Experimental Study on the Optimization for Neutron Emission in a Small Fast Plasma Focus Operated at Tens of Joules

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Abstract. This work reports results of a systematic experimental study dealing with the optimization for neutron emission of the PF-50J plasma focus. The device was operated in a repetitive mode at repetition rates of 0.1-0.5 Hz. Optimal configurations, neutron emission rates, observed anisotropy, analysis and contrast of "good" and "bad" shots are currently presented. Additionally, engineering aspects on the neutron emission were also studied, such as contaminants removal circuit and chamber design.

1. Introduction.

PF-50J is a small fast plasma focus device operated at CCHEN in Chile. The device has characteristic parameters given by: $160nF$ equivalent capacitance, ~ $40nH$ total inductance in short circuit, $150ns$ first quarter of period, 25 - 35kV charge voltage, energy E ~ 50 - 100J, 50-70kA peak current in short circuit. In the past, this device has been reported to be the first plasma focus which emits fusion neutrons when operated with deuterium at energies of only tens of joules [1]. It has been also demonstrated that this device reproduces the dynamics and high density scenarios observed in machines operated at energies several orders of magnitude higher [2]. Notwithstanding the systematic research already done in PF-50J, the optimization of the device as a neutron has not been studied in detail. In comparison with other devices, PF-50J is a extremely fast and low energy plasma focus. While in conventional devices the complete evolution of the discharge to form the pinch last typically 0.5-10μs, in PF-50J all the process including sheet formation and lift-off, axial and radial transit, pinch and rupture of the column last around $150ns$. Consequently, the electrodes results in a hybrid configuration ($L_{eff}/2r_a < 1$, L_{eff} effective anode length and r_a anode radius), where the effective insulator length (L_{ins}) is several times the effective anode length as well. With this electrode geometry, the lift-off stage has similar duration than the axial and radial stages. In the most plasma focus devices the quotient L_{eff}/L_{ins} has a value in the range 2-10, while r_{cat}/r_a is around 2.5 (r_{cat} cathode radii), in PF-50J L_{eff}/L_{ins} ~ 0.17 and r_{cat}/r_a ~ 4.5 [3].

The drive parameter is defined as $S = I_{peak}/r_a \cdot P^{1/2}$ where I_{peak} is the peak of current and P the filling gas pressure. It has been found that S in the range 70-84 $kA/cm \cdot mbar^{1/2}$ for neutron optimized devices [4, 5]. Nevertheless, setting up device operation in this range for S does not ensure optimal operation. Optimization of plasma focus devices is usually done by an experimental survey in parameters as charge voltage (V_c), pressure, effective anode length and anode radii. In this work is presented an study on the optimization of PF-50J device as neutron source. Optimization is done at
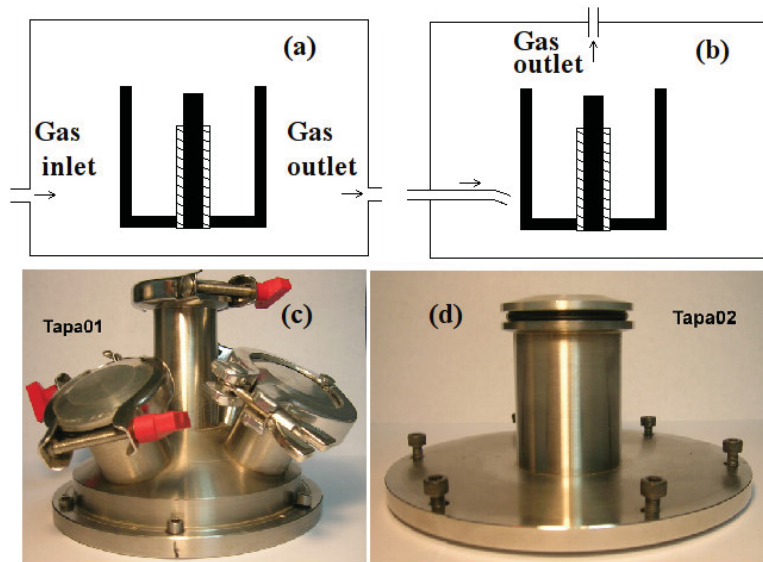
Figura 1. (a) Normal gas flow circuit, (b) Modified gas flow circuit, (c) Tapa01 chamber cup and (d) Tapa02 chamber cup.

