Upgrading of Mather-type Dense Plasma Focus Machine for Advanced Plasma Dynamic Studies

Student: Christos Karvounis [1,2]

PhD level, karvounis@hmu.gr

Mentors: A. Skoulakis[1,2], J. Chatzakis[1,2], I. Tazes[1,2], D. Mancelli[1,2], V. Dimitriou[1,3], N.A. Papadogiannis[1,3], M. Tatarakis[1,2], I. Fitilis[1,2]

[1] Institute of Plasma Physics and Lasers, University Research and Innovation Centre, Hellenic Mediterranean University, Rethymno, Crete, GR-74100, Greece
[2] Department of Electronic Engineering, School of Engineering, Hellenic Mediterranean University, Chania, Crete, GR-73133, Greece
[3] Department of Music Technology and Acoustics, School of Music and Optoacoustic Technologies, Hellenic Mediterranean University, Rethymno, Crete, GR-74100, Greece
{skoulakis,jchatzakis,tazes,dmancelli,dimvasi,npapadogiannis,mictat,fitilis}@hmu.gr

Abstract. *The plasma focus machine is a powerful tool for studying plasma dynamics and harnessing its potential in various applications like medicine and industry. In this paper, we present an upgrade version of the Mather-type plasma focus machine, focusing on the technical characteristics. The aim of the upgrade was to improve the performance of the machine, achieving a deeper understanding of the plasma behaviour. We investigate the plasma dynamics, more specifically the plasma expansion and compression velocity, through the three operating phases (breakdown, axial and radial phase) of the Mather-type plasma focus machine. Our results show the improvements achieved through the upgrade, highlighting the enhanced capabilities and potentials for further research and applications in the field of plasma physics.*

Keywords. Plasma physics, plasma focus, Mather-type machine, plasma dynamics, plasma speeds

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1 Introduction

Plasma exhibits unique properties that make it a subject of great interest in scientific research and technological advancements. Following the groundbreaking scientific accomplishment of laser fusion achieved at the National Ignition Facility (NIF), which resulted in the implosion generating a total of 3.15 megajoules (MJ) of fusion energy using 2.05MJ of input energy, the scientific community has experienced an increased emphasis on plasma studies. The plasma focus machine has been widely studied as a device for generating and accelerating plasma. Mather-type Plasma focus machines consist of two coaxial electrodes, where a high-voltage pulse is applied to generate and accelerate the plasma in order to focus it at the top of the anode, creating the pinching. Over the years, several studies have been made to improve the performance of plasma focus machines, aiming to achieve higher plasma densities, temperatures and more controlled plasma dynamics. In this paper, we focus on the upgrade of the Mather-type plasma focus machine of the Institute of Plasma Physics and Lasers (IPPL) of the Hellenic Mediterranean University (HMU) [1], highlighting the technical characteristics of both the old and the upgraded version. The upgrade was designed to overcome the limitations of the old machine and enhance its capabilities. Our object was to achieve better control over the plasma behaviour and improved overall performance. In this study, we specially investigate the plasma dynamics and the speeds of the plasma generated by the upgraded machine. By analysing the temporal and spatial evolution of the plasma, we aim to investigate the behaviour of the plasma and the improvements achieved through the upgrade. This will lead to a better understanding of the plasma physics and its possibilities for practical applications. This paper is organized as follows: Firstly, an overview of the technical characteristics of the old Mather-type plasma focus machine is presented. The next part is the presentation of the upgraded version of the machine, focusing on the modifications that were made. The next section describes the experimental setup and methodology used to measure the plasma dynamics and speeds. The following part of this paper is the presentation of the results obtained from the experiments and finally, in the last part there are the conclusions.

2 The old version of the machine

In Fig. 1A, a schematic design [2] of the electric circuit for the previous version of the Mather type plasma focus machine is depicted. The circuit comprises the energy bank, the pseudo spark switch, the pulse shaping circuit, 16 coaxial lines and the vacuum chamber. The energy bank includes a high voltage energy supply and 4 capacitors with the following specifications: $C = 200nF, V_{max} = 30kV, L = 15nH$. The power supply charges the capacitors and the machine obtains energy ranging from 100 to 360J based on the charging voltage across the capacitors. To initiate the discharge, a trigger unit is employed, generating a 2.5kV, 1μs impulse that is transmitted to the pseudo spark switch through the pulse shaping circuit, consisting of 2 coaxial lines and a spark gap [3]. The spark gap is utilized to achieve a reduced rising time and doubling the impulse. Eventually, the energy is transferred to the vacuum chamber via the 16 coaxial lines.

