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** See annex of F. Romanelli et al, "Overview of JET Results", (Proc. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).*

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ABSTRACT.
In ITER, alpha particle loss measurements will be required in order to understand the physics of the high energy alpha particle population. Techniques capable of operating in the ITER harsh environment need further development and testing. Recent experimental studies on JET have demonstrated the potential of nuclear activation to measure the flux of escaping MeV ions. New results from MeV ion induced activation of several metallic, ceramic and crystal samples placed near the plasma edge are reported in this paper. The position of the samples allowed for the distribution of activation products to be measured as a function of the orientation with respect to the toroidal magnetic field as well as function of the distance to the plasma. The activity in these samples was measured using an ultra low level background gamma ray spectrometry technique. Results show distribution of fusion proton induced activation products is strongly anisotropic due to the magnetic field and falls off rapidly with increasing distance to the plasma while fusion neutron induced activation products are rather uniformly distributed on the samples. The 14.7MeV fusion proton fluence was measured to within 4% accuracy. Finally, prospects for using this technique in ITER are discussed.

1. INTRODUCTION

Alpha particle behaviour will be a key point in ITER experiments. Despite nearly three decades of research, a particle loss measurements in large tokamaks remain a problematic task. In JET for instance, α particle loss measurements have not been demonstrated in D-T fusion conditions. Techniques capable of operating in ITER harsh environment need further development[1,2]. A number of measurement techniques have been proposed [3-9]. Probably several techniques will be needed in order to satisfy measurements criteria, minimize risks and increase measurements reliability. An EFDA diagnostic task has recently been launched to support the research efforts in this challenging area. Recent experimental studies[10] on JET have demonstrated the potential of nuclear activation to measure the flux of MeV range energetic ions. Nuclear activation is a reliable and robust method to measure time-integrated properties of radiation. The advantages of this technique are robustness, linear response, immunity to electromagnetic noise and temperature variation. Particle identification, pitch angle distribution and radial profile information are obtained. By selecting different nuclear reactions with different thresholds, multi-foil absolute measurements of spectral fluence are possible on a wide energy range. No possibility for real time measurements and a fairly limited time resolution are the main drawbacks. Measurements using prompt γ-ray emission were proposed[15,18] to remove these latter restrictions. One of the most difficult aspect of a prompt γ-ray emission based diagnostic is the provision of sufficient shielding for the detector with a small collimator tube filled with a neutron absorber so that the very high neutron and resultant scattered-γ fluxes do not dominate the signal.

The present paper describes new measurements using the activation technique. In a first study in JET D-^{3}He plasmas, two radionuclides (^{48}V, ^{7}Be) were identified as produced dominantly from charged particle induced nuclear reactions and quantitative data on fusion proton losses were obtained for the first time[10]. The new measurements reported in the present paper are from a second study conducted in D-^{3}He plasmas.

2. ACTIVATION PROBE

The activation technique is a two steps method: i) samples are activated due to nuclear reactions of type (z, n), (z, γ), where z is a light charged particle p, t, d, ^{3}He or α ii) a sample analysis is performed with a suitable activation detection method. Utra low-level gamma-ray spectrometry[12] is used in this work. The activation probe (fig.1a) is the first instrument of its kind in tokamaks to be specifically designed for charged particle activation. A manipulator arm system in the JET ceiling is the only available access for the probe to the plasma. The boronnitride probe head (figure.1) is 40 mm in diameter, 100 mm in length and has a hexagonal cross section. Each of the six sides has a slot which can be filled in with samples. Sample orientations are shown in figure 2. Samples in slot 1 are facing toward the inboard radial direction. In the here reported D-3He plasmas study, a new larger set of material sample including metallic, ceramic and crystal samples was used. There were 45 samples of which 6 of titanium (Ti), 6 of titanium alloy (TVA) $Ti_{0.9}V_{0.04}Al_{0.06}$, 4 of Vanadium (V), 4 of cobalt based alloy (C), 4 of Rhodium (Rh), 5 of Yttrium (Y), 9 of boron carbide (B4C), 5 of lithium fluoride (LiF) and 2 samples of tungsten (W) used in the experiment. Each sample was of natural isotopic composition. One sample of each type was characterized using neutron k0-nuclear activation analysis.

