P1-7 (ID:18)

The LHD Neutron Diagnostics

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Meeting on Energetic Particles in Magnetic Confinement Systems - Theory of Plasma Instabilities
Tuesday, 3 September 2019 - Friday, 6 September 2019 Shizuoka City, Japan

Outline

1) Neutron production and role of neutron diagnostics in the Large Helical Device (LHD)

2) A comprehensive set of neutron diagnostics in LHD
   - Neutron flux monitor (NFM)
   - Neutron activation system (NAS)
   - Vertical neutron camera (VNC)
   - Scintillating-fiber (Sci-Fi) detector
   - Neutron fluctuation detector (NFD)
   - Neutron energy spectrometer (NES)
   - Single crystal CVD diamond detector

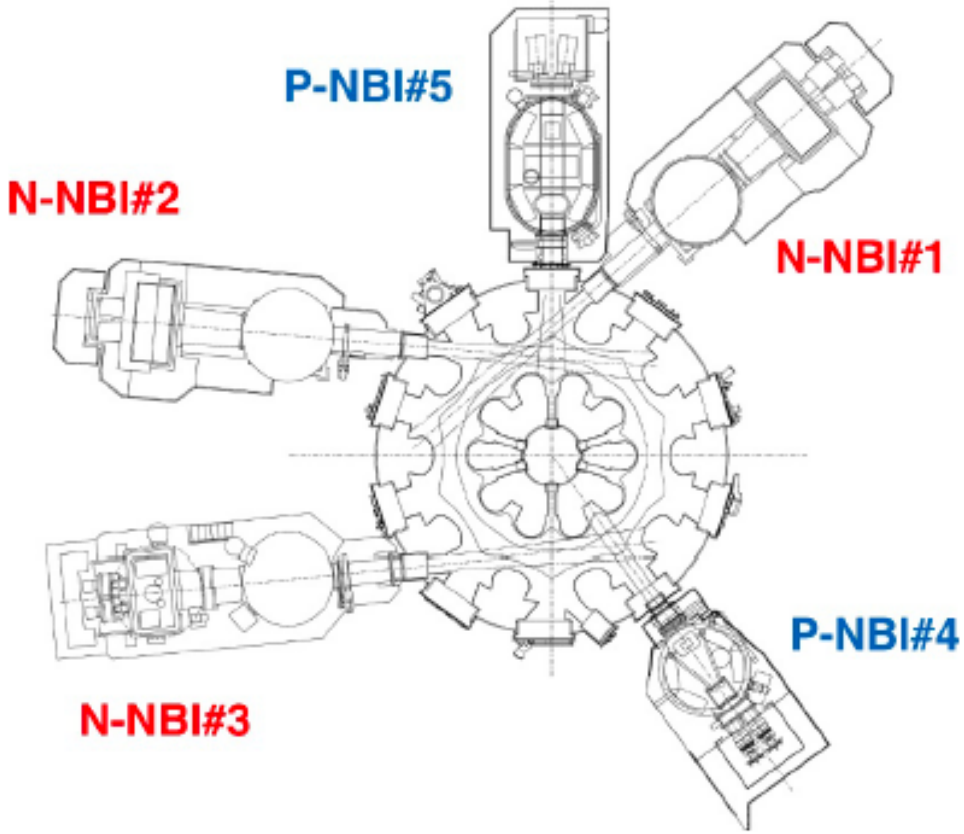
   and representative results of the measurements

3) Summary

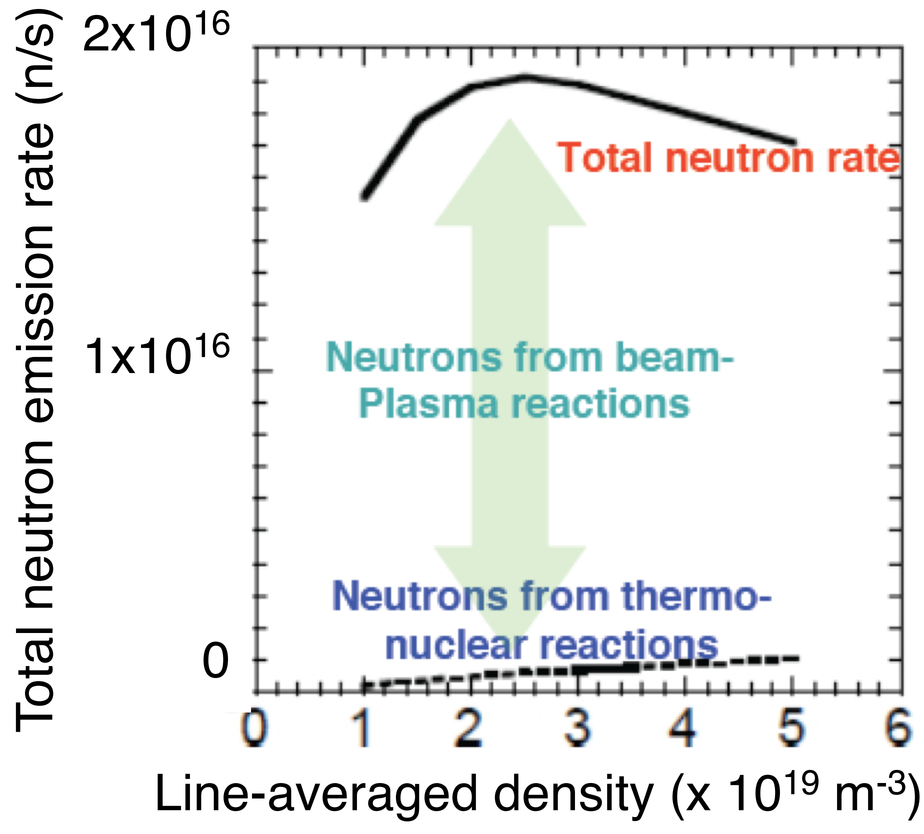
Neutron production in LHD and role of neutron diagnostics

Deuterium operation has begun in LHD in March, 2017 to explore higher-performance helical plasmas and enhance energetic-particle physics study.

Arrangement of five NBIs on LHD



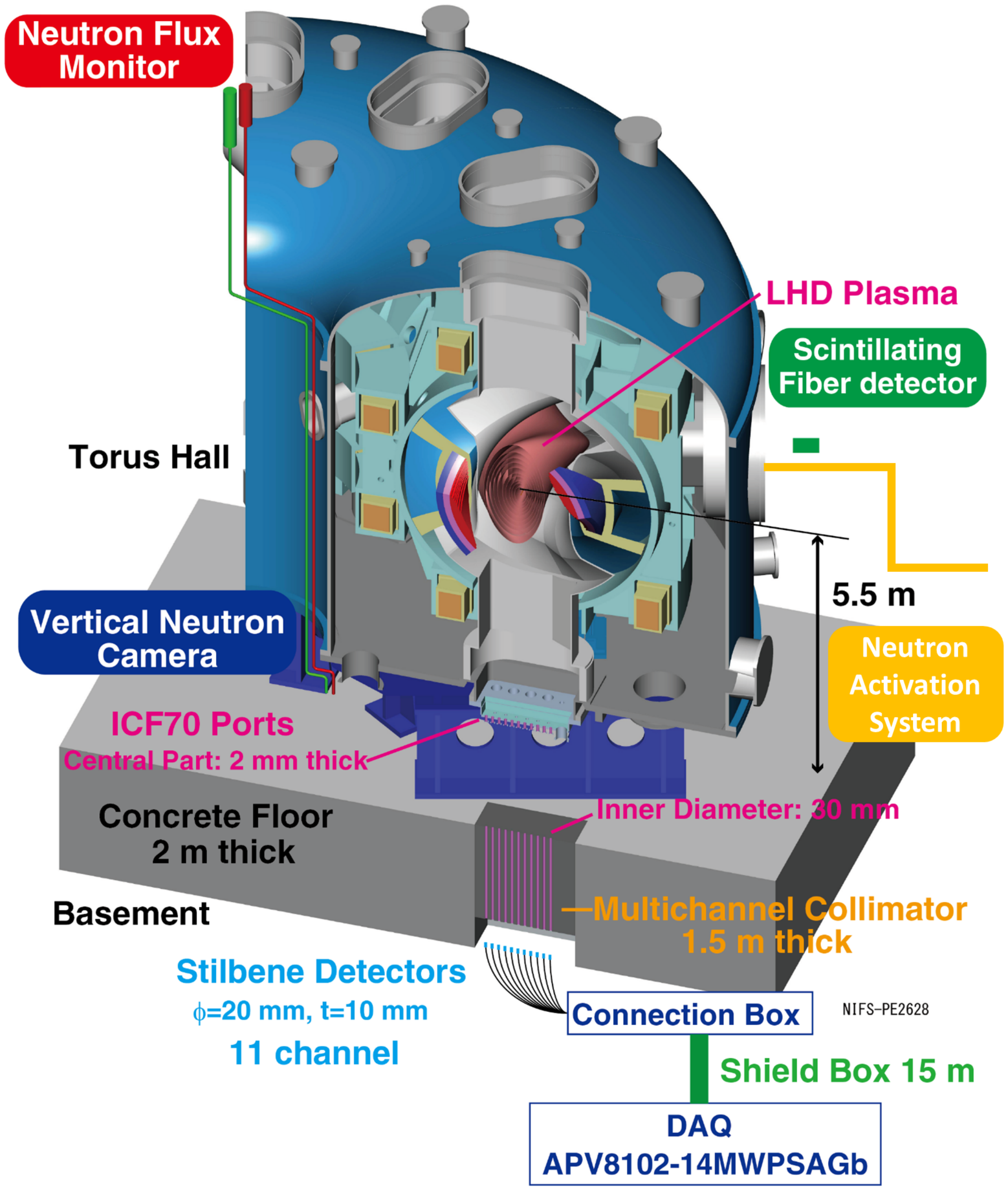
Predicted neutron emission rate



In LHD, generated neutrons are dominated by neutrons coming from beam-plasma reactions.

Neutron diagnostics play an important role to accelerate understanding of energetic-particle physics in LHD plasmas.

A comprehensive set of neutron diagnostics operated in LHD



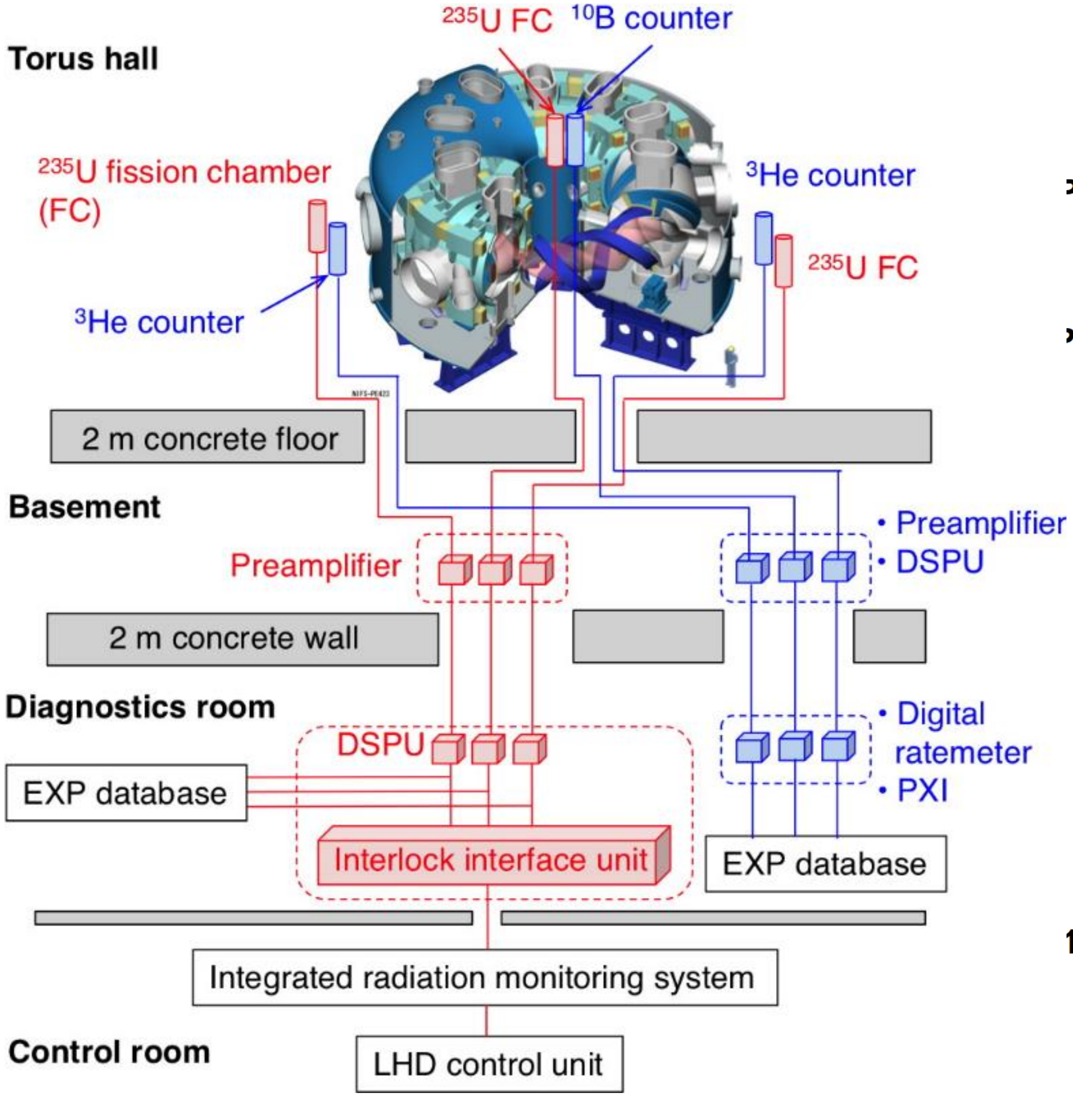
- **Neutron Flux Monitor (NFM)**
  Total neutron emission rate
  → Global beam ion confinement
- **Neutron Activation System (NAS)**
  Shot-integrated neutron fluence
  → Shot-integrated global beam ion & 1 MeV triton confinement
- **Vertical Neutron Camera (VNC)**
  Radial neutron profile
  → Radial profile of EP
- **Scintillating-fiber (Sci-Fi) Detector**
  Secondly DT neutron rate
  → Time-resolved 1 MeV triton confinement

