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PMT-Scintillator System Set Up for D-D Neutron TOF Measurements in INTI Plasma Focus Device

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Abstract. This paper summarizes a Photomultiplier-Scintillator diagnostic system for use in our plasma focus experiments at the Center for Plasma Research INTI IU. The system features an anode-grounded high pulse linearity voltage divider and uses NE102A plastic scintillators. It has detected D-D neutrons in INTI plasma focus device with clear and high signal to noise ratio. Neutron TOF of 120 ns has been measured from the time difference between hard x-ray pulse peak and neutron peak time over a flight path of 2.6±0.01 m; giving energy of 2.5±0.1 MeV for these side-on neutrons.

Keywords: *Photomultiplier, Scintillator, Neutron, Time of Fight, Plasma Focus*

INTRODUCTION

Deuterium-Deuterium nuclear fusion reaction is one of the most interesting phenomena happening in dense plasma focus devices operated in Deuterium. When INTI PF is operated in Deuterium as a filling gas, D-D neutrons are emitted. Together with these D-D neutrons there are other radiations such as visible light, x-rays including hard, soft, bremsstrahlung, etc. There are many references for studying plasma focus neutron production and measurements and related study of plasma focus dynamics [1, 2, 3, 4, 5, 6, 7, 8]. Modeling of neutron production in various plasma focus devices have also been carried out as far back as the work of Potter [9] who assumed a thermonuclear mechanism which however is contrary to more popular recent interpretation based on experimental results of a predominantly beam-plasma fusion mechanism [10, 11]. In more recent work based on Lee Code the number of D-D neutrons produced by a whole range of plasma focus devices has been simulated with reasonable agreement to experimental observations. The resulting neutron scaling laws agree with the experimentally developed scaling law in the low to

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medium energy range of $Y_n \sim E_0^2$, but shows considerable deviation (to which the term 'deterioration of scaling' has been ascribed) to $Y_n \sim E_n^m$ where m goes below 1 at multi-MJ regimes [12, 13, 14].

The Photomultiplier-Scintillator combination system is one of the best diagnostic systems for neutron time–of-flight measurements in plasma focus devices. In 1973 D-D Fusion neutrons were measured in Malaysian time-of-flight experiments by S. Lee et al in a 12.5 kJ, 20 kV plasma focus device which emitted 10^8 neutrons per shot measured in a backwards direction at 2.2±0.1 MeV energy using two NE102-coupled photomultipliers separated by a distance of 10 m. These were likely the first plasma fusion neutrons detected in Asia (excluding Russia). The results were published in 1975 [15]. These NE102-RCA6810A scintillator-photomultiplier systems were also used with detailed laser shadowgraphs and laser interferograms to correlate the neutron and x-ray emissions with the radial implosion phases of the plasma focus [15, 16].

The Investigation of High Energy Radiation from a Plasma Focus is a report by Charles E. Roos, and John P. Barach [17] which summarizes the results of radiation from a plasma focus conducted during the period from February 1969 to August 1975. They used NE102 Scintillator PMT combinations for observation of neutron time- of- flight. An experimental study on hard X-ray pulses emitted by a small plasma focus by F. Castillo-Mejía et al. shows that the relation between responses of Thermo-Luminescence Dosimeters (TLD) and scintillator-photomultiplier combination detectors is linear [18]. Furthermore, F. Castillo et al. in 2002 used two scintillator-photomultiplier systems for hard X-ray and neutron measurements [19]. They used NE-211 and NE-218 scintillators. In 2007, María Magdalena Milanese et al. correlated the different phases of the plasma focus with experimental discharge current signal and neutron and X-ray production [20]. F. N. Beg et al. in 2002 used Scintillator-Photomultiplier system for characterization and calibration of dark matter detectors by means of plasma focus as a neutron a source. [21] Neutron TOF measurements by means of three scintillator-photomultiplier combination systems by M. S. RAFIQUE in 2000 shows 2.48±0.04 MeV and 3.00±0.09 MeV neutrons in the radial and the axial directions of plasma focus device, respectively [22]. The HXR and neutron emission characteristics of a miniature sub-kilojoule plasma focus device in both radial and axial directions using two scintillator-photomultiplier systems were studied by Rishi Verma et al. in 2009 [23].

