Initial operation results of scintillating fiber detector for time-resolved measurement of triton burnup in KSTAR

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Abstract

For the purpose of time-resolved measurements on triton burnup in KSTAR deuterium plasmas with better time resolution, a scintillating-fiber (Sci-Fi) detector has been installed and tested during the 2017 KSTAR campaign. It is composed of photo-multiplier tube (PMT) and scintillating fiber bundles (1056 fibers) which are embedded in the lead matrix. The fiber has 1 mm^2 of cross-sectional area and 100 mm long. The scintillation light is detected by Hamamatsu R878 PMT and its anode signal is digitized and processed by CAEN DT5751. The detector was tested in the d-d neutron generator at National Fusion Research Institute (NFRI) and d-t neutron generator at Osaka University (the Intense 14 MeV Neutron Source Facility, OKTAVIAN, Osaka university, Japan). The detector tested in KSTAR discharge #19144 which has two different H-mode regions. The expected difference in d-t neutron rates of those regions is estimated based on triton prompt orbit loss and classical slowing down time. Mainly due to the longer slowing down time by 6 times in 2nd H-mode region, about 3-10 times higher d-t neutron rate is expected. In the measurement result, the probability to have d-t neutron signal is higher in 2nd H-mode which is generally consistent with simulation expectation. More quantitative analysis can be done after stabilization of PMT operation in high-counting rate condition.

1. Introduction

- ✓ Confinement of energetic particles (NB particles, RF accelerated particles, fusion products (alphas, tritons, etc.) → Heating the bulk plasma (slowing down)
- ✓ Fusion alpha → Burning plasma, machine protection
- ✓ **1 MeV triton confinement study in deuterium plasmas**[1]

  Two branches in D-D fusion reaction

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

  - Useful to study certain characteristics of alpha particle due to its similar kinetic properties

	Velocity distribution	Energy (Velocity)	Larmor radius ($v_{\|\|}/v = 0.1$)
Deuteron (NB)	Anisotropic	100 keV (3.1x10^6 m/s)	32 mm
Triton	Isotropic	1 MeV (8.0x10^6 m/s)	124 mm
Alpha	Isotropic	3.5 MeV (1.3x10^7 m/s)	134 mm

- Confined tritons slowed down through interaction with surrounding plasma

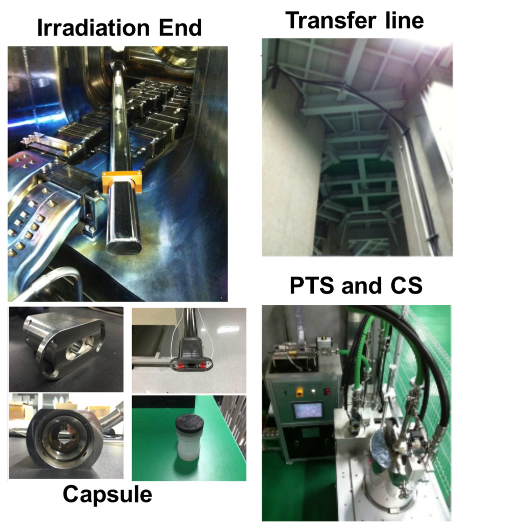
  $$\mathbf{d + t \rightarrow n\,(14.1\ MeV) + \alpha\,(3.5\ MeV)}$$

- The ratio of the amount of d-t neutron to the amount of produced 1 MeV triton represents global confinement characteristics of 1 MeV triton in certain plasma condition
- The amount of produced 1 MeV triton is nearly the same with that of d-d neutron
- Thus we can deduced the 1 MeV triton global confinement characteristics in deuterium plasmas by measuring d-d neutron and 14 MeV d-t neutron

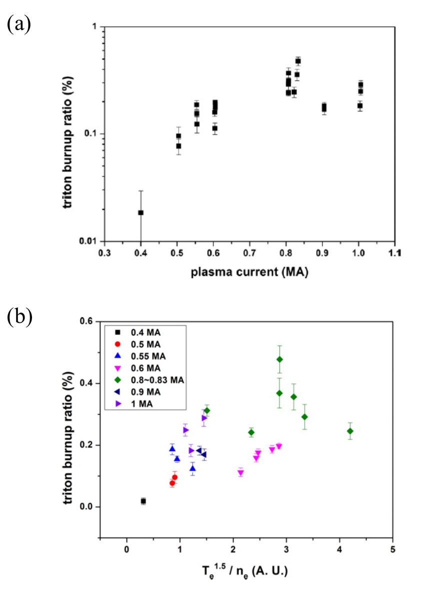
✓ **KSTAR**
– advanced scenario, versatile in-vessel control coil

