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On the absolute calibration of neutron measurements in fusion reactors

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HIGHLIGHTS

- This paper focuses on the issues of obtaining the absolute calibration of neutron measurements in fusion reactors, including also ITER and DEMO.
- Such absolute calibration is required to provide the fusion power, to account for burnt Tritium, and to derive plasma ion parameters.
- The calibrating procedure adopted so far appears to be very complex when applied in ITER, and probably unviable in DEMO and in the future reactors.
- An alternative solution based on the neutron activation technique using long-lived radioisotopes is proposed in this paper.
- Potential reactions are investigated and the expected activity levels are calculated for several materials in ITER.
- A test in JET is proposed.

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ABSTRACT

This paper focuses on the issues of obtaining and maintaining the absolute calibration of neutron measurements in fusion reactors, including also ITER and DEMO. Such absolute calibration is required to provide the fusion power, to account for burnt Tritium, and to derive plasma ion parameters. The usual calibrating procedure adopted so far in fusion devices appears to be very complex already when applied in ITER, and most probably unviable in DEMO and in the future power plants. An alternative solution based on the neutron activation technique using long-lived radioisotopes is proposed in this paper. Potential reactions are investigated and the expected activity levels are calculated for several materials in ITER. A test in JET is proposed.

1. Introduction

An accurate absolute calibration of neutron detectors is required in fusion reactors as they provide a measurement of the fusion power and of the Tritium burnt in fusion reactions, which must be known for Tritium accountancy, as well as other plasma parameters. The usual procedure adopted so far in fusion devices to calibrate neutron detectors is based on recording neutron detector signals when a calibrating neutron source of known intensity is deployed inside the machine at different toroidal and poloidal locations [1–3]. Generally, ^{252}Cf neutron sources and DT neutron generators have been used to calibrate neutron detectors at 2.5 MeV and 14.1 MeV energy, respectively [1,2]. Numerical simulations are used to estimates the effects of different circumstances of calibration as compared to the plasma volumetric source, due to the discrete positions and to different energy spectrum and angular emission distribution of calibrating (point) sources.

Most fusion experiments employ both active detectors located around the machine (fission chambers, proportional counters, scintillators etc.) to monitor the time evolution of the neutron emission rate, and activation systems which allow for a transfer of activation samples inside the machine and their removal, for instance on a shot by shot basis. Activation systems employ encapsulated foils pneumatically transferred from the in-vessel irradiation stations to the gamma-ray measurement station where the neutron-induced activity is measured. This system provides an absolute measurement of the local neutron fluence at the irradiation station during the irradiation time, which can be related to the total neutron yield in the same time interval by radiation transport calculations. Provided that the irradiation stations are sufficiently close to the first wall, and high-energy threshold activation reactions are used, the activation system can be considered to respond mostly to direct neutrons. However, detailed numerical calculations can provide

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the correct response including the contribution due to scattered neutrons.

Active detectors, fully characterized in the laboratory, respond only to the local neutron field, which is determined by radiation transport in the tokamak and in the detector itself. The materials, especially those between the neutron source and detector positions, cause neutron flux attenuation and affect the neutron spectrum. Usually, detectors do not distinguish between direct and scattered neutrons, and this is why in situ calibration of detectors complemented with neutron transport calculation are necessary.

The absolute calibration of neutron detectors in fusion systems is becoming more difficult as the size of devices increases, requiring calibrating sources of higher intensity and longer irradiation times. Recently, a new neutron calibration has been carried out at JET (after 24 years from the previous one) based on the use of a ^{252}Cf source with intensity equal to 2.7×108 n/s deployed inside the vacuum vessel in more than 200 toroidal/poloidal positions in two weeks by means of the JET remote handling boom [4]. A new calibration at 14 MeV neutron energy is being prepared in preparation of the new DT operations planned for 2019 [5]. It will use a DT neutron generator calibrated and characterized in laboratory before the in-vessel calibration.

In ITER, a comprehensive set of neutron detectors will be installed and will be calibrated through a complex calibration strategy [6]. The neutron diagnostics will allow evaluation of the neutron emissivity, i.e., the fusion power, and will play a key role for machine protection as well for plasma optimization and for achieving ITER goals, in particular the target fusion gain factor, Q. ITER expected neutron emission strength spans over 7 decades (from 10^{14} up to almost 10^{21} n/s). The various neutron diagnostic systems will have to be able to measure the neutron emissivity within 10% accuracy, with a temporal resolution of 1 ms and spatial resolution of a tenth of the minor plasma radius, i.e., 200 mm. These include neutron flux monitors (fission chambers coated with varying amount of ^{235}U and ^{238}U fissile material) installed in diagnostic ports and below the divertor dome, ^{235}U micro-fission chambers deployed between the blanket modules and the inner shell of the vacuum vessel, and the radial and vertical neutron cameras. A Neutron Activation System (NAS) will also be installed with irradiation ends inside the vacuum vessel.

