Dense Plasma Focus as Collimated Source of D-D Fusion Neutron Beams for Irradiation Experiences and Study of Emitted Radiations

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Abstract. A "table-top" 2 kJ, 250 kA plasma focus, the PACO (Plasma AutoConfinado), designed by the Dense Plasma Group of IFAS is used in its optimum regime for neutron yield for obtaining collimated pulsed neutron beams (100 ns). A simple and low-cost shielding arrangement was developed in order to fully eliminate the 2.45 MeV neutrons generated in the PACO device (10^8 per shot at 31 kV, 1-2 mbar). Conventional neutron diagnostics: scintillator-photomultiplier (S-PMT), silver activation counters (SAC), etc., are used to determine the minimum width of the shielding walls. Emission of very hard electromagnetic pulses is also studied. Collimation using lead and copper plates is made to determine the localization of the very hard X-ray source. The maximum energy of the continuum photon distribution is estimated in 0,6 MeV using a system of filters.

Keywords: Dense plasma focus, fast electrical discharges, pulsed neutron and X-ray generator
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INTRODUCTION

A plasma focus device [1, 2] essentially consists in a pair of coaxial electrodes into a gas atmosphere. A high voltage pulse power system discharges on the coaxial electrodes through a spark-gap. The gas disrupts on an insulating sleeve, generally made of Pyrex glass and a paraboloidally shaped current sheath (cs) is formed. A current density **J** circulates in the cs being the central electrode one of the circuit elements. The azimuthal magnetic field **B** generated by this current interacts with the cs through the Lorentz force **F** = **JxB**; the cs is then accelerated in its coaxial stage. It incorporates the neutral gas that strikes up, ionizes it and leaves vacuum behind. The roll-off stage develops and then there is a radial compression by Z-pinch effect (Fig. 1). In its final stage a plasma column is formed, reaching densities of 10^{26} m^{-3} and temperatures of about 1 keV. In deuterium plasmas these conditions are sufficient to produce nuclear fusion reactions. As is known, the plasma foci are relatively efficient sources of electromagnetic radiation and particles. They emit short pulses of fusion neutrons (around 100 ns long), soft and hard X-ray pulses (about 10 ns each) and energetic electron and ion beams. Research in order to optimize the emission performance has been made in the last decades. Applications cover a wide range: soft X-ray microscopy, soft X-ray and electron lithography, humidity measurement from neutron attenuation [3], material introspection from fast and thermalized neutrons, astrophysical laboratory simulations, etc. Attaining to specific neutron applications,

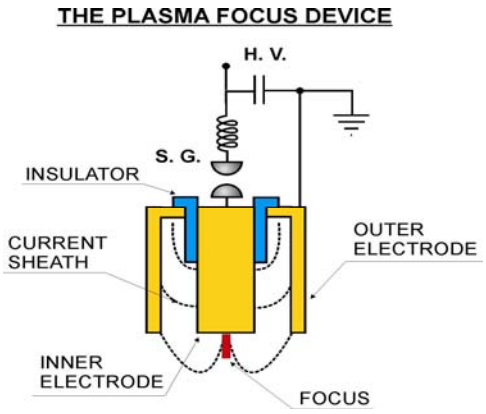


FIGURE 1: Schematics of the plasma focus. Dotted lines indicate the current sheath profile in different stages of its dynamics: formation on the insulator, coaxial acceleration, radial compression.

such as non-intrusive detection through irradiation with neutrons of chemical elements in molecular structures of dangerous substances for its identification, requires getting collimated beams of these.

In the following, some experimental studies to obtain collimated neutron beams in the table-top plasma focus PACO of Tandil, Argentina, are described. The detection of very high energy X-ray emitted from this machine is also described and analyzed.