Status of LHD neutron diagnostics

System	Ch.	Detector	Location	Purpose	Status
NFM	1	^{235}U fission chamber, ^{10}B counter	Top of LHD	•Fusion output and Q_{DD} •Time-resolved S_n	2017~
	2	^{235}U fission chamber, ^{3}He counter	10-O port		
	3	^{235}U fission chamber, ^{3}He counter	4-O port		
NAS	1	In, Al, and Si foils	2.5-L port	•Shot-integrated Y_n for DD and secondary DT neutrons	2017~
	2	In, Al, and Si foils	8-O port		
VNC	1	Stilbene	2.5-L port/vertical LOS	•Time-resolved DD neutron emission profile	2017~
	2-1	EJ-410 (ZnS:Ag + Plastic)	1.5-L port/diagonal LOS		2018~
	2-2	EJ-410 (ZnS:Ag + Plastic)	1.5-L port/vertical LOS		2019~
Sci-Fi	1	LANL Sci-Fi detector	8-O port	•Time-resolved DT neutron emission rate	2017~
	2	NIFS Sci-Fi detector	2.5-L port		
	3	TOYAMA Sci-Fi detector	2.5-L port		
NFD	1	EJ-410 (ZnS:Ag + Plastic)	2.5-L port	•Neutron fluctuation	2017~
	2	EJ-200 (Plastic)	2.5-L port		2019~
NES	1	TOFED	Basement beneath 2.5-L port	•DD and DT neutron spectrometry	2019~
	2	^{7}Li enriched CLYC	6-T port	•DD neutron spectrometry	
	3	EJ-301 (Liquid)	6-T port		
CVD-D	1	Single crystal CVD diamond	9.5-L port	•Evaluation of neutron field	2018~

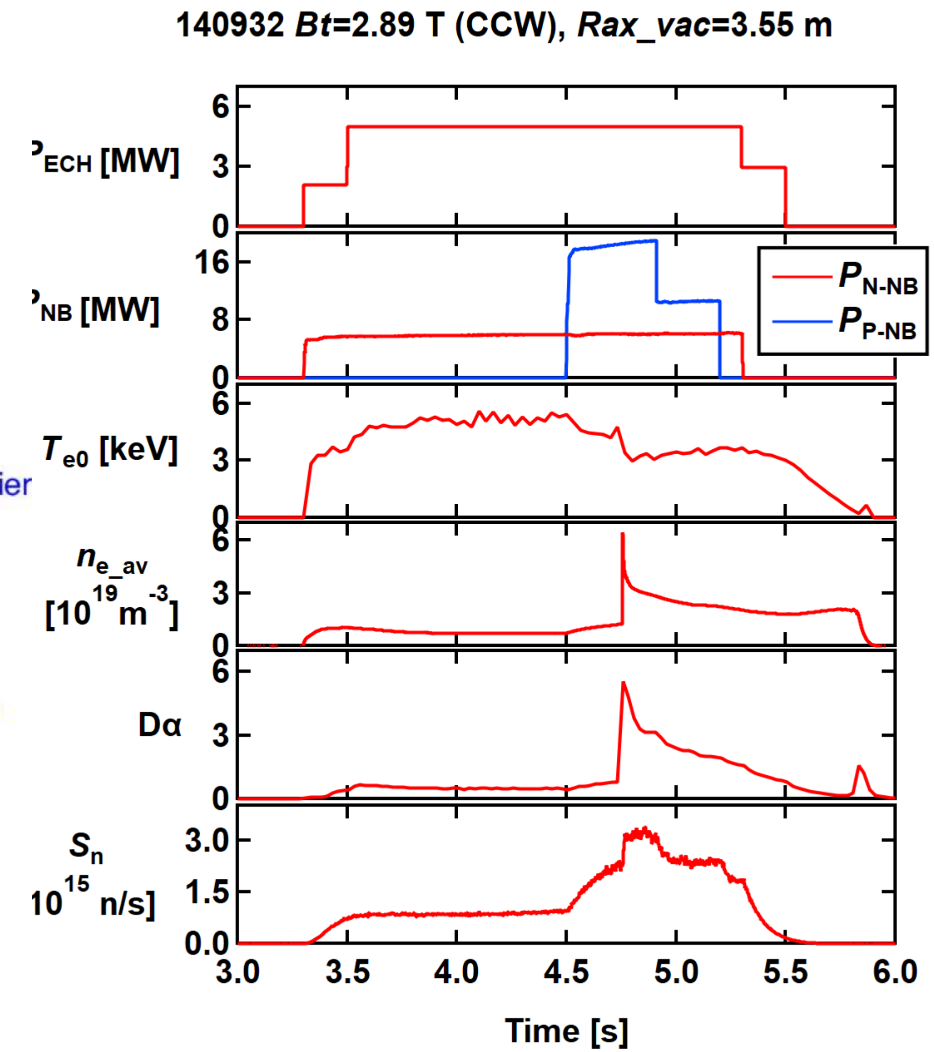
LHD is equipped with ex-vessel NFM characterized by fast-response and wide dynamic range capabilities

Arrangement of NFM



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

Highest neutron rate shot

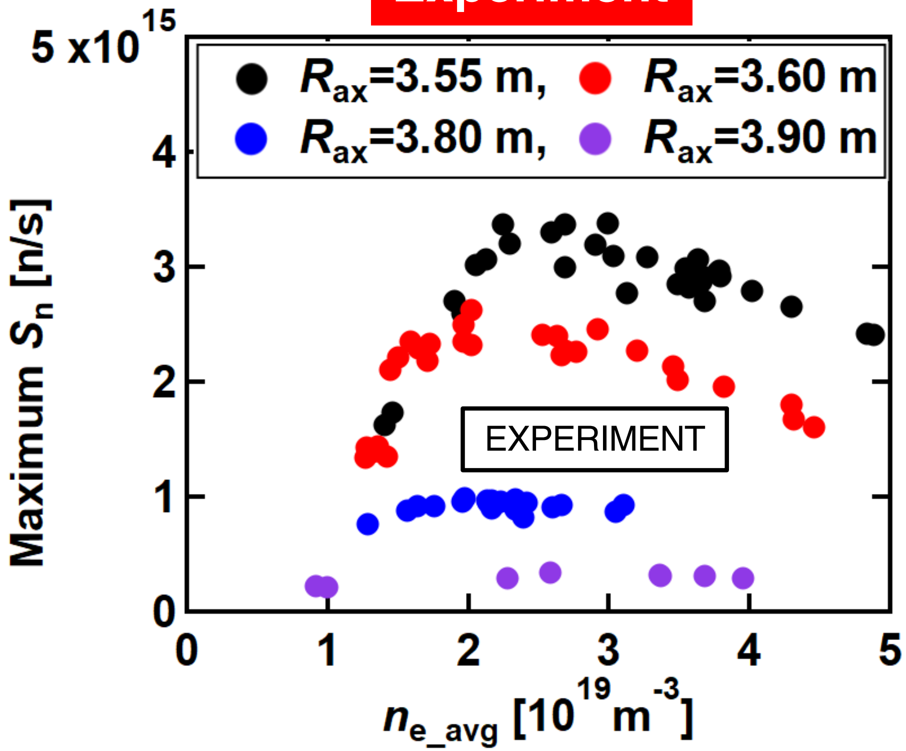


M. Isobe *et al.*, Nucl. Fusion. **58** (2018) 082004.

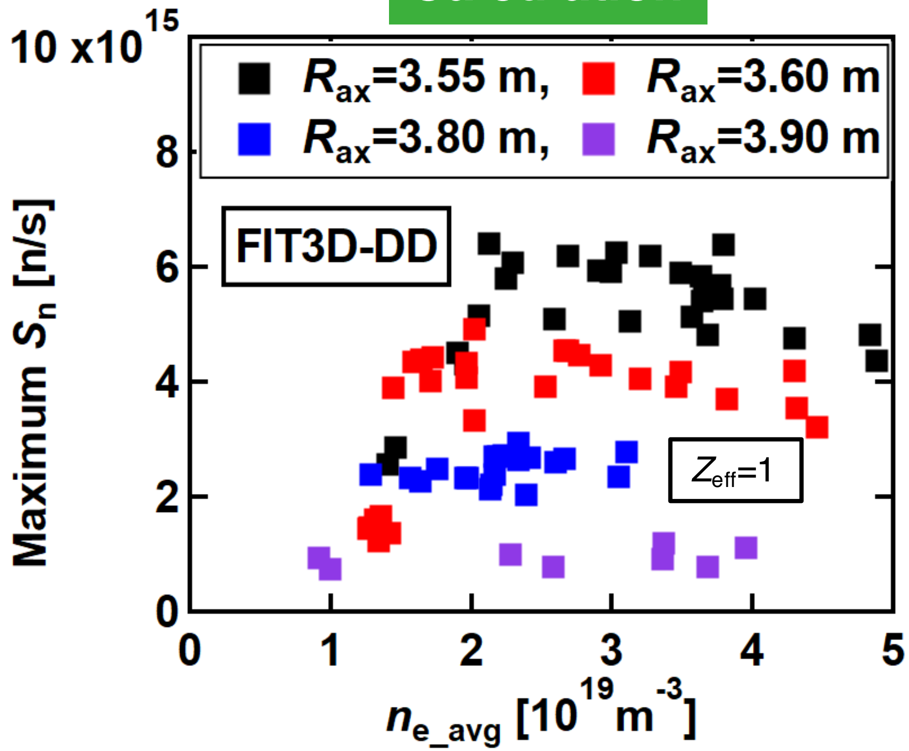
The maximum S_n have reached 3.3×10^{15} (n/s).

Dependence of total neutron emission rate on electron density

Experiment



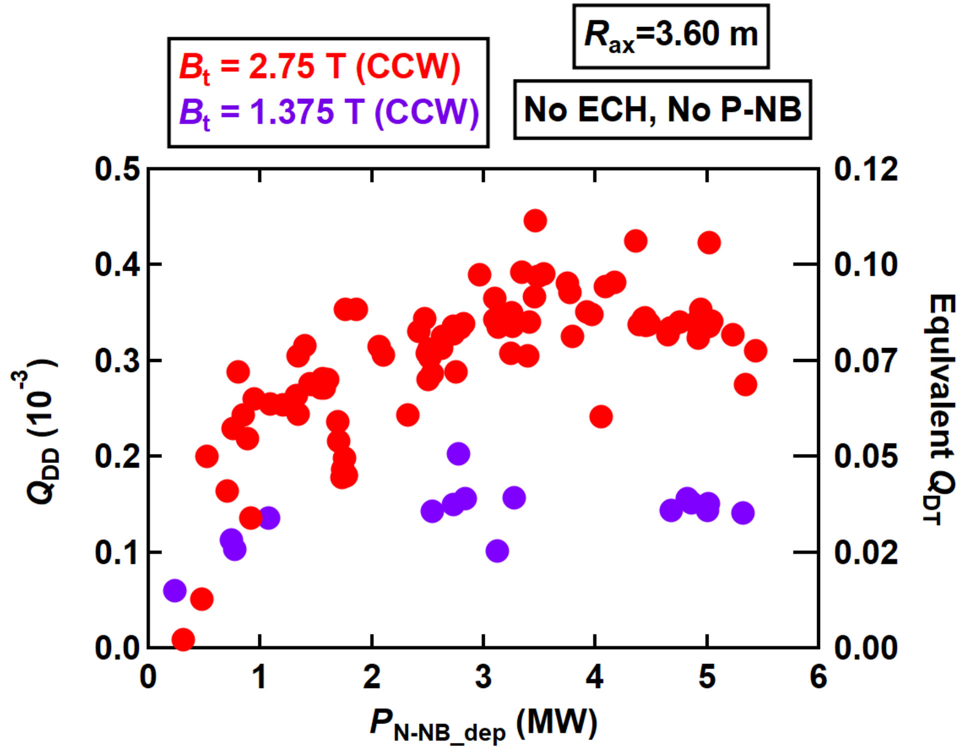
Calculation

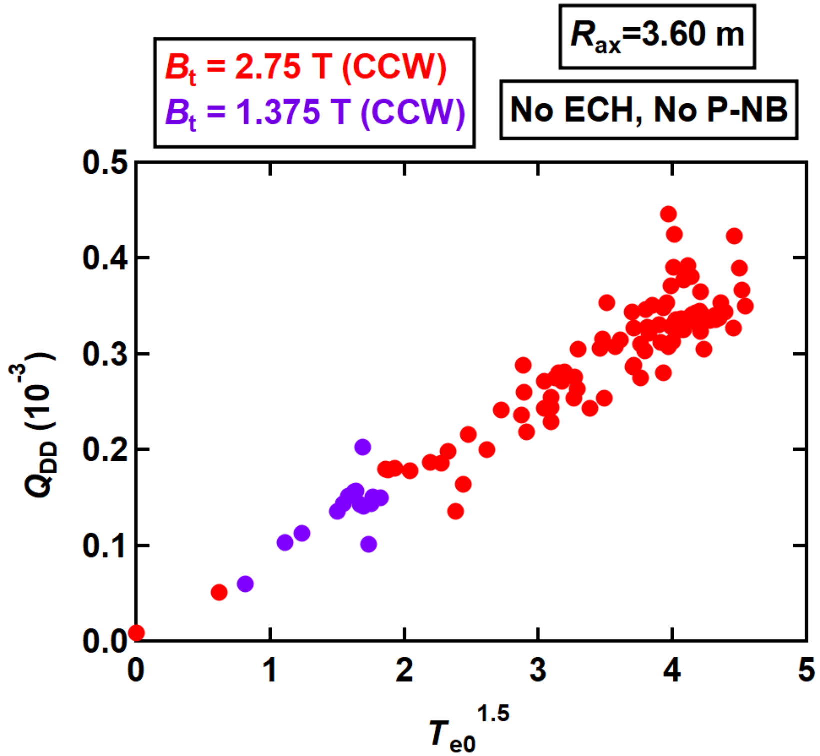


K. Ogawa *et al.*, Nucl. Fusion **59** (2019) 076017.

- The dependence of S_n on n_e is surveyed in different R_{ax} configurations.
- S_n is peaked around n_e of (2-3) x 10^{19} m^{-3}
- S_n decreases as R_{ax} is outwardly shifted.
- The FIT3D-DD code reproduces n_e dependence of S_n. The absolute value is almost two times higher than measured S_n because beam ion loss is not considered in the FIT3D-DD.

