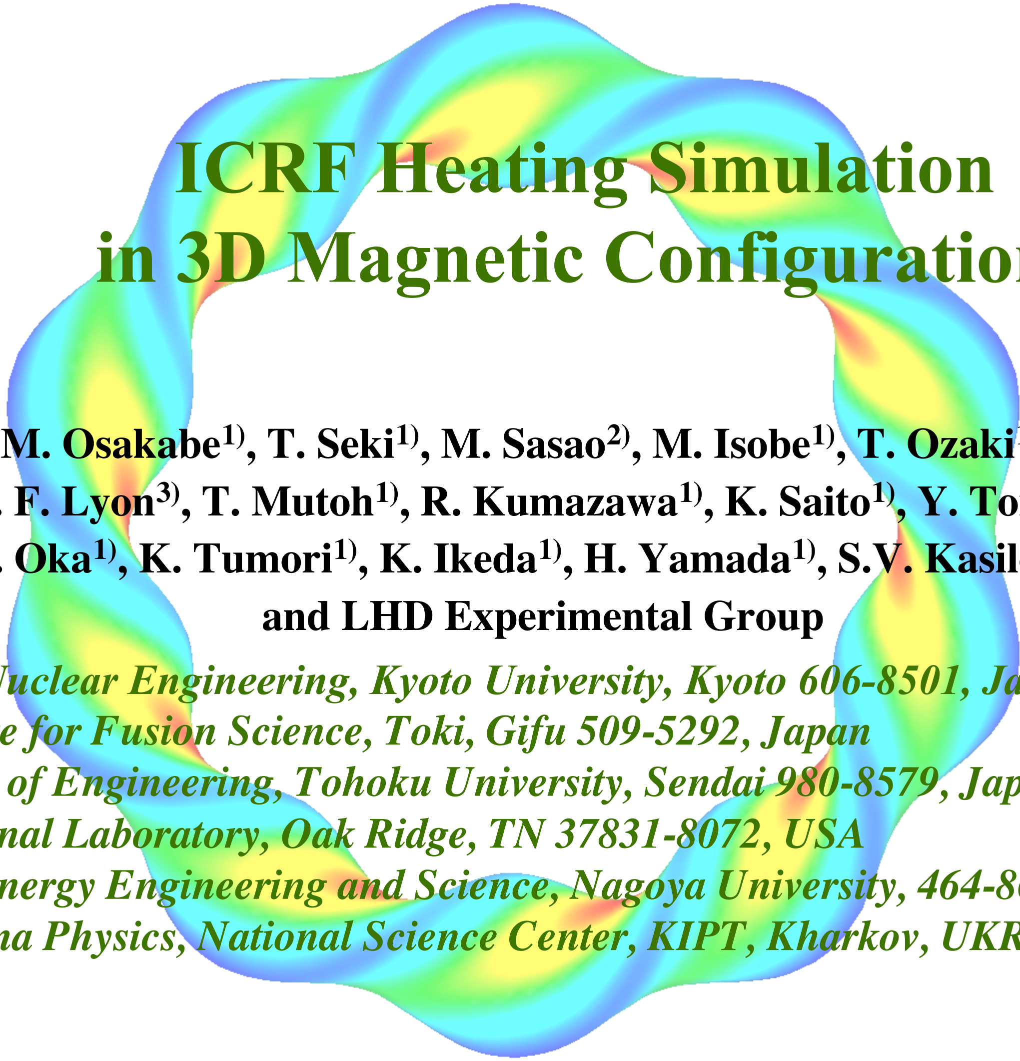

ICRF Heating Simulation in 3D Magnetic Configuration

S. Murakami, M. Osakabe[1), T. Seki[1), M. Sasao[2), M. Isobe[1), T. Ozaki[1), P. Goncharov[1), T. Saida[2), J. F. Lyon[3), T. Mutoh[1), R. Kumazawa[1), K. Saito[1), Y. Torii[4),T. Watari[1), Y. Takeiri[1), Y. Oka[1), K. Tumori[1), K. Ikeda[1), H. Yamada[1), S.V. Kasilov[5), A. Fukuyama, and LHD Experimental Group

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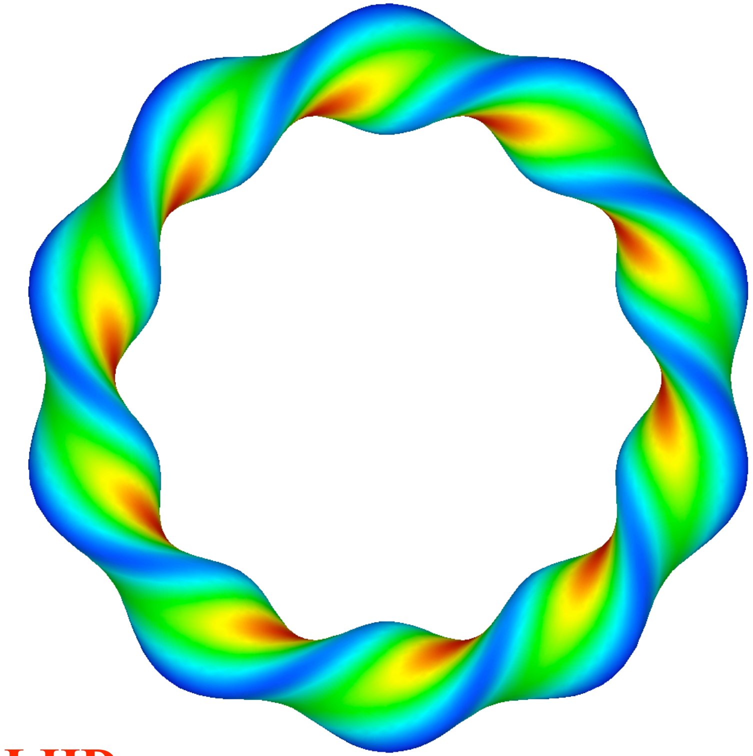
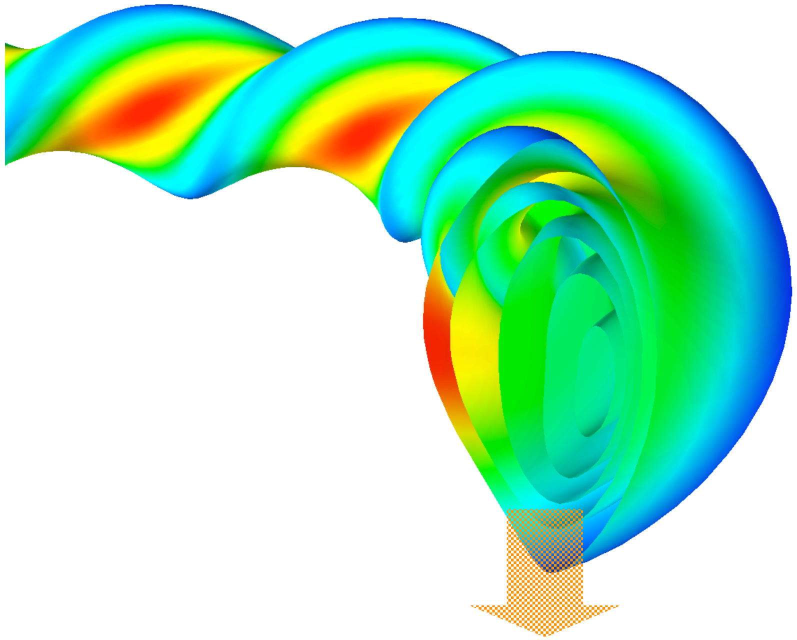
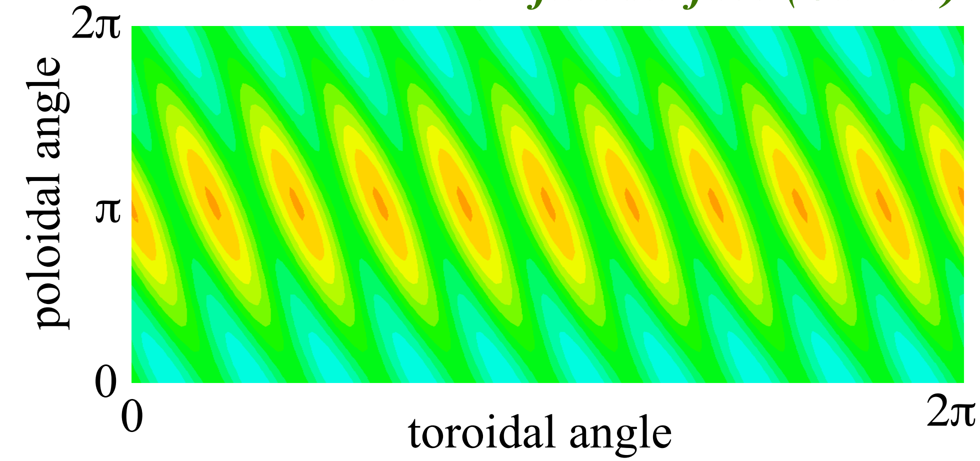
Magnetic Configuration of LHD





