O-16

Analysis of velocity distribution of D-D fusion products driving ion cyclotron emission on JT-60U

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in Magnetic Confinement Systems – Theory of Plasma Instabilities

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- Ion cyclotron emission (ICE)

2. Analysis method

- Resonant $v_{||}$: evaluated from measurement results with ICRF antennas
- Fast ion velocity distribution : evaluated with OFMC code

3. Analysis results

3.1. ICE1 (H?)

- Observation of ICE1
- Comparison of fast H ion velocity distributions with H ion cyclotron resonance condition

3.2. ICE2 (T?, D?)

- Observation of ICE2
- Comparison of fast T and D ion velocity distributions with each ion resonance condition
- Cal. of linear growth rate of slow wave

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Ion Cyclotron Emission

☐ Ion Cyclotron Emission (ICE)

: Emission of ion cyclotron range of frequency (ICRF) waves by fast ions

☐ Features of ICEs observed in large-sized tokamaks; *JET, TFTR, JT-60U*

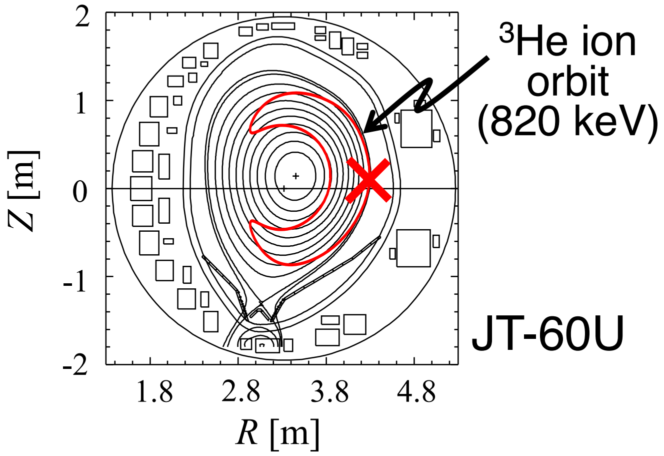
- ICE freq. ~ ion cyclotron frequency f_{ci} and lf_{ci} *at outer midplane edge*

  $f_{\mathrm{ci}} = q_{\mathrm{i}}B / 2\pi m_{\mathrm{i}}$, l : integer

- Correlation with Edge Localized Modes (ELMs)

→ Emission region

= ***Outer midplane edge***



☐ Near *outer midplane edge*

: Anisotropy in ion velocity distribution due to magnetic drift / finite orbit effect

→ A possible driving source for ICE through velocity-space instabilities

Previous ICE study in JT-60U

☐ Resonance condition for ICE

: *Ion Cyclotron Resonance Condition*

$$f_{\mathrm{obs}} = l f_{\mathrm{ci}} + \underbrace{\frac{k_\parallel v_\parallel}{2\pi}}_{\text{Doppler shift } \Delta f_{\mathrm{i}}}$$

$k_\parallel$: Parallel wavenumber
$v_\parallel$: Parallel velocity

To identify driving source for ICE

Doppler shift

→ $k_\parallel$ & $v_\parallel$ must be evaluated

Evaluation in JT-60U

$v_\parallel$ → f_v with OFMC code

$k_\parallel$ → with ICRF antennas

☐ Various ICEs observed in JT-60U

✓ Fast ion species

- NB injection : D(P-NB, ~80keV), D(N-NB, ~330 keV)
- DD fusion reaction : ^{3}He(~800 keV), H(~3000 keV), T(~1000 keV)

	Obs. freq.	Dispersion relation	Driving source
ICEs in JT-60U	$\sim l f_{\mathrm{cD}}$	Fast wave [1]	D(P-NB) [1]
	$\sim l f_{\mathrm{c3He}}$	Fast wave [1]	^{3}He [1,3]
	$\sim l f_{\mathrm{cH}}$	Fast wave [2]	?
	$\sim f_{\mathrm{cT}}$, $\sim f_{\mathrm{cD}}$	Slow wave [1]	?

→ ICE(D)

→ ICE(^{3}He)

In this study

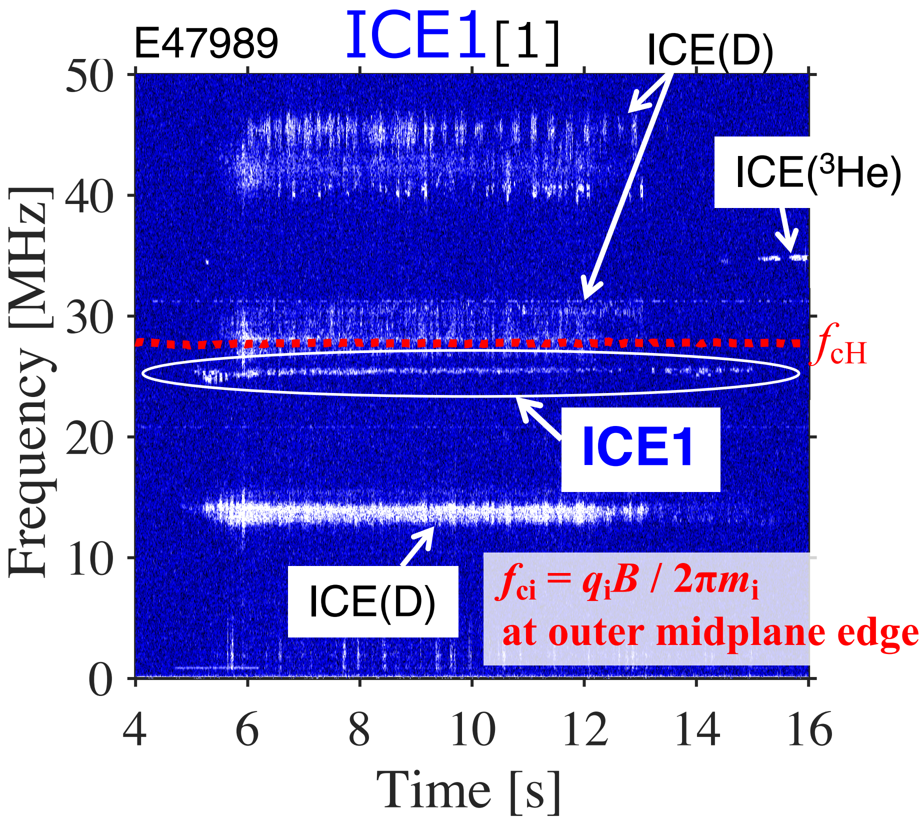
[1] M. Ichimura+ NF2008
[2] S. Sato+ PFR2010
[3] S. Sumida+ JPSJ2017, PPCF2019

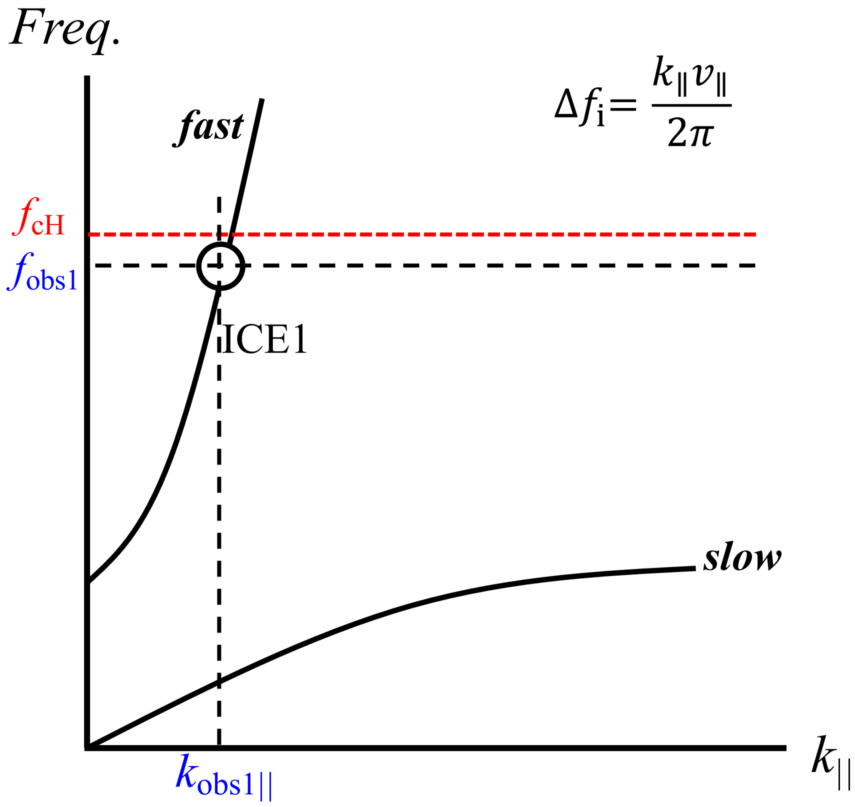
Possible driving sources predicted from measured dispersion information

	Obs. freq.	**Dispersion relation**
ICE1	$\sim lf_{cH}$	Fast wave [2]
ICE2	$\sim f_{cT}$, $\sim f_{cD}$	Slow wave [1]

Possible driving sources

- ICE1 :
- ICE2 :