Fusion gain : Q_{DD} and equivalent Q_{DT}

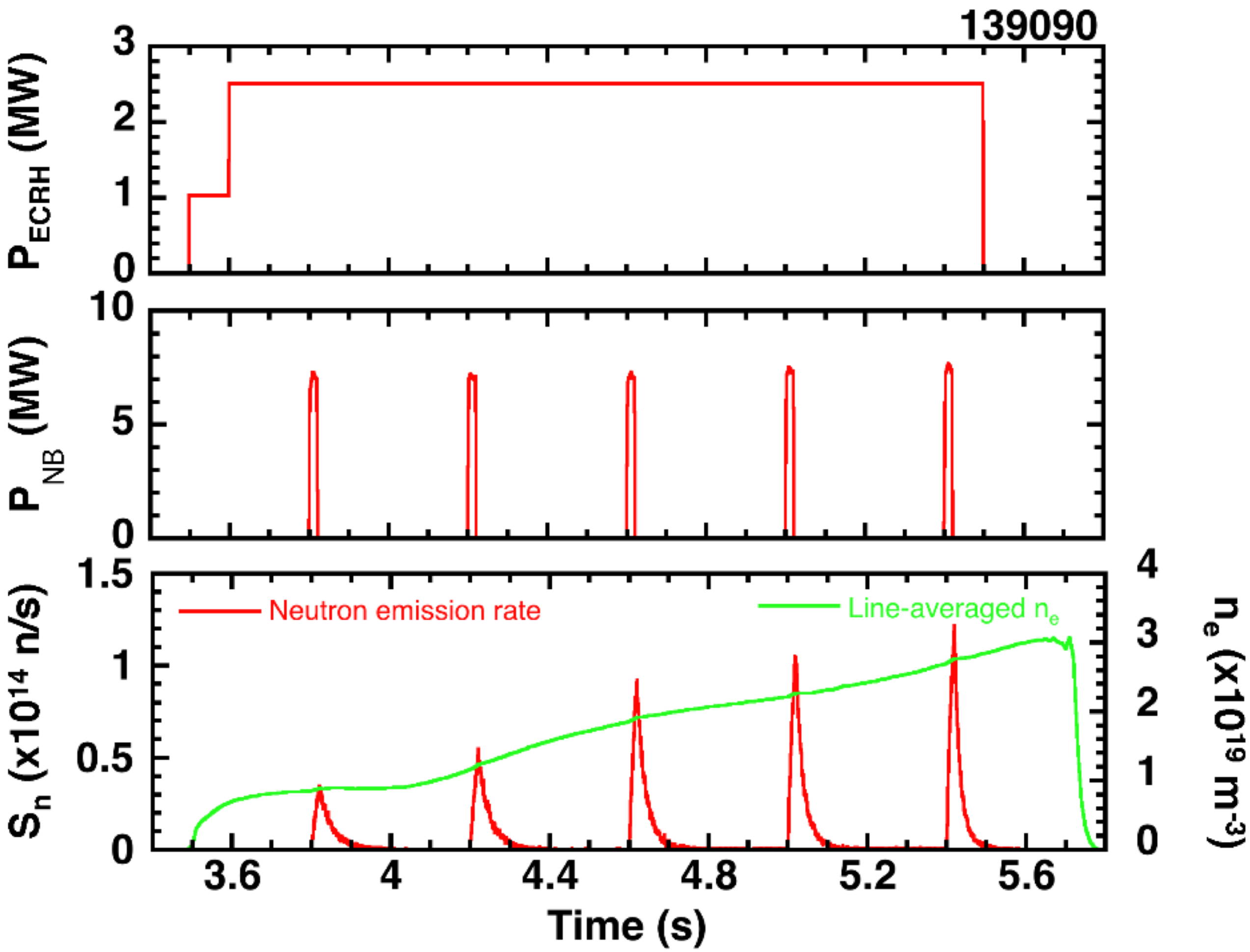




K. Ogawa *et al.*, Nucl. Fusion **59** (2019) 076017.

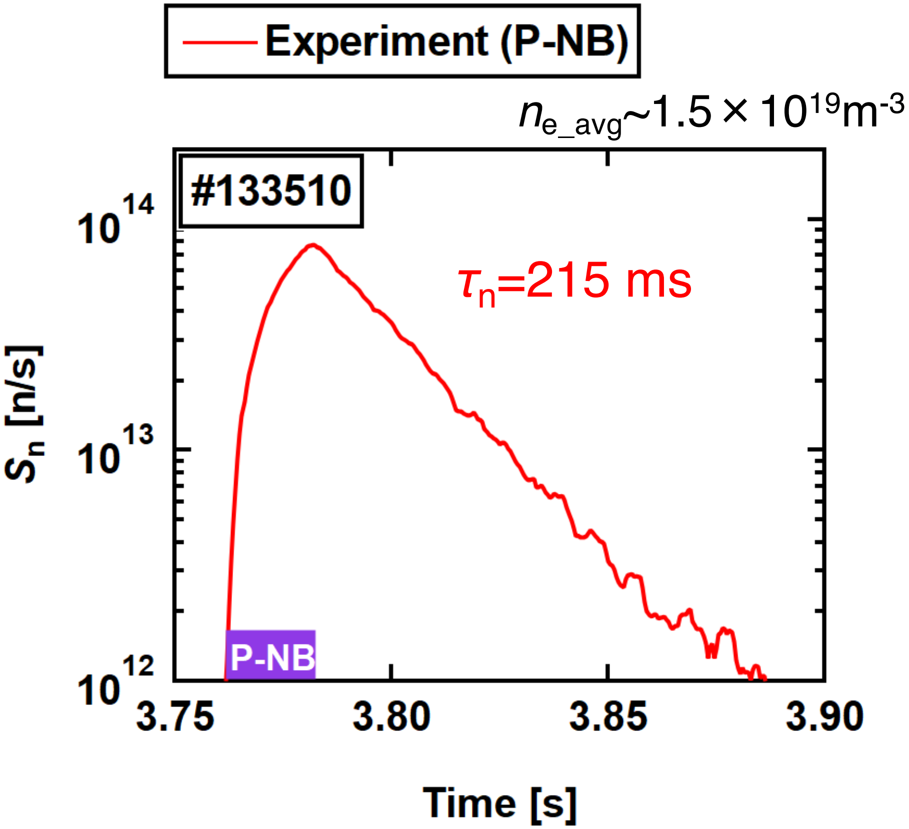
- Fusion gain Q is surveyed in N-NB heated LHD plasmas.
- Higher Q_{DD} is obtained in higher-B_t shots as expected.
- Equivalent Q_{DT} evaluated by the FBURN code reaches ~0.11.
- Linear dependence of Q_{DD} on $T_{e0}^{1.5}$ is consistent with neutrons mainly produced by beam-plasma reactions. This is because $Q_{DD} \sim S_n/P_{NB} \sim n_i \times P_{NB} \times \tau_s/P_{NB} \sim n_i \times T_e^{1.5}/n_e \sim T_e^{1.5}$.

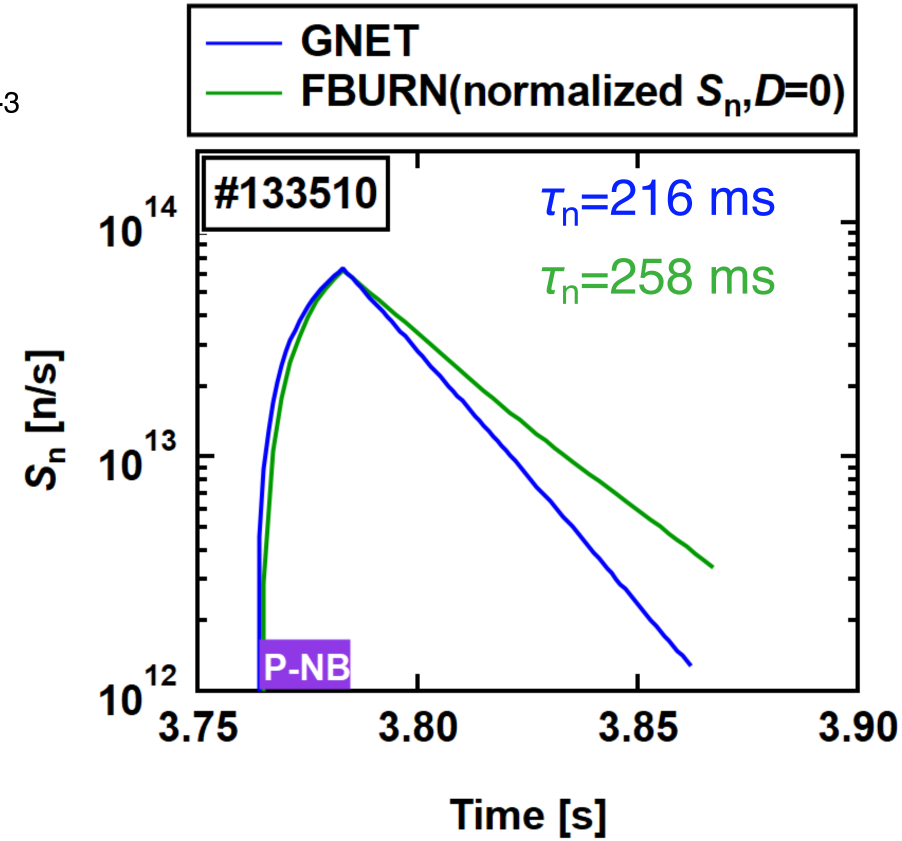
Typical time evolution of neutron emission rate due to NB blips



- Peak value of S_n increases as n_e increases as expected according to increase of NB deposition.
- Neutron decay time tends to be shorter as n_e increases and vice versa. This tendency is consistent with that predicted by classical slowing-down theory.

