ICF High-Current Experiments Aimed at the "Baikal" Program

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Abstract. On the S-300 pulsed power generator, within the frames of ICF program based on fast high-current Z-pinches, promising schemes of output units are studied. In particular, a device similar to the plasma flow switch is being investigated aimed at sharpening the pulse. The switching rate as high as 2.5 MA / 2.5 ns has been achieved. Numerical simulations of the plasma "washer" acceleration have been carried out. The experiments on the extrinsic magnetic field influence on the high-impedance plasma opening switch (POS) operation are reported. Also the possibility of the expansion of POS conduction phase duration by means of programmed fill of the gap has been presented. The study of the wire array implosion on the Angara-5-1 machine is reported. Magnetic probes and the X-ray backlighting technique were used to investigate a current and mass distribution during the implosion. The experimental data confirm the concept of prolonged plasma production.

1. Introduction

Fast compression of liners is a possible approach to the inertial confinement fusion (ICF). Cooperation including TRINITI, Kurchatov institute, Efremov institute, and VNIITF now develops the "Baikal" project [1] in which an inductive storage has to be used to produce an electric pulse with parameters adequate for ICF. In this report, experimental results are presented on sharpening the pulse by using plasma opening switches on the RS-20 machine, on the new type of tiny output units studied on the S-300 pulsed power generator, and also on implosion of wire arrays on the Angara-5 machine.

2. Nanosecond plasma flow switch on S-300 machine

We investigate especial output devices similar to the plasma flow switch but operating in the nanosecond range of pulse duration. The plasma bridge between the inner and outer cylinders is accelerated along the axis by the current pulse of generator (FIG. 1). Accelerated "plasma washer" moves along the coaxial. When it is flying through the break of the inner cylinder, the circuit breaks, as a result, the magnetic flux enters the central cavity where the load is situated. The plasma bridge was created by means of the current-driven explosion of a thin foil in the beginning of the current pulse. Diameters of inner and outer cylinders were equal to 4 and 10 mm, respectively. The break of inner cylinder was varied between 1 to 2.6 mm. The diameter and length of central cavity were equal to 3.6 mm and 10 mm, respectively. The maximal current value was close to 2.5-3.0 MA. We used the accelerated foils produced of different materials: metallic foils as thick as 5-10 μm, mylar films of 2-5 μm, nitro-cellulose films with thickness < 1 μm, and the aluminum-coated mylar films of 1.2-1.5 μm. The homogeneity of breakdown of foils and the velocity of their sliding along the inner electrode were recorded by means of both frame and streak ICT photographs in visible range. The maximal velocity of sliding recorded was up to 10^8 cm/s. The better results of the current series were achieved by using plastic "washers" of 1.5 μm thickness coated by very thin aluminum layer. As loads in the first experiments we used metallic wires or tubes with the diameter of 0.5 – 2 mm. The moment of current switching on the load and the current amplitude were determined by means of the shunt measurements. The shunt (see FIG. 1) was made of steel foil as thin as it was necessary to provide the time resolution $\Delta\tau < 2$ ns. As our simulations show, the heating of this shunting foil does not distort essentially the signal up to the moment of maximal current amplitude. The current rise time on the load varied from 2.5 ns up to 10 ns. The current pulse duration (half-width) was recorded in the range of 7–20 ns, depending on the gap between two cylinders. By means of the shunt measurements, the fact of the current switching onto the load has been proved, during the time of the order of 2.5 ns, by the amplitude 2.5 MA. Heretofore, such a switching rate (10^{15} A/s) has been achieved only in our experiments. In FIG. 2, on can see the oscilloscope traces of both input current and current switched onto the metallic tube of 1.5 mm in diameter that served as a load. The measurements of soft X-rays (SXR) were carried out by two vacuum X-ray diodes with the *Ni* photo-cathodes, supplied by mylar filters with the mass thickness 0.34 mg/cm^2 and 0.67 mg/cm^2. The load in this series was the wire array of 8-16 tungsten wires of 5-6 μm in diameter situated at the radius of 1 mm. The geometry and layout of output device and diagnostics allowed XRD "to see" only the inner surface of the cavity while the direct radiation of the load being screened. The temperature of inner wall thus determined was up to 50 eV. Unfortunately, the reproduction ability was low enough, because of the extreme sensitivity to the initial conditions. This feature of the physical scenario was confirmed by the series of numerical simulations on the base of 2.5-d MHD code including the radiation transfer.