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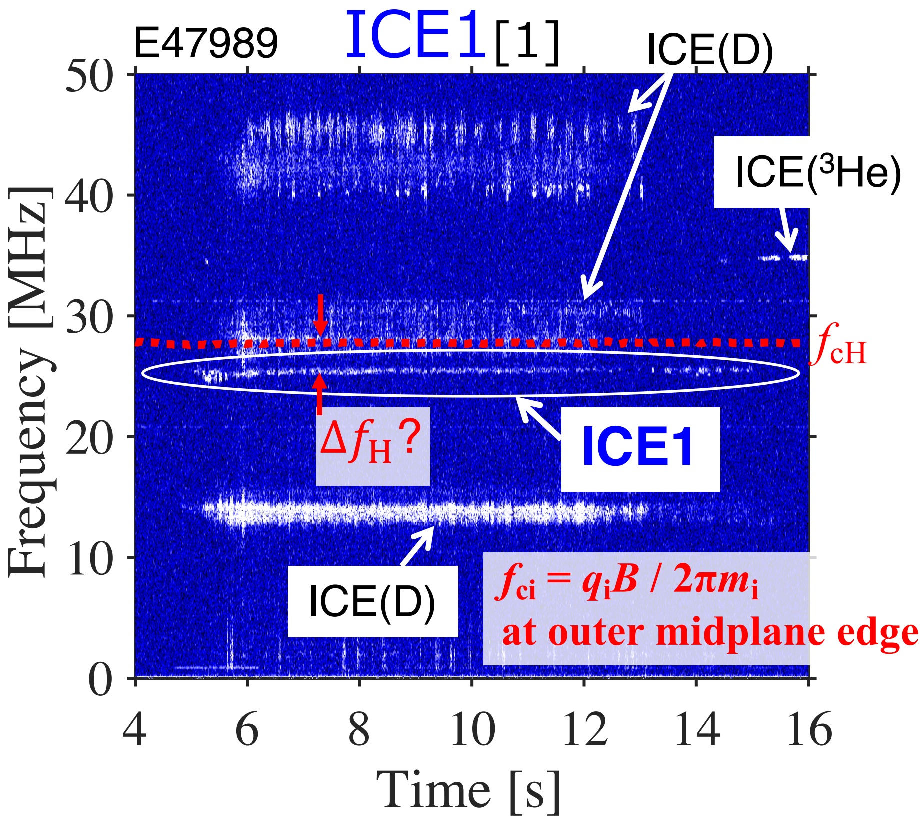
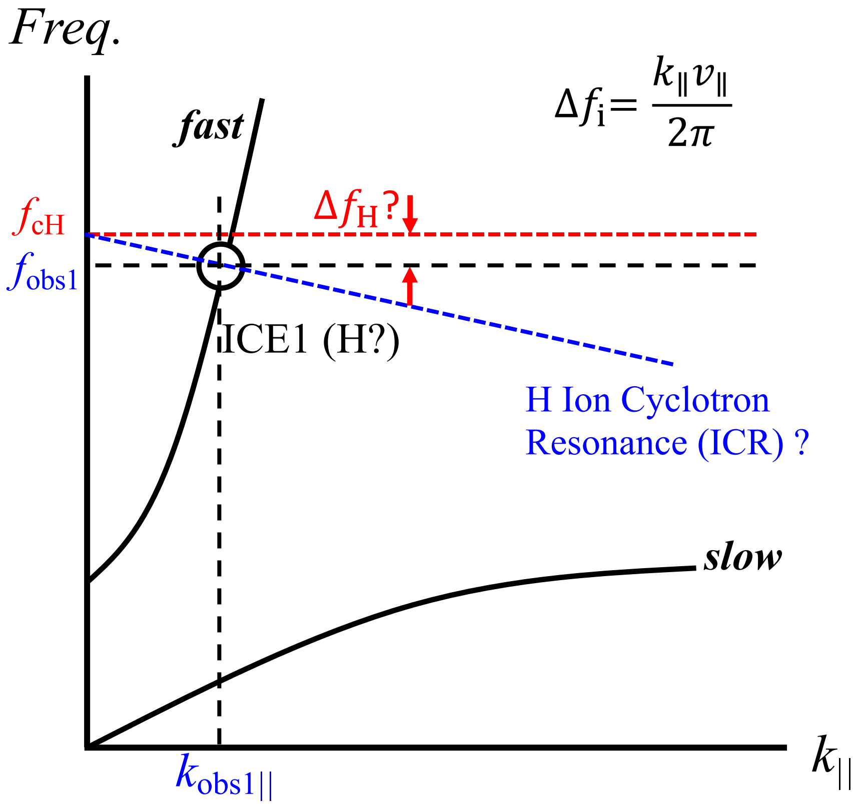


Possible driving sources

- ICE1 : H
- ICE2 :



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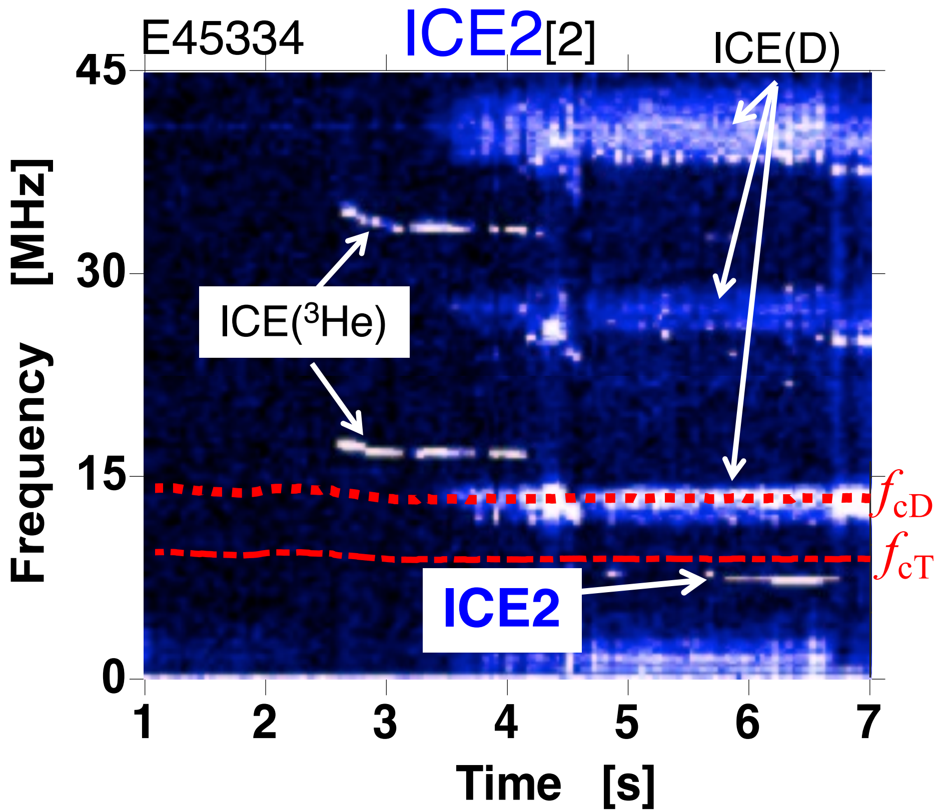

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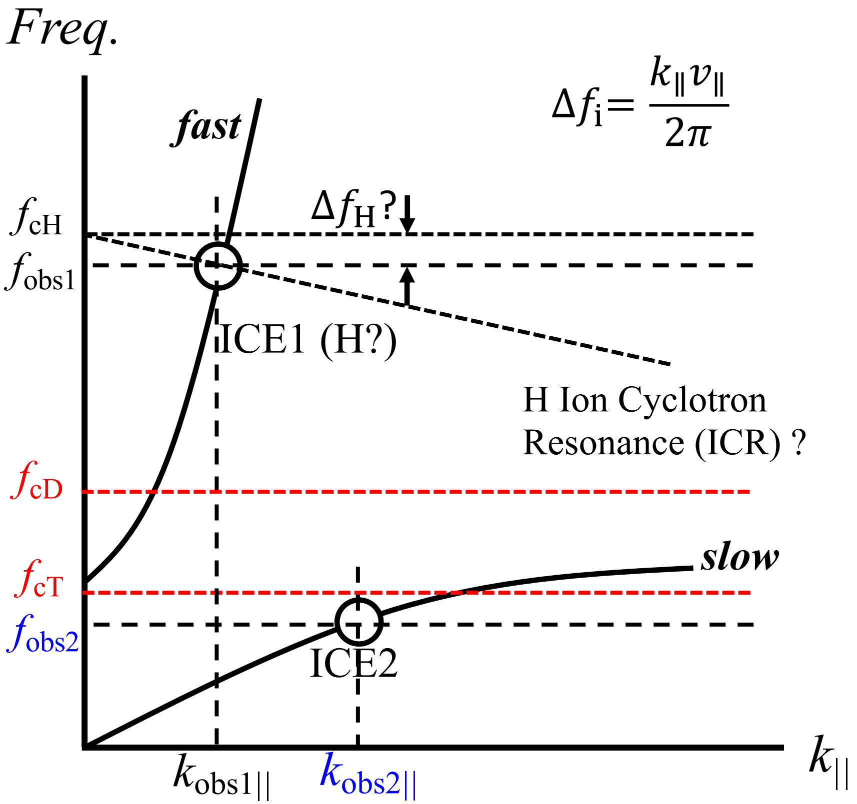
- ICE2 :



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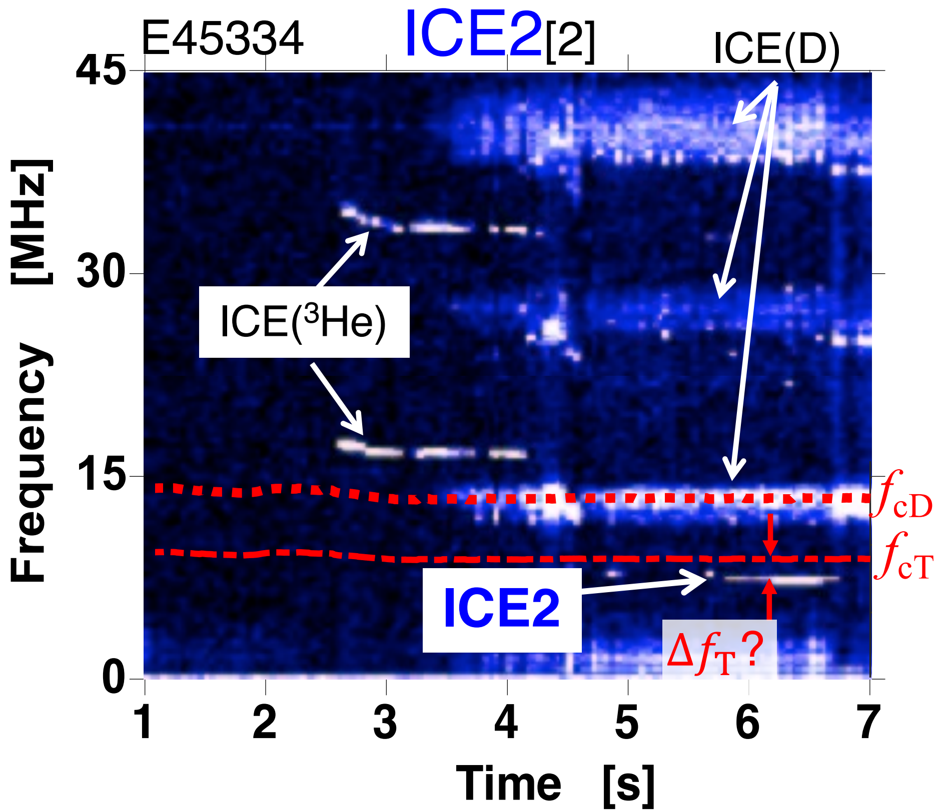
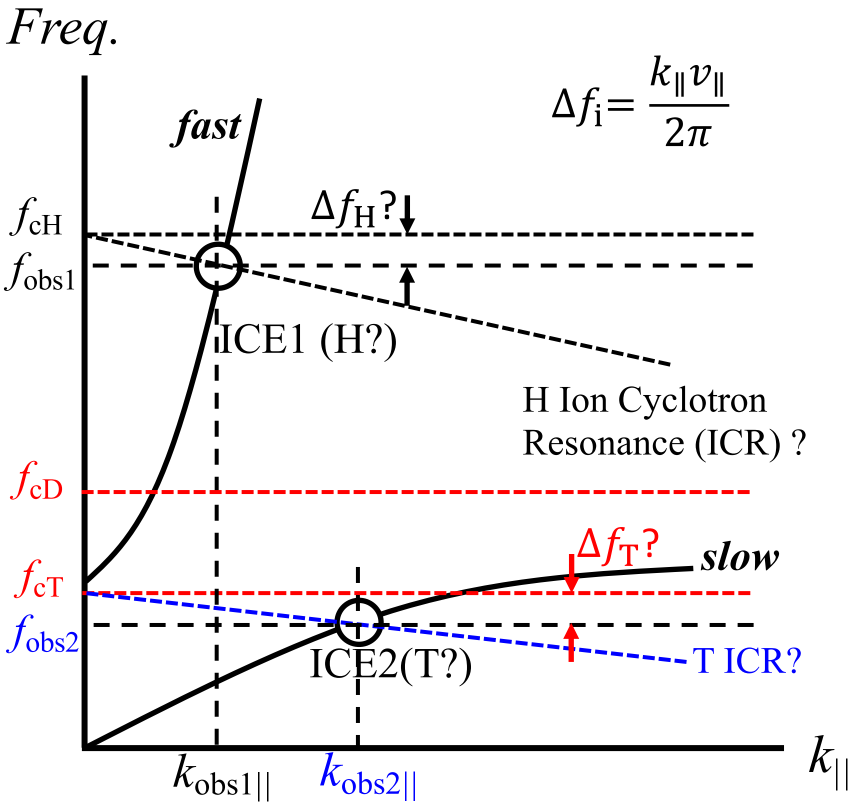