Comparison of neutron decay rate after NB is turned off

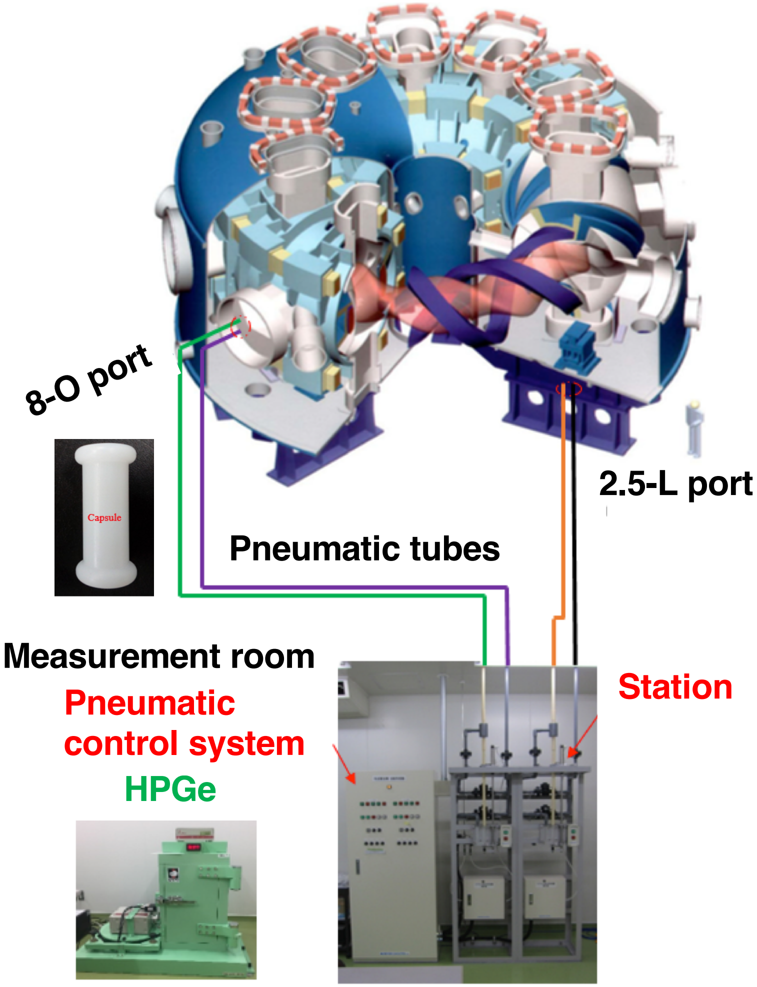




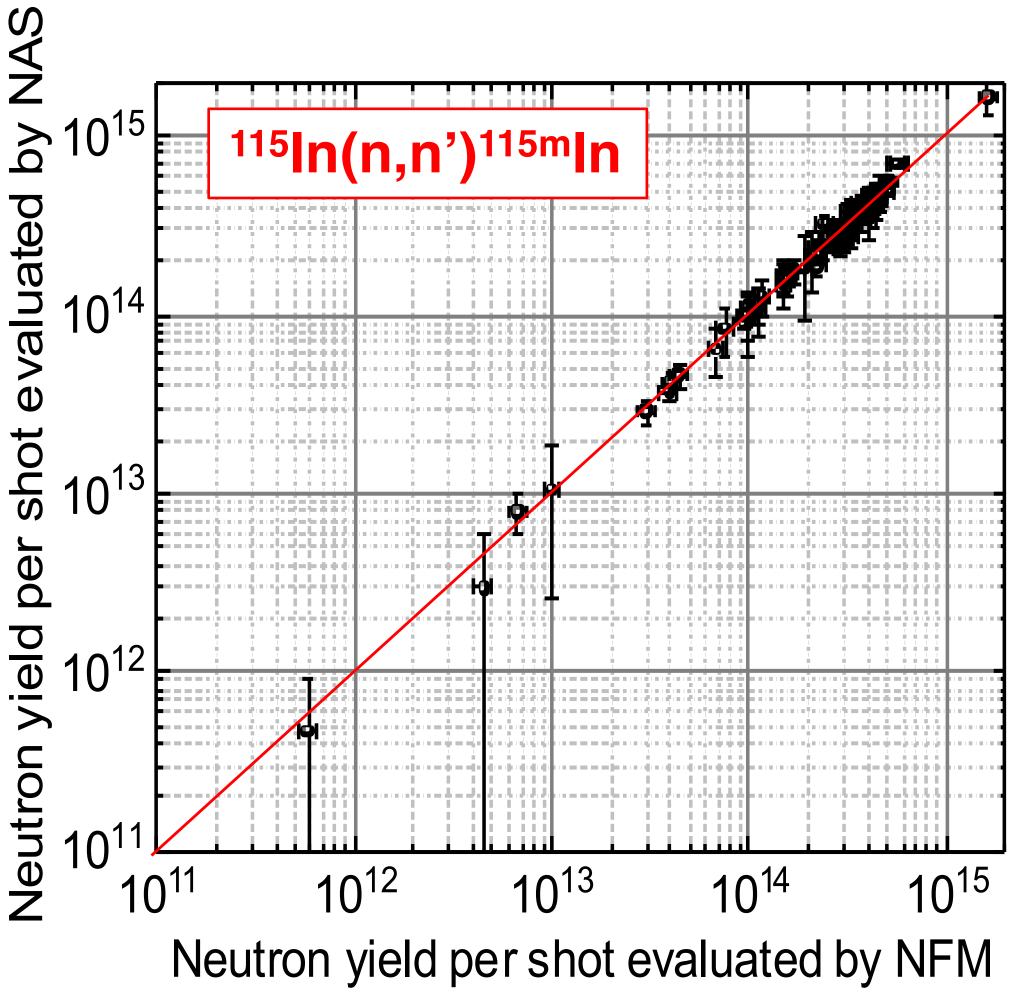
- Time evolution of S_n obtained in NB blip experiment is compared with the numerical simulations FBURN (1D classical model) and GNET (5D neoclassical model model).
- Measured S_n is successfully reproduced by the GNET code.
- Beam ion transport can be described with neoclassical models in MHD-quiescent low-β plasmas.

Neutron activation system on LHD

The NAS on LHD has two irradiation ends, which perform important roles in cross-checking neutron yield evaluated by the NFM.



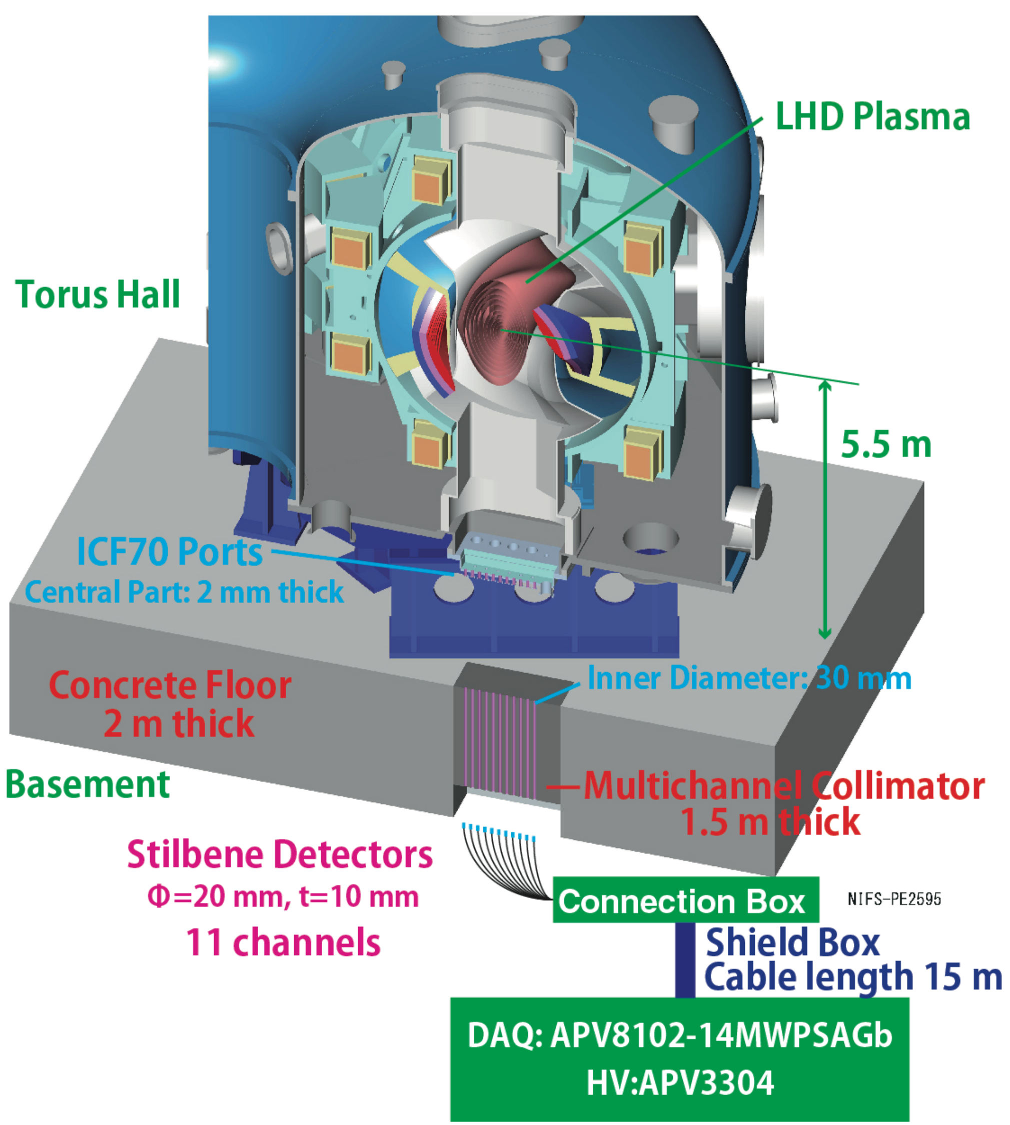
N. Pu *et al.*, Rev. Sci. Instrum. **88** (2017) 113302.



- Neutron yield evaluated by NAS agrees well with that measured with NFM.
- Also, NAS has been used to measure secondary 14 MeV neutron fluxes by using $^{28}Si(n, p)^{28}Al$ reaction to study 1 MeV triton's behavior.

