Orbit following code in real coordinate for ICRF fast ion and WM module of TASK3D to solve wave equation

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Background

〇In the Large helical device (LHD), a long time discharge with electron density, n_e~$1x10^{19}m^{-3}$, is maintained for more than one hour by the ICRF minority ion heating. To extend the operational density regime of the long time discharges by ICRF heating, the operating scenario is under development.

〇In the ICRF minority ion heating, the ICRF wave mainly heats the minority ions near the resonance layer and the absorbed power of the minority ions is transferred to bulk plasma through collisions. Thus, it is necessary to investigate the efficiency on the power transferred from the minority ions to bulk plasmas in addition to evaluation of the ICRF electric field distribution.

Outline

○Monte Carlo simulation of fast ion generated by ICRF based on orbit following in real coordinates in large helical device.

- Simple code for evaluation of transfer power efficiency.
- Analyses for ICRF fast ions.

○ WM module of TASK3D for full wave analyses.

- WM module.
- Analyses for cold plasma model.

Monte-Calro simulation of ICRF minority heating

Plasma velocity distribution function
(+ velocity distribution of minority fast ions)

Electromangetic wave equation

⇒ICRF electric field →

⇒Absorption power

power to bulk plasma

power to minority ions

Evaluation of source term of minority ions

Example of evaluation method of minority fast ion velocity distribution in ICRF electric field.

Drift-Kinetic equation
(Using the model for receiving power from ICRF wave to minority ions)

・Monte-Calro particles is Maxwell distribution at initial

⇒ Velocity distribution of minority fast ions

⇒Power received from ICRF wave to fast ions.

⇒Power transferred from fast ions to bulk plasma.

Developed code

Modeled ICRF electric field →

Evaluation of "Energy absorbed form ICRF wave to fast ions" and "Energy transferred from fast ions to bulk plasma" of each minority fast ions.
Using the model for receiving power from ICRF wave to minority ions

・Focusing on fast ions accelerated by ICRF wave
initial positions of Monte-Carlo particles are only on resonance layer and their pitch angle is 90 degree.

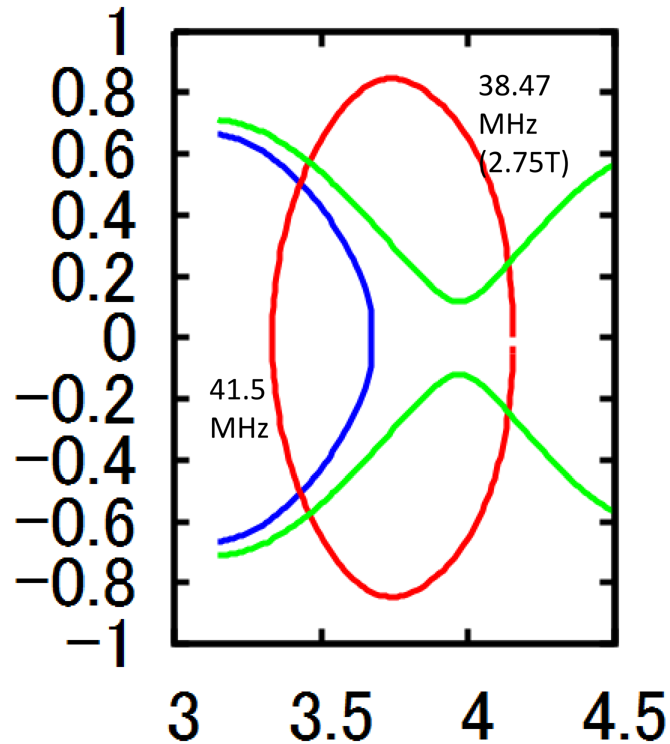
⇒ Transferred power efficiency ($\frac{\text{Energy transferred to bulk plasma}}{\text{Energy absorbed from ICRF wave to fast ions}}$)

⇒ Rate of transferred power to ions and electrons.

⇒ Profile of transferred power from fast ion

Analytical model

Start points
(Resonance layer)



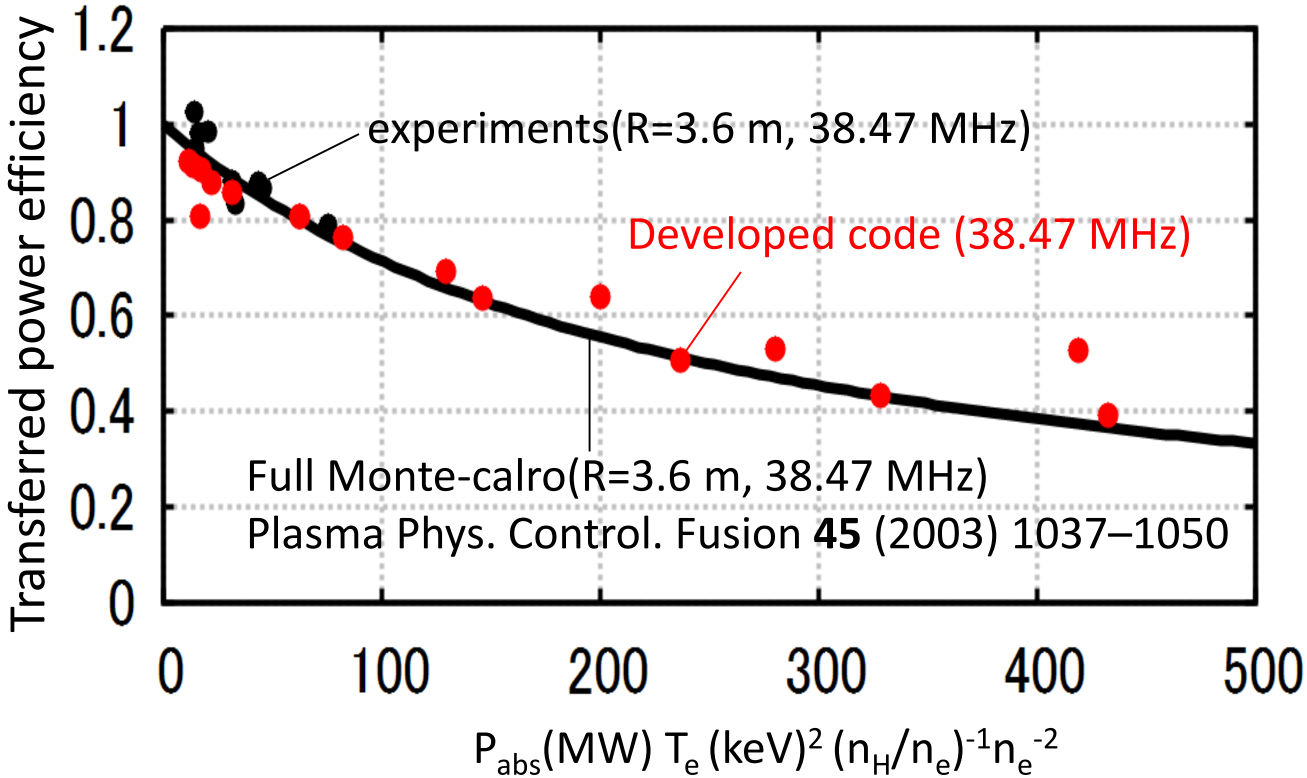
Magnetic configuration B_0 = 2.75 T
R_{axis} = 3.6 m
bulk plasma Helium ion and electron

Models

1. Fast ion orbits: Guiding center equation.
   Re-entering fast ions are included.
2. In an absorption model of the fast ion from ICRF, the fast ions are accelerated in a direction perpendicular to field line on the resonance layer.
3. Using the wave field model as ICRF electric field, ICRF electric field is uniform distribution only in half-helical-pitch (1/10)
4. Collision with bulk plasma: energy relaxation and pitch angle scatter.
   The profile of the bulk plasma is uniform.
5. Initial condition of fast ions: Pitch angle 90 degree, E_0= Ti
   Only ICRF fast ion are assumed.

In order to evaluate the transferred power efficiency of background plasma in a lot of cases, a Monte-Calro code with the above models was developed.

Comparison of efficiency with experiments



○A tendency of the transferred power efficiency (red) evaluated by developed code is almost same as that evaluated from experiments.

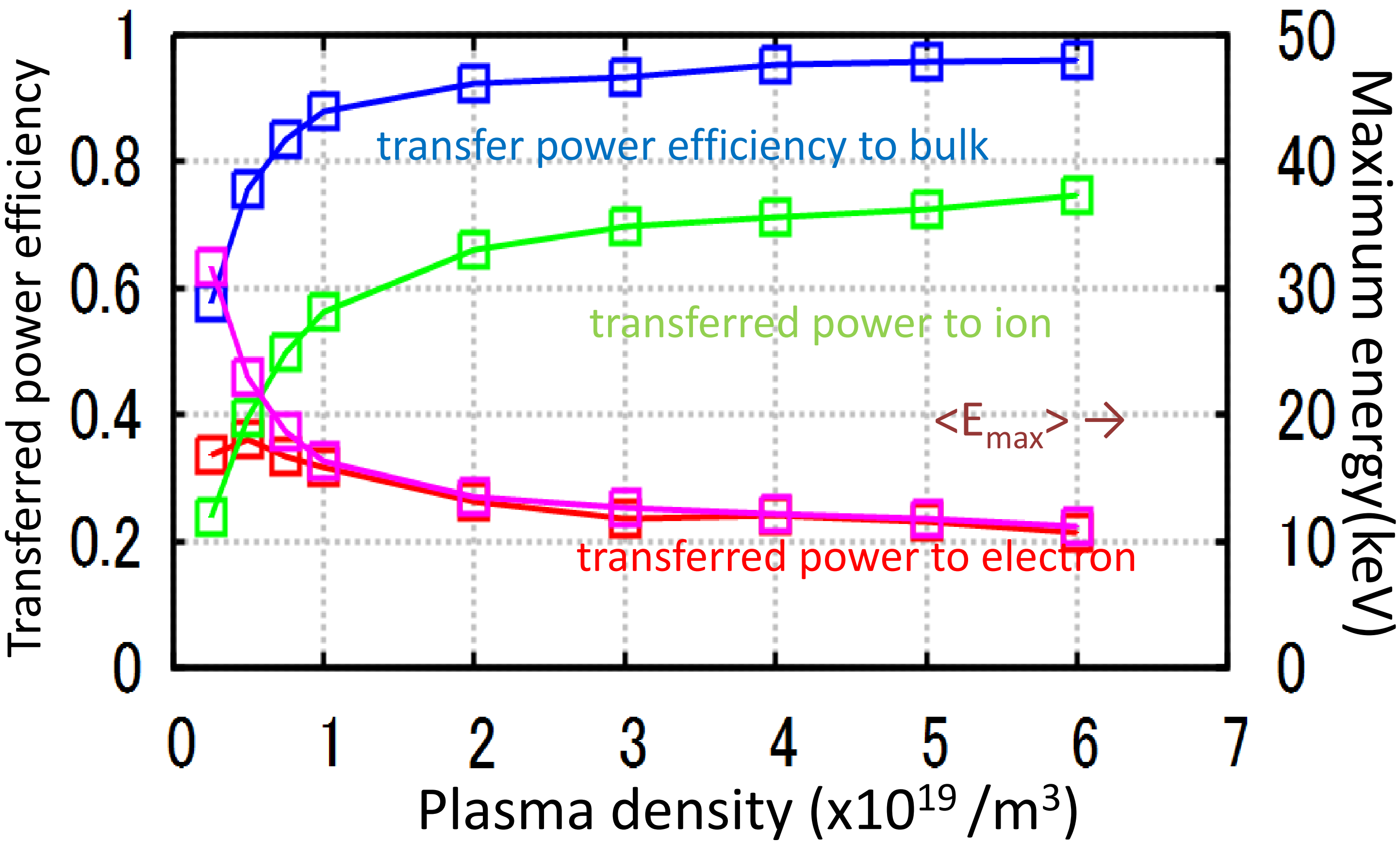
Difference from other code.

○Initial positions of Monte-Carlo particles are only on resonance layer
⇒Since this difference lead to save a calculation time, an index of the transferred power rate and its profile can be analyzed for less time.

○ The loss boundary is set on Vacuum Vessel wall.
⇒ Re-entering fast ions are included.
Re-entering fast ions is fast ions which re-enter in the region of the closed flux surfaces after they have once passed LCFS. There is a lot of re-entering fast ions in LHD high beta or low field strength case.
⇒ The lost point or rate of fast ions to diver tor can be analyzed.

