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CONDENSED ARGON ISENTROPIC COMPRESSION WITH ULTRAHIGH
MAGNETIC FIELD PRESSURE: EXPERIMENTAL DESIGN

Post-shot report

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Introduction

This report continues the series of works [1,2], devoted to experimental study of a high-dense condensed argon state. Remember that according to work [3], hexagonal close-packed structure is profitable in terms of energy rather than face - centred argon structure (stable with zero pressure). The most interesting and intrigue here is the issue of possible argon metallization, when it is compressed up to the densities more than 9.17 g/cm^3 [3]. In the experiment of 1995 (the arrangement and data are described in [2]) we recorded appearance of conductivity in argon, which is non-conductive in the initial state, when it is compressed more than a factor of four. The peak value of argon specific conductivity, recorded in this experiment did not exceed $10 \text{ (Ohm} \times \text{cm)}^{-1}$. This value of conductivity is characteristic of semiconductors, but not metals, which have $10^4 \text{ (Ohm} \times \text{cm)}^{-1}$. On this stage of our work the main attention is paid to recording of argon conductive state and studying the possibilities of multiframed radiography of the sample in the compressed state.

Arrangement of the experiment

The procedure of the experiment on frozen argon compression is similar in general to the one, described in the previous stages of the analysis [1,2]. The experimental device consists of the vertical two-cascade MC-1 generator, under which Dewar vessel with liquid nitrogen is located. Liquid nitrogen goes up the cryostat made of thin-walled tubes, passing along the axis of MC-1 generator, and cools the compression tube, inserted into the cryostat from above, where the sample is first frozen and then compressed. Further there will be described only the details of the experiment, which have been changed. The changes have been approved by the majority of the experiment participants and match with the pre-shot [4].

The changes in the compression unit design were aimed, first, to provide maximum high pressure in argon, keeping its transparency to the betatron radiation, second, to increase to the utmost the sensitivity of the system measuring the compressed sample conductivity. Fig. 1 shows the sketch of the longitudinal cross-section of the compression device with the main sizes. The tube has several layers: copper - outside, then tungsten and, finally, a thin layer of insulating Teflon. Layer thickness is determined by numerical calculation [4]. The tube length exceeds the length of the uniform compression region. The central rod - the electrode of the conductivity measuring system is located in the upper part of the tube on its axis. As it is seen from Fig. 1 the rod is multiple: the upper, longest part has larger diameter to decrease the inductance of the measuring circuit, the lower part made of thin insulated copper wire has much less diameter in order to decrease the sizes of the surface, contacting with the sample, which increases the sensitivity of the measuring circuit. The insulating layer of Teflon outside the electrode also has various thickness, the lower edge of the insulating layer does not reach the end of the copper wire by about 3mm, so in case the Teflon flows under compression, it can not overlap the sensitive area of the probe.

The measuring circuit was subject to the most significant changes. The method of sharing the conductivity of the compressed sample is the same, i.e. the measuring of voltage drop on the reference resistor, parallel to which the analysed sample is connected. The measuring current way in case conductivity appears in the sample is the following: central electrode - sample - second electrode on a sample periphery shaped as an aluminium ring with the width of 5 mm and the thickness equal to the thickness of a Teflon layer at the inner surface of a compression tube (aluminium compressibility is close to the one of Teflon) - tungsten and copper layers of a compression tube. As it has been already mentioned, in order to increase the sensitivity method, the part of non-insulating electrode surface, which contacts with the sample, is reduced practically to the minimum. To simplify calculations of the compressed substance conductivity the shape of the electrode surface contact area is made (in the initial stage) close to a spherical and is marked on the shadow microphotograph. Besides, to decrease the inductance of a measuring circuit (which decreases time constant of a measuring circuit, enabling quicker conductivity measurements to be recorded) the reference resistor is shifted to the end of the compression tube. It is made of several pieces of a

Compression device design

Fig. 1

constantan wire (to exclude temperature impact on the resistivity value); one end of the wire is connected with the compression tube, another one with the central electrode. The central electrode is attached rigidly, because of the conical copper connector, which is soldered to a copper part of the compression tube with its wide end. Both the narrow part of the connector, which is close to the central electrode and the electrode itself are soldered to a couple of twisted wires (current and potential terminals), which pass through vacuum tense joints in the upper part of a thin - walled tube, made of stainless steel, which is the continuation of the compression tube. Parts of thin coaxial cables about 1 m length are soldered to the joints. Also in the upper part of the steel tube 25 cm length there is a thin tube to feel a compression tube with gaseous argon (earlier the reference resistor for measuring circuit was located here). Conical connector with a reference resistor inside and powering and measuring circuits are shielded by an additional copper shield.

