Current Sheath Dynamics in a Coaxial Plasma Opening Switch

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Abstract – The paper presents the results of experimental studies on magnetic wave penetration into a plasma bridge in a coaxial microsecond plasma opening switch of megaampere current. The experiments were performed on a GIT-12 setup at an MPOS current amplitude up to 5 MA. Measurements were taken with magnetic B-dot probes arranged along the axis in the plasma region and optical probes synchronized with them in space and time. It is shown that the current sheath velocity near the cathode and the anode is (20–30) cm/μs, the current sheath thickness is ~ 2 cm, which makes up (10–15)% of the initial MPOS crosspiece length, and the sheath current density is (10–20) kA/cm^2. The magnetic field penetration is demonstrated to proceed faster than the plasma density redistribution in the shock wave.

1. Introduction

Recent interest in microsecond plasma opening switches (MPOS's) of megaamper currents is due to the feasibility of their use in shortening the current risetime in plasma loads. Thus, a crucial point is the structure of a current sheath formed during the magnetic wave penetration into a plasma crosspiece; namely, in what way the magnetic field evolution is associated with the plasma density redistribution in MPOS's. The current sheath dynamics in MPOS's was much addressed in the literature [1–3]. In one of the earlier works [1], the dynamics and the quantitative characteristics of the current sheath were studied using collectors arranged on the anode. The authors of [2] determined the current sheath velocity near the anode and the cathode for an MPOS in the EMH mode by magnetic probes arranged on the anode and on the cathode. Notewothy also is the study [3] where both magnetic and optical probes were employed to measure the plasma shell velocity in a megaampere PFS; unfortunately, the presented data of optical measurements are qualitative. In the present work, an attempt is made at simultaneous measurements of the magnetic field dynamics and the radiation intensity of the moving current sheath in a megaamper MPOS.

2. Experimental arrangement

Schematic of the experimental arrangement is shown in Fig. 1. The experiments were performed on a GIT-12 generator [4] comprising 12 modules connected in parallel to a common collector that mounts a unit with an MPOS and a load. Each module consists of nine parallel sections connected in the ***Marx generator circuit, a **vacuum insulator, and a self-magnetically insulated vacuum coaxial line connecting the module to the central collector. The MPOS is a coaxial section of diameters 370 and 320 mm with a total height of 230 mm. The load is a foil liner of diameter 100 or 30 mm located at the center of a radial line of height 30 mm. Several shots were made without the liner; in this case, the load was the MPOS itself and vacuum gap at the end of radial line. The derivative of the generator current at the MPOS input was measured by an inductive groove (*MG*) and the collector voltage *UL* by a voltage probe. The inductance between the collector and the MPOS was 12 nH.

Plasma was injected from the outer electrode (anode) along the coaxial axis. The plasma shell was produced by 48 capillary-type plasma guns (PG's). The plasma guns were arranged uniformly in a circle of diameter 350 mm on the upper flange of the chamber. The discharge current in each gun is oscillatory with a risetime of 1.2 μs and an amplitude of 9 kA with damping factor of 1.6 (see *Ip* in Fig. 2). Capillary plasma guns provided highly ionized plasma of hydrogen (precursor with $v \sim 9$ cm/μs) and carbon ions. The velocity and the electron density of the main carbon plasma flux were ~ 2 cm/μs and ~ 10^{15} cm^{-3}, respectively [5]. On operation of the plasma guns 8 μs ahead of the Marx generator, the entire interelectrode region of the MPOS coaxial (~ 20 cm long) between the guns and the check ring of the anode was filled with the plasma. The experimental conditions chosen made it possible to obtain an MPOS current of amplitude ~ 5 MA with a 1-μs risetime at a 50-kV Marx generator charge voltage. Typical waveforms of the PG and POS currents for a ∅100 mm liner are shown in Fig. 2.

