Radiation Measurements 71 (2014) 421–424

Contents lists available at ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas

# Solid state detectors for neutron radiation monitoring in fusion facilities

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## HIGHLIGHTS

- A state-of-the-art summary of solid state based detectors are described.
- Conditions and restrictions for their applicability are described.
- A list of the 38 more relevant references has been included.

ARTICLE INFO

*Article history:*
Available online 20 May 2014

*Keywords:*
Solid state detectors
Fusion
Radiation monitoring

ABSTRACT

The purpose of this communication is to summarize the main solid state based detectors proposed for neutron diagnostic in fusion applications and their applicability under the required harsh conditions in terms of intense radiation, high temperature and available space restrictions. Activation systems, semiconductor based detectors, luminescent materials and Cerenkov fibre optics sensors (C-FOS) are the main devices that are described.



## 1. Introduction

Satisfying the operation requirements of fusion facilities, both ITER (Giacomelli et al., 2005) and future fusion reactors (Maisonnier et al., 2005) as well as the International Fusion Material Irradiation Facility (IFMIF) (Ehrlich and Möslang, 1998) requires an extensive set of diagnostic systems in order to detect abnormal events and to provide real-time control.

Foreseen fusion reactors and related facilities are expected to originate strong mixed neutron and gamma radiation fields. For D-T (deuterium tritium) fusion reactors, neutron spectrum (Fig. 1) is strongly peaked at 14.1 MeV, corresponding to primary neutrons, then scattered and moderated in the different structures of the reactor (walls, blanket, shielding, etc.). The neutron source strength in the Joint European Torus (JET) varies from $10^{10}$ $s^{-1}$ to about $10^{18}$ $s^{-1}$ with a pulse length about 20 s (Pamela et al., 2005; Bonheure et al., 2006). Expected neutron fluence rate values in ITER and future DEMO fusion reactors depend on the design of the reactor, plasma volume, fusion power and the measurement point but values in the range $10^{10}$–$10^{14}$ $cm^{-2}s^{-1}$ have been obtained by simulation (Fischer et al., 2009; Palermo et al., 2012).

IFMIF pretends to provide an intense neutron source for material irradiation tests using two linear accelerators, each generating a 125 mA beam of 40 MeV deuterons, to impact on a liquid Li target flowing at high velocity over a curved backplate. Nuclear reactions will produce intense high energy neutrons, up to 50 MeV (Fig. 1), to irradiate the specimens installed immediately behind the target, with neutron fluence rate values in the range $10^{13}$–$10^{15}$ $cm^{-2}s^{-1}$ (Fischer et al., 2006).

Neutron measurement is one of the main diagnostic methods to provide essential information on plasma physics (ion temperatures, fuel isotope ratio, fast ion behaviour, degree of confinement, loss mechanism, etc.) and real-time control in ITER and future fusion reactors (Sasao et al., 2008; Encheva et al., 2009). Potential detectors for neutron monitoring must be able to support the harsh conditions in terms of intense radiation, high temperature and available space restrictions. Such conditions will also affect related components: ceramics, cables, mirrors, optical fibres, etc. (Yamamoto et al., 2000). Miniaturized fission chambers are commonly used for online irradiation control and fluence rate mapping (Ishikawa et al., 2008; Rapisarda et al., 2011) because of their small size, radiation hardness and photon insensitivity. In addition, semiconductor detectors and activation systems are also successfully used for neutron monitoring in JET (Bonheure et al., 2006) and will be incorporated for ITER fusion experiments.

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http://dx.doi.org/10.1016/j.radmeas.2014.05.003
1350-4487/

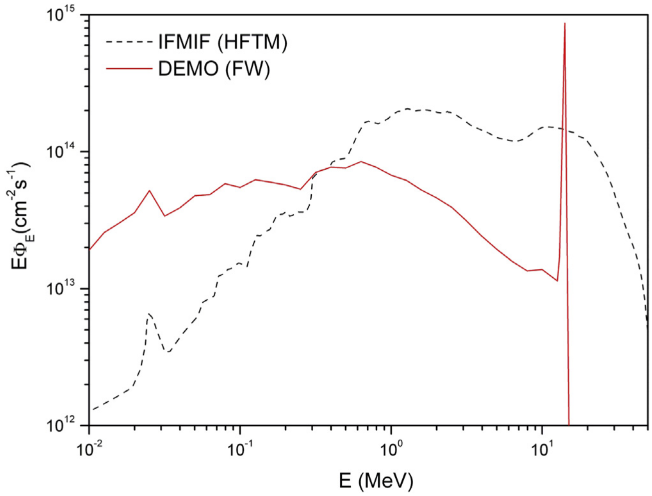


**Fig. 1.** Comparison of calculated neutron fluence rate spectra for IFMIF (high flux target module) and a DEMO reactor (first wall) (Fischer et al., 2002; Rapisarda et al. 2009; Palermo et al., 2012).

A summary of the solid state based detectors presently used and foreseen for radiation monitoring in fusion facilities is presented below. Activation systems, semiconductor based detectors (silicon, silicon carbide and diamond), luminescent materials (radioluminescence and thermoluminescence) and Cerenkov fibre optics sensors (C-FOS) are examined and discussed.

## 2. Radiation diagnostics systems for fusion facilities

### 2.1. Activation systems

Neutron activation method provides robust time-integrated measurements of the neutron fluence and total neutron yield in Tokamak facilities, JT-60U, JET, ITER, with a dynamic range of 10 orders of magnitude by appropriately selecting foils materials. Moreover, they allow an absolute calibration of fusion power production (Barnes et al., 1997; Sasao et al., 2008; Bertalot et al., 2012).

