Characteristics of fast ion profile with MHD activities and improvement of fast ion confinement with AE suppression by counter-ECCD in LHD

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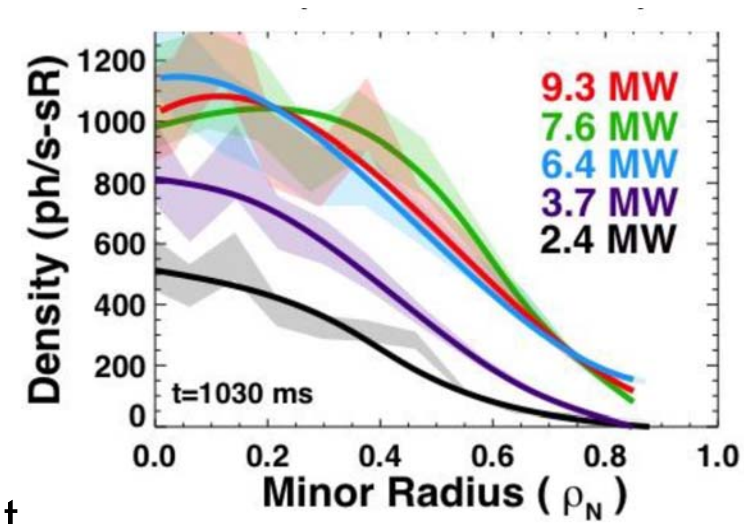
Contents

Background and Motivation

Precise prediction of EP profile in fusion burning plasmas is an important subject;

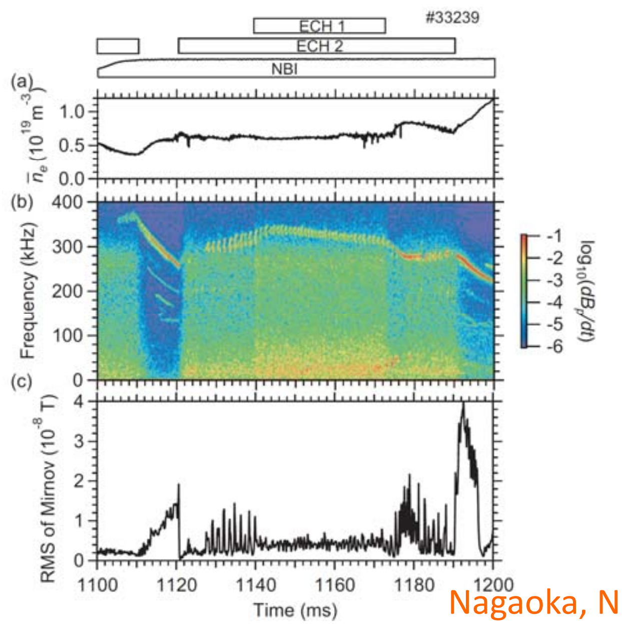
- Modeling of EP transport and EP profile with AE activities
  - kick model
  - critical gradient model/EP profile stiffness
- External control knob for EP confinement
  - RMP
  - pellet
  - ECH/ECCD



Colliins, PRL 2016

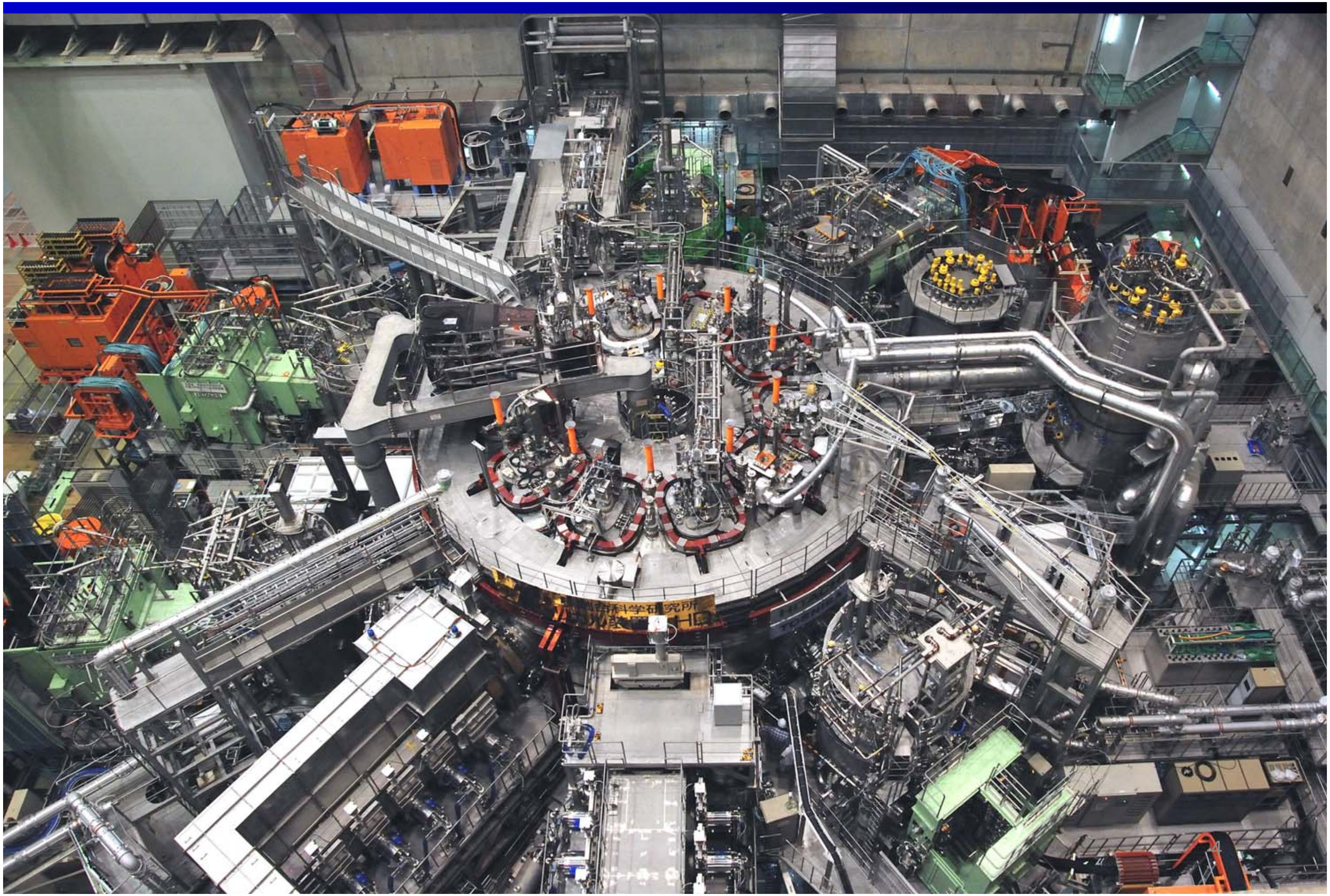
Targets of this study;

- **EP profile stiffness in 3D system**
- **ECH/ECCD impacts on EP confinement**

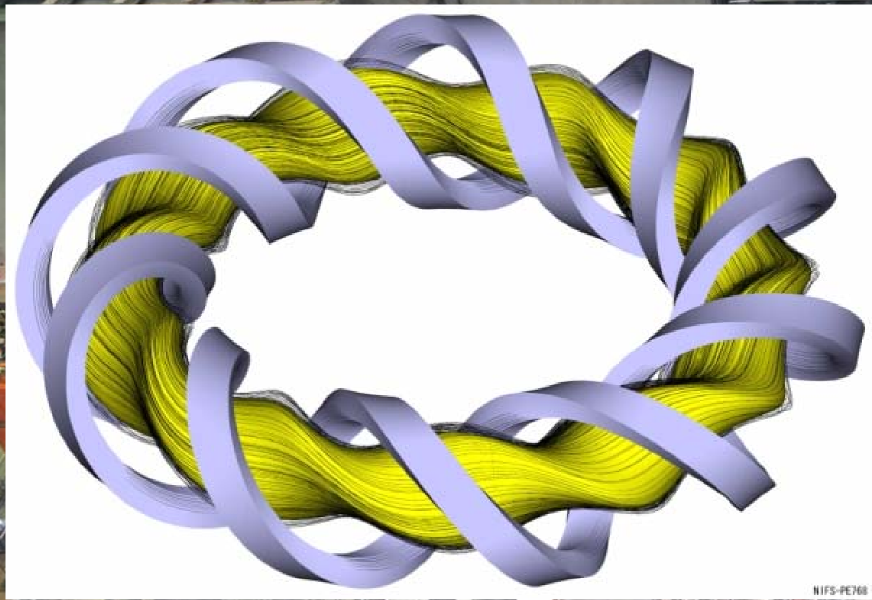


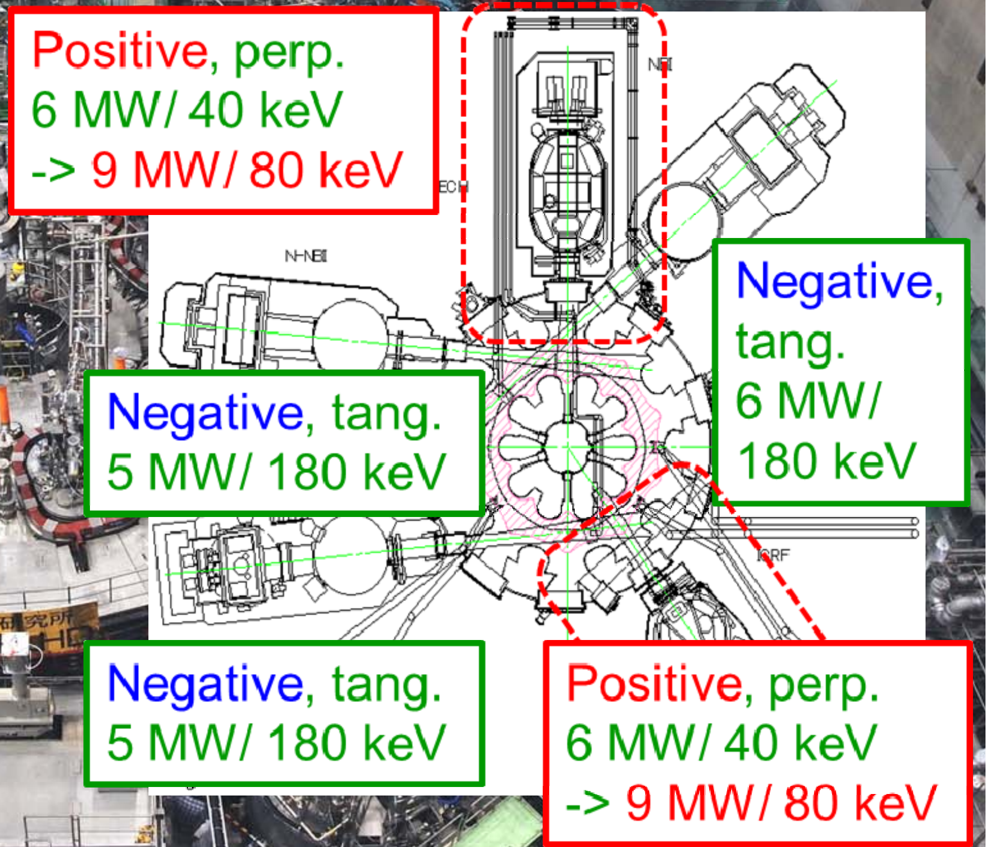
Nagaoka, NF 2013

Large Helical Device (LHD)



