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SPECTROSCOPIC ANALYSIS OF INTENSITY, THERMAL AND RADIAL VELOCITY OF OIV IN Z-PINCH PLASMA

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This paper describes measurements and calculations with the ions OII, OIII and particularly OIV in z-pinch plasma. The equipment, which has extremely high time, spatial and spectral resolution (streak camera), allows us to obtain accurate data of the intensity of the emitted light, thermal and radial velocities as functions of time for OIV. As a result of this experiment, it was found that these 3 quantities increase, in general, from the moment of creation of plasma, until about 20 ns before the pinch time, when they sharply decrease. A hypothesis for that is a high ionization rate near the pinch.

Introduction

Plasma is a quasineutral gas consisting of charged (ions and electrons) and neutral particles, which exhibits macroscopic behavior. The macroscopic behavior is influenced by any change of electromagnetic field, densities of various ions and electrons and their velocities. Plasma research is important because of its applications in thermonuclear fusion, laser, solid state and astrophysics.

Z-pinch plasma, the type of plasma used in this project, is produced by short pulse high power devices. This plasma produces a high amount of X-ray radiation, displays strong interaction with magnetic fields and has interesting magnetic confinement properties. The z-pinch plasma is created in a vacuum chamber by applying high voltage over a hollow cylindrical body of gas. The gas ionizes and becomes plasma. A high current is produced in z-direction and creates a magnetic field. A strong force ($\vec{J} \times \vec{B}$) is produced to compress the plasma to the axis. The density and temperature increase to a critical point, after which the plasma flows away. This critical state is called the pinch.

The most important parameters of any body of plasma are N_e (electron density), T_e (electron temperature), N_i (ion densities) and ion velocities distribution. If these parameters are known, information on other parameters and properties of the plasma can be acquired. The pinch efficiency, determined by the plasma behavior, is dependent on the initial phase parameters, which we will measure.

In this experiment we use spectroscopy instead of another detection method, because with this method the plasma and therefore the results are not influenced. With

probes or other devices this would be the case.

We measured the ion velocity distribution, behavior of different charge states as a function of time, the electron density and temperature at the pinch time. The ion velocity distribution was measured using line emission from the plasma, in this case an OIV line (wavelength 3063.6\AA). The wavelength is altered because of certain phenomena such as doppler shift. Using absolute calibration we measured continuous light emission in two wavelengths, assuming bremsstrahlung, to calculate electron density and temperature. We also used absolute calibration to measure light intensity from certain lines in different charge states as function of time.

Experimental setup

The z-pinch device (Fig. 1) is composed of four $10\mu\text{F}$ parallel capacitors connected to a vacuum chamber ($P=2\times 10^{-4}$ torr), charged to 25 kV, that reach a current of 250 kA after 600 ns. Z-pinch plasma in this experiment was produced by discharging a gas with the 4 capacitors. The gas CO_2 is injected into the vacuum chamber. The magnetic field produced by a coil pushes back the fast valve and allows CO_2 ($P=5$ atm.) through a nozzle, forming a hollow cylinder between the nozzle (cathode) and the tube (anode-ground) in z-direction. Now, the probe checks the pressure near the nozzle and when the pressure is high enough, it sends a trigger to the screen room. After a delay, another trigger is sent to the big capacitor that opens the 4 switches of the capacitors simultaneously during a few ns. Previously, the gas wasn't ionized and its high resistivity caused the current to go through a load ($10\text{ k}\Omega$). After the discharge, the CO_2 gets ionized and becomes plasma due to the strong electric field between the anode and the cathode. The ionization lowers the resistivity and a strong current will be driven through the plasma cylinder in the z-direction. This current generates a magnetic field, according to the law $F=B\times I\times l$. The force due to the magnetic field compresses the cylinder of plasma, which leads to the pinch. The whole experiment lasts less than $2\mu\text{s}$.

In order to control the behavior of the plasma, probes like the Rogowski coil can be used. This probe shows, while measuring the total current induced in the coil, the variation in the plasma-current as function of time. This gives information about the homogeneity of the plasma before the pinch time, the depth and the time of the pinch. This information allows us to check the efficiency and reproductivity of the experiment.

However, in order to measure plasma parameters with good accuracy we use plasma

spectroscopy. In the sides of the vacuum chamber we have windows made by fused silica that allow us to observe light with the spectral range of 2000 Å to 8000 Å. The light is guided by fused silica mirrors and fused silica lens to a spectrometer. To analyze the light emission of the plasma, we use a 1.3m spectrometer of Spectra, characterized by a grating with 2400 grooves per mm and a spectral resolution of 0.005 nm; this spectrometer is linked to a streak camera, defined by a time resolution of 100 ps and 1.5mm (height) by 5 μm (width) spatial resolution. We aligned the system with a He-Ne laser and calibrated it using a lamp with a known light intensity as a function of wavelength, solid angle and width.