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



LHD

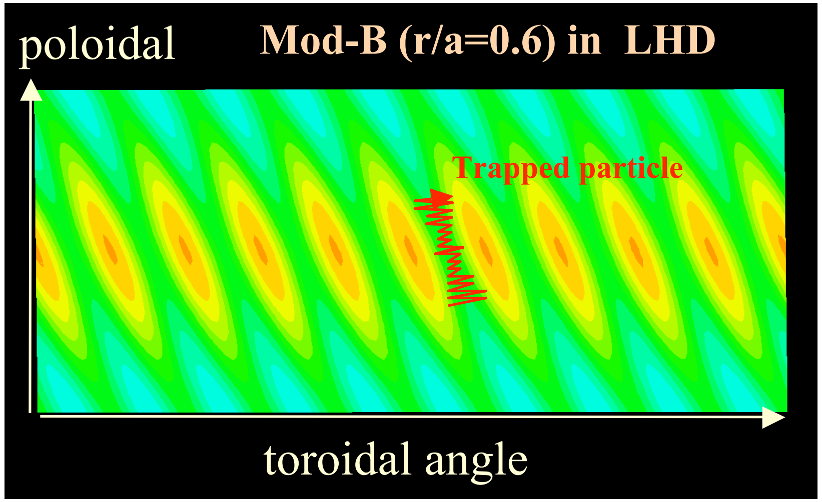
l=2, m=10 heliotron

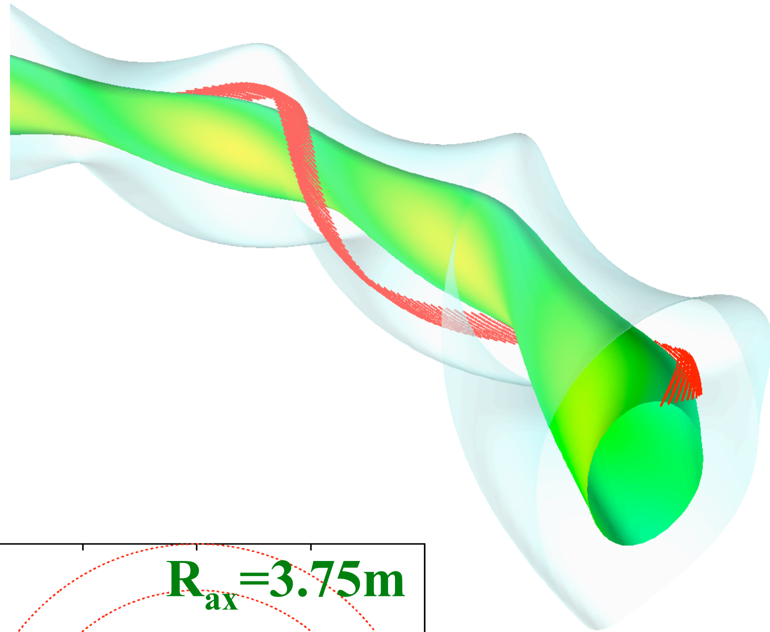
Major radius: R=3.9m

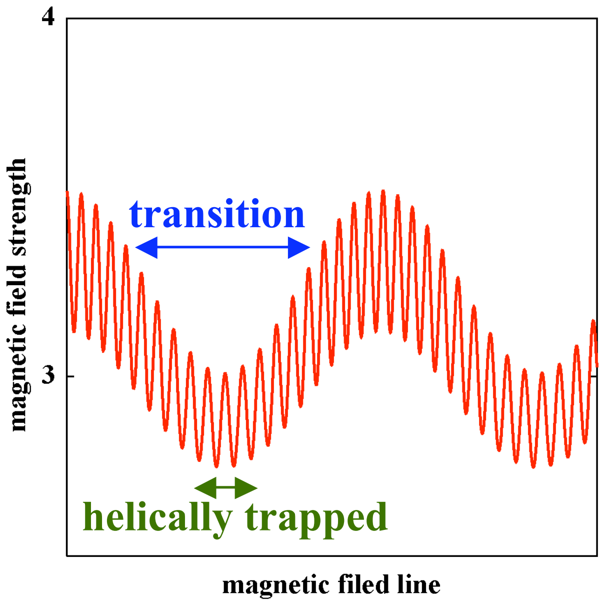
Averaged plasma radius: a < 0.6m

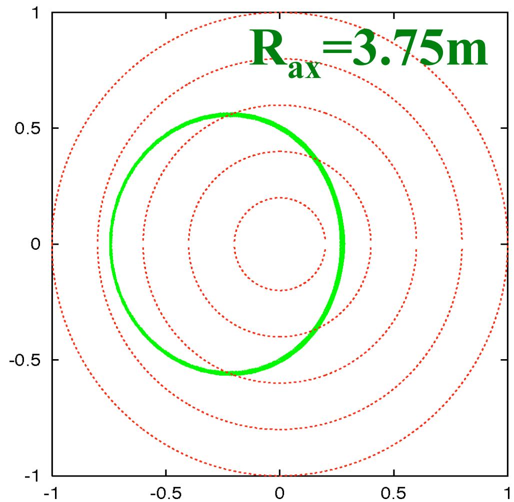
Magnetic filed: B=3.0T

Trapped Particle Orbit in LHD









Toroidal projection (Boozer co.)

GNET: Simulation Model (I)

- We solve the **drift kenetic equation** as a (time-dependent) initial value problem based on **the Monte Carlo technique**.

$$\frac{\partial f}{\partial t} + (\mathbf{v}_{//} + \mathbf{v}_D)\cdot\nabla f + \dot{\mathbf{v}}\cdot\nabla_{\mathbf{v}} f - C^{coll}(f,f) - L^{orbit}(f) = S(f)$$

- Writing the gyrophase averaged distribution function as

$$f(x,v_{//},v_{\perp},t) = f_{bg}(r,v^2) + \delta f(x,v_{//},v_{\perp},t)$$

the linearized drift kinetic equation can be given with initial condition δf(x,v,t=0)=0 steady state solution (t=∞)

$$\frac{\partial \delta f}{\partial t} + (\mathbf{v}_{//} + \mathbf{v}_D)\cdot\nabla \delta f + \dot{\mathbf{v}}\cdot\nabla_{\mathbf{v}} \delta f - C^{coll}(\delta f, f_{bg}) - S(\delta f) - L^{orbit}(\delta f)$$
$$= S(f_{bg}) + S^{neo}(f_{bg}) + C^{coll}(f_{bg},\delta f)$$

- C^{coll}, L^{orbit} and S are the **linear collision operator**, **orbit loss** and the energy and particle source, respectively.
S^{neo} is the usual driving term for neoclassical transport.

$$S^{neo} = -(V_D)_r \frac{\partial f_{bg}}{\partial r} - \dot{v}\frac{\partial f_{bg}}{\partial v}$$

GNET: Simulation Model (II)

- It is convenient to introduce **the Green function $\mathcal{G}(x,v,t \mid x',v')$** which is defined by **the homogeneous F-P equation**

$$\frac{\partial \mathcal{G}}{\partial t} + (\mathbf{v}_{//} + \mathbf{v}_D)\cdot\nabla\mathcal{G} + \dot{\mathbf{v}}\cdot\nabla_{\mathbf{v}}\mathcal{G} - C(\mathcal{G}) - S(\mathcal{G}) - L(\mathcal{G}) = 0$$

with the initial condition $\mathcal{G}(\mathbf{x},\mathbf{v},t=0 \mid \mathbf{x}',\mathbf{v}') = \delta(\mathbf{x}-\mathbf{x}')\delta(\mathbf{v}-\mathbf{v}')$

- Then, **the solution of the inhomogeneous problem** is given by the **convolution with $\mathcal{G}$**;

$$\delta f(\mathbf{x},\mathbf{v},t) = \int_0^t dt' \int d\mathbf{x}' \int d\mathbf{v}' S(f_{bg})\mathcal{G}(\mathbf{x},\mathbf{v},t-t' \mid \mathbf{x}',\mathbf{v}').$$

- In this approach, only the **Green function $\mathcal{G}$ has to be determined** by the **Monte Carlo technique**.

