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Diagnostics of plasma target for ion beam: target interaction experiments

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Abstract

The investigation of beam-plasma interaction processes requires the development of plasma parameter diagnostic methods with high temporal and spatial resolution. The basic plasma parameters to be controlled when measuring the ion energy losses in ionized gases are the areal density of free electrons, the degree of ionization and the heavy element impurities during the electrical discharge in hydrogen. We present the relevant experimental results obtained by means of time-resolved, two-wavelength Mach-Zehnder interferometry based on He-Ne ($\lambda = 0.63$ μm) and He-Cd ($\lambda = 0.44$ μm) lasers. Optical emission line spectroscopy allowed us to follow the behaviour of the impurity concentrations with a high temporal resolution. Both methods have been used for diagnostic tests of a hydrogen plasma target.

1. Introduction

A new design of symmetrical discharge plasma target has been developed and test at ITEP for beam-plasma interaction experiments. As shown schematically in Fig. 1, the plasma is generated by igniting an electrical discharge in two collinear quartz tubes, each 6 mm in diameter and 75 mm long.

The capacitor bank of 3 μF, discharged at voltages of 2-4 kV, produces electric currents of 3 kA that flow in opposite directions in each of the two quartz tubes. Such a design for the plasma target enables us to suppress the well-known effect of the plasma lens [1] caused by the magnetic field of the current: the focusing effect of the first discharge shoulder is compensated for by the defocusing effect of the second shoulder. Symmetry of the discharge between the two shoulders is ensured by special inductivity coils included in the discharge circuit, with two wires for the two current branches wound in the opposite directions. For an initial pressure of the hydrogen gas rang-

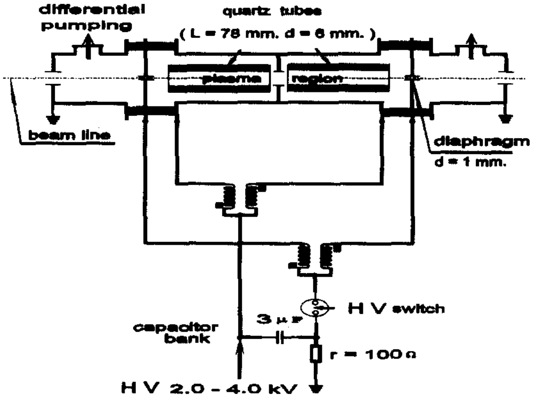

Fig. 1. Schematic overview of the plasma target.

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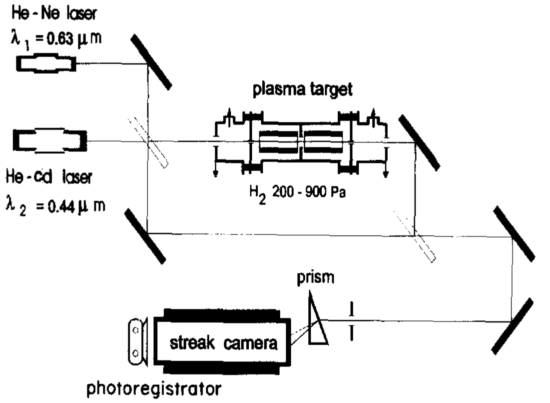

Fig. 2. Optical diagram (shown schematically) of the two-wavelength Mach-Zehnder interferometry plasma diagnostics.

ing from 200 to 900 Pa, a plasma electron density of up to 10^{17} cm^{-3} can be created in such a discharge.

The discharge current oscillates with a half-period of about 5 μs, which agrees fairly well with the calculated lifetime of the hydrogen plasma that spills out of the tube ends in the course of the hydrodynamic expansion.

2. Experimental details

The essential parameters to be measured in the experiment are the areal density of the free electrons and the degree of ionization. The measurements have been performed using the method of time-resolved, two-wavelength Mach-Zehnder interferometry in the axial direction. Only the plasma region where the proton beam passes, i.e. a region 1 mm in diameter and 150 mm long, has been probed. The electron areal density in this region is assumed to be independent of the radius, as is confirmed by the parallel lines of the interferometric pattern in the streak images. A Mach-Zehnder interferometer with two lasers—an He-Ne laser $\lambda_1 = 0.63$ μm and an He-Cd laser with $\lambda_2 = 0.44$ μm (see Fig. 2)—has been used.