Recent progress in a single-pulse Nanosecond Impulse Neutron Investigation System (NINIS) applicable for inspecting of hidden objects using elastically scattered neutrons measurements was presented by V A Gribkov et al. using DPF devices having bank energy in the range of 2–7 kJ. In this method very bright 10ns duration neutron pulses produced by dense plasma focus filled with pure Deuterium or DT mixture were used. Although the available distance for the TOF measurements was short, the small neutron pulse-width was sufficient to distinguish different hidden elements [24]. Signals obtained by means of scintillator-photomultiplier system 6m away from the tip of the anode in a low energy plasma focus device show that the FWHM of X-Ray pulse is 30-40 ns [25].

The above experience shows that scintillator-photomultiplier combination system is a useful diagnostic tool for neutron time- of- flight measurement especially in a plasma focus devices. We present INTI PF machine's Scintillator-PMT system design and its detected signal in the following section. Objective was to put together a system for TOF measurements for our INTI PF [26] so we made our own TOF measurements of D-D neutrons to be correlated with other detector's signals such as FC, SXR. This will enable us to correlate various radiations with each other and with the dynamics of the plasma focus when correlated with the Lee Code.

PMT-SCINTILLATOR SET UP

Neutron time- of- flight measurement may be used for measuring the energy of detected fast neutrons. In plasma focus device high energy electrons impact on anode producing hard x ray which is also detected by the PMT-Scintillator system. The hot dense plasma in the pinch column produces small amounts of thermonuclear neutrons. High energy ions are accelerated away from the anode by electric fields inductively generated by the pinch compression. Electrons are accelerated in the opposite direction towards the anode. These high energy ions lead to beam-plasma target fusion neutrons. If distance between the PMT and anode is 200 cm then the time difference between the arrival of hard x- rays and D-D fusion neutrons at the PMT is around 100 nano-second; assuming that the hard x-ray pulse and the neutron pulse start within a few ns of each other. PMT-Scintillator signals should have ns resolution with ultra-fast rise time. Because of FWHM of around 30-60 ns we need large signals without amplification circuit. Amplifier circuits distort and lengthen the signals duration, and this is not useful or necessary for plasma focus generated neutrons. For a suitable photomultiplier-scintillator system we need a PMT, scintillator, voltage divider, power supply and shielding.

For INTI plasma focus device, three pieces of 46 mm diameter and 36 mm height NE102A scintillator rods are available. After surface polishing, we coupled the clear and smooth face of NE102 scintillator to the 9813B photomultiplier tube window by means of a thin layer of clear silicone sealant. This method is very suitable when we want to maximize transmitted light, emitting from scintillator to the window of the PMT.

To operate the PMT, a high voltage of up to 3 kV is applied across the cathode and anode, with proper distribution of voltages tween the photoelectron focusing electrode F and dynodes. Typically (see Figure 1), the inter-stage voltage is supplied using voltage-dividing resistors of 100 kΩ to 1 MΩ between each two dynodes. The anode is grounded, eliminating the potential voltage differences between the anode and external electrical circuit. However, in this configuration there is possibility of electrical damage to the photocathode. There is an advantage then to ground the cathode instead. With a grounded cathode, a dc-decoupling capacitor is used so that the PMT will not respond to a DC signal, only to pulses. Whatever circuit scheme is adopted the question of PMT output saturation needs to be considered. Details of these issues are considered in depth in many references such as [27].

Based on following reasons and PMT 9813QB brochure information, a voltage-divider circuit with consideration for pulse output linearity, ringing and high-voltage power supply noise was designed and built for INTI plasma focus device as shown in figures 4 and 6. In this circuit the value of RL is 100 kΩ.

As shown in figure 1, in our design, decoupling capacitors have been connected to the last three stages to prevent deviation from linearity. The three 10 nF capacitors result in a major improvement in the output pulse linearity. In neutron time-of-flight experiments the pulse width is sufficiently short so that the duty cycle is really small so this method makes it possible to derive an output current up to the saturation level which is caused by the space charge effects in the PMT dynodes. In our voltage divider a high peak pulsed output current, more than several thousand times as large as the divider current can be attained.

