Parameters of high-pressure megaampere discharge channel during its contraction

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Abstract. Results of determination of the discharge channel parameters in iron plasma for a stage of its maximal contraction are presented. Amplitude of the discharge current was of 500–1500 kA, current rise rate of $5 \times 10^{10}$ A/s, surrounding gas pressure of 5–7 MPa. Results of intensity measurements for own plasma soft x-ray radiation and registration of radius evolution of current channel of the discharge, received with the help of magnetic probe diagnostics, confirm a hypothesis about radiative character of the discharge contraction. The developed system of soft x-ray radiation registration gives the discharge channel temperature of 72–73 eV and allows to register changes of temperature in some electronvolts.

1. Introduction

As is well known, at exceeding the Pease–Braginsky critical current $J_{cr}$ in discharges, in which the basic mechanism of energy losses is radiation and value of magnetic pressure is comparable with gaskinetic one, a contraction of the discharge channel is observed [1,2]. A brief summary about the mechanism of the radiative contraction, an opportunity of its realization in the selfconstricted discharges and restrictions of its applicability with references, in which models of the radiative collapse consistently developed, it is possible to find in the review [3].

Value of $J_{cr}$ in megamperes for multicharged ions plasma [4] is expressed as

$$J_{cr} = 0.25 \sqrt{\frac{\ln \Lambda}{K}},$$

where $\ln \Lambda$ is Coulomb logarithm, and $K$ is the relation of total volumetric radiation power to power of bremsstrahlung radiation.

At research of discharges at current amplitudes of 0.5–1.5 MA with time length of the first half-cycle of a current of 100–150 $\mu$s and initial hydrogen and helium pressures of 5–30 MPa we observed contraction of the discharge channel at a stage of a current growth [5–8]. The current at which channel began to contract were varied from 0.48 up to 1.1 MA.

We assume, that it is probably caused by achievement of current more than $J_{cr}$ [6–8]. $J_{cr}$ depends on value of $\ln \Lambda$ and $K$. So, for a hydrogen–metal vapor plasma discharge channel
with prevalence of hydrogen $J_{cr}$ is 480 kA [5] as against value of $\approx 1.4$–1.7 MA for completely ionized hydrogen plasma [1,2]. In this case of hydrogen–metal vapor channel with prevalence of hydrogen surrounded high density hydrogen and relative lower plasma temperature value $K$ is more than one because of presence of recombination radiation. In case of the discharge in metal plasma the increase of $J_{cr}$ up to $\sim 1$ MA [7,8] in comparison with vacuum discharges, where $J_{cr} \approx 50$–150 kA [4], is stipulated by reduction of $K$ because of radiation absorption caused in high density transitive layer of the discharge channel.

The estimation of parameters of the discharge channel zone responsible for emission of soft x-ray radiation (SXR) is resulted at the moment of the deepest contraction. It is made with the help of absolute and relative measurements of intensity of SXR. Primary original realization of a these technique is described in [9,10].

2. Experimental setup

The discharge chamber for investigation of the high-current (up to 2 MA) discharges in gases of high density was designed for operation at initial pressure of gas up to 100 MPa, pulse pressure up to 1000 MPa and gas temperature up to 4000 K [11]. The discharge chamber and a scheme of its design with system of SXR registration are shown in figure 1. The internal free volume of the chamber with electrode units was of 250 cm$^3$. The distance from an axis to a chamber wall was 2.5 cm.

The energy source is the modular capacitive system [12]. Charge voltage of the bank changed in range of 8–16 kV, storage energy—0.5–2.0 MJ. The interelectrode distance was of 10 mm. The time-length of the discharge half-cycle was about 100 $\mu$s, a current amplitude was up to 2 MA, current rise rate was of $5 \times 10^{10}$ A/s. The voltage drop on an arc was within the limits of 3–5 kV. The energy input in an arc was 150–500 kJ.

