IRSTI 29.27.49 https://doi.org/10.26577/RCPh.2022.v81.i2.05

A.B. Tazhen*, M.K. Dosbolayev, T.S. Ramazanov
IETP Al-Farabi Kazakh national university, Kazakhstan, Almaty
*email: aigerim_kz271295@mail.ru

PULSED PLASMA FLOW DIAGNOSTICS

This paper presents the results of optical and probe diagnostics of hydrogen plasma flow in a coaxial plasma accelerator. The triple probe and the Optosky ATP2000P linear spectrometer with a spectral range of 200-1100 nm were used for measuring the electron current and obtaining the hydrogen plasma emission spectrum. The individual spectral lines were observed using an M833 monochromator spectrometer with a spectral resolution of 0.024 nm. From the measured electron currents and emission spectrums, the electron densities in the flux of a hydrogen pulsed plasma were calculated. We used the Stark method of H_β hydrogen line broadening for calculations of electron densities. The obtained experimental results from the probe and spectroscopic measurements of electron density correspond well. In this work, we also obtained the dependence of the electron density on the voltages applied to the capacitor bank. The electron density increases with increasing voltage, because of the increased energy applied to the discharge. The average electron densities in the plasma flux showed $n_e = 1.13 \cdot 10^{21}$ m^{-3}, $n_e = 4.14 \cdot 10^{21}$ m^{-3}, and $n_e = 5.57 \cdot 10^{21}$ m^{-3} at three values of voltages of 3 kV, 4 kV, and 5 kV, respectively.

Key words: coaxial plasma accelerator, hydrogen plasma flow, probe diagnostics, optical diagnostics, electron density, plasma emission spectrum

Ә.Б. Тәжен*, М.Қ. Досболаев*, Т.С. Рамазанов
ЭТФҒЗИ Әл-Фараби ат. Қазақ ұлттық университеті, Қазақстан, Алматы қ.
*email: aigerim_kz271295@mail.ru

Импульстік плазмалық ағынның диагностикасы

Бұл жұмыста коаксиалды плазмалық үдеткіштегі сутегі плазмалық ағынының оптикалық және зондтық диагностикасының нәтижелері ұсынылған. Электрондық токты өлшеу және сутегі плазмасының эмиссиялық спектрлерін алу үшін үшэлектродты зонд және 200-1100 нм спектрлік диапазонда зерттеуге мүмкіндік беретін Optosky ATP2000P сызықтық спектрометрі қолданылды. Жеке спектрлік сызықтар 0,024 нм спектрлік ажыратқыштық қабілеті бар M833 монохроматор спектрометрінің көмегімен алынды. Өлшенген электрондық токтар мен алынған эмиссиялық спектрлер негізінде импульстік сутегі плазмасының ағынындағы электрондардың тығыздығы есептелді. Электрондардың тығыздығын есептеу үшін H_β сутегі спектрінің Штарктық кеңею әдісі қолданылды. Электрондардың тығыздығын зондтық және спектроскопиялық өлшеудің тәжірибелік нәтижелері жақсы сәйкес келді. Сонымен қатар бұл жұмыста электрондар тығыздығының конденсатор батареясына түсірілген кернеуге тәуелділігі де алынды. Кернеудің жоғарылауымен электрондардың тығыздығы да артады, бұл разрядқа берілген энергияның артуымен тығыз байланысты. 3 кВ, 4 кВ және 5 кВ кернеуінің үш мәні үшін плазмалық ағындағы электрондар тығыздығының орташа мәндері сәйкесінше $n_e = 1{,}13 \cdot 10^{21}$ м$^{-3}$, $n_e = 4{,}14 \cdot 10^{21}$ м$^{-3}$, және $n_e = 5{,}57 \cdot 10^{21}$ м$^{-3}$ құрады.

Түйін сөздер: коаксиалды плазмалық үдеткіш, сутегі плазмалық ағыны, зондтық диагностика, оптикалық диагностика, электрон тығыздығы, плазманың эмиссиялық спектрі

А.Б. Тажен, М.К. Досболаев, Т.С. Рамазанов
НИИЭТФ Казахский национальный университет им. аль-Фараби, Казахстан, Алматы
*email: aigerim_kz271295@mail.ru

