A method of impurity diagnostics in dense plasma systems

Aleksandr V. Tsarenko,
Vladimir V. Chebotarev,
Marek J. Sadowski,
Vladimir I. Tereshin

Abstract The analysis of a plasma impurity composition in many plasma systems (such as coaxial plasma accelerators, magnetic-plasma compressors, plasma-focus devices, and others) is of great importance for plasma physics. In this work we have proposed a new spectral method for the determination of impurity concentrations in relation to the concentration of the main plasma (made of hydrogen in our case). This technique can be used e.g. for diagnostics of a peripheral zone in Plasma-Focus (PF) discharges, where LTE conditions must be fulfilled. Advantages of this method in comparison with other methods, as well as possible errors, are considered and discussed.

Key words impurity diagnostics • local thermodynamical equilibrium • plasma accelerator • plasma-target interaction • spectral line

A. V. Tsarenko$^{\boxtimes}$, V. V. Chebotarev, V. I. Tereshin
Institute of Plasma Physics,
NSC Kharkov Institute of Physics and Technology,
Akademicheskaya Str. 1, 61108 Kharkov, Ukraine
Tel.: +38 0572/ 356305, Fax: +38 0572/ 352664,
e-mail: tereshin@ipp.kharkov.ua

M. J. Sadowski
The Andrzej Sołtan Institute for Nuclear Studies,
05-400 Otwock-Swierk, Poland

Introduction

Prospects of the application of powerful plasma streams in different fields of science and technology induce a great interest in various plasma accelerators, which are capable of generating plasma flows with a wide range of energetic parameters. Among such facilities there are also quasi-stationary plasma accelerators (QSPA) with own magnetic fields, which were developed by Morozov [2]. During the past years at the Kharkov Institute of Science and Technology numerous experimental studies were performed with a QSPA Kh-50 facility [5]. The QSPA Kh-50 facility is a full-scale two stages accelerator with an active anode and semi-active cathode transformers. Plasma stream parameters, which are usually achieved within this system are as follows: proton energy – 1 keV, an average electron density (N_e) 2–3×10^{16} cm^{-3} (ranging up to 10^{17} cm^{-3} in a compression zone), electron temperature (T_e) ~ 2 eV, duration of the quasi-stationary phase >150 μs and maximum power density ~20 MW/cm^2. The equipment for diagnostics of a plasma flow within the accelerating channel and the emitted plasma streams consists of Rogowski coils, electric and magnetic probes, calorimeters and bolometers, monochromators, spectrometers, and a laser interferometer [5]. Since the parameters of the produced plasma streams are comparable with assumed parameters of plasma flowing to diverter plates of the future ITER facility, the QSPA system can be used for modelling situation corresponding to current disruption conditions. There are at least two important problems that must be investigated during the irradiation of a solid target with a plasma stream: energy balance at the plasma target interaction and the surface erosion of different materials. In both cases quantitative information about the plasma composition is needed since impurities determine values of

Table 1. The minimum values of the electron density N_e [cm^{-3}] which are required for LTE.

	Cu	Fe	C	O	F	N	Ca	Ti
I	8×10^{15}	3×10^{14}	7×10^{15}	10^{16}	8×10^{16}	2×10^{16}	10^{16}	5×10^{14}
II	5×10^{16}	3×10^{14}	3×10^{16}	5×10^{16}	2×10^{17}	2×10^{16}	10^{17}	2×10^{15}
III	10^{17}	4×10^{15}	3×10^{16}	3×10^{16}	8×10^{16}	4×10^{16}		2×10^{17}
IV		4×10^{17}	10^{17}		8×10^{16}	3×10^{17}	6×10^{17}	

radiation losses from plasma shielding layer. The main aim of this work was to develop a spectral method for the determination of the impurity concentrations in relation to the background concentration of our plasma (produced of hydrogen). Taking into account relatively high values of N_e ($>10^{16}$ cm^{-3}) and low values T_e ($\sim$2 eV), we have used a model of the local thermodynamic equilibrium (LTE) as the best approximation under our conditions.