3. RESULTS

The samples were irradiated in a total of 12 JET plasma pulses. All plasmas were in D-^{3}He fuel mixture up to 15% in ^{3}He concentration except the first reference plasma. In these plasmas, the toroidal magnetic fields were 2.2 to 3.45T and plasma currents were 1.5 to 2.2MA. Plasmas were heated with neutral beam injection NBI(D) heating only with power up to 18.5MW for up to 10s. The total number of neutrons measured by the fission chambers and summed over all plasmas was 3.2×10^{17} (with an uncertainty of ±10%). In total, 27 radionuclides were detected in this second experiment in D-^{3}He plasmas. Seven of these radionuclides were mainly produced by proton interactions. Proton activation observed in the first experiment [10] is thus confirmed. The seven proton induced activation products are given in table 1.

In addition to two charged particle induced radionuclides (^{48}V, ^{7}Be) observed previously, 5 new ones were found. Note that the transfer time to the detector is such that it not possible to use radionuclides with shorter half live than one day. The range of photon energies covered a few keV up to above 2MeV. Remarquably in the case of Rhodium, somewhat a lower range energy than conventional gamma-ray spectrometry energy range could be used. X-ray lines in the ~20keV region were used. In Yttrium samples, protons were measured using the nuclear reaction ^{89}Y(p,n)^{89}Zr, which has a threshold energy of 3.65MeV. A gamma-ray peak of Zirconium ^{89}Zr ($T^1/_2 = 78$h) decay emission at 909keV is shown in figure 2. The angular distribution of the charged particle activation in the azimuthal direction was also measured.

The relative angular distribution of the fusion proton loss is shown in figure 3 and a radial profile of fusion proton loss is shown in figure 4 for slot 2 (see in figure 4)- showing a very sharp decrease of a factor 50 in the loss in only a few cm. A preliminary simulation of the relative angular distribution and comparison with experimental data is shown in figure 3. Looking at table 1, the proton flux was detected with several reactions.

The ^{48}V ($t^1/_2$ = 15.98d)production yield from the $^{48}Ti(p,n)$ rection is high and suitable for the detection of high energy fusion proton 14.6MeV (energy threshold of 4.9MeV) and was used in the previous study. In practice, $^{48}Sc(t_{1/2 = 1.82d}$)a neutron induced activation product from $^{48}Ti(n,p)$ has gamma photons that interfere with ^{48}V ($t_{1/2= 15.98d}$) measurements which then require either some cooling time or the use of a weaker photon branch of ^{48}V. 7Be($t_{1/2= 53.3d}$) was also used in the previous study. Disadvantages are the low photon branching ratio (10.39%) of $^{7}Be(t_{1/2= 53.3d}$), low atomic fraction due to compound form and low isotopic abundances of ^{10}B (19.9%). However, the 10B(p,±) reaction is useful for lower energy proton detection, such as ICRF accelerated protons, because of the absence of threshold. $^{51}Cr(t_{1/2= 27.7d}$) production yield from the $^{51}V(p,n)$ reaction is high and suitable for the detection of fusion proton (energy threshold of 1.5MeV) and thus can detect both 3.0MeV and 14.6MeV protons. One disadvantage is the somewhat low branching ratio(9.83%). $^{56}Co(t_{1/2= 77.7d}$) and 52Mn($t_{1/2= 5.59d}$) are both useful to detect high energy fusion proton (threshold of 5.4 and 5.6 MeV respectively) however their activity was somewhat lower compared to other activation products due to the low atomic fraction of Fe and Cr in the cobalt alloy (19.5%). Zr-89 produced by proton reaction on Yttrium had the highest activity. Yttrium is suitable for detecting the high energy fusion protons with energy threshold 3.7 MeV. It has high isotopic abundance (100%) and high branching ratio (99.01). Rhodium is another suitable sample material with lower threshold (1.3MeV) than Yttrium. Pd-103 has relatively strong X-ray lines in the 20keV range. The potential benefit is the gain in detection efficiency. It has high isotopic abundance (100%). On the other hand, Rhodium is a relatively expensive material to use and photon detectors with thin windows are needed.

