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Configuration Control Experiment in Heliotron J

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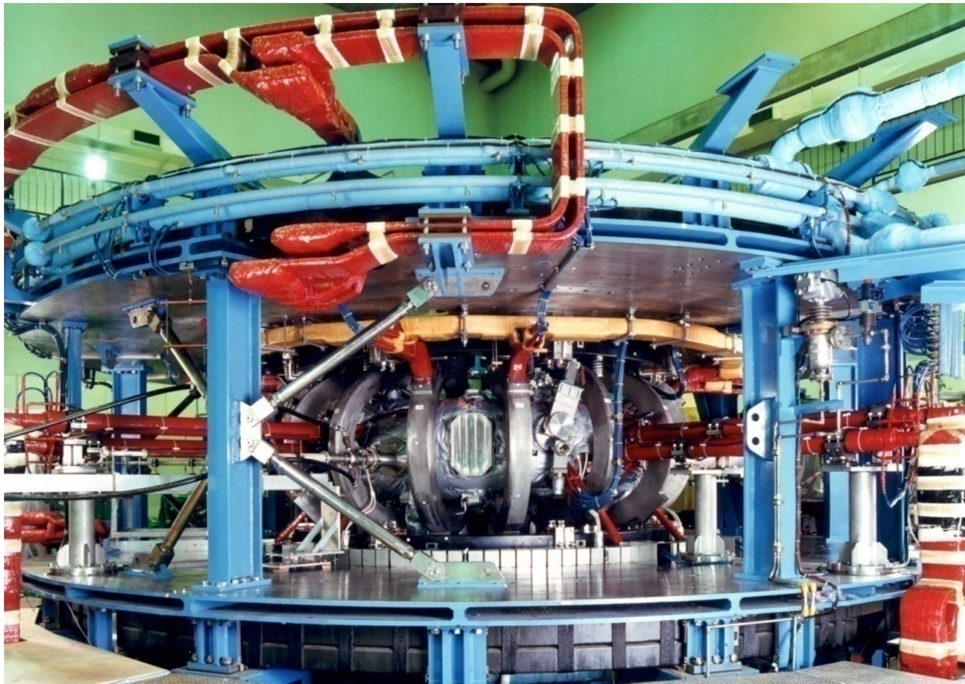


Heliotron J Device

Introduction

Heliotron J is a helical-axis heliotron device based on the quasi-omnigeneous concept.

Experimental survey of the guiding principle for optimizing the confinement-field structure is a major issue for Heliotron J.

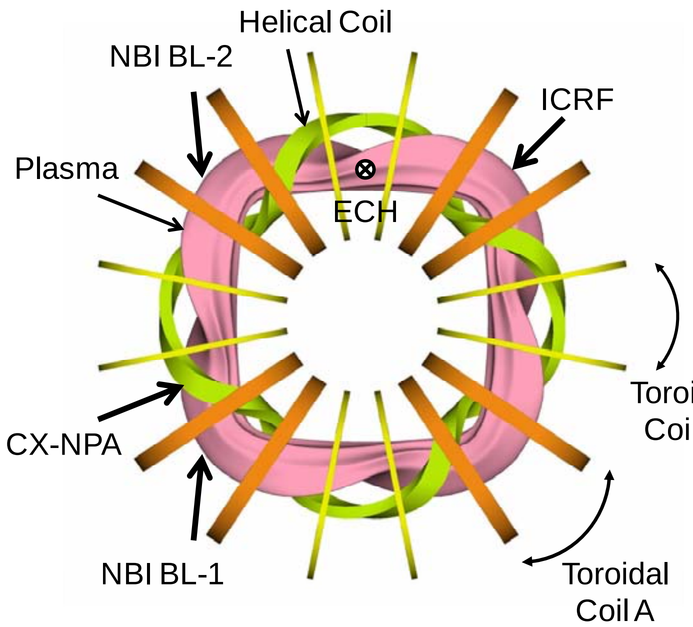
Using five sets of coils fed by individual power supply, the toroidicity, the helicity and the bumpiness can be changed.

Here, the role of the bumpiness is presented for fast-ion confinement, non-inductive currents and bulk plasma confinement.

The bumpiness is controlled by changing the current ratio of Toroidal coil A to Toroidal coil B.

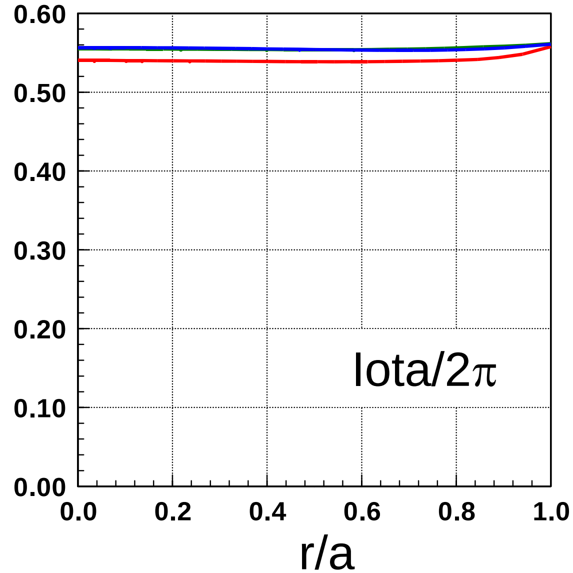
Heliotron J Device

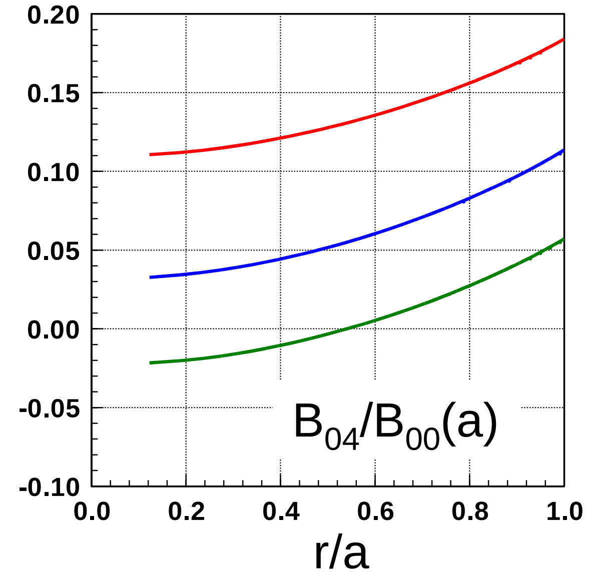
Major Radius: 1.2 m
Minor Radius: 0.1-0.2 m
Helical Coil: L=1, M=4
Magnetic Field Strength: 1.5 T
Rotational Transform: 0.3-0.8
Heating Systems
NBI: 30 kV, 0.7 MWX2
ECH: 70 GHz, 0.45 MW
ICRF: 19-23 MHz, 0.4 MWX2

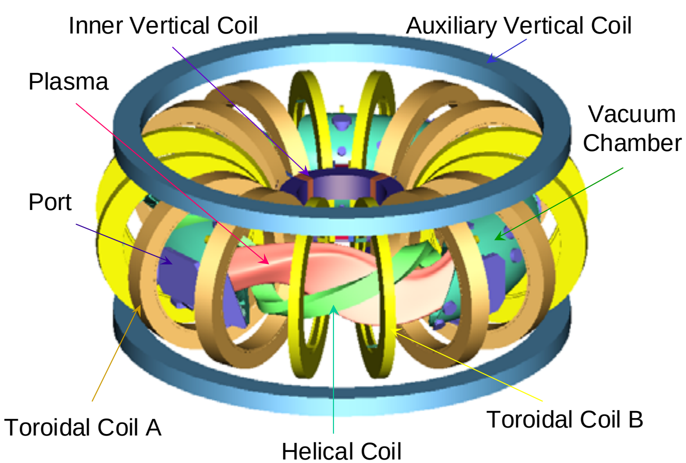


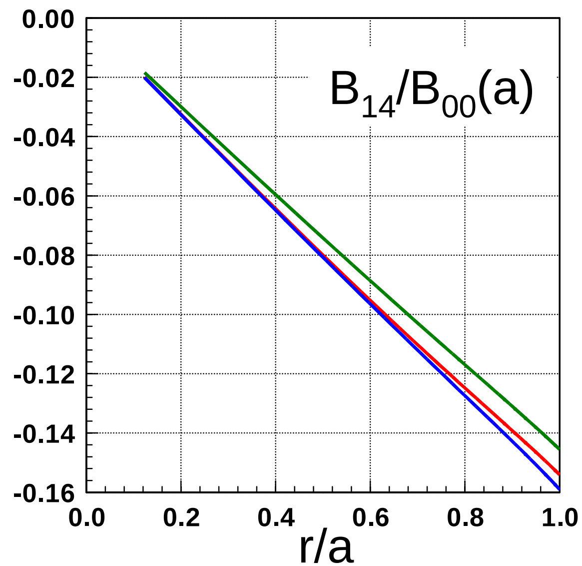
Iota and Fourier Components

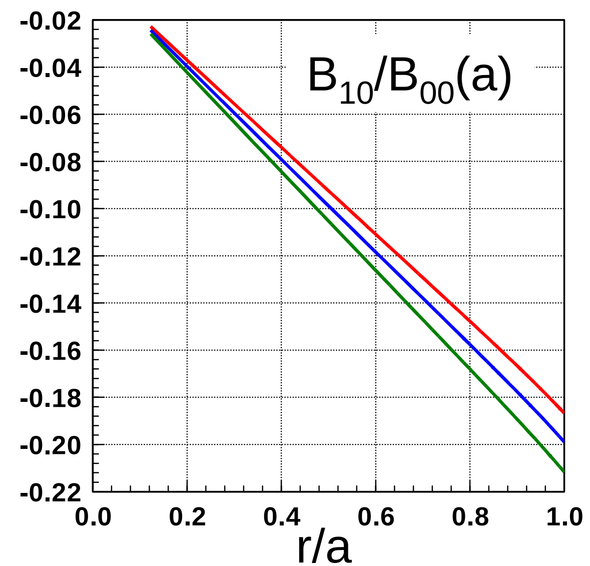
	High	Med.	Low
Vp (Volume)	0.73	0.68	0.67
R (Major radius)	1.19	1.20	1.20
a (Minor radius)	0.18	0.17	0.17
<B> (Averaged Field on the axis)	1.36	1.26	1.19