Theoretical analysis

In order to use correctly the LTE correlation for impurity elements, which are present in the QSPA plasma stream, we applied the Griem criterion [1]:

$$(1) \quad N_e \geq 9\times10^{17}\left(\frac{\Delta E}{J}\right)^3\left(\frac{T_e}{J}\right)^{1/2} [\text{cm}^{-3}]$$

where N_e is the electron concentration [cm^{-3}], T_e is the electron temperature [eV]; J is the ionization potential [eV]; and ΔE is the maximum difference in the spectrum [eV].

For all elements and ionization states (significant for our plasma) an electron density range, for which LTE conditions are fulfilled, have been estimated during the elaboration of corresponding energetic spectra [3, 4] – for some elements and ionization states. At T_e = 1 eV the minimum values of N_e [cm^{-3}], (for the LTE conditions), have been presented in Table 1.

One can easily see that in most cases it is possible to apply the LTE relations up to the third ionization state.

On the other hand it is well known, that under the LTE conditions the total concentration of a given element may be expressed by summarizing populations of excited levels and spectral line intensities accordingly. Therefore we may calculate a ratio between two chosen lines by summarizing over the ionization states concentrations, i.e.

$$(2) \quad \frac{N_{imp}}{N_H} = KII(N,T)\frac{I_{iimp}}{I_H}$$

where $N_{imp} = N^{(0)}_{imp} + N^{(+1)}_{imp} + N^{(+2)}_{imp}$ is the sum of the concentrations of all ion species (up to three ionization states), $N_H = N^{(0)}_H + N^{(+)}_H$ is the sum of the concentrations of neutral hydrogen atoms and protons, I_H is the spectral line intensity of neutral hydrogen, and I_{imp} is the spectral line intensity of impurity element appearing in the second

ionization state. For the first ionization state, we can use the coefficient $KI(N_e,T_e)$, correspondingly. For this purpose we may calculate functions $KI(N_e,T_e)$ and $KII(N_e,T_e)$, from the Saha-Boltzman equations. These functions can be written as follows:

$$(3) \quad KI(N_e,T_e) = \frac{g_0 f_0 \lambda_1^3 s_1 e^{-\frac{E_0}{T_e}}}{g_1 f_1 \lambda_0^3 \exp\left(-\frac{E_1}{T_e}\right)} \times$$

$$\times \frac{1+6\times10^{21}\frac{s_2}{s_1}\frac{T_e^{3/2}}{N_e}\exp\left(-\frac{J_1}{T_e}\right)+3.6\times10^{43}\frac{s_3}{s_1}\frac{T_e^3}{N_e^2}\exp\left(-\frac{J_1+J_2}{T_e}\right)}{1+3\times10^{21}\frac{T_e^{3/2}}{N_e}\exp\left(-\frac{13.6}{T_e}\right)}$$

$$(4) \quad KII(N_e,T_e) = \frac{g_0 f_0 \lambda_2^3 s_2 \exp\left(-\frac{E_0}{T_e}\right)}{g_2 f_2 \lambda_0^3 \exp\left(-\frac{E_2}{T_e}\right)} \times$$

$$\times \frac{1+\dfrac{N_e s_1}{6\times10^{21} s_2 T_e^{\frac{3}{2}}\exp\left(-\dfrac{J_1}{T_e}\right)}+6\times10^{21}\dfrac{s_3}{s_2}\dfrac{T_e^{\frac{3}{2}}}{N_e}\exp\left(-\dfrac{J_2}{T_e}\right)}{1+\dfrac{3\times10^{21} T_e^{\frac{3}{2}}\exp\left(-\dfrac{13.6}{T_e}\right)}{N_e}}$$

where g_i, s_i are the statistical weights, f_i are the oscillator forces and λ_i are the wavelengths of corresponding lines and transitions; J_i are the ionization potentials; E_i – and are the considered energy levels.

In our case all the calculations have been performed using atomic parameters, which are given in known reference books [3, 4] for such impurity elements, as copper, carbon, iron, calcium, and others. In Figs. 1–3 results of some calculations for copper and carbon ions, which are the most important impurities in QSPA experiments, are presented.