SUMMARY AND PROSPECTS

Several metallic, ceramic and crystal samples were found suitable to measure the flux of escaping high energy protons (14.68MeV) at JET. Seven radionuclides produced by fusion protons were measured using an ultra low level background gamma ray spectrometry technique which confirm the findings of the first D-^{3}He study[10]. The distribution of activation products could be measured as a function of the orientation with respect to the toroidal magnetic field (pitch angle) as well as function of the distance to the plasma. The preliminary modeling of the pitch angle distribution shows good agreement with experimental data. Comparing the several proton induced reactions, Yttrium gave the best results for the measurements of the loss of D-^{3}He fusion protons 14.68MeV by the charged particle activation method in JET. The results with Yttrium could be even further improved by using purer Yttrium foil. Good results were also found with Rhodium which opens the way to use the technique in the X-ray range.

Further activation studies are planned for JET. A new D-^{3}He experiment with reversed toroidal magnetic field would allow to increase the alpha loss to the JET ceiling in order to better measure the alpha induced activation. For the development in the modeling, the fusion product loss will be compared to ASCOT simulations [16] and results possibly used to cross-calibrate JET faraday cups and scintillator. Unfolding experimental data is also planned to determine the fusion products spectrum and possibly identify other energetic ions. Performance achieved so far at JET indicate that activation can measure fusion product loss as low as < 0.1% with no noticeable signal background and a very high S/N ratio. The local neutron fluence divided by local charged particle fluence is of order $O(10^4)$ in these JET experiments. These encouraging results obtained with the first activation probe prototype have prompted the design preparation of new charged particle activation probe for JET and the design preparation of charge particle activation monitors for ITER. The main work areas are: i)Identify potential best candidate reactions (see in table 2) for charged particle activation. ii) Irradiations of activation monitors by neutrons and in charged particle beams. iii) Tests of activation monitors in real fusion conditions(e.g JET). iv) Determine expected performance of activation monitor under ITER conditions. One of the most important parameter for the activation technique is the half life which determine when the information is available. In the case of the first reaction (see in table 2), $^{51}V(a,n)^{54}Mn$, a preliminary feasability study with the FISPACT code[17] shows that fluence information can be retrieved from commercial grade vanadium (with iron impurity content Fe < 80mg/kg) if sufficient cooling time is allowed. In the search for better detector materials, materials such as enriched Ge-76 of both high purity and isotopic abundance seem promising and will be investigated.

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REFERENCES

[1]. S.J. Zweben *et al,* Nuclear Fusion **40** 1 91 (2000)
[2]. A.J.H Donne *et al,* Nuclear Fusion **47** S337-S384 (2007)
[3]. M. Sasao *et al,* Fusion Scientific Technolnology **53** 2 604 (2008)
[4]. E. Cecil *et al,* Review Scientfic Instruments **57** (1986) 1777
[5]. E. Cecil *et al,* see this conference B44
[6]. D. Darrow *et al,* see this conference B43
[7]. R.K Fisher *et al,* see this conference B42
[8]. E.A. Veshev *et al,* see this conference B23
[9]. M.Nishiura *et al,* see this conference B32
[10]. G.Bonheure *et al,* Fusion Scientific Technolnology **53** 3 806 (2008)
[11]. E.Wieslander *et al,* Nucl. Instr. Meth **A. 591** 383 (2008)
[12]. M.Hult *et al,* Appl.Radiat.Isotopes **53** 225 (2000)
[13]. S.Sharapov *et al* Proc.Conf. 11th IAEA TCM on Energetic Particles, Kiev, Sep 21- 23, P-33 (2009)

[14]. R. González de Orduña, accepted for publication in Appl.Radiat.Isotopes
[15]. V.G. Kiptily, Fusion Technology **18** (1990) 583
[16]. T.Kurki-Suonio *et al*, Nucl. Fusion **49** (2009) 095001
[17]. R.A.Forrest, UKAEA FUS 534 (2007)
[18]. G.Bonheure *et al,* Review of Scientific Instruments **75** 3540 (2004)

