Energetic particle transport in NBI plasmas of Heliotron J

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Outline

1. Introduction
2. Heliotron J device and configuration characteristics
3. Fast ion transport induced by
   energetic-ion-driven MHD activities
4. Summary

Acknowledgements

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Introduction (1)

Physical Issues in energetic particle confinement for reactor

- Good energetic particle confinement is required for self-ignition

\ Reduction in trapped particle loss by tailoring magnetic configuration

- Interactions between energetic ions and fast-ion-driven MHD activities

\ Study the behavior of anomalous transport of energetic ions

*** Mechanisms of fast-ion losses in tokamak AEs have been discussed[1,2]**

Dependence of radial transport of the fast-ion on magnetic fluctuations

Direct measurement of lost fast-ions

1. Scintillator-based lost fast-ion probe (LIP)[3-6]

2. Directional Langmuir probe (DLP)[7]

- In CHS[7], a hybrid directional Langmuir probe (HDLP) system has been applied for lost-ion measurements in Alfvénic modes (TAE, EPM).

\ Fast ion behavior inside and outside LCFS

[1] E.M. Carolipio, et al., POP **8**, 3391 (2001).[2] W. W. Heidbrink, POP **15**, 055501 (2008).
[3] D.S. Darrow et al, J. Plasma Fusion Res. Ser. **1** 362 (1998). [4] M. Isobe et al., NF **46** S918 (2006).
[5] A. Werner et al., Proc 27th EPS Conference Budapest, 2000 ECA Vol. **24B** (2000) 988.
[6] A. Weller, et al., POP **8** 931 (2001). [7] K. Nagaoka, et al., PRL. 100 065005 (2008).

Introduction (2)

In shearless helical/stellarator configurations.

Global Alfvén eigenmode (GAE) is a candidate of most unstable mode

- **Observation in Heliotron J[8] and W7-AS[5,6],**
- **Lost fast-ion measurement in W7-AS using LIP[5]**

In Heliotron J,

- Observed GAE has a dependence on magnetic configurations.
***Strong bursting GAEs appeared under the condition where the energetic particle confinement was fairly good.**

- Recently, HDLP system is installed into Heliotron J[9] to investigate
- **Anomalous fast-ion transport through the consequence of the interaction with GAE**
- **Response of fast-ion transport to mode amplitude and its radial structure**

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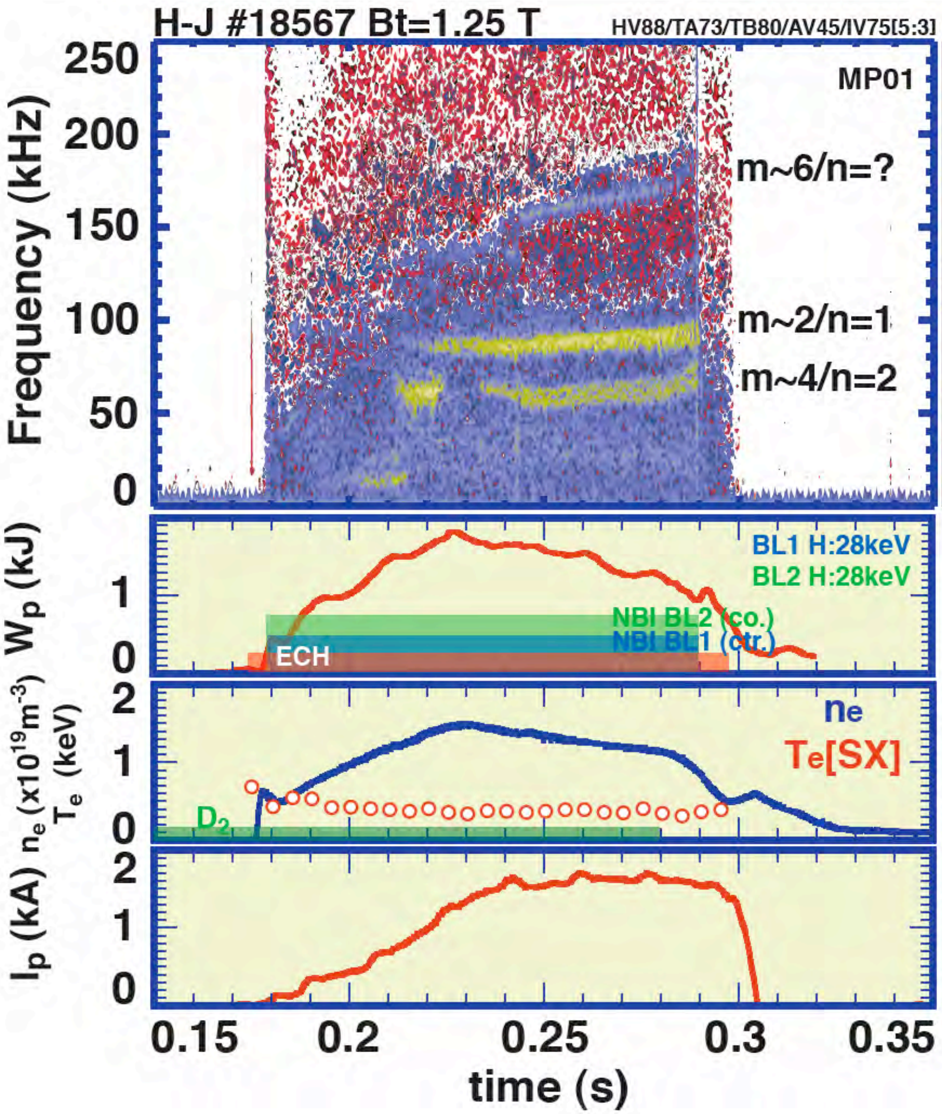
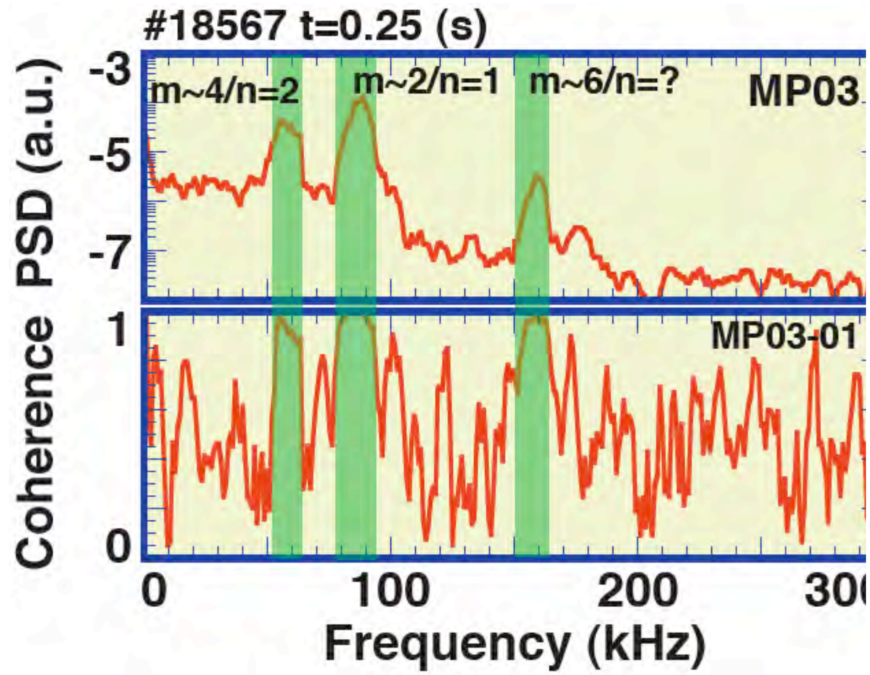
[8] S. Yamamoto, et al., Fusion Sci. Tech., **51**, 93 (2007).
[9] K. Nagaoka, et al., Proc. Int. Cong. Plasma Phys. 2008 (2008) BEH.P2-156.

Coherent magnetic fluctuations in NBI plasmas

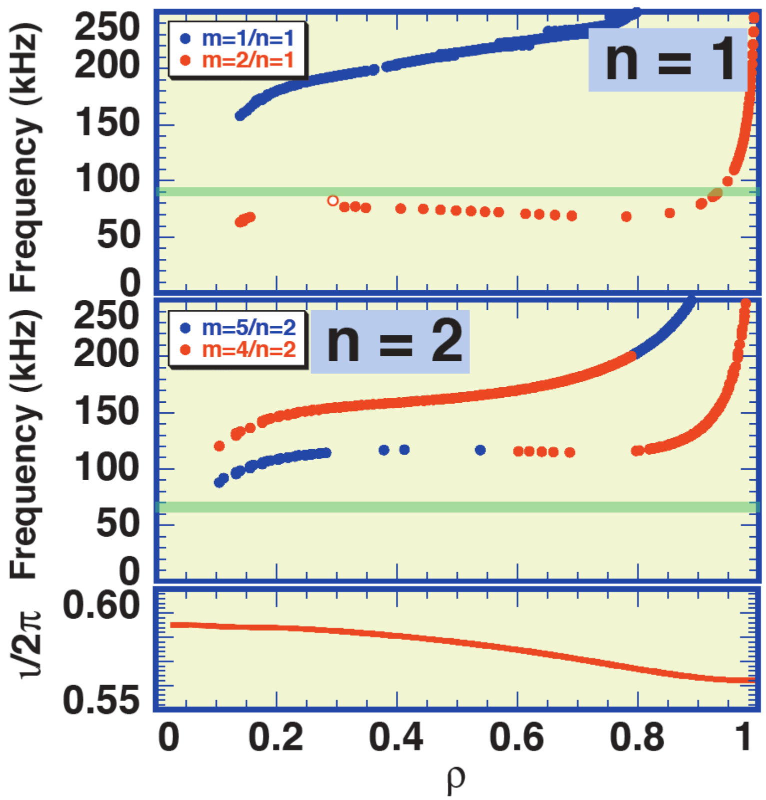




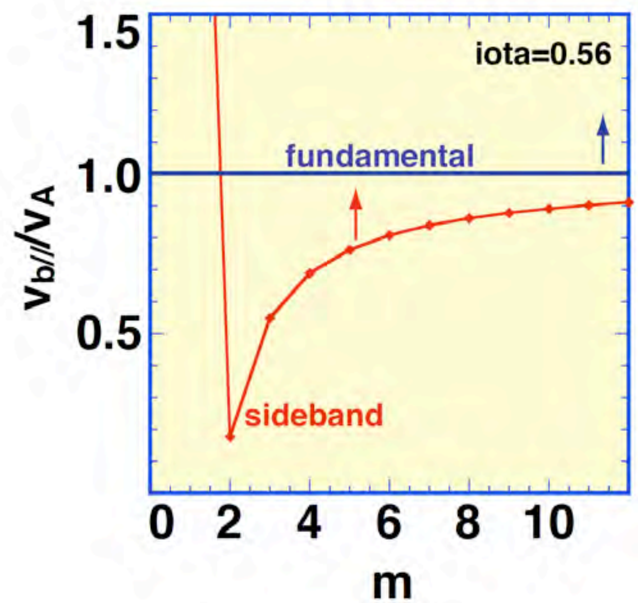
- After t = 0.21 s, the coherent magnetic fluctuations having the frequencies f_{exp} = 50~200 kHz and m~2/n=1 and m~4/n=2 a observed.
- The observed modes propagate in the diamagnetic drift direction of energetic i
- Amplitude of the observed MHD instabilities are about $b_\theta/B_t \sim 10^{-6}$.

