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ABSTRACT.

A polycrystalline CVD diamond detector was installed on JET tokamak in order to monitor the time dependent 14 MeV neutron emission produced by D-T plasma pulses during the Trace Tritium Experiment (TTE) performed in October 2003.

This was the first tentative ever attempted to use a CVD diamond detector as neutron monitor in a tokamak environment. Despite its small active volume, the detector was able to detect the 14 MeV neutron emissions ($>1.0 \times 10^{15}$ n/shot) with good reliability and stability during the experimental campaign that lasted five weeks.

The comparison with standard silicon detectors presently used at JET as 14 MeV neutron monitors is reported, showing excellent correlation between the measurements.

The results prove that CVD diamond detectors can be reliably used in a tokamak environment and therefore confirm the potential of this technology for next step machines like ITER.

1. INTRODUCTION

In future fusion tokamaks devices, detectors and radiation monitors will operate in harsh environments characterized by high level of nuclear radiation and by temperatures higher than the standard room temperature.

The present available silicon diodes detectors are not suitable to withstand these working conditions despite the efforts done to develop more radiation hard devices such as those based on oxygenated silicon. For many years scientists have been studying new materials that could substitute silicon for detecting medium in harsh environments. Currently several candidates have been proposed as alternatives to silicon, among them polycrystalline Chemical Vapour Deposited (CVD) diamond seems to be the most promising one.

Diamond has a large band gap energy (5.5eV); a high breakdown voltage ($\approx 10^7$ Vcm^{-1}); high radiation hardness ($>3.0 \times 10^{15}$ n/cm^2); large saturated carrier velocities and low atomic number. Because of these outstanding electronics properties fast and low-noise diamond detectors detectors can be obtained [1]. Indeed, the development of a new class of detectors based on polycrystalline CVD diamond films is of interest not only for fusion reactors but also for high energy physics [2] and dosimetry (in the latter case it must also be stressed that the atomic number of Carbon is very close to that of human tissue).

In the published literature there is an increasing number of papers concerning the use of CVD diamonds as particles detector in several fields [2,3,4], but application in a tokamak environment is missing. This is mainly due to the harsh tokamak's environment and the difficulty in locating and operating a charge sensitive preamplifier (needed by the CVD detector) close to a tokamak. Another point of concern, when using CVD diamond, is the problem linked to polarization effects that usually become evident after a short time, so that long lasting measurement cannot be performed.

Recently it has been proven [5, 6] that polycrystalline CVD diamond detectors are able to detect 14MeV neutrons with good reliability even in long lasting irradiation and they can withstand 14

MeV neutron flux higher than 3.0×10^8 n/cm^2 s), still operating in a linear mode [6]. These fluxes are those expected, for example, around the JET tokamak when it is operating with D-T plasmas. Presently the time dependence of 14MeV neutrons emission are measured at JET using silicon diodes, whereas the total neutron yield is measured using fission chambers. To reliably use these silicon detectors it is however necessary to monitor their dark current increase versus neutron damage since it influences the radiation charge-output relation detector efficiency. The procedure used at JET is to change the detectors when their dark current reaches a certain threshold. Presently the neutron monitoring in the future international tokamak ITER [7] is a matter of concern, due to the expected high neutron and gamma fluences.

In the past Natural Diamond Detectors (NDD) have been used as 14MeV neutron detectors as well as neutron spectrometers in tokamak environment [8. 9]. The main limitation in using NDD is their very scarce availability, the small size and the high cost. On the contrary, CVD diamond can be produced at low cost, with large surfaces and thickness ranging from a few microns up to more than 1mm.

For many years high quality polycrystalline CVD diamond films have been produced at the Faculty of Engineering, Rome "Tor Vergata" University. In 1998 a collaboration with ENEA Frascati was established to study the application of CVD diamond films as fast neutron detectors mainly devoted to fusion reactor environment. This collaboration led to the present use of CVD diamond detectors at JET in the frame of JET Task Force D activities whose results are presented in this paper.

For the Trace Tritium Experiment (TTE) campaign performed at JET tokamak during the end of 2003, a polycrystalline CVD diamond detector was installed at JET and used as 14MeV neutron monitor working in a pulse mode. NDD diamonds, belonging to a Russian group from Trinity laboratory, were used as well.