Density dependence

$$\frac{\text{Average energy transferred from ICRF fast ions to bulk plasma}}{\text{Average energy absorbed from ICRF wave to fast ions}} \Rightarrow \text{transferred power efficiency}$$

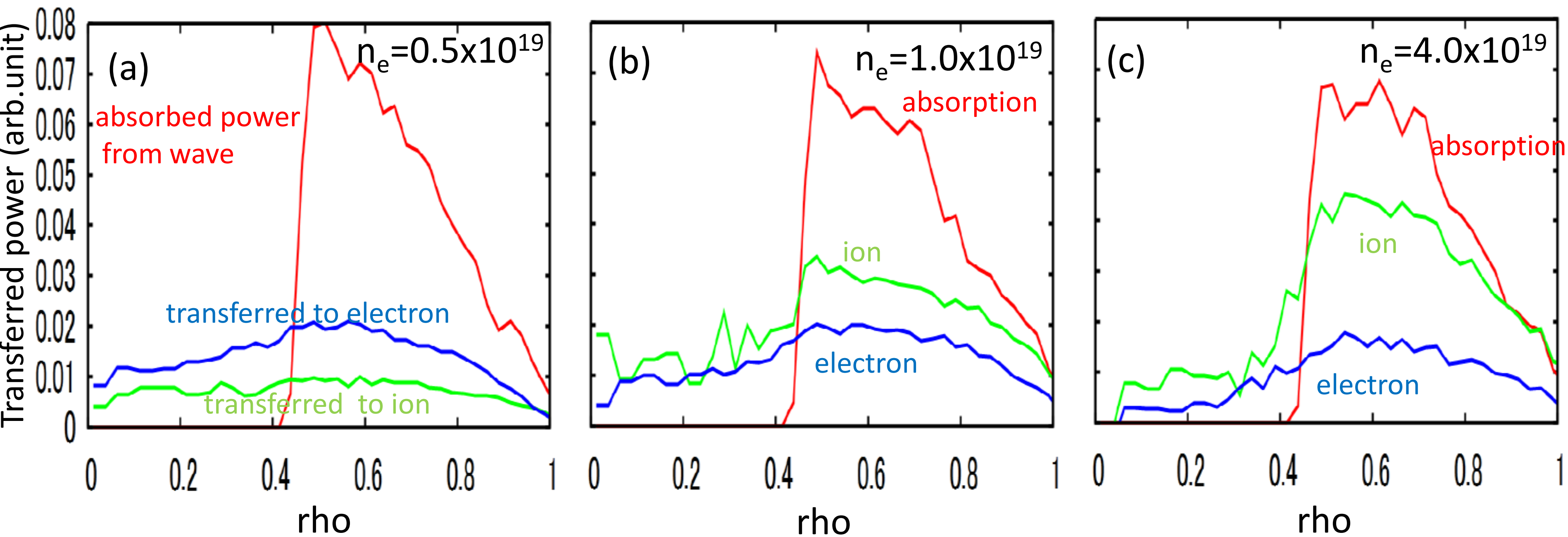


Te= 1 keV

E_{icrf}=1 kV/m

○In the high density case where the collision time is quite short , efficiency to ions > efficiency to electron.
→ the transferred power efficiency is about 0.9.

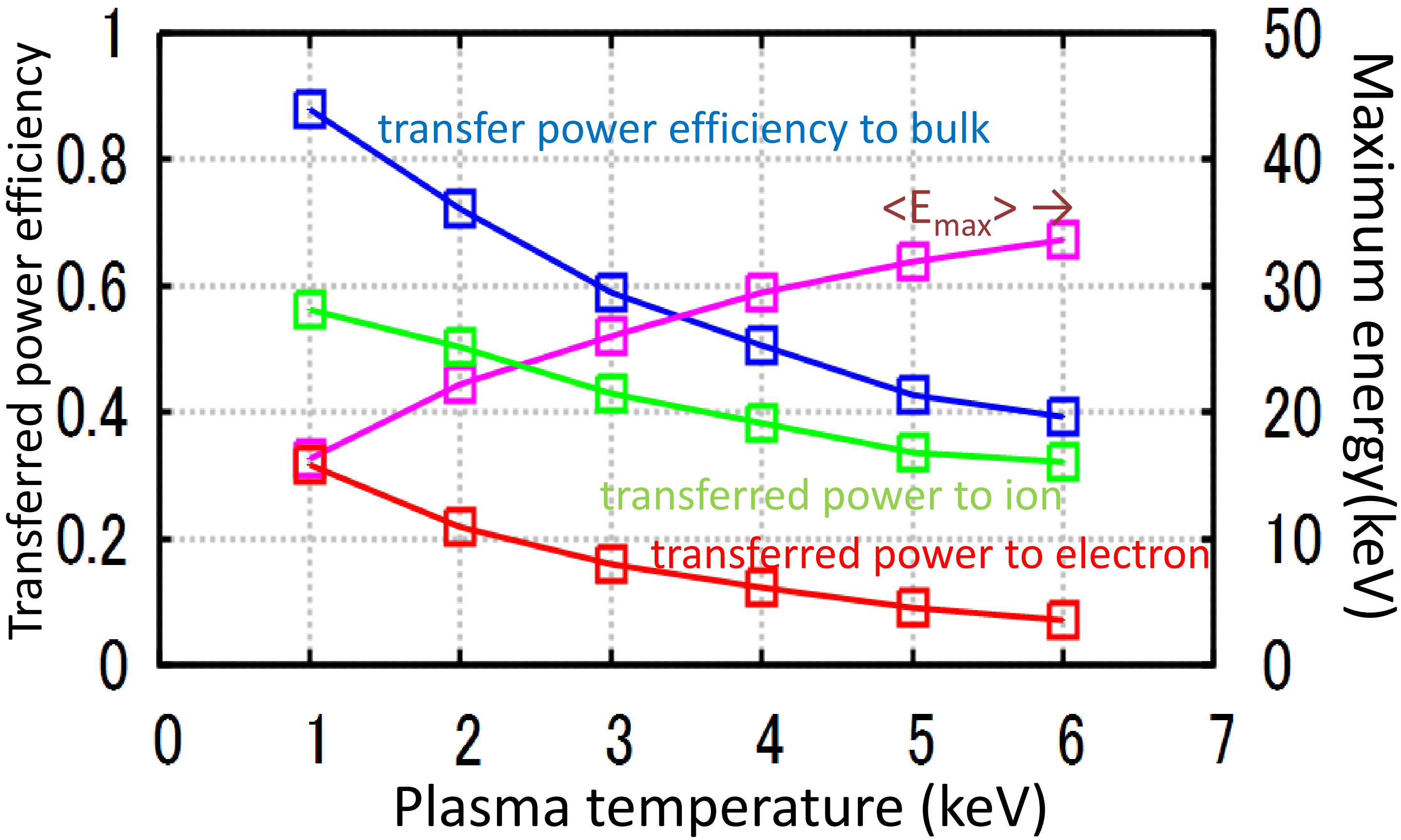
Transferred power profile（density）



○ In the high density case where the collision time is quite short ,
→ the ion transferred power profile is close to absorbed power profile.

temperature dependence

Average energy transferred from ICRF fast ions to bulk plasma / Average energy absorbed from ICRF wave to fast ions => transferred power efficiency



○ In the high Te case where the collision time is long ,

→ The energy of ICRF fast ions becomes large.

○ In the high Te case, main component of collision is ions.

○ Since pitch angle scatter is large (ions collision frequency > electrons) and the energy of ICRF fast ions is large, transfer power efficiency decreases in the high Te case.

Summary of orbit following

In order to optimize the transferred power from ICRF fast ions to bulk plasma, we develop a code, where models of behaviours of ICRF fast ion are minimally adopted from the view point to save a calculation time. On the transferred power index from ICRF minority ion to bulk plasma in the ICRF discharge, we obtain the following results.

〇In the cases with the high collision frequency, the transferred power to bulk ions is more than that to electrons, and the the transferred power becomes high.

〇 In the cases with high collision frequencies, the profile of transferred power has the peak close to that of the absorbed power from ICRF wave to the fast ions.

In the future plan, the models such as wave field model and assumption as ICRF minority fast ions is improved and the calculation is optimized. The evaluated properties is validated though a comparison with experiments.

Outline

〇 WM module of TASK3D to solve wave equaion.

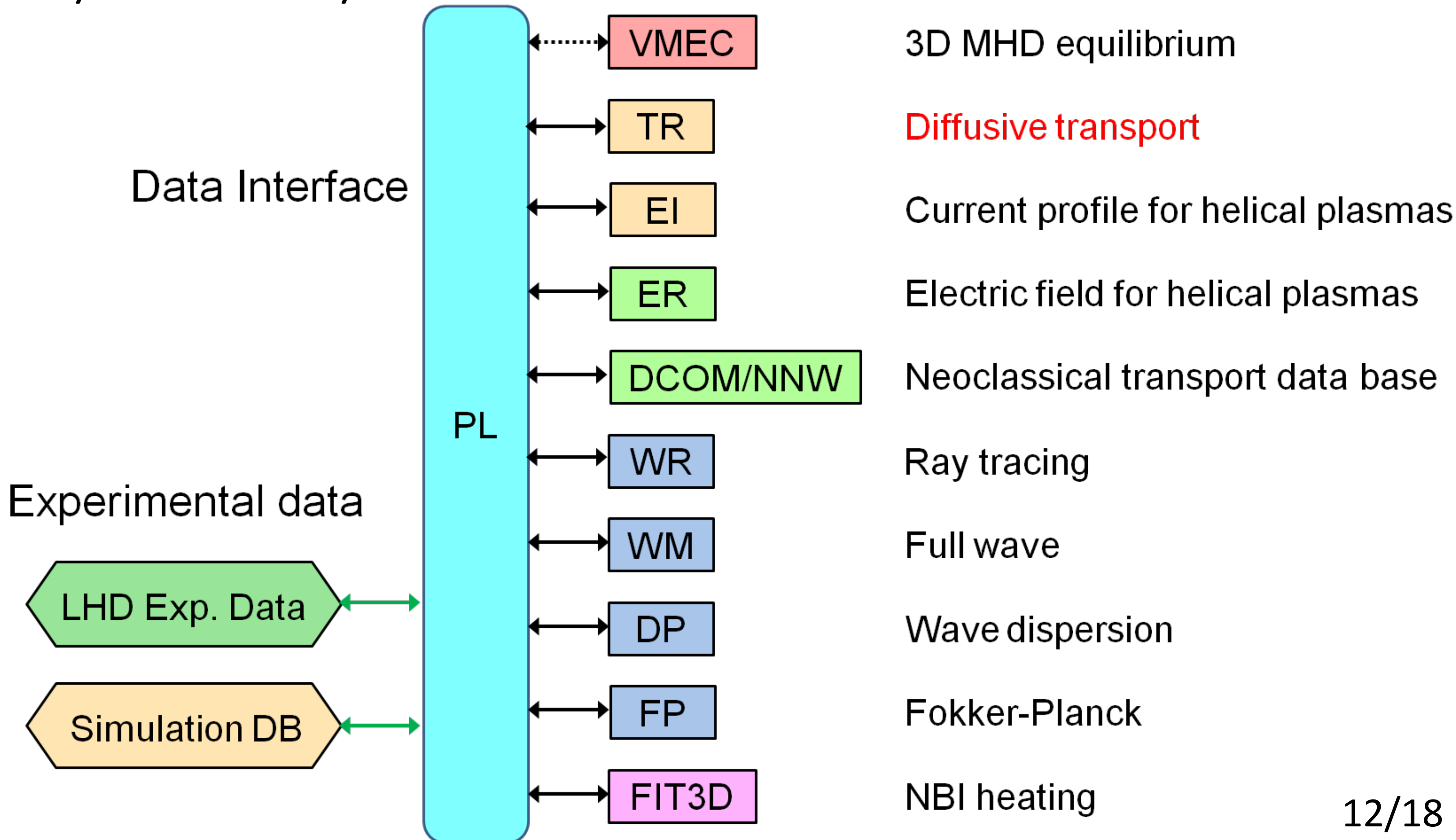
- WM module.
- Analyses for cold plasma model.

〇Monte Carlo simulation of fast ion generated by ICRF based on orbit following in real coordinates in large helical device.

