Oral 14.2

Energetic-particle physics studies with an integrated set of neutron and energetic-particle diagnostics in LHD deuterium discharges

M. Isobe[1,2], K. Ogawa[1,2], S. Sangaroon[1,3], S. Kamio[1], Y. Fujiwara[1], M. I. Kobayashi[1,2], R. Seki[1,2], H. Nuga[1,2], S. Murakami[4], Y. Matsumoto[5], T. Homma[5], and M. Osakabe[1,2]

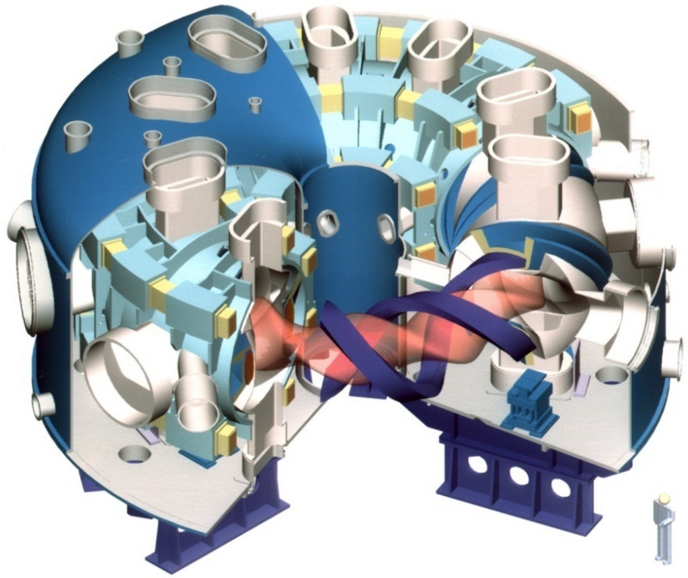
[1]National Institute for Fusion Science, National Institutes of Natural Sciences
[2]The Graduate University for Advanced Studies, SOKENDAI, Toki, Japan
[3]Mahasarakham University, Maha Sarakham, Thailand
[4]Kyoto University, Kyoto, Japan
[5]Hokkaido University, Sapporo, Japan

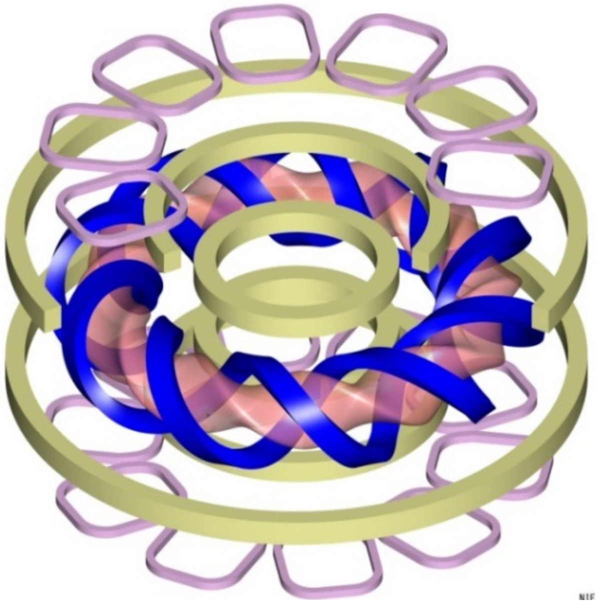
Outline of Talk

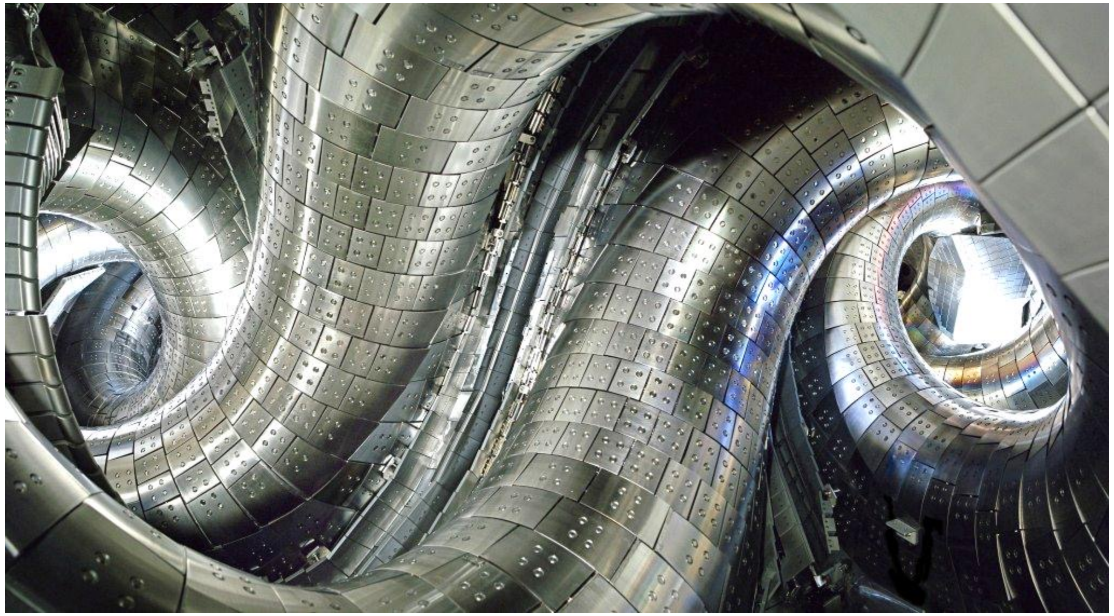
- Large Helical Device (LHD)
- A comprehensive set of neutron diagnostics and representative results, e.g. neutron emission rate, fusion output, neutron emission profile, triton burnup etc.
- New energetic-particle diagnostics ; single crystal CVD diamond detector-based NPA, and FIDA
- Summary

LHD has been successfully operated since 1998 without any severe troubles

- LHD is one of the largest superconducting magnetic confinement devices with simply and continuously wound helical coils, providing high-T_i, high-β, and steady-state operation capabilities.





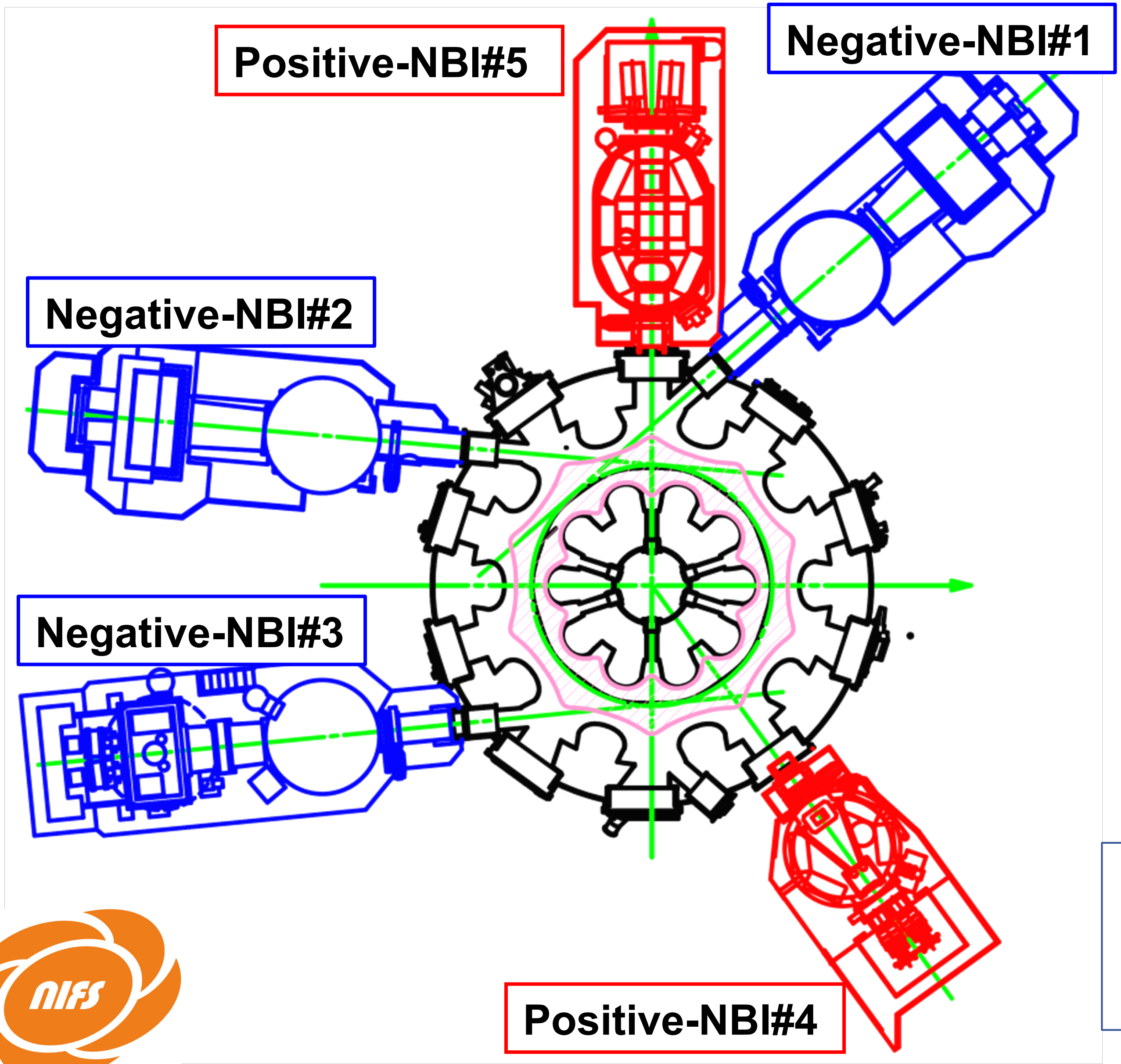


LHD machine parameters

- Helical mode numbers: *l*/*m*=2/10
- Plasma major radius: 3.5-4.1 m
- Plasma minor radius: ~0.6 m
- Plasma volume: ~30 m^3
- Toroidal field strength: ~3 T
- 20 RMPcoils

LHD has been operated with deuterium since March, 2017 in order to explore a higher confinement regime in helical/ stellarator plasmas

LHD is characterized by intense NBI heating system



Five NB injectors

- Negative-NBI (x 3)
  E_{inj} : 180-190 keV
  P_{nb} : 16 MW (H), 8 MW (D)

- Positive-NBI (x 2)
  E_{inj} : 40-80 keV
  P_{nb} : 12 MW (H), 20 MW (D)

In addition to NBIs, ECRH up to P_{ECRH} of 5 MW and ICRH up to P_{ICRH} of 3 MW are available.

- Total heating power in LHD goes over 30 MW.
- LHD is a good platform to investigate energetic particles.