Possible driving sources

- ICE1 : H
- ICE2 : T



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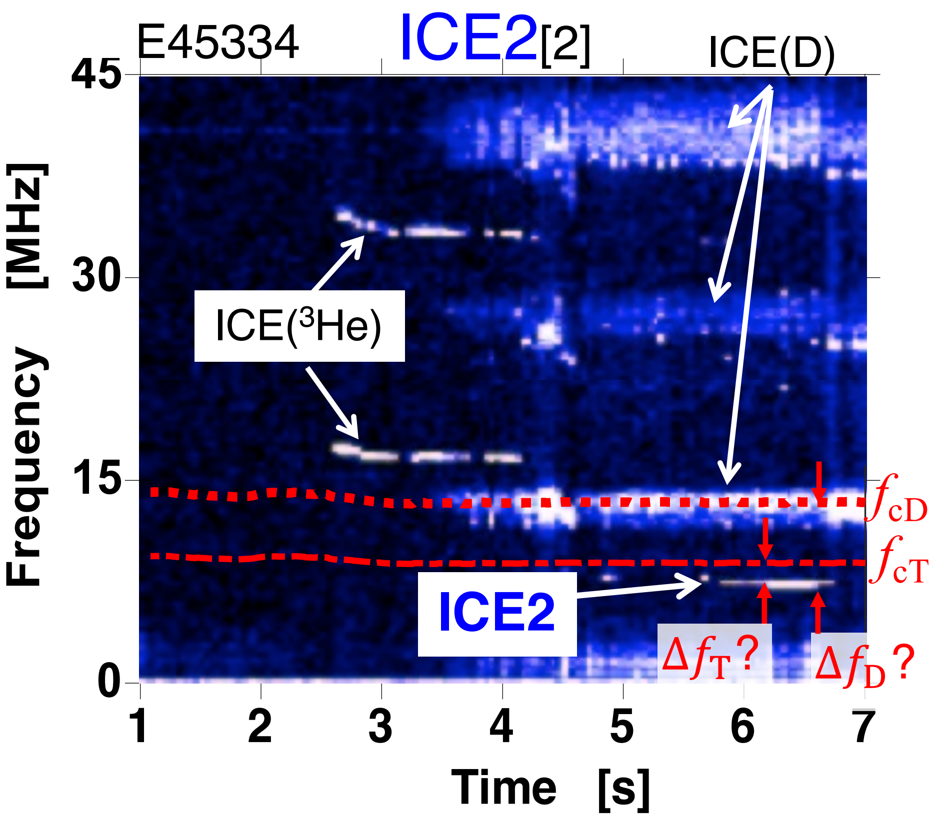
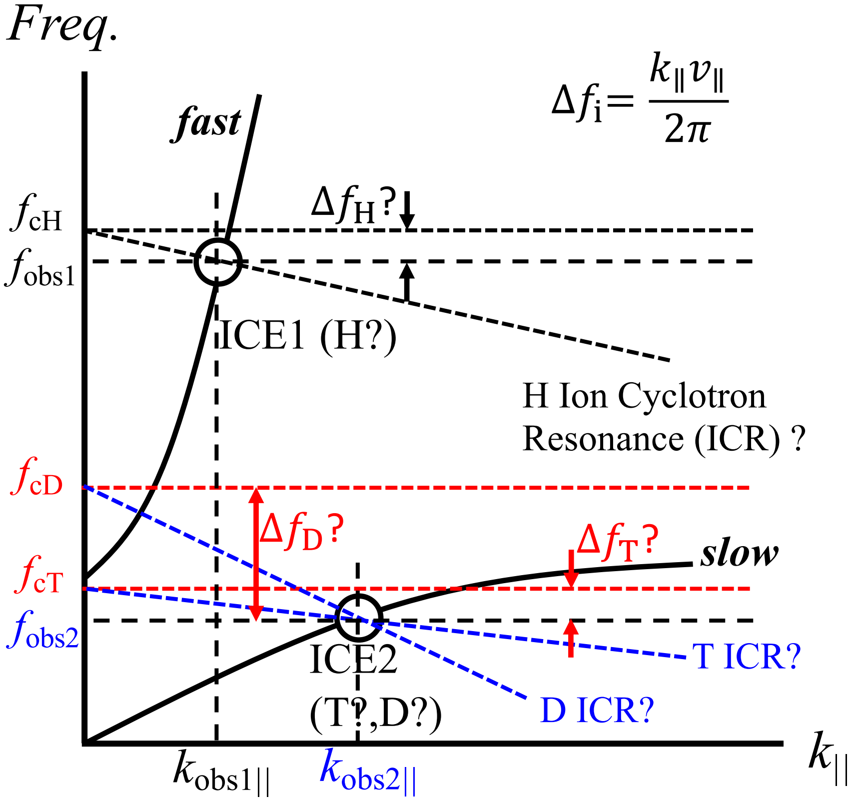


Possible driving sources

- ICE1 : H
- ICE2 : T, D



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Possible driving sources

- ICE1 : H
- ICE2 : T, D

Freq.

- **Purpose** : *Identify driving sources for ICE1 & ICE2*

→ Investigate whether fast ion velocity distributions are consistent with the resonance condition

1. *Evaluate resonant* $v_{||}$ *from freq. &* $k_{||}$ Measured with ICRF antennas
2. *Compare fast ion distribution with resonant* $v_{||}$ Evaluated with OFMC code

Frequency [MHz]

$k_{||}$

Time [s]

[1] M. Ichimura+ NF2008
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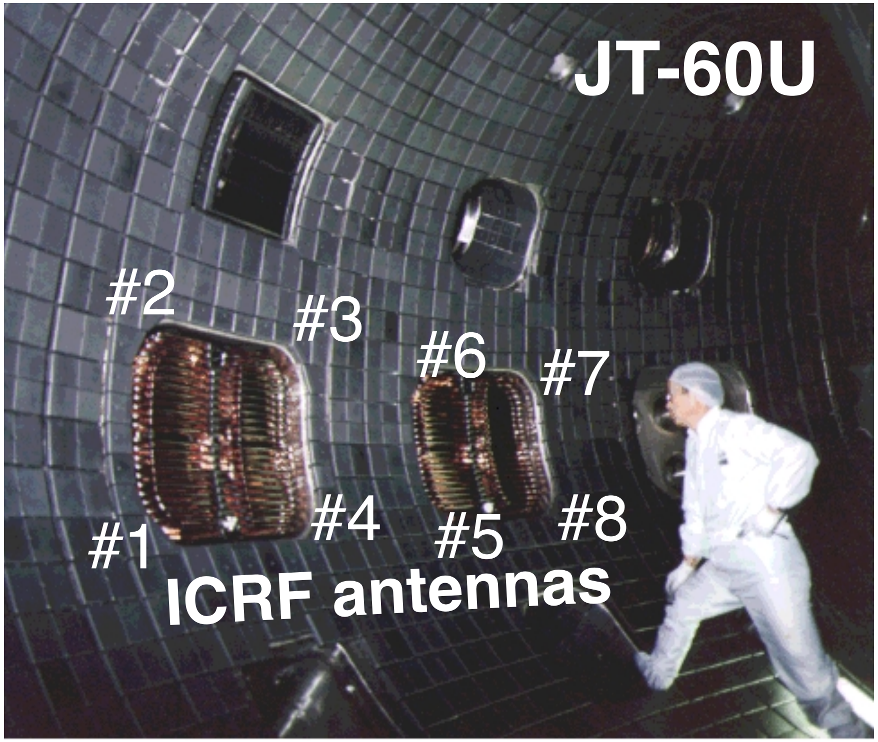
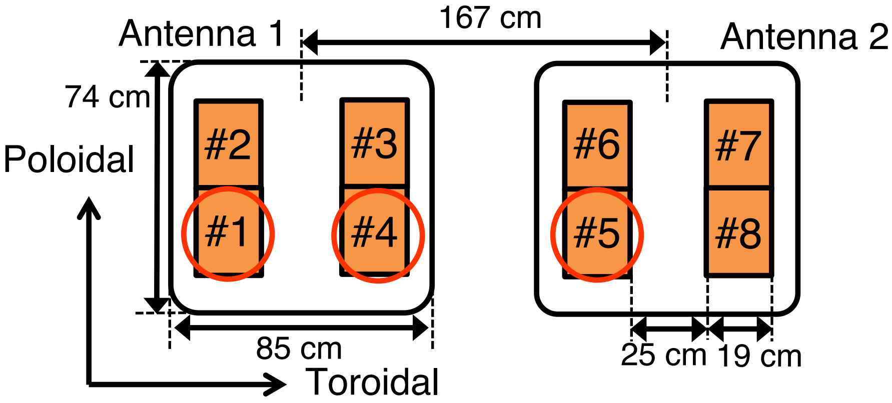
4. **Summary**

To evaluate $k_\parallel$, toroidal wavenumbers k_φ are measured with 3 ICRF antenna straps





☐ Toroidal wavenumber k_φ

$$k_\varphi = \frac{\Delta\theta_{14} + 2\pi j_{14}}{\Delta L_{14}} = \frac{\Delta\theta_{45} + 2\pi j_{45}}{\Delta L_{45}} = \frac{\Delta\theta_{15} + 2\pi j_{15}}{\Delta L_{15}}$$

$\Delta\theta$: Phase difference
ΔL : Distance btw straps
j : Integer

✓ Standard deviation σ

$$\sigma = \sqrt{\frac{\sum\left(k_\varphi - \overline{k_\varphi}\right)^2}{N-1}}$$

→ Search for a j combination when σ becomes the minimum.

☐ Assume $k_\parallel = k_\varphi$

←
- B direction ~ toroidal direction (/ large q_{safe} near plasma edge)
- Measured poloidal wavenumber is small [1].