Complexity of a problem in registration of the discharge SXR radiation has consisted in necessity to protect the detector from influence of high pressure (initial 5–30 MPa, pulsed—up to 300 MPa), high temperature (up to 3000 K) and shock waves. For this purpose the special chamber in which the detector of x-ray radiation was located has been designed. The semiconductor x-ray diode SPD-8UVHS [13,14] was used as the receiver of radiation. Diameter of active area of the detector is 3.2 mm. The continuous spectral range of SPD-photo diodes lays within the limits of 0.02–1100 nm, sensitivity within energy range of incident radiation of

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**Figure 1.** Discharge chamber (a) and a scheme of SXR registration (b): 1—SXR registration unit; 2—buffer volume; 3—registration path; 4—discharge chamber case; 5—igniting wire; 6—insulation; 7—current lead; 8—anode; 9—cathode; 10—discharge volume; 11—SXR diode; 12—place for SXR filter-foil.
Figure 2. Oscillograms of signals for discharge in hydrogen at initial pressure of 5.4 MPa (10 mF with initial voltage of 10 kV): (a) current $J$ and voltage $V$; (b) signals of x-ray sensors with Al-foil filter thicknesses of 10 and 18 $\mu$m; steel electrodes, interelectrode gap of 1 cm.

Figure 3. Oscillograms of signals for discharge in hydrogen at initial pressure of 7 MPa (5 mF with initial voltage of 12 kV): (a) current $J$ and voltage $V$; (b) signals of x-ray sensors with Al-foil filter thicknesses of 10 $\mu$m and 18 $\mu$m; steel electrodes, interelectrode gap of 1 cm.

20–20 000 eV is 0.25 A/W. Two identical SXR gauges were located symmetrically as shown in the scheme in figure 1(b). Aluminum foil of different thicknesses for each recording gage was used as a filter.

3. Experiment results and discussions
Estimations of discharge channel temperature at the moment of its most contraction had been done both on the basis of absolute measurements of SXR intensity, and from the relation of SXR signals passed through the foils of different thicknesses. It has been earlier established [7, 8], that same moment the “features” on oscillograms of a current and a pressure and maximal SXR intensity were observed. Oscillograms of current, voltage and SXR intensity for experiments at initial pressure of hydrogen in the discharge chamber of 5.4 and 7 MPa are presented in figures 2, 3 and 4.

At estimation of signal intensity $I$ getting on the receiver, SXR absorption in the aluminum foil and in the 25 cm of high density hydrogen was taken into account. At calculation of
Figure 4. Oscillograms of signals for discharge in hydrogen at initial pressure of 7 MPa (5 mF with initial voltage of 16 kV): (a) current $J$ and voltage $V$; (b) signals of x-ray sensors with Al-foil filter thicknesses of 10 $\mu$m and 18 $\mu$m; steel electrodes, interelectrode gap of 1 cm.

SXRF intensity the Plank free path of radiation $l_p$ was estimated from results of preliminary experiments on photometry of photostreaks and magnetic probe measurements. Value of $l_p$ was more than discharge channel radius. For iron plasma parameters calculated below, $l_p$ is 130 cm for $P_0 = 5$ MPa and 46 cm for 7 MPa, according to [15]. Therefore, it was considered that the discharge channel is translucent with distribution of intensity on the of wave lengths corresponding to black body.

Power of the discharge channel radiation was calculated as $JEl$. Here $J$ is the current, $E$ is the electric field strength in the channel, $l$ is the discharge channel length. It is supposed at the moment of the maximal contraction that the discharge is in condition of thermal balance, when Joule heating is equal radiative losses. Intensity of registered SXRF signal $I$ is expressed as

$$I = JEl\Gamma \frac{\int_0^\infty (x^3 f(x))/[\exp(x)-1]dx}{\int_0^\infty (x^3/[\exp(x)-1])dx}; \quad x = \frac{h\nu}{kT}$$  \hspace{1cm} (2)

Alongside with a magnetic probe technique [16, 17] value of $E$ was defined by conductivity and pressure magnitude, which for the moment of the maximal contraction was equated to magnetic. The value $\Gamma = 4.0 \times 10^{-8}$ took into account the geometrical size of the installation and part of radiation incident on the receiver.