Fusion reactions and neutron emission rate in LHD deuterium plasma

Fusion reactions in a deuterium plasma

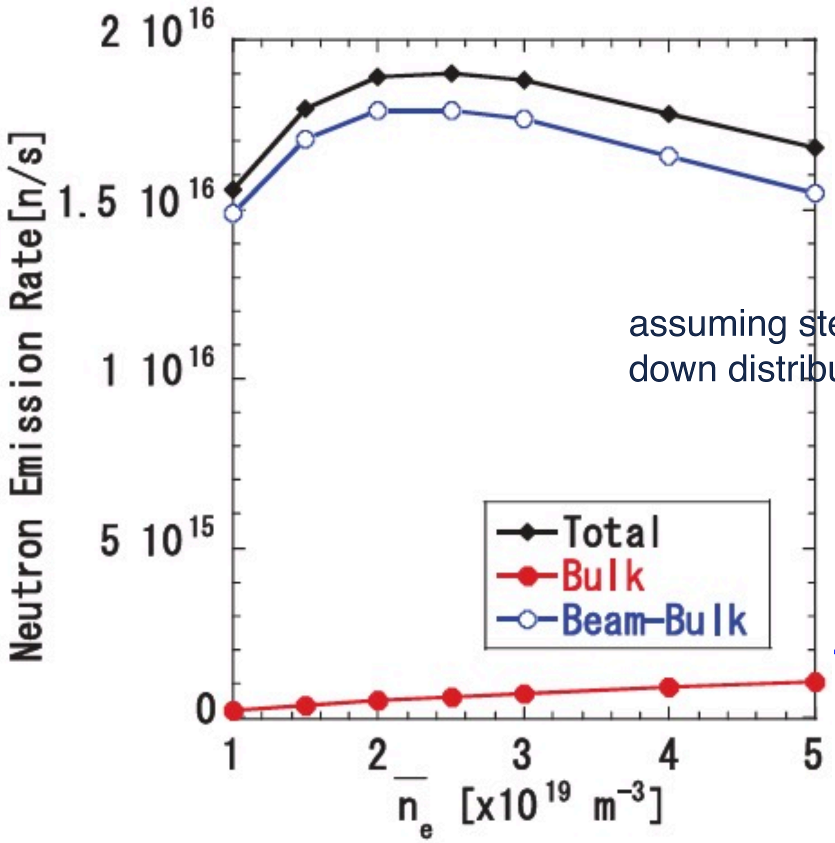
Primary d-d reactions

- d + d → ^{3}He (0.8 MeV) + n (2.45 MeV)
- d + d → t (1 MeV) + p (3 MeV)

Secondary d-t reaction

t + d → ^{4}He (3.5 MeV) + n (14 MeV)

Expected neutron emission rate in full power NB heating



assuming steady-state slowing down distribution of beam ions

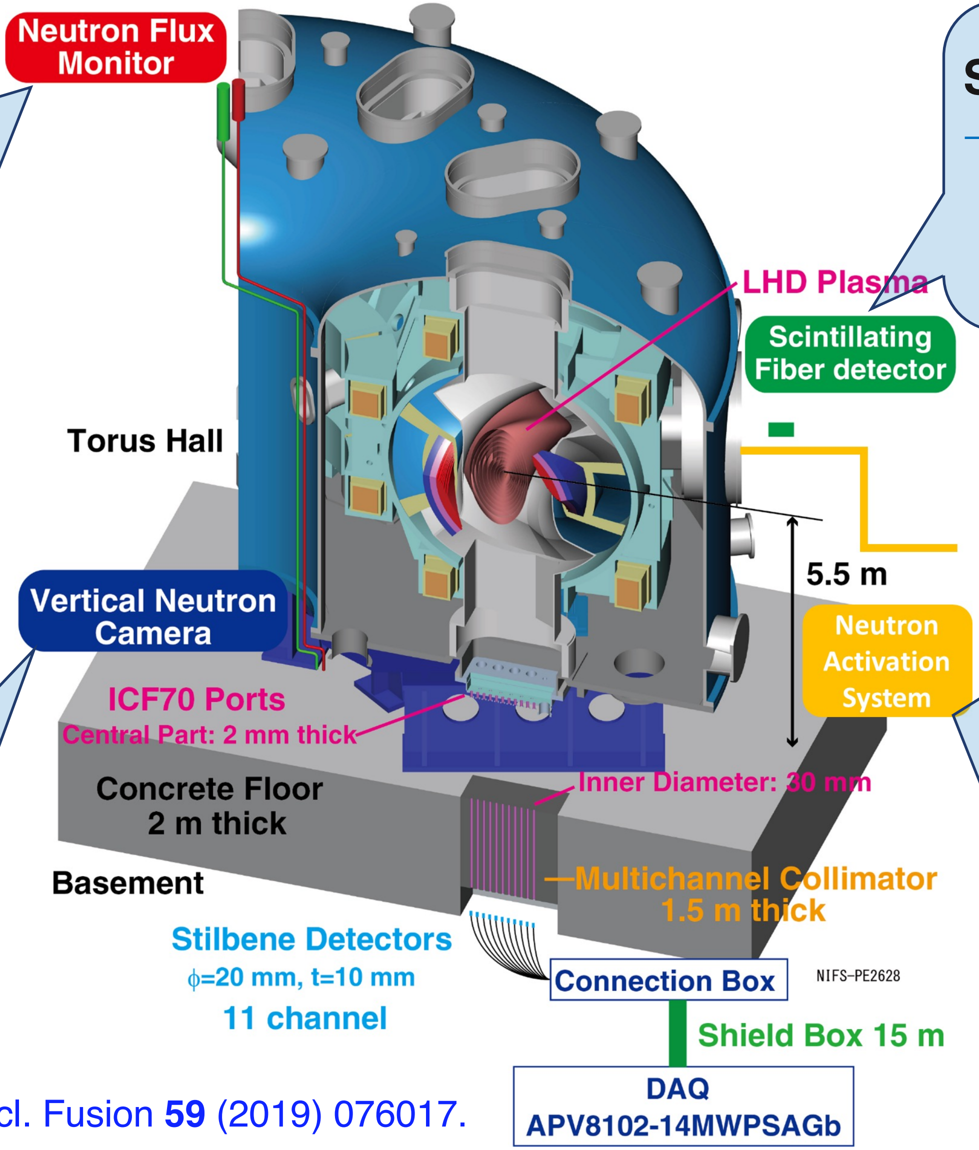
M. Osakabe *et al.*, Fus. Sci. Technol. **72** (2017) 1999.

- **Beam-driven neutrons are dominant in LHD** because of high energy (180-190 keV) of N-NBI.
  - *-> Confinement study for beam ions*
- In addition to primary d-d neutrons, small amount of secondary d-t neutrons are generated due to D-D born 1 MeV triton simultaneously.
  - *-> Triton burnup study, i.e. alpha particle simulation experiment*

A comprehensive set of neutron diagnostics on LHD to extend energetic-particle physics studies

Neutron Flux Monitor (NFM)
→ Total neutron emission rate
→ Neutron yield management
→ Global confinement property of beam ions
→ Q_{DD} & equivalent Q_{DT}

Vertical Neutron Camera (VNC)
→ Radial neutron profile
→ Radial profile of beam ions
→ Effect of MHD instabilities on beam ion profile



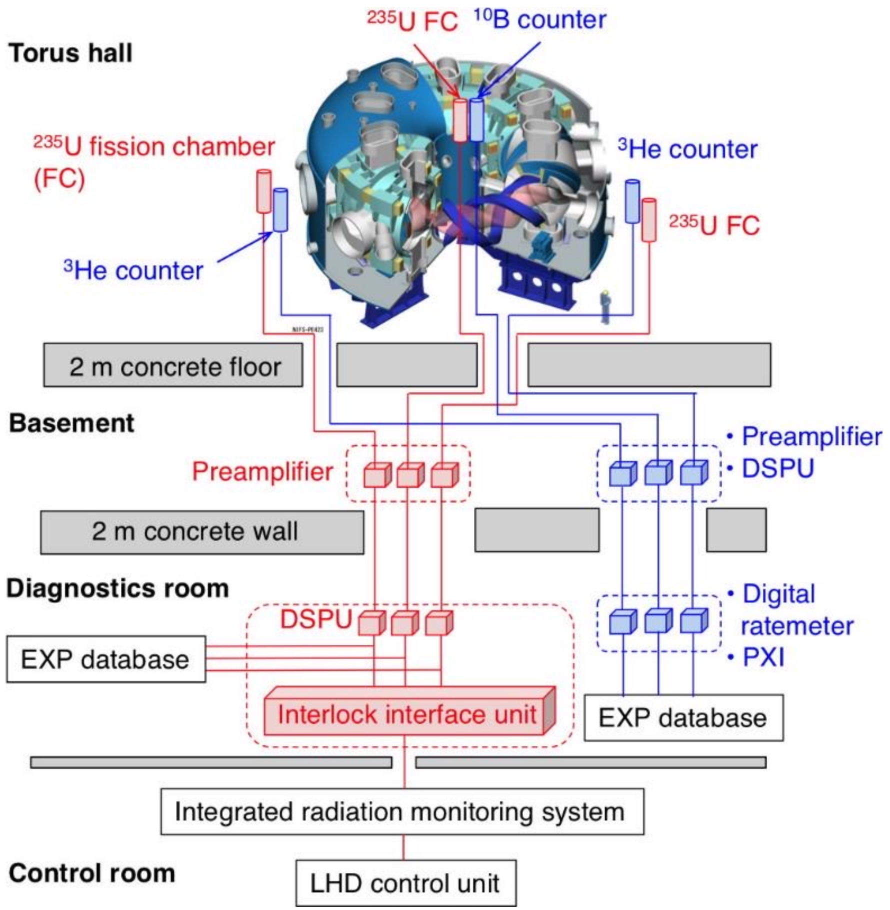
Scintillating-fiber (Sci-Fi) Detector
→ Secondly DT neutron rate
→ Time-resolved 1 MeV triton confinement

Neutron Activation System (NAS)
→ Shot-integrated neutron fluence
→ Shot-integrated global beam ion confinement
→ 1 MeV triton confinement properties

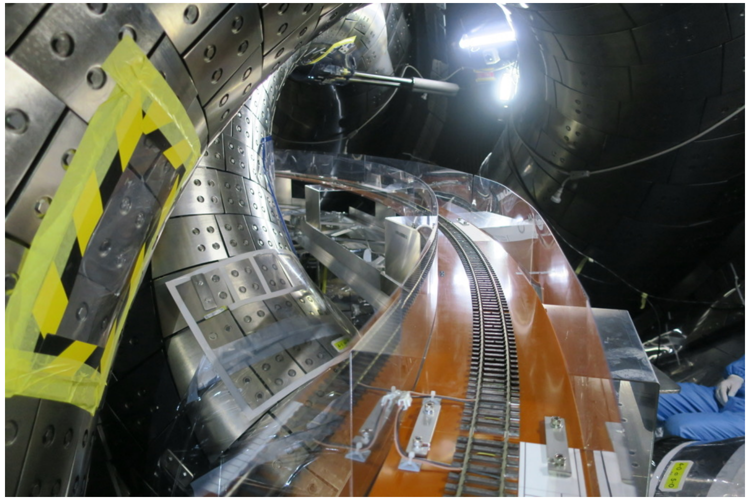
K. Ogawa, M. Isobe *et al.*, Nucl. Fusion **59** (2019) 076017.

LHD ex-vessel NFM is characterized by fast-response and wide dynamic range capabilities, and is essential in neutron yield management and physics studies