The distributions of the magnetic field and of the luminous radiation of the MPOS in time and lengthwise of the MPOS were measured using B-dot probes and photodiode-based optical probes (PD's). The anode and the cathode each mounted four *B-dot* probes (A1–A4 and K1, K3–K5, respectively) along the generatrix. The probes were inserted in holes made in the electrodes and protruded 2 mm in the discharge gap. The optical probes PD2, PD3, and PD4 were in the same plane as A2 and A3–K3 and on the same radius as A4–K4, respectively. The spacing between a *B-dot* and a PD along the azimuth was 1.2 cm. Two probes were employed for measurement of X-rays: the first

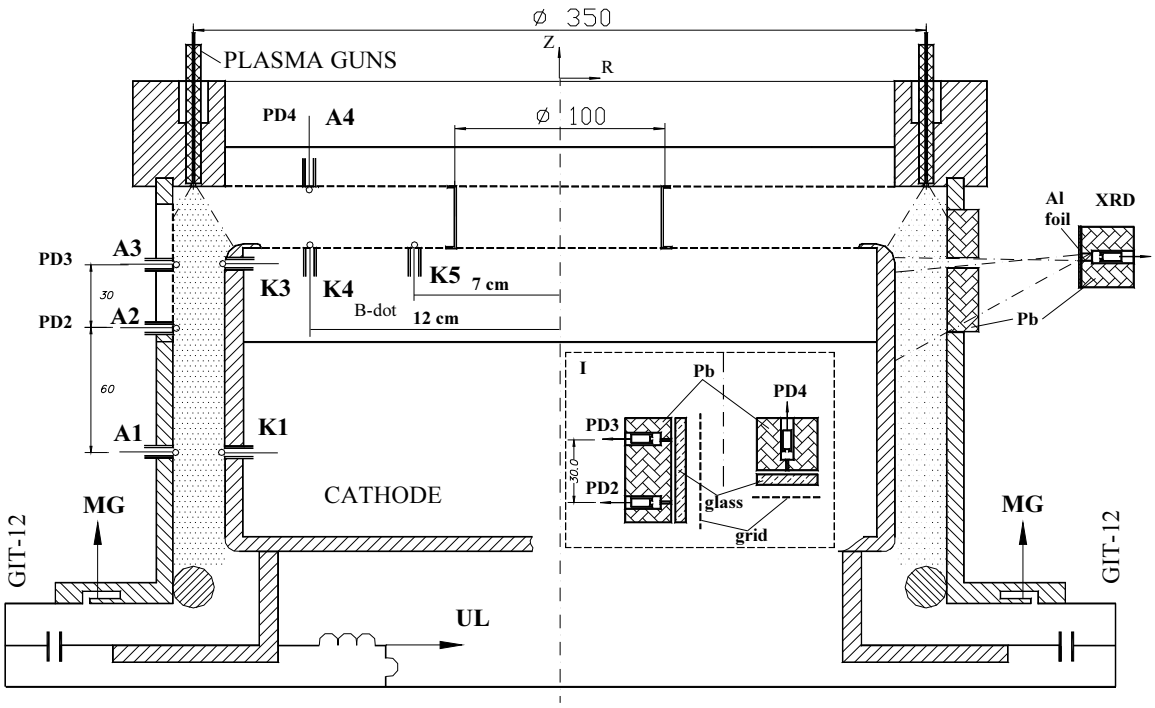

Fig. 1. Schematic of the experimental arrangement

one is an x-ray diode (XRD), shown in Fig. 1, is placed in vacuum chamber behind the anode window and intended for soft X-ray; the second probe is a pin-diode, mounted behind the 5 mm stainless steel flange, measures x-rays with energy ≥ 50 keV.

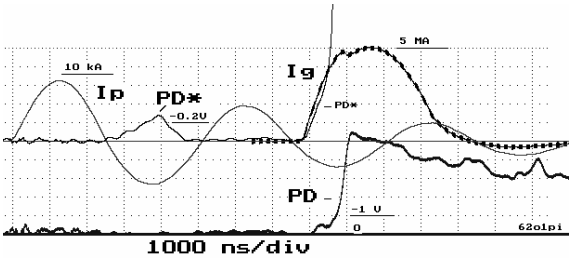

Fig. 2. Typical waveforms of the currents and photodiode signals in the microsecond range

3. Experimental diagnostics

The magnetic field distribution in the MPOS and load regions, and the velocity and the parameters of the plasma shell were measured by *B-dot*, PD, and x-ray probes. The *B-dot* probes were an insulated wire (wire diameter 200 μm, wire and insulation diameter 300 μm) with a ∅1-mm winding frame. The signal was transmitted via a 75 Ω cable. A photo of this type probe is shown in Fig. 3. The *B-dot* probes fixed the instant at which the current sheath passes the probe region. The current sheath velocity was determined by measuring the time interval between the instants the signals arise on the identical probes arranged along the path of the power flow to the load.