Streak images of the interferometric fringes have been recorded with an FER-7 camera. The dimensionless shifts of the fringes k_1 and k_2 with respect to the neutral gas target state, as determined by the refraction index of matter along the target axis, can be expressed as linear combinations of the areal densities of the bound and free electrons along the line of sight, i.e.

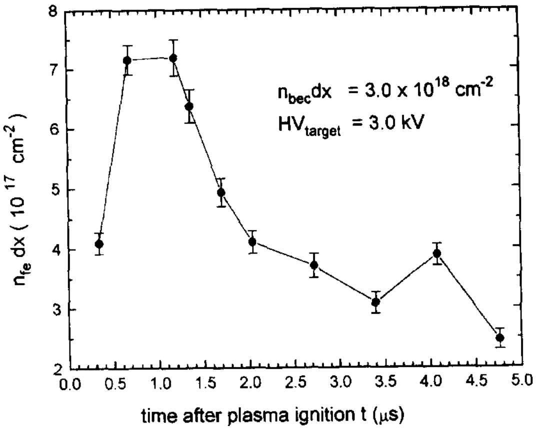

Fig. 3. Areal density of the free plasma electrons along the ion beam path as a function of time during the discharge.

$$k_1 = \frac{1}{\lambda_1} C_H(n_{bep}\,dx - n_{bec}\,dx) - \lambda_1 C_e n_{fe}\,dx \tag{1}$$

$$k_2 = \frac{1}{\lambda_2} C_H(n_{bep}\,dx - n_{bec}\,dx) - \lambda_2 C_e n_{fe}\,dx \tag{2}$$

where $C_H = 0.51 \times 10^{-23}$ cm^3 and $C_e = 4.48 \times 10^{-14}$ cm are the refraction indexes for hydrogen atoms and for free electrons, n_{bec}, n_{bep} and n_{fe} are respectively the number densities of the bound electrons in the cold case, and of the bound and free electrons in the partially ionized target.

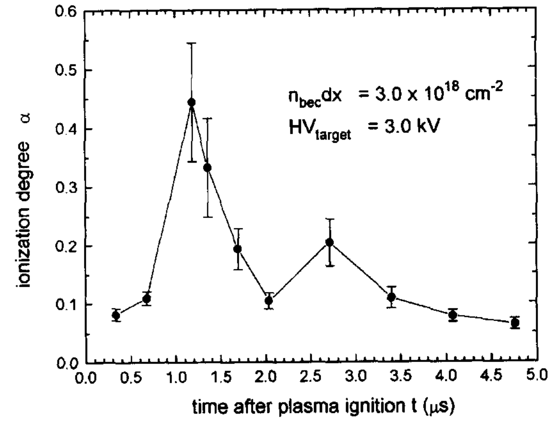

Fig. 4. Mean degree of ionization of the hydrogen plasma as a function of time during the discharge.

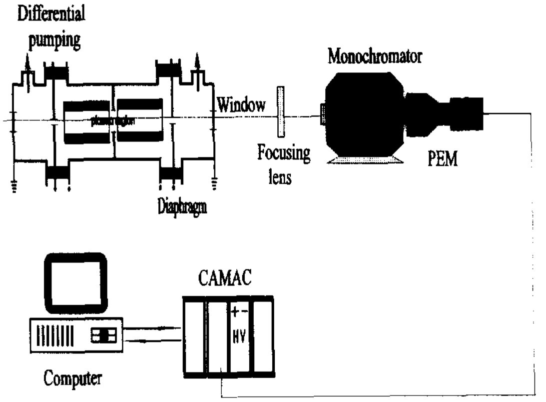

Fig. 5. Experimental set-up for measuring the optical emission spectrum of the plasma discharge.