2. HIGH QUALITY POLYCRYSTALLINE CVD DIAMOND FILM FOR RADIATION DETECTION

Any radiation that generates free carriers (electron and holes) in diamond can be detected, provided that their energy is higher than the band gap (5.5eV). So in principle radiation such us UV, gamma rays, neutrons and charged particles can be detected by using a diamond film.

To work properly as a neutron detector, a polycrystalline CVD diamond film must be of high quality, because long drifting distances Charge Collection Distances (CCDs) for holes and electrons are required to get an efficient detector with energy discrimination properties. It is well known that this means the production of diamond films with low defect concentration (the so called detector or electronics grade CVD diamond) since the defects trap the carriers, thus reducing the CCD and the collection total efficiency.

Two different type of defects have been recognized and studied in polycrystalline the CVD films. The grain-boundary defects are due to the columnar and polycrystalline structure of the film,

while the in-grain defects are due to impurities located inside each crystal grain. According to their action as traps, these defects can be divided in deep traps (located near the mid-band-gap) and shallows traps (located near the edges of the band-gap). The former do not allow de-trapping and limit the detector signal, while the latter allow thermal de-trapping and therefore produce a slow component in the detector signal, rather than reducing its overall amplitude [10].

The production of polycrystalline CVD diamond films with low defect concentration represents the goal of present activities on CVD diamond. Whilst the amount of boundary defects can only be reduced by improving the films' quality, the in-grain defects can be saturated by the so called pumping procedure [11]. This consists of the irradiation of the diamond film with ionising radiation (e.g. β-particles) prior to detector operation, leading at to a saturation of the empty traps, a condition which can last for several months if the films are not exposed to UV light or to high temperatures.

The film quality depends upon several growth plasma parameters like; temperature, gas composition and its impurities. A good control of the plasma stability is also a crucial factor, which due to the intrinsic instability of the plasma is difficult to obtain since the growth rate is very low (<1μm/h). As an example a CVD diamond film suitable for neutron detection must be at least 100μm thick, the thickness of the film being directly related to the detector efficiency

The certification of the films quality is the second step in the production of detector grade polycrystalline CVD diamond films. A detector can be obtained by producing onto the film a simple metal-semiconductor insulator-metal detector structure (MISM) and studying the free charge carriers collection distance and its detection efficiency.

In the MISM configuration the diamond is un-doped, and the contacts are assumed to be pure ohmic to avoid the polarization effect and, no junctions are used. This last point is crucial to understand the basic differences between silicon and diamond based detectors, and is one of the reasons for the higher neutron radiation hardness of diamond respect to silicon. Neutron radiation indeed produce an inversion zone in junction based detectors that in turn is responsible for performance degradation.

The detector efficiency and CCD and thus its behaviour as a particle detector is studied by our group using alpha particles [11] from radioactive sources (e.g. the 5.5MeV alphas from ^{241}Am). In a diamond film the charge produced by a ionising particle is given by $Q_0 = eE_i/13.2$, were e is the electron charge, E_i is the energy (in eV) of the detected ionising particle and 13.2 eV is the energy necessary to produce an electron-hole pair. The collected charge is related to the detector thickness L by the relation: $Q = ex/L$, where x is the thickness of diamond travelled by the carrier before trapping. The ratio $\eta = Q/Q_0$ defines the detector efficiency that in turn depends upon the Charge Collection Distance (CCD) via the Hecht theory [12], under the simplifying assumption that the electron and hole mobility m_e and m_h are equals.

For the polycrystalline CVD diamond produced in the Rome "Tor Vergata" University high values of CCD (160μm) and η (up to 70%) have been reported [13] demonstrating that these films are suitable for radiation detection. The standard electronics used for a CVD detector consists of a

charge preamplifier, a shaping amplifier and pulse height single channel or a multichannel analyser. The height of the voltage output is thus directly proportional to the energy of the incident radiation. The energy resolution depends upon the CCD respect the detector thickness and usually range from 20% to 40% in our samples. The CVD films were already used to detect proton beams [14] and 14MeV neutrons [5,6] as well as alphas with the detector operating at high temperature [15]. All these application have demonstrated the capability of the polycrystalline CVD diamond detector to operate in harsh environments and overall that the problem of the polarization effects hasve been overcome. This last point is crucial when CVD diamond detectors are needed to be operated for long periods such as that required for the present application in the JET tokamak.

