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M. Angelone, D. Lattanzi, M. Pillon, M. Marinelli, E. Milani, A. Tucciarone,
G. Verona-Rinati, S. Popovichev, R.M. Montereali, M.A. Vincenti, A.Murari
and JET EFDA contributors

Development of Single Crystal Diamond Neutron Detectors and Test on the JET Tokamak

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

[1]Associazione EURATOM-ENEA sulla Fusione, C.R. Frascati, C.P. 65, I-00044 Frascati (Roma) Italy
[2]Associazione EURATOM -Università di Roma "Tor Vergata", Dipartimento di Ingegneria Meccanica, Via del Politecnico 1, I-00133 Roma, Italy
[3]EURATOM-UKAEA Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, 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.
During the 2005-2007 JET experimental campaigns a Single Crystal Diamond detector (SCD) covered with a 2μm thick LiF film 95% enriched in ^{6}Li, was installed at JET and operated continuously during the whole experimental campaign with the goal to measure both the total and the time dependent neutron emission from plasmas. After reviewing the history of diamond as neutron detector for tokamak application, this paper reports on the experimental measurements performed during that time window. The obtained results are compared with those obtained with detectors routinely working at JET (fission chambers and silicon diodes). In particular it was demonstrated that using a SCD detector covered with a ^{6}LiF film it has been possible to discriminate between the total and the 14MeV neutrons coming from triton burn-up. This allowed, for the first time using a single detector, the contemporary measurement of the total and 14MeV neutron yields as well as their time dependency with very good reliability and stability.

1. INTRODUCTION

The fusion community is presently involved in the construction of the International Tokamak Experimental Reactor (ITER) [1]. This project is supported by seven partners (EU, USA, RF, Japan, China, South Korea and India) and the tokamak is going to be built in France (at Cadarache). The ITER project is very challenging and many are the scientific and technological problems to be faced and solved. Among them, the detection of neutrons emitted from ITER plasmas represents a challenge due to the expected large neutron and gamma fluence. Some of the presently used techniques, for example at JET (e.g. silicon and scintillators detectors), cannot be used or will suffer serious radiation damage problems. Another problem to be considered for the proper functioning of the detector is the working temperature which in ITER is well above the ambient temperature. The development of neutron and radiation sensors capable to withstand ITER working conditions is one of the key issues of fusion neutronic activities. Since many years several attempts were made to use both natural and artificial diamond as detecting medium. In principle, all kind of radiation (from charge particles to UV and neutrons) are detectable by diamond. Many application have been proposed and tested, they span from fundamental and high energy physics to dosimetry, from UV and X and gamma-rays to neutrons. Just as an example see [2, 3, 4, 5].

The choice of diamond as detecting material is related to the many outstanding properties of this material [6], such as radiation hardness [7], low sensitivity to gamma rays, fast response and high energy resolution. Due to these particular properties and its very fast response it is considered as one of most promising detecting materials [8] despite the many problems encountered in its production, among them the difficulty to produce films with standard and reproducible properties. This problem is intrinsically due to the used CVD technique which is based upon plasma deposition. The future of CVD diamonds is the production of electronic grade single crystals which up to now has been reported by a few groups [9, 10, 11, 12]. A single crystal has 100% collection efficiency, energy resolution comparable to that of silicon detectors (values up to 0.3% were reported [13]), no

polarization effects and do not need priming, i.e. irradiation with electromagnetic or beta radiation prior to the use so as to passivate internal traps.

In the field of neutron detectors ENEA C.R. Frascati and Rome "Tor Vergata" University are cooperating since many years to develop electronic grade artificial diamond films grown by Chemical Vapour Deposition (CVD) and to be used as neutron detectors in ITER. A systematic study of the diamond properties and behaviour is being conducted.

The development of CVD diamond detectors by our group started with the production of polycrystalline films at the end of the 1990's and after several attempts led to the production of monocrystalline films which promise to fulfil the requests for ITER neutron detectors. Since many fundamental improvements of diamond films have so far been obtained, it is perhaps time to briefly review the story of diamond neutron detectors pursued by our group in order to set the achieved points and to discuss what needs to be further investigated. In the next section the development of CVD diamond neutron detectors is shortly reviewed before discussing their construction (sect. 3) and the result of their test at JET tokamak during the 2005-2007 experimental campaigns (Sect.4). Foreseen developments are also highlighted in section 4.

