29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. ***26B****, P-2.118 (2002)*

Experimental Investigation of Pulsed Hydrogen Plasma in RPI-type Device

J. Baranowski, E. Skladnik-Sadowska, K. Czaus, Marek J. Sadowski
The Andrzej Soltan Institute for Nuclear Studies 05-400 Otwock-Swierk , Poland

Abstract The paper presents results of recent measurements of the basic characteristics of pulsed plasma-ion streams generated within the modified IBISEK experimental system [1], which was equipped with coaxial multi-rod electrodes of the RPI type [2]. The facility was also equipped with a fast-acting electromagnetic valve used for the injection of the working gas into the inter-electrode volume, and the pulsed current generator with initial energy W_o = 12 kJ at the initial charging voltage U_o = 28 kV. The optical spectra, as measured within the 200-1100 nm wavelength range, were analyzed. Particular attention was paid to the broadening of some selected spectral lines. Taking into account electron density values (n_e), the measurements make possible to estimate that hydrogen plasma (produced under favorable conditions) reached the local thermal equilibrium (LTE). The emission characteristics of the studied spectral lines were measured as a function of the initial gas conditions in the IBISEK vacuum chamber. The conclusions should be verified by measurements in more powerful facilities.

Introduction

Recent experimental studies of pulsed plasma-ion streams within the RPI-IBISEK device [1] have been the continuation of our previous investigations carried out with coaxial multi-rod electrodes of the RPI-type [2]. In fact, in the middle 80s, during experimental studies of deuterium plasma in the MAJA-RPI device [3], it was observed that a fusion neutron yield can rise considerably (even by one order of magnitude) under appropriate gas conditions. The X-ray pinhole pictures demonstrated that it is possible to obtain an almost spherical region (cloud) of relatively dense deuterium plasma, which emits soft X-rays [4]. In such cases there was observed a decrease in kinetic energy of the emitted deuterons from several dozen keV to several keV [5]. Since those effects could not be explained by the interaction of high-energy deuterons with a gas- or plasma-target, it was assumed that a local thermal equilibrium (LTE) state is achieved within the plasma region. Such phenomena can of course appear in various RPI-type systems. In order to verify the hypothesis it appeared necessary to apply techniques of the optical spectroscopy.

Experimental setup

A scheme of the experimental arrangement, which has been realized with the RPI-IBISEK (called also the IONOTRON-93) facility, is presented in Fig.1. Details of the Fig.1.

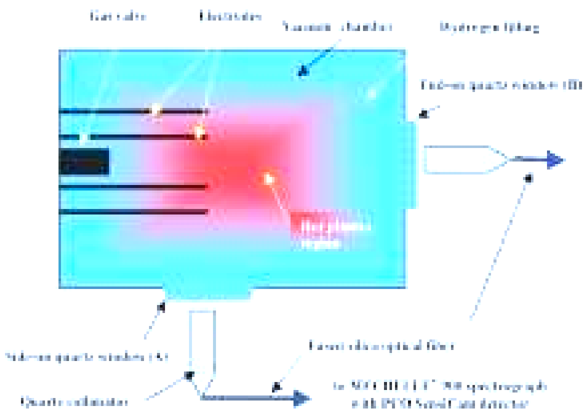

Fig.1. Scheme of the experimental configuration used for spectroscopic studies at the RPI-IBISEK device.

construction and operation of this device have been described in the previous papers [8-9]. An optical spectrum of plasma, which was produced by pulsed high-current discharges in the considered facility, has been measured by means of a Mechelle® 900 spectrometer, which can be applied within the wavelength range from 200 nm to 1100 nm [6]. This spectrometer is equipped with a PCO SensiCam detector, which can be coupled with a standard PC. The detector is operated with the software compatible with Windows 9x. It means that the observed spectrum can be immediately registered, and after that analyzed automatically. For the detailed analysis of the registered spectrum the use is made of a GRAMS/32D program [6]. In order to perform the calibration of the Mechelle® 900 spectrometer there is applied an internal spectral lamp of the Philips PL-S 9W TUV type, which uses a mixture of Ar and Hg vapors (as the working gas).

Experimental results

Measurements of the emission spectrum of hydrogen plasma have been performed perpendicularly (position A) and along (position B) to the symmetry axis of the RPI electrodes. It made possible to determine and eliminate influence of axial motion of the pulsed plasma stream.
The spectroscopic measurements have been carried out at different values of a time delay (τ = 130, 190, 210, 250, 270, 300, and 320 μs) between gas puffing and the application of a high-voltage pulse. The registration of the optical spectrum has been performed at the exposition times equal to 5 μs and 100 μs.
Particular attention has been paid to the H_β 486.133 nm, and H_γ 434.047 nm spectral line. It should be noted that the working gas was pure hydrogen, the initial charging (supply) voltage was U_0 = 28 kV, and total energy (stored within the condenser bank) was equal to about 10 kJ. During side-on measurements (position A) the viewing field of the quartz collimator was about 5 mm in diameter, at a distance of 5 mm from the electrode outlets. The spectral resolution of the applied spectrometer was $(\lambda/\Delta\lambda)_{FWHM}$ = 900. An example of the optical spectrum, which was registered within the RPI-IBISEK device, is presented in Fig. 2.