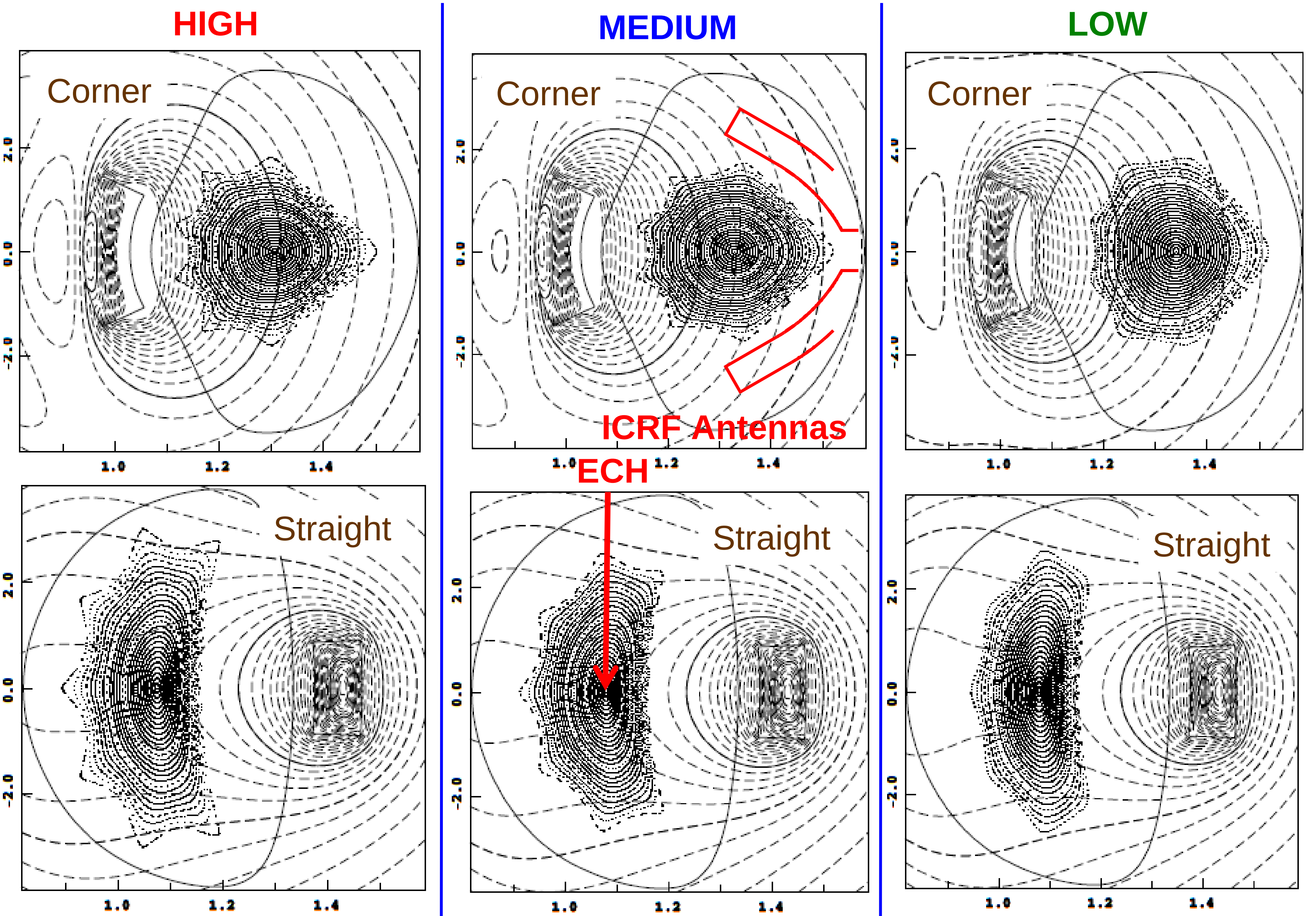








Magnetic Surfaces



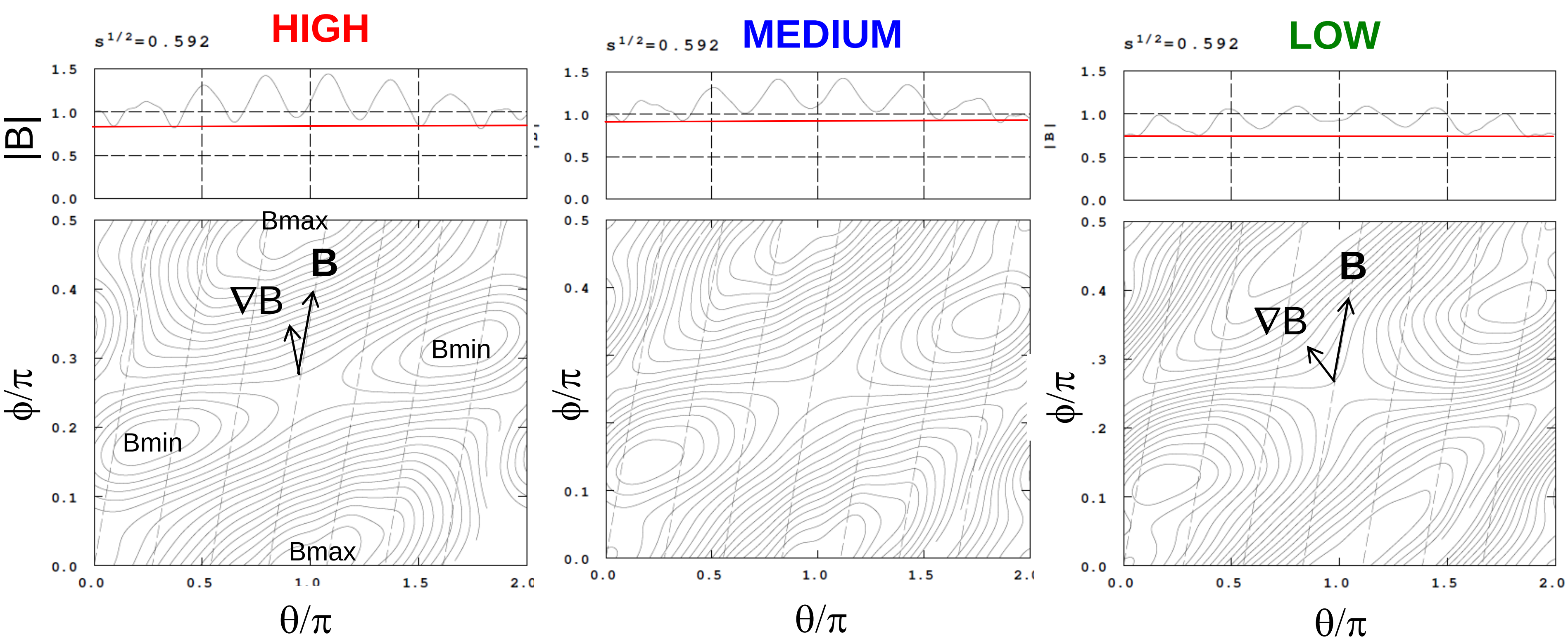
Configuration Characteristics

In the case of the high bumpy configuration;

the minimum values of field strength are relatively flat, and

the angle between the field line and ∇B is small.

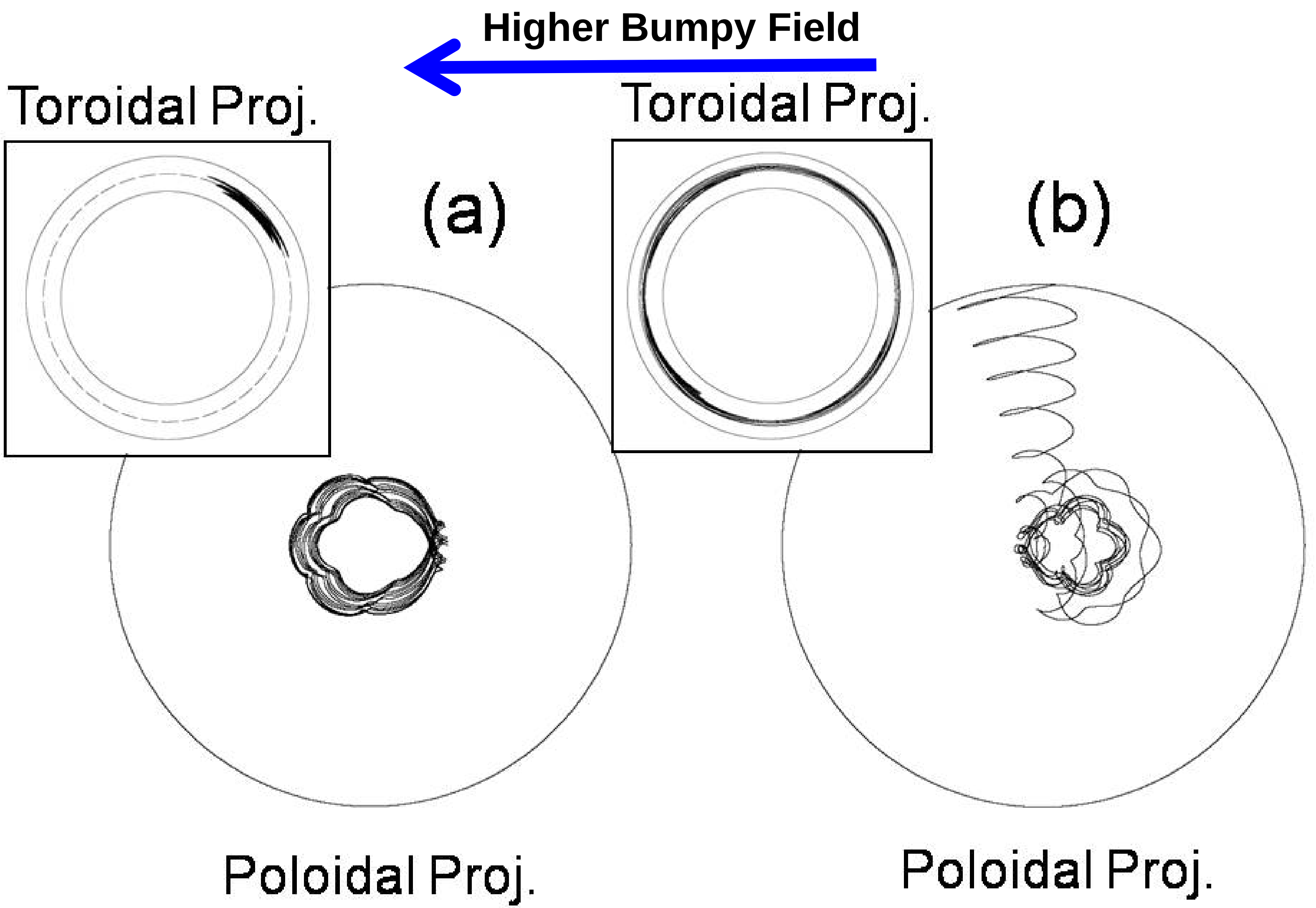
The shift of the drift orbit from the flux surface is expected to be smaller in the higher bumpy configuration.



Poloidal profiles of |B| along a field line (Upper) and |B| contour (Lower) at ρ = 0.592.

Trajectory Change by the Bumpiness

E = 1 keV, ρ = 0.3, θ = 0 °, ϕ = 45 °, θ_{pitch} = 80°

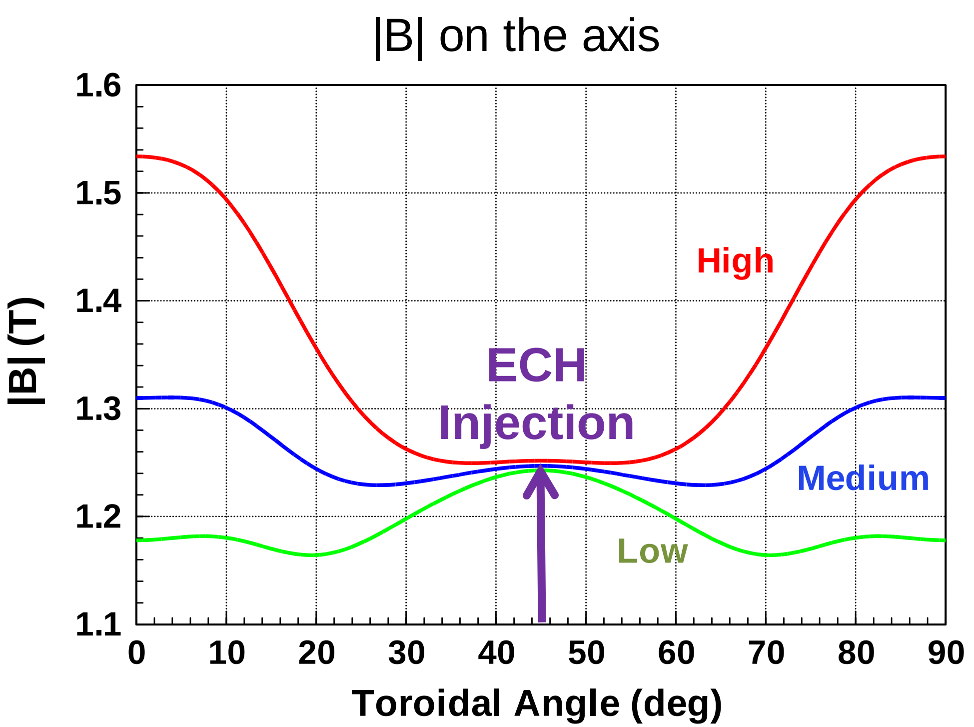


Fast Ion Confinement Control by 'Bumpiness'

- Fast ion confinement is investigated by using ICRF minority heating (H-minority and D-majority) for the three bumpiness.
- An ICRF wave in the minority heating accelerates protons in the perpendicular direction. ICRF heating is suitable for the confinement study of trapped ions.

