Configuration effect on energetic particle and energy confinement in NBI plasmas of Heliotron J

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Acknowledgements

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- This work was partly supported by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science No. 20686061.

Introduction (1)

Issues toward helical fusion reactor

- Reduction in ripple loss of helically trapped particle, control of neoclassical transport
- Mitigate anomalous transport

Drift optimization is one of the key subjects

In planner-axis heliotron devices such as LHD, CHS and Heliotron E[1-3] , inwardly-shifted configuration

=> Alignment between drift and flux surfaces

=> Improve neoclassical transport and energetic particle confinement

-Experimentally obtained improvement in the energetic particle confinement

-Reduction in neoclassical transport coefficient. [4]

- Also preferable energy confinement toward ISS scaling[5,6]

=> Considered to be one of the candidates to mitigate anomalous transport

[1] O. Motojima, et al., Nucl. Fusion **47** (2007) S668-S676. [2] S. Okamura, et al., Nucl. Fusion **45** (2005) 863–870.
[3] T. Obiki, et al., IAEA-CN-56/C-1-2 (1996).[4] S. Murakami, et al., Nucl. Fusion **42** (2002) L19–L22.
[5] H. Yamada, et al., Plasma Phys. Control. Fusion **43** (2001) A55–A71.[6] S. Okamura, et Al 1999 Nucl. Fusion 39 (1999) 1337.

Introduction (2)

Helical-axis heliotron device Heliotron J*

=> Based on **omnigeneous optimization** scenario.**

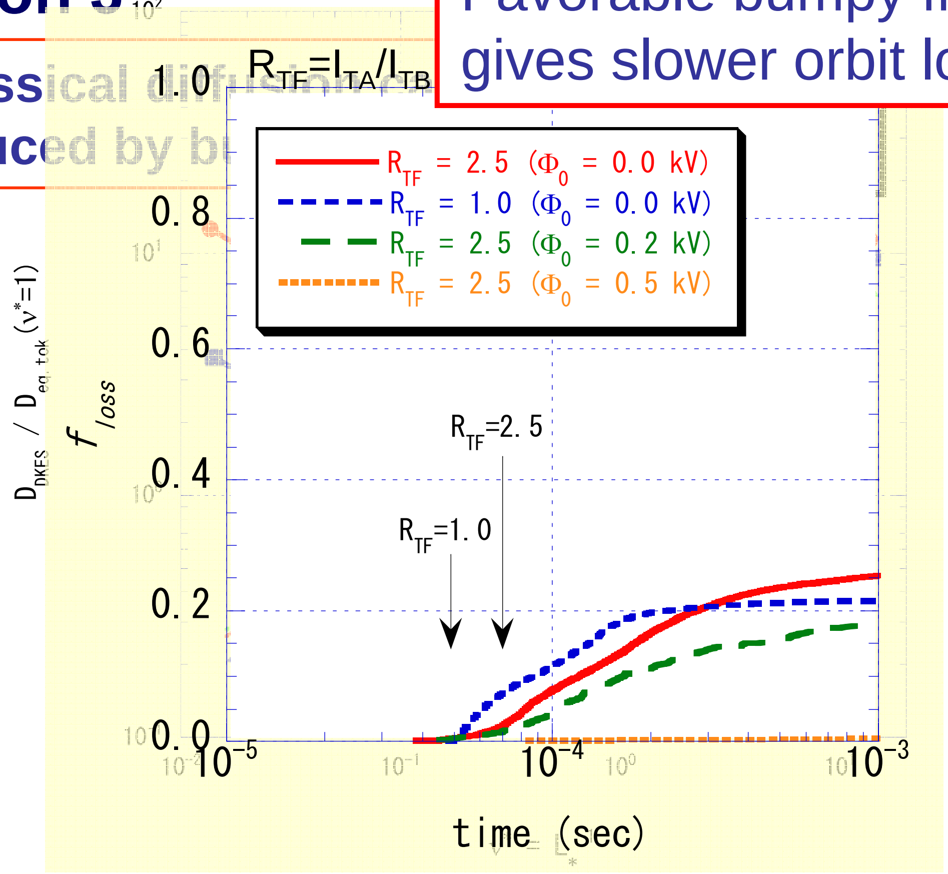
- Control of the toroidal mirror ratio “**bumpiness**” is important to reduce ripple loss and neoclassical transport.

=> Theoretically predicted

Importance in experimental study for bumpiness effect

neoclassical diffusion
be reduced by bu

Favorable bumpy field gives slower orbit loss



*T. Obiki, et al., Nucl. Fusion **41** (2001) 833.

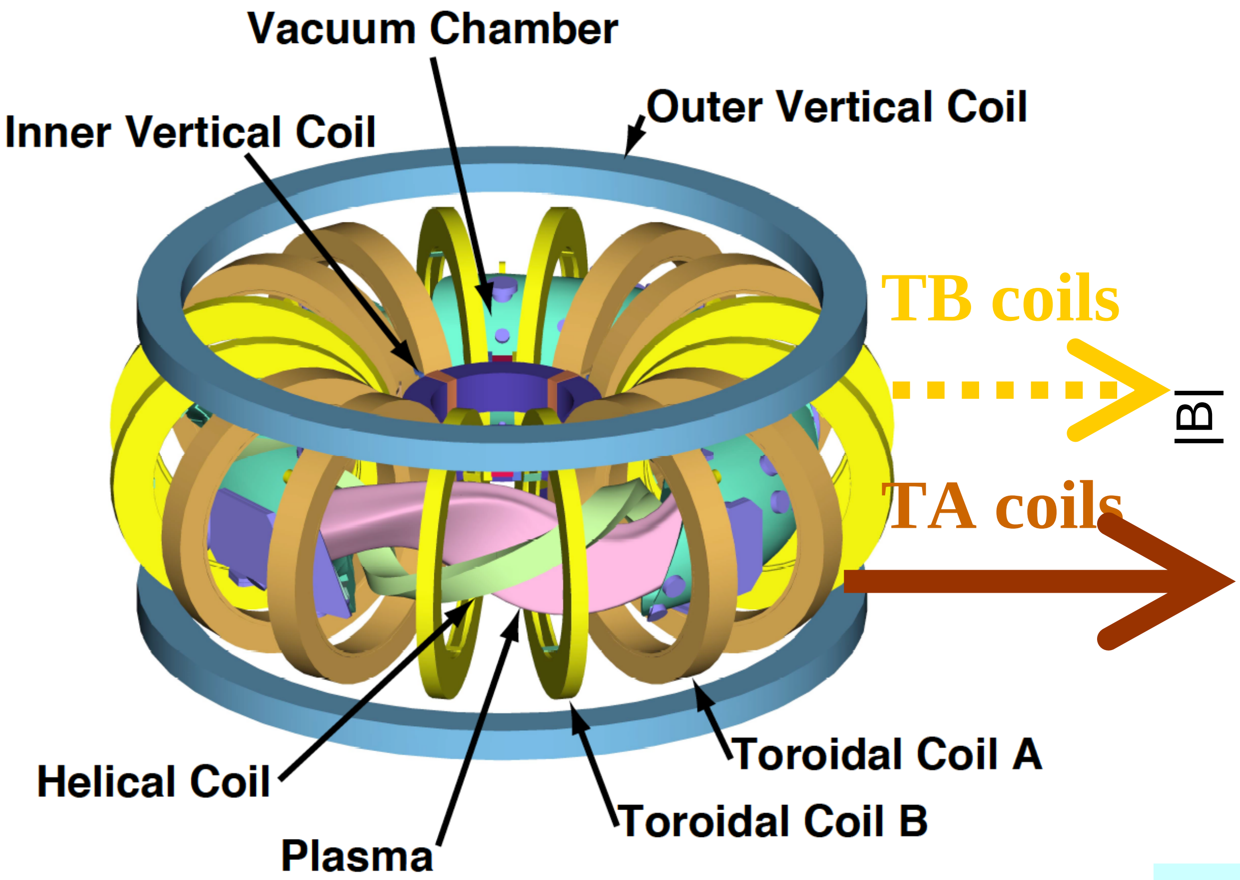
M. Wakatani, et al., Nucl. Fusion **40 (2000) 569.