2. A SHORT STORY OF CVD DIAMOND NEUTRON DETECTORS

The development of nuclear detectors based upon artificial diamond films started about ten years ago with the first radiation detectors produced with the goal to study the physical properties of the CVD films. The basic idea was to use charged particles as probes. Since efficient particle detectors require high drift lengths of the carriers produced by the ionizing radiation, the presence of defects severely limits the performances of the device. From the study of the response of artificial diamond detectors irradiated with charged particles (alphas and betas) it is thus possible to get information about the different kind of defects formed inside the film and affecting the detector response. The analysis of the response of CVD diamond-based detectors was used to extract both qualitative and quantitative information on the properties of the various defects limiting the free movement of electrons and holes carriers produced by the radiation in the detector (e.g. type of defects, activation energy, geometrical distribution etc.). In the early days of our work only very simple sandwiched detectors were realized made of CVD polycrystalline film with gold or aluminium contacts deposited by evaporation processes. Despite the simplicity of the system many and fundamental improvements were obtained by studying the response of these devices when irradiated with 5.5MeV alphas produced by ^{241}Am source and/or betas from ^{90}Sr. The results concerning these studies are reported in [14] and references therein. Here it is stressed the importance that the study of the priming procedure and the identification of defects had on the development and improvement of polycrystalline CVD detectors performances.

Owing to the well known (n, α) reactions of carbon with fast neutrons that led in the past to use natural diamonds as fast neutron detectors [2], it was almost natural to extend the study of these devices to irradiation with 14MeV neutrons produced by the 14MeV Frascati Neutron Generator

(FNG) [15]. The first positive test with 14MeV neutrons dates on fall 2002. A 500μm thick polycrystalline film sandwiched with gold contacts of 2 mm diameter was irradiated at FNG for about 15000 sec showing good stability and negligible polarization effects [16].

The first successful application of a polycrystalline CVD diamond as 14MeV neutron detector in a tokamak dates on November 2003 during the JET Trace Tritium Experiment (TTE) and represents a milestone for artificial diamond films studies [17]. In this first attempt 14MeV neutrons emitted from JET operating with DT plasmas were detected. Total and time dependent 14MeV neutron emission during each shot were measured with the diamond detector and the results correlated very well with the same data recorded by the conventional silicon diodes. Since this date many relevant improvements were obtained, among them the production of Single Crystal Diamond (SCD) with excellent spectrometric performance (energy resolution lower than 1%) and good stability [18] which did not require the priming procedure to work properly.

A further step was represented by the fabrication of diamond layered detectors with a boron doped conductive layer [19] grown on the substrate (Fig.1) prior to intrinsic diamond layer (active region) deposition. The layered SCD detectors proved to be both well reproducible in the detector performances (e.g. resolution within 1-2% for all the produced samples) and unaffected by polarization effects as well. This layered structure enabled to realize diamond detectors without the need to remove the growing substrate that usually is made of a commercial low grade HTHP single crystal diamond and which is not suitable as a detector medium. The substrate removal procedure is expensive and dangerous since there is the possibility to break or damage the high quality diamond film.

Last, but not least, the production of layered SCD detectors covered with Lithium Fluoride (LiF) films 95% enriched in ^{6}Li was achieved soon after [19]. The latter detectors, through the ^{6}Li(n, α)T reaction in ^{6}Li and the direct detection of α, T and fast neutrons in the diamond bulk, allow for contemporary detection of thermal and 14MeV neutrons [19]. It was also demonstrated that these detectors can withstand high neutron fluxes [20], up to 2E+9 ncm^{-2} sec^{-1}. Work is in progress to demonstrate that this detector can be used as an active tritium production monitor as well.

To conclude this short review about diamond neutron detectors, it ought to be mentioned that SCD films are also applied for X-ray and UV detection [21] and this seems to be very promising for ITER.

The continuous improvement of the diamond film quality and thus of the detector performances has been possible tanks to their test at JET under very challenging tokamak working conditions. In the recent 2005-2007 experimental campaigns two artificial diamonds detectors both covered with ^{6}LiF films were installed at JET. The first detector was of polycrystalline type with traditional sandwiched structure while the second was a SCD diamond with layered structure. Both detectors operated continuously during the whole experimental campaigns. Since polycrystalline films are no longer of interest to us as neutron detectors and, also, accounting for the fact that results obtained with detectors based on them were already published [22], this paper reports about the results

obtained for the Single Crystal Diamond (SCD) detector during the whole JET experimental 2005-2007 campaigns and addresses some future work.

3. EXPERIMENTAL

3.1 DETECTOR FABRICATION

A layered SCD detector was grown on top of a commercial high pressure high temperature HPHT Ib single crystal diamond used as growing substrate. The substrate was 3mm × 4mm in surface and about 400μm thick. The layered detector was produced by means of a two steps CVD homoepitaxial process. In the first step a boron-doped (conducting) diamond buffer layer of about 15μm thickness and resistivity of about 5Ω is deposited on top of the HPHT substrate. In the second step, performed in a separated CVD reactor to avoid unwanted boron contamination, an intrinsic diamond film deposition is performed. This deposition thickness is in the range 5-200μm depending upon the detector's use. In our case, since the main goal was to test the performances of new layered detectors, the bulk of the intrinsic deposit was 35μm. The backing contact was thus realized by using the B-doped layer while on the growing surface a 2.5mm diameter and 100nm thick Al contact was thermally evaporated. This multilayered structure (Fig.1) allows separating the response of the high quality intrinsic bulk diamond from that originated inside the thick HPHT diamond substrate, if any. The electrical signal to be processed arises only inside the high quality CVD layer avoiding the need for mechanical removal of the HPHT substrate. Usually at this stage a test of the film quality is performed by a multi-peaks alpha source (^{241}Am+^{240}Pu+^{244}Cm) whose energy ranges in between 5.5 and 5.8MeV. This test allows verifying: a) stability during long lasting irradiations to check whether or not the detectors are affected by polarization effects; b) charge collection efficiency, c) the energy resolution (Fig.2).