[1] M. Ichimura+ NF2008

To evaluate velocity distribution of fast D ion & DD fusion produced ions, OFMC code is used

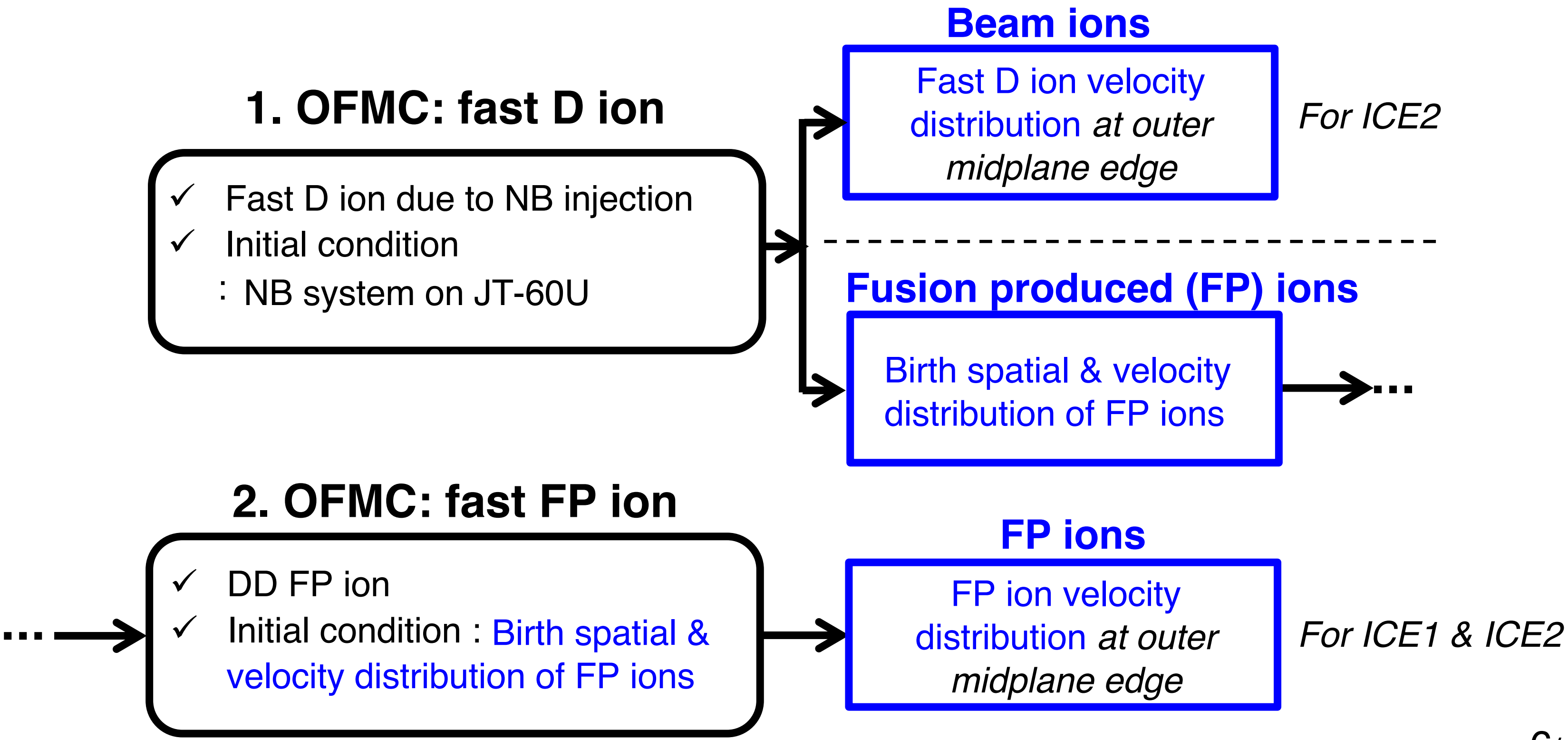
☐ OFMC code [4]

: traces guiding-center and/or full-gyro orbits of fast ions in 3-D magnetic field.

✓ *Assumptions* in this study,

- Orbit calculation : Guiding-center, neo-classical
- Evaluation of velocity distribution under *stationary* condition

✓ Can take into account quantitatively evaluated birth distribution of fusion produced (FP) ions



1. OFMC: fast D ion

✓ Fast D ion due to NB injection

✓ Initial condition

: NB system on JT-60U

Beam ions

Fast D ion velocity distribution *at outer midplane edge*

For ICE2

Fusion produced (FP) ions

Birth spatial & velocity distribution of FP ions

2. OFMC: fast FP ion

✓ DD FP ion

✓ Initial condition : Birth spatial & velocity distribution of FP ions

FP ions

FP ion velocity distribution *at outer midplane edge*

For ICE1 & ICE2

[4] K. Tani+ JPSJ1981

Direction of operator for cyclotron resonance in velocity space

☐ Operator L for wave-particle interaction [5]

$$L = \omega\frac{\partial}{\partial E} + \frac{l\Omega_{\mathrm{ci}} - \Lambda\omega}{E}\frac{\partial}{\partial\Lambda} + N\frac{\partial}{\partial P_\varphi}$$

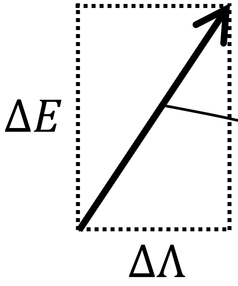
$$\Lambda = \frac{\mu B}{E} = \frac{v_\perp^2}{v^2} = \sin^2\phi_{\mathrm{pitch}}$$

Distribution function f_{dis}

- $L \cdot f_{\mathrm{dis}} > 0$: particle → wave
- $L \cdot f_{\mathrm{dis}} < 0$: wave → particle

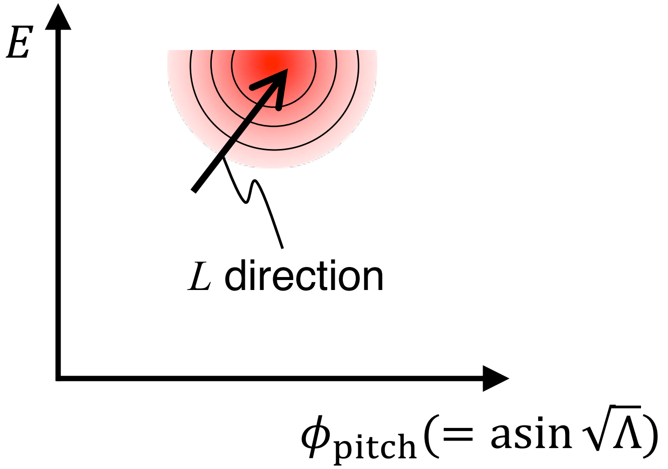
In velocity space,

$$\Delta E = \frac{\omega E}{l\Omega_{\mathrm{ci}} - \Lambda\omega}\Delta\Lambda$$



Operator L direction at a resonance point

✓ $L \cdot f_{\mathrm{dis}} > 0$: particle → wave



[5] *e.g.* L. -G. Eriksson+ PoP1999

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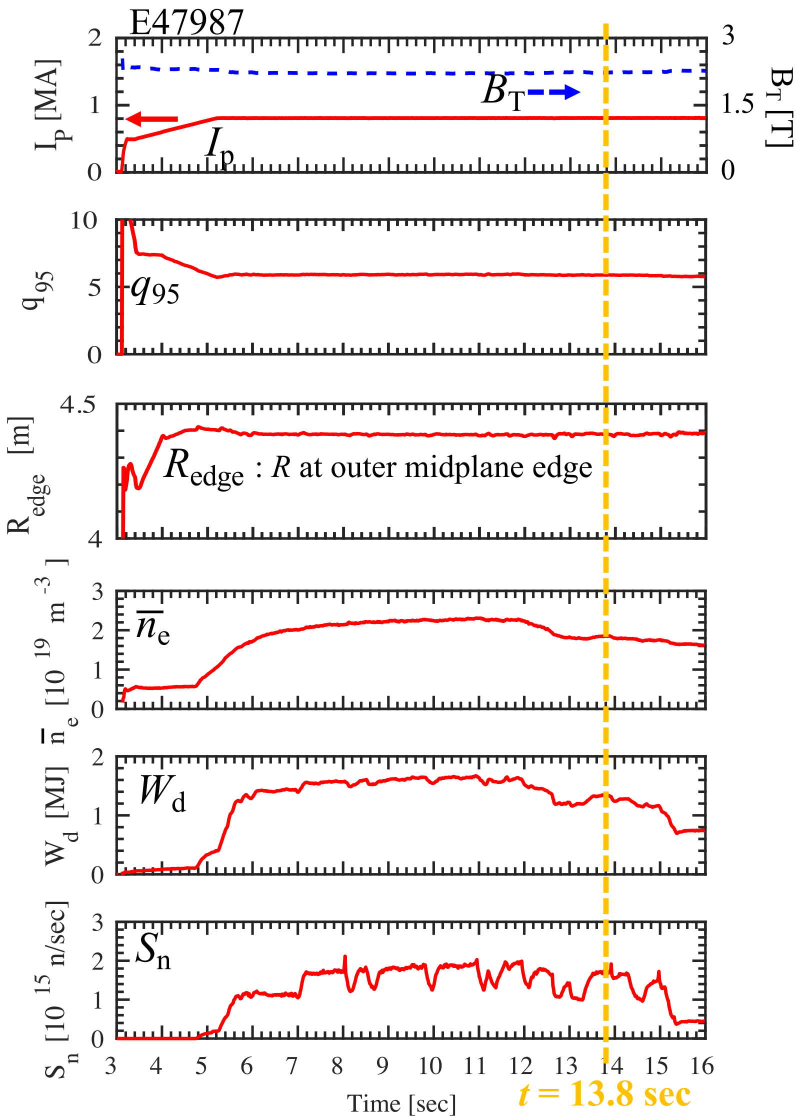
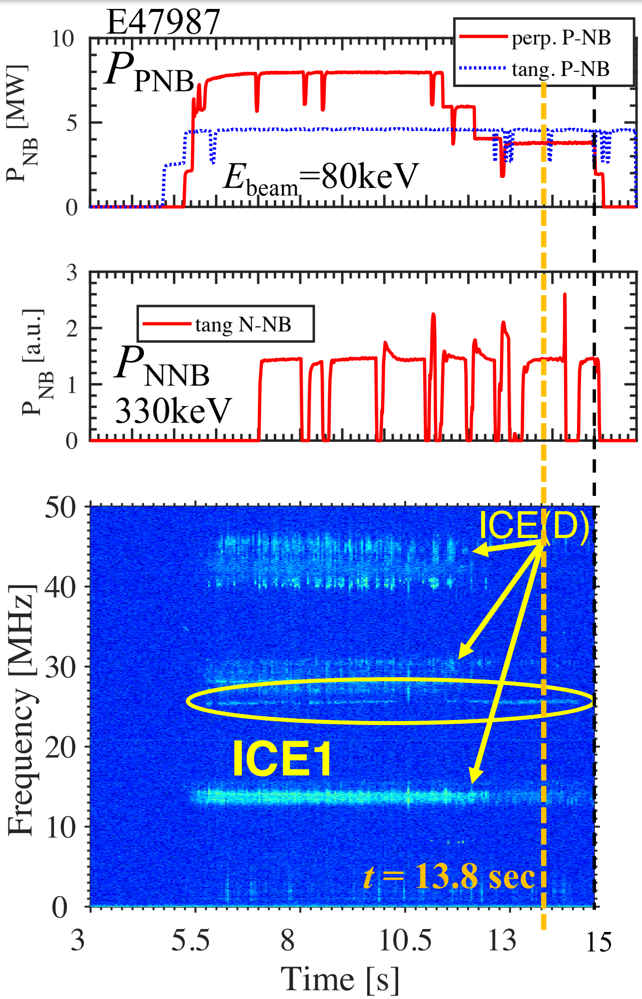
ICE1