As a result a modernised compression tube has a longer current way and checked joint sizes; the reference resistor is shifted close to the sample; stainless steel tube is removed from the circuit, its resistance is not added to the sample resistance; the reference resistor is made of 5 or 6 parallel constantan conductors, the material non-dependent on the temperature, when it is measured by the resistance in a wide range.

Specific data on size parameters and other characteristics of the measuring circuit, MC-1 generator and betatron operation conditions are given in Table 1. Remember that this report gives data from two experiments on argon compression, because in the first shot not all the equipment worked as it was planned and some important data was lost. The Table refers to the prints of central electrode contact surfaces, given in Fig.2.

Table 1. Initial parameters of the shot.

Data	Characteristics of a thin part of a central electrode				Capacitor bank charging voltage kV	Betatron operation conditions
	Wire parameters	Wire length	Resistance of a reference resistor	A picture of a contact surface		
25.09.96	Enamel winding wire of PETB-2 type; Diameter of copper basement is 0.28 mm	26 mm	0.284 Ohm	Fig. 2(#4)	14.5	3 pulse.
04.10.96	The outer diameter of wire with polyether insulation 0.33 mm	39 mm	0.33 Ohm	Fig. 2(#3)	15	1 pulse.

Central electrode contact surfaces

Probe # 3

Probe # 4

Scale: 1 div=0.1 mm

Fig. 2

Experimental data

Data summary from each shot on isentropic compression covers: 1) oscillograms of initial current derivative of MC-1 generator, which integration provides the value of the initial magnetic field B_0 ; 2) t_0 - the onset of compression process time scale; 3) x-ray radiation pulse oscillograms, using which x-ray picture exposure time t_r is determined; 4) x-ray picture of a compression device; 5) signal oscillograms of the method of measuring the compressed sample conductivity. The new thing for the experiments described is, first of all, wide application of fast digitizer both to measure the signal cables and record measuring method signals, and also to synchronise shot events by simultaneous recording of fiducial and trigger pulses; second of all, an attempt to record three x-ray images in one shot.

The following pictures give the initial experimental data as the prints of analogue oscillograms and signals, recorded by digital oscilloscopes (Fig. 3-7), and x-ray picture prints. The quantitative data resulted from oscillogram analysis is given in Table 2 (time intervals are measured with the accuracy 20 nsec).

Table 2. Experimental data.

Data	Initial magnetic field B_0 , kG	Onset of time scale t_0 , μ s	X-ray pulse exposition time t_r , μ s	Conductivity appearance t_R , μ s	Sample compression
25.09.96	90 ± 4	88.85	15.94 (third pulse)	?	1.3 ± 0.1
04.10.96	115 ± 2	87.87	16.81	16.9	5.1 ± 0.3

The given oscillograms require some comments. First, the initial magnetic field in both shots somehow differs from 100 kG, which was planned. Second, the ratio of x-ray pulse intensities in a three-pulse mode also differs from that, planned in the pre-shot, the third pulse has been made more intensive in order the image on the x-ray film was determined mainly by this pulse. Third, the signal of conductivity in a compressed argon, which was lost in the first experiment, looked like the one recorded in the second experiment, which speaks about reproducibility of the signal and, hence, the conductive properties of compressed argon. When analysing the signal from

Oscillograms of initial current derivative of MC-1 generator
and the signal of the compressed sample conductivity.