Bumpiness

The configurations used in these studies were as follows; the bumpiness (B_{04}/B_{00}, where B_{04} is the bumpy component and B_{00} is the averaged magnetic field strength) are 0.15 (high), 0.06 (medium) and 0.01 (low) at the normalized radius of 0.67

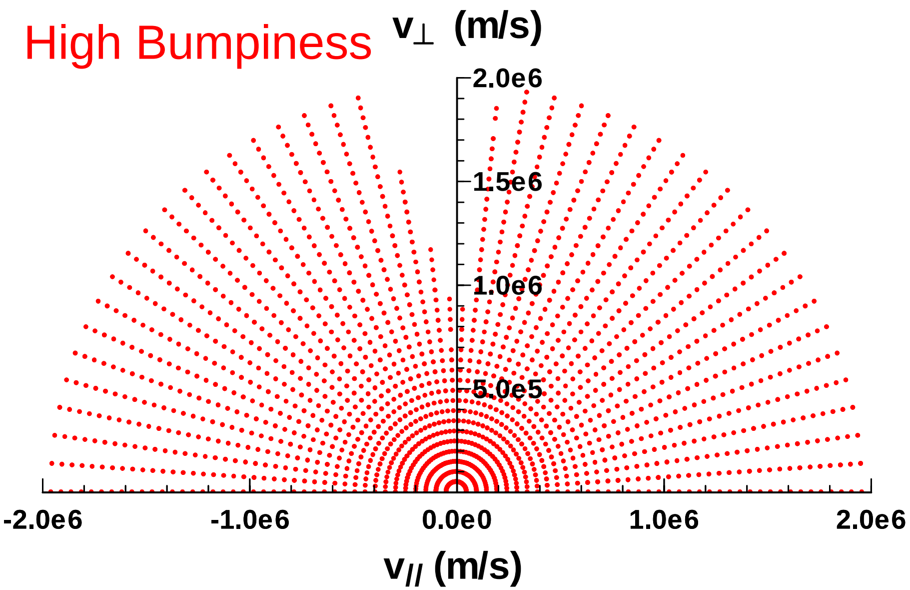


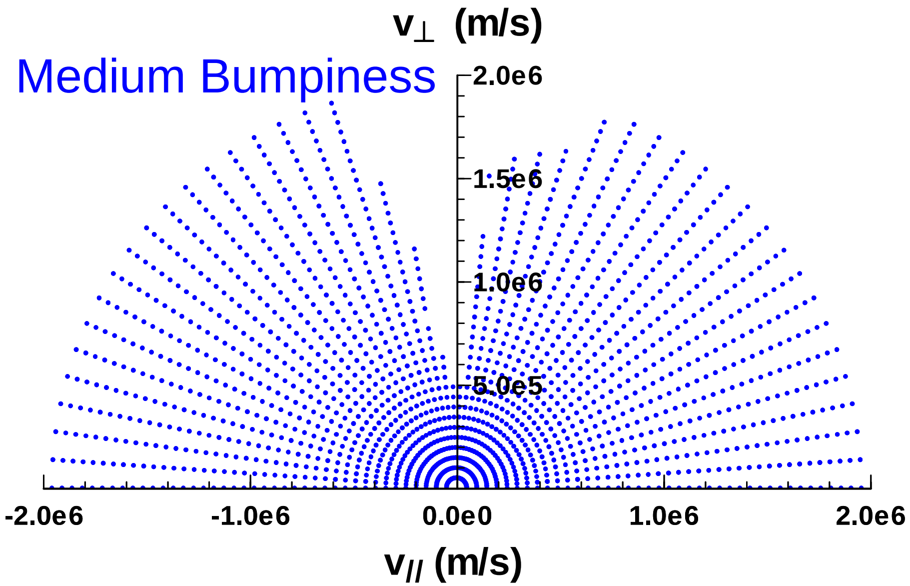
Loss Region is Changed by the Bumpiness

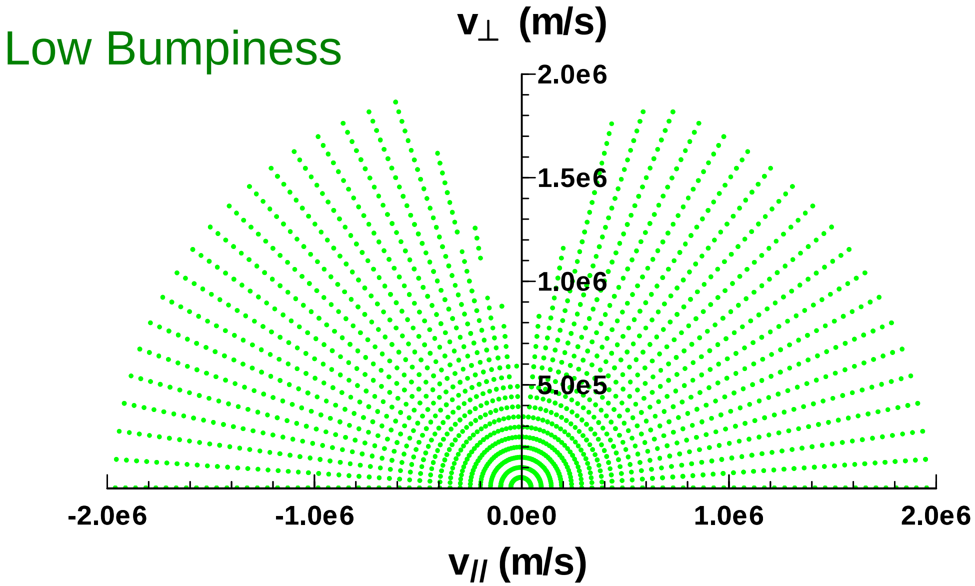
Collisionless Orbit Calculation
No beta, No potential
Maximum Energy is 20 keV (H^+)

Starting point: Corner Section (Inside of the torus) $(\rho, \theta, \varphi) = (0.3, 180.0, 0.0)$

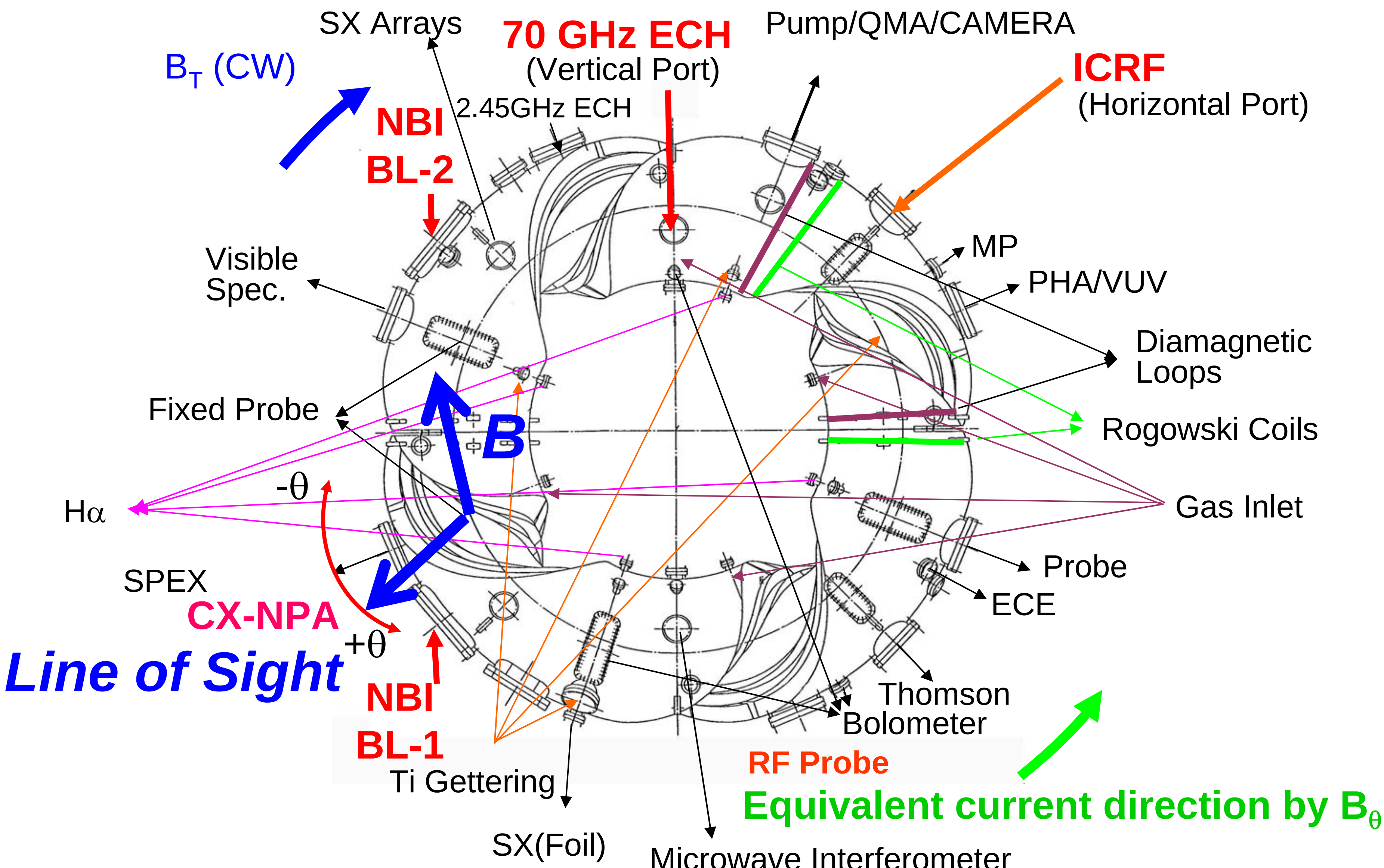
There is a loss region near the perpendicular direction.
It is smallest in the high bumpy case.





