Radiating Z-Pinch Investigation and “Baikal” Project for ICF

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Abstract. Compression of emitting Z-pinches is one of the methods to provide desirable conditions for ignition of a thermonuclear (TN) target in IFC. Recent investigations including those conducted on the “Angara-5-1” facility have demonstrated a considerable difference in the dynamics of Z- pinch against a classical model of “snow-plough”. The main factor defining the current compression of multiple wire arrays is a phenomenon of “prolonged plasma production”. This lies in the separation (during the whole pulse of compression) of a wire array material into two parts, i.e. a relatively dense part of weak conductivity and a rarefied part of high conductivity.

In the SRC RF TRINITI the problem of the wire array compression is under thorough investigation using some diagnostic means that make it possible to measure the spatial mass and magnetic field distribution in the process of compression inside a multiple wire array.

Together with the investigations into the physics of array compression carried out by a cooperation of the Rosatom research institutes , such as - SSC RF TRINITI, RRC Kurchatov Institute, Efremov Institute, and RFNC VNIITF a project of a generator with a current of 50 MA is being carried out. At compression of the wire arrays the generator is to provide an X-ray pulse with an energy above 10 MJ. Such a generator known as “Baikal” will make possible investigations into the problem of ignition of a thermonuclear target. The development of the “Baikal” facility is being performed on the module prototype of this facility, i. e. the “Mol” facility.

1. Introduction

Among the promising energy sources for CTF are high power radiating Z-pinches producing X-ray pulses of power sufficient for ignition of a thermonuclear target. At present, Z-pinches on the basis of multiwire arrays from materials with large Z are capable of producing the highest energy pulse of X- radiation. The investigations of process of implosion oz wore produced Z pinch are carried out by the co-operation of the RRC the Kurchatov Institute, the SRC RF TRINITI, the SUE NIIFA and RFNC VNIITF. Physical investigations are carried out in the RRC the Kurchatov Institute and the SRC RF TRINITI. The works with a current of up to 5 MA and a pulse rise time of 100 ns are performed on the Angara-5-1 facility located in the SRC RF TRINITI. The basic efforts are focused on studying multiwire Z-pinches consisting of several tens – hundreds of tungsten wires 4-6 μm in diameter. When such wires compressed, a radiation pulse of a 6-12 ns duration and a power of up to 7 TW is generated. The radiation spectrum is of a quasi-thermal character with a temperature of 80 to 100 eV. The investigations of the wire array compression process have been carried out on the Angara -5-1 facility earlier [1] where the number of wires was from 2 to 20 and their diameter from 10 to 15 μm. Their results showed that when a megaampere current with a rise time of 80-100 ns flows through the wires, they do not displace to the axis as a whole, and their substance flows to the array axes for almost the full time of the current pulse.

The work deals with the investigation into the implosion of wire arrays. The arrays under study include both single and double nested arrays with a linear mass of 130- 1300 μg/cm, 2-20 mm diameter, 15 mm high, from W (6 μm),Cu (20 μm) and Al (15μm). To monitor the discharge power delivered to the array the pulse profiles of the total current were measured by means of eight magnetic probes, while those of the voltage between the anode and cathode (in the region of convolution of eight vacuum transmitting lines) by means of an inductive divider [1]. To measure the profile of the X-ray power output a set of four vacuum X-ray detectors was employed on the basis of open vacuum photodiodes with sets of X-ray filters [2]. The X-ray output was measured by calorimeter. To obtain an ***R***-t-diagram of motion of the outer array border a visible streak camera was employed. Pinhole cameras with sets of X-ray filters were used.

2. Modified 0-D equation for array implosion describing

For describing the implosion of arrays at stagnation phase we modified the 0-D equations. 0-D descriptions of the liner compression are well-known, e.g. in [3]. Despite the wire array compression is substantially 3D, these equations make it possible to predict the time of compression. This occurs since a 0-D equation with a good accuracy describes the motion of the array sheath center of mass. The measured experimentally temporal profiles of current and voltage are determined by spatial distribution of a current and density of substance that is averaged on initial array volume naturally. For the description of changes of average radius and position of the center of mass of a plasma sheath we have added in the 0-D equations additional terms that describe movement of the liner and its interaction with installation more precisely. The purpose of this complication is the opportunity of calculation without heavy 2D- and 3D- simulations of *U*(t) and *I*(t) profiles at a final phase of compression. The applied system of the equations allows on experimental *U* (t) and *I* (t) to estimate average radius of distribution of a current (average current radius) up to which the substance of array is compressed. The modified 0-D system of equations describing the motion of the surface of an infinitely thin cylinder of a mass ***m*** under the action of the Ampere force of the current of generator with an internal resistance Z_0 is of the following form:

$I' = I(\frac{2hv}{r} - \frac{zZ_0}{Z_0+z})/L(r) + 2\frac{z}{Z_0+z}U(t)/L(r)$; where: *I* [A];*U*[V]; $L(r) = L_0 + 2h\ln(\frac{r_0}{r})10^{-9}$ [H]; (1)

$mv' = 10^{-9}h\frac{I^2}{r} - 0.5mv\frac{1}{t_{eff}}(\frac{r_{eff}}{r})^4$ z=$z(t)=10(\pi/2-\mathrm{Arctan}[(t-t_1)/\tau_1])$, [Ohm]; τ_1=3 ns

The first equation describes the change of the magnetic flux around the pinch and in the lead-in electrodes affected by incident voltage pulse *U (t)* of the generator. The generator (Fig. 1) is considered here as a long line with an internal resistance Z_0, consistent with the parallel switching of eight generator modules. The profile of the incident voltage pulse, *U* (t) is equal to the averaged voltage pulse of all the modules. This equation is added with a term being equal to $zZ_0/(z+Z_0)$, which describes the breakdown of the vacuum insulator as the resistance z(t) at the moment t_l when the voltage signs changes on the insulator [4]. Its moment in our case, is within ±30 ns with respect to the moment of the peak X-ray pulse. Into the second equation describing the motion of the mass center under the Ampere force action the term $0.5vm\frac{1}{t_{eff}}(\frac{r_{eff}}{r})^4$ is included. It describes the brake force acting on the array as its kinetic energy $mv^2/2$ converts to the internal energy of the array and the radiation in time t_{eff}. We suppose, as the radiation is proportional to the square of density, the brake force is inversely proportional to r^4. With that we neglect the time of the power exchange between different plasma components. The equation system received permits calculating the following experimental magnitudes: a pulse of the current through the liner

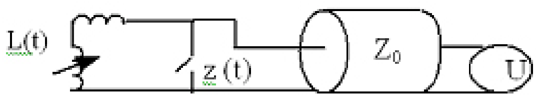

Fig.1. An equivalent generator U (t) circuit with an internal resistance Z_0 and a load in the form of a variable pinch inductance L (t). z (t) is the discharge resistance across the vacuum insulation.

including the value of its reduction at the moment of compression and a derivative of the current through the liner measured in the experiment; the voltage in different VTL sections. We calculate the voltage on the concentrator separatrix that is usually measured on "Angara-5-1" [8]. We also calculate the power of mechanical work against the brake force, which in this approximation describes the X-ray power. The coefficient $\frac{r_{eff}^4}{t_{eff}}$ is fitted in terms of the best agreement among the measured experimental values and the curves obtained in the calculations. An example of their comparison is displayed in Fig.2 (shot #4408: m = 530 μg, R_0 = 6 mm, the incident voltage pulse U amplitude is 0.9 MV, r_{eff} = 1.5 mm, t_{eff} = 3ns and t_l = 815 ns. As seen from the comparison of the curves, the modified system of the equations well predicts the time of the liner compression and the current through the liner. These values have a weak dependence on the brake force. The calculation describes the characteristic form of experimental profiles of the voltage on the separatrix and the current derivative at the moment of stagnation. Solutions of routine 0-D dimensional equations become infinite at this moment. The proposed modified approach to the 0D- description of liner compression allows us to involve the both voltage profile form on the array and the current drop rate on compression into the analytical treatment.

