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TECHNICAL DESIGN NOTE

System for measurement of low yield neutron pulses from D–D fusion reactions based upon a ^{3}He proportional counter

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Abstract
A conventional neutron detection technique was adapted to measure low neutron yields from D–D fusion pulses. This method uses a ^{3}He proportional counter surrounded by a paraffin moderator. Electric signals generated in the ^{3}He tube are fed into a preamplifier. The output of the preamplifier is directly connected to a digital oscilloscope. The time-integrated signals represent the charge generated in the ^{3}He tube which is proportional to the total neutron yield. The integration time is determined by the preamplifier and moderator characteristics within some hundreds of microseconds. No meaningful neutron background was detected during this time window. The system, previously calibrated, was used to measure the neutron yield ($<10^6$ neutron/pulse) generated in a fast and very small plasma focus device designed to operate with energies of tens of Joules. Neutron yields as low as 10^3 neutrons per pulse were measured.

Keywords: neutron pulses, neutron yield, plasma focus

1. Introduction

The generation of pulsed neutrons is a common process of many dense transient pinch plasmas (z-pinches, plasma foci, etc). The pinch also generates beams of ions, electrons and ultra-short x-ray pulses. When using deuterium gas, plasma focus devices produce fusion D–D reactions, generating fast-neutron pulses (with energies around 2.45 MeV) and protons (leaving behind ^{3}He and ^{3}H ions). The neutron bursts usually last for about tens to hundreds of nanoseconds [1–3].

Most neutron detectors have been designed for measurements in a continuous mode of emission, and their use is generally not applicable in the same manner as in the case of very short neutron bursts. However, some of these detection systems are appropriate to be used for the detection of short neutron bursts (∼100 ns), as in the case of the silver activation counter.

Neutron emission from plasma foci has been found ranging from 10^7 to 10^{12} neutrons per pulse with 1 kJ and 1000 kJ drivers, respectively [1–4, 12–17]. The region corresponding to a total neutron yield of less than 10^6 neutrons per pulse has been less explored. However, the development of small plasma focus devices operating with energies lower than 1 kJ (total neutron yield less than 10^6 neutron/pulse) has had renewed interest in order to produce non-radioactive portable neutron sources [2–7]. The consequence of this is that measurements of very low levels of fast neutron emission become very important to consider.

A very small plasma focus operating at an energy level in the order of ∼100 J or less (160 nF capacitor bank, 38 nH, 20–35 kV, 32–100 J, ∼150 ns quarter of period) was constructed. The design calculations indicate that neutron yields of 10^4–10^5 neutrons per shot [5, 6] are expected, with a lifetime of ∼10 ns per neutron pulse. For neutron yields of less than 10^6 neutron/pulse, the well-known techniques (activation counter, bubble counter system, etc) are not effective. Particularly, the most common technique to measure the total neutron yield in deuterium z-pinches is the activation counter [4, 12–17]. The limitation of these counters for measuring low neutron yields is the level of the background radiation. As a reference, in a typical silver activation counter the background radiation contributes with 100–150 counts in 30 s. These numbers of counts would correspond to 5 × 10^5–10^6 neutrons. This is the lowest limit of detection of a typical silver activation counter

2. Detection system

2.1. ^{3}He in a charge integration mode (CIM)

^{3}He proportional counters are well-known neutron detectors whose detection principle is based on the nuclear reaction, ^{3}He(n, p) ^{3}H [8]. They show a high sensitivity (∼5300 barn) to thermal neutrons (<0, 1 eV). The detection system used in this work consists of a cylindrical ^{3}He neutron detector (model LND 2523). The energy of the emitted neutrons from a plasma focus is about 2.45 MeV. To increase the detector efficiency, moderation was required. This was achieved by using a block of paraffin.

Dimensions of the moderator were 45 × 15 × 15 cm^3, including also an axial hole of 1 inch diameter and 39 cm in length (the detector dimensions). In addition, to minimize the thermal neutron background, the system was covered with a cadmium sheet. The system was finally encapsulated in an aluminum box.

Signals were fed to a Canberra 2006 preamplifier. The output of the preamplifier was directly connected to a digital oscilloscope. In this way, the ^{3}He proportional tube is employed in a manner which we may call the 'charge integration mode' (CIM). In spite of the presence of any wall effect among others [8–11], it was experimentally verified that the time-integrated signal is still proportional to the neutron yield [19].