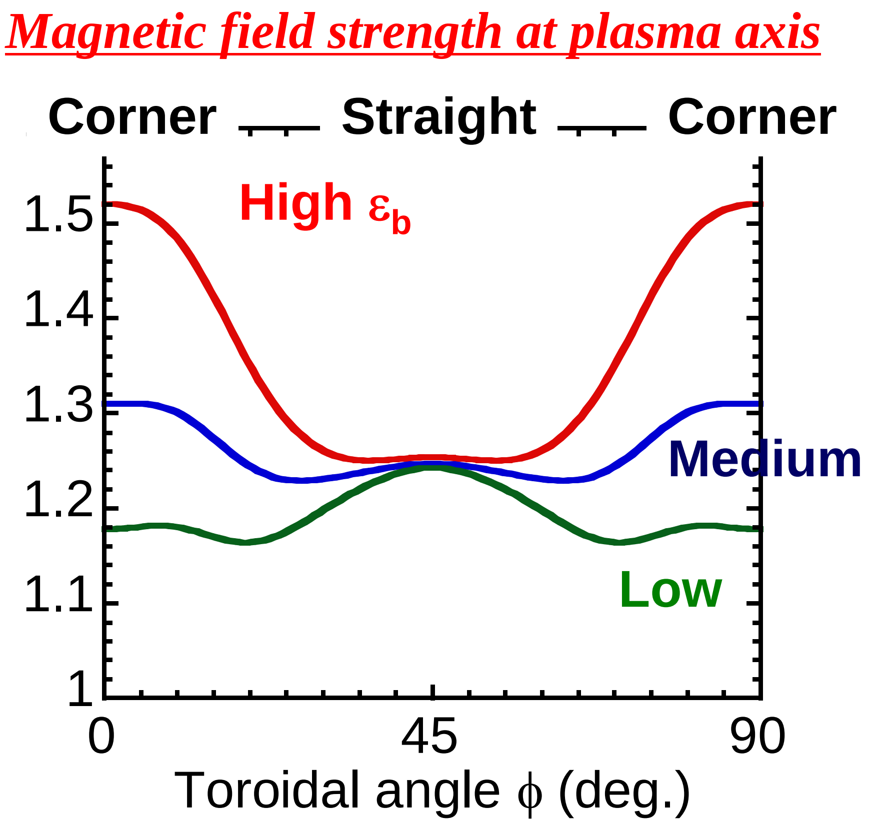
In this study, we investigate

1. **Energetic ion transport and its influence on MHD activities**
2. **Global energy confinement**

in NBI plasmas of Heliotron J with regard to bumpiness magnetic field component.

Bumpy magnetic field (ε_b) control (1)



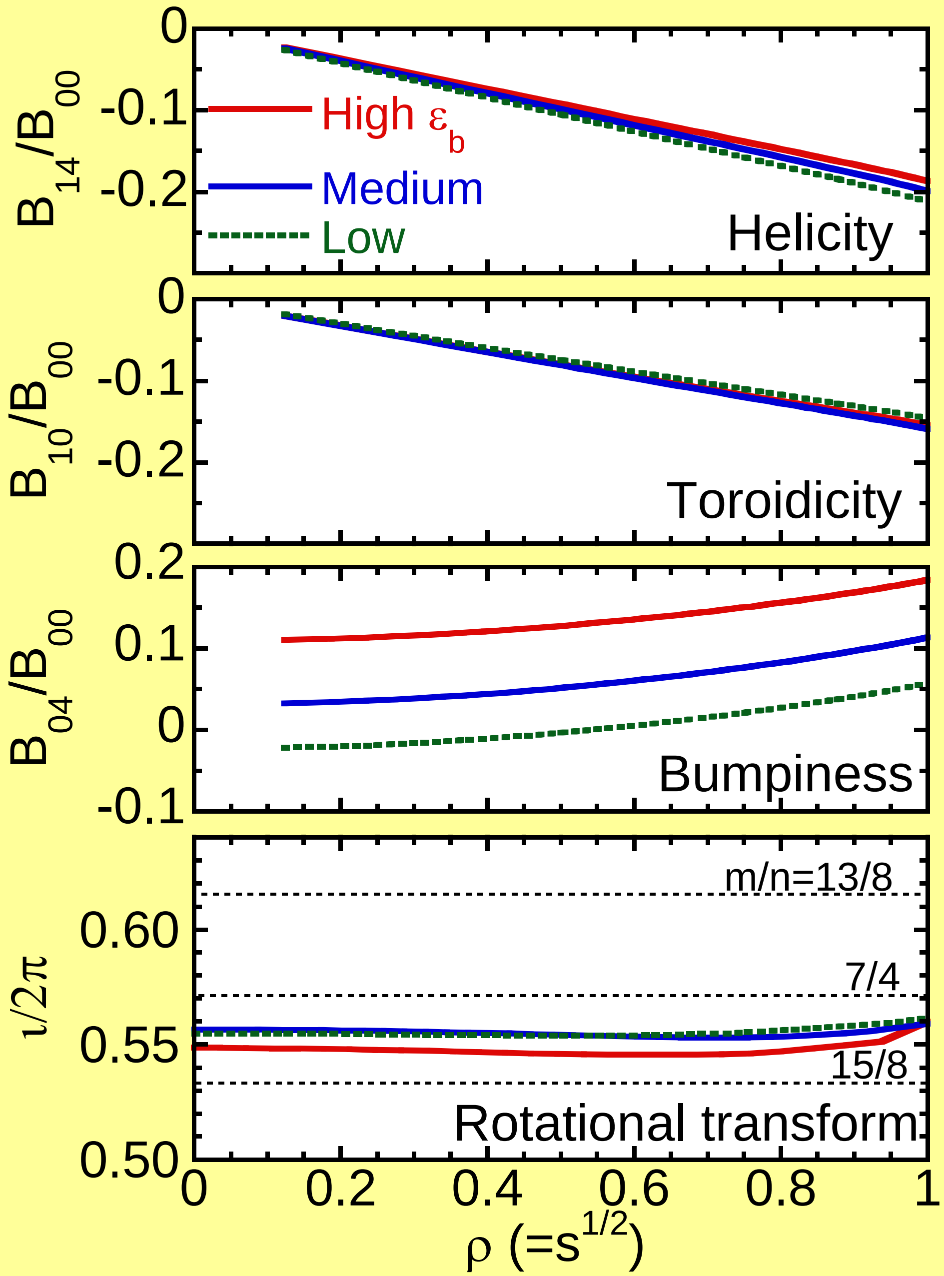


Control of bumpy magnetic field strength (mirror ripple, ε_b) by changing TA and TB coil currents

High ε_b : Higher mirror ripple
Low ε_b : Mirror field reversal (at axis)
Constant parameters :
- $R_{ax}/\langle a_p\rangle = 1.2$ m/0.17 m, $V_p \sim 0.7$ m^3
- Edge rotational transform
- Magnetic well in entire region

Bumpy magnetic field (ε_b) control (2)

