Electrical Characterization and Experimental Results in the SPEED4 Plasma Focus Device

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Abstract. The pulsed power SPEED4 generator has a capacitor bank system of 1.25 µF in a Marx configuration to produce up to 100 kV, a maximum current up to ~700 kA, and 6.25 kJ of stored energy. In the plasma focus mode, this device has been prepared for the study of the emission of X-rays and neutrons in the Laboratory of Plasma Physics and Plasma Technologies of the Chilean Nuclear Energy Commission. The present experimental results report about the electrical characterization as well as preliminary results using Hydrogen like filling gas. Pinch evidences in the high voltage and current derivative electrical signals are presented in this work and preliminary arguments are given in order to achieve an optimal operation.

1. Introduction
There is a permanent and growing interest in the research community for understanding and determine the generation properties of X-rays, neutrons and charged particles emitted from a high-temperature high-density laboratory plasmas, especially in the Plasma Focus (PF) configuration. The SPEED4 experimental device is a compact pulsed power generator whose configuration of electrodes is in the PF mode, but in a Mather-Filipov mixture [1,2]. Technically, the SPEED4 has been designed with the purpose of to study the neutron emission as well as the X-rays [3], with particular emphasis in the mechanisms that generate them. The experiment is run using a charging voltage that rise up to 60 kV and, with the eight capacitor forming the capacitor bank system (1.25 µF), a maximum stored energy of 2.25 kJ is obtained.

2. Experimental set up, results and discussion
The figure 1 shown the scheme of the SPEED4 device, it consists of two coaxial electrodes where a high voltage is established by using eight capacitors (0.625 µF each); these capacitors form the capacitor bank consisting in four Marx lines symmetrically (axial direction) connected in parallel (0.313 µF each), each Marx line is forming by two capacitors (C in fig. 1) connected in series but a spark gap (SG in fig. 1) is placed between them (one Marx line is shown in fig. 1). To obtain a low inductance for the experimental device, the capacitors were connected in a compact layout close to the 2250 cm³ volume discharge chamber. The charging voltage was in the range between 26 kV and 60 kV; meanwhile the bottom pressure was of the order of 6 × 10⁻⁵ mbar, the working pressure was in the range between 1.7 mbar to 15 mbar when Hydrogen is used like filling gas. The total inductance is
determined (37 \text{nH}) in a shot at high pressure (around 10 \text{mbar} in our case, figure 2) when the equivalent electrical circuit is considered in a “short-circuit” mode.

The most important electric signals, to define the good and adequate perform in its plasma focus mode, are the evolution in time of both high voltage and current meanwhile the discharge exists. When the plasma focus discharge behavior is clearly revealed through the previous mentioned signals, as much the voltage as the current (derivative) signal shows the classical spikes \cite{3,4} that gives evidence of the pinch effect.

Four coaxial electrode dimensions are used to improve the experiment in the plasma focus mode (see Table 1). In this table, the first column make reference to figure 3 and the different parameters (A, B, h, r and R) of the electrode dimensions are related with figure 1.

 Depending on the charging voltage and filling gas pressure, a spike appears in the voltage signal between 1.7 \text{µs} to 2 \text{µs} (Fig. 3a, 3b, and 3c), and at around 400 \text{ns} to 500 \text{ns} if the voltage is higher (Fig. 3d). The preliminary results shown that the corresponding detected spike at the voltage probe is a single event and, systematically, it disappears at higher pressures (for example, see the feature voltage signal at 1.38 \text{µs} in Fig. 2).
in the figure 2). From this evidence it is necessary to give an interpretation to the nature of the spike appearing in the voltage signal and if it is related to the pinch effect. Following this way, at similar voltage the described spike moves towards minor times, from around 2 µs (Fig. 3c) to 1.7 µs (Fig. 3a and 3b) when the pressure decrease. By other hand, at lower pressure but higher voltage (Fig. 3d) the corresponding spike moves towards the first quarter of the period at around 500 ns. For our purpose, if the pinch effect is done, the suitable spike feature is waited for around 400 ns, in the first quarter of the period (T/4 = 345 ns like it is shown in the Fig. 2).

| Table 1 |
|----------------------|------|------|------|--------|---------|
| **Fig. 3** | A | B | h | 2R | \( a = r \) | \( I_0/ap^{1/2} \) |
| (a) | 1.8 | 1.3 | 5.0 | 80.5 | 1.58 | 83.76 |
| (b) | 1.8 | 0.4 | 5.0 | 80.5 | 1.58 | 69.80 |
| (c) | 1.8 | 0.7 | 5.0 | 80.5 | 1.24 | 72.72 |
| (d) | 2.2 | 0.7 | 2.7 | 60.0 | 1.24 | 170.50 |

Electrode and insulator dimensions in cm, and the respective calculated drive parameter in \( kA/cm/mbar^{1/2} \).

Fig. 3 Voltage and current derivative signals obtained at different experimental conditions. A spike is observed in the voltage signal. The graphs (a) to (b) are linked with the corresponding dimension electrodes specified in the Table 1.

Figure 3 shows the voltage and current derivative signals obtained, for different charging voltage and working pressure, when the electrodes dimensions are changed like is specified in the Table 1.

Our preliminary results may be compared with the analysis of the behavior and evolution of the current sheath [4], and the subsequent spike presence under the Lee’s model view [5]. The dimension of the electrodes is confronted with the drive parameter; this one shows that the axial and radial speed of the current sheath – which evolves as soon as the voltage is applied – are proportional to the “speed or drive factor” \( I_0/ap^{1/2} \), where \( I_0 \) is the peak current intensity, \( a \) is the anode radius and \( p \) is the gas filling pressure. For plasma focus devices of some kilo-joules (to 1 MJ), and operating in Deuterium, the typical values for the drive parameter is of the order of 77 \( kA/cm/mbar^{1/2} \) [4]. In spite of the fact that the Lee’s model was conceived and developed for Mather-type plasma focus devices, the drive parameter values calculated for the SPEED4 are in the order of magnitude for the (a), (b) and (c) configurations (Fig. 3 and Table 1), but it is close to the double one when the voltage is increased like...
is shown in the (d) configuration, indicating that geometrical or physical parameters modifications must be considered (for example, anode diameter, pressure).

3. Conclusions
Hundreds of electrical discharges in Hydrogen allow us to improve the plasma focus device SPEED4. An inductance of $37 \, \text{nH}$ is obtained for this experimental device. Voltage and current derivative are measured for a wide range of pressure and charging voltage. The feature of the voltage signal shows the possible and expected spike marking the pinch effect, but depending in pressure and charging voltage, this one appears at around $1.5 \, \mu s$ to $2 \, \mu s$ or in the first quarter of the period, around $500 \, \text{ns}$.

When the SPEED4 device is compared with similar experimental devices by means of the drive parameter, it is found experimental values of the same order of magnitude, or close to the double of the theoretical one when the spike signal appears in the first quarter of the period.

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