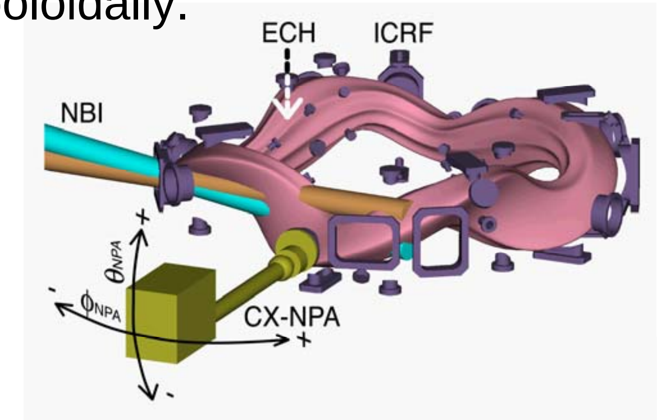


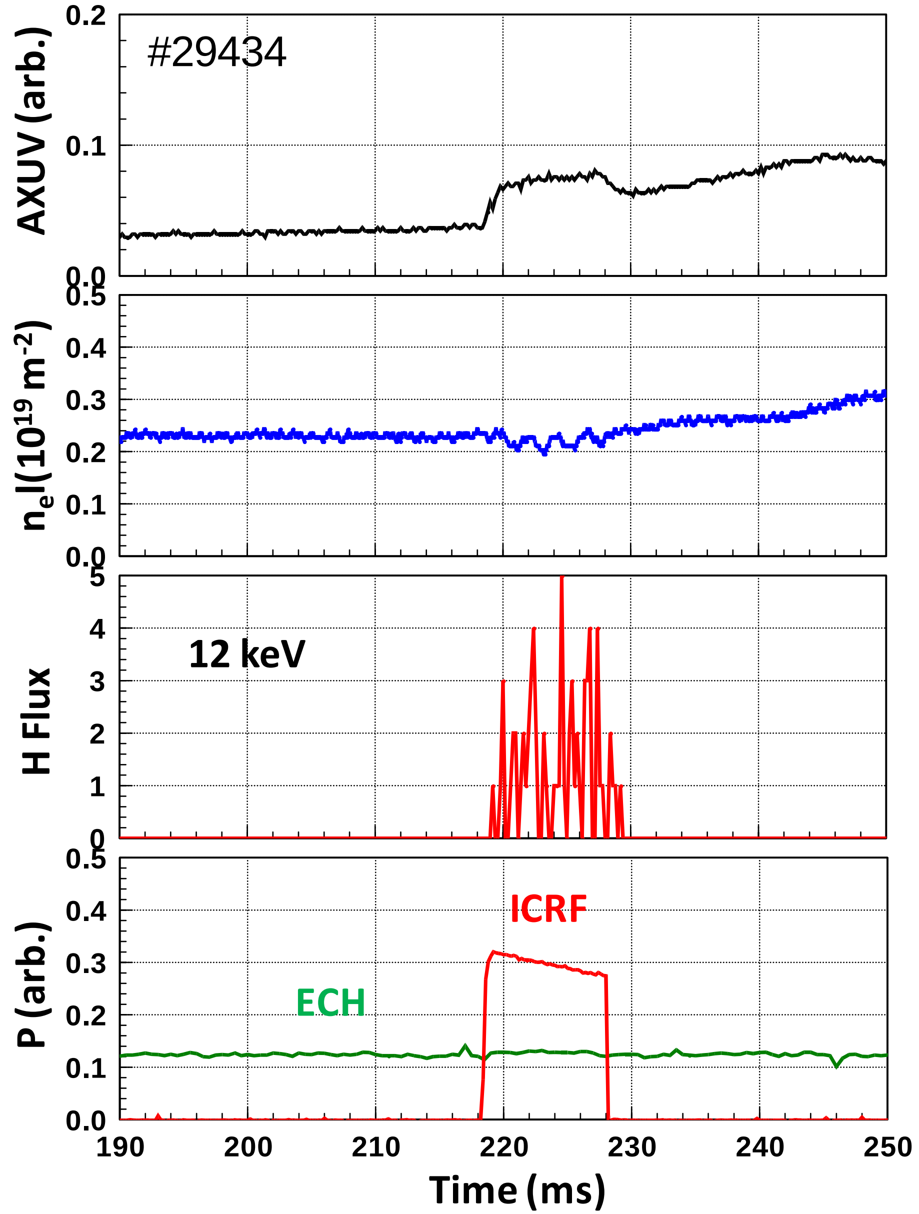
Heating and Diagnostic System



Time Traces of Heating and Plasma Parameters

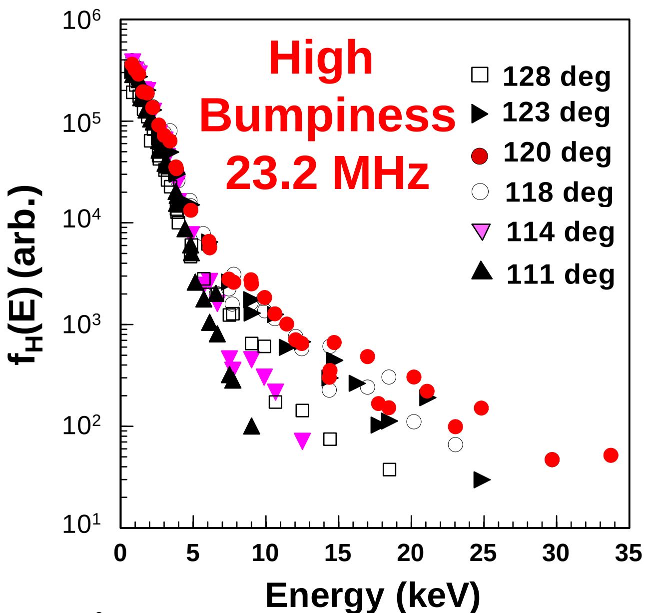
- A plasma is generated by an ECH pulse. ECH power is about 300 kW.
- An ICRF pulse is injected during ECH. ICRF heating power is 250 – 300 kW.
- The density is not changed during the ICRF pulse. The line averaged density is 0.4 x 10^{19} m^{-3}.
- Hydrogen and deuterium fluxes are measured by a charge-exchange neutral particle analyzer (CX-NPA).
- CX-NPA can be changed the angle of the line-of-sight toroidally and poloidally.



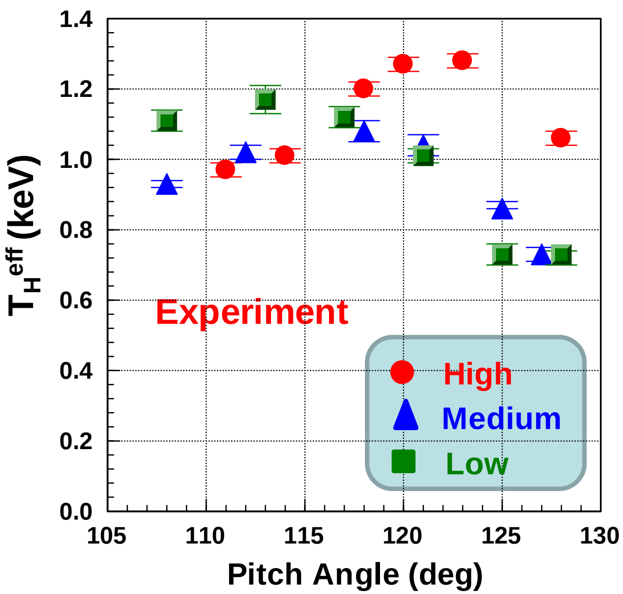


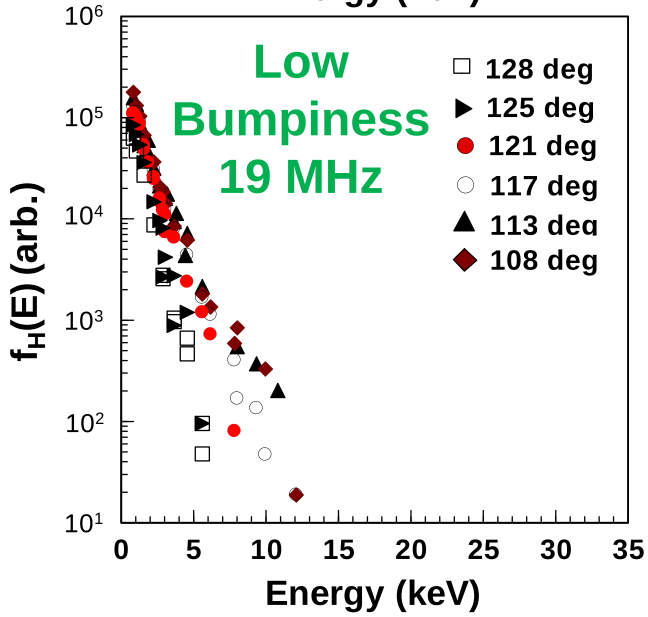
Bumpy Dependence of Proton Energy Spectrum

- An ICRF pulse of 23.2 MHz or 19 MHz is injected into an ECH target plasma where $T_i(0)$ = 0.2 keV, $T_e(0)$ = 0.8 keV and $\bar{n}_e$ = 0.4 x 10^{19} m^{-3}. ICRF injection power is 250-300 kW.
- In high bumpy case, the ion flux is measured up to 34 keV at the pitch angle of 120 deg.
- In the medium and the low cases, the change in energy spectrum is small. In low bumpy case, the fast ion flux is increased continuously towards 90 deg.



- The effective temperature for the minority protons is estimated from the slope of the energy spectra below 7 keV.
- In high bumpy case, the peak is near 120 deg. In the medium and low bumpy cases, the effective temperature is almost constant from 108 deg to 120 deg, and is deceased rapidly at 125 deg.

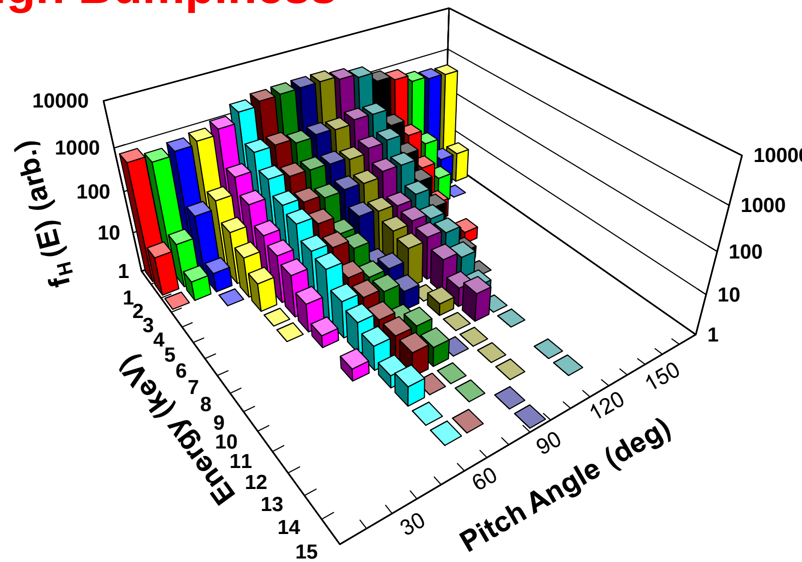




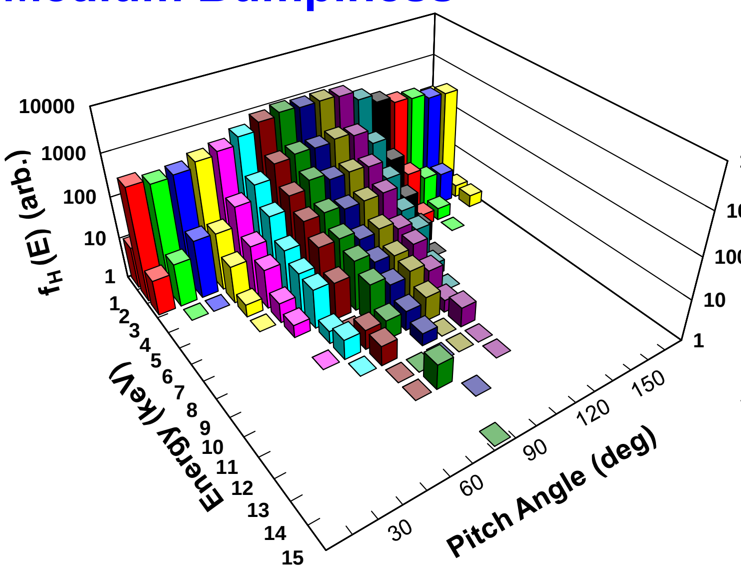
Calculated Pitch Angle Distributions

- The high energy ions are generated near 60 deg and 120 deg in pitch angle in the bumpy case. The higher energy flux can be observed in the high bumpy case in comparison with other cases. The 60 peak is larger than another.
- In the medium and low bumpy cases, the high energy component is smaller than that in the high bumpy case.
- One of the reasons of these tendency is the orbit loss structure near the perpendicular direction.