The luminous radiation was measured using commercial Si photodiodes (PD) FD-256 (time resolution ~ 2 ns). In measurements of the luminous flux, a positive bias of +10 V was applied to the PD's. The negative signal was transmitted to an oscilloscope through a 4-μF capacitance via a 75 Ω measuring line (τ = 300 μs). The photodiodes were placed in Pb containers (see block I in Fig. 1) for x-ray protection at a quantum energy less than 300 keV. Input window of 1 mm diameter was made in the containers, which provides spatial resolution of 1.5–2 mm of the collimation system on the object. The optical measuring circuit was chosen assuming that on arrival of the current sheath in the PD region, the radiation intensity increases many times. Preliminary experiments show that the radiation intensity in the current sheath is at least two orders of magnetite higher than that from the plasma produced by the plasma guns. Figure 2 shows an oscillogram of the signal from a PD* located 4 cm from the PG's in the A3–K3 region near the anode hole without entrance diaphragm and light filter. The sensitivity of the measuring line was increased ten times. It is seen that within ~ 2.5 μs after the onset of the current in the PG's, a PD* signal of amplitude ~ 0.2 V develops. On operation of the Marx generator, current arises in the plasma crosspiece and the amplitude of the PD* signal increases many times. For the radiation on the PD's to be less intense, neutral light filters NS7 with a tenfold attenuation were used in addition to diaphragming. The plasma shell velocity was determined from the time interval Δt at half the amplitude of the light pulse risetime from the PD's located at a distance Δz: $v_{pd} = \Delta z/\Delta t$.

Fig. 3. Magnetic B-dot probe

Soft x-rays were measured using an XRD based on a FD-256 photodiode in which an Al foil 8 or 16 μm thick was placed instead of the glass window. The x-ray probe located downstream of the vacuum chamber was an SKD-01 pin-diode with a time resolution no worse than 3 ns.

Fast signals were digitized using a twelve-channel system (three TDS-640A oscilloscopes) with a band of 0.5 GHz and a time resolution of ~ 2 ns.

4. Experimental results

B-dot measurements

For the most part, measurements were performed with a cylindrical liner made of ∅10 cm stainless steel foil. In this case, the voltage across the MPOS and the load was no greater than the output voltage of the Marx generator, and the energy released in the MPOS was moderate. Nevertheless, the *B-dot* probes were to be replaced after each shot. The technology of manufacture and arrangement of the *B-dot* probes allows an estimate of the measurement error no worse than 20%. The reliability of absolute B-dot measurements of dB/dt in the current-carrying plasma at current densities of tens of kA/cm^2 is ambiguous and disputable. Therefore, the emphasis was on the time characteristics and qualitative tendencies.

Figure 4 shows signals from the anode *B-dot* probes and inductive groove *MG* at the MPOS input and oscillograms of the corresponding currents obtained by integrating the *B-dot* signals. Figure 5 shows signals from the cathode *B-dot* probes and oscillograms of the corresponding currents. At the end of the conducting stage, the rate of the current rise peaks, reaching $7 \cdot 10^{13}$ A/s in the A3–K3 region. The average velocity of current sheath in the region between probes $(k + 1)$ and k was defined as $vzk = \Delta Z(k + 1)_{-k}/\Delta t(k + 1)_{-k}$. The current sheath velocity from *MG* to A4 in the anode sections was 19, 20, 30, and 50 cm/μs, respectively. The current sheath velocity from *MG* to K4 in the cathode sections was ~ 15, 25, and ~ 35 cm/μs, and in the section K4–K5, it was 80 cm/μs. The velocity of the magnetic field toward the A1–K1 plane along the anode is much higher than that along the cathode, whereupon the velocities level off. Thus at the conducting stage, the current sheath velocity in the coaxial increases slowly from 20 to 30 cm/μs and at the instant the current is switched to the load (on entering the radial line), it increases rapidly to 80 cm/μs. Note that with a high-impedance load (with a ∅3 cm liner and with no liner), the current sheath velocity in the K4–K5 region increases to 120 cm/μs, while the characteristics in the coaxial section of the MPOS remain unchanged. As this takes place, the current switched into the region downstream of K5 decreases from 3 MA/200 ns to ~ 1.5 MA/200 ns and to ~ 0.2 MA/200 ns, respectively. This is direct evidence that the current sheath carries a small amount of the plasma from the MPOS region to the region of a load of diameter less than 14 cm. The switched current depends on the load impedance.

