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## ABSTRACT

Artificial diamond neutron detectors recently proved to be interesting devices to measure the neutron production on large experimental fusion machines. Diamond detectors are very promising detectors to be used in fusion environment due to their radiation hardness, low sensitivity to gamma rays, fast response and high energy resolution. High quality “electronic grade” diamond films are produced through microwave Chemical Vapour Deposition (CVD) technique. Two CVD diamond detectors have been installed and operated at Joint European Torus (JET), Culham Science Centre, UK. One of these detectors was a polycrystalline CVD diamond film, about  $12\text{mm}^2$  area and  $30\mu\text{m}$  thickness while the second was a monocrystalline film of about  $5\text{mm}^2$  area and  $20\mu\text{m}$  thick. Both diamonds were covered with  $2\mu\text{m}$  of Lithium Fluoride (LiF) 95% enriched in  $^6\text{Li}$ . The LiF layer works as a neutron-to-charged particle converter so these detectors can measure thermalized neutrons. Their output signals were compared to JET total neutron yield monitors (KN1 diagnostic) realized with a set of Uranium fission chambers. Despite their small active volumes the ~~our~~ diamond detectors were able to measure total neutron yields with good reliability and stability during the recent JET experimental campaign of 2006.

## INTRODUCTION

In the recent JET Trace Tritium Experiment (TTE-2003) a CVD polycrystalline diamond detector was used to measure the time dependent 14MeV neutron production [1]. Previously and also in the TTE campaign, natural diamond detectors have been used as 14MeV neutron detectors as well as neutron spectrometers. The advantage of CVD diamonds in comparison with the natural ones is their low costs and ~~in~~ the possibility to produce detectors with desired surfaces and thickness. In the recent literature striking improvements on the electronic quality and on the detection capability of single crystal synthetic diamonds grown by chemical vapour deposition (CVD) have been reported both by commercial providers [2,3,4] and by University research groups [5,6]. High detection efficiency and good energy resolution were reported, for example, when testing such materials as nuclear detectors for a particles and fast neutrons [4,5,6]. However, the device reproducibility is extremely poor at present and still only very few “spotty” results were reported in the literature. Even more important, the tested devices often suffer from some memory effects such as “priming” (pumping) [7,8,9] and polarization effects [4,5]. In particular, a gradual worsening of the detector response is noticed during long lasting irradiations with high energy nuclear particles and a recovery treatment is to be periodically performed, even after a few hours or less of operation, in order to maintain the required spectroscopic performance.

For many years high quality, initially polycrystalline and recently monocrystalline, CVD diamond films have been produced at the Faculty of Engineering, Rome “Tor Vergata” University and since 1998 collaboration with ENEA Frascati has been established to study the applications of CVD diamond films as radiation detectors. The problems of reproducibility and memory effects have been practically overcome especially in the monocrystalline films with the technique of the Boron-

doped diamond buffer layer adopted by Rome “Tor Vergata” University [10].

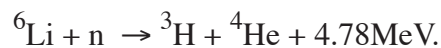
## **CHARACTERISTICS OF THE CVD NEUTRON DIAMOND DETECTORS INSTALLED AT JET**

Two CVD diamond films are currently ~~used~~ installed and operating at JET: one is a polycrystalline one, about 12 mm<sup>2</sup> area and 30µm thick, while the second is a monocrystalline of about 5 mm<sup>2</sup> area and 20µm thickness. The polycrystalline film was grown on a silicon substrate (~ 300µm thick) which works as the negative contact while the positive contact is realised with a 100nm thick Al contact, thermally evaporated on the intrinsic growth surface.

The monocrystalline film was grown on a commercial High Pressure, High Temperature made (HPHT), Ib type, single crystal diamonds substrate. The dimensions of the substrate was 3×4mm<sup>2</sup> in size and approximately 400mm thick. A two-step homoepitaxial CVD deposition process was adopted. In this process an initial 15mm thick Boron-doped diamond buffer layer with approximately 5Ω·cm resistivity was deposited onto the HPHT substrate, then an intrinsic, 20mm thick, diamond film deposition, was grown. The detector was then realised using the conductive B-doped layer as a backside negatively biased contact, while, just like the polycrystalline diamond, the positive contact was made with a thermally evaporated 100nm thick Al layer on the intrinsic growth surface. The justification for such a construction procedure is given in ref. 10.