2.1 NEUTRON-CARBON INTERACTIONS AND THE DISCRIMINATION BETWEEN 2.5 MEV AND 14 MEV NEUTRONS

Neutron-Carbon interactions are well studied since the early days of nuclear physics due the performance of Carbon as neutron moderator in for the nuclear reactors but also because carbon is fundamental for organic materials and living tissues.

Neutron-carbon interactions depend upon the neutron energy and they are of elastic, inelastic and capture type [8].

A typical tokamak neutron spectrum includes 2.5MeV and 14MeV neutrons as well as a continuous produced by the neutron scattering in the tokamak structure (Fig.1). This picture applies to either D-D plasmas (where 14MeV neutrons came from triton burn-up [16] and D-T plasmas. The ratio between 2.5MeV and 14MeV and 2.5MeV neutrons for D-D plasmas is about 0.0199, while for D-T plasmas it depends upon the D/T ratio.

In Carbon, neutrons of energy < 4.8 MeV (i.e 2.5 MeV neutrons from D-D plasma) interact mainly by elastic scattering, while at higher neutron energies the several inelastic reactions with different energy threshold occur. These reactions are reported in REF-8 and for incident 14 MeV neutron they lead to the production of charged products with kinetic energy ranging about from 0.03 up to 9.1MeV. $^{12}C(n,n')^{12}C^*(\alpha) \rightarrow {}^{9}Be$ and the (n, α) reactions also occur. The excited $^{12}C^*$ produced by the inelastic reaction can decay via alpha emission into ^{9}Be. The emitted alphas are spread into an energy range from about 0.5MeV up to 7MeV.

The (n, α) reaction is fundamental for the detection and discrimination of 14MeV in tokamaks. Alpha particles are produced in Carbon by fast neutrons via the $^{12}C(n, \alpha)^{9}Be^*$ nuclear reaction, where E* = 2.43MeV and energy threshold of 8.8 MeV, or $^{12}C(n, \alpha_0)^{9}Be$ reaction with threshold energy of 6.2 MeV. The kinetic energy of α_0 is 9.1MeV.

The discrimination between 2.5 and 14MeV neutron signal in a diamond detector is simply obtained using a threshold in the pulse height. 2.5MeV neutrons produce indeed only very low voltage output since their interaction via elastic scattering with carbon leads to carbon recoils of 0.21MeV maximum energy (1/12 of the neutron energy). The electronic threshold is however applied after the amplification, to overcome the total noise.

In the context of Nuclear Fusion the intrinsic capability of the detecting device to discriminate between 2.5 and 14MeV neutrons is essential, particularly in order to reduce pile-up problems. Table I clearly shows that the use of carbon leads to an advantage respect to silicon when for the discrimination between 2.5MeVD-D and 14MeVD-T neutrons is required. This is due thanks to the higher cross section ratio (R) between 14MeV and 2.5MeV neutrons for carbon (R = 0.83) with respect to silicon (R = 0.41). Another advantage of carbon as detecting medium respect to silicon is the lower sensitivity to X-ray and gamma radiation because of its lower atomic number. The sensitivity to X-rays and gamma radiation is a limiting factor for silicon toif the detection of 2.5 MeV neutrons is required since this signal due to neutrons is often covered by photon signal. Further the electrical pulse produced by the interaction of 2.5MeV neutron with carbon is much lower than that due to 14MeV neutrons. This is due to the fact that 2.5 MeV neutrons interact only by elastic scattering thus producing Carbon nuclei recoils having a maximum energy that is 1/12 of the neutron energy.

The above discussion together with that reported in the previous section explain why 14MeV neutrons can be detected and discriminated from the other energies by using CVD diamond films. Using an electronic threshold it is easy to separate the high energy pulses from the others. With this techniques it is possible, at least in principle, discriminate the 2.5MeV neutrons from the 14MeV neutrons.

3. CVD DIAMOND DETECTOR AND EXPERIMENTAL SET-UP AT JET

A typical CVD diamond detector is made of a film of variable thickness, usually in the range 100-500μm. Two gold pads of 2mm diameter areis deposited on both the growth side of the film to form theelectrical contact. Usually for neutron measurement silicon substrate is maintained and it is used as the ground electrical contact. The detector is made using the as grown film, that means the silicon substrate is not removed and the growth surface is not polished.

