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Experimental Study on the Plasma Dynamics in the Magnetically Insulated Transporting Lines Aimed at the Conceptual Project of Z-Pinch IFE Reactor

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A series of experiments has been carried out on the S-300 pulsed power machine, devoted to the study of a section of magnetically insulated vacuum transporting line (MITL). The length of MITL section was 1 cm, the current flow density up to 500 MA/cm^2 by the linear current flow density being up to 7 MA/cm. These parameters fairly correspond to those of the Sandia Laboratories' conceptual project of IFE reactor based on the fast Z-pinch [1,2].

Except of loads with two plane parallel outer electrodes playing the role of anode by the distance between them varied in the range of 5-12 mm, the segments of coaxial line were used, as well; they allowed to enhance our diagnostic abilities. The spatial layout of output device included the return conductor in form of 3 rods with the diameter 3-5 mm, made of tungsten or stainless steel and placed at the diameter 15 mm. In the experiments, the tubes made of stainless steel or nickel with the outer diameter 0.75, 1 or 1.2 mm and the wall thickness 100 or 200 μm were used as cathodes. The inner negative electrode of MITL was situated symmetrically between return conductor rods. MITL section was joined to the output unit of the S-300 generator. The experimental scheme is described in [2].

Our experiments have demonstrated the efficiency of current transport almost independent upon the form of outer electrode; therefore, we used just the last geometry in most shots. The current amplitude in the load was up to 1.7 MA with the rise time ~ 160 ns. The input and output current were recorded by means of calibrated magnetic loops and shunts, respectively. The signal taken from the shunt was corrected by taking into account the field/current diffusion through the shunt wall.

The data on near-electrode plasma dynamics were based on the multi-frame shadow and Schlieren photographs in the light of second YAG:Nd laser harmonics (λ = 532 nm, τ =

0.3 ns), ICT chronography and also frame ICT photography with the nanosecond temporal resolution in the visible range, VUV and SXR as well.

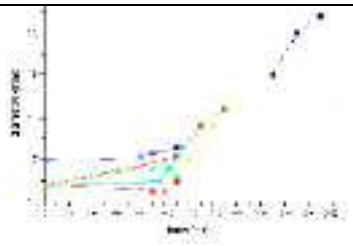

Fig.1. Cathode plasma diameter derived from the shadow and Schlieren images. Lines of particular color join together the points got in the same shot.

Fig.2. Superposition of the visual light chronogram contours (sky blue-violet-yellow in the ascending order) to calculated curves (black and brown solid lines). Full blue curve is an electrical current.

Collected laser probing data (Fig.1) show that up to 240 ns from the current beginning, dense plasma (N_e>5•10^{17} cm^{-3}) expands no more than to 3.2 mm in diameter.

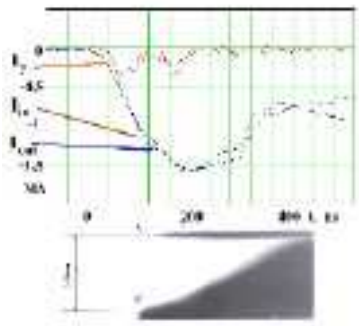

Fig.3. Top: oscillograms of both input (I_{in}) and output (I_{out}) current and also of the HXR radiation intensity from the MITL model. Bottom: the chronogram of the near-electrode plasma expansion (the negative). The gap reconnection by plasma and essential divergence of current oscillograms occur some at 400 ns from the current start.

After the current maximum, 200-220 ns from its start, the dense plasma becomes sharply accelerated up to 1–2·10^6 cm/s. Soft X-ray plasma images are similar to the visible light pictures at the appropriate moments. Pipe cathode compression was seen at the middle part of the discharge, that coincides with numerical simulation fairly good (Fig.2).

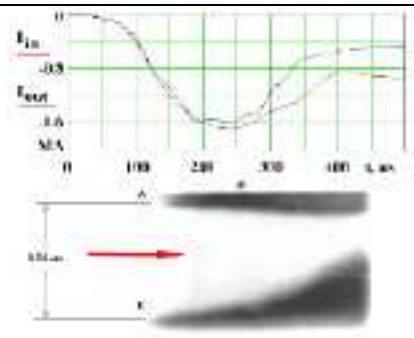

Fig.4. Top: oscillograms of both input (I_{in}) and output (I_{out}) currents. Bottom: the chronogram of the near-electrode plasma expansion (the negative). The strike points the moment of appearance of rare slightly luminous plasma in the gap.