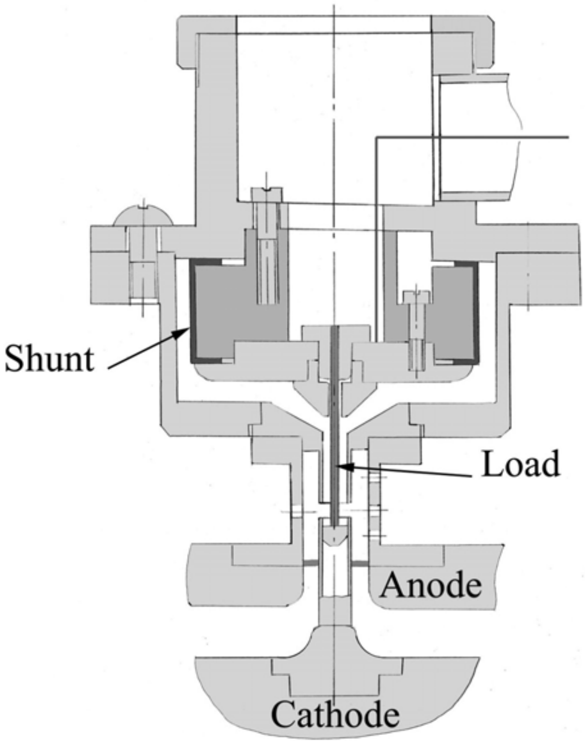


FIG. 1. The sketch of output device

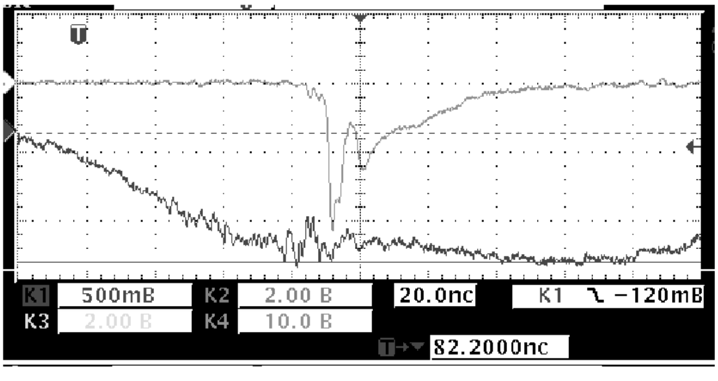
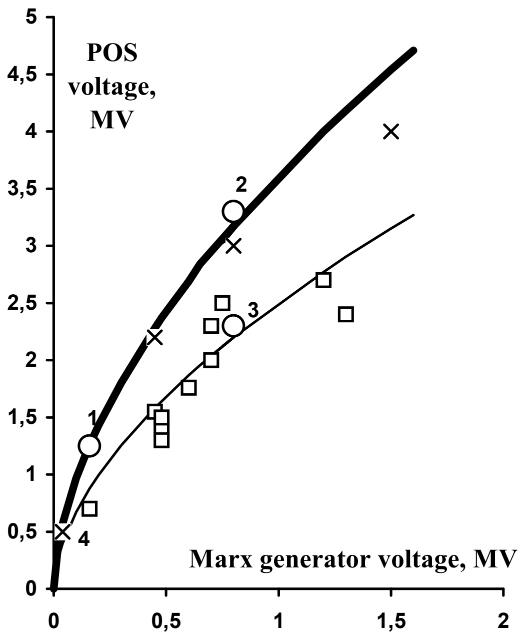


FIG. 2. The current on a load (top) and total current (bottom)

