GNETコードによるプラズマ加熱解析の現状と今後の発展

村上定義

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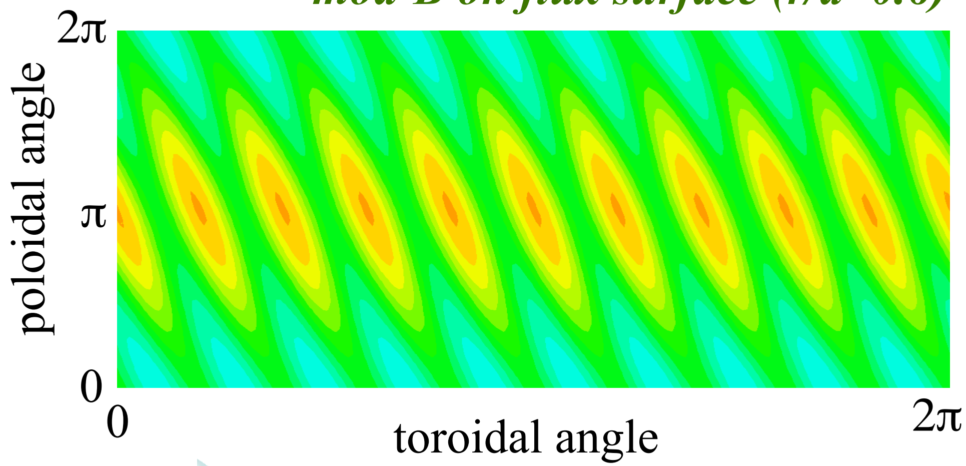
Energetic Particle Confinement in Heliotrons

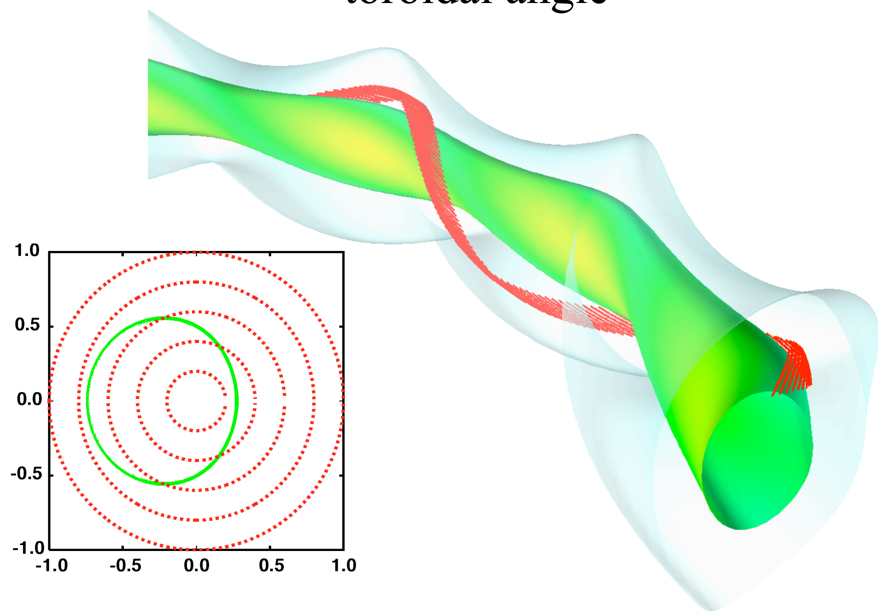
- **Confinement of energetic particle is an important issue for fusion reactor.**
  - **α-particle**
    α-particle heating efficiency (20% of thermonuclear power)
  - **Enegetic particle due to plasma heating**
    heating efficiency, broadening of heating profile
- **Because of three dimensional magnetic configuration, the behaviors of trapped particles in helical ripples are complicated and would enhance the radial transport in heliotrons.**
- **Thus the confinement of energetic particle is an important issue for a future reactor based on the helical system.**

Physical understanding

Quantitative estimation

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





Simulation Model

- 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=∞)

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

- C^{coll}, L^{orbit} and S are the linear collision operator, orbit loss and the energy and particle source, respectively.

Simulation Model (II)

- It is convenient to introduce the Green function $\mathcal{G}$(x,v,t | 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 $\mathcal{G}(\mathbf{x},\mathbf{v},t=0|\mathbf{x}',\mathbf{v}')=\delta(\mathbf{x}-\mathbf{x}')\delta(\mathbf{v}-\mathbf{v}')$

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

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

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

Monte Carlo Simulation for 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

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

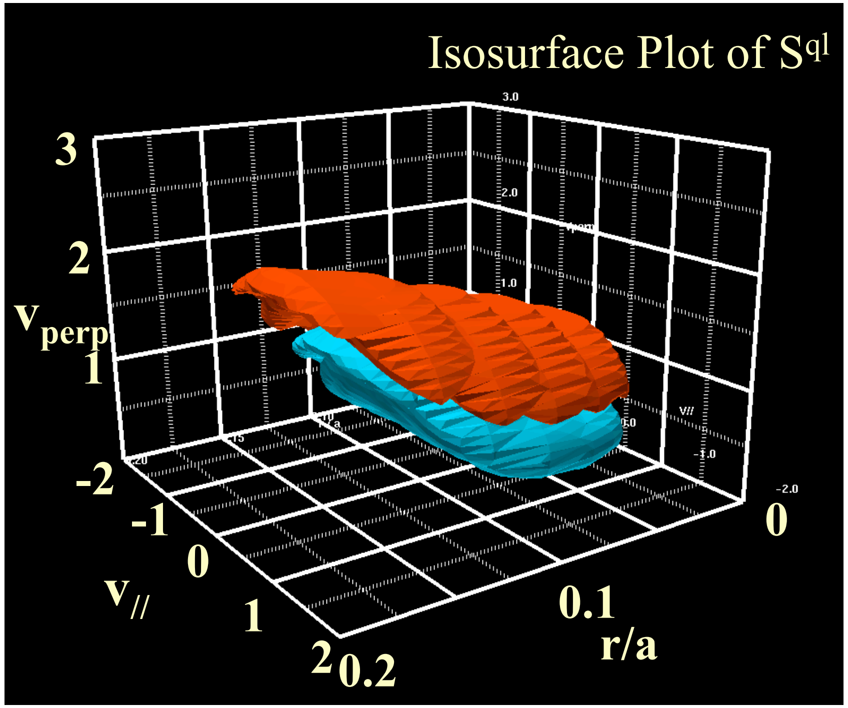
ECH Simulation Model

- **The drift kinetic equation for ECH can be written with initial condition δf(x,v,t=0)=0** **steady state solution (t=inf.)**

