Measurements of electric characteristics in high-current high-pressure discharge with current amplitude of 590–1200 kA by magnetic probe

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Abstract. Soft x-ray radiation (SXR) oscillation were registered for discharge with current amplitude of 1200 kA at initial hydrogen pressure of 5 MPa. Near current maximum the fluctuations of SXR from the channel have been registered. Speed of current channel contraction, channel radius and its oscillation amplitude for current amplitude of 1200 kA were measured by magnetic probe with extrapolation for currents of 590 and 900 kA. The electric field strength in discharge channel and near electrode voltage drops was determined by comparison of channel radius oscillations with synchronous voltage changing. Also this method was used for oscillation amplitude estimation at current of 1200 kA. Satisfactory agreement for the estimations was received. Oscillation amplitudes are needed for calculation of x-ray intensity modulation. Channel plasma parameters were determined for contraction near current maximum.

1. Introduction
The physics of powerful gas discharges at high and ultrahigh pressure is a part of high energy density physics and researches of extreme conditions of matter [1]. In the pulse discharge with current of megaampere range a plasma with extreme parameters is formed [2]. At research of the discharge with current amplitude of 1200 kA and initial pressure of hydrogen of 5 MPa near the current maximum the fluctuations of the channel soft x-ray radiation (SXR) [3, 4] have been registered. With the help of magnetic probes by a technique consistently developed in works [5–8], for current amplitude of 1200 kA the estimation of channel radius and amplitude of its fluctuations has been made in the present work on the basis of extrapolation of measurements for a current of 590 and 900 kA.

Via comparison of a channel radius changing with synchronous voltage oscillations on a discharge gap the electric field strength in the discharge channel and the near-electrode voltage drops are determined. This method also has been used for an estimation of amplitude of fluctuations of the discharge channel radius for current of 1200 kA. The satisfactory consent of results in an estimation of amplitude of the discharge radius fluctuations is received by two various ways. These estimations are necessary for definition of the channel plasma parameters causing the modulation of SXR.
Figure 1. Oscillograms of signals for discharge in hydrogen at initial pressure of 5 MPa (2.2 mF with initial voltage of 11 kV): 1—full current $J$ by Rogowski coil; 2—current $J_m$ by magnetic probe; 3—voltage across the discharge gap; $t_0 = 30 \mu s$, $t_1 = 33 \mu s$ and $t_2 = 42 \mu s$.

2. Experiments and discussion

The discharge in hydrogen at initial pressure of 5 MPa was investigated with current of 590–1200 kA. Steel electrodes of 20 mm in diameter and interelectrode distance of 1 and 2 cm were used. The discharge was initiated by wire explosion. The energy source is the modular capacitive system [9]. Maximal storage energy was of 500 kJ with initial voltage of 15 kV. The detailed description of installation one can find in [10]. Oscillograms of the current with amplitude of 590 kA, the voltage and the signal from magnetic probe are presented in figure 1. For this experiment with the help of magnetic probes by a technique from [7], where the value $r$ was defined from the relation of a probe signal to the full discharge current, the channel radius $r$ was measured, figure 2(a). Because at the deepest first contraction the current channel had radius smaller than the magnetic probe position, it is impossible to measure the position of the channel border and the minimal radius of contraction.

The subsequent fluctuations of the channel radius can be analyzed in more details by means of the data received by magnetic probes techniques. Consider time period near to the current maximum, corresponding to the following fluctuation of radius with the greatest amplitude.

The greatest voltage $V_1$ corresponds to the least radius $r_1 = 0.71$ cm at the instant in time $t_1$, and voltage $V_0$ to radius $r_0 = 0.79$ cm in the moment $t_0$ (before the contraction): $V_1 = V_{d1} + lE_1$ and $V_0 = V_{d1} + lE_0$, where $V_{d1}$—total near electrode voltage drops, $l$—arc length, and $E_0$ and $E_1$—electric field strength in the discharge channel before and after contraction.

