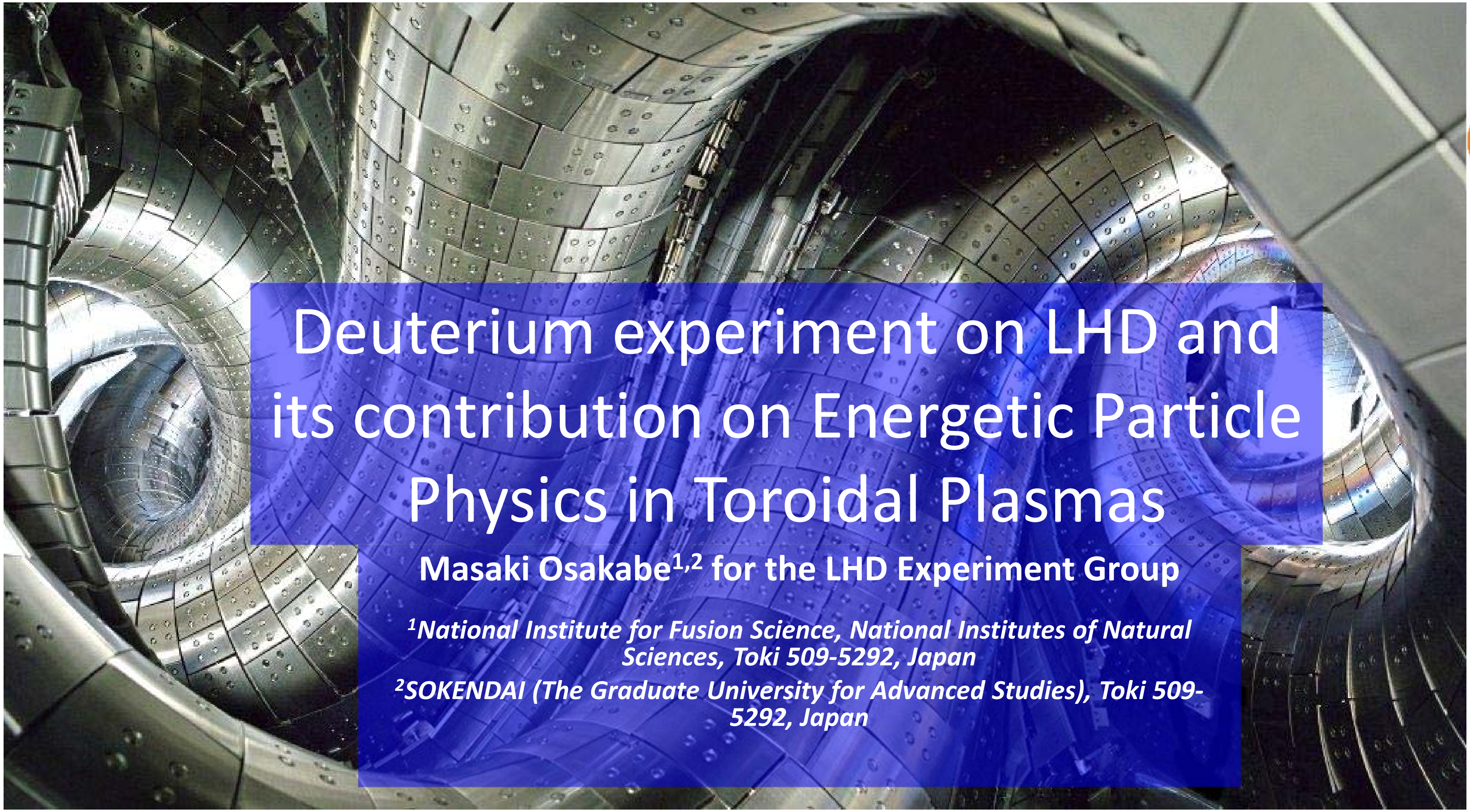

Deuterium experiment on LHD and its contribution on Energetic Particle Physics in Toroidal Plasmas

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   - LHD Deuterium Experiment
2. Energetic Particle Confinement Study at D-exp.
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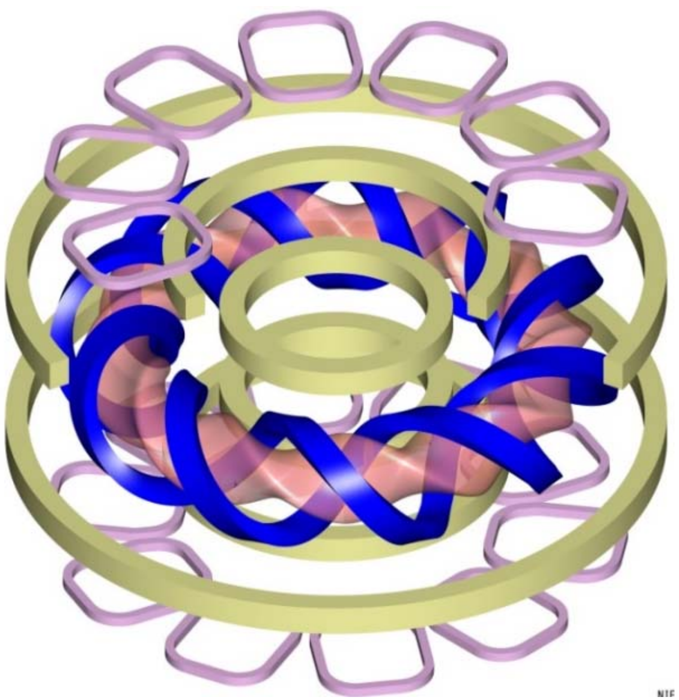
4. Summary

INTRODUCTION

LHD (Large Helical Device)



One of the largest superconducting magnet plasma confinement devices in the world

Specifications

- Mode numbers : *l/M*=2/10
- All superconducting system for confinement magnetic field: helical and poloidal coils
- Plasma major radius: 3.42-4.1 m
- Plasma minor radius: ~0.6 m
- Plasma volume: 30 m^3
- Toroidal field strength: 3 T
- 10 pairs of RMP coils

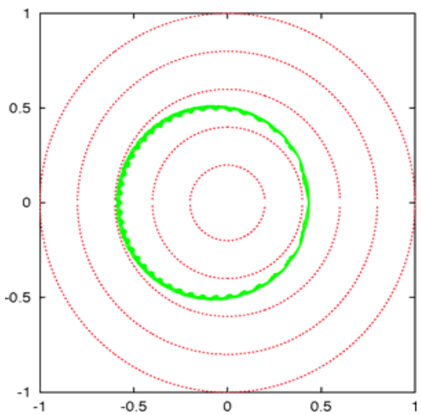
March 31st, 1998 1st plasma

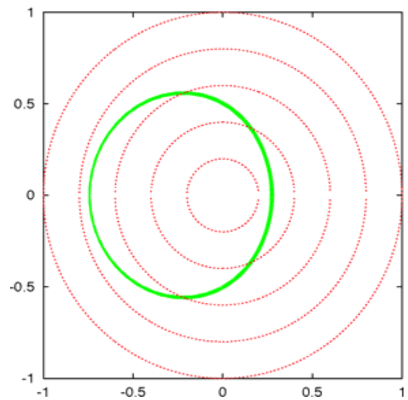
March 7th , 2017 Deuterium Experiment

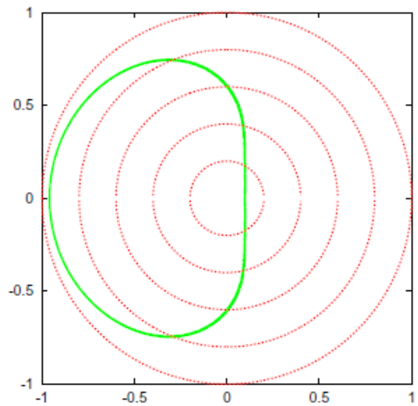
Magnetic-axis location changes characters of LHD-plasmas, significantly

