Triton Burnup Analyses with Fusion Neutron Measurements for 1 MeV Triton Confinement Study in KSTAR

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Abstract

The behavior of 1 MeV triton in KSTAR deuterium plasma is studied using triton burnup neutron (TBN) diagnostics and classical burnup calculation code. In KSTAR, TBN is measured by neutron activation system (NAS) and scintillation detectors. Shot-integrated TBN yield is evaluated by NAS with silicon sample. Two kinds of scintillation detectors, stilbene and scintillating-fiber detectors, provide TBN emission rate. Measured TBN emission is analyzed using classical burnup calculation code. The code evaluates expected TBN emission by considering prompt loss rate and Coulomb drag in certain plasma condition. The amount of prompt loss is statistically evaluated using full orbit following code LORBIT. In addition to prompt loss and Coulomb drag, finite confinement time effect can be considered by volume averaged effective diffusion coefficient. Measured and calculated TBN emission are compared in two timing of Alfvén eigenmodes control experiment, with and without Alfvénic activity. Without Alfvénic activity, calculated TBN emission generally matched with measured value within experimental error. During the Alfvénic activity however, measured value is about half of the calculated value. The amount of confinement degradation due to Alfvénic activity is estimated in terms of volume averaged effective diffusion coefficient.

1. Introduction

❖ 3.5 MeV fusion alpha Burning plasma, machine protection

ITER: Q = 10 (P_α = 0.67 · P_{Loss})

→ Understanding alpha confinement physics is essential

❖ 1 MeV triton in deuterium plasmas[1]

➢ Two branches in D-D fusion reaction

$d + d \rightarrow {}^3He\,(0.82\ MeV) + n\,(2.45\ MeV)$, (~50%)
$d + d \rightarrow t\,(1.01\ MeV) + p\,(3.02\ MeV)$, (~50%)

✓ Similar kinetic properties with the fusion alpha
✓ KSTAR plasma: various advanced scenarios

➢ Information on triton confinement

- Triton burnup: $d + t \rightarrow {}^4He(3.5\ MeV) + n(14.1\ MeV)$ Triton burnup neutron (TBN)
- Triton burnup ratio (TBR)

$$TBR = \frac{Y_{n-dt}}{Y_{n-dd}} \rightarrow f(\text{confinement, slowing down, burn-up})$$

❖ Triton burnup analyses

$TBR_{Measured} \longleftrightarrow TBR_{Calculated}$
✓ The amount of anomalous effect

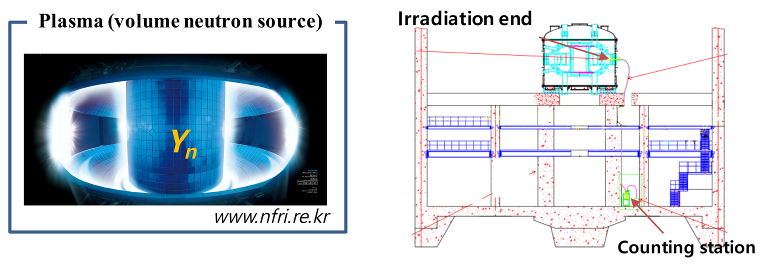
➢ Requirements

- *Measurements*: fusion neutron diagnostics (n_{dd}, n_{dt})
  - ✓ Neutron activation system: shot-integrated yield
  - ✓ Organic scintillator: emission rate
- *Calculation*
  - ✓ Model: classical burnup model[2]
    - Loss: prompt loss, thermalize
    - Slowing down: Coulomb collision
  - ✓ Simulation:
    - Prompt loss: LORBIT[3] (full gyro-orbit following code) → Statistical evaluation of f_c
    - Slowing down and burnup: developed code