Let us estimate size of change in the discharge channel radius, which necessary to receive the registered voltage difference at the moments of time $t_0$ and $t_1$. The electrode erosion value is so high due to high current density, so the channel plasma, as suppose, entirely consists from metal vapors of electrodes material [2,11,12]. The changing of value $E$ synchronously with the channel radius changing $r$ can be caused by variation of channel inductance and conductivity:

$$\Delta E = J(\mu_0/2\pi r(t))dr/dt.$$
Figure 2. Channel radius (a) and speed of current channel border by magnetic probe (b) for experiment in figure 1: $t_0 = 30 \mu s$, $t_1 = 33 \mu s$ and $t_2 = 42 \mu s$; interelectrode gap of 2 cm; the horizontal line shows magnitic probe position $r_{pr} = 0.5$ cm.

Speed of channel contraction and expansion determined with the help of magnetic probes shown in figure 2(b) was $\sim 10^4$ cm/s. In these conditions the value $\Delta E$ which arises due to change of channel inductance not exceeding 10% and it is possible to neglect it.

If assume that the channel contraction occurs adiabatically, it is easy to show that

$$\frac{E_1}{E_0} = \left( \frac{r_0}{r_1} \right)^{1.8}. \quad (1)$$
Really value $E$ is governed by the following equation: $E = j/\sigma; \sigma \sim T^{3/2}/z$, where $\sigma$—Spitzer conductivity for multicharged plasma. In a temperature range of $\sim 10^8$ K and ions concentration of $\sim 10^{18} - 10^{20}$ cm$^{-3}$ the ions charge $z$ is well approximated by expression $z \sim T^{1/2}$ [13], where $j$—current density, $T$—temperature, $z$—ions charge. From here, $E \sim J/(r^2 T)$. At adiabatic contraction $T_1 = T_0(r_0^2/r_1^2)^{\gamma - 1}$. Then supposing $J = \text{const}$ at maximal current $E_1/E_0 = (r_0/r_1)^{\gamma - 2}$, and for adiabatic index $\gamma = 1.1$ for iron vapor plasma with temperature $T \sim 10^8$ K and ions concentration of $\sim 10^{18} - 10^{20}$ cm$^{-3}$ [14], the expression (1) is right.

According to the measured values of voltage $V_0$ and $V_1$ and to corresponding values of $r_0$ and $r_1$ the $V_{el}$ was determined. The ratio (1) is valid if the value $V_{el}$ = 1.6 kV. Similar measurements with using of magnetic probes for $J_m$ = 900 kA give value $V_{el}$ = 2.0 kV. As well as in work [15] the total nearelectrode voltage drops in a range of $j \sim 10^5$ A/cm$^2$ are proportional to $j$.

One of the tasks of this work was the definition of the discharge plasma parameters for current amplitude of 1200 kA, figure 3(a), when fluctuations of SXR intensity were observed, figure 3(b). At such current amplitude measurements of channel radius with the help of magnetic probes had not been authentically carried out because of destruction of a probe during experiment. Under our assumption based on definition of the channel radius by magnetic probes at current of 590 and 900 kA, in case of a current of 1200 kA after contraction at the instant in time of $t_m = 55 \mu s$ (figure 3) as well as at smaller currents there should be an expansion of the discharge channel. Therefore the value of the channel radius at its greatest contraction near maximum current and expansion between time instants $t_1$ and $t_2$ (figure 1) have been received by extrapolation of measurements for current of 590 and 900 kA (figure 4).

Research results of the first maximal channel contraction with more powerful SXR splash at 20–23 $\mu s$, caused, in our opinion, by radiative contraction, are reported in [2].

Let us calculate discharge channel parameters for the moment of its contraction near to a current maximum $t_m = 55 \mu s$, see figure 3(a), considering that it is under Bennett equilibrium. This means that at current $J_B = 1200$ kA plasma pressure is approximately balanced against the magnetic forces. The electric field strength in the discharge channel $E$ was defined from ratio $V = V_{el} + lE$. The value $V_{el}$ was defined from experiments for 900 kA and an that fact, that its value is proportional to a current density $j$. The arc length $l$ was defined as $l = l_{AC} - \Delta l = 0.8$ cm, where $l_{AC} = 1$ cm—distance between the anode and the cathode, $\Delta l = 0.2$ cm—total length of near electrode voltage drop $V_{el}$ zone [16]. At $V = 3.58$ kV; $V_{el} = 2.87$ kV and $l = 0.8$ cm value $E = 0.89$ kV/cm. For $J = 1200$ kA, $r_1 = 0.75$ cm and $E = 890$ V/cm and for iron plasma of the discharge $\sigma = 6.9 \times 10^{14}$ cm$^{-1}$, $p = 3.98 \times 10^8$ dyn/cm$^2$.