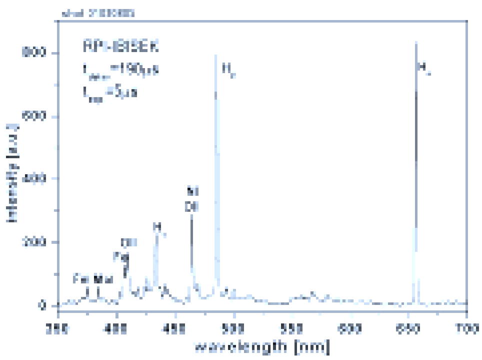

Fig.2. Optical spectrum of hydrogen plasma obtained from a single discharge in the RPI-IBISEK device at the initial charging voltage U_0 = 28 kV, the time delay τ = 190 μs, and the exposition time equal to 5 μs.

As described above, the main aim of the spectral measurements was to check whether the observed plasma region can achieve the LTE state and what are values of plasma temperatures (T) at different initial gas conditions (i.e. at various τ values). The measurements of T values have been based on the Doppler effect observed for the investigated spectral lines.

Analysis of the results

As mentioned above, the spectral measurements were performed with exposition times equal to 5 μs and 100 μs. The choice of those exposition times was substantiated by values of
time needed for the thermal equilibration of different ion species (τ_{ii}) as well as ions and electrons (τ_{ie}). Under assumption that ion temperatures were considerably higher than electron ones, taking into account that the plasma concentration was above 10^{16} cm^{-3}, the known Spitzer formula [10] has given the value $\tau_{ie} = 10^{-9}$ s. Hence, at the described experimental conditions the exposition time should be considerably longer than 100 ns.

A quantitative analysis has been based on the spectra registered side-on (position A). In order to estimate the ion temperature values, the use has been made of the known formula for the spectral line with the Gaussian profile:

$$\Delta\lambda = 7.16 \text{ x } 10^{-7} \lambda \, (T / A)^{1/2} \qquad (1)$$

where: $\Delta\lambda$ – the half-width of the considered line [nm], λ – the wavelength corresponding to the line maximum intensity [nm], T – the estimated temperature of atoms [K], A – the mass of the considered atoms. It should be noted that the $\Delta\lambda$ values must include the apparatus constant, and the formula assumes that no re-absorption of the lines in question.
It should be noted that for the temperature assessments it was necessary to take into account the apparatus FWHM value. For this purpose the use was made of the calibration spectral lamp operated with Ar and Hg vapors. For a comparison, in the investigated optical spectrum there were selected spectral lines of Fe and Mo (i.e. the present heavy metals) with the wavelength close to H_β and H_γ, and there were measured their FWHM values. In order to estimate corresponding temperature (T) values there were chosen the cases when

$$\Delta\lambda_{\text{FWHM (H-beta, H-gamma)}} \gg \Delta\lambda_{\text{FWHM (calibration, Fe- and Mo-lines)}} \qquad (2)$$