High Bumpiness

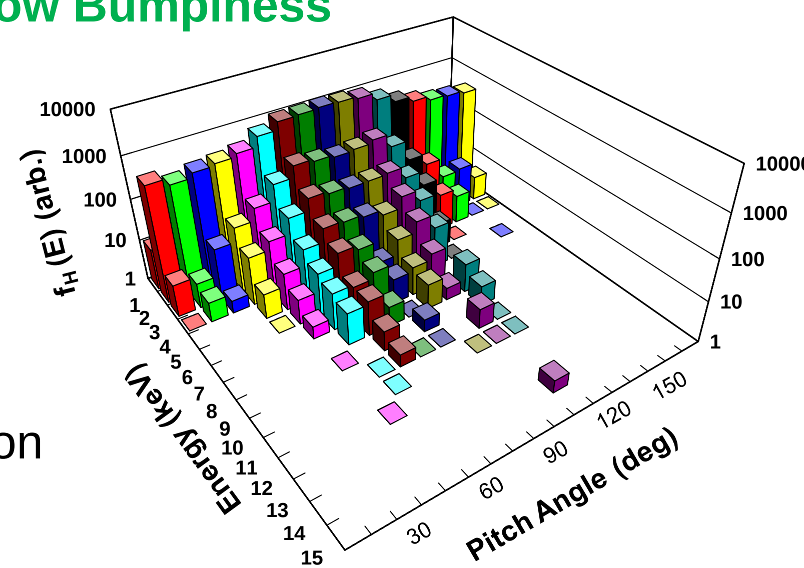


Medium Bumpiness



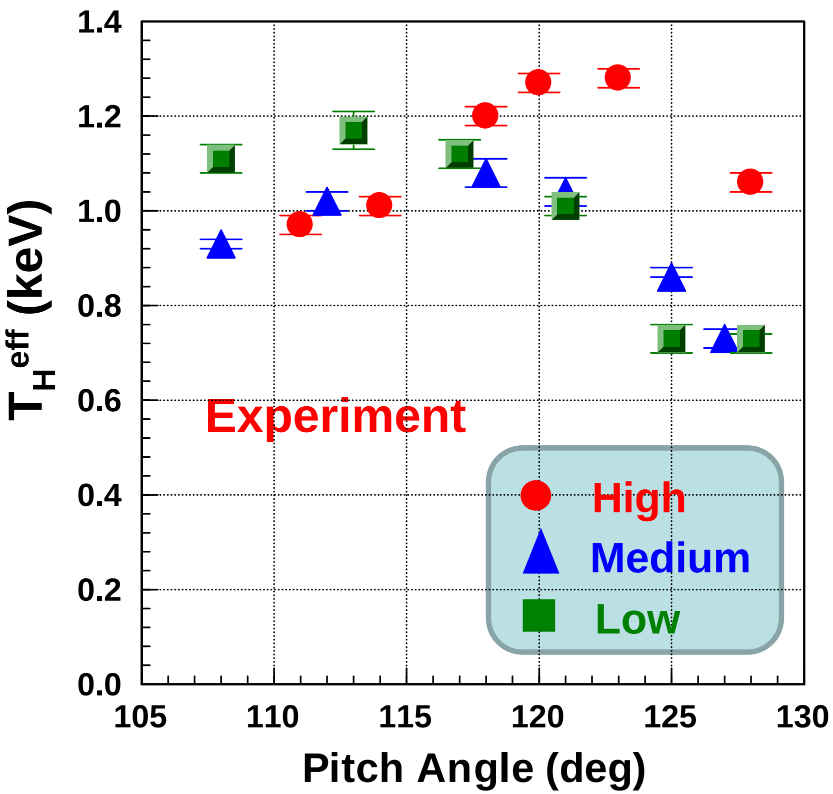
Monte Carlo Analysis with an ICRF Acceleration term

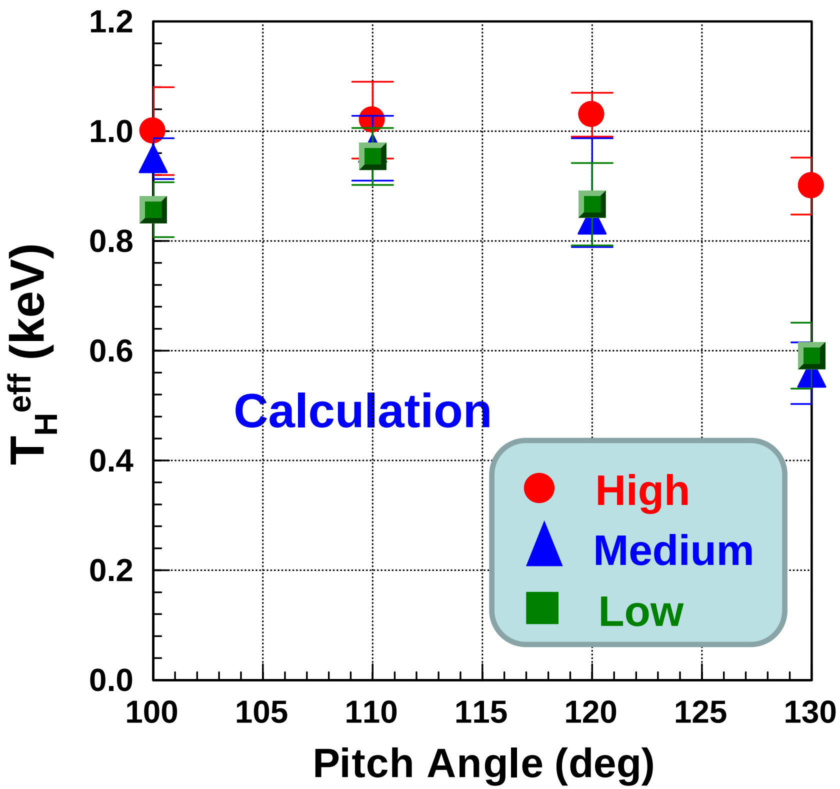
Low Bumpiness



Pitch Angle Dependence of Effective Temperature from Experiment and Calculation

- The effective temperature for the minority protons is estimated from the slope of the calculated energy spectra below 7 keV (Right).
- In the medium and low bumpy cases is decreased rapidly at 130 deg.
- The spectra from the calculation is volume-averaged. However, the measurement is line-averaged. It is necessary that the model include the same geometry of the CX-NPA.





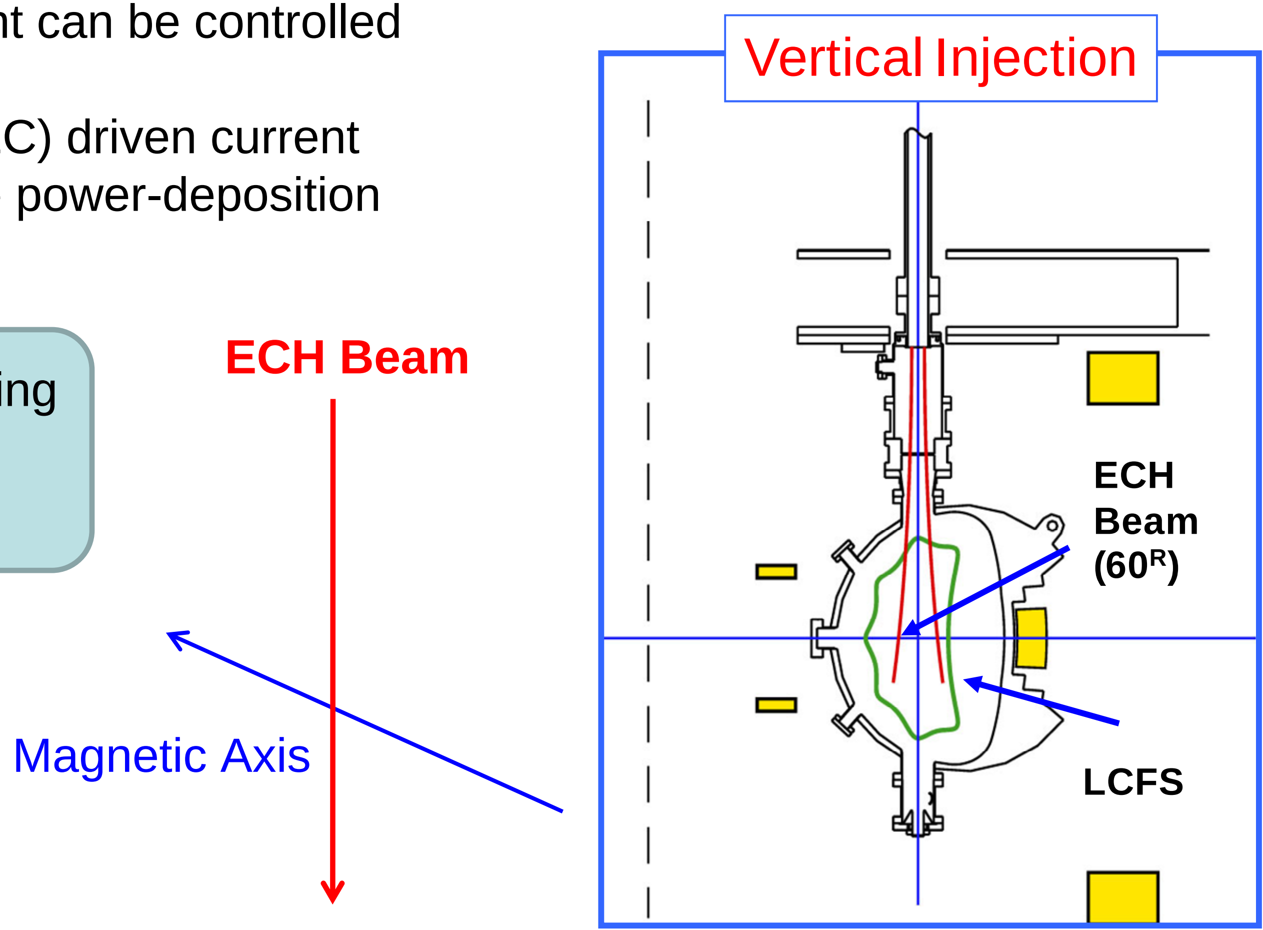
Non-Inductive Toroidal Current Control by Bumpiness and Heating Position

A toroidal current is not required for attaining plasma equilibrium in Heliotron J. However, if it flows spontaneously, it affects the equilibrium and stability since it modifies the rotational transform.

- A boot strap (BS) current can be controlled by the bumpiness.
- An electron cyclotron (EC) driven current can be controlled by the power-deposition position.

