Study of Imploding Plasmas

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Abstract Experimental results of the micro-liner implosion study on S-300 and “Angara-5” machines have been presented as well as some theoretical results. Our investigations were carried out in a broad range of liner constructions, masses, and chemical compositions. On the S-300 machine with a current value up to 3.5 MA, 1.5 TW X-ray pulse was obtained as a result of multi-wire liner implosion. The measurements of X-ray spectra have been presented. Theoretical investigations and 2.5-d simulations were devoted to some critical points. Double liner implosion approach for X-ray production and distinction between gas-puff and wire array implosions on “Angara-5” have been described. The test-bed for multi MJ X-ray generator “Baikal” named as “MOL” is presented.

1. Study of Imploding Plasmas on the S-300 Machine.

The goal of our experiments on S-300 machine (4 MA, 100 ns) [1] was to study and to model various schemes of generation of sharp powerful X-ray pulses aimed to the inertial fusion and some other applications. 1.5 TW of the soft X-ray radiation ($\hbar\omega \geq$ 100 eV) was achieved as a result of implosion of the multiwire tungsten liner. The total energy of the pulse was ~ 20 kJ. The spectrum of X-rays was recorded in the range of 50 – 500 eV by the 10-channel polychromator.

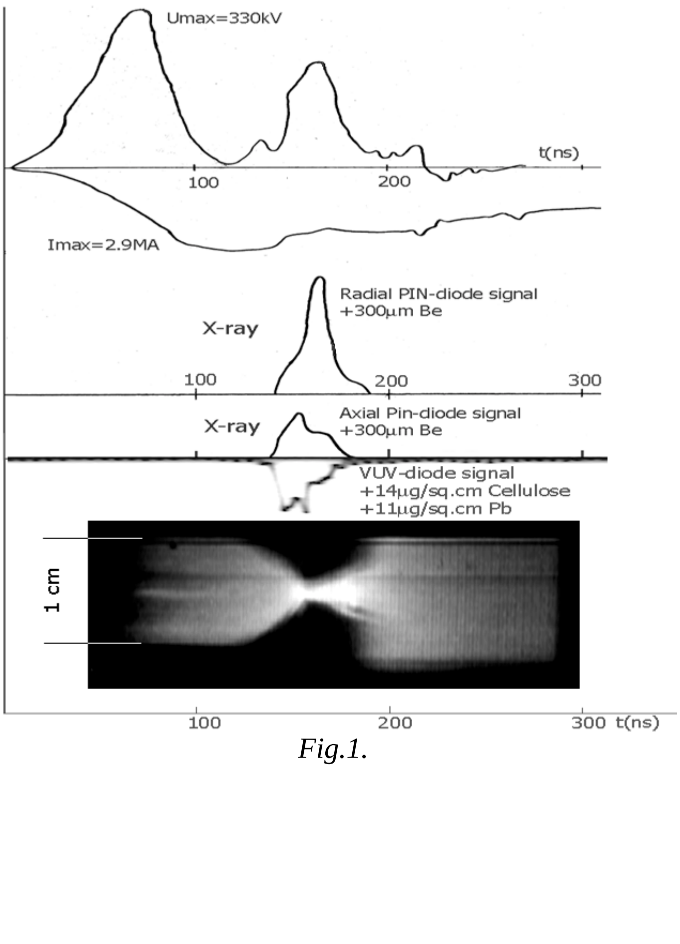

Fig.1.

The traces of voltage, current, and X-ray signals registered by filtered PIN-diodes located in axial and radial directions, a signal from the filtered vacuum diode, and optical streak-camera photographs are shown in *Fig.1*. In this shot an array of 80, 6μm-diameter tungsten wires was used.

From the soft X-ray ICT-camera photographs shown in *Fig.2a*, one can see that the plasma luminescence on the axis appears at the moment about 75 ns after the current start, although at the same time the radiation from the periphery plasma is recorded. At the moment close to 105 ns only a plasma formation of ~1 mm diameter may be observed. Hot plasma spots with less size of ~100 μm were observed by two pin-hole, time-integrated camera (see *Fig.2b*) provided with a pair of filters: 1.5 and 12 μm of mylar.

