3 kJ Plasma Focus System: Design, Construction and Experiments

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Abstract

Design, construction and experiments of the 3 kJ Mather type plasma focus device is described in order to carry out fusion researches. This device is especially established for neutron yield and fast neutron radiography by *D-D* reaction which is given by $D + D \rightarrow {}^{3}He\ (0.82\ MeV) + n\ (2.45\ MeV)$. Preliminary results which are found in air atmosphere are given with the focus parameters. Experiments have shown that more than 125 kA peak current at 15 kV flows between electrodes for each shot which are operated in 17 mbar air pressure. Structural neutron shielding computations for safety has been completed and the setup is covered by paraffin walls with 40 cm thickness in order to thermalise the 2.45 MeV neutrons for near future radiography studies.

Keywords: Plasma focus, neutron, D-D reaction, fusion, magnetic field, pinch, radiography

1. Introduction

Controlled nuclear fusion has been considered as a feasible solution to the energy problem since 1950’s due to the exhausted natural sources. Thus, the formulations of plasma devices and important plasma parameters for instance energy confinement time, temperature, particle densities have a great importance in fusion studies.

A well-known plasma device, plasma focus (PF), has been studied for a few decades [1,2]. Plasma focus devices take interest for their simple geometry, pulsed characters and low cost [3]. In addition, one can easily operate them as sources of neutrons, electron and ion beams as well as x-rays depending on the operating gas and reactions [4,5]. In literature, plasma focus devices are classified as Mather and Filippov types. [6,7]. Both of them include mainly three individual phases when they operate [8]. First phase is the initial gas breakdown which constructs a current sheath. Second one, namely acceleration phase forms the plasma and pushes it by the Lorentz force toward the open end of the electrode. The last phase of the discharge is the collapse of the current sheaths as a pinch form.

Because of our experimental goal, it is convenient to mention about the earlier PF fusion studies which present *D-D* reactions. A number of studies which purpose high rates of neutron generation (i.e. maximal energy yield) from this reaction have been reported [1,5]. According to the literature, studies also intense on the optimization of the neutron generation mechanism such as the optimal chamber pressure, anode-cathode formation and the spatial scattering of neutrons [1,9].

Recent studies have shown that PF devices can operate at high pulse repetition rate – namely at the repetitive mode [10]. These are important attempts in order to obtain continuous fusion products and energy from a PF. However, electrode heating process is a vital obstacle for the repetitive mode since the structural components of PF device can be damaged by successive shots.

There exist a number of studies on the efficiency of PF devices. Many attempts have been made on the formation of device, for instance the manufacture of short and long insulators, type of insulator materials, shape of central anode, etc [11,12,13]. Besides, the particle densities can also be increased up to a certain value by adjusting an optimal gas pressure inside the chamber [1]. Operation pressure, voltage and current values play an important role to observe a good-shaped plasma sheath in order to achieve a fruitful nuclear reaction result. In this paper, we would like to introduce a new-built *ODAK-3K* PF device with its design, construction in our laboratory initially. Some experimental results from this device are presented in the following section. Finally, conclusions and some remarks are given.

2. Design and Setup

A simple schematic representation of the plasma focus is given in Figure 1 as a 3 kJ Mather type device which is based on S. Lee's model [14]. *ODAK-3K* has a cylindrical glass "T" shape chamber with a diameter of 120 mm and length of 246 mm. A cylindrical hollow copper anode and 12 bronze rod-type electrodes are located inside this chamber. The copper anode, which has a length of 88 mm and 37 mm diameter, is located at one side of the chamber. Cathode, the outer electrodes are 102 mm length and 8 mm in diameter. Rods are placed coaxially at a diameter of 85 mm around the anode. Pyrex insulator sleeve is 2.5 mm in thickness and 36.3 mm in length. Two Rogowski coils are placed outside the chamber in front and rear of anode to measure the discharge and pinch currents respectively. In order to measure the voltage across the device, a voltage probe is attached on the electrodes. In addition, a magnetic probe was situated on the outer side of chamber just near the tip of cathode.

