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JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Associazione EURATOM-ENEA sulla Fusione, C.R. Frascati, ENEA, C.P. 65, I-00044 Frascati (Roma) Italy
[2]Associazione EURATOM-Universit‡ di Roma “Tor Vergata” , Dipartimento di Ingegneria Meccanica, via del Politecnico 1, I-00133 Roma, Italy
[3]EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon OX14 3DB, UK
[4]ENEA, Physical Technologies and New Materials Dep., C.R. Frascati, C.P. 65, I-00044 Frascati (Roma) Italy
[5]Consorzio RFX-Associazione EURATOM-ENEA sulla fusione, Corso Stati Uniti 4, 35127 Padova, Italy
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ABSTRACT
This paper reports on the three new Single Crystal Diamond (SCD) detectors installed at JET for the 2008 campaigns. The yields of both total and 14-MeV neutrons produced during DD plasma pulses as well as the time dependent neutron emission have been measured.

The first detector, installed in the Vertical Port (Oct-1) of JET, is 200μm thick and is embedded in paraffin. It has a detection efficiency of about 2.9*E-05 counts/$n_* cm^2$ for the 14MeV neutrons. The second detector, located in Oct-1 Limb $^1/_2$, is 104μm thick and is covered by a thermally evaporated 3 ºm thick ^{6}LiF film in order to detect the total and the 14MeV neutrons. In addition, it is surrounded by a 2.5-cm-thick polyethylene shield to enhance its thermal neutron response. The third detector is mounted in the main horizontal port (Oct-6) and it is operated in an innovative way, that is with a single low capacitance super screened cable and the whole electronic chain is outside the JET Torus Hall. Furthermore it uses fast electronics, suitable to the fast diamond response pulse (<1ns). It is 75μm thick, covered by a 3μm thick ^{6}LiF film and surrounded by a 2.5cm-thick layer of polyethylene. All the detectors have been previously tested and qualified at the ENEA-Frascati Neutron Generator with 2.5MeV and 14.7MeV neutron beams.

After the description of their main features, the results of the measurements so far performed are reported showing a very good matching with other standard detectors, such as fission chambers and Si diodes, routinely used at JET.

1. INTRODUCTION
The field of neutron diagnostics for nuclear fusion plasmas is receiving more and more attention especially in view of the construction of the next fusion machine ITER [1], a project supported by seven international partners to be built at Cadarache (F). Among the many challenges the detection of the neutrons and gammas emitted by the ITER plasma represents one of the major issues, owing to their high fluencies. The working temperature of the detectors is another severe problem to deal with. For these main reasons some of the presently-used neutron detection techniques (e.g. Si and scintillation detectors) cannot be used and innovative neutron and radiation sensors are to be developed. Since many years diamond has proved to be one of the best detecting media. ENEA Frascati and Rome “Tor Vergata” University have been cooperating since many years to develop electronic grade artificial diamond films grown by Chemical Vapour Deposition (CVD) technique to be used as neutron detectors. These diamond detectors are characterised and tested at ENEA Frascati Neutron Generator (FNG) [2] and since 2003 [3] they are tested at JET during various experimental campaigns.

2. THE DETECTORS
Due to its many outstanding properties, diamond is well suitable to detect fast neutrons via the $^{12}C(n, \alpha_o)^9Be$ reaction [4] ($E^{th} > Q = 5.701$ MeV).

In the latest years high electronic grade Single Crystal Diamonds (SCDs) - grown by the microwave plasma Chemical Vapour Deposition (CVD) technique on a commercial High Pressure High Temperature Ib (HPHT) single crystal diamond - have been developed at Rome “Tor Vergata” University. These SCD films have such interesting spectroscopic performances that they have been proposed as novel detectors in future fusion machines and tests have started at JET since 2003. The detector fabrication is based on a commercial HPHT diamond as a substrate on which the SCD detector is grown. The detectors have a layered structure obtained by a two-step growing procedure [5,6]. In a first step a boron doped SCD layer (about 15μm thick) is grown. This is acting as backing contact. A second layer of intrinsic and high purity diamond (the active region) is thus grown; its thickness ranges from a few microns up to more than 200μm depending on the application. An electrical contact made of aluminium or other adequate metals is deposited on the top of the sensing diamond.

