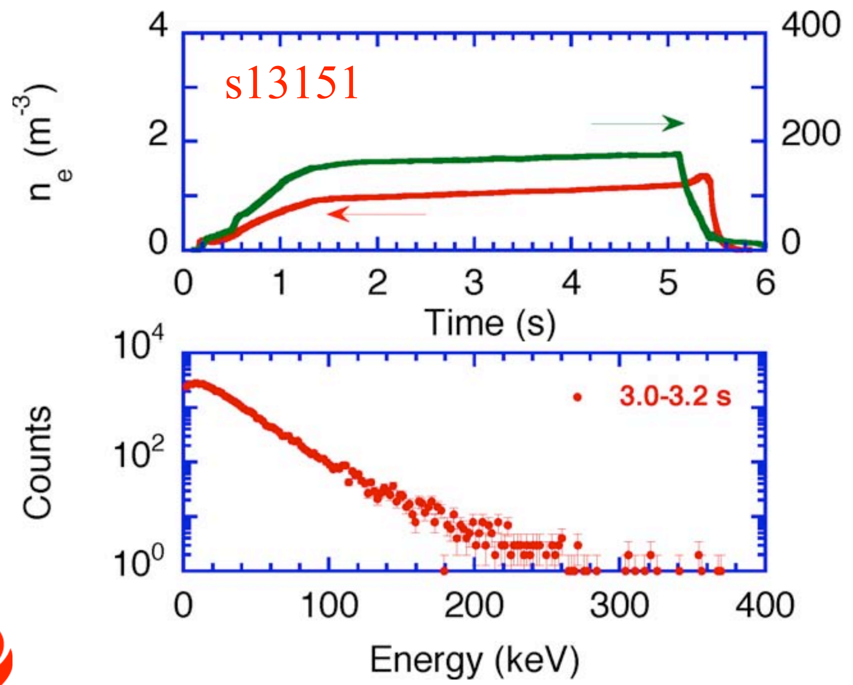
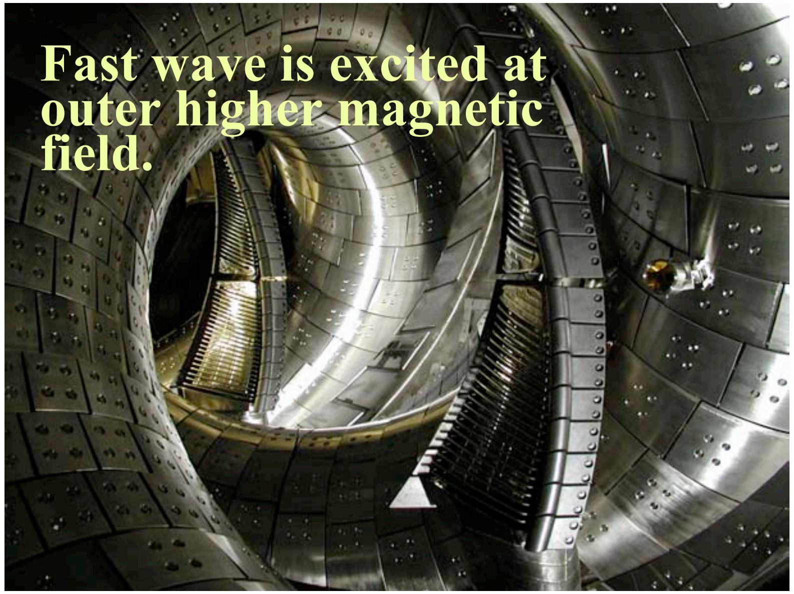
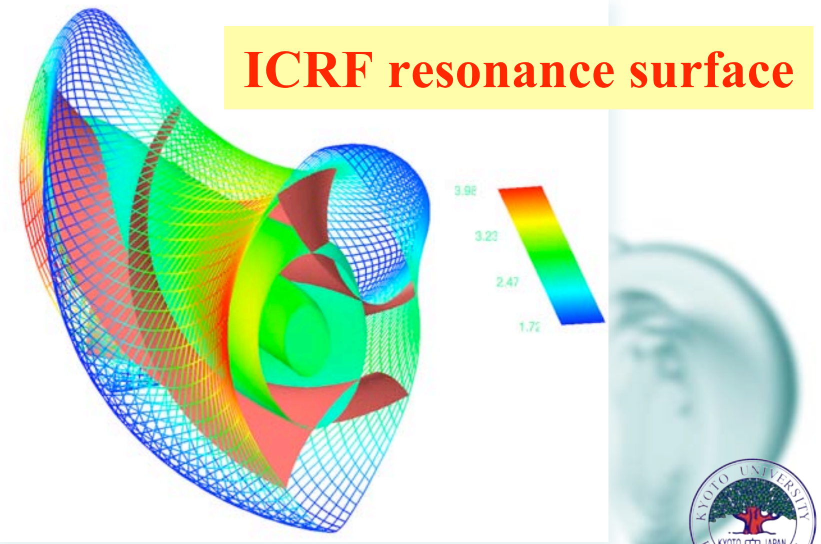
ICRF Heating Experiment in LHD

- **ICRF heating experiments have been successfully done and have shown significant performance (steady state experiments) of this heating method in LHD.**
  (Fundamental harmonic minority heating)
- **Up to 800keV of energetic tail ions have been observed by NDD-NPA.**

