MEASUREMENTS OF EVAPORATED ALUMINIUM CONCENTRATION ON SELF-ABSORBED SPECTRAL LINES

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In the paper we discuss the experimental results of powerful plasma-stream interaction with aluminum target at the presence of the magnetic field. The plasma streams are generated by a quasi-stationary plasma accelerator (QSPA Kh-50). Such experiments performed with QSPA facility during last years [1-3] are of great interest for current disruption simulation in ITER tokamak and testing divertor materials. Some experimental series in our activity were devoted to the problem of mass losses of target under the high power plasma stream irradiation. This work presents the spectral method of determination of the evaporated material quantities in plasma-target interaction experiments. The distinctive feature of the offered work is follows – all spectral measurements were carried out using aluminum spectral lines only. There are two mechanisms of mass losses – evaporation and splashing melt layer. We succeeded in the evaluation of the evaporation mechanism contribution to the mass defect for aluminum target.

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INTRODUCTION

The problem of the interaction of powerful plasma streams with materials presents a large interest for many physical and technical areas. Especially, it concerns the materials of the candidates on manufacturing ITER divertor plates. Erosion of the divertor plates material during a tokamak disruption event restricts the divertor plates lifetime and presents an important problem of ITER fusion technology. So the present work was done in the frame of ITER tasks and it was aimed at investigations of plasma-target interaction under conditions simulating disruption in ITER.

The dense shielding layer that consists of ionized vapors of target material is formed during interaction of high power plasma stream with the target. The main part of the energy of the stream is absorbed and radiated in the shielding layer that comes to the screening effect. The screening effect is amplified in the presence of the magnetic field [2]. The main aim of the present work is determination of the evaporated material quantities using spectral technique.

EXPERIMENTAL SETUP AND DIAGNOSTIC FACILITIES

Experiments were carried out on installation QSPA Kh-50. Detail descriptions of the installation, experimental conditions, diagnostic facility (including spectroscopy) are adduced in series of publications [1-3]. It is necessary to point basic characteristics of plasma stream – power density ~ 10 MW/cm^2 (it is so called "soft" regime of QSPA), plasma stream duration ~ 150 μs and diameter of the stream ~ 10 cm.

The spectral diagnostic technique elements and its assignment:

- diffractive spectrograph DFS-452 (resolution – 0.3 Å, dispersion – 8 Å/mm) - integral spectra registration of plasma radiation;
- monochromator MDR-23 (resolution – 0.5 Å, dispersion – 13 Å/mm). Monochromator with the electron-optical converter (EOC) serves for receiving optical spectra with the temporary and spatial resolution. The monochromator was coupled with the photomultiplier for the registration of separate spectral lines. Signals from the photo multiplier were recorded with the help of oscillograph C8-17;
- photo diodes - monitoring of the integral plasma radiation, plasma velocity measurements;
- micro photometer IFO-451 – spectral data processing

The optical technique in details is described in [4].

The scheme of experiment is presented in Fig.1. Aluminum target (diameter – 12 cm) was located perpendicularly to the plasma stream. Spectral measurements were performed in two sections (horizontal and vertical) as shown in Fig.1.

DIAGNOSTIC PROCEDURE

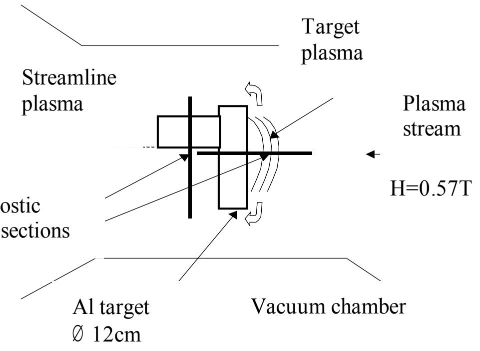
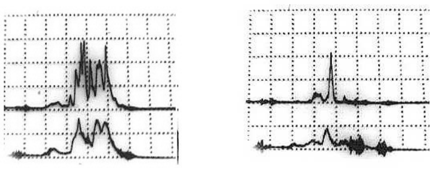


Fig.1 Scheme of experiment

Some intensive spectral lines of aluminum were registered by the help of photomultiplier for the definition of luminescence time of spectral lines. The examples of oscillograms are represented in Fig.2. They were received as follows: the upper line is a radiation of a spectral line Al III (5696 Å), and lower one – integral radiation of plasma on the photodiode. It is visible, that the luminescence time of aluminum in a shielding layer makes 50 μs, and in the ambient plasma stream this time is almost twice less (20 μs).