Arrangement of ex-vessel NFM on LHD



In-situ NFM calibration

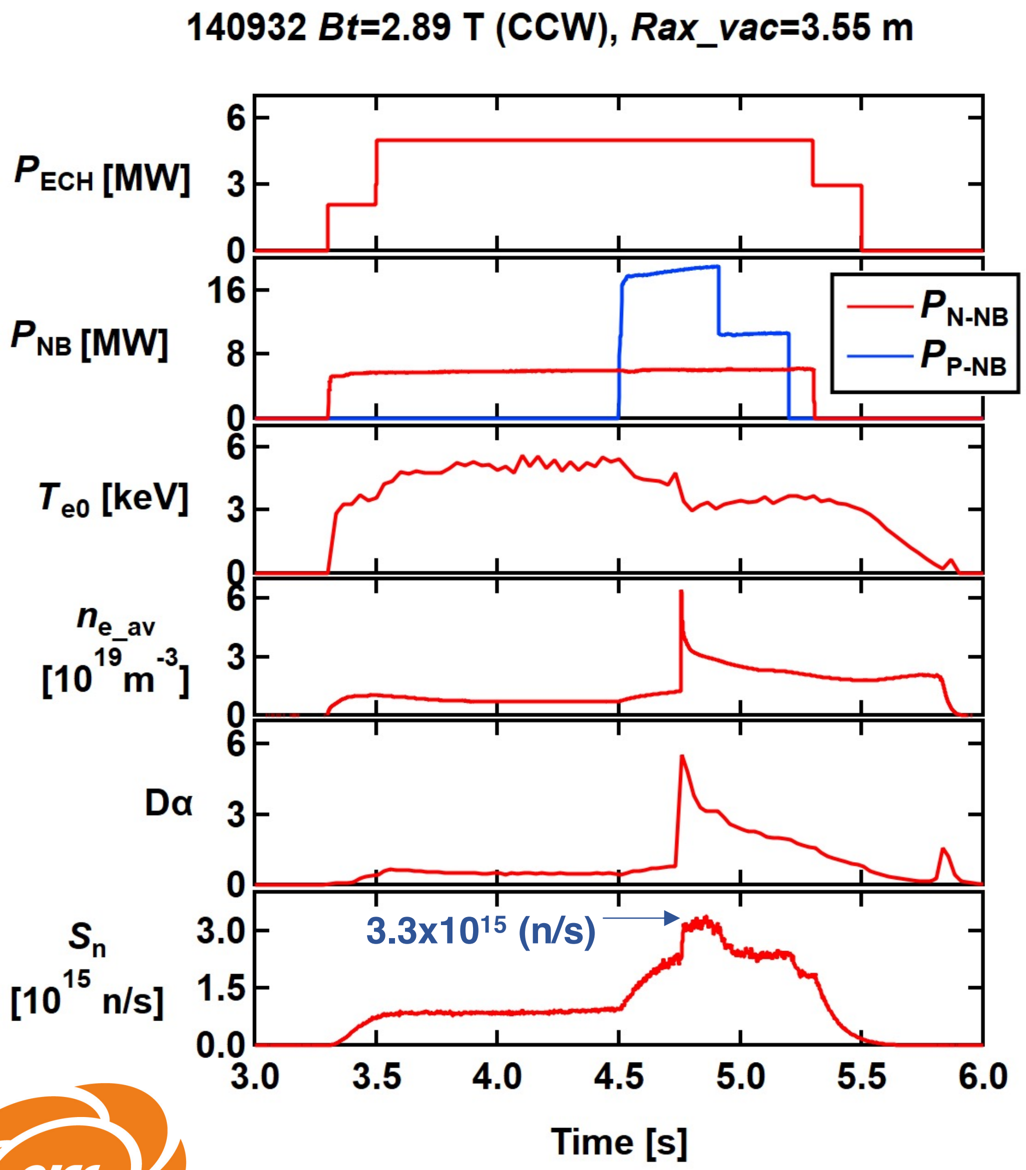


M. Isobe *et al.*,
IEEE Trans. Plasma Sci. **46** (2018) 2050.

- *In-situ* NFM calibration was carried out before the start of deuterium operation.
- The train loaded with ^{252}Cf of 800 MBq ran continuously inside the vacuum vessel to simulate ring-shaped fast-neutron source.
- The reason why we used ^{252}Cf is that averaged neutron energy from ^{252}Cf is 2.1 MeV, similar to D-D neutron energy.

- Three ^{235}U fission chambers (FCs) work in high-neutron yield shot, playing an important role in neutron yield management and physics studies.
- High sensitivity ^{10}B and ^{3}He counters are also used for a low-neutron yield shot, e.g. ECRH plasma w/o NBI.
- Both pulse and Campbelling modes are embedded in ^{235}U FC lines. The NFM on LHD can cover S_n up to ~10^{18} (n/s).

Typical high neutron emission rate shot

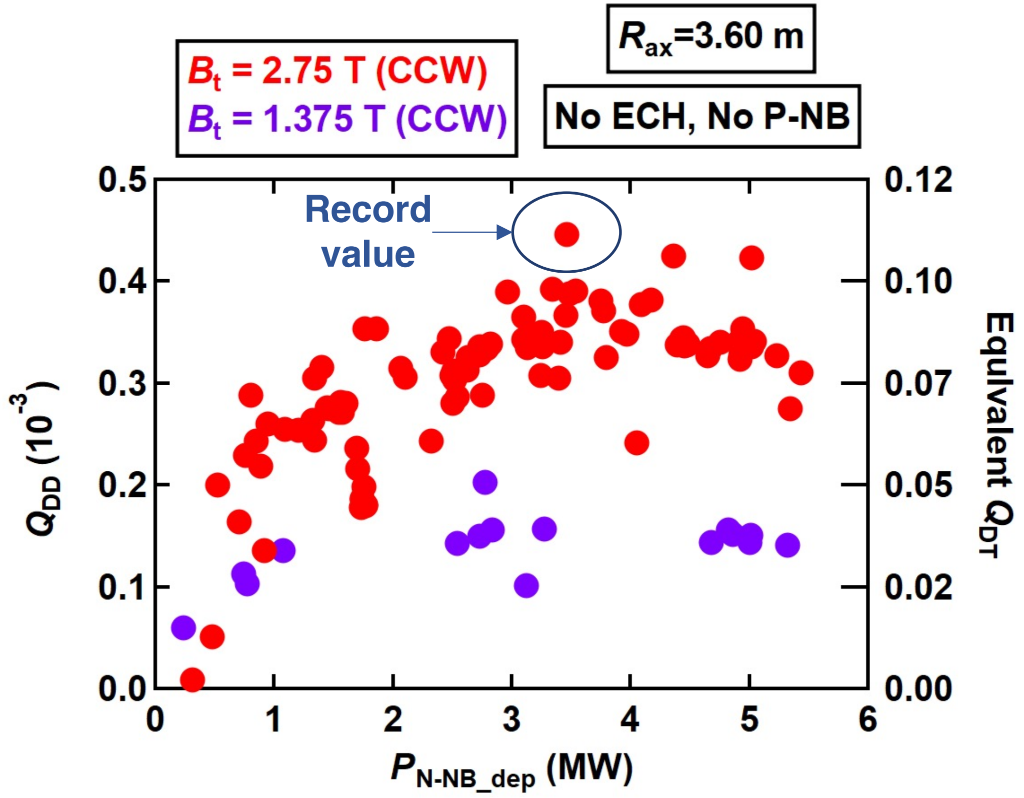


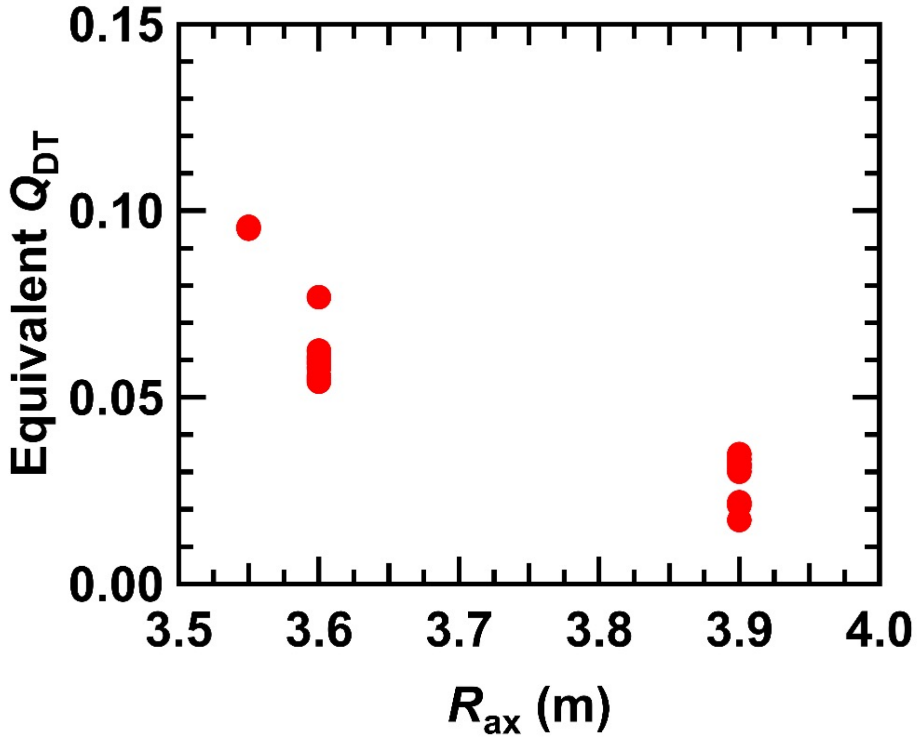
M. Isobe *et al.*, Nucl. Fusion. **58** (2018) 082004.

- High neutron emission rate (S_n) shot is achieved in an inward shifted configuration with high B_t (R_{ax}/B_t of 3.55 m/2.89 T) that provides high performance in terms of high T_i, longer τ_E, and good confinement property of helically trapped energetic ions.
- In this particular shot, $P_{N\text{-}NB}$ and $P_{P\text{-}NB}$ were 5.9 MW and 19 MW, respectively, and **S_n reached 3.3×10^{15} (n/s)** with the help of fueling deuterium pellet injection.
- So far, S_n has reached **4.1×10^{15} (n/s)** in LHD.

Q_{DD} and equivalent Q_{DT}-values

Q_{DD} and equivalent Q_{DT}-value has been systematically investigated in N-NB heated plasmas.



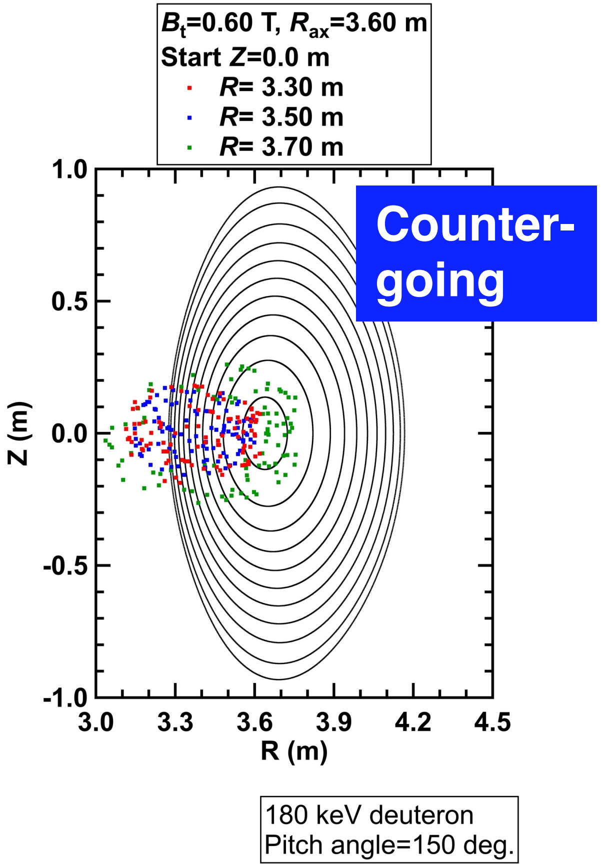


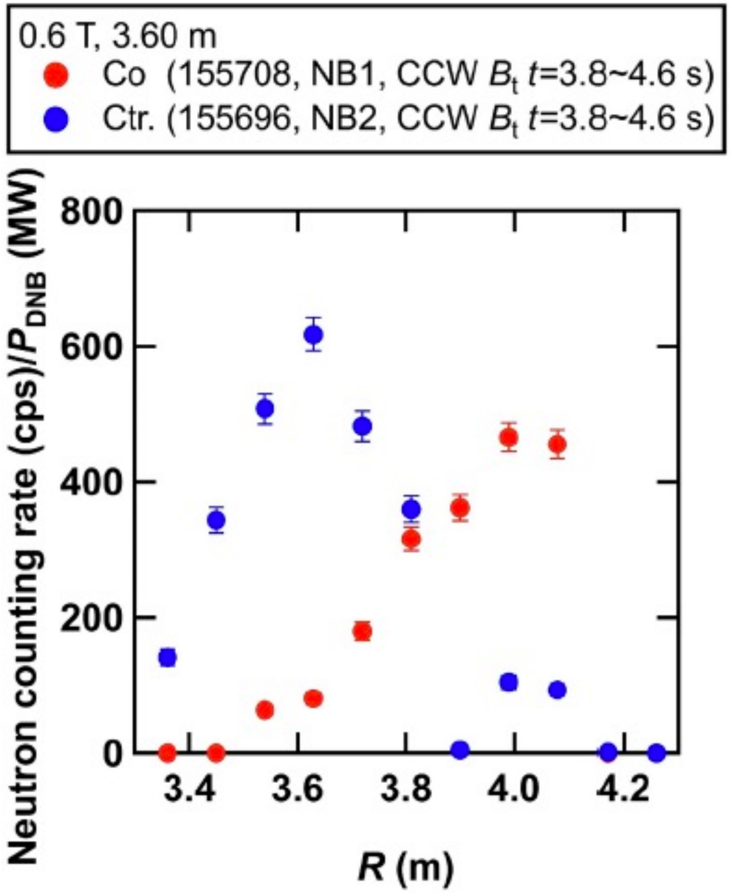
K. Ogawa, M. Isobe *et al.*, Nucl. Fusion **59** (2019) 076017.