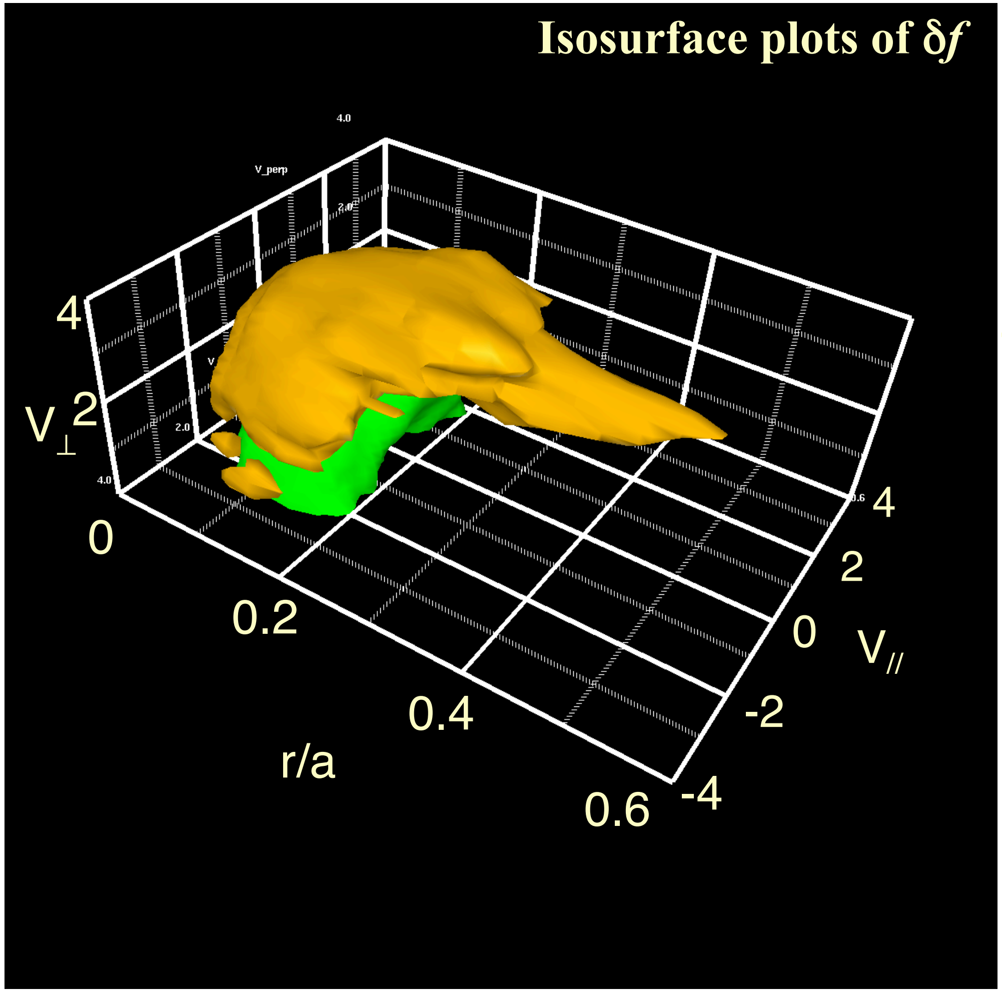
$$\frac{\partial \delta f}{\partial t} + (\mathbf{v}_{//} + \mathbf{v}_D)\cdot\nabla\delta f + \dot{\mathbf{v}}\cdot\nabla_{\mathbf{v}}\delta f - C^{coll}(\delta f) - L^{orbit}(\delta f) = S^{ql}(f_{Max})$$

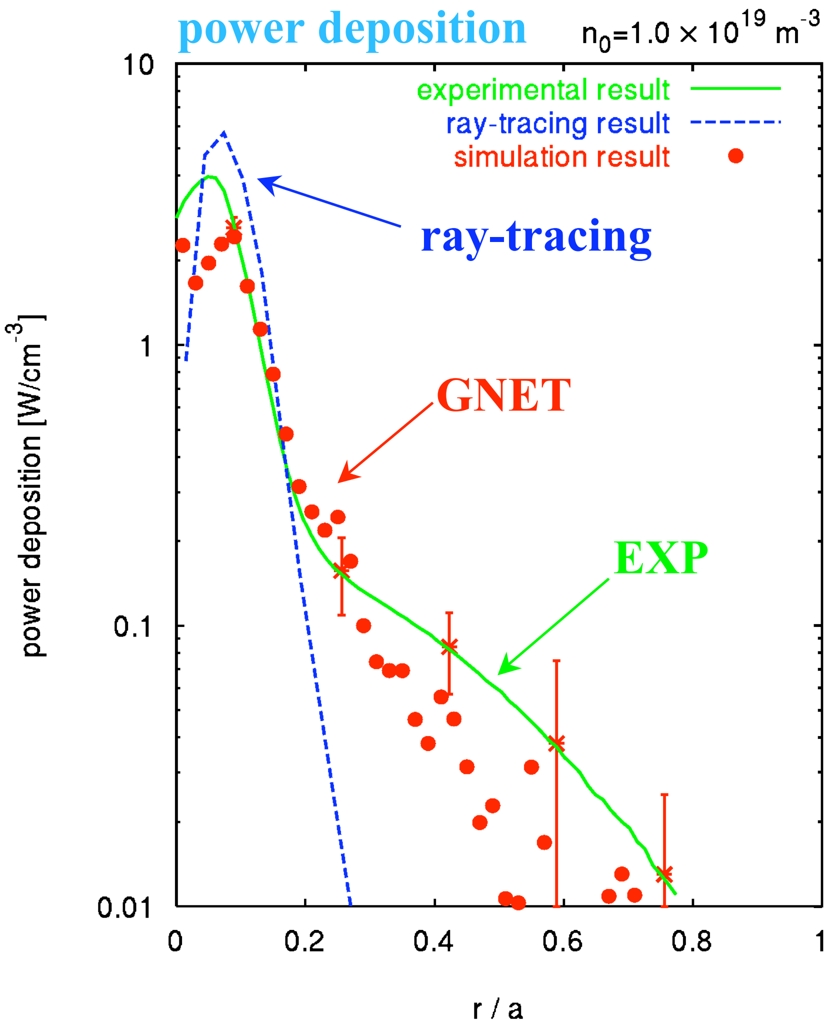
- **C^{coll}, L^{orbit} and S^{ql} are the collision operator, orbit loss and the quasi-linear diffusion operator for the ECRH, respectively.**

