Neutron emission from a Plasma Focus device: a neutron radiography diagnostic?

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Abstract. The Plasma Physics and Plasma Technologies Laboratory of the Chilean Nuclear Energy Commission (CCHEN) has been working on pulsed power devices, in a plasma focus configuration and using Deuterium as a filling gas to produce neutron emission, – over some tens of nanoseconds – in the range of $10^4$ to $5 \times 10^9$ neutron/pulse. The present report shows a comparative analysis of this kind of neutron emission and its development both as a diagnostics method for the plasma itself, as well as for its potential application towards ultra-fast neutron radiographies.

1. Introduction
The advantage of non-invasive diagnoses, as much in high technology systems, as in biological tissues, is undisputed. Neutron radiography is a one of the classical diagnostic methods that apply with great advantage in these fields [1,2]. However, using neutrons as a diagnostics method for the accomplishment of neutron radiographies has been limited as much by the kind of source that generates neutrons as by the associated monetary costs. Meanwhile the time allows that new applications appear, different kind of neutrons sources are developed [3]. The present work makes a brief analysis about the conventional neutron radiography diagnosis as a reference for the viability and potentiality of the fast pulsed power neutron generators – that use the Plasma Focus mode of its electrode configuration [4-6] and Deuterium as filling gas – to produce ultra-fast neutron radiographies.

It is possible to separate in two groups the existing traditional neutron sources: those that have a permanent radioactive source (radioisotopes, sub-critical sources and nuclear reactors, for example); and those that are known as “on-off” sources because a permanent radioactive source does not exist in this case (linear accelerators and cyclotrons, for example). For neutrons, different ranges of energy exist available to be used in order to obtain images. The slow neutrons are the most important ones to obtain images, and between them it is possible to discriminate between the slowest ones, so called cold neutrons ($< 0.01 \text{ eV}$); and then, the so called thermal neutrons ($0.01 \text{ eV}$ to around $0.3 \text{ eV}$). The latter present the best characteristics in terms of neutron attenuation for imaging purposes. Thus, most neutron radiographies are produced with neutrons in that energy range [7]; finally the epithermal neutrons (around $0.3 \text{ eV}$ to $10^4 \text{ eV}$) are useful for just some neutron radiography images depending of the analyzed object. As well as the epithermal neutrons the fast neutrons (between $10 \text{ keV}$ and $20$...
MeV) are also useful when the object to diagnose is strongly absorbent of thermal neutrons or due to objects of important thickness (10 cm of steel, for example).

The neutron flux for neutron radiographies have a wide range of values, from $10^1$ to $10^9$ n/cm$^2$/sec, to produce images of a wide range of resolutions; but the typical values are normally in the range of $10^6$ to $10^9$ n/cm$^2$/sec of thermal neutrons [2]. The Figure 1 shows some examples of neutron radiographic images obtained when the nuclear experimental reactor of the CCHEN, RECH-1, is used. For this particular case, the images of Fig. 1, the neutron flux of thermal neutrons, in a radiation exposition surface of 200 cm$^2$, is of the order of $10^7$ n/cm$^2$/sec; and for exposition times between 1 and 3 min, the obtained spatial resolution is of the order of 25 mm.

Also, an important and critical procedure or technique is the method to impress the image in a film. The most popular technique is the X-ray film-plate converter combination, where an image is obtained when the constitutive element of the plate converter captures neutrons emitting a radiation able to impress an X-ray film. Recently the CCD cameras with intensifiers are replacing the X-ray films, and it has been tested using a nuclear reactor (10$^7$ n/cm$^2$/s) and a portable neutron generator (a penning source type) whose neutron output is 5×10$^4$ n/cm$^2$/s and 5 min exposure time [8].

Two kinds of plate converter are used to impress subsequently an X-ray film, those ones that have an immediate radiation emission when neutrons are captured, and those ones that are activated when neutrons are captured but it radioactively decays in a time depending of the elements of the converter. These two kinds of used plate converter give place to two methods of radiation exposition of the X-ray film: in a direct method both plate converter and X-ray film are exposed to the radiation meanwhile, in an indirect method just the plate converter is exposed to the radiation. These two modes are usually implemented but, in both cases, when the emitted radiation from the source is contaminated with $\gamma$ rays, it is impossible to use any of the conventional converters (for example: Ga, In, Cd, and Ag among others).

2. Pulse power neutron generators and experimental results
The pulse power generators that their electrodes are in a plasma focus (PF) configuration can generate neutrons when deuterium (D$_2$) gas is used as filling gas. In spite of everything, there exists a scientific discussion about the mechanisms which produce neutrons, but the D-D nuclear reaction (thermonuclear fusion) and the atomic ion beam-target scattering mechanisms are widely accepted [6]. In any case, PF devices produce fast neutron pulses (~ 2.45 MeV) of some tens to hundreds of nanoseconds. In our laboratory we have three PF devices that it has been studied when producing neutrons. Using deuterium as filling gas, and depending in charging voltage and pressure discharge,
2.45 MeV neutrons have been detected with a mean neutron yield from $10^4$ to $10^9 \text{n/pulse}$ depending which experimental device is used for it (see Table 1) [6]. These devices are of the type “on-off” previously described, and not any more radiation or neutron emission is generated when the gas discharge has finished [9].

| PF device | Neutron yield (n/pulsed) |
|-----------|-------------------------|
| PF-50J    | $\sim 3.6 \times 10^4$  |
| PF-400J   | $\sim 1.2 \times 10^6$  |
| SPEED2    | $\sim 10^{10}$          |

Now, for the purpose of to appreciate the pulsed neutrons produced by the PF device to obtain neutron radiographies, it is necessary to determine the quantity of neutron corresponding to the images shown in the figure 1. So, considering a continuous thermal neutron flux of $10^7 \text{n/cm}^2/\text{sec}$ arriving into a film that the exposed area is $200 \text{ cm}^2$, and with an irradiation time of $1 \text{ min}$, the exposed film would receive around $6 \times 10^8 \text{n/cm}^2$ to impress the image in it. By other hand, considering $10^{10}$ neutrons per pulse emitted isotropically from a PF device (the SPEED2, for example), the quantity of neutrons per pulse and per $\text{cm}^2$, at 10 cm far away from the pinch source, will be close to $3 \times 10^7 \text{n/cm}^2/\text{pulse}$. It means around 20 pulses of neutrons to impress a film with an adequate quality of contrast and resolution of images like those shown in the figure 1. However, using recording systems based on intensified CCD cameras, a single shot would be enough for the SPEED2 machine and $10^4$ for the PF-400J.

Actually, just one PF device is commercialized in the world market. This device is a compact device (250 Kg) with a stored energy of 5 kJ, and it produces $10^{10} \text{n/pulse}$ from D-D y D-T nuclear reactions [10]. In spite of not having much technical information, it is possible to known that this pulsed neutron generator have some elements and technology to enhance the neutron emission, different to the conventional one existing in the experimental devices (for example, accelerated ions colliding targets of Ti, Sc, or Zr, atomic elements which allow to enhance the neutron production).

3. Conclusions
To produce neutron radiographies using PF devices it is necessary to improve its technological performances, indeed its repetition rate for example. In the case of a hundred of joule device, as the PF-400J, a repetition rate of 1 kHz could be enough after 10 integrated shots. On the other hand, materials with high efficiency to convert fast neutrons (with energy of some MeV) to photons are required.

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