Диагностика импульсного плазменного потока

В работе представлены результаты оптической и зондовой диагностики водородного плазменного потока в коаксиальном плазменном ускорителе. Для измерения электронного тока и получения эмиссионных спектров водородной плазмы были использованы тройной зонд и соответственно линейный спектрометр Optosky ATP2000P со спектральным диапазоном 200-1100 нм. Отдельные спектральные линии были сняты с помощью спектрометра-монохроматора M833 со спектральным разрешением 0,024 нм. На основе измеренных электронных токов и отождествленных эмиссионных спектров были рассчитаны плотности электронов в потоке импульсной водородной плазмы. Для расчёта плотности электронов был использован метод Штарковского уширения водородных линий H_{β}. Полученные экспериментальные результаты зондового и спектроскопического измерения плотности электронов хорошо согласуются. В этой работе также была получена зависимость плотности электронов от приложенного к конденсаторной батарее зарядового напряжения. С увеличением зарядового напряжения увеличивается плотность электронов, что связано с увеличением энергии вложенной в разряд. При трех значениях зарядового напряжения 3 кВ, 4 кВ и 5 кВ, средние значения плотности электронов в плазменном потоке составили $n_e = 1{,}13 \cdot 10^{21}$ м$^{-3}$, $n_e = 4{,}14 \cdot 10^{21}$ м$^{-3}$, и $n_e = 5{,}57 \cdot 10^{21}$ м$^{-3}$, соответственно.

Ключевые слова: коаксиальный плазменный ускоритель, водородный плазменный поток, зондовая диагностика, оптическая диагностика, плотность электронов, эмиссионный спектр плазмы

Introduction

Pulsed plasma flows in plasma accelerators are widely used for solving some fundamental and practical problems. Particular interest among various applications of pulsed plasma flows represents fusion, and astrophysical researches [1-4]. For example, an experimental study of the interaction of pulsed plasma flow with materials [5]. The use of plasma flows for specific applications is determined by the formation, acceleration, and structure of the plasma plume. It depends on the geometry of the electrodes system, the way of filling and the type of used plasma-forming gas. A variety of plasma diagnostic methods are available to investigate the structure; processes caused by the formation and acceleration of the plasma flux. They are divided into contact and non-contact methods. The diagnostics of pulsed plasma flows is a difficult problem in comparison with stationary plasma. The complexity is the character of plasma that we study: high plasma velocity, short-lived plasma processes, high temperature. Nevertheless, regardless of this, the methods of diagnostics of no stationary flows of pulsed plasma such as the probe and optical and Interference methods exist. The electrical and magnetic probes are widely used among probe methods. The application of probe diagnostic methods is limited by perturbations induced in plasma. The optical methods have an advantage in comparison to probe methods and are used extensively in diagnostics. Its main advantage is the nonperturbative character. The optical and probe diagnostics of the pulse plasma flux was carried out in this work for measuring the electron density. This is important from a scientific and practical viewpoint for two reasons:

I In relation to the variety of applications of plasma flow;

II For understanding of plasma physics in plasma accelerators.

This work is organized as follows: the second and third chapters provide a brief overview of the experimental setup and plasma diagnostic methods; the fourth chapter contains an analysis and discussion of the experimental results; the fifth chapter consists of a conclusion.

Brief overview of the experimental setup

The optical and probe diagnostics of pulsed plasma flow was carried out in a coaxial plasma accelerator. This setup uses hydrogen as plasma-forming gas. The duration of a single pulse is an average of $\tau \sim 300$ μs. The main operating unit of the setup is the coaxial electrode system. The electrode system was placed in a vacuum chamber. A chamber is pre-pumped to a pressure of $\sim 10^{-5}$ Torr. The vacuum station for evacuating the vacuum chamber consists of a forevacuum and diffusion pump. Before the shot, the chamber is filled with plasma-forming gas. The experimental setup is powered by a capacitor battery with a capacitance of 1.4 mF. The pulse discharge in the interelectrode space is ignited when the vacuum arrester is turned on. The plasma is accelerated towards the output of the accelerator by the $\mathbf{J} \times \mathbf{B}$ force acting on plasma current bridging the electrodes. The schematic diagram and parameters of the experimental setup are described in detail in [6-8].

Brief overview of plasma diagnostic methods

The Optosky ATP2000P spectrometer with a spectral range of 200-1100 nm, and the M833 monochromator spectrometer with a spectral resolution of 0.024 nm were used in this work for conducting probe and optical diagnostics of hydrogen plasma flow.

Hydrogen spectral line broadening is an important tool for optical diagnostics of plasma. Micro fields of electrons, ions, etc. in plasma cause various types of Stark broadening. One of the well-known Stark broadening of hydrogen lines by electrons is theoretically well studied and successfully used in practice. The relation between the spectral line half-width and the electron density is given by expression (1). This equation is used for diagnostic purposes for measuring the electron density.

$$\Delta\lambda_{1/2} = 2{,}50 \cdot 10^{-9} \alpha_{\frac{1}{2}} n_e^{2/3} \text{Å}, \qquad (1)$$

where $\alpha_{1/2}$ – theoretical values of the half-width $\Delta\lambda_{1/2}$. The theoretical values of the half-width of the hydrogen line H_β are determined. In [9, 10] this method was applied to measure the electron density in the plasma flux.