The polycrystalline CVD diamond detector installed at JET was manufactured using a film 126μm thick with a gold contact of about 2mm diameter. Its The active volume was given by the usual product of the film thickness times the gold contact surface. The detector was enclosed in a small aluminium case box for reducing noises and a SMA-type connector is used for cable connection. To operate in pulse mode the CVD diamond detector signal was sent to a charge preamplifier (ORTEC Mod. 142A) and a pulse shape amplifier (ORTEC Mod. 472). The detector operateds with a bias voltage of 1V/μm, the typical count rate is lower than 10^4 counts/s.

Before its use on JET the detector was characterized at the 14MeV Frascati Neutron Generator (FNG) [17]. The time long lasting irradiation stability, the response versus the neutron flux and the efficiency were studied [6]. A good stability for long lasting irradiation with 14MeV neutrons and a linear response versus neutron flux up to the maximum flux provided (3.0×10^8 n/cm^2/s) were observed [6]. The efficiency versus total neutron counts was also constant. Its measured value for incident However, the experimental conditions at JET were different and due to electrical noises the electronics thresholds were set to higher level respect to that used at FNG during

calibration. As a result this datum could not be used to extract absolute 14MeV neutrons, setting the lower threshold of the acquired counts just above the maximum pulse height of 3 MeV neutrons, yields. We mention that the absolute efficiency measured at FNG was 2.7×10^{-5} (±10 %) counts/ n*cm^2*sec.

The CVD diamond detector was then located installed on JET in near oOctant-8, in at the mid plane height, inside the torus hall (TH) but quite far from the plasma (about 7 m). The detector was connected to the charge preamplifier and both were inserted inside a metallic box used as electromagnetic interference shield. The shaping amplifier and the bias voltage unit were placed outside the TH, about 90m far. Connections to the preamplifier signal output and test input were made throughout long superscreened 50Ω cables. The amplifier signal was split into three signals using a fan-in/fan-out unit. The signals were processed by three single channel analysers with three different thresholds. The TTL outputs thus were finally collected by the JET data acquisition system CODAS. The signal output was indeed split into three equal signals by sending the output signal from the amplifier into a Fan-in/Fan-out unit. Three electronic thresholds levels were settled (namely at 140mV, 180mV and 270mV respectively)in such a way to allow the neutron signals to be well separated from the electronic background noise and above the maximum 2.5MeV neutrons pulse height, but with the three thresholds different were spaced to have different count rate versus neutron flux to prevent pulse pile-up in case of anomalous electromagnetic noises. The experimental set-up and electronic scheme is reported in Fig.2.

During the whole five-weeks experimental campaign the biasing potential was never switched-off and while little adjustments of the three thresholds were performed just during the first week of measurements to optimise the signal to noise ratio. The data collected in the first week of the TTE campaign will not be used in the following, despite this the electronic signal was very stable and last, but not least, no polarization or de-pumping effects were observed.

4. RESULTS AND DISCUSSION

The output of the acquisition system for CVD diamond detector is either the time dependent 14 MeV neutron emission and its integral over the JET pulse duration (in terms of detector counts). Both these CVD diamond detector responses are here after compared with the corresponding data from the Silicon detectors (KN-7 JET diagnostic system).

Silicon diodes are used routinely at JET to measure both 14 MeV absolute neutron yields and time dependent 14 MeV neutron emission. For this purpose they are routinely calibrated. Their response is reliable and a total uncertainty of ±10% was established [18] for the 14MeV neutron yield measurement . The quoted uncertainty is determined mostly by the accuracy of calibration by activation system (not better that ±8%) and it includes the statistical error that depends upon statistics but for TTE shots is usually < ±3%, and the systematic error (~5-6%). When JET is operating using D-D plasma these detectors are able to detect and quantify the 14MeV neutron emission due to triton burn-up [19].

Three different (in size) silicon diodes were used at JET during the TTE experiments to cover the whole 14MeV neutron emission range. In the following they will be labelled as small (S), medium (M) and large (L) size respectively. The comparison between the CVD results and the silicon diode data both in terms of total counts and time dependent neutron emission profiles, is a direct way to show weather or not the CVD data are sound.

The main limitation encountered using our CVD diamond detector at JET was due to its small active volume compared with that of the silicon diodes. This fact limited the counting statistics. For the purpose of this paper the reported CVD data have a statistical uncertainty ranging from ±3% up to ±10% (square root of the total counts). The comparison is made in the 14MeV neutron yield range between 1.0 10^{15} n and to 6.0 10^{15} n. Lower neutron yields produced a signal not statistically acceptable whereas higher neutron yields were not produced by JET during the TTE campaign.