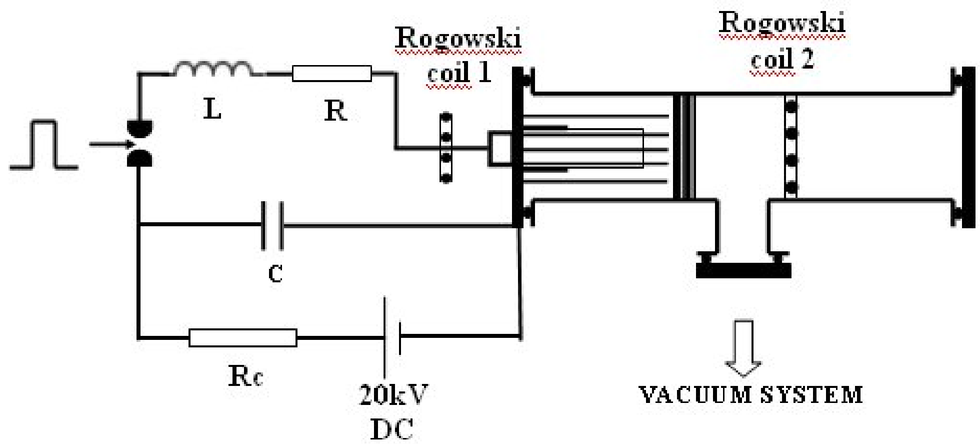


Figure 1. The schematic of *ODAK-3K*.

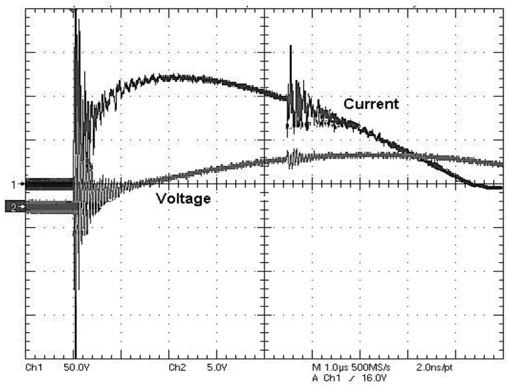
Figure 2.a) High voltage power generator, capacitor and vacuum system.

Figure 2. b) The vacuum chamber with electrodes inside, field coils and spark gap.

To initiate the discharge through the electrodes a high voltage trigger (20 kV with 20 ns rise time) was located near the spark gap. Spark gap is a vital element since it is responsible to start the breakdown just before the shots. The other components in Figure 1 are L=1.3 μH (total inductance, PF, spark gap and capacitor) R=16 mΩ and R_c= 1 MΩ. The capacitance of the storage capacitor, $C=15\mu F$ is fed by a 20 kV high voltage generator. For the formation of an initial plasma pinch, level of vacuum can be adjusted by turbo molecular and mechanical vacuum pumps (Fig. 2a). For the security reasons, paraffin walls with 40 cm thickness were positioned close to PF for shielding to conduct radiography experiments in near future. In Figure 2a and 2b, photos taken from different units of *ODAK-3K* device are shown.

3. Experimental

For the experiments, 3-17 mbar pressures were generally found to be sufficient in order to generate a plasma sheath. Due to the optimization of the focus, the sinusoidal voltage and current characteristics for the short-circuit discharges were collected using a first Rogowski coil (Fig. 2b) and a high voltage probe. In principle, any focus system shows this kind of sinusoidal behavior due to its short-cut nature. It corresponds to the case that the plasma current inside the chamber oscillates between two electrodes. In this frame, once a critical-damping case is caught, the oscillations decay and a smooth discharge regime appears as usual.



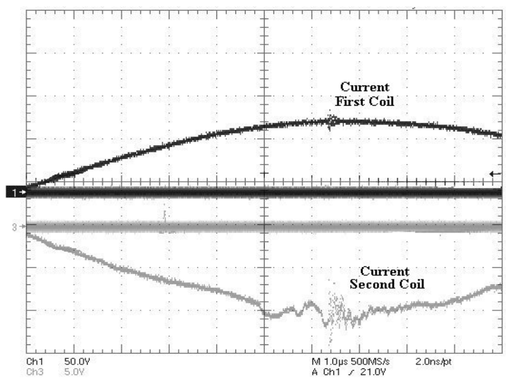


Figure 3. a) Voltage and current characteristics and pinch formation. b) Current curves from Rogowski coils. Bottom curve denotes the pinch current (i.e. magnetic field curve).

