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Measuring of high current channel parameters in high pressure gas by combined using of magnetic probe and high speed streak photography

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Abstract. Experimental results for discharge in hydrogen with current amplitude up to 1 MA, current rise rate of $\sim 10^{10}$ A/s, and at initial pressure up to 30 MPa are presented. A series of channel contractions was observed at a current rise stage. Estimation of plasma channel parameters was made for equilibrium state at the channel diameter oscillations. The speed of the discharge channel contraction was determined by the specially developed magnetic-probe technique. Comparison of these magnetic probe measurements with high-speed optical photostreaks was carried out.

Earlier a series of discharge channel contractions at current rise stage had been observed in our experiments at initial working gas pressure of 5–35 MPa and current amplitude of 0.5–1.6 MA [1–3]. The contraction was accompanied by soft x-ray radiation [4]. On our opinion [1,3] the first deepest contraction [1,3] can be discribed by a radiative contraction mechanism [5–7].

But each contraction was accompanied by the fall of the channel brightness. And the channel image in photostreak disappeared over time at high current amplitudes because of radiation absorption in heated transmitting zone between the channel and the surrounding gas. It causes some problems in the analysis of the channel behavior.

Subsequent researches has been done with the help of a new original magnetic-probe technique [8,9] in which the probe size is comparable with the discharge channel radius. Also it were used an photostreak analysis [3] and soft x-ray registration [4] from the discharge channel.

In the paper an estimation of plasma channel parameters for an equilibrium state at the channel diameter oscillations was made by this experimental data.

The discharge was initiated by copper wire with diameter of 0.6 mm. Discharge chamber was designed with axisymmetric geometry. Interelectrode gap was 2 cm. Hemispherical steel electrodes with radius 1 cm was used. Capacity of energy storage was changed. It was 1.2, 2.4 or 4.8 mF. Charging voltage was varied from 1 to 15 kV. Energy input was up to 300 kJ. The scheme of probe placement into a current channel is shown in figure 1. Experimental plots for discharge with current amplitude of 0.95 MA and initial hydrogen pressure of 5 MPa are presented in figure 2.

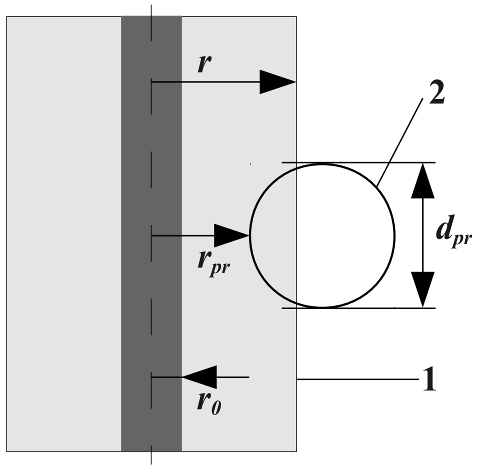

Figure 1. Scheme of magnetic probe position into the discharge channel: 1—discharge channel; 2—magnetic probe coil; r—channel radius; $r_{\mathrm{pr}} = 0.5$ cm—distance from the discharge chamber axis to probe coil; r_0—channel radius at the contraction; $d_{\mathrm{pr}} = 0.3$ cm—probe coil diameter.

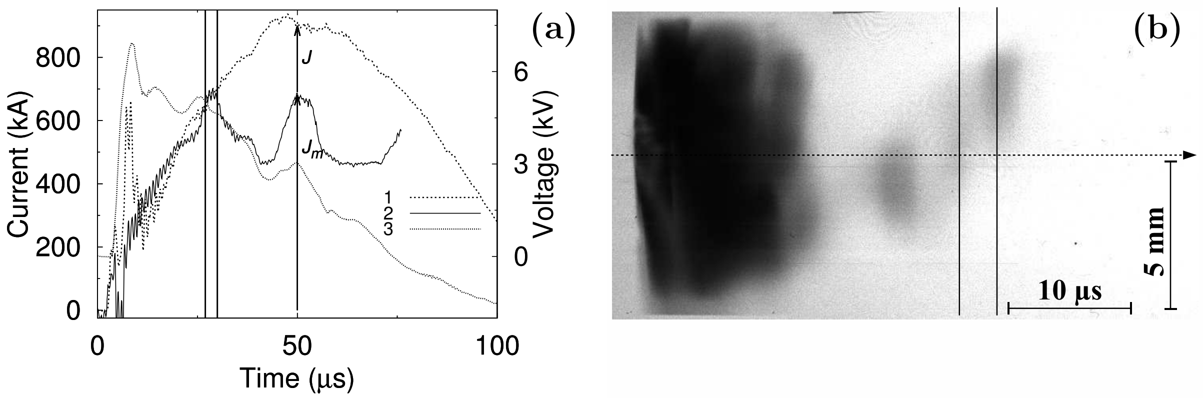

Figure 2. Oscillograms of signals (a) and photostreak (b) for discharge in hydrogen at initial pressure of 5 MPa (4.8 mF with initial voltage of 12 kV): 1—full current J by Rogowski coil; 2—current J_m by magnetic probe; 3—voltage across the discharge gap; two vertical lines mark the time interval of 27–30 μs.

Light diameter of the channel from the photostreak was calculated by procedure similar to [3, 10].

Discharge radius from magnetic probe signal was received by the procedure described in [9]. In particular, in the case of expansion of current channel out of the magnetic probe position, the discharge channel radius is calculated by the following expression:

$$\frac{J_m}{J} = 2.34\left(\frac{r^2 - 0.5^2}{2r^2} + \ln\frac{0.77}{r}\right).$$

The formula is valid at $0.77 \geqslant r \geqslant 0.5$ cm. All terms are explained in figures 1 and 2. The channel radius versus time is shown in figure 3a.