D-D experiment since 2017

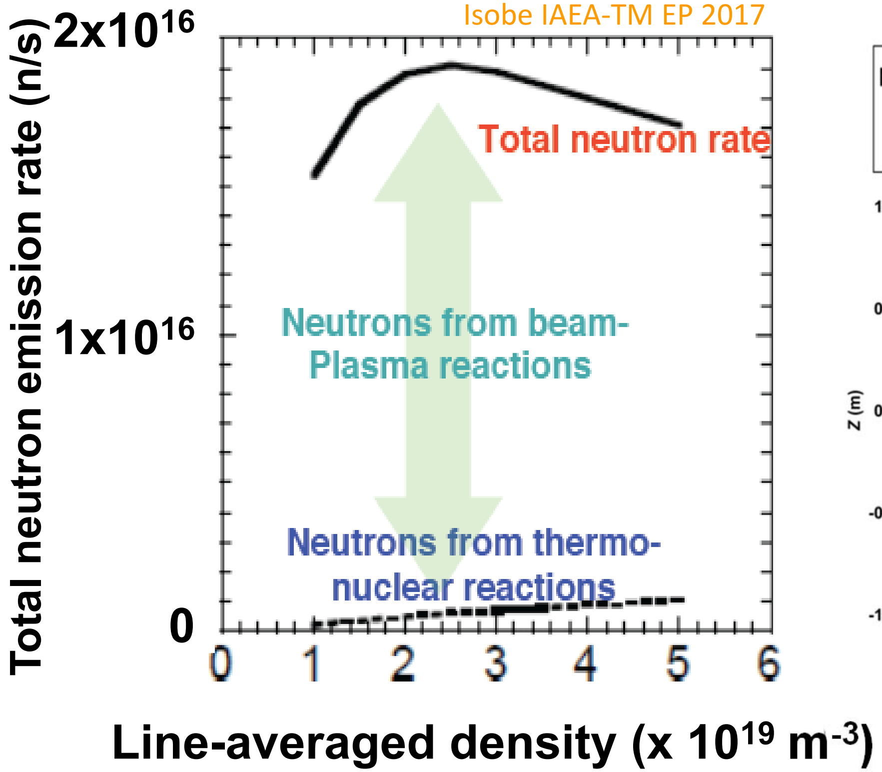


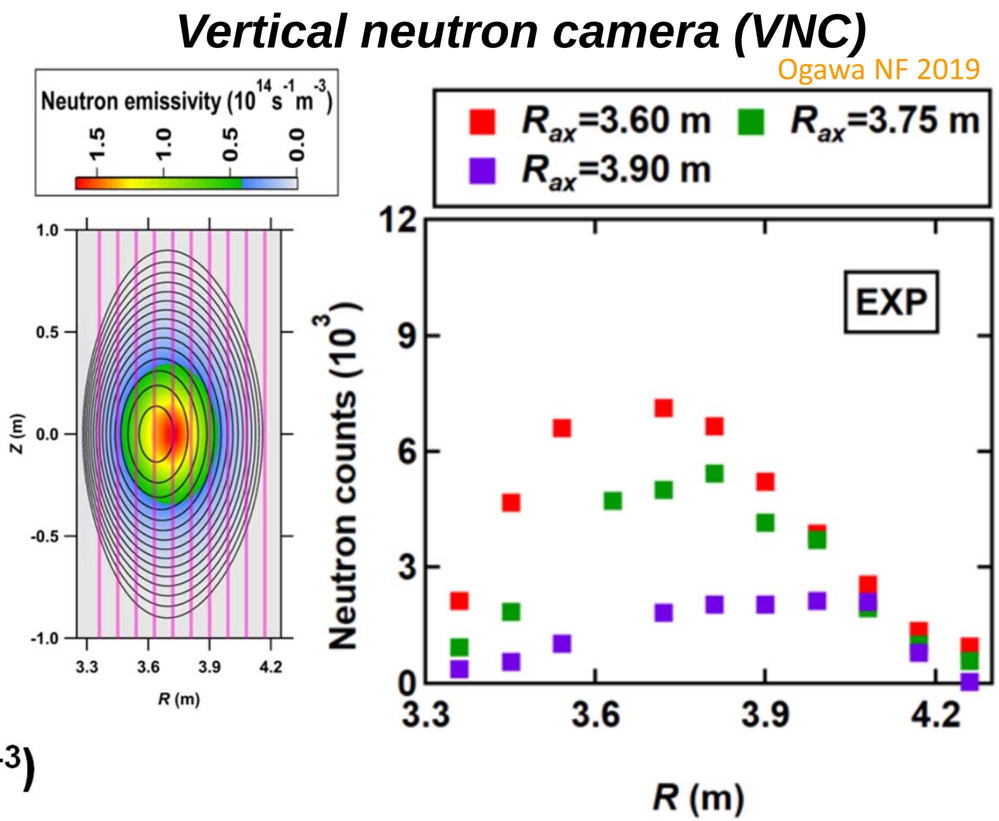


Specifications

- Helical mode numbers: *l*/*m*=2/10
- All superconducting coil system
- Plasma major radius: 3.42-4.1 m
- Plasma minor radius: 0.63 m
- Plasma volume: 30 m^3
- Toroidal field strength: 3 T
- 20 RMP coils
- **H and D beams from all NBIs**

Neutron Emission is dominated by beam-plasma interaction





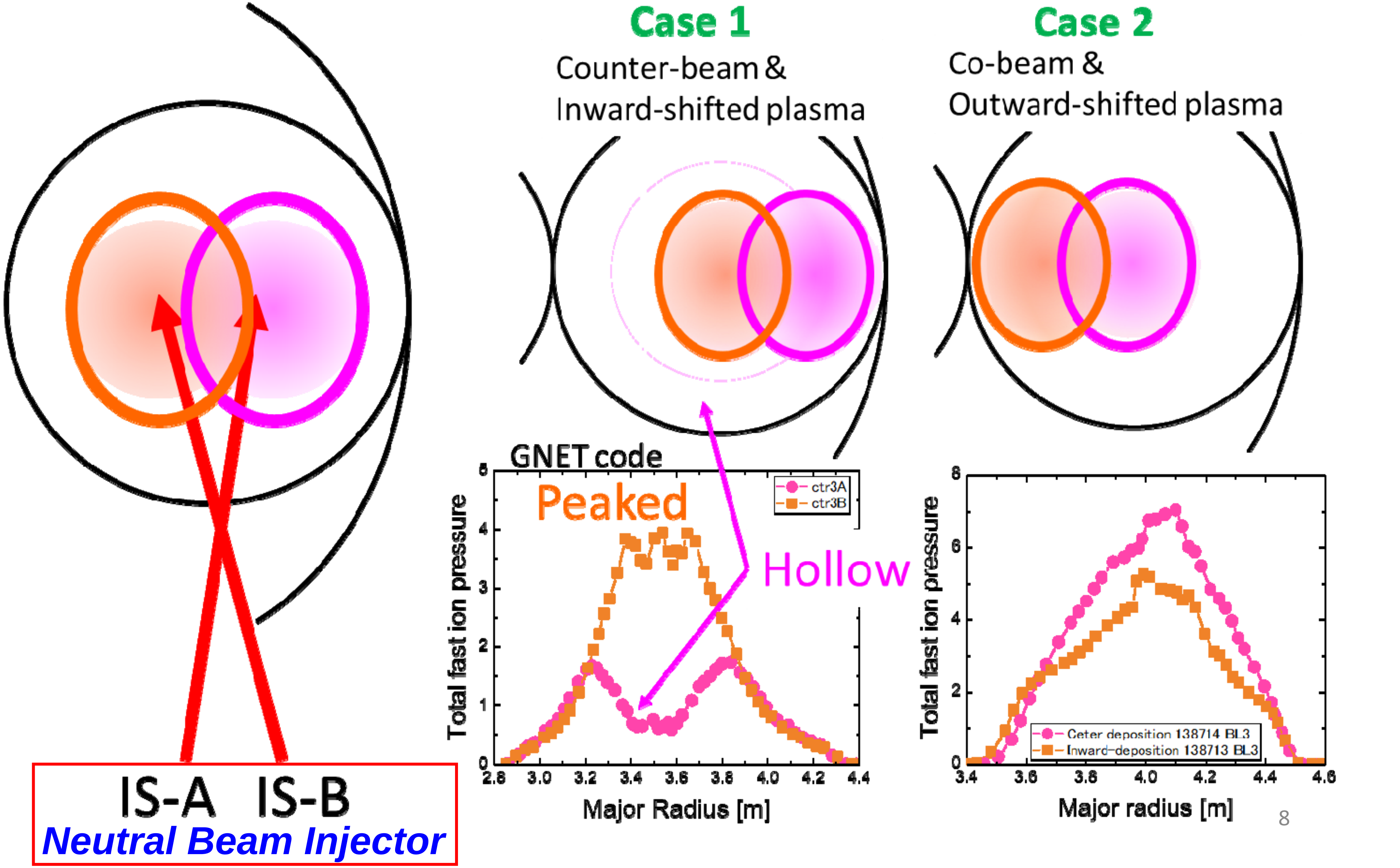
- Beam-Plasma interaction dominates the neutron emission

＝＞Neutron emission corresponds to EP density

- Vertical Neutron Camera reveals EP density profile

Contents

Beam deposition profile can be controlled with combination of IS operation and plasma position



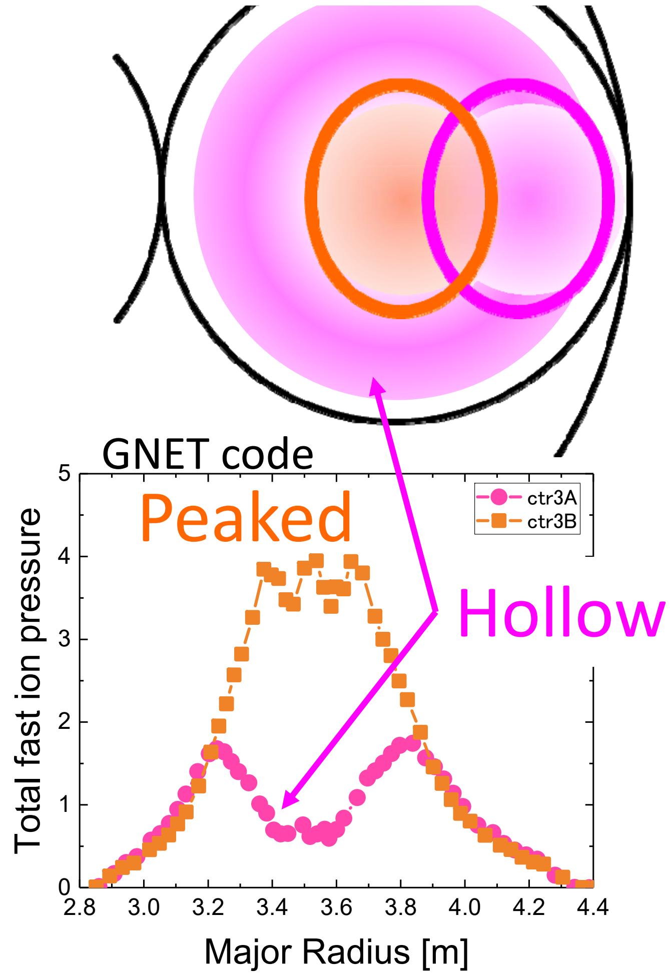
Demonstration of beam deposition control