- **Isofurface Plot of QL diffusion term in W7-AS plasma (2nd X-mode ECRH).**
  n_0=2.0x10^{19}m^{-3}, T_0=2keV
  3D space (r, $v_{//}$, v_{perp})
  red : positive region
  blue : negative region



Distribution of δ*f* (W7-AS)





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Beam Ion Transport Simulation

- **We solve the drift kenetic equation as a (time-dependent) initial value problem in 5D phase space using the Boozer coordinates (VMEC+NEWBOZ code) .**
- **The drift kinetic equation for a beam source plasma can be given with the initial condition f(x,v,t=0)=0 [steady state solution (t=inf.)]**

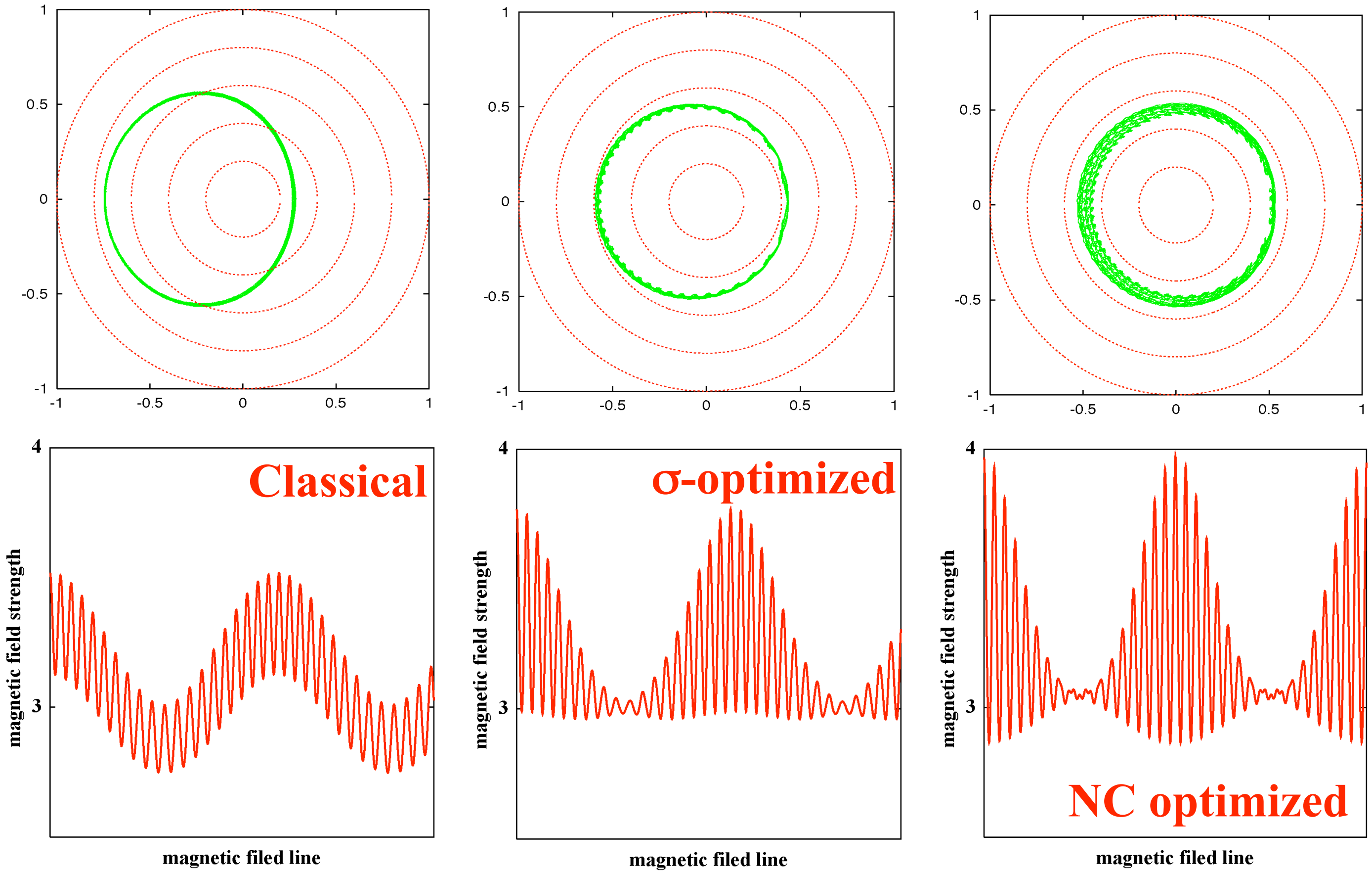
$$\frac{\partial f}{\partial t} + (\mathbf{v}_{//} + \mathbf{v}_D)\cdot\nabla f + \dot{\mathbf{v}}\cdot\nabla_{\mathbf{v}} f = C^{coll}(f) + L^{particle}(f) + S^{NBI}$$

  - **C^{coll} is the collision operator, where we assume a linear collision operator (*energy and pitch agnle scattering*).**
  - **$L^{particle}$ is the sink of the distribution; the orbit loss at the outermost flux surface and the CX loss.**
  - **S^{NBI} is the heat and particle source by the NBI heating.**
- **The beam distribution f is evaluated through a convolution of S^{NBI} with a characteristic time dependent "Green function".**
- **In this approach, only the Green function has to be determined by the Monte Carlo technique.**