The capability to operate in a harsh neutron environment makes these innovative detectors promising candidates for future Tokamak machines. Up to now very relevant results have been obtained, such as 100% charge collection efficiency, high energy resolution (lower than 1%), good detection efficiency and the capability of detecting and discriminating both fast and thermal neutrons at the same time. The latter feature can be achieved through a suitable converting medium, a layer of LiF 95% enriched in ^{6}Li (Fig.1), which is deposited on the top electrode by the evaporation method. The SCD detectors have been tested both with a standard multi-peak alpha source (^{241}Am + ^{240}Pu + ^{244}Cm at energies E_{α} = 5.15MeV , 5.5MeV, 5.8MeV respectively) and with 14.7 MeV neutrons produced by FNG in order to find-out the optimal working conditions and the best performances at various parameters, such as High Voltage, pulse shaping time, discriminator threshold.

Finally the ^{6}LiF SCD counting efficiency and energy resolution have recently been obtained through numerical simulation [7] showing good agreement with experimental data.

3. MEASUREMENTS AT JET

In the latest years many measurements have been performed at JET with different kinds of Diamond detectors [8] getting interesting and promising results. In the present 2008 JET experimental campaigns three single crystal diamond detectors (here after labelled SCD-242, SCD-236 and SCD-234 respectively) are in operation; they have different features and characteristics and are arranged in different manners. The goal is to detect simultaneously both slow and 14 MeV neutrons, as well as to get the time dependent neutron emission during each single JET pulse. All the three detectors were installed at JET in November 2007 and they are in operation since the restart. JET is operating with D-D plasmas so the 14 MeV neutron emission is due to triton burn-up, accounting for about 1% of the total neutron rate. This is the main reasons for the poor counting statistics of the 14MeV neutrons.

SCD-236 is 200μm thick, has an Al contact (Φ = 4mm) and it is embedded in paraffin in order to enhance the response to 14MeV neutrons through the recoil protons since the scattering cross section is of the order of 1 barn. The goal is to detect both total and 14MeV neutrons. An absolute yield measurement performed at FNG has led to a value of y=2.9E-05 counts/n*cm^{2} with a threshold value put at 2.6V , corresponding to E_{α} = 4MeV, a cut-off for the recoil protons produced by D-D neutrons. The electronic chain consists of a modified ORTEC 142A pre-amplifier (located in the Torus Hall inside a shielding metal box) + Shaping Amplifier + Thresholds. The SCD-236 detector is located in Octant-1 Vertical Port of JET.

SCD-234 (^{6}LiF) is 104μm thick + 3 ºm ^{6}LiF (95% ^{6}Li enriched) layer, Al contact (Φ = 3mm) and it has a polyethylene shield (25mm thick) in order to enhance the thermal neutron response. In this case the goal is to detect mainly the total neutron emission and at high neutron yields also the 14 MeV neutron emission. Its electronic chain is the same as that reported above. The detector position is Octant-1 Limb Ω.

SCD-242 (^{6}LiF) is 75μm thick + 3μm ^{6}LiF (95% ^{6}Li enriched) layer, Al contact (Φ = 3mm) and it is devoted to operate with a fully different approach. Future fusion Tokamaks will produce huge neutron and gamma fluxes; while presently available SCD detectors can withstand such conditions so cannot their related electronics. An ideal working scheme is to put the diamond detector inside the radiation field and all the electronics far away from it using a special cable (low impedance, low attenuation, super-screened) and a Diamond Broad Band Amplifier (DBA). The DBA is suitable to boost the very fast electronic signal typical of diamond (tens of ps wide). However, as DBA does not allow spectrometry, this detector acts just as a neutron counter for total and time dependent neutron emission. The electronics, fully located outside the T.H., consists of a DBA-IV amplifier + a special single super-screened cable (about 100m long) + Bias Supply Unit. The detector is located in OCTANT-6, Main Horizontal Port and surrounded by a 25mm thick polyethylene box. The goal is to get both total and time dependent neutron emission.

The signals were acquired by means of the JET CODAS acquisition system.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Since all the three detectors used have not yet been absolutely calibrated as for the neutron yields, the results reported here are just comparisons with the standard detectors presently used at JET, that is ^{235}U fission chambers for total neutron emission and Si diodes for 14MeV neutrons. The behaviours of the three Diamond detectors during 2008 JET Restart have been examined. The measurements have considered more than 900 JET shots, each of them with an integrated neutron yield in the range $4.9E^{13} – 7.2E^{16}$.