Radial profile of field components and iota



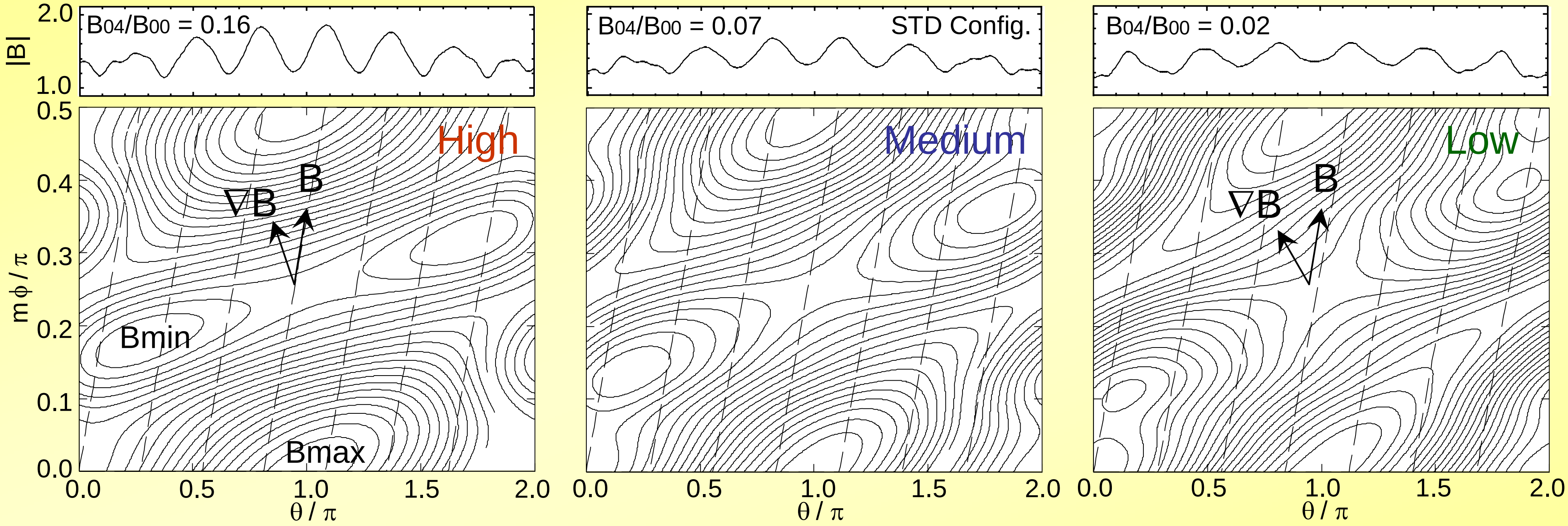
Basic characteristics of configurations

Config.	High ε_b	Medium	Low
R_{ax} in m	1.189	1.197	1.200
V_p in m^3	0.66	0.68	0.67
$\langle a \rangle$ in m	0.169	0.167	0.170
$\langle B \rangle$ in T	1.357	1.261	1.193
$\iota(a)/2\pi$	0.560	0.560	0.561
Edge well in %	1.2	1.5	0.5
ε_b (2a/3)	**0.15**	0.06	0.01
ε_{eff} (2a/3)	0.22	**0.13**	0.26

Control of bumpiness with keeping R_{ax}, $\langle a \rangle$, edge rotational transform and other main Fourier components (Toroidicity, Helicity)

∇B drift becomes smaller with bumpiness (ε_b)

Poloidal profiles of |B| along a field line (upper) and |B| contour plots (lower) in Boozer co-ordinate (r/a=0.52)



ε_b = 0.15 (High) ⟷ 0.06 (STD config.) ⟷ 0.01 (Low)

- In the high ε_b case, minimum values of field strength at the ripple bottoms are flattened

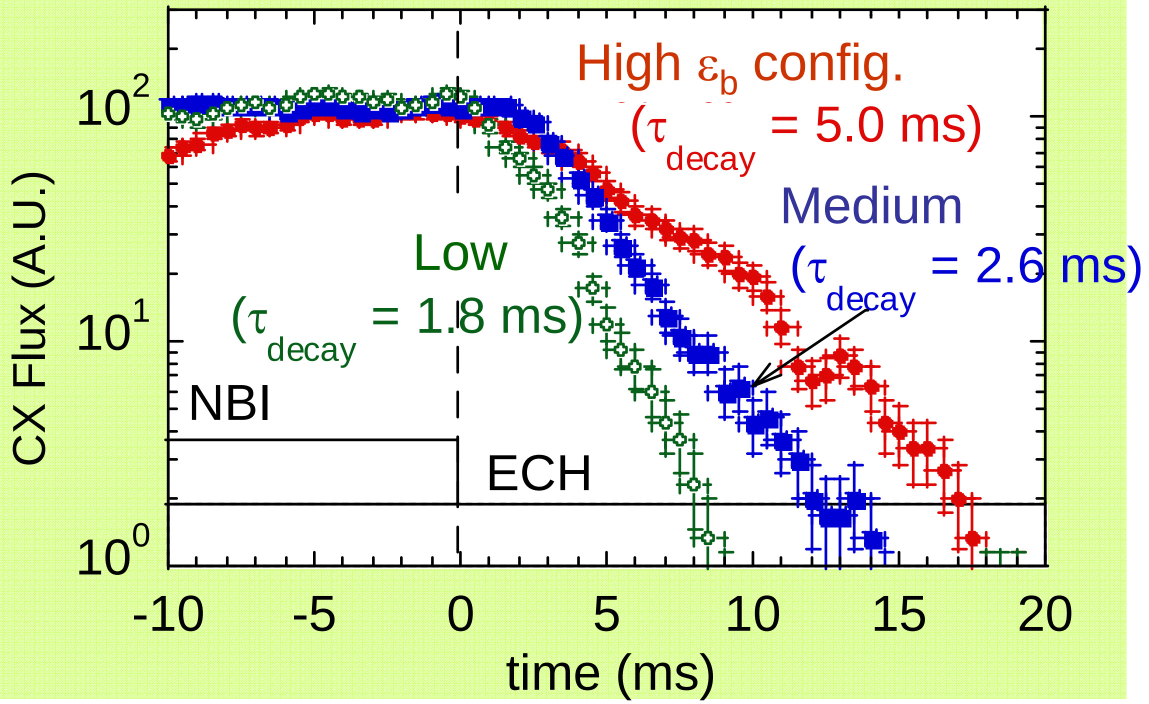
- Angle between the field line and ∇B becomes relatively acute.

=> Difference between flux surface and drift orbits by ∇B drift becomes smaller in the high ε_b configuration.

<=> In low ε_b case, the strength of the ripple bottoms varies along field line

1/e decay time of energetic CX flux becomes longer with ε_b *

Decay of CX flux after NB turn-off



- Decay of CX flux after NBI turned-off in ECH sustained plasmas, (E_{NB}=28kV & $\langle\lambda_{NBI}\rangle$ ~ 155° deg. ⇔ E_{CX}=18kV, λ_{pitch}~130° => passing)

- $n_e=0.8\times10^{19}m^{-3}$

=> 1/e decay time becomes longer as bumpiness increased

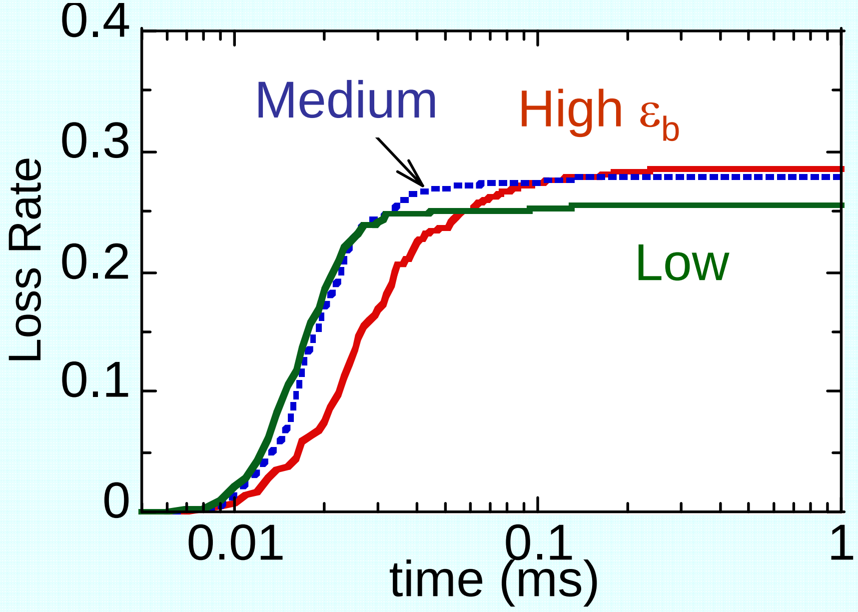
*S. Kobayashi, et al., IAEA-CN-116/EX/P4-41 (2004)

- Under the experimental condition, slowing-down time and CX loss time are expected to be unchanged in the experiments.