Knowing the experimentally measured velocities v_k of the current sheath at different points in time and the FWHM for *B-dot* signals $\tau^k 1/2$, we can estimate the current sheath thickness $\delta_k \approx \tau^k 1/2 v_k$. For the anode probes A1, A2, and A3, the current sheath thickness δ_A is ~ 1.2, 1, and 0.9 cm, respectively, and for the cathode *B-dot* probes K1 and K3, δ_K ~ 1–1.4 and 1 cm, respectively. For an amplitude level of 0.1, the current sheath thicknesses are doubled. Thus, it may be considered that the current sheath thickness δ ~ 2–2.5 cm or 10–15% of the initial MPOS length. Both the anode and cathode measurements show that the current sheath draws no less than 90% of the MPOS current. The obtained experimental data make it possible to determine the current density in the sheath $j_r \approx I_{Ak}/(2\pi r_e \delta_k)$. In the A1-K1 region, the current density is 12–15 kA/cm^2 and in the A3–K3 region, it is 19–22 kA/cm^2.

The oscillograms from the anode and cathode *B-dot* probes (A1–K1 and A3–K3) located in one plane along the z coordinates are indicative of more rapid (advance) penetration of the magnetic field along the anode. This fact is also supported by the difference in the velocities along the anode and the cathode obtained above. In the A1–K1 plane, this advance is 1.2–1.5 cm and in the A3–K3 plane, it is 2 cm. This corresponds to the deflection of the current sheath from a straight line between the cathode and the anode by an angle of 30–40°. The signals from the *B-dot* probes A4–K4 located in the radial line on one radius appear nearly at a time and in synchrony with the signal from the pin-diode located outside the vacuum chamber for measuring the high-voltage phase of the switch opening (see Fig. 7).

It should be noted that all signals from the cathode probes have a precursor of polarity opposite to that of the main pulse. Reversing the polarity of the main signal by changing the position of the *B-dot* probes relative to the magnetic flux laves the situation unaltered. The signals from the anode probes lack this precursor. Part of the anode signals has a small prepulse of the same polarity as the main pulse. The occurrence of the precursor can be associated with the existence of a region at the current sheath front where the direction of the electric field is opposite to that of the main generator field. The drift of electrons in the magnetic field may result in Hall electric fields ($E_z = j_r H_\varphi / enc$) up to (30–50) kV/cm. In these fields, plasma ions are accelerated and a structure (a precursor) in the form of

a double layer is formed [6]. The magnetic field has maximum at the cathode, penetration of the electron cloud is also maximal in the cathode region, and hence the observed situation is possible (see precursors on the K1–K4 signals in Fig. 5)

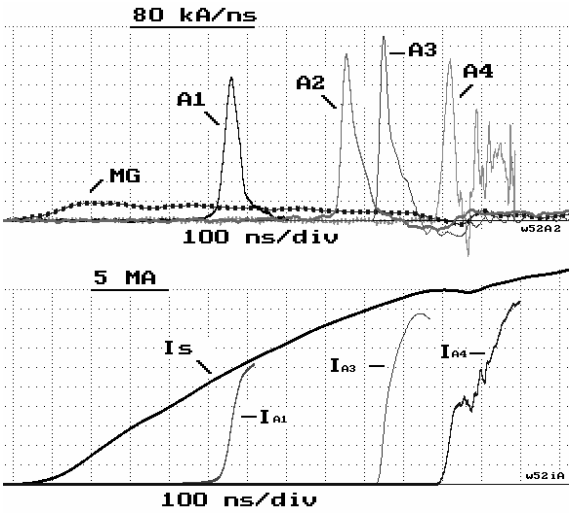

Fig. 4. Typical oscillograms of the signals from the anode *B-dot* probes and calculated currents ($I = \int B\text{-}dot$)