Light emitted from plasma goes through the spectrometer slit. The slit is made as small as possible for a better resolution. Light is then reflected from the first mirror to the grating that splits the different wavelengths into different directions. Small changes in the angle of reflection on the grating allow us to select a certain wavelength reflected on the second mirror to be directed through 2 lenses. In the streak camera, the photons hit metal plates and remove electrons. The beam of free electrons is accelerated and bent through both horizontal and vertical electric fields; the second field changes as a function of time. The electrons hit the Multichannel Plate (MCP) emitting photons of different wavelengths to the Charged Coupled Device (CCD) Camera that displays the intensity as a function of time.

Measurements

In the experiment we measured the parameters in order to understand the compression of plasma and the mechanism of its ionization. These parameters are the intensity, thermal and radial velocity.

The charge states of the plasma are studied, knowing the characteristic wavelengths of each of the ionized states of O and C: we tried to see the states on the streak camera by selecting that particular wavelength during the shot. The volume of the plasma and the intensity of emitted light as functions of time (see Fig. 2 for OIV) were obtained experimentally for OII, OIII and OIV. This allows us to calculate the number of ions in the same state:

$$n_{\alpha} = \frac{I}{V} \frac{4\pi c \Delta \lambda_D}{g_{\alpha} A_{\alpha} \hbar \omega 10^{-7}}, \quad (1)$$

where I is the intensity, V is the volume, g_{α} is the degeneracy of level, A_{α} is the Einstein coefficient, $\hbar \omega$ is the energy of photons of that wavelength, c is the calibration coefficient.

cient, and $\Delta\lambda_D$ is dispersion. It is possible to use this formula because the energy levels are quantified. The emitted light is actually the scattered light due to the electrons changing energy levels.

The velocities (Fig. 3 and 4) can be calculated from the graph of the intensity as a function of wavelength. This graph, given for every 11.5 ns, usually consists of the 2 gaussians for each wire of plasma. The difference between those 2 gaussians, the doppler shift, is due to the radial velocities relative to the outside observer that cause a shift in wavelength:

$$\lambda = \lambda_0(1 - \frac{v}{c}), \quad (2)$$

where λ_0 is the center of the shift. Besides, the effect of the Doppler broadening caused by thermal velocities of particles (v_{th}) takes place. The Maxwellian distribution of velocities is given by the formula:

$$f(v) = (\frac{m}{2\pi KT})^{1/2} \exp(-\frac{1}{2}mv^2/KT). \quad (3)$$

Now, v_r and v_{th} can be calculated:

$$v_r = \frac{\Delta\lambda_0}{\lambda_0}c, \quad (4)$$

$$v_{th} = \frac{\Delta\lambda_d}{\lambda_0}c. \quad (5)$$

Here $\Delta\lambda_0 = \lambda - \lambda_0$ (doppler shift) and $\lambda_d = \frac{FWHM}{2\sqrt{\ln 2}}$ (doppler broadening).

Bremsstrahlung radiation (E_λ) is the emission of light resulting from acceleration of charged particles due to collisions. It is a continuous emission of light that allows us to calculate the density of electrons (N_e) and that of ions (N_i):

$$E_\lambda = 1.9 \times 10^{-28} N_e N_i Z^2 (KT_e)^{-\frac{1}{2}} \lambda^{-2} \exp(-\frac{12395}{\lambda KT_e}) \quad (6)$$

where Z is the effective charge of the atom, e is the elementary charge, (T_e) is the temperature of electrons, and K is the Boltzmann's constant.

Discussion

The main goal of this experiment is to see what happens to the thermal and radial velocities and intensity near the pinch time. The profiles of v_{th} , v_r and intensity

as function of time give the following picture: the value of the three parameters increase until 20 ns before the pinch ($v_{th}=7.5\text{cm}/\mu\text{s}$, $v_r=7.0\text{cm}/\mu\text{s}$), after which they decrease. This is not the expected result: near the pinch, N_e and T_e still increase, as calculated using the bremsstrahlung. As N_e (from 10^{17} to 10^{18}) and T_e increase, normally v_{th} , v_r and intensity should increase: v_{th} due to thermal distribution, v_r due to $\vec{J}\times\vec{B}$ and I due to the emission of photons (more collision, thus more emission). The solution must be found in another phenomena. Possible explanations are the superposition of the two gaussians due to a low spectral resolution, or thermalization causing a coarse broadening. But the most plausible hypothesis is the theory of ionization. As the density (N) and the temperature (T) increase, the ionization time decreases (this parameter is dependent on N and T) to about 1 ns. High velocity OIV ions moving inwards will ionize quickly and we observe only slow OIV ions or ions of lower charge state that ionize, becoming OIV, and have a low inward velocity. This means that even if N and T increase, the velocities and intensity of the ions in low charge state, such as OIV, will decrease drastically. In other experiments conducted at the same laboratory OII and OIII show the same phenomena. However, in higher charge states, such as OV and OVI, the measured velocities and intensities of those ions do not decrease near the pinch, as we had expected: these ions ionize very slowly, because much energy is needed. These results coincide with our results and confirm the theory.