Function $f(x)$ took into account SXRF absorption in hydrogen on length of 25 cm at pressures of 5.4 MPa and 7 MPa and in aluminum foils with thicknesses of 10 and 18 $\mu$m in a range of quantum energy $h\nu = 600–1500$ eV. Feature of $f(x)$ is those, that quanta with smaller and greater aforementioned energy practically are not registered. The data on absorption of quanta with energy of 600–1000 eV were taken from works [18, 19]. For a range of 1000–1500 eV tables from [20] were used.

As far as $\int_0^\infty (x^3/[\exp(x)-1])dx = 6.49$, the relation $6.49F = \int_0^\infty (x^3 f(x))/[\exp(x)-1])dx$ shows the part of energy from total radiated energy that has passed on the gauge through a buffer zone and filters depending on temperature. Calculation results of dependence of signal SXRF intensity $I$ from plasma temperature for experiments which oscillograms are shown in figures 2, 3 and 4 are presented in table 1.

It is visible from the table 1 that the little change of temperature in a range of 60–75 eV cause considerable changes in the signal. So, for calculated values in experiment at pressure of 5.4 MPa the change of temperature on 15% gives conversion in SXRF intensity more than
\[ J = 0 \]

Temperature of 72–73 eV.

an order of magnitude. Experimental data correspond to the averaged over discharge radius

Table 1. Calculated \( I_c \) and experimental \( I_{\text{exp}} \) values of SXR intensity upon plasma temperature; foil thickness 10 \( \mu \text{m} \).

| \( T \) (eV) | \( P_0 = 5.4 \text{ MPa}, \ J = 0.7 \text{ MA} \) | \( P_0 = 7 \text{ MPa}, \ J = 0.95 \text{ MA} \) |
|---|---|---|
| 58 | 62 | 73 |
| 62 | 68 | 73 |
| \( F \) | \( 3.5 \times 10^{-6} \) | \( 8.6 \times 10^{-6} \) | \( 5.5 \times 10^{-5} \) | \( 2.6 \times 10^{-6} \) | \( 8.2 \times 10^{-6} \) | \( 2.0 \times 10^{-5} \) |
| \( I_c \) (W) | \( 8.4 \times 10^{-5} \) | \( 2.1 \times 10^{-4} \) | \( 1.3 \times 10^{-3} \) | \( 9.9 \times 10^{-5} \) | \( 3.1 \times 10^{-4} \) | \( 7.6 \times 10^{-4} \) |
| \( I_{\text{exp}} \) (W) | \( 1.3 \times 10^{-3} \) | \( 6.7 \times 10^{-4} \) |

Table 2. Dependence of relative spectral SXR intensity upon quantum energy; \( P_0 = 7 \text{ MPa}, \ J = 0.95 \text{ MA}, \ T = 73 \text{ eV} \), foil thickness is 10 \( \mu \text{m} \).

| \( h\nu \) (eV) | 700 | 800 | 900 | 1000 | 1100 |
|---|---|---|---|---|---|
| \( f_0^\infty \frac{x^3 f(x)}{\exp(x) - 1} dx \) | \( 3.4 \times 10^{-7} \) | \( 3.4 \times 10^{-6} \) | \( 9.1 \times 10^{-6} \) | \( 1.2 \times 10^{-5} \) | \( 2.6 \times 10^{-5} \) |
| \( h\nu \) (eV) | 1200 | 1300 | 1400 | 1500 |
| \( f_0^\infty \frac{x^3 f(x)}{\exp(x) - 1} dx \) | \( 1.6 \times 10^{-5} \) | \( 1.6 \times 10^{-5} \) | \( 7.2 \times 10^{-6} \) | \( 2.8 \times 10^{-6} \) |

an order of magnitude. Experimental data correspond to the averaged over discharge radius temperature of 72–73 eV.

