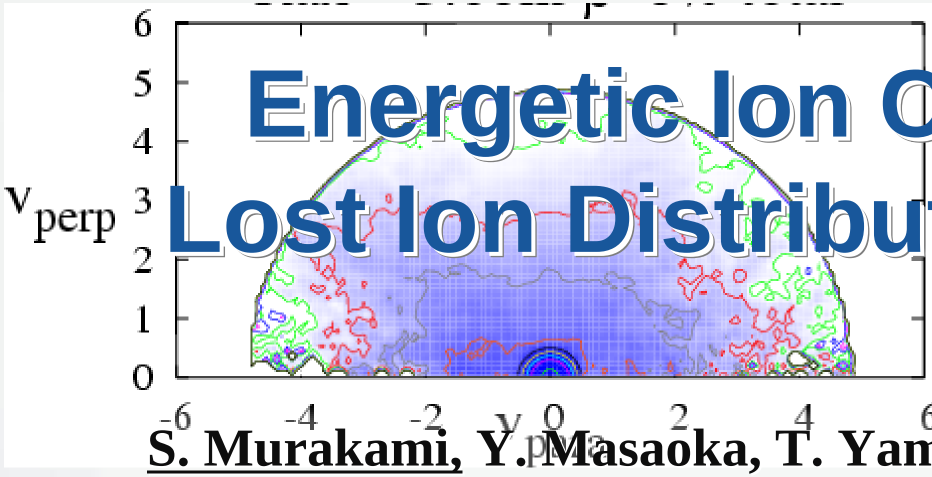
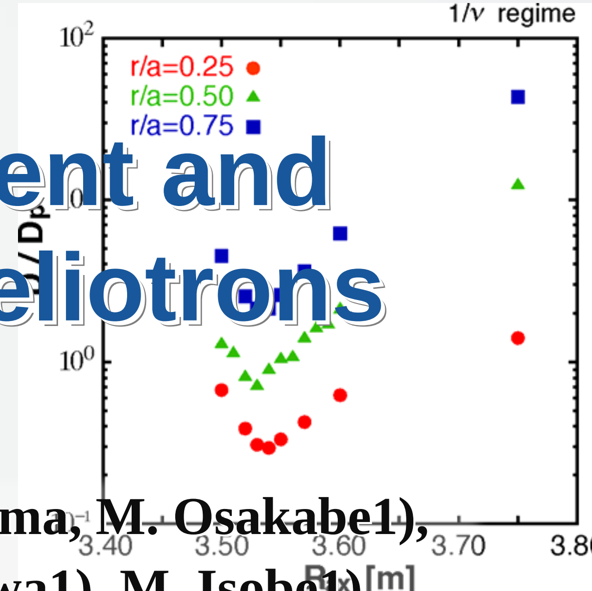
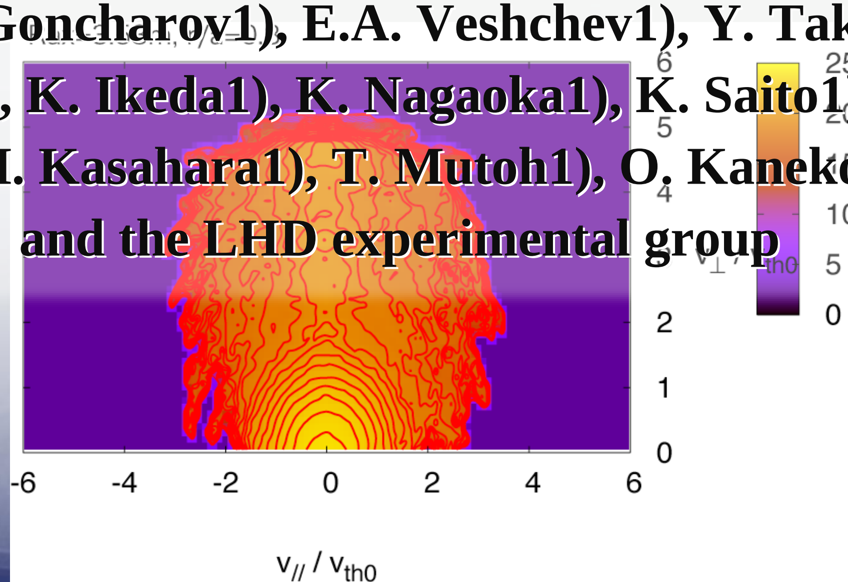
Energetic Ion Confinement and Lost Ion Distribution in Heliotrons





S. Murakami, Y. Masaoka, T. Yamamot, A. Fukuyama, M. Osakabe1),
K. Ida1), M. Yoshinuma1) T. Ozaki1), T. Tokuzawa1), M. Isobe1),
M. Nishiura1), P. Goncharov1), E.A. Veshchev1), Y. Takeiri1), Y. Oka1),
K. Tsumori1), K. Ikeda1), K. Nagaoka1), K. Saito1), T. Seki1),
R. Kumazawa1), H. Kasahara1), T. Mutoh1), O. Kaneko1), A. Komori1)
and the LHD experimental group



Energetic Particle Confinement

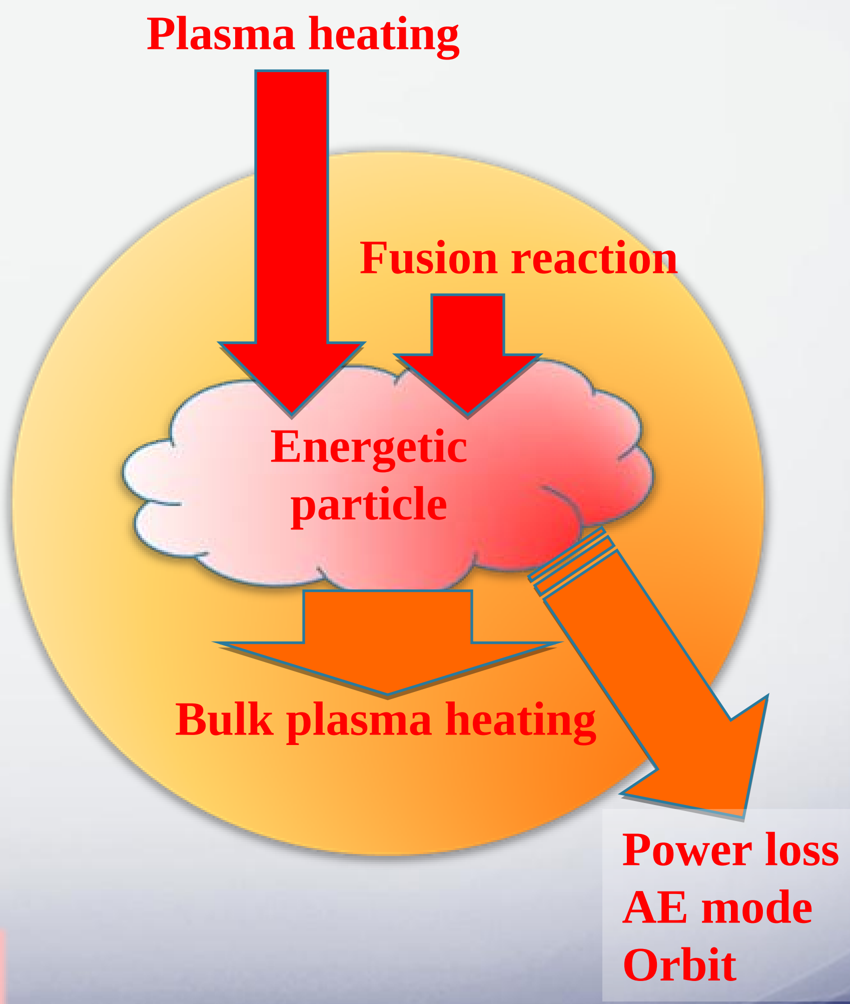
- **Energetic ion in fusion reactor**
  Plasma heating (NBH and ICH)
  Fusion reaction (α −particle)