Magnetic field dependence

High B (Bax=-2.75T)
Low beam beta (β_{beam}~0.1%)
$$V_b < V_A$$

Case 1

Counter-beam &
Inward-shifted plasma



Demonstration of beam deposition control

High B (Bax=-2.75T)
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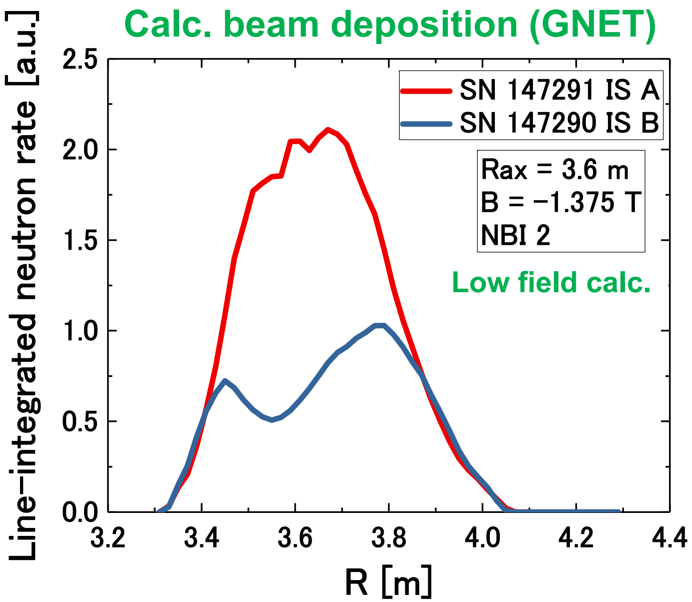
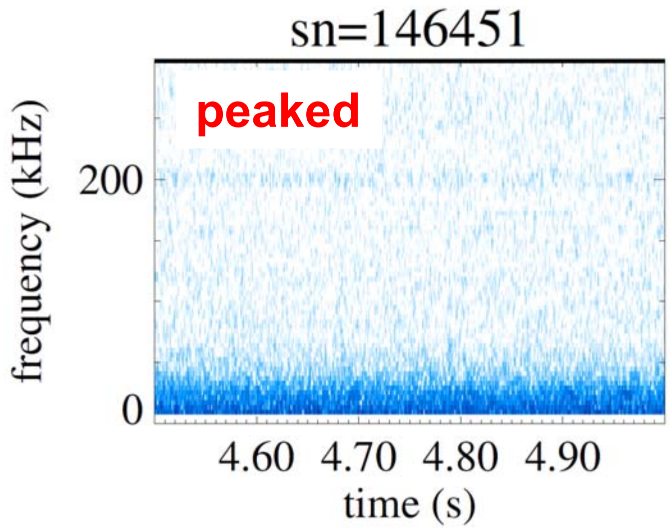
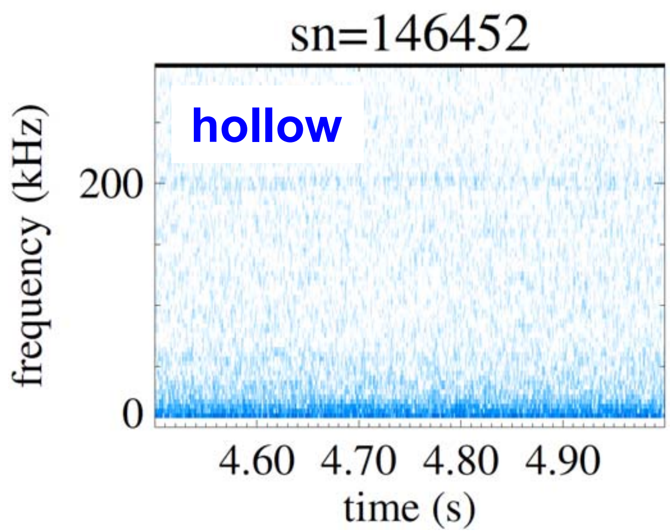


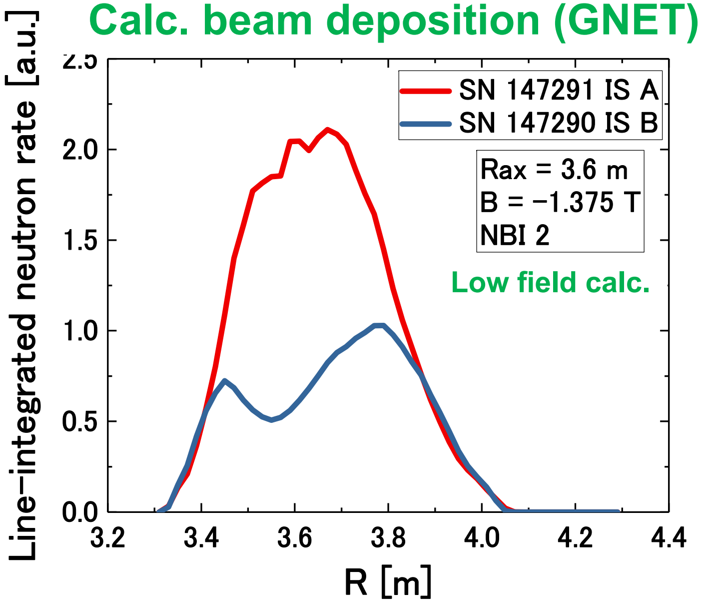


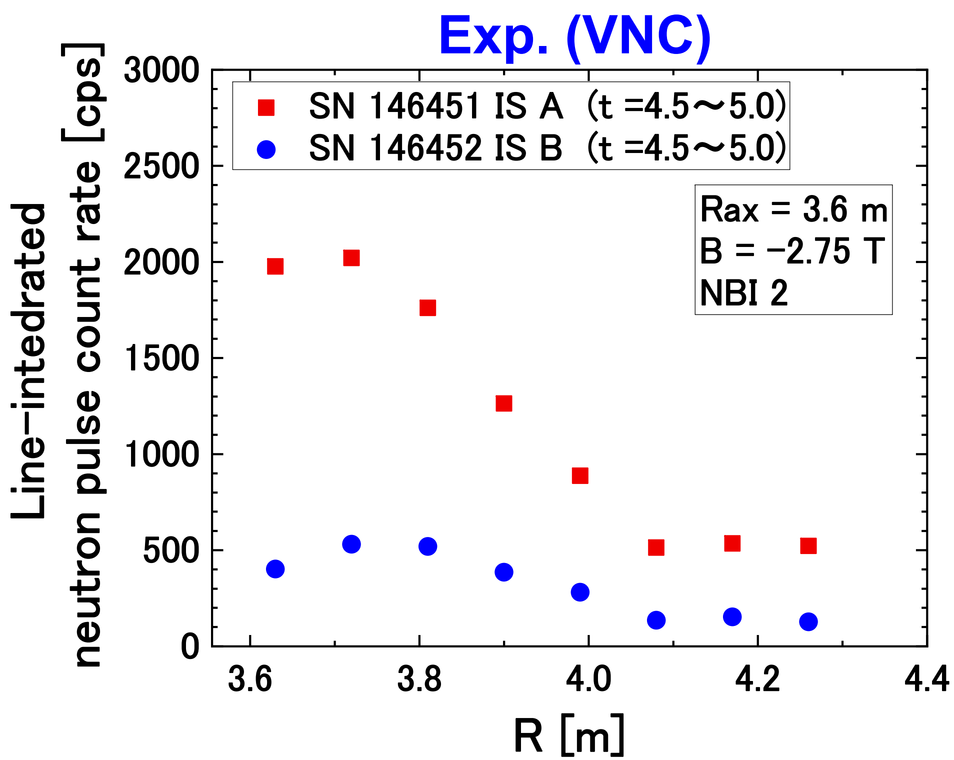


- No significant AE activities can be seen in both peaked and hollow beam deposition cases

Demonstration of beam deposition control

High B (Bax=-2.75T)
Low beam beta (β_{beam}~0.1%)





- Neutron emission profiles (**EP profiles**) depend on the beam deposition profile

=>> Beam deposition control was demonstrated

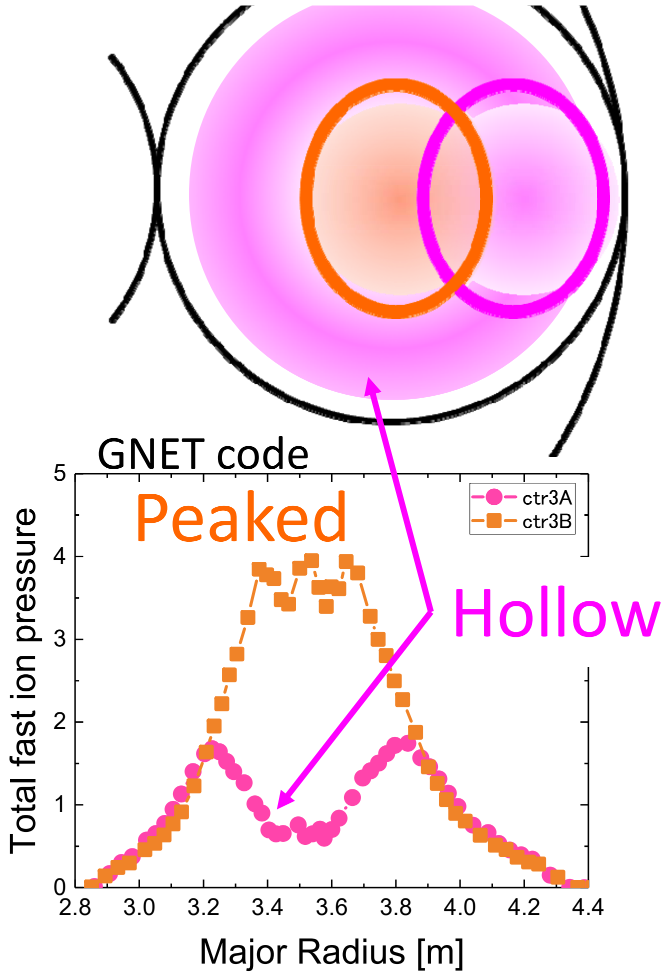
Demonstration of beam deposition control

