Analysis of the Toroidal and Poloidal Magnetic Field Behaviors in the Conical Z Pinch Plasma Thruster

M. E. Abdel-kader\textsuperscript{a}, M. A. Abd Al-Halim\textsuperscript{b*}, H. A. Eltayeb\textsuperscript{a}, and A. M. Shagar\textsuperscript{a}.
\textsuperscript{a} Plasma and Nuclear fusion Dept., N.R.C., Egyptian Atomic Energy Authority, Egypt.
\textsuperscript{b} Physics Department, Faculty of Science, Banha University, Egypt.
\* Corresponding author email: mohamed.abdalhalim@fsc.bu.edu.eg

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ABSTRACT

The Cone Z-Pinch Experiment with 5 kJ is designed, constructed and operated. The electric discharge takes place between an upper ring electrode and a lower pin electrode creating plasma sheath in shape of cone. The discharge current reached maximum with rise time of 7 µs and the pinch effect takes place in shape of sharp crevice. The magnetic field distribution is measured axially by magnetic probe. The experimental results proved the existence of the axial magnetic field especially above the ring electrode where all the axial current changes direction toward the radial one, creating the poloidal field. The toroidal magnetic flux of about 13 kG is measured for 5 kV discharge voltage, while the poloidal magnetic flux is about 5.5 kG. The toroidal magnetic field is lower above the ring electrode due to the lower plasma current passes at the center. The plasma sheath velocity varies between 2.6 and 1.1 cm/µs in the axial direction above the pin electrode.

Key Words: Conical Discharge, Z-Pinch, Plasma Current, Toroidal Magnetic Field, Poloidal Magnetic Field.

INTRODUCTION

The experiments explored the role of the magnetic pressure in creating the outflow\textsuperscript{(1)} The diagnostics of plasma is obtained using magnetic probes\textsuperscript{(2)} and other electrical measurements in a coaxial gun indicates that the snow plow model is adequate to describe the plasma sheet dynamics\textsuperscript{(3)}. The magnetic probes was used to measure the azimuthal magnetic field and the time evolution to measure the axial velocity which showed a sheared plasma flow during the Z pinch formation\textsuperscript{(4)}. The flow shear during quiescent phase exceeds the theoretical calculations\textsuperscript{(5)}.

The application of an axial magnetic field in the magneto plasma dynamic thruster increases the thrust and enhances the plasma jet focusing but it does not affect other plasma parameters at the exit section\textsuperscript{(6,7)}. The radial magnetic field distribution in a high density z-pinches plasma was calculated and compared with the experimental results and found that the plasma electrical conductivity is in agreement with the Spitzer value\textsuperscript{(8)}. The dynamics of plasma imploding in an oxygen Z-pinches plasma was studied numerically using ionization balance equations and MHD equations\textsuperscript{(9)}. Simulation results show the formation of a reversed current profile when a expansion of shock wave occurs after it reflects at pinch axis\textsuperscript{(10)}. The hollow z-pinches plasma allows the presence of the axial magnetic field and the same phenomena was observed in plasma focus devices\textsuperscript{(11,12)}.

The aim of this work is to study the toroidal and poloidal magnetic field behaviors in the Conical Z Pinch (CZP) Plasma Thruster. The magnetic flux is measured axially and as using single magnetic probe. Also, plasma sheath velocity in the axial direction is measured using double magnetic probes.
EXPERIMENTAL SETUP

Figure (1) shows a schematic diagram of the discharge chamber for the conical Z-Pinch device. The CZP had been operated using electric circuit includes 108 µF main condenser bank, ignitron, and power supply up to 10 kV. The discharge chamber consists of two identical Pyrex glass cylindrical tubes, each of them is 3 mm thickness, 10 cm diameter, and 10 cm length. The lower tube is considered as the discharge chamber tube while the upper one is considered as the expansion chamber. The discharge tube contains two electrodes, the upper one, is a 6 cm hollow radius ring shaped electrode made of copper. It is fixed between the two glass tubes and connected to capacitor bank via the ignitron. The lower electrode is a spike with sharp end. It is made of stainless steel to reduce the corrosion which occurs in as a result of the collision with plasma ions. This pin is fixed with a screw on a disc of 20 cm diameter, hence it is easily moved in the vertical direction to control the distance between the two electrodes. In the present work, the distance between the two electrodes is fixed at 3 cm. Also, eight external rods were use as current-return rods to reduce the circuit inductance to achieve better confinement.

Figure (1): Schematic diagram of the discharge chamber

PLASMA SHEATH DYNAMICS

When the electric discharge occurs, the gas between the Pin-Ring electrodes is ionized, forming a cone of plasma sheath as shown in Figure (2). The high current, I, flows between the two electrodes induces the magnetic field $B_0$ in $\Theta$ direction. Hence Lorentz force will be generated, confining the plasma sheath toward the axis of the discharge chamber and forming the pinch because the magnetic pressure is higher than the kinetic pressure. Then, the plasma column will be created and expelled in
the vertical opened direction through the hollow ring electrode into the upper expansion chamber\cite{13,14} in which we call this process the electromagnetic propulsion\cite{15,16}.