Typical plasma parameters for ICE1 observation





- Evaluate velocity distribution under stationary condition by using parameters at t = 13.8 sec

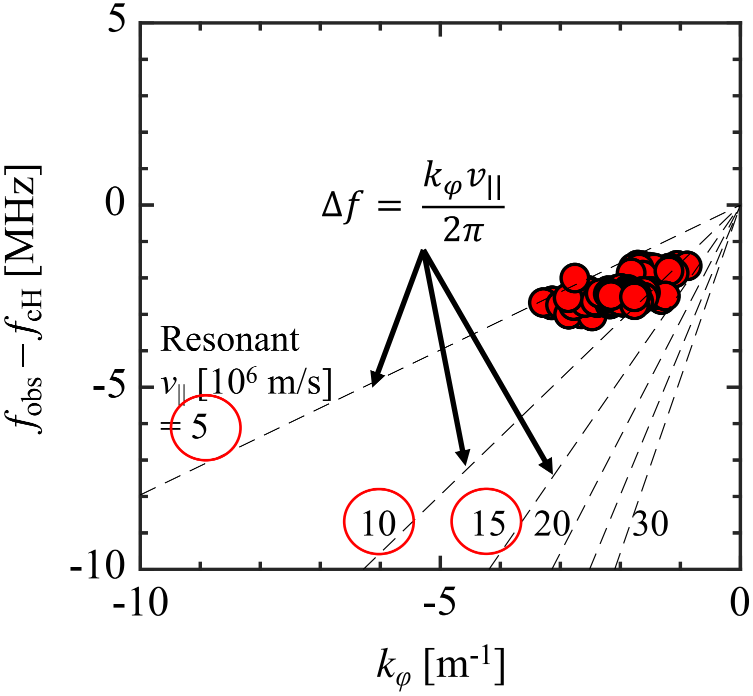
Comparison of fast **H** ion velocity distribution with ion cyclotron resonance condition ICE1

- Doppler shift Δf_{H}

Resonant $v_{\parallel}$

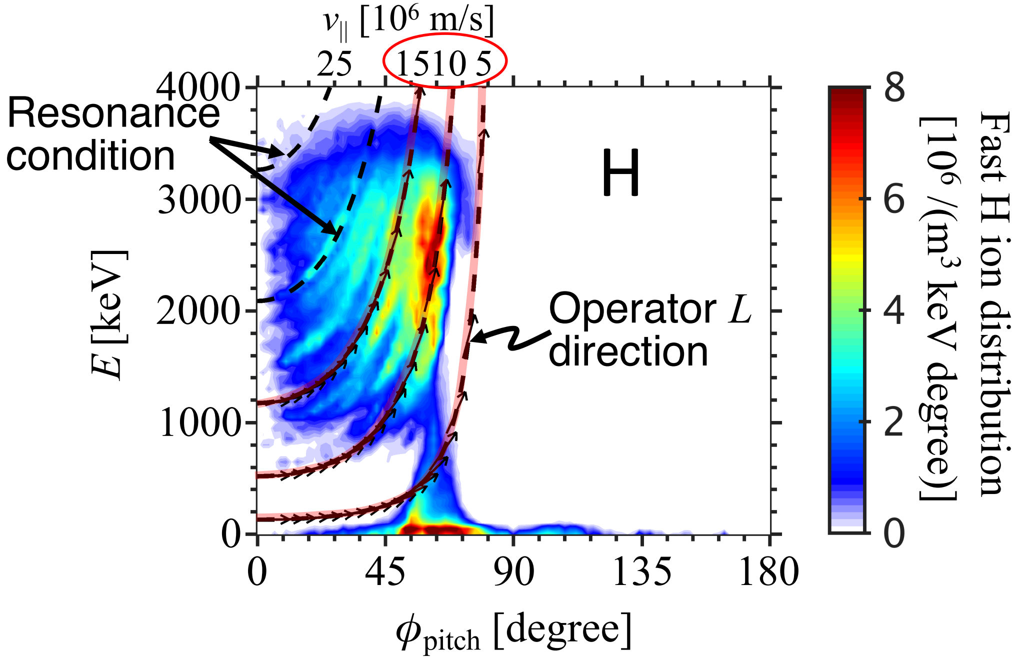
$$\Delta f_{\mathrm{H}} = f_{\mathrm{obs}} - l f_{\mathrm{cH}} = \frac{k_{\parallel} v_{\mathrm{H}\parallel}}{2\pi}$$

Measured Δf_{H} vs k_{φ} in several discharges



- Resonant $v_{\parallel}$ is 5-15 × 10^6 m/s

Typical **H** ion velocity distribution



- **Fast H ions can satisfy the resonance condition.**
- **$L \cdot f_{\mathrm{dis}} > 0$ exists near birth-E region.**

→ Driving source for ICE1
= *DD fusion produced H ions* !

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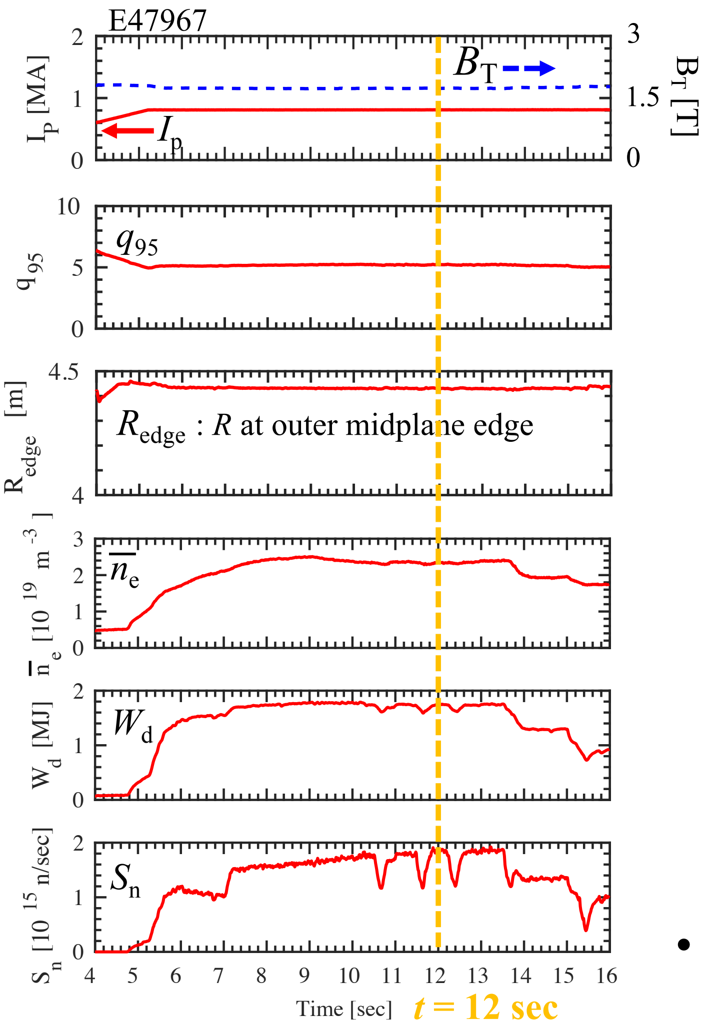
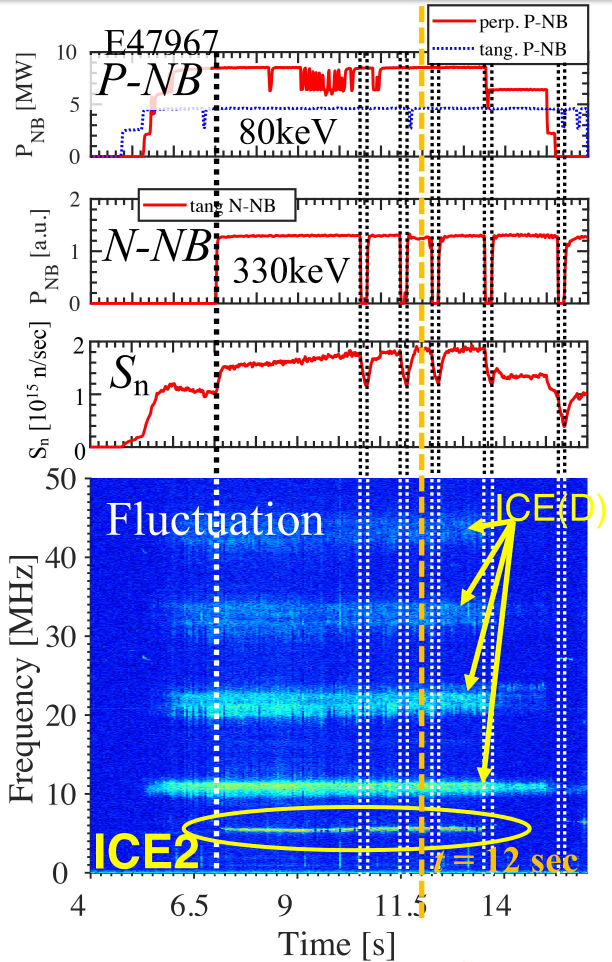
ICE2

Typical plasma parameters for ICE2 observation





- ICE2 begins to appear *just after N-NB injection* (or *increment of fusion reaction rate*)
- Evaluate velocity distribution under stationary condition by using parameters at *t* = 12.0 sec

Comparison of fast T ion velocity distribution with ion cyclotron resonance condition