Magnetic field dependence

Low B (Bax=-1.375T)
higher beam beta
$V_b > V_A$

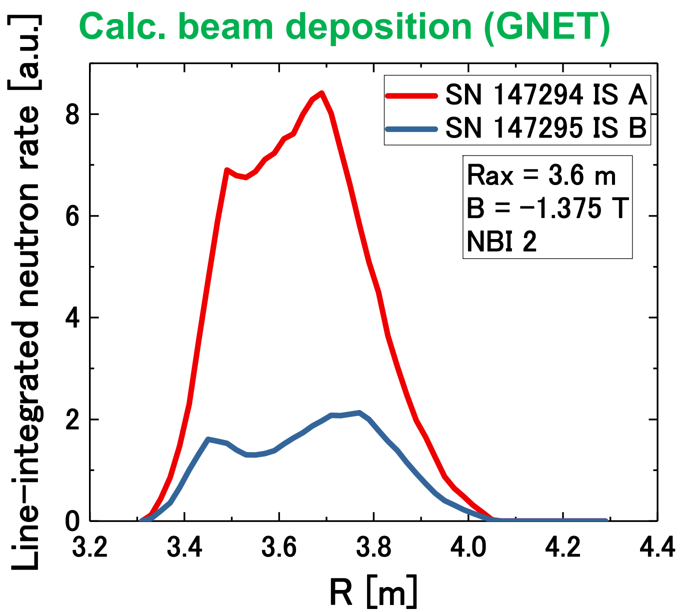
Case 1

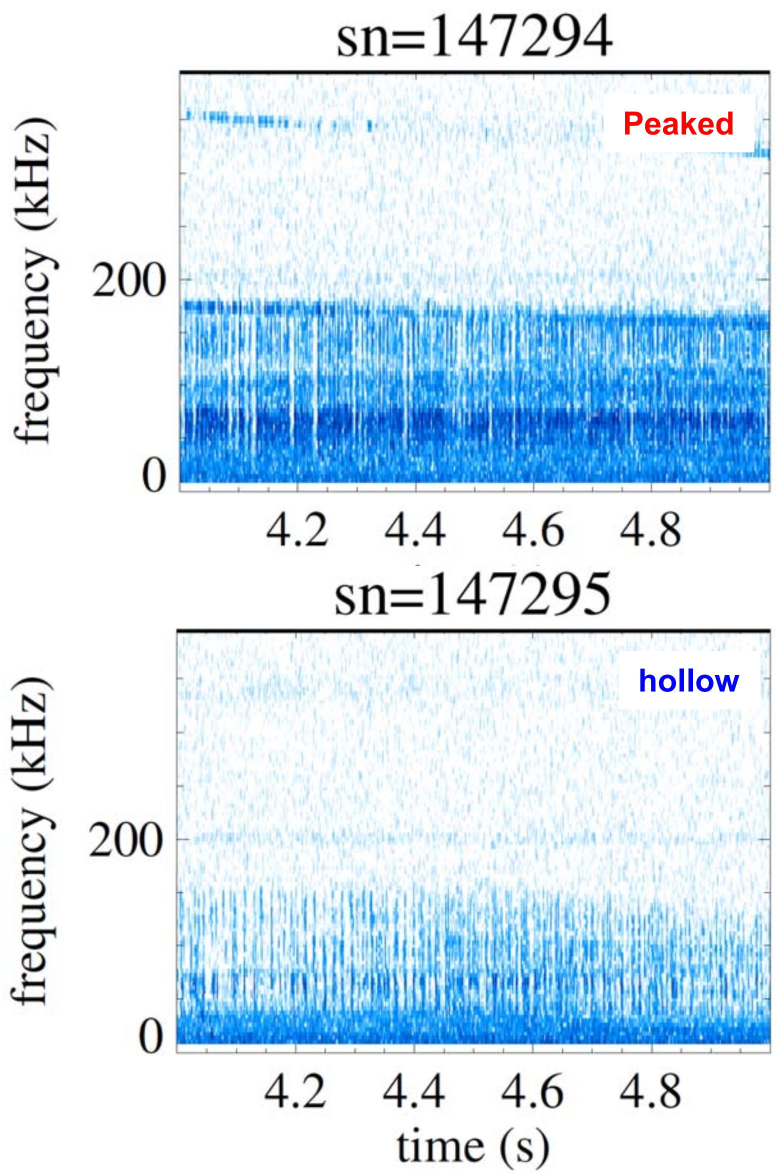
Counter-beam &
Inward-shifted plasma



AE activities depends on beam deposition profile

Low B (Bax=-1.375T)
Higher beam beta

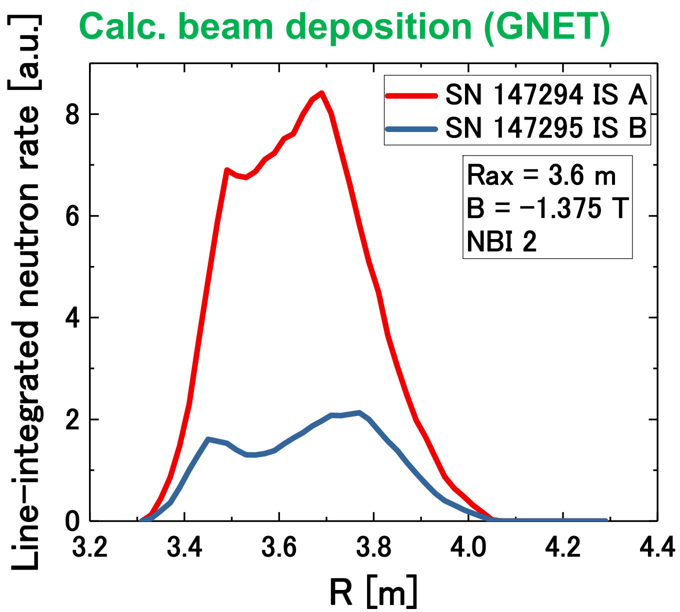


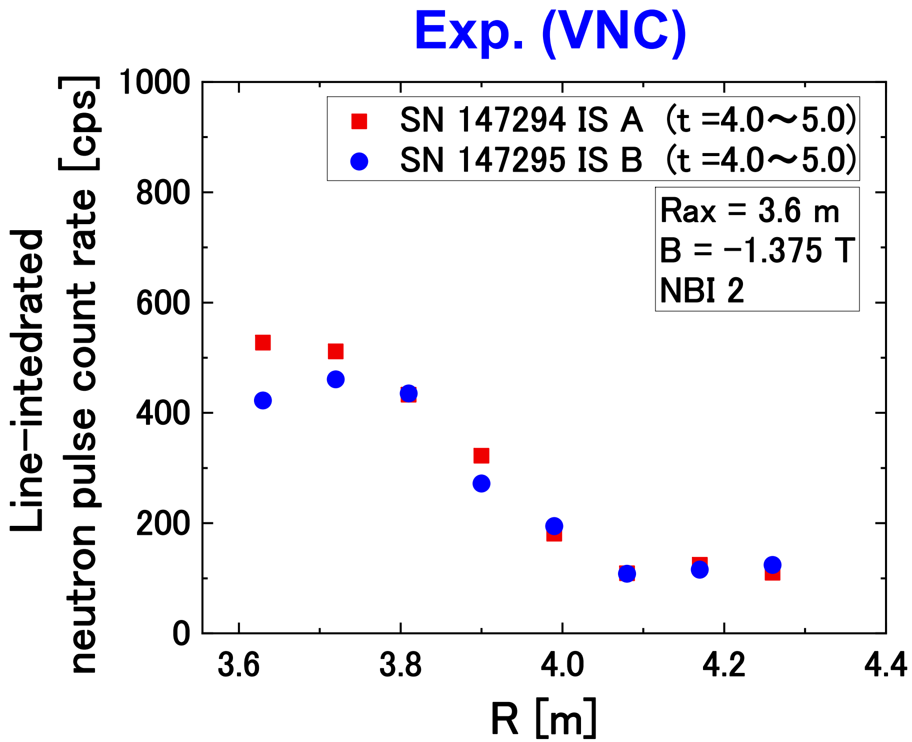


- Many MHD activities in AE frequency range can be seen in both cases
- MHD activities are stronger in peaked beam deposition case

AE activities depends on beam deposition profile

Low B (Bax=-1.375T)
Higher beam beta

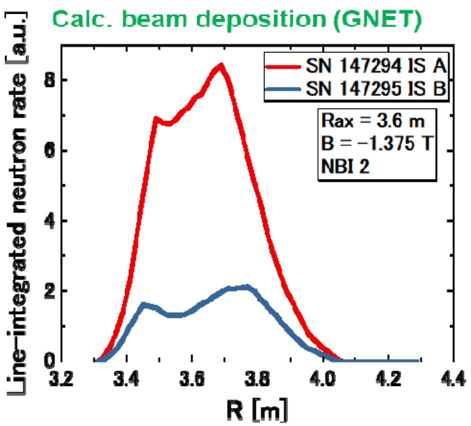


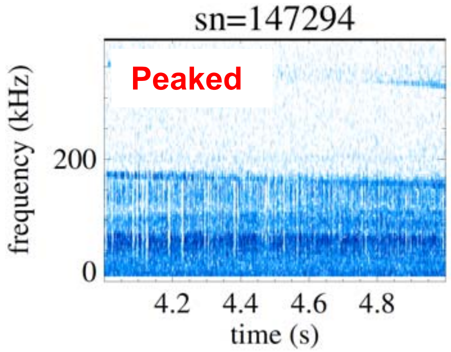


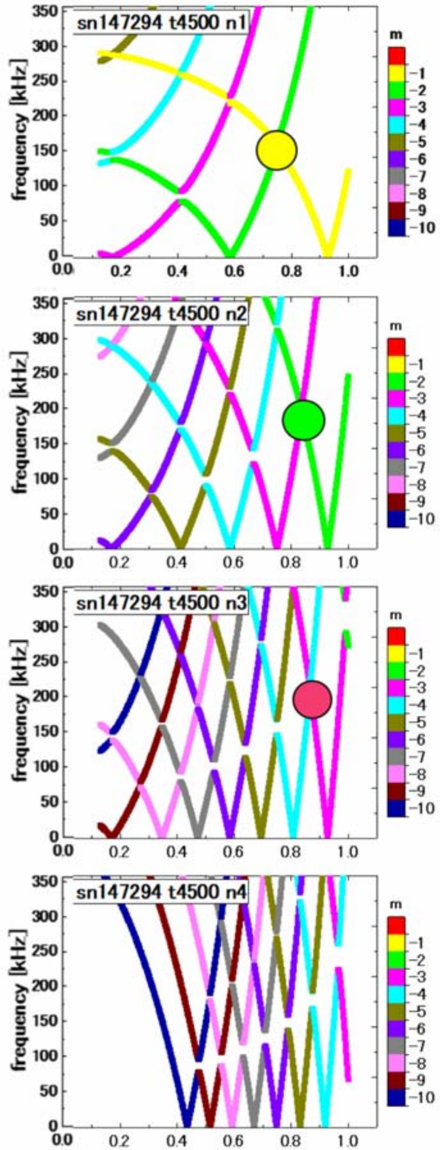
- Similar neutron emission profiles are observed between peaked and hollow beam deposition profile cases.

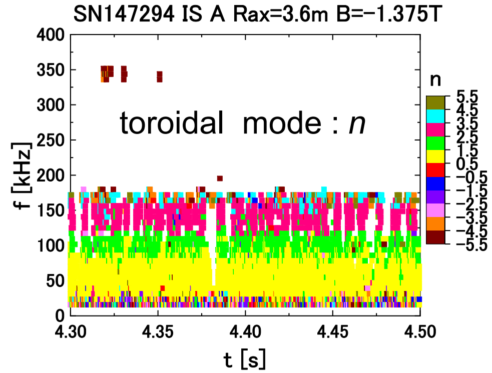
=>> EP profile stiffness with AE activities