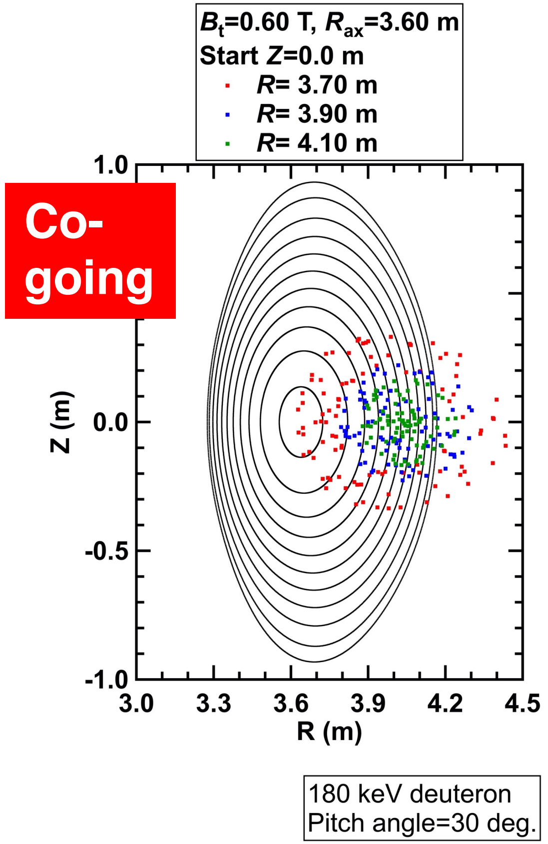
- Higher Q_{DD}-value was obtained in higher-B_t shots compared with that in lower-B_t shots, as expected.
- Based on measured Q_{DD}, Q_{DT} was evaluated using the FBURN code assuming classical confinement of beam ions.
- **Highest equivalent Q_{DT} is evaluated to be 0.11 in LHD.**
- Equivalent Q_{DT} tends to be higher as magnetic axis position is inwardly shifted.

Response of vertical neutron camera signal in low-B_t shot

Response of vertical neutron camera was checked in low-B_t, i.e. 0.6 T shots where orbits of passing beam ion injected by N-NBI are significantly deviated from magnetic flux surfaces.





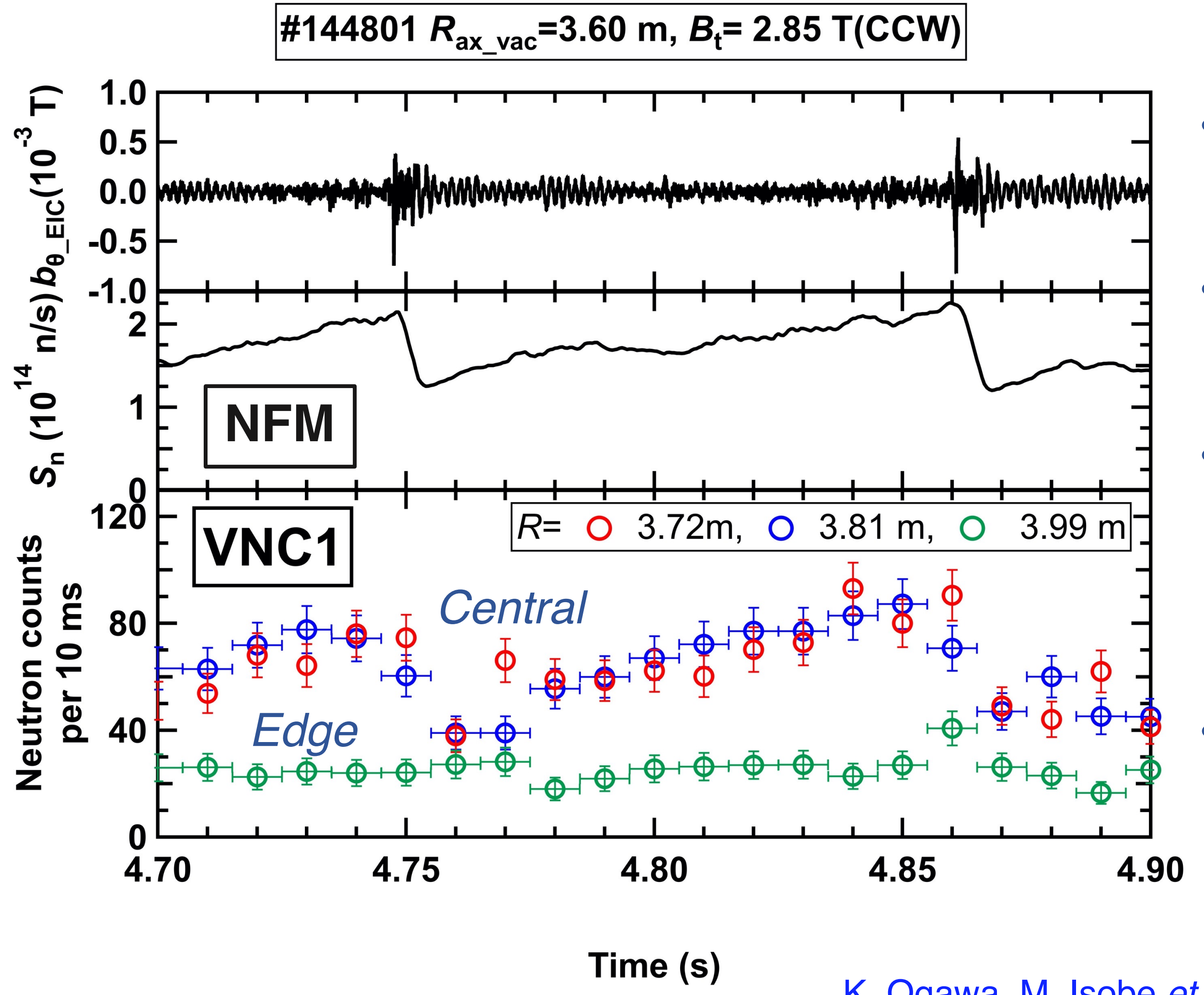


Significant inward/outward shift of neutron emission profile in low-B_t condition is visible as expected by means of a vertical neutron camera.

K. Ogawa, M. Isobe et al., Plasma Phys. Control. Fusion **63** (2021) 065010.

Effect of energetic-ion-driven MHD instabilities on neutron emission profile, i.e. beam ion profile

Neutron behaviors associated with resistive interchange modes destabilized by helically trapped beam ions called EIC.

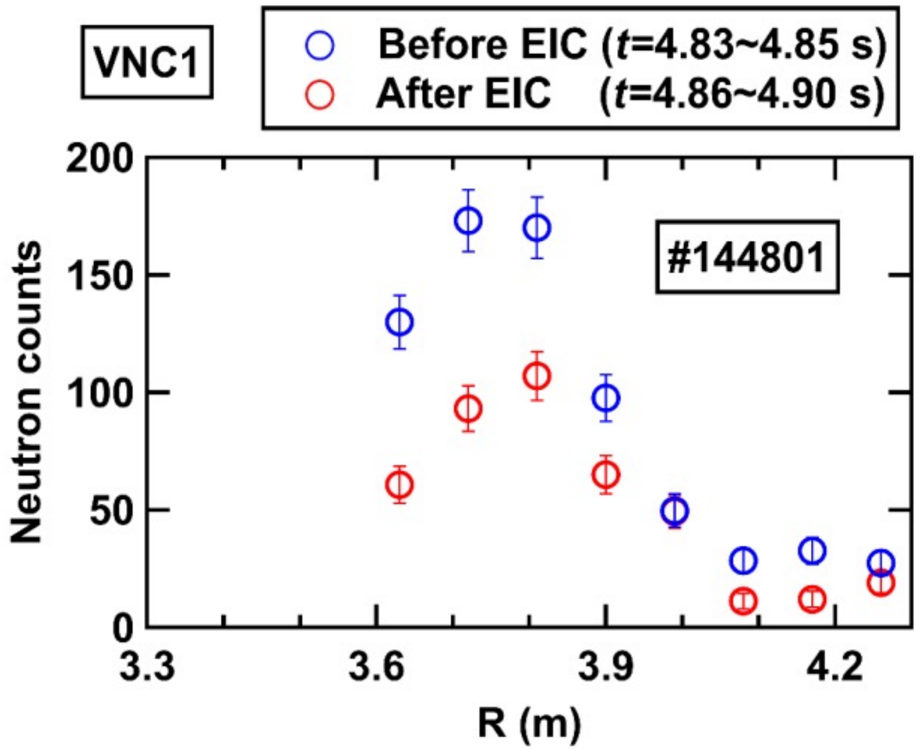


- The time evolution of the line-integrated neutron emission profile has been measured in EIC discharges.
- Total neutron emission rate (S_n) drops by about ~50% due to each EIC burst.
- Vertical neutron camera (VNC) show that the neutron signal in the central channel decreases significantly due to EIC, whereas neutron signal at the edge channel almost remains the same.
- Decay time of VNC signal in the central channel is almost the same as the decay time of S_n.

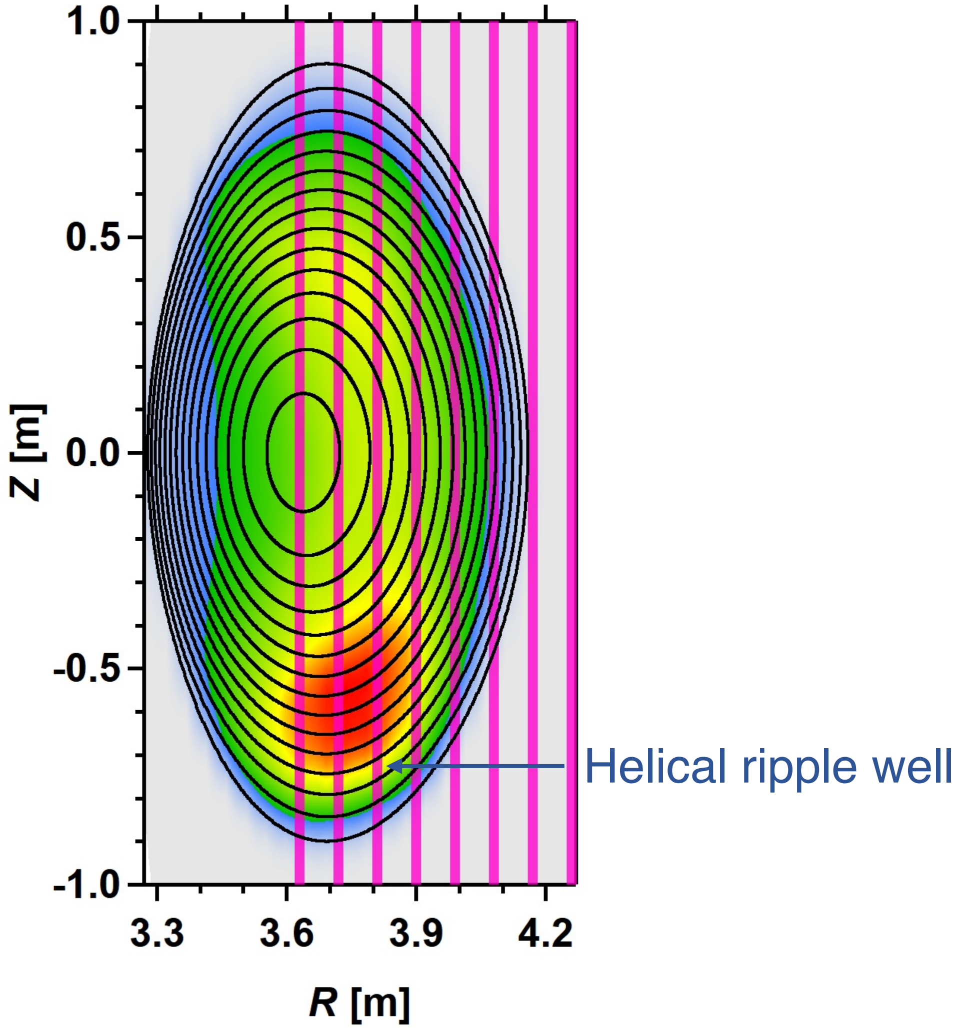
K. Ogawa, M. Isobe *et al.*, Nucl. Fusion **60** (2020) 112011.