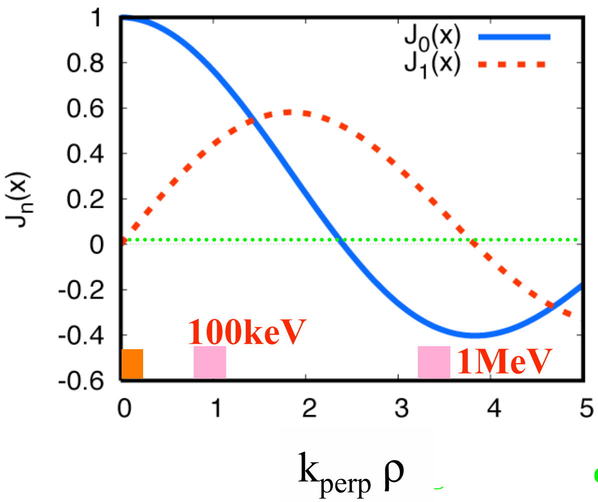


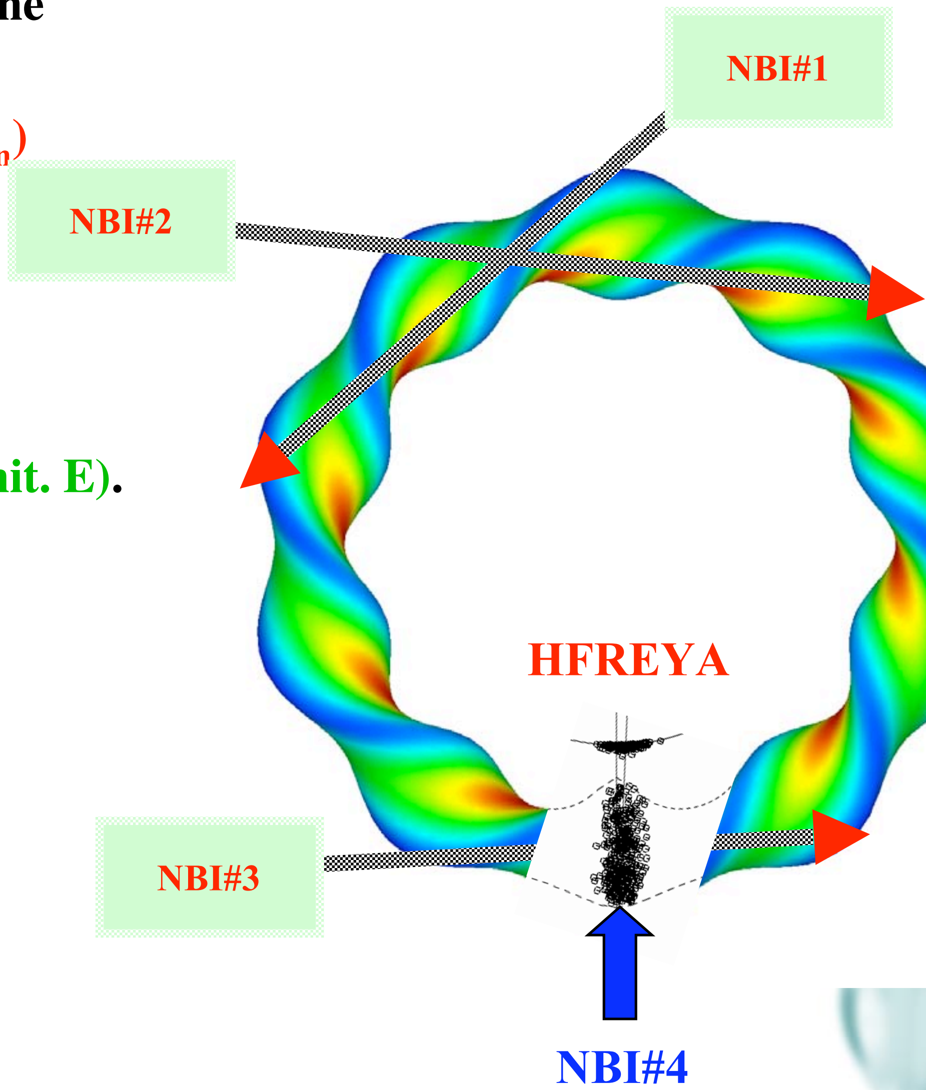




Perpendicular NBI and 2nd Harmonic ICRF Heating

- **Higher harmonic heating is efficient for the energetic particle generation.**
  (Acceleration, Δv_{perp}, is proportional to J_n)
- **The perpendicular injection NBI has been installed in LHD (2005).**
  NBI#4 P < 3MW (<6MW), E= 40keV
- **The perp. NBI beam ions would enhance the 2nd-harmonics ICRF heating (high init. E).**
- **We investigate the combined heating of perp. NBI and 2nd-harmonics ICRF.**