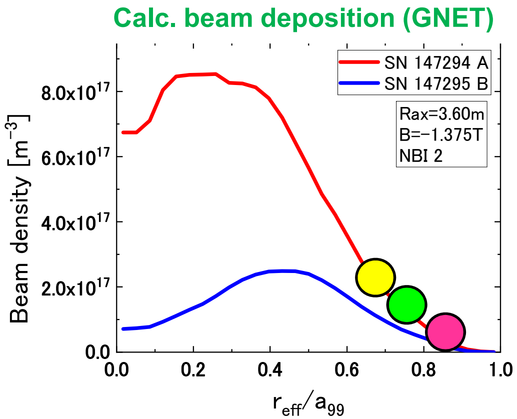
AE Mode analyses

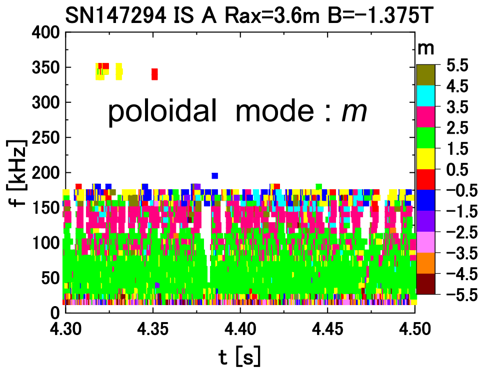






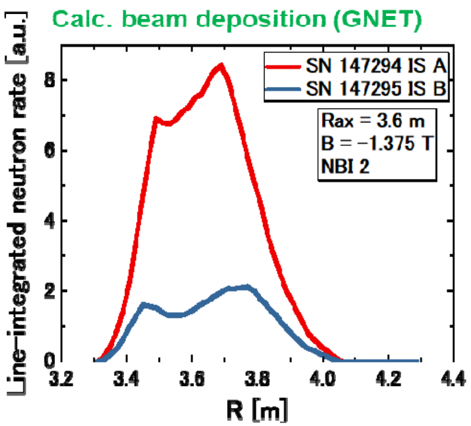


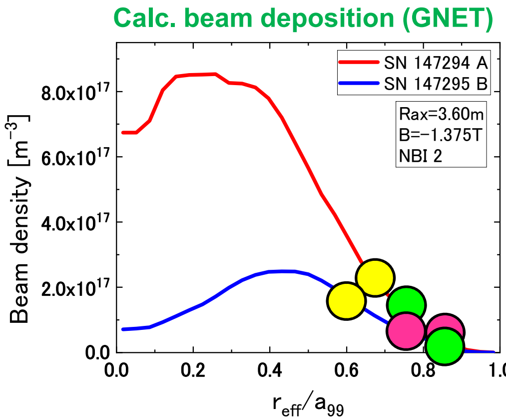


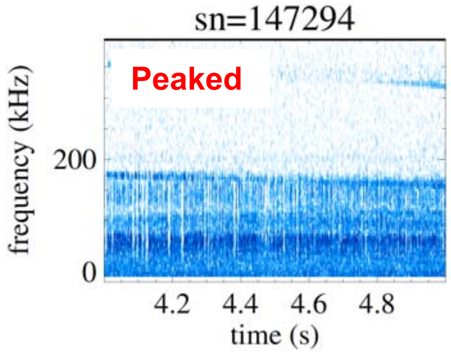


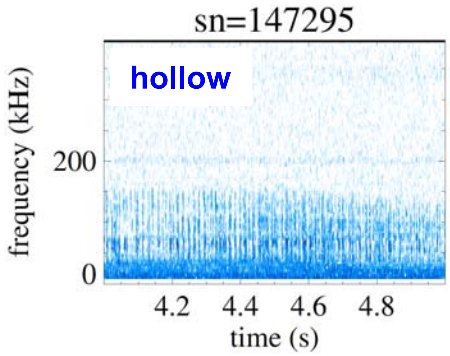
- AEs near the edge are excited

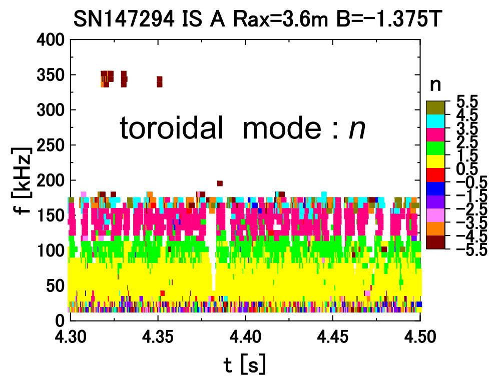
AE Mode analyses

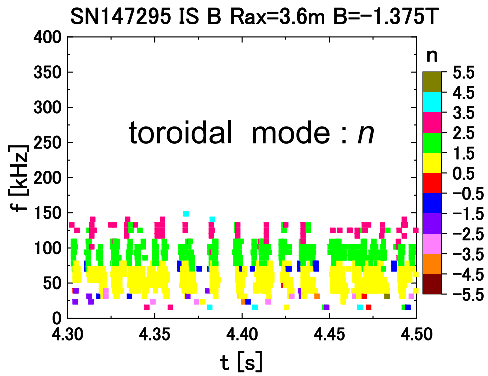


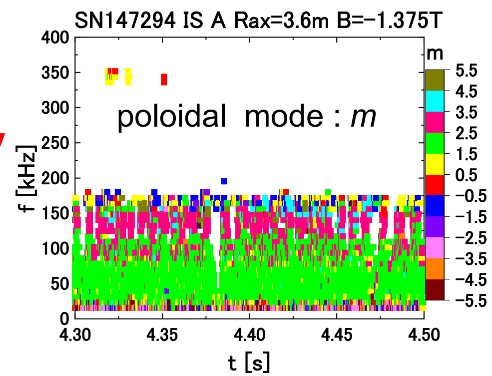


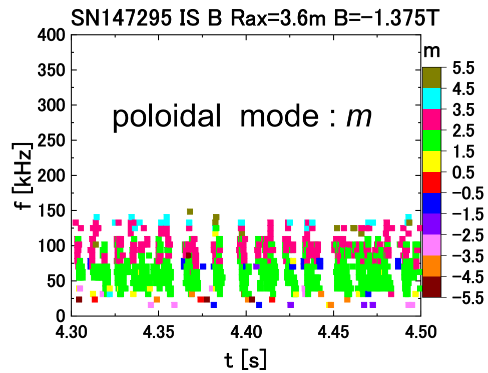












- **EP profile is affected by the AE near the edge**

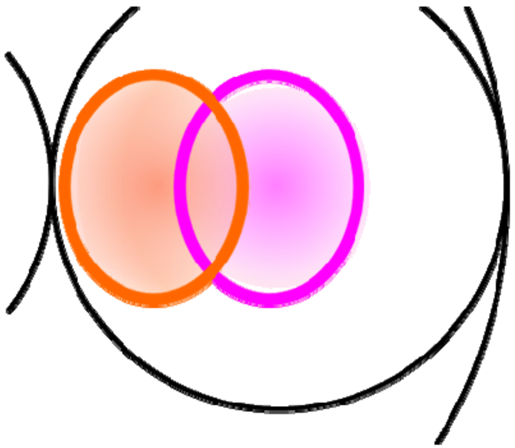
EP confinement with beam deposition control

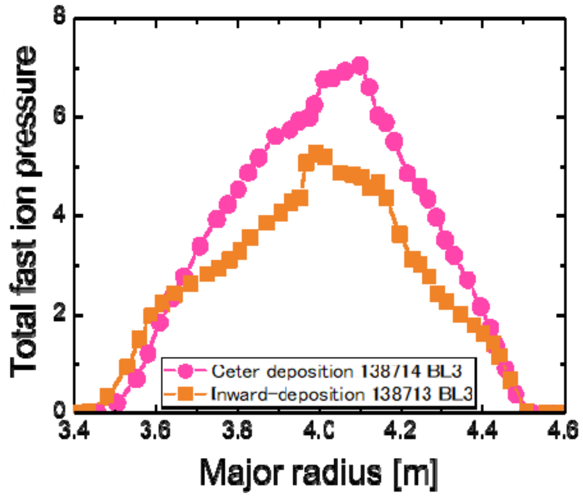
Case 2

Co-beam &
Outward-shifted plasma

Density dependence

Low B (Bax=-1.375T)
higher beam beta



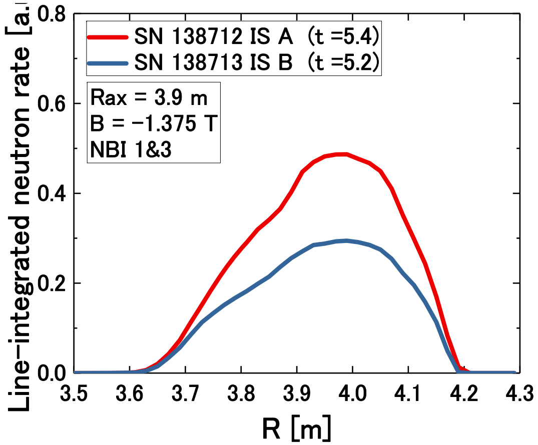


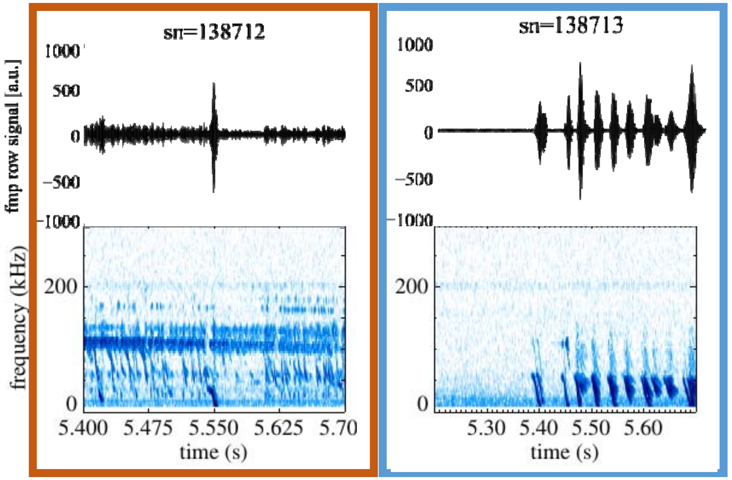
AE activities depend on beam deposition profile

$n_e \sim 0.4 \times 10^{19}\ m^{-3}$

- Bursting AEs can be seen in both cases
- Different burst intervals and different frequency range

Calc. beam deposition (GNET)

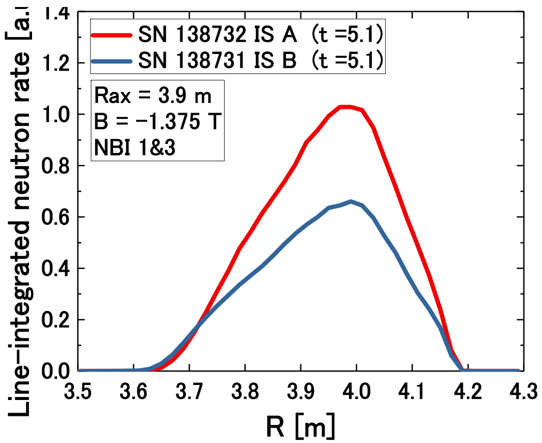


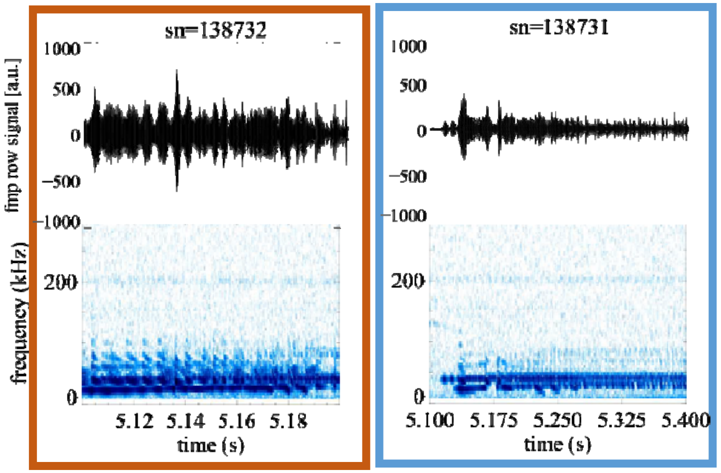


$n_e \sim 1.4 \times 10^{19}\ m^{-3}$

- AE activities with larger amplitude and wider frequency range was observed with peaked beam deposition condition

Calc. beam deposition (GNET)





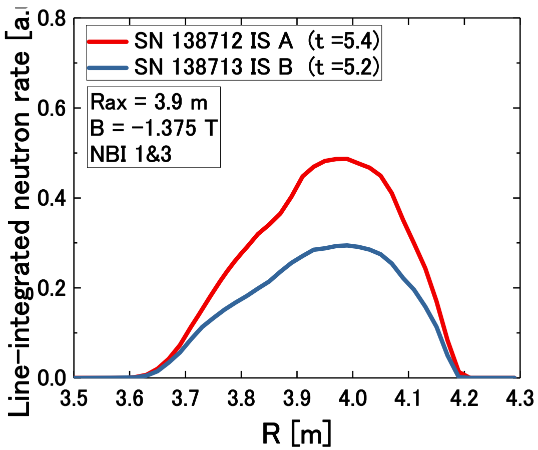
EP profile with beam deposition control

Low B (Bax=-1.375T)
Higher beam beta

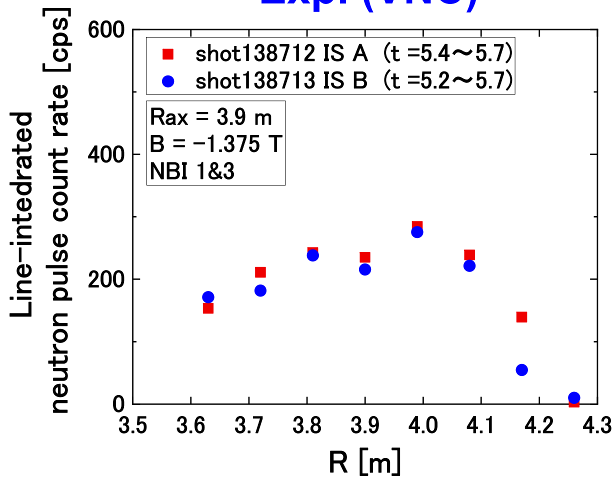
n_e~0. 4×10^{19} m^{-3}

- Neutron emission profiles are almost identical with different beam deposition conditions
=> EP profile stiffness

Calc. beam deposition (GNET)



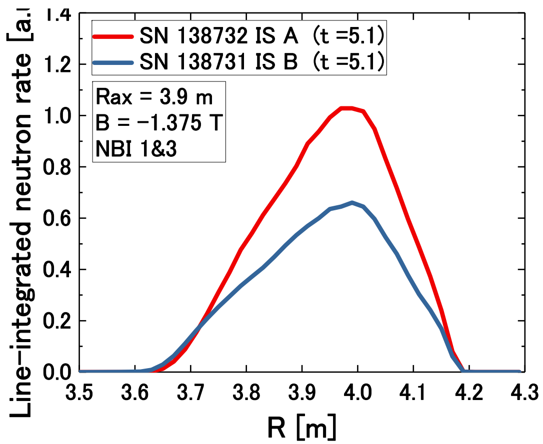
Exp. (VNC)



n_e~1.4×10^{19} m^{-3}

- Different neutron emission profiles are observed in the higher density regime
=> EP profile depends on the beam deposition profile