Small ← R_{ax} → Large

better ← **Partilce Confinement**







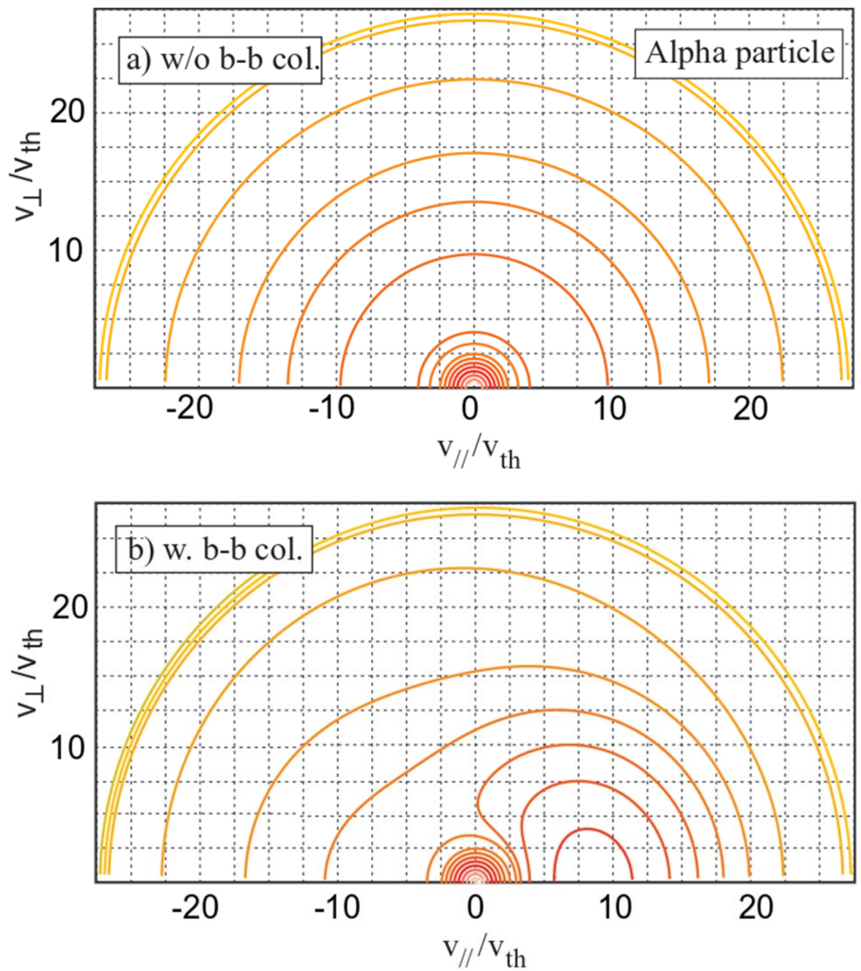
R_{ax}=3.6m (σ-optimized) R_{ax}=3.75m (Standard) R_{ax}=3.9m(Outwardly shifted)

Deviation of orbit's drift-surfaces are minimized as the magnetic axis locations are inwardly shifted.

MHD stability → **better**

EP confinement study is one of the main subjects at LHD D-exp.

- LHD D-exp. is the first opportunity in the helical devices to explore the global confinement study on EPs.
  - The database construction and its experimental validation of EP for future helical type reactor can only be done at LHD D-exp.
- LHD is the only machine running the multiple high energy negative-ion based NBIs as the main heating device, which is the primal heating/current-drive source for ITER/tokamak-DEMO, in the world.
  - Many experimental validations/demonstrations related to high energy NB can be done on LHD for ITER.
    - ✓ Beam-beam collision effect by EPs,
    - ✓ NBCD validation at high energy NB at 3D configuration,
    - ✓ EP diagnostic development using N-NB,
    - ✓ Neutron emission anisotropy, and etc.