Trapped Particle Orbit

R_{ax}=3.75m | R_{ax}=3.6m | R_{ax}=3.53m

Toroidal projection

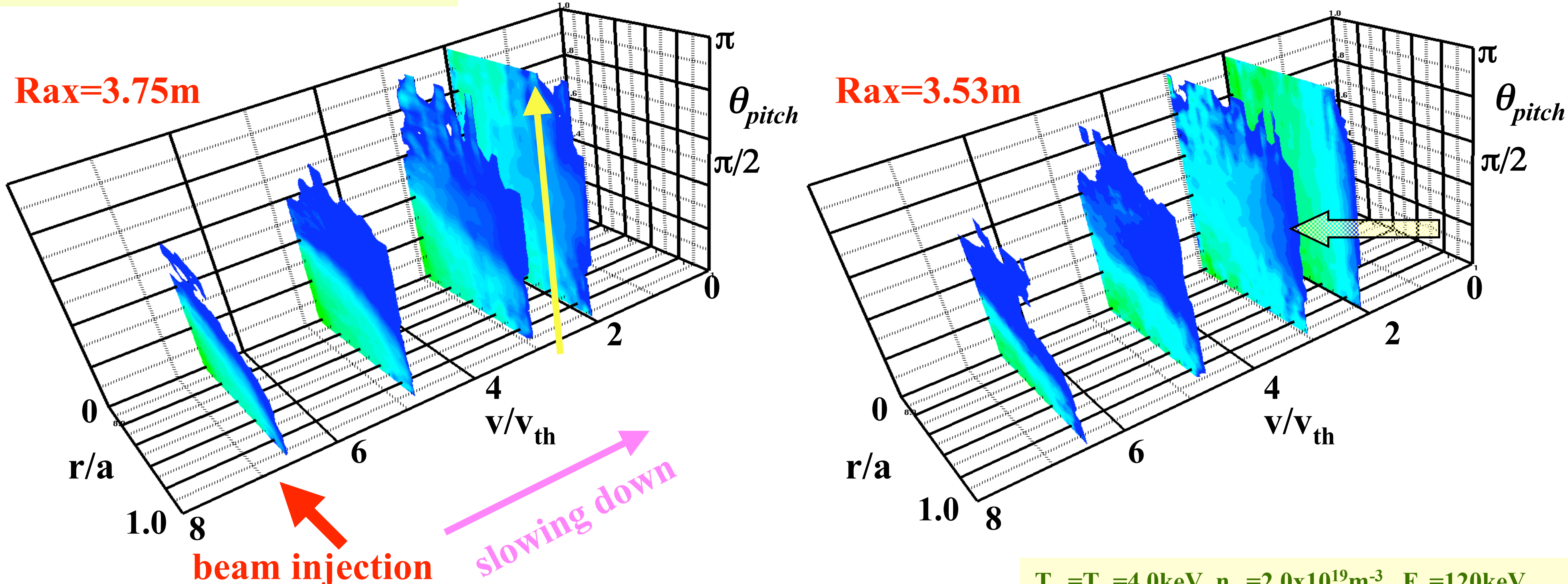


$E=3.4MeV$
$\theta_p=0.47\pi$
$r_0=0.5a$
$\theta_0=\pi/2$
$\phi_0=0.0$

- **Inward shift of Rax improves the trapped particle orbit.**

Simulation Results (GNET)

NBI beam ion distribution

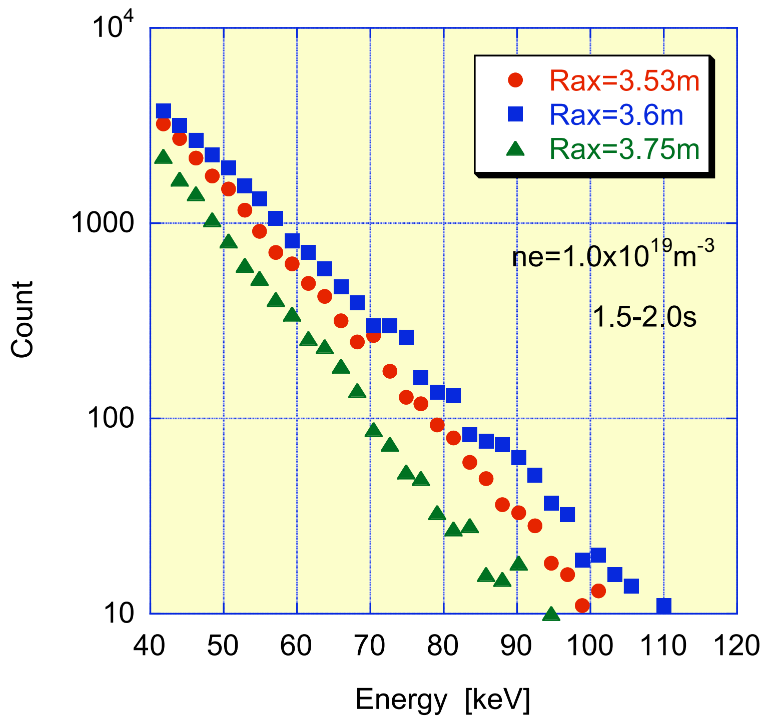


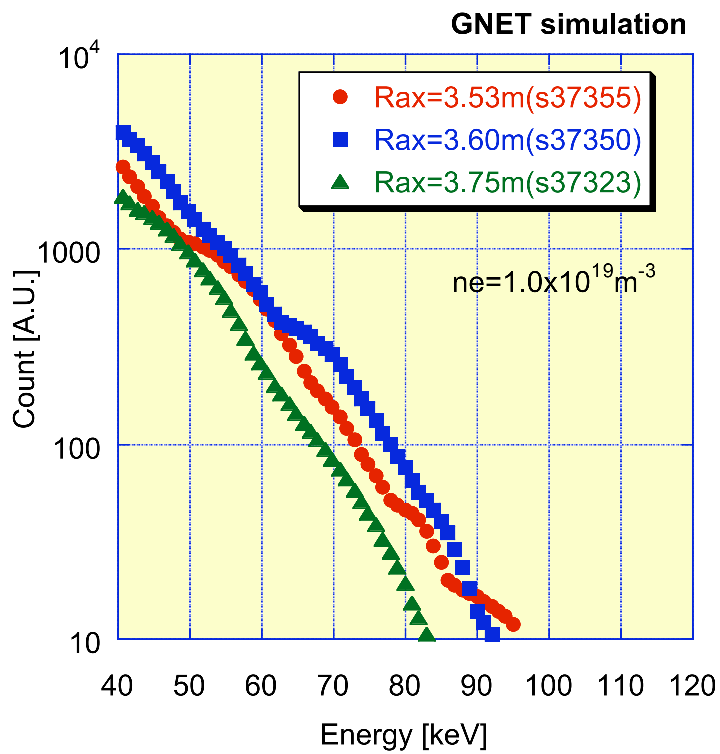
$T_{eo}=T_{io}=4.0keV,\ n_{e0}=2.0x10^{19}m^{-3},\ E_b=120keV$

- The beam ion distribution by GNET shows increase of the distribution of trapped particle.
- The energy loss rate by orbit loss decreases in the Rax=3.53m config.