The first comparison between CVD diamond detectors and silicon diode is reported in Fig.3 and 4. The CVD detector count-rates (measured with threshold 1 and 2 respectively) versus the medium size (DD/M10-CME5/11) silicon detector (M-diode) count-rates, is shown. The M-diode was chosen for this intercomparison since its count rate was always unaffected by saturation problem (at high neutron yields) and its statistical error was of the order of ±1% even at low neutron yield.

Figure 3 and 4 also report the calculated linear fit and the resulting correlation parameter (> 0.996) for both thresholds. The vertical bars are the statistical uncertainties (assuming a Poisson statistics) of the CVD detector count-rate. The results refer to all the measured statistically meaningful JET pulses (142 pulses).

Another interesting result is that shown in Figure 5 and 6. In these pictures the count rate ratio between diamond and M-diode is reported as function of neutron yield (Fig.5) and of the JET pulse number (Fig.6). Figure 5 shows the stability of the diamond response as a function of neutron yield and thus of the counting rate, while Fig.6 shows the stability over the whole TTE campaign. Both pictures refer to the second threshold (190mV) of the CVD diamond detector. Again the vertical bars are the total error on the ratio calculated using the propagation law. In these pictures the central horizontal line is the average values while the other two lines correspond to the standard deviation (at 1σ).

A different statistical approach to these data is to plot the statistical distribution of the ratio between CVD-detector and M-diode total count as an histogram and to fit it using a gaussian curve as shown in Fig.7.

The comparison was also made in terms of the temporal response measured during each JET pulse. Figures 8 and 9 report as an example the comparison among the CVD diamond detector and, the M-diode and the fission chamber time dependent behaviour for two JET pulses. In these figures also the fission chamber signal, which provides the sum of 2.5 and 14MeV yields, is reported. Fig.8 refers to a pulse using the neutral beam, while Fig. 9 refers to a pulse during which both neutral beam and Tritium gas puffing were used.

Last, but not least, since during plasma discharge hard X-rays and gamma-rays are produced, it is necessary to verify the insensitivity of the CVD diamond detector signal to such radiation. As an example, Fig.10 reports the measured hard X-rays signal compared with the CVD diamond and M-diode response for a pair of JET pulses, showing the detector immunity to hard X-ray radiation.

The results reported in this paper clearly demonstrate the capability of polycrystalline CVD diamond detectors to measure 14MeV neutrons in a tokamak and to work properly in this environment.

For a tokamak it is very important to measure both the 14MeV neutrons and the 2.5MeV neutrons. In the currently used CVD diamond detector work the signal pulse produced by 2.5MeV neutrons in the CVD diamond detector has an amplitude lower than the lowest threshold used for the measurements (threshold 1 at 140mV) so this emission was not measured. Indeed the signal due to 2.5MeV neutrons was just above the amplitude of the total noise. produced by the electromagnetic systems and lowering the threshold even a bit below the minimum threshold value it was easy to collect also the noises. This avoided the measure of the triton burn up during DD pulses as well as the collection of the data about the whole discharge during D-T phase.

Another problem to be solved is the detector volume. Our detector had an active volume of about 0.7 mm^3, and as a consequence also of the large distance from the plasma this reduced the the measurable JET yields, with reasonable statistic, dynamic range of the detectorwas limited. Work is in progress to increase the sensitive volume of the detector by a factor of ten. This can be achieved by increasing the thickness of the diamond film up to 500μm and by enlarging the gold pad surface. The goal is to install new more sensitive and efficient detectors in view of the 2005 experimental campaign during which only D-D plasma will be used, aiming to measure both the 14 MeV produced by the neutron burn-up and the 2.5 MeV neutrons. This test will be very helpful in view of ITER.

CONCLUSIONS

The results obtained during the first test of a polycrystalline CVD diamond detectors to measure 14MeV neutrons at JET clearly demonstrate the capability of this new class of detectors to withstand tokamak environments and to operate reasonably well for a long time.

The response of the polycrystalline CVD diamond detector was compared with that of the silicon diodes that are in operation at JET (for 14MeV neutron detection) since many years. The small dimension of the present CVD diamond detector limited its response range. Despite this, the correlation with the silicon data is well within the statistical uncertainty even at a low count rate. Long-term stability and reproducibility of the response were demonstrated to be already attainable with polycrystalline CVD diamond detectors.