- **Good confinement of Energetic ions**
  To sustain the high temperature plasma
  To avoid first wall damage by lost EP

- **Thus the confinement of energetic ions is one of key issues in the fusion reactor design.**

- **Because of the 3D magnetic configuration the behaviors of trapped particles are complicated in a helical plasma.**
  => Orbit loss

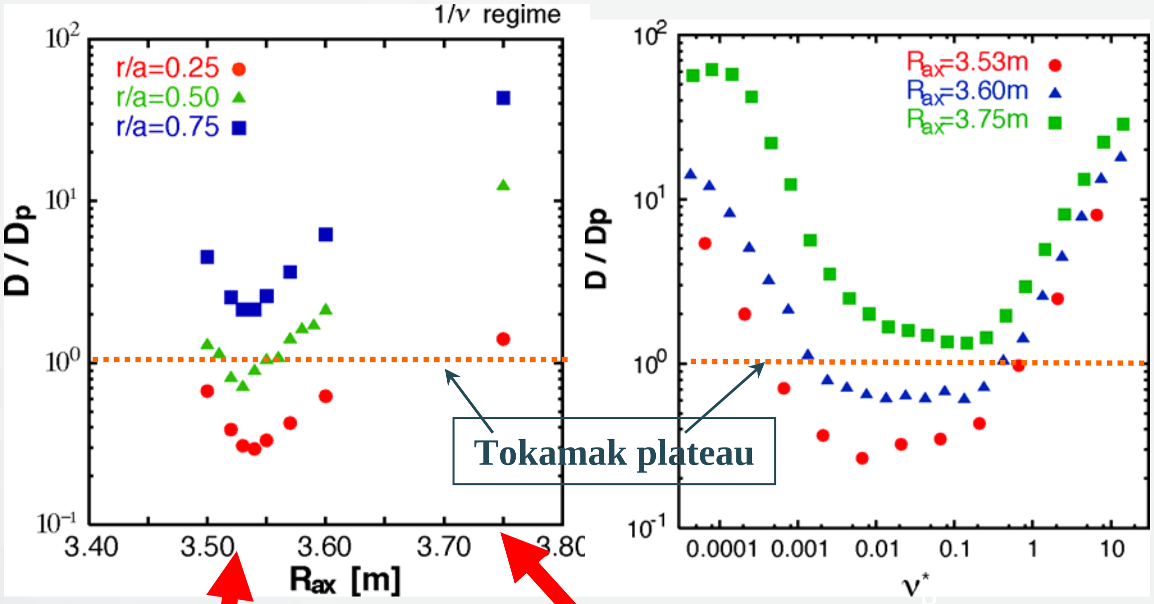
The detail study of energetic ion confinement is required in prospect of the heliotron reactor.



Outline

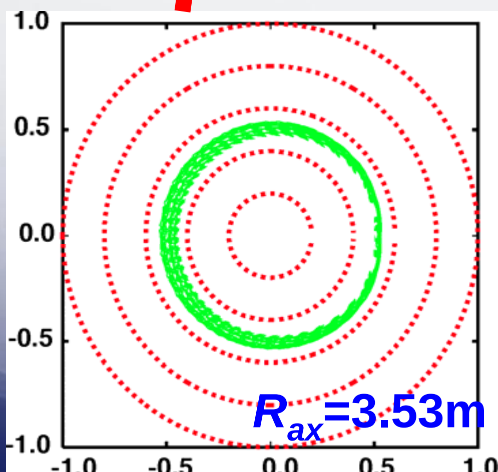
- Introduction
- LHD experiment and simulation results
  - Magnetic configuration of LHD
  - Perpendicular NBI beam confinement
  - P-NBI+2^{nd} harmonics ICH
- Simulation of α-particle confinement
  - Configuration dependence and velocity space distribution
  - Effective helical ripple vs. energy loss rate
- Summary

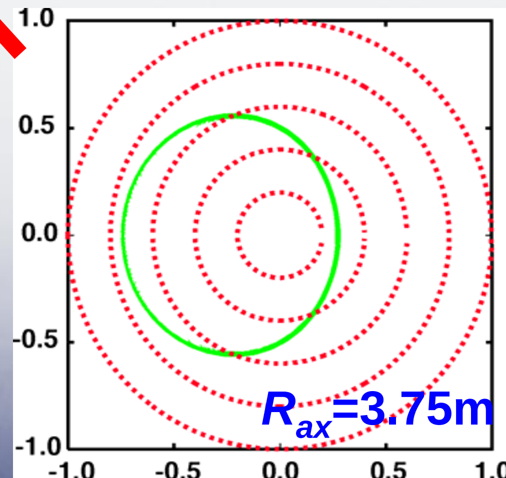
Neoclassical Transport Optimized Configuration

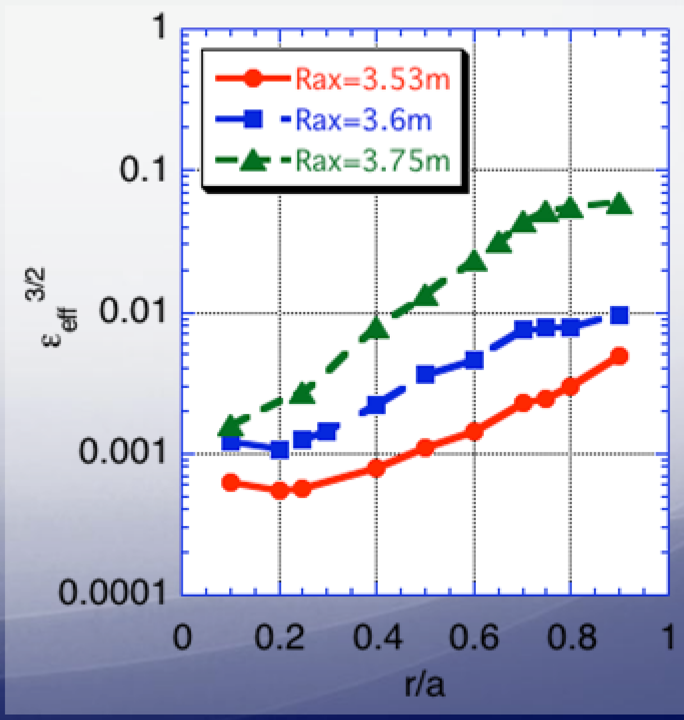


Neoclassical transport analysis (by DCOM)

- The optimum configuration at the 1/ν regime => R_{ax}=3.53m. (ε_{eff} < 2% inside r/a=0.8)
- A strong inward shift of R_{ax} can diminish the NT to a level typical of so-called "advanced stellarators".