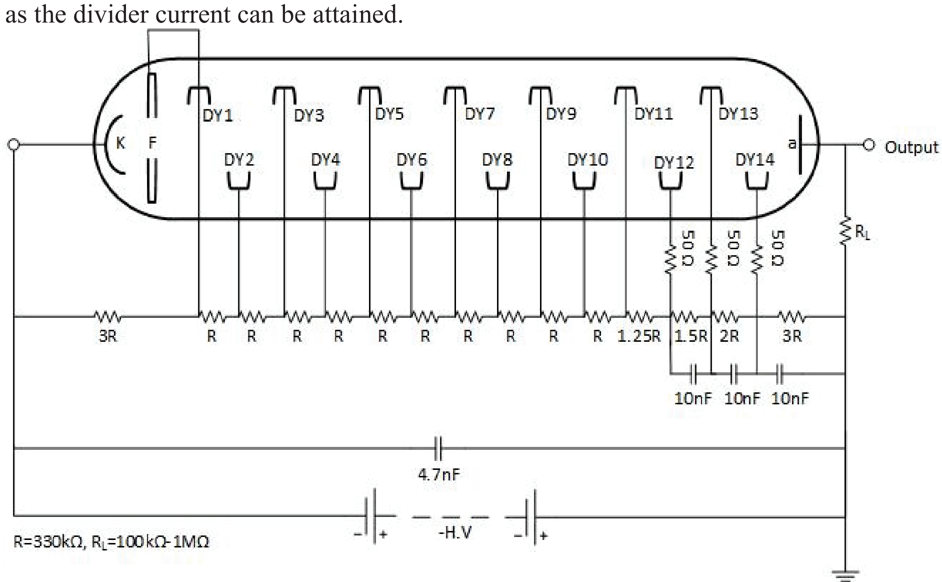

FIGURE 1. 9813QB PMT Voltage-divider circuit with consideration of pulse output linearity and to minimize ringing and high-voltage power supply noise is designed for INTI PF device.

There are two different methods of using the decoupling capacitors: serial connection and parallel connection methods. The serial connection is widely used because the parallel connection requires high voltage capacitors. As shown in figure 1 a serial connection method has been used for our PMT voltage-divider. The following explains how to calculate the decoupling capacitor values. In this calculation we have assumed that all resistors between dynodes have same value, 330kΩ. If we assume the output-pulse peak voltage as V_O, and the pulse width as T_W and the load resistance as R_L, the output pulse charge Q_O per pulse is expressed by $Q_O = T_W \frac{V_O}{R_L}$ .Then we can find the capacitance values of the decoupling capacitors C1 to C3, using Q_O. Also we assumed that C_1, C_2 and C_3 are capacitors connected to DY12-DY13, DY13-DY14 and DY14-Anode respectively. If the charge stored in capacitor C3 be Q3, then to achieve good output linearity of better than ±3 percent, the following relation should generally be considered; $Q_3 \geq 100Q_O$ .Since Q=CV, C_3 is given by $C_3 \geq 100 \frac{Q_O}{V_3}$ .Normally, the secondary emission ratio δ per stage of a PMT is 3-5 at the around 100 V inter-stage voltage. However, we consider the inter-stage voltage drops to about 70 or 80 volts then the charges Q_2 and Q_1 stored in C_2 and C_1 respectively are calculated by assuming that δ between each dynode is 2, as follows: $Q_2 = \frac{Q_3}{2}$, $Q_1 = \frac{Q_2}{2} = \frac{Q_3}{4}$.