It is also necessary to mention that the moderator offers two other additional and useful characteristics with this type of detector that are worth mentioning. On the one hand, neutrons generated in the PF pulse (∼10–100 ns) are dispersed in time (∼800 μs) depending on the moderator volume and geometry. This reduces any saturation effects in the detector. On the other hand, PF devices generate intense electromagnetic pulses associated with the main discharge (∼1 μs). This could contribute to a very significant distortion of the measured signal. A moderator will ensure that neutron signals and electromagnetic pulses (figure 1) are separated in time.

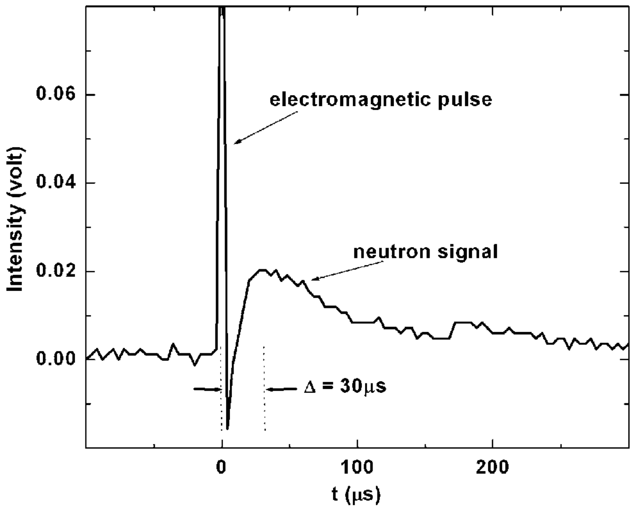

Figure 1. The signal registered by the oscilloscope for the detector system in a plasma focus discharge in deuterium. The electromagnetic pulse corresponds to the plasma focus electrical discharge, and the next signal corresponds to the neutrons which is correlated with the plasma focus discharge. The neutron detection is in temporal coincidence with the plasma discharge.

2.2. Application to plasma focus devices. Testing and performance

Simultaneous measurements with the ^{3}He system detector in the CIM and the silver activation counter were performed with two very small plasma focus devices. The plasma focus devices used have energies of 50 and 400 J (PF-50J [5, 6, 18] and PF-400J [4]) with an expected yield between 10^4 and 10^6 neutrons per pulse respectively. The level of the neutron emission was varied by tuning the deuterium pressure in the plasma focus devices. Figure 2 shows the signals obtained with the ^{3}He detector and the count-rate characteristics for both devices. For the case of the PF-400J device (figure 2(a)), in which the activation detector was placed 28.5 cm from the emission point, the mean counting rate was around 100 count/30 s above the background. However, in the case of the PF-50 J device (figure 2(b)), where the activation detector was positioned at 16.5 cm distance, the count rate did not exceed the background level. A conclusion may be extracted from the previous results in the sense that the activation detector is not sensitive enough in the case of the PF-50J device. The ^{3}He detector instead is perfectly useful in this range.

In addition, attention must be paid to the fact that the ^{3}He-based system does not have the background limitation drawback at low neutron yields (typical of the silver activation counter). As the mean lifetime of the silver activation is 24.6 s, it is necessary to integrate its decay counts along a greater time span. An integrating time of 30 s was chosen. The background radiation in our laboratory contributes with 150 ± 20 counts in 30 s; therefore, it was decided to consider only those measurements that are 60 counts above the background. For the silver activation counter placed at 28.5 cm, 60 counts correspond to ∼5 × 10^5 neutrons. On the other hand, the ^{3}He-based system integrates in a time of the order of hundreds of microseconds (the total duration of the signal) in time correlation with the plasma discharge.

