Fast Z-Pinch Experiments at the Kurchatov Institute Aimed at the Inertial Fusion Energy

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Abstract. A series of experiments has been carried out at the linear current flow densities up to 7 MA/cm, aimed at physical modeling of magnetically insulated transmission line (MITL) of the Inertial Fusion Energy (IFE) reactor based on the fast Z-pinch. The goals of these experiments were as follows: a) the study of the near-electrode plasma and its effect on the energy transfer; b) determination of the critical MITL parameters to foresee possible restrictions on the efficiency of IFE reactor. As a rule, in our experiments, the MITL reconnection occurred at 220-260 ns, by the width of the gap 3.5 mm. As a whole, these experiments allow to draw a positive conclusion concerning prospects of use the recyclable MITL for transportation of energy onto the target of Z-pinch IFE reactor.

1. Introduction

In Ref. [1] the Sandia Laboratories' conceptual project of Inertial Fusion Energy reactor based on the fast Z-pinch has been presented. One of the key points in this project is the idea of using the recyclable transmitting lines (RTL) with the magnetic self-insulation. Magnetically insulated vacuum transporting line (MITL) is the traditional device aimed at the energy transport in pulsed power systems. An important feature of MITL in the project [1] is enormously high-energy flux and current amplitude compared to those they operate with nowadays (I ~ 20-90 MA). A series of experiments has been carried out on the S-300 pulsed power machine (3.5 MA, 100 ns, 0.15 Ohm) devoted to the study of a section of magnetically insulated vacuum transporting line (MITL). The goals of experiments were as follows: 1) study of the near-electrode plasma dynamics and its effect on the energy transfer; 2) forecast on the recyclable MITL use in the Z-pinch driven IFE reactor.

2. Effect of the MITL Gap Reconnection

The length of MITL section was 1 cm, the current flow density up to 700 MA/cm^2 by the linear current flow density being up to 7 MA/cm. These parameters fairly correspond to those of the project of IFE reactor based on the fast Z-pinch [1, 2]. Except of loads with two planar 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 enhancing 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]. In Fig.1, the schematic of S-300 output device is shown.

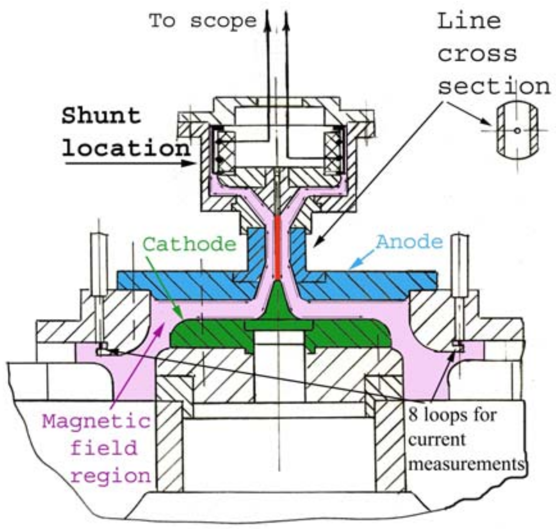

FIG. 1. Scheme of the RTL experiment with a shunt

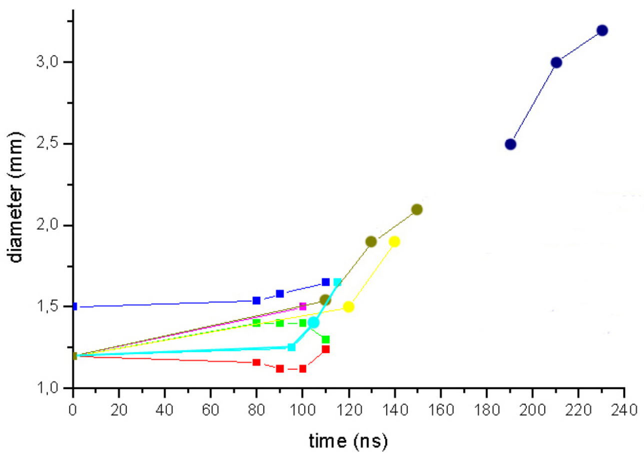

FIG. 2. Cathode plasma diameter derived from the shadow and Schlieren images. Lines of particular color join together the points got in the same shot.