Then, we yield in the same way as in C_3; $C_2 \geq 50\frac{Q_O}{V_2}$ and $C_1 \geq 25\frac{Q_O}{V_1}$ .Here, as an example we consider the output pulse peak voltage is V_O=15mV, pulse width T_W=200 ns, load resistance R_L=50 Ω, inter-stage voltage $V_1 \approx V_2 \approx V_3 \approx 100$ V, so each capacitor value can be calculated in the following steps:

We can calculate the amount of charge per output pulse as $Q_0 \geq \frac{15\text{mV}}{50\Omega} \times 200\text{ns} = 60\text{pC}$. The capacitance values required of the decoupling capacitors C_3, C_2 and C_1 are calculated respectively as $C_3 \geq 100\frac{60\text{pC}}{330\text{k}\Omega \times 0.3\text{mA}} = 0.06\text{nF}$, $C_2 \geq 50\frac{10\text{nC}}{330\text{k}\Omega \times 0.3\text{mA}} = 0.03\text{nF}$ and $C_1 \geq 25\frac{10\text{nC}}{330\text{k}\Omega \times 0.3\text{mA}} = 0.015\text{nF}$. These calculated capacitance values are minimum values required for proper operation. We choose capacitance values 10 times larger. In pulse operation, the output deviates from the linearity range when the average output current exceeds 1/20th to 1/50th of the divider current [27]. Moreover to overcome space charge effects, the voltage applied to the last few stages, which carry large electron densities, are set at higher value to provide tapered voltage-dividing as shown in Figure 1. Typical voltage gain characteristics have been presented in Figure 2 for two kinds of voltage dividers; 'A' and 'B'. Voltage divider 'B' has low gain but it is very suitable for pulse operation. Regarding to figure 2, if the supplied voltage between PMT cathode and Anode be -1600 V, PMT gain will be a bit more than 10^6. For our pulsed signals we use divider B.

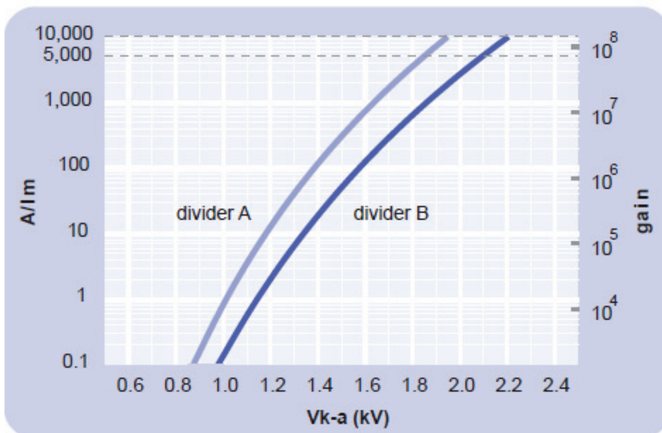

FIGURE 2. Typical voltage gain characteristics for 9813QB PMT

We insert a low-pass filter (resistor- capacitor) into the high-voltage supply line to reduce noise pickup. As shown in Figure 1, we use a 4.7 nF, 2 kV capacitor for this purpose. We used non-induction type of 50Ω damping resistors in last three dynodes to reduce ringing in the output waveform. Figure 3 shows a photo of INTI PF voltage divider circuit.

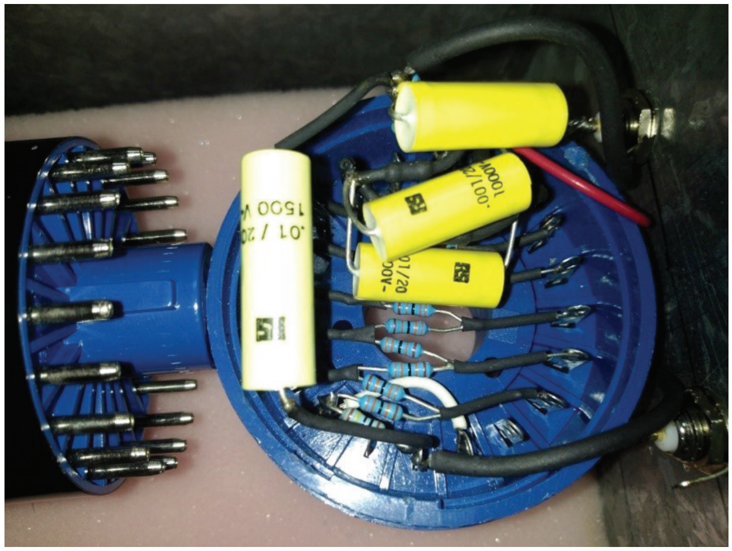

FIGURE 3. INTI PF PMT Voltage Divider

INTI PMT power supply can supply up to ±5 kV voltage at 2 mA current. It can be used for both anode grounded and cathode grounded voltage dividers. Our high-voltage power supply is sufficiently stable and has sufficient capacity to supply a maximum output current which is at least 1.5 times the current actually flowing through the voltage-divider circuit used with the PMT.