Vertical neutron camera indicates expulsion of perpendicularly injected helically trapped beam ions due to EIC

Line-integrated neutron emission profile



Density profile of helically trapped beam ion



- Before EIC, the neutron emission profile has a peak around *R* of 3.75 m which is consistent with the helically trapped beam-ion density profile.

- Due to EIC, neutron counts in the central channel drops largely by about 40%.

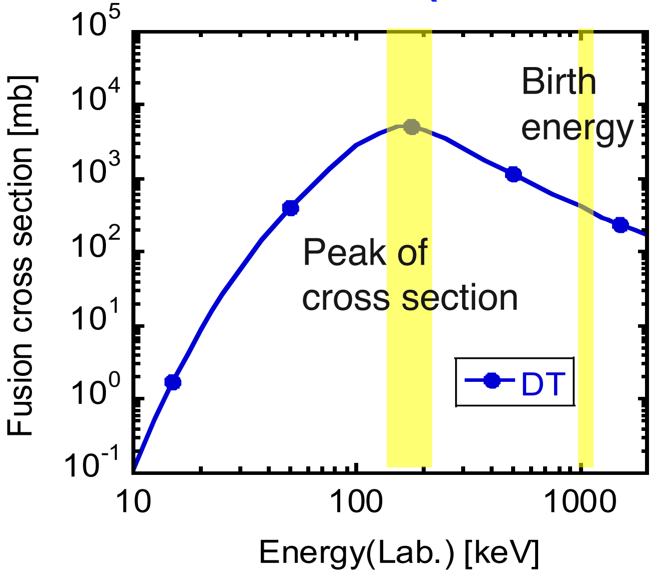
K. Ogawa, M. Isobe et al., Plasma Phys. Control. Fusion **60** (2018) 044005.

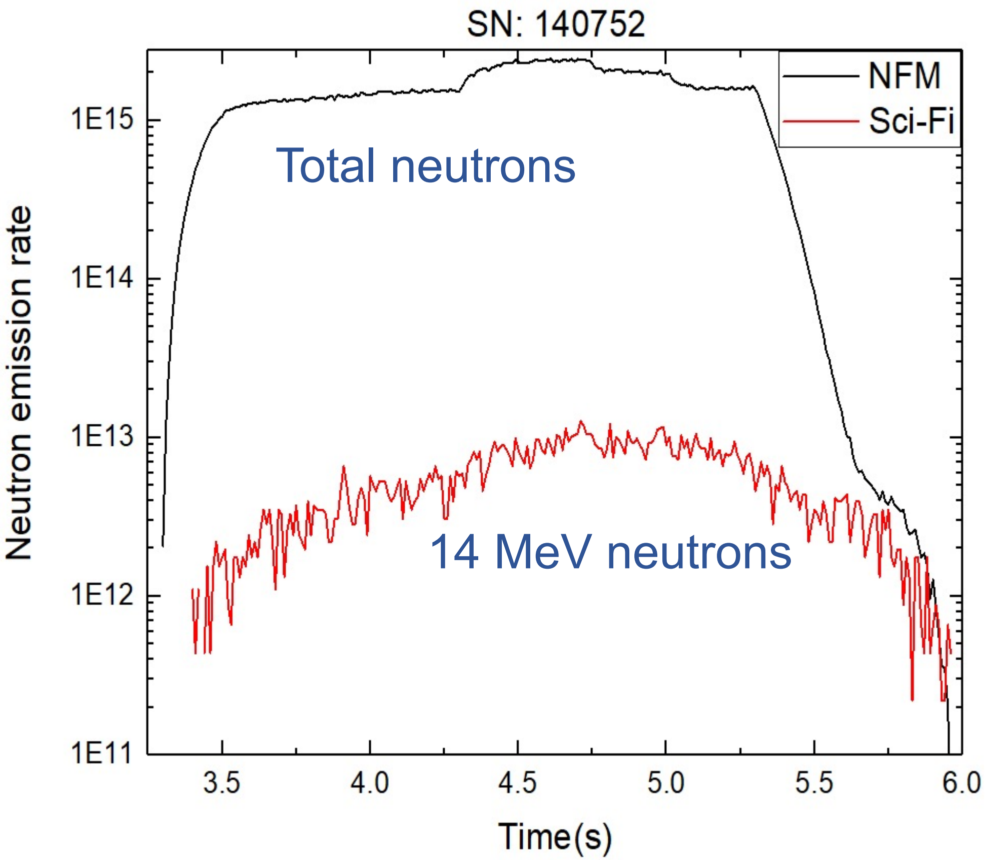
Triton burnup experiment, i.e. α-particle simulation experiment through measurement of secondary D-T neutrons

- 2.45 MeV neutron provides the birth information of 1 MeV triton, and secondary 14 MeV neutron provides slow-downed information of triton (~200 keV).
- DD-born 1 MeV triton is isotropic in velocity space and its Larmor radius is similar to DT-born α.

d + d → ^{3}He + **n (2.45 MeV)**
d + d → **t (1.01 MeV)** + p

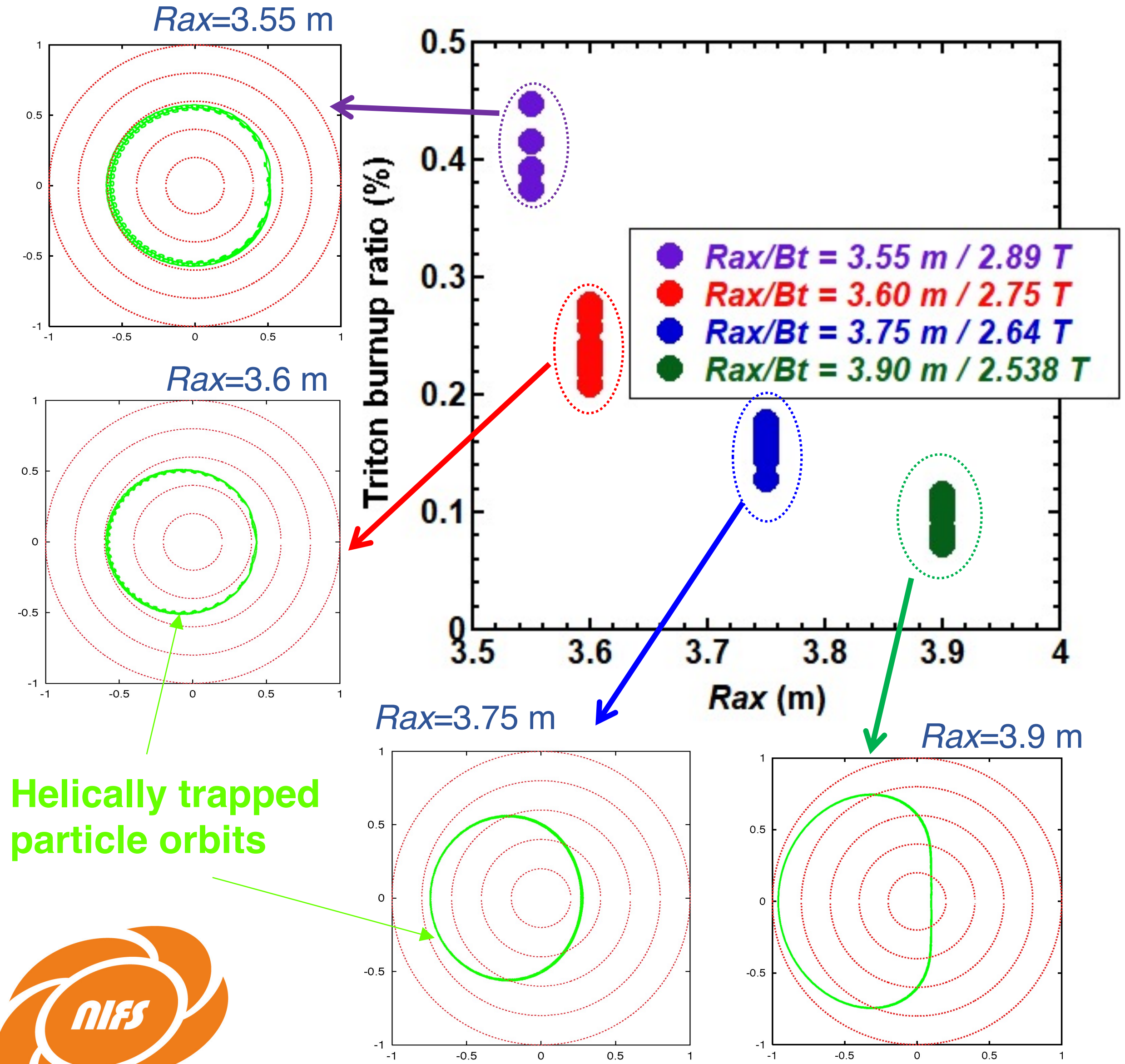
t + d → α + **n (14.03 MeV)**





- Buildup rate of secondary D-T neutron is much slower than that of primary D-D neutron.

Triton burnup measurement has demonstrated good energetic-particle confinement property in inwardly shifted configuration



Red line represents magnetic flux surfaces

Triton burnup ratio : $Y_n^{\ 14\ MeV}/Y_n^{\ 2.45\ MeV}$

Triton burnup ratio in tokamaks :

TFTR~1%*, KSTAR~0.45%**

*C. Barnes *et al.*, Nucl. Fusion **38**(1998)597.
** J. Jo *et al.* Rev. Sci. Instrum. **87**(2016)11D828.

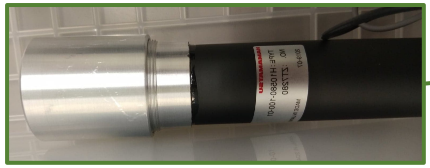
- Highest triton burnup ratio is obtained in inwardly shifted configuration where helically trapped beam ion orbit matches magnetic flux surfaces.
- In LHD, triton burnup ratio is comparable to that in similar size tokamaks in minor radius.

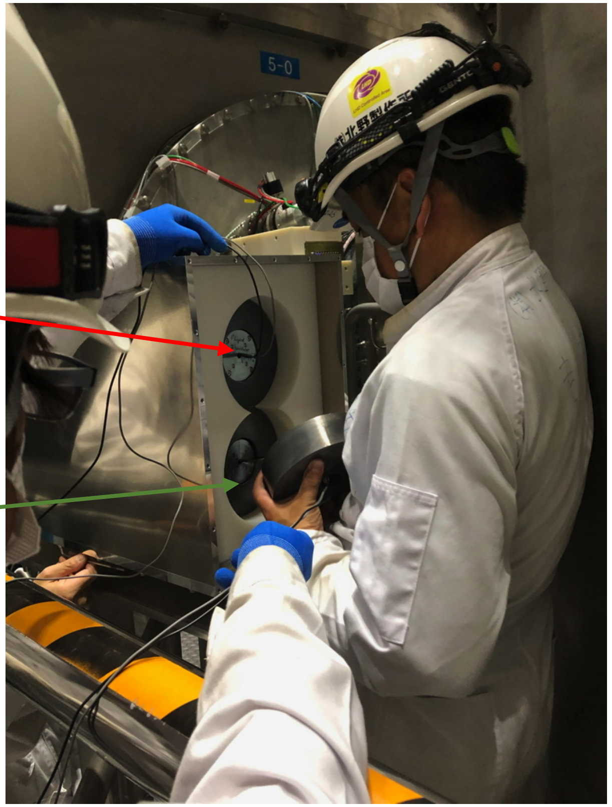
Efforts on DD neutron spectrometry

- Two compact spectrometers with tangential line of sight have been installed, and the other ToF-type spectrometer called TOFED with vertical line of sight has been installed.
- Commissioning of three different neutron energy spectrometers is now ongoing.

