Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

X-ray diagnostics of plasma generated during collisions of plasma flows

X-ray diagnostics of plasma generated during collisions of plasma flows

V V Gavrilov[1], A G Eskov[1], A M Zhitlukhin[1], D M Kochnev[1], S A Pikuz[2], I M Poznyak[1], S N Ryazantsev[2], I Yu Skobelev[2], D A Toporkov[1] and N M Umrikhin[1]

[1] State Research Center of the Russian Federation—Troitsk Institute for Innovation and Fusion Research, Pushkovykh Street 12, Troitsk, Moscow 108840, Russia

[2] Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia

E-mail: sergryaz@mail.ru

Abstract. Diagnostics of the high-temperature plasma formed during plasma flow collisions by comparing observable intensities of various x-ray spectral lines to accurate kinetic calculation results is discussed. Kinetic calculations have shown that using the resonance line intensity ratio of He-like Ne IX and 3p–2s Li-like Ne VIII is the most convenient way to measure neon-containing plasma temperatures. Experimental research results of the pulse soft (0.1–1 keV) x-ray source with a total energy up to 50 kJ are shown. The radiation pulse is generated during a head-on collision of two low-temperature plasma flows immersed in a longitudinal magnetic field. The plasma flows with the velocities up to 4×10^7 cm/s and total energy up to 200 kJ are formed by a coaxial accelerator operating in pulse gas puffing mode. Neon was used as an inflating gas. Electron temperature for a plasma containing Ne ions is about 160–170 eV. Electron density around the collision region is in the range 10^{16}–10^{17} cm^{-3}.

1. Introduction

Strong interest to caring out the diagnostics of multicharged plasma generated during a plasma flows head-on collision has appeared due to at least two modern problems.

One of them is the creation of a powerful x-ray source. Transformation of the plasma flows kinetic energy to the energy of emitted photons can be a very effective way to generate shortwave radiation. In that case the flows are generated by pulse electrodynamic plasma accelerators while power and spectral composition tuning is implemented by varying the flows velocity and the plasma chemical composition. The possibility of such an energy transformation was first demonstrated in [1, 2] and preliminary experiments for nitrogen plasma flows interaction which were carried out in SRC RF TRINITI confirmed the results of theoretical and numerical analysis and demonstrated that the efficiency of transformation of the plasma flows kinetic energy to the energy of radiation consisted of photons with energies from 50 up to 500 eV is about 50–60%. Measurements of plasma parameters, especially of the electron temperature are necessary to optimize the shortwave radiation source performance.

The second problem originates from modern researches in the field of laboratory astrophysics. Recent laboratory studies [3,4] have shown new evidence of plasma jet formation in astrophysical systems, such as young stellar objects (YSO). In particular, a relatively stationary conical shock

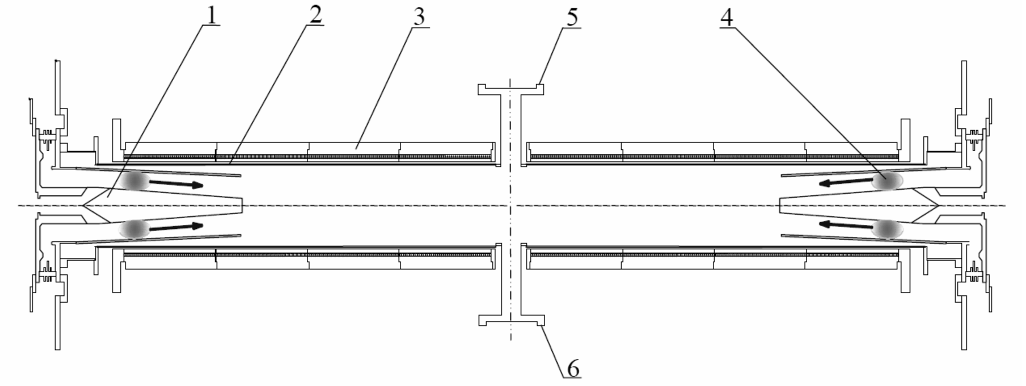


Figure 1. The scheme of the 2MK-200: *1*—pulse plasma accelerator; *2*—cylindrical vacuum camera; *3*—solenoids; *4*—plasma bunch; *5* and *6*—diagnostic ports for photodiodes and spectrograph with transmission grating.

is suggested to be the origin of long-time x-ray emission observed in such objects (e.g. Hebrig-Haro 154). YSOs are associated with the accretion phase of stellar evolution, which can last for about the first 10^5 years of life of a star. The jets are seen propagating away from a star with speeds of the order of hundreds km/s, with lengths up to 0.1 parsec, and with aspect ratios (jet length/jet width) of 10 or more. The laboratory-produced jets are fully scalable to such YSOs as both are ideal magnetohydrodynamic systems [5, 6]. The generated plasma flows collide during the accretion phase and it is possible to model this phenomenon in laboratory experiments. So it is necessary to obtain all the data concerning parameters of the plasma generated during the plasma flow collisions.