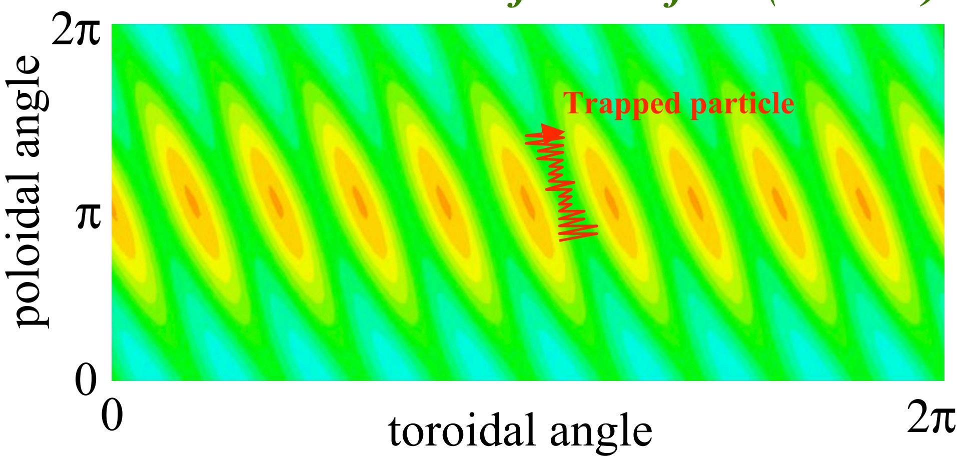


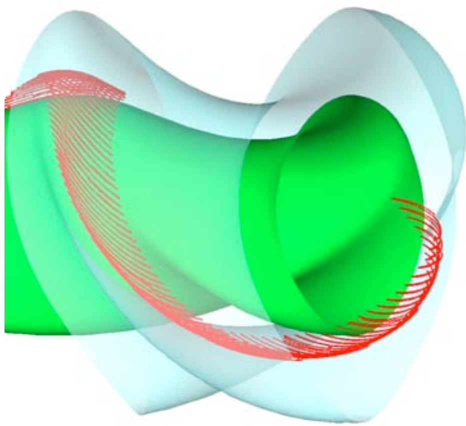


ICRF Heating in Helical Systems

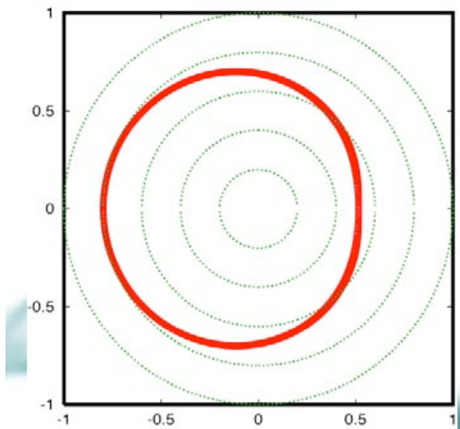
- ICRF heating generates **highly energetic tail ions**, which **drift around the torus** for a long time (typically on a collisional time scale).
- Thus, the **behavior of these energetic ions** is strongly affected by the characteristics of the drift motions, that **depend on the magnetic field configuration**.
- In particular, in a 3-D magnetic configuration, **complicated drift motions of trapped particles** would play an important role in the confinement of the energetic ions and the ICRF heating process.
- **Global simulation is necessary!**

mod-B on flux surface (r/a=0.6)





Orbit in the real coordinates.



Orbit in Boozer coordinates.

ICH+NBI Simulation Model by GNET

- **We solve the drift kinetic equation as a (time-dependent) initial value problem in 5D phase space based on the Monte Carlo technique.**

$$\frac{\partial f_{beam}}{\partial t} + (\mathbf{v}_{//} + \mathbf{v}_D)\cdot\nabla f_{beam} + \mathbf{a}\cdot\nabla_{\mathbf{v}} f_{beam} - C(f_{beam}) - Q_{ICRF}(f_{beam}) - L_{particle} = S_{beam}$$

$C(f)$: linear Clulomb Collision Operator

Q_{ICRF} : ICRF heating term
wave-particle interaction model

S_{beam} : beam particle source
=> by NBI beam ions
(HFREYA code)

$L_{particle}$: particle sink (loss)
=> Charge exchange loss
=> Orbit loss (outermost flux surface)

- **The energetic beam ion distribution f_{beam} is evaluated through a convolution of S_{beam} with a characteristic time dependent Green function, $\mathcal{G}$.**

Monte Carlo Simulation for $\mathcal{G}$

- **Complicated particle motion**
  Eq. of motion in the Boozer coordinates (ψ,θ,ϕ,ρ_c)
  3D MHD equilibrium (VMEC+NEWBOZ)
- **Coulomb collisions**
  Liner Monte Carlo collision operator *[Boozer and Kuo-Petravic]*
  Energy and pitch angle scattering

$$C^{coll}(\delta f) = \frac{1}{\upsilon^2}\frac{\partial}{\partial \upsilon}\left[\upsilon^2 \nu_E \left(\upsilon \delta f + \frac{T}{m}\frac{\partial \delta f}{\partial \upsilon}\right)\right] + \frac{\nu_d}{2}\frac{\partial}{\partial \lambda}\left(1-\lambda^2\right)\frac{\partial \delta f}{\partial \lambda}, \qquad \lambda = \frac{\upsilon_{//}}{\upsilon}$$

- **The Q_{ICRF} term is modeled by the Monte Carlo method.**
  When the test particle pass through the resonance layer the perpendicular velocity of this particle is changed by the following amount

$$\Delta \mathrm{v}_\perp = \sqrt{\left(\mathrm{v}_{\perp 0} + \frac{q}{2m} I\left(\underline{E_+}\left(J_{n-1}(k_\perp \rho)\right.\right.\cos\phi_r\right)^2 + \frac{q^2}{4m^2}\left\{I\left(\underline{E_+}\left(J_{n-1}(k_\perp \rho)\right.\right.\right\}^2 \sin^2\phi_r} - \mathrm{v}_{\perp 0}$$

$$\approx \frac{q}{2m} I\left(\underline{E_+}\left(J_{n-1}(k_\perp \rho)\right.\right.\cos\phi_r + \frac{q^2}{8m^2 \mathrm{v}_{\perp 0}}\left\{I\left(\underline{E_+}\left(J_{n-1}(k_\perp \rho)\right.\right.\right\}^2 \sin^2\phi_r$$