Shear Alfvén spectra & resonance condition+

Shear Alfvén Spectra (n = 1, 2)



Resonance conditions for n = 1 GAEs



⎱We compared the observed frequencies with shear Alfvén spectra using CAS3D3* (in 2D)

⎱The observed frequencies exist on above and below the shear Alfvén continua, respectively.

⎱Frequency of discrete mode agrees with that of observed mode (n = 1) ⎝ global AEs (GAEs)

⎱GAEs with m/n =2/1 have been observed under the resonance condit of $v_{b//}/v_A > 0.25$ by changing n_e

⎝ observed GAEs are excited via sideband excitation.

+S. Yamamoto, et al., FS&T, 51, p93 (200

* C. Nührenberg, Phys. Plasmas 6 p137(1

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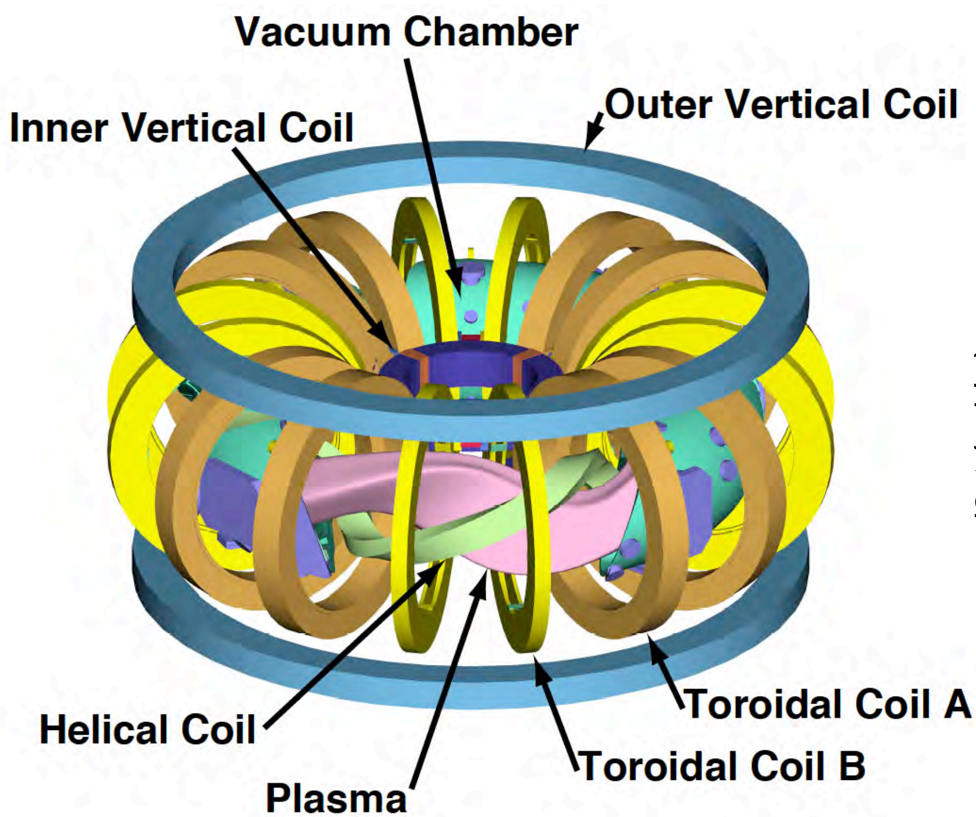
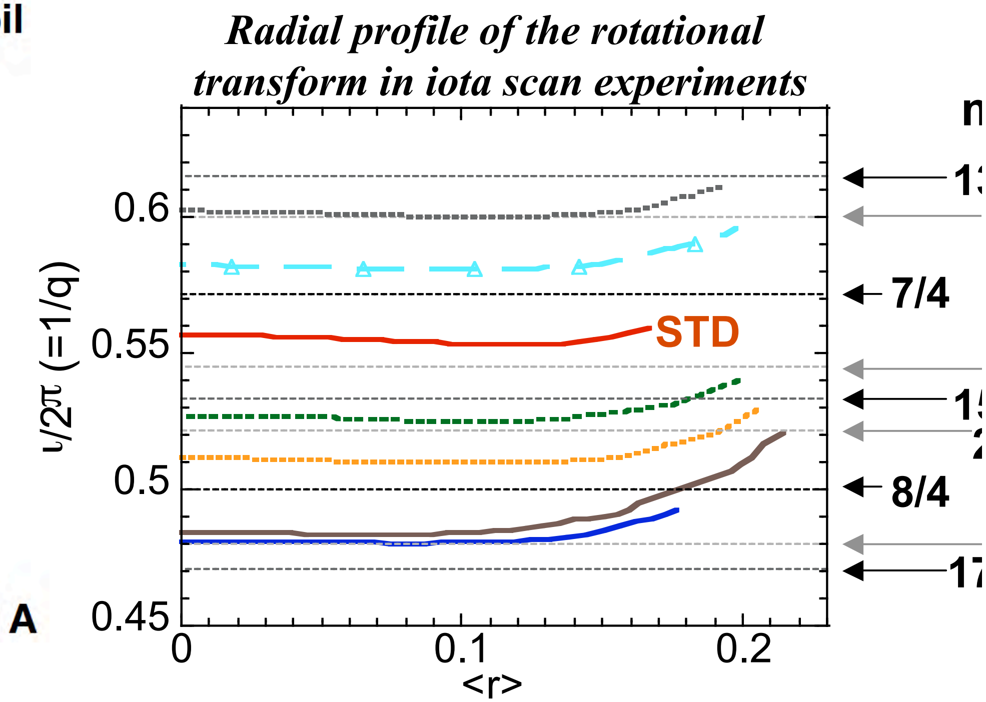
Heliotron J device and configuration characteristics

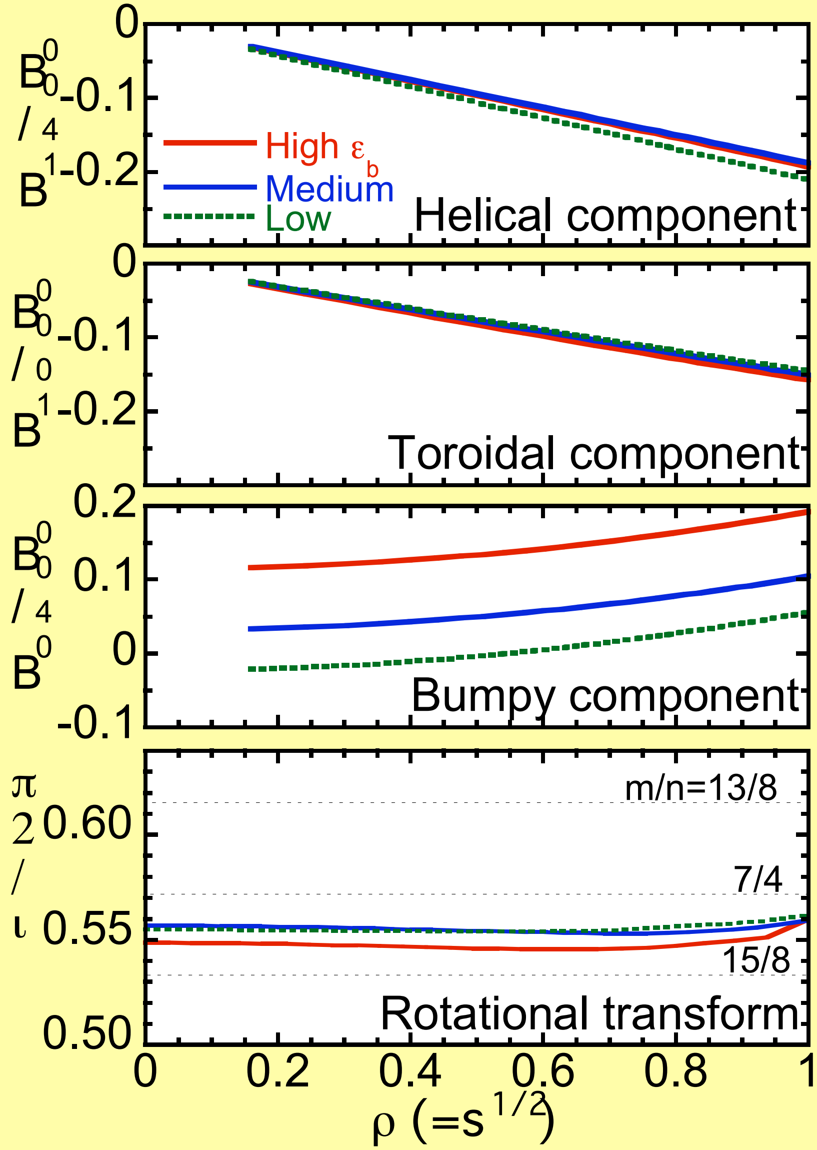




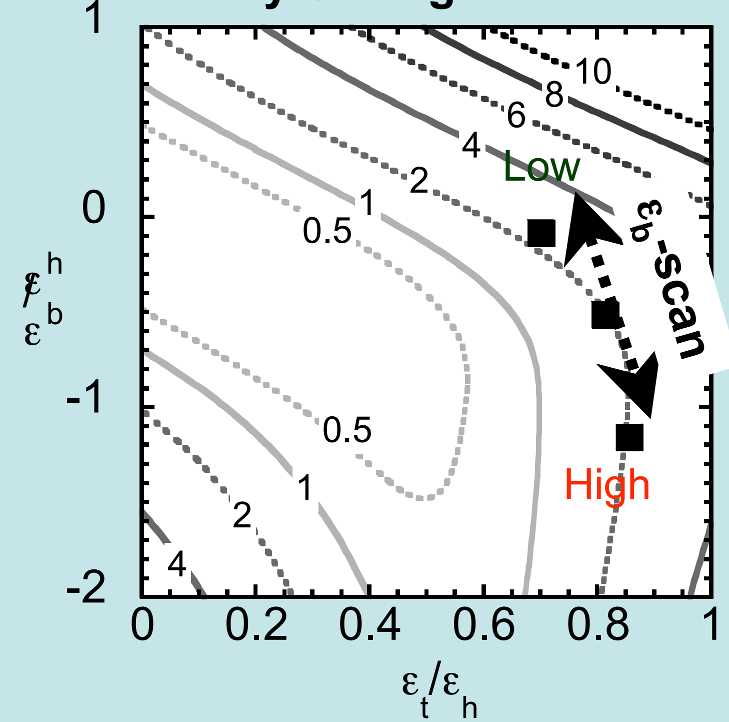
- R/a=(1.2/0.17m), L/M=1/4, |B| < 1.5T
- Low magnetic shear, (Δι/ι < 0.04), well (>0.5%),
- Configuration charcteristics can be controlled by changing the five sets of the coil curren
(Helical, Toroidal A (TA), Toroidal B (TB) and Two vertical coils (AV, IV)