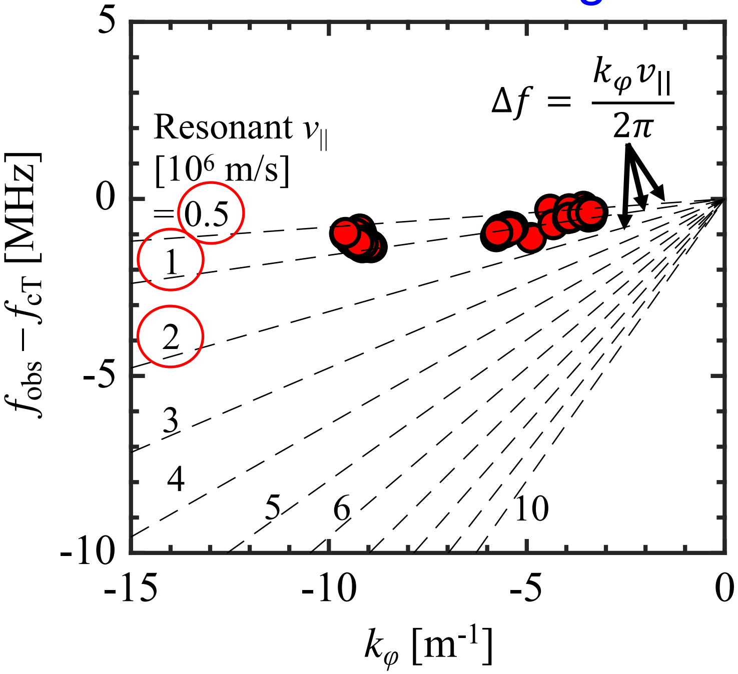
ICE2

☐ Doppler shift Δf_{T}

$$\Delta f_{\mathrm{T}} = f_{\mathrm{obs}} - l f_{\mathrm{cT}} = \frac{k_{\parallel} v_{\mathrm{T}\parallel}}{2\pi}$$

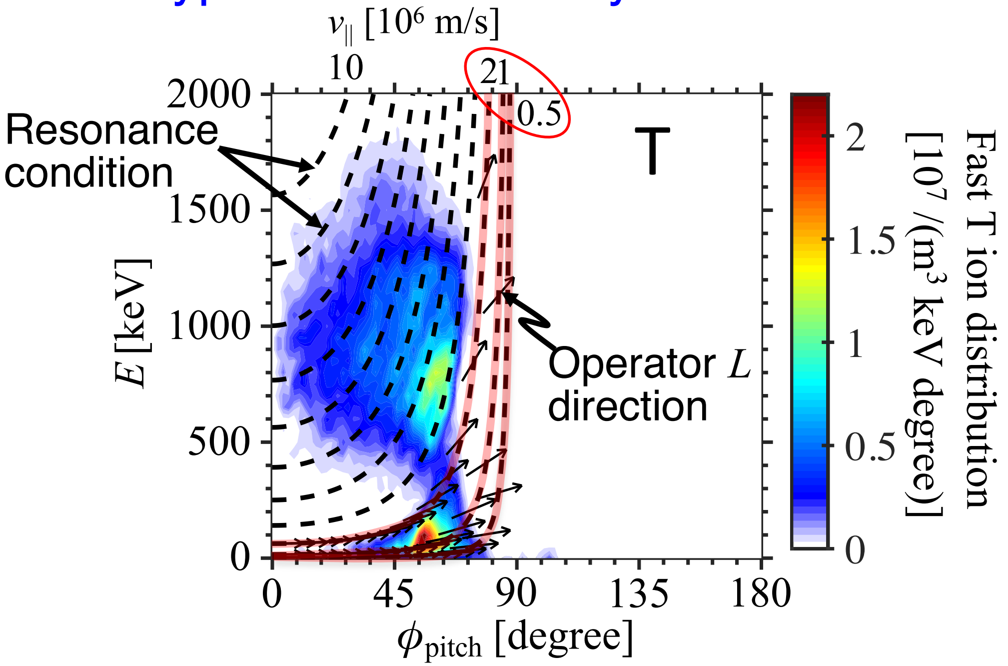
Resonant $v_{\parallel}$

Measured Δf_{T} vs k_{φ} in several discharges



- Resonant $v_{\parallel} = 0.5\text{-}2 \times 10^6$ m/s

Typical T ion velocity distribution



- Only low-E fast T ions can satisfy the resonance condition
- $L \cdot f_{\mathrm{dis}} > 0$ exists only in low-E region.

A time scale of slowing-down time elapses for formation of *low-E* component.

↔ "ICE2 begins to appear *just after increment of T ion birth rate* (or *N-NB injection*)" in *Exp.*

Time scales are ***in**consistent*

Driving source for ICE2
≠ DD fusion produced T ions

Comparison of fast **D** ion velocity distribution with ion cyclotron resonance condition

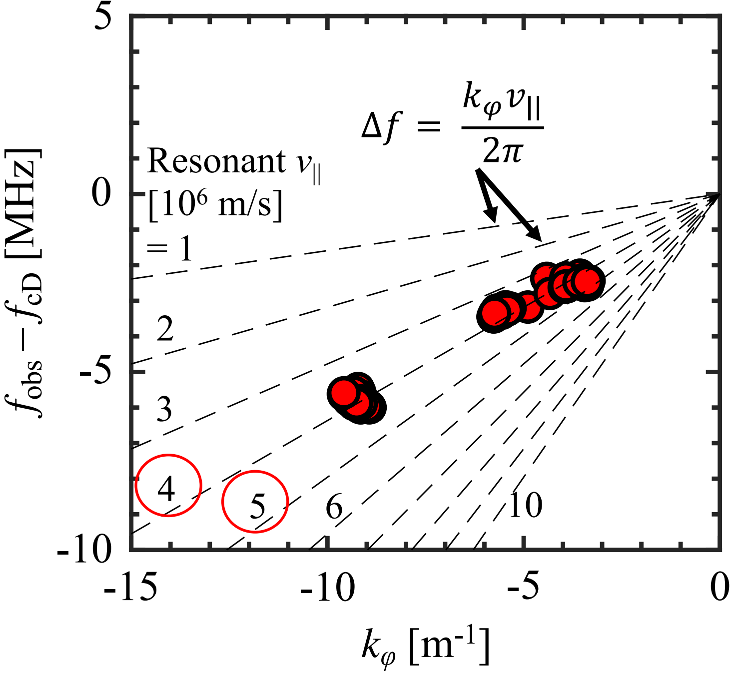
ICE2

- Doppler shift Δf_{D}

Resonant $v_{\parallel}$

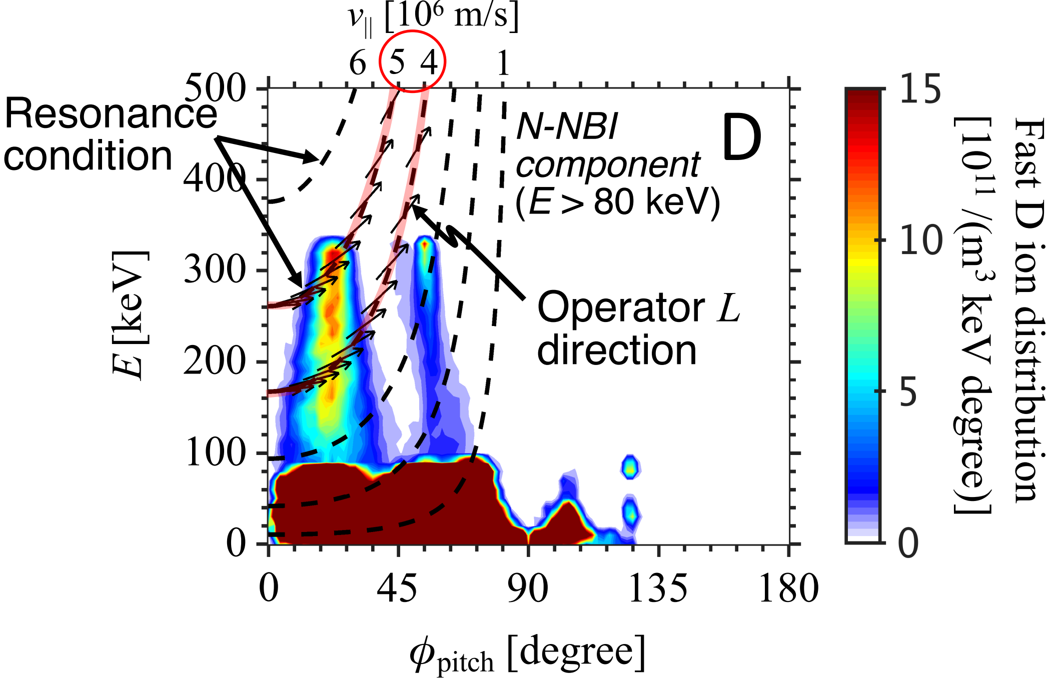
$$\Delta f_{\mathrm{D}} = f_{\mathrm{obs}} - l f_{\mathrm{cD}} = \frac{k_{\parallel} v_{\mathrm{D}\parallel}}{2\pi}$$

Measured Δf_{D} vs k_{φ} in several discharges



- Resonant $v_{\parallel} = 4\text{-}5 \times 10^6$ m/s

Typical **D** ion velocity distribution



- **Fast D ions (N-NBI) can satisfy the resonance condition**
- $L \cdot f_{\mathrm{dis}} > 0$ **exists near beam-E region.**

(→ Consistent with its appearance condition)

→ **Driving source for ICE2**
= *N-NB injected D ions* !

To confirm whether slow waves become unstable by N-NB injected D ions, dispersion relations are calculated ICE2

☐ Wave dispersion code [6]

Assumptions : Linear theory and uniform plasma

- Maxwell's equation

$$k \times (k \times E) + \frac{\omega^2}{c^2}\overleftrightarrow{\varepsilon}\cdot E = 0$$

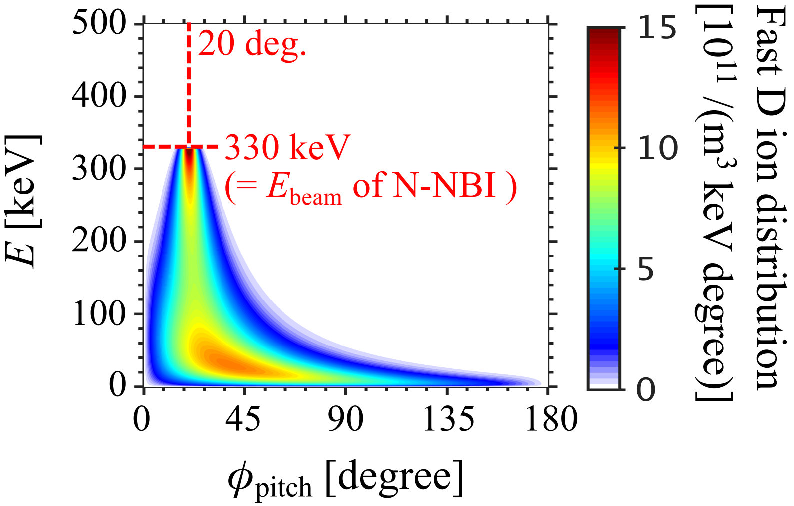
- Dielectric tensor $\overleftrightarrow{\varepsilon}$ for arbitrary velocity distribution function f_s

$$\overleftrightarrow{\varepsilon} = \left(1 - \sum_s \frac{\omega_{ps}^2}{\omega^2}\right) I + \sum_{s,l} \frac{\omega_{ps}^2}{\omega^2} \int \frac{\overleftrightarrow{H}_{s,l}}{\omega - k_\parallel v_\parallel - l\Omega_s} \left(\frac{l\Omega_s}{v_\perp} \frac{\partial f_s}{\partial v_\perp} + k_\parallel \frac{\partial f_s}{\partial v_\parallel} \right) \frac{1}{n_s} d^3 v$$