Photomultiplier tube housing is primarily used to contain and secure a PMT, however it also has to provide [27]; light shielding, electrostatic shielding and magnetic shielding. So we used galvanized iron for INTI PF PMT tube housing. Actually galvanized iron sheet is suitable for both reducing the external magnetic fields and eliminating the effect of external electrostatic fields. We used some foam inside the housing to protect PMT tube from external harmful physical shocks. Also this structure of foams can prevent diffuse reflection of light.

Since our PMT housing is made of metal, maintaining the housing at ground potential provides an effective shield with respect to external electrostatic fields. As mentioned, photomultiplier tubes are very sensitive to a magnetic field. Therefore, the use of a magnetic shield case is essential for PMT. However, unlike the electrostatic shield, there are no conductors that carry the magnetic flux, it means shielding a magnetic field completely is not possible. However, we used a common technique for reducing the effect of an external magnetic field by using a galvanized iron shield having high permeability around the PMT bulb.

RESULTS AND DISCUSSION

INTI PF is a 3 kJ plasma focus device. It consists of a 16cm height 0.95cm radius copper anode surrounded by six 16 cm height cathode copper bars with 3.2 cm radius. Pyrex tube is used as an insulator between cathode plate and anode bar. Its capacitor bank is 30 μF, 14 kV, 30 nH and total static inductance is around 120 nH. Its mild steel vacuum chamber is evacuated by means of a 12 m^3/h rotary vacuum pump till 10^{-3}mbar. Then working gas is released into chamber at proper working pressure.

We positioned PMT tube 2.6±0.01 m away from the tip of anode; in a side-on geometry. PMT voltage was -1600 V. All signals have been recorded by 3034C 300 MHz oscilloscope. Channel 1, 2, 3, and 4 of oscilloscope used to record dI/dt, PMT, Faraday Cup and X-Ray signals respectively. The length of each RG58 cable for faraday cup, x-ray and Rogovski coil was 3 m. We fired INTI PF device at different pressures of Deuterium gas.

Based on numerical experiments run on the Lee Code, 2.5 Torr and 3 Torr Deuterium pressure are the optimum working pressures for INTI PF at 12 kV. So we fired INTI PF device at 2.5 Torr and 3 Torr Deuterium pressure at 12 kV charging voltage with storage energy of 2.2 kJ. During experiments we realized that number of neutrons per shot for refilled fresh Deuterium is much more than non-refilled Deuterium. In most shots, we could not record neutron signals from non-refilled working gas. The experiments were carried out without proper conditioning of the INTI PF. Conditioning could require more than 50 shots because the INTI PF had been used for carbon deposition experiments with graphite-tipped anode and graphite target. When properly conditioned and regularly used, the INTI PF should be able to be operated consistently for at least several shots before requiring to be refilled. It seems D-D nuclear fusion in plasma focus device is very sensitive to impurity. Also during experiments we observe that PMT-Scintillator system is very sensitive to spark gap radiations. Without suitable light shielding, we could record current-like signals by means of PMT-scintillator system from spark gap radiation. Also our experiments shows that this kind of PMT-Scintillator system is so sensitive even to background light or cosmic ray, so by using proper set up for our oscilloscope we could record cosmic ray signals by our designed PMT-Scintillator system.

Figure 4 shows expanded signals of 2.5 Torr Deuterium and 12 kV. We surmise from the PMT-Scintillator system that first peak corresponds to hard X Ray at time 2810 ns;, and second peak records D-D nuclear fusion neutrons, detected at time 2930 ns. The time differences 120 ns between these two peaks, is time of flight of D-D neutrons. With a flight path of 2.6 m, the speed of the D-D neutrons was found to be 2.17×10^7 m/s. Using kinetic energy equation $E = \frac{1}{2}mv^2$ shows that this time of flight corresponds to 2.5±0.1 MeV neutrons where we have taken the mass of the neutron to be: $m_n = 1.675\times10^{-27}$kg.