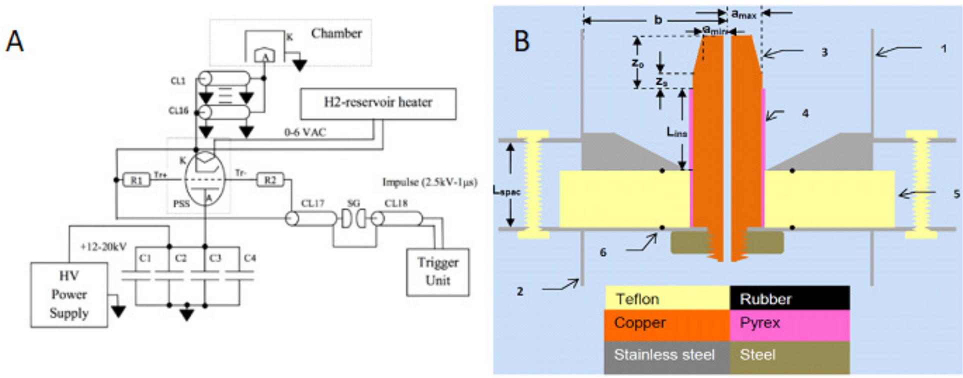

Figure 1. A. Electric circuit of the old version of the machine. B. A full sectional side view of the vacuum chamber. 1. Part of the chamber tube (cathode), 2. Part of the chamber tube (anode), 3. Main electrode of the anode (hollow cylinder), 4. Insulator sleeve, 5. Electrical insulation spacer, 6. O-ring for maintaining the vacuum.

The vacuum chamber comprises 2 coaxial cylinders: the anode and the cathode. Figure 1 B showcases the design of the vacuum chamber, highlighting its main components and the materials used in construction. Noteworthy parameters include the free path above the insulator sleeve until the anode becomes tapered (z_s), the free path above the insulator sleeve until the top of the anode (z_0), the radius of the anode (a) and the radius of the cathode (b). For this specific machine version, these parameters possess the following values: $z_s = 2.8mm, z_o = 9.5mm, a = 5.7mm, b = 23.8mm$.

3 The upgraded version of the machine

To enhance control over plasma behaviour and optimize machine performance, several modifications were implemented. The first change involved replacing the 16 coaxial lines with planar transmission lines made of copper. This substitution was necessary to achieve better matching between the capacitors and the vacuum chamber. The planar transmission lines facilitate energy transfer to the vacuum chamber with reduced resistance and inductance, enabling high current values. The subsequent and most significant change entailed replacing the original 4 capacitors with 6 new ones, The characteristics of these new capacitors are as follows: $C = 0.56\mu F, L = 15nH, V_{max} = 30 - 60kV$. These capacitors allow the transfer of higher energy to the vacuum chamber, ranging from 500 to 700J depending on their charging voltage. The pseudo spark switch and the pulse shaping circuit remained unchanged. Fig. 2 displays an image of the upgraded version of the plasma focus machine, featuring the capacitors, the vacuum chamber, the pressure gauge, the planar transmission lines and the latter part of a two frame shadowgraphy. Also the upper part of the anode can be seen in the right part.

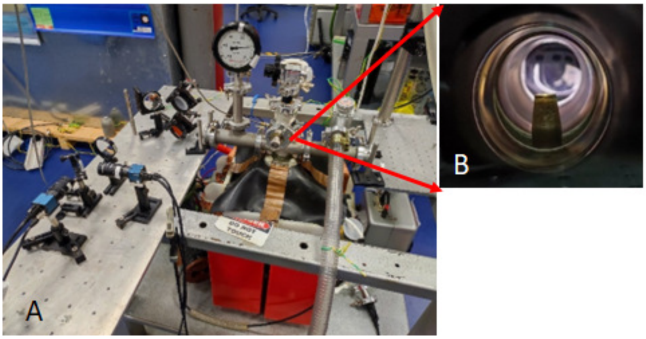

Figure 2. A. Photo of the upgraded version of the plasma focus machine. B. The new anode that was used for the upgraded version.

The final modification during the machine upgrade pertained to the characteristics of the anode. A tapered anode with similar properties was employed, albeit with slight adjustments to achieve improved pinching conditions. The updated anode characteristics are as follows: $z_s = 13.4mm, z_o = 23.4mm, a = 4.75mm, b = 23.8mm$.

4 The two frame shadowgraphy

In order to gain a better understanding of plasma behaviour and accurately measure plasma speeds, a two frame shadowgraphy technique way employed, as depicted in Fig. 3. Two frame shadowgraphy was chosen due to its ability to capture plasma screenshots with an adjustable time difference. The setup involved the use of a beam splitter to separate the laser beam into 2 separated beams. These beams pass through the vacuum chamber and reach 2 CCD cameras. The time difference between the 2 beams for this specific experiment was determined to be 9ns through measurements conducted using a photodiode. By utilizing two frame shadowgraphy, it was possible to capture sequential images of the plasma with precise timing, enabling analysis of plasma movement and velocity.