2. Fusion neutron diagnostics

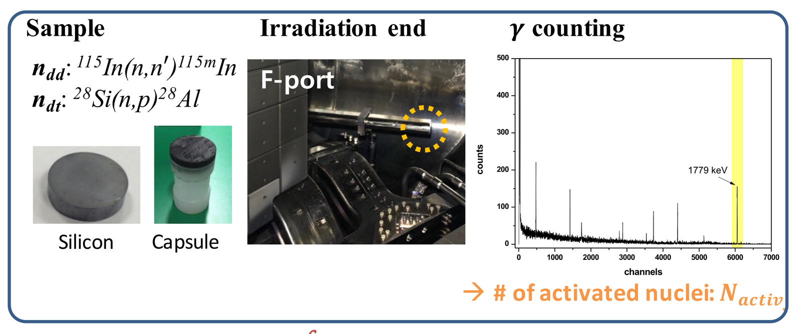
❖ Neutron Activation System (NAS)[4]: Y_{n_dd} & Y_{n_dt}

➢ Operation principle and experimental setup



Sample: n_{dd}: $^{115}In(n,n')^{115m}In$; n_{dt}: $^{28}Si(n,p)^{28}Al$

Irradiation end — γ counting



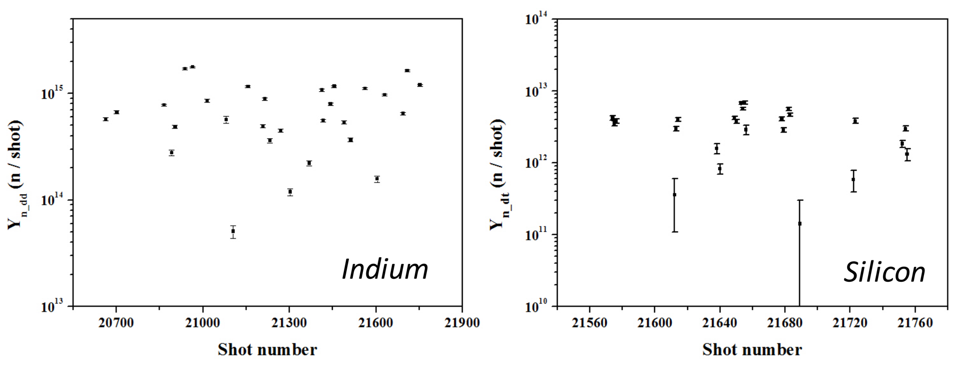
→ # of activated nuclei: N_{activ}

$$N_{activ.} = N_{target} Y_n f \int \phi'(E)\sigma(E)dE$$

# of reactions / neutron yield / sample nuclei

➢ Operation result

$f \int \phi'(E)\sigma(E)dE$ - Obtained by neutronics calculation

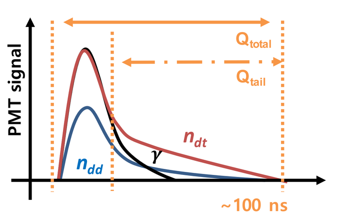


- Neutron emission rate (averaged over NB duration time):
  - 2.45 MeV D-D neutron (Indium sample): ~10^{14} n/s
  - 14.1 MeV D-T neutron, (Silicon sample)[5]: ~10^{11} n/s

❖ Organic scintillators (NE213[6], stilbene) : S_{n_dd} & S_{n_dt}

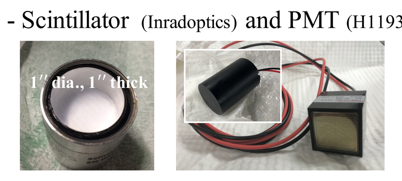
➢ Operation principle: different response for incident radiation species

- Pulse shape: n, γ discrimination
- Pulse height: n_{dd}, n_{dt} discrimination



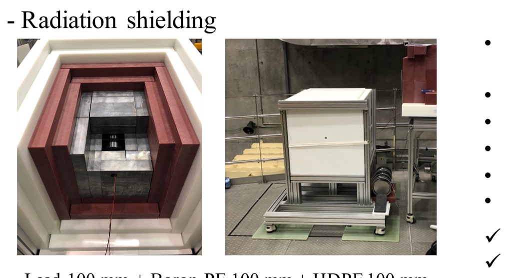
➢ Experimental setup

- Scintillator (Inradoptics) and PMT (H11934-100-10)



- Digitizer (NKFADC500)