When the plasma cone is formed, Lorentz force will confine the plasma, creating the pinch column. According to the recorded current signal, a sharp crevice will appear as an evidence of the pinch\cite{14}. The sharp crevice is a dip in the current trace followed by a current rise. This crevice means that the plasma is confined and formed the pinch at the time of the dip due to the higher magnetic pressure as compared with the kinetic pressure. Then the plasma in the pinch is expanded leading to the current rise due to the higher kinetic pressure in this case. The time at which the pinch occurs is affected by the charging voltage, the gas pressure, and the system dimension\cite{17,18}.

![Figure (2): Schematic diagram of the discharge shape and force directions.](image)

**EXPERIMENTAL RESULTS**

**Breakdown Curve:**

The CZP Experiment is operated using Argon gas at different pressures and charging voltage. The pressure is changed by needle valve and the capacitor bank is charged in range between 300 V and 1 kV to discharge between Pin-Ring electrodes. The relation between the breakdown voltage $V_{br}$ and the pressure $P$ is shown in Figure (3) where the vertical distance between the pin electrode and the center of the ring electrode is 3 cm. The breakdown voltage $V_{br}$ is characteristic of the gas and the electrode can be related to the mean free path $\lambda_{e-n}$ of the charged particles. There is a minimum $(V_{br})_{min}$ value which is given from the breakdown curve as in the relation\cite{19}.

\[
(V_{br})_{min} = B \cdot (pd)_{min} \quad \text{with} \quad (pd)_{min} = (2.72/A) \ln (1+1/\gamma)
\]

Where $\gamma$ is the number of secondary electrons produced by each positive ion arriving at the cathode. $A$ and $B$ are two constants given by $A = 1/\lambda_1$, $B = V_1/\lambda_1$, and $\lambda_1$ is the electron mean free path at $p = 1$ torr.

Figure (3) shows that the 'Pd' product is varied between 0.18 torr cm and 6 torr.cm. For large values of $(Pd)$ the breakdown potential, $V_{br}$, rises nearly linearly with $(Pd)$ because the logarithmic term varies slowly. For small values of $(pd)$ the numerator of above equation decreases linearly with decreasing $(pd)$, but $\ln (pd)$ decrease faster, with the result that $V_{br}$ rises when $(pd)$ is lowered.
Discharge Current Measurement:

The total discharge current is measured by Rogowski coil, which connected to integrator circuit, and the output is taken to one channel of oscilloscope. When the plasma cone is formed, Lorentz force will create a pinch column and a crevice shape is observed in the discharge current. The crevice shape is a clear dip in the current trace followed by a current rise as shown in Figure 4 which is confirmed experimentally (14, 20). This indicates that the plasma is pinched at the time of the dip because the magnetic pressure is larger than the kinetic pressure then it is expanded at the current rise because the kinetic pressure is larger than the magnetic pressure. The experimental values of the discharge current is calculated according to the relation.

\[ I = 0.5 \times 10^{-7} \frac{r_{\text{max}} \times R \times C}{nA} V_{\text{out}} \]  

(2)

Where \( R = 100 \, \text{k}\Omega \), \( C = 10 \, \text{nF} \) in integrator circuit, "\( n = 189 \) turns" is the number of turns, \( A = \pi r^2 = 3.14 \times (0.25 \times 10^{-2})^2 \, \text{m}^2 \) is the cross-section of area for every turns of coil, "\( r_{\text{max}} = 3.25 \, \text{cm} \)" is the main radius of coil. The equation (2) becomes

\[ I (kA) = 43.810 \times V_{\text{out}} (V) \]  

(3)

The discharge current increases from zero to maximum value with rise time 7 \( \mu \)s, then it decreases to zero after 16.5 \( \mu \)s. The discharge voltage has a large value at zero time, then it decreases due to increasing of plasma inductance. It is found that the rise time of 7 \( \mu \)s is constant for different gas pressures and is characteristic of the electrical system. The peak of the discharge current is given by

\[ I_{\text{Dis}} = \frac{2\pi C_{\text{ch}} V_{\text{ch}}}{\tau} \]  

(4)

Where \( C_{\text{ch}} \) is the capacitance of the condenser bank of 108 \( \mu \)F, \( V_{\text{ch}} \) is the charging voltage of 4 kV, and \( \tau \) is discharge current time period which is about 35 \( \mu \)s. The peak discharge current value calculated equals to 77.5 kA.
Figure (4): Waveform signal of both the discharge current and discharge voltage for argon gas at \( V_{ch} = 4 \text{ kV}, P = 0.5\text{torr}. \)