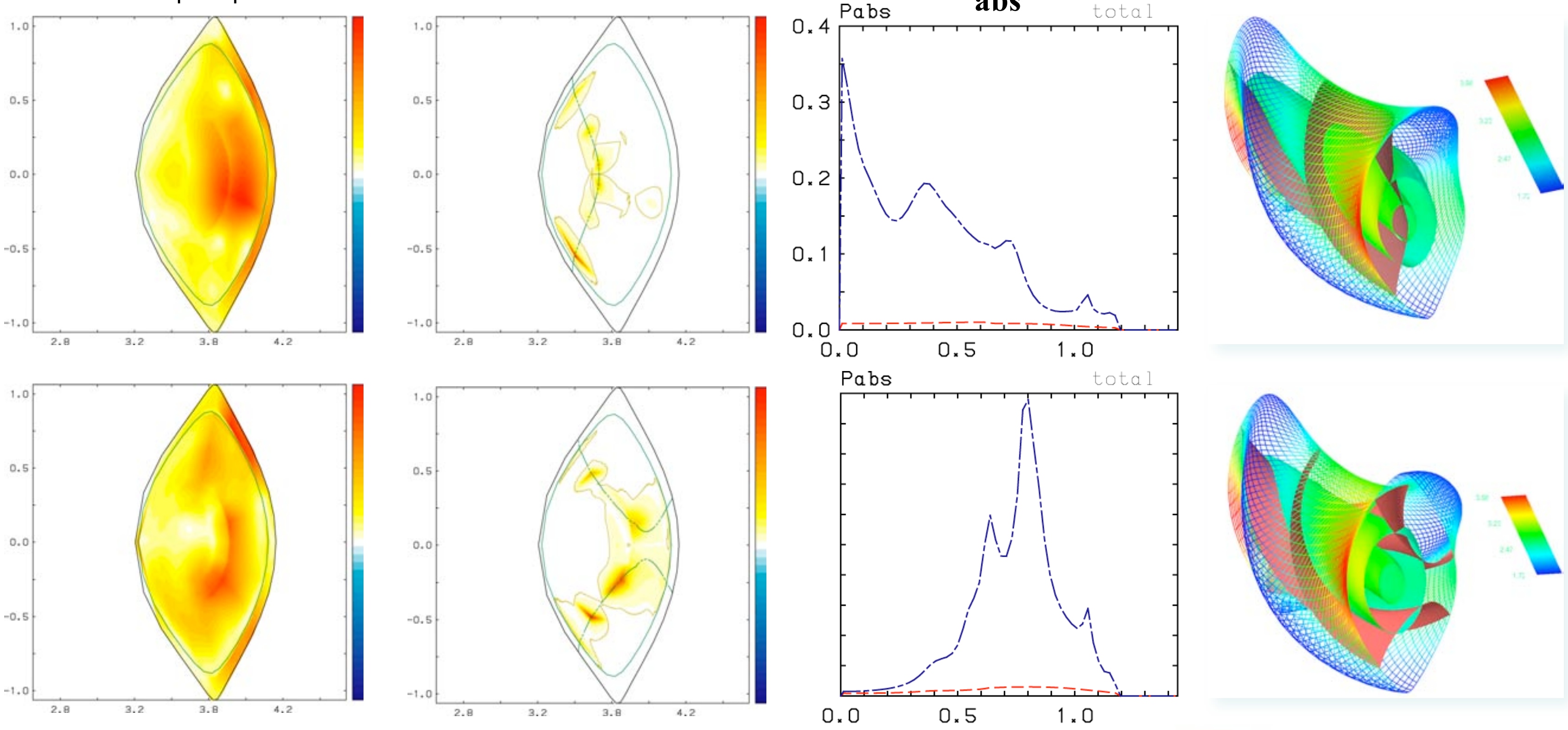
$$I = \min\left(\sqrt{2\pi / n\ddot{\omega}}\ ,\ 2\pi (n\ddot{\omega}/2)^{-1/3} Ai(0)\ \right)$$

RF Electric Field by TASK/WM

$\phi \times 10 = 0$

On-axis

Off-axis



Simplified RF wave model

RF electric field: $E_{rf}=E_{rf0}\tanh((1-r/a)/l)(1+\cos\theta)$, $E_{rfo}=0.5\sim1.5$kV/m

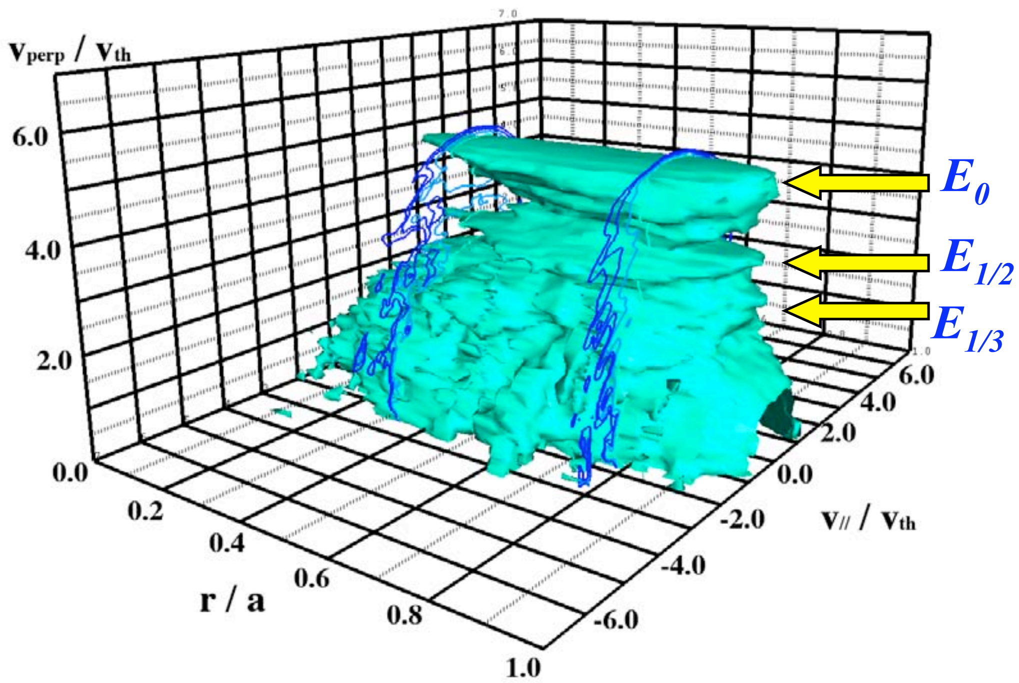
$k_{perp}=62.8\text{m}^{-1}$, $k_{//}=0$ is assumed.