☐ N-NB injected D ion model [7]

$$f_{NNB} = \frac{3n}{2\pi \ln\left(1 + \left(\frac{v_b}{v_c}\right)^3\right)} \frac{\eta(v_b - v)}{v^3 + v_c^3}$$

$$\times \sum_{l=0}^{\infty} \left(l + \frac{1}{2}\right) u^{l(l+1)} P_l(p) K_l\, \eta(v_b - v)$$



[6] S. Sumida+ EPS2018
[7] *e.g.* J. G. Cordey+ PF1974

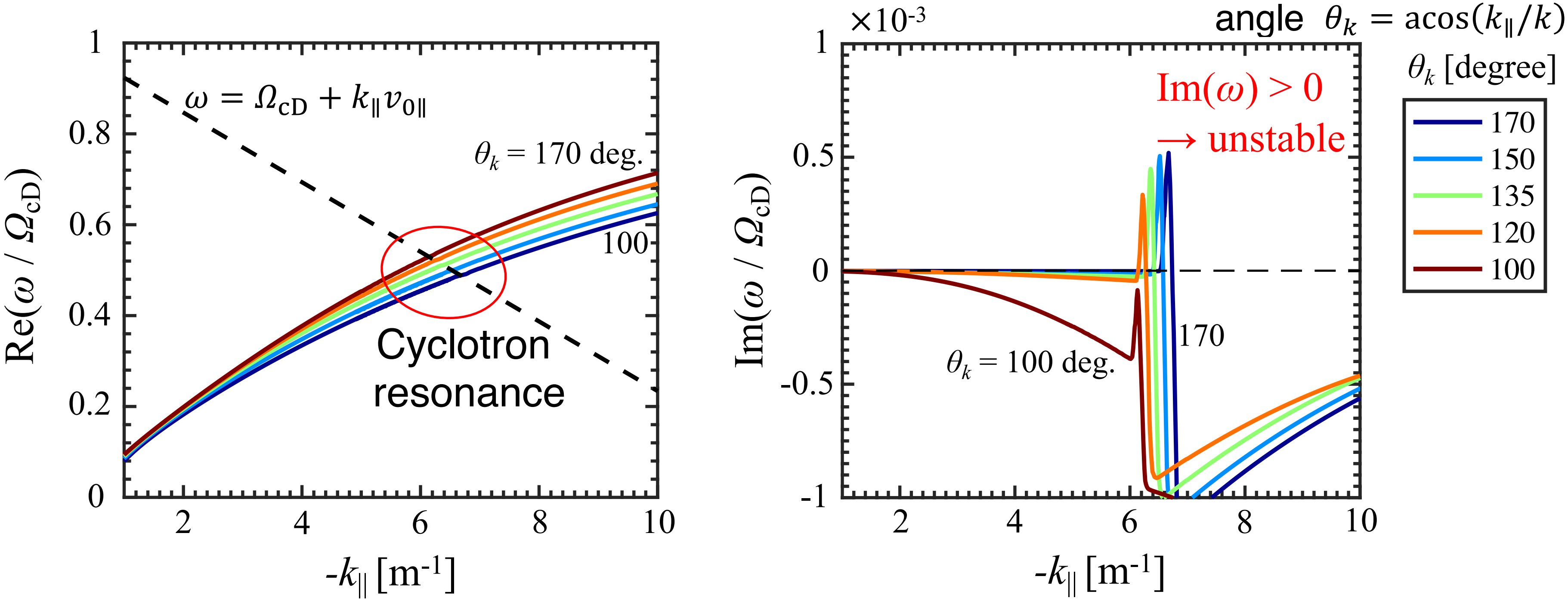
Slow waves become unstable due to N-NB injected D ions

☐ D plasma including fast D ions

$B = 1.44$ T, $n_e = n_D = 10^{19}$ m^{-3}, $T_e = T_D = 500$ eV, $n_{fast} = 8.0 \times 10^{15}$ m^{-3},
$v_0 = \sim 5.6 \times 10^6$ m/s ($E_{N\text{-}NB} = 330$ keV), $\phi_{pitch} = 20$ degree (referred from parameters at $\rho_{out} \sim 0.95$ in E47967)

Dispersion relation of slow wave

Wave propagation angle $\theta_k = \mathrm{acos}(k_\parallel / k)$



- N-NB injected D ions can destabilize slow waves propagating in the oblique direction

→ **Growth rate of slow wave supports driving source for ICE2 = N-NB injected D ions**

Summary

We identified driving sources for ICE1 & ICE2 by using a simple qualitative method with the resonance condition and the operator direction based on ...

- ✓ *Dispersion relation measured with ICRF antennas*
- ✓ *Fast ion velocity distribution evaluated with OFMC code*

☐ **ICE1** (Fast wave)**:** ***DD fusion produced H ions***

- Fast H ion distribution can satisfy the resonance condition & its gradient is consistent with the operator L direction.

☐ **ICE2** (Slow wave)**:** ***N-NB injected D ions***

- N-NB injected D ion distribution can satisfy the resonance condition & its gradient is consistent with the operator L direction.
- Time scale is consistent with the observation.
- Destabilization of slow waves due to N-NB injected D ions was confirmed

In JT-60U	**Obs. freq.**	**Dispersion relation**	**Driving source**
ICE(D)	$\sim lf_{\mathrm{cD}}$	Fast wave	D(P-NB)
ICE(^{3}He)	$\sim lf_{\mathrm{c3He}}$	Fast wave	^{3}He
ICE1	$\sim lf_{\mathrm{cH}}$	Fast wave	**H**
ICE2	$\sim f_{\mathrm{cT}}$, $\sim f_{\mathrm{cD}}$	Slow wave	**D(N-NB)**

In this study

→ **ICE(H)**

→ **ICE(D)**

Acknowledgements

- This research was conducted using the supercomputer SGI ICE X in the Japan Atomic Energy Agency.
- The authors would like to thank Dr. Satoshi Yamamoto of QST for giving useful suggestions and Dr. Takahiro Bando of QST for his supply of an analytical tool.

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- Destabilization of slow waves due to N-NB injected D ions was confirmed

In JT-60U	**Obs. freq.**	**Dispersion relation**	**Driving source**
ICE(D)	$\sim lf_{cD}$	Fast wave	D(P-NB)
ICE(^{3}He)	$\sim lf_{c3He}$	Fast wave	^{3}He
ICE1	$\sim lf_{cH}$	Fast wave	**H**
ICE2	$\sim f_{cT}$, $\sim f_{cD}$	Slow wave	**D(N-NB)**

In this study

→ **ICE(H)**

→ **ICE(D)**

To confirm whether slow waves become unstable by N-NB injected D ions, dispersion relations are calculated ICE2

Wave dispersion code [6]

Assumptions : Linear theory and uniform plasma

- Maxwell's equation

$$k\times(k\times E)+\frac{\omega^2}{c^2}\overleftrightarrow{\varepsilon}\cdot E=0$$

- Dielectric tensor $\overleftrightarrow{\varepsilon}$ for arbitrary velocity distribution function f_s

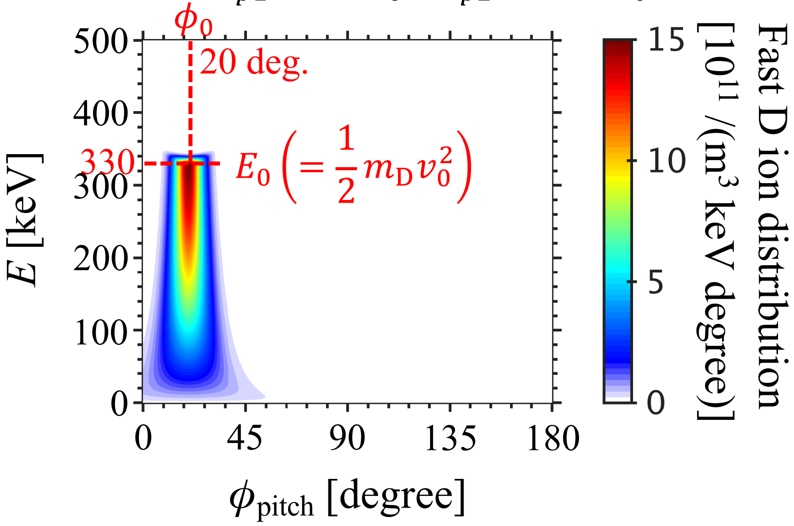
$$\overleftrightarrow{\varepsilon}=\left(1-\sum_s\frac{\omega_{ps}^2}{\omega^2}\right)I+\sum_{s,l}\frac{\omega_{ps}^2}{\omega^2}\int\frac{\overleftrightarrow{H}_{s,l}}{\omega-k_\parallel v_\parallel-l\Omega_s}\left(\frac{l\Omega_s}{v_\perp}\boxed{\frac{\partial f_s}{\partial v_\perp}}+k_\parallel\boxed{\frac{\partial f_s}{\partial v_\parallel}}\right)\frac{1}{n_s}d^3v$$

Fast D ion model

$$f\propto\eta(v-v_0)\exp\left[-\frac{\{(v_\parallel-v_{0\parallel})\cos\phi_0+(v_\perp-v_{0\perp})\sin\phi_0\}^2}{\delta v_{E1}^2}\right]$$
$$\times\exp\left[-\frac{\{-(v_\parallel-v_{0\parallel})\sin\phi_0+(v_\perp-v_{0\perp})\cos\phi_0\}^2}{\delta v_{p1}^2}\right]$$
$$+\eta(-v+v_0)\exp\left[-\frac{\{(v_\parallel-v_{0\parallel})\cos\phi_0+(v_\perp-v_{0\perp})\sin\phi_0\}^2}{\delta v_{E2}^2}\right]$$
$$\times\exp\left[-\frac{\{-(v_\parallel-v_{0\parallel})\sin\phi_0+(v_\perp-v_{0\perp})\cos\phi_0\}^2}{\delta v_{p2}^2}\right]$$

η : Heaviside step function

$n_{\mathrm{fastD}}=4\times10^{15}\ \mathrm{m}^{-3},\phi_0=20$ deg.
$\delta v_{E1}=0.7v_0,\delta v_{E2}=0.1v_0$
$\delta v_{p1}=0.1v_0,\delta v_{p2}=0.01v_0$