The measurement of 2.5MeV neutrons was not possible due to the small value of the pulse height produced by these neutrons that resulted at the limit of the signal noise. Work is in progress to produce CVD diamond of large volume that should also be able to give signal of higher amplitude suitable for the 2.5MeV neutron measurement.

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Cross-section (barns)	***2.5MeV***		***14MeV***	
	Si	***C***	***Si***	***C***
Elastic	*3.7*	*1.6*	*0.73*	*0.82*
Capture	*1 (10^{-5})*	*1 (10^{-5})*	*5 (10^{-4})*	*1.2 (10^{-4})*
n, n′	*0.54*		*0.52*	*0.42*
n, particle			*0.42*	*0.064*

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Table I: Comparison of cross-section data between Silicon and Carbon at 2.5 and 14MeV.

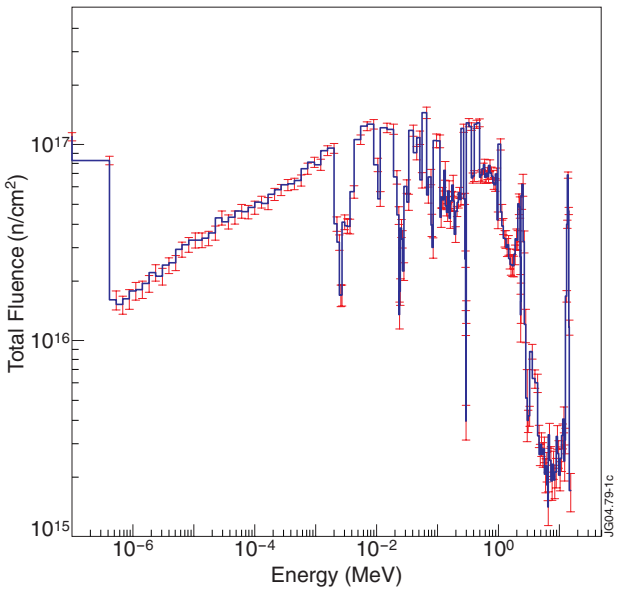

Figure 1: Neutron spectrum for the TTE experiment calculated using Monte Carlo Code MCNP-4C.

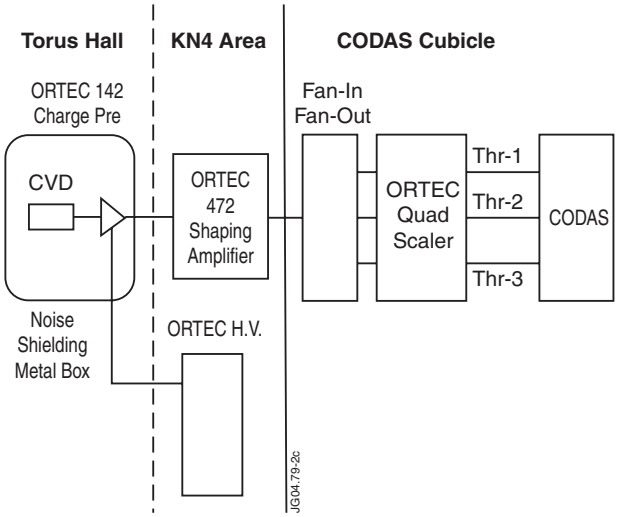

Figure 2: Detector set-up and connection to CODAS acquisition system.

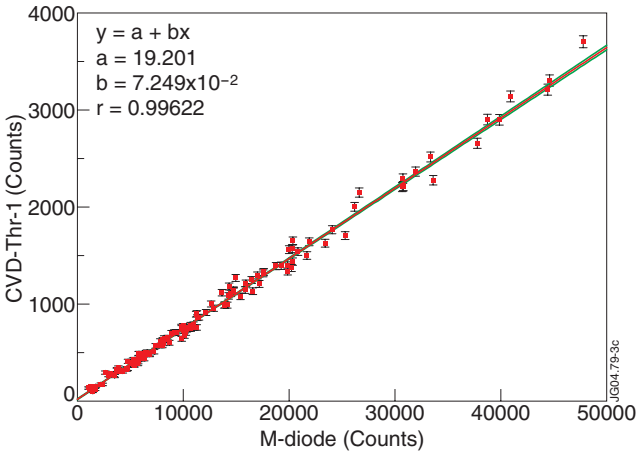

Figure 3: CVD detector count rate for Threshold-1 versus M-Diode count rate. The picture shows the calculated fitting and the correlation coefficient.