Vertical Neutron Camera (VNC) #1 optimized for high-S_n shot

Arrangement of VNC #1



Multichannel collimator made of heavy concrete

- High-shielding performance
- Low cross-talk

Stilbene scintillation detector

- High n-γ discrimination ability
- High gain-stability

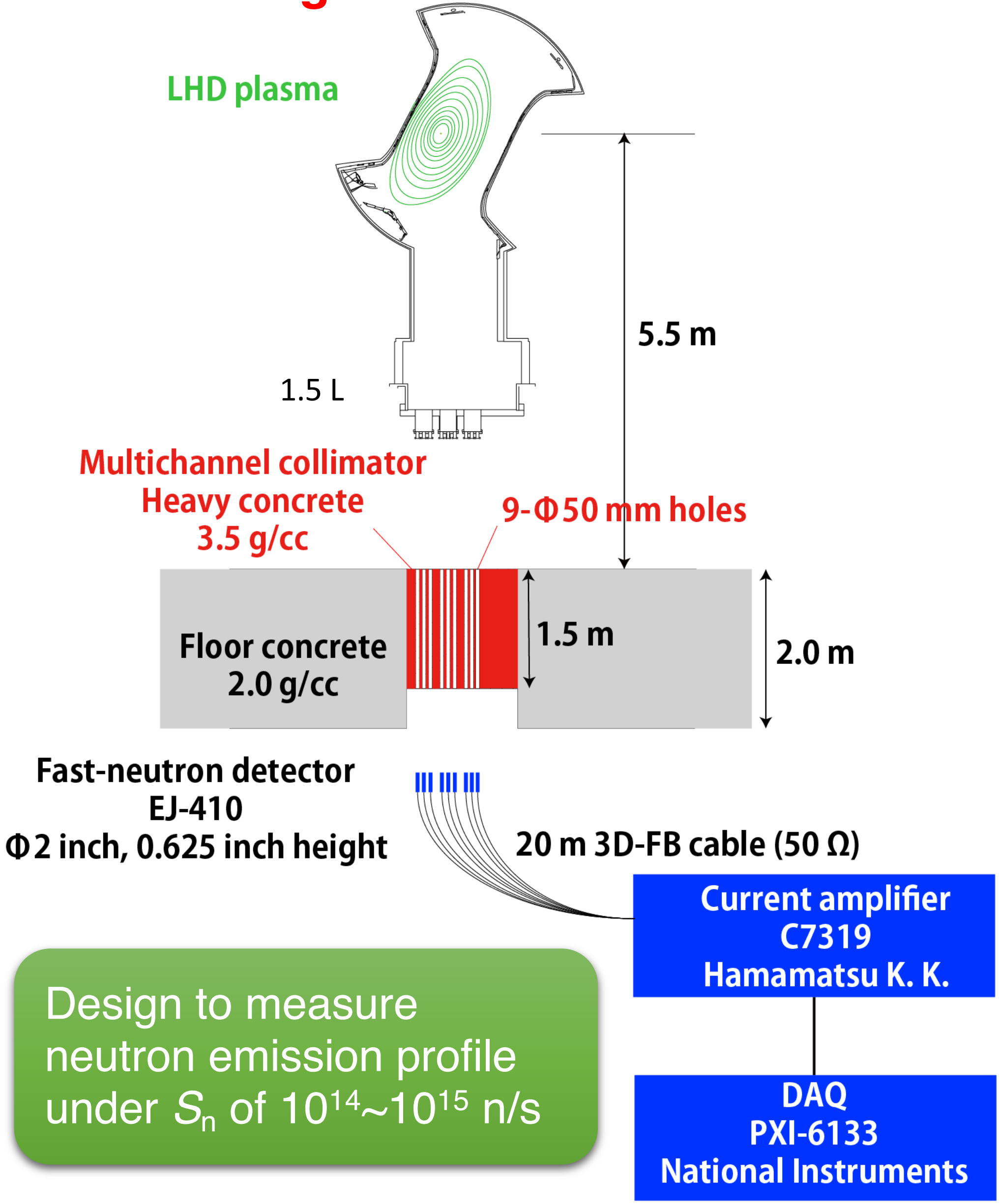
1 GHz ADC + FPGA

- Online and offline n-γ discrimination
- Wide dynamic range up to 10^6 cps

K. Ogawa *et al.*, Rev. Sci. Instrum. **89** (2019) 113509.

Vertical Neutron Camera (VNC) #2 optimized for relatively low-S_n shot

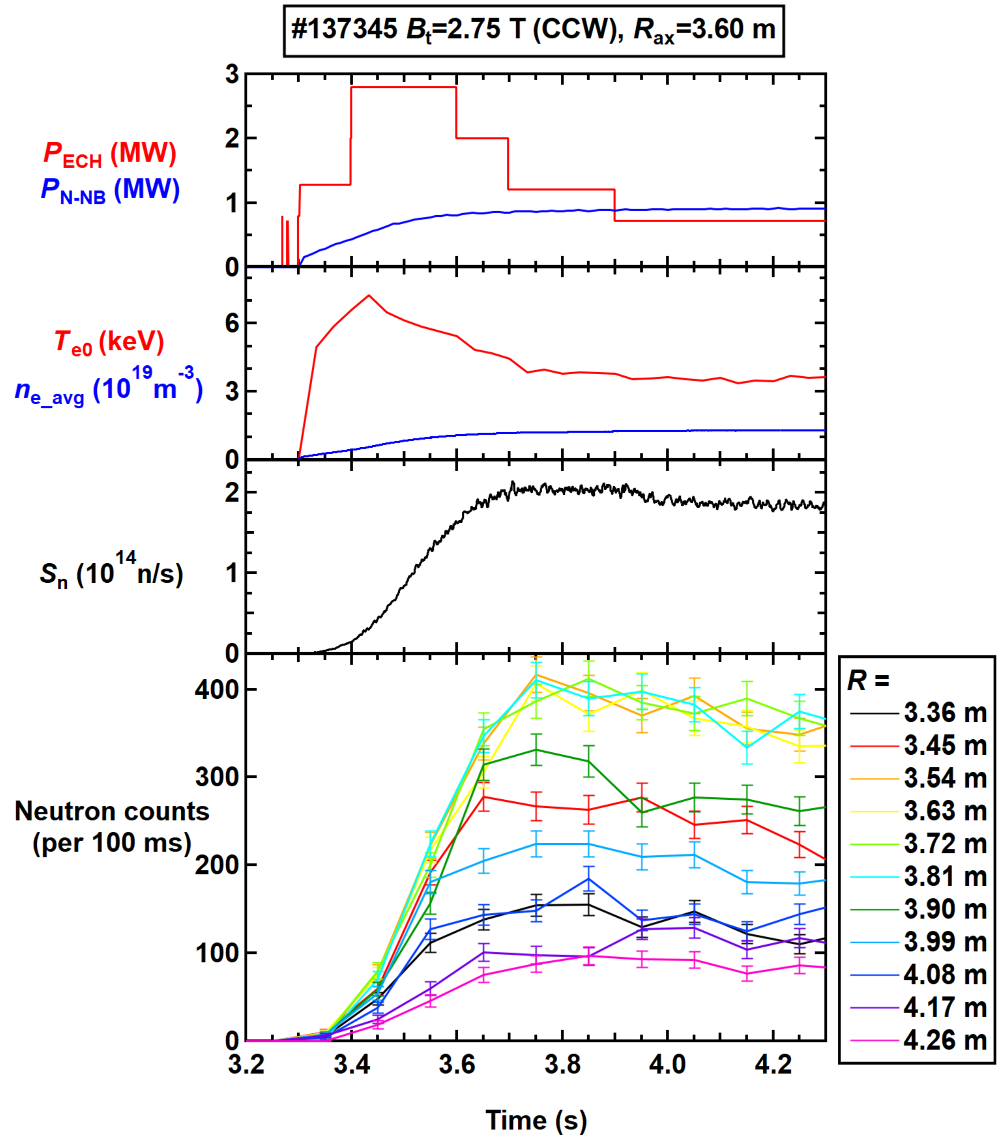
Arrangement of VNC #2

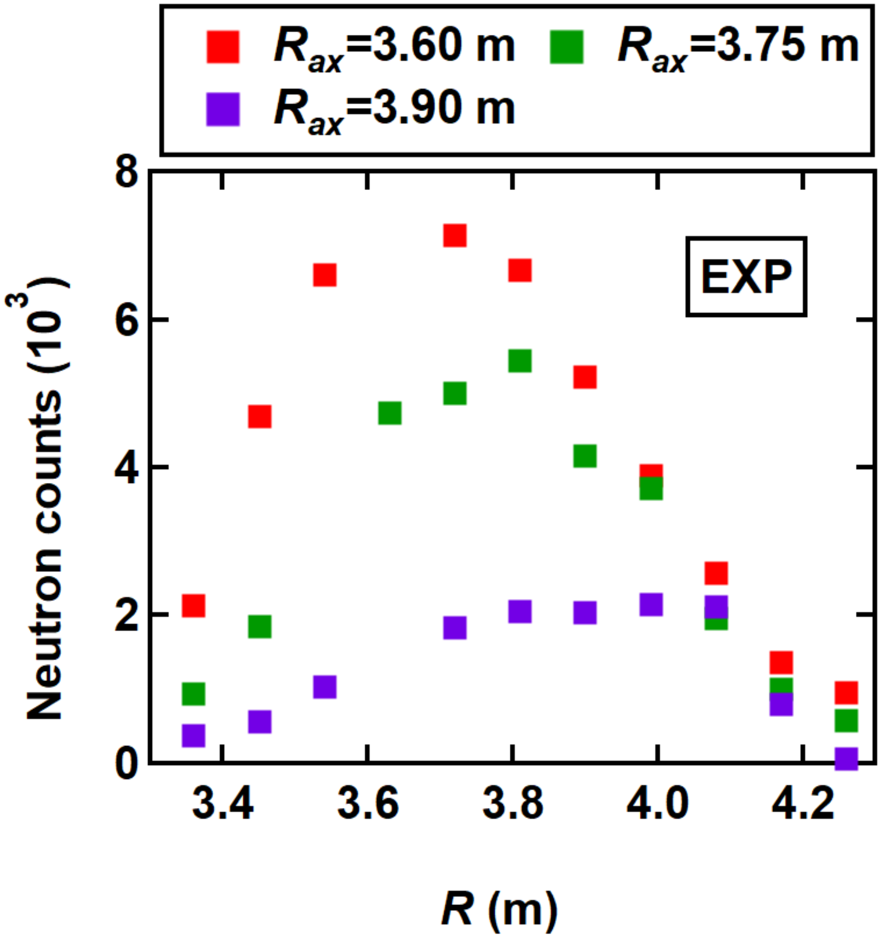


Design to measure neutron emission profile under S_n of 10^{14}~10^{15} n/s

- **Multichannel collimator**
  - Hematite-doped heavy concrete
    - 9 sight lines
    - Diameter of hole : 50 mm
- **Fast-neutron detector**
  - EJ410 fast-neutron scintillator
    - Diameter: 2 inch
    - Height: 0.625 inch
    - Photomultiplier tube
    - H7195, Hamamatsu K.K.
- **Current amplifier**
  - Gain: 104 to 106 V/A (selectable)
  - Bandwidth: 200 kHz
- **Data acquisition system**
  - PXI-6133, National Instruments
  - Sampling frequency: 1 MHz

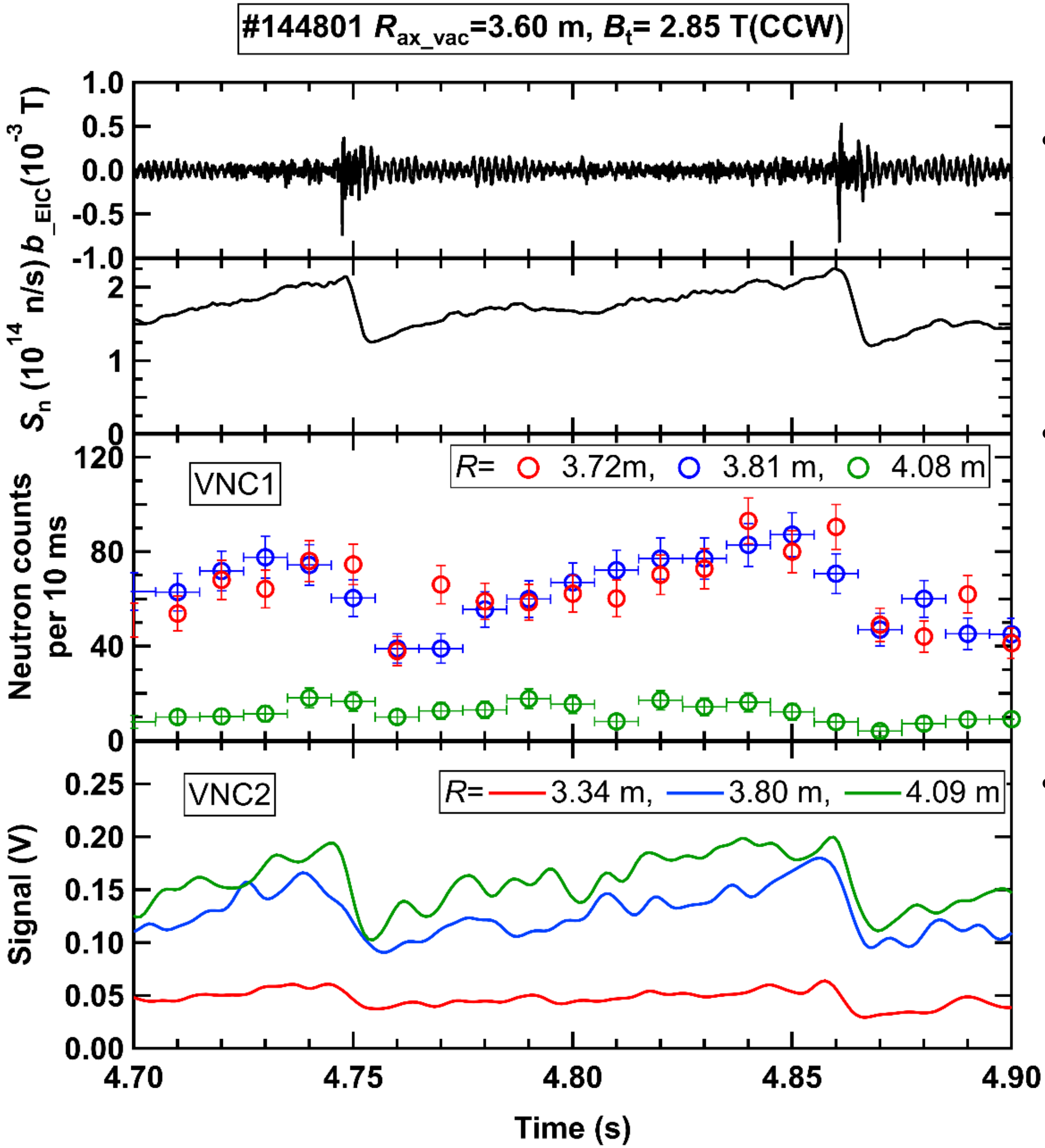
Neutron emission profile measured with VNC#1 while tangential N-NB is injected





- Line-integrated neutron profile is measured in N-NB heated deuterium LHD plasmas.
- The peak of neutron counts shifts outwardly as R_{ax} is shifted outwardly.

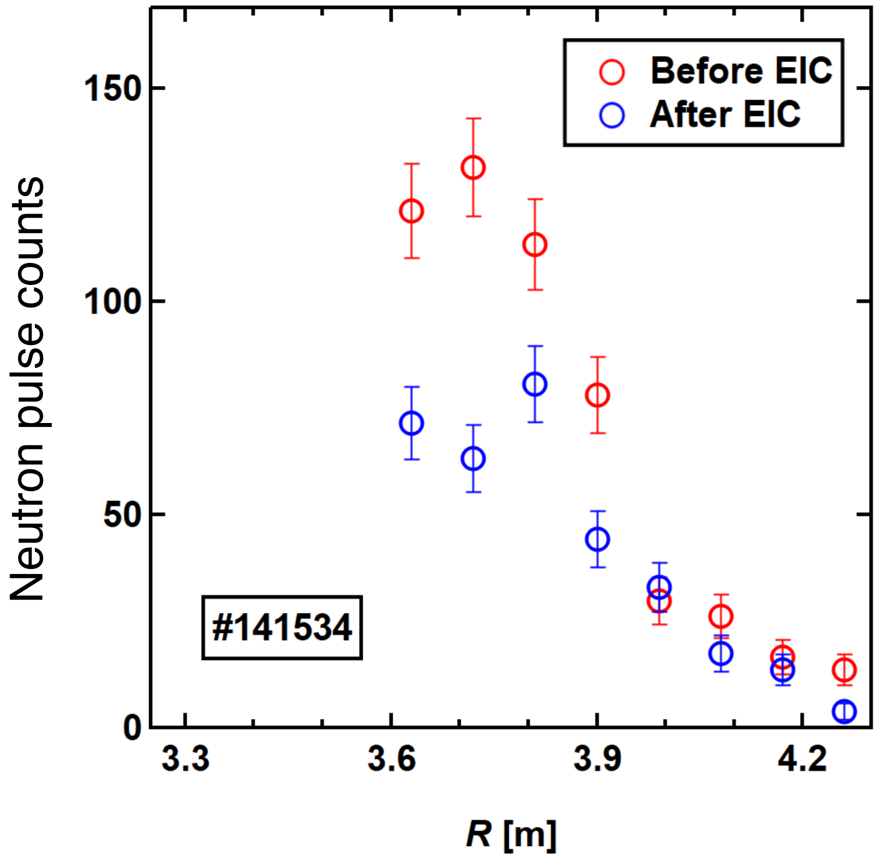
Drop of neutron rate measured with VNC#2 is much clearer than that with VNC#1



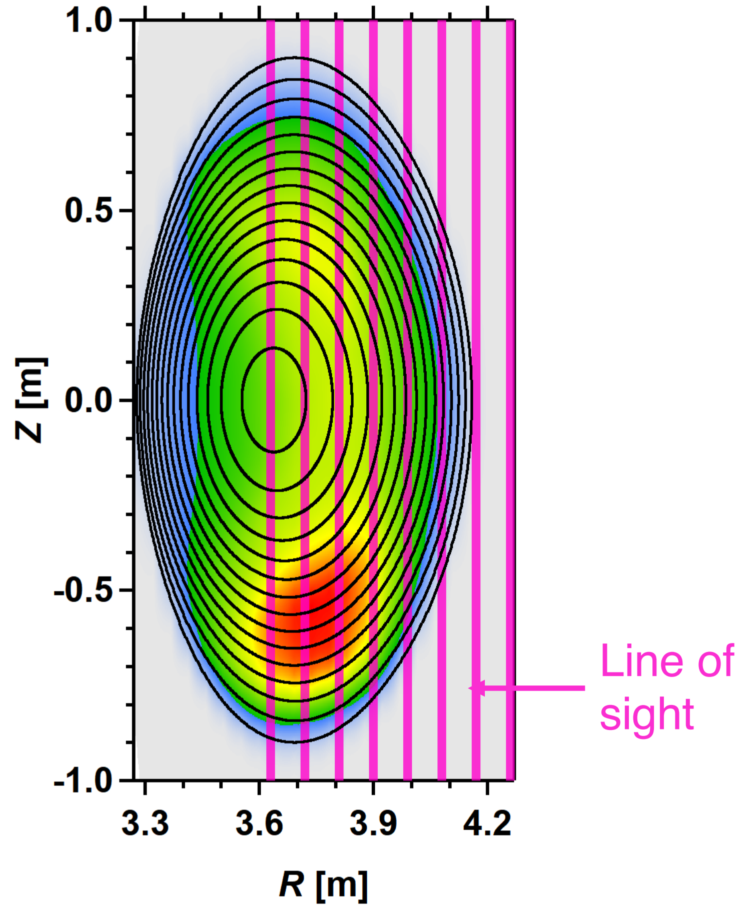
- Time evolutions of line-integrated neutron emission profile in EIC discharge are measured with VNC#1 and #2.
- In VNC#1, neutron counting rate in the central channel decreases significantly due to EIC. On the other hand, neutron counting rate in the edge channel stays almost the same.
- In VNC#2, signal in relatively outer channel decreases dramatically due to EIC. Decay time is almost the same as the decay time of S_n.