fixed charge voltage and anode radii. One of the motivations is to study experiments with $r_{cat}/r_a \sim 2.5$, as well as to study influence of gas flow and chamber geometry in neutron emission.

2. Experimental setup and diagnostics.

The electrode configuration consist of an central stainless steel anode of 3 mm radii and a hollow of 4.5 mm diameter. The hollow deep is 18 mm. The insulator is made from alumina, 1/4" inner diameter and 3/8" outer diameter. The insulator effective length is 24.5 mm. The cathode is made from six stainless steel 5 mm diameter rods, 34 mm effective length. The inner cathode radius is 6.5 mm and the rod axis radius 8.75 mm. At the base of the bottom cathode plate and next to the insulator base a field distortion element was placed. Discharge is operated in autorupture at 28.5 kV charge voltage. Deuterium in flow is used as filling gas.

Neutron diagnostics consist in two detection systems based on [3]He proportional counters tubes for neutron yield measurements [6, 7] and arranges of plastic scintillators coupled to photomultipliers neutron measurements with temporal resolution. The [3]He detection systems were calibrated in efficiency only by using a standard isotopic fast neutron source ([252]Cf). Neutron production is obtained by the use of a recently developed methodology to count events from the net output detector signal area and detector's efficiency [7].

3. Description of experimental studies.

The first study is related with optimization of PF-50J as neutron source. For this purpose effective anode lengths of 3.7 *mm*, 4.6 *mm*, 5.5 *mm*, 6.3 *mm* and 6.8 *mm* were used. Filling gas pressure was varied in the range 2-12 *mbar*. This study was done at normal flow circuit (see fig. 1.a). Neutron emission rate per pulse was measured from series of experiments at different operative conditions (*P* and L_{eff}). Besides the emission rate, some pieces of the neutron yield distribution are obtained. In particular,

- *Non null emission rate (NNE)*. It is the emission rate calculated only from shots registering neutron emission.

- *10% highest emission rate (10%S)*. It is the emission rate calculated from the 10% of shots with highest emission.

- *Best shot (BS)*. It is the neutron emission of the best shot in each series of experiment.

Each series of experiments has a sample size in the range of 150-300 observations.

The second study is focused on some engineering aspects of PF-50J device as a neutron source. The interest is to study the influence of the level of gas flow, gas flow circuit and size of the discharge chamber in the pulsed emission rate. Two setups for the level of gas flow were tested: medium and high. For the gas flow circuit two configurations were studied, in the first namely "normal", gas inlet and outlet are placed side in the chamber and far from the electrode configuration (fig 1.a). In the second namely "modified", gas inlet is placed side-on close to the electrode configuration, while gas outlet is placed end-on (fig. 1.b). Size chamber is modified by using two kinds of chamber cups, namely "Tapa01" and "Tapa02", as could be seen in figs. 1.c and 1.d. Four experiments were done with different setups as shown in table 1.

Table 1. Experimental setup for study on engineering issues.

Experiment	Chamber		Gas Flow Level		Flow Circuit	
	Tapa01	*Tapa02*	*High*	*Medium*	*Normal*	*Modified*
Serie1		●		●	●	
Serie2	●			●	●	
Serie3		●		●		●
Serie4		●	●			●