Fig. 3

Oscillogram of initial current derivative of MC-1 generator

Fig. 4

Oscillogram to determine t_0 - the onset of compression process time scale

Fig. 5

Fragment of a conductivity signal

Fig. 6

the conductivity measuring system in the second experiment, one should take into consideration the noise, appeared (as it is shown in oscillograms Fig. 3) when capacitor bank discharger on a solenoid shell of MC-1 generator. We assumed it happened as a result of a mistake, when the power source of the measuring system was not separated from "the earth". Looking at the plots of stretched fragments of the signal, it should be kept in mind that the zero line is shifted down by the value of the induced potential. The nature of the noise induced on the same signal in the region, where conductivity appears, is more complicated. It turned out (see Fig.7) that the similar noise is on the oscillogram of the fiducials, recorded on a digitizer, which is not connected electrically with the circuit, measuring conductivity. By the time of conductivity appearance in a compressed sample the noise is negligible

Conductivity signal with the reference pulse

Fig. 7

MHD calculations

Because the initial magnetic field in the experiments differed from that in the preshot, we have conducted additional calculations, some of the results are presented further.

Fig. 8 provides radial density distributions in the analysed substance at the time of maximum compression t_m and also at the times $\pm 0.2 \mu s$ or $\pm 0.6 \mu s$ away from t_m . Fig. 9 presents time dependant radius, average pressure and temperature in argon for the case when the initial field equals 120 kG.

It is obvious that close to maximum of compression gradient densities do not exceed 10%. Application of greater initial field (120 kG) decreased the value of the maximum pressure in argon and the existence of the phase with $\rho > \rho_c$ in the whole volume is not reached. It results on reliability of conductivity recording of the analysed substance in the given phase.

Radial distribution of argon density at various times

Fig. 8

Time dependant radius, average pressure and argon temperature

Fig. 9

Argon conductivity measurement

The method to measure conductivity is described in details in work [4], so this paper presents only experimental data. Remember that the signal of conductivity in the first experiment was lost, in the experiment of 04.10.96 the signal was recorded completely, its shape repeats the signal of the preliminary experiment. Fig. 7 presents the oscillogram of voltage drop at the reference resistor.

Fig. 10 presents corresponding to this oscillogram plot of integral sample conductivity (the value opposite to the sample resistance, switched on to the reference resistance). Transfer to the specific argon conductivity is done by division of integral conductivity by the factor G of a measuring circuit. The value of the factor G at the time of radiography is 0.05 ± 0.02 cm. The absence of conductivity in the material of insulators during compression was assumed. Hence, maximum conductivity, which is achieved in the maximum of compression is within 70 ± 5 (Ohm $\cdot$ cm) $^{-1}$. The more accurate and detailed analysis of the data on compressed argon conductivity is in future, the most likely it will require more experiments. Right now the easiest explanation for the increase of compressed argon conductivity as compared with the former result is the greater maximum pressure in the experiment of this year resulted from the decrease of the initial magnetic field.

Conductivity

Fig. 10

Radiographic method

At this stage of work it was assumed to implement multiframe x-ray recording of the compressed sample. For this purpose we have modernised betatron, the results were presented in [4], American collaborators have prepared the recorder, based on electron optical converter "Imacon". During the week before the shot the recording system has been tried out, the sensitivity threshold has been determined, the issues associated with the diffuse radiation impact on the operation of the image amplifier based on a microchannel plate (MCP) have been solved, synchronisation system has been developed, configuration of the optical system has been specified, applicability of NaI(Tl) scintillator in the similar shots has been shown. Spatial resolution of the recording system, achieved at this stage, turned out to be too low (probably, as a result of aberrations in an optical tract) to hope to get the valuable data with its help, so during the first explosive experiment only methodical issues of recorder operation have been solved. As a result the camera operated at a good time, three radiation pulses in a streak mode were recorded (Fig. 11) and, what is the most important, we have proved that the expensive equipment is save in the protective device. So, we have got the initial data for creation of a functional version of the recorder. After the experiments we have done the work on determining the spatial resolution and relative yield for various scintillator radiation converters.

In the described experiments the main recorder of the shadow x-ray image was x-ray film. In the first experiment, when the betatron operated in a three-pulsed mode, radiation distribution between pulses (Fig. 12) differed from the one, which was planned in the preshot [4]. Instead of amplitude ratio 2:3:8 (15:23:62 in percent from the full pulse) this experiment implemented three-pulsed betatron operation mode with pulse distribution of intensity 10:12:78. As it was shown in the preshot even with more uniform intensity distribution argon compression can be determined with good accuracy at the time of pulse with the maximum amplitude. Radiograms from the shot of 25.09.96 are given in Fig. 13.