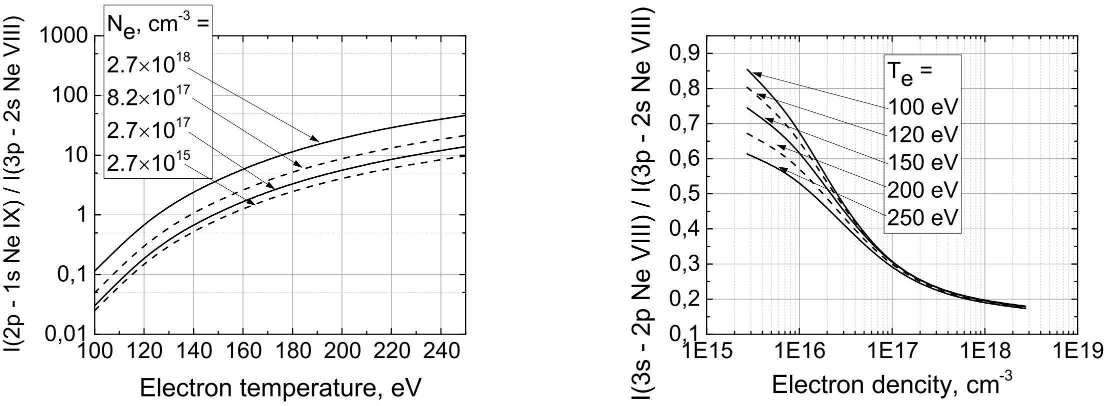
It is shown that methods of x-ray emission diagnostics based on the detecting of soft x-rays radiated by a plasma are applicable for determination of the parameters of the plasma generated during head-on collisions of the plasma flows. Experiments were carried out for head-on collisions of two low-temperature Ne-plasma flows with velocities up to 4×10^7 cm/s immersed in a longitudinal magnetic field.

2. The 2MK-200 experimental setup and diagnostic suite

Detailed description of the 2MK-200 experimental setup is given in [7–9]. A scheme is shown in figure 1. The experimental setup consists of two identical coaxial electrodynamic pulse plasma accelerators (PPA) and a vacuum chamber in the form of a cylindrical pipe approximately 300 cm in length and 20 cm in diameter. In a central cross-section there are two rectangular ports using for diagnostics.

Power supply of each PPA is performed by parallel connected 50 kV capacitors. Voltage on the capacitor battery for the experiments was varied in the range from 20 to 23 kV. The ratio of conversion of capacitor bank energy into total (not only kinetic) energy of the jet is approximately 30%. Therefore, for example, under the capacitor bank voltage of 23 kV the accumulated energy in each bank is about 300 kJ and the total energy of one of two jets is approximately 100 kJ. The quasi-stationary longitudinal magnetic field inside the cylindrical chamber is generated by several solenoids.

Spectral distribution of the soft x-rays radiated from the flows collision point is measured by a transmission grating which consists of gold stripes lithographically manufactured by Massachusetts Institute of Technology (USA). Groove density of the grating is 5000 lines/mm while width and thickness of the stripes are 100 nm and 220 nm correspondingly. Resolution of



(*a*) (*b*)

Figure 2. (*a*) The dependence of the intensity ratio of a He-like ion Ne IX resonance line to 3p–2s line of Li-like ion Ne VIII on electron plasma temperature for different plasma electron densities; (*b*) The dependence of the intensity ratio of the 3s–2p line of Ne VIII to 3p–2s line of Ne VIII on the electron plasma density for different plasma electron temperatures.

such spectrograph is determined by a number of stripes, size of a source (in our case the size is determined by the collimating slit size), a grating slit and distances between a detector, a grating slit and a collimating slit. The resolution equals 0.2 nm for 1–10 nm spectral range in all the experiments. X-rays spectra were recorded by a CCD camera Andor DO420A-BN-995 (matrix size 1024×255, pixel size 26×26 μm^2). Quantum efficiency of the camera is given in [10].