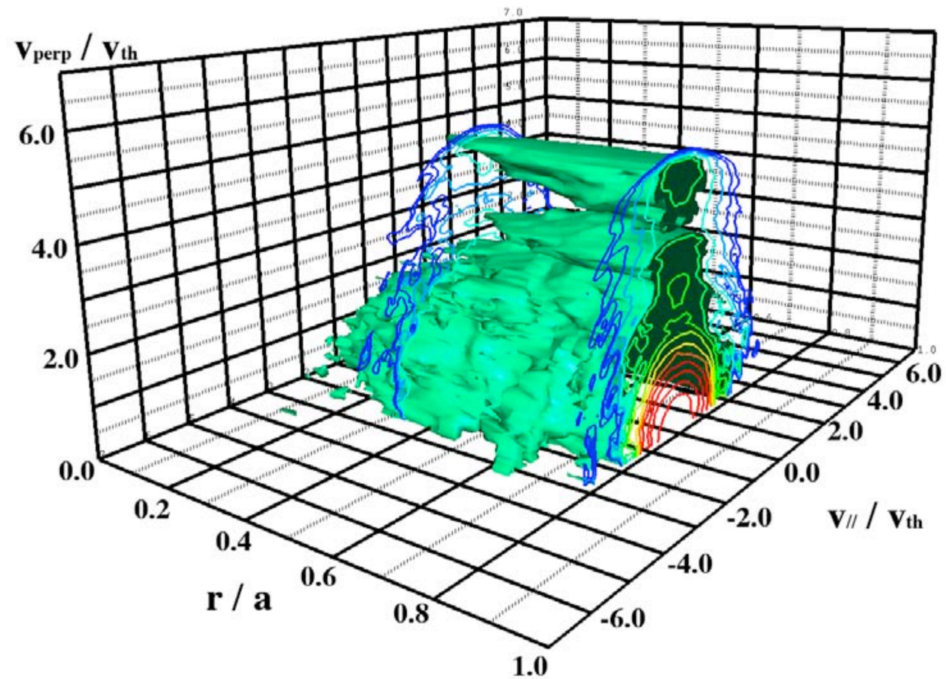
Wave frequency: $f_{RF}=38.47$MHz,

Beam Ion Distribution of Perp. NBI w/o ICH (v-space)

Perp. NBI beam ion distribution
R_{ax}=3.60m

$T_{eo}=T_{io}$=3.0keV, $n_{e0}=2.0\times10^{19}m^{-3}$, E_b=40keV



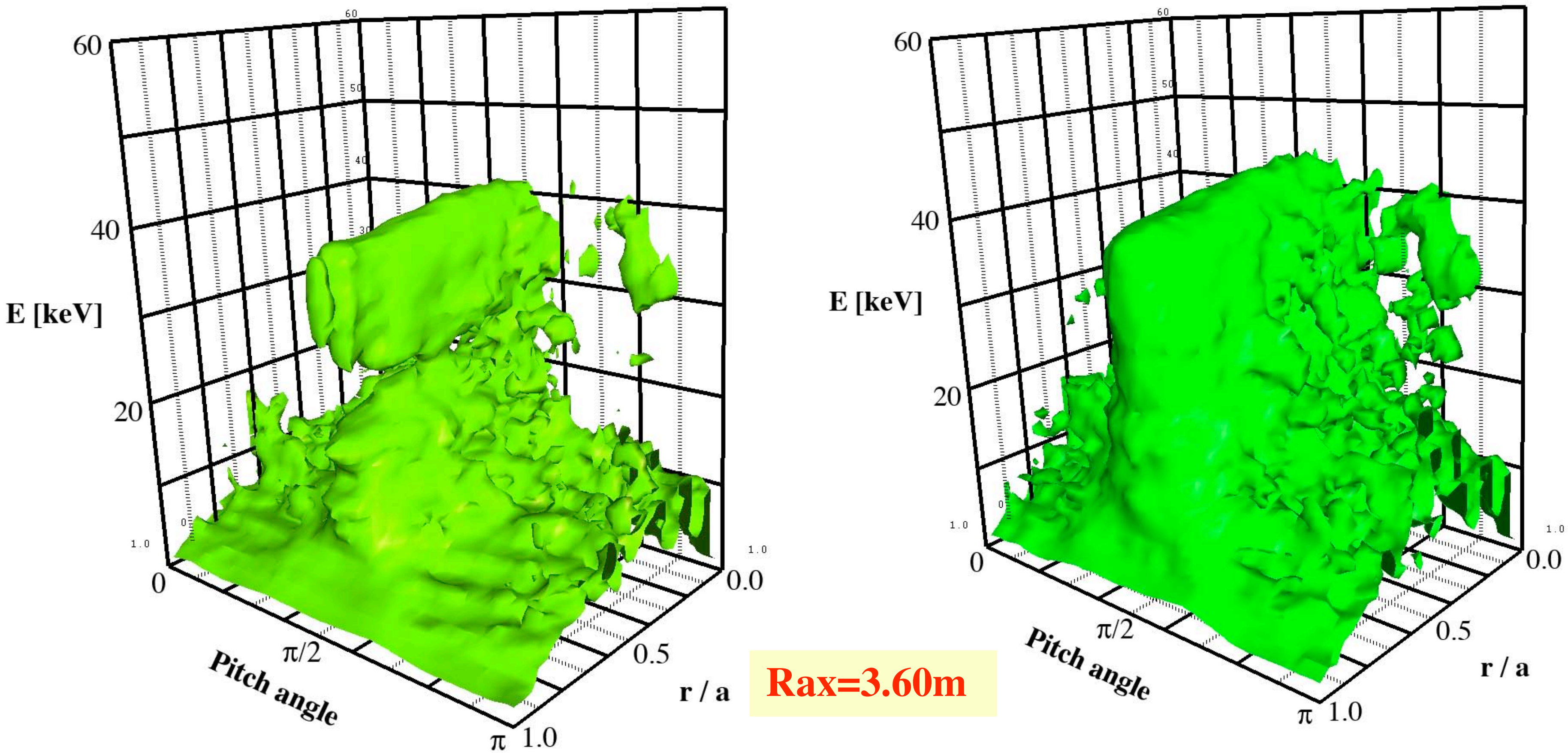


- **Higher distribution regions can be seen near the beam sources (E_0, $E_{1/2}$, $E_{1/3}$).** ***(left: lower level, right: higher level and cutting at r/a=0.8)***
- **The beam ion distribution shows slowing down and pitch angle diffusion in velocity space.**