It is planned to apply the in situ calibration also to ITER neutron detectors. A powerful DT neutron generator – with intensity $\sim 10^{10}$ – is needed and will have to be developed. This intensity is, however, many orders of magnitude lower than the plasma neutron intensity, and the huge differences in neutron flux the detectors experience during the ITER operations as compared to the calibration procedures requires many cross calibration steps. The use of a DT neutron generator introduces additional sources of uncertainties in the calibration as compared to ^{252}Cf sources. DT neutron generators, in fact, present very complex characteristics, such as the dependence of the neutron energy on the emission angle, and need to be carefully characterized and calibrated before they can be reliably used as calibration sources. Given the neutron emission intensity required, the neutron generator itself will be massive and will have to incorporate a cooling system. Account needs to be taken of the potential screening and scattering effects of the structure that will support the neutron source by means of neutron transport code calculations. In ITER it is estimated that it will take eight weeks at least with this source to calibrate flux monitors, profile monitors, and the activation system [7]. Full in-situ calibration experiments are planned only before the beginning of the ITER nuclear phase. During ITER life the characteristics of the detectors may vary due to environmental changes. These changes have to be tracked by measurements using weak neutron sources, and cross-calibration with activation measurement using reference discharges (long-term and periodic calibration) [8].

Therefore, the activation system plays a fundamental role in the ITER neutron calibration strategy because it is the only neutron diagnostic having a dynamic range of many orders of magnitude thanks to appropriate selection of mass and foil materials. However, high thermal loads are expected at the irradiation ends because of the plasma radiation and nuclear heating. This fact precludes a number of materials for the capsule or sample, such as polyethylene, In and Al, and in any case active cooling is needed, introducing complexity in the system design. EM forces induced by plasma disruptions require the design of dedicated strong supports. R&D activity is on-going on the selection of material and mass of the samples. The location of irradiation ends has to take into account a number of constraints that prevent an optimal positioning to be obtained. The optimal location would be as close as possible to the first wall, with a complete view of the emitting plasma and in the absence of collimating effects. In ITER, several irradiation stations will be positioned between various blanket modules and on the vessel inner wall as well in the Upper and Equatorial Ports.

The implementation of diagnostics systems in DEMO and in future power plants will be even more challenging and will require a new and very pragmatic approach. This will be true in particular for neutron diagnostics that will be undeniably essential. Activation systems with the current design, i.e., with irradiation ends close to the first wall, will be most probably unviable in DEMO and in future power plants, for which new concepts for neutron diagnostics will have to be developed. Proposals have been made of using the activation of circulating water in a dedicated loop as a fusion monitor in future fusion reactors. The method is based on the measurement of the ^{16}O(n,p)^{16}N reaction that has a threshold energy of 10.4 MeV [9].

An alternative solution for DEMO, based on the complementary use of the neutron activation technique employing long exposure times and using long-lived radioisotopes together with short lived ones, is proposed in this paper and aims at providing a periodic calibration of neutron detectors along the reactor lifetime. This proposed solution partially disentangles the problem of accurate absolute calibration from the time resolved measurement of fusion power, and requires a first, dedicated nuclear phase of operations devoted to calibration of the activation system at the beginning of the reactor life. This approach should be tested in ITER. Potential reactions are investigated and the expected activity levels are calculated for several materials in the ITER case. A test in JET is proposed.

2. A new calibration approach

The proposed approach aims at providing a first, and then a periodic, calibration of time resolved neutron monitors, and is based on the use of activation samples, made of suitable metals, attached to in-vessel components (or sub-components) that are expected to be refurbished/replaced at a frequency of a few years, such as the divertor cassettes, port plugs or blanket modules. The samples will have to be located close to the plasma facing side of such components so that they are exposed to fusion neutrons and, at the same time, protected from direct plasma interactions. The system, which we will call Long term Neutron Activation System, L-NAS, would involve simple attachment of very small samples (a few grams) not requiring any dedicated cooling system. A second, 'traditional' activation system with pneumatic transport of samples at irradiation ends, and employing activation reactions producing radioisotopes with both long and relatively short half-lives (S-NAS), would be cross calibrated with the L-NAS and would record neutrons with a desired time resolution (one discharge or a few days, or weeks).