Absolute values of the x-ray intensity with temporal resolution were obtained with help of covered by different filters photodiodes manufactured by Ioffe Institute (St. Petersburg, Russia). Photodiode spectral sensitivity which is available in the wide wavelength range in [11] allows to carry out the measurements with 10% accuracy. Three photodiodes covered by filters consisted of different materials with different thickness were used in each experiment. It allowed to realize the classical absorber-foil method [12] with temporal resolution.

Also four magnetic probes were installed inside the vacuum chamber to measure with temporal resolution the magnetic field within the clearance between the vacuum chamber wall and the plasma.

3. X-ray spectroscopy diagnostics

In the present work, we have used plasma diagnostics methods based on observation of the soft x-ray line and continuum plasma emission spectra.

During the collision of the plasma flows, the plasma temperature increases very fast, further ionization takes place and plasma of the multicharged ions is formed. Measurements of the magnetic field variatios within the clearance between the plasma and inner surface of the vacuum chamber show that the plasma lifetime is in the range of 10–15 μs in the area of the flows collision. On the other side an estimated duration of collisional ionization-recombination processes for our experimental conditions is not more than 1 μs. It means that the stationary kinetic model can be used for calculation of the x-ray spectral line intensities.

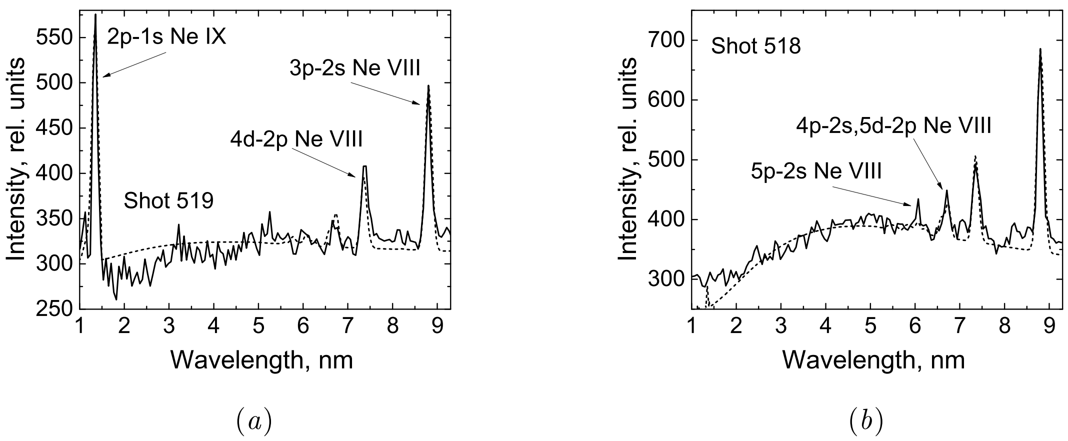


Figure 3. The experimental spectra (solid lines) and the calculation results (dashed lines) for shots 519 (a) and 518 (b). The calculated spectra are the sum of the Ne-ion line spectra and continuum spectra and are obtained for the plasma with electron density 10^{17} cm^{-3} and electron temperature 160 (a) and 110 eV (b).

Sets of stationary kinetic equations were solved to calculate the radiation spectra of Ne ions:

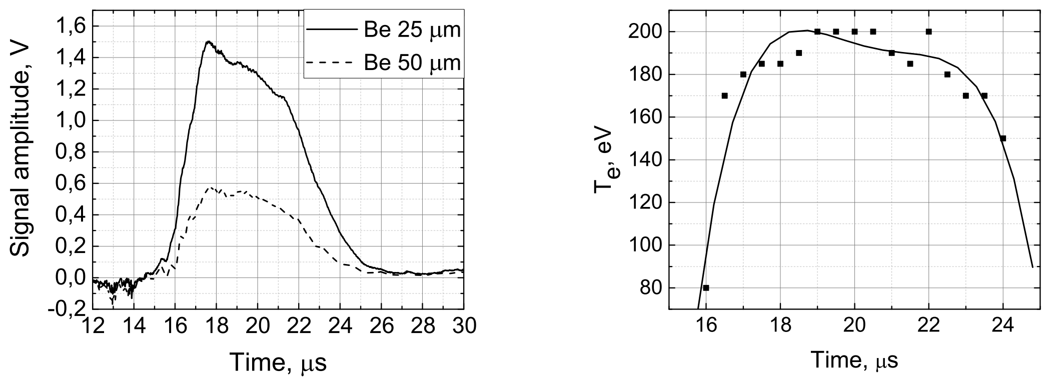
$$\frac{\mathrm{d}N_i^Z}{\mathrm{d}t} = \sum_{i',Z'} K_{ii'}^{ZZ'} N_{i'}^{Z'}, \qquad (1)$$