One should pay attention to a sharp dependence of the $KI(N_e,T_e)$ and $KII(N_e,T_e)$ on the electron temperature. For the determination of T_e in the previous experiments we used the traditional technique, based on the measurements of the ratio of two selected spectral-line intensities (so-called spectral line thermometer), and in particular CIII and CII lines, as well as HeII and HeI lines. Within the frame of this work we have expanded this technique for
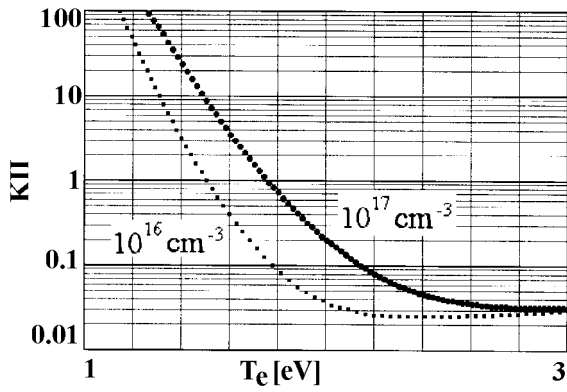
Fig. 1. Calculations of KII(T_e) for carbon (CII λ = 4267 Å) and hydrogen (H$_\gamma$ λ = 4340 Å).
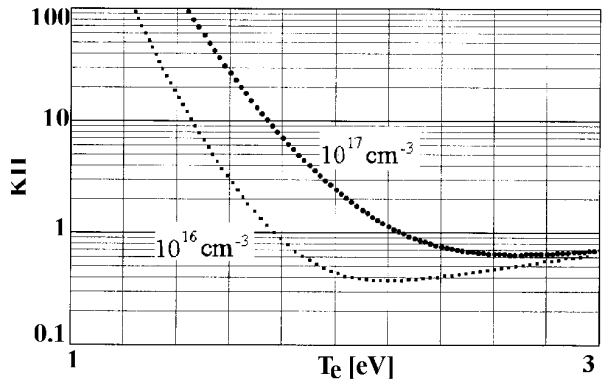
Fig. 2. Calculations of KII(T_e) for carbon (CII λ = 6580 Å) and hydrogen (H$_\alpha$ λ = 6561 Å).
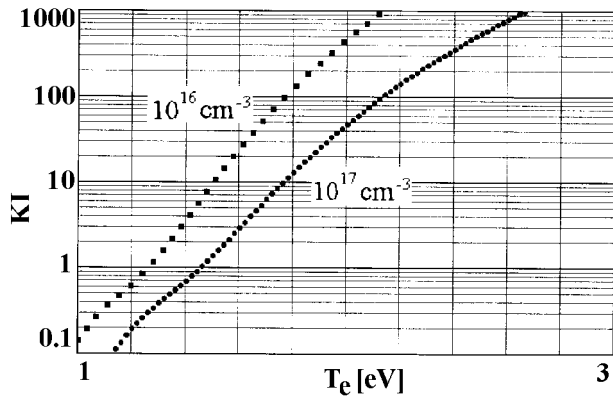
Fig. 3. Calculations of KI(T_e) for copper (CuI λ = 5218 Å) and hydrogen (H$_\beta$ λ = 4861 Å).
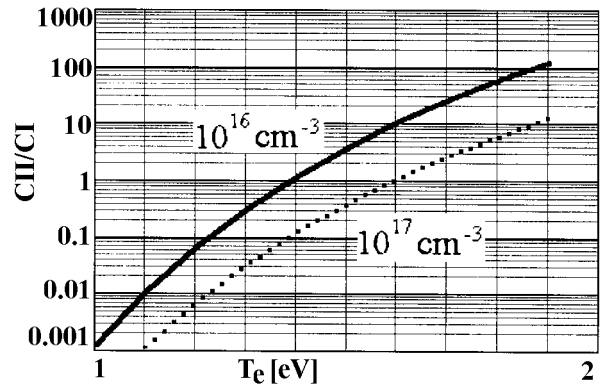