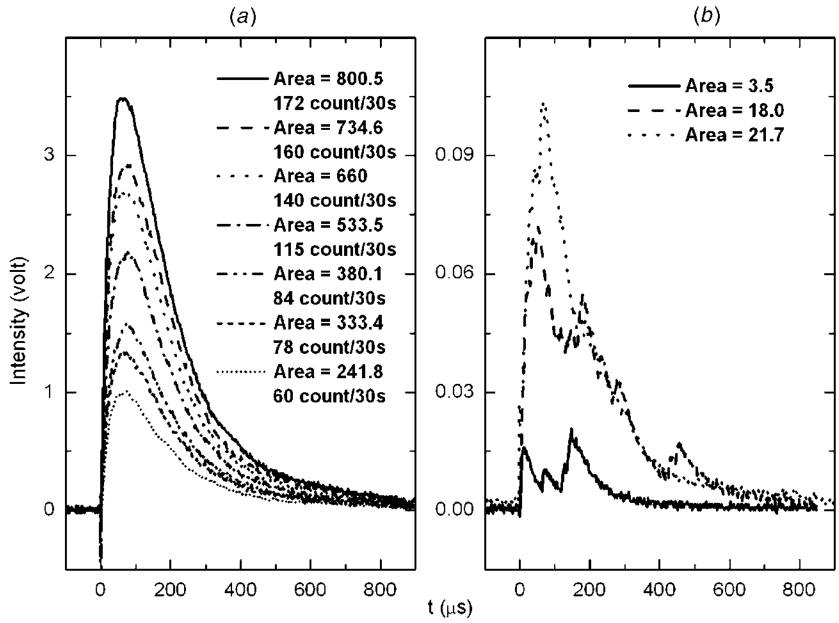

Figure 2. Characteristic neutron signals of the ^{3}He system detector. (*a*) PF-400J with the activation silver counter at 28.5 cm and the ^{3}He system detector at 33.5 cm from the emission point, (*b*) PF-50J with the activation silver counter at 16.5 cm and the ^{3}He system detector at 23.5 cm from the emission point. Areas are in volts microseconds (V μs).

Figure 1 puts in evidence the separation between the electromagnetic noise of the electrical discharge and the neutrons' signal in the ^{3}He-based system, whereas for discharges in hydrogen in which neutrons are not emitted, only the electrical noise is registered in the signal. In the case of background radiation, no contribution is detected in that small time window of hundreds of microseconds.

Another important observation is that plots of count rate versus area under the curve of the signal and the count rate versus the maximum intensity of the signal show that a linear relation exists in both cases [19]. The integration is made numerically after the signals are extracted from the oscilloscope. Linearity with the area under the curve in the region of very low neutron emission was used. It becomes evident in figure 2(*b*) that independent pulses may not contribute to the 'height' of the recorded signal, but will contribute to the total area under the signal. In fact, individual neutrons produce a voltage signal following the relation $V_i \exp(-t/RC)$, where RC is the decay time of the preamplifier (50 μs in this case) and its integrated area is $A_i = RCV_i$. From the nominal gain, $\alpha = 47$ mV/Mpi (Canberra preamplifier, model 2006), the charge per volt of the preamplifier is $1/\alpha = 3.4 \times 10^{-12}$ C V^{-1}. Therefore, the charge collected for one neutron is $Q_i = V_i/\alpha = A_i/RC\alpha$. The total charge produced, Q_T, is obtained by a summation of all the individual events. As a result, $Q_T = A_T/RC\alpha$, where A_T is the total area under the curve of the signal. Therefore, the total number of neutrons is proportional to the total charge collected (total area under the signal curve).

3. Calibration

To calibrate the ^{3}He detection system (moderator included), a silver activation counter (previously calibrated with a ^{241}Am–Be neutron source, the available source in our laboratory) was used as a calibration reference. It is important to mention that calibrations involving the use of ^{241}Am-based neutron sources require that their neutron energy distribution should be similar to the neutron energy distribution obtained from PF devices. This is the case of ^{241}Am–B sources. It is clearly not the case for ^{241}Am–Be sources. In principle, this could prevent the use of such sources in this type of calibration. However, Gentilini *et al* [12] provides an alternative in allowing the use of a Be-based neutron source by providing an appropriate correction factor. Their correction factor was experimentally obtained by measuring the calibration constant (K (neutron/pulse-count)) for both types of neutron sources under the same experimental conditions. The ratio of the two calibration constants ($f = K_{\text{Am-B}}/K_{\text{Am-Be}} = 1.14 \pm 0.41$) would provide the correction factor needed in the present work where a ^{241}Am–Be source was available.

The activation system used has a 15×20 cm^2 active area with a paraffin moderator 3 cm thick, a planar Geiger counter and a paraffin neutron reflector (figure 3). The procedure applied to calibrate the silver activation counter has been widely used in several laboratories [15–17] and is the same described in [12].

With these considerations, simultaneous measurements with both neutron detectors exposed to the PF-400J device were carried out (figure 3). By using the calibration of the reference detector, a calibration for the ^{3}He detector, i.e. neutron yield versus area (or total charge), could be obtained. In this manner, the neutron yield of a pulsed source is obtained by direct integration of the signal, for a particular plasma focus shot.