Afterwards both detectors were covered by a uniform 2 µm thick polycrystalline LiF film of high optical quality. The films were grown by thermal deposition [11] on the top of the detector Al contacts. The samples were clamped to a rotating plate, kept at ambient temperature during the deposition process, performed under a vacuum pressure below 5×10<sup>-6</sup> mbar. The starting material consists of <sup>6</sup>Li enriched (95.62%) LiF tablets (3×3×1)mm<sup>3</sup>, heated at about 800°C in a tantalum crucible, placed below the substrate at a distance of 22cm. The evaporation rate, monitored in situ by an INFICON quartz oscillator, was controlled at a fixed value of 1 nm/s during the growth. The thickness of the deposited films was also directly measured by using a Tencor P10 profilometer on LiF films grown on glass and silicon substrates in the same evaporation run.

The LiF layer on the diamond detectors acts as a neutron-to-charge particles converter through the well-known nuclear reaction:



The cross section of this reaction exhibits the typical inverse velocity law versus the incident neutron energy with a thermal value of about 950 barns. The reaction products, Alpha particles and Tritons, are thus mainly produced by low energy neutrons with 2.06MeV and the 2.73MeV respectively. These reaction products are responsible for the main part of the signal detected by the CVD neutron monitors.

The neutron detection properties of the two CVD diamond detectors were first characterized at

the Frascati Neutron Generator (FNG) [12] showing excellent short and long time stability of the detection efficiency with no priming or polarization effects.

Both CVD diamond detectors were then installed inside JET Torus Hall in two different positions. The polycrystalline monitor, from now referred as CVD1, was in full operation at JET since April 2006 and began to acquire data starting from Pulse No: 66139. The monocrystalline detector, CVD2, was installed during a following shut down of JET in June 2006 and its data acquisition began from JET Pulse No: 66654.

CVD1 was mounted on the Limb1/2, Octant 1, at the level of the torus midline, approximately 7.8 m from the plasma centre. CVD2 was mounted near the main vertical port in Octant 1, approximately 4 m apart from the centre of plasma. Both detectors respond mainly to the neutrons slowed down by JET facilities hardware and the bunker walls.

The monitors use two ORTEC 142A charge preamplifiers located near the diamonds in the torus hall and connected by long cables ( $\approx 100\text{m}$ ) to shaping amplifiers and threshold discriminators located in the diagnostic area. The logic pulses produced by the discriminators were acquired in terms of count rate versus time by the JET acquisition system CODAS. Two discriminator threshold levels were set for each detector. For the polycrystalline  $^6\text{LiF}$  monitor, which has quite poor energy discrimination properties, the first threshold (THR1-CVD1) was set just above the typical noise level during plasma pulses, while the second threshold (THR2-CVD1) was adjusted in such a way the detected counts were only those due to neutrons produced by D-D fusion reactions. On the other hand, the monocrystalline  $^6\text{LiF}$  monitor exhibits good spectroscopic properties [10] thus the electronic thresholds were set in such a way that all neutrons produced during a pulse are counted with threshold THR1-CVD2 while 14 MeV neutrons produced by triton burn-up are counted with THR2-CVD2. The shaping time in the shaping amplifiers was set to 1.0ms for both monitors.

## RESULTS

CVD1 and CVD2 were not absolutely calibrated during Frascati Neutron Generator (FNG) laboratory tests so their response has been compared just relative to the JET total neutron yield measured by KN1 diagnostic, both in terms of temporal response during single plasma pulses and in terms of the total counts vs. total neutron yield.

KN1 is the main system used at JET to measure the instantaneous total neutron yield produced during a pulse. It consists of a three sets of fission chambers arranged around the machine. Each set comprises a  $\text{U}^{235}$  and  $\text{U}^{238}$  chambers operating in pulse-counting and current mode [13]. Together, the two types of chambers allow reliable detection of the neutron emissions from  $10^{10}$  to  $10^{20}$  n/s.

Instead the set-up of the electronics of CVD1 and CVD2 allows the detection of neutrons in count mode. The minimum measurable neutron rate is determined by counting statistics while pile-up effects fix the maximum rate. For the purpose of this paper only the results obtained by the signal produced by THR2-CVD1 and THR1-CVD2 are reported.