Beam Ion Distribution of Perp. NBI w/o ICH

Perp. NBI beam ion distribution

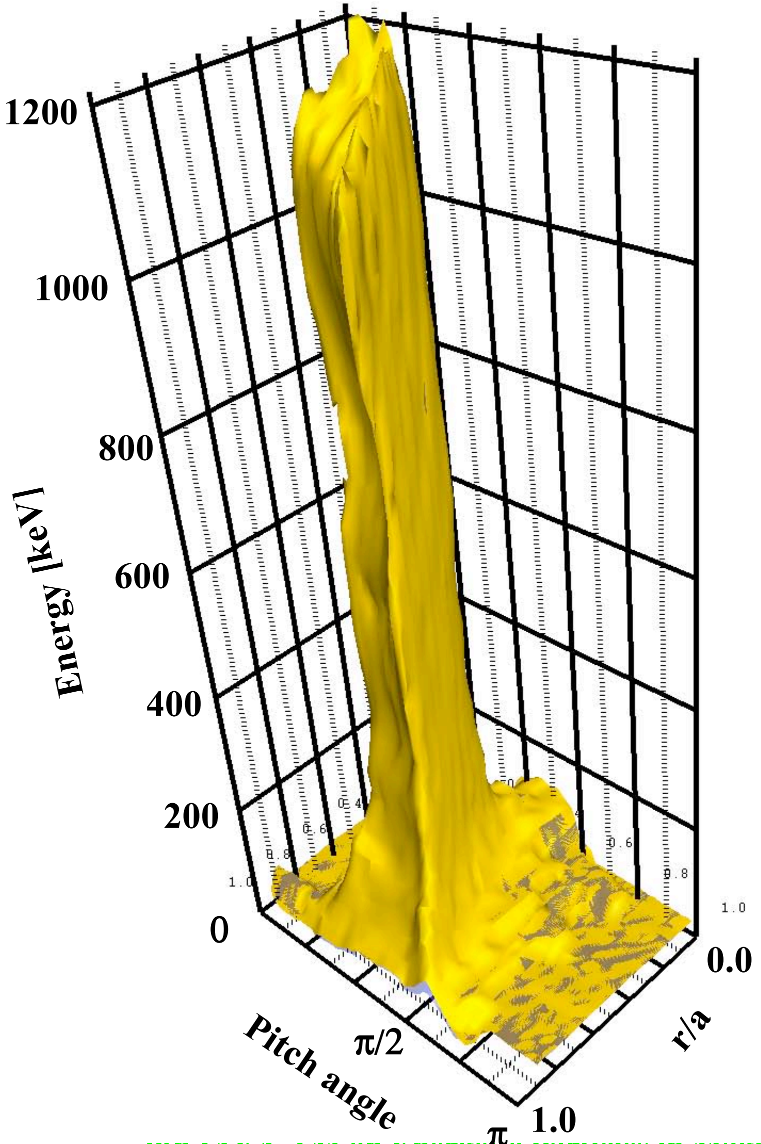
$T_{eo}=T_{io}=3.0\text{keV}$, $n_{e0}=2.0\times10^{19}\text{m}^{-3}$, $E_b=40\text{keV}$



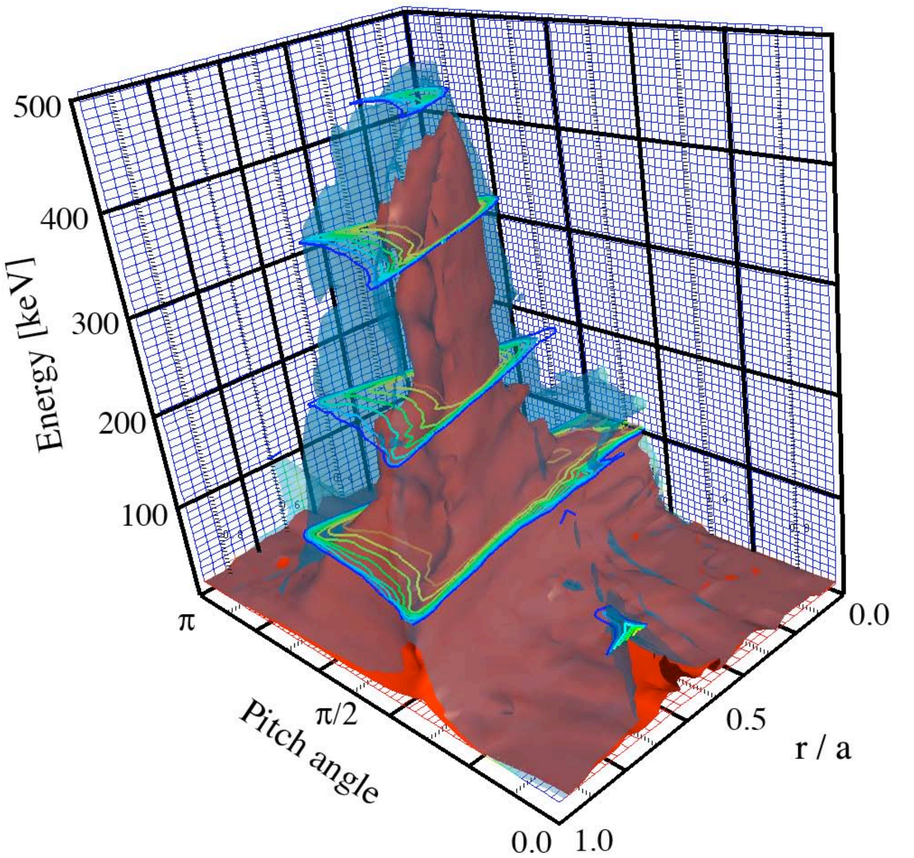
- Iso-surface plots of beam **ion distribution without ICH** in the 3D space, (E, pitch angle, r/a). *(left: higher level, right: lower level)*
- The **beam ion distribution** shows slowing down and pitch angle diffusion.