Heliotron J device and configuration characteristics

Radial profile of field components and iota



Particle Flux in 1/ν regime by Shaing model



Config.	High ε_b	Medium	Low
R_{ax} in m	1.189	1.197	1.200
<a> in m	0.169	0.167	0.170
<B> in T	1.357	1.261	1.193
$\iota(a)/2\pi$	0.560	0.560	0.561
ε_b (2a/3)	**0.15**	0.06	0.01
ε_{eff} (2a/3)	0.22	**0.13**	0.26

ε_b control has an effect on energetic particle confinement

NBI

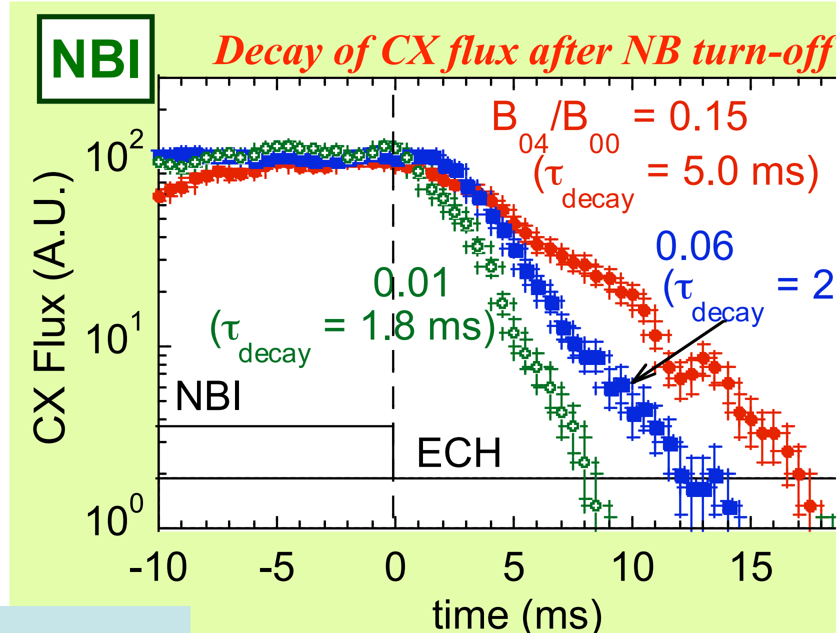
- Observation of decay of CX flux after NBI turn off in ECH sustained plasmas,

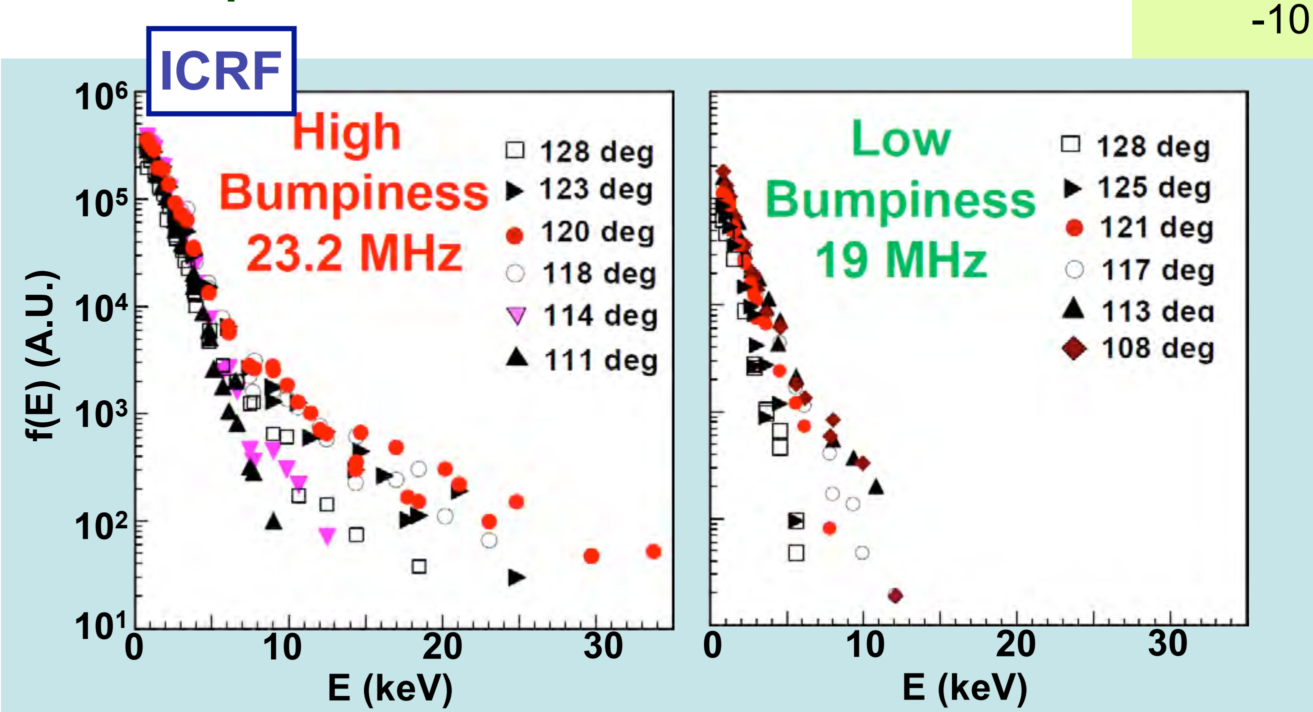
(E_{NB}=28kV & <λ_{NBI}> ~ 155 deg.

∫ E_{CX}=18kV & λ_{pitch}~130deg.)

- n_e=0.8x$10^{19}$$m^{-3}$

\ 1/e decay time becomes longer as bumpiness increased



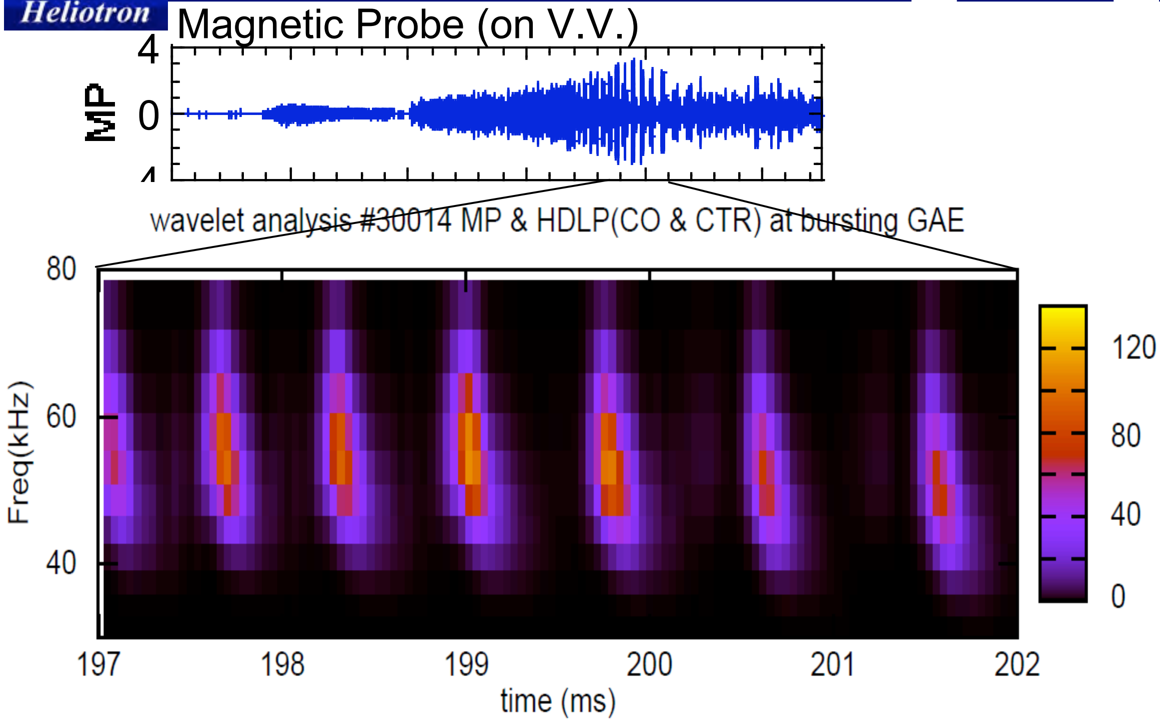


ICRF

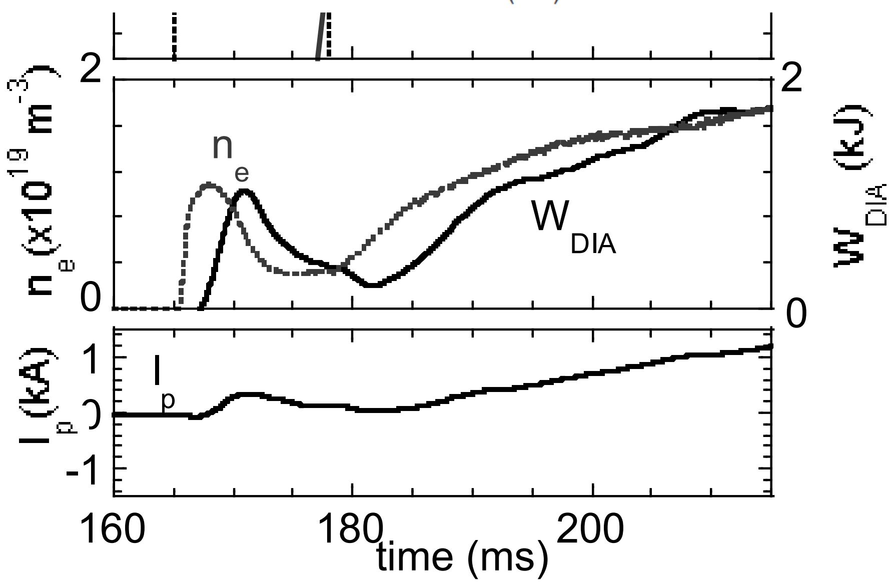
- In high bumpiness case, high energy ion flux is measured up to 34 keV.

