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# Experimental study of a small gas-puff Z-pinch device

**Chengmu Luo,**
**Xinxin Wang,**
**Xiaobing Zou**

**Abstract** A small gas puff Z-pinch device has been constructed and operated. The device has the parameters: the capacitance of energy storage capacitors 16 μF, charging voltage 22 kV, peak current 210 kA and a quarter of current period 2.4 μs. A three-frame Mach-Zehnder interferometer and a compact Thomson ion energy analyzer were developed for Z-pinch plasma experiment. According to the results of diagnostics, the electron density $n_e$ of the plasma right before pinch instant is larger than $5.4 \times 10^{19}/\text{cm}^3$, the corresponding pinch velocity $v$ of the plasma sheath is 9.0 cm/μs. Clear parabolas produced by neon ions $Ne^+$, $Ne^{2+}$, $Ne^{3+}$ and $Ne^{4+}$ on CR-39 target have been observed. The energy spectra $dN/dTd\omega$ for $Ne^+$, $Ne^{2+}$, $Ne^{3+}$ and $Ne^{4+}$ ions were determined. The highest energies of $Ne^+$, $Ne^{2+}$, $Ne^{3+}$ and $Ne^{4+}$ ions emitted from our Z-pinch plasma are below 1.3 MeV.

**Key words** Z-pinch plasma • plasma diagnostics • multi-frame interferometry • electron density • energy spectra of ion beams

## Introduction

Gas puff Z-pinch plasma device is a typical dense magnetized plasma device and one of excellent soft X-ray generators; the advantages of the device are high efficiency of X-ray production, low construction cost and simple operation procedure. An application of X-rays emitted from the device can be found in many scientific and technical fields, such as X-ray lithography, X-ray microscopy, micro-fabrication, etc. [1]. In order to understand the physical properties, two diagnostics have been established. One was a three-frame Mach-Zehnder interferometer that was used to determine the velocity of plasma movement and the density of plasma. Another was a Thomson ion energy analyzer that was used to determine the ion beam energy spectra and the ion species.

## Experiment facility

The scheme of the gas puff Z-pinch plasma device we used is shown in Fig. 1. The capacitor bank consisted of four capacitors of 4 μF. A field distortion switch was connected to each energy storage capacitor to reduce the total inductance of discharge circuit and to increase the peak value of discharge current. A hollow gas shell was produced by gas injection through a supersonic nozzle from a fast-acting electromagnetic valve. The mass of the gas shell can be varied using different plenum pressure and changing the time delay between the beginning of gas injection and the initiation of the

C. M. Luo[✉], X. X. Wang, X. B. Zou
Department of Electrical Engineering and Applied Electronic Technology,
Tsinghua University, Beijing 100084, P. R. China,
Tel.: +8610 6279 2280; Fax: +8610 6278 3057,
E-mail: lcm-dea@tsinghua.edu.cn

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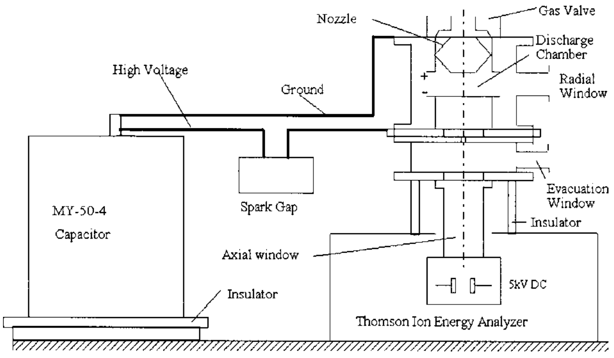