Second Harmonic Heating
X-mode injection
$N_{//} = 0.44$

- Vertical Injection
- Oblique to the magnetic field line (helical-axis device)



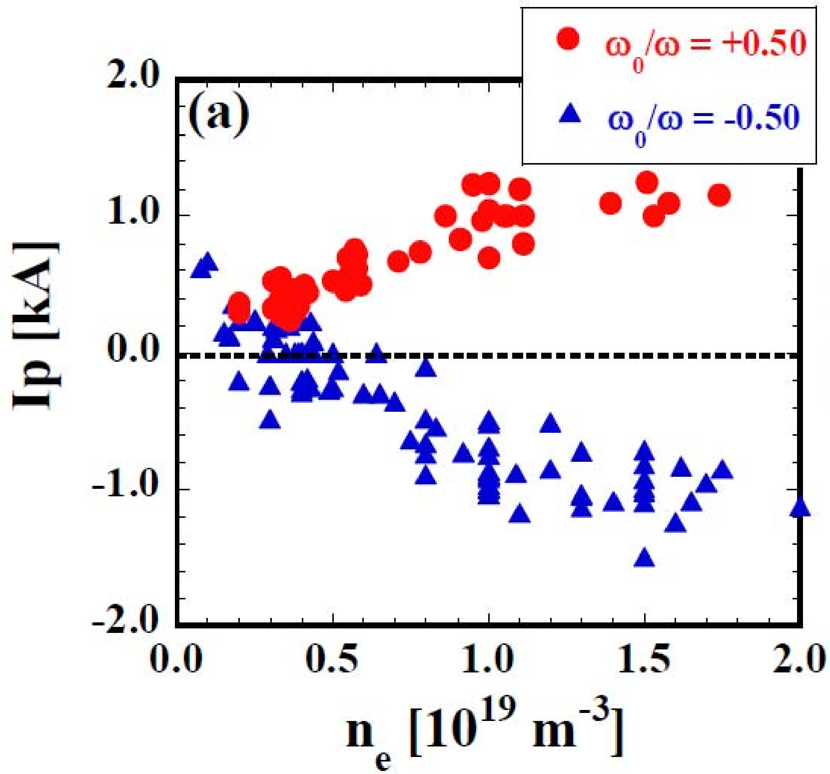
Estimation of the Bootstrap Current and the Electron Cyclotron Driven Current

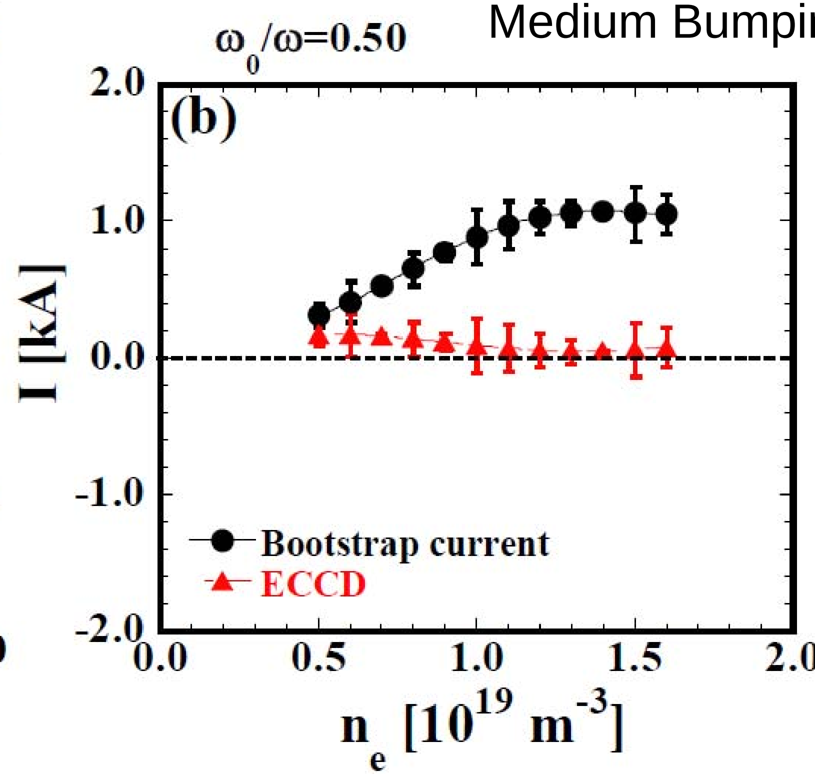
In ECH plasmas, the toroidal current is composed of the bootstrap current and the EC driven current. Two kinds of currents are separated by changing the direction of the confinement field (Normal direction and reversed direction).

$$I^{NORM} = I_{EC} + I_{BS}$$

$$I^{REV} = I_{EC} - I_{BS}$$

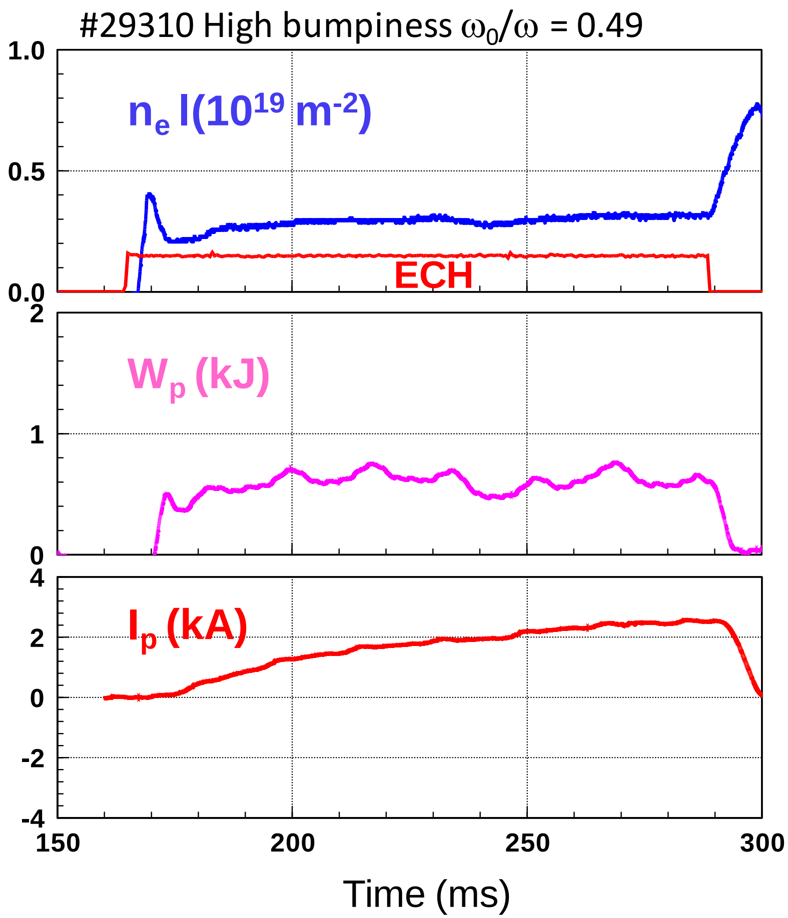
Medium Bumpiness

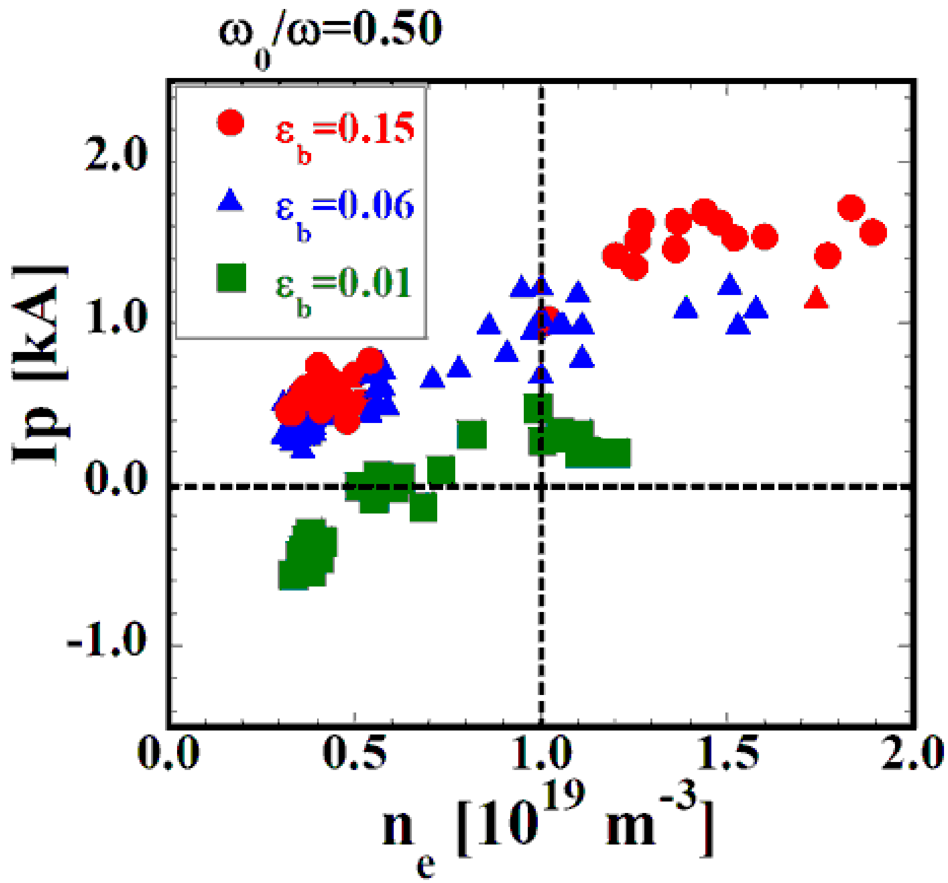




Bumpy Component Dependence of the Toroidal Current in ECH Plasmas

- The toroidal current is increased with electron density and gradually becomes saturated for the three bumpy cases.
- By changing the bumpiness, the toroidal current (BS current) can be controlled by about 1 kA . ECH power is about 300 kW.





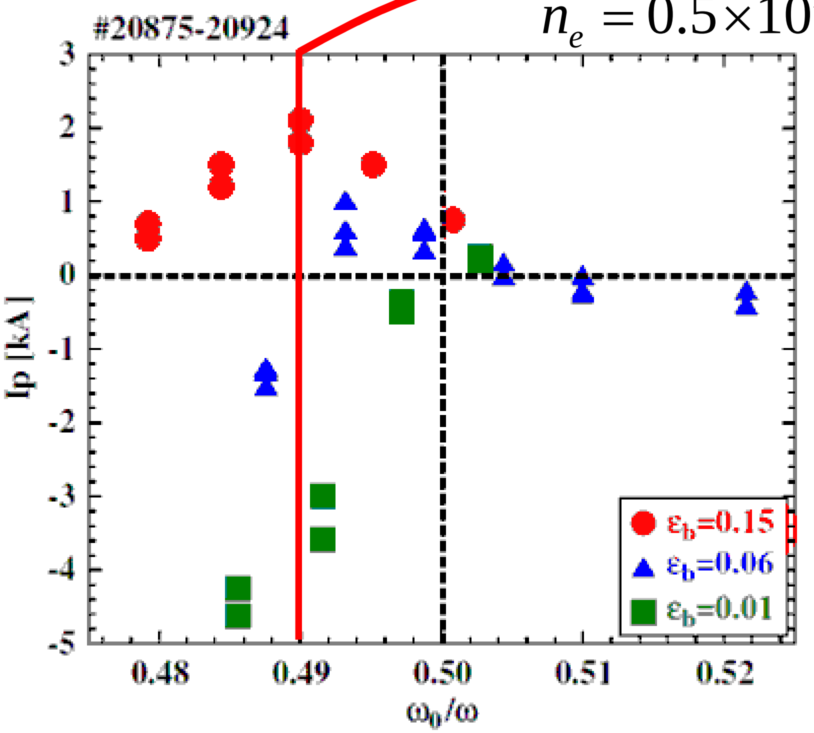
EC driven current can be controlled by changing the location of the ECH power deposition

The toproidal current can be controlled by changing the deposition location of the ECH beam. In the high and medium bumpiness, the current direction is reversed at a fixed density. The maximum current (-4.6 kA) flows in the low bumpy case.