3. POS experiments

To provide the necessary output parameters of "Baikal" facility (50 MA, 150 ns, up to 10 MV), the powerful system of plasma opening switches has to be constructed. Nowadays, the experiments are being carried out on the RS-20 generator (1 MV, 350 kA, 2 μs/300 ns) by the current flow density level the same as in future "Baikal" machine. The POS design includes 78 plasma guns, extrinsic magnetic field solenoid and POS electrodes. The maximum linear charge density (along the circle of the outer POS electrode) is ~ 9 mC/cm. POS electrodes are made of pirolized carbon which has high strength to the power flow. Diameters of electrodes are 10 and 18 cm, respectively. Main electric parameters of the experiment were as follows: 4 Marx cascades, capacitor charging voltage 32-48 kV, output Marx generator voltage 128-192 kV, drive current amplitude 200-320 kA, linear POS charge density (5-9) mC/cm. In this mode of operation we succeeded to transport all

FIG. 3. POS voltage (U_{POS}) as a function of Marx voltage (U_{Marx}) with and without extrinsic magnetic field (bold line and hair-line, respectively). Pulsed power facilities with extrinsic magnetic field marked with -x- symbol, and facilities without extrinsic magnetic field marked with -□- symbol. New points are added from recent experiment at RS-20 (marked with -0- symbol). Number legends: point 1 – Marx voltage U = 160 kV and longitudinal magnetic field B_Z = 10 кGs, point 2 – 840 kV and 16 kGs, point 3 – 840 kV and B_Z=0.



the charge through the POS and the switching voltage could increase up to 3-3.5 MV. These results were obtained only by using the extrinsic longitudinal magnetic field (see FIG. 3). One of the important features of "Baikal" generator is the current prepulse, as long as 40 μs, hence, POS has to allow such a prepulse to pass through the gap before breaking the circuit. This problem has been solved on the base of some predictions of electron magnetohydrodynamics. To increase the charge value passing through the POS, it was necessary to slow down the density decrease inside the gap. Plasma guns were switched consequently 3 times by using separate capacitors with 5-10 μs time delay intervals. As a result, the efficient POS operation delayed up to 40 μs after the current start has been demonstrated. It was extremely important to perform the detailed output voltage measurements. Direct measurements on the base of shunts and voltage dividers in the range of several MV are very difficult and not so reliable. To overcome this obstacle, photo-nuclear reactions were used to measure the high-energy limit of the electron Bremsstrahlung spectrum in a vacuum diode. The method of filters cannot be used because of the essentially non-monotonic dependence of the X-ray absorption upon the energy in the 2.5-3 MV range. Meanwhile, the cross-sections of the reactions $\mathbf{Be^9(\gamma,n)Be^8}$ and $\mathbf{D^2(\gamma,n)p}$ with the thresholds 1.65 MeV and 2.25 MeV, respectively, are growing very sharp in this range with the photon energy. These features of reactions we have used provide very good quality of the voltage measurements. After all, we confirmed our result based on the conventional procedure, i.e., $\boldsymbol{U}_{\max} \approx 3.2$ MV.

4. Direct implosion of wire arrays on Angara-5-1 machine

It was shown [2,3], that in first several nanoseconds from the driven current start the plasma corona would be generated on the wires surface and the current switches from the wires to the plasma corona. The further heating of wire material is due to the heat transfer from plasma corona to wires. The wire cores remain at their initial positions during the significant part of the current pulse and are the fixed sources of the plasma. The permanently generated plasma is accelerated to the array axis by Lorenz force. Initially empty internal region of the array is filled by a plasma with some fraction of the current. Mass and current distributions in the array during implosion were investigated on Angara-5-1 facility to understand the physics of implosion. In present experiments the anode-cathode gap was 10 mm, the array radius – 6-10mm. Arrays consisted of 40-120 tungsten wires with the diameter 5-10 μm.