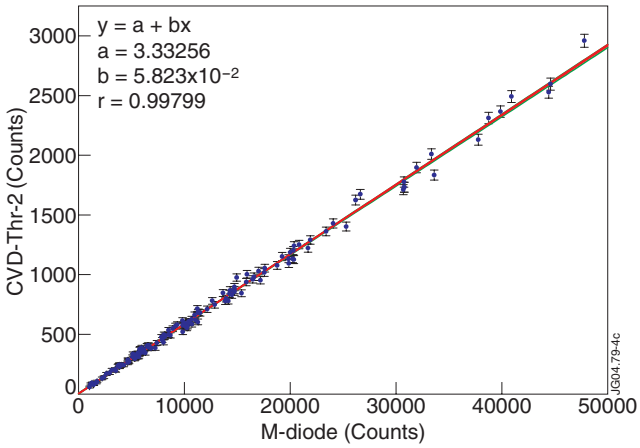

Figure 4: CVD detector count rate for Threshold-2 vs. M-Diode count rate. The picture shows the calculated fitting and the correlation coefficient.

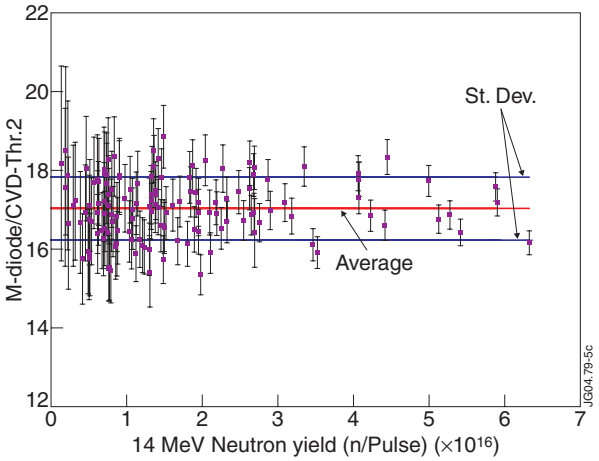

Figure 5: M-diode counts/CVD Diamond Threshold-2 counts ratio versus 14MeV neutron yield.

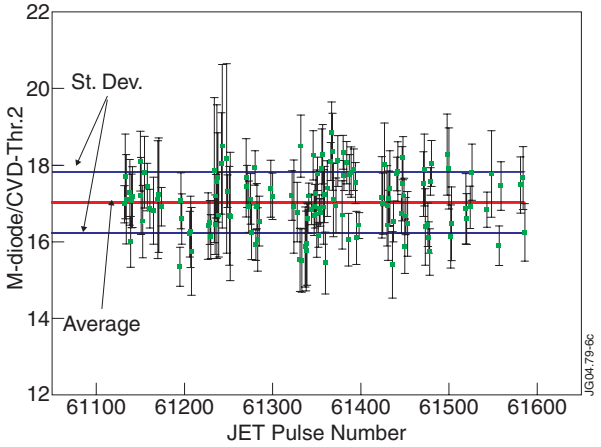

Figure 6: M-diode counts/CVD Diamond Threshold-2 counts ratio versus JET Pulse Number.

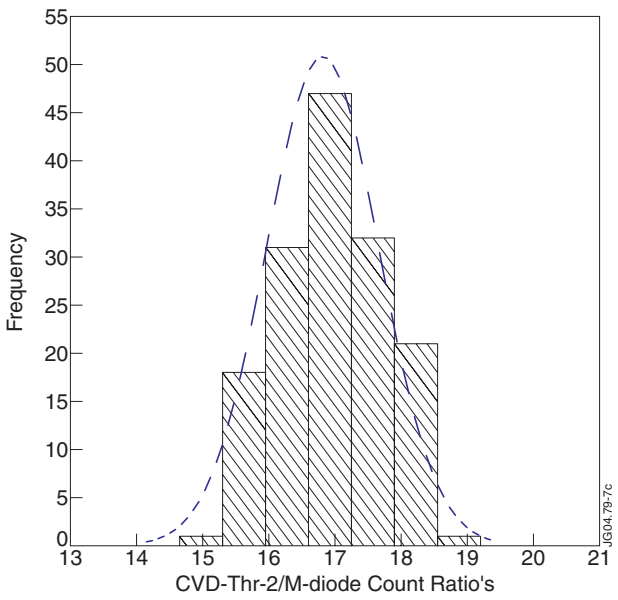

Figure 7: Distribution and Gaussian fit for the data reported in Fig.6 (Threshold-2)