- Radiation shielding



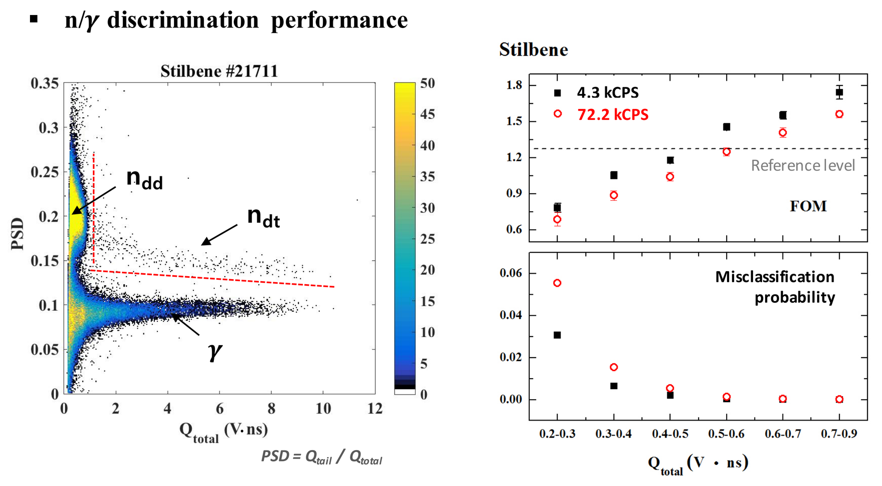
Lead 100 mm + Boron-PE 100 mm + HDPE 100 mm

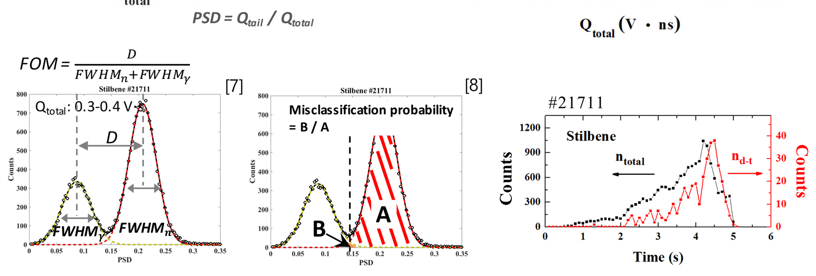
- Raw waveform recording FADC (4 Ch) (116, 244, … 8,180 ns)
- 500 MHz sampling rate
- 12 bit-resolution
- Input voltage range: 2 V_{pp}
- 8 GB onboard memory
- Readout: USB3

✓ Semi-automated data acquisition
✓ Offline data processing: trigger time, pulse height, Q_{total}, Q_{tail}, PSD (Q_{tail}/Q_{total})

➢ Operation result

- n/γ discrimination performance

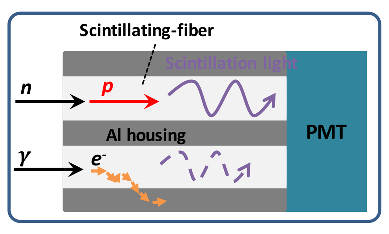


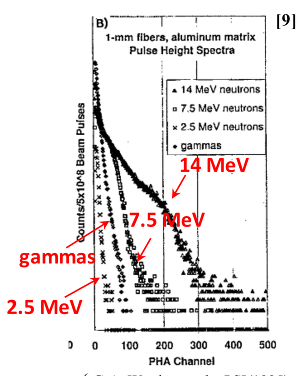


❖ Scintillating-fiber (Sci-Fi) detectors[9]: S_{n_dt}

➢ Operation principle

- Operation principle: high pulse height for axially incident d-t neutron
  - Pulse height: n_{dt} discrimination

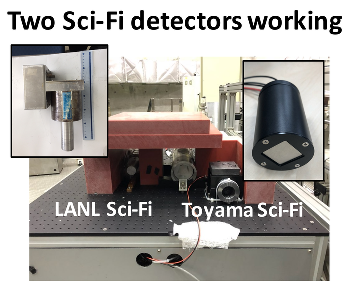




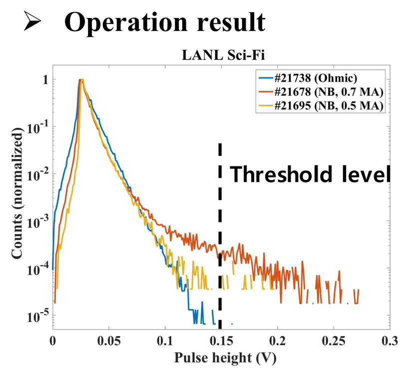
[9] G.A. Wurden et al., RSI (1995)