- Time evolution of loss rate by orbit calculation at E = 18keV & ρ = 0.25

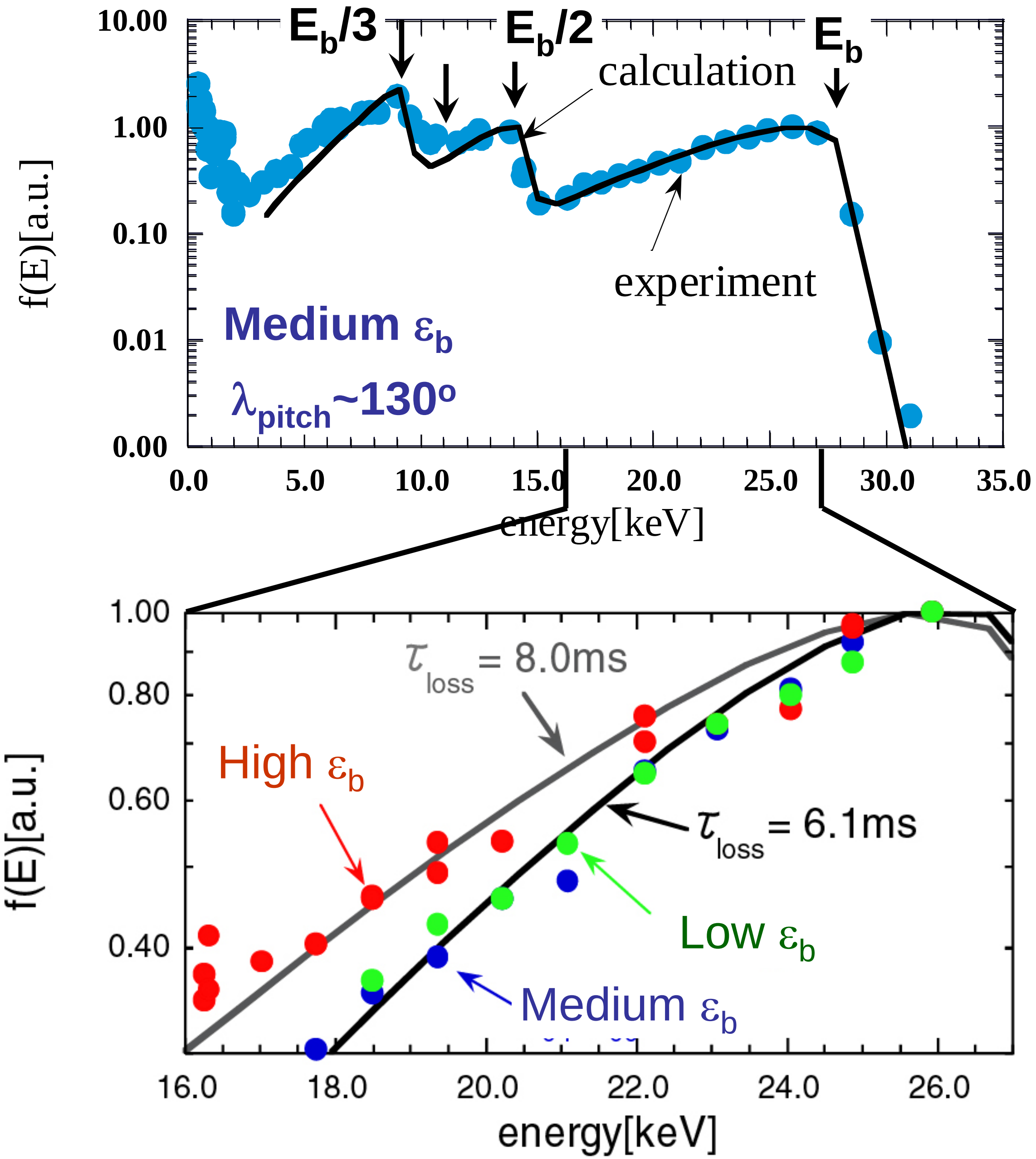
- Slower grad-*B* drift with increasing ε_b

Loss rate from orbit calculation



Longer effective loss-time in high-ε_b configuration[+]

Comparison with Fokker-Planck calculation



- The energy spectrum is calculated using Fokker-Planck equation for ion.[++]
- The observation result can be interpreted with FP analysis by taking effective loss time into account.

[+] M. Kaneko,, et al., Fusion Sci. Tech. 50 (2006) 428.
[++] R.H.Flowler *et al*. ORNL/TM-5487 (1976)]

- Effective loss time in the high-ε_b configuration is longer than the others.
  => These results revealed that effectiveness of ε_b to energetic particle confinement

Outline

1. Introduction
2. Configuration characteristics in bumpiness scan experiments
3. Energetic particle transport in NBI plasmas
    - 3.1. Bumpiness effect
    - **3.2. Energetic-ion-driven MHD activities**
4. Global energy confinement in NBI plasmas
5. Summary

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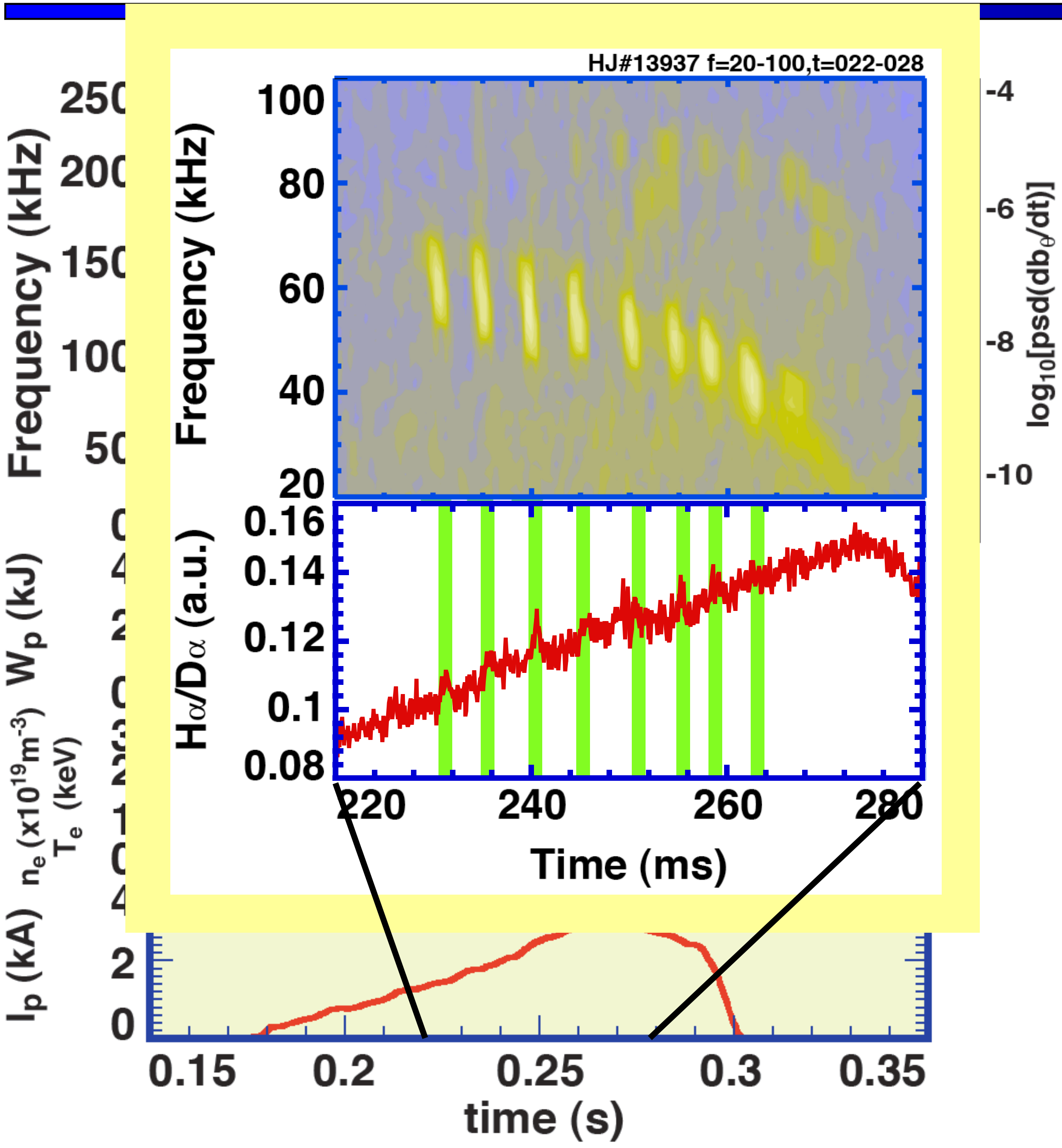
Observation of bursting GAE in high ε_b configuration[+]



- Bursting GAEs (m ~ 4/n =2, f_{exp}= 40 ~ 70 kHz) with rapid frequency chirping.