Figure 4 shows the calibration curve for the ^{3}He detector at 33.5 cm from the plasma focus source. Each point corresponds to the average over ten shots (including the correction for

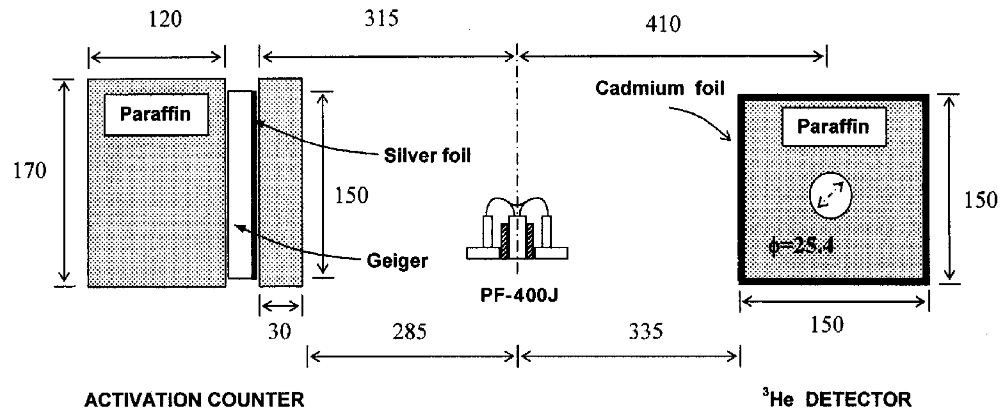

Figure 3. The PF-400J plasma focus was used to calibrate the ^{3}He-based system. A previously calibrated silver activation counter was used as the reference detector. Distances are in mm.

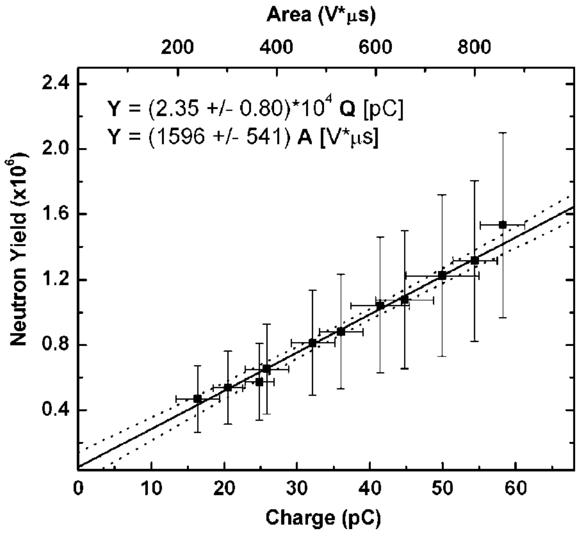

Figure 4. Relation between the counts of the silver activation counter (proportional to the total neutron yield, *Y*) and the area under the curve of the signal, *A* (proportional to the total charge, *Q*), of the ^{3}He-based system. The calibration of the ^{3}He-based system, placed 33.5 cm from the source, is $Y = 1596A$, with *A* in units of volts microseconds (V μs) ($Y = 2.35 \times 10^4\ Q$, with *Q* in picocoulombs (pC)).

spectral difference between the two neutron sources) for the PF-400J device operating under identical conditions of pressure and charging voltage. The error bars correspond both to the error in the average over ten shots and to that associated with the correction factor (f). The calibration factor is possible to obtain directly from the slope measured. As far as the vertical axis intercept in figure 4 is concerned, the regression line clearly crosses the zero charge point (within experimental uncertainties) as expected. It is important to remark that, for discharges in hydrogen in which neutrons are not emitted, only the electrical noise is registered in the signal, and background radiation is not detected in those small temporal windows of hundreds of microseconds. The slope is calculated through the weighted linear regression calculations. The 'confidence bands' are defined for a 95% confidence level. Therefore, by using a proportional relation between the neutron counts and the area under the curve, it is possible to extrapolate the results to obtain the neutron production for low yield cases.

The proportional relation between the neutron yield N_n and the area A is $N_n = (1596 \pm 541)A$, with A in units of volts microseconds (V μs). The linear relation obtained from the experimental data is enough to establish the calibration. Nevertheless, it is necessary to mention that this is valid only for the geometry for which the measurements were obtained. For other geometries, the system should be recalibrated in order to obtain the calibration factor.

By using the above-described detection system, it was possible to obtain a measure of the total neutron emission in a very small plasma focus of only tens of Joules, PF-50J. The results of these measurements were 3.6×10^4 neutron/pulse, when operated in D_2 at 8–9 mbar with an initial stored energy of 67 J, and 1.2×10^4 neutron/pulse at 6 mbar and 50 J [18]. A minimum area in the order of 0.4 V μs has been measured up to now from the ^{3}He detector; thus, a neutron yield in the order of 640 neutrons per shot can be detected.

