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# Activation measurements in support of the 14 MeV neutron calibration of JET neutron monitors

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ABSTRACT

In preparation for the upcoming deuterium-tritium campaign at the JET tokamak, the ex-vessel fission chamber neutron diagnostics and the neutron activation system will be calibrated in absolute terms at 14 MeV neutron energy, to a required accuracy of less than 10%. Two nominally identical DT neutron generators were chosen as the calibration sources, both of which were fully calibrated and characterized at the UK's National Physical Laboratory. The neutron activation method was adopted as a complementary method for the purpose of determining the absolute value of the neutron yield from the neutron generators and to provide a means of cross check for the active detection methods being employed. The work being presented here shows the derivation of the neutron emission rate from the neutron generators based upon experimental activation foil measurements.

## 1. Introduction

The absolute measurement of neutron yield ($Y_n$), in a fusion device, is needed to provide the fusion power output along with other plasma parameters, such as the ion temperature and density.

The system of neutron yield monitors used to monitor the Joint European Torus (JET) consists of $^{235}U/^{238}U$ fission chambers (KN1), located outside the tokamak, and an internal, in-vessel, activation system (KN2). An absolute calibration of both KN1 $^{235}U/^{238}U$ fission chambers and KN2 was performed in 2013, using a $^{252}Cf$ spontaneous-fission source, having a mean energy of 2.1 MeV and a source strength of $2.4{\cdot}10^8\ n{\cdot}s^{-1}$. JET operating in deuterium (D) mode produces 2.5-MeV neutrons by the (d,d) fusion reaction, the $^{252}Cf$ neutron energy spectrum is sufficiently similar to the (d,d) fusion energy distribution; that it serves as an adequate calibration measure for neutrons of such similar energies [1]. Additionally, MCNP [2] calculations were used to determine the correctional factors arising from the differences in the neutron spectrum from that of a pure D plasma and other geometrically dependant calibration factors.

The neutron source (NS) was placed at different points inside the vacuum vessel, from which neutron induced activation and fission chamber pulses were recorded by KN1 and KN2 systems, respectively. In KN2 the $^{115}In(n,n')^{115m}In$ nuclear reaction is used as the monitoring reaction in D operations. The cross section has a maximum at an energy of 2.7 MeV, which is useful for measuring the 2.5 MeV neutrons released during deuterium fusion, and has a threshold of approximately 0.4 MeV. The moderated $^{235}U/^{238}U$ fission chambers can measure a broad energy range of neutrons and have a relatively flat response over these energies. During the 2013 calibration campaign, both KN1 and KN2 were calibrated with a total uncertainty of approximately ± 10%; these results were successfully verified during the following D campaign [S. Popovichev, private communication].

A new Deuterium-Tritium Experimental Campaign (DTE2) on the JET tokamak is planned in the near future [3]; in which up to $1.7{\cdot}10^{21}$,

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[1] See the author list of "Overview of the JET results in support to ITER" by X. Litaudon et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 26th Fusion Energy Conference (Kyoto, Japan, 17–22 October 2016).

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14.1 MeV neutrons will be produced, a new calibration of JET monitoring systems for higher energy neutrons therefore is required.

JET calibration, at 14.1 MeV neutron energy, requires the use of a different set of nuclear reactions, with higher energy thresholds, and at the same time, sufficiently high cross section and convenient decay times of the reaction products. Moreover, the tokamak transparency to neutrons alters as the neutron energy increases from 2.5 MeV to 14.1 MeV, thus, causing a change in the response of the $^{235}$U fission chambers. To accurately determine calibration coefficients, it is therefore necessary to conduct a JET neutron diagnostic calibration with a NS that emits 14.1-MeV neutrons from a (d,t) reaction. The 14-MeV calibration will be based on the procedures and experience gained during the 2.5-MeV calibration [3]. The experience gained during the 14.1-MeV calibration of JET neutron diagnostics will serve as a good methodology when calibrations are carried out on ITER, which is currently under construction in Cadarache, France.

The ING-17 neutron generator (NG) [4] manufactured by the All-Russia Research Institute of Automatics (VNIIA) Moscow, Russian Federation [5] was chosen as the continuously neutron source for neutron calibration of JET. It has a nominal yield of approximately $2{\cdot}10^8$ n·s$^{-1}$. The NG comprises of an accelerated beam consisting of deuterium and tritium ions and of ionized molecules, striking a target made of tritium and deuterium implanted onto titanium. Beam as well as target contain approximately 50/50 % ratio of D/T. The yield of neutrons emitted is strongly dependent upon the beam acceleration voltage.