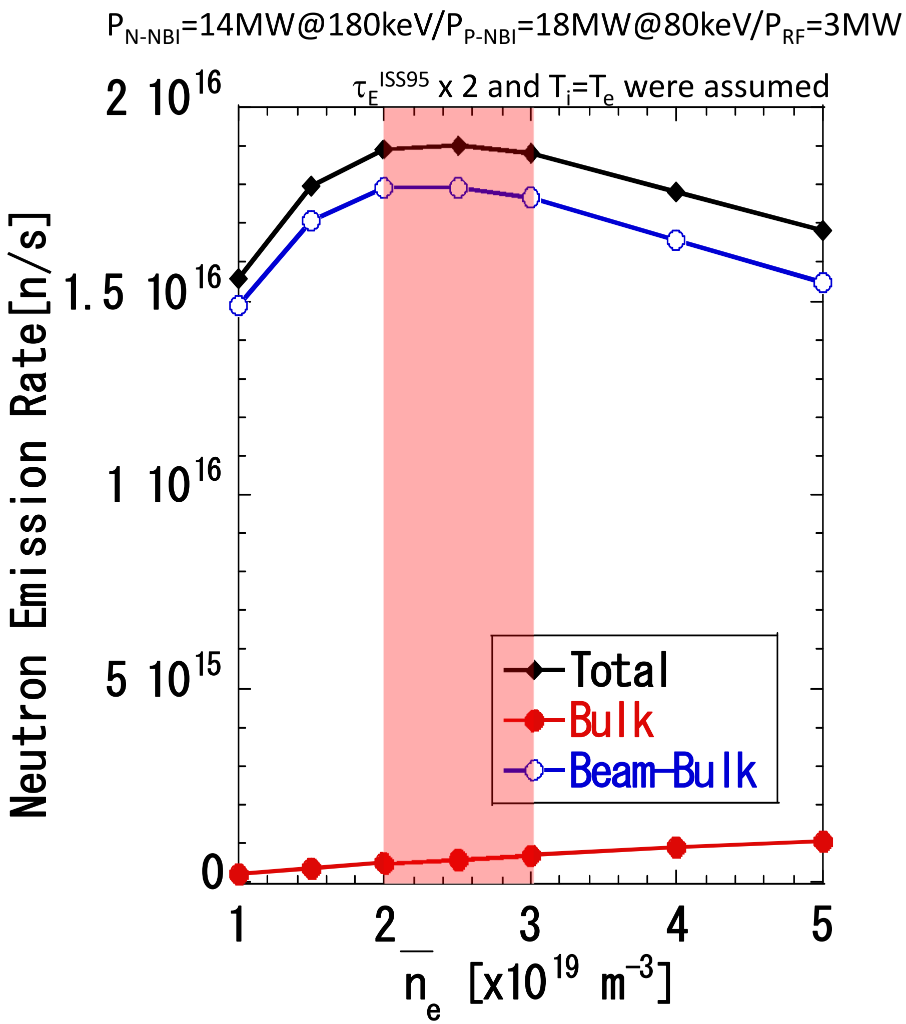


H. Nuga *et al.*, NF 59(2019)016007

Neutron Budget & Expected neutron emission rate

- **9 years of deuterium experiments are planned and are divided to 2 periods based the Neutron budget;**
  - ✓ **The First 6 years: 2.1x 10^{19} n/year**
  - ✓ **The Last 3 years: 3.2x 10^{19} n/year**
- **Neutrons are mostly produced by beam-thermal reaction**
  - ✓ **High-energy N-NB contributes to the production of neutron.**
  - **⇒ Energetic Particle (EP) confinement study will be accelerated on LHD**
- **Maximum neutron emission rate of 1.91×10^{16} /s* is expected at $n_e^{avg.}$~2.5x10^{19}m^{-3}.**

*Osakabe, *et al.*, FST**72**(2017)199

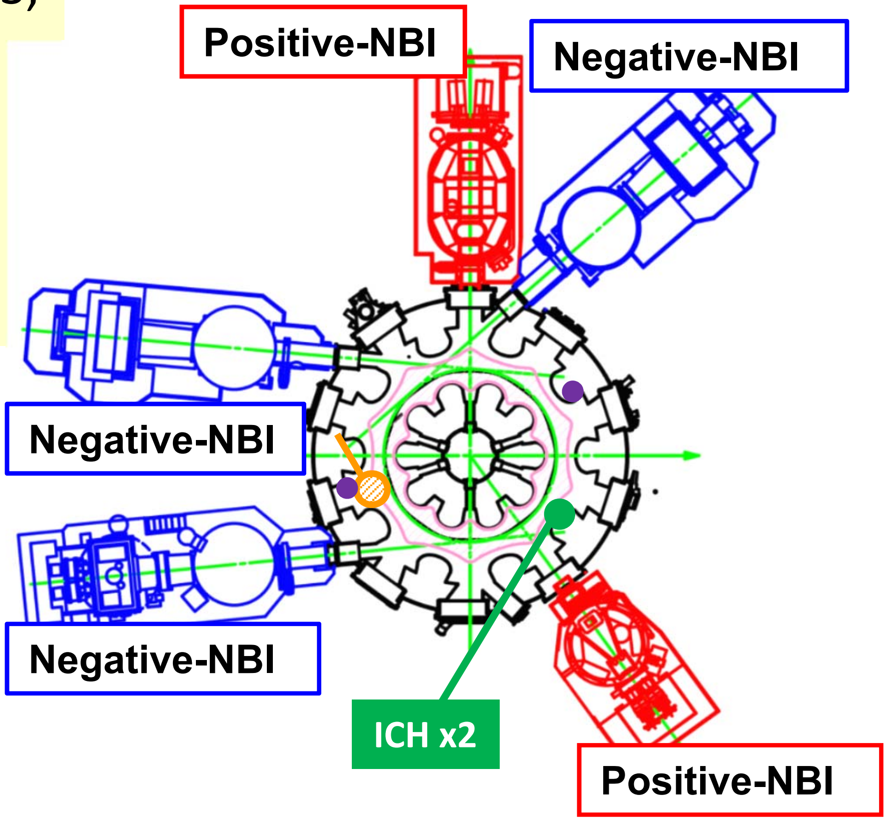


EP CONFINEMENT STUDIES ON LHD AT D-EXP.

LHD D-Exp. is a unique platform for the EP confinement studies

Powerful EP sources

- **Negative-NBI** (tangential)x 3, H16MW, D8MW@ 180keV
- Positive-NBI (radial) x 2 , H:12MW@40keV, D:18MW@60/80keV
- ICH (38.47MHz) x 2 1 MW



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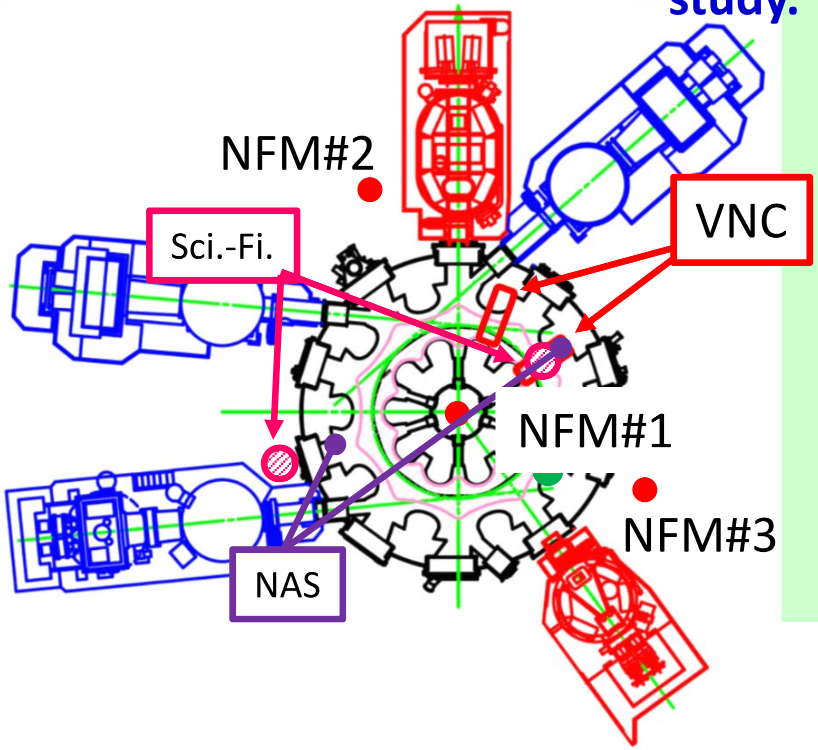

Neutron Diagnostics enable the global EP confinement study.

- 3 sets of Neutron Flux Monitors (U-235 Fission Chamber and He-3/B-10 proportional chamber)
- 2 Vertical Neutron Cameras
- 2 Sci.-Fi. 14MeV neutron detectors
- 2 Neutron Activation foil System