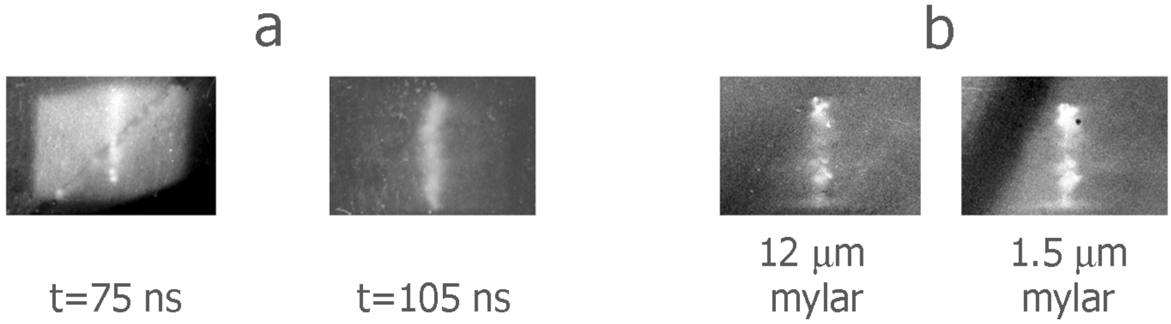

Fig.2

X-ray spectra in the range of 20-500 eV obtained by the current ~ 2 MA are close to the black body radiation corresponding to the 40 eV temperature. The only difference (probably conditioned by the hot spots) is respectively high yield of radiation in the hard region of spectrum.

Another typical load was the heterogeneous Z-pinch based on the gas jet produced by the supersonic nozzle and an array of thin glass fibres situated inside the gas jet. In particular, we have first achieved a regime of stable implosion of "thick" *He* liner $8 \div 10$ times in radius, with resulting velocities up to $5 \cdot 10^5$ m/s [2]. By means of shadow- and Schlieren photography we could identify the fibre explosion at the moment of time when the thermal wave initiated by Z-pinch compression reached the radius fibres were situated at. In principle, such an explosion could be provoked by the magnetic forerunners. We can differ, however, the current-driven fibre explosion scenario from the explosion that we could observe.

Theoretical investigations were devoted to some critical points. Analytical study showed the possibility of "overheating" in the current-carrying layer resulting in the quite observable effect of enormous Z-pinch resistance (up to 1 Ohm) as well as the small-scale Rayleigh-Taylor instability, intrinsic breakdown, and formation of the magnetic forerunner. As a final result, temperatures determined by radiation could remain invariant while varying liner material from *Ne* to *Xe*. This effect, however, is typical of the cylindrically symmetrical gaseous liners but of the wire arrays. Effect of the fast purely electron instability of thin ($\delta < c/\omega_{pi}$) current-carrying sheath was predicted resulting in the current filamentation violating the symmetry of implosion. Self-consistent EMHD penetration of both magnetic field and current was considered and the effect of KMC-wave disruption was predicted by fluctuations level δn_0 exceeding some threshold value.

2. Prolonged Plasma Production of Wire Liners.

Within the frames of double liner approach, evidence of prolonged plasma production in outer wire liner comparable with the current pulse duration was presented in [3]. For the arrays with a large number of wires and small gap of hundreds of microns between wires similar to those used in experiments on Z [4], the data which clearly indicated that the scenario of hot plasma production was delayed in time depending on the wire material were received in [5]. This phenomenon is a distinctive feature of wire array unlike a gas puff liner. Wire liners were made of tungsten wires of diameter 4-10 μm. The wires (from 8 to 180) were situated uniformly along the cylindrical surface of diameter from 8 to 20 mm. Current of 3-4 MA with the rise time of 90-120 ns flew through the liner. Fast optical streak camera and X-ray frame camera recording were used to study the process of prolonged plasma production. From the liner streak camera images it was obvious that wires were staying at their initial positions up to moment close to the pinching time. At the same time plasma leaving the wires were moving to the liner central axis. Dynamics of plasma stream formation was also able to be observed in X-ray images. Thus, plasma filling of internal cavity of liner was clearly recorded. Forerunner or pre-pinch was formed on the array axis by the plasma streams which arrived to the axis. Wires were staying close to the initial radius during about 100 ns. The wire images in the X-ray frame disappeared as dense plasma object only 30 ns before the moment of final plasma pinching. The size of wire array in X-rays turned out to be only a little less than the initial liner size up to the moment of wire image disappearance. Plasma uses to move to the axis with the typical velocity of 10^5 m/s. Thus, the wire array up that critical moment consists of plasma streams flowing to the array axis and dense wire substance which remains to stay close to their initial position.