Tangential line of sight

Traditional liquid scintillator EJ301





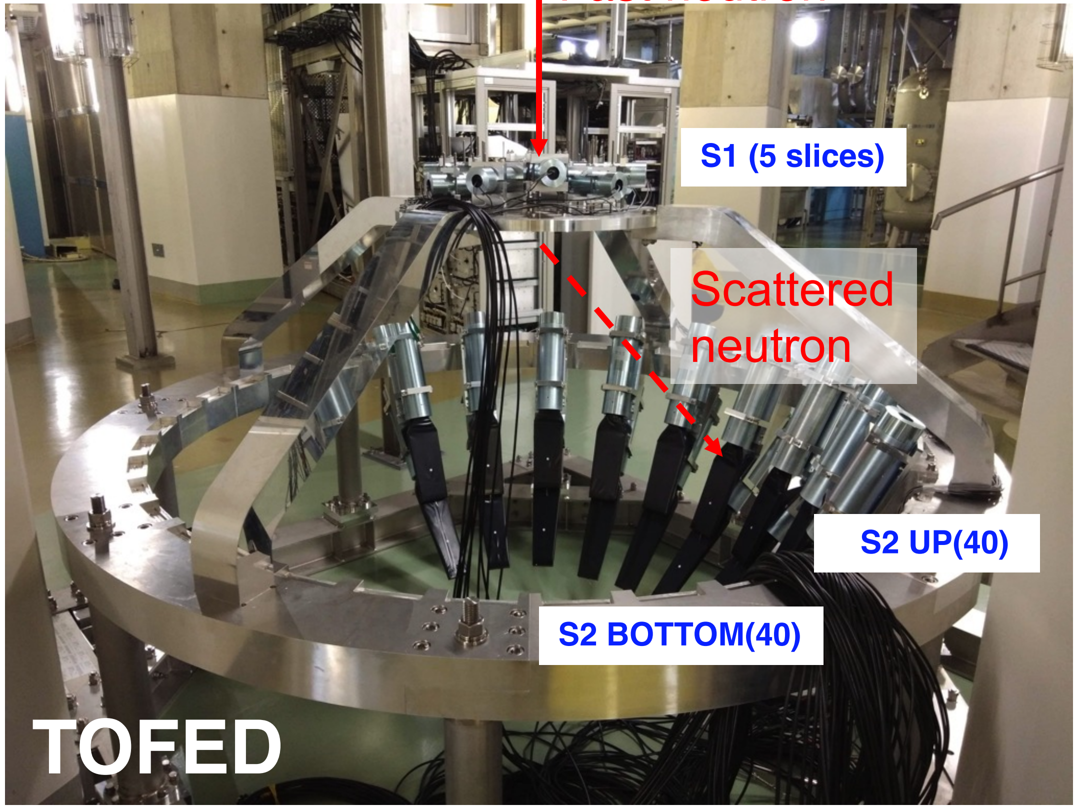
New CLYC7* scintillator

***Cs2LiYCl6:Ce enriched in 7Li**

S. Sangaroon *et al*. submitted to JINST.

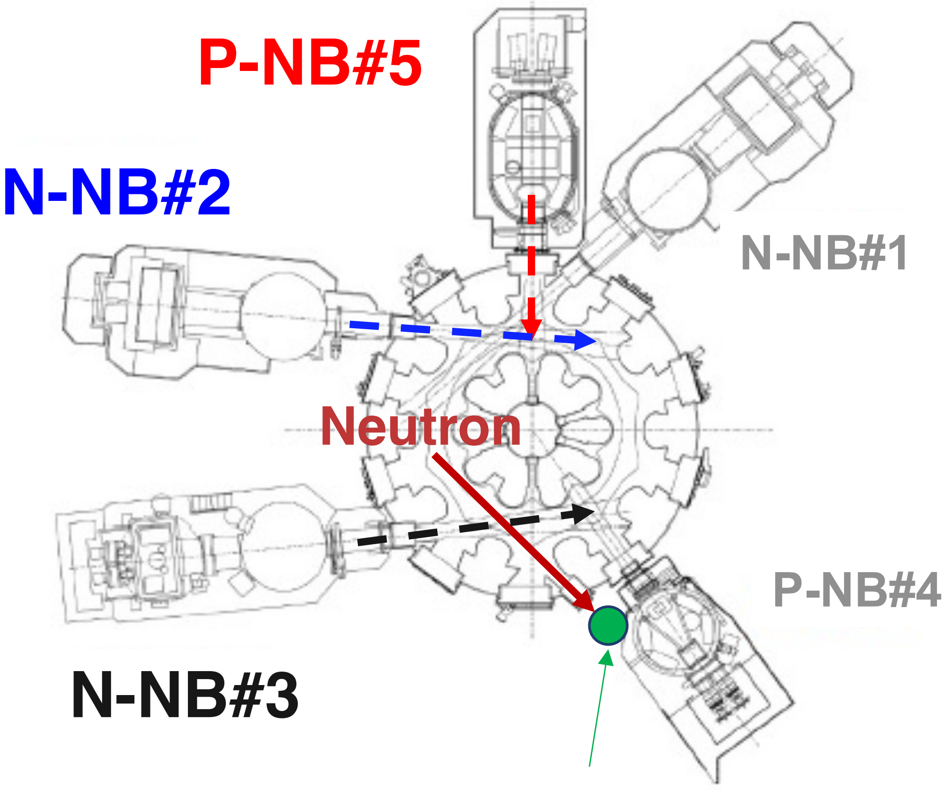
Perpendicular line of sight

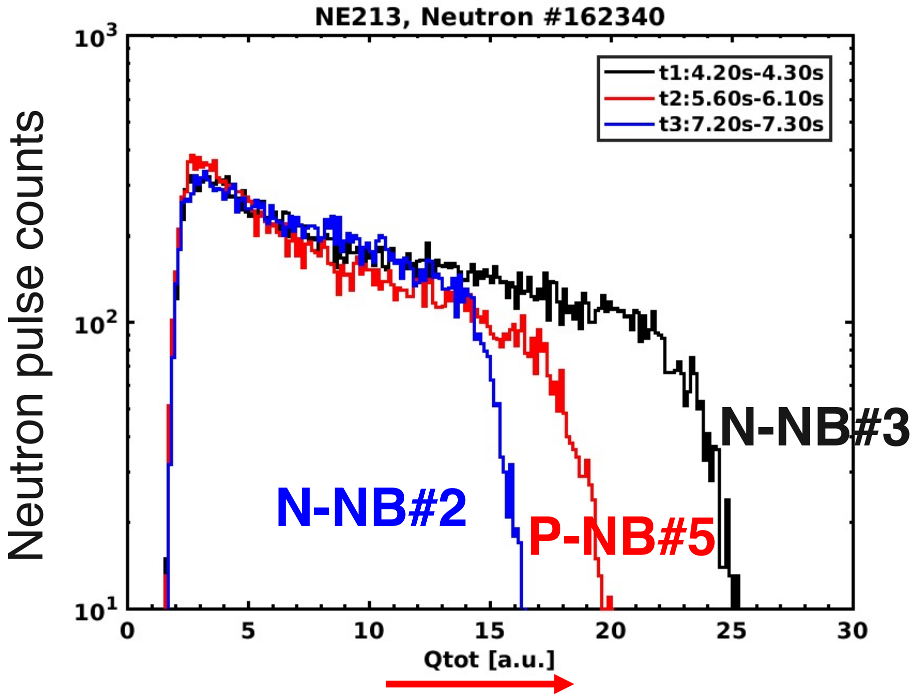
Fast neutron



In collaboration with Peking Univ. in China

Doppler shifted energy of beam-driven DD neutron has been successfully measured using the EJ301 compact neutron spectrometer having a tangential line of sight



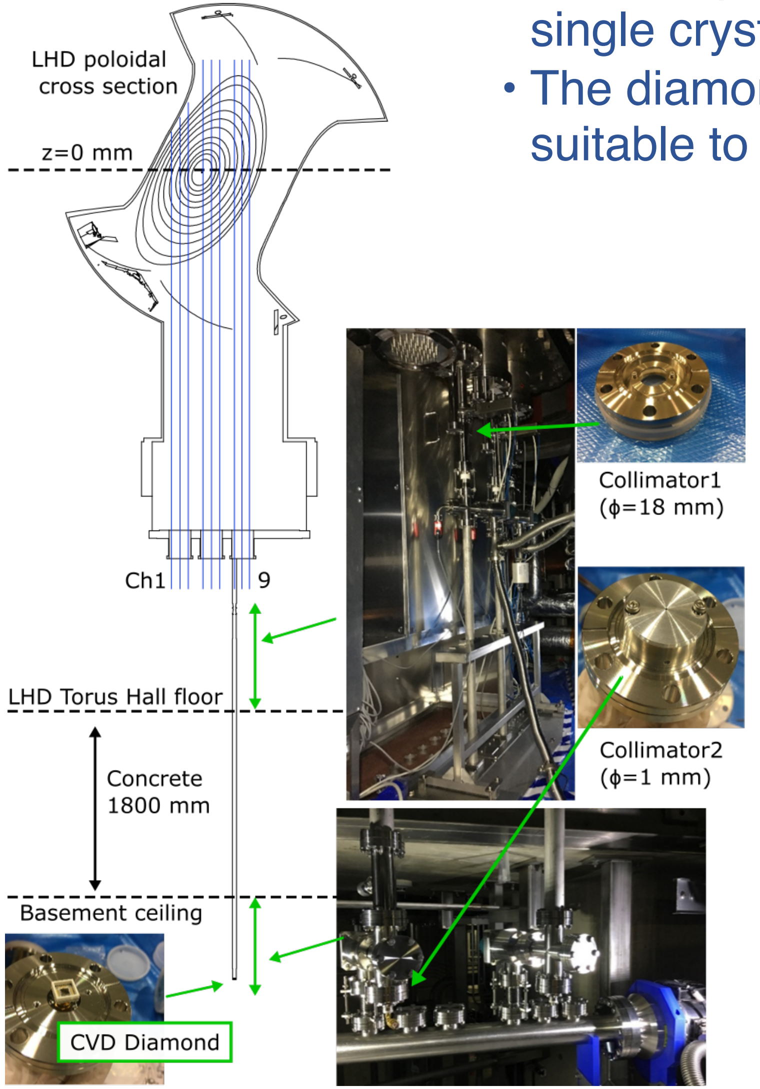


Proportional to recoil proton energy

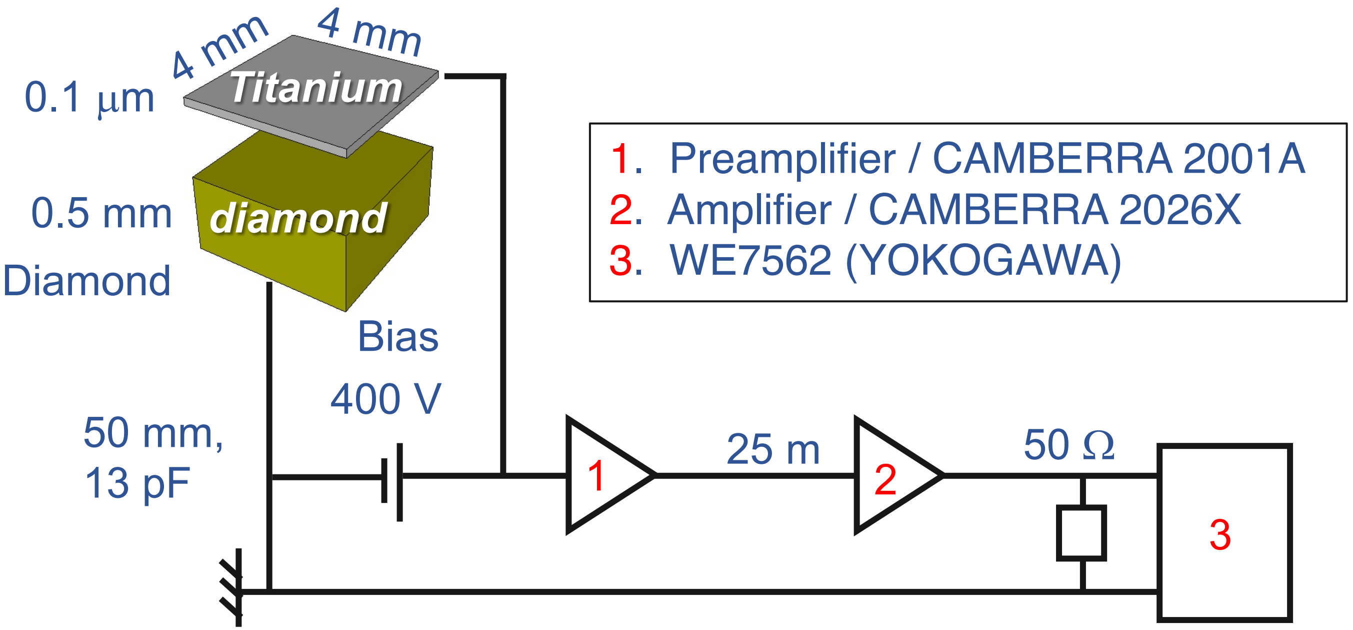
- During **N-NB#3**, the pulse height spectrum (PHS) of the recoil proton (RP) increases. This suggests **increase of neutron energy** as expected due to **the center of mass (CM) moving toward to the detector.**
- During **N-NB#2**, the PHS of the RP decreases, suggesting **decrease of neutron energy** as expected due to **CM moving away from the detector.**

Perpendicular NPA array based on single crystal CVD diamond detectors

- The compact neutral particle analyzer (NPA) array has been newly developed by using single crystal CVD diamond detectors.
- The diamond detectors are chosen because of its high radiation hardness which is suitable to withstand the high neutron flux in the deuterium discharges.