(H. Okada, et al., in this conference)

Bursting GAEs in Heliotron J ($\iota(a)/2\pi = 0.54$)



ɾrence of Bursting GAE in NB heated
ꞩ (#30014)
m ε_b ($I_{TA}:I_{TB}$ = 5:2), $\iota(a)/2\pi = 0.54$
V_{ACC} = 23kV, P_{NBI} = 570kW
Deuterium
al Beam : Hydrogen
7 x $10^{19}m^3$, T_i ~ 300eV
~ 0.5 (> 0.2 : m/n=2/1 sideband excitati



- The frequency of GAE chirps down quickly from 70 to 40kHz.
- m/n =2/1 mode propagates in the ion diamagnetic drift direction.

*Note that no strong bursting GAEs have beer observed in the low bumpiness configuration.

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

Targets

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

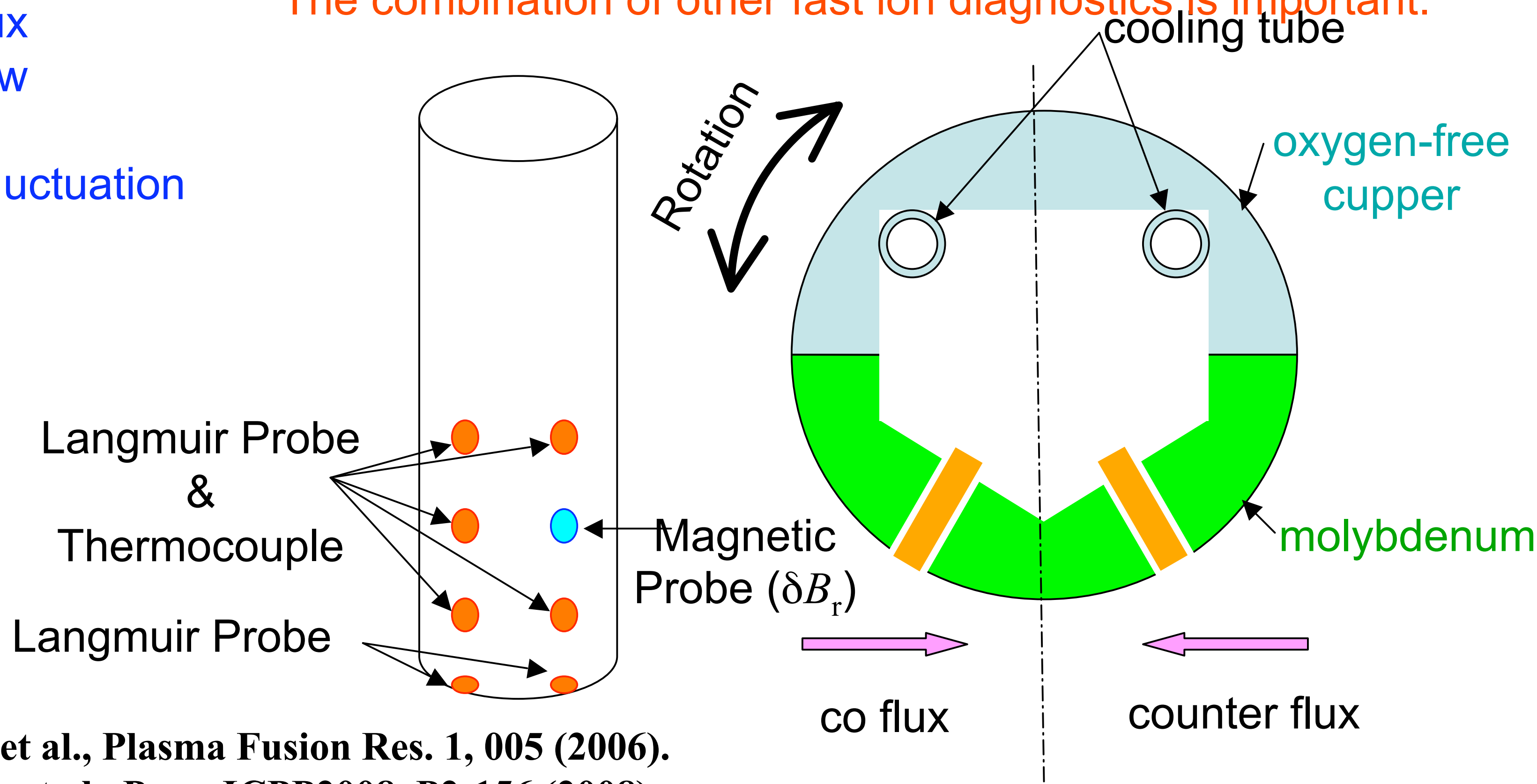
Advantages

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

Disadvantages

- No Energy spectrum （NPA,
- Less Pitch angle resolution （

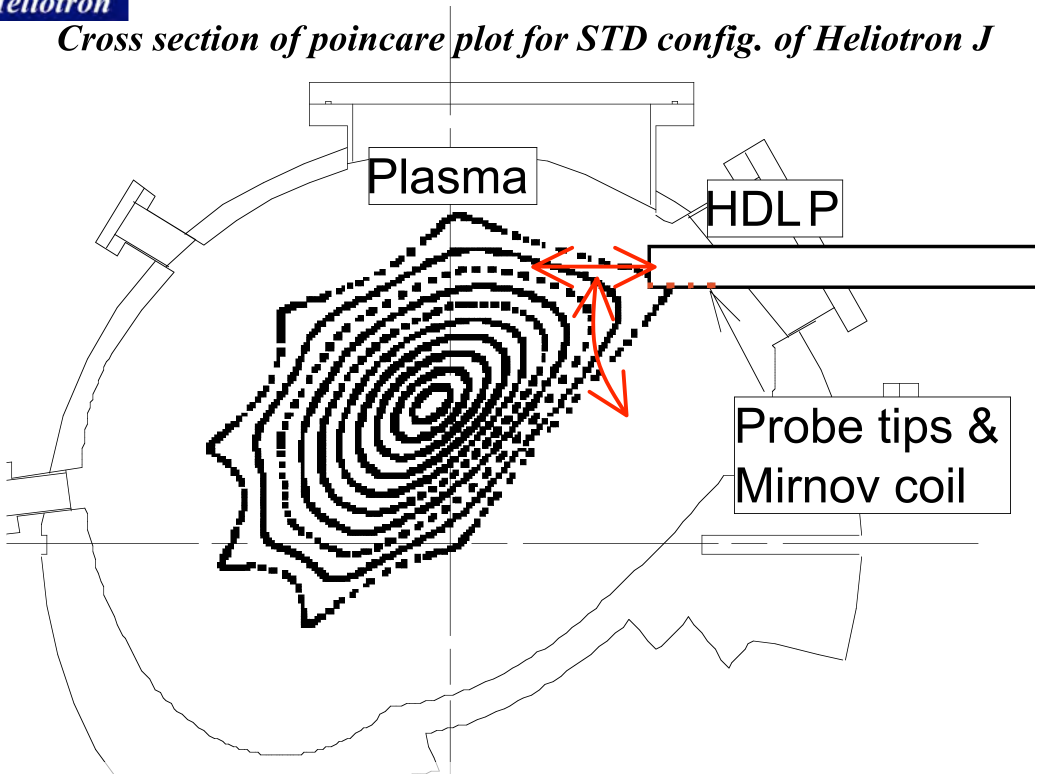
The combination of other fast ion diagnostics is important.



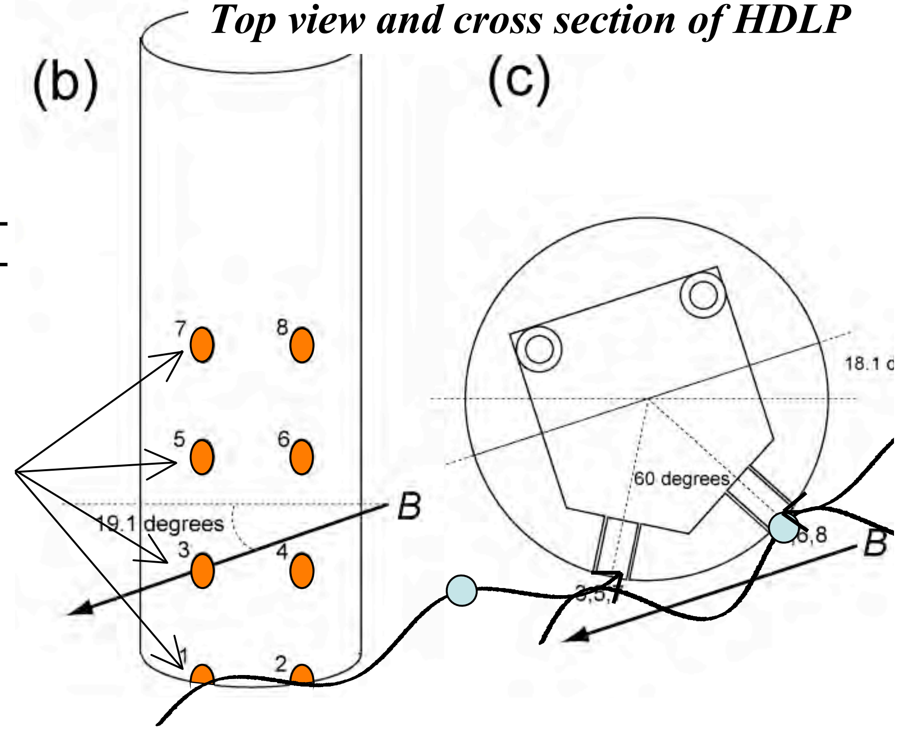
***K. Nagaoka, et al., Plasma Fusion Res. 1, 005 (2006).**
****K. Nagaoka, et al., Proc. ICPP2008, P2-156 (2008).**

Hybrid Directional Langmuir Probe installed in Heliotron J*

Cross section of poincare plot for STD config. of Heliotron J



Top view and cross section of HDLP



- Simultaneous measurements of particle and heat fluxes (equipped TC)
- Enable to change insertion depth and poloidal angle (0 to -5 deg.)
- Probe angle in z-ϕ plane is flexible (set angle 20 degrees in this experiment).