2. Previous triton burnup measurements on KSTAR

✓ **Shot-integrated measurements on triton burnup using neutron activation system (NAS)** [2]

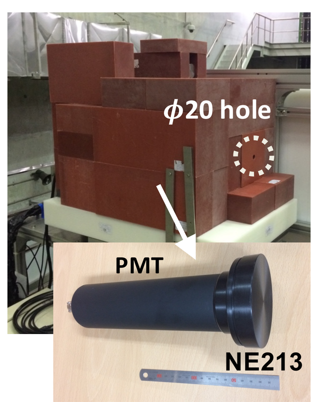


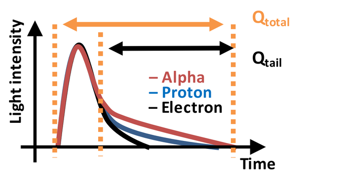
- ITER prototype NAS[3]
- Appropriate sample material selection and gamma measurement strategies for KSTAR environment[4]
- Neutron emission rate (averaged over NB duration time):
  - 2.45 MeV D-D neutron (Indium sample): ~10^{14} n/s
  - 14.1 MeV D-T neutron, (Silicon sample): ~10^{11} n/s
- Triton burnup ratio dependence on plasma current and classical slowing down
  - (a) Triton burnup ratio increases as plasma current increases. (*orbit-squeezing*)
  - (b) Triton burnup dependence on classical slowing down time
    - 1 MeV triton slow down mainly by interaction with electrons
    - Frequent interaction with electrons i.e. high Coulomb collision frequency leads to rapid energy transfer to bulk plasma. Thus it has lower probability of d-t fusion reaction compare with low Coulomb collision frequency condition.

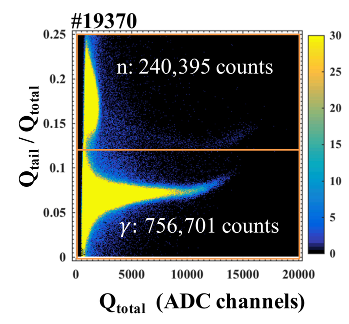


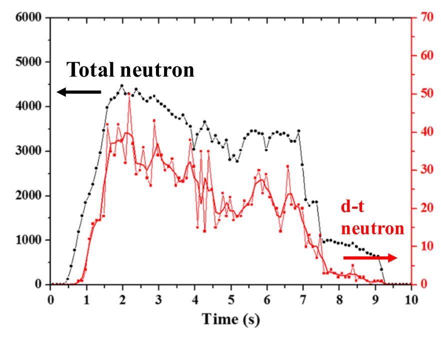
Triton burnup ratio dependence on (a) plasma current and (b) $T_e^{1.5}/n_e$.

✓ **Time resolved measurements using NE213 liquid scintillation detector** [5]







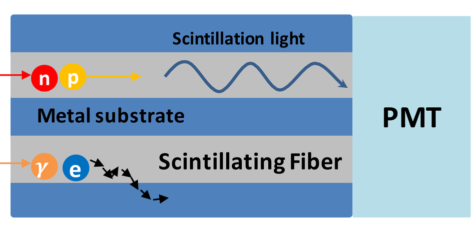


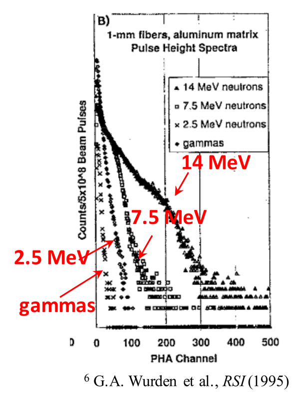
- NE213 is sensitive both neutrons and gammas
- The acceptable counting rate in this diagnostics: ~200 kCPS
- There is clear limitation in achievable counting rate of 14 MeV neutron
  - 200,000 CPS x 0.32 x 0.01 = 640 CPS
    - The ratio between neutron signals to gamma signals: 0.32
    - Triton burnup ratio: ~ 1%

3. Experimental setup

✓ **Scintillating-fiber (Sci-Fi) detector**[6]