**Fig. 1.** Layout of Z-pinch plasma experiment.

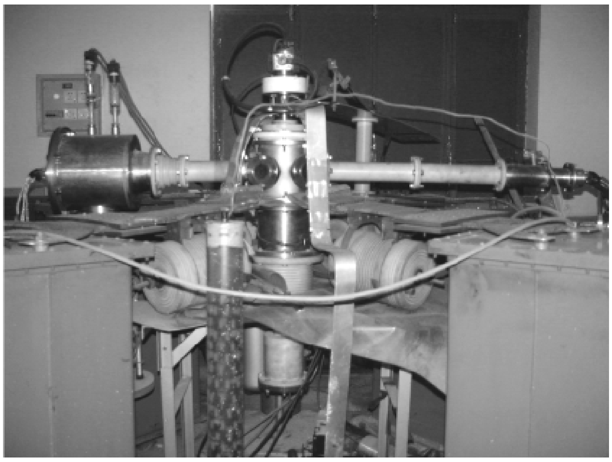

**Fig. 2.** Picture of gas-puff Z-pinch plasma device.

discharge. The nozzle is also treated as one of electrodes and has an outer radius of 1.8 cm and an inner radius of 1.5 cm. The distance of the electrodes is 1.2 cm. In our experiments, the capacitor bank was charged to 22 kV. The peak discharge current was about 210 kA with a quarter period of 2.4 μs. The discharge chamber was made of stainless steel. Figure 2, is a picture of gas-puff Z-pinch plasma device. Neon was used in the operation of the plasma device.

In order to maximize the X-ray emission from the Z-pinch, the gas shell should be designed with a suitable line mass density $m_0$ and radius $r_0$. For this purpose, Z-pinch plasma implosion was numerically simulated and this simulation was based on a one-dimensional snowplow model with differently presumed gas shells. An equivalent circuit model of Z-pinch discharge was also established for numerical calculating of the load current. The results showed that the most suitable neon gas shell is 10 mm in outer radius, 4 mm in thickness and 6 μg/cm in line mass density [5].

## Diagnostics and results

### A three-frame Mach-Zehnder interferometry

Interferometry is a powerful diagnostics in plasma research. It can be used to get much information on plasma, for example, in our experiment the configuration of plasma source, speed of plasma sheath movement and electron density of plasma column can be determined with this diagnostics.

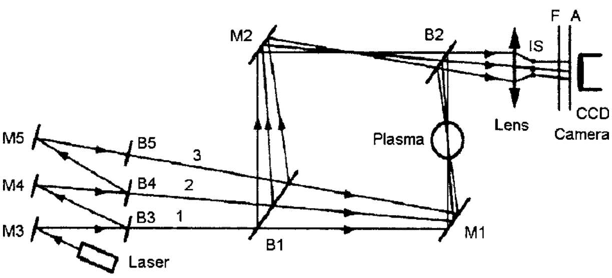

**Fig. 3.** A scheme of multi-frame interferometer. M1–M5 – fully reflecting mirror; B1–B5 – partially reflecting mirror; IS – spectroscopic prism; F – interferometric filter; A – attenuator.

A three-frame Mach-Zehnder interferometer was used for taking 3 pictures (5-ns exposure and 13-ns time interval between pictures) of the imploding plasma in one Z-pinch shot, which provided us a series of 3 interferograms showing the evolution of electron density profile during Z-pinch implosions [4].

The layout of three-frame Mach-Zehnder interferometer is shown in Fig. 3. It consisted of a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser, a beam-splitter and a Mach-Zehnder interferometer. The YAG laser and the beam-splitter were mounted on a heavy optical bench of 1.2 m × 2.4 m in area. The YAG laser was Q-switched and its frequency was doubled to deliver on the wavelength 532 nm a 35 mJ pulse in 5 ns. The laser beam was expanded and collimated to 40 mm diameter by a combination of negative and positive lenses. The broadened beam was directed to fully reflecting mirror M3, and beam splitter B3. A part of this beam passed through B3 to produce beam 1; another part of the beam was reflected by B3 towards mirror M4 and beam splitter B4. In the same way, beams 2 and 3 were produced. Because of the difference of light path, there were time delays of 13 ns between beams 1 and 2, and 2 and 3. Three reference beams were produced with B1 and M2. When probing light beams 1, 2 and 3 with different delay passed through the plasma, they were combined on B2 with three reference beams creating a sequence of three frames of plasma interferogram that were recorded with a CCD camera.