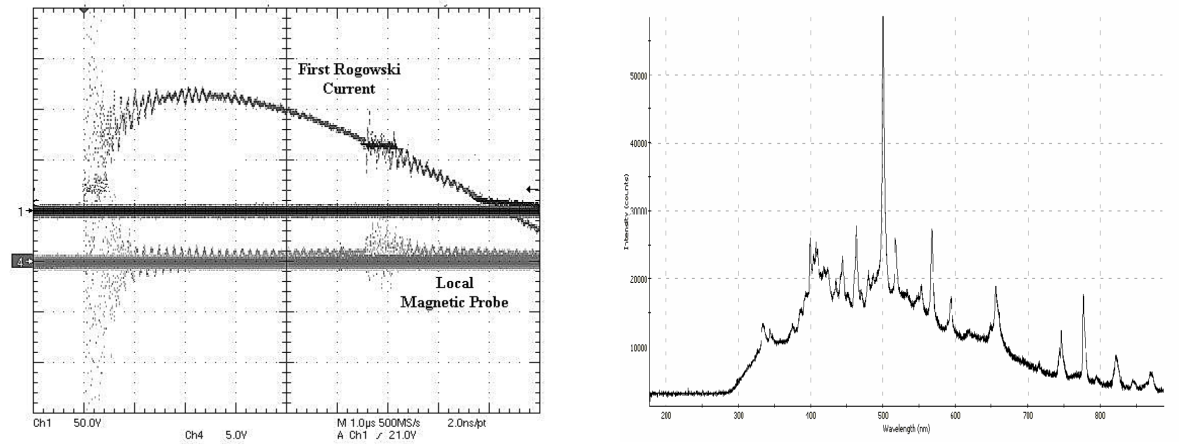


Figure 4. a) Current (top) and local magnetic field (bottom) curves. b) Air spectrum of foci.

In order to produce an effective discharge, impedance matching was realized by changing the circuit elements and air pressure in vacuum chamber. Typical curves of voltage, current and pinch currents are shown in Figure 3a. According to the calibrated current values from the Rogowski coils and voltage values from a high voltage probe, 125 kA (peak) and 15 kV values were found at 17 mbar air pressure. In addition to the Rogowski coils, a home-made magnetic probe was used to observe the dynamics of plasma sheath when the compression (radial inward) phase occurred (Figures 3b,4a). Furthermore, the spectral analysis of the plasma radiation after the compression phase was measured by a USB4000 Ocean spectrometer which operated between the wavelengths of 200 nm - 900 nm.

4. Discussion and Remarks

In this section, commends and remarks will be presented on the findings in the previous section. Initially it starts with Figure 3a and shows a sample of voltage-current characteristics of a typical discharge starting with breakdown to the end of the formation of foci. At the beginning of the surface discharge, a breakdown phase was clearly seen for almost 1 μs duration since strong voltage fluctuations appeared. This starting phase was nothing else than the sudden voltage increase inside the chamber as a reasonable result of electrical anode-cathode discharge. Furthermore, an axial phase followed the breakdown for nearly 3 μs. At the beginning of this phase, the discharge column between the electrodes was transformed into a plasma column. This plasma column, which had a non-cylindrical funnel shape moved through the anode tip. The decrease in the current curve proved the inductance increase by the formation of plasma between the electrodes. The averaged plasma velocity was found as v_p=1.12 cm/μs. Finally, a radial compression phase grew just near the anode tip and the compression of plasma columns was observed during the strong peaks in V and I curves as in Figure 3a. The compression time was measured around 0.7 μs. Some additional studies will be carried out both to stabilize the compression phase and to shorten the compression time in order to achieve a better foci by changing the circuit parameters.

According to the magnetic field measurements, which are given in Figures 3b and 4a, strong magnetic field changes were observed during the radial compression since the ions and charged particles had maximal acceleration rates. According to the measurements of second Rogowski coil in Figure 3b, current and magnetic field curves follow similar behaviors. When the current increases, measured field also increases. Note the strong field fluctuations during the compression phase. A measurement from the local magnetic probe, which was located around the cathode electrode, is shown in Figure 4a. The field curve indicated the maximal magnetic field around B_{loc}= 1.7 Gauss by using the calibration factor. Moreover one expects that the field should be higher than this value around the anode tip. In Figure 4b, a typical spectral behavior of air atmosphere is shown just after the compression phase. The spectrum mainly includes the atomic lines of nitrogen, oxygen and carbon elements since the excited states cause to emit visible light as well as x-rays.

Since ODAK-3K is a newly-developed device, it still needs some operational studies in order to perform a D-D reaction. In this frame, a more detailed and systematic study of the plasma focus characteristics by using several diagnostics in parallel seems essential to fully understand the role of different parameters and the neutron yield as well.

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