Monte Carlo Simulation for $\mathcal{G}$

- **Magnetic configuration**
  Finite β effects *(magnetic configuration change due to Shafranov shift)*
  3D MHD equilibrium (VMEC+NEWBOZ)
- **Complicated particle motion**
  guiding center motion (μ is conserved.)
  Hamiltonian of charged particle

$$H = \frac{q^2}{2m}\rho_c^2 + \mu B(\psi,\vartheta,\phi) + q\Phi(\psi)$$

  eq. of motion in the Boozer coordinates (ψ,θ,ϕ,ρ_c)
- **Coulomb collisions**
  Liner Monte Carlo collision operator [Boozer and Kuo-Petravic]
  energy and pitch angle scattering

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

Global Transport Simulation by GNET

- We have developed a GNET(Global NEoclassical Transport) code solving drift kinetic equation in 5D phase-space.
- We study the energetic particle transport in non-axisymmetric configurations by GNET code.
  - ECRH generated suprathermal electron transport
    W7-AS, CHS, LHD
    (collaboration with Max-Planck IPP)
  - NBI generated beam ion transport
    LHD, CHS
  - ICH generated energetic tail ion transport
    LHD, W7-X

ICH 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.

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

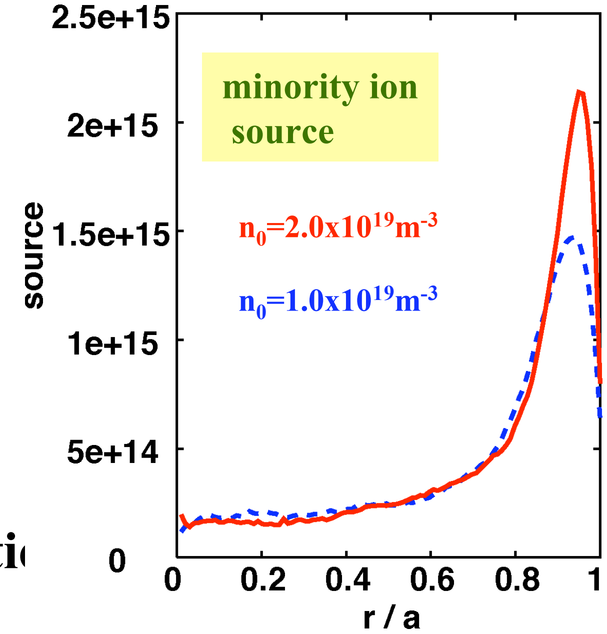
C(f) : linear Clulomb Collision Operator

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

$S_{particle}$: particle source
=> by ionization of neutral particle
(AURORA code)

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

- The minority ion distribution *f* is evaluated through a convolution of $S_{particle}$ with a characteristic time dependent Green function.



Wave-Particle Interaction (Q_{ICRF})

Change velocity due to RF wave when a particle passes through the resonance layer.

$$\Delta v_\perp = \frac{q}{2m} I |E_+| J_{n-1}(k_\perp \rho)\ \cos\phi_r + \frac{q^2}{8m^2 v_{\perp 0}} \left\{ I |E_+| J_{n-1}(k_\perp \rho) \right\}^2\ \sin^2\phi_r$$

$$I = \sqrt{2\pi / n\dot{\omega}}\ \ \text{or}\ 2\pi (n\ddot{\omega}/2)^{-1/3} Ai(0) \qquad \phi_r :\ \text{phase (random number)}$$

For the averages over the random phase we obtain up to the leading order terms

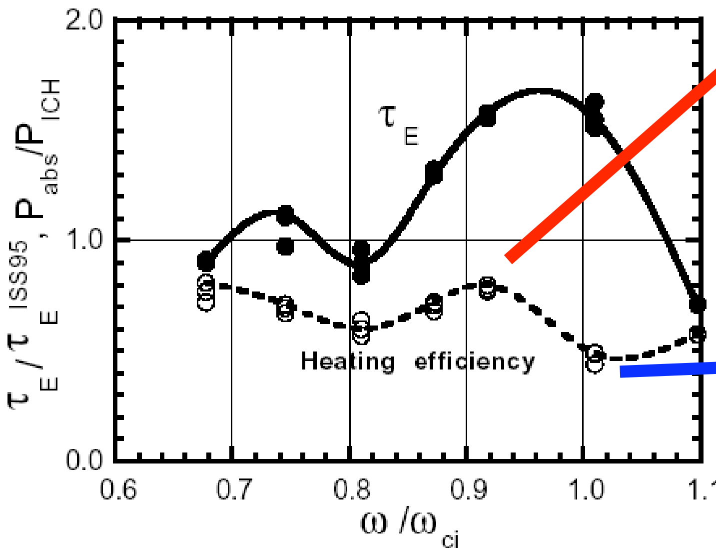
$$\langle \Delta v_\perp \rangle \approx \frac{q^2}{16 m^2 v_{\perp 0}} \left\{ I |E_+| J_{n-1}(k_\perp \rho) \right\}^2 \qquad \langle \Delta v_\perp^2 \rangle \approx \frac{q^2}{8m^2} \left\{ I |E_+| J_{n-1}(k_\perp \rho) \right\}^2$$

$$\langle \Delta v_\perp \rangle = \frac{1}{v_{\perp 0}} \frac{\partial}{\partial v_{\perp 0}} \left(v_{\perp 0} \frac{\langle v_{\perp 0}^2 \rangle}{2} \right)$$

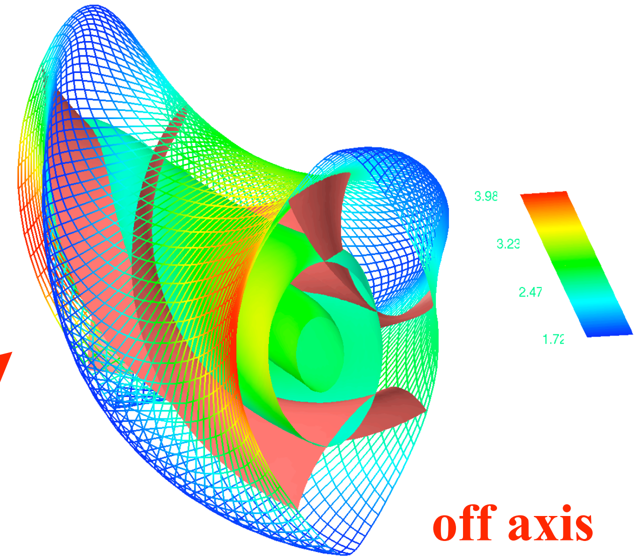
This relation means absence of convection in velocity space during the resonance wave-particle interaction.