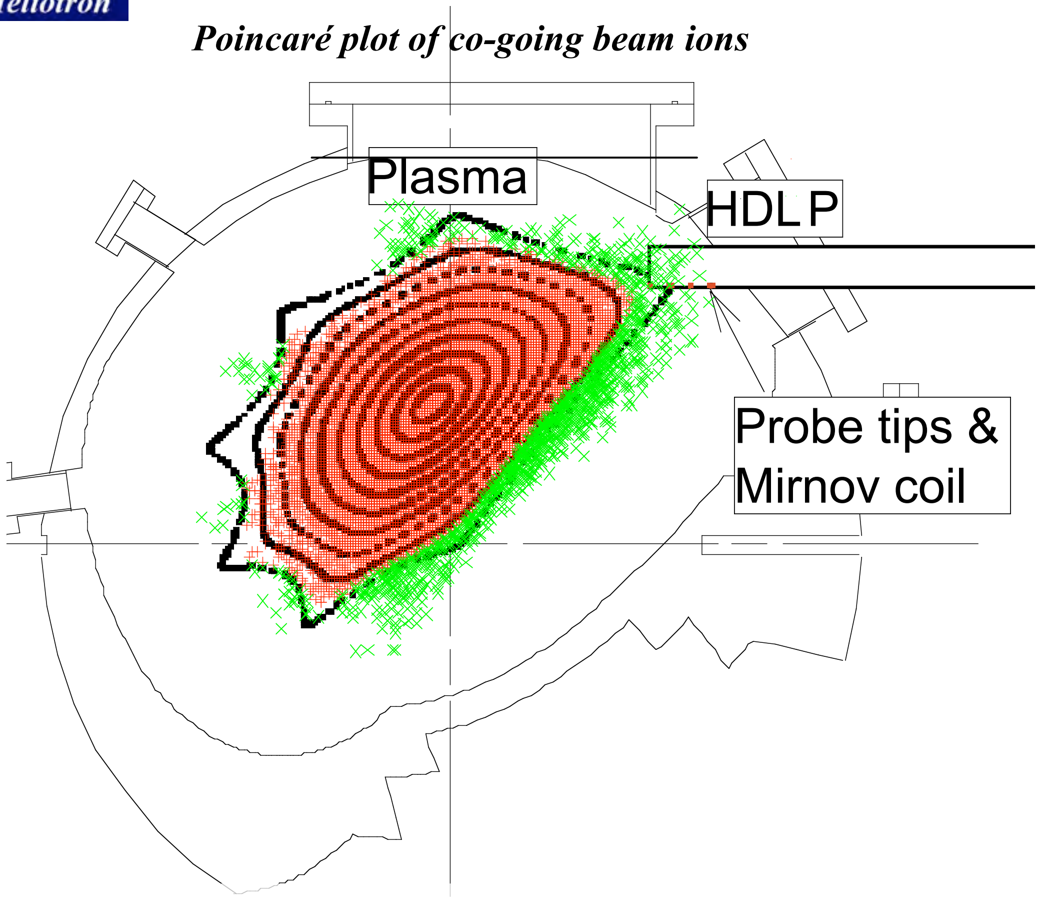
  | To align HDLP probe tips to magnetic field
- Almost separate Co- and Ctr-going ion fluxes, however, some highly and vertically accelerated particles are still detectable with the opposite side probe

*K. Nagaoka, et al., Plasma Fusion Res. 1, 005 (2006).

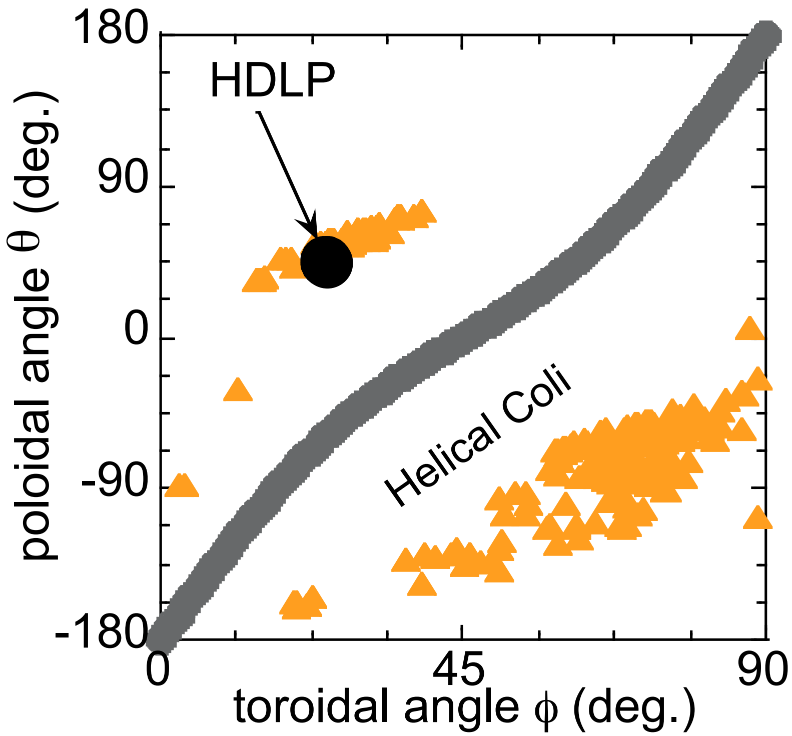
**K. Nagaoka, et al., Proc. ICPP2008, P2-156 (2008).

Collisionless orbit calculation for beam ions.

Poincaré plot of co-going beam ions



Footprints on vacuum wall of Co-injected beam io

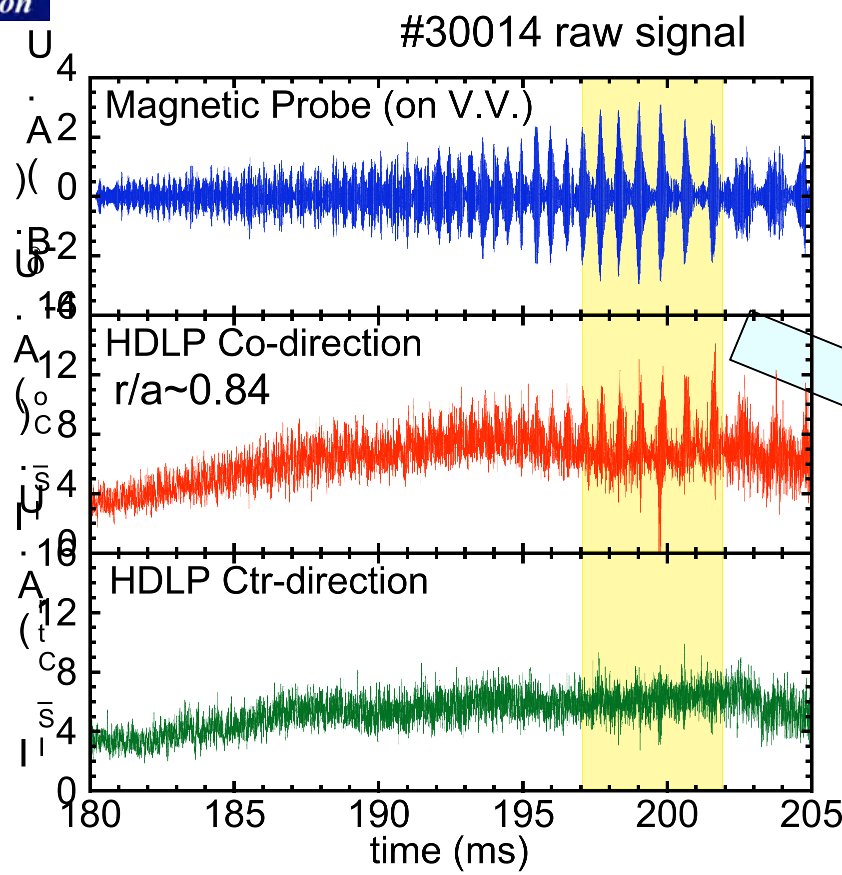


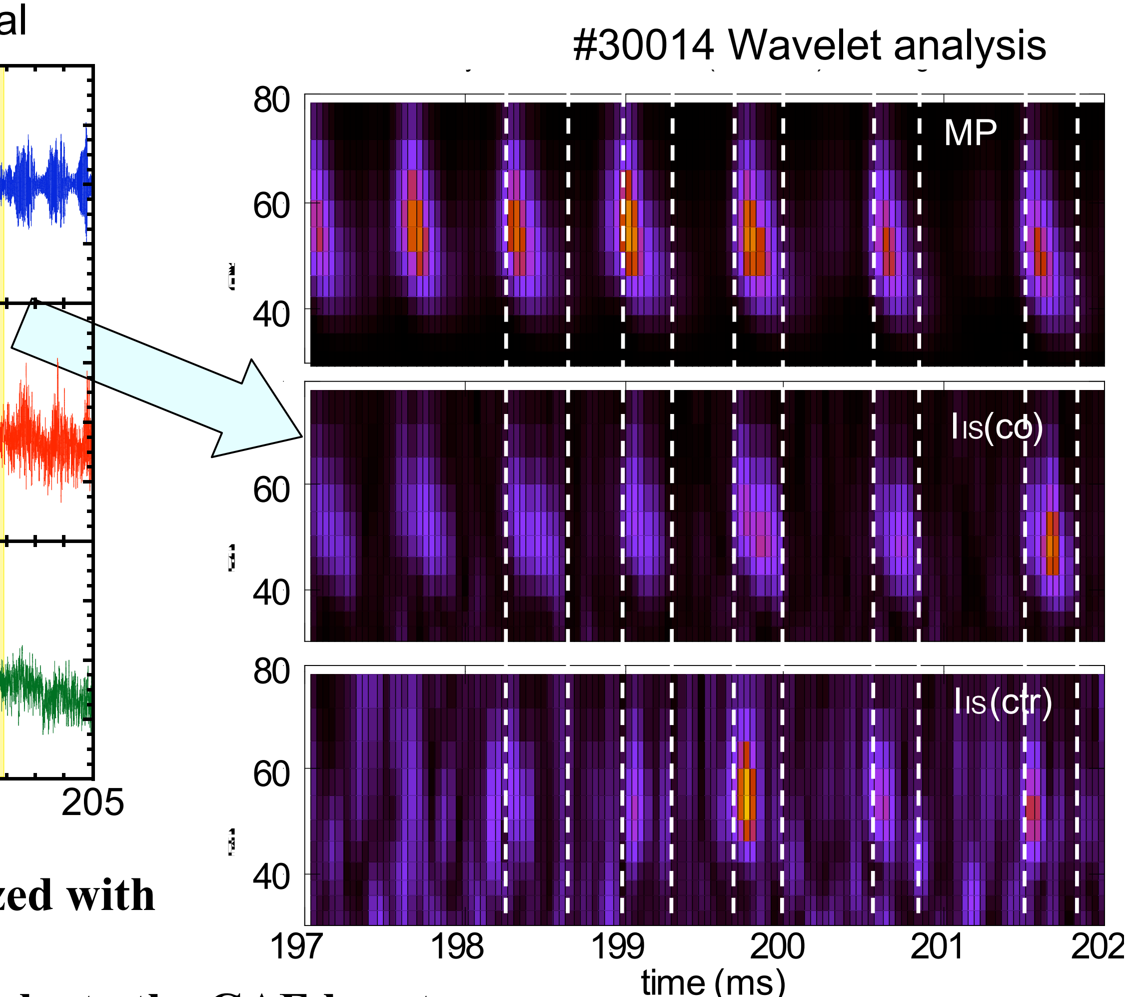
- **Poincaré plot of Co-injected beam ions at the cross section of HDLP on the cross section at HDLP installation position.**
- **Capable to measure both Co-injected beam ions and lost ions to wall.**