The typical feature of most experiments was almost exact (with the accuracy exceeding 10%) coincidence of input and output current, at least, till the maximum of the latter (see Fig. 3 and Fig. 4). The cathode luminescence (i.e. appearance of plasma on it)

starts at some 80-100 ns from the current start. The anode luminescence is delayed some at 10-20 ns. Usually, this moment was correlated with the input and output current divergence.

The divergence of oscillograms, which serves as a witness of essential reconnection current, corresponds to the MITL reconnection by rare plasma. One readily can see this effect in Fig.4. The strike points at the front of weakly luminous rare plasma reconnecting the gap with the velocity observed equal to $2.5*10^7$ cm/s. At the moment of its coming to the anode (200 ns), the output current drops compared to the input current. The rare plasma inside the gap has been recorded also by means of frame ICT photographs in both visible range and SXR. Examples of these pictures are given in Figs 5 and 6.

When the dense plasma reaches anode, the magnetic self-insulation becomes completely destroyed.

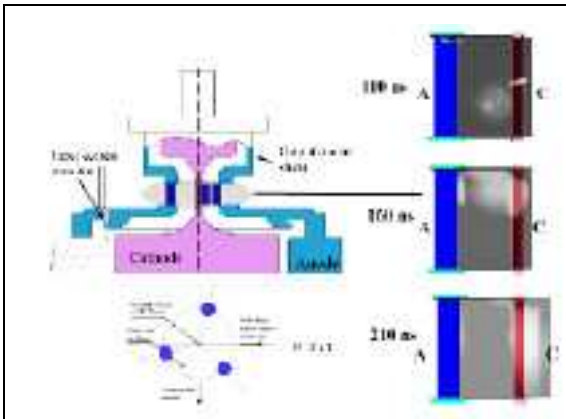

Fig.5. Images of rare plasma in the visible range. LHS: the output unit

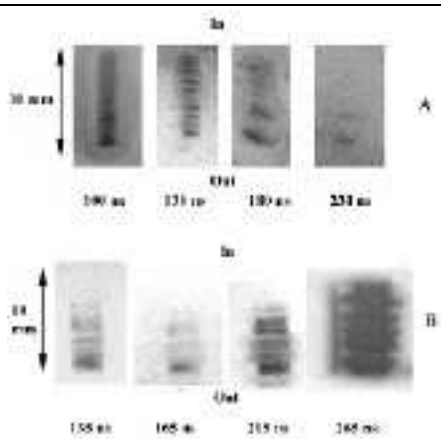

Fig.6. The X-ray images of plasma in the gap: A – metallic cathode, B – metallic cathode coated by the ceramic tube.

These ICT images demonstrate the luminous formations born either on the cathode or inside the gap at ~110 ns, which move towards the end of MITL section with the velocity ~10^7cm/s (160 ns). Besides, in all the images, at the end of the line, at 175-185 ns, a region of luminous plasma arises between the inner electrode and anode rod. That does not result in the MITL reconnection. Such dynamics seems to correspond to the plasma drift in the crossed fields.

In Fig.6, one can see the X-ray ICT images of plasma in the gap. They show that some luminescence arises on the cathode close to the shunt approximately at 100 ns after the current start. Little by little, the region of luminescence in the range $h\nu \geq 10$ eV is

slowly expanding in both radial and axial directions. In a whole, the picture probably corresponds to the development of instability, which spatial period increases in time.

By absolute Bremsstrahlung recording, the estimation was made of the leakage current, which value was about some dozen of kiloamps; the maximal value recorded was 100 kA. Thereby, it is obvious that such electron leaks cannot effect essentially on the current balance. However, the fact of their existence under the condition of strong magnetization of electrons is interesting enough; perhaps, it is worth further investigation.

Conclusions

The temporal behavior of both input and output current is identical up to the moment 220-260 ns after the current start, by the gap width equal to 3.5 mm. After that, the MITL reconnection happens; its moment coincides with that of sharp growth in the dense plasma expansion velocity. However, this plasma closes the gap much later, at the moment ~ 400 ns, thereby it cannot be responsible for the MITL reconnection. The process of electrodes explosion and subsequent dense plasma dynamics fairly corresponds to the predictions of numerical simulations based on the 1-D MHD NPINCH code.

Most likely, the MITL gap reconnection is conditioned by the rare plasma. The fast expansion of rare plasma reconnecting the MITL may be conditioned by the fast instability corresponding to the window of parameters of EMHD.

Electron leaks cannot effect essentially on the current balance. The value of leakage current was about some dozen of kiloamps, the maximal one recorded was 100 kA.

As a whole, our works allow to draw a positive conclusion concerning prospects of use the recyclable MITL for transportation of energy onto the target of Z-pinches IFE reactor.

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