Effect of Resonance Position on RF Heating

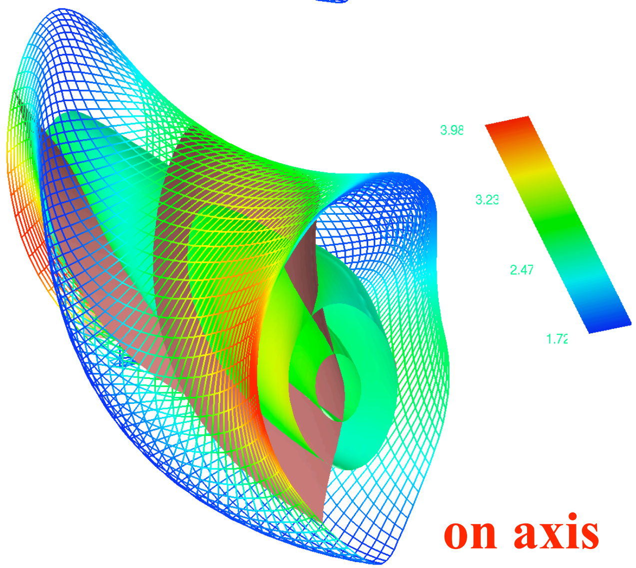
- **ICRF heating experiment has been performed also changing RF resonance position relative to magnetic flux surface in LHD.**
- **We found that the difference in the heating efficiencies and the decrease of energetic particle counts of NDD-NFA.**