In order to check the matching of each SCD with the fission chamber some statistical comparisons have been performed.

Figure 2 shows the correlation between each SCD and the FC for all the ≈900 shots examined: the correlation coefficient R^2 ranges from 0.980 (SCD236) through 0.998 (SCD234).

Figure 3 shows the correlation between the three diamond detectors and the Fission Chamber for the shots with the lowest total neutron yields, ranging from $4.9\ E^{13}$ to $1.\ E^{15}$. The same correlation coefficients are achieved at these low rates, thus showing the high linearity over the whole neutron yield range.

Another statistical analysis useful to check the matching between each SCD and the FC concerns the average relative yields <ε> of the formers vs. the latter, again for all the 900 shots, which have been examined; they range from <ε> =1.32E-12 (SCD236) through 2.01E-12 (SCD234) to <ε> = 6.70E-12 (SCD242), while the related values of the standard deviations range from 2.34% <ε> (SCD242) to ≈ 6% <ε> (SCD236). In Fig. 4 the Gaussian fit to experimental data for SCD242 gives a correlation value $R^2 = 0.971$. For all the three cases there are very low values of the skewnesses of the statistical distributions.

The SCD-234 has proven to be a good spectrometer as shown in Fig.5 that reports the energy spectrum as obtained over more than 800 pulses (summed). The highly resolved peaks at 2.07MeV (α) and 2.73MeV (T) of $^6Li(n_{th},\alpha)T$ reaction are clearly visible.

Further even some typical single JET shots have been analysed in detail to compare the above detectors. The relative detection efficiency of all the three Diamond detectors in comparison to the fission chamber have been calculated inside some typical single JET pulses. Figure 6 shows the Pulse No: 72231 (length 6.2s) as seen by FC, SCD-242, 234 and 236. The data are normalised in order to allow a suitable comparison. Statistical analysis performed inside each one of some selected single shots have given results in accordance with those reported above.

CONCLUSIONS AND FUTURE DEVELOPMENTS

The fabrication of highly reliable single crystal diamonds as neutron detectors has proven to be feasible almost on a routine basis. These detectors have shown to match the standard fission chambers in use at JET in all the conditions presently encountered and over a wide neutron yield range, so going along this way is a must. Nonetheless many problems remain to be solved and items to be examined, so some future developments have to be considered.

As already said, in order to withstand the very high neutron and gamma fluxes foreseen in future Tokamak machines, special ultra-fast electronics, more apt to the diamond ultra-fast pulses, and special cables (low impedance, low attenuation, super-screened) are to be qualified, so as to put the diamond detector inside the field and all the electronics far away. At present time new and special-designed ultra-fast pre-amplifiers (UFP) and related cables are under tests at FNG. Other investigation areas, necessary to get a reliable detector to be used in future plasma machines, are the optimization of the fabrication process with special attention to reproducibility aspects of the neutron detection properties, the radiation hardness tests and the measurement of the detection absolute efficiency versus neutron energy. Response function measurements are necessary for spectroscopy analysis. Further upgrades will be the improvement of the detector features with a special attention to the energy resolution and to higher sensitive volume in order to increase the detector's sensitivity and efficiency as well as the counting statistics; the studies on the effects of different ^6Li films thicknesses and finally the tests under high neutron fluxes to check radiation hardness. The aim is to get final prototypes for standard use with neutrons and in fusion facilities like ITER in the next years.