The probe diagnostic methods have always been widely used for studying the properties of plasma and gaseous discharges. This method is a useful tool for local determination of the density, temperature of charged plasma particles and the space potential. Of known probe methods, triple probe allows measuring the local plasma parameters without external voltage sweep. This is particularly important in our case, because in pulsed plasma the discharges do not repeat from shot to shot. Moreover, this method allows measuring the temperature and electron density simultaneously in one shot. Another advantage is that using this method it is possible to obtain the temporal distribution of plasma parameters. The operation of a triple probe is as follows: three similar electrodes are located in plasma being studied. In voltage mode of operation, only V_{12} voltage is applied between two probes, and the third probe will be at floating potential V_{23}. Temperature and electron density are calculated according to equations (2) and (3):

$$kT_e = \frac{eV_{23}}{ln2}, \qquad (2)$$

$$n_e = \frac{-I}{0{,}61Se\sqrt{\frac{kT_e}{m_i}}} \cdot \frac{\exp\left(-\frac{eV_{23}}{kT_e}\right)}{\left(1 - exp\left(-\frac{eV_{23}}{kT_e}\right)\right)}, \qquad (3)$$

where S is surface area of probes, m_i is ion mass, e is elementar charge, $I = \frac{V_{12}}{R_{shunt}}$ is ion saturation current. A triple probe method for measuring electron density in a plasma flux has been used in works [11, 12].

Analysis and discussion of the experimental results

The emission spectrum of the hydrogen plasma flux was obtained and analyzed in the 350-900 nm wavelength range by means of the Optosky ATP2000P linear spectrometer, it is shown in Fig. 1. As seen from this figure, the composition of the hydrogen plasma flux contains such impurities as iron, chromium, carbon, copper, hydrogen and residual air elements. The copper and iron, chromium, carbon are formed as a result of erosion of the electrode surface and the vacuum chamber wall.

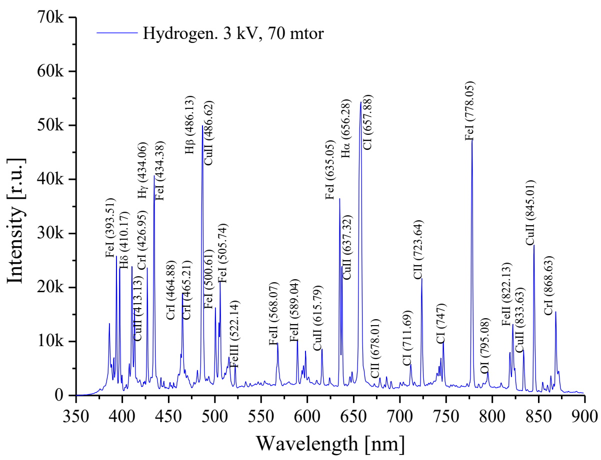

Figure 1 – Emission spectrum of the hydrogen plasma flux

A typical spectrum of the hydrogen line H_β was obtained at a pressure of 70 mTorr and at different values of voltages applied to the capacitor bank of 3-5 kV by using the spectrometer monochromator M833 with a spectral resolution of 0.024 nm (Fig. 2).

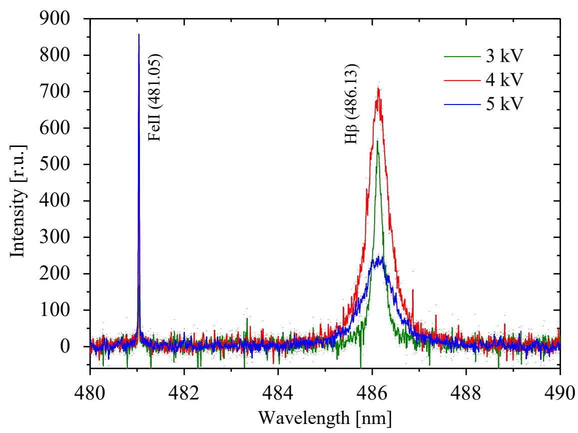

Figure 2 – Plasma flux spectrum in the H_β region

It can be seen that the half-width of the H_β line increases with increasing voltage applied to the capacitor bank. These indicate increasing electron density in plasma. This is caused by increasing the energy attached to the discharge. Averaged electron density for applied voltage of 3 kV is $n_e = 1.13 \cdot 10^{21}$ m^{-3}, for applied voltage of 4 kV is $n_e = 4.14 \cdot 10^{21}$ m^{-3}, for applied voltage of 5 kV is $n_e = 5.57 \cdot 10^{21}$ m^{-3}. The dependence of calculated electron density on applied voltage at gas pressure of 70 mTorr is shown in figure 3.