R. Kumazawa, et al., Phys. Plasmas 8 (2001) 2139.



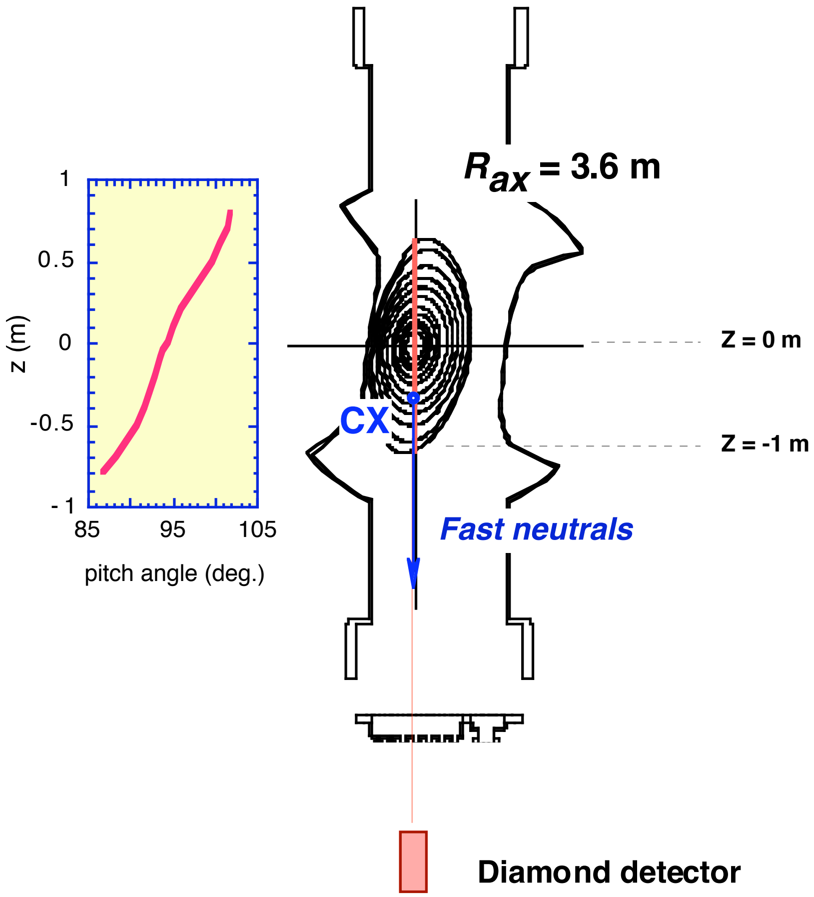
off axis

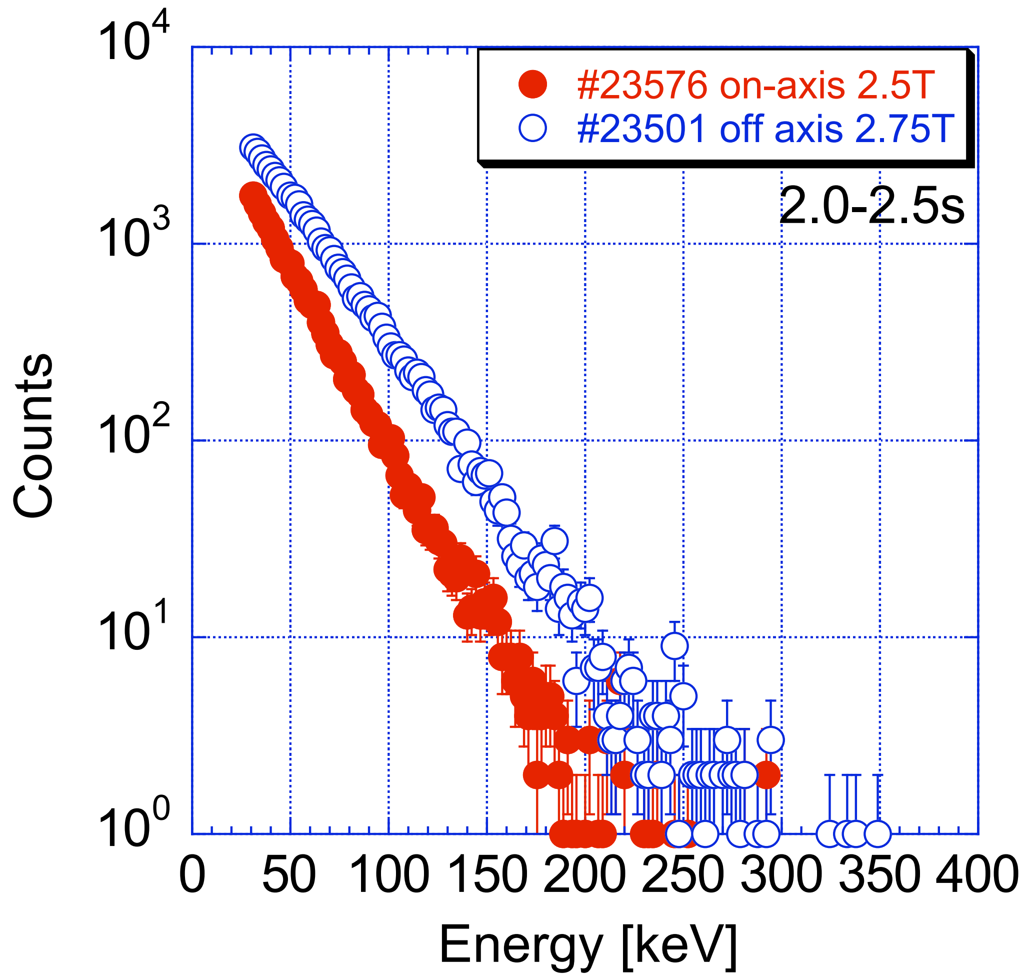


on axis

Energetic Particle Measurements

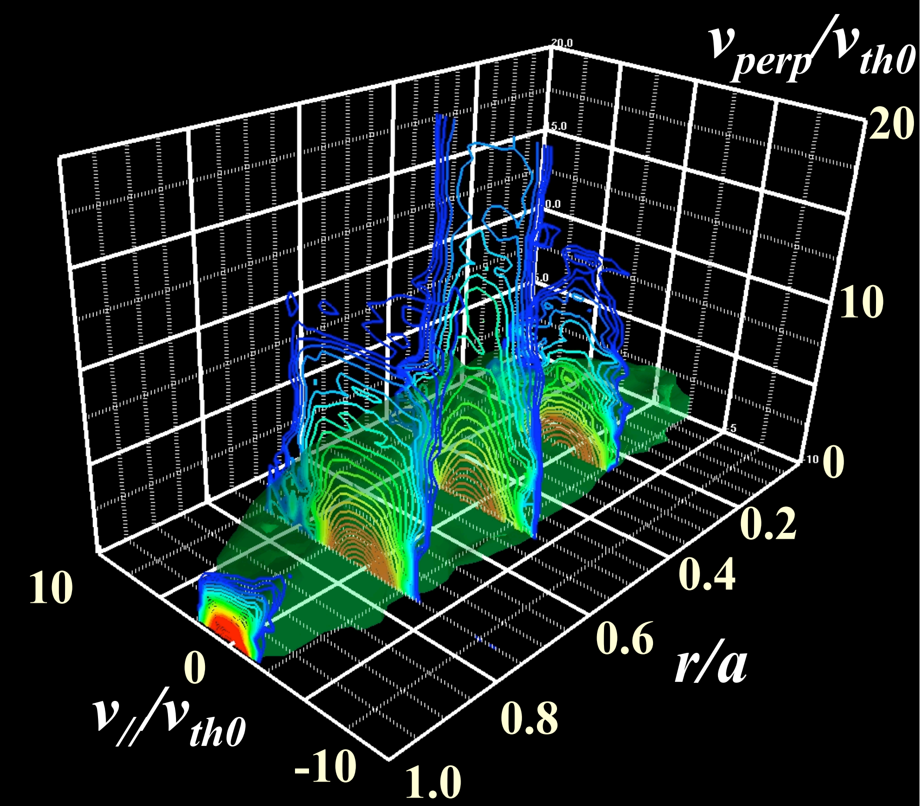
NDD-FNA





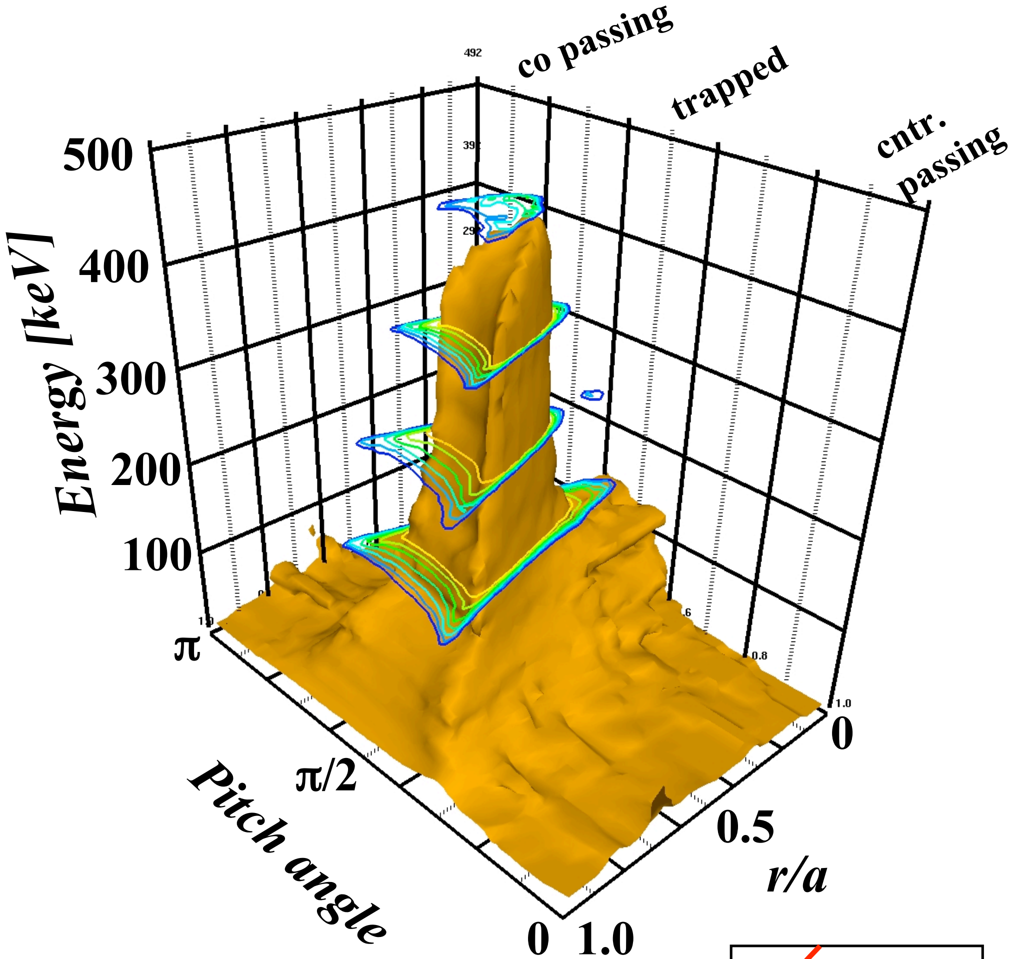
Energetic Ion Distribution by ICH

Contour plot of minority ion $\langle f(v_{//}, v_{perp}, r)\rangle$

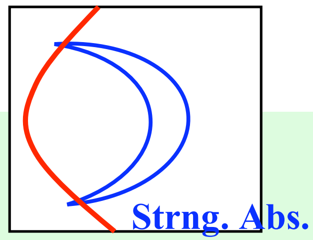


GNET

R_{ax}=3.6m

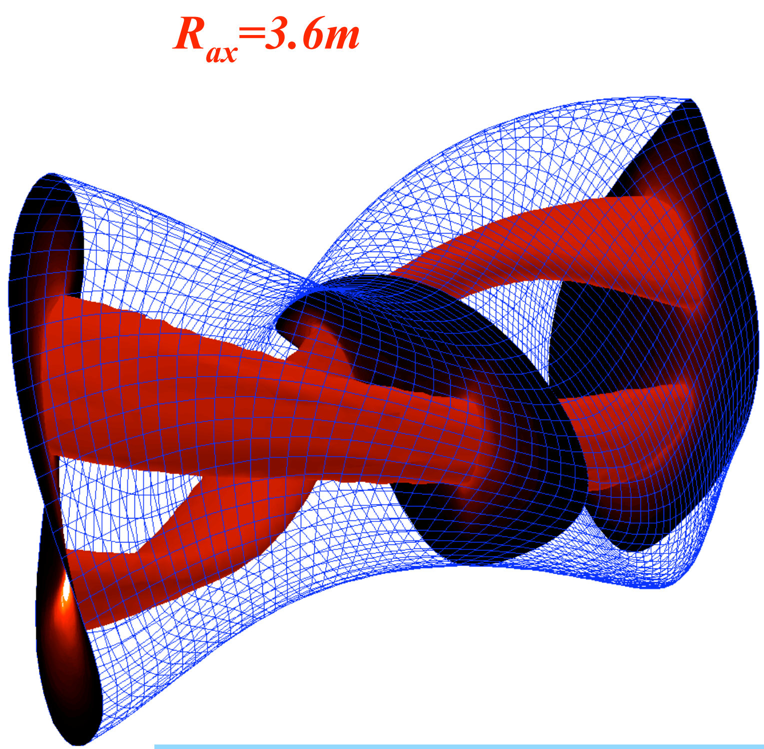


R_{ax}=3.6m

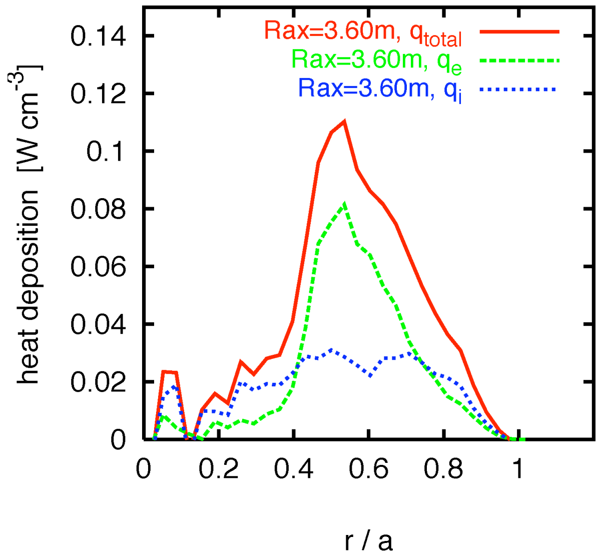


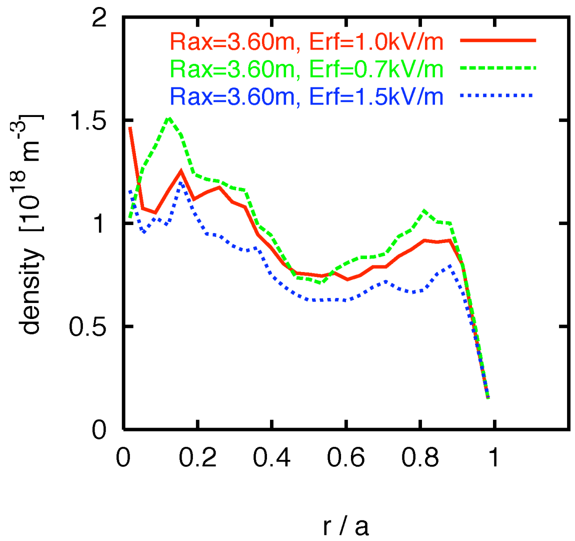
$T_{eo}=T_{io}$=1.6keV, $n_{e0}=1.0\times10^{19}m^{-3}$ B=2.75T@R=3.6m,
f_{RF}=38.47MHz, $k_{//}=5m^{-1}$, $k_{perp}=62.8m^{-1}$, P_{ICH}~2.5MW