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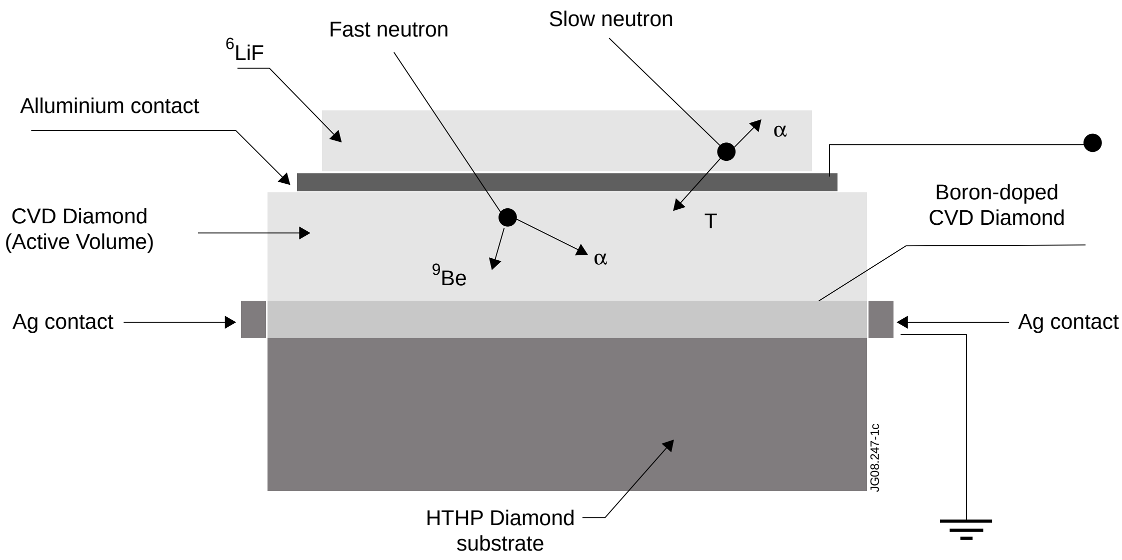

Figure 1: The multi-layered structure of the SCD detectors.

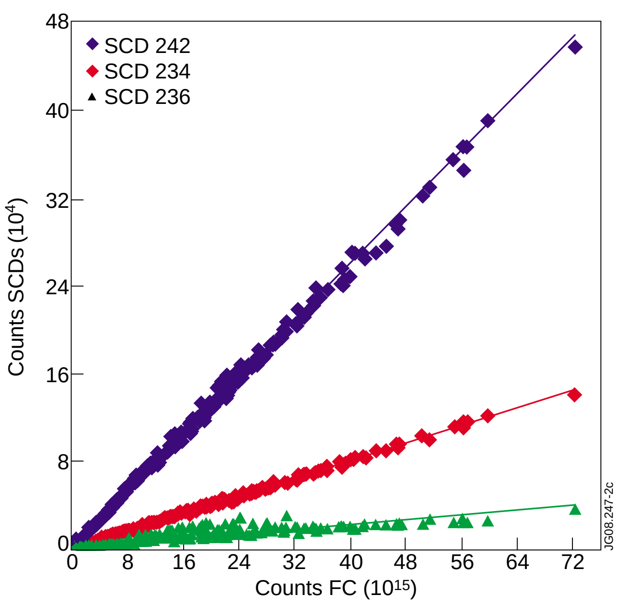

Figure 2: Correlation between the three diamond detectors and the FC for the 900 JET shots examined.

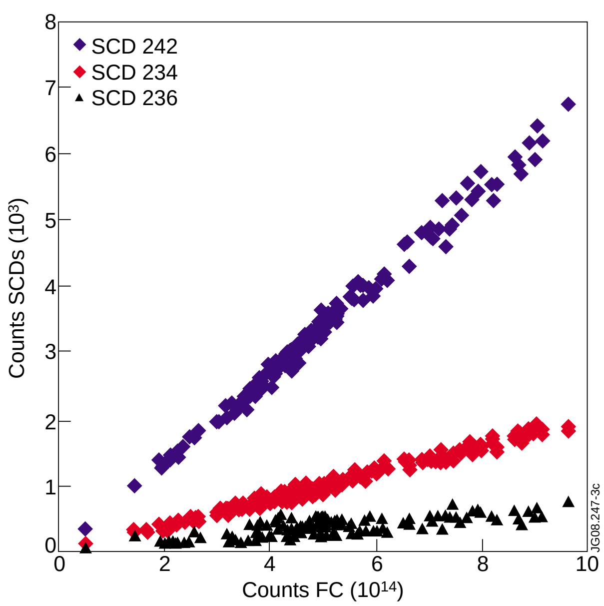

Figure 3 : Correlation between the three diamond detectors and the FC for the shots with low total neutron yields (< 1. E15).