I – SPECIFIC CHARACTERISTICS OF THE DPF PACO

The DPF PACO (Mather type) has a coaxial gun made with cylindrical OFHC copper anode, 40 mm long, 40 mm in diameter, brass cathode composed by 12 bars regularly disposed on a circumference 10 cm in diameter. The glass insulator sleeve is 15 mm long and 40 mm in diameter. The energy is stored in a capacitor bank of 4 μF, 20 nH, 31 kV. The pure deuterium filling pressure for optimum neutron yield is on the range 1–2 HPa. Neutron yield, measured with silver activation counters (SAC) resulted of $3x10^8$, averaged on more than two thousand discharges. The angular dependence with spatial resolution by means of CR-39 nuclear track detectors [4] was measured (see Fig. 2). The neutron anisotropy value, calculated as ϕ_0 / ϕ_{90} where ϕ_0 and ϕ_{90} are the neutron flux values measured through SAC in end-on and side-on directions, respectively, and averaged on several hundred discharges, resulted to be 2. Hard X-ray pulses were also detected, apart from many other radiations [5].

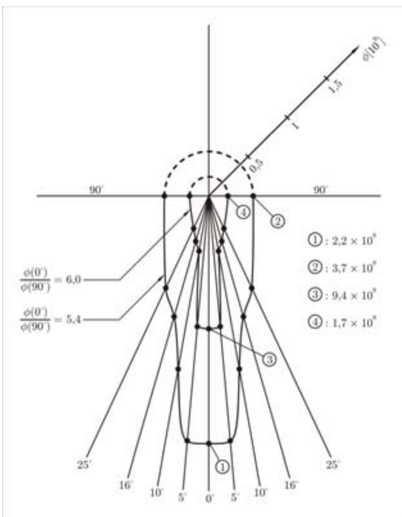


FIGURE 2 Angular dependence of the neutron flux in PACO measured with CR-39 detectors

II – BASIC CONSIDERATIONS FOR SHIELDING REQUIREMENTS

Experiments involving sample irradiation experiences with neutron beams require the energetic neutrons (2.45 MeV) as the only directly emitted from the source. Floor and walls mainly of cement and brick and objects of different materials surrounding the source (metallic tubes, capacitors, etc.) can produce several effects in its interaction with neutrons. In particular, for elastic scattering the transferred energy is less as the higher value according to the atomic mass. Then, it is possible that undesirable scattered neutrons with energy not much different than that original one could be detected if materials with high atomic mass are present. On the other hand, as a result of inelastic interactions of energetic neutrons with this type of materials (for instance, metals) emerge ionizing radiation, including X or γ. These effects would produce measurements with not enough clear results, for which is important to minimize the possibility that the emitted neutrons do scattering in the objects into the laboratory. In order to perform reliable irradiation experiences an adequate shielding for the DPF PACO discharge chamber was searched. A 2.45 MeV neutron interacting with highly hydrogenated materials, like water or paraffin wax, transfer efficiently its energy through elastic scattering. In fact, on 27 neutron-proton collisions in average, a 2 MeV neutron reduces its energy up to $2.5\text{x}10^{-2}$ eV. The fast neutrons are then thermalized by hydrogenated material. The shielding must be complemented with another material able to absorb thermal (10^{-3} eV) and epithermal (10^{-1} eV) neutrons. In those energy ranges, cadmium and boron result very effective for this purpose. Even if Cd has higher cross section than B, it produces very high energy γ radiation as result of one of its possible interactions with neutrons. The reaction $^{10}B\ (n,\alpha\gamma)^{7}Li$ gives also γ radiation, but it is not so energetic (0.48 MeV) requiring then less shielding.