Energetic Ion Pressure Profile in 3D



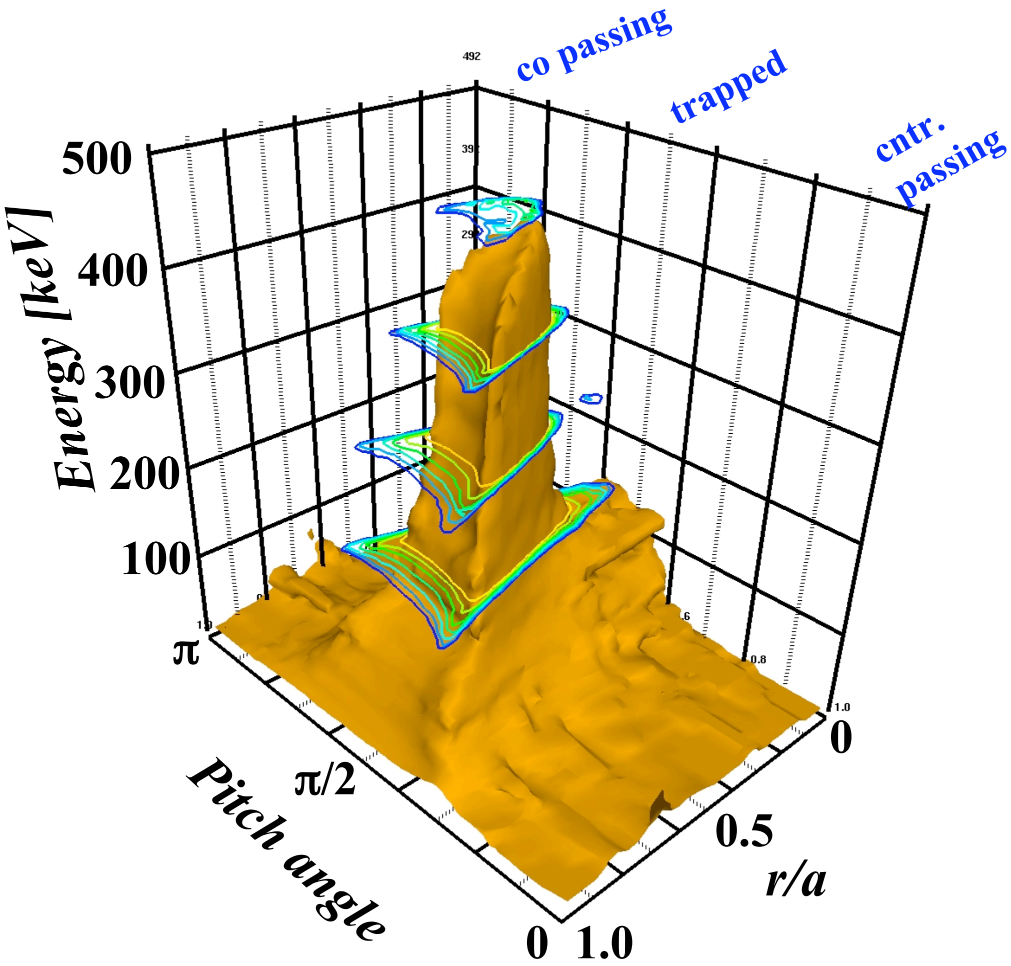
$$p_{minority} = 2\pi \int \frac{1}{2} m v^2 f(v_{//}, v_{\perp}) \mathrm{d}v_{//} v_{\perp} \mathrm{d}v_{\perp}$$



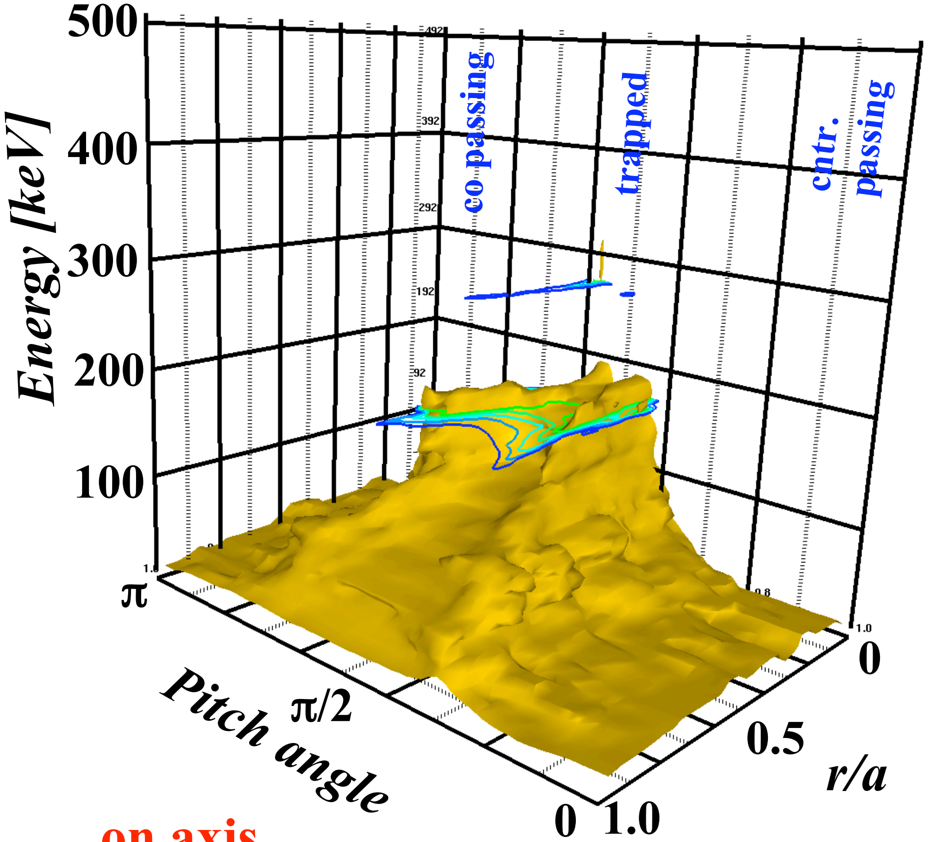


T_{eo}=T_{io}=1.6keV, n_{e0}=1.0x10^{19}m^{-3} B=2.75T@R=3.6m,
f_{RF}=38.47MHz, $k_{//}$=5m^{-1}, k_{perp}=62.8m^{-1}, P_{ICH}~2.5MW