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.

Collected laser probing data (Fig.2) show that up to 240 ns from the current beginning, dense plasma ($N_e > 5 \cdot 10^{17}$ cm^{-3}) expands no more than to 3.2 mm in diameter. After the current maximum, 200-220 ns from its start, the dense plasma becomes sharply accelerated up to 1–2$\cdot 10^6$ 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.3).

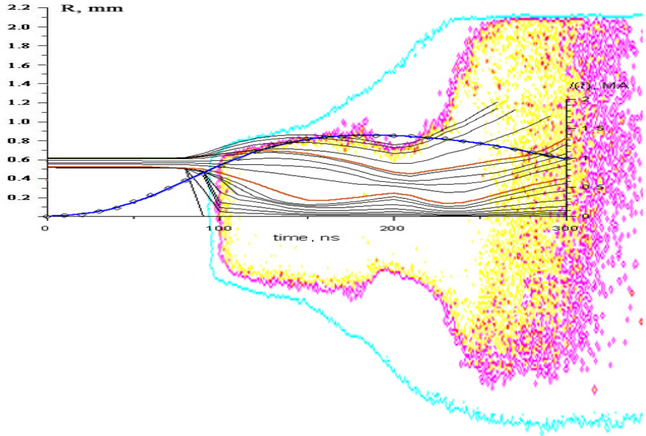

FIG. 3. Superposition of the visual light chronogram contours (sky blue-violet-yellow in the ascending order) to calculated curves (black and brown solid lines). Full blue curve is an electrical current.

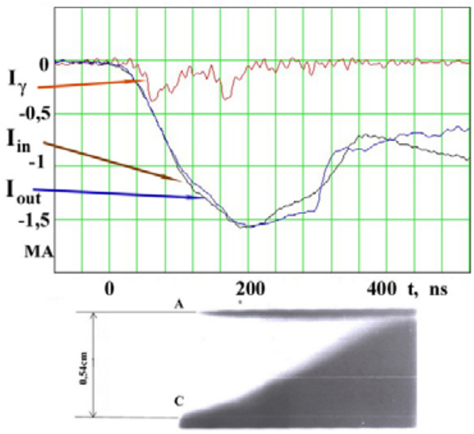

FIG. 4. Top: oscillograms of both input (I_{in}) and output (I_{out}) current and HXR radiation intensity. Bottom: the chronogram of the near-electrode plasma expansion (the negative).

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. 4 and Fig. 5). The gap reconnection and essential divergence of current oscillograms occur some at 400 ns from the current start. 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.5. 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. When the dense plasma reaches anode, the magnetic self-insulation becomes completely destroyed.

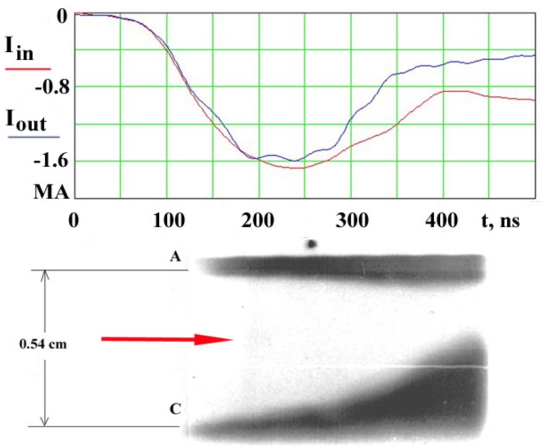

FIG. 5. Top: oscillograms of both input (I_{in}) and output (I_{out}) currents. Bottom: the chronogram of the near-electrode plasma expansion (the negative). The strike points the moment of appearance of rare slightly luminous plasma in the gap.