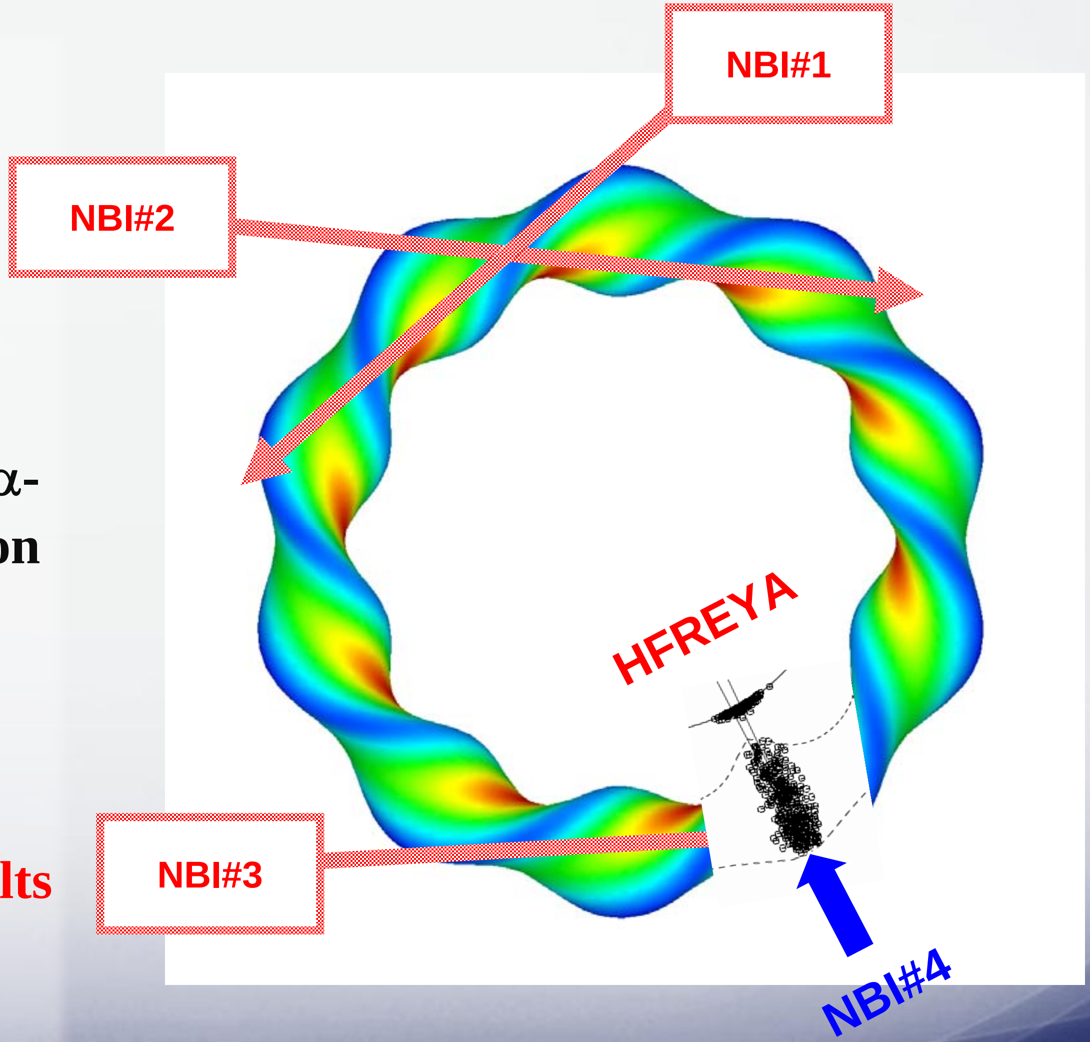


Perpendicular NBI System

- Because of a good confinement of trapped particle in inward shifted configuration (R_{ax} =3.53m, 3.6m), the perp. NBI is installed in LHD. NBI#4 (P< 7MW, E= 40keV)

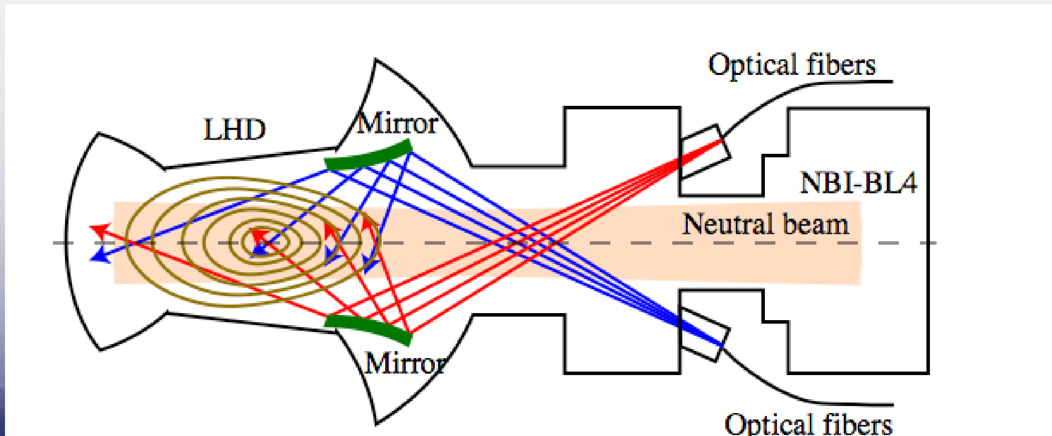
- ρ/a~1/50 and a good simulation of α-particle confinement in the heliotron reactor.

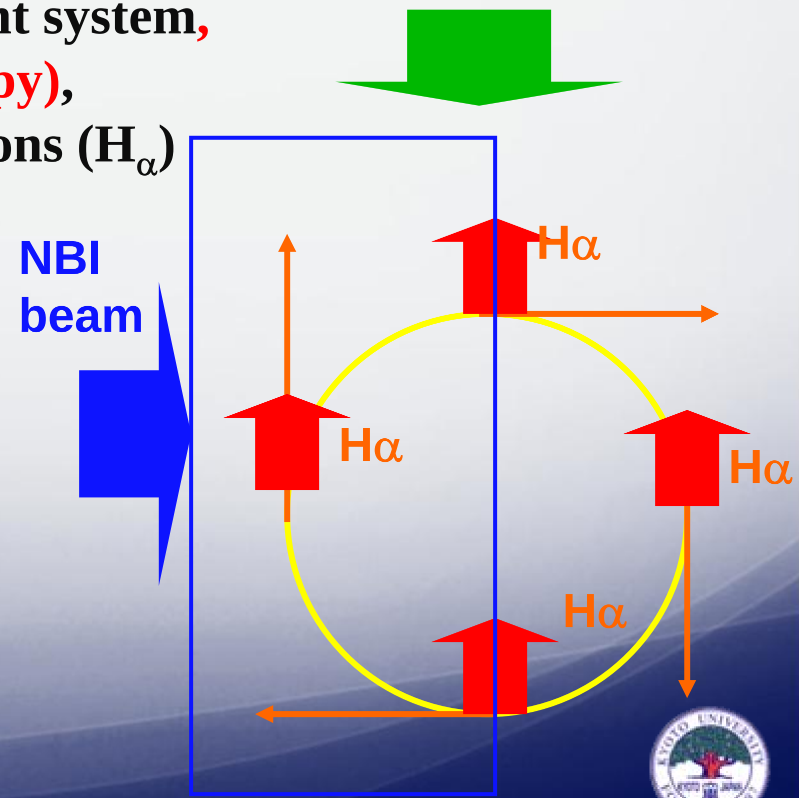
- We study the perp. NBI beam ion confinement and the results are compared with the simulation results by GNET (DKE in 5D).