III – THE EXPERIMENT

The shielding concept for neutrons in the present device is an enclosure of composed structure. A first wall is made of paraffin wax bricks, 8 mm thick. Another wall, following the former one, was made of polyethylene containers 150 mm thick, fulfilled with a concentrated chemical solution of $Na_2B_4O_7$, 1 Molar in water. The paraffin wax moderates the fast neutrons and the chemical solution has two main functions: water thermalizes neutrons that eventually would emerge very energetically from paraffin and boron absorbs thermal neutrons. Polyethylene containers have been chosen because of properties of this material as neutron moderator. Paraffin and solution of B in water were used as they shows good collimating properties, are inexpensive and easily obtainable. The entire experiment is surrounded by the absorbing fast neutron material. A preliminary experiment of fast neutrons collimation by interposing bricks of iron forming a channel was performed at IFAS producing unsatisfactory results. Iron has a resonance for capture neutrons at two hundred keV, far from the 2.45 MeV fusion neutrons, giving gamma rays hard, of 7 MeV, very difficult to stop. Nevertheless, it is possible that neutrons scattered in floor, walls, roof, etc, have such kind of energy, becoming dangerous the use of iron. A more important effect of using iron is that it has a high cross section with neutrons for elastic scattering, striking neutrons in other direction and making possible its detection and a confuse measurement. The mentioned preliminary experiment was made with a

scheme of three sets of couple of iron bricks forming a channel of rectangular cross section aligned with the source and the detector. A pulse very wide and noisy in the zone hard X-ray and neutrons was obtained from the SPMT system. The use of a cylindrical tunnel performed in a big iron block would get better results, but this way has high cost, is heavy and unpractical for use in applications. In the literature are presented moderating materials (wax) with absorbing thermal neutrons (boron) and also very thin metal (as lead) plates to absorb the not much hard (0.48MeV) X radiation. By example, Ref. 6 says that inclusive for fissile material transportation, highly hydrogenated material is used as shielding. Even if an easily commercially available shielding is taken into account, it had a compound of LiF into a plate of highly hydrogenated material (wax). Form Ref. 7, when LiF compounds are interposed between fast neutron source and detector, a very thick wall of Plastic (or similar hydrogenated material, such wax) doped with Boron, was necessary, because of the reaction of Li with neutrons, that gives Tritium which after, fast neutrons from the tritium-Li reaction. This reaction, anyway, has a low probability, for which the possibility of using the commercial compounds, searching also some with B, is not detached, but for feasibility tests in the present particular experiment, the collimation system presented here was preferred. It is observed that the scheme here shown is very low cost, light, easy to get everywhere and efficient. Anyway, it is planned to do future tests by using commercial materials.
The plasma focus here used is a tabletop pulsed neutron generator with an output of around $3x10^8$ per pulse. The combination between the low cost shielding and a portable neutron pulsed source makes it very interesting in the field of applications.

a) Minimum Paraffin Thickness for an Efficient Shielding

The DPF PACO discharge chamber was totally surrounded with 40 mm-thick paraffin plates, with a window opened in the end-on direction (at the bottom of the chamber, see Fig. 3). A SAC was located there to register the neutron yield in every shot. Series of discharges have been made totalizing about a hundred of them. The average neutron yield was 2×10^8 neutrons per pulse. A scintillator-photomultiplier system (S−PMT) was located (side-on) at 2.5 m from the focus to detect time-resolved neutron and hard X-ray pulses. The thickness of the walls was increased up to detect no neutron signal in the S−PMT. The minimum necessary thickness found for getting null neutron detection was 80 mm. Fig. 4 a) and b) shows two typical oscillograms, each one corresponding to a discharge with $3x10^8$ neutrons (measured with the SAC). Fig. 4a) (without shielding) shows in the upper trace a short hard X-ray pulse followed by a neutron pulse meanwhile the Rogowski coil signal is observed in the lower trace. The separation corresponds to the time-of-flight of neutrons from the focus up to the S−PMT. In Fig. 4 b) (paraffin shielding of 80 mm) only the hard X-ray pulse can be observed.

b) Collimated Neutron Beam Obtaining and measurement

For obtaining a collimated neutron beam respective orifices were performed through the paraffin plates located at both sides of PACO. Both orifices have been aligned with the pinch zone using a laser beam passing through the device’s lateral windows. Neutrons have been registered by means of the SAC and the S−PMT located in front of respective orifices (see Fig. 3). More than 50 measurements have been made; a half with cylindrical orifices 8 mm – diameter and in the other half the diameter of the orifice has been increased up to 15 mm. The average counts registered by the SAC increase less than those registered by the S−PMT. This fact is due that neutrons thermalized by the paraffin shielding can still be detected by the SAC. Contrarily, S−PMT only detects neutrons that are not stopped by collisions with the hydrogenated material, as can inferred from the better concordance between solid angles and S−PMT measurements. See obtained average values in the following table:

	8 mm orifice	15 mm orifice	Ratio
SAC counts	50 ± 3	68 ± 5	0,73 ± 0,10
SPMT trace area	17 ± 3	57 ± 5	0,30 ± 0,07
Solid angle	0,0032 ± 0,0001 sr	0,0112 ± 0,0001 sr	0,29 ± 0,01

IV.-HIGH FREQUENCY ELECTROMAGNETIC (hard X-RAY) EMISSION

Another characteristic oscillogram obtained during the normal operation of PACO discharges is shown in Fig. 4 c). Lower trace: dI/dt; upper trace: hard X-ray and

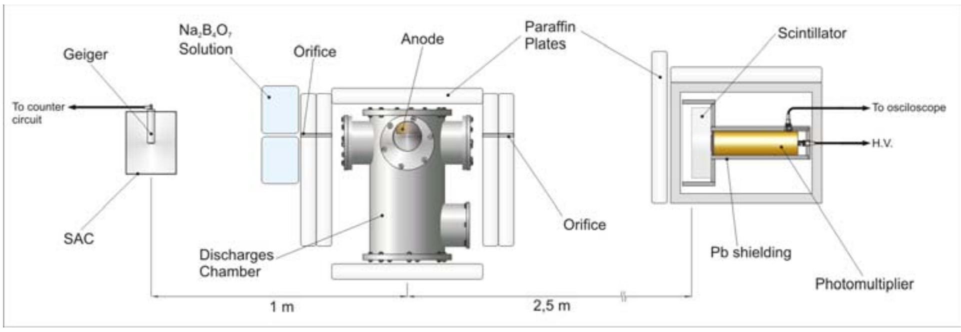
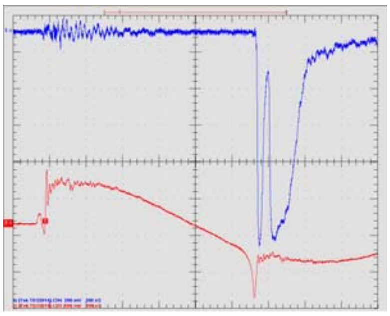
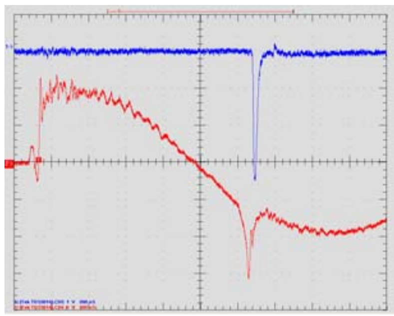


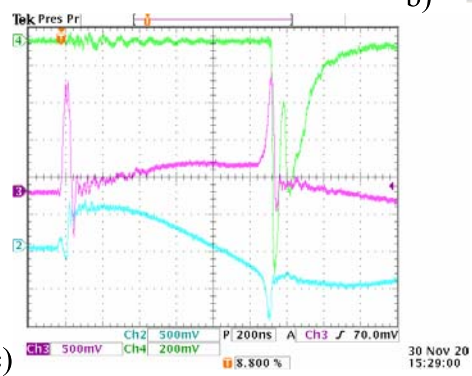
FIGURE 3- Experimental setup for obtaining collimated neutron beams and diagnostics



a)



b)



c)