In order for the NG to be used as a calibration source, the yield must be known with a high accuracy, possibly better than ± 5%. The emitted neutron energy spectrum characteristics must also be known. The NG emission characteristics were measured during two experimental campaigns at the UK National Physical Laboratory (NPL) by the NPL Neutron Metrology Group, using their low-scatter cell neutron facility. Two nominally identical NGs (NG1 and NG2) were examined one at a time. They were mounted in the centre of the large hall (see Fig. 1), where the conditions support the low scatter requirements. The emission rates and energy spectrums of both NGs were measured by "characterization" neutron detectors: an absolutely calibrated De Pangher long counter; an absolutely calibrated NPL Long Counter; two Single Crystal Diamond Detector (SDD) − neutron spectrometer; a NE-213 scintillator based neutron spectrometer [6] and activation foils. From these measurements, the two NGs total neutron yield in 4π was derived.

The NG emission rate and energy spectrum vary over the course of a single run [7]. It is therefore necessary to monitor the varying yield during the whole calibration process. In order to do this, the NG was equipped with "monitoring" detectors, both active and passive. These comprised: i) the SDD and the Silicon diode in the first campaign, two SDD in the second campaign, and ii) a set of 12 activation foils, all

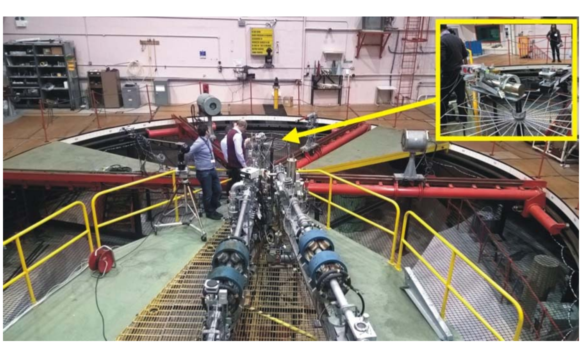

**Fig. 1.** Experimental hall inside the Chadwick facility. The NG is located in the centre of the hall (in the right upper corner is enlarge photo of NG). The two long counters and the NE-213 scintillator are situated above the red rails in the centre of the above image. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

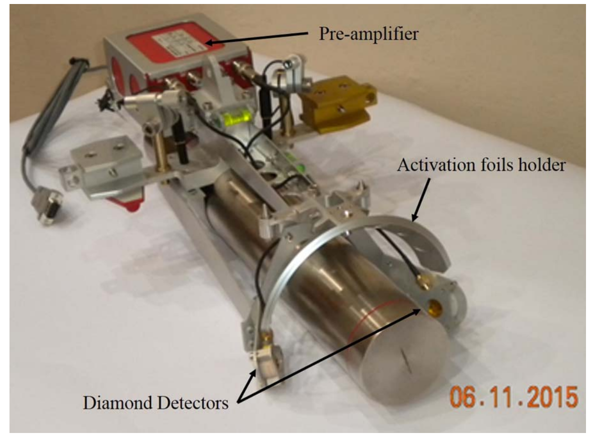


**Fig. 2.** Neutron Generator with the mechanical support needed for remote handling gripping during the JET in-vessel calibration, and to support the "monitoring detectors" and pre-amplifier (the first NPL campaign).

located in well-defined, stable positions relative to the neutron generator target; where the neutrons are produced. These monitoring detectors were attached to the NGs by means of a mechanical support (see Fig. 2).

The SDDs measurements, combined with the measurements by the absolutely calibrated Long Counter measurements carried out at NPL, provide the absolute time resolved emission rate from the NG. The activation foils provide a complementary and independent measurement of the absolute neutron emission rate (n·s$^{-1}$) for a given exposure period. This paper focuses on the measurement and analyses of the monitoring activation foils, and on the comparison with the active monitoring detectors. The uncertainty of the derived absolute neutron emission rate of the NGs is also discussed.

## 2. Experiment set up

A set of monitoring activation foils were attached to a custom made holder and mounted on the NG mechanical support (Fig. 2). The holder was designed to allow for retrieval by the JET remote handling system during the in-vessel calibration of the JET tokamak. The mechanical support used in the second campaign was a slight variation on the one used in the first campaign; which was modified to improve the positioning of monitoring detectors with respect to the NG target. Both the SDDs and the activation foils will be used during the in-vessel calibration at JET, which will implement the same mechanical support and positioning system used in the second NPL campaign.

The NG irradiation schedule at NPL consisted of a series of 20-min irradiations followed by 10 min of NG cooling. During the cooling periods, the positions of the non-attached neutron diagnostics were changed. The daily operational cycle consisted of 11–13 irradiations, except for the first day, where only two irradiations were completed. The monitoring activation foils were normally removed after the ninth irradiation cycle; to allow the gamma spectrometry measurements to be complited before next operational cycle.

## 3. Activation measurements and analyses

### 3.1. Neutron activation reactions and their products

The activation reactions chosen for the monitoring foils were selected based on numerous requirements. Specifically, the cross section for the reaction products needed to be relatively large and well known. Also, the reaction thresholds should be sufficiently high in order to discriminate lower energy neutron scatter. The reaction products should emit gamma radiation that can be clearly measured using gamma spectrometry methods. The latter requirement mainly limits