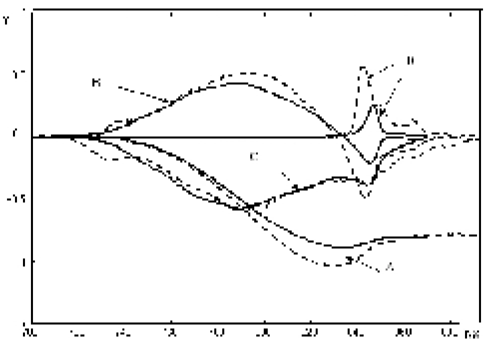

*Fig. 2. Dotted line - experimental curve. Solid line – calculation.Y-axis: A) the current through the liner (*3 MA); B) the current derivative (*1013 A/sec); C) the voltage on the separatrix (*1 MW); D) the power of X-ray pulse (*10 TW)*

3. Joul heating in final stage

On measurements of a current and a voltage it is possible to calculate a flux of the energy which is taking place through initial radius of the liner r_0. In the assumption of absence of ohmic resistance on a final phase of compression using these signals it is possible to calculate also temporal dependence of average inductance of array L (t). Knowing value of inductance L_0 of the VTL site between initial position of array and a place of measurement of a voltage from testing measurements, it is possible to calculate average current radius of pinch r from expressions

$$\mathbf{L}(\mathrm{t}) = \frac{\int_{t_0}^{t} \mathbf{U}(t)dt + \mathrm{C}}{\mathbf{J}(\mathrm{t})}, \text{ where: } \int_{-\infty}^{t0} \mathrm{RI}dt \sim C$$

On installation "Angara - 5-1" consistently with wire array the vacuum switch representing the cylinder from polythene and intended for suppression of residual voltage prepulse on array is established. Operation of this switch can be submitted as variable resistance during the initial moment of a pulse. This resistance becomes neglecting through 5-7 nanoseconds after occurrence of a voltage pulse on the concentrator. The final value of $\int_{-\infty}^{t0} \mathrm{RI}dt \sim C$ is connected to presence of this switch. The average radius of a current is calculated from the formula (1), where: *h* - height of array in cm; r_0 - initial radius of array, *r* - radius of array at present time. The energy enclosed in array grows monotonously as *r* decreases. We have revealed regimes when the assumption of the resistance absence (of a small contribution from ohmic plasma heating) at the late time of compression phase finds no confirmation. The treatment data for one of such shots (Single wire array: 60 W 6 μm wires, 12 mm array diameter, *m* - 495 μg. Energy input $\int_{-\infty}^{t0} U_{r0} I dt$ =85kJ is in accord with Fig. 3.

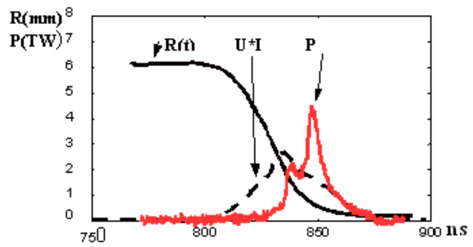

*Fig. 3. Profiles calculated in terms of current and voltage measured. Y-axis: U*I [TW] is the electric power input r_0, P[TW] is the X-ray power and R (r) (mm) is the average current radius,*

The calculated average current radius at the end of compression is 25 μm. This is much less than radius measured in terms of R-t-diagram of motion recorded by streak camera in the visible range and observed on the time integral pinch image in the energy quantum range below 1 keV, with its size of about 500 μm. It means that the energy input to the wire array material exceeds the evaluation of the kinetic energy by formula: $W \sim I^2 2d \ln(\frac{r_0}{r})10^{-9}$, that specifies presence of a term: $\int_{-\infty}^{t0} RIdt$ and comparable with kinetic energy the contribution of Joule heating of plasma in energy of the compressed substance of array. It is important, that this conclusion does not demand absolute measurement of energy of an x-ray pulse.

4. The MOL module. Inductive stages of power peaking over the range from 1sec to 100 msec.

A design project of the laboratory generator “BAIKAL”, a source of soft X-radiation, obtained at compression of wire arrays with a current of 50 MA and a length of 150 ns is being considered [5,6]. The work on the project is performed in close cooperation with RRC “Kurchatov Inst.”, SRC RF TRINITI, Efremov Inst. of electrophysical apparatus, and RFNC VNIITF[1,2]. The investigation of the electrical pulse generation circuit is carried out in TRINITI where an experimental module, the “MOL” module, is under construction. It is aimed at the engineering development of explosive and electrical explosive interrupters for currents of up to 1 MA, an inductive storage with current multiplication , a magnetic field compressor with electromagnetic acceleration of the liner and a plasma current interrupter with a voltage of up to 5 MV.