Up to now this test was very positive since all the grown layered detectors (almost one hundred) shown high time stability, 100% efficiency and resolution lower than 2% regardless of detector thickness. The best detector, with an intrinsic CVD layer of 100μm, showed a resolution as low as 0.5%. The above data demonstrate that production of CVD films with homogeneous response is no longer a dream.

Last, but not least, a 2μm thick ^{6}LiF film was directly grown on top of the Al contact by thermal evaporation [23] at ambient temperature and at vacuum pressure lower than 5×10^{-6} mbar. The deposition was performed at the Solid State Lasers Laboratory of ENEA C.R. Frascati. ^{6}LiF tablets (3mm × 3mm × 0.9mm) enriched to 95.62% in ^{6}Li were used as starting material for the deposit. The tablets were heated at about 800^{o}C in a tantalum crucible placed below the CVD substrate. The sample was clamped on a rotating holder. The evaporation rate was fixed to a value of 1nm/s and controlled by an INFICON quartz oscillator. The thickness of the ^{6}LiF film was also directly measured by means of a Tencor P10 profilometer on ^{6}LiF films grown on a glass and silicon substrates during the same evaporation run. After production, the SCD detector was tested again with 5.5MeV alpha particles from 241Am source in order to check its stability and collection efficiency.

The ^{6}LiF layer deposited on top of the SCD detector acts as converting medium by taking advantage of the well known $^{6}Li + n \rightarrow {}^{3}H + {}^{4}He$ nuclear reaction, which converts slow energy neutrons into two charge particles (^{3}H with energy of 2.73MeV and ^{4}He with energy of 2.06MeV, respectively) which are emitted in opposite directions and directly absorbed into the high purity diamond layer producing two peaks which are clearly resolved by the detector. At the same time diamond is sensitive to high energy neutrons which produce the (n, α) reactions in Carbon [2]. In particular the so called (n, α) reaction with a threshold at about 5.7MeV produces a well isolated peak which is easily resolved by the detector. The performances of the detector can be easily described by looking at Fig.3, where a typical Pulse Height Spectrum (PHS) recorded at FNG by means of MCA is reported. The detector was inside a 5cm thick polyethylene phantom in order to slow down some of the 14MeV neutrons produced by FNG and to enhance the interaction with ^{6}Li. The spectrometric performances are clearly pointed out by the wide separation among the various peaks.

It is important to point out that, due to the adopted layered structure, only (n, α) reactions produced inside the high quality SCD film are recorded in the spectrum while those produced, if any, in the HTHP substrate are grounded by the boron layer. The SCD detector with ^{6}LiF layer thus allows for the contemporary detection of slow energy and 14MeV neutrons. In the following it will be labelled LiDia detector (Lithium Diamond detector).

The contemporary detection of slow energy and 14MeV neutrons is particularly relevant to fusion neutronics since in DD and/or DT plasmas both 2.5MeV and 14MeV neutrons are produced. Presently they are measured with different detectors (e.g. fission chambers and silicon diodes).

It ought to be stressed that when operating with DD plasmas the 14MeV neutrons are only produced by the triton burn-up i.e. the tritons slowing-down in the plasma before reacting with Deuterium. The 14MeV neutron emission is then delayed by about 300−400ms with respect to the 2.5MeV neutrons produced by DD reaction. This delay time is the typical slow down time of tritons born with about 1MeV energy in the JET tokamak. Furthermore, the intensity of the delayed neutron emission is about 1% of that due to DD neutrons. For a detector to work properly one must expect it to be able to separate the two components also from a temporal point of view.

3.2 DETECTOR INSTALLATION AT JET

The LiDia detector was installed at JET in June 2006 inside the Torus Hall near the main vertical port in Octant 1, at about 4m apart from the plasma centre. Its data acquisition began from JET Pulse No: 66654. The detector worked with a bias of +3 V/μm for the whole duration of the JET experimental campaigns, which ended in April 2007.

The LiDia detector was directly connected to a charge preamplifier ORTEC Mod. 142A and both detector and preamplifier were located inside a metallic box (Fig.4). The connection to shaping amplifier and threshold discriminators, located outside the torus hall in the diagnostic area, was obtained by means of long 50Ω coaxial cables (about 100m). The shaping amplifier was working with shaping time of 1μsec. The logic signals produced by the discriminators were acquired in

terms of count rate versus time by the JET acquisition system CODAS. Two discrimination thresholds were set. The lowest (THR-1) was able to detect all the signals produced by the neutrons regardless of their energy (total neutron yield), the second threshold (THR-2) was set well above the first one in order to detect only the signals due to 14 MeV neutrons and produced by the (n, α) reaction. To set this threshold the standard three-peaks alpha source was used to calibrate the voltage output signal versus radiation energy.

