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Stability assessment and operating parameter optimization on experimental results in very small plasma focus, using sensitivity analysis

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A B S T R A C T

Regarding the importance of stability in small-scale plasma focus devices for producing the repeatable and strength pinching, a sensitivity analysis approach has been used for applicability in design parameters optimization of an actually very low energy device (84 nF, 48 nH, 8–9.5 kV, ∼2.7–3.7 J). To optimize the devices functional specification, four different coaxial electrode configurations have been studied, scanning an argon gas pressure range from 0.6 to 1.5 mbar via the charging voltage variation study from 8.3 to 9.3 kV. The strength and efficient pinching was observed for the tapered anode configuration, over an expanded operating pressure range of 0.6 to 1.5 mbar. The analysis results showed that the most sensitive of the pinch voltage was associated with 0.88 ± 0.8 mbar argon gas pressure and 8.3–8.5 kV charging voltage, respectively, as the optimum operating parameters. From the viewpoint of stability assessment of the device, it was observed that the least variation in stable operation of the device was for a charging voltage range of 8.3 to 8.7 kV in an operating pressure range from 0.6 to 1.1 mbar.

1. Introduction

Plasma focus device (PFD) is a popular pinched plasma generator due to its high intensity radiation yields, low cost of management, compactibility, reliability, and high performances in plasma physics research and industrial applications [1–3]. The PFD, as a compact and portable nuclear fusion apparatus, is also complex involving electrical and mechanical systems as well as different phases of plasma dynamics.

During the last decades, most of the experimental studies on PFDs have been performed in very low energy devices, operating in the range of less than one joule to a few hundreds of joules of capacitor bank energy [4–11]. With increasing the penetration level of small-scale PFDs into the various potential applications, their pinch formation stability and operating parameter optimization are of great importance to be properly investigated.

The purpose, which plasma-physics scientists and researchers are always looking for, is the higher pinching efficiency. Indeed, as a sign of appropriate PFD operation, it is defined as the strong pinch formation in the transition of plasma dynamics in going to the radial compression phase. Most experimental studies on very low energy PFDs have shown that the pinching efficiency considerably depends on the conditions of breakdown initiation, operating gas pressure, charging voltage level, effective insulator length and electrode dimensions [12,13]. Accordingly, in order to have a better operating regime in the very low energy PFDs, all the device components and discharge operating parameters must be determined as precisely as possible, leading to time coincidence between the peak current and pinching occurrence [14].

It is well known that monitoring of the discharge current and voltage of energy bank is an efficient technique for providing appropriate information about the pinch compression. To measure the pinching efficiency, one can consider the magnitude of the voltage spike/current dip in the electrical discharge signals, associated with pinch compression. The higher magnitude of the voltage spike/current dip implies stronger pinching, resulting in efficient radiation emission from the pinched plasma column [5,13]. This outcome is due to the direct relation of energy transferred to the plasma with the pinch voltage [12].

In recent years, some researchers studied the stability of small-scale PFDs with only the visual investigation of change in main electrical and radiation characteristics of the system [4,5,13]. However, the stability analysis is absent from an analytic perspective. Since, the pinching occurrence in very low energy devices is remarkably affected by energy loss at the different phases of plasma

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Table 1
The sensitivity analysis calculation procedure for plotting the sensitivity profiles.

Charging voltage	Gas pressure	Voltage spike	Sensitivity	
$V_{ch,1}$	P_1	$V_{spike,1}$	$\left(\frac{V_{spike,2}-V_{spike,1}}{V_{spike,1}}\right)/\left(\frac{P_2-P_1}{P_1}\right)$	
$V_{ch,2}$	P_2	$V_{spike,2}$		$\left(\frac{V_{spike,3}-V_{spike,2}}{V_{spike,2}}\right)/\left(\frac{P_3-P_2}{P_2}\right)$
$V_{ch,3}$	P_3	$V_{spike,3}$	$\left(\frac{V_{spike,4}-V_{spike,3}}{V_{spike,3}}\right)/\left(\frac{P_4-P_3}{P_3}\right)$	
$V_{ch,4}$	P_4	$V_{spike,4}$		

dynamics due to inappropriate initial breakdown [15], it is important to know how sensitive the pinching efficiency will be for the variation of different parameters. Therefore, practical analysis of PFD stability will have to involve different experiments along with an admissible assessment method.

In this paper, the impact of different electrode designs and other operating parameters (the change of gas pressure and charging voltage) on the results of optimization of an actually very low energy PFD (PFD-3J) is investigated. To achieve such a purpose, a sensitivity analysis approach for applicability in design parameter optimization is utilized.