See more detail at P1-18: Isobe & I-16: Ogawa

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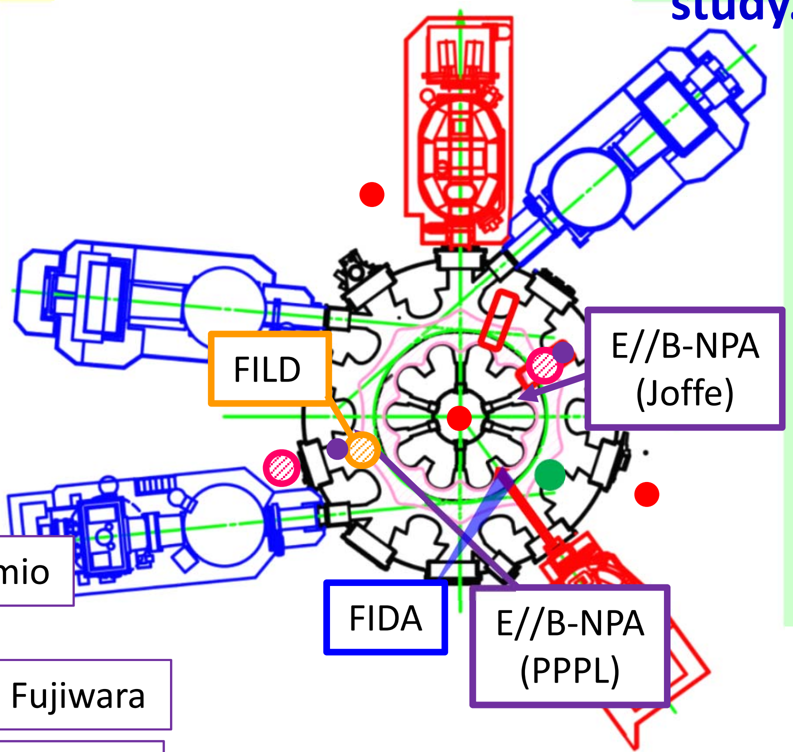


See more detail at
P1-18: Isobe & I-16: Ogawa

Other EP Diagnostics

- E//B-NPA
  - ✓ Tangential (PPPL-type)
  - ✓ Radial (Joffe-type)

  O-18: Kamio
- Fast Ion D/H Alpha (FIDA) Tangential/Radial

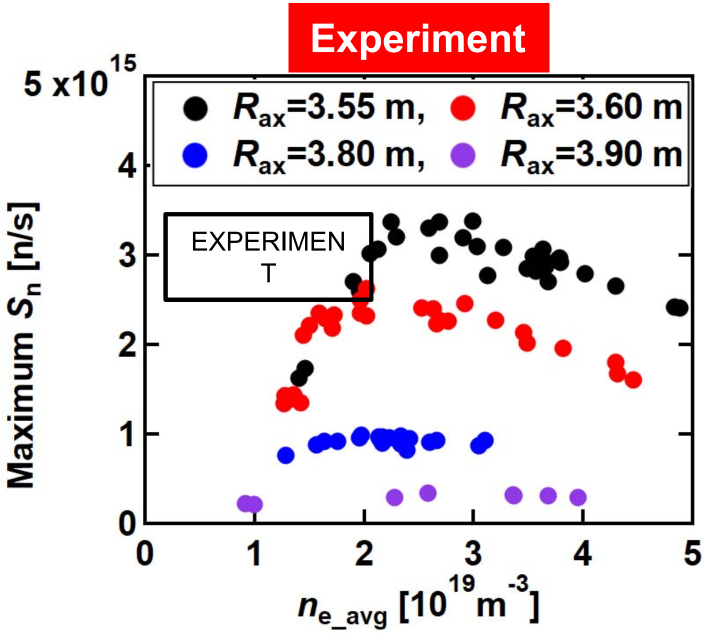
  P1-10: Fujiwara
- Fast Ion Loss Detector (FILD)

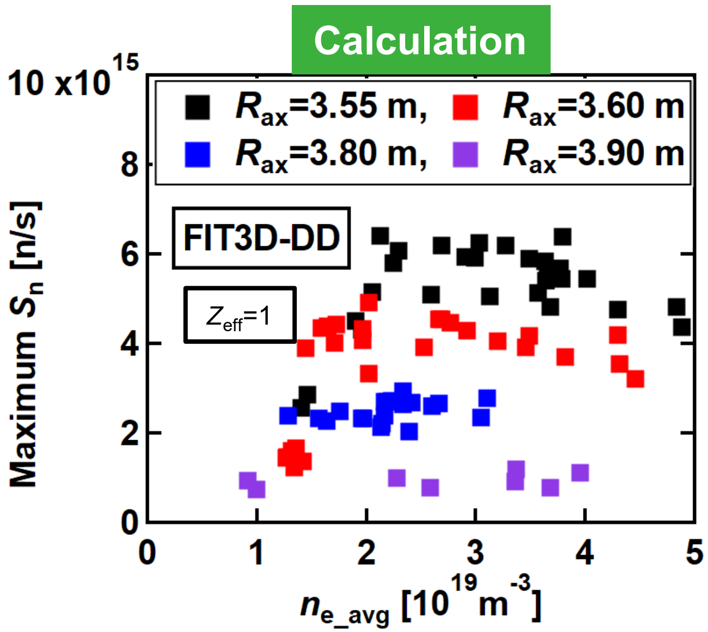
  O-13: Seki

etc

Evaluation and validation of Neutron Emission rate

- The maximum neutron emission rate of ~3x10^{15} n/s was achieved at n_{e_avg}~2.5x10^{19}m^{-3}, which is consistent to the preliminary evaluation.
  - ✓ Primal difference in the neutron emission rate from the preliminary evaluation was due to the reduction of N-NB injection power , which came from the isotope effect in negative-ion production.
  - ✓ The evaluated neutron emission rate was twice as large as the observation by the experiment.
    - ⇒ This difference was due to the finite confinement time of EP's and the dilution of bulk-ions by impurities.