The determination of plasma electron density was carried out on the base of Stark broadening measurements of spectral lines Al II after exception of a measured contour Doppler and instrumental broadening with using the Foigts contour method. Such lines of Al II: 5593Å, 3900Å, 3587Å, 2816Å and 2631Å were used.



a) b)

Fig.2. Upper line - radiation of Al III (λ=569.6nm) 50μs/cell; Lower line - integral radiation:
a) in front of the target(1-2 cm)
b) behind the target (1-2cm)

The Fig.3 presents radial distribution of plasma electron density depending on the distance from the target.

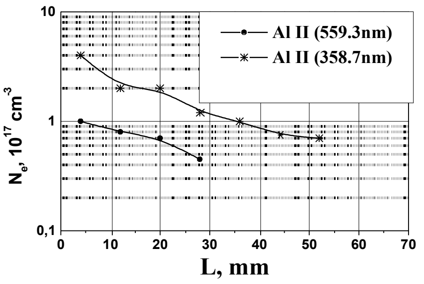


Fig. 3. Plasma electron density

Differences in the density values may be explained by self-absorption of multiplet – λ=3587 Å and considerable error under reconstruction the Stark broadening. In the consequent evaluations of Te and aluminum concentration we used data, obtained from Al II 5593 Å.

The electron temperature was determined from the ratio of intensities of spectral lines of Al II (5593 Å, 3900 Å, 3587 Å, 2816 Å, 2631 Å) and Al III (5722 Å, 5696 Å, 4512 Å, 3612 Å, 3601 Å). The average value of the electron temperature in a plasma shield is equal 1.9-2.1 eV.

The analysis of experimental data – intensities and profiles lines - shows that some spectral lines of Al II (3587Å, 2816Å) and Al III (3601Å, 3612 Å) are self-absorbed. It is possible to calculate optical thickness using proportion of the true width of spectral line to experimentally measured one. Particularly, the measured half width ($\Delta\lambda$=1.1Å) of Al II spectral line 3p $^1P^0$ – 4s ^1S (λ=2816Å) significantly exceed its calculated value for the optically thin plasma - $\Delta\lambda\approx0.15\div0.2$Å. Calculations of contour parameters for λ=2816Å Al II, namely Doppler and Stark contributions, were executed by Foigt function technique using N_e data from Stark broadening of λ=5593Å as standard. All necessary data are available for these procedures in [4]. Thus, we may obtain the value of optical thickness – τ, using the well-known formula for the Lorenz contour, counting the Stark broadening mechanism as a dominant:

$$\frac{\Delta\lambda}{\Delta\lambda_L} = \sqrt{\frac{\tau}{\ln\frac{2}{1+\exp(-\tau)}} - 1} \qquad (1)$$

Here $\Delta\lambda$ - observed half width, $\Delta\lambda_L$ - half width for the optically thin plasma. For example, optical thickness (λ=2816Å) for the near target region amounts to $\tau \sim 20\div30$.

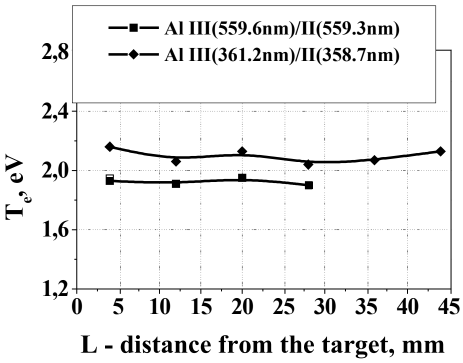


Fig.4. The electron temperature distribution

Somewhat different technique was used for the determination of optical thickness for the Al III spectral multiplet 3d^{2}D – 4p^{2}P^0 – λ=3601.6 Å and λ=3612 Å. It is common knowledge that intensities proportion for components of spectral multiplets is defined by ***gf*** proportion only, and is independent of N_e, T_e in the case of neglible optical thickness (usually values of T_e considerably larger than fine structure of corresponding terms). Generally differences of λ for multiplets are neglible also. Equally it is concerned to τ, because of the same broadening parameters. Distortion of the "atomic" line intensities ratio indicates on a large optical thickness. We have possibility to evaluate τ in such a way:

$$R = \frac{1-\exp(-\tau)}{1-\exp\left(-\tau/\alpha\right)} \qquad (2)$$

Where ***R*** – observed ratio intensities; α – "atomic" ratio between ***gf***; τ – optical thickness for center of strongest line. When $\tau \to \infty$ (Plank limit), $R \to 1$; given $\tau \to 0$, $R \to \alpha$ – optically transparent plasma. In the Eq. 2) the matter concerns brightness in a center of line, the whole intensity distort too, but slightly complex. For the mentioned above Al III multiplet, ***R*** is equal to 1.3 (region behind target), under $\alpha \sim 2$. We have the value $\tau \sim 2$ for the spectral line λ=3601.6 Å. There is necessary to mark that the ratio intensities is more "sensitive" to optical thickness in comparison with line shapes. Namely, distortions of contour are observable under the significant values of optical thickness - τ »1.