Conclusion

The model we get of the plasma is the following: as the plasma is compressed and the particles accelerate, v_{th} , v_r and I increase (because N and T increase). This process continues until a certain value for N and T. When this point is reached, the influence of the ionization time (dependent on N and T) increases, and due to ionization the faster particles will be in a higher charge state. Because of this we only see light emission from slower OIV ions. Therefore, there is a decrease in the parameters v_{th} , v_r and I.

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Z-PINCH

DETECTOR SYSTEM

Figure 1. EXPERIMENTAL SETUP:

- S = Switches
- C = Capacitor
- = Lens
- = Mirror
- ▨ = Grating

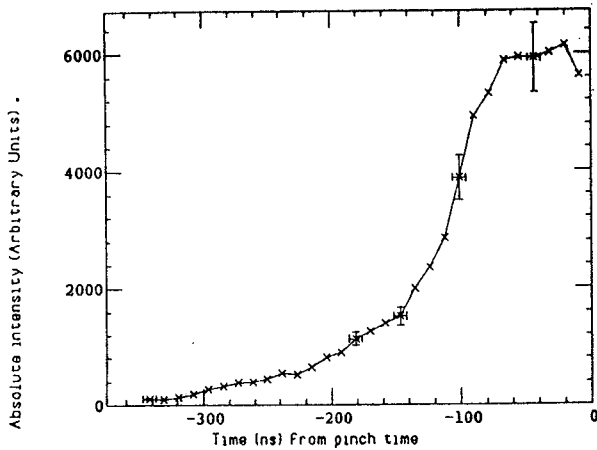
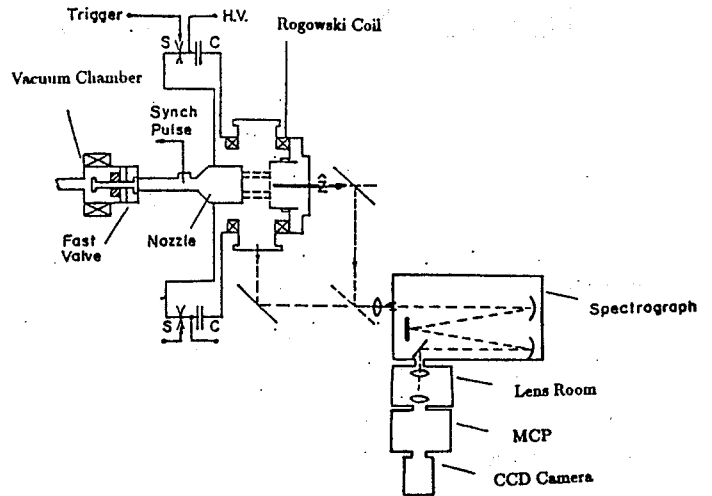


Figure 2. Absolute intensity measured for line, $\lambda = 3063.6\text{\AA}$ for OIV 1.0 mm from the anode as function of time (ns). $t=0$ is the pinch time.

Figure 3. Thermal velocity calculated from line, $\lambda = 3063.6\text{\AA}$ for OIV 1.0 mm from the anode as function of time (ns). $t=0$ is the pinch time.

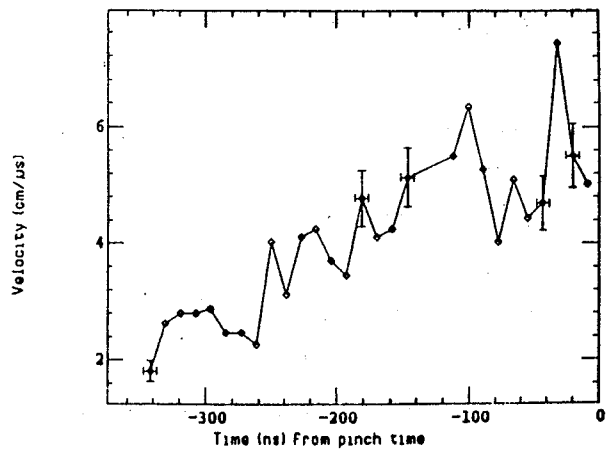


Figure 4. Radial velocity calculated from line, $\lambda = 3063.6\text{\AA}$ for OIV 1.0 mm from the anode as function of time (ns). $t=0$ is the pinch time.