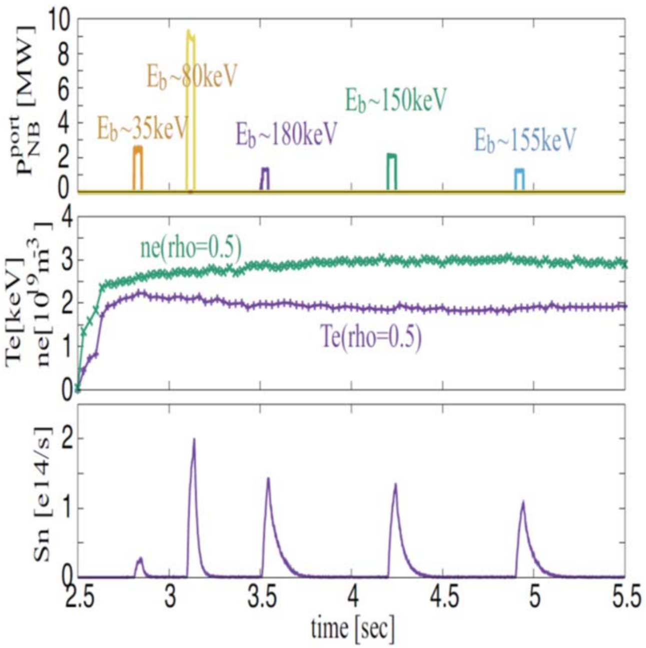


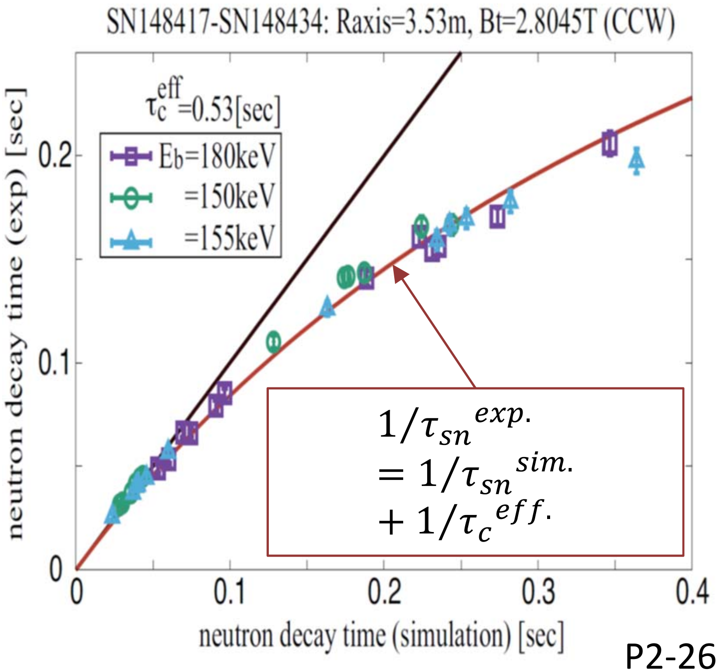


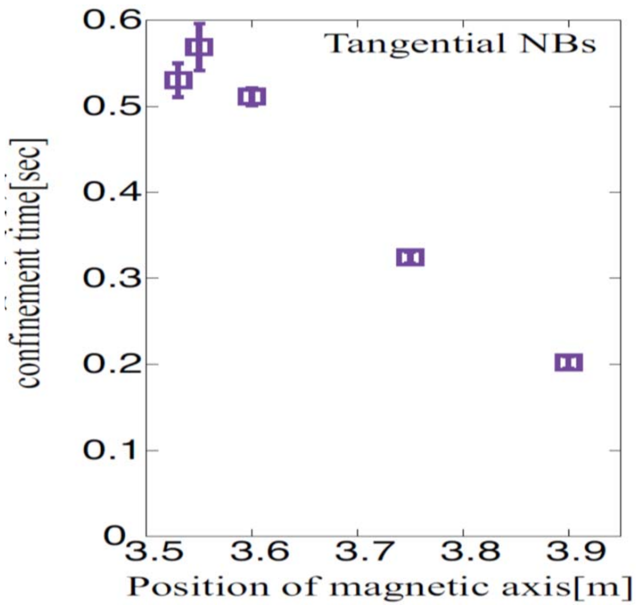
P1-18: M. Isobe *et al.*

Construction of EP confinement database for 3D-magnetic configuration

- To evaluate the effective confinement time of EPs, NB-blip experiments were performed.
  - ✓ GNET simulation well reproduces the neutron flux waveforms for NB-blip experiment.
  - ✓ The effective confinement time of EP can be evaluated from the neutron decay time which is evaluated by F-P simulation to the results of the experiments.
  - ✓ The magnetic axis location dependence of the effective confinement time is consistent to the theoretical prediction.
    - ⇒ Relation between the effective confinement time and the Fourier components of magnetic field strength will be explored.



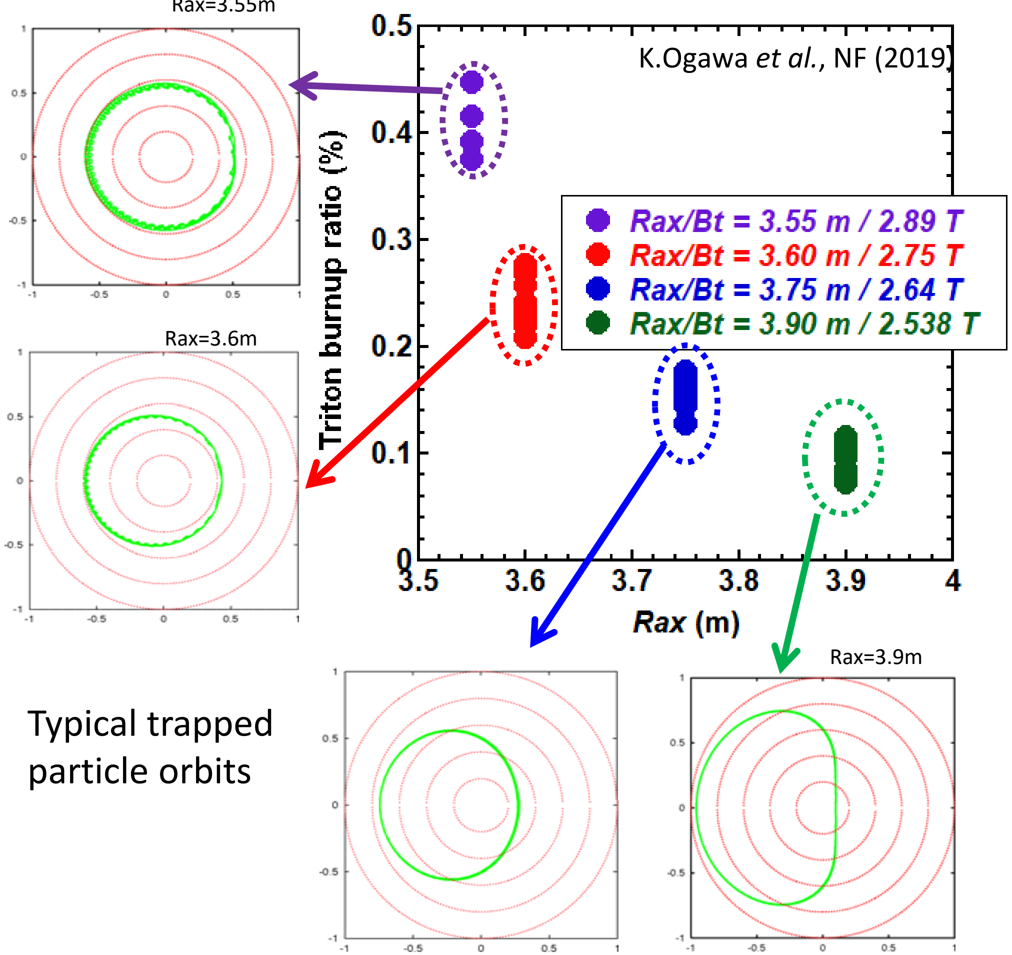




P2-26 H. Nuga et al.