Circuit of the DNPA

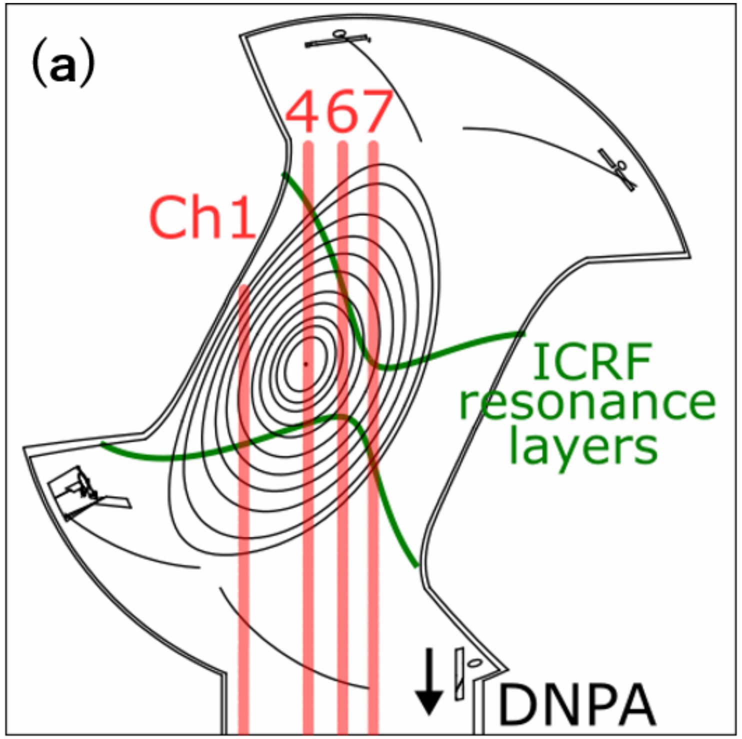


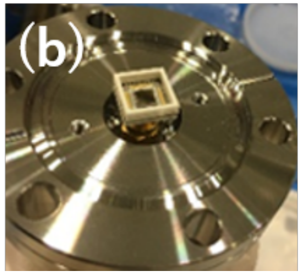
S. Kamio *et al.*, *JINST* **14**, C08002 (2019).

Energetic-ion tail over 1 MeV is confirmed by CVD diamond NPA in LHD ICRH discharges

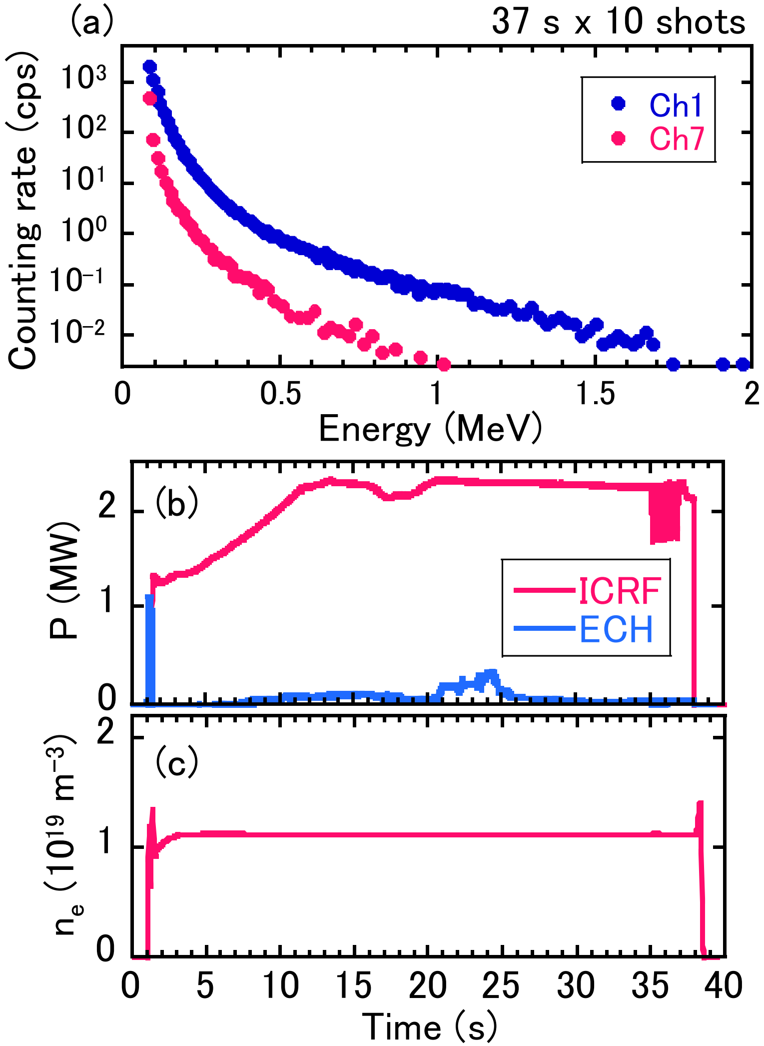
Lines of sight of the DNPA in the poloidal cross-section of LHD, together with the ICRF resonance layers.

Energy distributions of the energetic-ion tails produced by ICRH measured by DNPA Ch. 1 at inboard side and Ch. 7 at outboard side.





CVD diamond
(7.77 m below z_{ax})



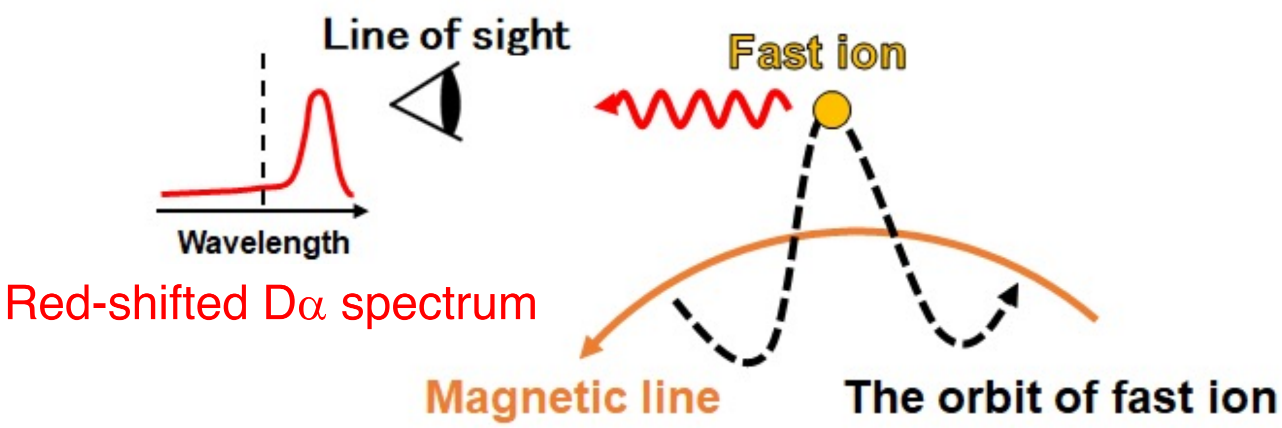
Tangential Fast Ion D Alpha (FIDA) diagnostic for beam ion study

- FIDA diagnostic is an active beam probe diagnostics, measuring **Doppler-shifted D_α lights from re-neutralized fast ions**.
- **For FIDA, modulated NBI as a directional neutral source** is used to separate the FIDA component from the contribution of the neutral in the peripheral region or the other unnecessary component caused by injected NB.