4. RESULTS AND DISCUSSION

Since the LiDia detector was not absolutely calibrated, the results reported in the following are compared with respect to the standard detectors in use at JET, that are the ^{235}U fission chambers (KN1 diagnostic) for total neutron emission and silicon diodes (KM7 diagnostic) for 14MeV neutron emission. Both integral and time dependent emission data will be considered.

It ought to be stressed that during the whole experimental campaign JET operated with DD plasmas so the 14MeV emission was due to triton burn-up, that is about 1% of the total neutron emission. This, together with the low reaction cross section (about 70mb) and the very small detector volume is the reason for the poor counting statistics obtained for 14MeV neutrons with the SCD detector.

In Fig.5 the correlation between LiDia detector and the KN1 diagnostic versus the total neutron yield is reported. Data refer to more than 800 JET pulses and cover the whole 2005-2007 experimental campaigns during which some high current and high neutron yields pulses were produced. As can be seen from Fig.5 the correlation is very strong both at the lowest and highest neutron yields.

In Fig.6 the ratio between LiDia and KN1 counts is plotted versus the JET pulse number, e.g. as function of time. Again an excellent stability is observed and most of the data lie within one standard deviation which is lower than -3%. A further proof of the capability of the LiDia detector to properly operate in a tokamak is given in Fig.7, where the distribution function (histogram) of the above mentioned ratio is plotted. It is fitted by a Gaussian function demonstrating that the observed variations are due to counting statistics.

Figures 8 and 9 report just an example of how the LiDia detector can reproduce the time dependent total neutron emission by comparison with KN1 data. The reported figures point out that even sudden variation in the neutron production are perfectly reproduced by the SCD detector (Fig.9). It ought to be stressed that this comparison was made for all JET pulses over the whole experimental campaign and the results again confirmed the capability of the SCD diamond detector to properly work. When considering Fig.9 another point to be considered is that fission chambers at JET work in current mode while our detector operates in pulse mode. Furthermore, while the fission chambers are embedded in a thick polyethylene shield to slow down neutrons, our detector was naked so there was an huge difference in the counting efficiency. Despite this the results are very good.

The most important feature of the LiDia detector is the already mentioned capability to contemporary detect total and 14MeV neutron emission. This is proven by Fig.10, where both neutron emissions as recorded by LiDia, KN1 (for the total emission) and Silicon diode (for 14MeV neutrons emission)

are compared for Pulse No's: 68934 and 68935. The sum of at least two pulses is necessary for 14MeV neutrons only due to the low counting statistics. It ought to be stressed that since JET operated in DD and the volume of the SCD was very small the comparison is meaningful only for the highest neutron yields. Despite this limitation the analysis clearly points out that the time dependent 14MeV neutron emission is well reproduced by the LiDia detector. Also the time delay due to triton slow down is well reproduced as it is evidenced by comparing with silicon diode output.

Last, but not least, also the total 14 MeV neutron yield was recorded but only for pulses showing acceptable statistics (e.g. fusion yield > 5.0E+16). The correlation between LiDia and one of the silicon diodes operating at JET is reported in Fig. 11. Despite the very large statistical errors for SCD (never lower than −10%) the correlation is good, within the uncertainties.

The results so far obtained at JET clearly indicate that SCD detectors are suitable to operate in a tokamak environment. Despite their small volume a SCD diamond detector covered with LiF film 95% enriched in ^{6}Li is suitable to contemporary detect and discriminate total and 14 MeV neutron emission. One more task is to demonstrate the spectrometric performances of SCD detectors. This is already feasible when working with a monochromatic beam of 14 MeV neutrons, but needs dedicated experiments using DT plasma for a full demonstration in a tokamak environment.

However, the electronic chain adopted at JET, consisting of detector plus charge preamplifier located in the same box inside the torus hall, cannot be proposed for ITER where neutron and gamma fluences are orders of magnitude higher than in JET and these fluences cannot be withstood by charge preamplifier even considering the very high counting rate. To overcome these problems, a new and more advanced configuration is under study by the authors. The idea is to locate the whole electronics far away from the detector. One problem arises from the fact that the signal produced by the diamond is very fast, of the order of tens of pico-seconds. This requires low capacitance, superscreened coaxial cables with low attenuation per unit length. Instead of charge preamplifier, a fast broad band (GHz) preamplifier will be used at the cable end to boost the signal prior its sending to the threshold discriminator and data acquisition. Such new scheme is going to be tested at JET during next experimental campaigns in 2008. Preliminary tests performed at FNG are encouraging.

As far as the detector volume is concerned, SCD detectors as thick as 200μm are now available. Indeed this is a problem in JET but it will be of less importance in ITER. In any case, apart from a higher thickness, another studied solution is the increase of the active surface by connecting a matrix of at least four SCD detectors. Prototypes of such a detector were already produced and successfully tested.

