TIME RESOLVED TRITON BURNUP MEASUREMENTS USING THE SCINTILLATING FIBER DETECTOR ON KSTAR

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Abstract

For the purpose of time resolved measurements on triton burnup in KSTAR, square shaped scintillating fiber (Sci-Fi) detector has been installed and tested during the 2017 KSTAR campaign. It is composed of scintillating fiber bundles which are embedded in the lead matrix and photo-multiplier tube (PMT). Inside the lead matrix, 1,056 scintillating fibers whose cross-sectional area is 1 mm² are embedded. The scintillation light is detected by Hamamatsu R878 PMT and its anode signal is digitized and processed by CAEN DT5751. From the d-d neutron irradiation experiments in National Fusion Research Institute (NFRI) and d-t neutron irradiation experiments in the Intense 14 MeV Neutron Source Facility, OKTAVIAN, of Osaka University, the discrimination level for 14 MeV neutron signal is determined. The pulses larger than the discrimination level show different temporal behavior with conventional neutron detectors, e.g., ²³⁵U fission chamber. The initial operation results are analyzed by considering available orbits and slowing down characteristics of 1 MeV triton.

1. INTRODUCTION

In deuterium operation of magnetic confinement fusion devices, the behaviour of the 1 MeV triton created by the d(d,p)t reaction has been studied in order to understand certain characteristics of alpha particle confinement because kinetic parameters of the 1 MeV triton such as Larmor radius and precession frequency are similar to those of 3.5 MeV alpha particles [1]. Depends on the plasma condition, produced 1 MeV triton can be confined inside the plasma without prompt loss then slowed down by Coulomb collision with background plasma. During the slowing down, some of tritons are burned-up by fusion reaction with background deuteron, and 14 MeV neutron produced. By measuring the 14 MeV neutrons from deuterium plasma, triton confinement characteristics can be investigated. In this way, triton burnup in deuterium plasma has been studied in many fusion devices [2-11].

In KSTAR, time integrated measurements on triton burnup has been successfully carried out by using neutron activation system (NAS) since 2015 campaign [11]. In addition to time integrated measurements, by using NE213 liquid scintillation detector, time resolved measurements on triton burnup was successfully implemented in last campaign [12]. NAS with silicon sample can provide absolute number of produced 14 MeV neutrons with reliable accuracy. NE213 liquid scintillation detector can provide d-d and d-t neutron production rate simultaneously. In these diagnostics however, there is clear limitation in available time resolution as well as counting statistics. In order to have faster time resolution with good counting statistics, square shaped scintillating-fiber (Sci-Fi) detector was tested during the 2017 KSTAR campaign.

2. EXPERIMENTAL SETUP

The Sci-Fi detector shown in Fig. 1 is composed of detector head and photo-multiplier tube (PMT). In the Sci-Fi detector head, 1,056 scintillating fibers whose cross-sectional area of 1 mm² and length of 100 mm are embedded inside the lead substrate. Because of the fiber shape and metal substrate, the signals from low energy neutrons and gamma rays can be discriminated by setting appropriate threshold level [13, 14]. Scintillation light from the detector head is detected by Hamamatsu R878 PMT. The scintillation light pulse width is less than 100 ns. The anode signal of the PMT is directly fed into CAEN DT5751 digitizer via 50 Ohm co-axial cable. Sampling rate and acceptable input voltage range of the digitizer are 1 GHz and 1 Vpp (10-bit resolution) respectively. The recording length for each induced pulse is 132 ns and charge integration gate length is 100 ns. Only event triggered timing and total induced charge were saved during test experiment.
The detector response was tested in d-d and d-t neutron generators. In the National Fusion Research Institute (NFRI) the d-d neutron response was tested using commercial d-d neutron generator (NG). At the test, the beam acceleration voltage was 160 kV and the total neutron emission rate was around $5 \times 10^7$ n/s. The d-t neutron response was tested in the Intense 14 MeV Neutron Source Facility (OKTAVIAN) in Osaka University. The beam acceleration voltage was 250 kV and the total neutron emission rate was around $10^8$ n/s.

The energy histograms from d-d and d-t neutron irradiation tests are shown in Fig. 2-a. The high voltage setting was -1200 V in both cases. In this high voltage setting, the maximum $Q_{\text{total}}$ of gamma-rays from $^{60}$Co is 1100 ADC channels. Energy histograms in different high voltage setting are also shown in Fig 2-b.

During the 2017 KSTAR campaign, the detector was installed in front of D-port. The distance from magnetic axis (R=1.8 m) is around 4 m and the detector is heading for plasma radially. In order to shield from stray magnetic field, the detector is surrounded by cylindrical shape iron magnetic shield whose length is 500 mm and thickness is 10 mm.

3. INITIAL OPERATION RESULT ON KSTAR

During the 2017 KSTAR campaign, the Sci-Fi detector was tested with high voltage setting of -1000 V. In Fig. 3, energy histograms of plasma discharge #19144 (black line) and d-t neutron irradiation experiment (red line) are shown. The maximum $Q_{\text{total}}$ of d-d neutron and gamma rays from $^{60}$Co are also depicted in Fig. 3. The maximum counting rate of the Sci-Fi detector in this discharge is around 140,000 CPS. Different with a Sci-Fi detector operation result in other device [8], clear two components on energy histogram are not observed. Although no clear two components are shown in energy histogram of discharge #19144, high pulse height
region could contain triton burnup information. Based on maximum $Q_{\text{total}}$ of d-d neutron and the d-t neutron irradiation experiments, discrimination level of 2100 ADC channels is selected.