This procedure made possible to subtract the measured apparatus FWHM values from the observed ones. At the considered experimental conditions it was estimated that other optical effects (i.e. Stark-, Zeeman-, and Van der Walls-effects) could be neglected. Hence, appropriate fits of the analyzed spectral lines by the Gaussian profiles (after the elimination of the Lorentz profile) delivered information about the Doppler broadening.
The spectra registered for discharges performed at the delay time τ = 210 μs were analyzed first. On the basis of the spectrum obtained with the exposition 5 μs it has been estimated that for H_β line $\Delta\lambda$ = 0.84 nm, T $\approx$ 6 x 10^6 K, and for H_γ line $\Delta\lambda$ = 0.71 nm, T $\approx$ 5 x 10^6 K. From the spectrum obtained with the exposition 100 μs it has been estimated that for H_β line $\Delta\lambda$ = 0.21 nm, T $\approx$ 0.36 x 10^6 K, for H_α line $\Delta\lambda$ = 0.10 nm, and for H_γ line $\Delta\lambda$ = 0.35 nm, T $\approx$ 1.2 x 10^6 K.
The spectra registered at the delay time τ = 190 μs were also analyzed. From the spectrum obtained with the exposition 5 μs it has been estimated that for H_β line $\Delta\lambda$ = 0.99 nm, T $\approx$ 8.1 x 10^6 K, and for H_γ line $\Delta\lambda$ = 1.1 nm, $T_i \approx$ 12 x 10^6 K. From the spectrum obtained with the_exposition 100 μs it has been estimated that for H_β line $\Delta\lambda$ = 0.19 nm, T $\approx$ 0.3 x 10^6 K, and for H_γ line $\Delta\lambda$ = 0.39 nm, $T_i \approx$ 1.6 x 10^6 K.
These results demonstrate how the estimated plasma temperature values T depend on the operational regime (defined by the delay time) and the used exposition time. The appearance of relatively high temperatures (> 10^6 K), especially at the delay time τ = 190 μs, could be a reason of an enhanced X-ray emission and higher neutron yields from deuterium shots.
Since studies of deuterium discharges have been carried out within other RPI facilities of energy higher than that of the RPI-IBISEK device, one can not exclude that the achieved deuteron temperatures were also higher. This hypothesis has been partly confirmed by deuteron parabolas, which were registered with a Thomson analyzer in the MAJA-RPI facility, at a similar delay time [9]. An average kinetic energy of those deuterons was of the order of several keV, and it could be treated as a temperature measure.
It should here be noted that in general the broadening of spectral lines of plasma is caused not only by chaotic motion of ions. In many cases parameters of the spectral lines depend also on the apparatus constant, the reabsorption, the Stark and Zeeman effects, as well as the Lorentz broadening. It was shown that the plasma streams, as produced within the RPI facilities, have concentration $n_e \geq 10^{16}$ cm^{-3}, internal magnetic fields < 10^4 G, internal electrical fields > 1 kV/cm, and temperatures >10^5 K [10]. Therefore, all the effects mentioned above can be neglected. The linear Stark effect can also be neglected due to the fact that $(\Delta\lambda/\lambda)_{H\beta} \approx (\Delta\lambda/\lambda)_{H\gamma}$ [7, 10], what was confirmed experimentally.

Conclusions

The main results of this paper can be summarized as follows: The comparison of the selected lines (H_β, and $H_{\square}$) has shown that for the exposition times of 5 μs and 100 μs the computed values of plasma temperatures were different by about one order of magnitude. It should be noted that temperatures, which were estimated for the 5-μs exposition case, appeared to be higher. Within the RPI-IBISEK device the temperatures values of hydrogen-plasma achieved 10^6 -10^7 K. The higher ion temperature, which were observed for discharges performed at the shorter delay time (e.g. τ = 190 μs), might be the reason of an enhanced neutron yield observed for the deuterium discharges. In order to verify this hypothesis, it is necessary to repeat the experiment within another larger facility, operated with pure deuterium.

Acknowledgements

The authors would like to express their sincere thanks to Prof. A. Bielski and Dr. J. Domyslawska of the M. Kopernik University in Torun, for their consultations on the interpretation of the spectral measurements. The authors wish also to thank Mr. W. Pijanowski for his technical assistance during the experiments with the RPI-IBISEK device.

References

1. Baranowski J, Skladnik-Sadowska E (1995) Studies of mass-and energy-spectra of ions emitted from IONOTRON-93 device. Proc. 2nd Nat. Symp. PLASMA'95, Warszawa, 1:47-50
2. Baranowski J, Czaus K, Sadowski M, Skladnik-Sadowska E (2000) Studies of hydrogen discharges in RPI-type devices with different electrode configurations. Czech J Phys 50;S3:101-107
3. Baranowski J, Sadowski M, Skladnik-Sadowska E (1997) Research on influence of experimental conditions on the emission of plasma streams from RPI facilities. Proc. Int. Symp. PLASMA'97, Warszawa, 1:429-432
4. Baranowski J, Sadowski M, Skladnik-Sadowska E (1999) Behaviour of a deuterium plasma in special operational regime of RPI devices. Journ Tech Phys 40;1:399-402
5. Baranowski J., Sadowski M, Skladnik-Sadowska E (1999) Research on deuterons and neutrons from plasma discharges in IBIS-device. Proc. 24th ICPIG, Warszawa, III:113-114
6. GRAMS/32® A I, User's Guide, Galactic Ind. Corp. 1991-2000
7. Gryzinski M, et al. (1983) Structure of ion beams generated in RPI imploders. Proc. 11th EPS Conf. on CF&PP, Aachen, I:517-520
8. Gryzinski M, Nowikowski J, Sadowski M, Suckewer S (1968) Review of research on hot plasma performed at the Department of Plasa Physics and Technology, Institute of Nuclear Research, Nukleonika 13:719-750
9. Skladnik-Sadowska E, Baranowski J, Gryzinski M, Langner J, Sadowski M (1982) Intense ion beam generation in "RPI" and "SOWA" ion-implosion facilities. J Physique 43:715-721
10. Suckewer S (1966) Spectroscopic plasma research in a device with the rod gun DP. Reports INR No. 717 and 718/XVIII/PP, Swierk - in Polish