  Usable for measuring heat flux of re-entering particles.*

**** K. Nagaoka, et al., Rev. Sci. Inst., 79 10E523 (2008).**

Bursting GAEs in Heliotron J ($\iota(a)/2\pi = 0.54$)

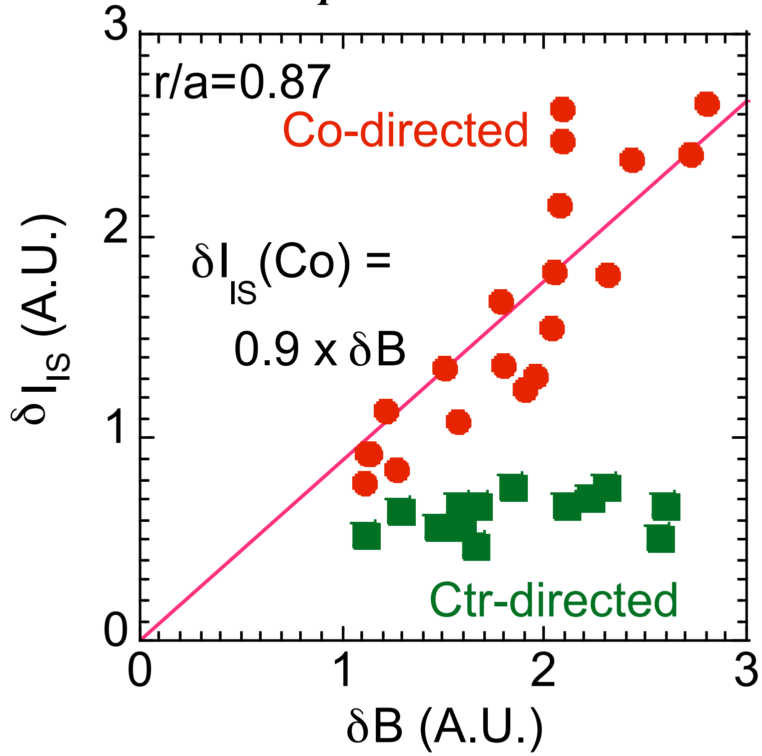




- Observation of ion fluxes synchronized with GAE burst using HDLP.
- Sensitive response in Co-directed probe to the GAE bursts.
  (High coherence > 0.8 during bursts)
- Small response (~1/5) of CTR-directed probe in growth phase of burst
  (disappeared quickly after peak of magnetic fluctuation) \ before re-distribution of fast ions
- No significant oscillation of fast ion flux outside LCFS

Dependence of fast ion flux on mode amplitude

Fast ion flux as a function of mode amplitude in GAE burst



- **Comparison of amplitude between ion flux (δI_{IS}) at Co-directed probe and magnetic probe signal (δB_{Θ} :mounted on V.V) during GAE bursts.**
- **For Co-directed probe, (δI_{IS}) increases with δB_{Θ} linearly.**
  \ indicates convective oscillation*

$$\tilde{\Gamma}_i = \frac{\partial \Gamma_{\text{fast ion}}}{\partial r} \cdot \tilde{\delta}_r = \frac{\partial n_{\text{fast ion}}}{\partial r} \cdot V_{\text{fast ion}} \cdot \frac{\tilde{B}_{\text{GAE}}}{B_{\text{t}}}$$

- **Correlation in Ctr-directed probe is not clear**

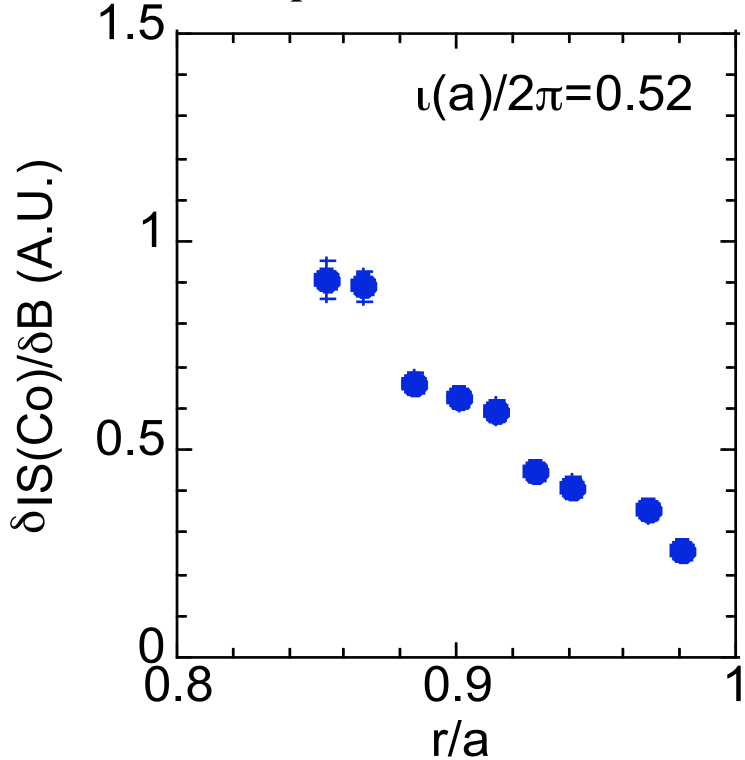
***K. Nagaoka, et al., Proc. ICPP2008, P2-156 (2008).**

Dependence of fast ion flux on mode amplitude

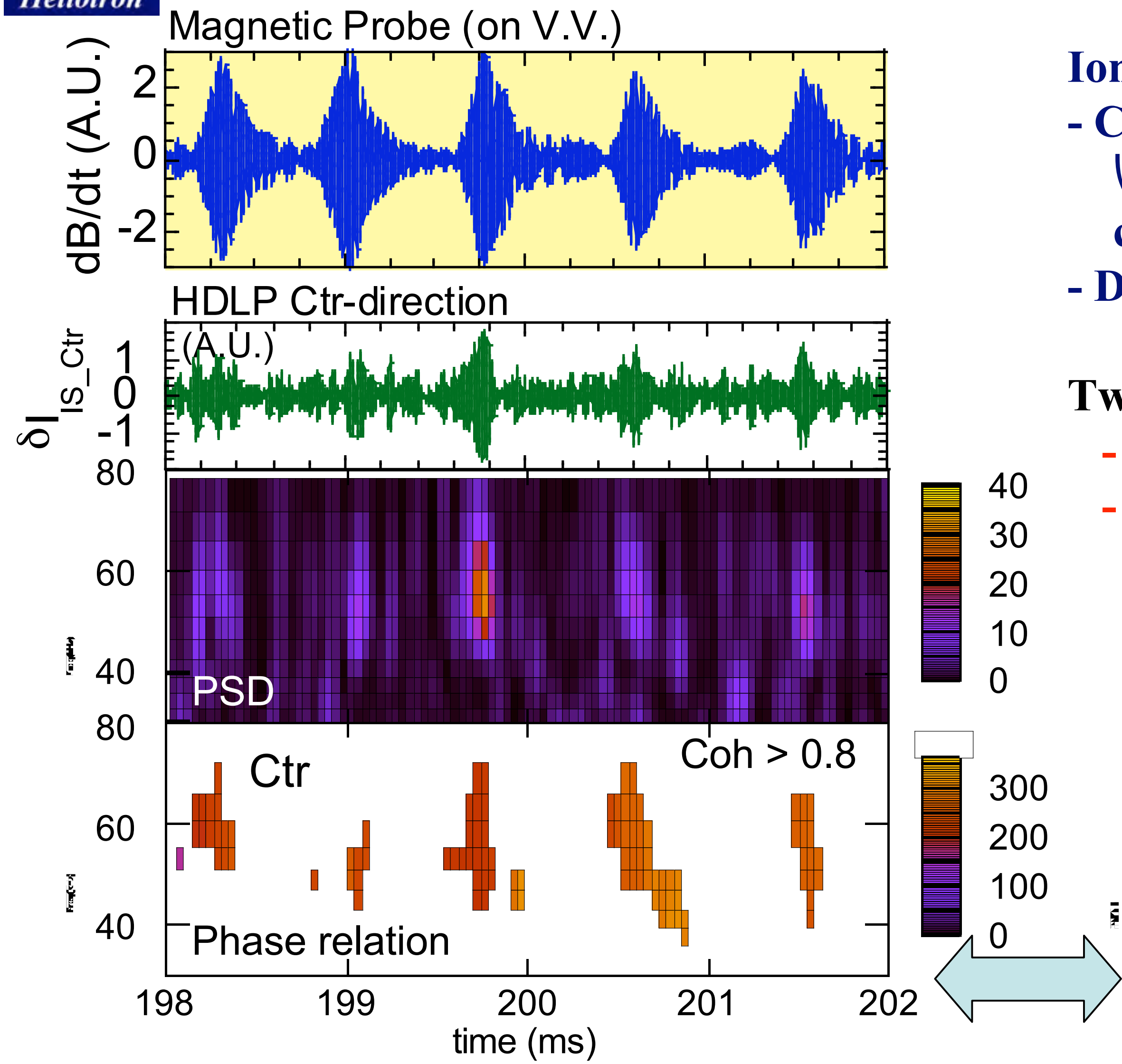
- Radial profile of fast-ion flux normalized by amplitude of magnetic fluctuation
- Fast-ion response decreases with minor radius.
- No significant fast-ion bursts outside LCFS

  ⇒ consistent with convective transport

Radial profile of normalized fast ion response in GAE burst



Characteristics of ion flux with Ctr-directed probe



Ion flux measured by Ctr-directed probe

- Clear response in growth phase of burst

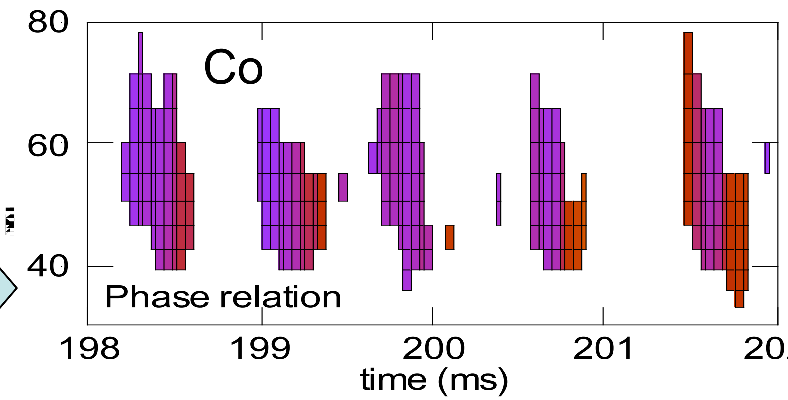
\ Under a high beam-ion pressure condition before re-distribution of fast