The rare plasma inside the gap has been recorded also by means of frame ICT photographs in both visible range and SXR. An example of these pictures is given in Fig. 6. 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 an effect of “plasma wind” has been predicted analytically [2], and the predicted velocity of “plasma wind” fairly corresponds to the experimental value.

In Fig.7, 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 [2].

By absolute Bremsstrahlung recording, the estimation was made of the leakage current, which value was about some dozen of kA; 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.

3. Influence of Materials and Impurities

On the S-300 machine, a series of experiments has been carried out devoted to the study of cathode material effect, as well as that of gases and oil layer absorbed by its surface, on the near-electrode plasma dynamics and the current pulse transport along the short MITL segment. The "cold" linear current flow density reached 6 MA/cm. The return conductor consists of three rods, 3 mm in diameter, made of the stainless steel and situated at the radius 7.5 mm (Fig. 6). Both dimensions and material of surface of the inner electrode were varied; to wit, Al, Au, W, Pb were used, as well as Ni (with and without a heating).

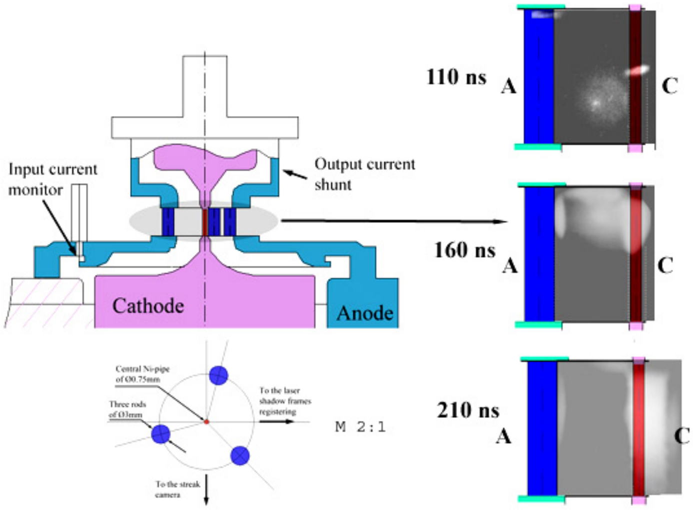

FIG. 6. Images of rare plasma in the visible range. LHS: the output unit

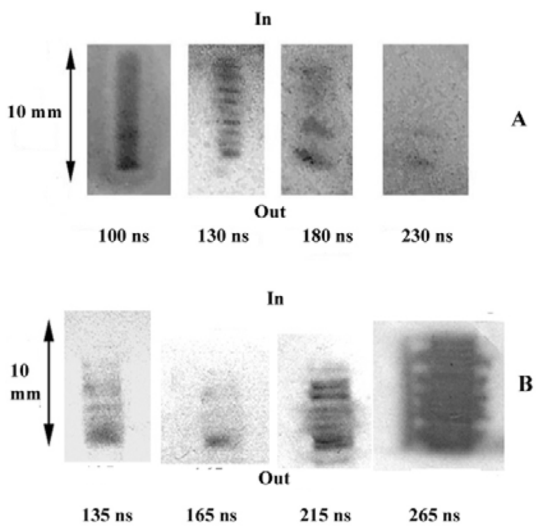

FIG. 7. The X-ray images of plasma in the gap: A – metallic cathode, B – metallic cathode coated by the ceramic tube

In the first experimental series, the effect of cathode surface purity on the gap reconnection rate was studied. As a cathode, the Ni tube was used with the diameter 0.75 mm and thickness 100 μm. To exclude the influence of plasma formed by the surface oil layer, as well as the gas absorbed by the surface, the inner conductor (cathode) was supported heated starting from the beginning of high-vacuum pumping out till the shot, by the temperature 200-600 C. Such heating removes the oil layer and decreases the concentration of gas absorbed some 2 orders of magnitude. The heating was brought about by passing the direct current ~ 10-40 A through the conductor. Fig. 7 demonstrates the oscillograms of both input and output current in the experiments with and without heating. The feature of these two experiments is the very good (with the accuracy better than 10%) coincidence of temporal dependences of input and output current up to the moment 240-260 ns. The chronograms of cathode plasma (Fig. 8) show the same dynamics of its expansion.