- Simple code for evaluation of transfer power efficiency.
- Analyses for ICRF fast ions.

TASK3D

An integrated transport code for three dimensional configurations (TASK3D) has been developed in order to systematically clarify the confinement physics in a toroidal helical plasma. TASK3D is mainly based on a transport simulation combining various simplified models. It is being developed on the basis of an integrated transport code for tokamak plasmas, TASK [3] (Transport Analyzing System for tokamaK), which was developed in Kyoto University.



Simulation Model

TASK/WM

Maxwell's equation is solved for the electric field, *E*, with a complex frequency, *ω*, as a boundary value problem. In the radial, finite-difference method is used. In the poloidal, Furier expansion is used.

$$\nabla \times \nabla \times \boldsymbol{E} = \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \cdot \boldsymbol{E} + i\omega\mu_0 j_{\text{ext}}$$

Here, the external current, j_{ext}, represents the antenna current density in ICRF heating. Assuming a cold plasma and a simple collisional dumping, the dielectric tensor is

$$\overleftrightarrow{\epsilon} = \begin{pmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{pmatrix},$$

$$S = 1 - \frac{1}{\epsilon_0} \sum_s \frac{\omega_{\text{ps}}^2}{\omega} \frac{\omega + i\nu_s}{(\omega + i\nu_s)^2 - \Omega_s^2},$$

$$D = \frac{1}{\epsilon_0} \sum_s \frac{\omega_{\text{ps}}^2}{\omega} \frac{\Omega_s}{(\omega + i\nu_s)^2 - \Omega_s^2},$$

$$P = 1 - \sum_s \frac{\omega_{\text{ps}}^2}{\omega} \frac{1}{\omega + i\nu_s},$$

where *s* and ε_0 are the particle species and dielectric constant in vacuum, and ν_s, ω_{ps}, and ω_s are the collisionality, plasma frequency, and cyclotron frequency, respectively, for the *s* particle species.

Analyses of ICRF wave (cold plasma approximation)

Frequency Property

Majority ion: He, Minority ion: H

$n_e = 2x10^{19}\ m^{-3}$, Minority ratio: 5%

B_{ax} = 2.75 T, R_{ax}=3.6 m

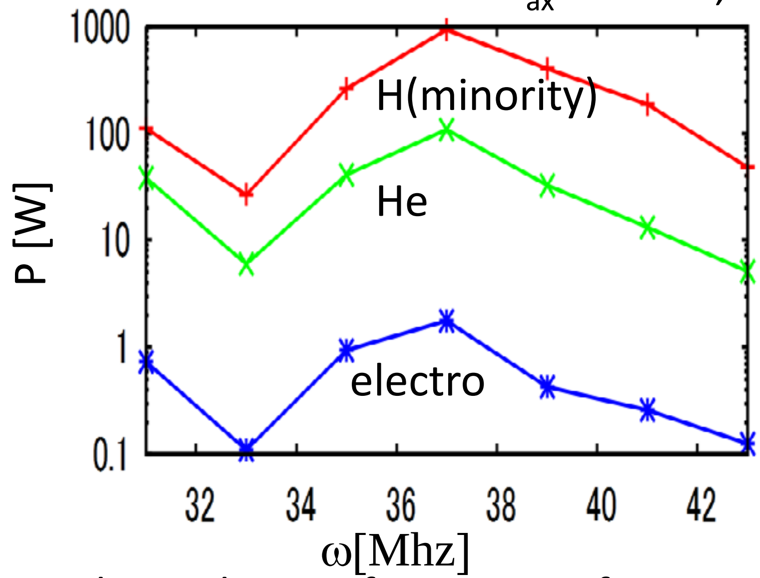


Fig. 1 dependence of ICRF wave frequency on absorption power .

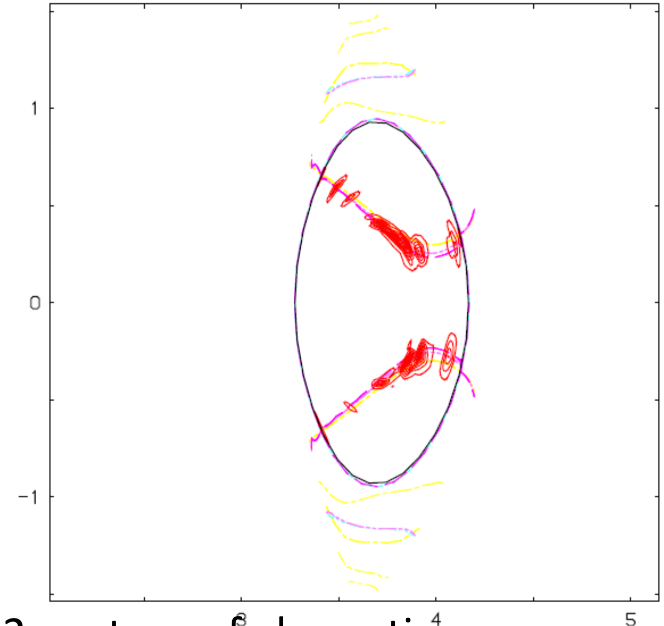


Fig. 2 contour of absorption power profile and resonance layer in 37 MHz case.

○The absorption power to the minority ion (H) is the largest than others and the absorption power to helium and electron is one tenth and one hundredth of the minority ion's absorption power, respectively.

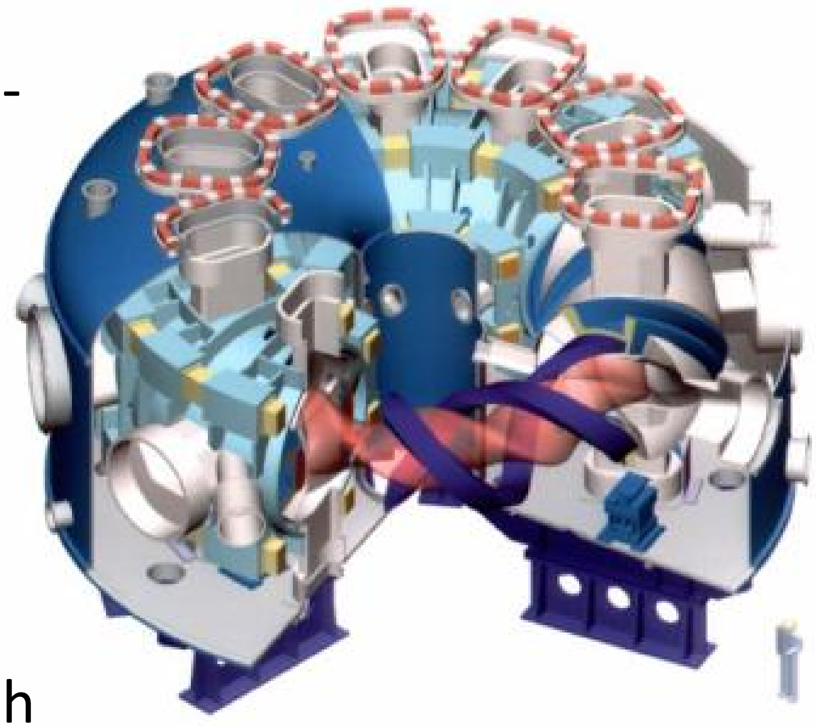
○The absorption power near 37~39 MHz is the largest in each particle species.

3D Absorption Area of ICRF heating

○The magnetic field of the LHD is non-axisymmetric.

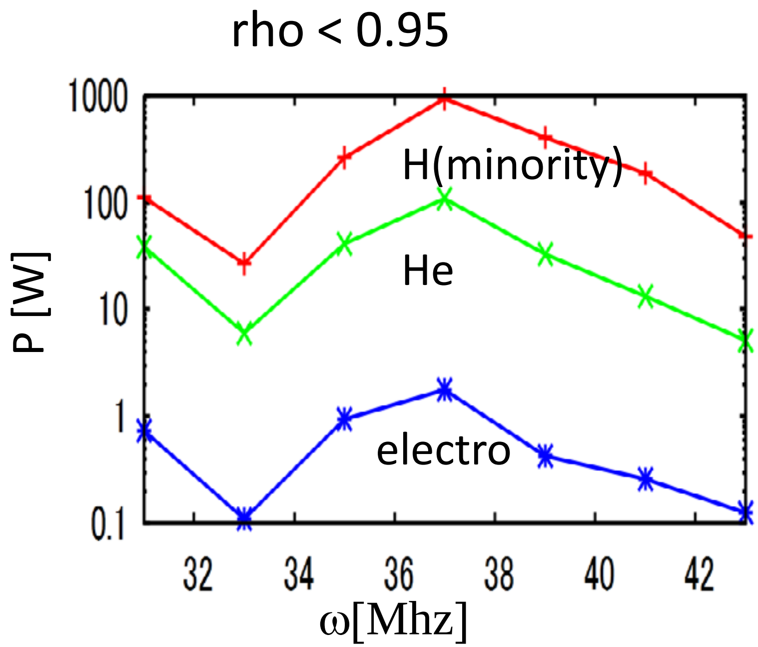
○In the LHD, two main coils which make the magnetic field are helically-twisted, and the field strength profile change in each poloidal plain.

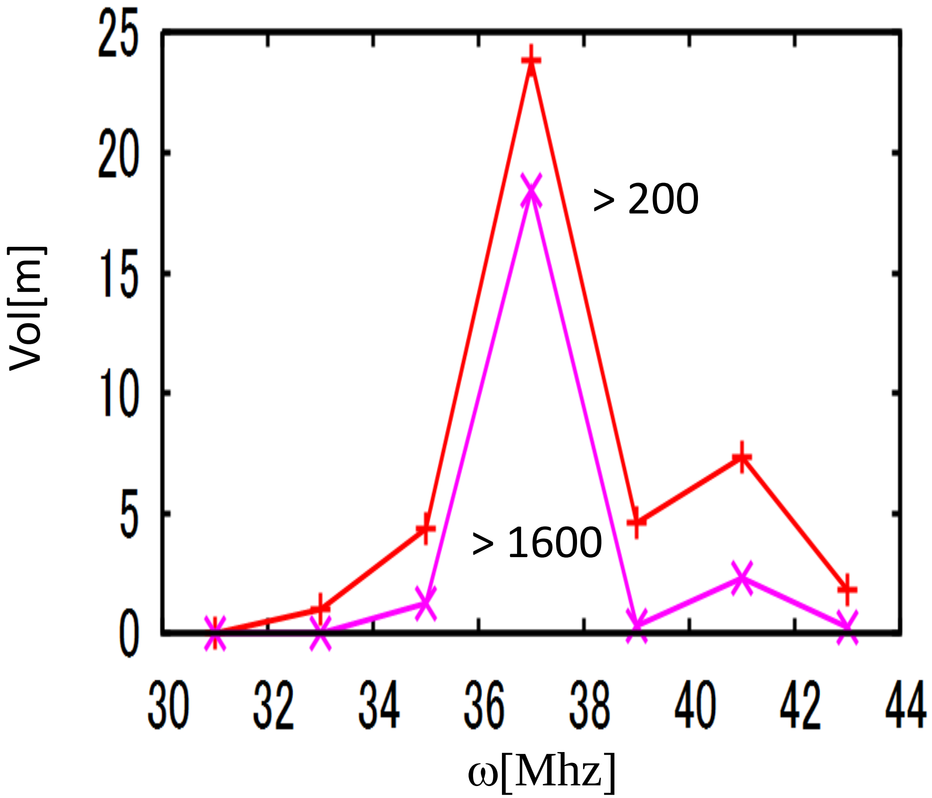
○The volume of absorption area, which dependents on the field strength profile, may be important for the production of the high energy particle.



We evaluate the 3D absorption area of ICRF heating in the LHD plasma.

