Laser spectroscopy for investigation of argon plasma on PS-1 device

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Introduction. Maintenance of outer space exploration programs demands considerable reduction in time and transportation price of people and cargoes in space. Only plasma propulsion engine (PPE) [1] have characteristics required for it (speed, specific impulse, operation time). The PS-1 device [2] uses the ECR heating for PPE plasma generation.

The first results of laser-induced fluorescence (LIF) method implementation on the PS-1 device are presented. The LIF provides good spatial and time resolution. Radial profiles of Ar II ions concentration distribution in the region of ECR heating are measured at various operation modes. Various optical schemes of fluorescent radiation excitation are tested. The system of fluorescent radiation collection and registration is developed and tested.

Experimental setup. The PS-1 device is a mirror magnetic trap with a toroidal divertor and a magnetic nozzle. Basically the PS-1 device consists of four vacuum volumes – gas volume, a source of plasma, ion cyclotron resonance (ICR) heating volume, and receiving chamber (Fig.1). Gas is injected into device in the first volume, microwave power is injected into the source volume, helical antenna is placed in the ion heating volume, the configuration of magnetic field with "magnetic nozzle" configuration with diverging field lines is implemented in the receiving chamber. Gas pump out is performed in the receiving chamber. The ICR heating was not used in the present experiments, and the solenoid was simply a long mirror trap with mirror ratio ~3, the gas volume has been disconnected and replaced with system of longitudinal input of microwave power.

Table 1. The basic parameters of the PS-1 device:

Length of the vacuum chamber, m	3.75
Separatrix diameter in the plasma, m	0.352
Maximum diameter of plasma, m	0.15
Maximum magnetic field in the plasma center, T	0.25
Frequency of the microwave generator, GHz	7
Highest input microwave power, kW	20

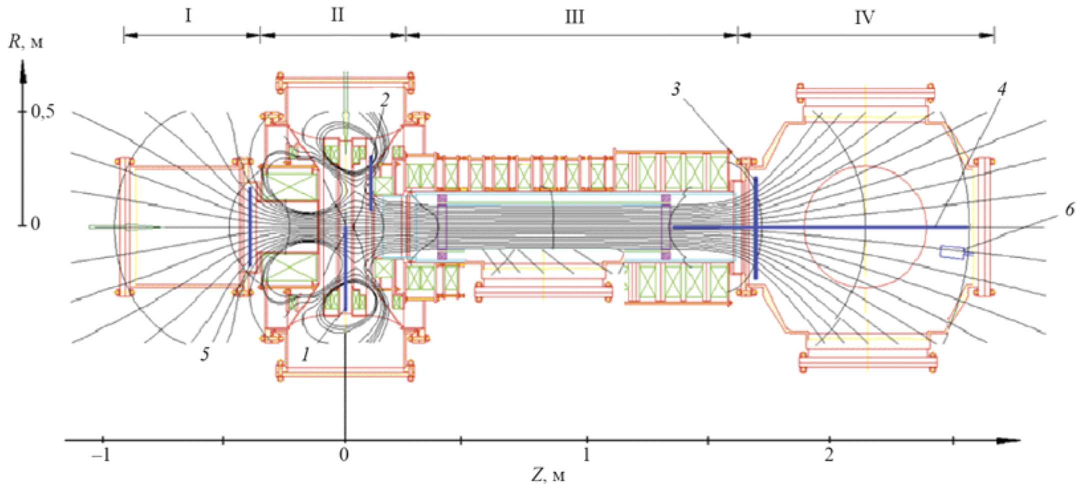

Fig.1. Schematic view of the PS-1 device and the layout of diagnostics. Vacuum volumes of the device: I—gas volume ; II—ECR heating; III— ICR heating; IV— receiving volume; *1*, *2*—mobile Langmuir probes; *3*, *4*, *5* — rows of probes; *6* — grid analyzer.