where N_i^Z is the population of the i-level of an ion with the spectroscopic symbol Z and $K_{ii'}^{ZZ'}$ is a kinetic matrix, nondiagonal elements of which correspond to probabilities of transitions between $i'Z'$ and iZ states due to all elementary events, while the diagonal elements with a minus sign equals to a sum of the probabilities of transitions from the iZ state into all other states. Following processes are included in the calculation model: collision ionization, recombination, excitation and deexcitation, photorecombination, radiative decay, dielectronic recombination and autoionization. Probabilities of all the processes and energy level structure were obtained from the built-in database of the PrismSPECT software [13]. 11481 ion states of Ne ions with all possible ionization multiplicities were considered.

The kinetic calculations show that the multicharged ions emission spectra are sensitive to both the plasma temperature and density. It should be noted, that the spectra dependence on temperature is much stronger than on density. It means that temperature measurements can be done with the better accuracy then density one. It becomes clear by figure 2. Note, that the intensity ratio of the He-like ion Ne IX resonance line and 3p–2s line of Li-like ion Ne VIII is the most convenient for electron temperature determination, see figure 2(a), while intensity ratio of Li-like ion 3s–2p and 3p–2s transitions is suitable for electron plasma density estimations, see figure 2(b). Unfortunately, in the described experiments we could not measure intensity of the 3s–2p line (wavelength 10.3 nm) with good accuracy.

4. Experiment results for plasma consisted of Ne and D ions

The results submitted below correspond to the collisions of plasma flows containing 25% Ne and 75% D ions in the plasma forming gas and for different charging voltages of the capacitor batteries. Measurements of the spectra radiated from the central region of the collision point were observed in the range of 1–10 nm by the spectrograph described above.



(*a*) (*b*)

Figure 4. (*a*) Real signals of photodiodes covered by Be foils of 25 (solid line) and 50 μm (dash line) thicknesses. (*b*) Temporal evolution of the plasma electron temperature determined by the absorber-foil method; accuracy of the temperature determination is about of $\pm 15\%$, time reading starts from the discharges beginning; solid line corresponds to a polynomial spline curve with the best fit to the experimental points.

Comparison of the observed spectra with the calculation results are shown in figure 3 for two shots. For the shot 518 primary voltage of the capacitor battery was 20 kV, while for the shot 519 voltage was slightly higher (22 kV). It is clearly seen that the experimental and calculated spectra are quite similar. The best fits of the model spectra to the experimental ones were reached for the plasma electron temperatures 160 eV (shot 519) and 110 eV (shot 518). For the both cases we estimated the electron plasma density from 8×10^{16} to 2×10^{17} cm^{-3}. Widths of the calculated spectral lines were set in the correspondence to the spectral resolution of the spectrograph with transmission grating. The obtained results of the comparing for the values of the plasma parameters are in the good accordance with the results of the other diagnostic methods and confirmed the general idea of the processes taking place within the collision region.

Comparison between the experimental and calculated spectra indicates increasing of the electron temperature from 110 to 160 eV during the voltage increasing from 20 to 22 kV. It accords to previously obtained estimations [8, 9] for the plasma velocity increasing from 2×10^7 to 4×10^7 cm/s corresponding to the voltage changes. It results in a plasma spectrum shift to the shorter wavelength region. Detailed spectrum measurements indicated that the energy from the interaction zone of the plasma flows consisted of neon and deuterium mainly radiated as the He- and Li-like Ne-ion lines: 1.34 ($1s^2$–1s2p) and 8.8 nm ($1s^2 2s$–$1s^2 3p$). Optimization of the plasma accelerators operation regime allows us to reach 90% line radiation yield in the resonance line (1.34 nm) of an Ne IX ion.