Triton burn-up ratio measurement demonstrates good Energetic Particle (EP) confinement property of LHD at inwardly shifted axis configuration

Selected as a Research Highlight in July 2019 by *Nature Physics*



Typical trapped particle orbits

D + D => ^{3}He + **n**(2.5MeV)

D + D => p + **T**(1 MeV)

T + D => **n**(14MeV) + ^{4}He (3.5 MeV)

Max. @ ~40keV(COM)

$$\text{(T burn-up ratio)} \equiv \frac{S_n{}^{14MeV}}{S_n{}^{2.5MeV}}$$

T burn-up ratio in similar size tokamaks :

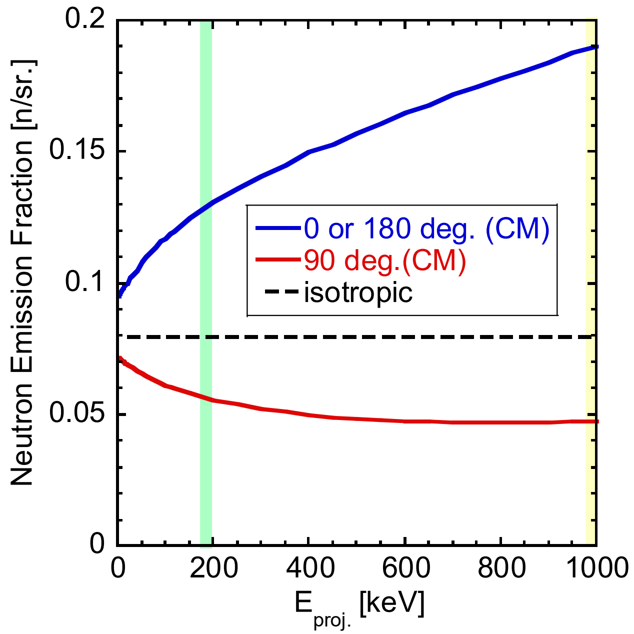
- TFTR~1%*, KSTAR~0.45%**

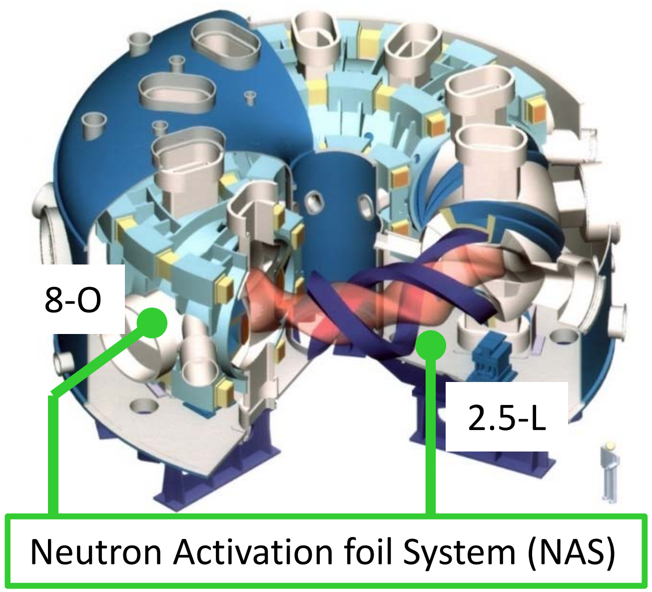
T burn-up ratio comparable to similar size tokamaks is achieved

*C.Barnes, *et al.*, NF**38**(1998)597, ** J. Jo, *et al.* RSI**87**(2016)11D828

Neutron Emission Anisotropy in DD reaction

- Anisotropy of neutron emission from DD-reaction becomes significant for high energy deuteron.
  - ✓ The anisotropy should be taken into an account properly for the neutron flux measurement at ITER D-exp.
- On LHD, the neutron emission anisotropy can be evaluated from the difference of measured neutron flux at different two locations of Neutron Activation foil System(NAS).



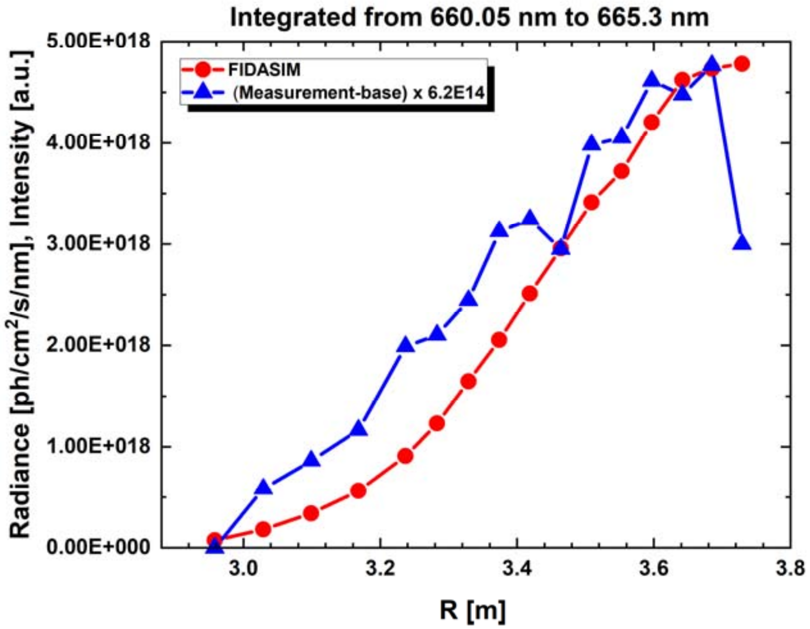


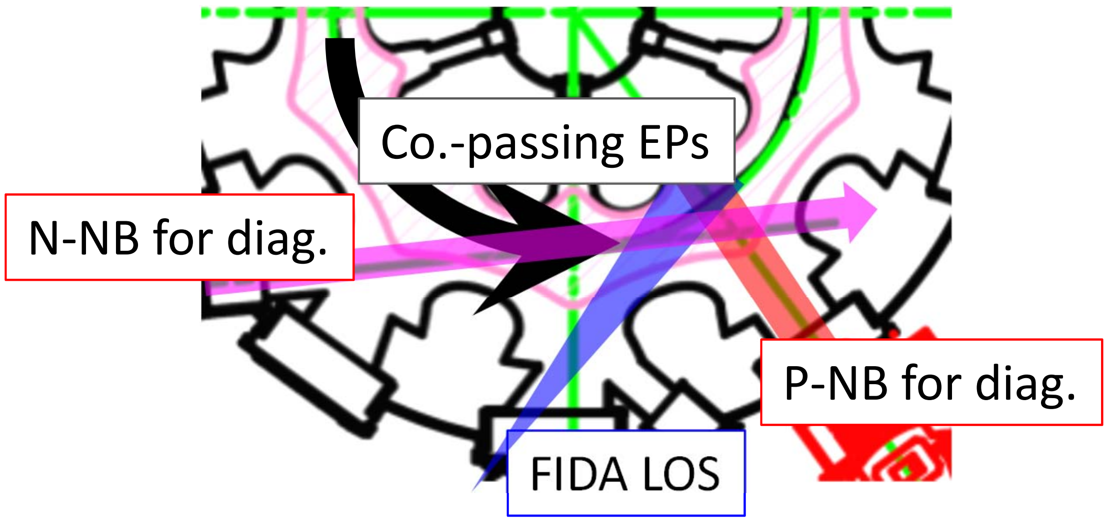
P1-9: S.Sugiyama *et al.*

	N-flx ratio at 8-O / 2.5-L	
	Exp.	Cal.
Radial-NB	3.35	2.90
Tangential-NB	5.63	3.78

Comparison of FIDA with FIDASIM (using measurements Ti)

- FIDASIM-3D using GNET simulation well reproduces the FIDA spectra for (co-)passing particle.
  - This will extend the global EP confinement studies for Hydrogen operations.
  - Further development of FIDA diagnostic using N-NBI as an active neutral source is planned under the collaboration with UCI.