After fast expansion of the discharge channel and the beginning of intensive SXR fluctuations the discharge channel radius $r_1$ and the metal vapor concentration in channel $n_1$ were defined from the following system of equations:

$$\begin{align*}
&n_1r_1^2 = n_2r_2^2, \\
&\tau = \frac{56r_2^2}{J} \sqrt{\frac{mn}{\gamma - 1}}.
\end{align*}$$

The second equation of the system (2) from [17] connects the period $\tau$ of fluctuations of the discharge channel radius $r_2$ with current $J$ and concentration $n_2$. Here $m$—atomic weight of iron, $\gamma$—adiabatic index. These fluctuations are caused by magnetic and gaskinetic pressure alignment. Values $r_2$ and $n_2$ are average values for the period $\tau$.

The solution of system at $n_1 = 1.65 \times 10^{19}$ cm$^{-3}$, $r_1 = 0.75$ cm, $J = 1200$ kA, $\tau = 3.5$ $\mu$s, $\gamma = 1.14$ gives $r_2 = 0.95$ cm, $n_2 = 1.03 \times 10^{19}$ cm$^{-3}$. In calculation of the channel conductivity under these conditions it is necessary to take into account changes of the current density, resulting to change in $V_{el}$ as it was note earlier, and, accordingly, $E_1$. For this case $V_{el} = 1.79$ kV, $E_1 = 1.12$ kV/cm, $\sigma = 3.4 \times 10^{14}$ s$^{-1}$, that for $n_1 = 1.03 \times 10^{19}$ cm$^{-3}$ according [14] gives plasma temperature average for the period of fluctuations $T = 8.2$ eV.
By the above-mentioned technique (formula 1), it has also been determined the amplitude of fluctuations of the discharge channel radius after loss of stable equilibrium and occurrence of SXR fluctuations with greater amplitude and well defined periodicity (figure 3(b) between $t_m$ and $t_e$). Growth of amplitude of channel radius fluctuations from 0.15 cm up to 0.36 cm was accompanied by increase in SXR intensity. These values of channel radius are close to results received by extrapolation ones from smaller currents (figure 4). Thus, average for the fluctuation period value of temperature $T = 8.2$ eV, and average value of concentration is close to one for an
equilibrium condition. Average value of radius \( r_2 = 0.95 \text{ cm} \) lies between minimal and maximal channel radii received by extrapolation of measurements for currents 590 and 900 kA (figure 4).

In our opinion, the loss of stability of the discharge channel occurs due to change opacity of the gas surrounding discharge channel. Close results are presented in [18] where calculations of dynamics of contraction of heavy elements plasma find out the connection of radius and temperature fluctuations with instability of an equilibrium condition at change of a mode of radiation from volumetric to superficial. Change of radiating characteristics of the discharge channel proves to be true also by change of frequency and amplitude fluctuations of channel radius according to [19].

3. Conclusions

Parameters of the discharge channel for the current of 1200 kA in a steady condition \( (T_1 = 19 \text{ eV}, n_1 = 1.6 \times 10^{19} \text{ cm}^{-3}, r_1 = 0.75 \text{ cm}) \) and after loss of stability and the beginning of intensive SXR fluctuations \( (T_2 = 8.2 \text{ eV}, n_1 = 1.0 \times 10^{19} \text{ cm}^{-3}, r_1 = 0.95 \text{ cm}) \) are determined with the help of magnetic probes diagnostics.

The near-electrode voltage drop and electric field strength in the discharge channel for a current range of 590–1200 kA are determined.

Close values for amplitude of the discharge channel radius fluctuations are received at current of 1200 kA by means of extrapolation results received for smaller current amplitudes and by an estimation done on the basis of comparison of voltage fluctuations amplitudes.

The received data for amplitude of fluctuations will be used in the further work for an estimation of channel plasma temperature during SXR at the contraction moments.

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