VNC#1 suggests losses of helically trapped beam ions due to EIC

Line-integrated neutron emission profile



Density of helically trapped beam ions



- Correlated with EIC bursts, neutron counts in the core channels decreases dramatically.
- Decrease of neutron counts in central channels shows the loss of helically-trapped beam ions.

Scintillating-fiber detectors for triton burnup study

Time-resolved 14 MeV neutron flux is measured by Sci-Fi detectors calibrated by NAS.

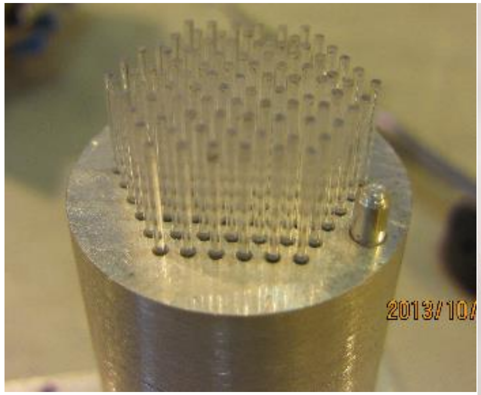
Fusion reactions in a deuterium plasma

Primary d-d reaction

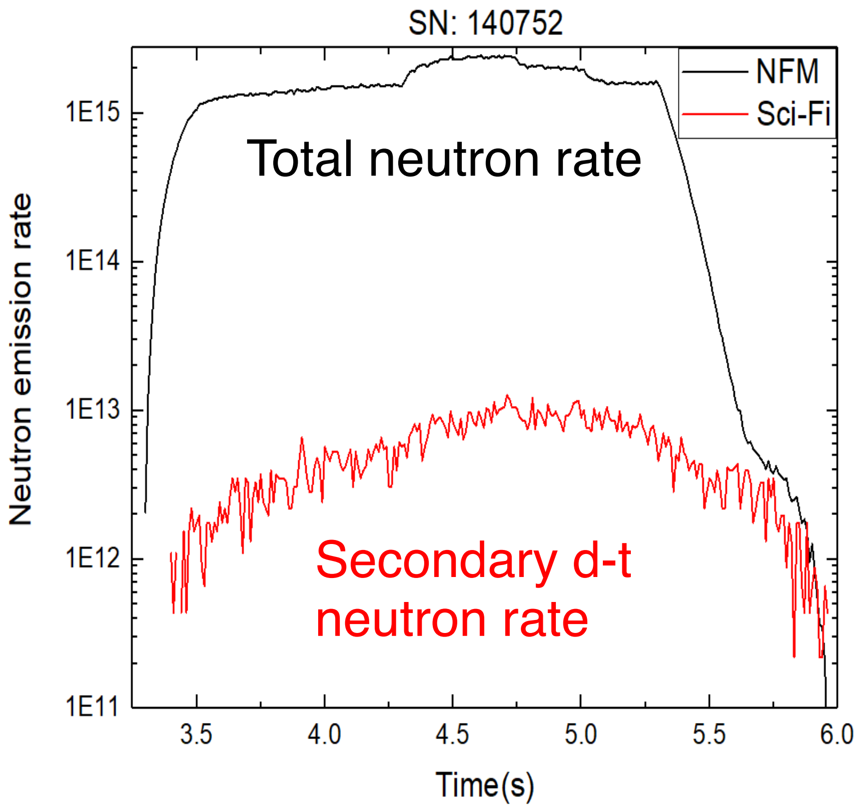
- d + d → ^{3}He (0.8 MeV) + n (2.5 MeV)
- d + d → t (1 MeV) + p (3 MeV)

Secondary d-t reaction

t + d → ^{4}He (3.5 MeV) + n (14 MeV)

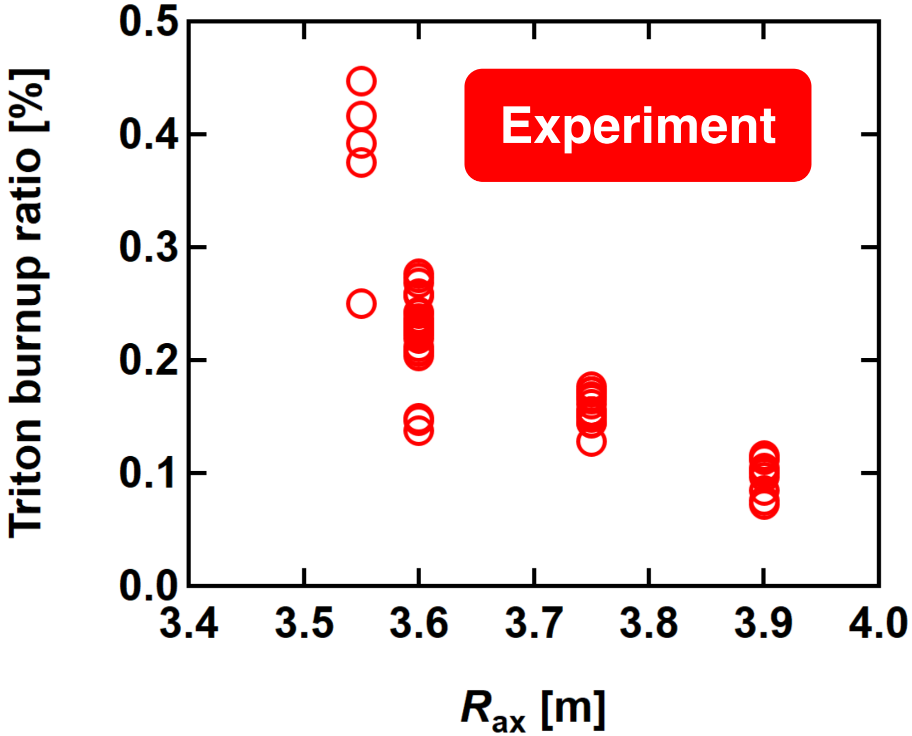


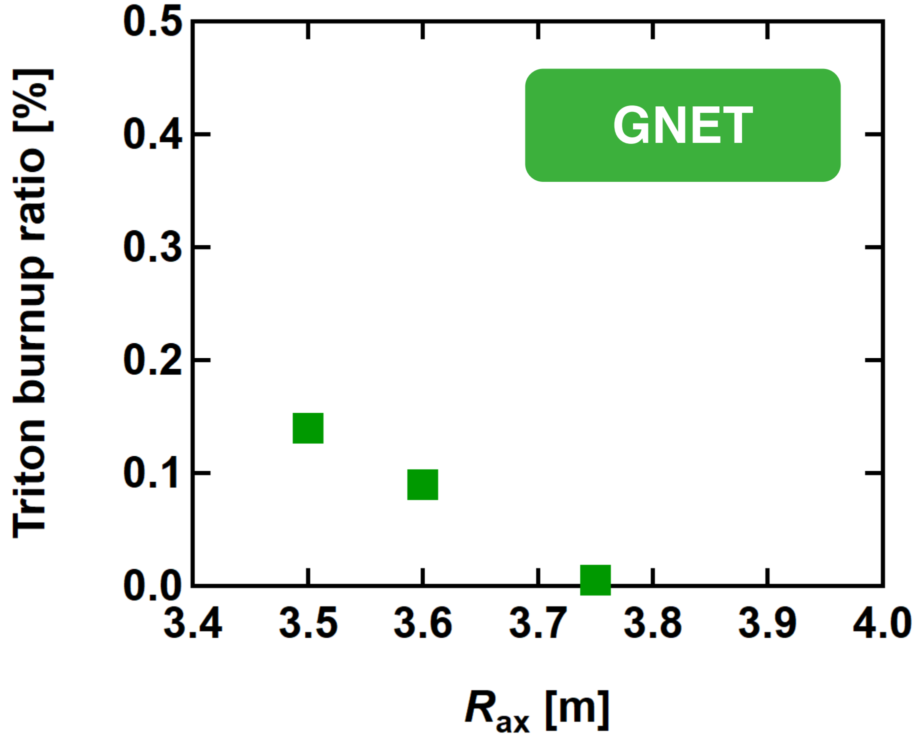
Time evolutions of total and 14 MeV neutron rates



- Build-up rate of 14 MeV neutron flux is slower than that of total neutron rate.
- It comes from cross section curve for d-t reaction.

Triton burnup ratio significantly depends on magnetic field configuration

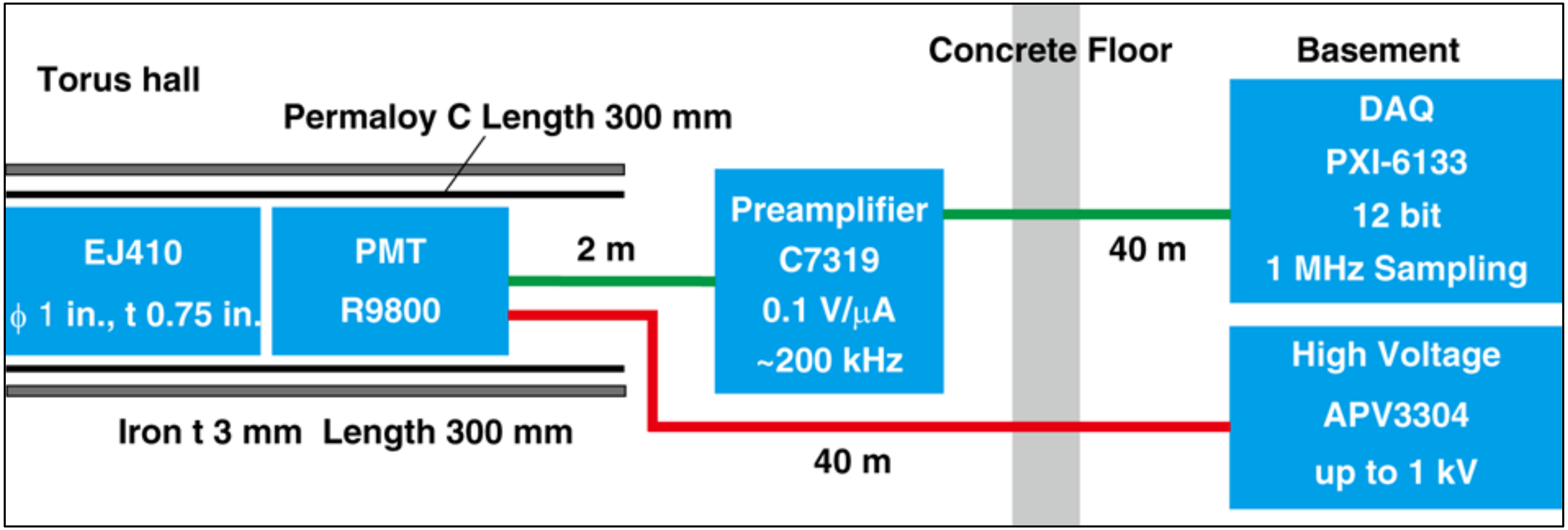




- Triton burnup ratio ($Y_{n\ d\text{-}t}/Y_{n\ d\text{-}d}$) increases dramatically with the inward shift of R_{ax}.
- The GNET code shows the similar tendency but the absolute value is relatively lower.
- The difference between measurement and GNET comes from the finite Larmor radius and re-entering effects because the GNET code follows the GC orbit in the Boozer coordinates and the loss boundary is placed at the last closed flux surface.