In the second experiment of 04.10.96 a standard radiography method with monopulse operation of a betatron (there was no equipment of multiframe record) was used. Fig. 14 shows preliminary and test radiograms.

Fig. 15 shows densitograms from both experiments to measure argon compression by digitizing of radiograms. Processing of x-ray images was made both by known methods and by original filters, developed by the authors. The curves give a precise picture of the minimum, corresponding (as densitogram simulation using MHD calculation has shown) to the interface insulator-tungsten. Using the method of measuring the sizes of shell boundaries, we reached the argon compression 1.3 ± 0.1 in the shot of 25.09.96 and 5.1 ± 0.3 in the shot of 04.10.96.

Three radiation pulses in a streak mode

Fig. 11

X-ray pulses oscillograms

Fig. 12

Pre-Shot 25.09.96

SHOT 25.09.96

Fig. 13

Pre-Shot 04.10.96

Shot 04.10.96

Fig. 14

Densitograms from both experiments

Fig. 15

Findings

As a result of changes in the compression tube design and the system measuring argon conductivity the following has been achieved: First of all, high argon compression (5.1 ± 0.3) as compared to the shot of 1995, second of all, argon conductivity of 70 ± 5 (Ohm·cm)⁻¹ was recorded, which is in an order higher than the one measured in the shot, mentioned earlier.

Betatron has been modified. We conducted the experiment, using combination of electronic recording means and traditional radiography system based on x-ray films. Work with multiframed radiography showed the necessity, to increase both BIM intensity and to increase sensitivity of electronic recording means.

The main result of this stage of work is the absence of argon metallic phase, predicted by theory.

Two experiments with different initial magnetic fields (though not equal to the planned 100 kG, but close to it) show that the recorded maximum final value of compression argon conductivity is about 100 (Ohm·cm)⁻¹.

The complete interpretation of experimental data requires, apparently, some additional experiments and theoretical calculation process in MC-1 and compressed argon properties as well.

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JOINT VNIIEF-LANL EXPERIMENT WITH 5-MODULE 1 M
DIAMETER DISK EMG AND A HIGH ENERGY LINER (HEL-1)

(The postshot on the subcontract N 0002P0004-95, task order 032, task C.2.
High energy liner experiment)

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INTRODUCTION

High-power facilities able to deliver into the load tens megaamperes of current for microseconds are applied now world wide to solve a whole set of scientific and applied issues. Now more and more energy and power are required from these facilities. By now several stationary machines have been created such as Pegasus-II (with the energy more than 1 MJ), Shiva-Star (up to 9 MJ), new Atlas facility (for 25 MJ) is in the process of construction and the idea of creating Jupiter (for ~ 100 MJ). Large experience in creation of single action explosive magnetic generators - EMG has been accumulated. VNIIEF has created EMG which can deliver more than 200 MA of current into the load with the full magnetic energy more than 100 MJ. Stationary facilities are more expensive than EMG, but they enable many experiments to be conducted, because the cost of one shot with a stationary machine is less than EMG cost. However, with the increase of energy, released in one shot on a stationary machine the cost of disposable elements increases, so the cost for one shot increases faster than the energy increases. It is estimated that if the energy of a shot is about 100 MJ (this is equivalent to the explosion of about 25 kg of trotyl), the cost of one shot may exceed the cost of EMG. That is why the use of high-energy EMG is very reasonable not only because the stationary facilities of required energy and power have not been yet created, but for the purpose of saving money now and in future.

The experiments with high-energy liners are interesting in terms of DT-gas compression, to clarify such issues as liner flight stability, substance strength impact on growth of perturbations, interactions between the cylindrical liner end and walls, parameters of substances under high pressures and other. The present paper describes arrangement and the results of the first joint experiment between VNIIEF and LANL with EMG of 1 m diameter and a non-exploding liner.

The experiment took place in August 22, 1996. The goal of the experiment was to accelerate magnetically cylindrical relatively thin aluminum liner and to get kinetic energy 20 MJ or more.