CONCLUSIONS

Single crystal diamond detectors with excellent detection properties are fabricated at Rome "Tor Vergata" University and used as neutron monitors at JET in collaboration with ENEA Frascati and JET team. The SCD detector installed during the 2005-2007 experimental campaigns demonstrated to be stable and reliable. The use of a SCD detector covered with a LiF layer enriched in ^{6}Li

allowed the contemporary detection of the total and 14MeV neutron emissions from JET plasmas. For both quantities, the time dependent neutron emission was also recorded. This result was achieved making use, for the first time in a tokamak, of a single detector.

The excellent results so far obtained call for further work, with emphasis on development of fast electronics and neutron spectrometry.

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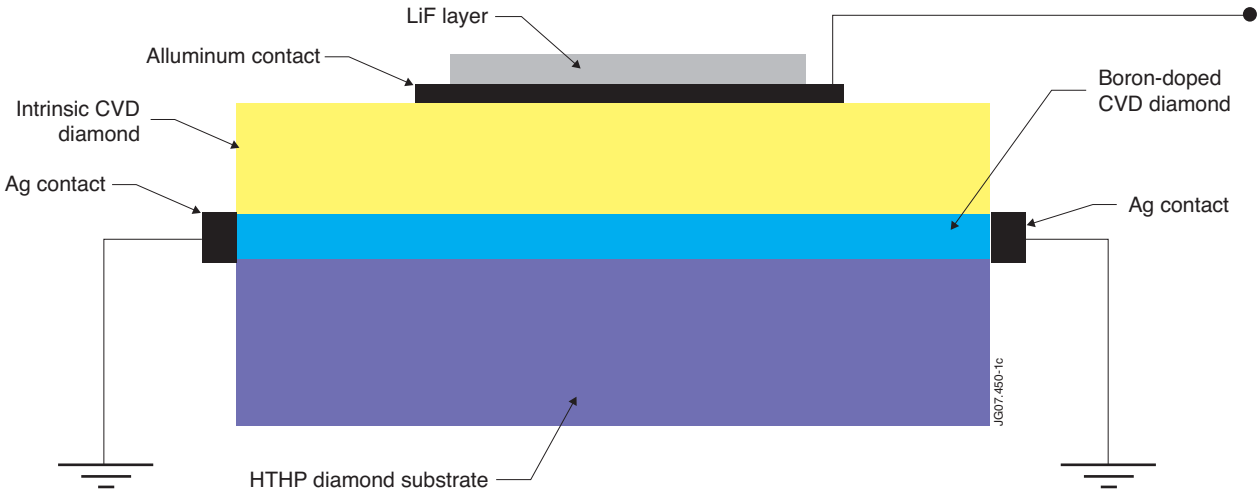

Figure 1: Scheme of the detector configuration, from bottom to top : HPHT substrate, boron doped layer, high purity SCD layer, Al contact, ^{6}LiF layer.

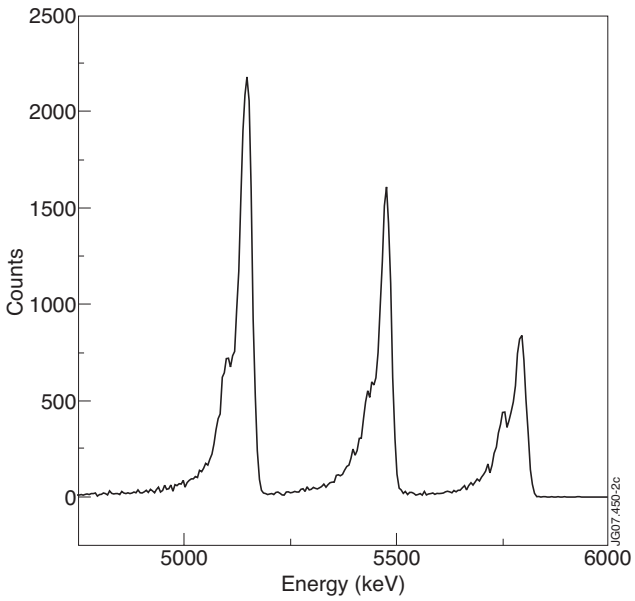

Figure 2: ^{241}Am+^{240}Pu+^{244}Cm alpha source: PHA spectrum recorded before ^{6}LiF film deposition with a layered SCD detector.