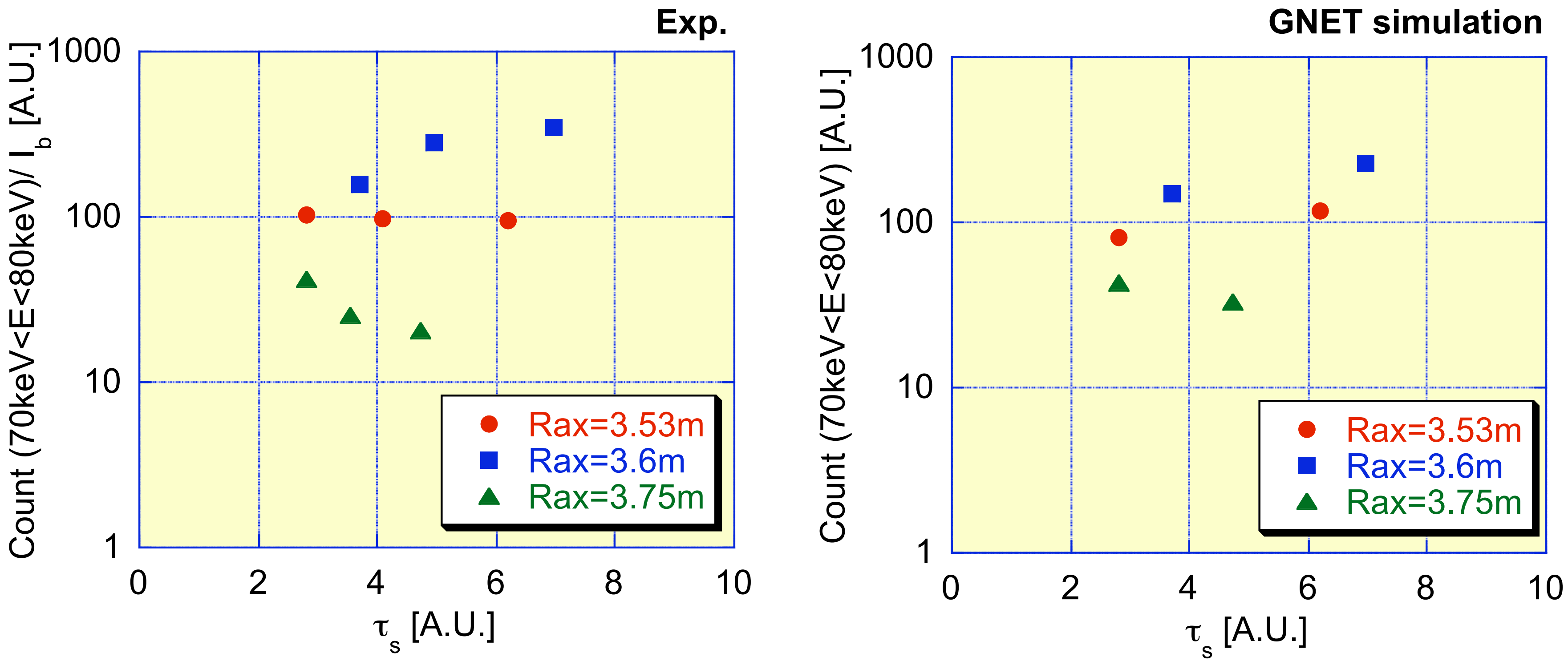
Comparisons with Simulation Results

- The count rates are evaluated using a flux averaged beam ion distribution by GNET simulation.
- We can see the similar tendency of beam ion distributions.