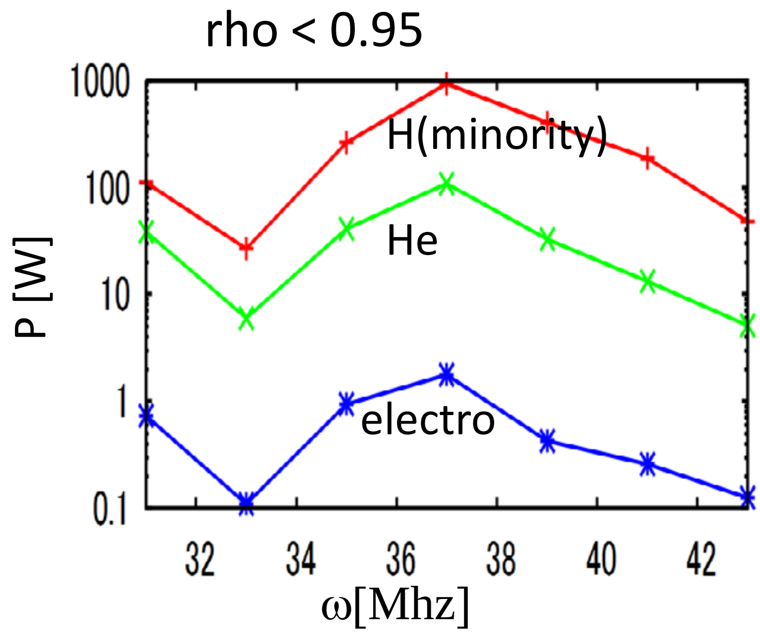
Frequency property of Absorption Volume

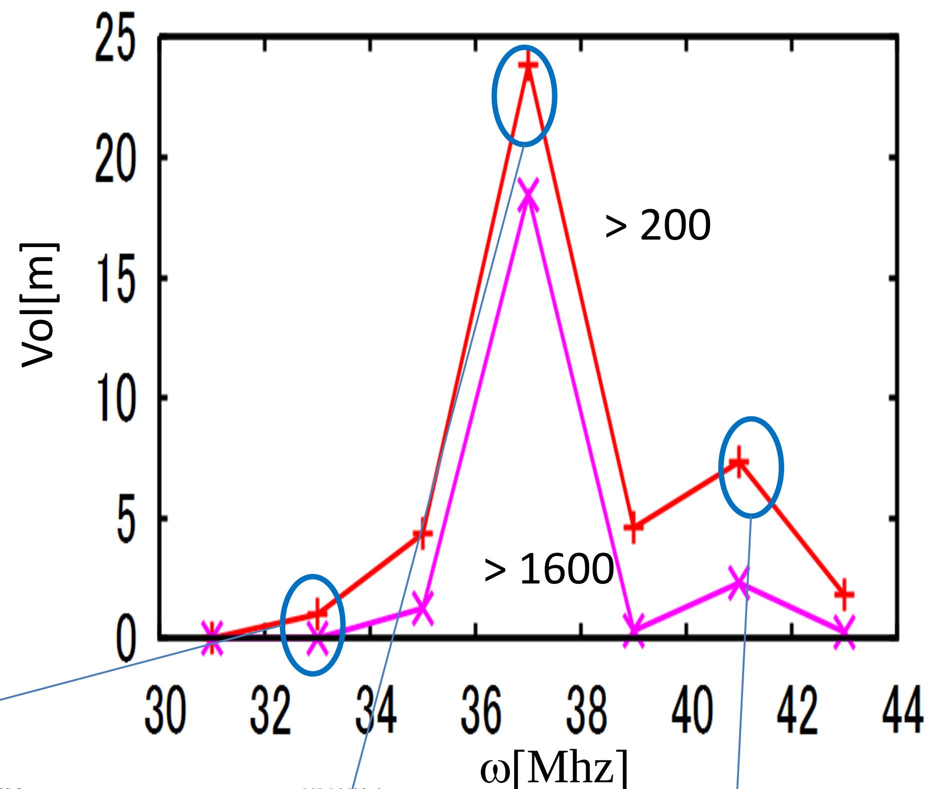


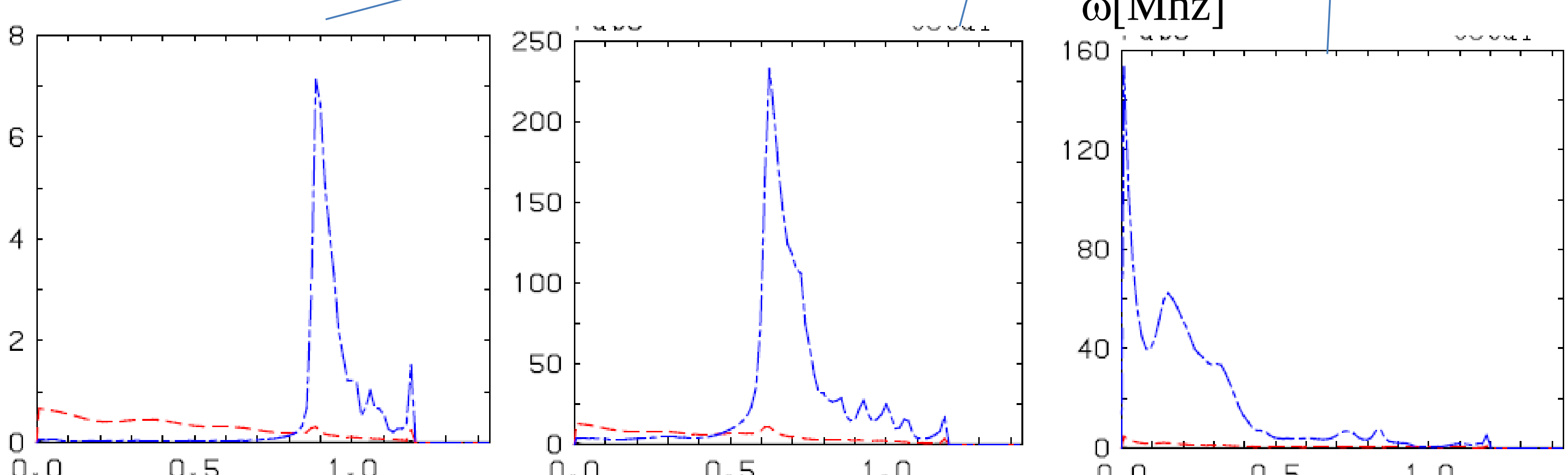


The volume near the 37 Mhz is the biggest. In the frequency, resonance layer is near the saddle point of magnetic field strength In the other frequencies, the volume is about 5 cubic meters.

Frequency dependecy of Absorption Volume







Future plan

○In the LHD, ICRF wave analyses is calculated by using the WM/TASK3D with cold model.

○Now,　in order to Hot plasma model, Fukuyama sensei and me will be developing WM(WMF) module where E// and E⊥ is solved because of improvement of precision.　And in radial, a method changes from finite-difference method to finite-element method.

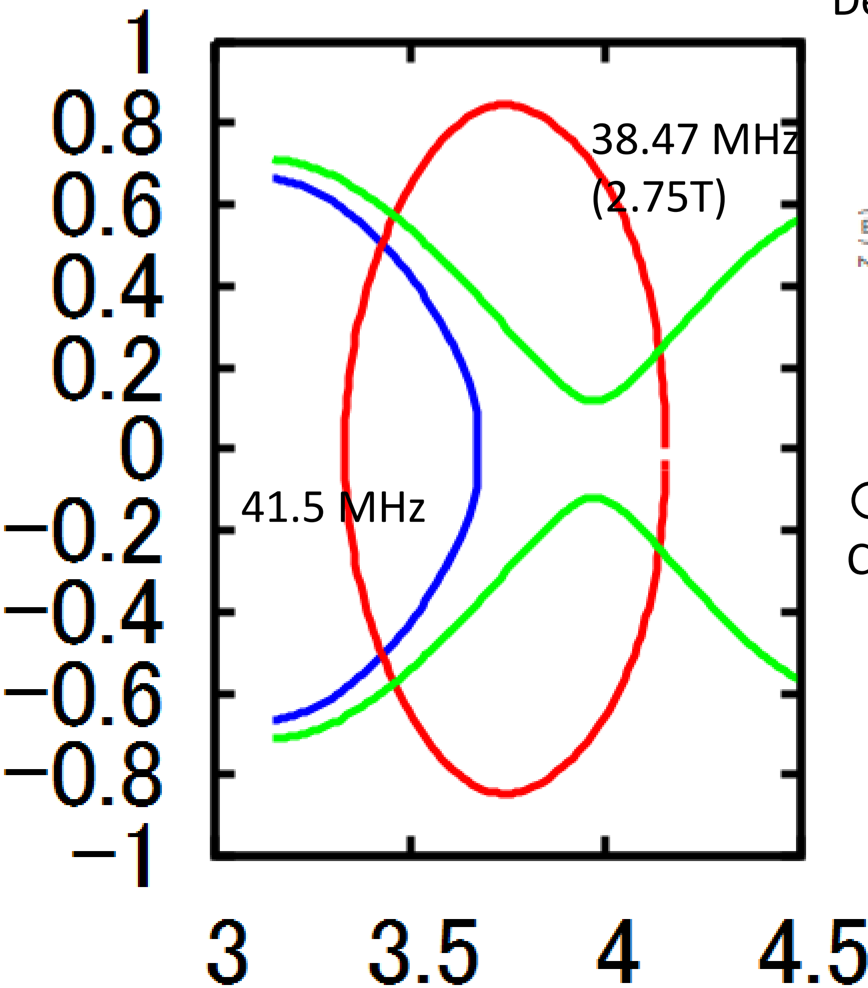
Full wave analyses in TASK3D

- **Method**
  - **ML**: Multi-layer: many uniform layers, six eigen modes in each layer, $E_\rho, E_\chi, E_\varphi$
  - **MM**: Multi-mode: Fourier in poloidal, Finite-difference method in radial, $E_\rho, E_\chi, E_\varphi$
  - **MF**: Multi-mode: Fourier in poloidal, Finite-element method in radial, $E_\rho, E_\perp, E_\parallel$
  - **FF**: Finite element: Finite-element method in poloidal and radial, $E_\rho, E_\perp, E_\parallel$

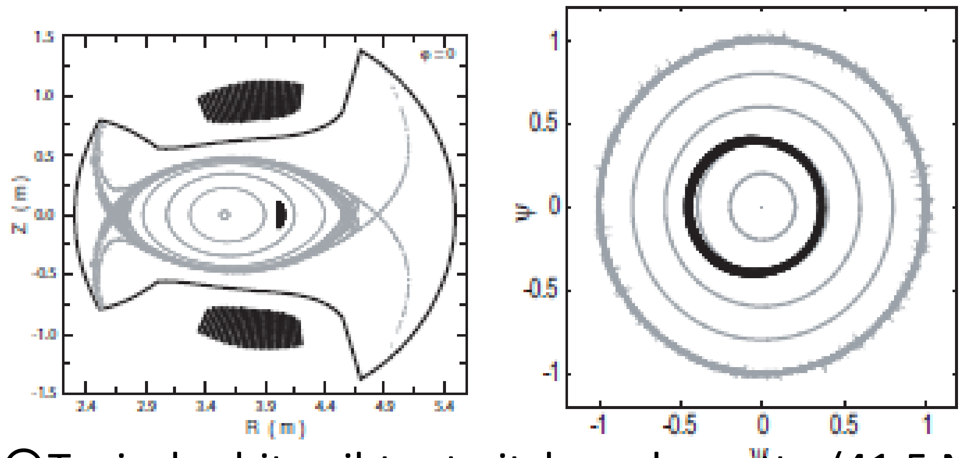
- **Modules**
  - **W1**: 1D: ML
  - **WM**: 2D: MM: helical (VMEC wout, Boozer)
  - **WMF**: 2D: MF: helical (VMEC wout) not tested yet
  - **WF2**: 2D: FF
  - **WF3**: 3D: FF

Typical orbit of fast ion reflected on resonance layer

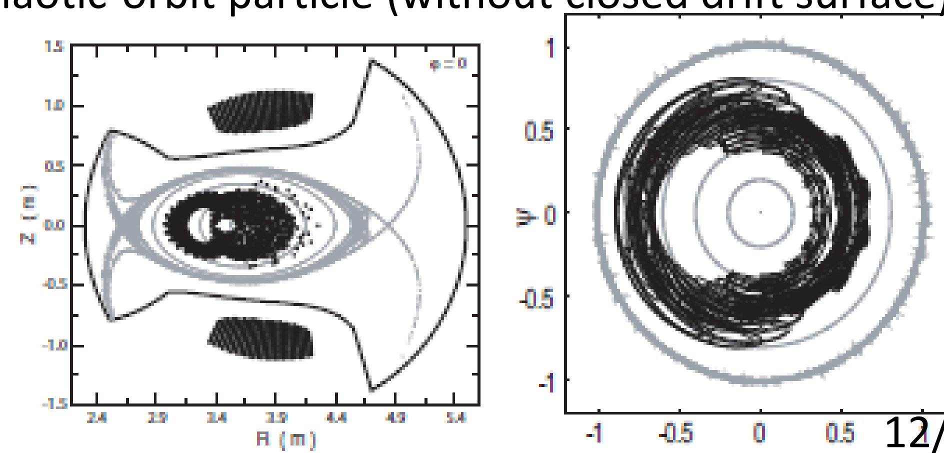
○The fast ions heated by ICRF wave becomes “banana orbit particle (helical trapped particle)” which forms a closed drift surface or “chaotic orbit particle” which does not form the closed drift surface depending on the shape of the resonance layer.