3. Determination of the Plasma Production Rate.

Assumption that the Ohmic heating power in the plasma corona of the wires is responsible for the plasma production from the dense substance of wires results in the following relation for plasma production rate:

$$\frac{\partial m}{\partial t} = 0.2[I(\mathrm{MA})/R(\mathrm{cm})]^{1.8}\,\frac{\mu\mathrm{g}}{\mathrm{cm}^2\mathrm{ns}}.$$

Here I is the total current through the liner in MA and R is initial liner radius in cm. In *Fig.3* the correspondence is shown, between the calculated and measured time of the array evaporation. In the experiment, this time was determined by two methods, to wit, by the moment of the increase of liner inductance, and by the moment of start of liner external boundary motion recorded by the optic streak camera image.

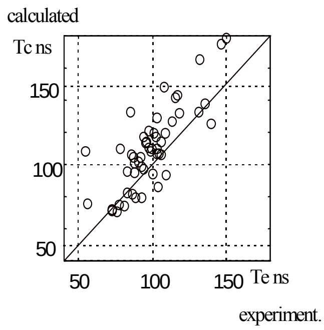

Fig.3. Experimental and calculated time of complete wire plasma disappearance in initial position. T_c – calculation T_e – experiment.

4. Compact Compression of Liners with Prolonged Plasma Production.

Prolonged plasma production effects on the compression of wire array plasma. Main distinctions of such a plasma from the gas puff liner implosion are as follows: thickness of plasma shell is comparable with the initial array radius and much more than the skin depth, more energy is associated with the magnetic field captured in the plasma shell. Increase of the thickness can probably

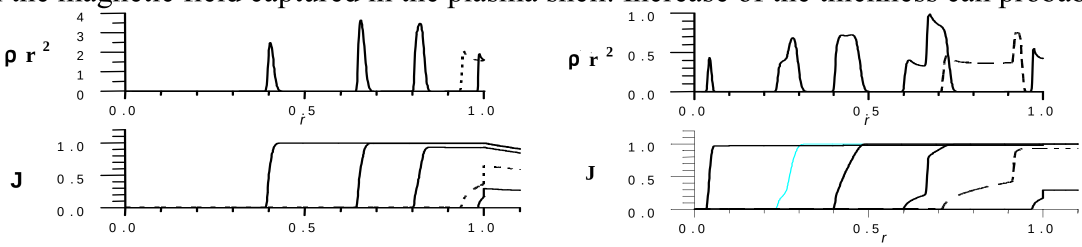

*Fig.4. Results of the calculation of plasma shell motion. Left-hand side: the ratio of time of complete wire plasma disappearance (**T_d**) to pinching time (**T_p**) is equal to 0.6, right-hand side: to 0.8. Top – density times the radius squared, a.u.; Bottom - current within the radius **r**, a.u. Time moments for which calculations were made are: left **t/T_p** =0.36, 0.84, 0.96, 1.08, right **t/T_p** =0.36, 0.84, 0.96, 1.08, 1.14, 1.2 .*

result in better stability of this shell. However, such an increase results also in the increase of the X-ray pulse duration. It is evident from *Fig.4* where calculated spatial profiles of the shell density at different moments of time are presented. In spite of prolonged plasma production peculiarities that were recorded experimentally the soft X-ray output pulse for wire array of 1 cm height comprised 120 tungsten wires located at 8 mm diameter does not exceed 6.5 ns at FWHM.