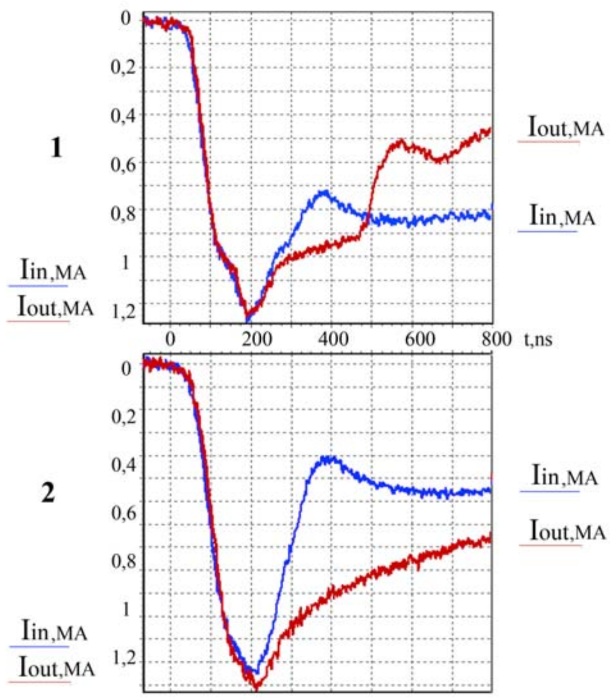

FIG. 7. Oscillograms of both currents, input one (I_{in} , blue curve) and output one (I_{out} , red curve): 1 – without preheating, 2 – with preheating.

In the second experimental series, the effect of electrode material on the plasma expansion velocity and, hence, the time of gap reconnection was studied. The material of electrode with maximal linear current flow density (i.e. that of cathode) was varied. Except of Ni and Al, both lead and gold were used as the inner electrode material. The loads were performed as tubes with the outer diameter 200-250 μm, that is more or of the order of skin depth. Experiments have confirmed the assumption about slower expansion of plasmas with greater Z. In Fig. 9, the oscillograms of both input and output current are presented, synchronized with the chronogram of Pb plasma expansion started from the lead cathode, without a preheating.

These oscillograms show the divergence of input and output currents as late in time, as at 300-320 ns from the current start, i.e. 50-70 ns after corresponding moment for the nickel tube. The visible overlap of electrode plasmas occurs after 500 ns from the current start.

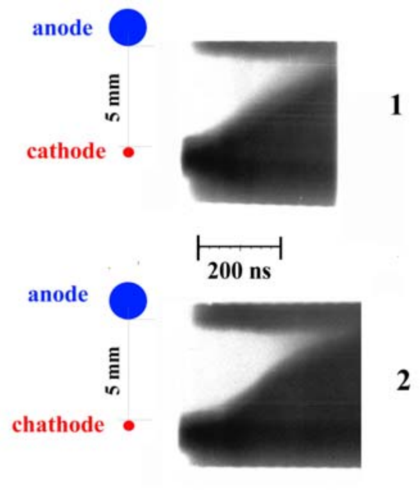

FIG.8. The chronograms of near-electrode plasma expansion (negative picture): 1 – without preheating, 2 – with preheating.