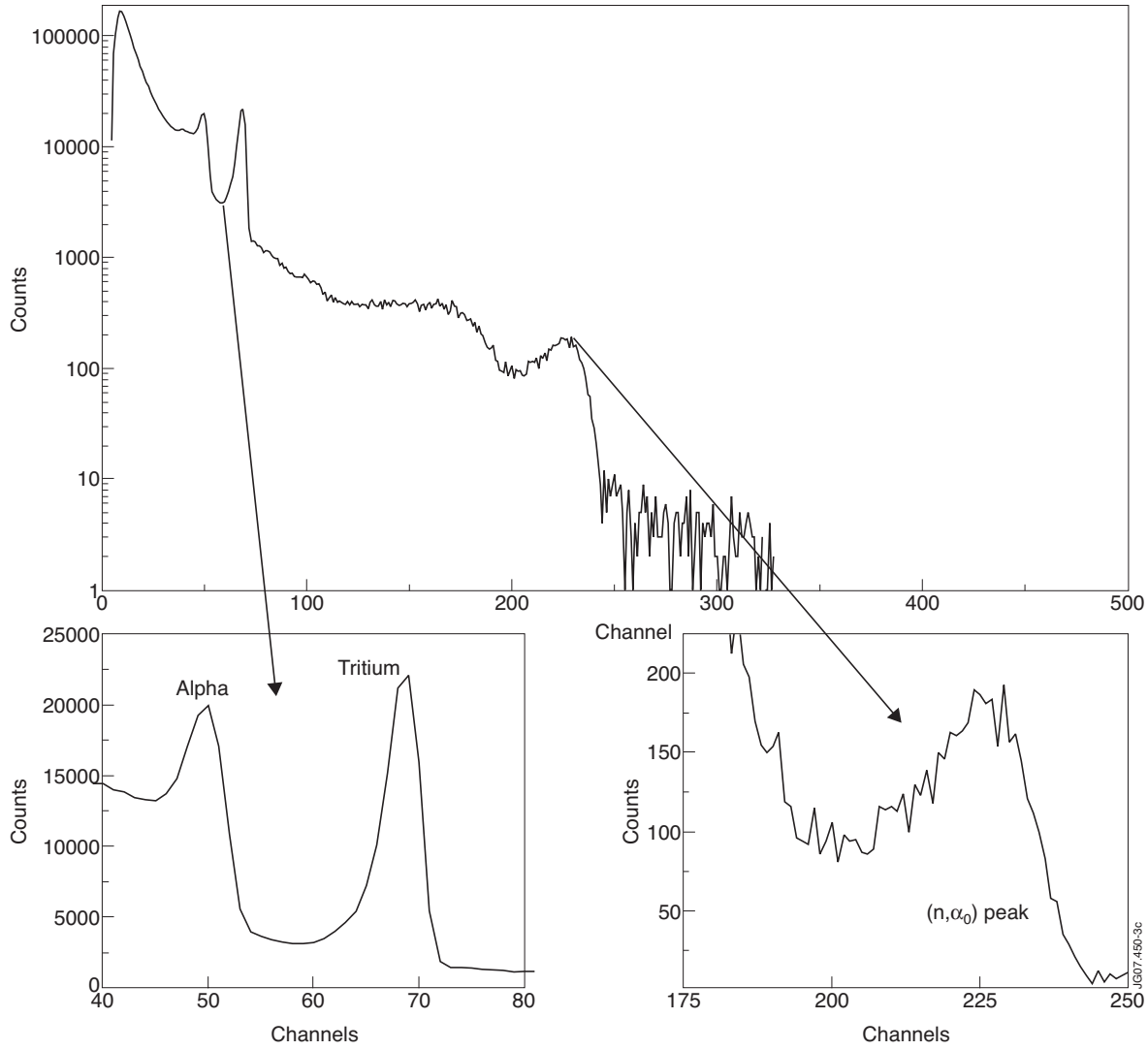

Figure 3: Typical PHS spectrum for a SCD covered with a ^{6}LiF layer containing both α, T and (n, α) peaks as recorded at FNG.

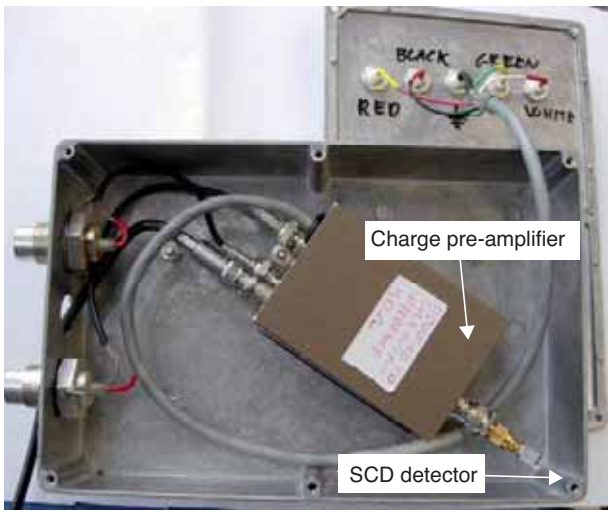

Figure 4 : Picture showing the SCD and the charge preamplifier inside the shielding metallic box used at JET.