In our opinion, they are caused by fluctuations of the discharge channel radius which in turn are caused by violation of equality between magnetic and gaskinetic pressure. The estimations show amplitude of temperature fluctuations can be much less, than it was supposed earlier [22]. In earlier estimations the spectral distribution of radiation energy was not taken into account and was considered as well as in [4] that for metal plasma the basic part of energy radiate by quanta with energy of (1.5–2)\( kT \).

Another way to estimate temperature is to determine the ratio of the intensity of the radiation passing through different absorbing filters. The estimation of channel temperature from the relation of signals passed through filters of different thicknesses does not demand knowledge of values \( \Gamma \) and \( E \) (table 3). For thicknesses of aluminum foils of 10 and 18 \( \mu \text{m} \) the relation of signal intensities \( I_{10\mu m}/I_{18\mu m} \) calculates as

\[
I_{10\mu m} = \frac{\int_0^\infty (x^3 f_1(x)/[\exp(x) - 1])dx}{\int_0^\infty (x^3 f_2(x)/[\exp(x) - 1])dx}, \quad x = \frac{h\nu}{kT},
\]
Table 3. Calculated and experimental dependences of intensity relation $I_{10\mu m}/I_{18\mu m}$ of SXR overpassed through filters of 10 and 18-μm thicknesses upon plasma temperature; $P_0 = 7$ MPa, $J = 0.95$ MA.

| $T$ (eV) | 50   | 100  | 200  |
|----------|------|------|------|
| Calculated $I_{10\mu m}/I_{18\mu m}$ | 14   | 4.1  | 3.6  |
| Experimental $I_{10\mu m}/I_{18\mu m}$ | $\geq 10$ |

However, this estimation has rather rough character and demands more exact measurements. According to table 3 the channel temperature lays in a range of 50–100 eV.

For check of the estimations, the channel temperature was also determined by value of plasma conductivity and pressure. Thus values of channel radius and the electric field strength were used, received via photometry of photostreaks and magnetic probe measurements at the moment of the most deep channel contraction [16].

At $P_0 = 5.4$ MPa for channel radius $r = 0.3$ cm and $E = 860$ V/cm for iron plasma, according to [23], we receive value $T = 73$ eV and $n_i = 6.1 \times 10^{18}$ cm$^{-3}$, conterminous with the data of table 1. A technique of determination of electric field strength in the discharge channel and values of nearelectrode drops under the given discharge parameters and results of corresponding measurements are presented in [17].

At equilibrium the radiated energy is equal to the Joule energy. Under formula (1) we shall estimate value of $J_{cr}$ for this case and in view of absorption in a transitive zone we shall receive $K = mK_1$, where $K_1 = 22$ is the relation of total power of volumetric radiation to bremsstrahlung power without taking into account the transitive zone. Value $K_1$ is taken from work [4] at temperature of 73 eV. Here $m = J E l_p/(4\pi r^2\sigma T^4) = 0.025$ is a part of radiated energy overpassed through a transitive zone.

At $\ln \Lambda = 7$ we get calculated values $J_{cr} = 0.9$ MA for $P_0 = 5.4$ MPa and $J_{cr} = 1.3$ MA for $P_0 = 7$ MPa. Experimental currents at maximal contraction were 0.7 and 0.95 MA, respectively. Calculated values are close to experimental currents at the moment of the maximal contraction. This fact confirms an opportunity of radiative contraction.

4. Conclusion
Parameters of central discharge zone for the iron plasma surrounded with hydrogen of high pressure, responsible for emission of SXR radiation are determined: $T = 72$–73 eV; $r = 0.3$ cm; $n_i = 6.1 \times 10^{18}$ cm$^{-3}$.

Change in the spectral SXR intensity with a small temperature changing in the range of 65–75 eV by an order magnitude conduces considerable accuracy increasing of the SXR measurement system for the discharge at hydrogen pressure of 5–7 MPa.