The first deepest contraction in photostreak was not detected by the magnetic probe because channel radius did not exceed the probe position. But the second one was detected by both

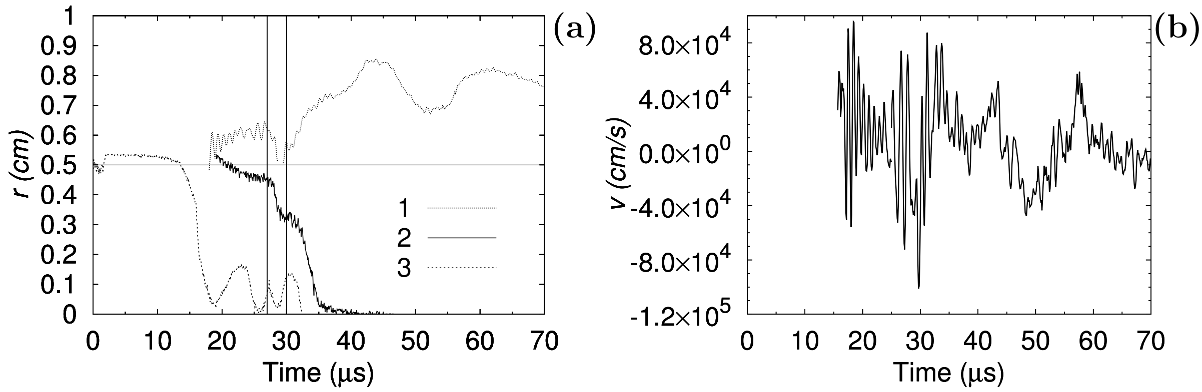

Figure 3. Channel radius (a) and speed of current channel border by magnetic probe (b) for experiment in figure 2: 1—by magnetic probe; 2.3—by photostreak at relative brightness of 0.5 and 0.6, correspondingly; two vertical lines mark the time interval of 27–30 μs; the horizontal line shows magnitic probe pozition $r_{\rm pr} = 0.5$ cm.

photostreak and magnetic probe signal. This contraction occurred between 27 and 30 μs. Therefore estimation of channel contraction using experimental data was carried out for the given time interval, marked by two vertical lines in figures 2 and 3a.

According to the magnetic probe measurements the maximal speed of contraction was of 1.1×10^5 cm/s, and speed of expansion 1.0×10^5 cm/s (figure 3b).

Using a probe signal directly is not possible for measuring of minimal channel radius because the magnetic probe is outside of the current channel at the moment of maximal contraction. Therefore the value r_0 (figure 1) is determined by a ratio:

$$\Delta t = \frac{0.5 - r_0}{u_c} + \frac{0.5 - r_0}{u_e},$$

where $\Delta t = 3$ μs corresponds to the period between two vertical lines in figure 2, u_c and u_e are the maximal speeds of contraction and expansion during the period from the magnetic probe measurements.

From here, the value of current radius $r_0 = 0.34$ cm. Let us determine the level of relative brightness in photostreak that corresponds to magnetic probe signal. For this time interval the speed of contraction obtained by the magnetic probe is equal to the speed of contraction from the photostreak image at the relative brightness level of 0.5. For this brightness level a steady radius was $r = 0.3$ cm for time near 30 μs. Thus the channel stagnation phase is observed for $r = 0.3$ cm, and the same result was obtained from the calculation procedure done above for magnetic probe measurements. Further contraction in the photostreak does not correspond to a real radius change because of the increasing opacity for the radiation of the peripheral gas surrounding the channel (figure 2b).

A metal plasma channel surrounded by hydrogen was assumed. High metal concentration for current amplitude above 0.5 MA inside channel core was registered by x-ray flash diagnostics [11, 12] of discharge channel. We supposed, that magnetic pressure is close to gaskinetic, i.e. Bennet equilibrium is hold.

For channel equilibrium state with the radius of $r_0 = 0.3$ cm, current $J = 0.7$ MA and electric field strength in the channel $E = 1.96$ kV/cm a conductivity is $\sigma = 1 \times 10^{15}$ s^{-1}. According to work [13], the concentration and temperature, determined by the conductivity and pressure, are of 5×10^{18} cm^{-3} and 34 eV respectively. Also the values of the radiated power

$P_R = \sigma_B T^4 r_0^2 / l_{\rm Pl} = 2.4 \times 10^9$ W/cm and deposited power $P_J = JE = 1.4 \times 10^9$ W/cm are close to each other at the stagnation stage. Here, T—temperature, σ_B—Stefan–Boltzmann constant, l_P—Planck mean free path; $l_P \approx 60$ cm according to [13].

Fluctuations with the period $\tau \sim 1$ μs are observed on oscillograms of x-ray radiation, magnetic probes signals and radius by photostreak for the stagnation stage. According to ratio [14] for equilibrium Z-pinch state:

$$\tau = \frac{56 r_0^2}{J}\sqrt{\frac{mn}{\gamma - 1}},$$

where $[J] = 1$ A, $[m] = 1$ g/cm^3, $[n] = 1$ cm^3, $[r] = 1$ cm. This ratio is approximately valid for our conditions: $J = 0.7$ MA, $r_0 = 0.3$ cm, $\gamma = 1.14$, $n = 5 \times 10^{18}$ cm^{-3} and $T = 34$ eV.

So, the temperature and channel radius were determined for equilibrium channel state at the channel diameter oscillations. For experiment on figure 2 temperature and concentration in second contraction were 34 eV and 5×10^{18} cm^{-3} at channel radius 0.3 cm. The speed of the discharge channel contraction was determined by the specially developed magnetic-probe technique. And comparison of these magnetoprobe measurements with high-speed optical photostreaks was carried out.

Acknowledgments

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