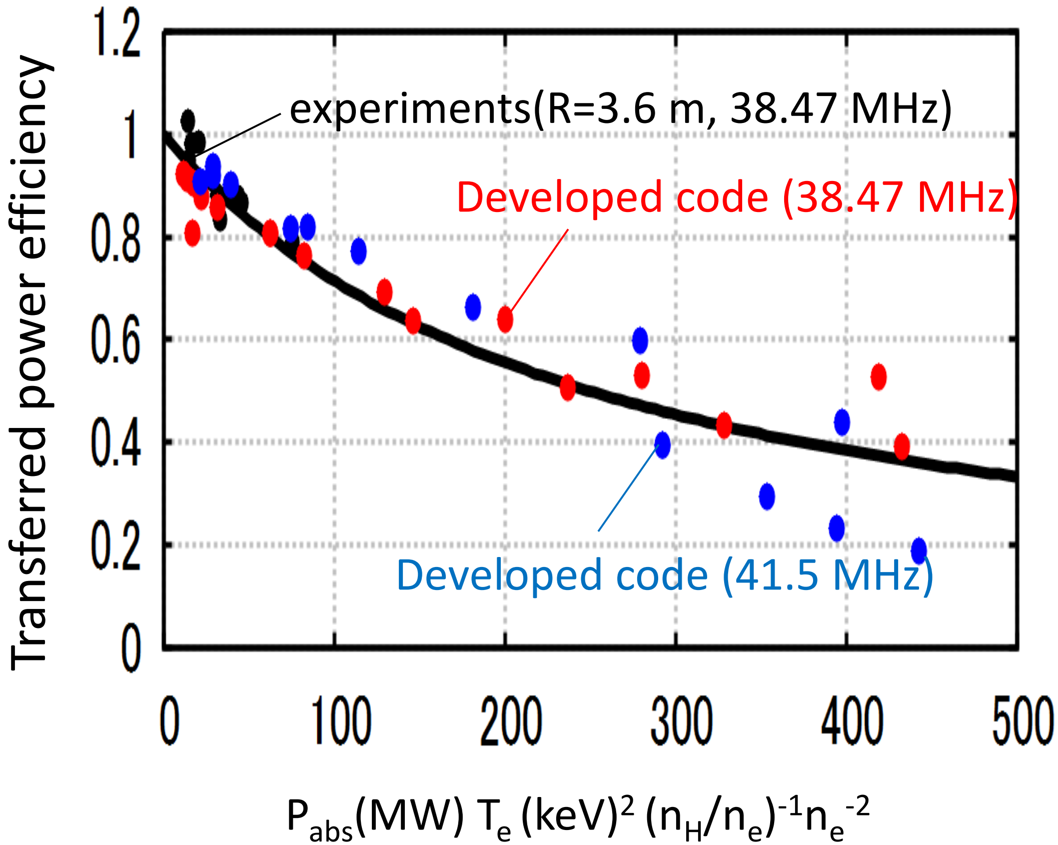
○Typical orbit without pitch angle scatter(38.47 MHz)
Deeply trapped particle (with closed drift surface)

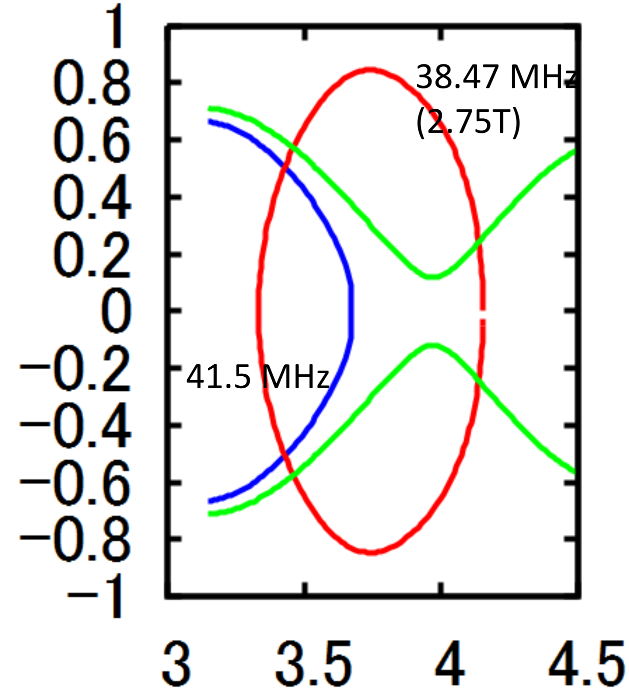


○Typical orbit wihtout pitch angle scatter(41.5 MHz)
Chaotic-orbit particle (without closed drift surface)



Effect of location of resonance layer.



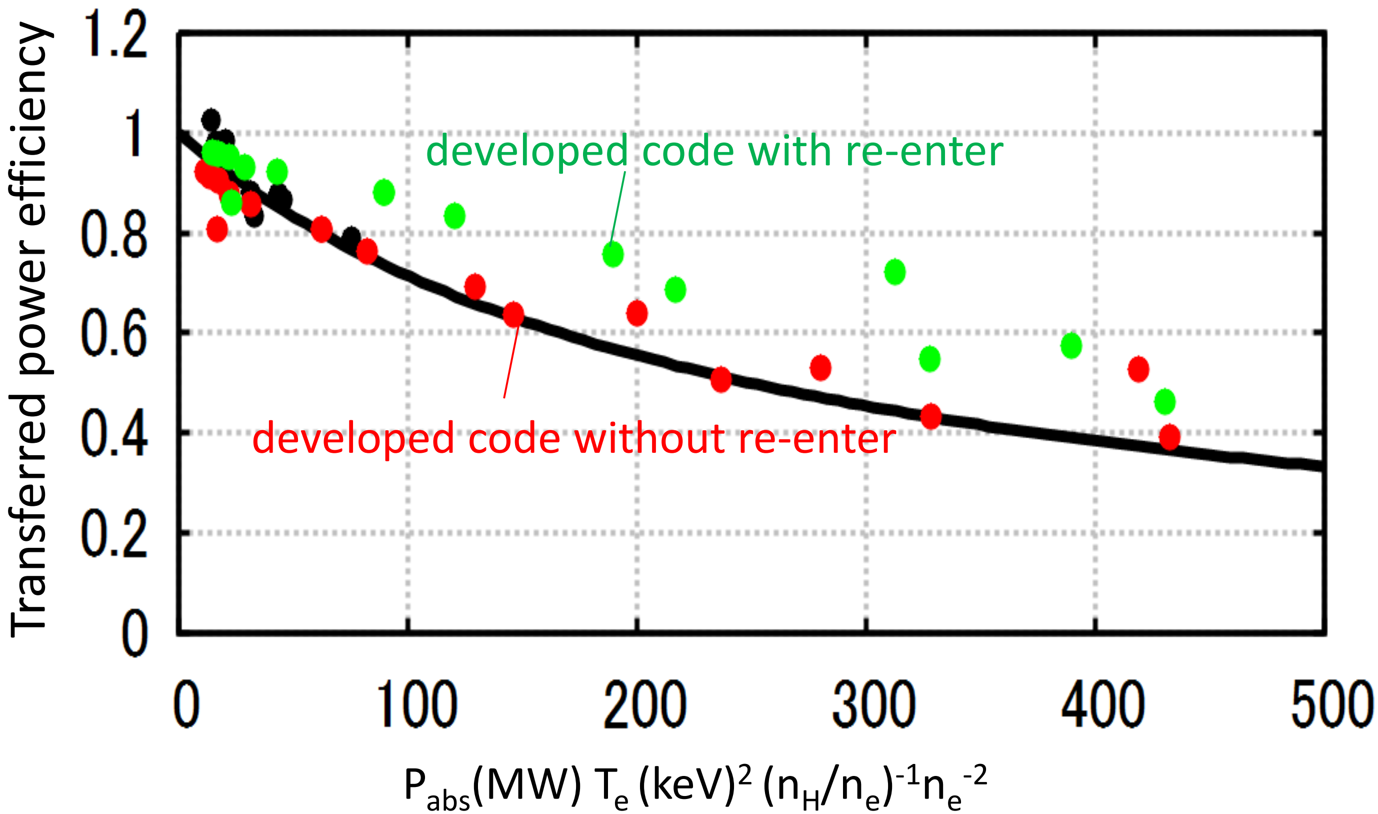


○In the transferred power efficiency ~ 1.0,
a tendency of the efficiency in case of 41.5 MHz is almost same as that of 38.47 MHz.

○When absorbed power is larger and/or density is smaller,
the efficiency in case of 41.5 MHz is smaller than that of 38.47 MHz

Effect of the Re-entering ions

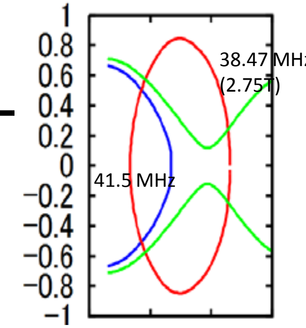
In the LHD, there is a lot of re-entering ions which re-enter in the region of the closed flux surfaces after they have once passed LCFS.



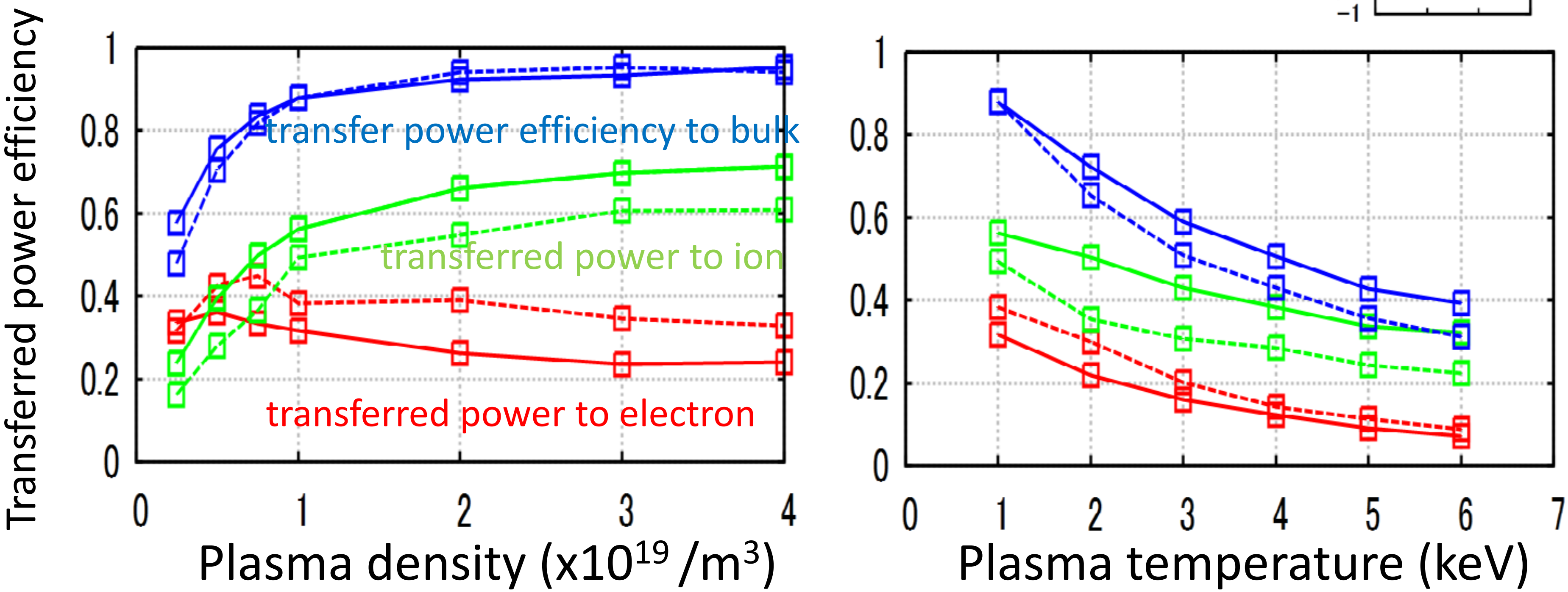
○The efficiency with re-entering ions is larger than that without re-entering ions. And, the tendency of the efficiency with re-entering ions changes from case without re-entering ions.