Provided the influence of collisions and magnetic field, and the non-linearity could be neglected, the fringe shift $\Delta N$ on the interferogram is related to electron density $n_e(r)$ via the equation:

$$\Delta N = \frac{e^2 \lambda}{2\pi m_e c} \int n_e(r) dy \tag{1}$$

where: $e$ and $m_e$ are the electron charge and mass, respectively; $c$ is the light speed; $\lambda$ is the wavelength of the probing light; $y$ is the propagation direction of laser light. Using the Abel inversion method and the known values of the parameters, the electron density profiles of the plasma shell could be derived. For a rough

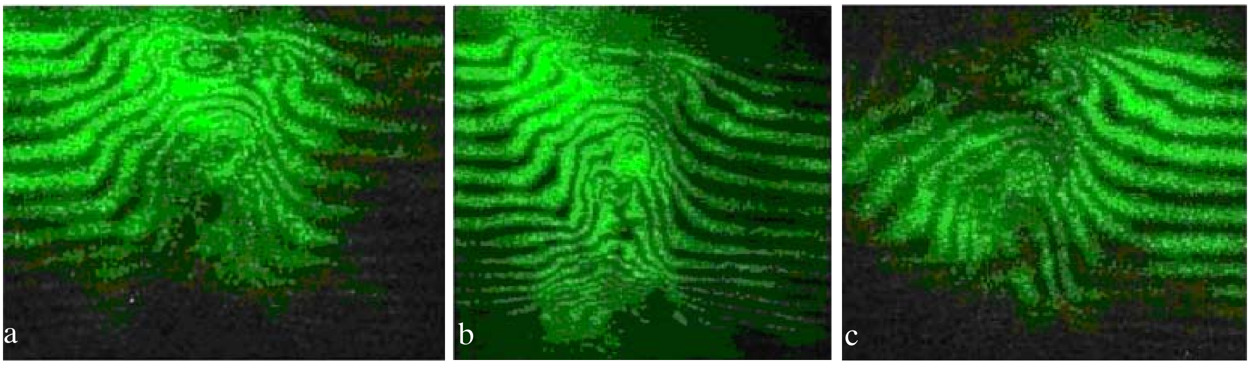

**Fig. 4.** Interferograms taken at the final pinch of the imploding plasma; (a) $t = -13$ ns, (b) $t = 0$, (c) $t = 13$ ns.

estimate of the electron density, it is assumed the $n_e(r)$ along the detecting light path is constant. Thus, the expression for electron density $n_e(r)$ in cm$^{-3}$ can be simplified to

$$n_e(x) = 4.1793 \times 10^{17} \times \Delta N/\Delta Y \tag{2}$$
$$n_e(x) = 4.215 \times 10^{17} \times \Delta N/\Delta Y$$

where $\Delta Y$ is the chordal length of plasma shell in cm.

The most concerned period of plasma movement is in the time interval around the pinch moment. Figure 4 are the interferograms that were taken around the final pinch stage of the imploding plasma. For taking these interferograms, the zero field of the interferometry (interference pattern without any plasma) was adjusted to have fringe spacing in image plane 0.8 mm. The moment of the final pinch was set as the instant of $t = 0$. From these interferograms, we could see the movement of plasma shell. Figure 4a shows the situation 13 ns prior to the pinch. The smallest radius (0.7 mm) of the plasma shell is shown in Fig. 4b that was taken at the pinch time $t = 0$. At $t = 13$ ns (Fig. 4c), the plasma shell was already expanding. From the interferograms mentioned above, it was estimated that the speed of plasma sheath movement was about $9 \times 10^6$ cm/s, the average electron density was $\geq 5.4 \times 10^{19}$/cm$^3$.

## Thomson ion energy analyzer

A Thomson ion energy analyzer was installed in gas-puff Z-pinch plasma [2, 3]. The Thomson ion energy analyzer is a simple and efficient tool to determine the characteristics of ion beams. It can provide information on ion energy, ion momentum and the ratio of charge to mass simultaneously. In this work, it was mainly used to determine the ion energy spectrum of ion beams produced in gas-puff Z-pinch plasma.