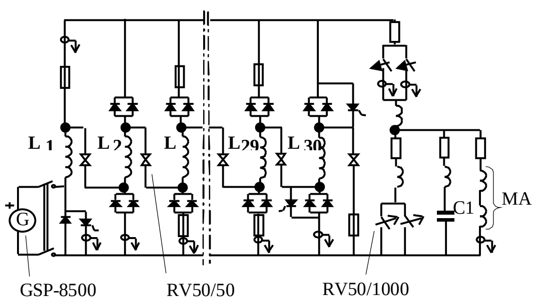

Fig.4. A circuit of the first two stages of the MOL module

In comparison to earlier reported results the current switch design both on the first stage through which the inductive storage IS-1 is charged (shown in Fig. 4) and on the second stage which provides the transfer of energy to the magnetic amplifier (MA) has been significantly modified.

The inductive energy storage IS-1 is charged by a current of up to 50 kA from an electrical machine of a shock-type GSP-8500. Earlier it was described in detail in [7]. The magnetic amplifier with a toroidal winding is a new device. It has been manufactured and mounted. The appearance of the components assembled on the MOL module is shown Fig. 5. The solenoidal coil IS-1 with 30 current multiplication interrupters is presented at the right of the photo and the magnet of the current amplifier with its toroidal winding is at the left. Part of the magnetic amplifier is switched off after current charging with an amplitude of up to 1.5 MA. In the remaining MA turns the current amplitude must rise up to 4 MA The experiments on the energy transfer to MA where a matching capacity is used have been performed. The full current multiplication from 20 kA to 600 kA and the pulsed charging of the magnetic amplifier were achieved. A current oscillogram obtained in one of the experiments is presented in.

Fig. 5. A general view of the first stages on the MOL module.

This result was preceded by a good deal of efforts undertaken at operational development of the facility components. First of all, this concerned the current interrupters RV 50/50 placed in the circuit multiplying the IS-1 current. The velocity of moving the contacts apart was measured by means of optic sensors. The geometry of the switch contacts was changed that made possible to increase the velocity from 25 m/sec to 40 m/sec at reducing the mass of the explosive drive component from 2.2g to 1.5g. The switch was tested on a separate module at applying a probing pulse of 45 kV after switching off a current of 60 kA and demonstrated high reliability of operation. It should be noted, that during one of the shots of the MOL module one of the switch insulators failed at a voltage pulse of 20 kV, i.e. broke down. Despite the insulator damage (the place of brakedown shown in Fig. 6), this caused no fault in the regime of the energy extraction from IS-1, since each of 30 current multiplication lines exhibits a sufficient value of its own impedance. Later the material of all the insulators was replaced.

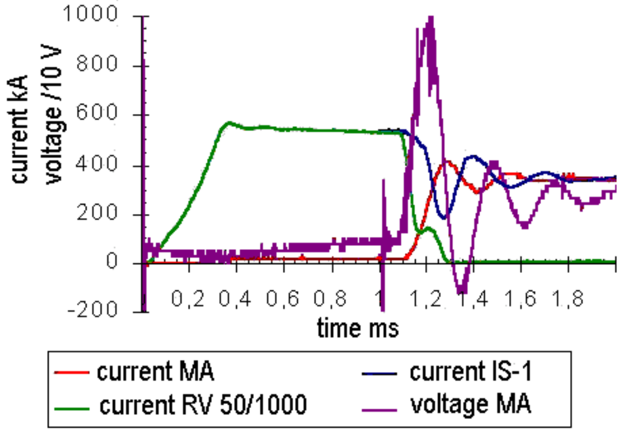

Fig.6. Current and voltage oscillograms at the energy transfer from IS-1 to MA

5. The magnetic compressor (MC)

A breadboard of the plate-type magnetic compressor mounted on a separate module "PUMA" is fed from a capacity bank and shown in Fig. 7. Some preliminary results obtained at the acceleration of the liner to a velocity of 0.8 km/sec was discussed in [8].

Fig. 7. An MC breadboard on the "PUMA" module

During 2004-2005 an analysis of some magnetic field configuration features in a longitudinal system of this type was performed. The following results were obtained in these works:

1.) in a liner system with electromagnetic acceleration the process is more efficient at a circuit where the liner and the accelerating turn are connected in series;

2.) the accelerating current generates a magnetic field inside the liner which may be "captured" by the accelerated liner in the cavity of compression. A new circuit has been already discussed in [9], a comparison of the calculated data with those obtained in later experiments is presented in [10]. The velocity of the liner plate acceleration reached more than 1 km/sec, and the induction value of the captured magnetic flux in the area of compression proved to be over 25 T. An experimentally obtained plot of rising the magnetic flux induction is displayed in Fig. 8.