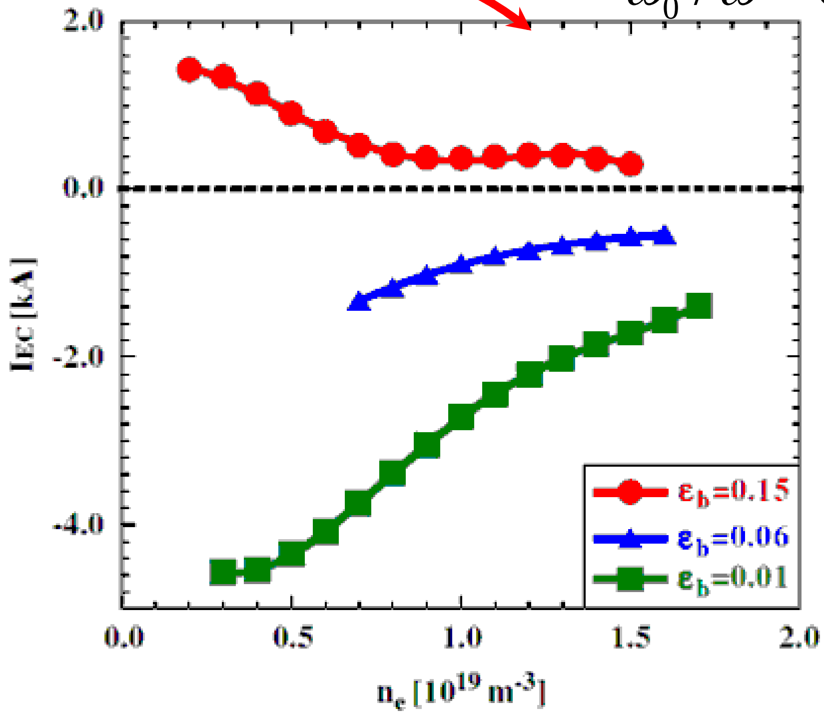
Fisch-Boozer Effect ↔ **Ohkawa Effect**

Deposition Location | **Electron Density**

$\overline{n}_e = 0.5\times10^{19}\mathrm{m}^{-3}$

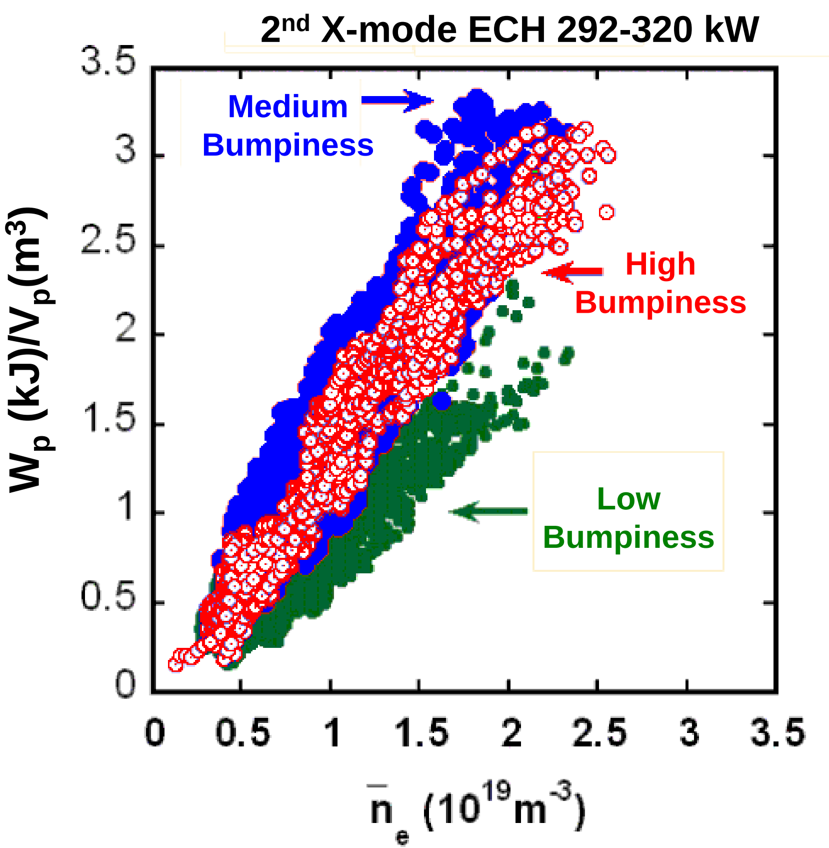


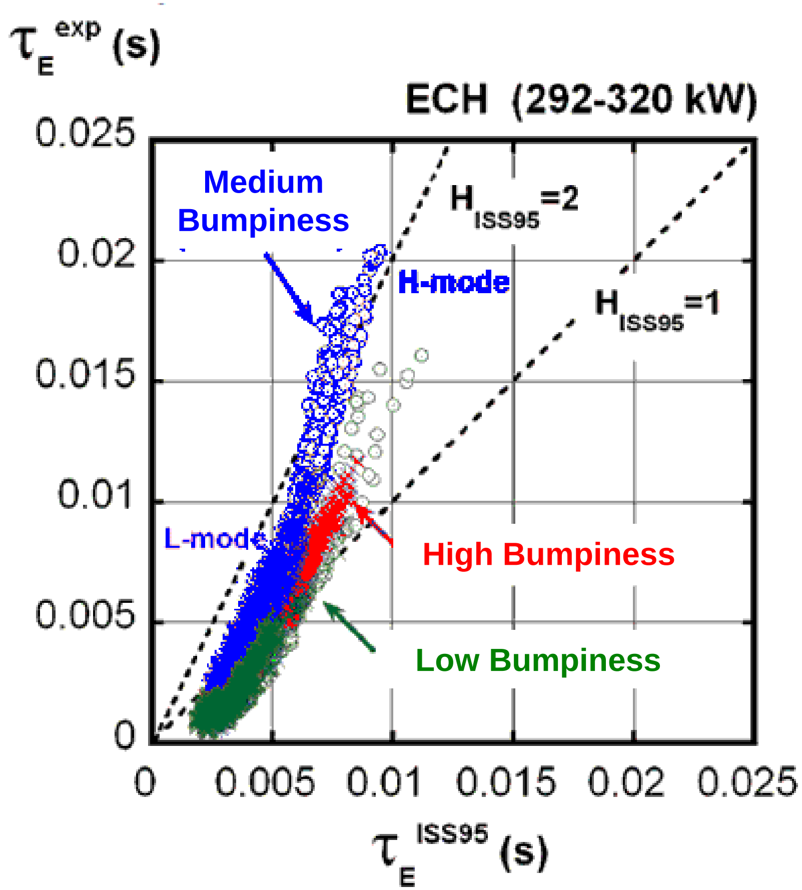
$\omega_0/\omega = 0.49$



Bulk Confinement for ECH Plasmas

- For ECH plasmas, the medium and high bumpy configurations are favorable for the bulk confinement.
- The effective helical ripple, ε_{eff} in the 1/ν collisionless regime is lowest in the medium bumpiness(0.22, 0.13, 0.26 at 2/3a for the high, medium and low bumpiness).
- The H-mode was not observed in the high bumpy case under the same condition as the medium and low bumpy cases.

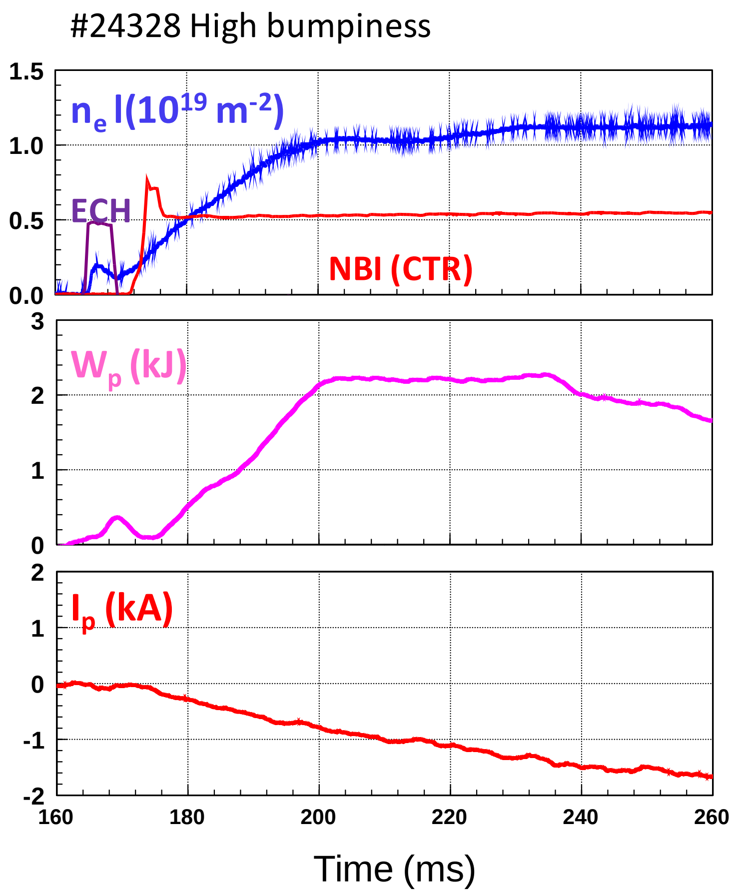


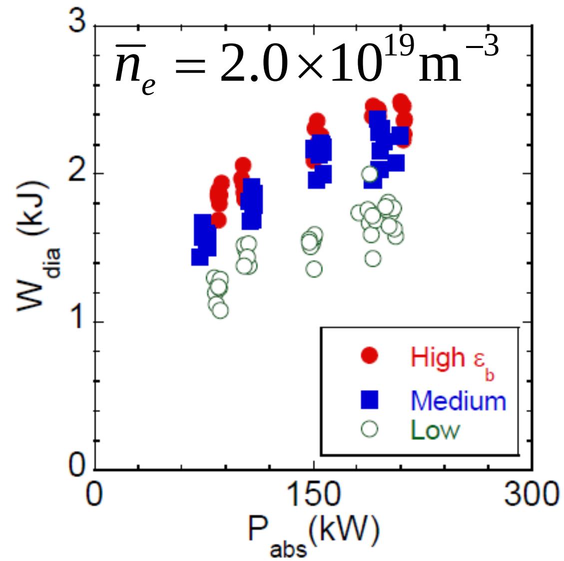


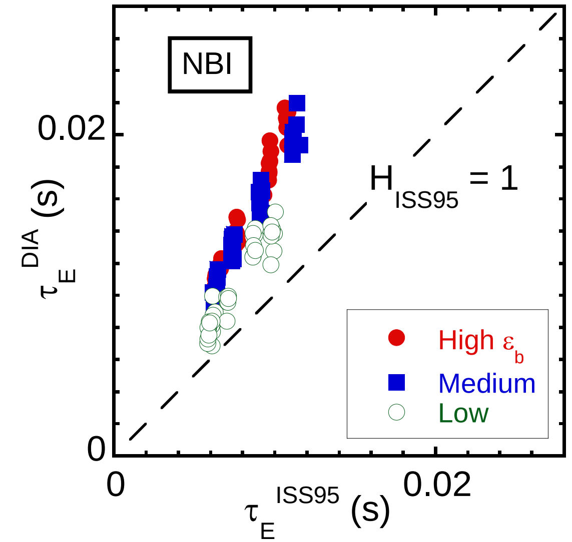
Bulk Confinement for NBI Plasmas

S. Kobayashi: I-16, Tomorrow

- The injection of NB is counter-direction.
- In NBI plasmas, the W_p of the high and medium bumpiness is higher than that in the low bumpiness.
- The enhancement factor of the energy confinement time for the ISS95 scaling is 1.8, 1.7 and 1.4 in the high, the medium and the low bumpy configurations.