- Some plasma parameters such as H_α and T_e (SX foil) are simultaneously modulated with the bursting GAEs.

➔ indicates that GAE would affect energetic ion transport.

most unstable mode when fast ion pressure becomes fairly high.

- GAEs have been observed at several magnetic configurations in NBI plasmas of Heliotron J, however, strong bursting GAE is observed in high ε_b configuration.

[+] S. Yamamoto, et al., FS&T, 51, 93 (2007)

Hybrid Directional Langmuir Probe (HDLP) installed in Heliotron J*

- Hybrid Directional Langmuir probe (HDLP) system is installed into Heliotron J.
(under collaboration research with Dr. Nagaoka NIFS)
- Can measure Co-going and CTR-going ion fluxes separately.

*K. Nagaoka, et al., Proc. ICPP2008, P2-156 (2008).

Targets

- Core plasma
（Te, ne, potential）
- Fast ion flux
- Plasma flow
- Heat flux
- Magnetic fluctuation

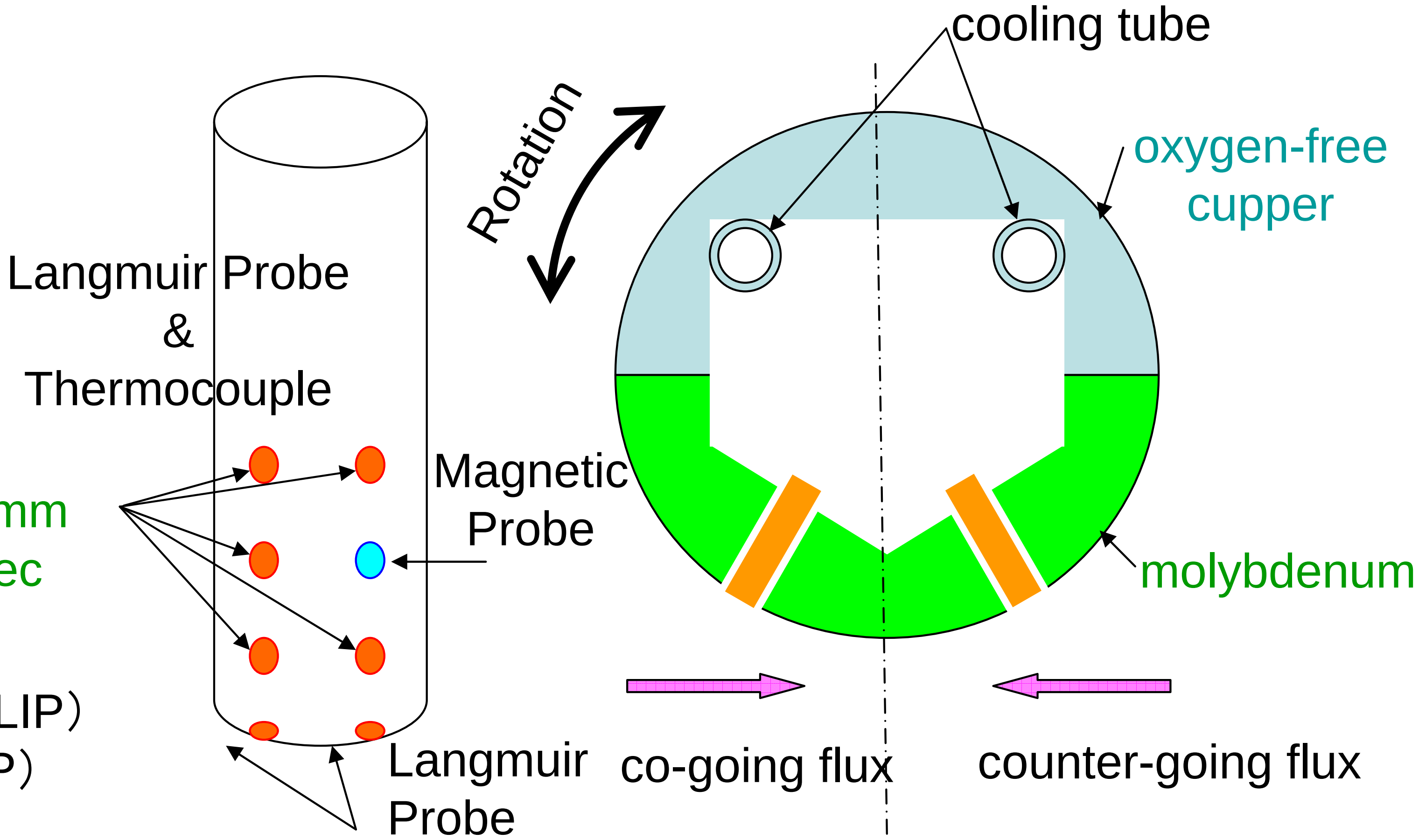
Advantage

- High heat resistance
- High spatial resolution ~4mm
- High time resolution ~1μsec

Disadvantage

- Energy spectrum（NPA, LIP）
- Pitch angle resolution（LIP）

The combination of other fast ion diagnostics is important.