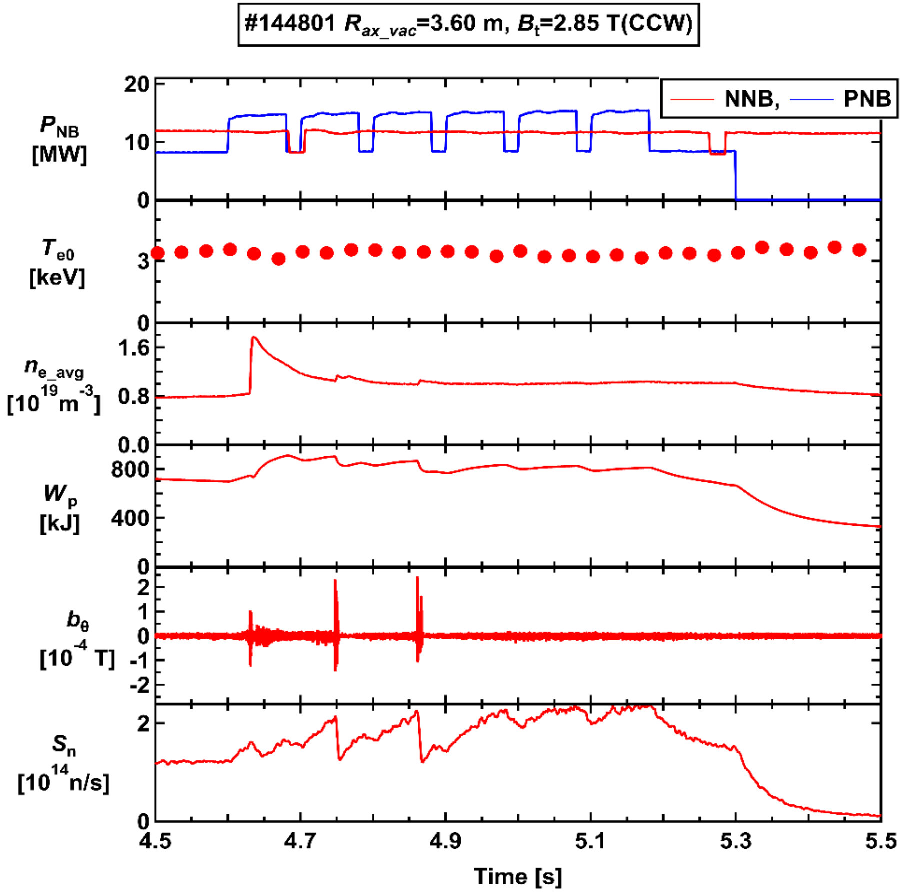


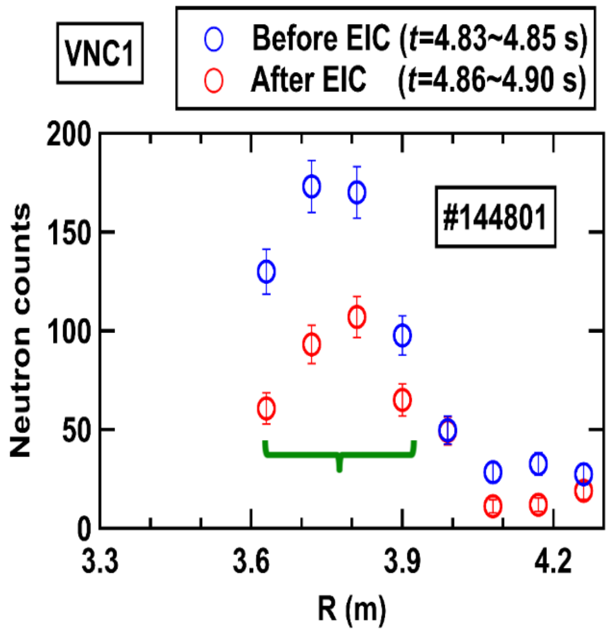


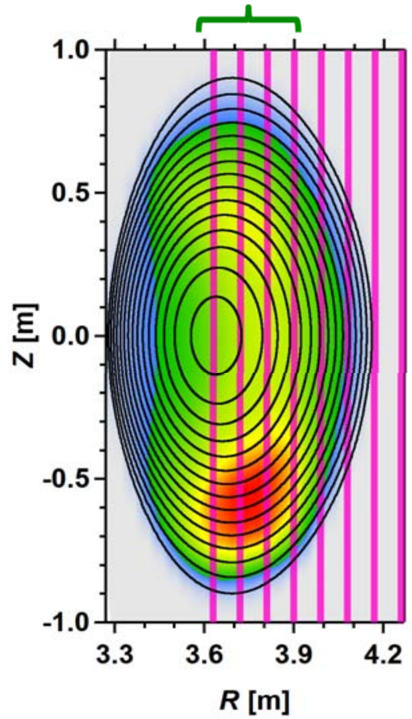
P1-10: Y. Fujiwara, P1-13: A. Garcia

INTERACTION OF EP WITH INSTABILITIES

Neutron diagnostics accelerates the understanding of the interaction between EP and instabilities







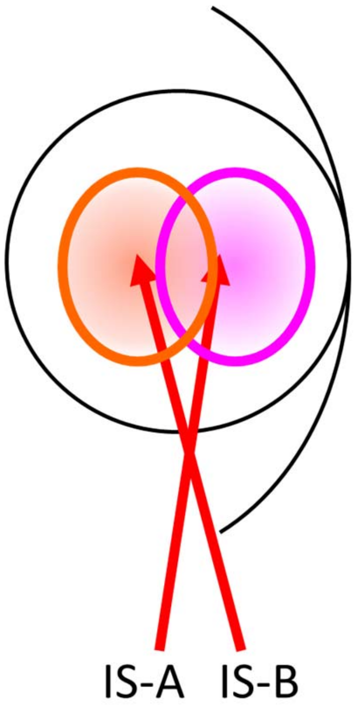
(a)Change of line integrated neutron emission profile before and after EIC(Energetic particle driven InterChange mode) measured by VNC, (b)Calculated 2D Neutron emission profile along the sight line of Vertical Neutron Camera (VNC)

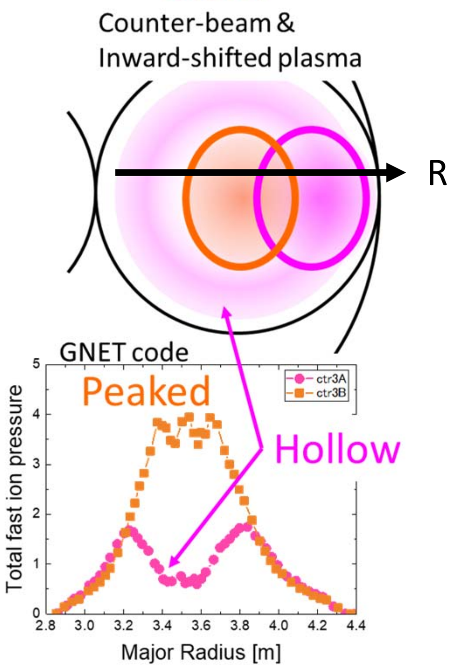
I-16: K. Ogawa *et al.*

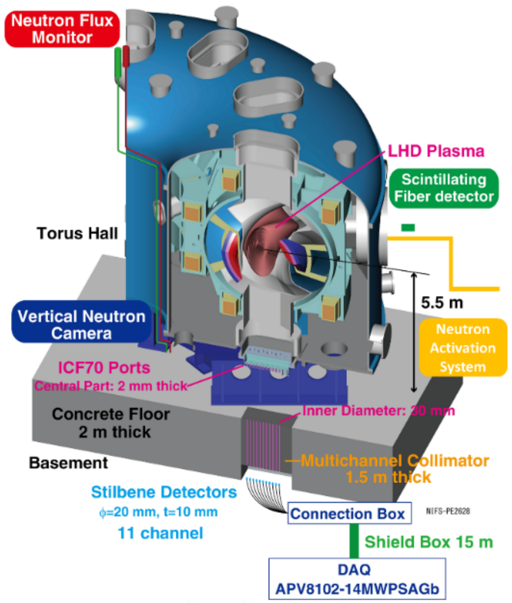
EP profile stiffness were also observed by VNC