Calc. beam deposition (GNET)



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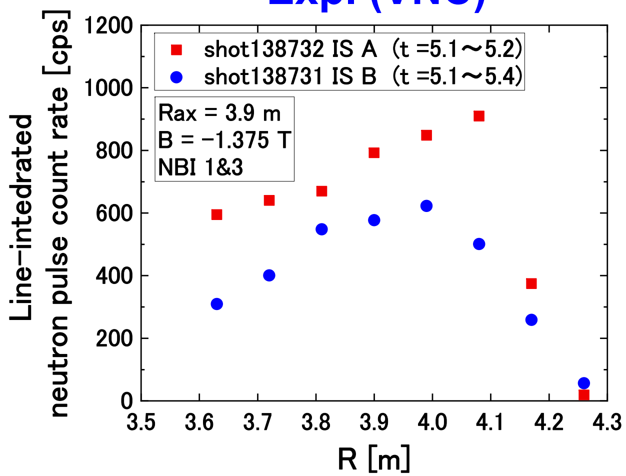
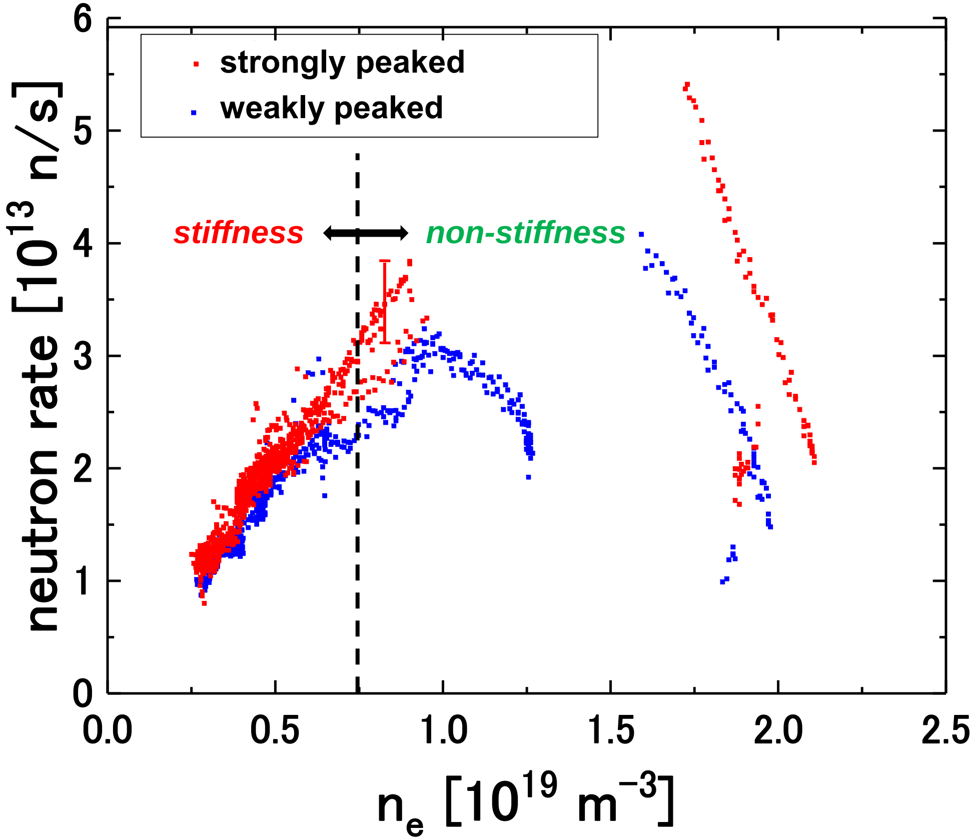


Density dependence of neutron emission rate



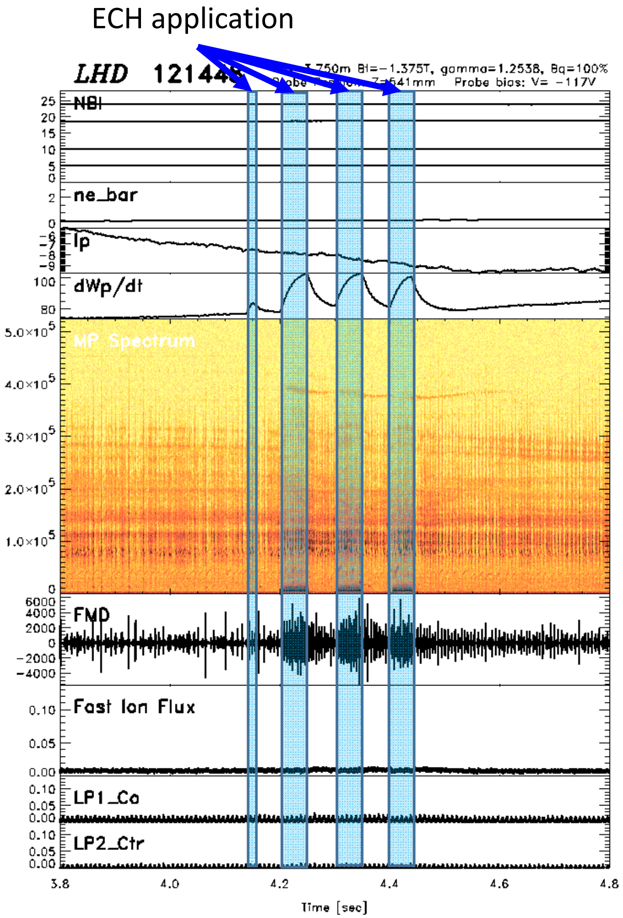
- Neutron rate does not depend on the beam deposition profile in low density regime
  => EP profile stiffness
- Difference in neutron rate can be seen in higher density regime
  => ***Density dependence of EP profile stiffness was identified***

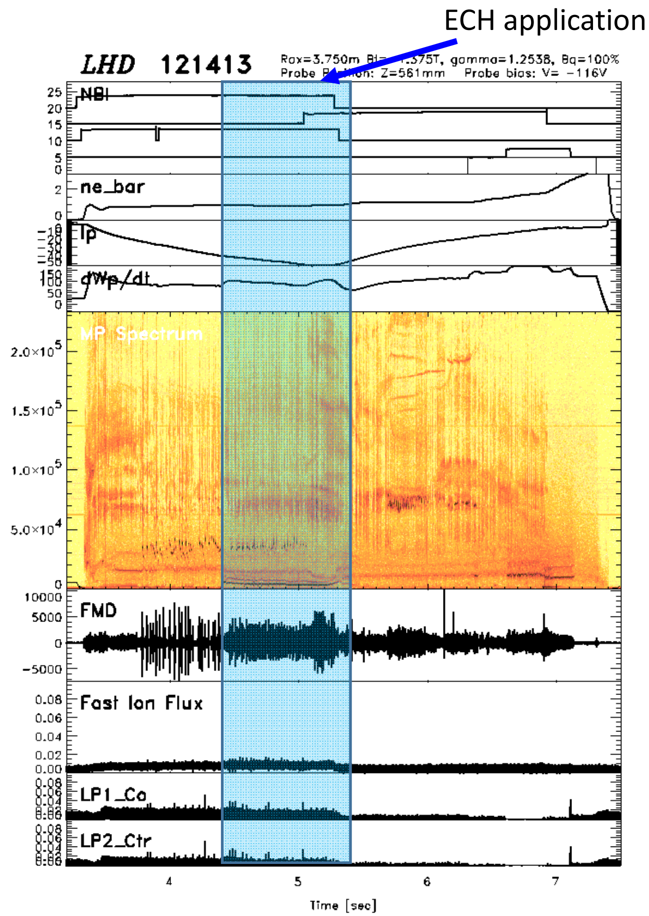
Contents

- Introduction
  - ✓ Back ground and motivation
  - ✓ D-D experiments in LHD
- Experimental Results
  - ✓ Control of beam deposition profile
  - ✓ EP profile with AEs
  - ✓ AE control with ECH and ECCD
- Summary

A variety of AE responses to **ECH** application

Destabilizations of MHD activities

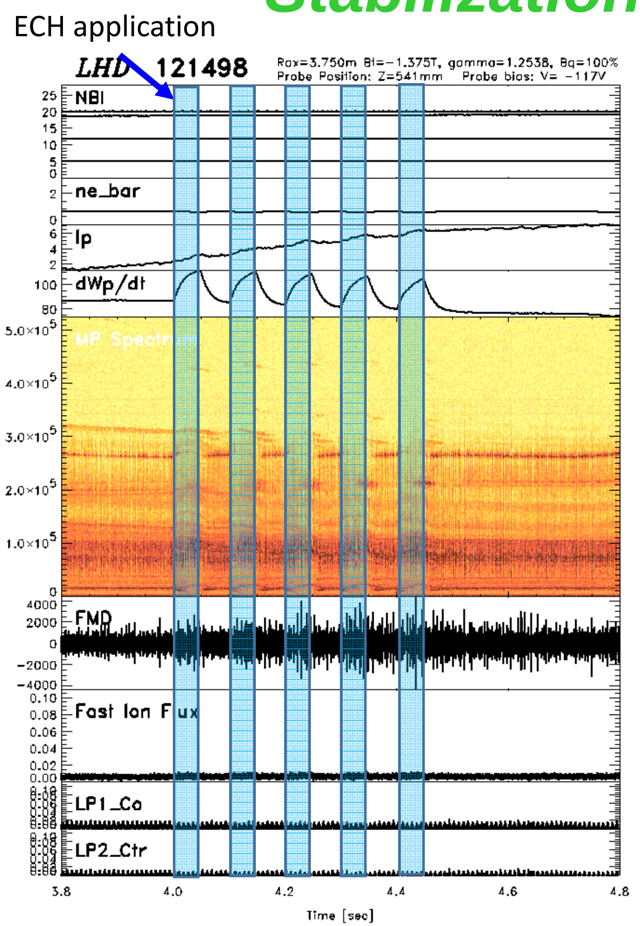


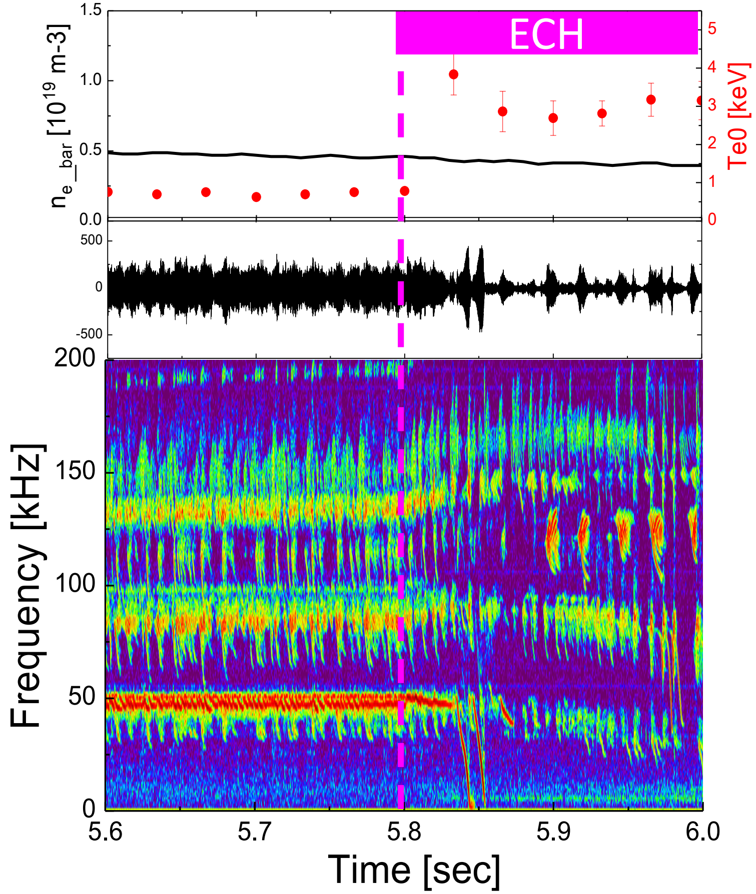


- ECH application destabilizes MHD activities in low frequency and AE frequency ranges in some conditions