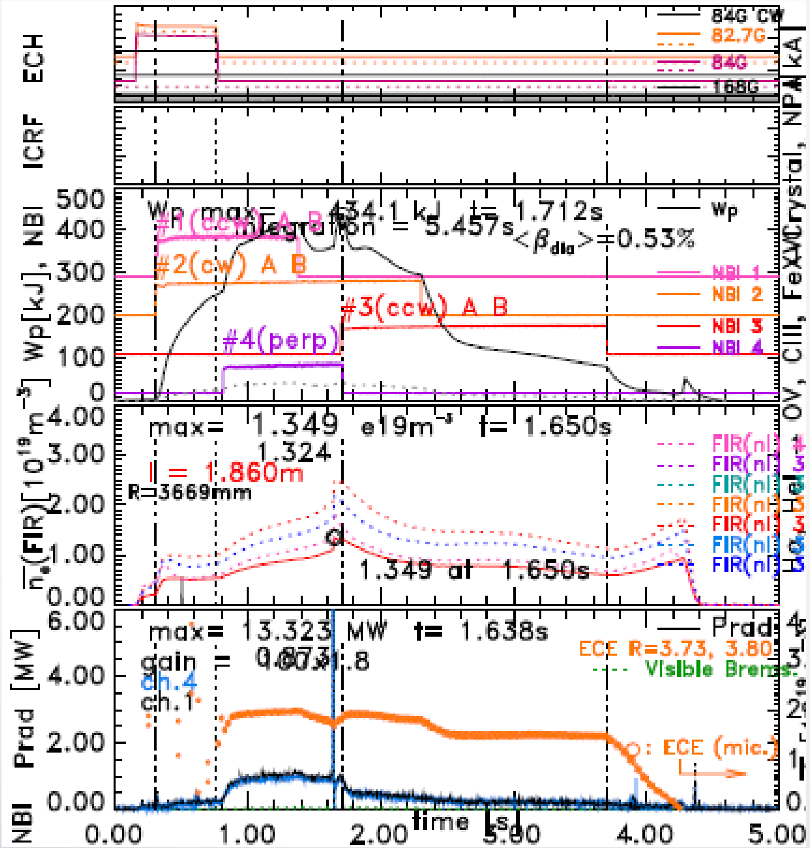
Profile Measurement by Beam Ion H_α Emission

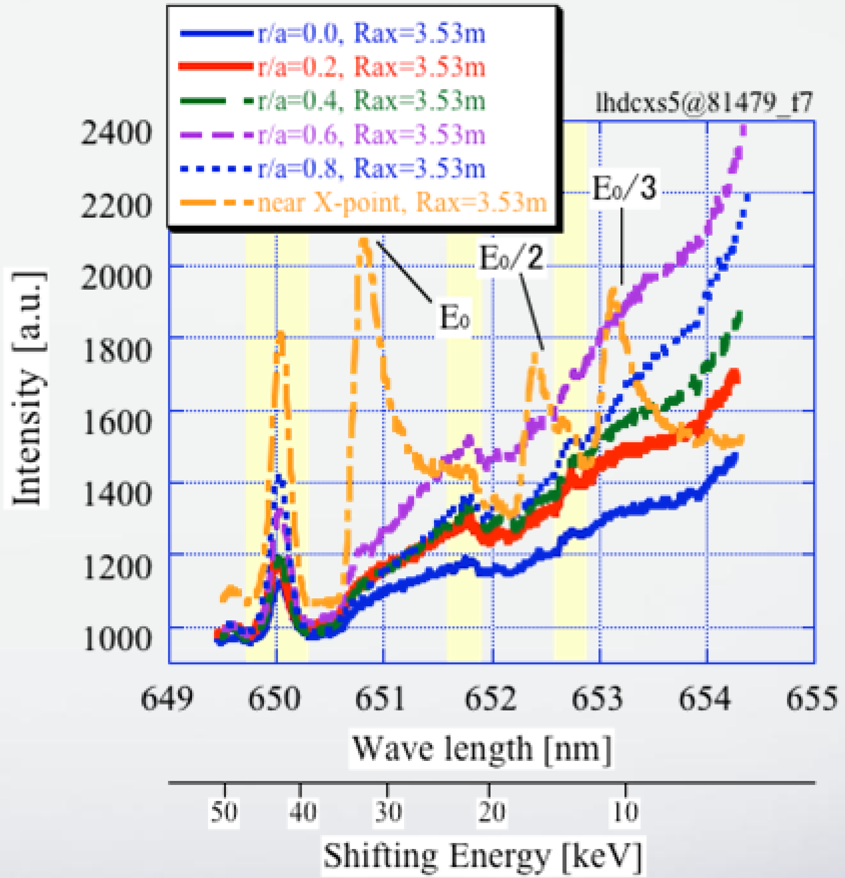
- A large Doppler shift of H_α line is expected for P-NBI beam ions, while the H_α emission from bulk plasma has a smaller Doppler shift.
- We can separate H_α emission from beam ions and obtain information about the energetic beam ion distribution.
- We have developed a radial profile measurement system, FICXS (Fast Ion Charge Exchange Spectroscopy), where the Doppler shifted Balmer-alpha emissions (H_α) from the charge-exchanged energetic ions