4.1. Distribution of the current inside array

Axial and azimuthal magnetic field were recorded inside the array (∅20 mm) by magnetic probes. Diameter of probes was from 260 μm to 880 μm. Temporal profile of the current measured inside the cylinder (∅10 mm) has the following shape: signal appears in ~35ns after the current start, slowly increases up to the level 60-100 kA (that is the current of precursor, ~3% of the total current), and then increases sharply due to the transfer of the main current shell inside the cylinder (∅10 mm). It is possible to estimate the velocity of current-carrying plasma as $\sim 2\cdot 10^7$ cm/s. The estimation of the current-carrying shell thickness gives more than 2mm. The continuous plasma shell is generated due to the merging of plasma jets of all wires. In special shots the external probing axial magnetic field was used to record the creation of the continuous plasma shell. Compression of such shell causes the compression of axial magnetic flux. The increase of axial magnetic field was recorded in 30 ns after the start of driven current, when the total current was ~0.3 MA. At this moment the continuous plasma shell (more thick than skin layer) was formed. The plasma shell passed to this time ~0.4 cm from the initial radius of array.

4.2. Backlighting of the wire array while implosion

An X-pinch was used as X-ray backlighting source [4] in our experiments on the Angara-5-1 machine. The flash of a X-pinch happened in 60-80 ns after the start of current through the liner. The space resolution capability of a method on the array was ~1.7 μm. The shadow of wire array during implosion was obtained. The experiments have shown that in 60-80 ns after the current start the wires of array are augmented in a diameter in 3-4 times at level of current ~ 30-50kA/wire. The evaluation of expansion velocity of dense cores gives the value $\sim 10^4$cm/s.

The transition from photometric density to density of substance was made taking into account the step attenuator from tungsten situated in the front of recording films. In FIG. 4 the integral of plasma density along a line of sight is presented. Two dense cores are visible. To the right of marked dense cores there are two poorly visible diffusion cores, which substance in a much more degree has passed in hot plasma. It testifies that the process of plasma production flows non-uniformly. The estimation of the mass in dense cores gives ~70% of initial wire mass. The rest mass of wires (~30 % of initial mass) is spread inside ~200 μm radius from initial position. The space scale of plasma expansion during the time of measurement is several times less than inter-wire gap. The axial non-uniformity of the plasma density with a space scale ~200 μm is visible near the core. The same size was recorded on the laser shadow and soft X-ray images. At some images, the axial spatial non-uniformity of the core substance with the space scale of 5-20 μm is observed. The main current shell when passing through the half of initial array radius has a front width of more than 2 mm, that is greater than skin-layer thickness. Compression of the axial magnetic flux by the current-carrying shell is demonstrated. The axial magnetic field attains the values not less than 20-30 T. The merger of separate plasma streams in the continuous shell and the beginning of axial magnetic flux compression takes place in ~30 ns from the current start at the distance of 0.4 cm from the initial liner radius.

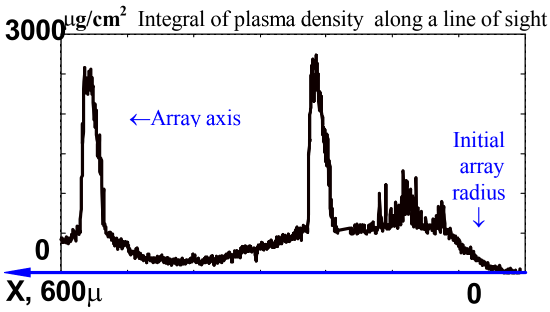


FIG.4. The results of X-ray backlighting

Conclusions

1. Scientific cooperation including TRINITI and Kurchatov institute develops the "Baikal" project aimed at the pulsed power machine of new generation. Nowadays, experiments in both Kurchatov institute and TRINITI are being carried out supporting this program.
2. The switching rate as high as ~ 2.5 MA/2.5 ns has been achieved by using nanosecond plasma flow switch on the S-300 machine, and the temperature of the inner wall of a microscopic Hohlraum as high as ~ 50 eV. Using of an extrinsic magnetic field allows to increase the switching voltage of the POS operating in erosion regime up to 3.2 MV. The programmed fill of the POS gap by a plasma may be used to provide the efficient POS operation with the 40 μs prepulse.
3. The data of experiments on the wire array implosion on the Angara-5-1 machine confirm the concept of prolonged plasma production: long time during an implosion the hot plasma flows down from the dense immovable cores and is accelerated to the center together with the frozen-in magnetic field.

References

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