FIGURE 4.- a): shot #24398; PACO without shielding; b): shot #24683 shielding 0.09 m thick. Upper trace: S-PMT; lower trace: total current time-derivative; c) Voltage between electrodes (medium trace)

neutron emission. At the maximum of the discharge current (I_o~ 250 kA), near the maximum compression, dI/dt experiments an abrupt change in coincidence with the hard X-ray emission. Voltage divider probe measurements show also an over-voltage peak when the hard X-ray occurs (middle trace). Fig. 5 shows a sequence of plasma column pictures (5 ns exposure time) in synchronism with the sharp current fall. It can be clearly appreciated, from left to right, the progressive narrowing of the column (m=0 instabilities). This behaviour is observed in many plasma focus experiments. A possible interpretation [8, 9] is that, in fact, MHD instability could be responsible for the generation of high electric fields that accelerates charged particles. A trapped magnetic flux cavity is formed (roughly toroidal geometry) and fast compressed. This sets up a strong transient electric field suitable for charged particles acceleration. Calculations of Ref. 6 give as a result electric fields of about 1 MV/cm. This is consistent with the very energetic (relativistic) and collimated electron beams measured in PACO [10] very hard X-ray generation into the column by bremsstrahlung on He^3 , H^3 and heavier nuclei coming from the anode and insulator. Subsequently, the electron beams (that through multiple collisions into the focus zone reduce their energies) shock on the anode producing hard X-ray pulses.

In the present experiment, such as reported before by other researchers, two sources were found to be the main sites of hard X-rays: the focus itself and the anode. A small tungsten cylinder, 5- mm- thickness, was inserted in the anode for maximizing the bremsstrahlung conversion process. For the first emission site, it is speculate that the highly collimated (on z –axis) and very high-energy electron beam generated, interacts through collision processes with the dense (~ 10^{20} cm^{-3}) and high temperature (some keV) ions (H isotopes, He, high Z impurities, etc.). Finally the components of the electron beam that pass the focus region, some of them losing energy by the mentioned collision processes, strikes a small tungsten cylinder into the anode generating the second and intense bremsstrahlung emission source. Interaction of the electron beam with the tungsten cylinder produces significant ablation of this metal (Fig. 6b). Emission from the anode was widely employed to obtain intro radiograph images with high spatial (indicating a small size source) and temporal resolution of different object types (see example in fig. 6a). To clearly distinguish between the high frequency electromagnetic emission from the focus and from the anode, a simple arrangement employing Pb plates (50x50 cm^2 and 10 mm thick) assembled with respective copper plates in parallel set up was used. The focus region and the SPMT (side-on) have been aligned with a laser passing through small orifices made in the lead plates. So, these acted as effective collimator for the electromagnetic radiation. The SPMT was completely shielded with lead to eliminate spurious hard X-rays reflected in walls, roof and different objects in the lab. This arrangement allowed the estimation of the maximum photon energy of the continuous emission that emerges from the focus, by interposing between orifices Pb sheets of four different thicknesses.

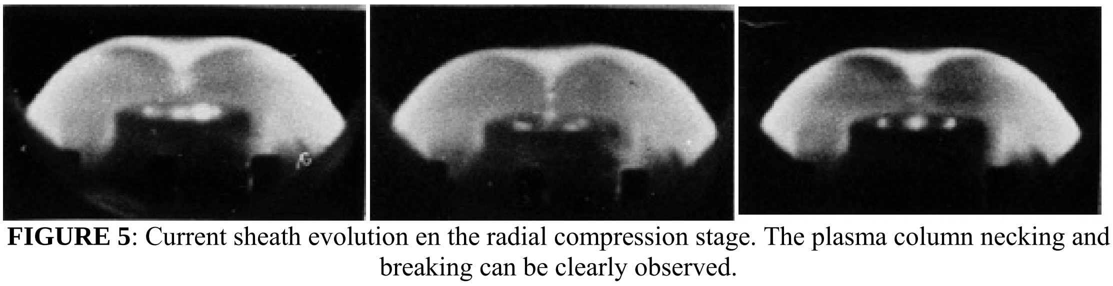
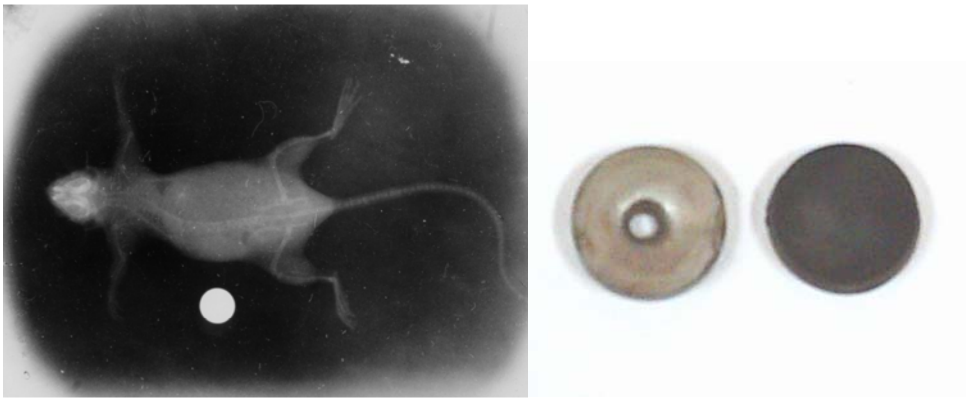