K. Ogawa *et al.*, Nucl. Fusion **59** (2019) 076017.
Highlighted in Nature Physics **15** July (2019) 622

Neutron fluctuation measurement

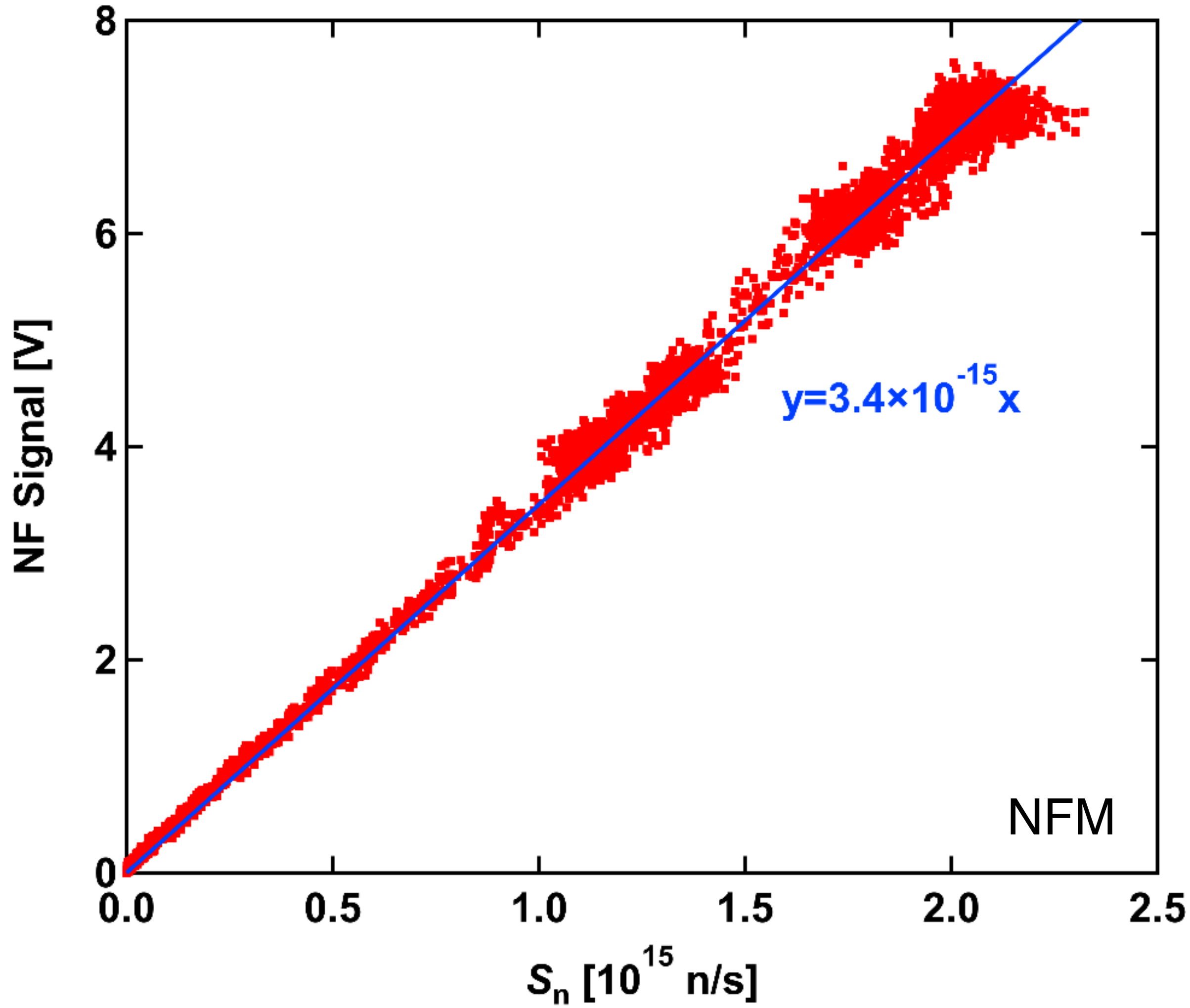


K. Ogawa *et al.*, Plasma Fus. Res. **13** (2018) 3402068.

- **Fast-neutron scintillator**
  - EJ410 : 1 inch ϕ, 0.75 inch thick
  - Low sensitivity to gamma-ray and low-energy neutron (< 1 MeV)
- **PMT**
  - H10580-100MOD35, Hamamatsu Photonics KK. : f = 1 inch
- **Current amplifier**
  - C7319, Hamamatsu Photonics KK.
  - Gain : 0.1 V/mA, Frequency response : 200 kHz
- **DAQ**
  - PXI-6133, National Instruments
  - VPP : 10 V, Bit resolution : 12 bits, Sampling rate : 1 MHz

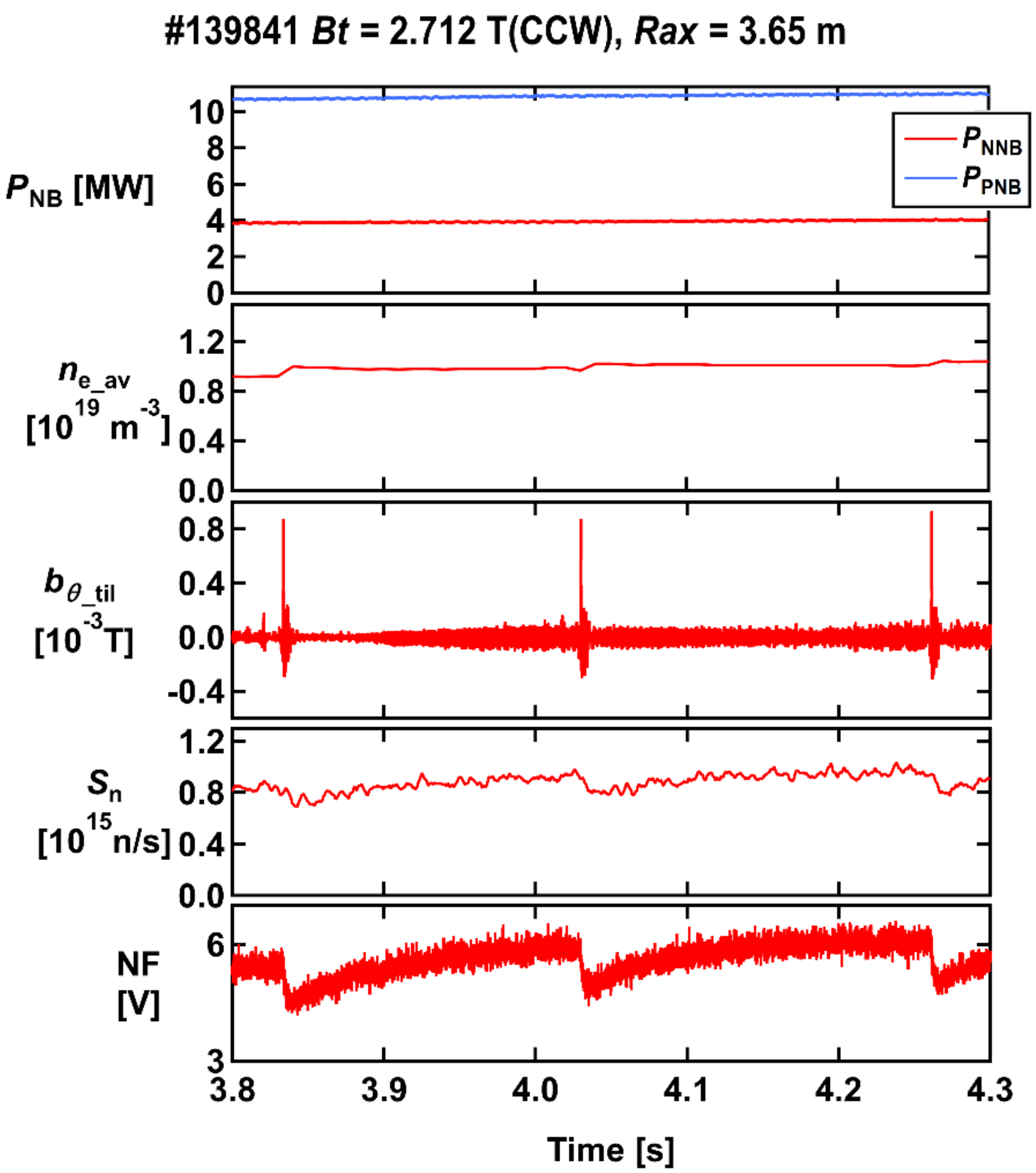
High time response
~ 5 ms is possible.

S_n measured with NFM versus neutron fluctuation detector signal intensity



- Signal intensity of NF detector linearly increases with increase of S_n as expected.
- S_n from NF detector signal can be evaluated using 2.9×10^{14} [(n/s)/V].

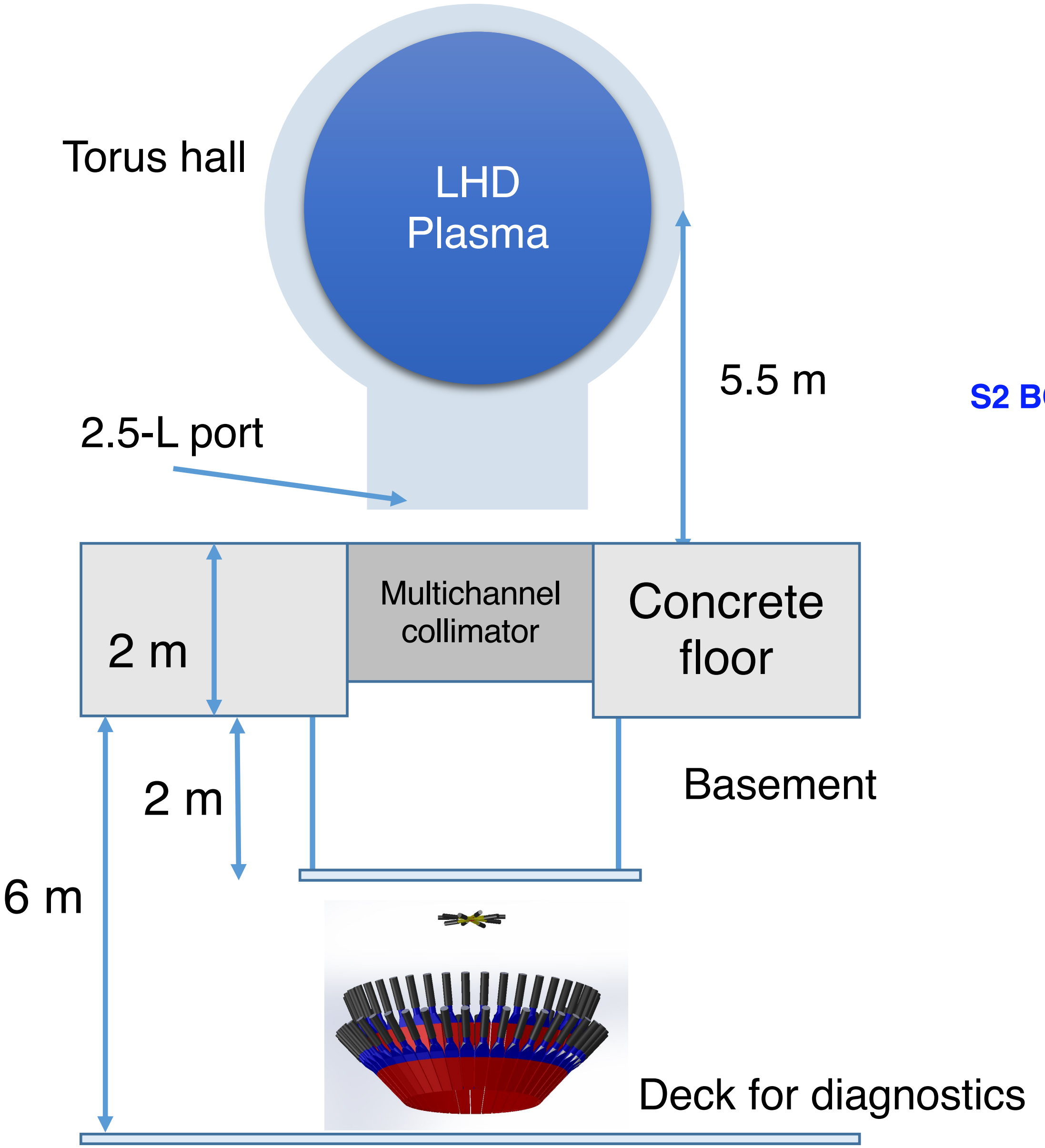
Rapid change of neutron flux can be detected



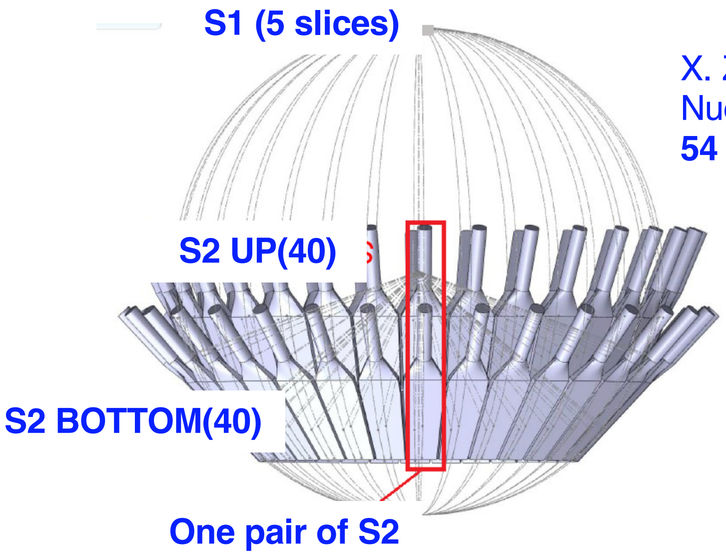
- Neutron flux is measured by NF in deuterium discharges with relatively strong MHD bursts.
- The intermittent decreases of neutron flux due to MHD bursts are observed.
- The signals of NF and S_n decrease by almost 20 % synchronized with MHD bursts.
- NF signal shows that the time scale of neutron emission decrease is around 0.5 ms.
- On the other hand, the decay time of S_n is slower, ~ 2 ms, resulting from intrinsic time response of NFM.