- **Operation principle**





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

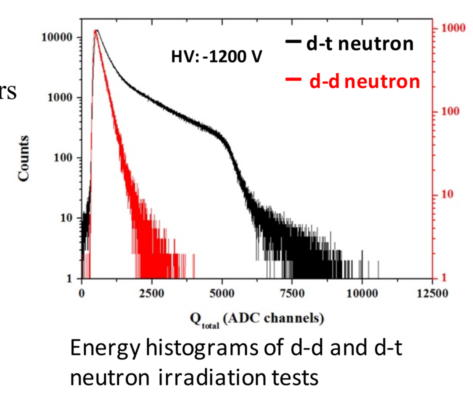
- Selectively sensitive to high energy neutrons whose incident direction is axial direction
- Scintillating fiber (polystyrene) inside the metal substrate
- Metal substrate: Absorption of secondary electron and recoiled proton energy which is escaped from the fiber

✓ **The Sci-Fi detector and installation on KSTAR**

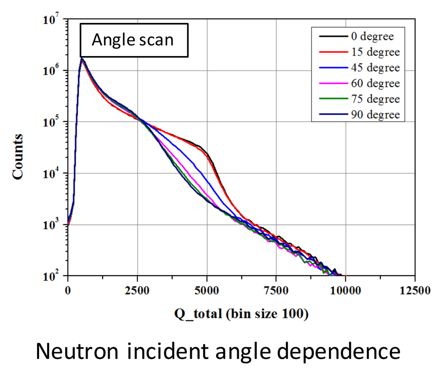
- Scintillating fiber size: 1 mm × 1 mm
- Metal substrate material: Pb
- Distance to adjacent fiber: 0.4 mm
- PMT: Hamamatsu R878
- Digitizer: CAEN DT5751 (1 GS/s, 10 bit, 1 V_{pp})
- Shielded by 10 mm thick soft iron magnetic shield
- The anode output is directly fed into the CAEN DT5751 digitizer via 50 Ohm coaxial cable (RG-58, 10 m)

✓ **Test in neutron generators**

- The Sci-Fi detector response according to the d-d and d-t neutron irradiation were tested at the accelerator based d-t neutron generators
  - d-d neutron generator test condition: 160 kV Acceleration voltage, 5×10^7 n/s neutron emission rate, 3.2 MeV (2.2 MeV) neutron in the beam acceleration (opposite) direction, the Sci-Fi detector was located about 1 m from neutron generation point.
  - d-t neutron generator (OKTAVIAN, Osaka Univ.) test condition: 250 kV Acceleration voltage, 10^8 n/s neutron emission rate, the detector was located about 0.35 m from neutron generation point.
- Maximum Q_{total} in d-t neutron irradiation test is about 3.5 times higher than that of d-d neutron irradiation test
- It showed clear neutron incident angle dependence.
  - Pointing factor(total counts at 0 degree to total counts at 90 degree): 1.93



Energy histograms of d-d and d-t neutron irradiation tests



Neutron incident angle dependence

8. Summary

- Shot-integrated and time-resolved measurements of triton burnup were successfully measured in KSTAR deuterium plasma using NAS and NE213 liquid scintillation detector.
- In order to have better time-resolution Sci-Fi detector was prepared and tested during 2017 KSTAR campaign.
- The Sci-Fi detector response was tested on d-d and d-t neutron generators.
- The detector was operated in KSTAR discharge #19144 and the measured results in two different H-mode regions in this discharge were compared.
- From the simulation results using LORBIT and FBURN codes and measured data from fission chamber, the later H-mode (region 'B') is expected to have about 3-10 times higher 14 MeV neutron rate.
- Measured results in two different H-mode regions are generally consistent with expected result from simulation and fission chamber data. The quantitative analysis can be done after stabilization of PMT in high-counting rate condition.
- The Sci-Fi detector has been improved in this 2018 KSTAR campaign based on this initial operation results.

