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First fusion proton measurements in TEXTOR plasmas using activation technique[a)]

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MeV particle loss measurements from fusion plasmas, in particular alpha particles, remain difficult in large fusion devices and further R&D is needed for ITER. This paper describes the first attempt to measure 3 MeV escaping fusion protons emitted from TEXTOR tokamak plasmas using activation technique. This technique was successfully demonstrated, initially, in 2006 on the JET tokamak. An ion camera equipped with a collimator and several types of activation detectors was installed inside the TEXTOR vacuum vessel to perform these measurements. After irradiation, the detectors were analyzed using ultra low level gamma-ray spectrometry at the HADES underground laboratory. 3 MeV escaping fusion protons were detected in larger number —∼6 times more - compared to earlier measurements using this technique on JET. Another major progress was the reduction of the cooling time by a factor of 50, which made possible to detect radionuclides with half-life of less than 90 min. [http://dx.doi.org/10.1063/1.4739228]

I. INTRODUCTION

Among diagnostic techniques developed for fusion plasmas, fusion product measurements play a crucial role. The fusion product emission is a direct indicator of fusion power. Therefore, fast neutrons are measured in almost every high-temperature plasma experiment. Beside neutrons, charged fusion products are also emitted

$$D + D \rightarrow p(3.0\ \text{MeV}) + T(1.0\ \text{MeV}), \qquad (1)$$

$$D + D \rightarrow n(2.5\ \text{MeV}) + {}^{3}\text{He}(0.8\ \text{MeV}), \qquad (2)$$

$$D + T \rightarrow n(14.1\ \text{MeV}) + \alpha(3.6\ \text{MeV}), \qquad (3)$$

$$D + {}^{3}\text{He} \rightarrow p(14.7\ \text{MeV}) + \alpha(3.7\ \text{MeV}). \qquad (4)$$

In TEXTOR, a medium size tokamak with maximum plasma current of ∼500 kA, the charged fusion products are not confined within the magnetic field and hit the walls in a few microseconds thereby carrying valuable plasma information. By contrast to neutrons, the charged fusion products above have been measured only in few experiments because such measurements are difficult to perform routinely. They are extremely difficult to perform in large fusion devices. Further R&D is, therefore, urgently needed for ITER.[1–3] In order to measure these charged particles, a detector must be placed inside the vacuum chamber and must (i) measure intense ion fluxes (up to $\sim 10^{18}$ ions/s m^2) (ii) be resistant to heat load, magnetic field, vacuum conditions, electromagnetic radiation, and electron fluxes up to high doses. Activation detectors are particularly adequate for such conditions. These detectors were successfully used, initially, in 2006 on the JET tokamak.[4–6] Their primary advantages are (i) absolute calibration and accuracy, (ii) particle identification and energy resolution, and (iii) immunity to electromagnetic, mechanical noise, heat, and radiation. The latter may prove particularly useful in view of applications to ITER.

This paper reports the first fusion proton measurements from TEXTOR plasmas by means of activation detectors. An ion camera equipped with a collimator and several types of activation detectors was installed inside the TEXTOR vacuum vessel to perform these measurements. After irradiation, the detectors were analyzed using ultra low level gamma-ray spectrometry[7] at HADES in Mol, Belgium. HADES is located at a depth of 225 m underground.

This paper is organized as follows: in Sec. II, the experimental set-up is described. In Sec. III, the experimental results are presented and followed by a summary.

II. ACTIVATION PROBE SET-UP

In order to install activation detectors inside the TEXTOR vacuum vessel, the ion detector shown in Fig. 1 was

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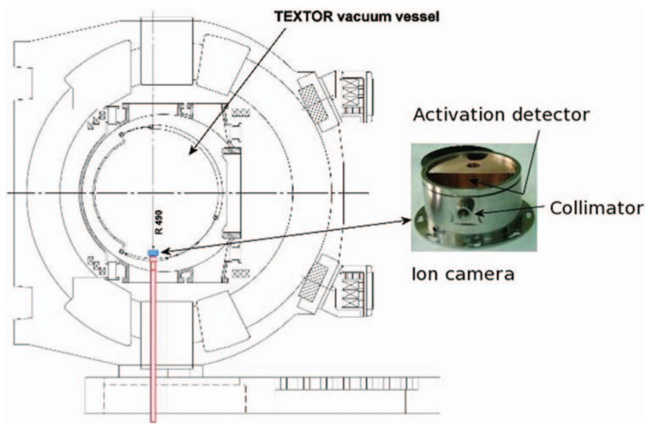

FIG. 1. Fast ion detector and its location in the TEXTOR tokamak (major radius $R_0 = 1.75$ m, minor radius a = 0.46 m).

used.[8] The aperture was 8.0 mm in diameter and 3.0 mm long. The activation sample was mounted inside the case 40 mm away from the aperture. The ion detector was mounted on a manipulator located below the bottom of TEXTOR vacuum vessel. The use of a manipulator allows to adjust the distance from the ion detector to the plasma. The measurements were performed at a distance of 490 mm from the plasma center, i.e., the detector aperture was 45 mm away from the last closed flux surface (Fig. 1).