Physical scheme of the experimental facility and diagnostics is described in details in the paper [1], which is a preshot of HEL-1 experiment. The report gives the ground for the main parameters of the experimental system and expected results of the measurements. We widely used two-dimensional hydrodynamic calculations of disk EMG and ponderomotive unit, made by various models. Besides, we analysed and took into account the results of previous similar experiments with non-exploding liners [2], where we faced the issue of additional magnetic flux losses as compared with the nominal numerical model of similar system with disk EMG [3].

As the energy source for the experimental device we chose 5-module DEMG of 1000 mm diameter, many times tested in the experiments for rigid and liner loads with the maximum degree of reliability.

This EMG can store more energy than any other EMG created at VNIIEF.

As DEMG preamplifier we used many times tested HEMG with the helix diameter of 240 mm.

To get more reliable experimental data from HEL-1 and to understand better the reasons of EMG parameter decrease in the previous experiments of May, 1996, we conducted a simplified experiment HEL-1P, where the generator worked for the rigid inductive load. The current achieved in the experiment was equal to the predicted one, about 170 MA [1]. The experiment confirmed the assumptions made for calculations of the systems with DEMG.

To get reliable experimental data on liner dynamics a special central measuring unit was designed. CMI included a large variety of probes, it could work with parasitic currents, in case they appeared as it happened in the experiment X-Ray-I [5]. To provide the same goal the pressure between the liner and CMI was less than 1mm Hg as a result of the continuous pumping out.

The report presents primary analysed experimental VNIIEF data [6] and some data from a similar LANL data packet [7].

1. EXPERIMENTAL FACILITY DESIGN SCHEME AND CURRENT CHARACTERISTIC MEASUREMENT

1.1 SHORT DESCRIPTION OF EXPERIMENTAL DEVICE

The facility tested in HEL-1 consisted of the following:

- five-module disk explosive generator (DEMG) with the diameter 1 m;
- helical explosive magnetic generator (HEMG) of 240mm diameter, powered using magnetic flux capture;
- transition line made of a horizontal and a vertical parts;
- ponderomotive unit with a liner (PU);
- central measuring unit (CMU);
- insulation system.

Fig. 1.1 shows disk EMG 1000 mm in diameter with a liner ponderomotive unit, the main dimensions are shown.

Fig. 1.2 shows the location of the experimental facility and cables on the firing point.

1.1.1 Transmission line design and geometric dimensions

The design of the transmission line and the load are given in Fig.1.3.

The transition line includes current carrying external 1 and internal 2 contour with the insulation between them 3. Electric contact between the internal contour 2 and disk explosive magnetic generator was done by a gasket method. Electrical contact between an external contour of a transmission line and a generator was done by expending of copper wires of the external casing 1 into the corresponding grooves in the outer walls of the experimental facility.

Fig 1.3. A shows a schematic of a transition line insulation and its main sizes.

1.1.2 Structural features of the load

The location of a liner in the load of the experimental device is given in Fig.1.4.

Before the PU was installed, current carrying contours of the transmission line have been centred and mutually oriented over the azimuth to provide coaxiality of the light probes, located in the lateral walls 2,3 of the acceleration chamber. The maximum possible offset of the contours 5,6 was 0,5 mm. Electric contact between the liner and the current carrying walls of the acceleration chamber and the transition line was made by squashing aluminum rings 7, 9 until the integral connection was provided. Volume sealing in the upper portion of the acceleration chamber was done by sealing rings 10, 11 and, partially by the rings 7, 9, made of annealed aluminum wire. Besides, to provide sealing of the upper section of the chamber plugs 12 were used, which were glued to the wall 2, after it was attached to the facility.

The walls 2, 3 were made of steel 3 with the cone angle 60° ; the rounding radius when touching the working portion of the liner did not exceed 0.1 mm. The height of profile non-uniformity in the working surfaces of the PU lateral walls did not exceed 0.1 mm.

1.1.3 Liner structural parameters

The liner was made of aluminum alloy AMg6, GOST 4784-74.

According to the chemical analysis the impurity percent was: Mg - 6.50; Mn - 0.52; Ti - 0.03; Be - 0.002; Si - 0.005; Fe - 0.34.