In fig. 1, 2 examples of the temporal response of CVD1, CVD2 and KN1 total yield monitor are

shown for two different pulses. The KN1 diagnostic is absolutely calibrated, thus, the yields shown in the figures correspond to the total neutron yields produced during those pulses. The diamond detector figures show the measured count rates. CVD1 has an efficiency about double that of CVD2. This result is consistent with the ratio of the sensitive volumes of the two detectors ( $12 \times 0.002 \text{ mm}^3$  CVD1;  $5 \times 0.002 \text{ mm}^3$  CVD2) apart from the different positions and distance from plasma where the levels of fast and slowed down neutrons are, presumably, different.

Figures 3 and 4 show the comparison of CVD1 and CVD2 counts vs. the total neutron yield measured with KN1 system for more than one hundred and fifty acquired pulses. In Fig.5 only the diamond monitors count ratio vs. JET pulse numbers is shown indicating a stable behaviour along time. The error bars are the standard deviations (1s) due to the statistical uncertainties of the counts.

## CONCLUSIONS

Diamond detectors covered with  $^6\text{Li}$  enriched LIF layer have shown to be an promising~~interesting~~ devices for total neutron yield measurements at JET. Besides their small dimensions which limit their yield measurements capabilities to pulses with  $>10^{14}$  neutrons, ~~the~~ two monitors have been shown to be reliable and complementary to JET total neutron yield diagnostics based on fission chambers detectors.. The CVD detectors will remain in operation during the JET 2006 experimental campaign to test their performances for long operation times.

## ACKNOWLEDGEMENTS

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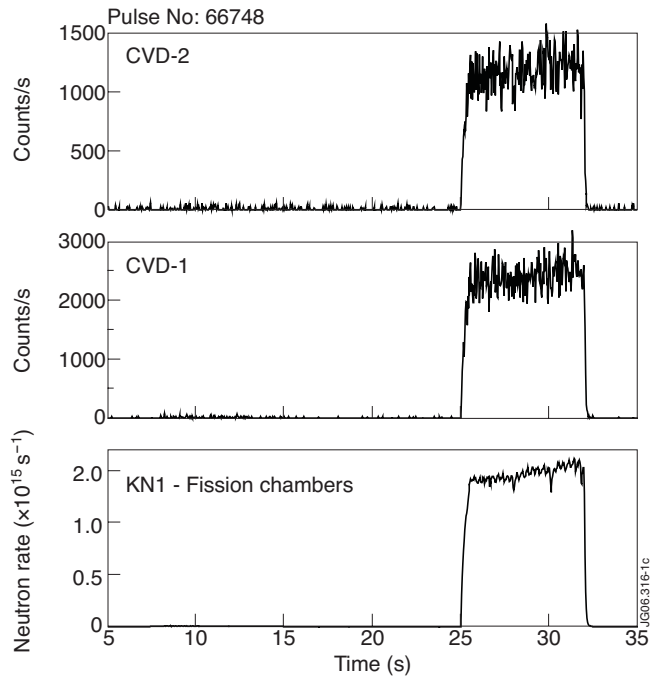


Figure 1: Comparison of time dependent neutron emission measured by KN1, CVD1 and CVD2 during JET Pulse No: 66748

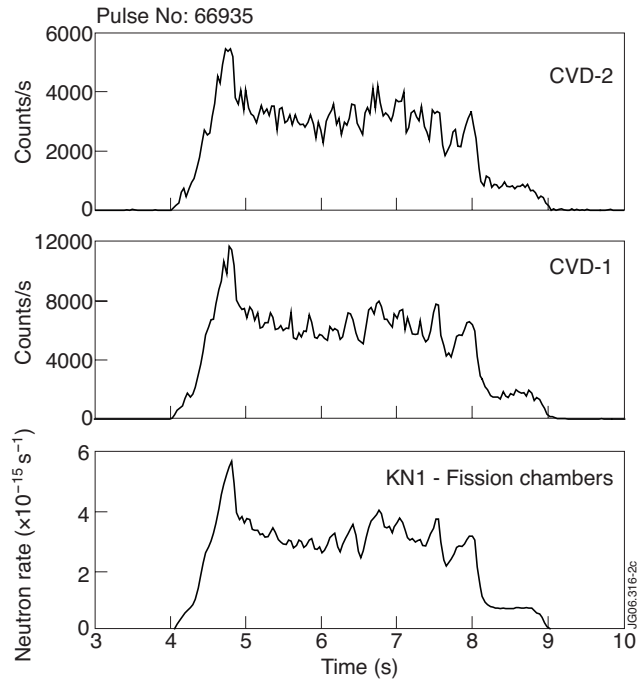


Figure 2: Comparison of time dependent neutron emission measured by KN1, CVD1 and CVD2 during JET Pulse No: 66935. Only the time where there is neutron production is shown.