Langmuir Probe
&
Thermocouple

Magnetic
Probe

Langmuir
Probe

Rotation

cooling tube

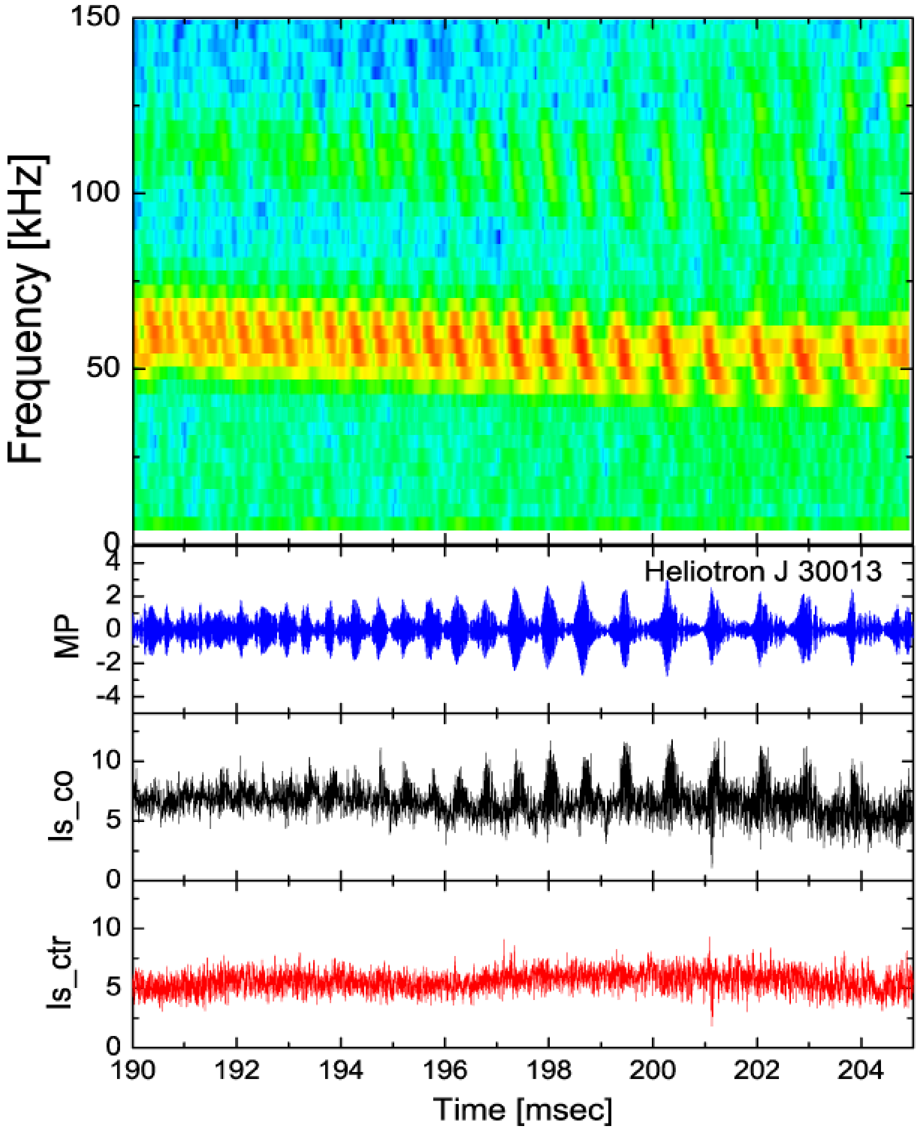
oxygen-free
cupper

molybdenum

co-going flux

counter-going flux

Fast Ion Response to bursting GAE



- Bursting GAE occurs in NB and EC heated plasma.
- The frequency of GAE chirps down quickly.
- The Co-directed ion flux synchronized with GAE burst is observed and it is sensitive to the burst interval and amplitude.
- The CTR-going ion flux is not response to GAE burst.
  => Considered as a resonant convective oscillation

- Influence of GAE on the energetic ion confinement should be taken into account for further optimization of the helical-axis heliotron configuration.

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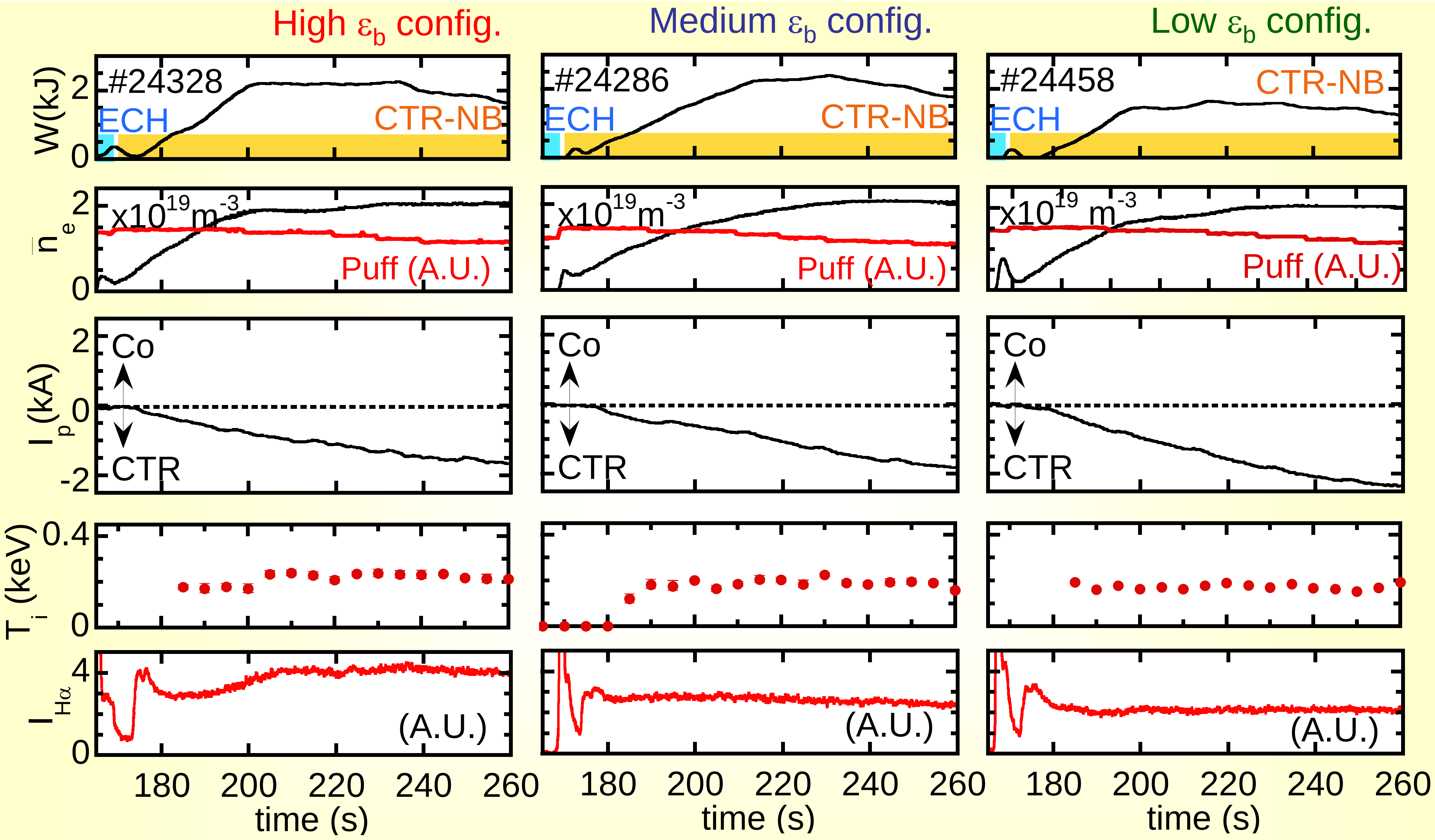
Typical time evolution of NBI sustained plasma



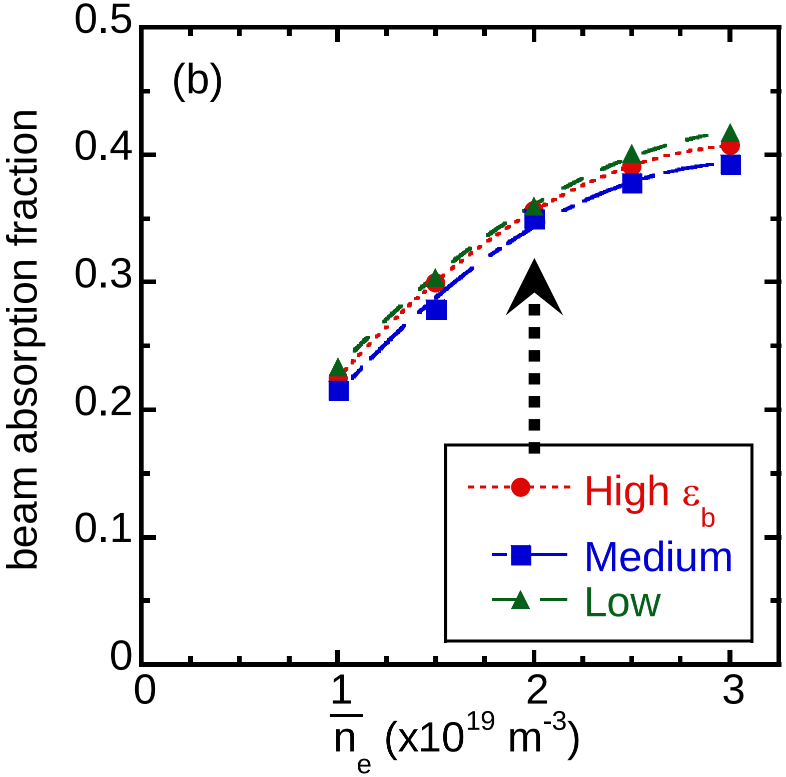
- CTR injection plasma (P_{INJ} = 550~560kW) (Initial plasma is produced by ECH)
- Density control by gas puffing (~2 x 10^{19} m^{-3})
- CTR direction I_p (BS;Co, NBCD;CTR) (reduce rotational transform)