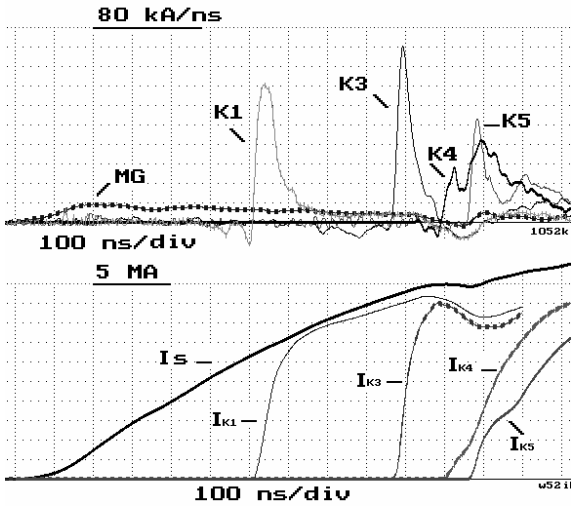

Fig. 5. Typical oscillograms of the signals from the cathode *B-dot* probes and calculated currents ($I = \int B\text{-}dot$)

The experimentally measured current sheath velocities allow us to conclude that the shock wave is initiated even in the A1–K1 region. Assuming, that in the shock wave there is a balance between the dynamic pressure of the plasma shell and the magnetic pressure of the current sheath, we can write $\rho u^2/2 \sim H^2/8\pi$. From this relation we can obtain the upper estimate of the plasma density in the shock wave region nch ~ (3–4)n_0.

Optical and X-ray measurements

Optical measurements were performed from the side of the anode. Three PD probes were located in the region of the *B-dot* probes A2, A3–K3, and A4–K4. Schematic of their arrangement is shown in Fig. 1 (block I marked by a dotted line). Figure 6 shows signals from the PD line and B-dot signals corresponding to them. The velocity of the luminous current sheath front at FWHM of the PD signals was ~ 30 cm/μs for $v_{PD3–PD2}$ and ~ 60 cm/μs for $v_{PD4–PD3}$ and was close to the velocity measured with the *B-dot* probes.

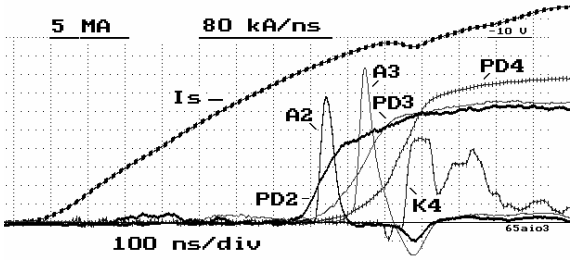

Fig. 6. Signals from the optical and *B-dot* probes

Noteworthy in the observed experimental fact are the following points. It is seen that the risetime of the light pulse is several times greater than that of the *B-dot* signals. After the passage of the current sheath, the plasma continues to glow for a long time. The *B-dot* probes indicate that the current is almost entirely switched into the load, but the radiation intensity is unaffected. Figure 2 shows the long time scale of the PD oscillogram. It is seen that the duration of intense glow is much longer than the current risetime in the MPOS and than the overall transient process in the generator. It would be reasonable to attribute this glow to the formation of dense near-electrode plasma during the passage of the current sheath of density 10–20 kA/cm^2. This fact is also pointed to in [3]. The PD signals with increased sensitivity of the measuring channels show that PD2 and PD3 signals appear within 150–200 ns after the onset of the current *Is*. They consist of two regions: a prepulse of amplitude $U_{PD,} \leq 10\%$ and the risetime of the main pulse. The risetime of the main PD pulse is 30–50 ns ahead of the magnetic field front in this MPOS region and corresponds roughly to the instant at which a small prepulse appears on the anode *B-dot* probes. The light prepulse can be associated with faster penetration of the magnetic field into the plasma bridge near the solid anode due to the near-electrode drift of electrons in a strong magnetic field. It is also conceivable that the second reason is the luminous radiation propagating from the formed current sheath. Nevertheless, the presented oscillograms allow the conclusion that the current sheath is at the front of the plasma shell involved in acceleration by the passed current sheath. At the magnetic field, frozen in the electron component due to a strong Hall effect, the current sheath penetration into the plasma shell is faster than the plasma density redistribution. In this sense, we can speak about a partially transparent current sheath. The path ranges of atoms before ionization λ_i and charge exchange λ_p for a density of ~ 10^{15} cm^{-3} are comparable

to the current sheath thickness $\delta \sim 1$–2 cm, and for the magnetic piston, the condition $\delta >> \lambda_i$, λ_p must be fulfilled. Thus, a multilayer structure can be formed: the undisturbed plasma crosspiece ahead of the current sheath, then the current sheath with a precursor whose front carries plasma electrons and fast ions accelerated in the Hall electric field E_z, and the gas-plasma region involved in the acceleration by the passing current sheath at the back.