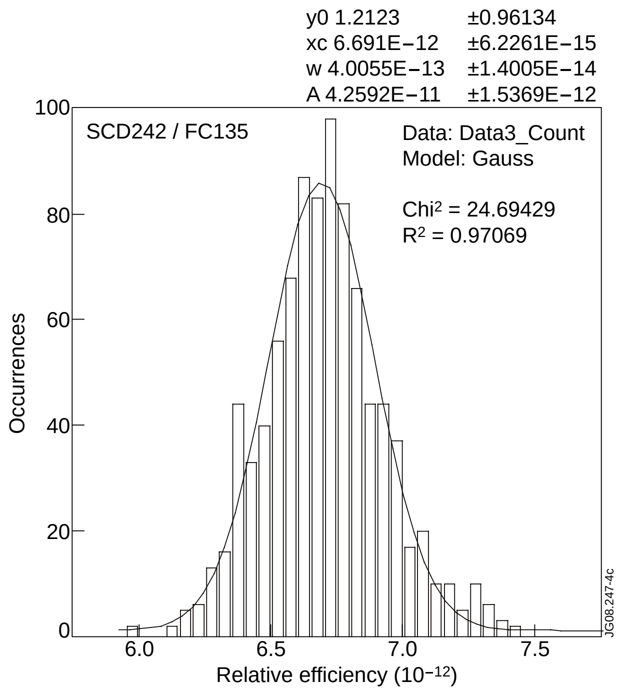

Figure 4 : Statistical distribution of the relative efficiency (SCD242 / FC135) for all the 900 JET shots .

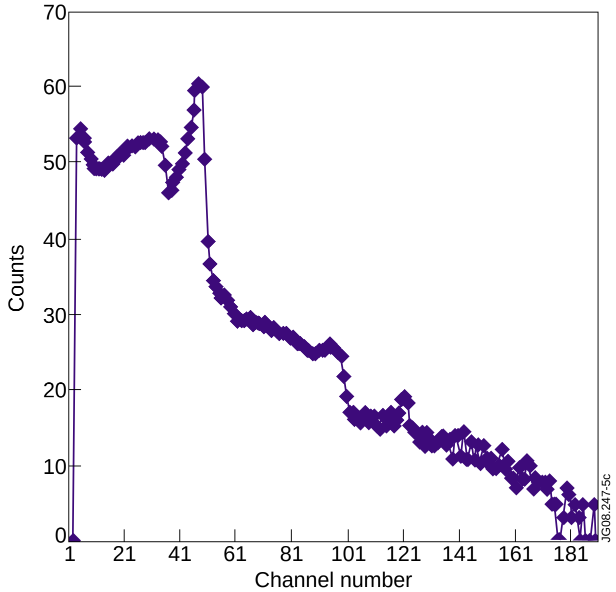

Figure 5: Sum of more than 800 JET spectra (total neutrons) as measured by SCD 234.

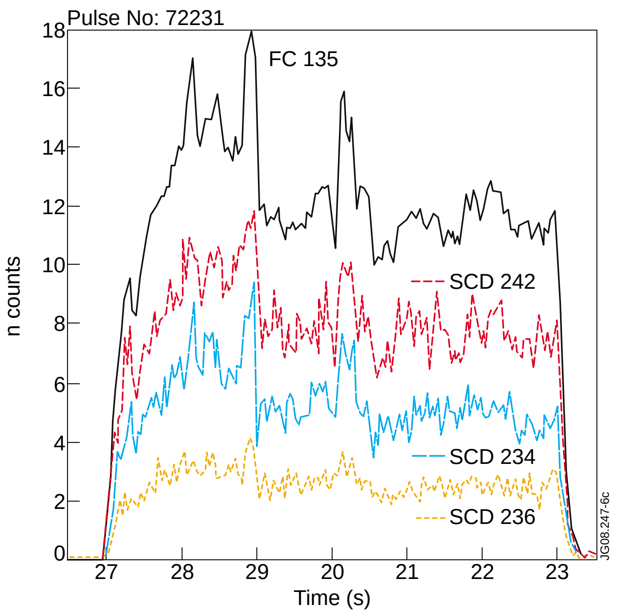

Figure 6: A typical JET Pulse No: (72331) showing the matching between the FC and the three SCD detectors (normalised counts). Pulse duration 6.2s; neutron yield = 1.109 E16.