➢ Experimental setup

Two Sci-Fi detectors working

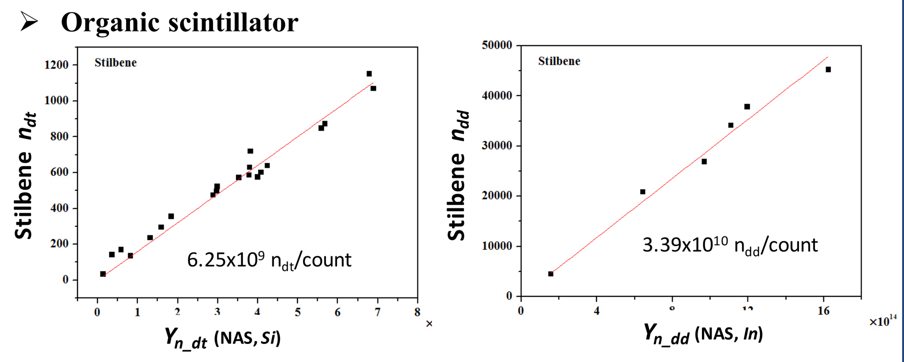


➢ Operation result

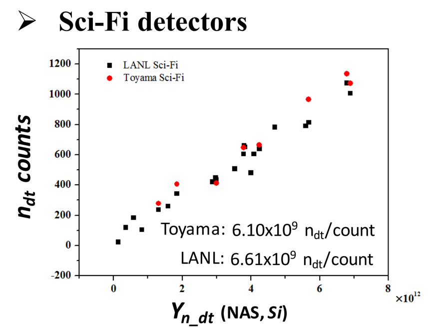


❖ Data cross-check and absolute calibration using NAS data

➢ Organic scintillator



➢ Sci-Fi detectors



✓ Good linearity between NAS and scintillation detectors
✓ Three kinds of independently operated triton burnup neutron diagnostics show well matched result
✓ From the calibrated detectors time-resolved d-d and TBN emission rates can be measured

3. Analyses tools

❖ Calculation of triton burnup neutron emission

- Classical model

$$Y_{n-dt} = n_t P_{dt}$$ [2, 10]

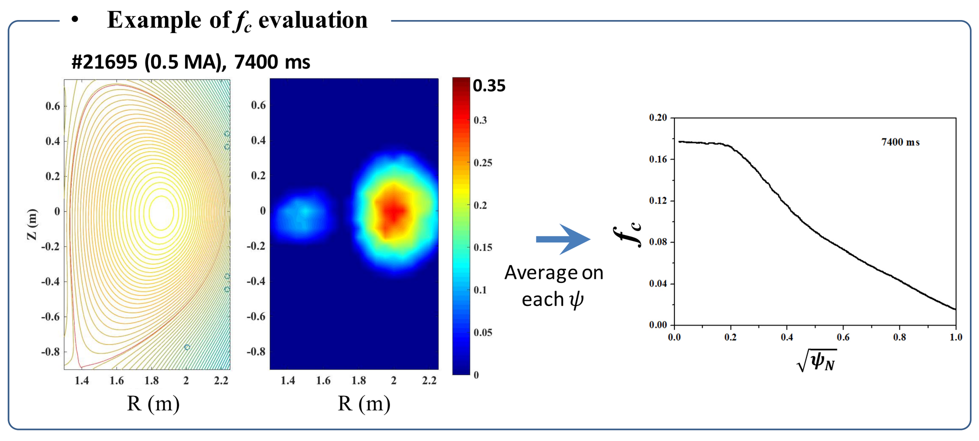
n_t: confined triton density
P_{dt}: expected # of d-t neutron production until thermalize