Time of Flight Enhanced Diagnostics (TOFED) on LHD in the collaboration with Peking University, China

Overview of TOFED

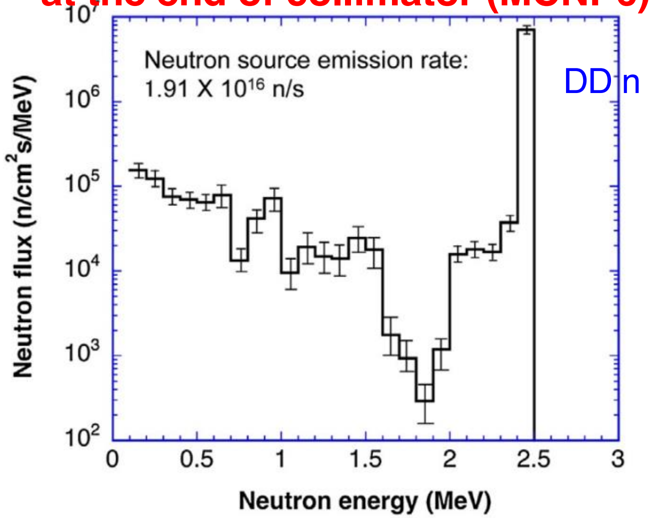


Structure of TOFED



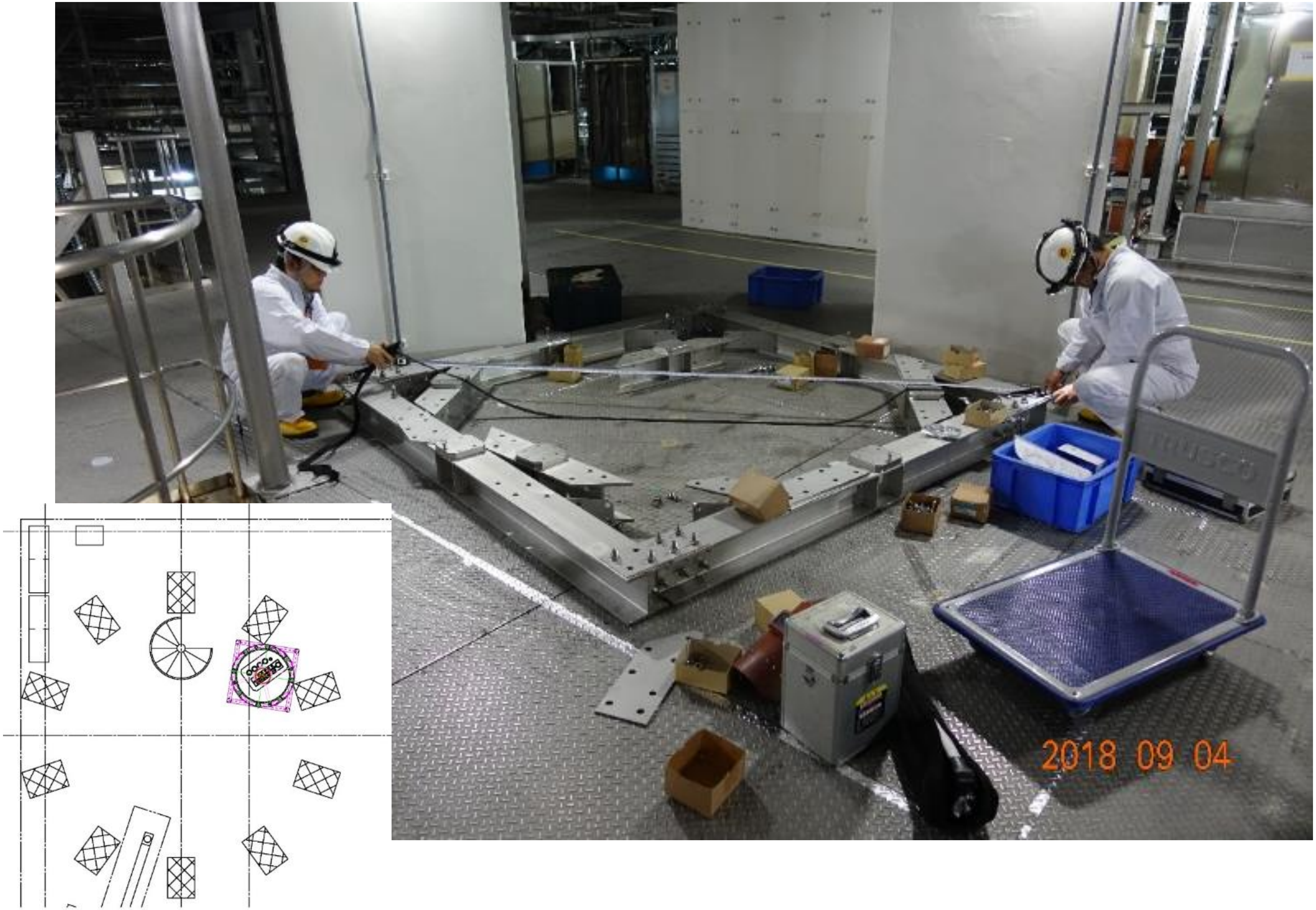
X. Zhang *et al.*, Nucl. Fusion **54** (2014)104008.

Neutron energy spectra at the end of collimator (MCNP6)

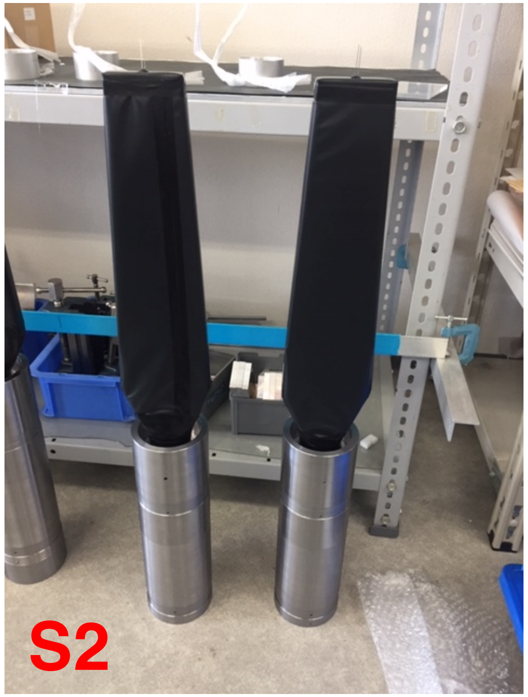


T. Nishitani *et al.* Fus. Eng. Des. **123** (2017) 1023.

Base of TOFED in the basement of torus hall

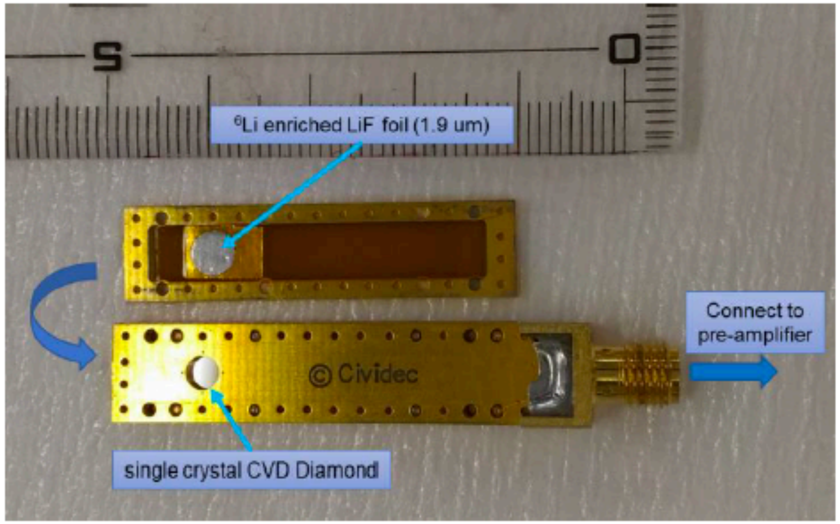


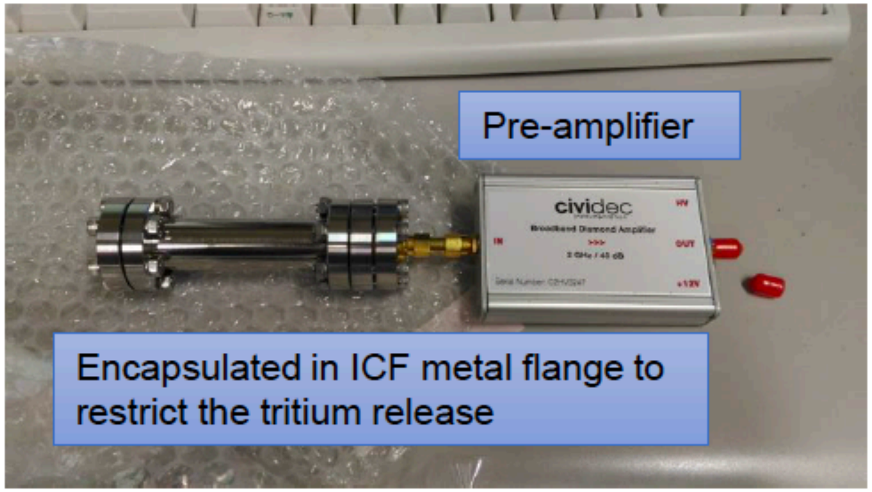
S1 and S2 detectors for TOFED

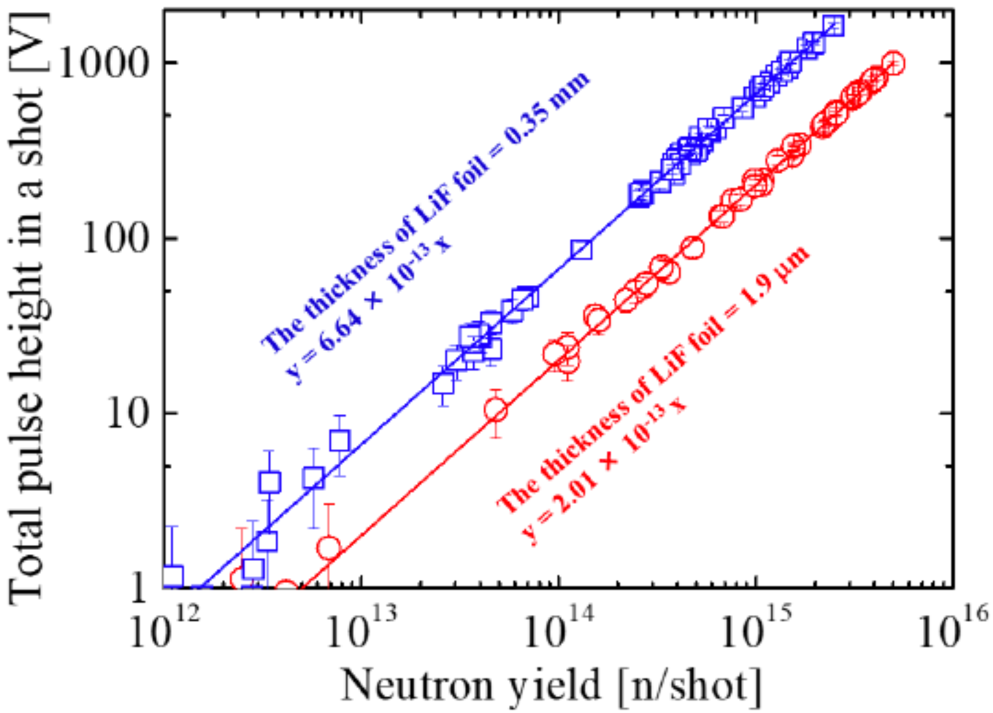


TOFED will be operated from this year.

Commissioning of single crystal CVD diamond detector on LHD







M. Kobayashi *et al.*,
accepted for publication in
Journal of Instrumentations

Summary

- Integrated set of neutron diagnostics has been operated in LHD for enhancement of energetic-particle confinement study, strict observance of neutron budget, and expansion of research field.
- Total neutron rate peaks around n_e of (2~3)x10^{19} m^{-3} as predicted by the FIT3D-DD code based on steady-state Fokker-Planck equation.
- The total neutron emission rate has reached 3.3x10^{15} (n/s).
- The equivalent Q_{DT} of 0.11 has been achieved which is comparable with that of large tokamaks with 5 MW NBI.
- As for NB blip injection, the 5-D GNET code reproduces total neutron rate in both the decay time and the absolute value in MHD-quiescent low-β plasmas.
- The VNC has shown that the peak position of the neutron profile shifts according to R_{ax} as expected.
- The VNC has revealed that rapid drop of neutron emission associated with EIC bursts is due to loss of helically trapped beam ions.
- Triton burnup experiment has been performed for the first time in stellarator/heliotron. The max. burnup ratio is 0.45% in the inward shifted configuration. The burnup ratio increases with the inward shift of R_{ax} in both experiment and numerical simulation.