- Different phase from MP and Co-ion flu

Two candidates for cause of bursting ion

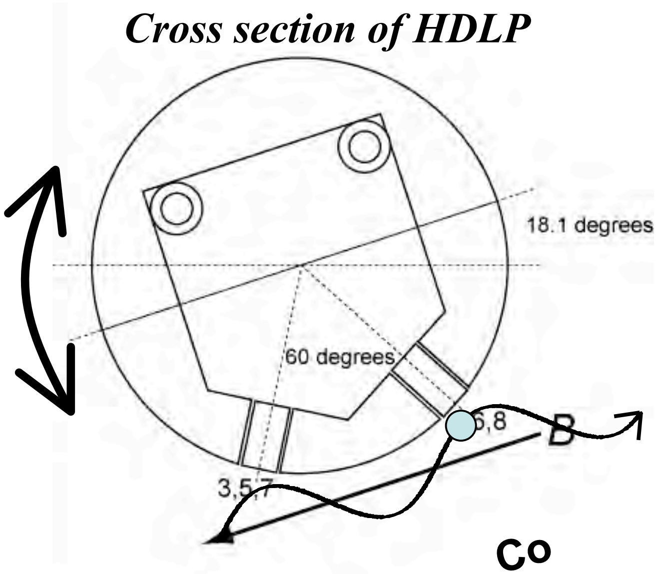
- Resonant oscillation of bulk-ions

- Pitch angle scattering of fast-ions



Characteristics of ion flux with Ctr-directed probe

Cross section of HDLP



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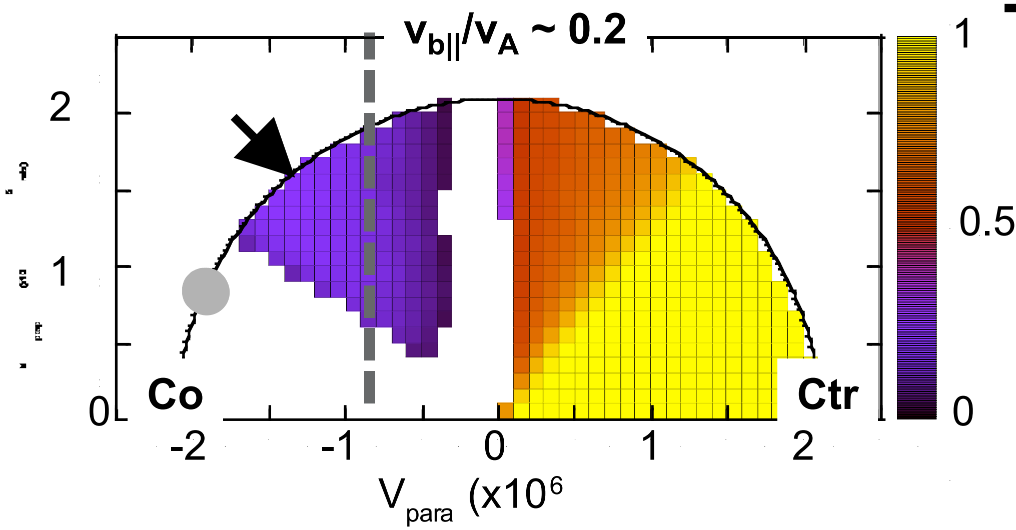
Detectable velocity space for HDLP



In this condition, Ctr-directed probe has a small sensitivity to Co-going high energy particles with peculiar pitch angle. (20% of 23keV ions with pitch angle of 130 deg.)

In that case, pitch angle of injected beam ions are around 160 deg.
\ satisfying resonance condition of m/n=2/1 through sideband excitatio

Summary

We investigated ion transport due to Global Alfvén Eigenmode in NBI plasmas of Heliotron J.

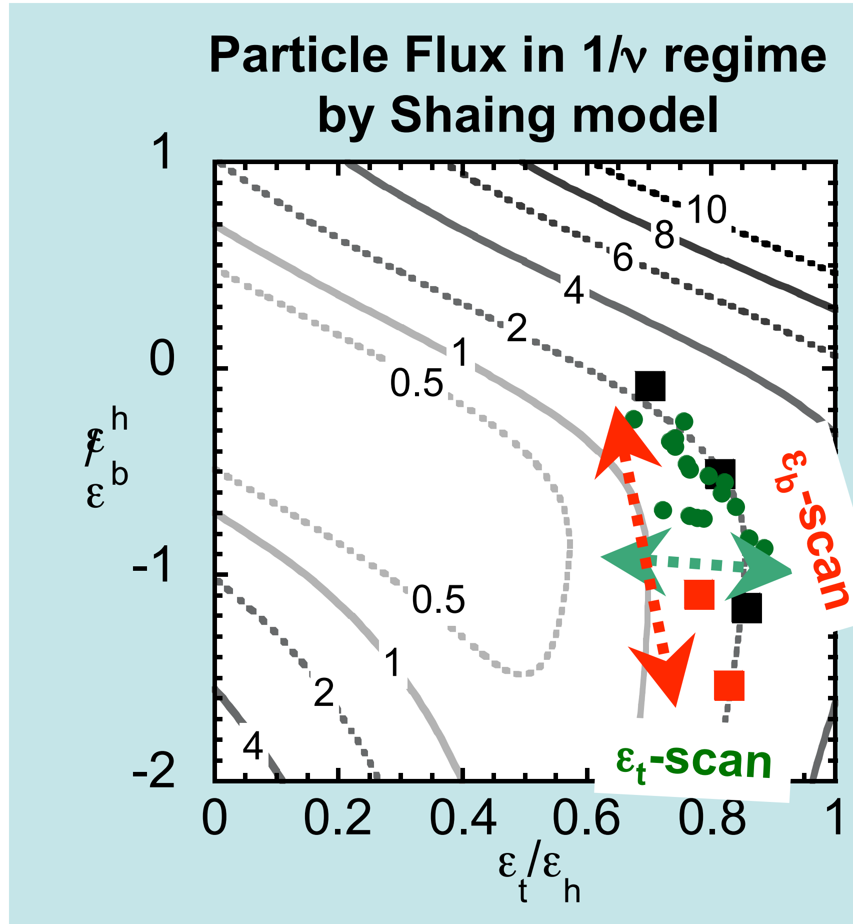
- Bursting GAEs were observed in NBI plasmas of Heliotron J under the configurations that the energetic particle confinement was fairly good.
- In the case of edge rotational transform of 0.54, the GAE frequency chirped down from 70-40kHz with m/n=2/1 mode under the condition of $v_{b//}/v_A \sim 0.5$, which was expected to be excited by the sideband excitation.
- Co and Counter directed ion fluxes under GAE bursts have been observed with HDLP…

Enable direct measurement of the resonant ion transport inside LCFS

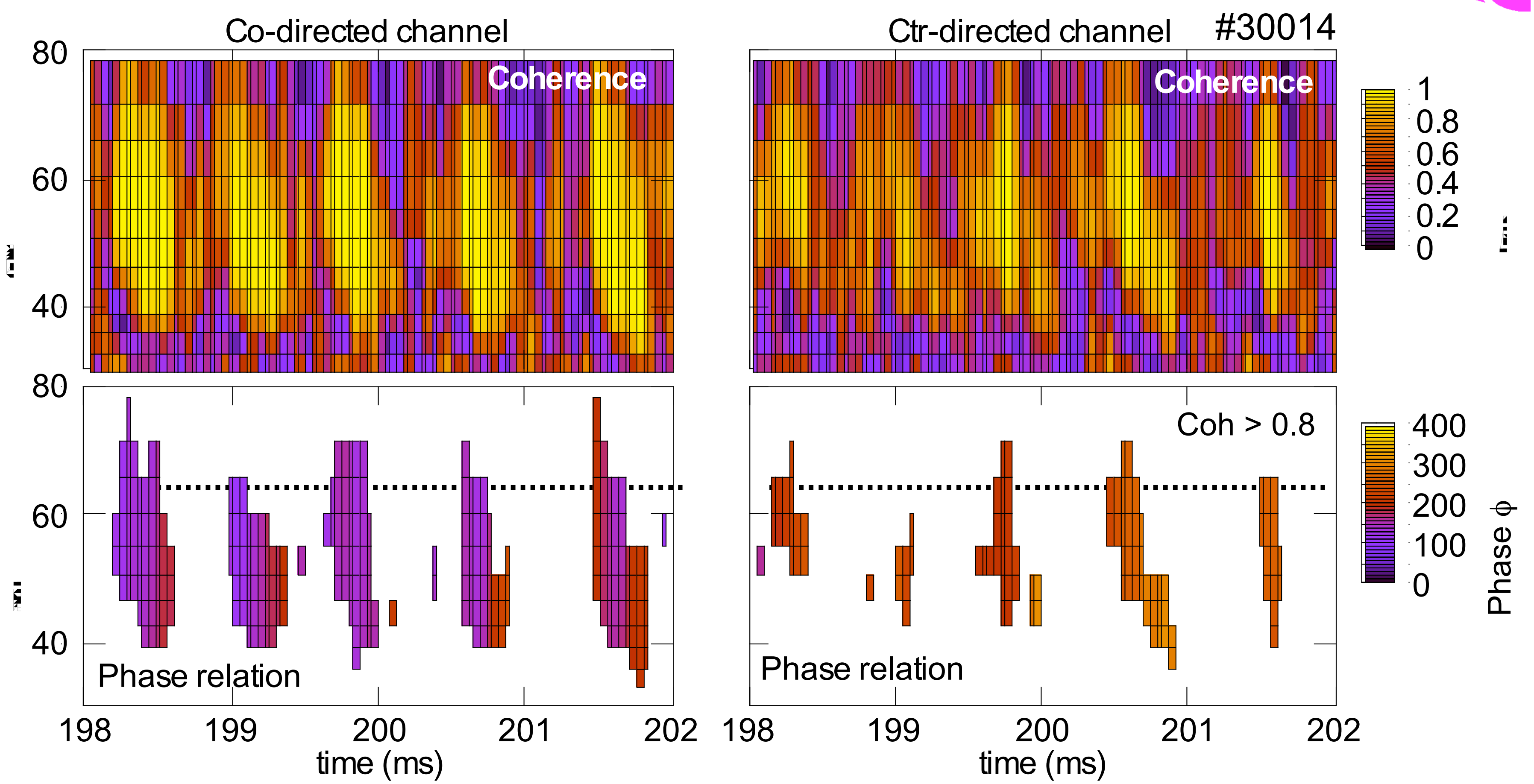
- The amplitude of the co-directed signal is proportional to δB, considered to be convective resonant transport.
- while that of the ctr-directed probe, high coherent oscillation was observed in the earlier phase of GAE bursts, indicating ion-flux transport before the re-distribution of fast ion due to GAE.
- In order to understand the phenomena, further experiments and measurements are required. i.e. velocity distribution measurement