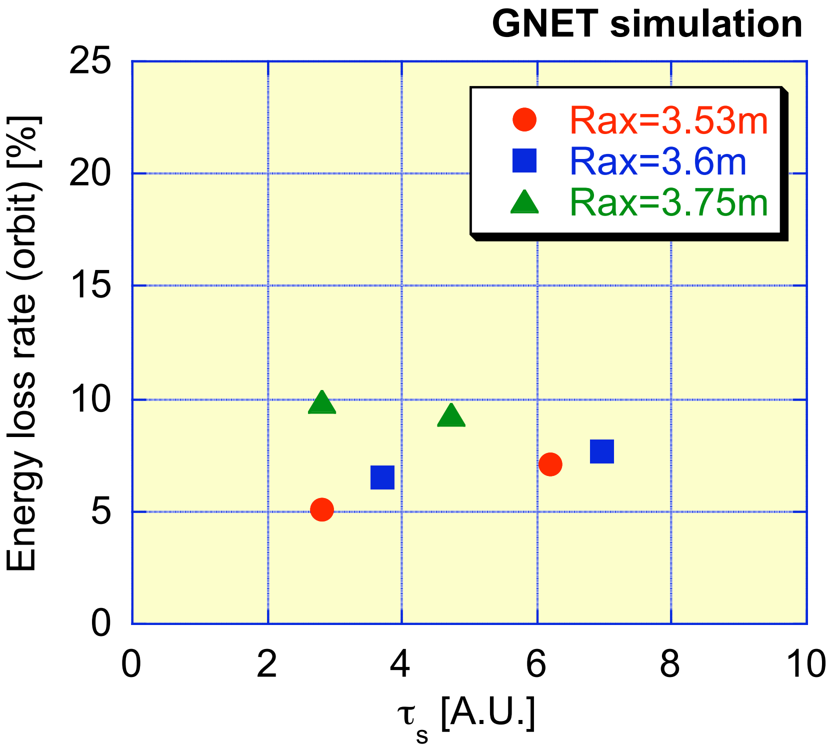
τ_s Dependence of NDD Count

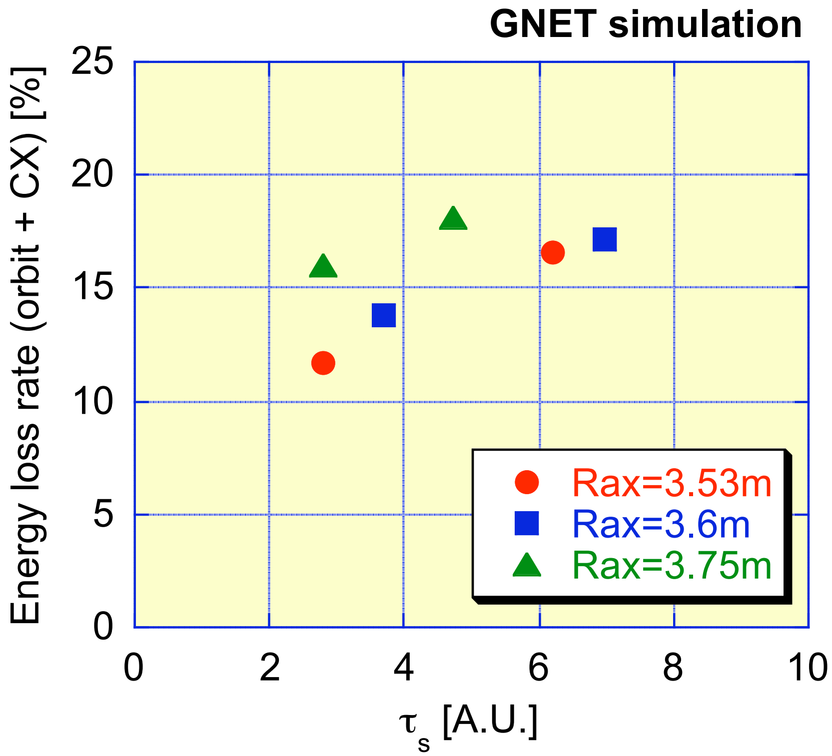


- We can see the **decrease of the count number** as the increase of τ_s in the R_{ax}=3.75m case.
- The count number of R_{ax}=3.53m is lower than that of Rax=3.6m case.
- **GNET simulation results** show **similar tendency** with experimental results.

NIFS

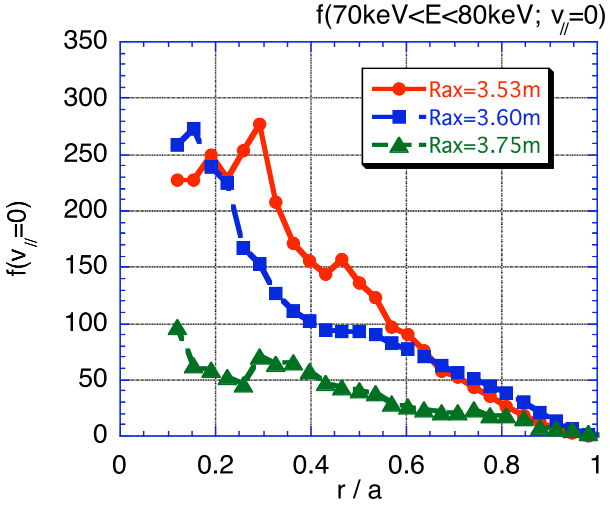
τ_s Dependence of Energy Loss Rate

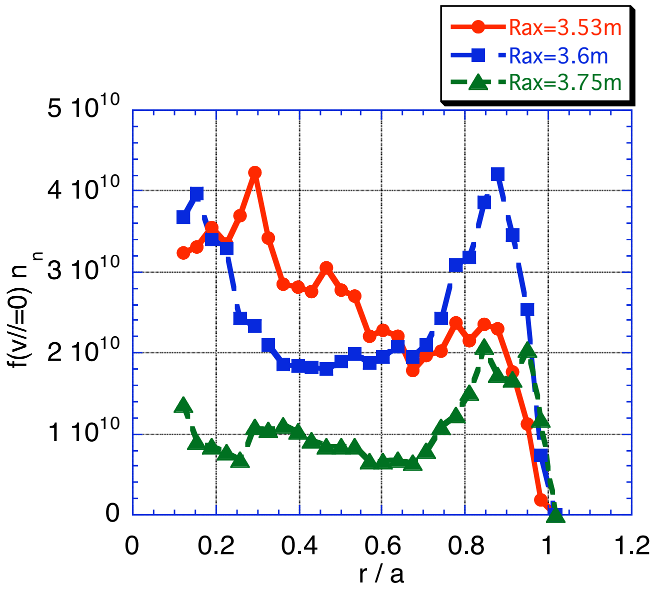


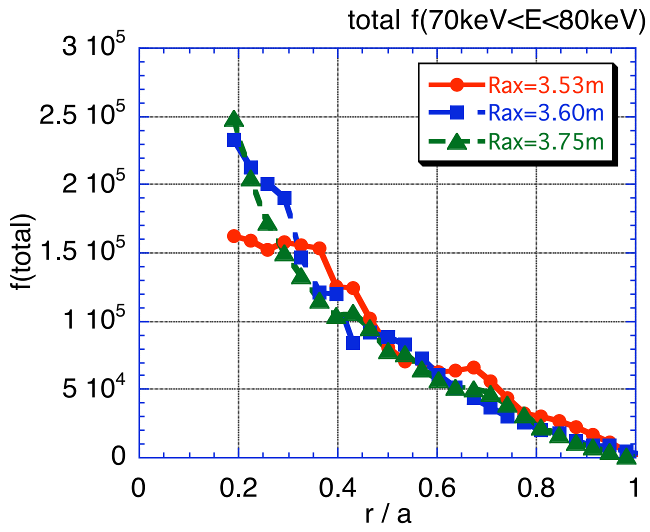


- **Energy loss rate is higher in the R_{ax}=3.75m case.**
- **No clear difference of the total loss rates between the R_{ax}=3.53 and 3.6m.**
  => Because of low electron temperature.

Radial Distribution of Beam Ions







- **Radial profile of trapped ions (70keV < E < 80keV) shows a good confinement in the R_{ax}=3.53 configuration.**
- **A larger distribution near the edge in the R_{ax}= 3.6m configuration.**
- **Neutral weighted distribution indicates a higher count rate in the Rax=3.6m.**