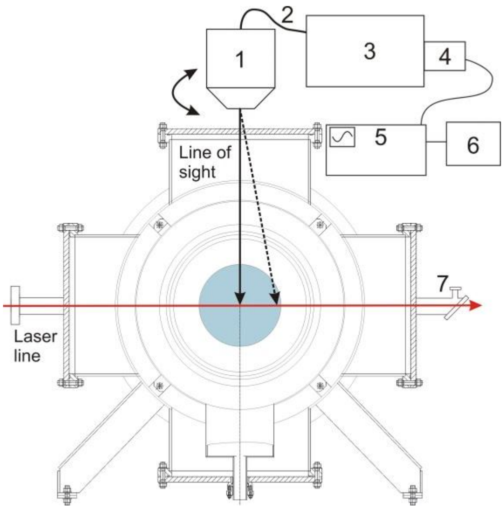

Fig.2. Layout of diagnostic:1-scanning module, 2-optical fiber, 3- monochromator, 4-PMT, 5-oscilloscope, 6-PC, 7-window with Brewster's angle

Diagnostic equipment. Laser beam is generated by tunable optical-parametric oscillator (OPO) ESTLA NT342A-SH-20-AW pumped by the third harmonic of the Nd:YAG laser at frequency 20 Hz. Laser spectral width is 5 $cm^{-1}$and suits the density measurements. OPO is tuned from 210 to 2100 nm. Maximum laser energy is attained at 450 nm wavelength and amount to 15 mJ. Laser beam is guided through device across transverse section in zero point (0 m in Fig.1). Device is equipped with output window with Brewster's angle used to decrease stray light for LIF measurements and calibration. Mechanical scanning module consists of a 175 mm focal length, 5.6 cm-diameter lens that collects the emitted fluorescence radiation from different points in plasma, and images it to the edge of the optical fiber. The observation length is 76 mm on the laser beam path and can be changed to improve special resolution. Collected light is sent by optical fiber to the monochromator MDR-23 slit. Monochromator is used as a tunable optical filter. Radiation is collected by the PMT 84-5. The PMT signal is registered by oscilloscope Tektronix-3032, connected to PC, with low-frequency fluctuation cutoff filter.

Collision-radiative model. Collision-radiative model (CRM) [3] is used for interpretation of LIF signals. According to modeled fluorescence scheme, the excitation is produced from metastable state *3d* $^2G_{9/2}$ to state *4p* $^2F_{7/2}$ on the wavelength λ_{LASER} = 611.5 nm, and fluorescent signal is registered at λ_{FLU} = 461 nm (transition *4p* $^2F_{7/2}$-*4s* $^2D_{5/2}$). The model considers 6 levels of Ar II ion. The number of used atomic levels could be increased, but due to lack of information about excitation cross-sections and lifetime of argon atomic states it is a difficult task. Alongside with LIF measurements we perform emission spectroscopy measurements for verification of the LIF scheme via observing the bright lines of Ar II. Alternative fluorescence scheme λ_{LASER} = 440.1 nm (3d $^4D_{7/2}$ - 4p $^4P_{5/2}$) λ_{FLU} = 480.6 nm (4p $^4P_{5/2}$ - 4s $^4P_{5/2}$) was applied with the view to examine the possibility of using different schemes. Using the three-level scheme allows to avoid the influence of scattered light.

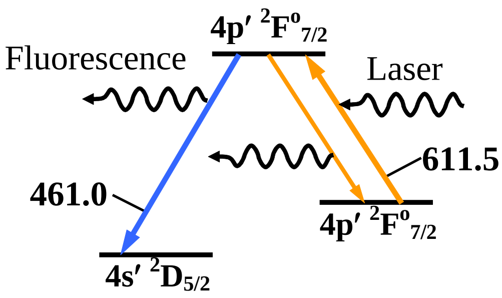

Fig.3. Applied fluorescence scheme.

Results. Results are obtained in the following device operation mode: gas pressure P=1,5*10^{-4} Torr, coils current I_k=1.2kA, injected ECR power W=5kW, discharge duration T=1s. ECR heating power is coupled into the device along transverse section in ECR heating volume. Device works in two submodes: with additional gas feeding (pressure in the chamber for the pulse duration is increased twice) and without additional gas feeding. The CRM requires input data on plasma parameters, electron density n_e and temperature T_e, received from Langmuir probe measurements performed in the same transection.

