Simulation and experimental investigation of hydrogen target plasma parameters for experiments on heavy ion beams deceleration

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Abstract. For the purposes of the experiments on heavy ions deceleration in ionized matter a plasma target based on a linear electric discharge in hydrogen has been designed. The two-dimensional hydrodynamic code was used for numeric simulation of the main stage of discharge. Estimated distribution of electron density and the degree of plasma ionization along the discharge tube axis of the target at the time of maximum discharge current corresponds to the experimental measurements of time dynamic of linear electron density and degree of plasma ionization in the target.

1. Introduction

Issues of charged particle beams energy losses in a cold matter and plasmas have a variety of practical applications: in the design of inertial confinement fusion targets, in material science, medicine, acceleration physics. Generally, energy losses of a charged particle in matter are caused not only by elastic and inelastic nuclear collisions, but also by the Coulomb interaction of a particle with target atoms [1].

In order to study the processes that take place with ions deceleration in an ionized matter, plasma targets, created by external energy sources such as a discharge in gas [2,3], capillary discharge [4], laser plasma [5,6], explosive generator plasma [7], and inserted into ion beam transportation line, are widely used.

The ion energy losses are difficult to estimate for a number of reasons. Calculation of ion charge variation dynamics requires the data for ionization and recombination cross sections. In the case of deceleration of ions with low energies in plasma, the required cross sections are practically unknown, and the results of estimation using different theoretical models may vary by an order of magnitude. Therefore it is relevant to perform direct measurements of the ion energy losses both in a “cold” and an ionized matter. One of the key aspects of these experiments is revealing the correlation between the ion energy losses and the ionized matter parameters: density, temperature and the degree of ionization.
The results of numerical simulation and experimental measurements of hydrogen target plasma electron density and the degree of ionization are presented in this article.

2. Numeric simulation of hydrogen target plasma parameters
At the Institute of Theoretical and Experimental Physics, a plasma target based on a linear electric discharge in hydrogen was designed for experiments on the charged particle beams deceleration in an ionized matter. The target plasma is obtained by an electric discharge in two 78-mm-long collinear quartz tubes of an inner diameter of 6 mm (figure 1). A 3-μF capacitor battery charged to 2–5 kV initiates a current of up to 400 A in each discharge channel. The currents in the discharge channels have opposite directions, due to which the effect of ion beam focusing, caused by the magnetic field of the discharge current decreases substantially. The vacuum system of the ion transportation line is protected from the gas load of the target by means of differential evacuation with the use of a turbo-molecular pump with an evacuation rate of 500 L/s. In this case, the length of the gas column in the target (l = 220 mm) is limited by two diaphragms with 1-mm-diameter apertures. The oscillograms of the current (1) and discharge luminosity (2) in the spectral range of 400–1100 nm, obtained at the charge voltage \( U = 5 \text{kV} \) and hydrogen pressure \( p = 1 \text{ mbar} \), are shown in figure 1b.

![Figure 1. Schematic of a hydrogen plasma target (a) and the current (1) and discharge luminosity (2) oscillograms (b).](image)

To perform numeric simulation of the discharge stage, where the electric fields in the tube are already formed (~0.5 μs after the discharge initiation and later), the two-dimensional hydrodynamic code was used [9]. The ohmic gas heating, thermal conductivity and radiation energy losses were taken into account in the calculations. The ionization and recombination processes were considered using the average ion charge approximation. The discharge current was derived from the external electrical circuit differential equation. It was shown that radiation losses caused by bound-bound transitions appear to be the main channel of plasma energy losses. The resonant radiation is substantially absorbed inside the target while the plasma remains transparent for the other radiation transitions. The radiation losses could not be derived using this approach, therefore the model of the black body with the grayness factor \( \varepsilon \) as a parameter was applied. Estimated discharge current
versus time at different $\varepsilon$ are shown in figure 2. As can be seen, theoretical estimation best fits the experimental results when $\varepsilon = 0.01$. The results of temperature distribution, electron density and plasma ionization degree along the target discharge tube axis at the time instant $t = 3.5 \mu s$, which matches the discharge current maximum, are presented in figures 3a-c.