Close calculated and experimental values of the critical current at the moment of the maximal channel contraction confirm an opportunity of the radiative contraction for megaampere range discharges at surrounding gas pressure of 5–7 MPa.

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References

[1] Braginskii S I 1958 Sov. Phys. JETP 6 494–501
[2] Pease R S 1957 Proc. Phys. Soc., Sect. B 70 11–23
[3] Haines M G 2011 Plasma Phys. Controlled Fusion 53 093001
[4] Vikhrev V V, Ivanov V V and Koshelev K N 1982 Sov. J. Plasma Phys. 8 688–92
[5] Bogomaz A A, Budin A V, Pinchuk M E, Rutberg Ph G and Savvateev A F 2005 Physics of Extreme States of Matter—2005 (Chernogolovka: IPSP RAS) pp 214–6
[6] Bogomaz A A, Pinchuk M E and Budin A V 2007 XXII Int. Conf. on Interaction of Intense Energy Fluxes with Matter, March 1–6, 2007, Elbrus, Russia p 189
[7] Bogomaz A A, Budin A V, Losev S Yu, Pinchuk M E, Pozubenko A A, Rutberg Ph G and Savvateev A F 2008 Plasma Phys. Rep. 34 366–75
[8] Rutberg Ph G, Bogomaz A A, Budin M E, Leks A G and Pozubenko A A 2011 Phys. Plasmas 18 122702
[9] Bogomaz A A, Budin A V, Zubrodskii V V, Kuznetsova I V, Losev S Yu, Petrenko M V, Pinchuk M E and Rutberg Ph G 2008 Instrum. Exp. Tech. 51 744–7
[10] Pinchuk M E, Losev S Y, Pozubenkov A A, Petrenko M V, Rutberg Ph G, Bogomaz A A and Budin A V 2009 High Temp. Mater. Processes 13 349–58
[11] Budin A V, Losev S Yu, Pinchuk M E, Rutberg P G and Savvateev A F 2006 Instrum. Exp. Tech. 49 549–52
[12] Enselin P Y, Fridman B E and Rutberg Ph G 1993 Instrum. Exp. Tech. 36 730–3
[13] Aldsevey A G, Belov A M, Zubrodsky V V, Sukhanov V L, Sorokin A A and Peterson B J 2007 Plasma and Fusion Research 2 S1061
[14] Artyomov A P, Bakshi E H, Tarasenko V F, Fedunin A V, Chaikovsky S A, Aruev P N, Zubrodskii V V, Petrenko M V, Sobolev N A and Suhano V I 2015 Instrum. Exp. Tech. 58 102–6
[15] Zel’dovich Ya B and Raizer Yu P 1966 Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena (New York: Academic)
[16] Bogomaz A A, Pinchuk M E, Budin A V, Leks A G, Leont’ev V V, Pozubenko A A and Kurakina N K 2016 J. Phys.: Conf. Ser. 774 012186
[17] Bogomaz A A, Pinchuk M E, Budin A V, Leks A G, Leontev V V and Pozubenko A A 2018 J. Phys.: Conf. Ser. 946 012138
[18] Henke B L, Gullikson E M and Davis J C 1993 At. Data Nucl. Data Tables 54 181–342
[19] URL http://physics.nist.gov/PhysRefData/contents-xray.html
[20] Blokhin M A and Shveitser I G 1982 Rentgenospektral’nyi Spravochnik (Handbook on X-ray Spectra) (Moscow: Nauka)
[21] Orlov N Yu, Denisov O B, Vergunova G A and Rosmej O N 2016 J. Phys.: Conf. Ser. 774 012111
[22] Pinchuk M E, Bogomaz A A, Budin A V, Rutberg Ph G and Pozubenko A A 2009 Physics of Extreme States of Matter—2009 (Chernogolovka: IPSP RAS) pp 238–41
[23] Zamyslyshyaev B V, Stupitskii E L, Guz’ A G and Zhukov V N 1984 Composition and Thermodynamic Functions of Plasmas (Moscow: Energoatomizdat)