R	A (mBq/g)	PR	Thr (MeV)
$^{48}V_{(}t_{1/2 = 15.98d)}$	626 ± 48.5	^{48}Ti(p,n)	4.9
$^{7}Be_{(}t_{1/2 = 53.3d)}$	161.6 ± 24.4	^{10}B(p,a)	–
		^{7}Li(p,n)	1.9
$^{51}Cr_{(}t_{1/2 = 27.7d)}$	673.4 ± 47.5	^{51}V(p,n)	1.5
$^{56}Co_{(}t_{1/2 = 77.7d)}$		^{48}Ti(a,n)	2.9
$^{52}Mn_{(}t_{1/2 = 5.59d)}$	31.5 ± 5.6	^{36}Fe(p,n)	5.4
$^{103}Pd_{(}t_{1/2 = 16.99d)}$	97 ± 12	^{52}Cr(p,n)	5.6
$^{89}Zr_{(}t_{1/2 = 78h)}$	2372 ± 162	^{103}Rh(p,n)	1.3
	3303.9 ± 130	^{89}Y(p,n)	3.7

Table I: List of measured proton induced radionuclides(R). Activity(A) refers to highest measured sample activity.

PR	Thr (MeV)	$T_{1/2}$	IA(%)
^{51}(a,n)^{54}Mn	2.5	312d	99.76
^{19}F(a,n)^{22}Na	2.4	2.6y	100
^{43}sc(a,n)^{48}V	2.4	16.0d	100
^{55}Mn(a,n)^{58}Co	3.8	70.8d	100
^{48}Ca(a,n)^{51}Ti	0.14	3.8h	1.8
^{40}Ca(a,p)^{43}Sc	3.9	3.9h	96.9
^{41}Ca(a,p)^{44}Sc	2.4	58.6h	–
^{43}Ca(a,p)^{46}Sc	1.7	83.7d	0.1
^{44}Ca(a,p)^{47}Sc	2.2	3.3d	2
^{45}Ca(a,p)^{48}Sc	1.3	43.7h	–
^{46}Ca(a,p)^{49}Sc	1.6	57m	0.004
^{48}Ti(a,n)^{51}Cr	2.9	27.7d	73.8
^{25}Mg(a,p)^{28}Al	1.4	2.2m	10
^{26}Mg(a,p)^{29}Al	3.3	6.6m	11
^{27}Al(a,p)^{30}P	3.0	2.5m	100
^{10}B(a,n)^{13}N	–	9.9m	20
^{14}N(a,g)^{18}F	–	109m	99.6
^{41}K(a,n)^{44}Sc	3.7	58.6h	6.73
^{49}Ti(a,p)^{52}V	2.2	2.2h	5.5
^{53}Cr(a,p)^{56}Mn	2.5	2.5h	9.5
^{76}Ge(a,n)^{79m}Se	3.2	3.9m	7.8

Table II: List of potential best candidate reactions for fusion α-induced activation

(a) *(b)*

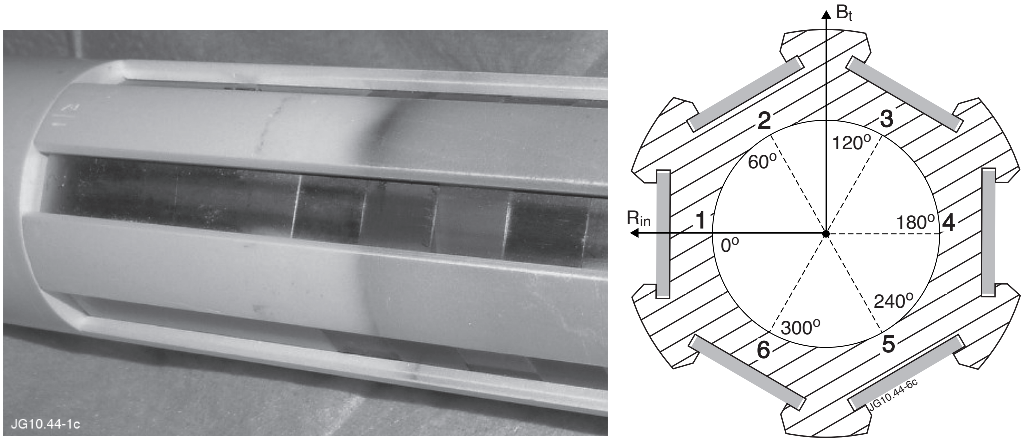

Figure 1:a) View of activation probe. b) A cross section of the probe. B_t is the standard direction of the toroidal magnetic field and R_{in} is the azimuthal direction along the major radius of the Tokamak and pointing radially inward. The numbers indicate the 6 sample positions.