Based on our equipment, in the measurement of the flight time under the circumstances of these measurements there is an uncertainly of at least 2 ns. So assuming the distance is correctly measured there is 2% uncertainty in measurement of speed and hence an uncertainty of 4% in energy. So we can claim 2.5±0.1 MeV neutrons; until we can improve the accuracy of the experiment in both time and space uncertainty percentages.

As shown in Figure 4, FWHM of pulsed obtained by hard x ray is around 30 ns while this value for D-D neutron pulse as a second peak is around 45 ns.

As shown in Figure 4, signals from dI/dt, PMT-Scintillator, Faraday Cup and Pin Diode X ray detector have been recorded in the same time. Correlation between these signals together accompanied by voltage probe and computed correlated radial phase dynamics from the Lee Code signals can improve understanding of neutron and hard x-ray radiation dynamic and timing generated by plasma focus pinch column. It seems for this purpose we need to prepare more experiments by means of at least two PMT-scintillator systems, High voltage probe, Faraday Cup, Rogovski coil and Pin Diode as diagnostic systems. High accuracy, high frequency, high signal to noise ratio and finally nanosecond rise time of all of these diagnostic systems are very important to obtain reliable correlation results.

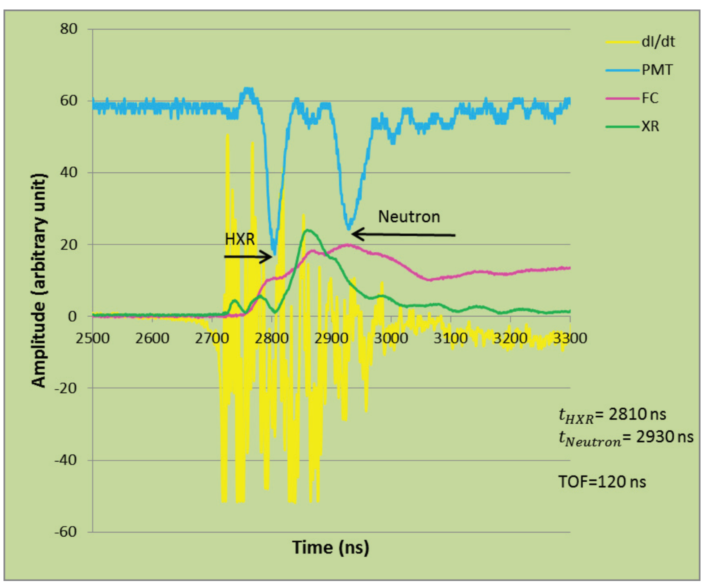

FIGURE 4. 2.45±0.1 MeV D-D neutron detecting from PMT-Scintillator detector in INTI PF, 12 kV, 2.5 Torr,

In summary, a Photomultiplier-Scintillator diagnostic system by anode grounded high pulse linearity voltage divider including NE102A plastic scintillator has been set up in Center for Plasma Research of INTI. It has detected D-D neutrons in INTI plasma focus device with clear and high signal to noise ratio. Neutron TOF of 120 ns has been measured from the time differences between hard x-ray peak time as a first peak and neutron peak time as a second peak while flight length was 2.6 m. Calculation shows these neutrons have 2.5±0.1 MeV kinetic energy.

CONCLUSION

A Photomultiplier-Scintillator diagnostic system by anode grounded high pulse linearity voltage divider including NE102A plastic scintillator has been set up in Center for Plasma Research of INTI. It has detected D-D neutrons in INTI plasma focus device with clear and high signal to noise ratio. Neutron TOF of 120ns has been measured from the time differences between hard x-ray peak time as a first peak and neutron peak time as a second peak while flight length was 2.6 m. Calculation shows these neutrons have 2.5±0.1 MeV kinetic energy.

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