5. Generator "Baikal" for "Kiloterawatt Soft X-ray Source"

Fast compression of liners is under consideration as a possible approach to electric energy conversion into X-ray pulse at the energy scale of dozens of megajoules. Scientific cooperation including TRINITI, Kurchatov institute, Efremov institute, and RFNC VNIITF develops the "Baikal" project in which an inductive storage has to be used which in the case of successive transformation procedure could produce an electric pulse with parameters adequate for liner compression.

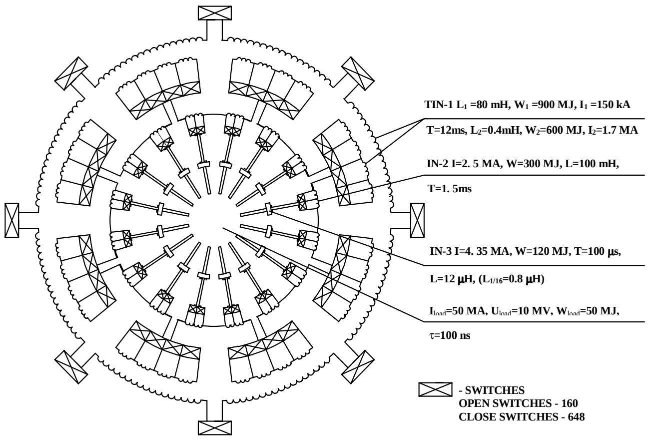

Fig.5. "Baikal" layout

The generator has to have the electric pulse power of the order of 500 - 1000 TW. TRINITI has a unique complex of 3 pulsed electric generators with inductive store and switches, originally built to feed the magnets of the T-14 tokamak. The complex is situated in special buildings in the vicinity of "Angara-5" machine. It is proposed as the primary energy source for "Baikal". New systems such as intermediate power amplifiers, reactor chamber, and the control system are to be created. A multiterawatt installation project is initiated now in TRINITI. Its main goal is the creation of generator for 10-20 MJ pulse of soft X-ray radiation. Parameters of proposed X-ray generator are the following:

X-ray pulse energy -	5–10 MJ
X-ray pulse duration -	10 ns;
Load current amplitude -	50 MA;

Load current pulse duration through the imploding load – 100 ns.

6. Plasma Shell Implosion as Method of X-ray Generation.

The layout of "Baikal" is presented in *Fig.5*. An energy of 3 GJ is stored in three mechanical generators TKD-200 (see *Fig.5*). These generators supply the primary windings of 32-sectional inductive store TIN-900 with a current of 150 kA for 6 seconds, delivering 900 MJ. The latter becomes disconnected from the generators and "crowbarred" by a mechanical switch. The store secondary winding has 32 sections as well, with each section generating a current of ~1.7 MA. The energy stored at the secondary winding is 600 MJ. Using a symmetric scheme of triple current doubling the energy transfers into transforming inductive store IN-2 having 16 groups of commutation, and its primary winding is "crowbarred" as well. The energy transfer into the IN-2 secondary winding coupled with vacuum inductive store IN-3 occurs during ~100 μs. The reduction of the electrical pulse duration from 100 μs to about 1 - 2 μs is supposed to execute by means of the magnetic field compression by impact of the heavy accelerated metal shell (metallic liner). This liner is accelerated by the primary current with the rise time about 100 μs which is generated in turn by the current from IN-2 power supply. The velocity of the metallic liner compressing magnetic field produced by the additional power supply in the secondary circuit, up to 2 km/s, was recorded in experiments in TRINITI.

An effective transformation of electric power in time interval from 100 μs to 100 ns is the most complicated problem. "MOL" test-bed based on application of 12 MJ inductive storage aimed to study proposed approaches for "Baikal" is under construction in TRINITI. Main problems to be solved at "MOL" pulse generator are the following:

compression of the electric pulse duration from 100μs to 1÷2 μs on the base of magnetic compressor (MC);

additional pulse compression on the base of plasma opening switch integrated into the common discharge circuit with MC.

The generator "Baikal" has to be erected in TRINITI. It will have to provide the electric pulse power of the order of 500 - 1000 TW and a soft X-ray output of 5 to 10 MJ. MOL test-bed is now under construction.

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