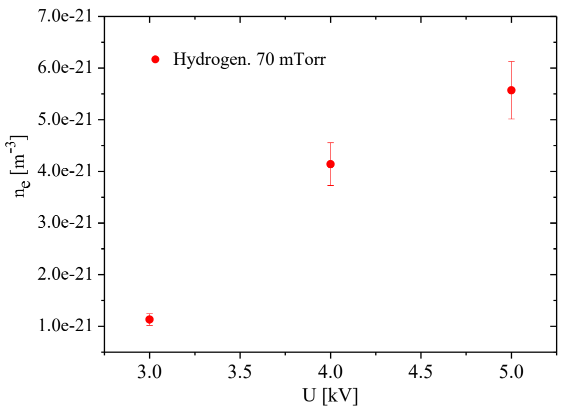

Figure 3 – The dependence of the electron density in the plasma flux on the voltage applied to the capacitor bank

The investigation of plasma flow using the triple probe method was performed at a capacitor bank voltage of 3 kV and a gas pressure of 70 mTorr. The probe was placed inside the vacuum chamber at a distance of 10 cm from the electrode system, and directed to plasma flow. The results of the measurements are shown in Figures 4 and 5.

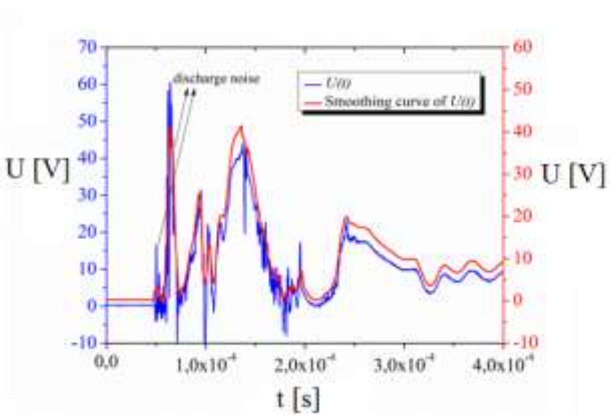

Figure 4 – Temporal characteristic of the floating potential and ion saturation current on the probe

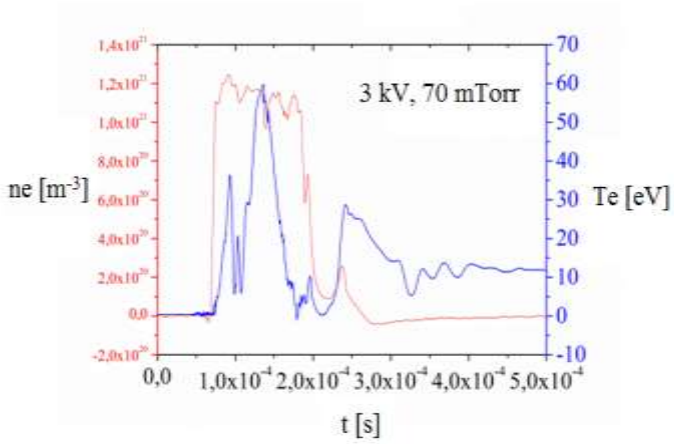

Figure 5 – Temporal characteristics of electron density and temperature

The obtained results by the Stark broadening method agree well with the results obtained by the probe method. As can be seen from Figures 3 and 5 the experimental results of electron density agree well.

Conclusion

Optical and probe diagnostics of the hydrogen plasma flux in a coaxial plasma accelerator were carried out. In particular, electron densities in the plasma flux were calculated by the Stark method of hydrogen line broadening and a triple electric probe. The obtained experimental results are in good agreement. The dependence of the electron density on the voltage applied to the capacitor bank was also obtained. It was found that with increasing voltage of charge, the energy attached to the gaseous discharge increases, and accordingly, the density of electrons increases. The temperature of electrons in the plasma flux was measured with a triple electric probe. The maximum value of the electron temperature was 60 eV at voltage of 3 kV and gas pressure in the vacuum chamber of 70 mTorr. Moreover, the time dependence of the temperature and electron density was obtained with the triple probe.

Funding

This research was funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP09259081).