○Since the re-entering fast ions may be lost due to a charge exchange reaction, we will investigate the efficiency including loss due to a charge exchange reaction.

Density and temperature dependence.



Solid line 38.47 Mhz
Dashed line 41.5 Mhz



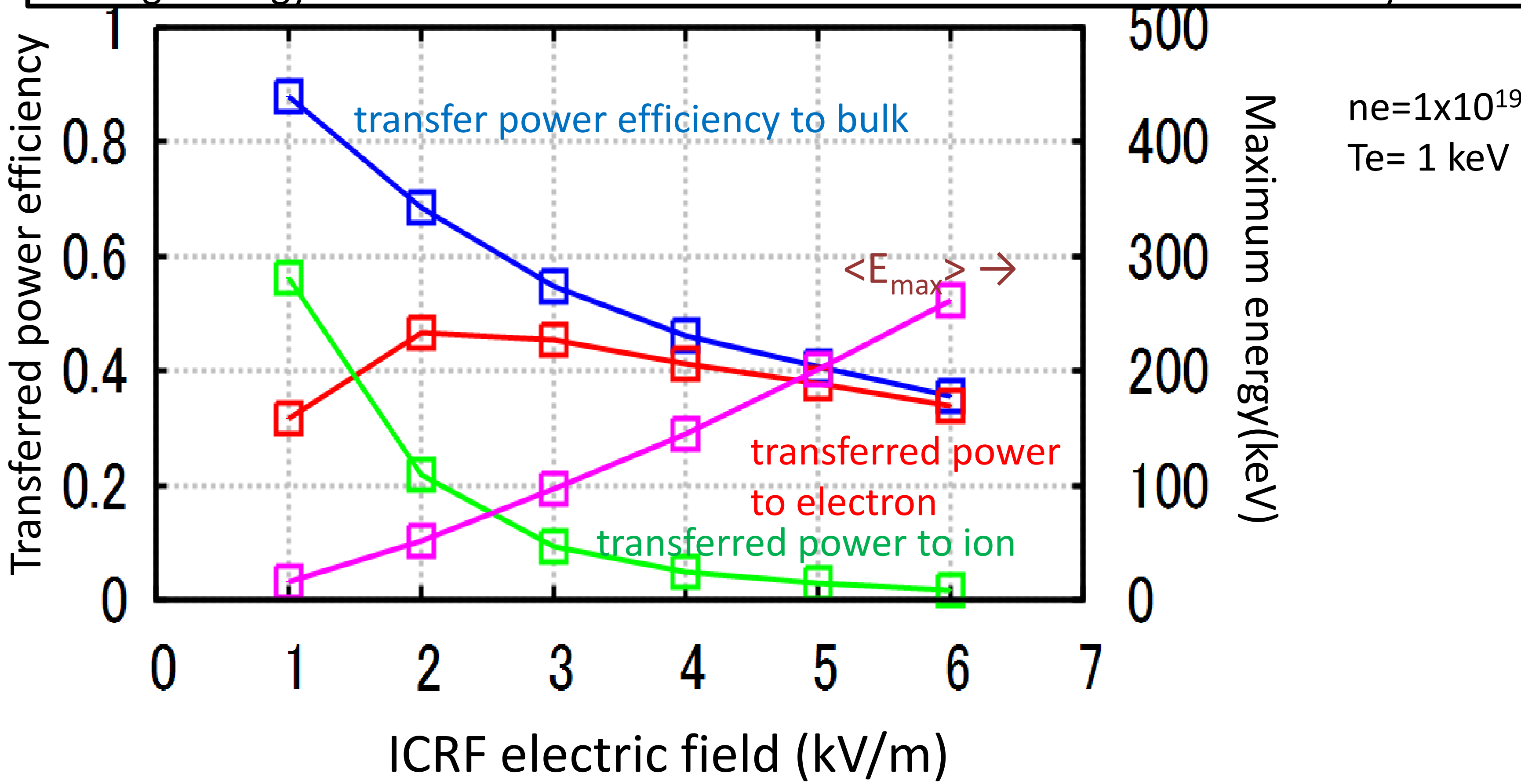
○In the high collision frequency(density ↑, temperature ↓),
there is no significant difference of transfer power efficiency between two cases.

○In the lower collision frequency(density ↓, temperature ↑),
the efficiency decrease when the resonance layer is set near the axis.(41.5 MHz)

○In the efficiency to ions, 38.47 MHz case > 41.5 MHz case while
in the efficiency to electron 41.5 MHz > 38.47 MHz case.

Wave field model dependence on transferred power efficiency and maximum energy

$$\frac{\text{Average energy transferred from ICRF fast ions to bulk plasma}}{\text{Average energy absorbed from ICRF wave to fast ions}} \Rightarrow \text{transferred power efficiency}$$



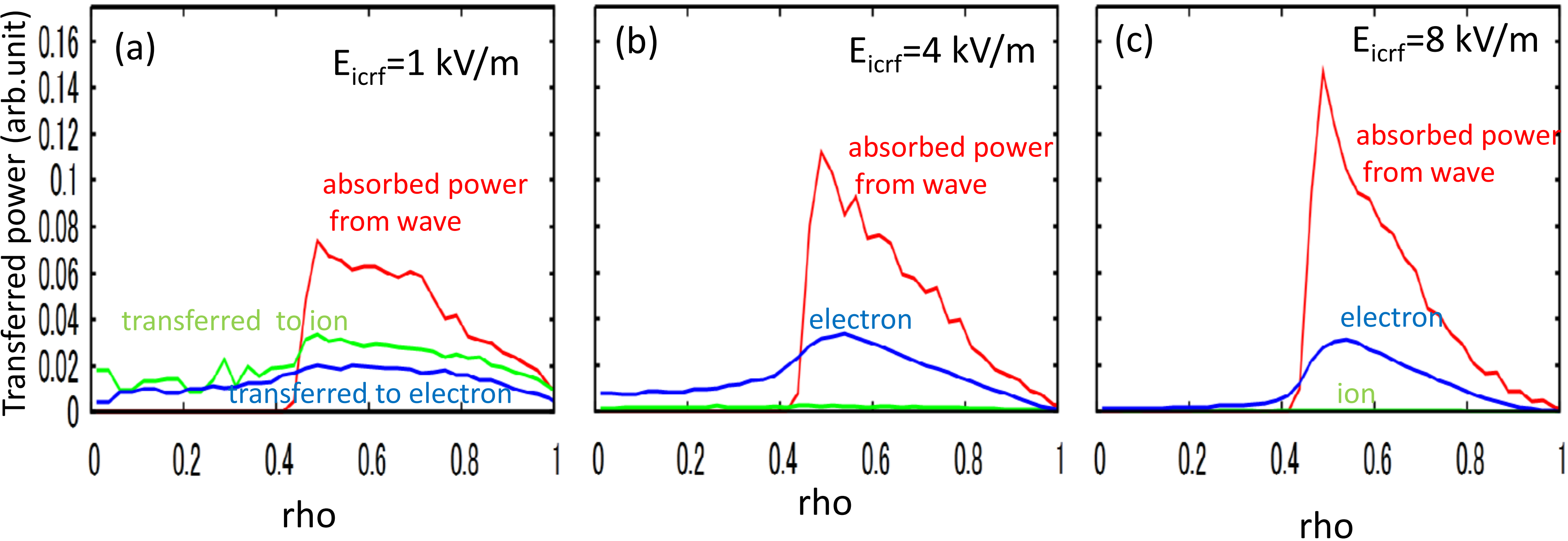
○In the low strength of wave field model, efficiency to ions > efficiency to electron

→ the transferred power efficiency is about 0.7 -0.8.

○In the high strength of wave field model, the efficiency to electron is larger

→ the transferred power efficiency is less than 0.5.

Transferred power profile（electric field ）



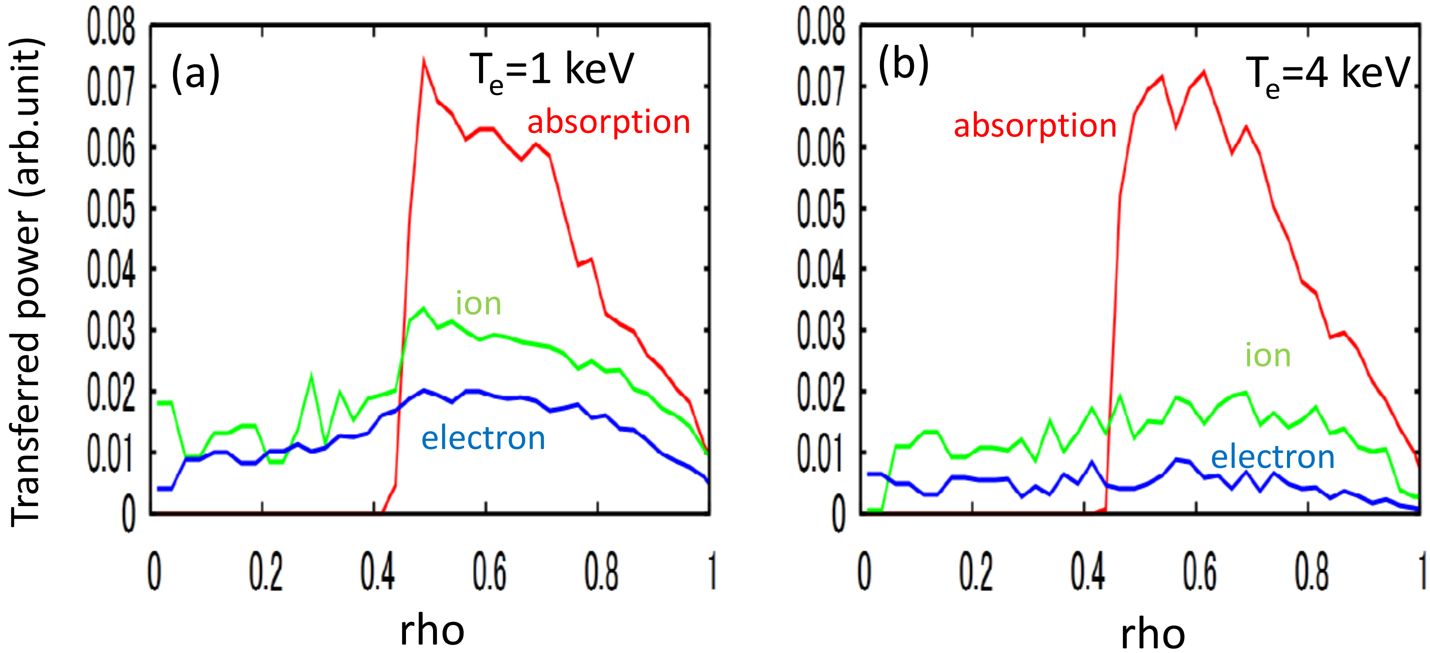
○ In the low field strength, efficiency to ions > efficiency to electrons

→ the ion and electron transferred power profile is flat.

○ In the high field strength, efficiency to electron is large.