Beam Ion Distribution with 2nd Harmonics ICH

2nd-harmonic heating

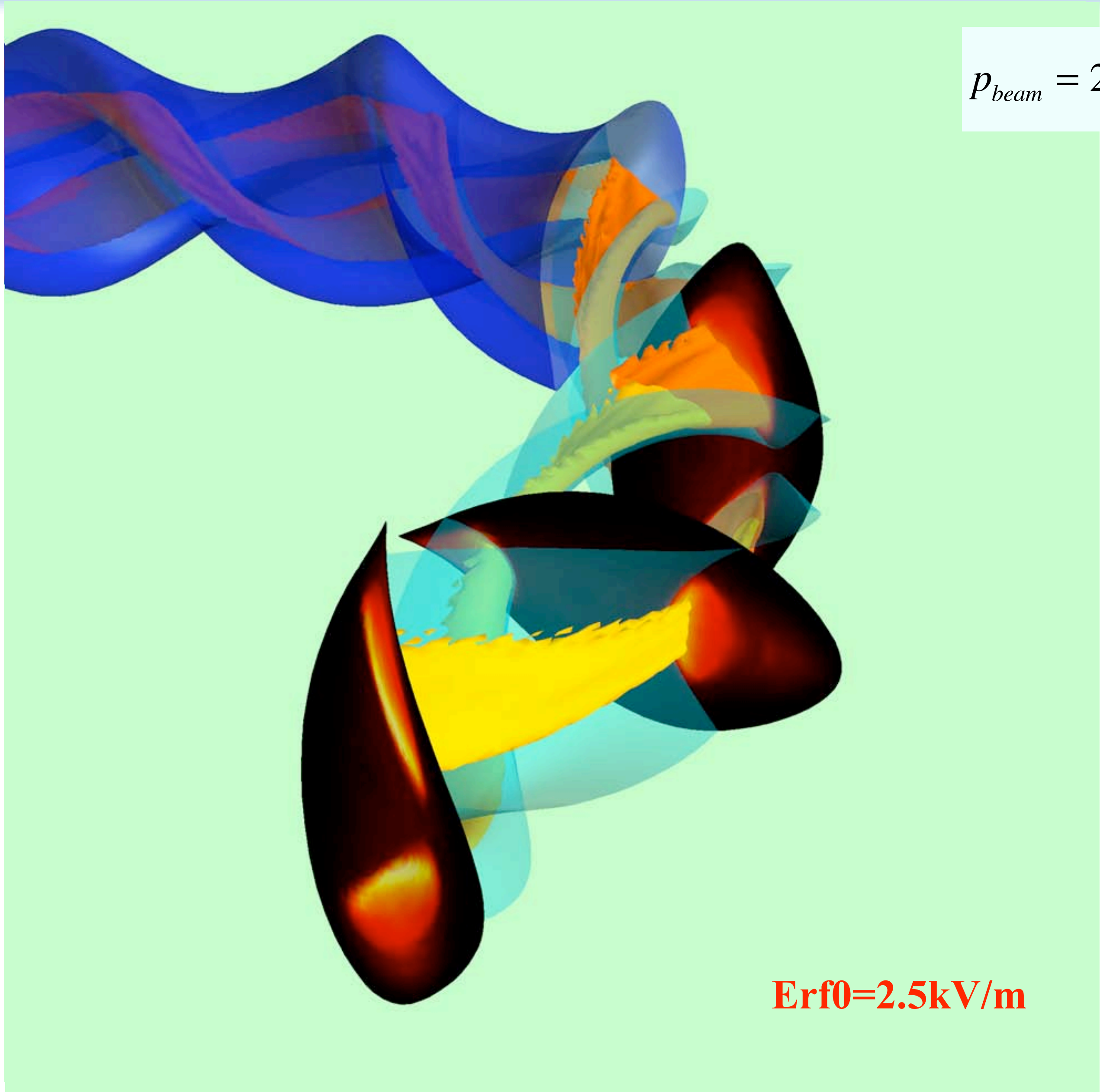


Fundamental heating



- We can see a large enhancement of the energetic tail formation by 2nd-harmonics ICH.
- It is also found that the tail formation occurs near r/a~0.5. (resonance surface and stable orbit)