Five activation samples were irradiated in these experiments. See in Table I below for the list of material samples and their characteristics. One boron nitride sample was irradiated. Boron nitride is a suitable material for in-vessel use and protons can be detected using ^{10}B(p, α) reaction as performed in previous JET experiments.[4] An interesting candidate alpha induced reaction for application in ITER is the ^{76}Ge (α, n)^{79m} with energy threshold of 3.2 MeV. The activation product Selenium-79m has a half-life of 3.91 min and emits a gamma ray at 95.7 keV with an emission probability of 0.095. Two isotopically enriched germanium samples were irradiated in order to investigate their activation properties in D-D fusion conditions. The germanium samples were borrowed from Gerda,[9,10] an experiment aimed at measuring the neutrinoless beta decay in Ge-76. The Ge-76 isotopic content was increased up to 87%. Finally, two 1 μm thick tantalum foils were activated in order to simultaneously monitor the neutron fluence.

TABLE I. List of material samples and their characteristics.

S[a]	Material	Isotopic content[b]	Thickness (cm)	Area (cm^2)	Mass (g)
BN	Boron nitride	Nat	0.285	23.041	12.80
Ta-1	Tantalum	Nat	0.0001	0.78	0.0019
Ta-2	Tantalum	Nat	0.0001	0.78	0.0017
Ge-1	Germanium	En	0.172	5.47	4.34
Ge-2	Germanium	En	0.353	8.37	17.42

[a]S: Sample.
[b]Isotopic content. Nat: natural, En: enriched.

TABLE II. Measured values for D-D 2.45 MeV time-integrated fusion neutron emission for selected plasma discharges.

Pulse number	Time integrated D-D emission in unit of 10^{13} neutrons
115 516	2.06
115 519	2.14
115 520	2.15
115 680	6.11
115 681	5.94
115 682	5.77

III. RESULTS

The five activation samples were irradiated in three sets of plasma discharges. Ge-1, Ta-1, and Ta-2 in set A (11 5504–11 512), BN in set B (11 5513–115 546), and Ge-2 in set C (115 660–115 683). All plasmas were in deuterium fuel with a small 5% hydrogen admixture and had similar machine parameters and plasma conditions - $B_t = 1.9$ T, $I_p = 300$ kA, respectively, for the toroidal field strength and plasma current and $T_e = 1.5$ keV, $n_e = 2 \times 10^{+19}$ m^{-3}, respectively, for electron temperature and electron density. Auxiliary heating power was up to 2 MW including a Neutral beam NBI(D) average power at ∼1 MW. In sets A and C, additional heating by means of ion cyclotron resonance heating of hydrogen minority was applied with a power at maximum of 0.8 MW. In Table II, values for the neutron emission time-integrated for selected discharges are presented. The values differ mainly due to a variation in the duration of the heating phase.

Note, the time delay between the last plasma and the first measurement was reduced to approximately 60 min compared to about 50 h in previous experiments at the JET tokamak. The aims of these first measurements were (i) to detect the short-lived activation products (see in Table III) (ii) to perform radiation measurements in order to comply with safety regulations before transport 126 km away for a detailed gamma-ray spectrometry analysis at the underground laboratory HADES. See Ref. 11 for details on the gamma-ray spectrometry.

The detected activation products are shown in Table III above. Proton induced activation was observed only in the boron nitride sample. Neutron activation results are not within the scope of this study and will be discussed elsewhere.

Beryllium-7 was found in the boron nitride sample. It is produced by fast protons through the ^{10}B(p, α) reaction. The beryllium-7 activity was calculated using the only gamma line that is emitted at 477.6 keV (see in Figure 2). The measured beryllium-7 line intensity corresponds to a fluence of (8.6 ± 1.0) × 10^9 D-D 3 MeV escaping fusion protons. This number is ∼6 times larger compared to previous measurements obtained in JET.[12,13] While in JET only a small fraction of fusion products is first orbit lost, in these TEXTOR plasma ($B_t = 1.9$T, $I_p = 300$ kA) experiments, all the DD 3 MeV protons are first orbit lost. Furthermore, the ion detector (see in Fig. 1) was placed at a more suitable poloidal position in TEXTOR than in JET.[12,13]

The total number of emitted 2.45 MeV D-D neutrons inferred from the induced activation product in tantalum foils is

TABLE III. Overview of the measured radionuclides.