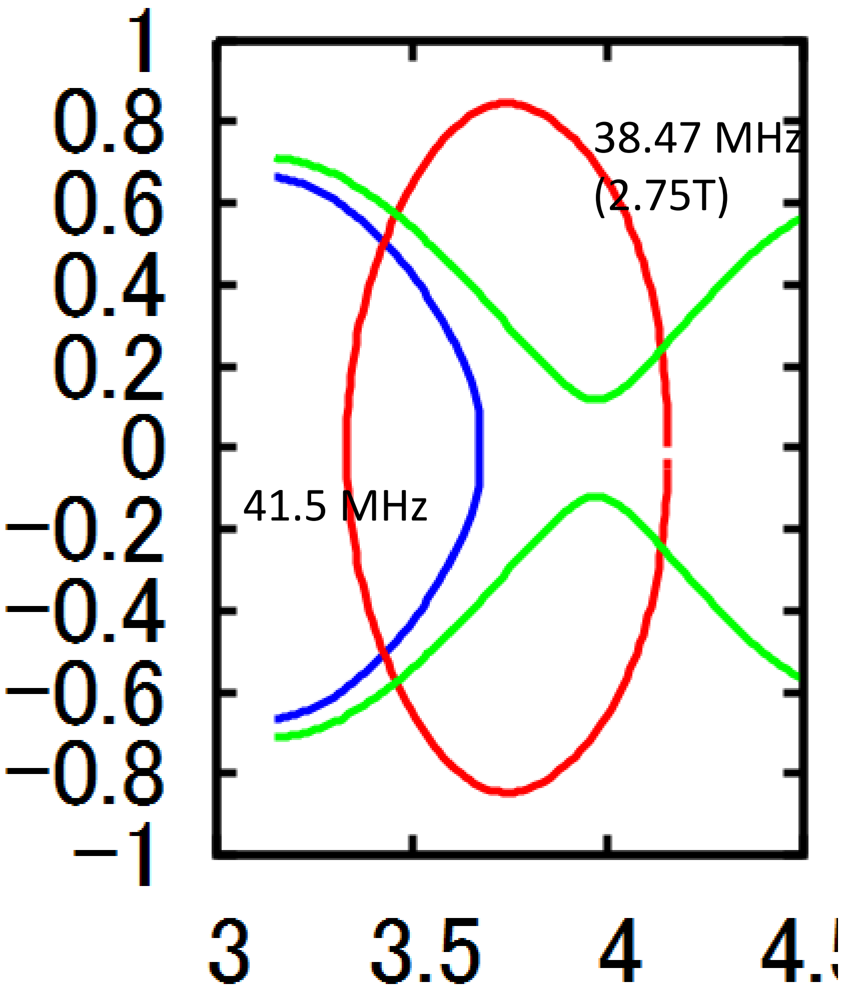
→ the electron transferred power profile is similar to profile of power absorbed from wave.

temperature dependence

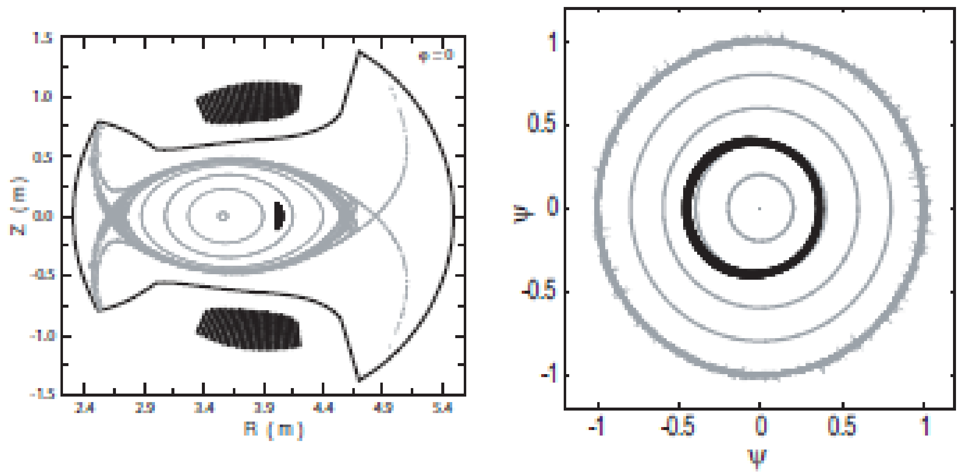


○ In the regime where efficiency to ions > efficiency to electron,
there is no significantly difference of the shape of the transferred power.

Effect of location of resonance layer.



○Typical orbit of no pitch angle scatter(38.47 MHz)
Deeply trapped particle (with closed drift surface)



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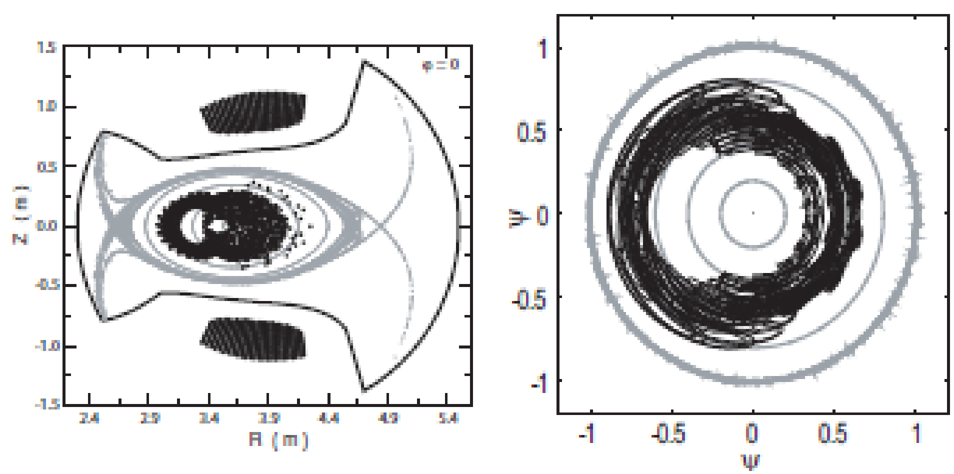
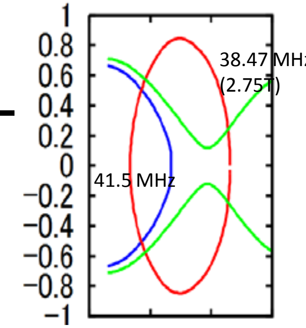


Difference of location of resonance layer.



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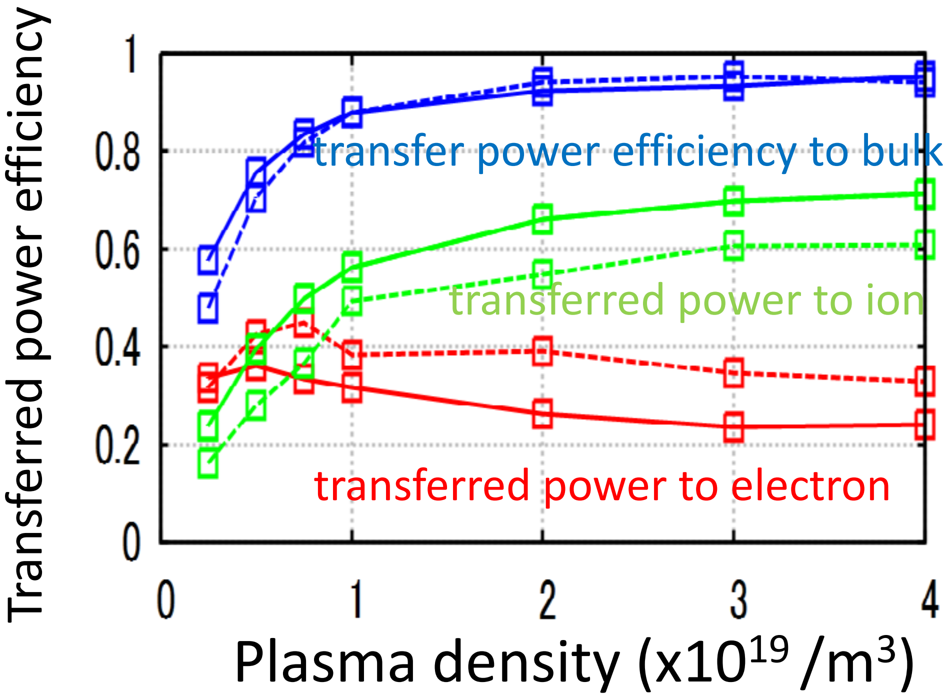

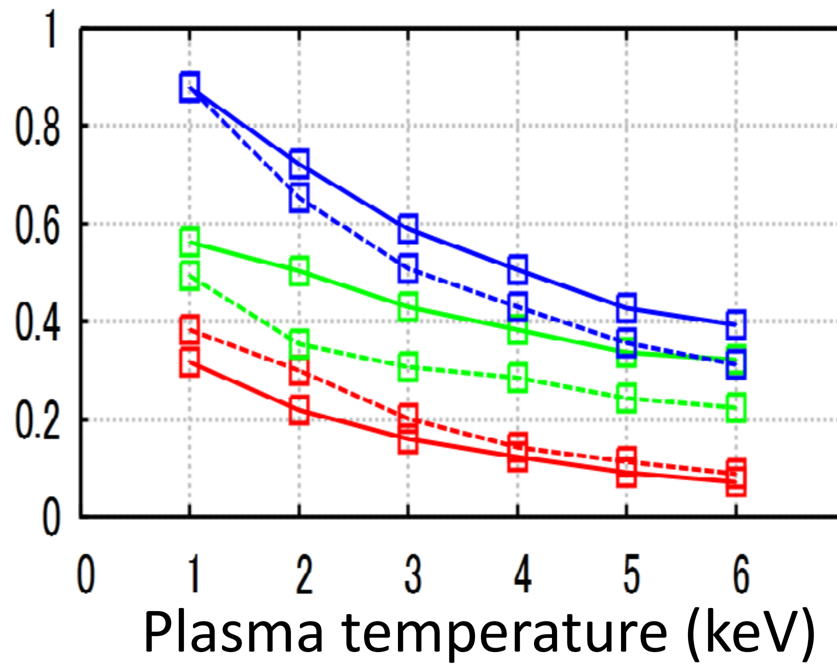

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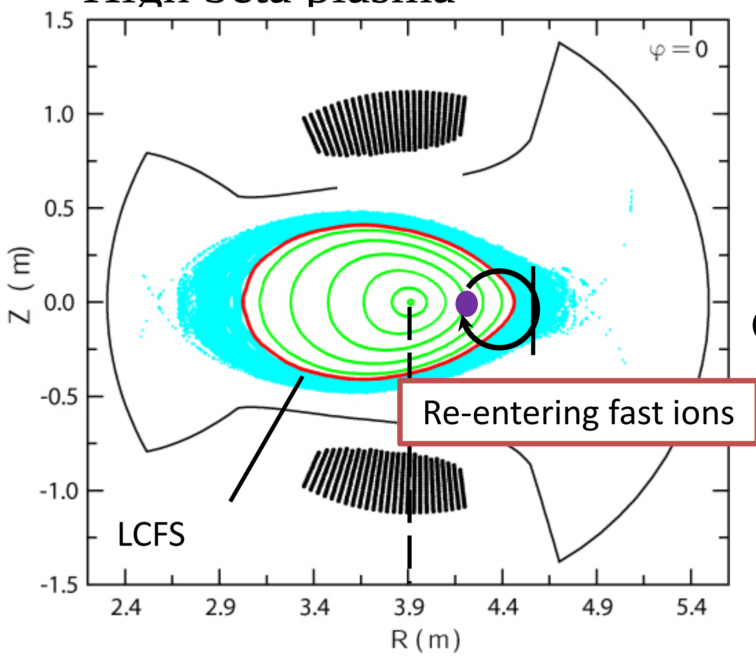
Effect of the Re-entering ions

In the LHD, there is a lot of re-entering ions which re-enter in the region of the closed flux surfaces after they have once passed LCFS.

Magnetic field

High beta plasma

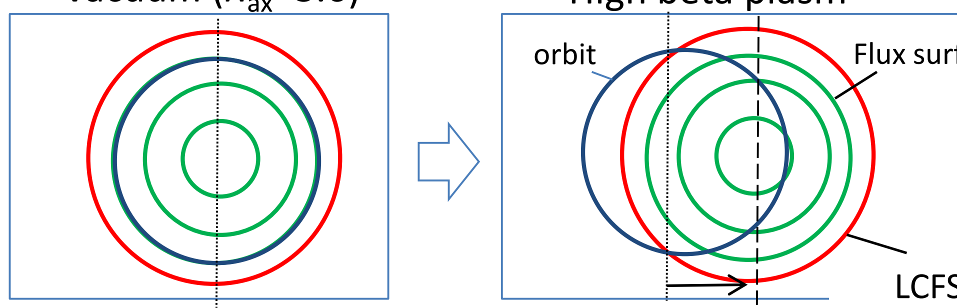


Re-entering fast ions

○High beta plasma (magnetic axis on R > 3.6)

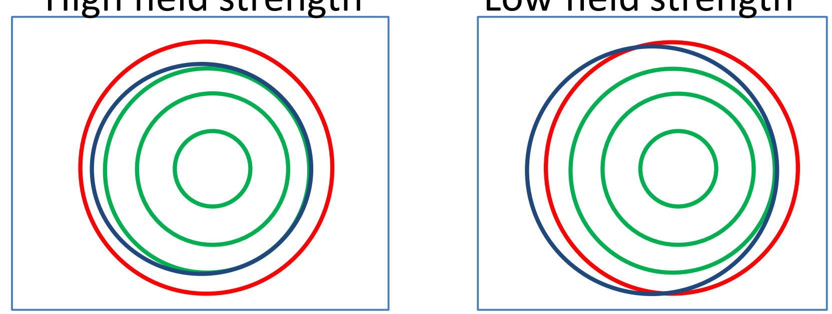
deeply trapped particle becomes Re-entering fast ions

Vacuum (R_{ax}=3.6) High beta plasm



○Low field strength (large drift velocity)

High field strength Low field strength



Passing particle become Re-entering fast ions too.