Fig. 4. Carbon spectral-line thermometer: λ = 2511 Å (CII); λ = 2479 Å (CI).

other lines and elements. For this purpose we used the well-known formula [1] for the ratio of two spectral line intensities:

$$(5) \qquad \gamma(T_e, N_e) = 6 \times 10^{21} \frac{f_2}{f_1} \frac{g_2}{g_1} \left(\frac{\lambda_1}{\lambda_2} \right)^3 \frac{T_e^{3/2}}{N_e} \exp\left(-\frac{J_2 + E_2 - E_1}{T_e} \right)$$

Results of such calculations performed for the most intensive lines in the time-integrated spectra have been presented in Figs. 4–6.

The presented data are of great importance for experimental applications of our method particularly in the cases of

non-homogeneous or asymmetrical plasmas, when one is compelled to operate with average values of N_e and T_e only.

Conclusions

The main advantage of the described method is that there is no necessity of complex and troublesome absolute calibrations of diagnostic equipment. There is a need of relative spectral calibration only. On the contrary to the known resonance line absorption technique, there is no need to use a powerful light source (in most cases within the VUV spectral range). Unlike the self-absorbed lines technique, the described method allows to use "weak" spectral lines, and it
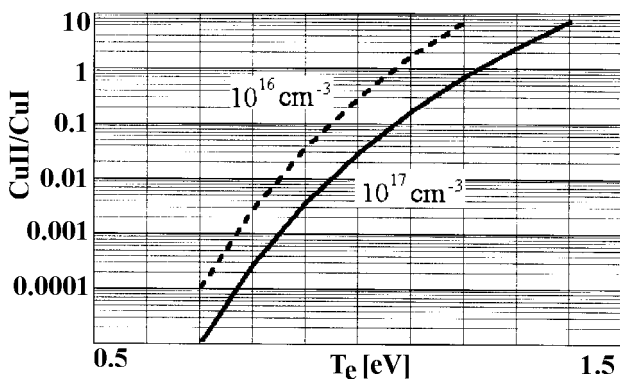

Fig. 5. Copper spectral-line thermometer: λ = 2506 Å (CuII); λ = 3247 Å (CuI).
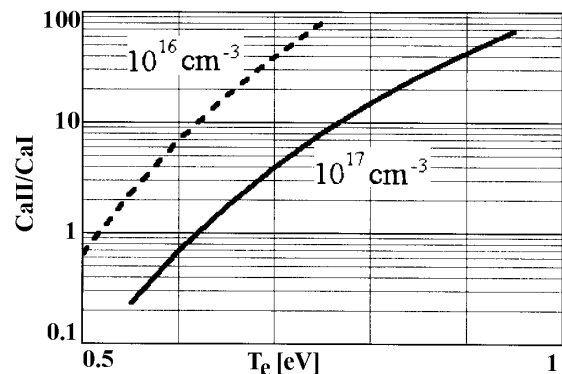

Fig. 6. Calcium spectral-line thermometer: λ = 3934 Å (CaII); λ = 4227 Å (CaI).

provides a spatial resolution in cases of cylindrical symmetry (when the Abel reconstruction is possible). The main problem of the developed diagnostic method is the accuracy and reliability of electron temperature measurements. However, it refers also to other spectral techniques because of their strong dependence on the electron temperature.

The presented approach and calculations can be easily expanded over other cases (not only for hydrogen plasma); they can be used for diagnostics in various high-density plasma systems.

References

1. Griem G (1969) Spektroskopia plasmy. Atomizdat, Moskva
2. Morozov AI (1969) Steady-state plasma accelerators and their possible application in thermonuclear research. Nucl Fusion, Special Suppl: 111–120
3. Radcig AA, Smirnov BM (1986) Parametry atomov i atomnych ionov. Energoatomizdat, Moskva
4. Striganov AR, Sventicki NS (1966) Tablicy spektral'nych linij neitral'nych i ionizovanych atomov. Atomizdat, Moskva
5. Tereshin VI (1995) Quasi-stationary plasma accelerators (QSPA) and their applications. Plasma Phys Control Fusion 37:177–190