A variety of AE responses to ECH application

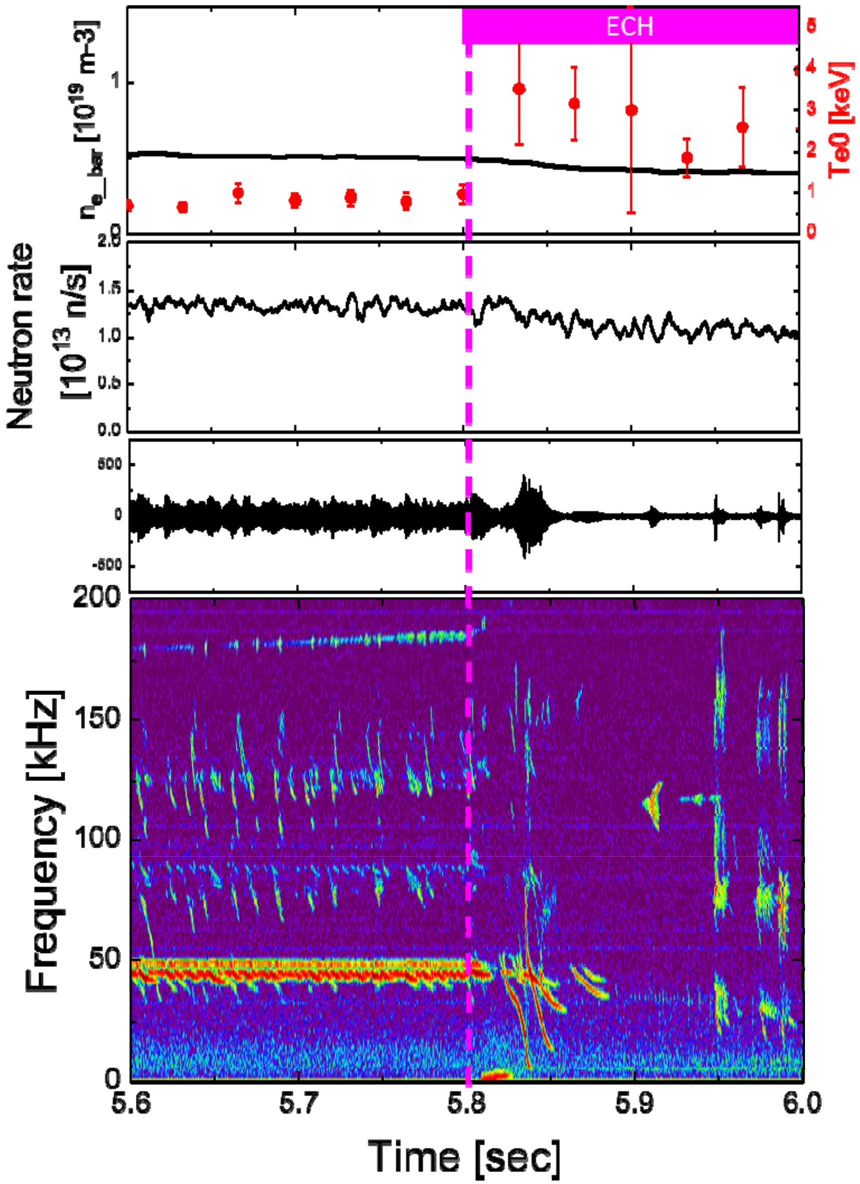
Stabilizations of MHD activities





- ECH application stabilizes MHD activities in AE frequency ranges in some conditions

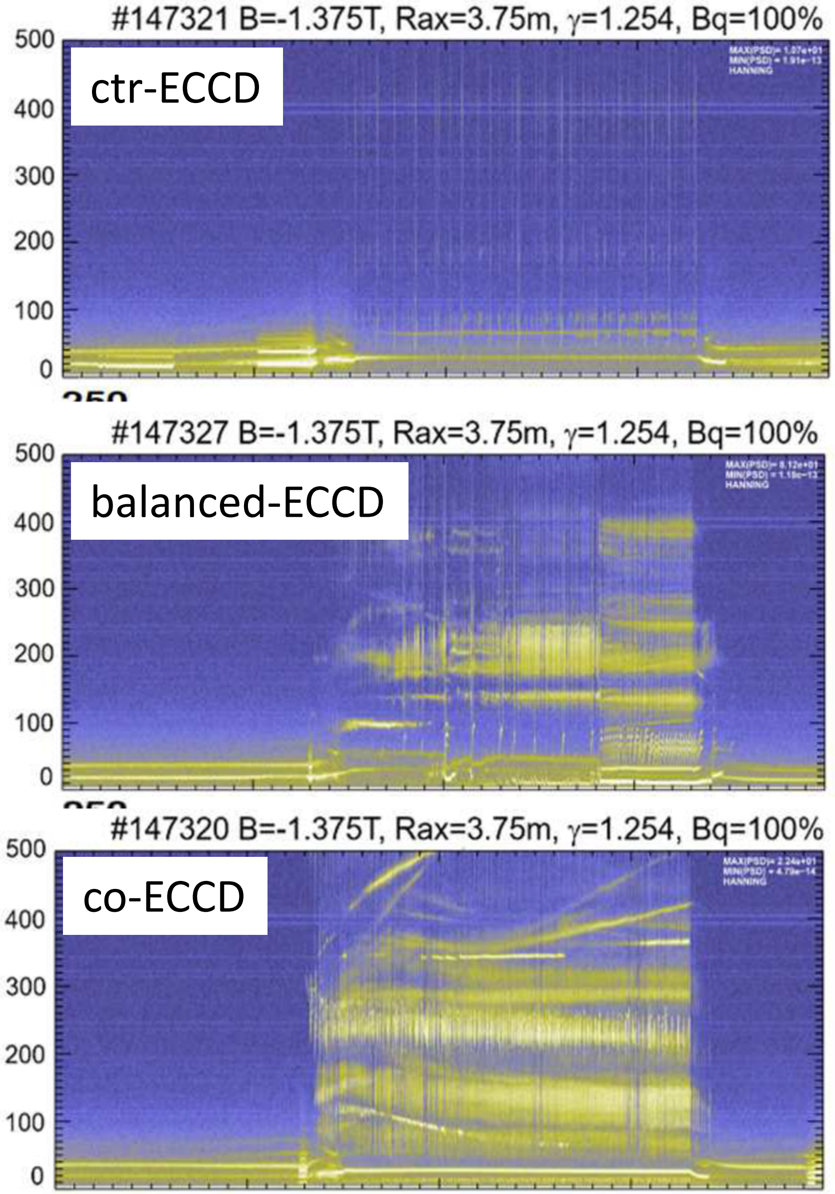
Effect of **ECH** application to EP confinement

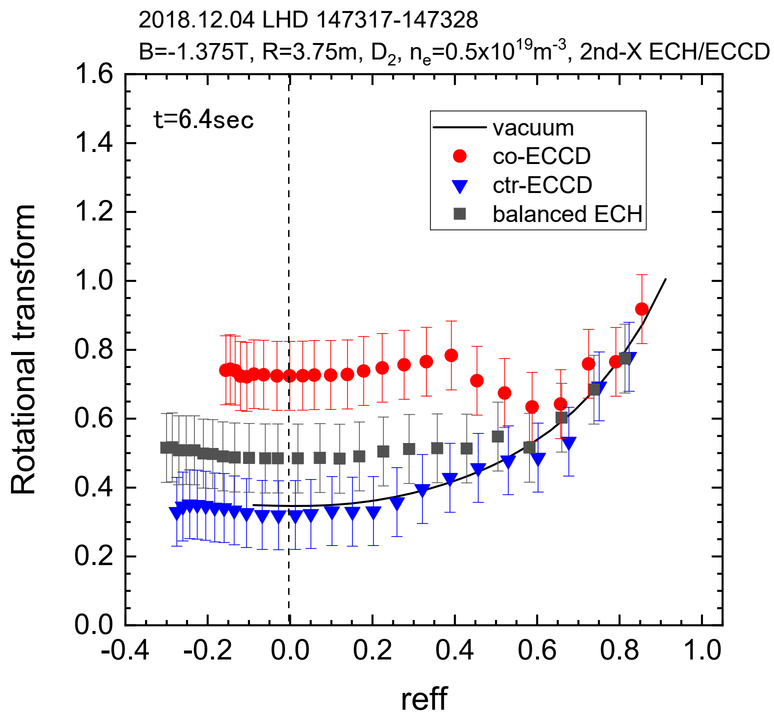


- Stabilization of AE activities was observed when ECH was applied
- Te0 increases clearly with ECH application
- However, no increase of neutron rate was observed.

=> Impact of ECH application on EP confinement is **NOT** clear, while AE activities are changed.