Figure 8 shows oscillograms of the MPOS current and voltage *Us*, *B-dot* signal (A2), XRD signals (X_1 and X_2 downstream of an 8-μm Al filter) and pin-diode signals (downstream of 5 mm Fe). The quantity $Us = Is(t)(dLs/dt) + Is(t)Rs(t)$ is an active component of the voltage drop across the MPOS. The signals X_1 and X_2 from the X-ray photodiode were obtained with an 8-μm Al filter. The signal X_1 is the radiation from the MPOS behind a grid-covered window (5 cm × 6 cm) in a stainless steel anode of thickness 8 mm. Thus, the probe X_1 measured the radiation from the region $\Delta z = 5$ cm, from the cathode top toward the GIT12 generator, where the *B-dot* probes A2 and A3 are located. The signal X_2 was obtained behind an 8-mm Pb diaphragm with a hole (0.5 cm × 2 cm) in the A3 region. The diaphragm was inserted in the anode window. Positioning of a 16 μm Al filter in the second case causes the amplitude of the probe signal to decrease 5–7 times and become very small. The obtained signals suggest that the x-rays from the near-anode plasma region of the MPOS appear on arrival of the current sheath in this region and exist within the overall time the power flux moves toward the load. For quantitative estimates, more detailed measurements should be taken. X-rays with high quantum energy (signal *pin*) appear near the maximum value of *Us* and its onset is synchronous with the onset of the K4 and K5 signals, i.e., with current switching into the load. There is a spike on the X_1 signal, which is synchronous with the pin signal, in the case with large window of XRD.

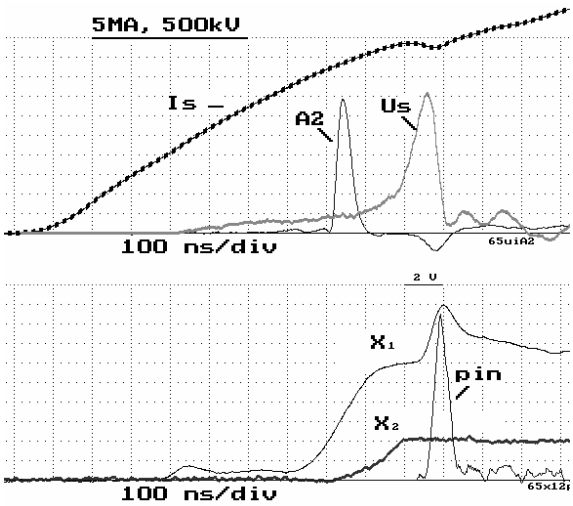

Fig. 8. Oscillograms of the MPOS current *Is* and voltage *Us*, signals from A2, X_1 and X_2 (behind the 8-μm Al filter), pin-diode (behind the 5 mm Fe)

5. Conclusion

The current sheath velocity in an MPOS of megaampere current was determined using two types of measurements. According to the readings of the magnetic probes, the current sheath velocity at the beginning of the conducting stage is 20 cm/μs, and at the end of the conducting stage, it is 30 cm/μs. Immediately before the opening and current switching into the load, the velocity increases to (50–80) cm/μs. Optical measurements suggest that at the end of the conducting stage, the current sheath velocity is ~ 30 cm/μs and on opening of the MPOS, it increases to (60–70) cm/μs.

The current sheath thickness is ~ 2 cm, which makes up 10–15% of the initial MPOS length. At the beginning of the conducting phase, the current density in the sheath is 10–15 kA/cm^2, and at the end of the conducting phase, it is 20–25 kA/cm^2. Both the anode and cathode measurements suggest that the current sheath draws no less than 90% of the MPOS current.

The brightness of the current sheath glow is at least two orders of magnitude higher than that of the preliminary injected plasma. Signals from the *B-dot* probes in different regions of the MPOS plasma crosspiece appear on fronts of the PD signals. This indicates that the magnetic field frozen in the electron component is ahead of the density jump ($n_{sh} \sim 3n_0$) in the shock wave due to a strong Hall effect. The data can be considered as an additional support of the validity of the Hall MHD-model of the MPOS [8].

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