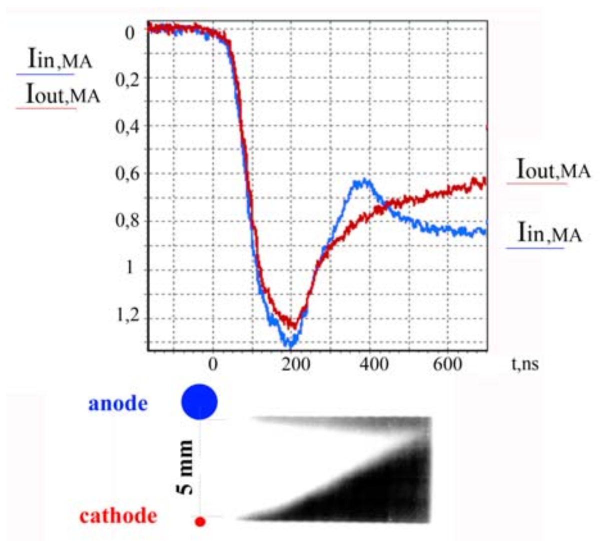

FIG .9. Oscillograms of the input (I_{in}) and output (I_{out}) currents by the lead cathode. Bottom: chronogram of Pb plasma expansion (negative).

Even more pure experiment on the heavy plasma dynamics was carried out with the golden cathode heated from the start of high vacuum pumping out, up to the basic current pulse. Thereby the effect of thin oil layer is eliminated since the absorption ability of Au is very low. An example of results are shown in Fig. 10. Some peculiarities were conditioned by the cathode construction: either the inner tube coated by the golden foil (Fig. 10), or the hollow golden tube with the wall thickness 200 μm. In both cases, the oscillograms are very close to each other; however, the plasma dynamics is different. The coincidence of input and output current behavior is kept up to 400 ns from the current start. The overlap of electrode plasmas happens after 600 ns.

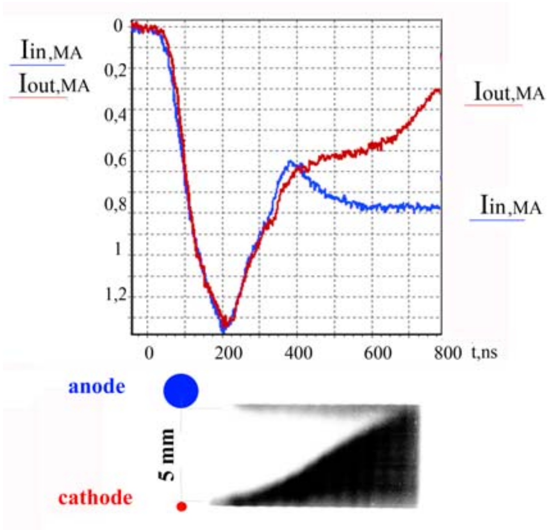

FIG. 10. Oscillograms of the input (I_{in}) and output (I_{out}) currents by the golden cathode with the Ni tube inside. Bottom: chronogram of electrode plasma expansion (negative).

4. Conclusions

It has been proved experimentally that by pass of the current with the linear current flow density up to 7 MA/cm along the MITL model, the input and output current coincide, within the frames of experimental accuracy, depending on the experimental conditions, during 200 to 400 ns from the current start.

It has been proved that the duration of such coincidence depends essentially on the electrode material. It is minimal in the case of light metals (200 ns for Al) and greater for heavier materials (320 ns for Pb and 400 ns for Au). We have not revealed any essential dependence upon the presence of light impurities on the electrode surface.

The electric explosion at the final recycled segment of magnetically insulated transporting line does not prevent from the energy transport towards the target. Apparently, it is reasonable to construct the electrodes of this fraction of MITL of lead. This material is favorable from the standpoint of energy transport, besides, conceptual reactor project already includes rather great amount of melted lead in the reactor camera.

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-pinch IFE reactor.

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5. References

1. OLSON C.L. and Z-pinch IFE Team. *Proc. 15-th Int. Conf. on High-Power Particle Beams, 2004*, Eds.: Engelko V., Mesyats G., Smirnov V., D.V. Efremov Institute, S-Petersburg, 2005, p.681.

2. CHERNENKO A. et al, *Proc. EPS Plasma Phys. Conf.*, Rome, 2006.