4. Target plasma

✓ **KSTSAR deuterium plasma discharge #19144**

Low q95 ELM control on ITER similar shape discharge (n=2 RMP applied)

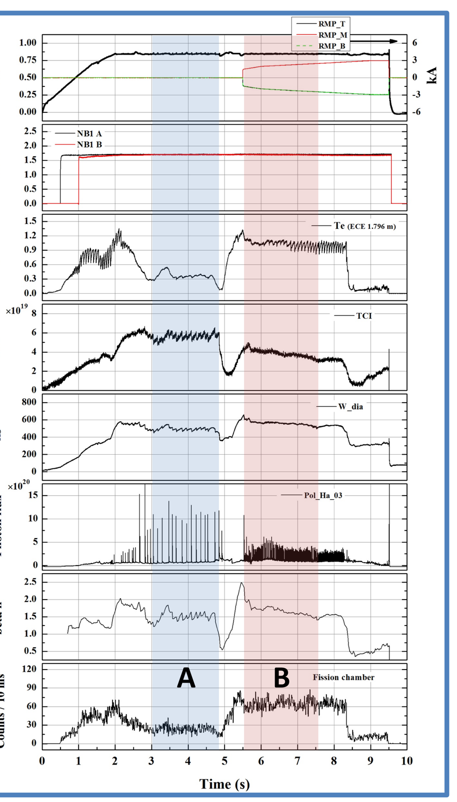
- There are two different H-mode regions
  - A: 3 – 4.85 s (weak)
  - B: 5.53 – 7.53 s (strong)
- About 3 times difference in neutron rate between two regions (P_{NB} and I_p are the same in both regions).
- Lower neutron rate represents lower 1 MeV triton birth rate. Thus higher 14 MeV neutron production rate is expected in region 'B'. If the triton burnup ratio is the same in both region, about 3times higher 14 MeV neutron rate is expected.
- From the prompt orbit loss and classical slowing down simulation result, expected difference in d-t neutron rate in two regions are estimated.

➢ **LORBIT code**[7]

- **Full orbit following code**
- Solving the Lorentz force equation using Runge-Kutta-Verner method.
- Vacuum RMP field
- Input: Plasma equilibrium (EFIT), RMP field configuration, triton initial condition (position and velocity)
- 1 MeV triton initial condition
  - Radially 9 positions (r/a = -0.8, -0.6, -0.4, -0.2, 0, 0.2, 0.4, 0.6, 0.8) 1000 test triton particles each.
  - Sampling uniformly distributed points on velocity space using random number generation

➢ **FBURN code**[8]

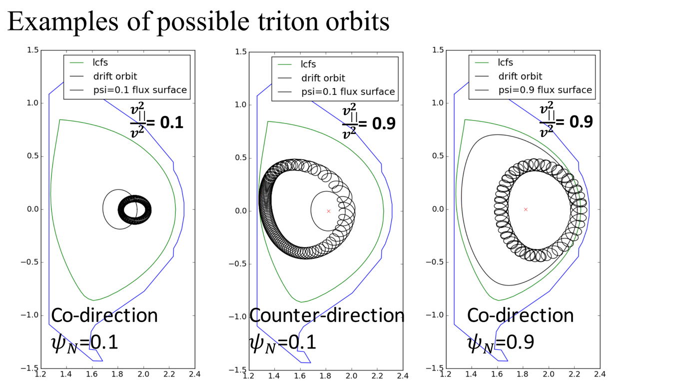
- Time-dependent analysis of **d-d and d-t neutron emission rate** in NB heated toroidal plasmas based on **classical energetic ion slowing down.**
  - 100 nested shells
  - Volume of each shell is given by the simple torus approximation
  - Uniform NB deposition profiles
  - Input: n_e, T_{e0}, NB power, NB acceleration voltage, major and minor radius
  - ne, Te profile: $n_e(\rho) = n_{e0}(1-\rho^2)^2$, $T_e(\rho) = T_{e0}(1-\rho^2)^2$
  - No diffusion mode



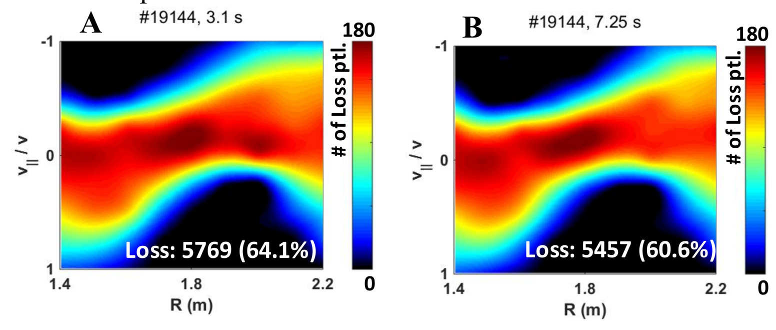
5. Triton confinement characteristics

✓ **Prompt loss fraction in each timing**

- Examples of possible triton orbits



- Interpolated results based on LORBIT calculation



- About 4% higher triton prompt loss fraction in region 'A'
- The effect of vacuum RMP field on triton prompt loss is about 0.2%