ICE2

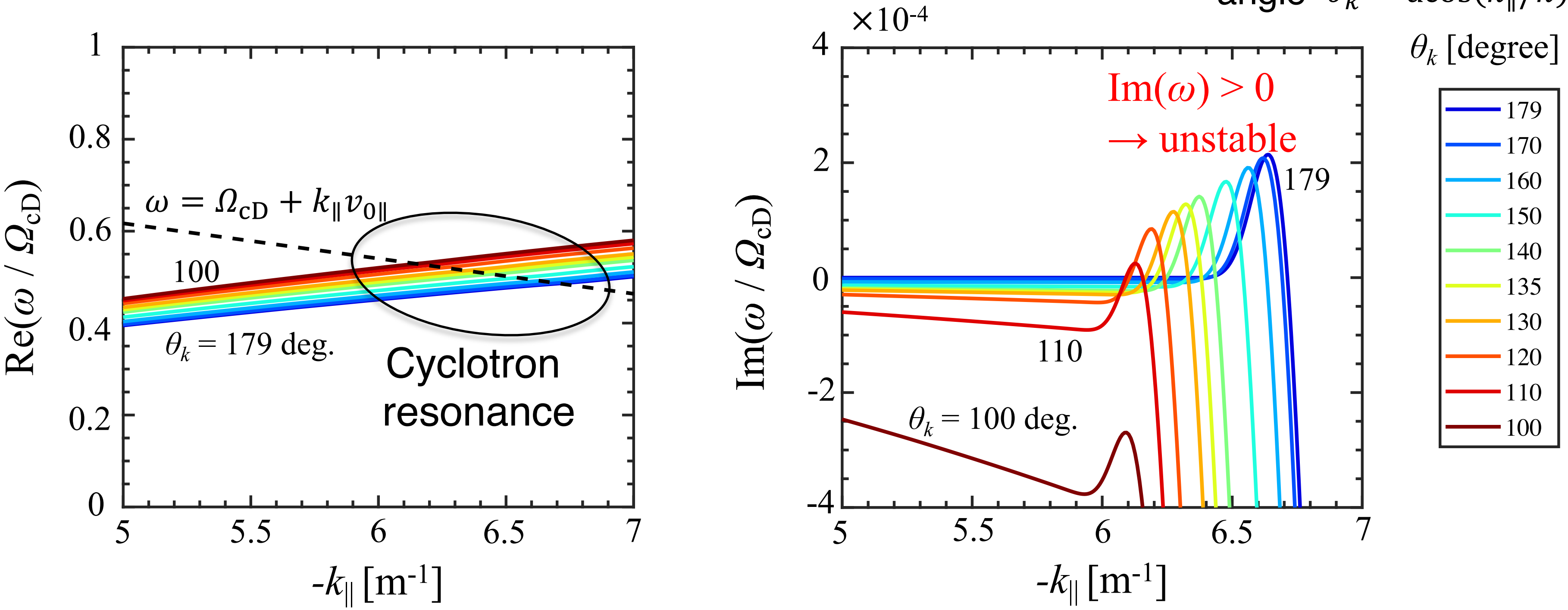
Slow waves become unstable due to N-NB injected D ions

☐ D plasma including fast D ions

$B = 1.44$ T, $n_e = n_D = 10^{19}$ m^{-3}, $T_e = T_D = 500$ eV, $n_{fast} = 8.0 \times 10^{15}$ m^{-3},
$v_0 = \sim 5.6 \times 10^6$ m/s ($E_{N\text{-}NB} = 330$ keV), $\phi_{pitch} = 20$ degree (referred from parameters at $\rho_{out} \sim 0.95$ in E47967)

Dispersion relation of slow wave

Wave propagation angle $\theta_k = \mathrm{acos}(k_\parallel / k)$

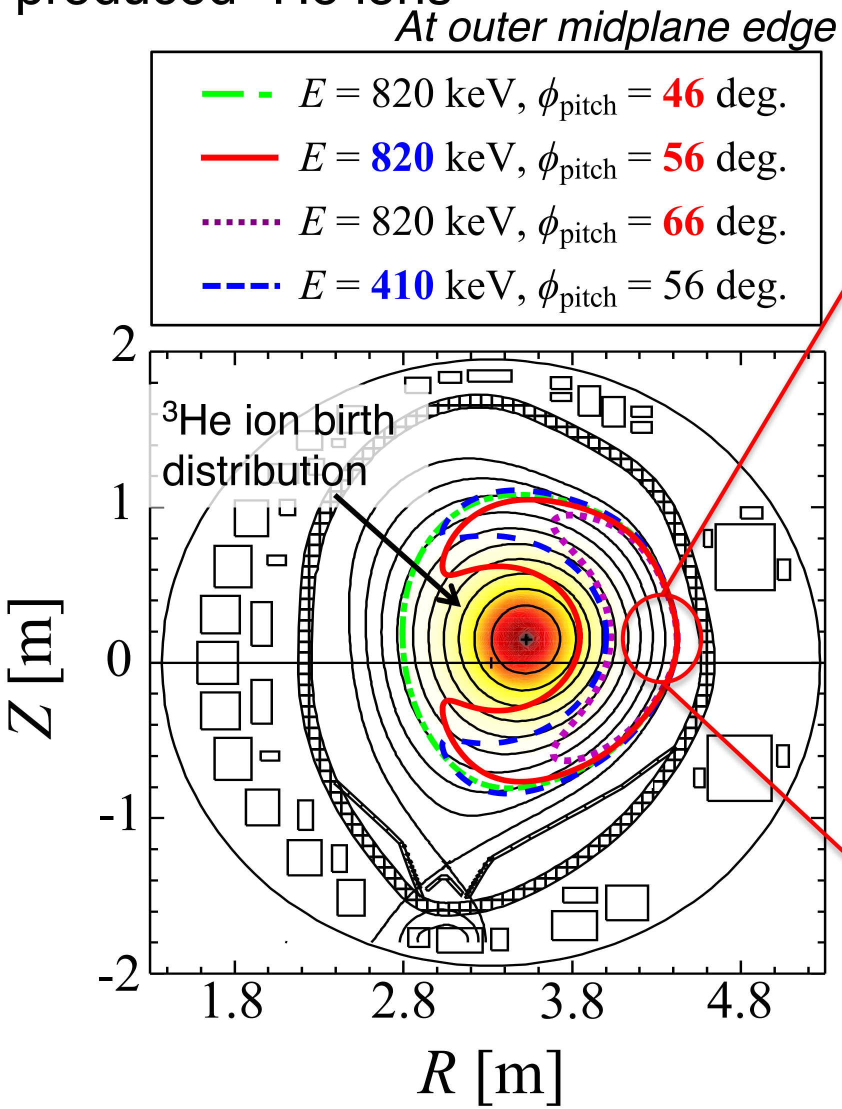


- N-NB injected D ions can destabilize slow waves propagating in the oblique direction

Non-thermal ion velocity distribution can be formed near outer midplane edge

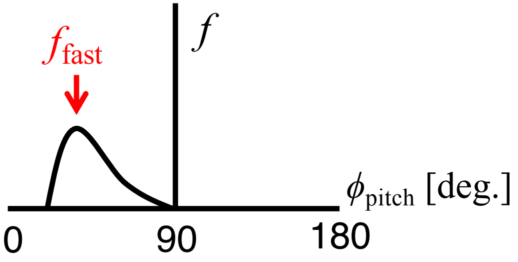
- Guiding-center orbits of DD fusion produced ^{3}He ions

$$D + D \rightarrow {}^3He(0.82\ MeV) + n(2.54\ MeV)$$
$$\rightarrow T(1.01\ MeV) + H(3.03\ MeV)$$

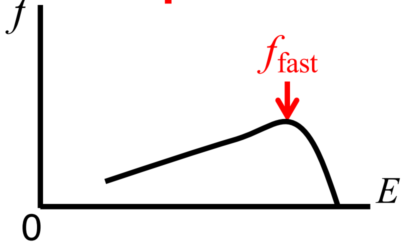


✓ **f_{fast} at outer midplane edge**

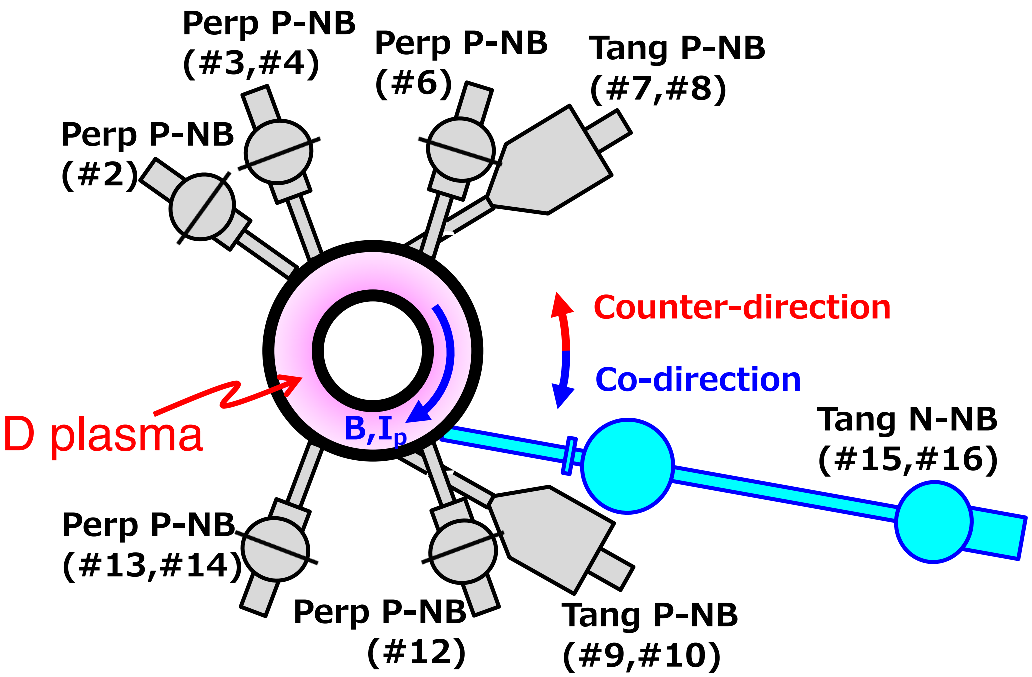
- **Pitch-angle anisotropy**



- **Bump-on tail structure**



JT-60U tokamak



Machine Parameters

Toroidal Field	4 T
Plasma Current	3 MA
Major Radius	3.4 m
Minor Radius	1 m
Plasma Volume	90 m^3
Pulse Length	65 sec
Heating Power (NB)	40 MW
Heating Power (RF)	15 MW

- Positive-D-ion source (P-NB) : ~80 keV
  - ✓ Perpendicular NB (Perp. P-NB) × 7
  - ✓ Tangential NB (Tang. P-NB) × 4
- Negative-D-ion source (N-NB) : ~350 keV
  - ✓ Tangential NB (Tang. N-NB) × 2

$$\begin{aligned} \mathrm{D} + \mathrm{D} &\rightarrow {}^{3}\mathrm{He}(0.82\ \mathrm{MeV}) + \mathrm{n}(2.54\ \mathrm{MeV}) \\ &\rightarrow \mathrm{T}(1.01\ \mathrm{MeV}) + \mathrm{H}(3.03\ \mathrm{MeV}) \end{aligned}$$