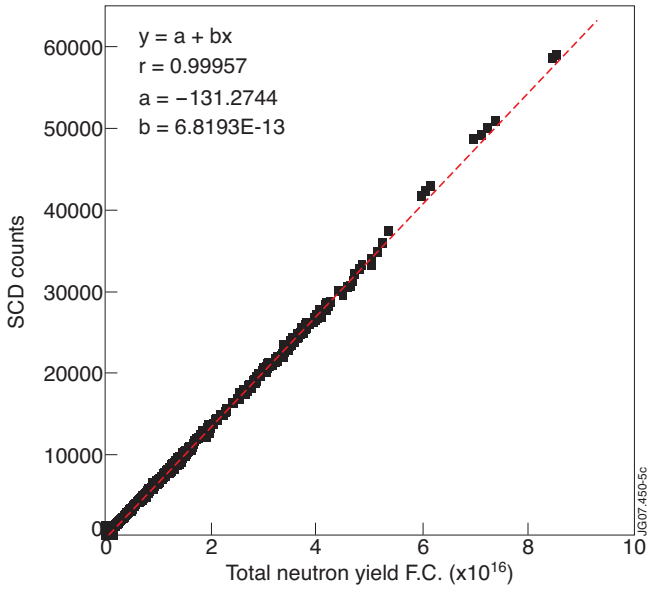

Figure 5 : Correlation between total counts recorded by LiDia detector and Fission chamber (KN3) total neutron yield. Data fitted by a linear regression. r is the correlation coefficient.

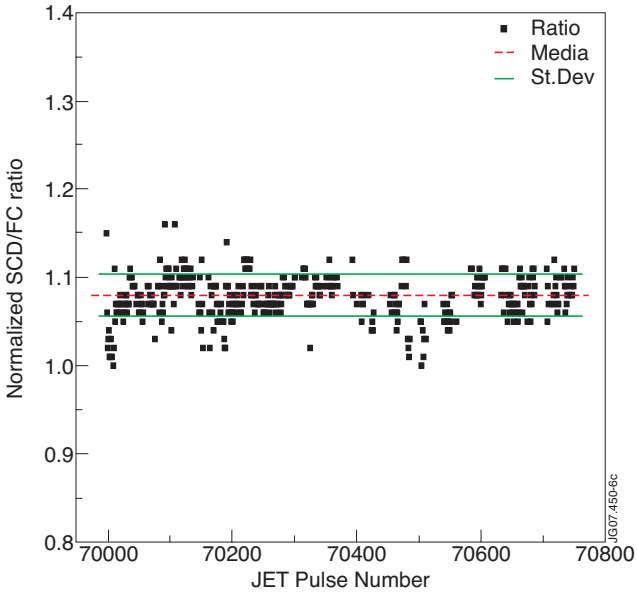

Figure 6 : Normalized Ratio between SCD total counts and Fission Chamber total neutron yield as function of JET Pulse No: (e.g. time).

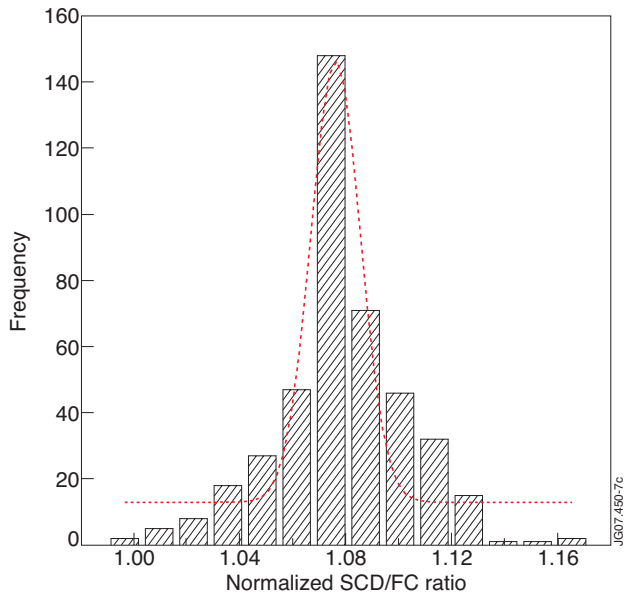

Figure 7 : Distribution of the normalized ratio for data reported in Fig. 5. The Gaussian fit is also shown.

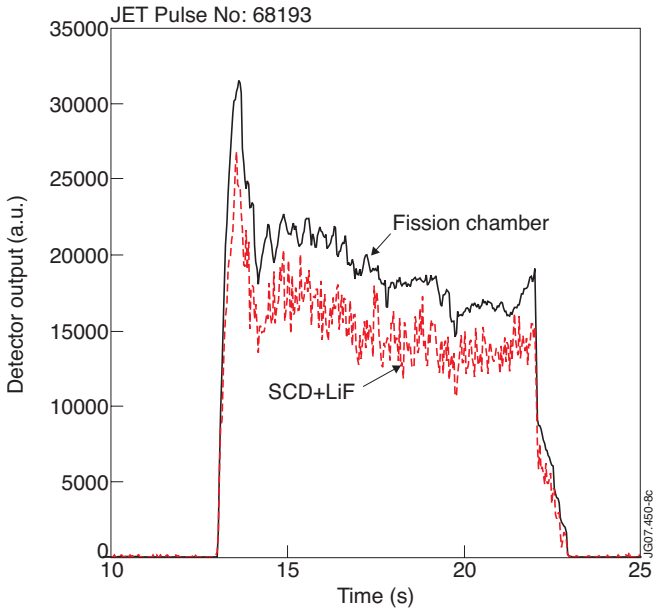

Figure 8 : Normalized time dependent neutron emission for Pulse No: 68193 recorded by JET fission chamber and LiDia detector.