References

1 Garkusha I.E., Aksenov N.N., Byrka O.V., Makhlaj V.A., Herashchenko S.S., Malykhin S.V., Petrov Yu.V., Staltsov V.V., Surovitskiy S.V., Wirtz M., Linke J., Sadowski M.J., Skladnik-Sadowska E. Simulation of plasma-surface interactions in a fusion reactor by means of QSPA plasma streams: recent results and prospects //Phys. Scr. – 2016. – Vol. 91. – Art.No 094001.

2 Lerner E., Hassan S., Karamitsos I., F.V. Roessel. Confined ion energy >200 keV and increased fusion yield in a DPF with monolithic tungsten electrodes and pre-ionization //Physics of Plasmas. – 2017. – Vol. 24. – Art.No 102708.

3 Yousefi H.R., Thornhill W., Sakai J.I., Nishino Y., Ito H., Masugata K. Dense plasma focus for laboratory astrophysics //Iranian Physical Journal. – 2009. – Vol. 2. – Art.No 17-20.

4 Dosbolayev M.K., Igibayev Zh.B., Tazhen A.B., Ramazanov T.S. Preliminary Study of the Solid-State Pulsed Plasma Thruster Model with Graphite as a Propellant //Plasma Physics Reports. – 2022. – № 48(3). – P.263-270.

5 Linsmeier Ch., Unterberg B., Coenen J.W., Doerner R.P., Greuner H., Kreter A., Linke J., Maier H. Material testing facilities and programs for plasma-facing component testing //Nuclear Fusion. – 2017. – Vol. 57. – Art.No 092012.

6 Tazhen A.B., Dosbolayev M.K. Measuring the self-generated magnetic field and the velocity of plasma flow in a pulsed plasma accelerator //Recent Contributions to Physics. – 2021. – № 2(77). – P.30-39.

7 Dosbolayev M., Raiymkhanov Zh., Tazhen A., Ramazanov T. Experimental Investigation of the Properties of Plasma-Dust Formations on Pulsed Plasma Accelerator //IEEE Transactions on Plasma Science. – 2019. – Vol. 47. – P.3047-3051.

8 Dosbolayev M.K., Tazhen A.B., Ramazanov T.S. Investigation and diagnostics of plasma flows in a pulsed plasma accelerator for experimental modelling of processes in tokamaks //Eurasian Journal of Physics and Functional Materials. – 2021. – Vol. 5. – P.198-210.

9 Wiechula J., Hock C., Iberler M., Manegold T., Schonlein A., Jacoby J. Experimental characterization of a coaxial plasma accelerator for a colliding plasma experiment //Physics of Plasmas. – 2015. – Vol. 22. – Art.No 043516.

10 Hong Y.J., Kwon G.Ch., Cho G., Shin H.M., Choi E.H. Measurement of Electron Temperature and Density Using Stark Broadening of the Coaxial Focused Plasma for Extreme Ultraviolet Lithography //IEEE Transactions on Plasma Science. – 2010. – Vol. 38. – P.1111-1117.

11 Borthakur S., Talukdar N., Neog N.K., Borthakur T.K. Study of plasma parameters in a pulsed plasma accelerator using triple Langmuir probe // Physics of Plasmas. – 2018. – Vol. 25. – Art.No 013532.

12 Yeong W., Ling L., Zhang Zh., Tang H., Liu X., Wang N. In-plume acceleration of leading-edge ions from a pulsed plasma thruster //Plasma Sources Sci. Technol. – 2018. – Vol. 27. – Art.No 104002.

References

1 I.E. Garkusha, et al., Phys. Scr. 91, 094001 (2016).
2 E. Lerner, et al., Physics of Plasmas 24, 102708 (2017).
3 H.R. Yousefi, et al., Iranian Physical Journal 2, 17-20 (2009).
4 M.K. Dosbolayev, et al., Plasma Physics Reports 48(3), 263-270 (2022).
5 Ch. Linsmeier, et al., Nuclear Fusion 57, 092012 (2017).
6 A.B. Tazhen, M.K. Dosbolayev, Rec.Contr.Phys., 2 (77), 30-39 (2021)
7 M. Dosbolayev, et al., IEEE Transactions on Plasma Science 47, 3047-3051 (2019).
8 M.K. Dosbolayev, et al., Eurasian j. phys. funct. mater., 5, 198-210 (2021).
9 J. Wiechula, et.al., Physics of Plasmas 22, 043516 (2015)
10 Y.J. Hong, et.al., IEEE Transactions on Plasma Science 38, 1111 – 1117 (2010).
11 S. Borthakur, et.al., Physics of Plasmas 25, 013532 (2018).
12 W. Yeong, et.al.,Plasma Sources Sci. Technol. 27, 104002 (2018).