NIFS

GNET Simulation Model

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

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

C(f) : linear Clulomb Collision Operator

Q_{ICRF} : ICRF heating term

wave-particle interaction model

$S_{particle}$: particle source

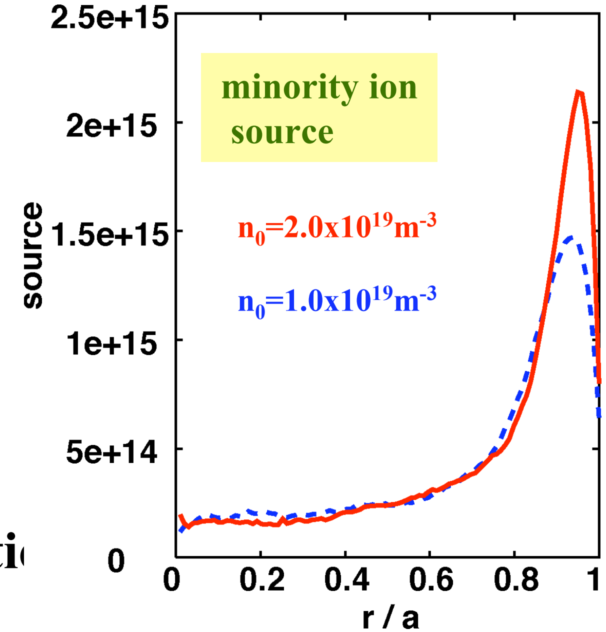
=> by ionization of neutral particle

(AURORA code)

$L_{particle}$: particle sink (loss)

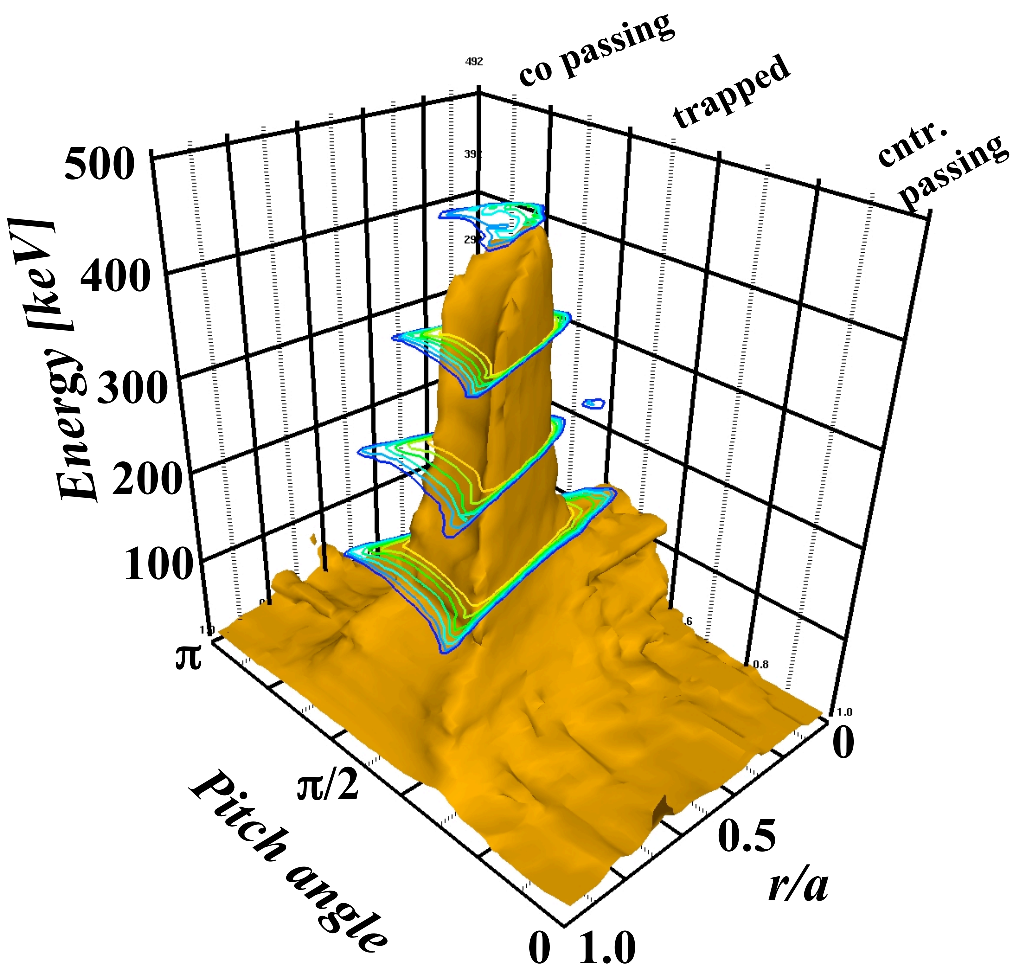
=> Charge exchange loss

=> Orbit loss (outermost flux surface)

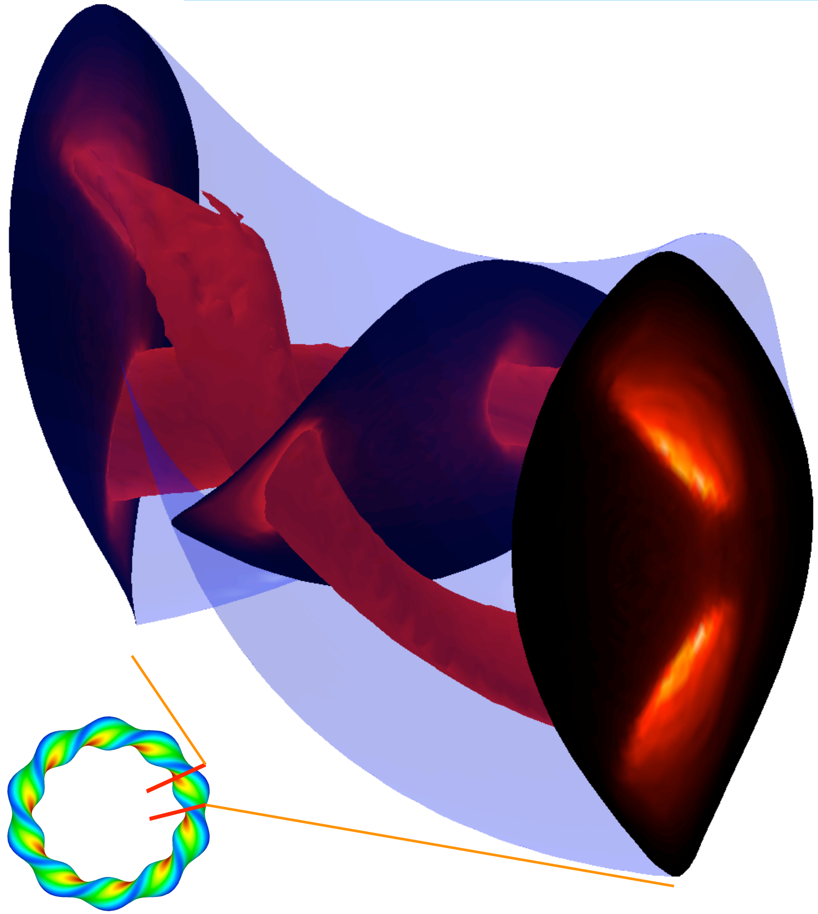


- The minority ion distribution ***f*** is evaluated through **a convolution of $S_{particle}$** with a characteristi time dependent **Green function**.