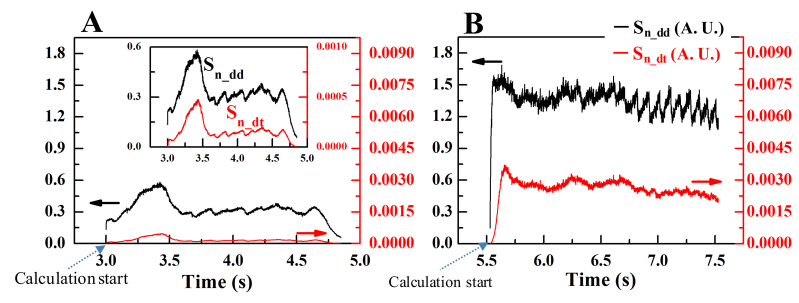
✓ **Classical slowing down characteristics**

- Region 'A' has faster slowing down time compare with region 'B'
  - Time for a typical fast ion of energy E_f to thermalize[1, 9]

$$\tau_{th} = \frac{\tau_{se}}{3}\ln\left[1+\left(\frac{E_f}{E_{crit}}\right)^{3/2}\right]$$

where, $\tau_{se} = 6.3\times10^{14}\frac{A_f T_e^{3/2}}{Z_f^2 n_e \ln\Lambda_e}$ and $E_{crit} = 14.8 A_f T_e \left(\frac{Z_i^2}{A_i}\right)^{2/3}$

  - Estimated S_{n_dd} and S_{n_dt} by using FBURN code



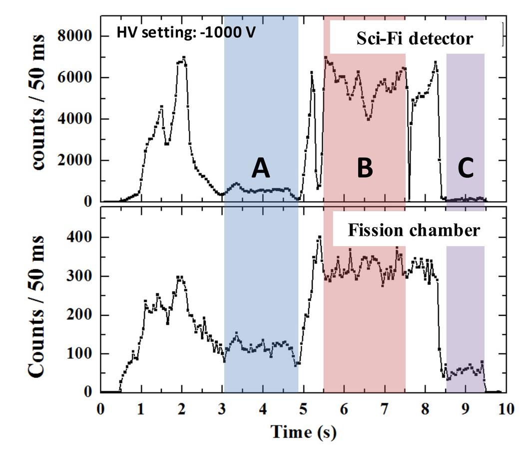
	n_e	T_e	τ_{th}	S_{n_dt} (A.U.)
A (3 s – 4.85 s)	6×10^{19} /m^3	0.4 keV	~ 0.05 s	~0.00025
B (5.53 s – 7.53 s)	4×10^{19} /m^3	1.1 keV	~ 0.3 s	~0.00300

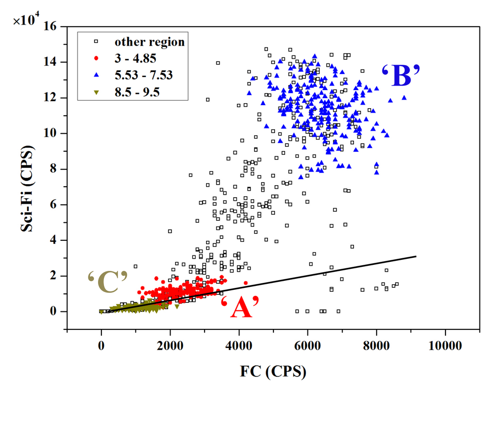
- This simplified modelling gives about 10 times difference in S_{n_dt}
- In this calculation triton loss mechanism such as prompt orbit loss is not considered. Only from the different slowing down time condition this amount of difference is occurred.