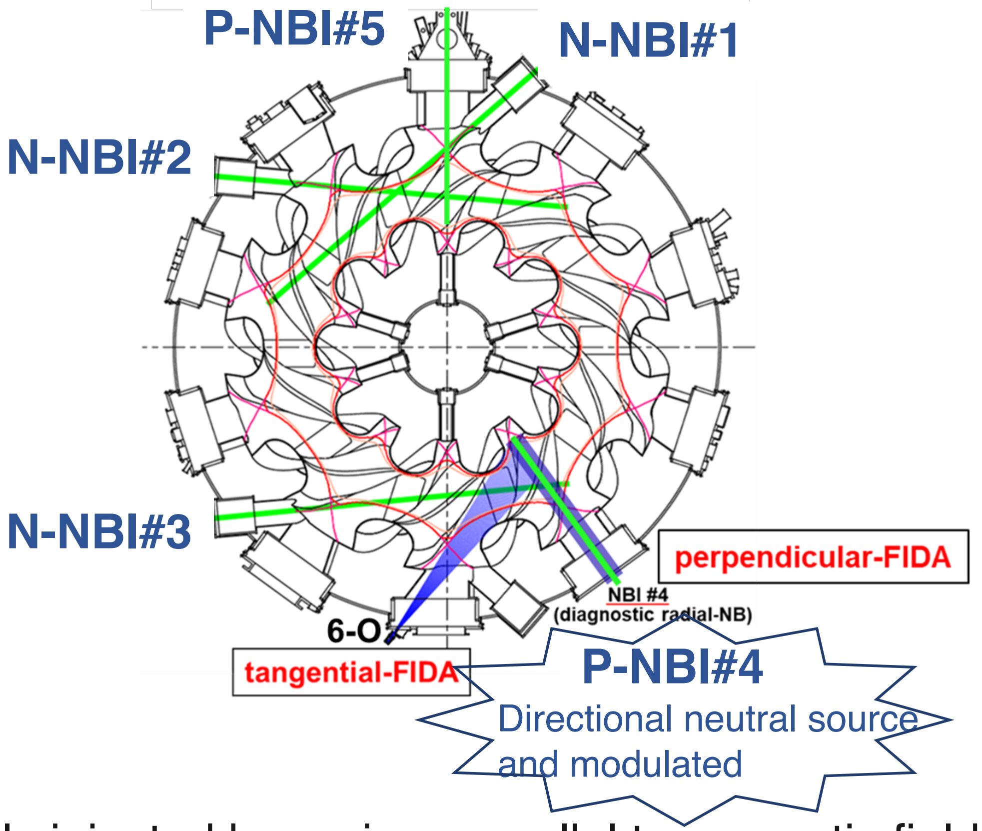
Principle of FIDA

Doppler-shifted Dα

$$D_{fast}^{+} + D_{NB}^{0} \rightarrow D_{fast}^{0} + D_{NB}^{+}$$

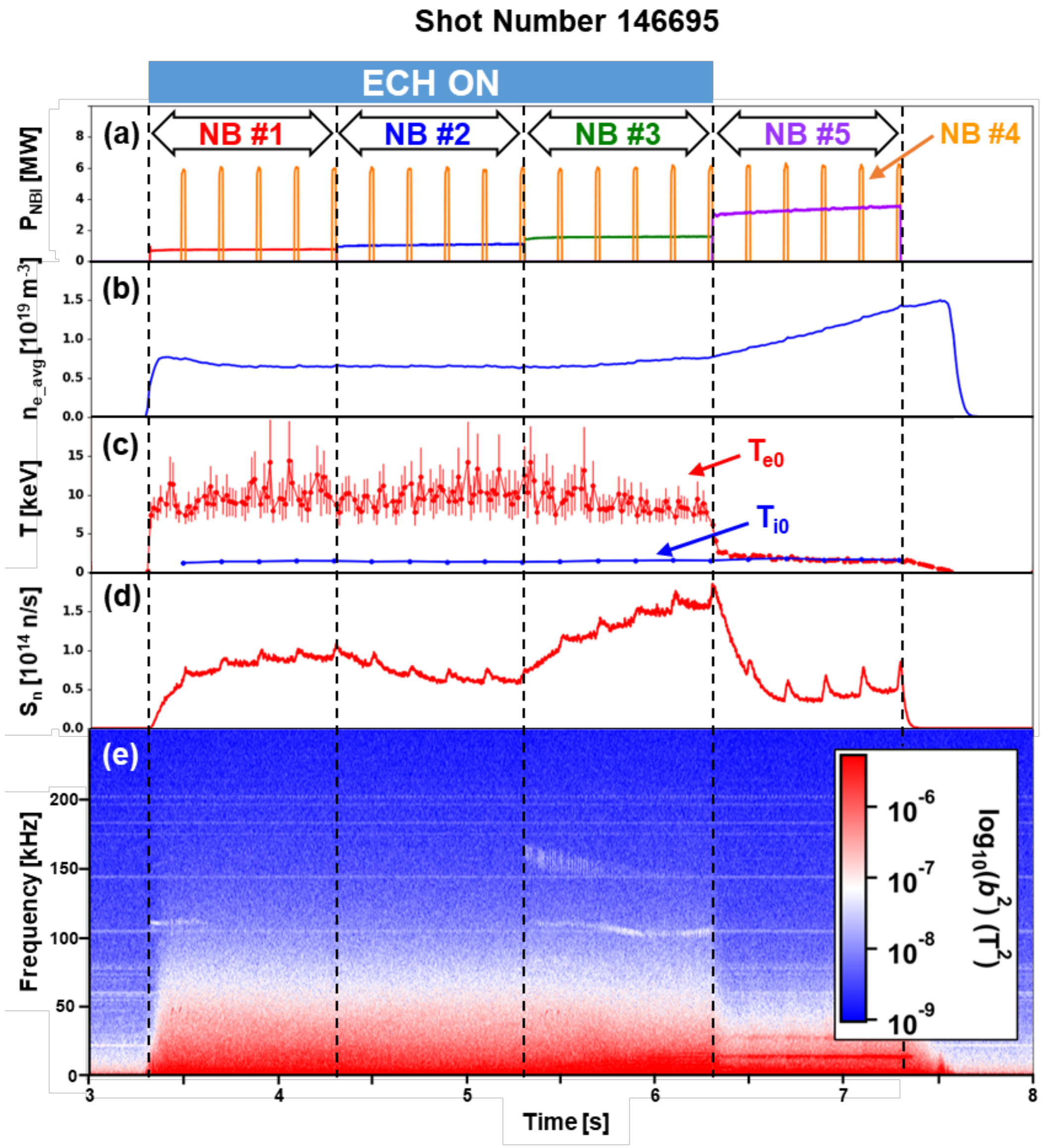


Top view of measurement system



Tangential viewing geometry is suitable for observing tangentially injected beam ions parallel to magnetic field.

Discharge for FIDA diagnostic



Experiment parameter and condition

Bt=2.75 T (CCW), Rax=3.6 m,
Gas: Deuterium

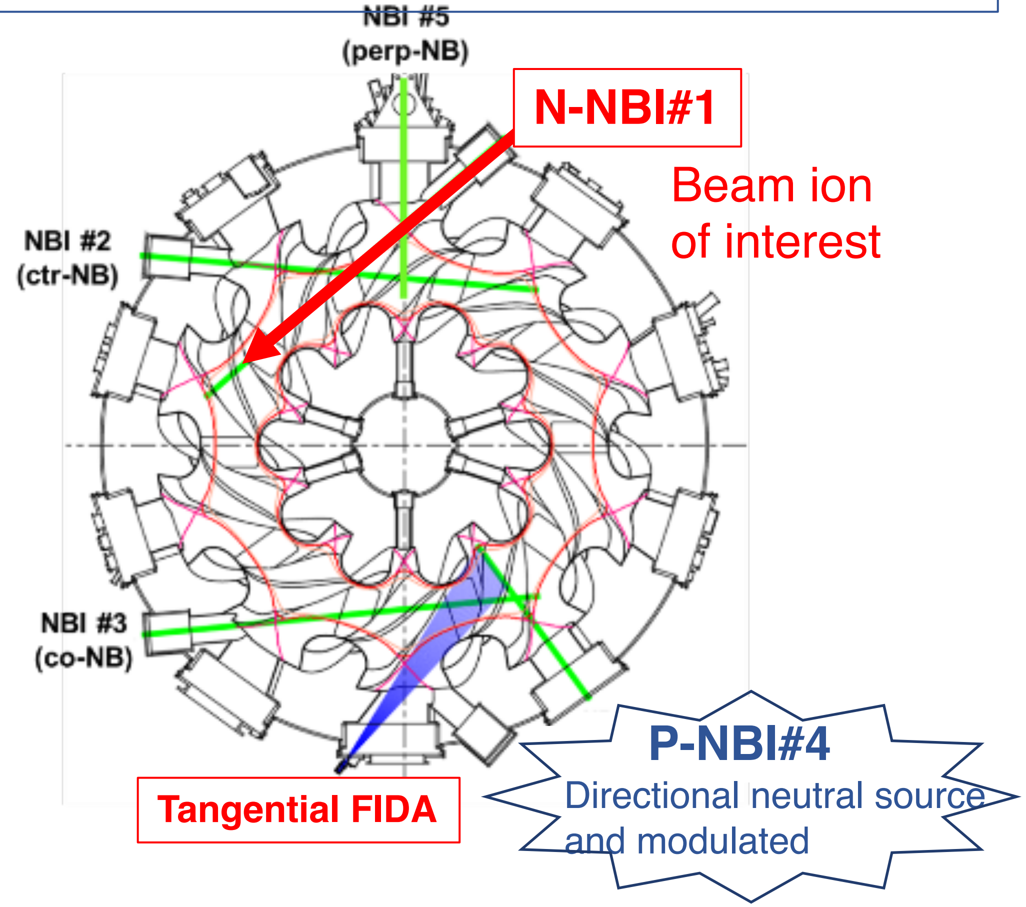
NB#1: 174 keV 0.8 MW (ion source A)
NB#2: 150 keV 1.1 MW (ion source A)
NB#3: 175 keV 1.5 MW (ion source A)
NB#4: 57 keV 5.9 MW

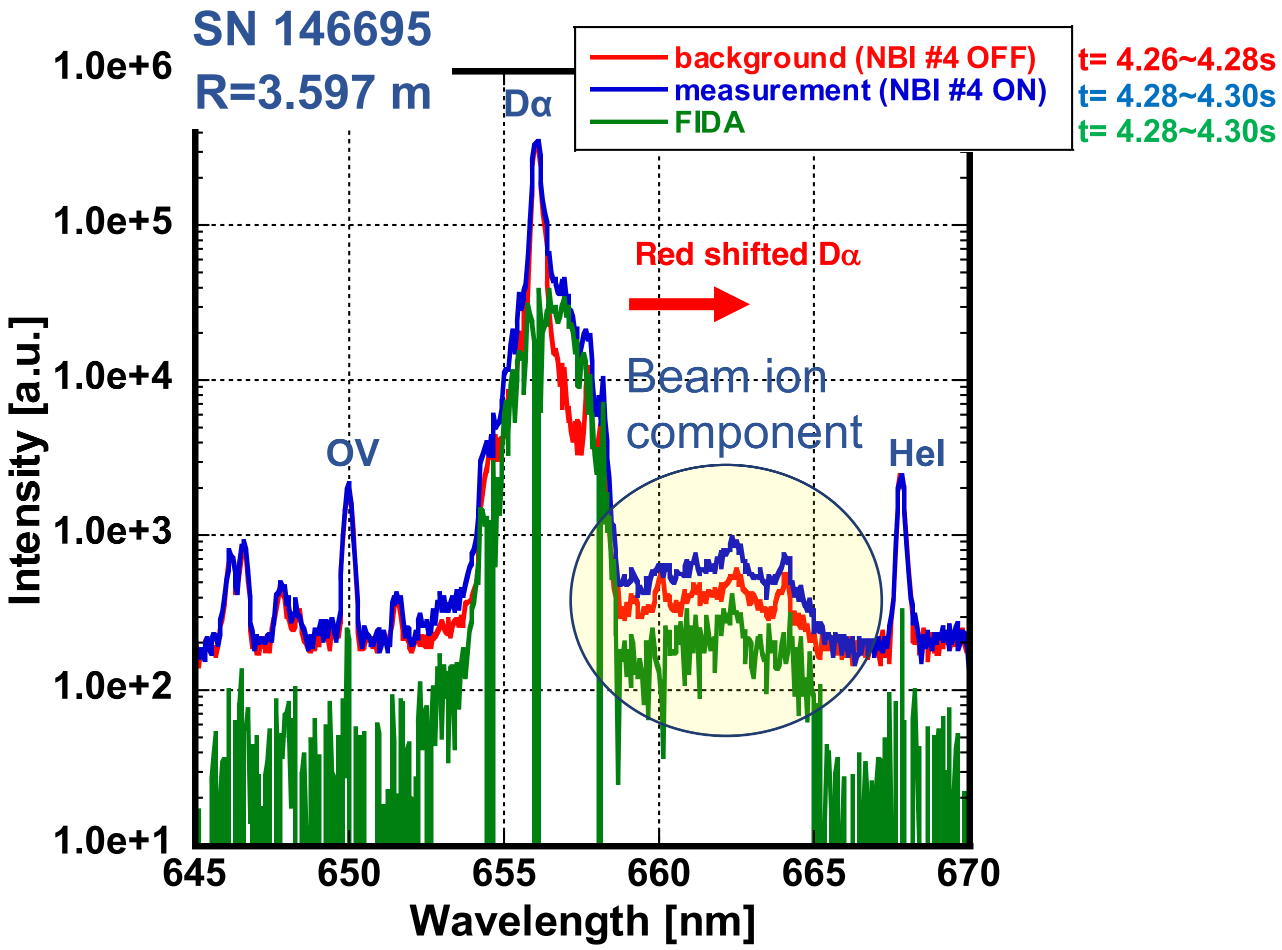
- To observe the beam ion profile in MHD-quiescent deuterium plasmas, each NB is injected in a sequence with low injection power.
- P-NB#4 as a directional neutral source is modulated to separate the tangential-FIDA component, thus the background signal can be removed from the tangential-FIDA signals.

Y. Fujiwara *et al*., Nucl. Fusion **60** (2020) 112014.

Doppler-shifted FIDA spectrum for passing beam ion injected by N-NB#1

T-FIDA views passing beam ion from behind





- Red-shifted FIDA spectra are obtained by subtracting the background spectra from the measurement spectra.
- Most of the impurity lines and the bremsstrahlung radiation were removed by the background subtraction.
- Analysis for radial profile and velocity distribution of beam ion is ongoing.

Summary

- LHD deuterium operation began in March 2017 to explore higher plasma confinement regime.
- A comprehensive set of neutron diagnostics has been developed to study *Q*-value, confinement properties of beam ions and fusion products, neutron energy spectrum etc.
- Max. neutron emission rate and equivalent Q_{DT} have reached 4.1×10^{15} (n/s) and 0.11, respectively, in LHD.
- The vertical neutron camera clearly shows redistribution/expulsion of beam ions due to EIC.
- Triton burnup ratio has reached 0.45% which is comparable to that obtained in similar size tokamak.
- Commissioning of neutron spectrometer is steadily ongoing. Doppler shifted neutron energy associated with co-going and/or counter-going beam ions is obtained.
- Single crystal CVD diamond detector-based compact NPA array and tangential FIDA have been developed to obtain deeper understanding of energetic-ion behavior in LHD.