Spectrum of Beam Ion H_α Emission

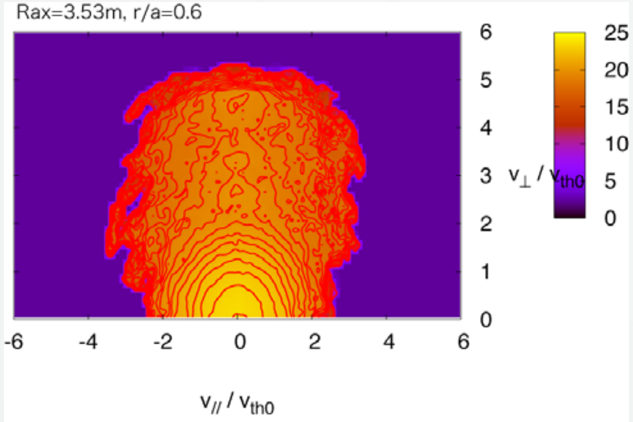


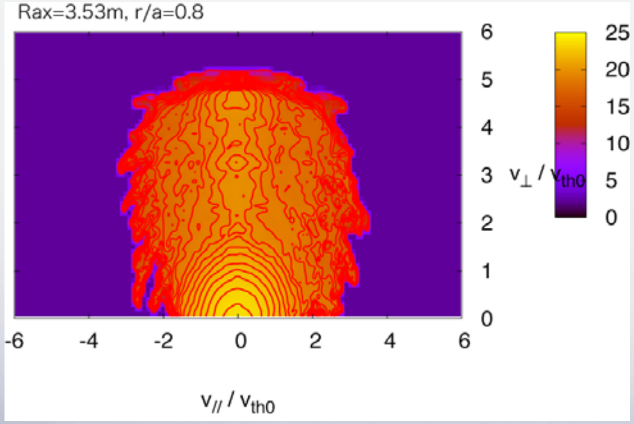


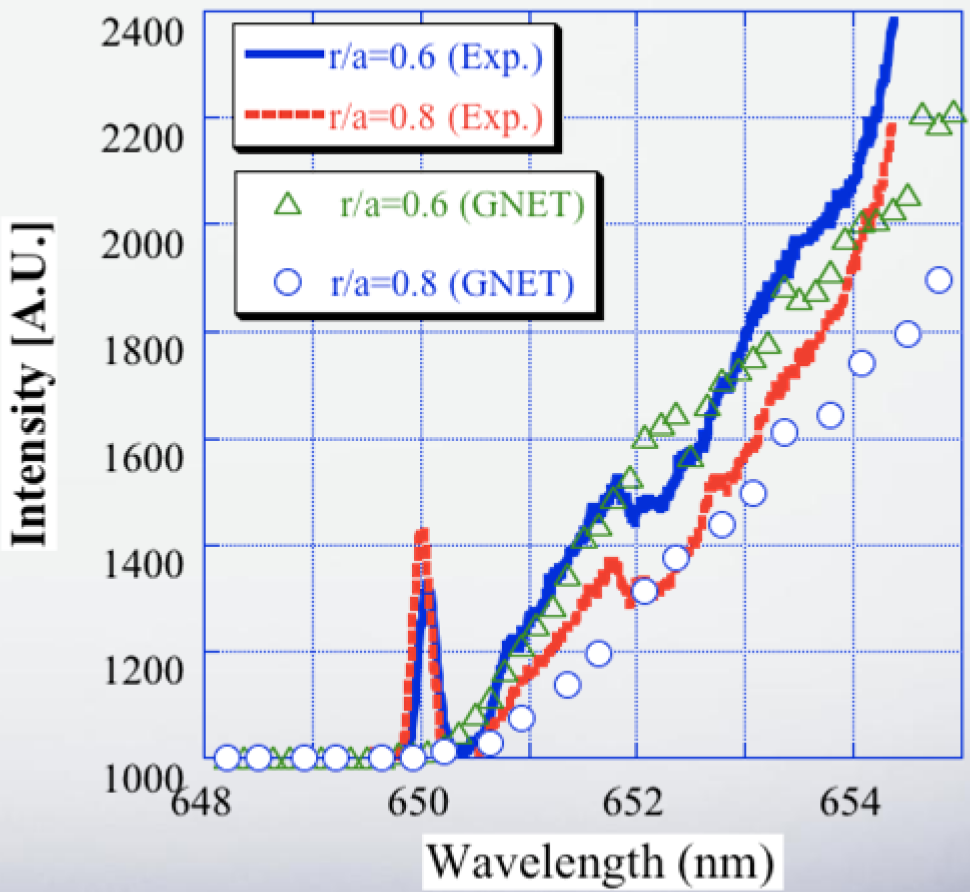
♦ We observed the H_α spectrum showing blue shift due to the beam velocity (T_{e0}~2keV and n_{e0}~$1\times10^{19}m^{-3}$).

♦ The blue shift of 40keV beam ion is about 6nm and we confirm that the obtained data is due to the pNBI beam ions.

Comparisons of GNET and Exp. Results

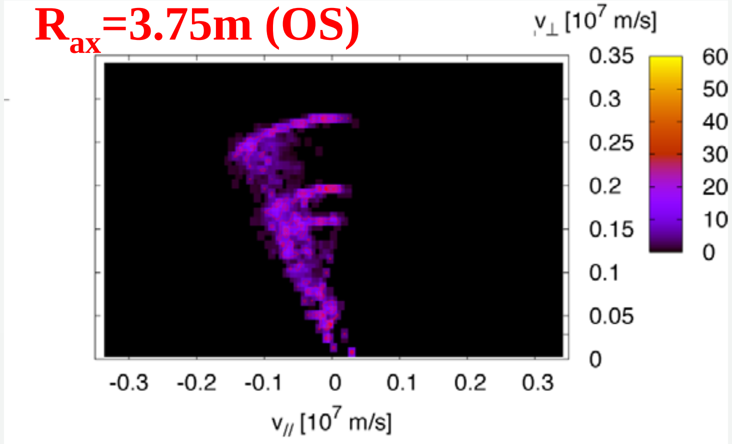


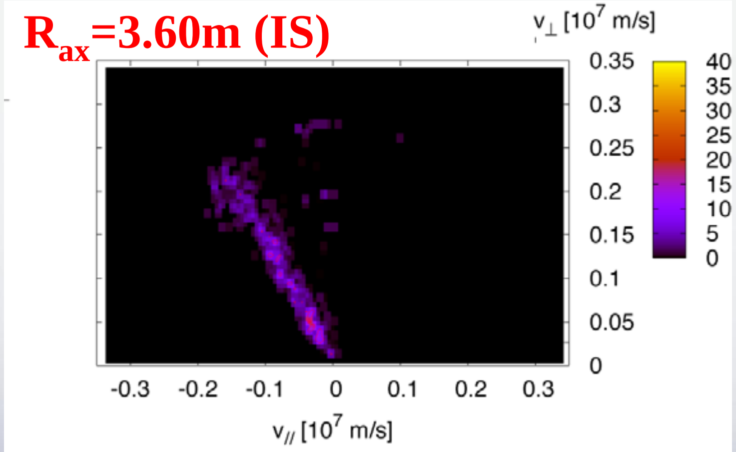


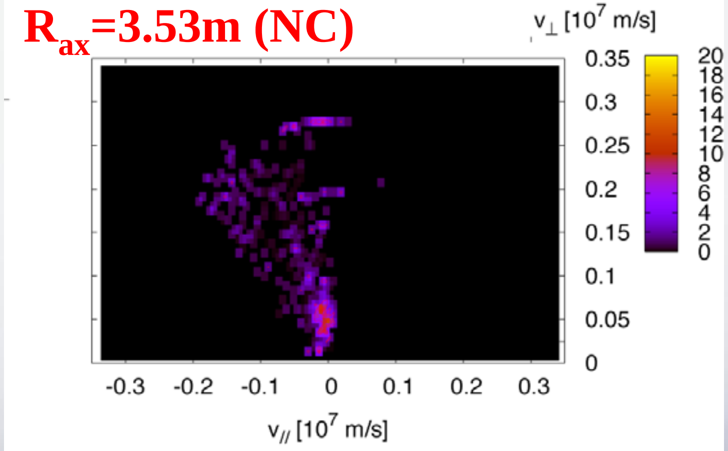


We obtain relatively good agreements between GNET and Exp. in the Rax=3.53m case.

Lost Beam Ion Distribution (GNET)







- **The almost lost ions are trapped ions.**
- **Number of lost ions decreases as the magnetic axis position shifts inwardly.**

Perp. NBI + 2nd Harmonics ICH

A B C Pellet

Shot61213

Power
[a.u.]