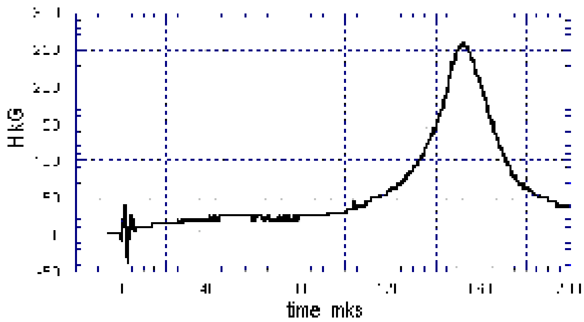

Fig.8. An oscillogram of the magnetic field in the area of compression. The maximum acceleration velocity V is ~ 900 m/sec.

At present the MC turn is being renovated with a view to transfering the pulsed energy into an external load. An electrical circuit of the MC alternative considered is given in Fig. 9.

6. Plasma open current switches

A plasma current switch (PCS) of the MOL module consists of six components operating in parallel. One of the them was manufactured and its tests at a different profile of the input current front were performed. Taking account of some known problems associated with the obtaining of very short current fronts at the MC outlet the PCS normal operation was tested at a front duration of up to 40 μsec. The PCS gap conduction was kept by periodic pulsed injection of plasma into the gap. In this case the current interruption was shown to occur on ending additional plasma injection. Current oscillograms in the PCS and load are presented in Fig. 10.

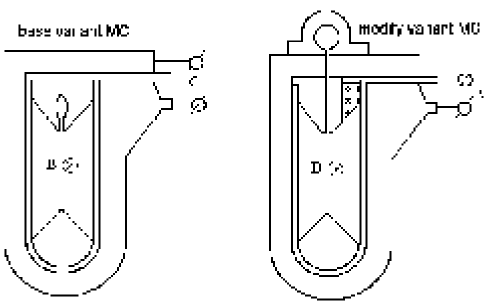

Fig. 9. A modification of the experimental MC.

Other experiments where two connected in parallel PCSs were employed have shown that during their operation the PCSs got autosynchronized redistributing the currents in such a

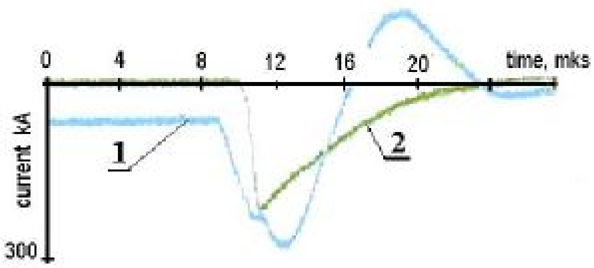

Fig. 10. PCS operation with a prepulse. 1 - current at the PCS inlet, 2 – current on load.

way as to equalize impedances of these paralleled components. Their parameters and experimental conditions were under detailed consideration in [11].

7. Conclusion.

The modified model of implosion in 0D-approximation allows on base experimental *U* (t) and *I* (t) to estimate average radius of current distribution (average current radius) up to which the substance of array is compressed.

Measurements of a current and voltage on array together with optical measurements of radius of array allow drawing a conclusion on presence of appreciable resistance of plasma of Z pinch on a final phase of compression.

The following experimental results were obtained when creating the "MOL module (the "BAIKAL" project, 2004 - 2006):

the first two stages of power amplification are in operation. The 30-fold multiplied current up to 150 mks at a voltage of over 20 kV was produced;

acceleration characteristics of the MC plates are well predicted using 2-d calculation models developed;

a method of initial magnetic flux generation in the area of liner compression using "capture " of a flux part from the accelerating contour and 20-fold magnetic induction amplification in the area of converging accelerated plates has been experienced;

the MC breadboard construction is being renovated with a view to transferring the energy into an external load;

the PCS can be connected in the MC circuit by means of plasma guns; a process of programmed filling the PCS gap with plasma makes it possible to solve the problem and to efficiently switch over current into load at a current pulse shape similar to that generated in MC.

8. References

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