**Figure 2.** The results of the hydrogen target plasma parameters simulation: time dependence of the discharge parameters, experimental (red) and estimated for $\varepsilon = 0.0001$ (green), $\varepsilon = 0.01$ (blue), $\varepsilon = 0.1$ (orange), is presented.

**Figure 3.** The results of simulating the hydrogen target plasma parameters: distributions of temperature (a), electron density (b) and the degree of plasma ionization (c) along the discharge tube axis of the target. Estimations for $\varepsilon = 0.0001$ (green), $\varepsilon = 0.01$ (blue), $\varepsilon = 0.1$ (orange) are presented.

3. **Measurement of electron density and degree of plasma ionization**

Among all the nonintrusive methods of plasma diagnostic the most accurate information about electron density $n$ can be derived by means of interferometric techniques. In a multicomponent plasma with a low degree of ionization, the contributions from different kinds of particles (electrons, ions in different charge states, and neutral atoms) to the refractive index can be considered additive.
In gases at temperatures below 10 eV, the maximum contribution to $n$ is made by neutral atoms in the ground state, and the refraction in the visible light spectral region is practically independent of the wavelength. In this case, the value of the phase shift $\delta$ of the probing electromagnetic wave is determined by the additive contribution of free electrons and variations in the neutral particle density caused by hydrodynamic processes in the heated gas. Due to strong plasma dispersion, it is possible to separate the contribution made by electrons to the phase shift of the probing electromagnetic wave from that made by heavy particles. To this end, it is necessary to perform the interferometric measurements simultaneously at two wavelengths.

Since the atom of hydrogen can exist in only two charge states – either neutral or fully ionized, it is possible to find the linear densities of electrons and hydrogen atoms $N_{H}$ in hydrogen plasma from the phase shifts of the probe electromagnetic wave, measured simultaneously at two wavelengths [10].

To investigate the temporal dynamic of electron density and the degree of plasma ionization a two-wavelength interferometer with the quadrature signal registration was designed previously [11]. The 25 mW He-Ne laser at $\lambda = 632.8$ nm and the 50 mW single-frequency solid-state YVO$_4$:Nd$^{3+}$ laser with intracavity second harmonic generation ($\lambda = 532$ nm) were used as the sources.

The linear density of free electrons and the degree of plasma ionization in a hydrogen target were measured for initial hydrogen pressures of 1–8 mbar and capacitor battery voltages of 2–5 kV. The linear electron density $[\text{cm}^{-2}]$ and the degree of ionization dependence on the initial hydrogen pressure at the maximum discharge current time are presented in figure 4.

![Figure 4](image-url)

**Figure 4.** Linear electron plasma density (a) and the degree of plasma ionization (b) at the maximum of the discharge current as functions of the initial hydrogen pressure for different values of the capacitor battery voltage.

As shown in figure 4a, with the voltage $U$ and the initial gas pressure increase, the linear electron density increases almost linearly and reaches its maximum of $(1.31 \pm 0.01) \times 10^{18}$ cm$^{-2}$ at the voltage of 5 kV and pressure of 8 mbar. As was expected, the maximum degree of hydrogen ionization is attained at the minimal amount of the plasma-forming gas (figure 4b). Within the experimental error, the degree of ionization at initial hydrogen pressures of 1–8 mbar is almost independent of the capacitor battery voltage $U$. The maximum degree of ionization $0.62 \pm 0.05$ was achieved at an initial pressure of 1 mbar.
4. Conclusions
Estimated distribution of the electron density and the degree of plasma ionization along the discharge tube axis of the target at the time of maximum discharge current corresponds to experimental measurements of time dynamics of the linear electron density and the degree of plasma ionization in the target. The measurements proved that the linear electron density can be varied in the range from $3.3 \times 10^{17}$ to $1.3 \times 10^{18} \text{ cm}^{-2}$ by varying the discharge current and the initial hydrogen pressure. The maximum degree of plasma ionization $0.62 \pm 0.05$ was achieved at the initial pressure of 1 mbar.

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