The structure of the analyzer is shown in Fig. 5. The analyzer consisted of an iron shell to enhance the magnetic field and to prevent the disturbance from outer electromagnetic field, a couple of permanent magnets made of Sm-Co to produce magnetic field of 0.564 T, a pinhole with the diameter of 40 μm, a CR-39 plastic target and insulators. A rectangle-shaped window of 8 mm × 18 mm was made in the iron shell for the detection of deflected ion beams. The couple of magnets were also treated as a pair of electrodes.

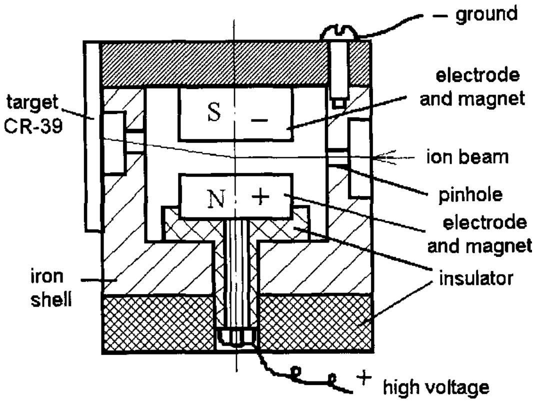

**Fig. 5.** The structure of Thomson ion energy analyzer.

In the experiment, the angles of ion beam deflected by electric and magnetic field usually were very small. The deflection angles of ion beam in $x$ direction (direction of electrical field $\vec{E}$) and in $y$ direction (direction of $\vec{v} \cdot \vec{B}$, $\vec{v}$ – the velocity of ion, $\vec{B}$ – magnetic field) can be expressed, respectively [3]:

$$\theta_x = \frac{q}{2T} \int_0^l E(z)dz \tag{3}$$

$$\theta_y = \frac{q}{\sqrt{2mT}} \int_0^l B(z)dz \tag{4}$$

where: $T = \frac{1}{2} mv^2$ is the kinetic energy of ion; $l$ is the field spread length; $q$ and $m$ is the charge and mass of ion, respectively. From Eqs. (3) and (4), one can get the following relation:

$$\frac{q}{m} = \frac{\theta_y^2 \int_0^l E(z)dz}{\theta_x \int_0^l B(z)dz} \tag{5}$$

Equation (5) is a typically parabolic equation. $\theta_x$ is corresponding to ion energy and $\theta_y$ is corresponding to ion momentum. According to Eqs. (3), (4) and (5) the information, such as the ratio of charge to mass, species of ions and ion energy spectrum can be obtained experi-