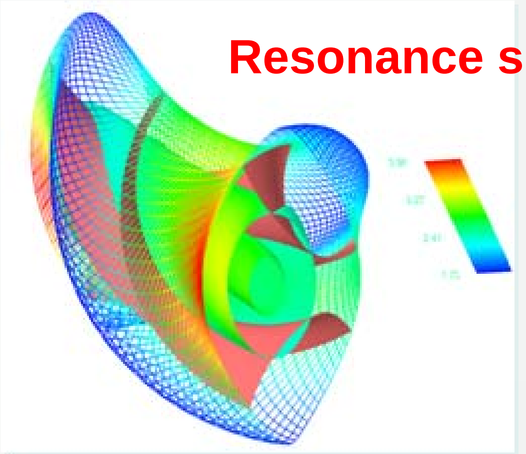
Wp
[kW]

ne
[$10^{19}m^{-3}$]

Te, Ti
[keV]

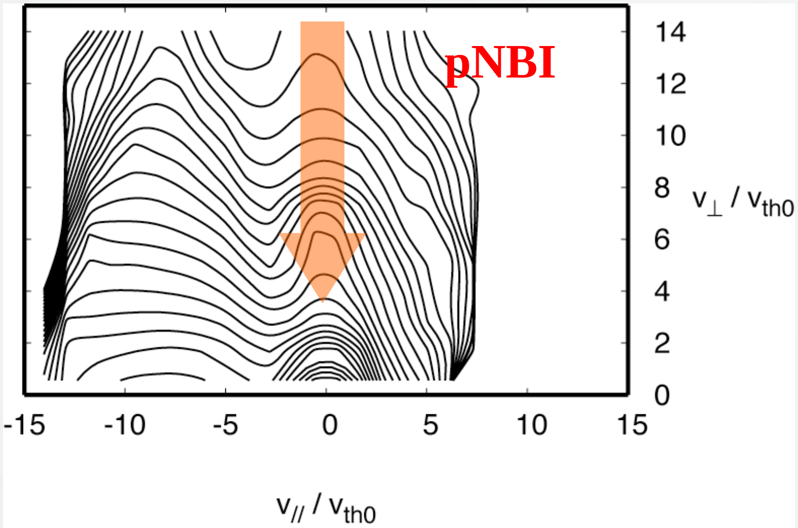
Hα
[a.u.]

Resonance surface

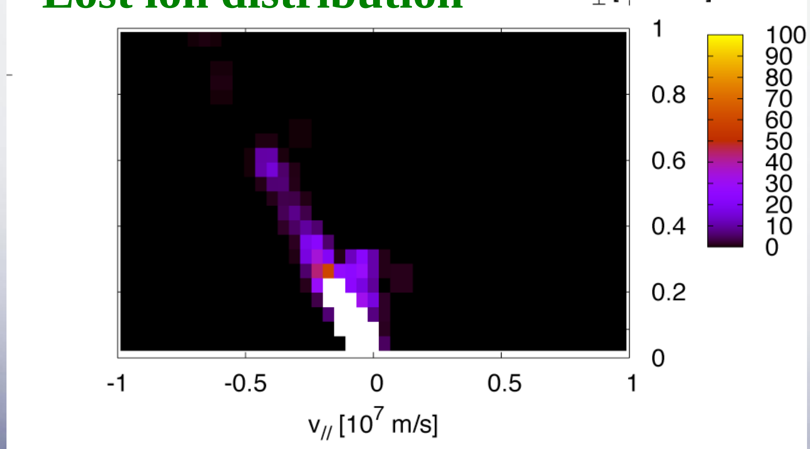


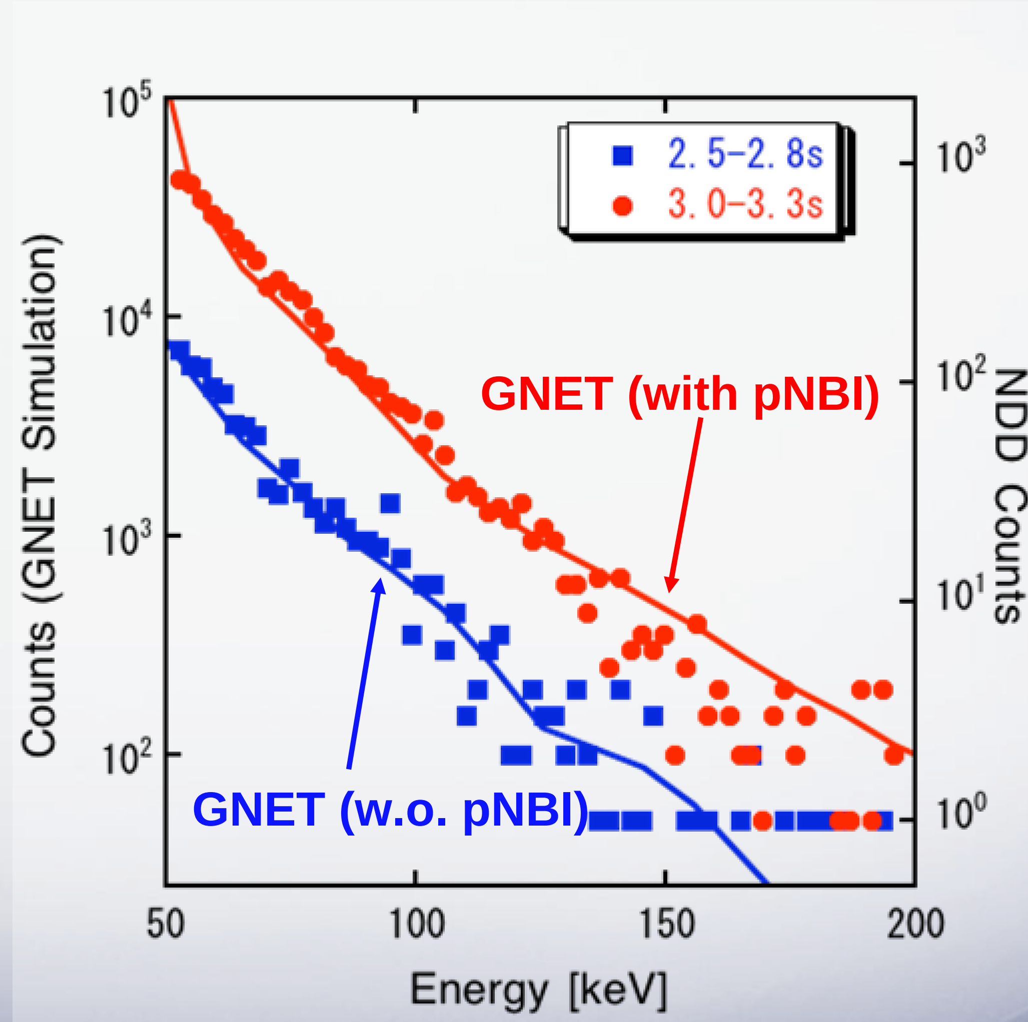
$H^+/(H^++He^{2+})=0.5$

Simulation of NPA (2nd ICRF+NBI)



Lost ion distribution





- We simulate the **NPA** signals using the **GNET** simulation results and obtain good agreements.

α-particle confinement in LHD type reactor

- **Assuming LHD type reactor as a typical helical reactor, we study α-particle confinement including the collisions with b.g. plasma (energy slow-down, energy scattering and pitch angle scattering).**
  =>Initial α-particle position: fusion reaction (n_{e0}~$2x10^{20}m^{-3}$, T_{e0}~10keV)