FIGURE 5: Current sheath evolution en the radial compression stage. The plasma column necking and breaking can be clearly observed.



a b

FIGURE 6 a) Radiographic image of an alive mouse (with PACO device) 10 ns exposure time and high spatial resolution; b) W disk in the free extreme PACO' anode.; right: new; left: after 500 shots

The intensity of this hard radiation not large, then SPMT was used, because the radiographic films have not sufficient sensitivity. More than ten discharges with each sheet thickness were made. Relative intensities and attenuation coefficient have been determined and a value of not higher than 0.6 MeV resulted.

As conclusion, making a very accurate collimation work, the presence of two hard X-ray (ten nanosecond long pulses) sources have been located in the plasma focus PACO such as in many other plasma focus previous experiments by other researchers: one into the focus zone (very hard and low intensity radiation) and other on the anode (less hard, high intensity), in accordance with the presence of energetic and collimated electron beams, detected in previous works [10]. Application for high resolution radiographs of very fast moving systems is a possibility for plasma foci. 100 ns long pulses of collimated pulsed 2.45 MeV neutron beams have been obtained, making possible experimentation of interaction of these neutron beams with different material, with many possible applications (water and different minerals detection in soil, non invasive inspection of luggage, etc.).

The plasma focus is a device very appropriate for applications as collimated pulsed source of neutron beams, hard X-ray and other radiation. It is very low cost, small size, reproducible, reliable, transportable, simple to construct and manage, very safe. The mentioned points (and other) make plasma foci to have comparative advantages with respect to other possible sources of radiation, such as accelerators or fission reactors.

RERERENCES

1. J. W. Mather, "Dense Plasma Focus" in Methods of Experimental Physics, R. Lovberg and H. Griem, Eds., Academic Press, New York (1971) 187.
2. V. Imshennik, N. Filippov, T. Filippova., Nuclear Fusion **30 (**1973) 929.
3. M. Milanese, R. Moroso and J. Pouzo , European Physical Journal **27** (2003) 77-81.
4. J. Pouzo, F.Castillo-Mejía, M.Milanese, R. Moroso, J. of Phys. D: Appl. Phys. **33** (2000 141-147.
5. J. Pouzo, F. Castillo, M. Milanese, R. Moroso, M. Santiago, IEEE Tr. Pl. Sci. **29** (2001) 921-926.
6. Coeck et al.(Nuclear Instr and Meth in Physics Research A 476 (2002) 273-276)
7. J. Osborn et al., Physica B: Condensed Matter, Vol. 385 (2006) 1321
8. H. Yousefi, S. Mohanty, Y. Nakada, H. Ito and K. Masugata; Phys. Plasmas 13, (2006) 4506
9. G. Nagafuki, R. Fahel, K. McLenithan, M. Sheppard, Chan Choi, B. Freeman, 1996 IEEE Int.l Conf. on Plasma Physics (1996) 239.
10. J. Pouzo, H. Acuña, M. Milanese, R. Moroso, European Physical Journal D **21** (2002), 97 - 100.