Parameters		Process		Evaluation
n_t (birth · f_c)	Prompt process	Birth	d-d fusion rate	- S_{n_dd} (measurement) + TRANSP fusion reaction profile
		Confinement	$f_c = (1 - f_{L\_prompt})$	- Statistical evaluation on each flux surface (LORBIT)
P_{dt} (slowing down and burnup)	Time-dependent process	Slowing down	Coulomb collision	$P_{DT} = n_D \int_0^{t_{th}} \langle\sigma v\rangle_{DT}\, dt = n_D \int_{E_0}^{E_{th}} \frac{\langle\sigma v\rangle\, dE}{dE/dt}$ (Developed code)
		burn-up	$\langle\sigma v\rangle_{bt}$	

➢ Confined fraction profile (f_c) calculation using LORBIT

- LORBIT code[3]
  - Full gyromotion of energetic ion under collisionless condition
  - Input: equilibrium (EFIT), test particle condition
- f_c evaluation procedure
  - Orbit following time: 0.1 ms
  - Confined fraction on real geometry (680 positions on a poloidal XS)
    - R = 1.3 – 2.25 m, 0.05 m interval
    - Z = -0.9 – 0.75 m, 0.05 m interval
    - 1000 test tritons on each position with isotropic velocity distribution
  - Mapping on each flux surface then average

- Example of f_c evaluation



➢ Slowing down and burnup calculation

Input EFIT, $n_e(\sqrt{\psi_N})$, $T_e(\sqrt{\psi_N})$, $T_i(\sqrt{\psi_N})$, Z_{eff} (2, flat assumed), $t_{birth\_rate}(\sqrt{\psi_N})$, $f_C(\sqrt{\psi_N})$

Main

$$Y_{n-dt} = n_t P_{DT} \begin{cases} n_t = t_{birt\_rate} \times f_c \\ P_{DT} = n_D \int_{E_0}^{E_{th}} \frac{\langle\sigma v\rangle\, dE}{dE/dt} \end{cases}$$

t_{birt_rate} → S_{n_dd} & $t_{birth\_profile}$
n_D: assumed Z_{eff} (2, flat)
Slowing down: Coulomb drag
Reactivity: beam(t)-target(d), (T_i considered)

Slowing down: Coulomb drag[2, 10]

$$\frac{dE}{dt} = -\frac{\alpha}{\sqrt{E}} - \beta E \quad , \alpha = 1.81\times10^{-7} ln\Lambda_{ii} A^{1/2} Z^2 \sum_j \frac{n_j Z_j^2}{A_j}, \quad \beta = 3.18\times10^{-9} ln\Lambda_{ie} \frac{Z^2}{A}\frac{n_e}{T_e^{3/2}}$$

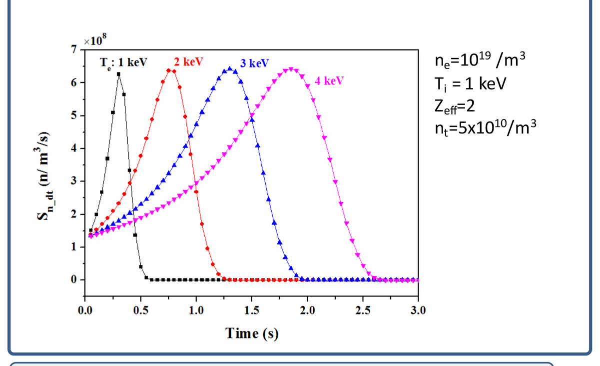
Reactivity (beam(t)-target(b))

$$\langle\sigma v\rangle_{bt} = \frac{1}{v_b v_{th}\sqrt{\pi}} \times \int_0^\infty \sigma v^2 \left[e^{-\frac{(v-v_b)^2}{v_{th}^2}} - e^{-\frac{(v+v_b)^2}{v_{th}^2}}\right] dv \quad , v_{th} = \left(\frac{2T_i}{m}\right)^{1/2}, \quad \sigma(E) = \frac{S(E)}{E\exp(B_G/\sqrt{E})}$$ [11]

Output Reaction rate $(\#/m^3/s)$ in each radial position
Reaction rate(r) · dV_ψ (r)
→ total emission rate (n/s)