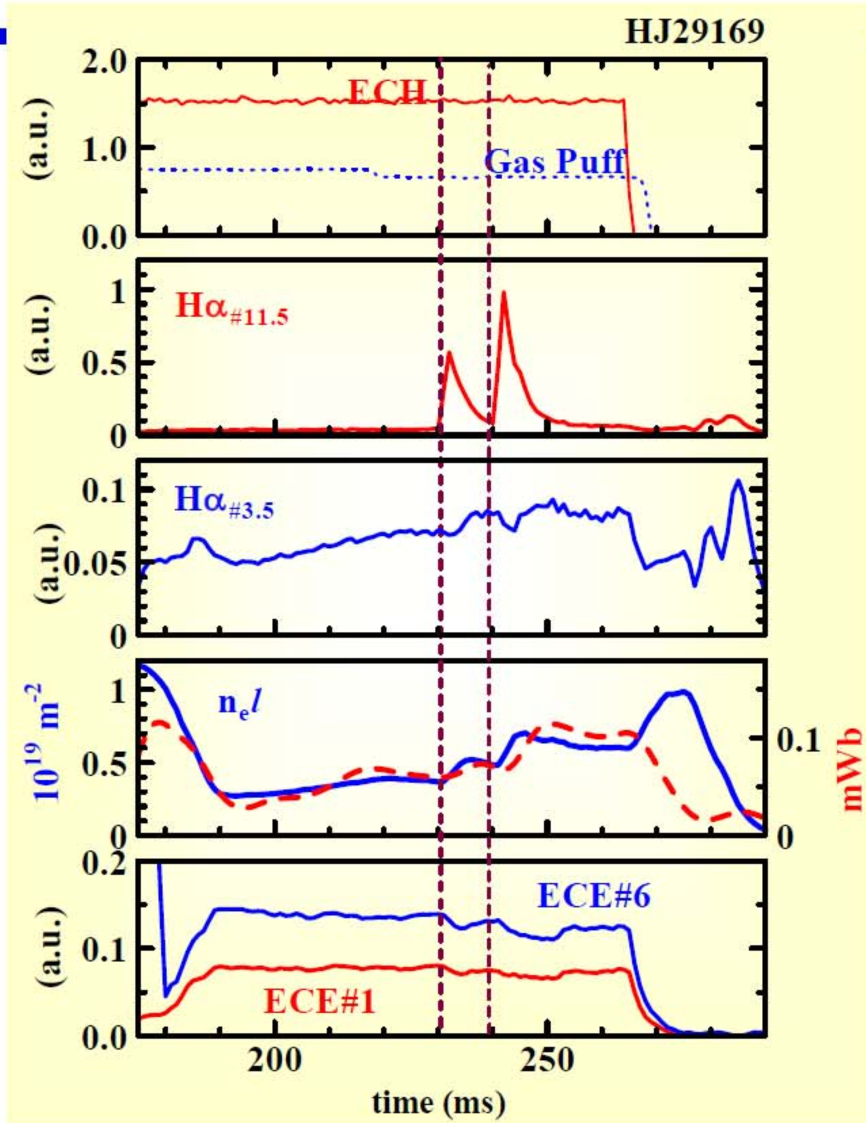


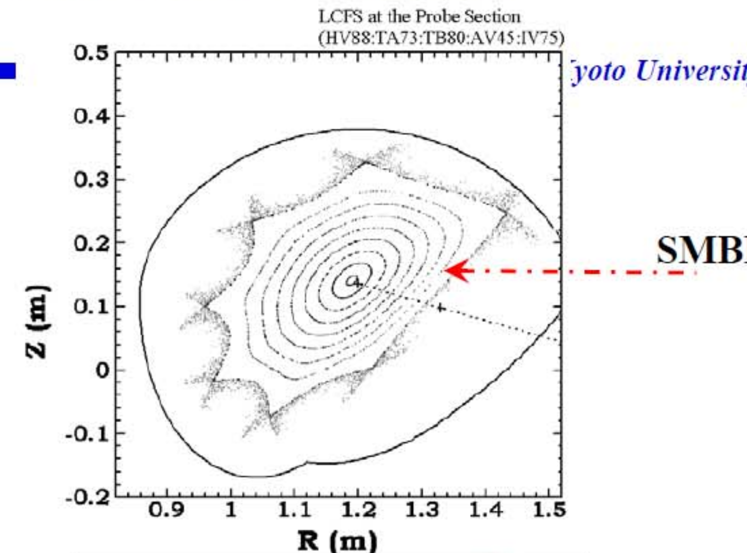


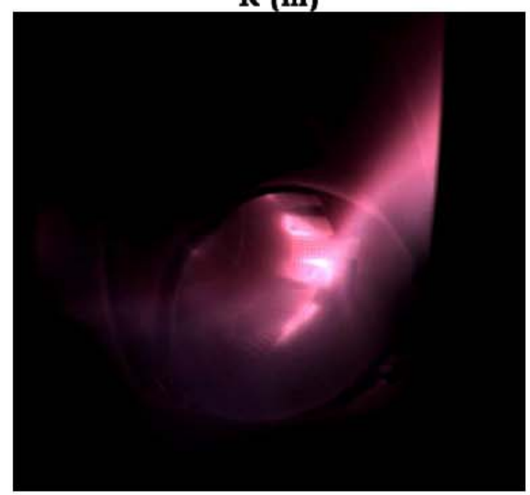


Example of SMBI Experiment in Heliotron J

two pulses of SMBI in to ECH Plasma



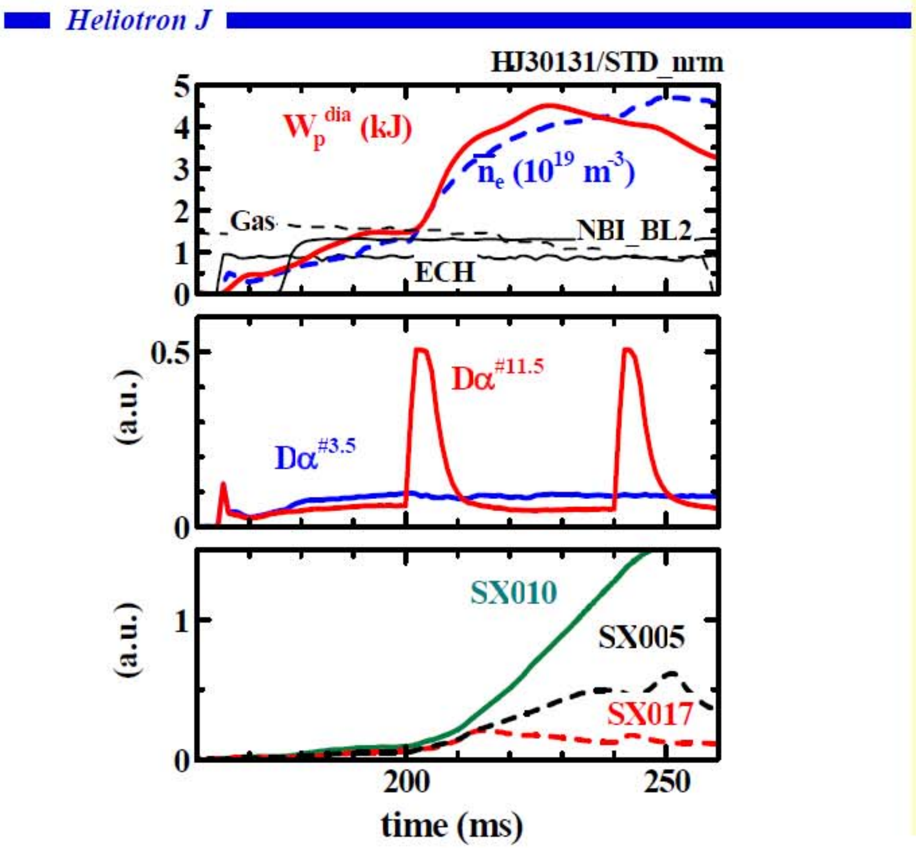


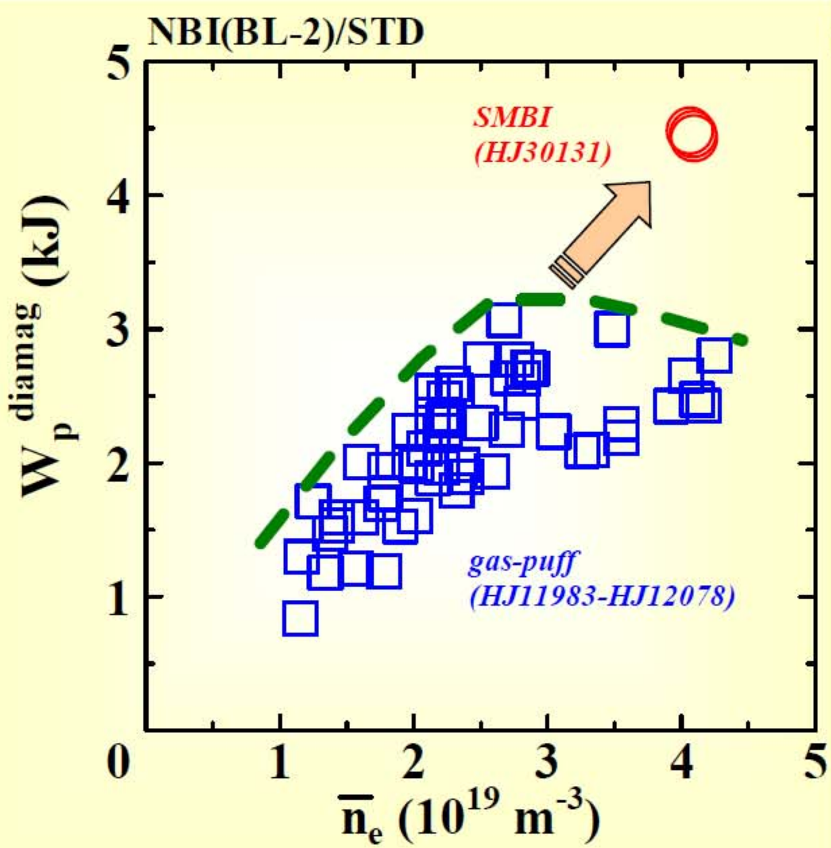


Tangential view of the injection section
250FPS, 1/5000

T. Mizuuchi: P2-16, Tomorrow

SMBI can expand the operation region of Heliotron J





- The stored energy reached ~ 4.5 kJ, about 50 % higher than the max. one achieved so far under the normal gas-puff fueling condition in Heliotron J.
  - ECH (~ 0.35 MW) and NBI (~ 0.6 MW)
- The optimization of this fueling method for Heliotron J is in progress.

Summary

- The effect of the bumpy component on energetic ion distribution in velocity space has been investigated using ICRF heating in the minority heating. In the high bumpy case, the ion flux is measured up to 34 keV at the pitch angle of 120 deg. The observed tail is largest in the high bumpy configuration. It is most favorable for the fast ion formation and confinement.

- The bootstrap current and the electron cyclotron driven current are estimated experimentally by changing the confinement field direction. They can be controlled by changing bumpy field and the deposition location. By using the combination of these control knobs, the toroidal current can be changed from 2 kA to -4.5 kA.

- In ECH plasmas, the medium bumpiness is most favorable in the bulk confinement. This result is consistent with the effective helical ripple, ε_{eff}. However, in NBI plasmas, the plasma stored energy of the high bumpy case is somewhat higher than that in the medium bumpiness. It is supposed that the good confinement of the slowing-down ions causes the effective heating for the bulk plasmas.

- SMBI experiment is started. It extends the operation region and offers the optimization tool for the fueling.