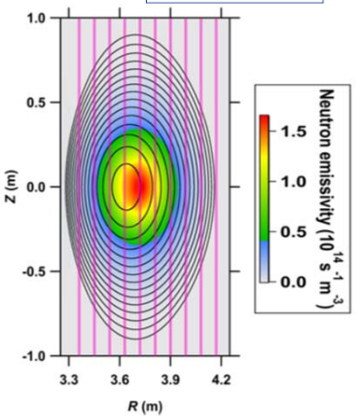
In high β_{EP} (low-B_t) operation, EP profile stiffness was observed with many EP induced instabilities.

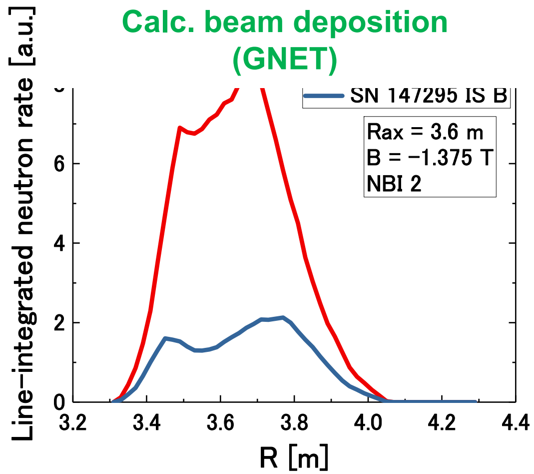
I-2: K. Nagaoka

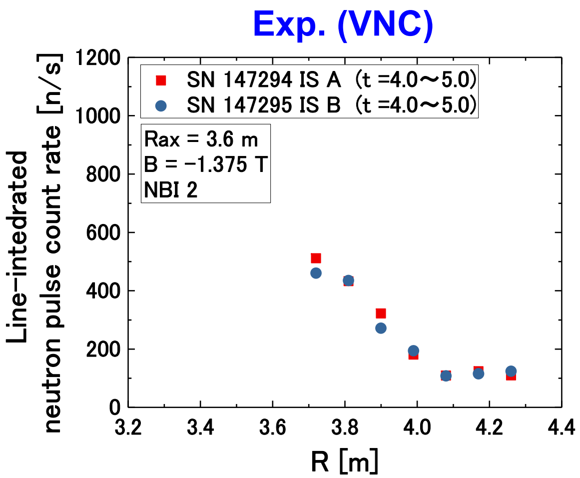








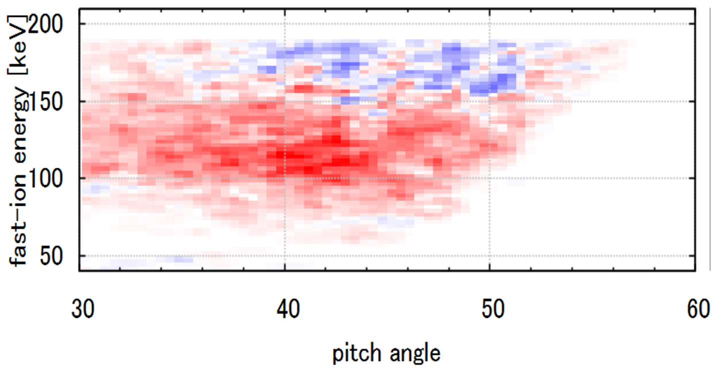




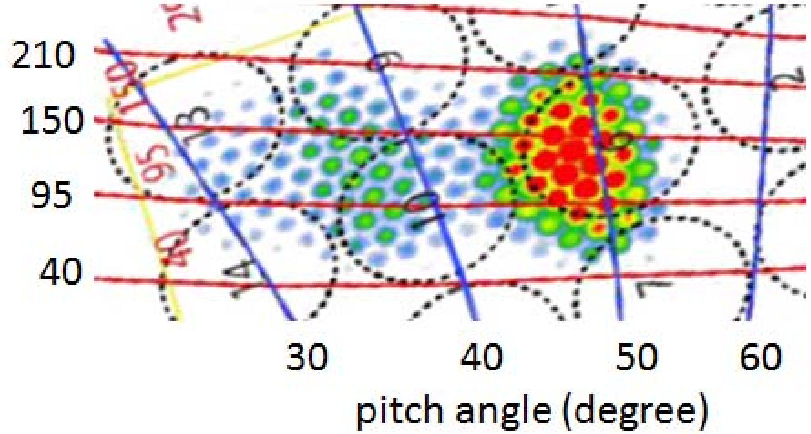
MEGA is now applied to the TAE analysis for 3D configuration

O-13: R. Seki

Synthetic FILD by MEGA



FILD measurement



○Synthetic FILD (Fast-Ion Loss Detector) diagnostic by MEGA reproduces well the experimental results.

○Farther comparison based on Neutron Diagnostic and tangential NPA will provide the comprehensive understanding of the interaction between TAE and EPs.

SUMMARY

- D-exp. on LHD was started since March 2017. This is a unique opportunity to study the EP confinement property in helical devices
- Maximum neutron emission rate of 1.9×10^{16} n/s were expected at n_{e_avg}=~2.5×10^{19} m^{-3}.
  - The maximum neutron emission rate achieved by the experiment is
  - The density dependence of the neutron emission rate is consistent to the theoretical prediction.
  - The discrepancy mainly comes from the reduction of N-NB injection power in Deuterium.
  - The effective confinement time of EP and bulk-ion dilution by impurity contribute the reduction of neutron emission rate by a factor of 2.
- The global confinement property of EP is examined by means of neutron diagnostics.
  - Good EP confinement property for inwardly shifted magnetic axis configuration is demonstrated both by NB-blip experiments and T-burnup experiments.
    - T-burnup ratio of 0.35%, which is comparable to a similar size TOKAMAK, like KSTAR, is achieved.
- Neutron diagnostic also accelerates the study of EP interaction with instabilities.
  - Helically trapped EPs are proved to be the driving source of EIC.
  - Profile stiffness of EP in helical system due to EP induced instabilities are also demonstrated.
- Many EP diagnostics and simulation code development are underway, e.g., FIDA, renewable of E//B-NPA and MEGA-code for 3D, and etc.

Many contributions to LHD D Experiment from EP communities are quite welcome !