Energetic Ion Distribution by ICH (B_{res})



off axis



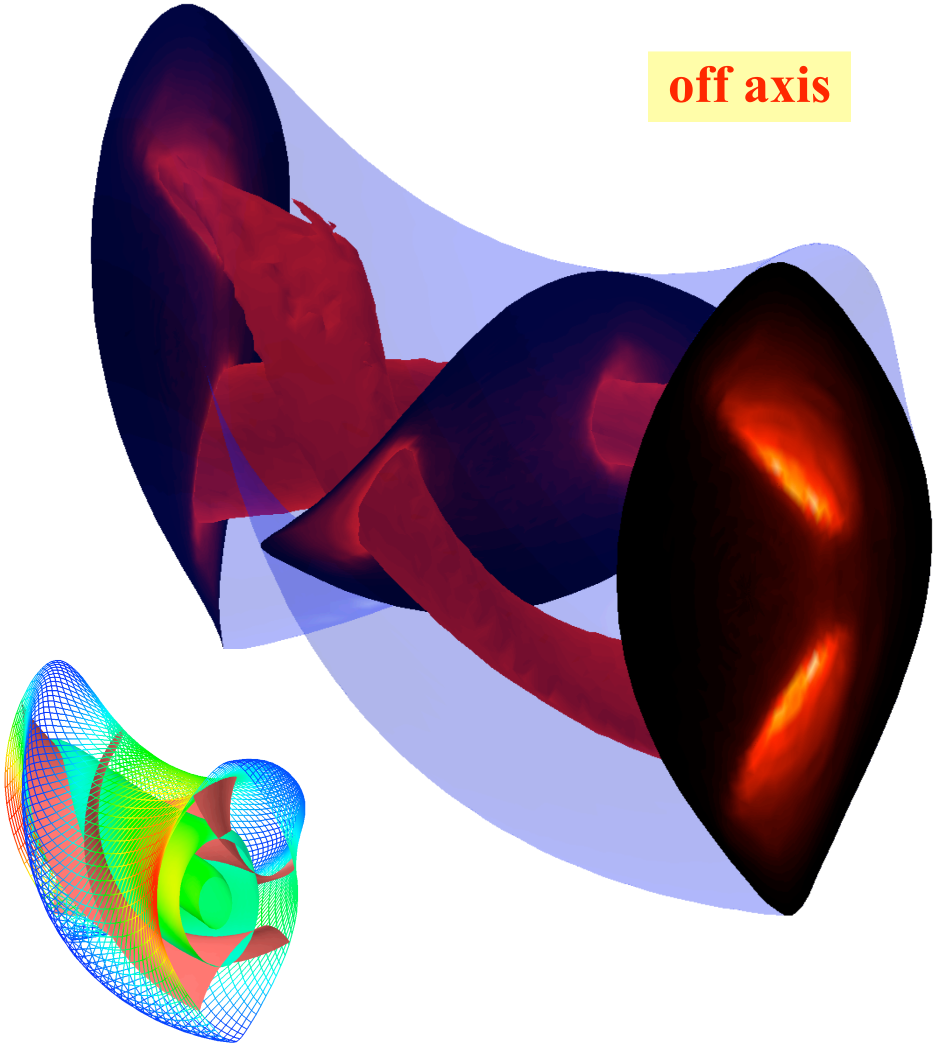
on axis

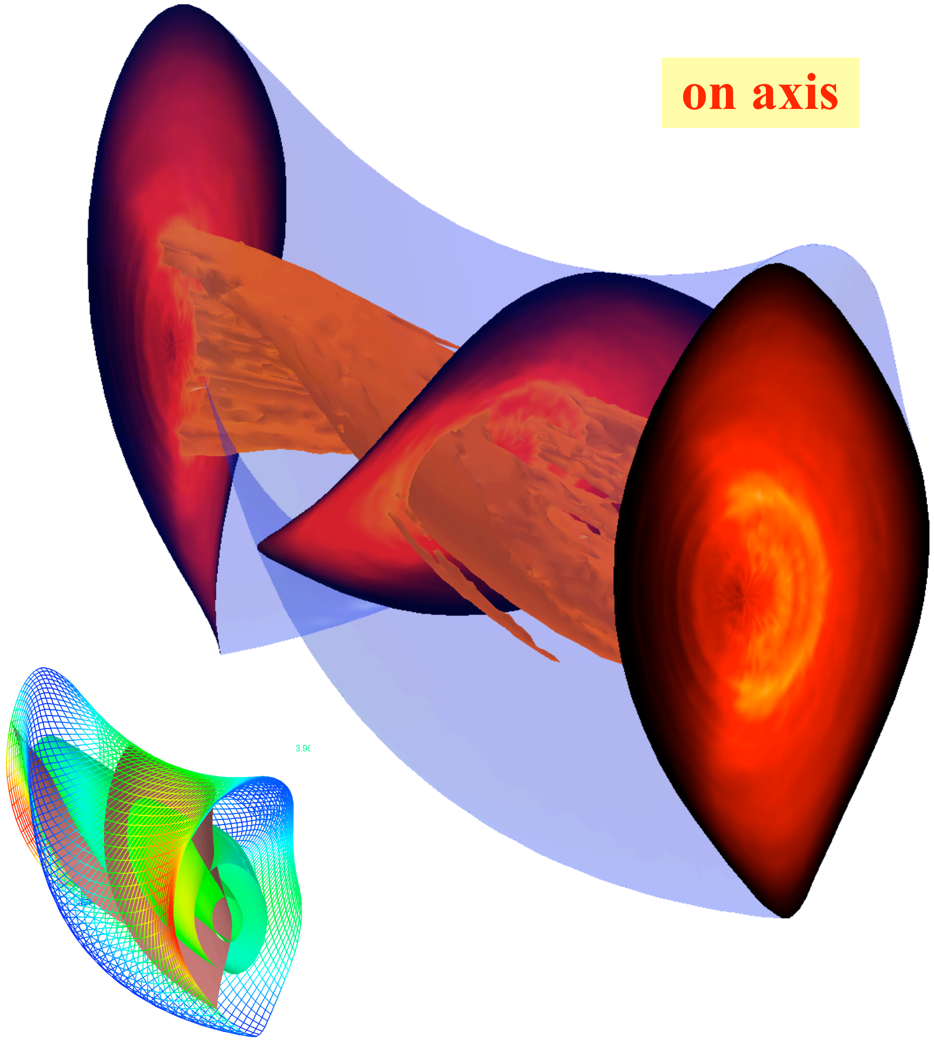
$T_{eo}=T_{io}=1.6keV$, $n_{e0}=1.0x10^{19}m^{-3}$ $B=2.75T@R=3.6m$,
$f_{RF}=38.47MHz$, $k_{//}=5m^{-1}$, $k_{perp}=62.8m^{-1}$, $E_{rf}=0.7kV/m$

Energetic Ion Pressure Profile in 3D (B_{res})

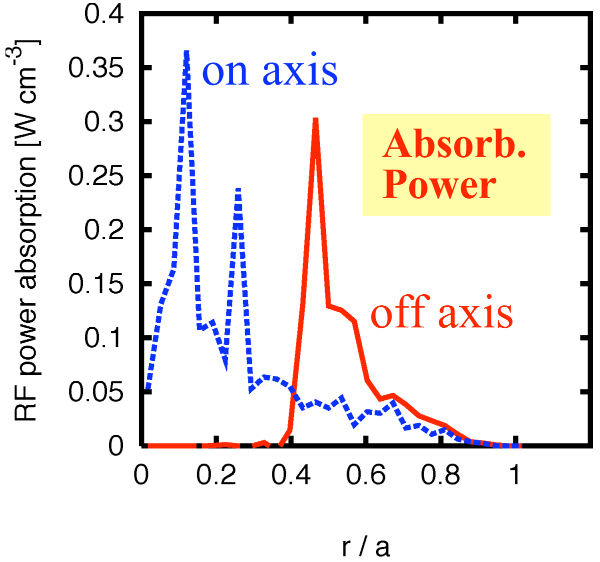
$$p_{minority} = 2\pi \int \frac{1}{2} m v^2 f(v_{//}, v_\perp) \mathrm{d}v_{//} v_\perp \mathrm{d}v_\perp$$

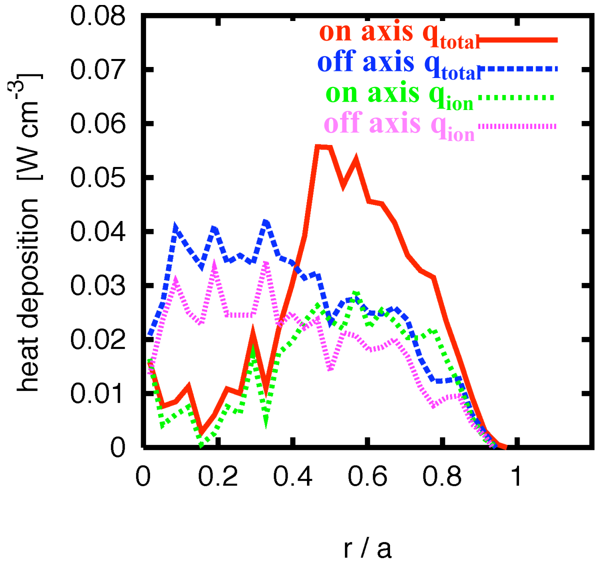
$T_{eo}=T_{io}=1.6\text{keV}$, $n_{e0}=1.0\text{x}10^{19}\text{m}^{-3}$ $B=2.75\text{T@R}=3.6\text{m}$,
$f_{RF}=38.47\text{MHz}$, $k_{//}=5\text{m}^{-1}$, $k_{perp}=62.8\text{m}^{-1}$, $E_{rf}=0.7\text{kV/m}$