![Energy histograms of KSTAR plasma discharge #19144 and d-t neutron irradiation experiment.](image)

The Sci-Fi detector signal and plasma parameters are shown in Fig. 4. In this plasma discharge, plasma current is 0.8 MA and injected NB power is 3.4 MW. In this plasma discharge, there are two distinguished H-mode regions. One is about 2-5 s (region ‘A’) and the other is about 5.5-8 s (region ‘B’). In both region, the stored energy and normalized beta are increased and D-alpha burst signal on the edge region is clearly observed. The stored energy in the region ‘B’ is around 10% higher than that of region ‘A’. Severe electron temperature degradation in region ‘A’ after 2 s might be due to the strong interaction between plasma and plasma facing components could be a reason for this degraded confinement characteristics in the region ‘A’. In fission chamber neutron signal case, region ‘B’ has 3 times higher signal compare with that of region ‘A’. In Sci-Fi detector signal over $Q_{\text{total}}$ of 2100 ADC channels, the signal difference in two regions is much larger than that in fission chamber. Since beam-plasma reaction is dominant neutron production mechanism, the fission chamber signal can be a representative for beam ion confinement. If the Sci-Fi detector provided reliable data, in region ‘B’ the triton confinement improved very much compared with that of beam ions.
Since other triton burnup detector such as NAS was not operated during this Sci-Fi detector test, in order to check the signal validity of the Sci-Fi detector, confinement characteristics changes in two regions in terms of prompt loss is investigated. Orbit classification on momentum phase space is carried out using magnetic equilibrium data which is reconstructed by equilibrium fitting (EFIT). Because of its high energy its drift orbit is very large and the fraction of prompt loss triton is sensitively affected by plasma condition. In Fig. 5, available orbits for 100 keV deuterons and 1 MeV tritons in region ‘A’ (3.1 s) and region ‘B’ (7.25 s) are depicted. In this figure $p_\phi$ is canonical toroidal angular momentum ($p_\phi = mv_\parallel g/B - e\psi_p$) and $\mu$ is magnetic moment ($\mu = 1/(2B)mv^2$), where $g \equiv R_0B_0$, $v_\perp = \vec{v} - \vec{v}_g$, $R_0$ is major radius, $B_0$ is toroidal magnetic field strength at $R_0$, $\psi_p$ is poloidal flux, $e$ is the unit charge and $m$ is the ion mass. [15, 16]

As shown in Fig. 5, in both regions the available orbits for 1 MeV triton is quite limited compare with that of 100 keV deuterons. Only certain fraction of co- and counter-passing particles can be confined. In the trapped triton case, it couldn’t survive due to its large drift orbit size. Compared with available orbit fraction in 3.1 s, that in 7.25 s is clearly increased. Especially in counter-passing triton case, the confined area is noticeably increased. Higher prompt loss fraction due to lack of available orbit as well as higher electron Coulomb collision frequency due to lower $T_e$ and higher $n_e$ in region ‘A’ compare with those of region ‘B’ makes poor triton confinement condition in region ‘A’.

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**Fig. 5.** (normalized) momentum phase space analysis result in KSTAR #19144. (a) 100 keV deuteron and (c) 1 MeV triton in 3.1 s. (b) 100 keV deuteron and (d) 1 MeV triton in 7.25 s. Each color lines represent the inner wall (left wall); red, the outer wall (right wall); aqua marine, inner LCFS (left bd); purple, outer LCFS (right bd); green, magnetic axis; blue, and maximum value; black dot-short dash. Black short dash line indicating trapped particle region. ‘P’ and ‘T’ represent passing and trapped particle. ‘+’ and ‘-’ sign indicating particle direction; ‘+’ for co-direction and ‘-’ for counter-direction. ‘L’ and ‘C’ indicating loss and confined respectively.
4. SUMMARY AND FUTURE WORK

The square shaped Sci-Fi detector has been tested during the 2017 KSTAR campaign. Based on the d-d and d-t neutron irradiation experiment, the discrimination level has been determined. The measured result from the Sci-Fi detector above discrimination level shows different result with conventional neutron flux monitor. In the discharge #19144, there is two different H-mode. From the fission chamber signal and the Sci-Fi detector signal, the confinement of triton looks much more improved in the later H-mode timing. From the momentum phase space analysis, in the later H-mode timing has more favorable magnetic configuration for beam ion and triton confinement. Although external RMP field is not considered in this calculation, general characteristics could be discussed. In addition to field configuration, the classical slowing down characteristics, especially electron Coulomb collision frequency is higher in earlier H-mode timing. Thus 1 MeV triton slowed down much faster in this region.

Up to now, only qualitative analysis was carried out. In order to compare the measured data with triton confinement, more quantitative analysis is required. For this purpose, the prompt loss fraction of 1 MeV triton under RMP applied field is planned to be calculated by using LORBIT code [17] and the slowing down and d-t fusion reaction will be calculated by using FBURN code [18].

In order to validate the square shaped Sci-Fi signal, flash analog to digital convertor (FADC) based raw waveform recording digitizer is planned to be used. From the recorded raw waveform, we can effectively evaluate certain kind of unfavorable behavior on the detector such as pulse pile-up rate. In addition to square shaped Sci-Fi detector, high detection efficiency Sci-Fi [19] and the Sci-Fi detector which was used in JT-60U [14] are installed in KSTAR and they will be operated in 2018 KSTAR campaign together with raw waveform recording FADC. Each Sci-Fi detector will cover different dynamic range. The reliability of measured signal will be verified using NAS and NE213 liquid scintillation detector signal.

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