RN[a]	PR[b]	Thr[c] (MeV)	Activity (Max-mBq)	S[d]
^{7}Be ($t_{1/2=53.22d}$)	$^{10}B(p, \alpha)$	...	41 ± 5[e]	BN
^{182}Ta($t_{1/2=115.0d}$)	$^{181}Ta(n, \gamma)$	...	56 ± 3[e]	Ta1, Ta2
^{77}Ge($t_{1/2=11.3h}$)	$^{76}Ge(n, \gamma)$	...	4878 × 10^3 ± 1854[f]	Ge-1, Ge-2
^{75}Ge($t_{1/2=82.8min}$)	$^{76}Ge(n, 2n)$	9.6	2439 × 10^3 ± 927[f]	Ge-1, Ge-2
	$^{74}Ge(n, \gamma)$	...		
^{77}As($t_{1/2=1.62d}$)	$^{76}Ge(p, \gamma)$	...	529 ± 3[e]	Ge-1, Ge-2
	^{77}Ge decay	...		

[a]RN: Radionuclide found.
[b]PR: Main production reaction.
[c]Thr: Energy threshold for the reaction.
[d]S: Sample.
[e]Detected in HADES.
[f]Detected in FZJ-JUELICH HPGe Laboratory.

$(7.8 \pm 0.4) \times 10^{14}$. The computer simulations for the escaping 3 MeV fusion proton trajectories as well as those of the detection efficiency were performed by means of the known Gourdon code (Gourdon, 1970).[14] The detection efficiency is about $\sim 10^{-5}$. Given that both D-D fusion reactions (1) and (2) have similar cross sections, this yields $(7.8 \pm 0.4) \times 10^9$ for the calculated number of protons which agrees within uncertainty with the above measured value of $(8.6 \pm 1.0) \times 10^9$.

In addition, further experimental verification of the proton induced activation was carried out. The range of 3 MeV protons in boron nitride is only a few tens of microns. Therefore, the radionuclide beryllium-7 must be localized on the front side. The first spectrometric analysis, whose measurement is indicated in Table III, was performed using the front side facing the gamma ray detector. After completing this measurement, two powder samples were prepared by scraping some boron nitride powder from both surfaces, the front and the back sides. These powder samples were then measured in HADES laboratory for 10 and 11 days for the front and back sides, respectively. The results of these measurements confirmed the presence of beryllium-7 on the front side, while no beryllium-7 was detected on the back side.

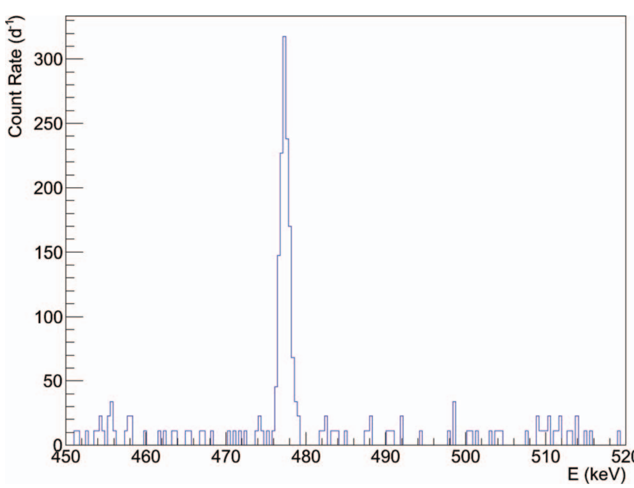

FIG. 2. Gamma-ray spectrum of the boron nitride sample measured in the underground laboratory HADES. The decay photon emission at 477.6 keV of the proton induced ^{7}Be radionuclide is shown. Note the scale is in counts/day.

IV. SUMMARY

First measurements of escaping fusion protons emitted from TEXTOR plasmas by means of activation technique were demonstrated. The 3 MeV escaping fusion proton fluence could be determined. In this experiment, the measured fluence was found in agreement with the expected first orbit loss of 3 MeV fusion protons. Further spectrometric analysis confirmed the proton origin of the activation. Finally, thanks to quicker sample removal, short lived radionuclides with half-life of ∼82 min were detected, a large progress compared to previous results.[12]

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