4. Results and analysis.

Plots for neutron emission rate as a function of pressure for different effective anode length are shown in figure 2. In this plot the second axis correspond to the emission rate estimated over a solid angle of 4π if source would be isotropic. Optimal configuration is obtained from the experiments to be

$$L_{ef} = 6.3\ mbar\ and\ P = 5.3\ mbar,$$

when device is operated at $r_a = 3\ mm$, $r_{cat}/r_a = 2.17$, $V_c = 28.5$, autorupture, 0.1-0.5 Hz. With this setup neutron emission rate end-on is 240,5 ± 28 *n/pulso·sr* and 198,4 ± 22 *n/pulso·sr* , the estimated total neutron emission is 214,2 ± 17,4 *n/pulso*. In the plasma focus literature is usually reported the device neutron yield. This quantity is related to the neutron production observed in the so called "good" shots. In our case, we define "good" shots as the experiments inside the 10%S piece of the neutron yield distribution. For PF-50J in the optimal configuration reported in this work, the neutron
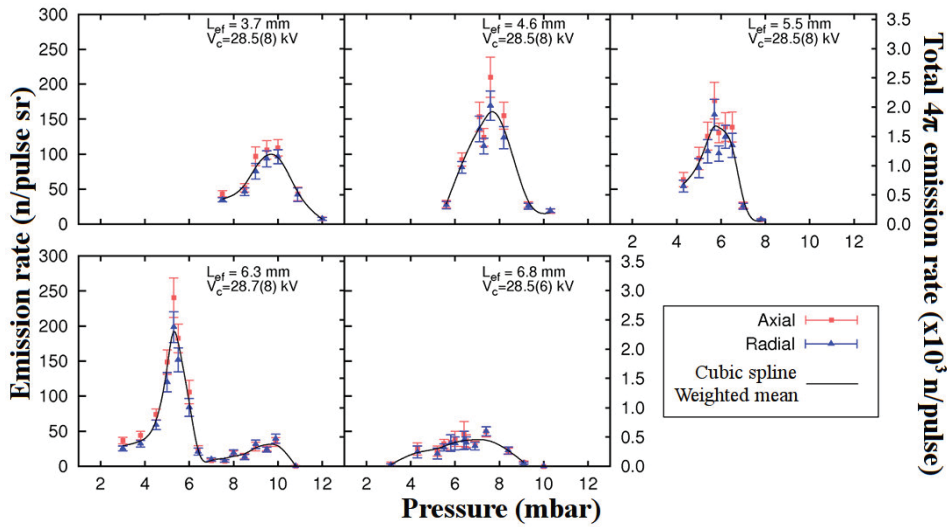
Figure 2. Neutron emission rates for different pressure and effective anode length. Operational conditions are D_2 in flow, $r_a = 3$ mm, $r_{cat}/r_a = 2.17$, autorupture.
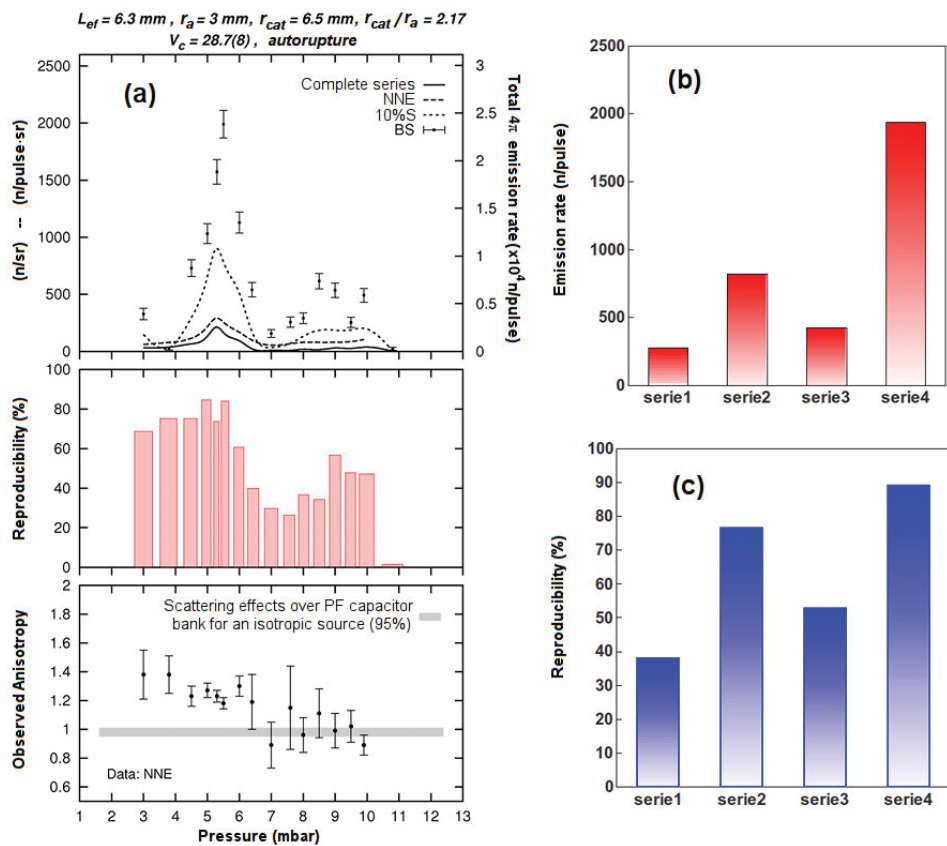