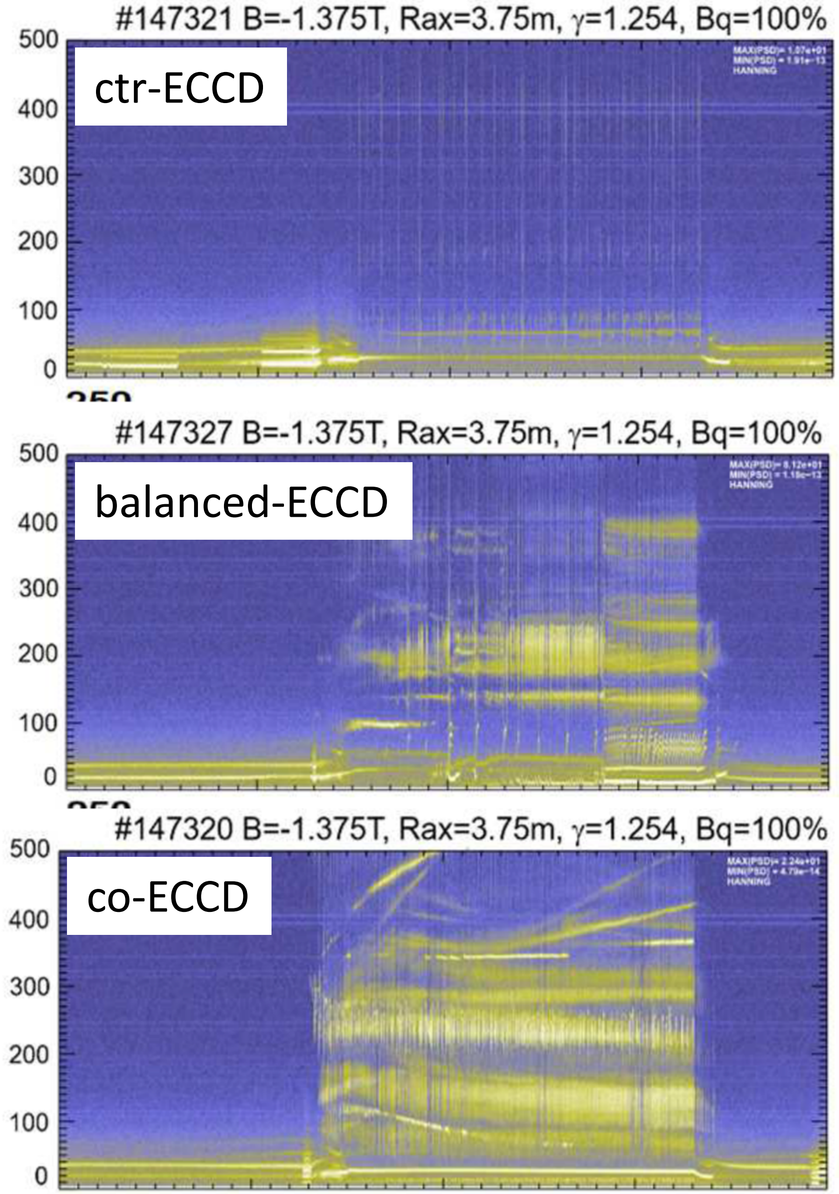
Clear AE responses to ECCD applications

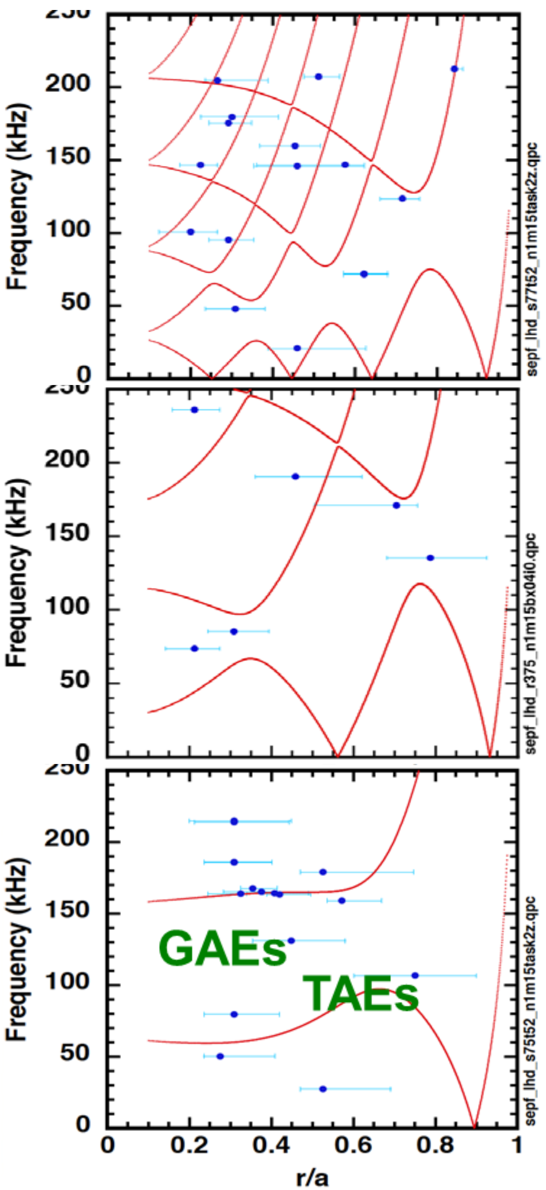




- ECCD can control iota profile
- **AE stabilization with Ctr-ECCD** application was observed
- **AE destabilization with Co-ECCD** was observed

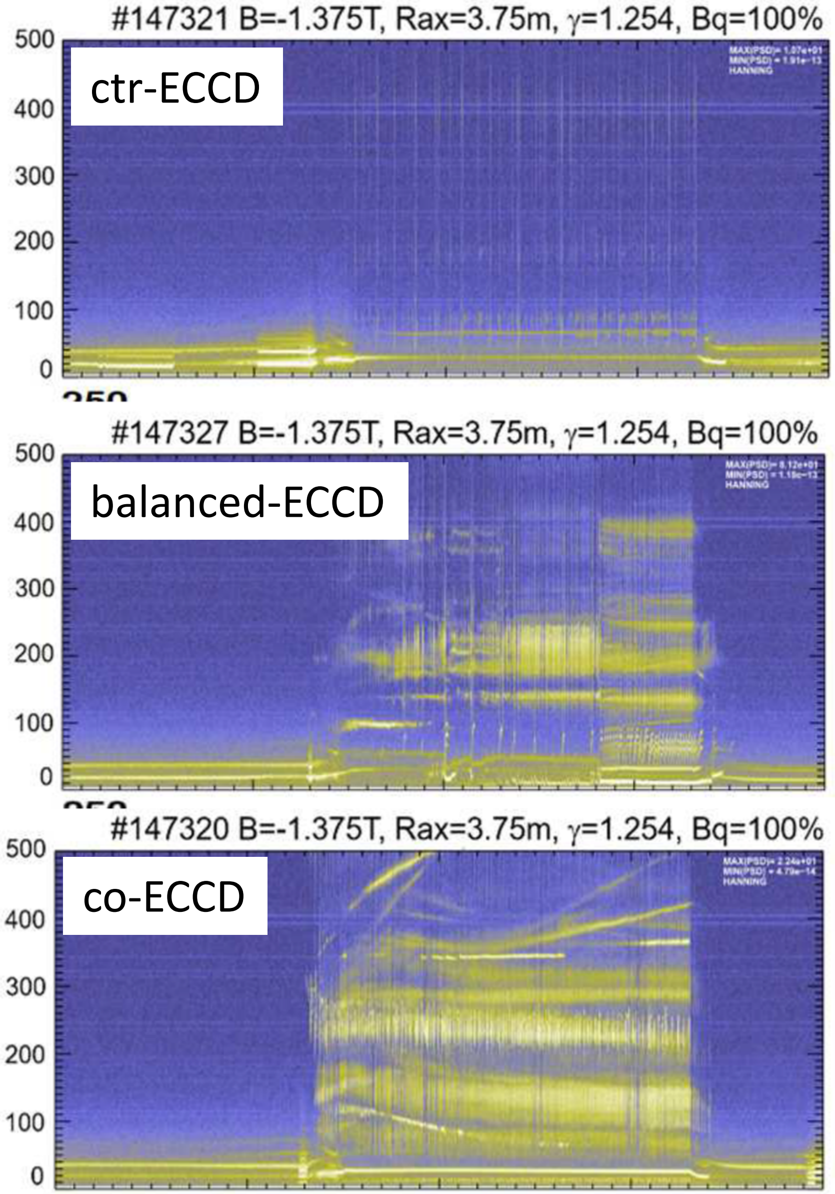
Clear AE responses to **ECCD** applications

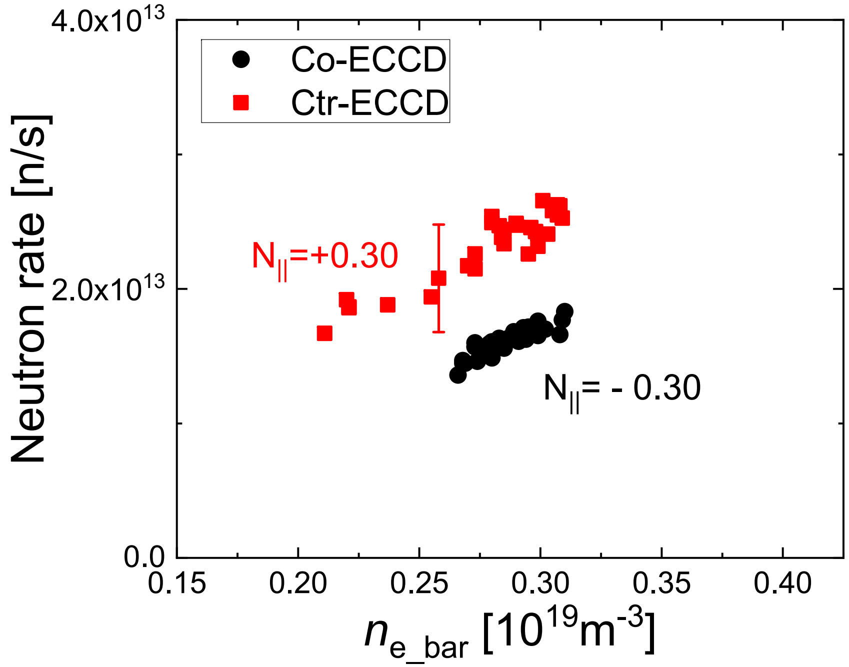




- **Change of Alfven continuum** contributes the AE stabilization (Yamamoto, IAEA-FEC, Nagasaki, EPS2019)
- **Increase of continuum damping** is suggested (*P1-1 J. Varela*)

Better EP confinement with **ctr-ECCD**





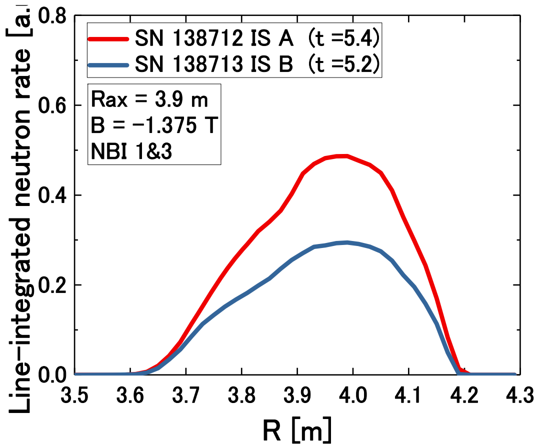
- Neutron emission rate strongly depends on ECCD direction

⇒ ECCD effect on EP confinement

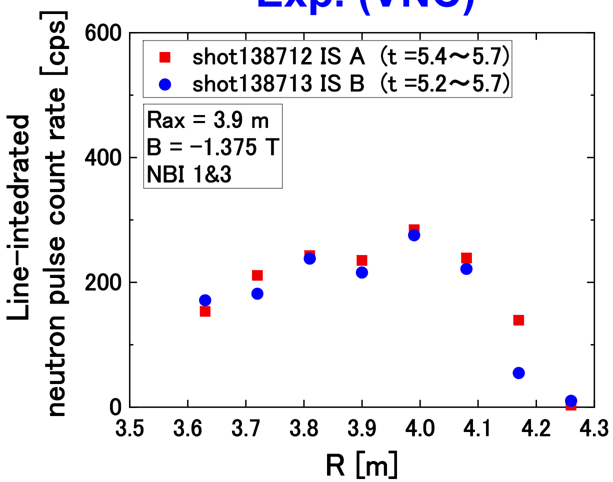
⇒ Ctr-ECCD may enhance EP confinement with suppression of AEs

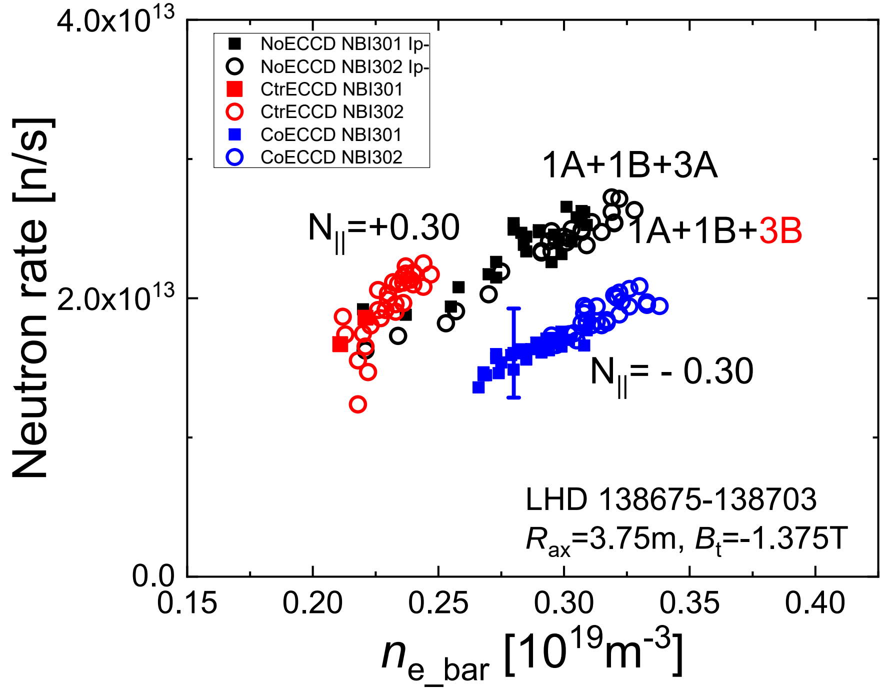
ECCD may violate EP profile stiffness

Calc. beam deposition (GNET)



Exp. (VNC)





- Change of neutron emission rate from EP profile stiffness level was observed with ECCD application.
  => Violation of EP profile stiffness with ECCD application was identified

Summary

EP confinement with AE activities has been investigated in D-D experiment on LHD

- **Control of beam deposition profile**
  - EP profile stiffness was identified in the low density regime with low magnetic field strength
  - Density dependence of EP profile stiffness was observed
- **Impact of ECH and ECCD on AE activities and EP confinement**
  - A variety of AE responses to ECH application were observed
  - Impact of ECH on EP confinement is NOT clear
  - AE suppression and EP confinement improvement were identified with ctr-ECCD
  - ECCD may violate EP profile stiffness