2. Sensitivity analysis

To study how the different sources of variation in the device input can influence the pinching efficiency as the most important output of the device, the sensitivity analysis calculation method is an invaluable tool [16]. Using the sensitivity analysis, one can identify the most contributing input variables to an output behavior for the attainment of different objectives such as design procedure verification, stability assessment and design parameter optimization.

According to our literature review, there are many application examples of the sensitivity analysis in nuclear engineering fields, environmental modelling and software, thermo-physics and heat transfer, and etc. The problem in the pinch formation stability and design parameter optimization of the plasma focus devices is similar in some aspects.

In experimental studies, the charging voltage level and operating gas pressure qualitatively and quantitatively have a remarkable impact on the occurrence of successful pinch compression, due to their relation to drive parameter and energy density parameter, respectively. In the event that the optimum values of these parameters are selected, one will observe the plasma instabilities at the pinch phase, leading to a fast and anomalous increase in the plasma impedance as a necessary condition for producing efficient neutrons and x-ray yields. It is found [17–19] that the large increase in the plasma impedance is due to (i) fast changing plasma inductance $L_p(t)$ and (ii) growth in anomalous resistance $R_p(t)$. In this case, the pinch voltage is given by

$$V_{pinch} = \left(\frac{dL_p}{dt}\right) I_{dis} + R_p I_{dis} \tag{1}$$

where I_{dis} is the discharge current of the capacitor bank, that grows very fast similar to the voltage spike, indicating the increase in the power of pinching. The use of sensitivity analysis is so important that the amplitude of the voltage spike in small-scale PFDs is considerably lower than that in large-scale PFDs, due to the lower energy and dimensions of electrodes, insulator sleeve and plasma column [12,20,21]. Therefore, in order to increase the pinching efficiency, any small adjustments of the gas pressure and charging voltage level should be done in an appropriate and certain manner.

As expressed in the scientific reports, the breakdown voltage is approximately proportional to the product of gas pressure and gap length. Then, a sensitivity analysis approach can be used to estimate the importance of the mentioned operating parameters in obtaining the optimum working region. For this purpose, the sensitivity of the voltage spike (V_{spike}) to gas pressure (p) due to the variation in charging voltage level (V_{charge}) is defined as [22]:

$$S_{V_{charge}} = \frac{\Delta V_{spike}/V_{spike}}{\Delta P/P} \tag{2}$$

Using the sensitivity value ($S_{V_{charge}}$), one can plot the sensitivity profile to show around what charging voltage levels, the relative variation of parameter p may have a greater effect on the amplitude of the voltage spike, and around what charging voltage levels the effect is less [23]. The sensitivity analysis calculation procedure is quantitatively described in Table 1.

3. Experimental setup and procedure

3.1. Miniature PFD

The DPF device used in this investigation was the 3-J miniature plasma focus device (84 nF, 48 nH, 8–9.5 kV, ~2.7–3.7 J), that was capable of operating with a charging voltage level of 8 to 9.5 kV, in a repetitive discharge rate of 0.5 to 5 Hz. The electrodes dimensions of the device were obtained using the two essential design parameters introduced in the well-known models of the small-scale PFDs [24,25], i.e. the energy density parameter and drive parameter, matching the axial transit time of the plasma sheath with the quarter cycle time of the discharge circuit [14]. The description with respect to the design and construction of PFD-3J has previously been reported in detail [12,15]. The coaxial electrode assembly of the PFD-3J consisted of a 2.5 mm effective long, 1.25 mm radius cylindrical stainless steel (SS) anode and a cylindrical SS cathode of 7.5 mm inner radius. An insulator sleeve of pyrex glass with a breakdown length of 13 mm was used to separate the electrodes. Regarding the significant importance in maintaining the stability of the operating gas pressure conditions, key considerations for dry gas seal performance was taken into account, while fabricating the vacuum chamber and its attachment to the base-unit cathode.

To provide an enhanced portability, compact and minimized-inductance system, a particular design of the high voltage (HV) capacitor bank and spark gap switch assembly was implemented in a completely coaxial configuration. The design of the 84 nF coaxial-configured capacitor bank consists of twelve ceramic HV capacitors (7 nF, 15 kV each) assembled in parallel through two circular HV transmission plates with a diameter of 30 cm. In order to transfer the energy stored in all twelve capacitors of the HV energy tank uniformly to the plasma chamber, an indigenously designed spark gap switch was employed, located in the middle of HV transmission plates to get a widespread transmission line of the discharge path. Then, the HV energy tank was integrated to the plasma chamber without using any cables. In view of these considerations, the inductance of the system becomes as low as possible which is one of the important requirements for increasing the pinching efficiency and also helps to make the device portable for in-situ applications of the PFD-3J as a pulsed radiation source.