Having measured the values of k_1 and k_2, we can calculate the quantities

$$n_{\mathrm{fe}}\,\mathrm{d}x = \frac{1}{C_{\mathrm{e}}}\frac{k_2\lambda_2 - k_1\lambda_1}{\lambda_2^2 - \lambda_1^2} \tag{3}$$

$$\frac{k_2^0}{k_1^0} = \frac{C_{\mathrm{H}}(1-\alpha) - \lambda_2^2 C_{\mathrm{e}}\alpha}{C_{\mathrm{H}}(1-\alpha) - \lambda_1^2 C_{\mathrm{e}}\alpha}\,\frac{\lambda_1}{\lambda_2} \tag{4}$$

where

$$\alpha = \frac{n_{\mathrm{fe}}\,\mathrm{d}x}{n_{\mathrm{fe}}\,\mathrm{d}x + n_{\mathrm{bep}}\,\mathrm{d}x} \tag{5}$$

is the mean degree of ionization and

$$\begin{aligned} k_1^0 &= k_1 + \frac{1}{\lambda_1} C_{\mathrm{H}} n_{\mathrm{bec}}\,\mathrm{d}x \\ k_2^0 &= k_2 + \frac{1}{\lambda_2} C_{\mathrm{H}} n_{\mathrm{bec}}\,\mathrm{d}x \end{aligned} \tag{6}$$

The values of $n_{\mathrm{bec}}\,\mathrm{d}x$ were determined experimentally by measuring the proton energy losses in the cold target state. As a result, the two-wavelength method gives us the possibility of monitoring the temporal evolution of the plasma areal electron density and the mean degree of ionization.

3. Results and discussion

Results of the two-wavelenth interferometry, as obtained for the same values of the initial hydrogen pressure and the capacitor voltage, are displayed versus time in Figs. 3 and 4. It can be seen that the areal density of the free electrons $n_{\mathrm{fe}}\,\mathrm{d}x$ and the mean degree of ionization α achieve maxima about 1 μs after the ignition of the discharge. The oscillatory behavior of these curves results from the oscillating current in the discharge circuit.

An important issue is the control of the contamination of the hydrogen plasma by heavy ions 'pulled out' from the quartz tube walls and the electrodes, which can lower the plasma temperature and induce rapid recombination of the free electrons. To reveal the presence of heavy ions in the hydrogen plasma, time-resolved measurements

Table 1
Optical emission lines measured in the spectrum of the hydrogen plasma target with a start-up pressure of $P = 340$ Pa and discharge voltage of 3 kV

Observed wavelength (nm)	Time of appearance (μs) (after plasma ignition)	Suspected element and its tabular wavelength (nm)
399.1	1.8	Si, $\lambda = 399.1$
403.9	2.2	Cu, $\lambda = 404.3$
409.8	1.7	H, $\lambda = 410.0$
419.3	2.8	Si, $\lambda = 419.0$
423.6	3.7	O, $\lambda = 423.3$
426.5	3.5	Cu, $\lambda = 426.9$
428.7	3.5	O, $\lambda = 428.5$
433.9	1.0	H, $\lambda = 434.0$
437.5	3.0	Cu, $\lambda = 437.8$
486.0	0.5	H, $\lambda = 486.1$

of the optical spectrum of the plasma emission in the wavelength range 0.35–0.6 μm have been carried out. A schematic diagram of the experimental set-up is shown in Fig. 5.

The results of these measurements (presented in Table 1), indicate that non-hydrogen emission lines appear in the plasma spectrum only 1.8 μs after the ignition. Though the optical thickness of the plasma column for these emission lines is considerably larger than unity and we do not actually 'see' the main plasma volume, these measurements provide satisfactory evidence that the hydrogen plasma is free of heavy ion impurities during the first half-period of the discharge. This conclusion is justified by the fact that at least some of the main contaminating target elements (the copper electrode and the quartz tube are located near the end of the plasma column, with the region between these elements and the monochromator filled with the room temperature hydrogen that is transparent for the radiation at the measured wavelengths.

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Reference

[1] E. Boggasch et al., Appl. Phys. Lett. 60, (1992) 2475.