**Plasma Current Sheath Axial Velocity:**

The axial distribution of the plasma current sheath velocity, \( V_{cs} \), is determined from the arrival time of peak of the azimuthal magnetic field at the point at which the magnetic probe is placed. When the plasma cone is pinched, it is extended into the upper tube via the hole of ring electrode, the distance between the lower pin electrode and the end of upper tube equals to 14 cm. The azimuthal magnetic field is detected axially by two magnetic probes separated by distance of 2 cm. The following relation may be calculated the axial velocity:

\[
V_{ch} = \frac{\Delta z}{\Delta t} \tag{5}
\]

Where \( \Delta z \) is distance between the probes which equal to 2 cm and \( \Delta t \) is the time difference between the two signal phase shifts at peaks. The sheath velocity is calculated at different capacitor bank charging voltage and different pressures. The relation between sheath velocity (\( dz /dt \)) and axially position is plotted in figure (5) for argon gas.

It is shown that the sheath velocity has high value of 2.6 cm/\( \mu \text{s} \) at 1 cm above the pin electrode, then it decreases toward the ring electrode ns reached 1.1 cm/\( \mu \text{s} \) parallel to the ring electrode where the current density is lower so that Lorentz force toward the ring is lower than that near the pin.

Figure (5): The axial sheath velocity as a function of the axial position for 2 kV charging voltage, \( P = 0.5\text{torr} \) using argon gas pressure.
Induced Magnetic Field with Axial Position:

The distribution of magnetic field inside the cone Z-pinch experiment will be studied in axial direction. The measurements includes the toroidal magnetic field T.M.F. and the poloidal magnetic field P.M.F. using magnetic probes at different position as a function of distance above the pin electrode. The first probe's axis is in theta direction to measure the toroidal magnetic field \( B_\theta \) while second probe's axis is in z-direction to measure the poloidal magnetic field \( B_z \). Each magnetic probe has 16 turns of copper wire of 1.5 cm diameter. The output of the magnetic probe is connected to an integration (RC) circuit and the magnetic field induction is related to the output voltage by the relation:

\[
B(\text{Gauss}) = \frac{RC}{nA} \times 10^8 \times V_{\text{out}}
\]

(6)

where \( n \) is number of turns and \( A \) is the cross sectional area of the probe turn. Figures (6) and (7) show the variation of the toroidal and poloidal azimuthal magnetic fields with different axial position at for charging voltages of 2 and 5 kV and 0.5 torr of Argon gas pressure. Figure 6 shows that the T.M.F. due to 5 kV charging voltage has low value at the pin electrode while it increases toward the ring electrode and reach 13 kG at 3 cm from the pin which means that the sheath is more confined at that distance so that the plasma current passes there is highest value. After plasma sheath passes the ring position it decreases at 5 cm because the sheath expands over wider area so that the current density is lower and an the field \( B_\theta \) is lower due to the lower current passes at the center. A similar behavior is also observed in case of 2 kV charging voltage as in figure 7 but with lower values of the T.M.F. due to the lower discharge current.

On the other hand, the P. M. F. has the same behavior of T. M. F., where it has low value also at pin electrode then it increases toward the ring electrode until it reaches maximum of about 5.5 kG at 8 cm. At this distance, it is clear that the P. M. F. is higher than the T. M. F.\(^{(12)}\) because according to Fig. 2 all the axial current transfers into radial, creating the poloidal field. At the distance above the pin electrode to the ring electrode, the plasma current is almost axial so that the T.M.F. dominates, while at the distances above the ring, the discharge current changes direction toward the radial one, creating the P.M.F. which dominates in this case.

\[\text{Figure (6): The variation of toroidal and poloidal magnetic field with axial position for argon gas at pressure 1torr and } V_{ch}=5kV\]
CONCLUSION

The conical z-pinch thruster is constructed, operated, and studied using Rogowski coil and magnetic probe. The discharge current is measured experimentally using Rogowsky coil and calculated theoretically where the discharge current peak occurred at 7 μs. A sharp crevice appeared in the discharge current signal as an evidence of confinement.

The axial magnetic field distribution was studied in conical Z-Pinch thruster using magnetic probes. The experimental results showed that the toroidal magnetic flux is about 13 kG, while the poloidal magnetic flux of about 5.5 kG for 5 kV discharge voltage. The P.M.F. is measured using magnetic probe in axial direction. Its existence referred to direction changes of the discharge current from the axial direction above the pin electrode to the radial direction above the ring electrode. The axial velocity which was measured using double magnetic probes showed that the plasma sheath velocity varied in the range between 2.6 cm/μs above the pin electrode and 1.1 cm/μs at distance of 4 cm above the pin electrode.

The experimental results showed that the plasma in the CZP is confined and propelled axially. The magnetic field changes its direction from the axial direction to the radial direction. This means that the CZP device could be used in the propulsion and confinement applications. The radial distribution of the magnetic field and plasma current density is preferred in future for better characterization of the system.

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