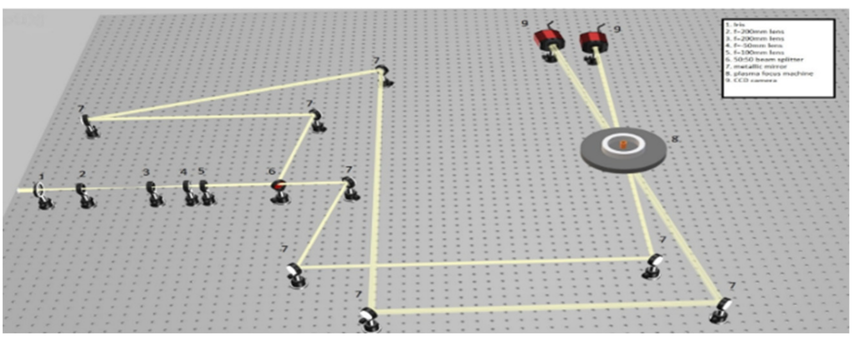

Figure 3. Schematic representation of the shadowgraphy setup

5 Results

The experiments were conducted multiple times to observe and record the plasma dynamics throughout the entire phenomenon. Fig. 4 presents the three phases of a Mather type plasma focus machine: axial, radial and breakdown. In Fig. 4a, the end of the axial phase is depicted, showing the sheath reaching the top of the anode. The subsequent figure illustrates the radial phase, where the plasma is compressed by magnetic fields. Figures c and d display moments a few nanoseconds before and after pinching, while the last two figures showcase the breakdown of pinching and the formation of bubble-like plasma observed at the conclusion of the phenomenon. The time indicated in each picture refers to the moment of pinching. Notably, Fig. 4 demonstrates the highly symmetric nature of the plasma sheath, which is crucial for successful pinching. Due to the higher velocity of the electron beam compared to their thermal speed, “beam plasma” instabilities arise. The electric field accelerates ions in the opposite direction with a higher velocity than the plasma sheath, resulting in the formation of bubble-like plasma, typically occurring after a strong pinching event. The images captured during the experiments were utilized to calculate the axial speed of the plasma, the radial speed of the shock front and the axial elongation speed of the plasma in the radial phase. For speed calculations, two images with a time difference of 9ns were used.

The operating pressure of the upgraded machine ranged from 8 to 13mbar, contrasting with the old version, which operated from 0.5 to 4mbar.

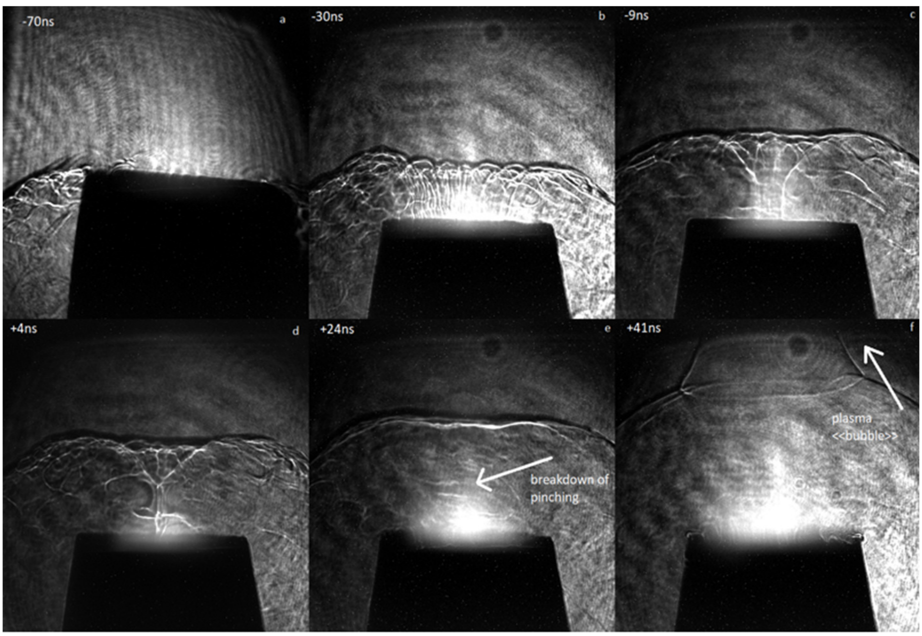

Figure 4. Dynamics of the plasma.

The speeds of two characteristic pressure values are presented in the table below.

Pressure(mbar)	Axial speed at the end of axial phase(cm/μs)	Axial elongation speed in radial phase(cm/μs)	Radial speed (cm/μs)
8	10.49 ± 1.17	8.95 ± 0.74	13.47 ± 0.86
13	2.88 ± 0.42	9.91 ± 1.10	8.58 ± 1.23

Although the values show a slight increase compared to the old version, where a maximum radial speed of 12cm/μs was measured, it should be noted that the upgraded version operates at higher pressures, indicating significant performance improvements. These experimentally calculated speeds align well with Lee's simulation model [4].

6 Conclusions

The upgrade of the Mather type plasma focus machine has resulted in significant improvements in its technical characteristics and overall performance. Through the implementation of enhanced energy supply and diagnostic tools, a higher level of control over plasma behaviour has been achieved, leading to increased precision and more accurate measurements. The measured speed of the plasma generated by the upgraded machine indicates comparable or slightly fasterplasma expansion compared to measurements that took place before the upgrade of the old version, but in a higher-pressure regime, primarily due to changes made to the anode. In conclusion, the upgrade of the plasma focus machine represents a substantial advancement, enabling enhanced performance, improved plasma dynamics and increased speeds. These achievements lay a solid foundation for further research, innovation and the exploration of practical applications in the fascinating realm of plasma physics.

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