Calculation of beam absorption profile*

1. HFREYA : beam birthpoints calculation using Monte-Carlo method
2. mcnbi : calculation code for estimation of re-distribution of fast ion
3. FIT : beam absorption profile calculation using Fokker-Planck equation

*S. Murakami, et al., Trans. Fusion Tech. 27 (1995) 259

- **Modified HFREYA to apply 3D shape of plasma & inner vacuum vessel of Heliotron J.**
- **Calculation of ion orbit without slowing down process at the initial energy of beam ions.**
  => Do not treat the orbit loss of fast ions including slowing down processes
- **The slowing down process of fast ions and the energy transfer to both the bulk electrons and ions are calculated by the Fokker-Planck analysis including CX loss of fast ions.**



Beam absorption rate v.s. n_e

Estimation of beam absorption under assumption of..

- Parabolic density profile
(line-averaged $n_e \sim 1\times10^{19}$ to 3×10^{19} m^{-3})

- Parabolic T_e (T_i) profiles with core temperature of 400 eV (300 eV).

- $Z_{eff} = 1$

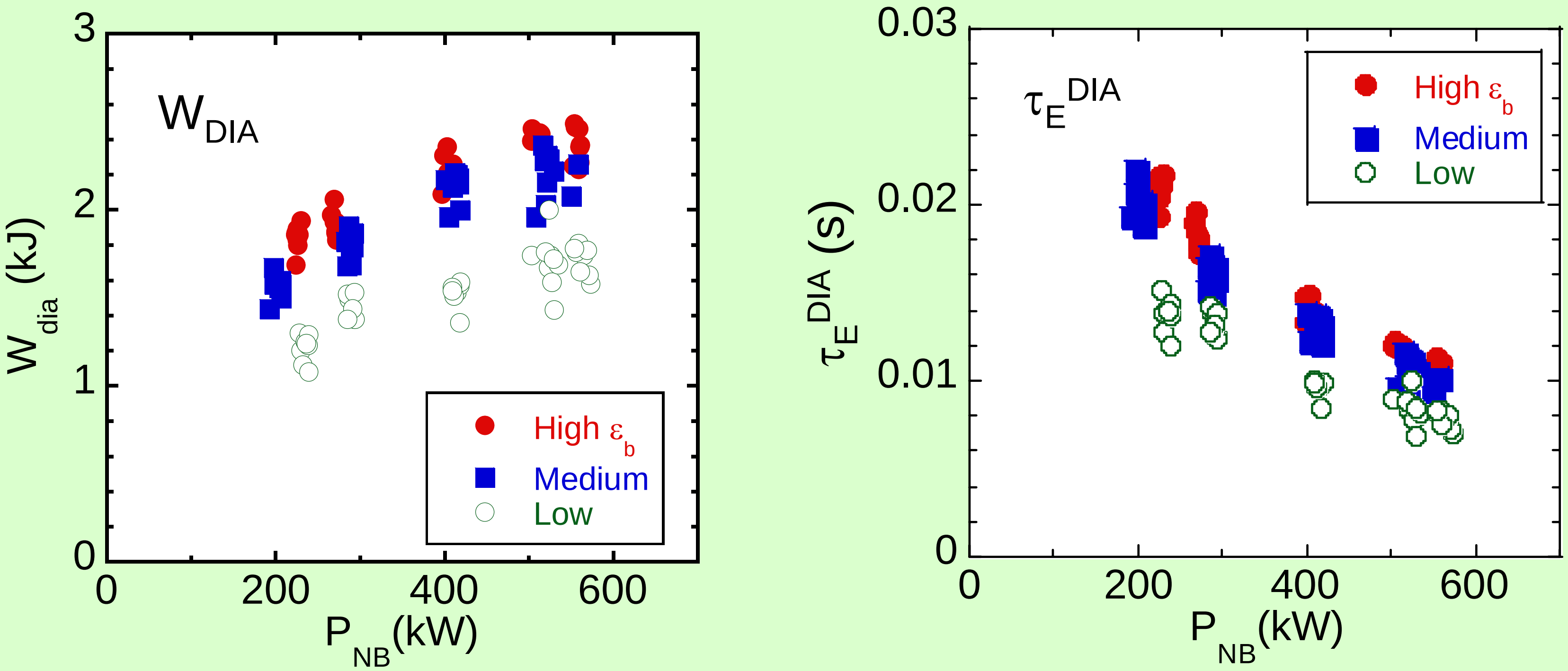
- Edge neutral density of 2×10^{16}m^{-3}

Neutral density profile will be estimated using Hα/Dα measurement and Monte-Carlo simulation.

Absorption rate of around 35% for three ε_b cases

Preferable energy confinement in both high and medium ε_b

Dependence of stored energy (left) and energy confinement time (right) on P_{NB}



- Power scan experiments at constant density ($2\times10^{19}m^{-3}$) for three ε_b configurations.
($200kW < P_{NB} < 600$ kW)

- Evaluation of W_{dia} by diamagnetic loop data.

- W_{dia} in the high- and medium-ε_b configurations is clearly higher than that in the low-ε_b case.

- The difference of W_{dia} between the high- and medium-ε_b configurations is small, but W_{dia} in high-ε_b case is more than 5% higher than that of the medium- ε_b configuration.

- Preferable energy confinement for high and medium ε_b configurations

Increase in temperature in high and medium ε_b configs

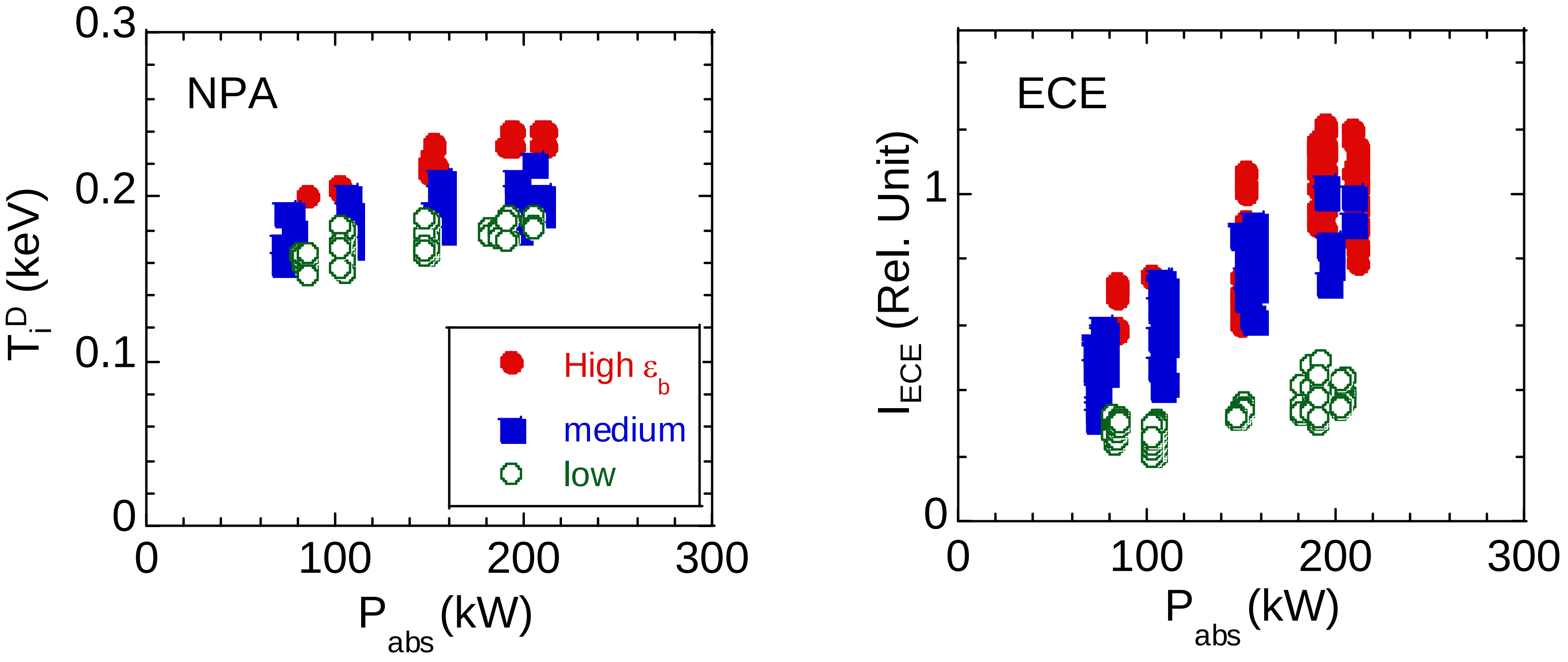
- Weak dependence of bulk ion temperature (deuterium) by CX-NPA on NB power, however, slightly increase in T_i with ε_b