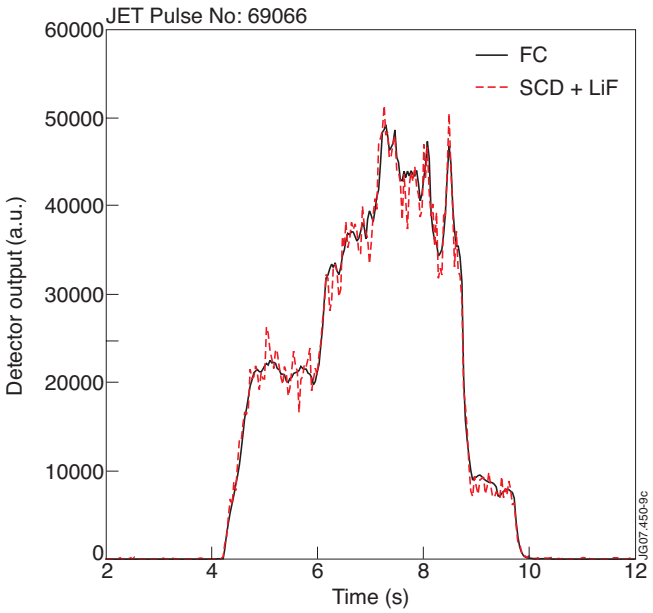

Figure 9 : Normalized time dependent neutron emission for Pulse No: 69066 recorded by JET fission chambers and LiDia detector.

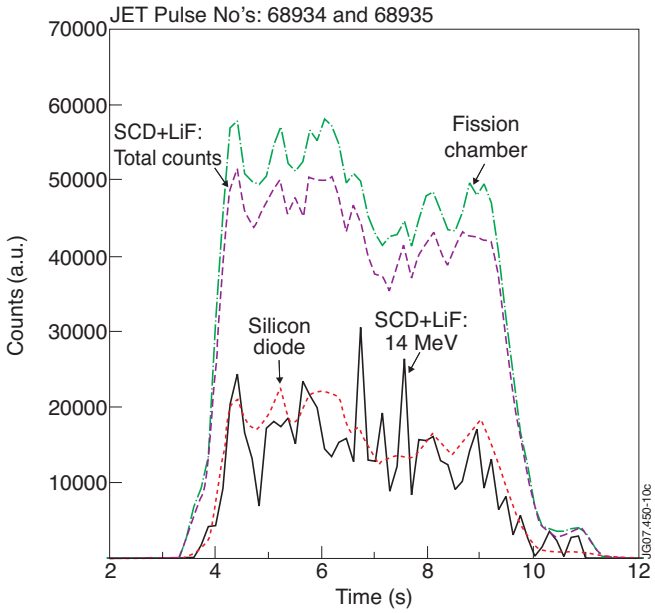

Figure 10 : Normalized time dependent Total and 14 MeV neutron emission for Pulse No: 68934+68935 recorded by JET fission chambers, JET silicon diode and LiDia detector.

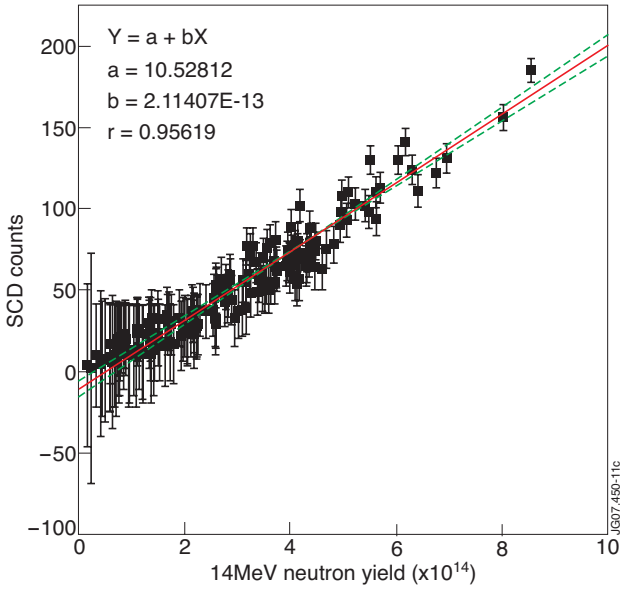

Figure 11 : Correlation between SCD counts (THR-2) and 14 MeV neutron yields measured by silicon diode.