The information about $\boldsymbol{\tau}$ permits us to determine the quantity of evaporated Al in the shielding layer and in the ambient plasma stream. We may use the following relation:

$$\tau = k\cdot 10^{-20}\cdot\frac{\lambda^{2}\cdot f}{\Delta\lambda}\cdot N^{*}\cdot L\cdot\left(1-\exp\left(-\frac{\varepsilon}{T_{e}}\right)\right) \qquad (3)$$

Where $\Delta\lambda$[nm] – half width for optically transparent plasma; λ[nm] – wavelength; f – absorption oscillator force; L[cm] – geometrical thickness of luminescence layer; N^*[cm^{-3}] (for Al in our case) – population on lower exciting level of corresponding transition; ε[eV] – photon energy; T_e[eV] – the electron temperature; k – coefficient depending on contour type k=5.6 for Lorenz type and k=8.2 for Gauss type. Under the commensurable contributions of both broadening mechanisms one may take k=7. For the determination N* from Eq.(3) we used values T_e presented on Fig.4. There are some differences in finding $\Delta\lambda$ – half width for optically transparent plasma. For the λ=2816 Å (the near target region) we have taken theoretically calculated half width by setting ion temperature of Al – T_i=T_e≈2eV. In the case of λ=3601.6 Å the measured and corrected $\Delta\lambda$ according to Eq.(1) have been used. For L in front of target we used geometric size – 12cm. Value L behind of target was determined from the spectra in vertical cross section (Fig.1), as the doubled thickness of ambient stream.

Further the concentrations of Al I – Al IV and the whole (sum on ionization states) density of Al have been calculated using well-known Saha-Boltzmann correlations, taking into account statistical sums. Application of these correlations is wholly justified because of large values of N_e at that significant magnitudes of $\boldsymbol{\tau}$ for resonance lines just promote the LTE conditions. All atomic data, constants, parameters of ions (ionization and excitation potentials, statistical weights, oscillator forces, Stark broadening parameters, etc.) that are necessary in this case are present at [4,5]. Fig.5 demonstrates results of the calculation of whole density of aluminum along with N_e and N_e^{Al}= $\Sigma z Al_z$ (Al_z – partial concentration of corresponding ion) – part of the electron density, caused by the evaporated aluminum.

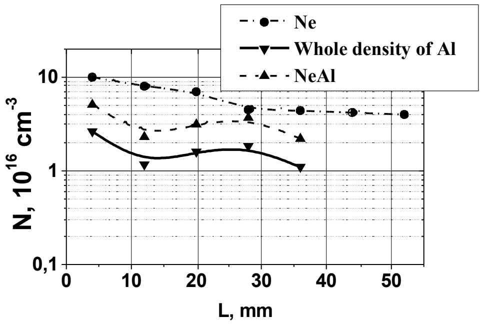


Fig. 5. Density distributions, depends on distance from the target

These data have been used for the evaluation of mass losses taking into account velocity of the ambient flow and geometry of the experiment. All main results of measurements and calculations are submitted in the Table. N_{Al} is regarded as a full quantity of evaporated Al atoms in the shielding layer or in the ambient stream, M – mass loss, t – lifetime of Al in front of or behind of target. One can see that the most part of the evaporated material is pressed out from the shielding layer and passed away with the ambient flow.

The values of mass loss obtained in such a way are in a good agreement with direct measurements of mass defect by weighing.

Table.

	Near the target 0.1 cm	Distance from the target 3.6 cm	Behind the target 2cm
Ne, cm^{-3}	1*10^{17}	0.45*10^{17}	0.5*10^{17}
Te, eV	2	2	2
N_{Al}, cm^{-3}	2.8*10^{16}	1.1*10^{16}	6.6*10^{15}
N_e^{Al} cm^{-3}	5*10^{16}	2*10^{16}	1.3*10^{16}
L, cm	12	12	6
S, cm^2 d~4cm	~110	V~500cm^3 V=Sd	V=1.5*10^4
N_{Al}	~10^{19}Al	½10^{19}Al Whole loss	~10^{20}Al
t, µs	100	100	20
M, 10^{-3}g	~0.5 per pulse	~0.2 per pulse	~4.6 per pulse

SUMMARY

The described method of determination of the plasma optical thickness starting from the distorted multiplet intensities is of great interest not only for the plasma-wall interaction problems, but also for the dense plasma spectroscopy, generally. Evidently our work is a first attempt of practical work with such effect.

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