Figure 3. (a) Neutron emission, reproducibility and observed anisotropy for optimal configuration. (b) and (c) Emission rate and reproducibility for experiments on engineering issues.

yield is 1.3×10^4 *n/pulse,* which is in agreement with neutron scaling laws for devices operated with energies up to 1 *MJ* [7, 8]. The most intense shot registered during the experiments was $2.6 \pm 0.2 \times 10^4$ *n/pulse.*

Pieces of the neutron yield distribution (NNE and 10%S) follow the same trend than neutron emission rate, as could be seen in fig. 3.a . Consequently, the found device neutron optimization is still valid if only non null emission shots or "good" shots were been considered instead of neutron emission rate. From the same figure is concluded that reproducibility does not change in the same way than neutron emission rate, it means that configurations with low emission rate could still a significant reproducibility. Nevertheless, high reproducibility ($R > 80\%$) is only obtained close to the optimal configuration.

Observed anisotropy is compared in figure 3.a with the anisotropy, for 95% confidence band, generated from an isotropic source when neutrons scatter in the capacitor bank of the device. This isotropic source anisotropy was obtained experimentally considering that detected scattered neutrons contribute in first order to the observed emission rate. From this results it is concluded that device emission is not isotropic and is more intense in the end-on direction. At this point it is necessary to point out that absolute anisotropy (without scattering contributions) is inaccessible to be measured in our device. The observed anisotropy for the optimal configuration is $A = Y_{end-on} / Y_{side-on} = 1.36$.

In figure 3.b and 3.c are shown histogram charts for emission rate and reproducibility of experiments in table 1. It is usually claim that contaminants removing by change the gas or working with gas flow is of importance for device performance. Our results indicate that gas flow circuit and chamber design are also of importance. The most efficient setup for impurities remotion (serie4) shows an improvement of almost nine fold over the worst setup (serie1). The effects of chamber design should be related with dispersion of remaining plasma which is ejected axially after pinch disruption.

5. Conclusions and final remarks.

The optimization of a small fast plasma focus device operated at 67 *J* was experimentally studied. It was found that the highest emission rate is obtained when device is operated with D2 in flow, 5.3 *mbar* 28.5 *kV* nominal charge voltage, autorupture, 3 *mm* anode radii, $r_{cat}/r_a = 2.17$ and $L_{ef} = 6.3$ *mm*. Neutron yield is 1.3×10^4 *n/pulse*. It was also observed that remotion of contaminants generated by the discharge are of supreme importance if a high emission rate per pulse is expected. A pulsed neutron source based on repetitive device similar to PF-50J should considering as a part of the engineering the gas flow level, gas flow circuit and a suitable chamber design in order to maximize neutron emission rate.

6. Acknowledgments.

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