- Intensities of electron cyclotron emission (I_{ECE}) at the core region increase with P_{NB} (ECE data has not been calibrated absolutely)

- Higher in high and medium ε_b

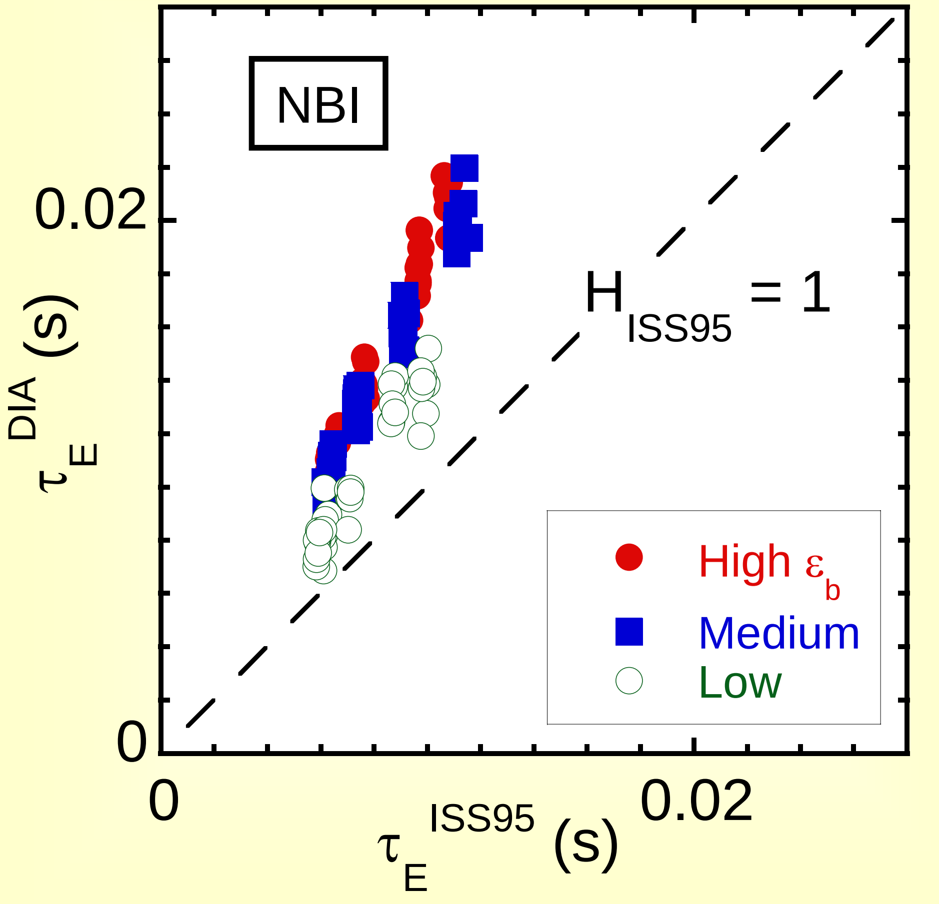
  ➔ Increase in electron temperature for the high and medium ε_b configs.

T_i and I_{ECE} vs. P_{NB}



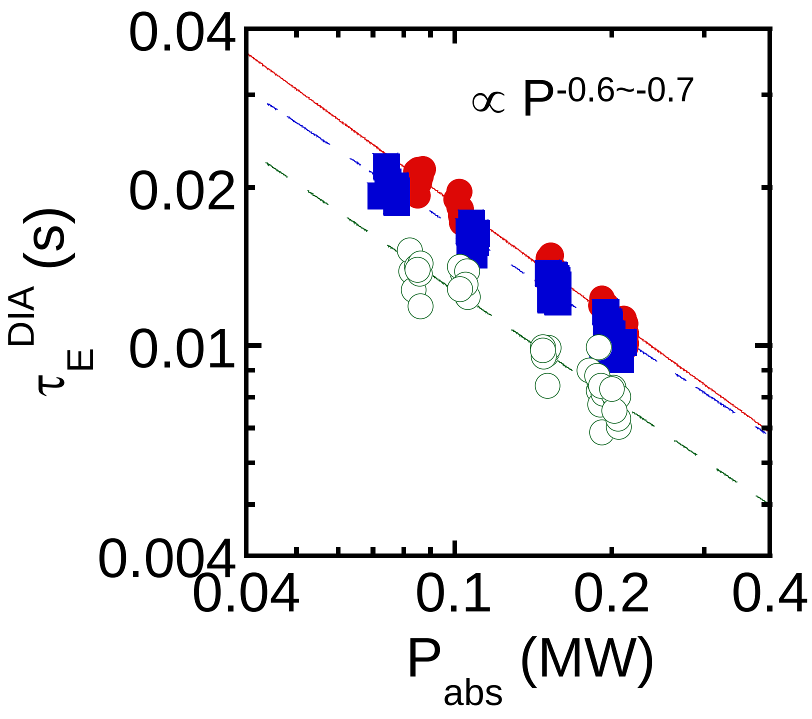
Comparison with ISS95 scaling

Comparison of energy conferment time to ISS95 scaling in NBI plasmas



- Comparison of energy confinement time τ_E^{DIA} with International Stellarator Scaling (τ_E^{ISS95})

- Enhancement factor ($H_{ISS95} = \tau_E^{DIA}/\tau_E^{ISS95}$) around 1.8 and 1.7 for high and medium ε_b cases, respectively, which is higher than the low ε_b condition around 1.4.



- Power dependence is similar to ISS scaling.

ISS95 scaling law

$$\tau_E^{ISS95} = 0.079\, P^{-0.59}\, n_e^{0.51}\, B^{0.83}\, R^{0.65}\, a_p^{2.21}\, \iota/2\pi(2/3a)^{0.4}$$

Summary

We investigated energetic particle and global energy confinement in NBI plasmas of Heliotron J, focusing on the bumpiness effect, being key factor for drift-optimization in helical-axis heliotron configuration of Heliotron J.

- 1/e decay time of high energy CX flux became better with increasing bumpiness, which shows bumpiness is effective to control of the energetic particle confinement.
- Co-going lost ion flux synchronized with bursting GAE can be measured with hybrid directional Langmuir probe (HDLP) system installed in Heliotron J. Influence of GAE on the energetic ion confinement should be taken into account for further optimization of helical-axis heliotron configuration.
- In the power scan experiment at a constant density condition, the good enhancement factor of the energy confinement time (H_{ISS95}) was obtained in high and medium-ε_b configurations.
- Bumpiness control experiments revealed the effectiveness of the control of bumpiness on the confinement both for the energetic particle and the bulk plasmas.

- Further experiment and analysis are needed to clarify the relation between bumpiness effect and anomalous transport with attention to turbulence, plasma flow, rotation and radial electric field.