Effect of the Re-entering ions

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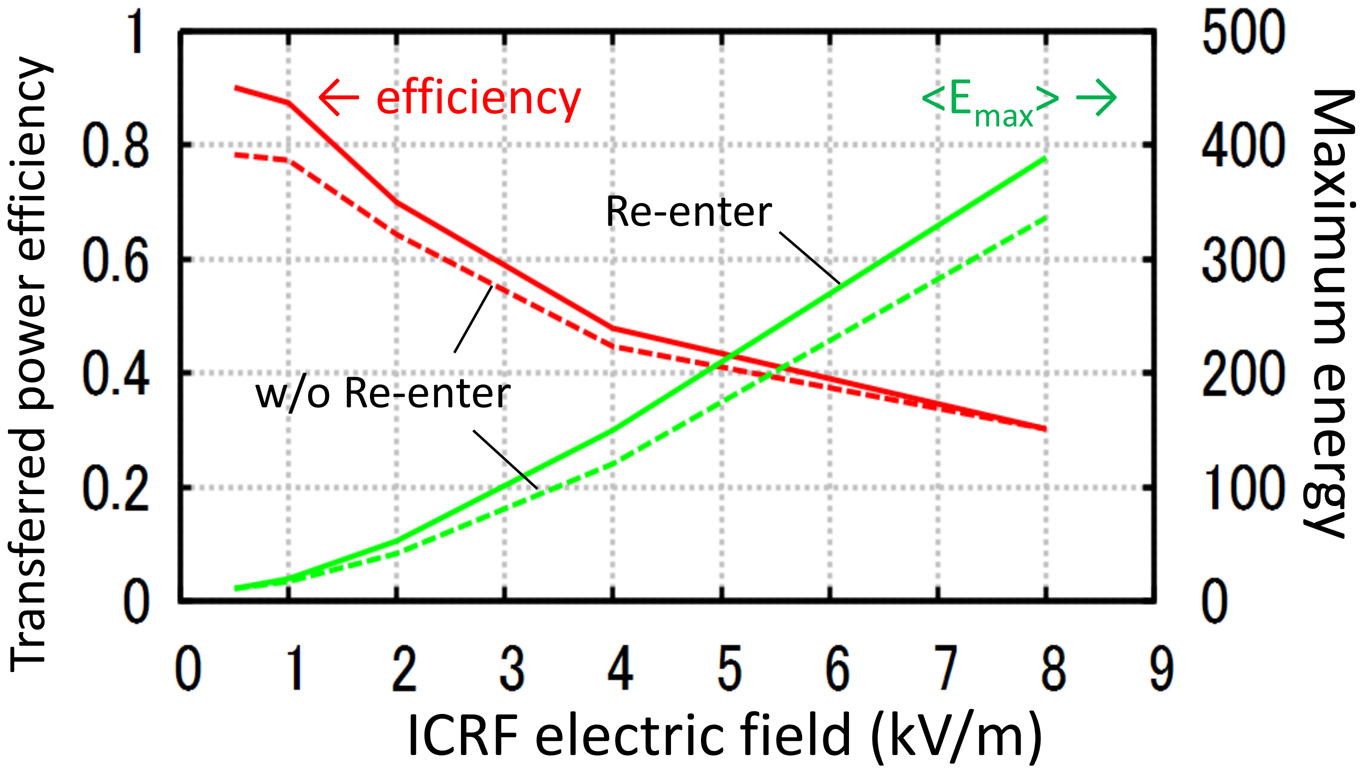


○There is a difference of the transferred power efficiency between with and without re-entering especially in region of low strength of wave field.

Summary

In order to optimize the transferred power from ICRF fast ions to bulk plasma, we proposal an index of the transferred power rate, and develop a code, where models of behaviours of ICRF fast ion are minimally adopted from the view point to save a calculation time. On the transferred power index from ICRF minority ion to bulk plasma in the ICRF discharge, we obtain the following results.

○In the cases with the low electric field of the wave field model or high collision frequency, the transferred power to bulk ions is more than that to electrons, and the index of the transferred power becomes high.

○ In the either cases with the low or high collision frequencies, the profile of transferred power has the peak close to that of the absorbed power from ICRF wave to the fast ions. In the regime between high density case, the profile becomes flat in the radial direction including near magnetic axis region.

In the future plan, the models such as wave field model and assumption as ICRF minority fast ions is improved and the calculation is optimized. The evaluated properties is validated though a comparison with experiments.

Collision operator (Plasma Phys. Control. Fusion **49** (2007) 1955)

- During δt , the velocity $(v_{\parallel},\ v_{\perp})$ change to

$$v'_{\parallel} = v_{\parallel} + \Delta v_v^{\mathrm{t/b}} \frac{v_{\parallel}}{v} - \Delta v_\chi^{\mathrm{t/b}} \frac{v_{\perp}}{v}$$

$$v'_{\perp} = \left[\left(v_{\perp} + \Delta v_v^{\mathrm{t/b}} \frac{v_{\perp}}{v} + \Delta v_\chi^{\mathrm{t/b}} \frac{v_{\parallel}}{v} \right)^2 + \left(\Delta v_\eta^{\mathrm{t/b}} \right)^2 \right]^{\frac{1}{2}}$$

t: test particle
b: background
χ: pitch angle
η: gyro-phase

- A set of $(\Delta v_v,\ \Delta v_\chi,\ \Delta v_\eta)$ is computed using normal random numbers with the mean values and the mean square deviations.

mean values:
$$\left\langle \Delta v_v^{\mathrm{t/b}} \right\rangle = -\left(1 + \frac{m_{\mathrm{t}}}{m_{\mathrm{b}}}\right) \frac{\Gamma^{\mathrm{t/b}}}{v^2} \left(\mathrm{erf}(u) - u\,\mathrm{erf}'(u)\right) \delta t$$

$$\left\langle \Delta v_\chi^{\mathrm{t/b}} \right\rangle = \left\langle \Delta v_\eta^{\mathrm{t/b}} \right\rangle = 0$$

mean square deviations:
$$\left\langle \left(\Delta v_v^{\mathrm{t/b}} \right)^2 \right\rangle = \frac{\Gamma^{\mathrm{t/b}}}{2v} \left[\frac{\mathrm{erf}(u)}{u^2} - \frac{\mathrm{erf}'(u)}{u} \right] 2\delta t$$

$$\left\langle \left(\Delta v_\chi^{\mathrm{t/b}} \right)^2 \right\rangle = \left\langle \left(\Delta v_\eta^{\mathrm{t/b}} \right)^2 \right\rangle = \frac{\Gamma^{\mathrm{t/b}}}{4v} \left[\left(2 - \frac{1}{u^2}\right) \mathrm{erf}(u) + \frac{\mathrm{erf}'(u)}{u} \right] 2\delta t$$

$$\Gamma^{\mathrm{t/b}} = n_{\mathrm{b}} q_{\mathrm{t}}^2 q_{\mathrm{b}}^2 \ln\Lambda^{\mathrm{t/b}} / \left(4\pi\epsilon_0^2 m_{\mathrm{t}}^2\right), \quad u = v/\left(\sqrt{2} v_{\mathrm{Tb}}\right), \quad v_{\mathrm{Tb}} \left(= \sqrt{T_{\mathrm{b}}/m_{\mathrm{b}}}\right)$$

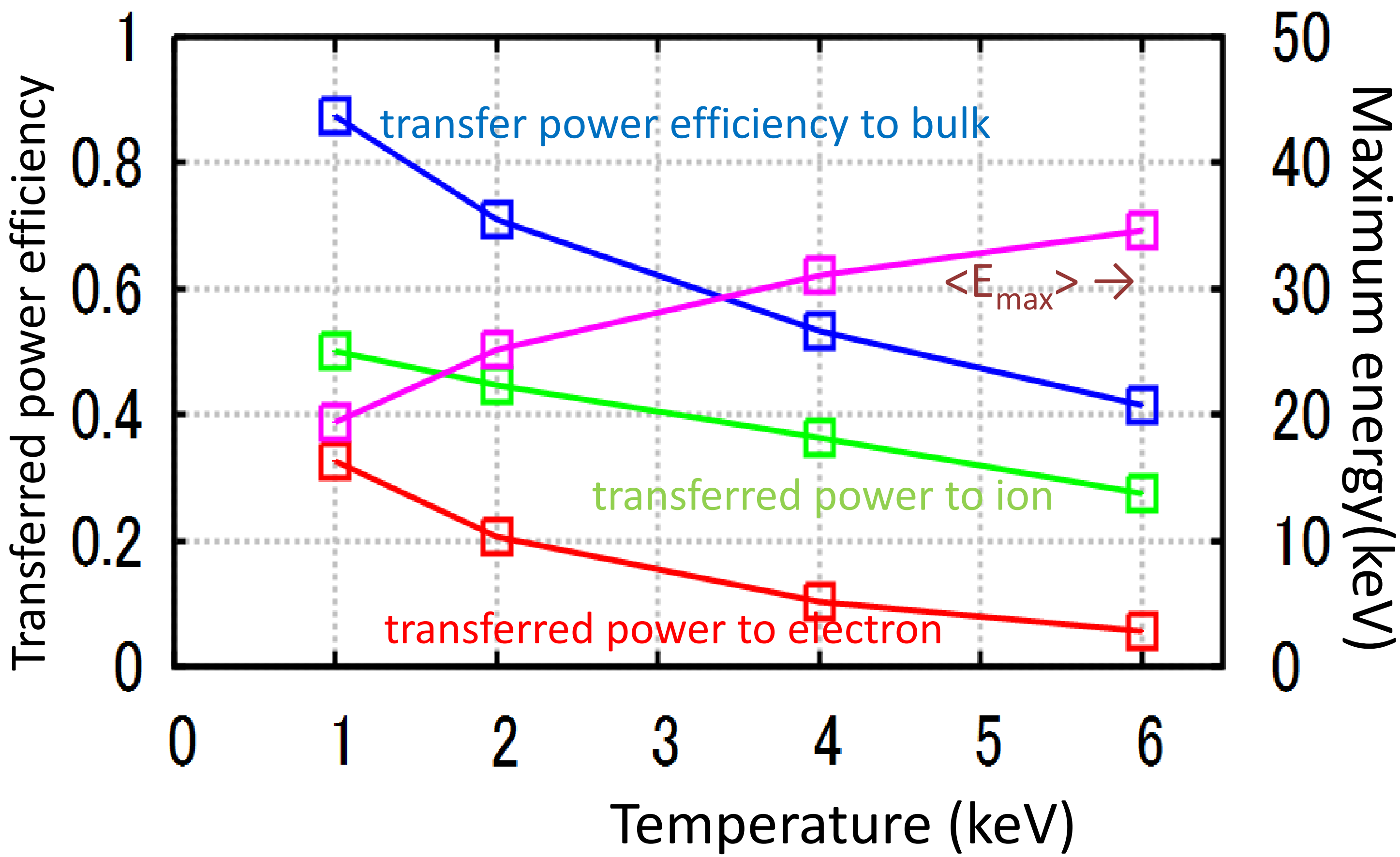
In an absorption model of the fast ion from ICRF,

- the fast ions are accelerated in a direction perpendicular to field line on the resonance layer.

- Here,

Temperture dependence

$$\frac{\text{Average energy transferred from ICRF fast ions to bulk plasma}}{\text{Average energy absorbed from ICRF wave to fast ions}} => \text{transferred power efficiency}$$



Transferred power profile（temperature）