4. Conclusions

In summary, a detection method based on the well-known ^{3}He proportional counter was adapted to measure neutron yields from sources of short pulsed emission nature. An analogue signal corresponding to the integrated charge from the ^{3}He tube is registered through a fast preamplifier whose time-integrated signal is proportional to the neutron yield. The integration time is determined by the preamplifier and moderator characteristics, and it corresponds to about some hundreds of microseconds. No radiation background is detected during this time window. A linear proportional relation was obtained between the ^{3}He time-integrated signal and the neutron yield. The other important result is that neutron yields lower than 10^3 neutrons per pulse are measurable with this technique.

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References

[1] Bernard A *et al* 1998 Scientific status of plasma focus research *J. Moscow Phys. Soc.* **8** 93
[2] Krauz V I 2006 Progress in plasma focus research and applications *Plasma Phys. Control. Fusion* **48** B221
[3] Soto L 2005 New trends and future perspectives on plasma focus research *Plasma Phys. Control. Fusion* **47** A361
[4] Silva P, Moreno J, Soto L, Birstein L, Mayer R and Kies W 2003 Neutron emission from a fast plasma focus of 400 joules *Appl. Phys. Lett.* **83** 3269
[5] Silva P, Soto L, Moreno J, Sylvester G, Zambra M, Altamirano L, Bruzzone H, Clausse A and Moreno C 2002 A plasma focus driven by a capacitor bank of tens of joules *Rev. Sci. Instrum.* **73** 2583
[6] Silva P, Soto L, Kies W and Moreno J 2003 Pinch evidence in a fast and small plasma focus of only tens of joules *Plasma Sources Sci. Technol.* **13** 329
[7] Milanese M, Moroso R and Pouzo J 2003 D-D neutron yield in the 125 J dense plasma focus nanofocus *Eur. Phys. J.* D **27** 1434
[8] Knoll G F 2000 *Radiation Detection and Measurement* 3rd edn (New York: Wiley)
[9] Shalev S, Fishelson Z and Cuttler J M 1969 The wall effect in ^{3}He counters *Nucl. Instrum. Methods* **71** 292
[10] Cuttler J M, Greenberger S and Shalev S 1969 Pulse risetime discrimination for ^{3}He counters *Nucl. Instrum. Methods* **75** 309
[11] Füzi J 2008 Spectral accuracy of multiwire proportional counter neutron detectors in time-of-flight regime *Meas. Sci. Technol.* **19** 034028
[12] Gentilini A, Rager J P, Steinmetz K, Tacchi M, Antonini D, Arcipiani B, Moioli P, Pedretti E and Scafe R 1980 Comparison of four calibration techniques of a silver activated Geiger counter for the determination of the neutron yield on the Frascati plasma focus experiment *Nucl. Instrum. Methods* **172** 541
[13] Rapezzi L, Angelone M, Pillon M, Rapisadra M, Rossi E, Samuelli M and Mezzetti F 2004 Development of a mobile and repetitive plasma focus *Plasma Sources Sci. Technol.* **13** 272
[14] Mahmood S, Springham S V, Zhang T, Rawat R S, Tan T L, Krishnan M, Beg F N, Lee S, Schmidt H and Lee P 2006 Novel fast-neutron activation counter for high repetition rate measurements *Rev. Sci. Instrum.* **77** 10E713
[15] Woo H-J, Chung K-S and Lee M-J 2004 Dependence of neutron yield on the deuterium filling pressure in a plasma focus device *Plasma Phys. Control. Fusion* **46** 1095
[16] Castillo F, Herrera J, Rangel J, Alfaro A, Maza M A, Sakaguchi V, Espinosa G and Golzarri J I 2002 Neutron anisotropy and x-ray production of the Fn-H dense plasma focus device *Braz. J. Phys.* **32** 3
[17] Waheed A, ur-Rahman A, Zakaullah M and Murtaza G 2001 High efficiency neutron detector for low neutron flux measurement *J. Energy* **19** 91
[18] Soto L, Silva P, Moreno J, Zambra M, Kies W, Mayer R E, Clausse A, Altamirano L, Pavez C and Huerta L 2008 Demonstration of neutron production in a table-top plasma pinch device operating at only tens of joules *J. Phys. D: Appl. Phys.* submitted
[19] Soto L *et al* 2004 Research on pinch plasma focus devices of hundred of kilojoules to tens of joules *Braz. J. Phys.* **34** 1814