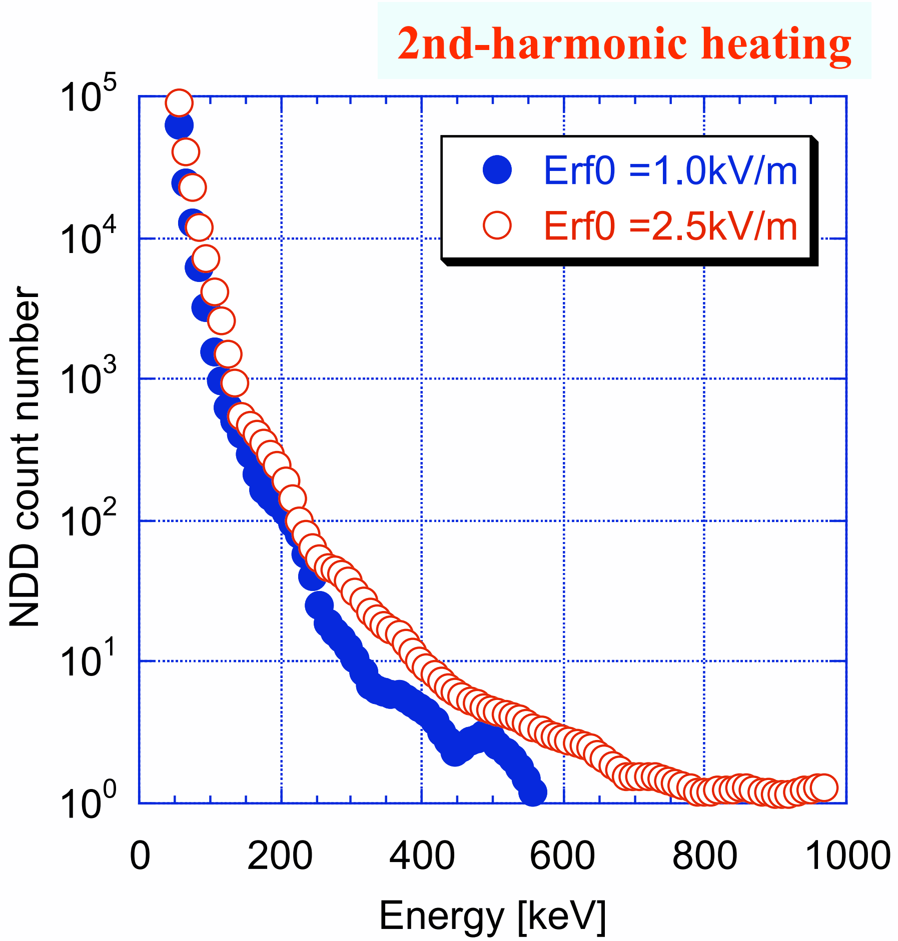
Beam Ion Pressure Profile with 2nd Harmonics ICH

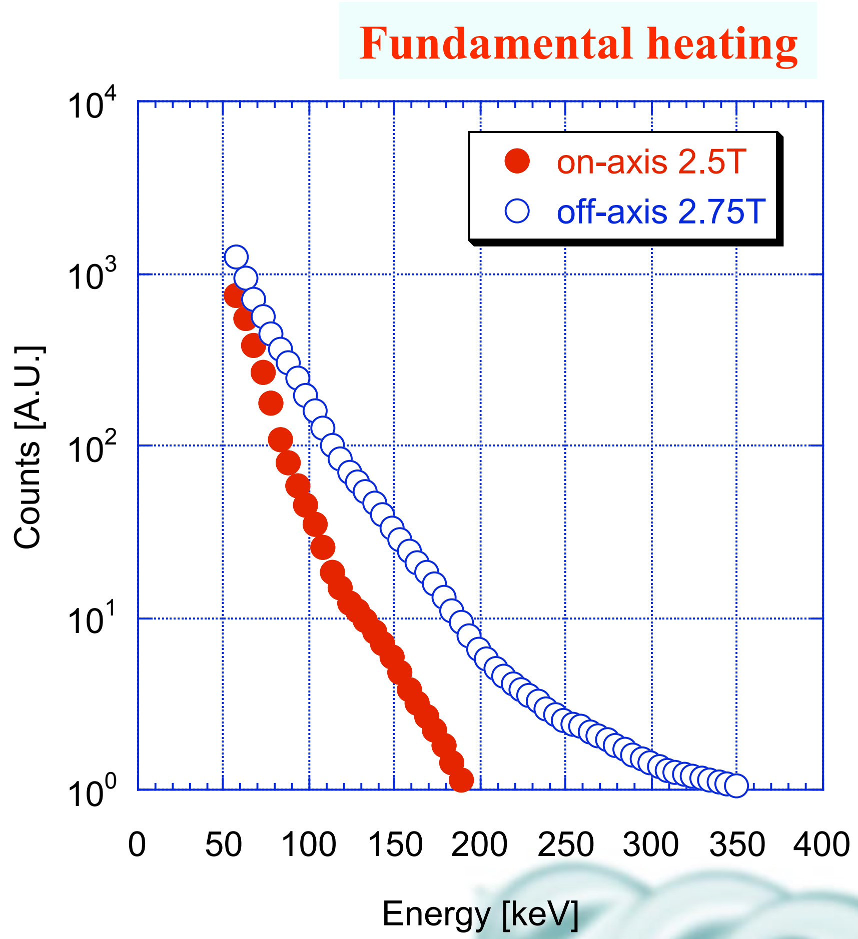


$$p_{beam} = 2\pi \int \frac{1}{2} m v^2 f(v_{//}, v_{\perp}) \mathrm{d}v_{//} v_{\perp} \mathrm{d}v_{\perp}$$

T_{eo}=T_{io}=1.6keV,
n_{e0}=1.0x$10^{19}$$m^{-3}$
B=2.75T@R=3.6m,
f_{RF}=76.94MHz, $k_{//}$=5m^{-1},
k_{perp}=62.8m^{-1}

Simulation of NDD-NPA (2nd ICRF+NBI)





- We have simulated the NDD-NPA using the GNET simulation results.
- The tail ion energy is enhanced to MeV order and a larger tail formation can be seen than that of the fundamental harmonic heating case.

Summary

- We have been developing an ICRF heating simulation code in toroidal plasmas using two global simulation codes: TASK/WM(a full wave field solver in 3D) and GNET(a DKE solver in 5D).
- The GNET (+TASK/WM) code has been applied to the analysis of ICRF heating in the LHD (2nd-harmonic heating with perp. NBI).
- A steady state distribution of energetic tail ions has been obtained and the characteristics of distributions in the real and phase space are clarified.
- The GNET simulation results of the combined heating of the perp. NBI and 2nd-harmonic ICRF have shown effective energetic particle generation in LHD
- The benchmarking with ORBIT-RF has been done assuming C-Mod plasma and preliminary results have been shown.
- Self-consistent analysis including the effect of energetic ion distribution on the fast wave propagation by TASK code is under way.