Two activation based methods are considered for ITER. One uses a pneumatic transfer system to situate the capsules containing the activation materials at the irradiation point, located inside the vacuum vessel, close to the plasma (Sasao et al., 2008; Cheon et al., 2012). The activated samples are transferred through port feedthroughs to the counting stations placed outside of bioshield where the induced radioactivity can be counted and the measured activity can be used to determine integrated neutron fluence at the measuring point. For the measurement of 14 MeV neutrons, some possible activation materials (Table 1) are $^{56}$Fe, $^{27}$Al, $^{48}$Ti and $^{63}$Cu (Sasao et al., 2008), all of them with threshold energies permitting to discriminate 2.5 MeV neutrons and half-life short enough to reach saturation (Knoll, 2010; Tsoulfanidis and Landsberger, 2011). Activation foils are also planned to be used to monitor the neutron fluence and energy spectrum in the IFMIF high-flux test module (HFTM) (Simakov et al., 2007). Neutron spectrum is determined by unfolding of multiple foils activation using SAND-II code (Griffin et al., 1994).

A second system (Konno et al., 2001) consists of the measurement of 6.13 MeV gamma rays emitted by $^{16}$N produced by $^{16}$O(n,p)$^{16}$N reaction in a water loop flowing from blanket to outside bioshield. Because of the high threshold energy of 10.24 MeV for the neutron capture reaction, water activation system is practically insensitive to scattered neutron and will mainly detect 14 MeV neutrons. A prototype tested at the JAEA proved to be able of measuring neutron source strength in the range $10^{16}$–$10^{21}$ s$^{-1}$ with time resolution lower than 0.1 s (Sasao et al., 2008).

### 2.2. Semiconductor detectors

Wide bandgap semiconductor detectors based on silicon (Si), silicon carbide (SiC) and diamond are potential candidates to be used for neutron diagnostics because of their radiation hardness and ability to operate at high temperature (beyond 200 °C). Detection of fast neutrons is achieved by neutron induced threshold reactions in Si and C nuclei (Tables 2 and 3) producing heavy secondary charged particles (Willander et al., 2006; Franceschini and Ruddy, 2011). Thermal and epithermal neutrons can be also detected using converter layers (e.g. $^{6}$LiF).

Silicon (Si) is still the most commonly used semiconductor and Si detectors have been used to discriminate between 14 MeV and 2.5 MeV neutrons and photons in JET (Conroy et al., 1988) because (n,p) and (n,$\alpha$) threshold reactions produced in Si by fast neutrons. Nevertheless radiation damage is a serious concern for neutron fluence above $10^{12}$ cm$^{-2}$ (Bonheure et al., 2006) and temperature operation is limited about 200 °C (Willander et al., 2006) so they need to be frequently replaced when used in high yield D-T reactors (JET). Therefore, increased radiation hardness will be demanded by ITER or DEMO reactors.

Silicon carbide (SiC) has larger bandgap and breakdown voltage properties which makes it a promising material for high fluence neutron detection in high temperature environments (Metzger et al., 2002; Manfredotti et al., 2005; Franceschini and Ruddy, 2011). Detection of fast neutrons in SiC detectors is based on secondary charged particles produced by neutron reactions in Si and C nuclei (Willander et al., 2006; Franceschini and Ruddy, 2011). Polymorphs of SiC include a large family of crystalline structures called polytypes, among which the most commonly used are the cubic 3C–SiC and hexagonal 4H–SiC, 6H–SiC structures. The 4H–SiC polytype has attracted more attention for its combination of better electronic properties, high bandgap 3.2 eV and electron mobility 500 cm$^{-2}$V$^{-1}$s$^{-1}$ (Table 2) and availability as substrate material (only 4H and 6H polytypes have been grown in that form). These detectors have not shown degradation after irradiation to 14 MeV neutrons up to $4 \times 10^{12}$–$10^{13}$ cm$^{-2}$ (Seshadri et al., 1999; Metzger et al., 2002), which is one order of magnitude higher than fluence limit for Si detectors.

Among wide bandgap semiconductors, diamond presents the best properties to be used for radiation detection under high temperature and high dose conditions (Brambilla et al., 2001; Willander et al., 2006). The limited availability of natural

**Table 1**
Activation reactions with threshold energy above 2.5 MeV (Knoll, 2010; Tsoulfanidis and Landsberger, 2011).

| Reaction | Threshold energy (MeV) | Half-life |
|---|---|---|
| $^{27}$Al(n,p)$^{27}$Mg | 3.8 | 9.46 min. |
| $^{56}$Fe(n,p)$^{56}$Mn | 4.9 | 2.56 h |
| $^{48}$Ti(n,p)$^{48}$Sc | 6.8 | 43.7 h |
| $^{63}$Cu(n,2n)$^{62}$Cu | 11.9 | 9.8 min. |

**Table 2**
Neutron induced reactions in silicon (Franceschini and Ruddy, 2011) .

| Reaction | Neutron energy threshold (MeV) |
|---|---|
| $^{28}$Si(n,n′)$^{28}$Si | 0 |
| $^{28}$Si(n,n′)$^{28*}$Si | 1.843 |
| $^{28}$Si(n,$\alpha$)$^{25}$Mg | 2.749 |
| $^{28}$Si(n,p)$^{28}$Al | 3.999 |