Assumption
- Each tritons are slowed down on birth position
- pitch angle scattering, energy diffusion neglected
- Thermalized triton neglected

- Calculated TBN emission rate according to slowing down time



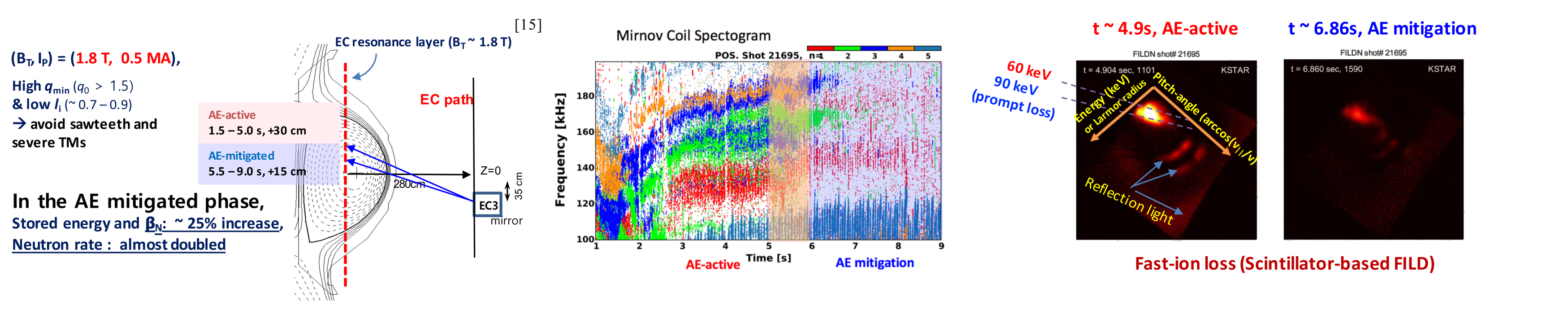
Ad-hoc diffusive model for n_t

- Volume avg. effective diffusion coefficient D[10, 12, 13]
- 1-D diffusion equation (Central diff., Crank-Nicolson)

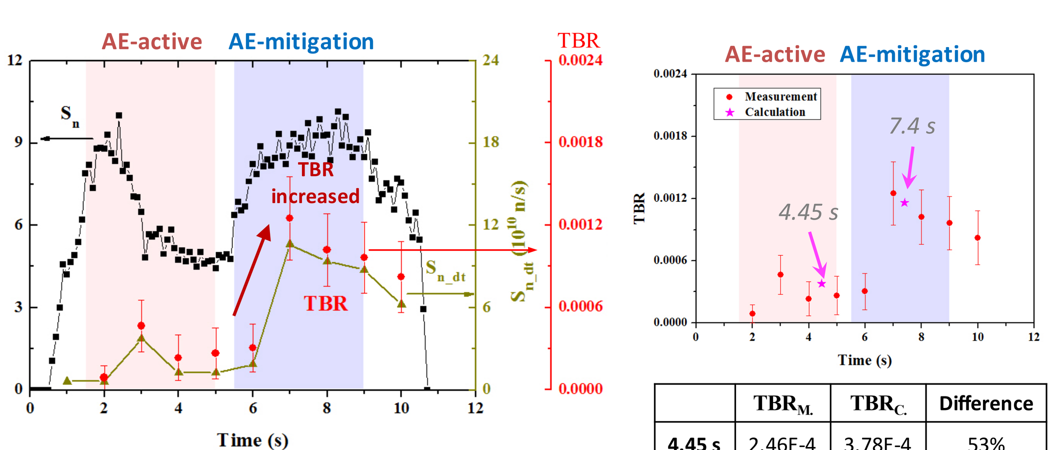
$$\frac{\partial n(\vec{r}, t)}{\partial t} = D \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial n}{\partial r}\right)$$