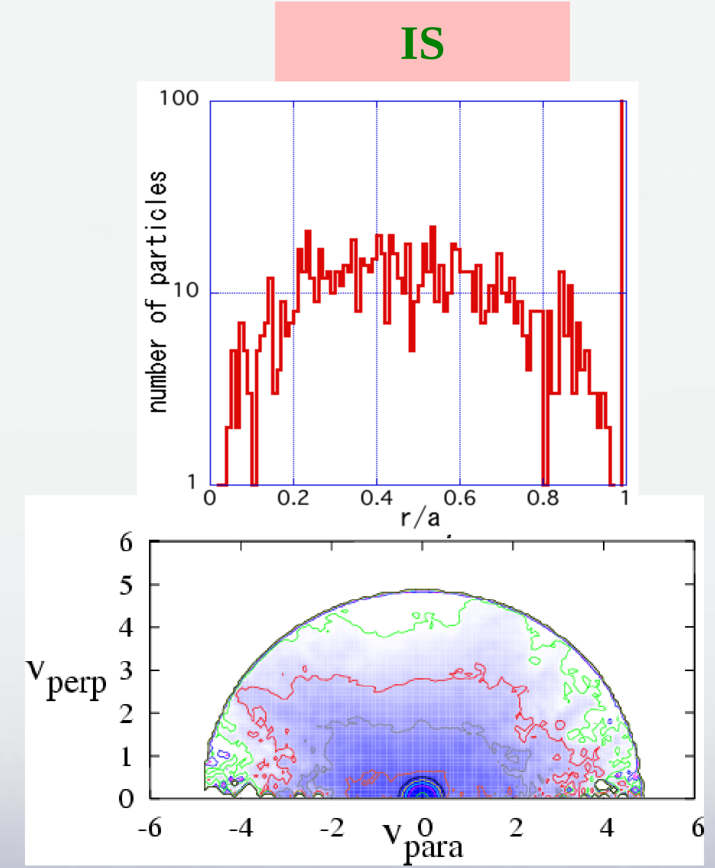
- **The loss boundary is the LCFS (last closed flux surface).**
  (Over estimation of loss rate because of the reentering effect)
  => Good measure for the confinement estimation.

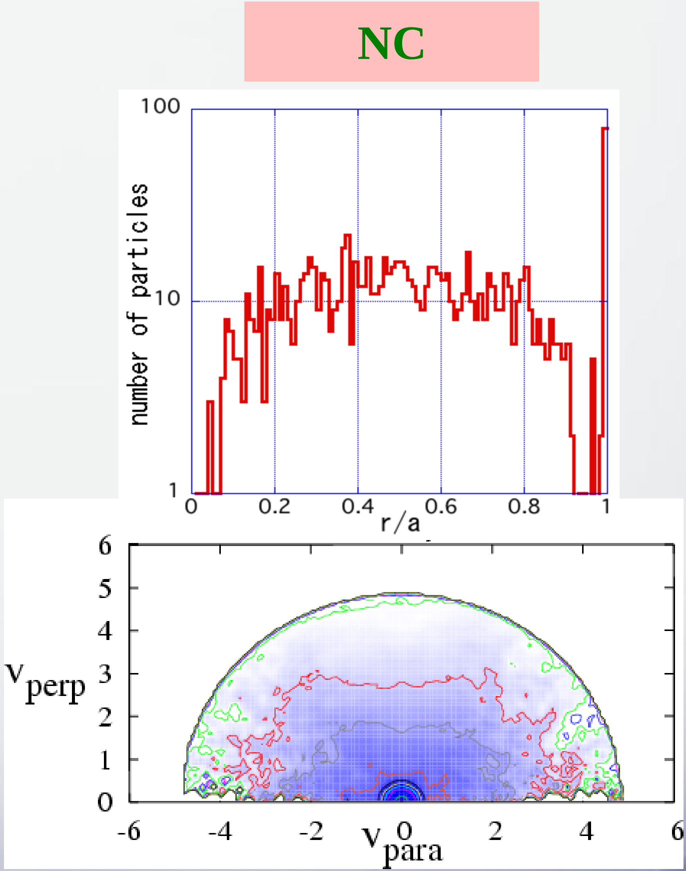
- **The assumed fusion reactor**
  ⇒Heliotron type fusion reactor extending the LHD magnetic configuration (R is about 4 times larger than that of the real LHD.)

  Plasma volume : $1000m^3$
  Magnetic field : 5T
  Magnetic configurations :
  NC) Near the NC optimized config. based on R_{ax}=3.50m
  IS) Inward shifted config. based on R_{ax}=3.60m

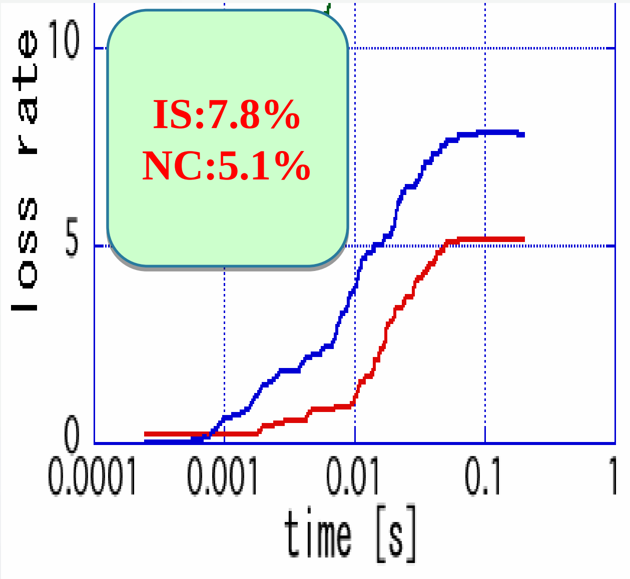
Configuration dependence of α-particle distribution

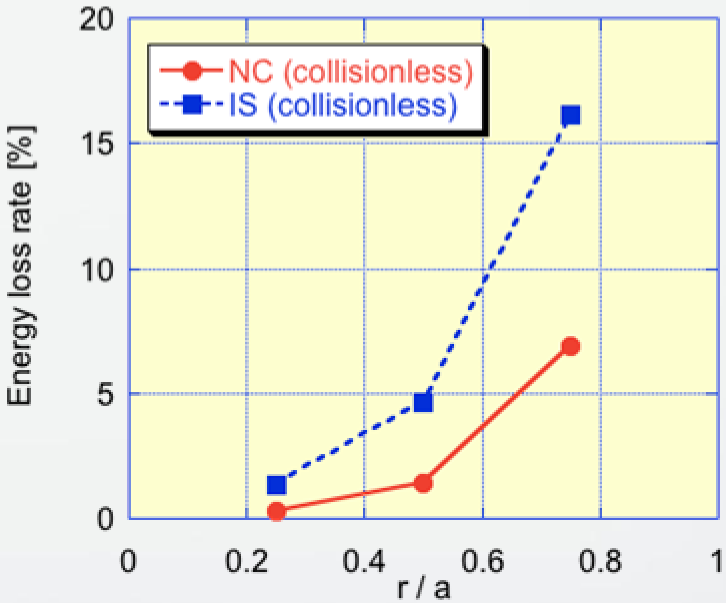
- We study the α-particle radial profile and velocity space distribution changing the configuration: SI and NC (β =0%).
- The trapped particle loss can be seen in the velocity distribution of the IS configuration.