Energetic Ion Distribution by ICH (LHD)



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



LHD(R_{ax}=3.6m)

$T_{eo}=T_{io}$=1.6keV, $n_{e0}=1.0\mathrm{x}10^{19}\mathrm{m}^{-3}$ B=2.75T@R=3.6m,
f_{RF}=38.47MHz, $k_{//}=5\mathrm{m}^{-1}$, $k_{perp}=62.8\mathrm{m}^{-1}$, P_{ICH}~2.5MW

Simulation, Modeling and Validation of ICRH Physics

ICHシミュレーションコード

GNET: S. Murakami

ORBIT-RF: GA理論グループ

- **共通の部分**
  - **Monte-Carlo codes following fast ion drift orbits in 2- and 3-D magnetic confinement topologies, under going Coulomb collisions and ICRF quasilinear heating modeled by Monte-Carlo techniques.**
  - **Both codes can be used to study fast ion generation by minority ICRF heating, self-consistent inclusion of neoclassical transport, enhancement of transport by 3-D magnetic fields, plasma rotation and momentum transport, and interaction with NBI fast ions.**
- **異なる部分：**
  - **GNET uses a particle source term to achieve steady-state**
  - **ORBIT-RF uses particle re-injection.**
  - **GNET includes charge exchange losses and its collision operator includes energy scattering. ORBIT-RF is implementing higher harmonic ICRH.**

Task 1

- Since the two codes are have been developed independently, it is useful to do detailed benchmarking of the two codes before proceeding with jointly development of new capabilities.
- Task 1. Benchmarking between GNET and ORBIT-RF
  Timescale: 6 months
  - Simulate minority ICRH at the fundamental frequency for a selected DIII-D discharge
  - Simulate NBI and evaluate NBCD for a selected DIII-D discharge
  - Simulate minority ICRH and NBI interaction for a selected DIII-D discharge
- In all cases, we will compare absorption power (location and amplitude), fast ion spectrum, particle flux, and detailed convergence studies. S. Murakami will implement an interface into GNET to use magnetic/equilibrium data files from EFIT as currently done in ORBIT-RF. M. Choi (GA) will provide DIII-D kinetic profiles and magnetic/equilibrium data files to S. Murakami.

Task 1

- **Longer-term Topics:**
  - **Both GNET and ORBIT-RF have plans to improve the RF wave-field calculation by coupling to a full wave-code. Benchmarking will be done following the implementation.**
  - **Identify momentum transport and plasma rotation problem for joint study**
  - **ORBIT-RF plans to implement multiple N-parallel wave capability and CX losses for comparison with GNET**

Simulation, Modeling and Validation of ECRH Physics

- **High power ECRH and ECCD for steady-state operation, profile control and tokamak performance improvement is a major element of the DIII-D experimental program.**
- **The research is highly relevant to ITER advanced operation. ECRH is also important for stellarator both for heating and controlling transport.**
- **The GNET code operated in the quasilinear mode can also be used for ECRH study. At GA, a state-of-the-art ray-tracing code TORAY-GA and the CQL3D Fokker-Planck code are being used for modeling and planning experiments.**
- **GA is interested in adding the GNET code to the suite of codes for study ECRH and ECCD. The following collaboration is proposed.**

Task 2

- **Task 2. Preparation of GNET code for study of DIII-D ECRH experiments.**
  Timescale: 6 months
  - **S. Murakami and S.C. Chiu (GA) will formulate and implement momentum conserving e-e collision operator in GNET for CD calculation**
  - **S. Murakami will add Ohmic heating capability to GNET**
  - **S. Murakami and V. Chan will complete calculation of self-consistent electrostatic potential generation by ECRH**
  - **GNET will be installed at GA after completion of the first three subtasks, and M. Choi will do comparative calculations against CQL3D**
  - **S. Murakami and GA will jointly investigate the effect of error field on fast electron transport using GNET**
- **Longer-term Topics:**
  - **Study effects of magnetic fluctuations and magnetic islands on electron transport and bootstrap current**
  - **Extend capability to EBW and IBW**

Simulation Model

- 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.

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

Energy and Momentum Conservation

- **Conservation of Energy and momentum is important in considering the current drive and the neoclassical transport.**
- **Energy and momentum conservation (locally) can be possible by solving the drift kinetic equation iteratively.** $\delta f = \delta f_0 + \delta f_1 + \delta f_2 + \ldots$

  for $l = 0$ (s-species)

$$(\mathbf{v}_{//} + \mathbf{v}_D) \cdot \nabla \delta f_0^s + \dot{\mathbf{v}} \cdot \nabla_{\mathbf{v}} \delta f_0^s - C^{coll}(\delta f_0^s) - S^{ql}(\delta f_0^s) - L^{orbit}(\delta f_0^s)$$
$$= S^{ql}(f_{Max}^s) + S^{neo}(f_{Max}^s)$$

  for $l = $ n(electron)

$$(\mathbf{v}_{//} + \mathbf{v}_D) \cdot \nabla \delta f_n^e + \dot{\mathbf{v}} \cdot \nabla_{\mathbf{v}} \delta f_n^e - C^{coll}(\delta f_n^e) - S^{ql}(\delta f_n^e) - L^{orbit}(\delta f_n^e)$$
$$= C^{coll}(f_{Max}^e, \delta f_{n-1}^e) + C^{coll}(f_{Max}^e, \delta f_{n-1}^i)$$

  for $l = $ n(ion)

$$(\mathbf{v}_{//} + \mathbf{v}_D) \cdot \nabla \delta f_n^i + \dot{\mathbf{v}} \cdot \nabla_{\mathbf{v}} \delta f_n^i - C^{coll}(\delta f_n^i) - S^{ql}(\delta f_n^i) - L^{orbit}(\delta f_n^i)$$
$$= C^{coll}(f_{Max}^i, \delta f_{n-1}^i) + C^{coll}(f_{Max}^i, \delta f_{n-1}^e)$$

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
- Future Plan (collaboration with GA group)
  - Benchmark with ORBIT-RF
  - Momentum and energy conserving collision operator
  - Investigation of 3D problem in tokamaks