✓ **Mainly due to the longer slowing down time as well as relatively favorable triton confined condition, about 3-10 times higher 14 MeV neutron rate is expected in region 'B'**

6. Initial operation result

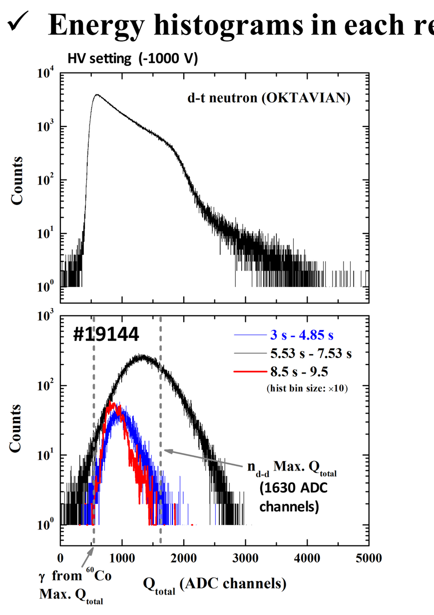
✓ **Comparison with conventional neutron flux monitor**





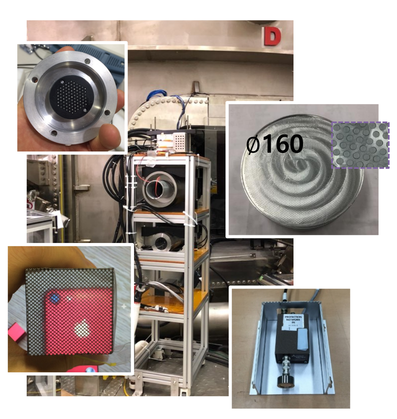
- Recorded maximum counting rate is about 150 kCPS
- In 7.5 s data readout was temporarily saturated
- Fission chamber was working properly in this discharge
- The linearity between FC and the Sci-Fi detector (w/o discrimination level) is broken from the Sci-Fi detector counting rate of ~10 kCPS
- Pulse width of the Square Sci-Fi is about 50 ns
  - Recorded maximum counting rate is about 150 kCPS
  - If pulse pile-up events are severely happened, Sci-Fi signal will be saturated in opposite direction
- In this result the PMT gain seems like upward shifted.
- Based on the Sci-Fi detector counting rate, relatively high gain shift is expected in region 'B' (~120 kCPS) and relatively reliable operation is expected in region 'A' (~10 kCPS).
- Region 'C' (180 CPS) as well as region A and B is selected for comparison which shows the lowest counting rate.

✓ **Energy histograms in each region**

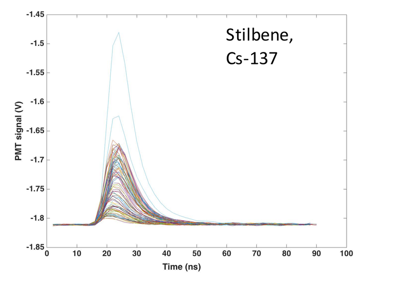


- In the region 'C' (8.5 – 9.5 s), the max. Q_{total} is similar with that of d-d neutron generator test. (The max. Q_{total} of prompt gamma-ray has similar level with that of d-d neutron.)
- In the region 'A' (3 s – 4.85 s), max. Q_{total} is about 20% higher than that of d-d neutron generator test. This could be due to the gain shift and/or small portion of d-t neutrons.
- In the region 'B' (5.53 s – 7.53 s), there are many pulses whose Q_{total} is larger than the max. Q_{total} of d-d neutron. But since this region is expected to have relatively large gain shift, all the pulses whose Q_{total} is larger than max. Q_{total} of d-d neutron cannot be considered as d-t neutron signal only. Pulse pile-up also can affect counting rate.
- In the triton burnup measurement using a Sci-Fi detector two decay components in energy histogram are expected. But only one decay component is observed.
- The effect from 14 MeV neutron on energy histogram might be obscured by high counting rate effect of PMT such as gain shift.
- Although, the Sci-Fi detector operated with un-reliable condition in high counting rate region, the possibility to have 14 MeV neutron signal in the measured data is higher in region 'B' compared with region 'A', since in region 'A' there is few counts over threshold level (max. Q_{total} of d-d neutron).

7. Status on triton burnup diagnostics in KSTAR



- PM base has been changed to active one
- 2 different Sci-Fi detectors are additionally installed
  - The same Sci-Fi detector which was operated in TFTR[5] and JT-60U[10]
  - High detection efficiency Sci-Fi detector[11] (Ø160, 5156 scintillating fibers)
- Raw waveform recording digitizer, NOTICE NKFADC500
  - 500 MHz sampling rate, 12 bit-resolution, 2 V_{pp}, 4 Ch., 8 GB memory
  - USB3 and 5 Gbps optical communication link
  - Waveform recording when event triggered during preset time window (128, 256, … 8,000 ns)



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27th IAEA Fusion Energy Conference
22-27 Oct. 2018, Gandhinagar, India

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