4. Analyses of triton burnup in KSTAR

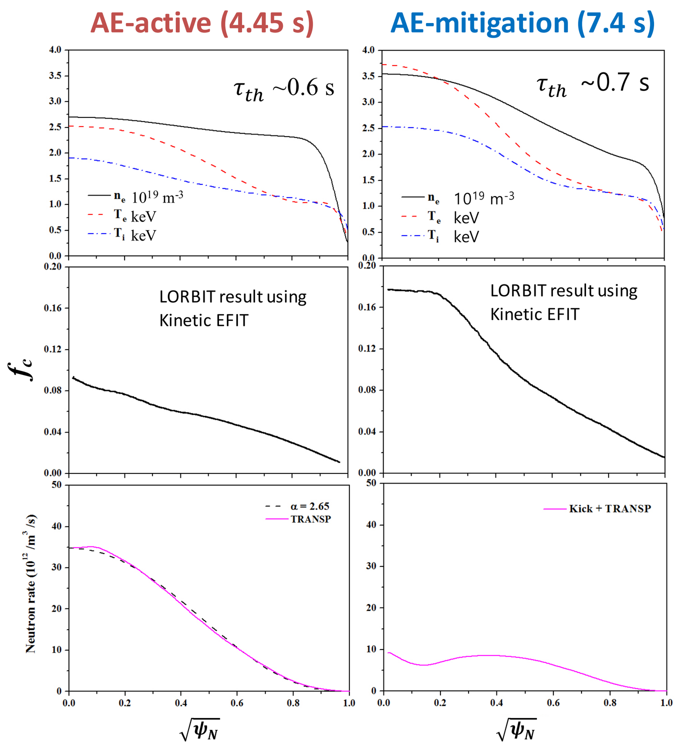
❖ Discharge #21695 (Alfvén eigenmode control experiment)[14]



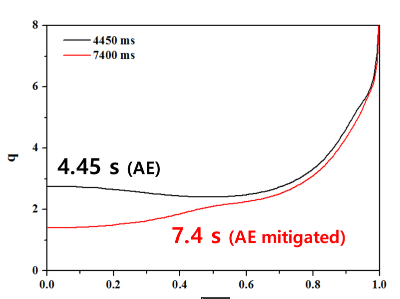
➢ Measured and calculated results



	TBR_M	TBR_C	Difference
4.45 s	2.46E-4	3.78E-4	53%
7.4 s	1.16E-3	1.16E-3	-



- AE mitigated phase
  - triton confinement improved (TBR 3-4 times increase)
  - no strong MHD activity: $TBR_{Measured} \sim TBR_{Calculated}$ expected
  - calculated result well matched with measured result
- AE-active phase
  - $TBR_{Measured} < TBR_{Calculated}$ expected
  - $TBR_{Calculated}$ is about 53% larger than $TBR_{Measured}$
  - Most TBR attenuation in AE active phase can be explained by changes in the classical parameters → Shorter slowing down time, flattened birth profile, lower confined fraction
  - D~0.05 m^2/s: matches the calculated and measured values



5. Summary

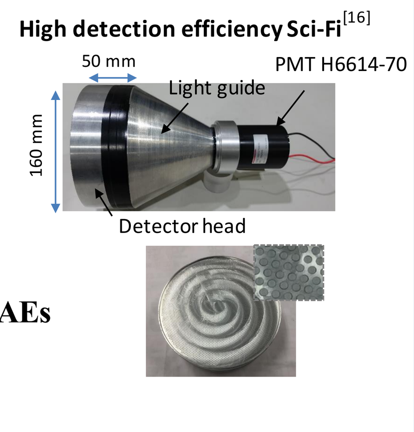
- ◆ For 1 MeV triton confinement study in KSTAR, diagnostics for d-d neutron and triton burnup neutron (TBN) are developed.
- ◆ The calculation codes for measured triton burnup ratio (TBR) analyses are prepared and TBN emission rate calculation routine is established.
- ◆ Under the stable plasma condition, the measured and calculated TBR matched within experimental error.
- ◆ Under the AE-active condition, the difference between measured and calculated TBR increased. In the #21695 case, most of triton confinement degradation (compare with AE-mitigated condition) is caused by changes in classical parameters.

6. Ongoing works

➢ Diagnostics

- High detection efficiency Sci-Fi detector optimization for fast time resolution

High detection efficiency Sci-Fi[16]



➢ Analyses codes

- Error evaluation

➢ Interaction between triton and AEs

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