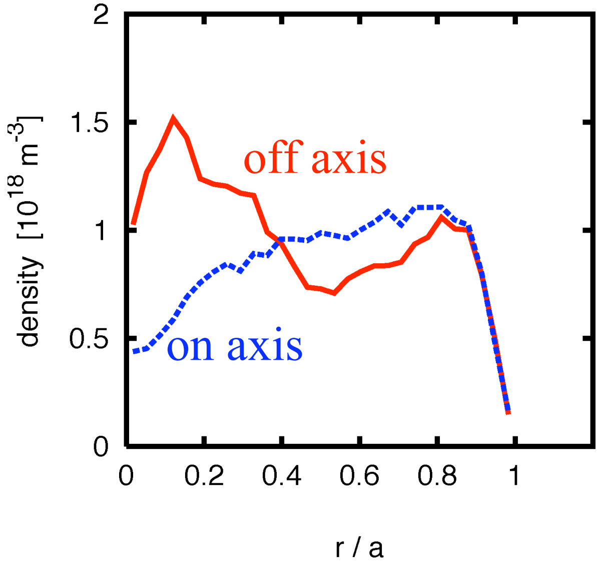


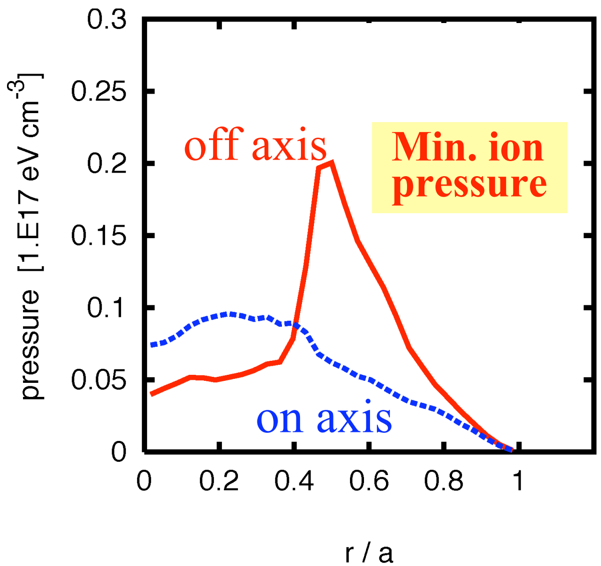


Power Absorption and Heat Deposition (B_{res})









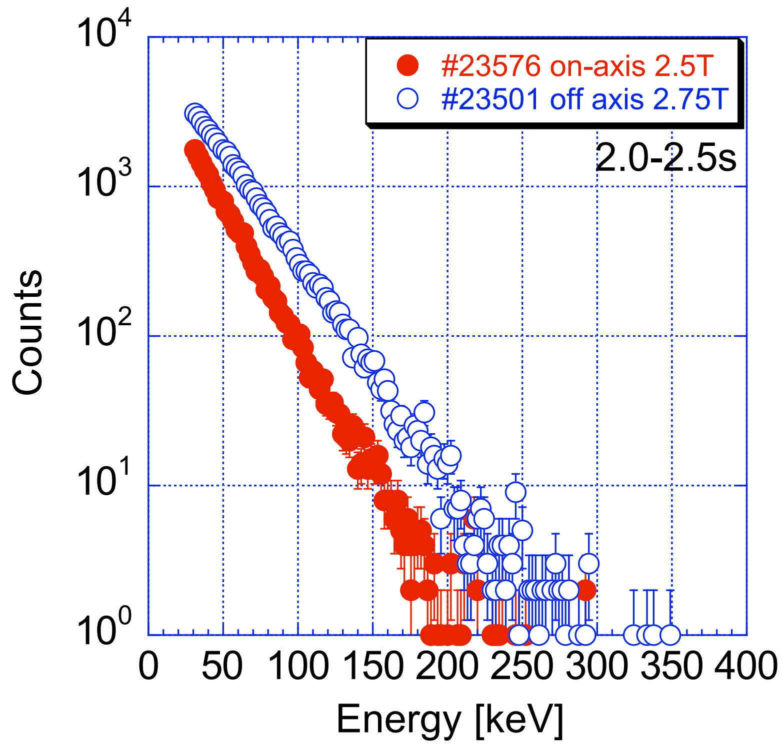
Heating efficiency=P_{dep}/P_{abs}

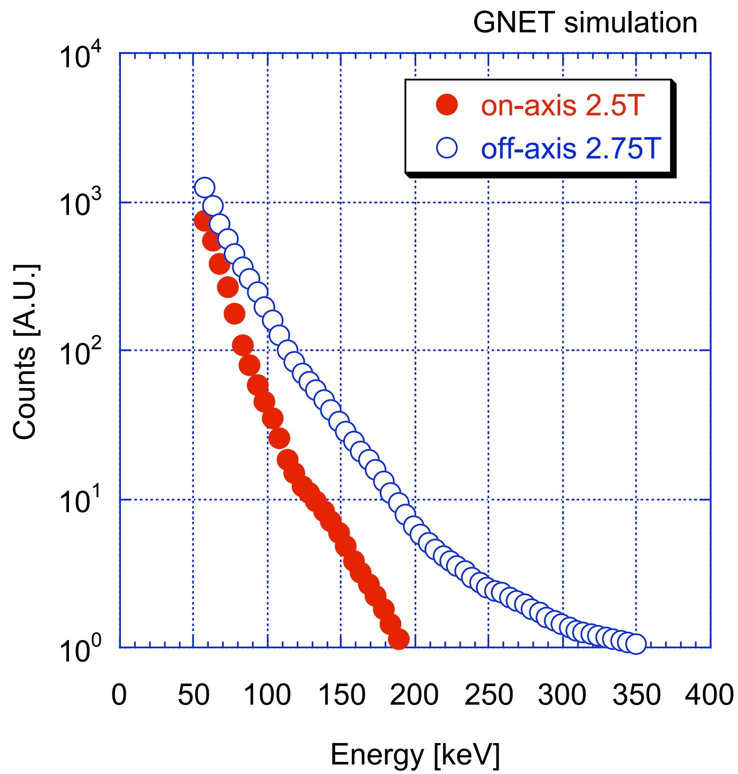
off axis : 0.52(+01.~02?) P_{abs} =1.4MW

on axis : 0.58(+01.~02?) P_{abs} =0.94MW

$T_{eo}=T_{io}$=1.6keV, $n_{e0}=1.0\times10^{19}m^{-3}$
B=2.75T@R=3.6m, f_{RF}=38.47MHz,
$k_{//}=5m^{-1}$, $k_{perp}=62.8m^{-1}$, E_{rf}=0.7kV/m

Comparisons with Experimental Measurements





- NDD count number was simulated using the GNET results.
- We obtain similar tendencies with the experimental results in qualitative sense.

Conclusions

- **We have developed a 5D (3D+2D) phase space simulation code, GNET, for studying the global collisional transport in non-axisymmetric configurations.**
- **The GNET code has been applied to the analysis of energetic tail ion transport during ICRF heating in LHD.**
- **A steady state distribution of energetic tail ion has been obtained and the characteristics of the distribution in the phase space are clarified. (on/off axis dependencies)**
- **Future Plan**
  - **Inclusion of RF wave field by the full wave code: TASK/WM is now under investigation.**
    [A. Fukuyama, E. Yokota and T. Akutsu, Proc. 18th IAEA Conf on Fusion Energy (Sorrento, Italy, 2000) THP2-26, published on CD-ROM (May, 2001)]
  - **Collaboration with GA group**
    - **Benchmark with ORBIT-RF**
    - **Momentum and energy conserving collision operator**