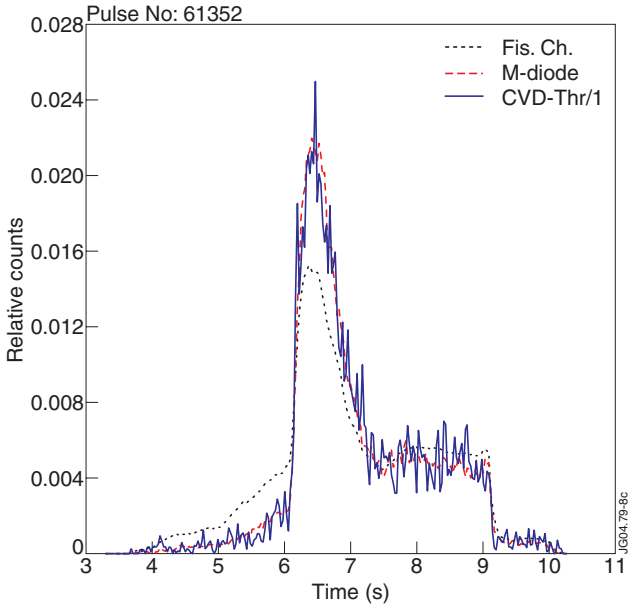

Figure 8: Example of CVD diamond detector temporal response compared to Fission Chamber (KN1) and M-diode (KN7)

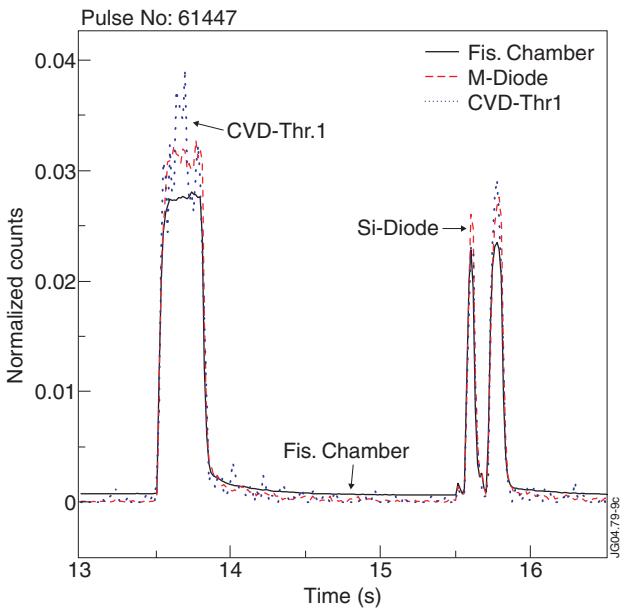

Figure 9: Example of CVD diamond detector temporal response compared to Fission Chamber (KN1) and M-diode (KN7)

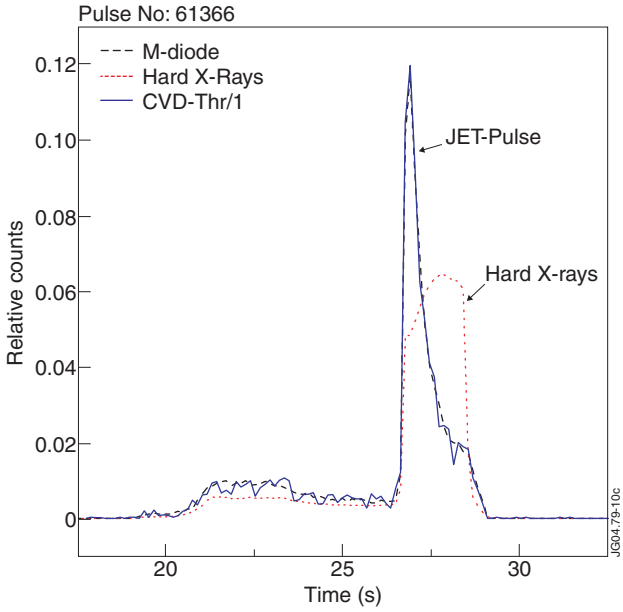

Figure 10: CVD and M-diode silicon signal compared with Hard X-ray signal for Pulse No: 61366