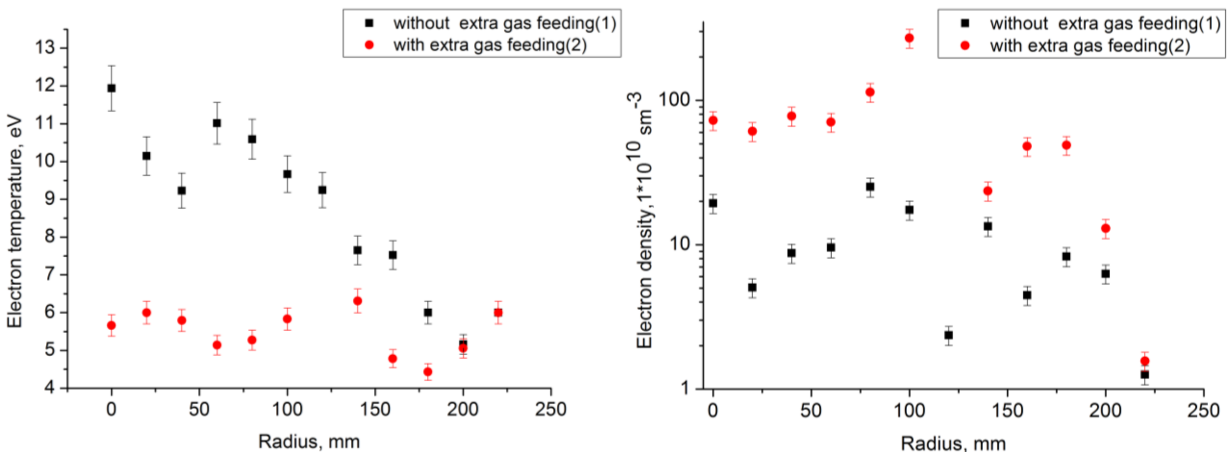

Fig. 4. Electron temperature and electron density as a function of plasma radius.

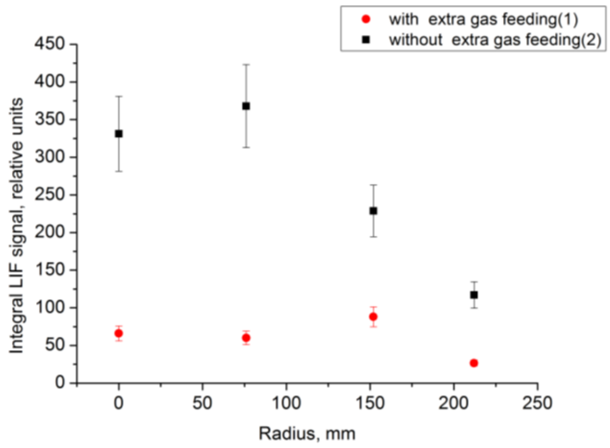

Fig.5. Radial distribution of relative intensity of integral LIF signal.

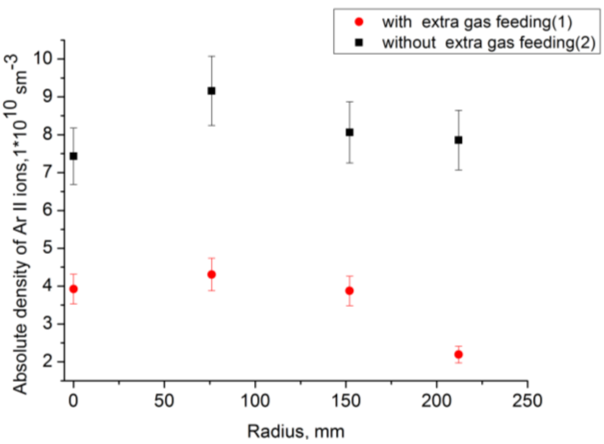

Fig.6. Argon ion Ar II density's radial distribution.

Integral relative fluorescence intensity correlates with electron temperature (Fig.5) due to mechanism of initial populating of the metastable level. Population of metastable state $3s^2 3p^4(^1D)3d^2G_{9/2}$ does not depend on electron density up to values of 10^{12} cm^{-3} according to modelling results. Relative integral intensity was obtained by summing area under the LIF signal.

Direct calibration of the optical path, using the calibrated tungsten light source, was performed. Calibration with Rayleigh scattering on the fluorescence wavelength was also performed. Thus, the CRM and calibration allow obtaining the absolute values of argon ion Ar II density across plasma radius (Fig.6).

Summary and future plans. First results of using the OPO for LIF measurements of Ar II on the PS-1 device are presented. Application of different LIF schemes is planned in the future.

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The list of references

[1] High Density Plasma Sources. Design, Physics and Performance, Ed. by O. A. Popov (Noyes Publ., Park Ridge, New Jersey, USA, 1996).

[2] A.V. Berezkin, E.Yu. Bragin, V.A. Zhil'tsov, V.M. Kulygin, S.V. Yanchenkov, Physics of Atomic Nuclei, Vol. **78**, No. 10, p. 1120-1127 (2015).

[3] I.V. Moskalenko, D. A. Shuvaev, Plasma Physics Reports, Vol. **29**, p. 978-982 (2003).