As it was mentioned above, soft x-rays radiated by the plasma were detected also by the semiconductor photodiodes with high temporal resolution. The experimental data obtained for the filters with different thickness were used to determine the temporal evolution of the plasma electron temperature within the interaction region. Figure 4 demonstrates the real signals of the two photodiodes covered by the Be-foils differed in thickness recorded in the experiment with the Ne-containing (75%) plasma and the temporal evolution of the plasma electron temperature obtained from the mentioned signals ratio.

It is necessary to report that after processing the data obtained by the photodiodes in the experiments with different (10%, 25%, 50%, and 75%) Ne concentration in the plasma forming matter the conclusion was made that the value of plasma electron temperature not depends on the Ne-concentration and varies in the range of 160–200 eV.

It can be seen from figure 4, that high temperature plasma object lives about 8 μs. During this time the electron temperature is varied in the interval 80–200 eV. The average plasma temperature is about 180 eV and accords the value 160 eV obtained for shot 519 from the spectra modeling. The small value of a temperature temporal gradients absolutely justifies the using of stationary kinetic approach to the spectra calculations.

5. Conclusions

Main results of the work are listed below:

- X-ray diagnostics can be successfully used to investigate a multicharged plasma generated during collision of plasma flows with kinetic energy up to 200 kJ.
- The intensity ratio of the He-like ion Ne IX resonance line to 3p–2s line of Li-like ion Ne VIII is the most convenient for the electron plasma temperature measurements and the intensity ratio of the 3s–2p line of Ne VIII to 3p–2s line of Ne VIII for the electron plasma density estimations. The best fit of the model spectra to the experimental ones was reached for the plasma electron temperatures 160 eV and the electron plasma density from 8×10^{16} to 2×10^{17} cm^{-3}. These parameters values were obtained in the experiment with the plasma flows containing 25% Ne and the voltage of the capacitor battery of 22 kV.
- Registration of soft x-rays radiated by the plasma with high temporal resolution by the several semiconductor photodiodes, covered by different filters, allowed to obtain the temporal evolution of the plasma electron temperature. The average temperature was about 180 eV and is in close fit with the value of 160 eV obtained from the spectra modeling.

Acknowledgments

This work was supported by the Russian Science Foundation (project No. 14-50-00124). We also thank SRC RF TRINITI employee I K Fasakhov for developing of the software which was very useful in processing of all the data obtained by the absorber-foil method.

References

[1] Hartman C W and Hammer J H 1982 *Phys. Rev. Lett.* **48** 929–32
[2] Stepanov A E and Sidnev V V 1989 *Fiz. Plazmy* **15** 1000–7
[3] Albertazzi B *et al* 2014 *Science* **346** 325–8
[4] Manuel M J E *et al* 2015 *High Energy Density Phys.* **17** 52–62
[5] Ryutov D, Drake R P, Kane J, Liang E, Remington B A and WoodVasey W M 1999 *Astrophys. J.* **518** 821–32
[6] Ryutov D D, Drake R P and Remington B A 2000 *Astrophys. J., Suppl. Ser.* **127** 465
[7] Vasil'ev V I, Gervids V I, Zhitlukhin A M, Lototskij A P, Lyashenko V N, Skvortsov Yu V, Strunnikov V M, Umrikhin N M and Tserevitinov S S 1975 Electrodynamic accelerator plasma and its use in research on controlled thermonuclear fusion *Proc. Int. Conf. Plasma Phys. Controlled Nucl. Fusion Res.* vol 2 (Vienna: IAEA) pp 741–52
[8] Sidnev V V, Skvortsov Yu V, Solovjeva V G and Umrichin N M 1984 *Fiz. Plazmy* **10** 392
[9] Skvortsov Yu V 1992 *Phys. Fluids* B **4** 750–6
[10] URL `www.andor.com/learning-academy/calibrated-soft-x-ray-spectrometer-characterisation-of-the-spectral-emission`
[11] URL `www.technoexan.ru/pdf/silicon_detector/fduk8uvsk.pdf`
[12] Jahoda F C, Little E M, Quinn W E, Sawyer G A and Stratton T F 1960 *Phys. Rev.* **119** 843–56
[13] Macfarlane J J, Golovkin I E, Woodruff P R, Welch D R, Oliver B V, Melhorn T A and Campbell R B 2004 *Inertial Fusion Sciences and Applications 2003 (IFSA 2003): State of the Art 2003* ed Hammel B A *et al* (La Grange Park, IL: American Nuclear Society) p 457