Extend configuration in ε_b-ε_t space

- Control of Fourier component is key issue for energetic particle (Neo-classical) confinement
  \ extend operation space in bumpiness (ε_b) as well as toroidicity (ε_t)
  \ progress optimization



Difference in phase relation both Co&Ctr fluxes to GAE bursts



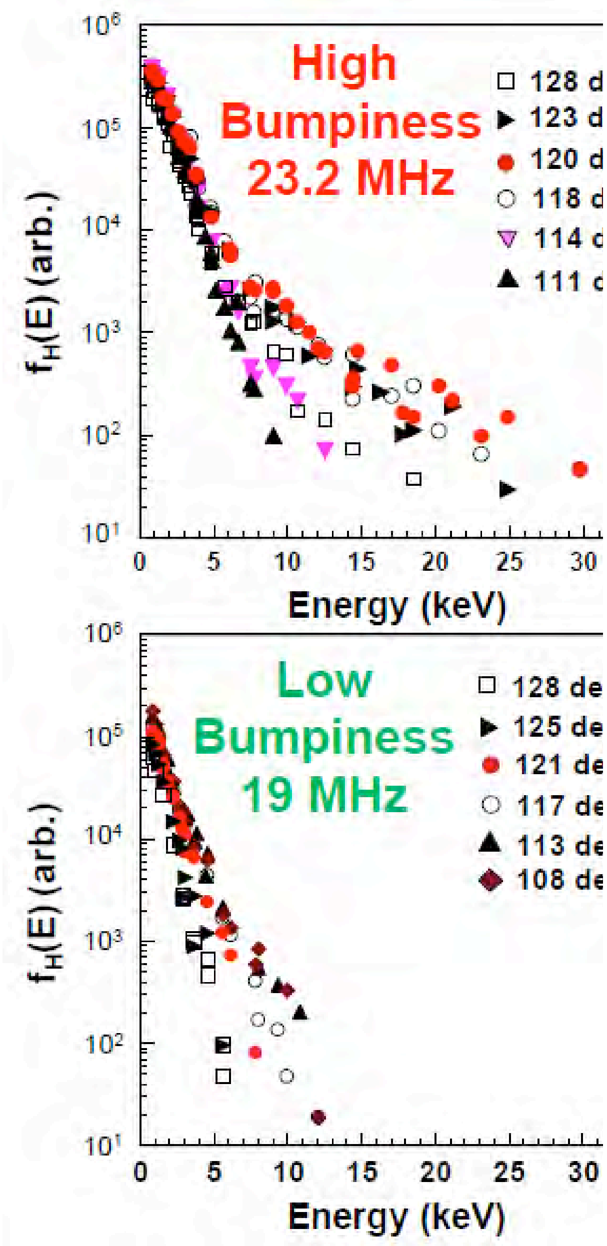
- Phase relations of Co- and Ctr-ion fluxes to GAE bursts (Mirnov signal on V.V)
- Phase of two signals are different from GAE bursts and each other
  (Co : ϕ ~ 90-180 deg, Ctr : ϕ ~ 200-270 deg)

Effectiveness of ε_b (in ICRF plasmas)

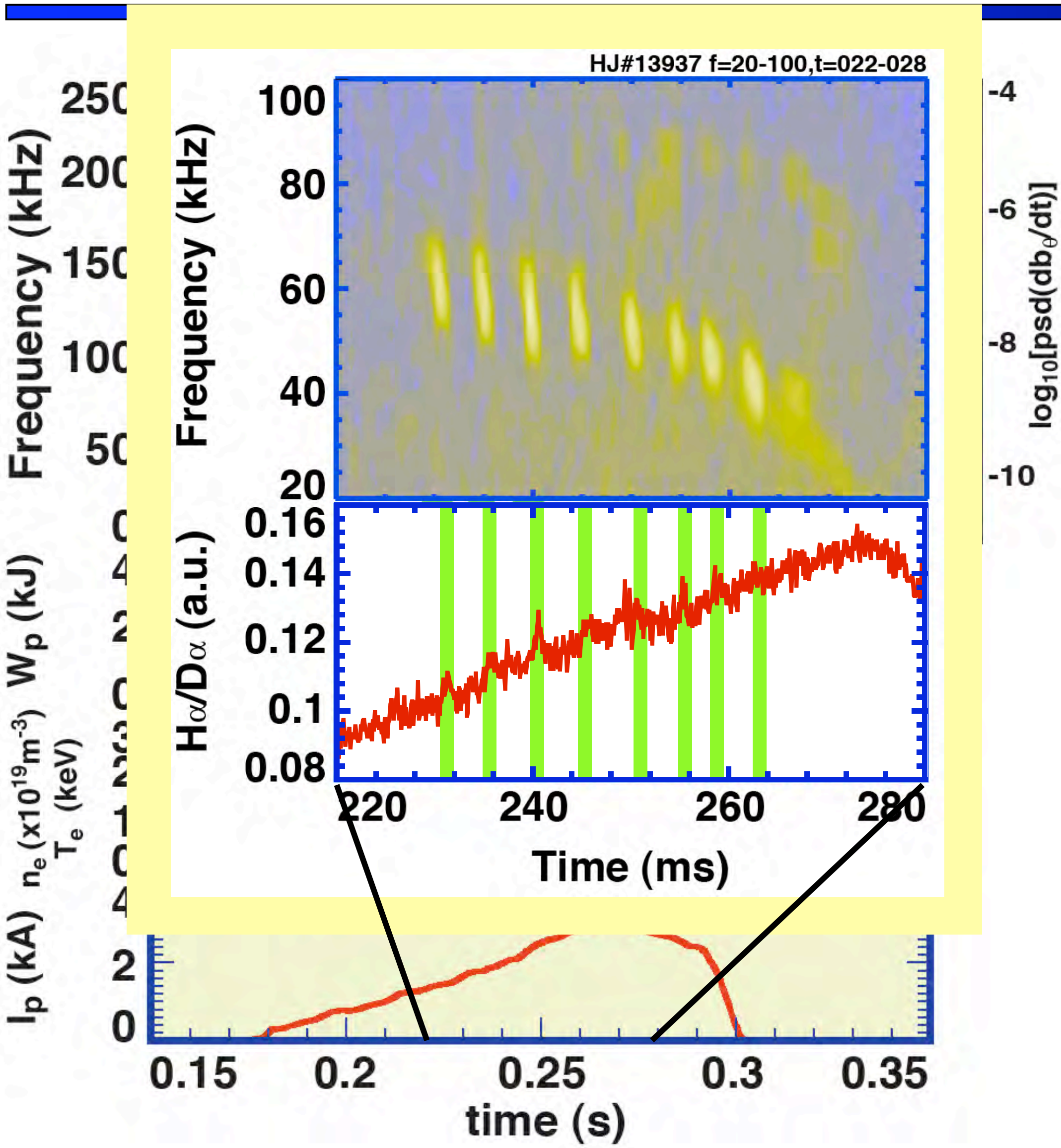
An ICRF pulse of 23.2 MHz or 19 MHz is injected into an ECH target plasma where *T*i (0) = 0.2 keV, *T*e (0) = 0.8 keV and = 0.4 x 1019 m-3. ICRF injection power is 250-300 kW.

• 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.



Observation of bursting GAE in high ε_b configuration[+]



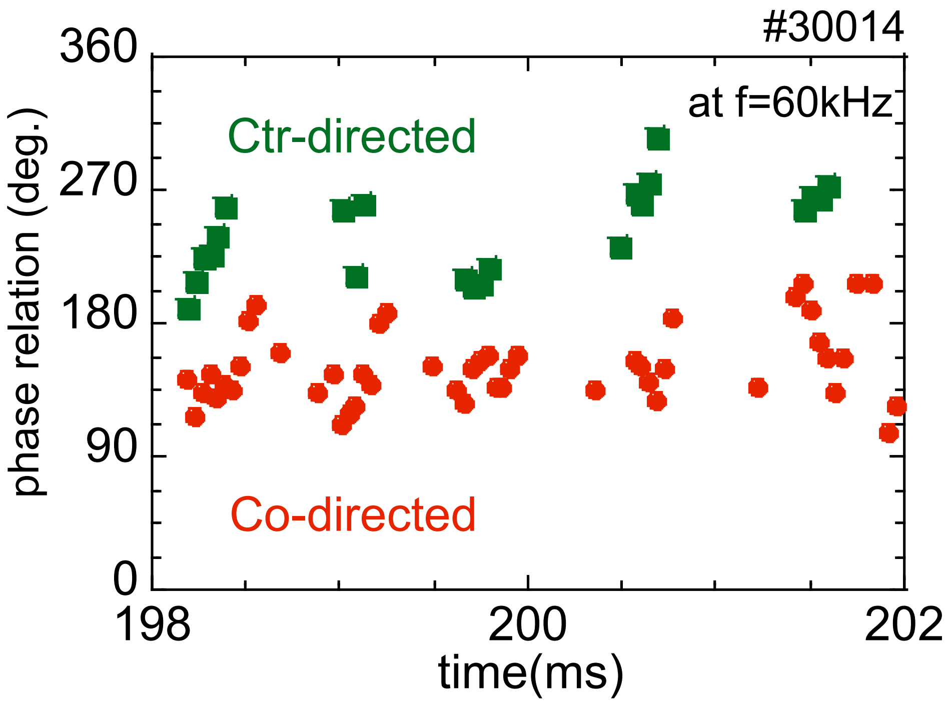
- GAEs have been observed in seve magnetic configurations in NBI plasmas of Heliotron J, and, strong bursting GAE has been observed in high and medium ε_b configurations

[+]S. Yamamoto, et al., FS&T, 51, 93 (20

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

- Some plasma parameters such as and T_e (SX foil) are simultaneously modulated with the bursting GAEs \ indicates that GAE would affect energetic ion transport.

Change in phase relation keeping a certain gap



-Temporal change in phase relation is similar to each other,
with keeping a certain difference around 100deg.
⎝ Require pitch angle distribution measurements by rotating HDLP

Energetic ion transport

- Effectiveness of ε_b on energetic ion transport in NBI and ICRF heated plasmas.

- Extend operational regime in ε_b-ε_t space.
  \ Progress optimization study