Energy loss rate of the α-particle



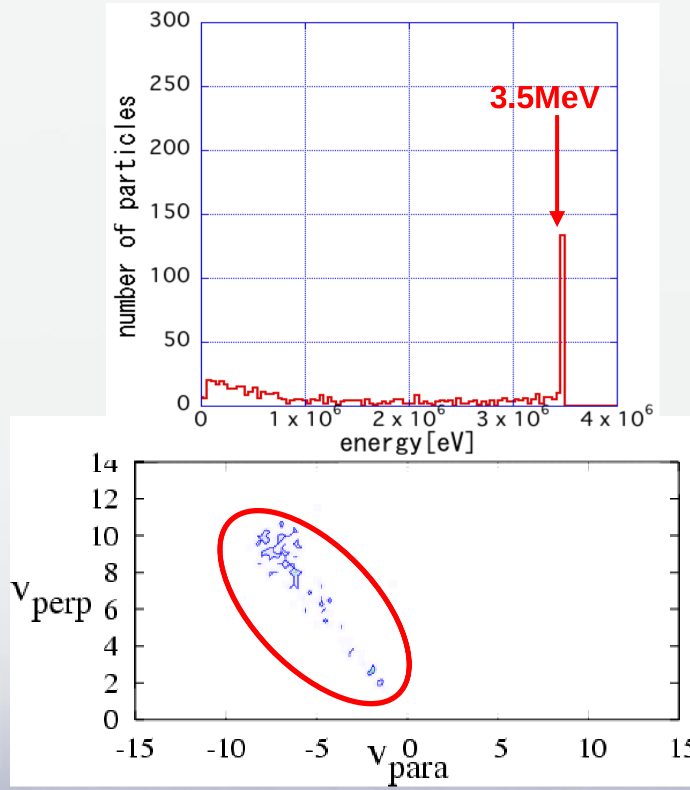


- **The energy loss rate is improved by further inward shift to NC config. from 7.8% to 5.1%.**
- **The obtained energy loss rates with the realistic α-particle profiles and collisions are roughly corresponds to the loss rate at r/a~0.6 of the collisionless case.**

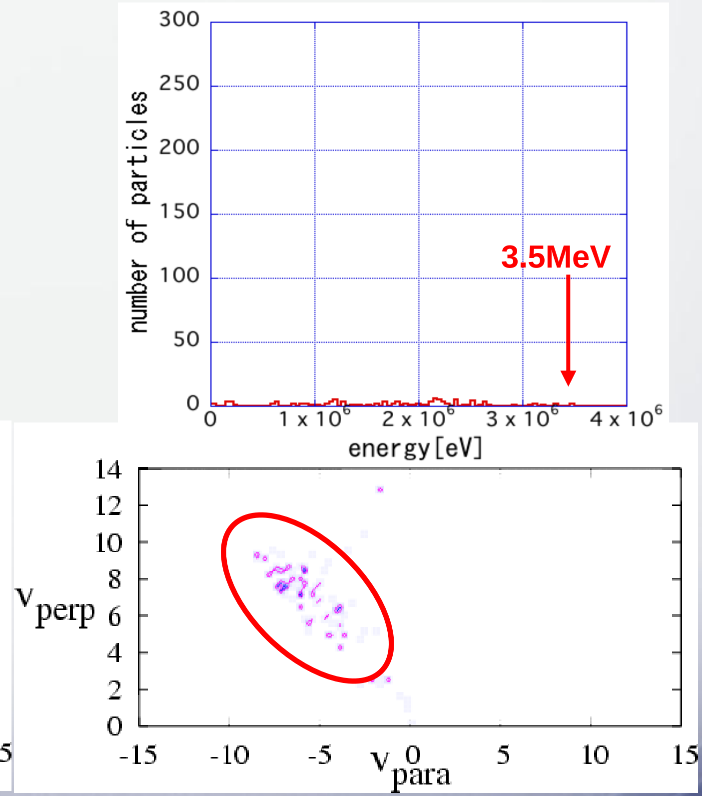
Configuration dependence of the α-particle loss

- **The loss of the high energy ions (>MeV) is reduced in the NC configuration.**
- **The lost ion distribution shows similar tendency.**

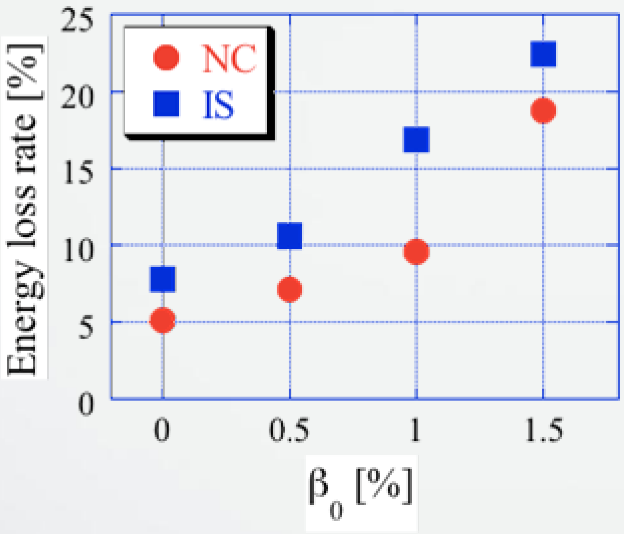
IS

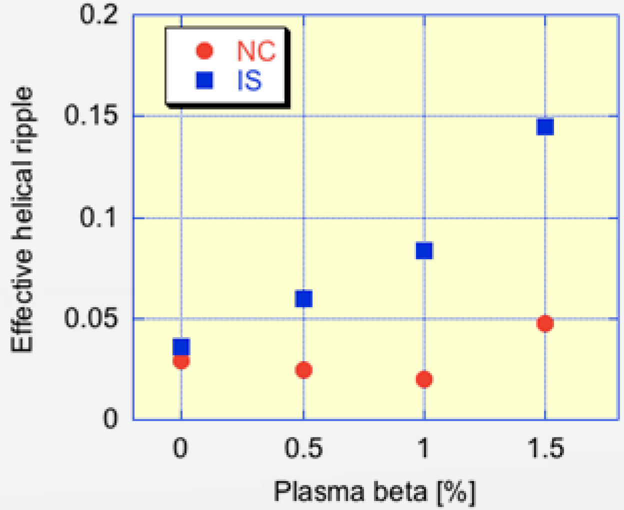


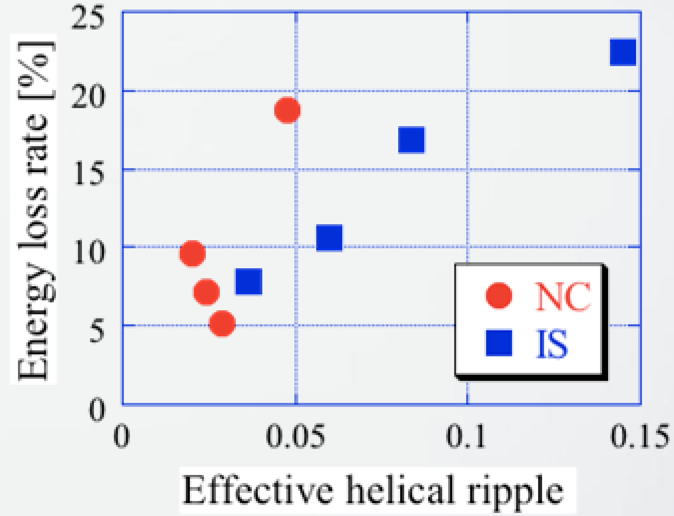
NC



Beta dependence of the α-particle loss rate







- **The energy loss rates monotonically increase as the plasma beta value goes up in both configurations.**
- **The ε_{eff} is a good measure of the NC transport, $D_{1/\nu} \sim C\varepsilon_{eff}^{3/2}$. Also for EIC?**
- **The clear ε_{eff} dependence of E_{loss} rate can be seen in the IS config. , while no clear dependence in the NC config.**
  => Large gard-B drift and finite banana size

Summary

- **We have studied the energetic ion confinement in heliotrons in prospect of the reactor device.**
- **The LHD experiments for the energetic ion confinement study have been done.**
  => The results have been compared with the GNET simulation results and relatively good agreements have been obtained.
- **α-particle confinements in NC and IS config. have been studied including the collisions by GNET .**
  => The effective helical ripple is not a good measure for the NC config.
- **Further effort is necessary to find a compromised configuration between the α-particle confinement and the plasma performance obtained by the LHD experiments.**