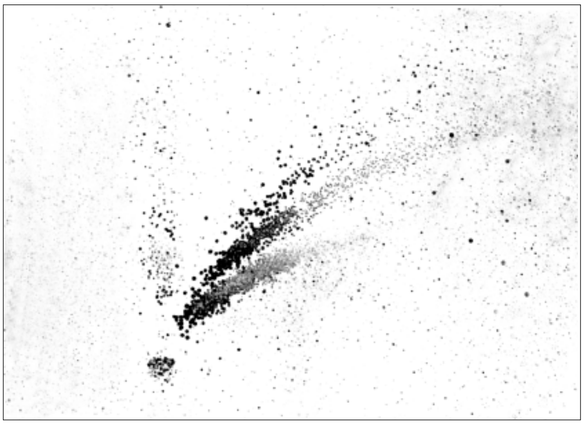

**Fig. 6.** Parabolas of Ne ion beams on CR-39 target.

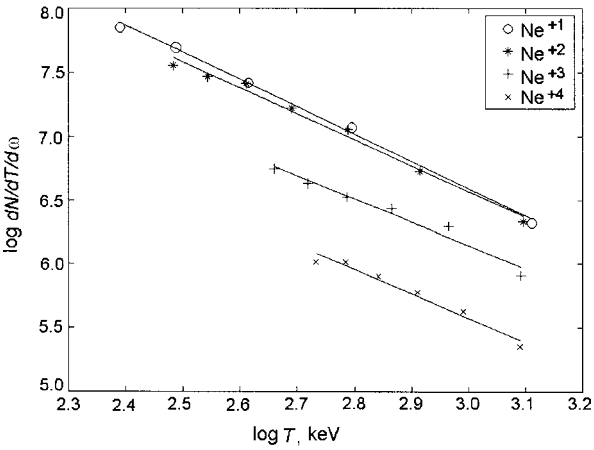

**Fig. 7.** Relationship between log(*dN*/*dEd*ϖ) and log*T*.

mentally. When the ions have a different ratio of charge to mass, or different energy, they experience different deflections in the electromagnetic field, and then they will hit the target (CR-39 plastic) at different positions forming parabolic tracks. The ions with the same ratio of charge to mass but different energies will be on the same parabola, but at different positions. The ions with different mass to charge ratios will be on different parabolas.

The magnetic field distribution was measured with a gauss-meter. The integration of $E$ and $B$ in Eqs. (3) and (4) were determined as $3.34 \times 10^4$ V and 0.012 tesla-meter, respectively. According to Eqs. (3) and (4), the energy and the momentum of an ion particle could be determined, if $\theta_x$ and $\theta_y$ of the ion on the parabolic tracks are measured.

Figure 6 is a picture of parabolas produced by ion beams bombarding CR-39 plastic target. On the picture up to five parabolas can be recognized, which are formed by ions with different charge-to-mass ratios. According to Eq. (5), if $m$ is constant, the vertical spacing of the parabolas ($y$-direction) at the fixed horizontal ($x$) co-ordinate is proportional to the square root of the ion charge $q$. In our case, the ratios of $\theta_y$ at fixed $\theta_x$ for different parabolas are $1{:}\sqrt{2}{:}\sqrt{3}\ldots$ According to the reading from the picture, these parabolas are identified to belong to $Ne^+$, $Ne^{2+}$, $Ne^{3+}$ and $Ne^{4+}$ ions. The energy and the momentum of an ion can be determined, when $\theta_x$ and $\theta_y$ of the ion on the parabolic tracks are measured. Figure 7 shows the energy spectra $dN/(dTd\omega)$ for $Ne^+$, $Ne^{2+}$, $Ne^{3+}$ and $Ne^{4+}$ ions, where $T$ is the energy of neon ions; $N$ is the number of ions, $\omega$ is the solid angle at plasma center subtended by entrance pinhole. From the ion energy spectra, it is concluded that the highest energies of $Ne^+$, $Ne^{2+}$, $Ne^{3+}$ and $Ne^{4+}$ ions emitted from our Z-pinch plasma are below 1.3 MeV. But the ions with higher charged state have higher energy in the low end of energy spectra.

## Conclusion

A small gas puff Z-pinch plasma device has been installed. The device has the following parameters: capacitance of energy storage capacitors 14 μF, charging voltage 22 kV, peak current 210 kA and a quarter of current period 2.4 μs. The device has been operated successfully, and it was used for diagnostic research and student training.

A three-frame Mach-Zehnder interferometer was developed for Z-pinch plasma experiment. According to interferograms, the electron density $n_e$ of the plasma right before pinch instant is larger than $5.4 \times 10^{19}/\text{cm}^3$, the corresponding velocity $v$ of collapsing plasma sheath is 9.0 cm/μs.

A compact Thomson ion energy analyzer was developed for determining ion energy spectra in Z-pinch plasma device. Clear parabolas produced by neon ions $Ne^+$, $Ne^{2+}$, $Ne^{3+}$ and $Ne^{4+}$ on CR-39 target have been observed. The energy spectra $dN/dT/d\omega$ for $Ne^+$, $Ne^{2+}$, $Ne^{3+}$ and $Ne^{4+}$ ions were determined. The highest energies of $Ne^+$, $Ne^{2+}$, $Ne^{3+}$ and $Ne^{4+}$ ions emitted from our Z-pinch plasma are below 1.3 MeV. But the ions with higher charged state have higher energy in the low end of energy spectra.

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