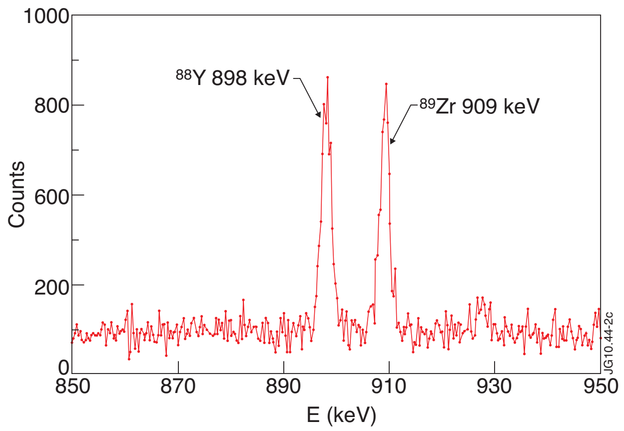

Figure 2: Gamma-ray spectrum (Y ttrium sample) showing a peak at 909keV from the decay of proton induced 89Zr (t1/2=78 h).

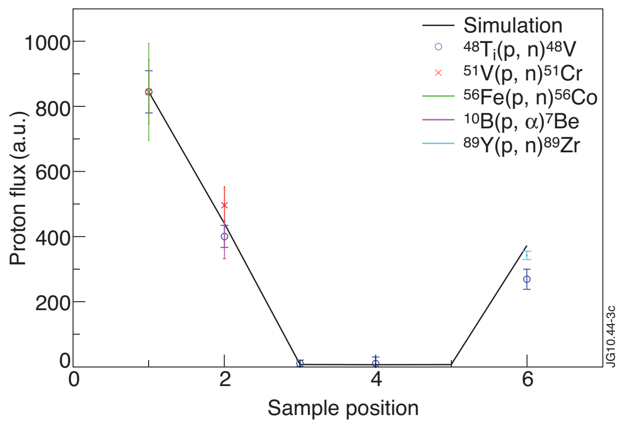

Figure 3: Relative angular distribution (pitch angle) of fusion proton loss. Comparison between simulation and activation data from several proton induced nuclear reactions. A strong anisotropic distribution is observed. Main production reactions(PR) and (Thr) energy threshold are indicated.

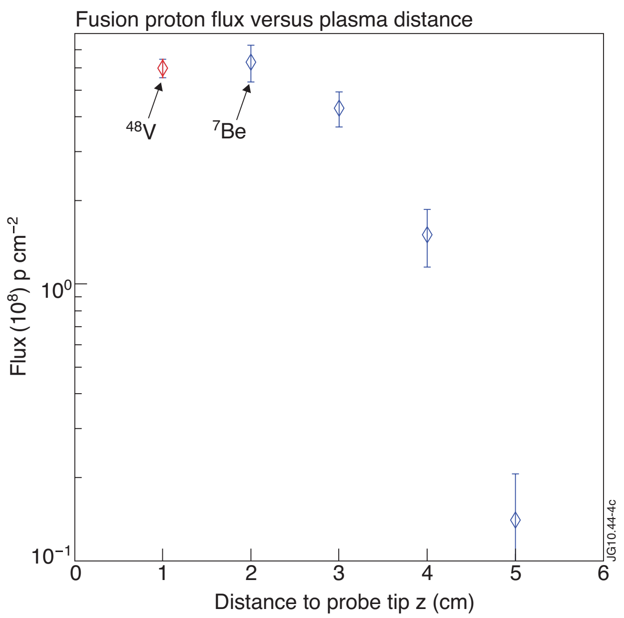

Figure 4: Radial profile of fusion proton loss. A sharp decrease (factor 50) in the loss is observed moving 4cm away only from the plasma.