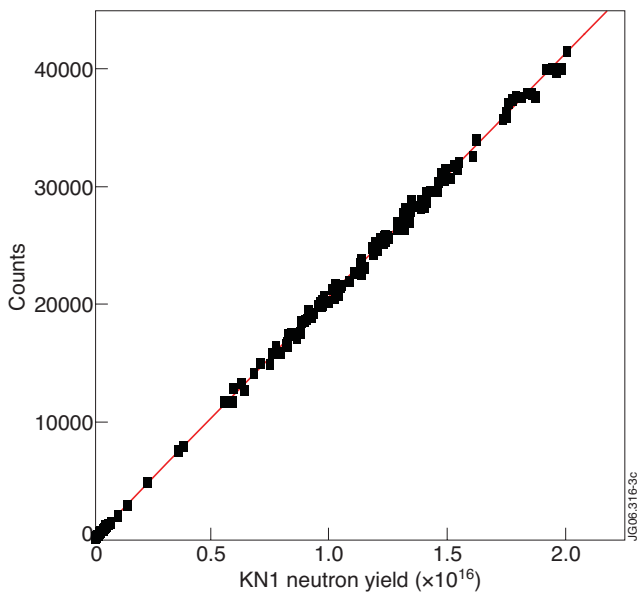


Figure 3: CVD1 counts versus neutron yields measured by KN1 fission chambers. The figure shows the calculated fitting and the correlation coefficient.

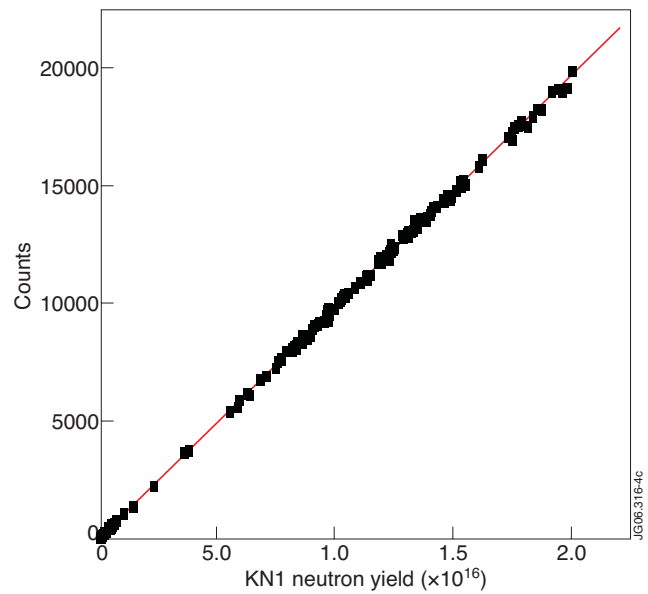


Figure 4: CVD2 counts versus neutron yields measured by KN1 fission chambers. The figure shows the calculated fitting and the correlation coefficient.

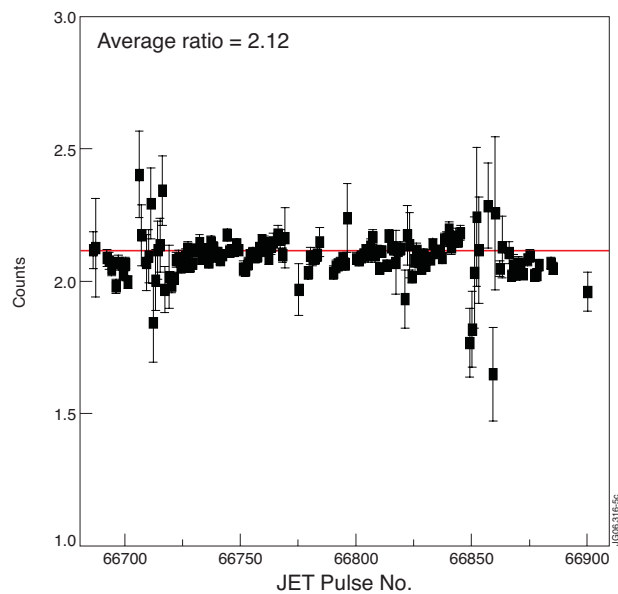


Figure 5: Ratio of CVD1 and CVD2 counts as a function of JET Pulse Number. The error bars indicate one standard deviation uncertainty due to statistical fluctuations of the counts.