Before the liner was fabricated the preliminary ultra-sonic test had been done to check the absence of inner defects in a semiproduct and its mechanical characteristics had been determined: ultimate strength $\sigma_t = 35$ kg/mm, strength yield $\sigma_{0.2} = 15$ kg/mm, relative lengthening $\delta = 28.4\%$ ($P=700$ kg).

When fabricating liner the final processing of internal and external surfaces were made through one setting. So, after the surfaces A and B had been processed, the liner was located on the special holder 1, fixed in a lathe, where the bore surfaces had been preliminary prepared (Fig.1.5). The liner was attached to the holder by the supporting disk 2.

After the turning and grinding processes of liner external and internal surfaces had been done, the accuracy of fabrication was measured.

The measurements were done using the clock type indicator with a scale factor of 1 μ m.

The indicators were located towards each other in a radial direction (Fig. 1.5).

The measurements were done in the working area of the liner in 14 cross sections in 8 mm over the length and in 90° over azimuth and in the cross section 7 in 15° over azimuth.

At the beginning of each series of measurements indicators were set for zero, after that indications were read at each following point, according to which the deviations of the surface shape from a cylindrical one and liner thickness tolerance were determined.

According to the measurements we got the following data.

Nominal liner thickness is 3.98 mm.

Liner conicity is less than 0.02 mm.

The deviations of a liner outer surface profile in μ m from a conventional average ruling are given in Table 1.1 each 8 mm over liner length.

Table 1.1

N сеч	1	2	3	4	5	6	7	8	9	10	11	12	13	14
φ°														
0	0	0	+1	+2	+2	+1	+1	+1	+1	+1	+	+1	0	-2
90	+1	+1	+1	+2	-1	-5	-4	-4	-1	0	-3	-1	0	0
180	+4	+4	+4	+4	+2	-2	-1	-2	-1	0	-2	0	+1	0
270	+2	+2	+1	+2	0	-3	-3	0	0	0	-1	+2	+3	-3

Table 1.2 presents the values of liner thickness tolerance in μ m, measured over the ruling and the circle.

Table 1.3 presents the values of liner thickness tolerance in μ m, measured over the circle in the cross section 7.

Height measurements of profile non-uniformity in liner working surfaces were done by a digital profilometer of 296 type.

Arithmetic mean of inner surface profile shift did not exceed 0.6 μ m. The measurement was conducted in several arbitrary points within the liner working zone at a distance of 6 mm.

The accuracy was the following: the deviation from the given profile over the length 3 mm did not exceed 0.22 μ m.

After the liner had been fabricated the liner working surfaces were detected for faults and microcracks.

Table 1.2

Values of liner thickness tolerance in mkm														
N cut φ	1	2	3	4	5	6	7	8	9	10	11	12	13	14
0	+	+	+	+	+	-	-	-		+	+	+	+	
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	+	+	+	+	-	-	-	-	-	+	-	+		
	+8	+10	+10	+8	+13	+14	+9	+9	+13	+16	+16	+10	+15	+16
180	+	+	+	+	+	-	-	-	+	+	-	+	+	
	+5	+6	+5	+1	+6	+5	+4	+2	+4	+6	+2	+4	+8	+6
270	-		-	-	-	-	-	-	-			+	+	
	+2	+2	+2	-1	+5	+6	+1	0	+5	+3	+3	0	+3	+4

Note:

upper values are those, measured according to the ruling,
lower ones are those, measured according to the circle.

Table 1.3

Values of liner thickness tolerance measured according to the circle in the cross section 7

φ	0	15	30	45	60	75	90	105	120	135	150	165	180	195
	0	+4	+6	+8	+10	+10	+14	+11	+12	+9	+4	+3	+4	+2

Continuation of Table 1.3

φ	210	225	240	255	270	285	300	315	330	345	360
	+4	+6	+1	+4	+1	0	0	-2	-2	0	0

1.1.4 Arrangement of the experiment and PU installation

Before the liner was installed it had been attached to the left lateral wall 2 using the gasket 7 (Fig.1.4).

The wall 2 with the liner 1 were attached to the facility by the screws 13, under their heads annealed copper heads were located. After that the plugs 12 were glued.

The next operation in the procedure was to install wall 3 at the required distance from the wall 2. For that purpose we measured the sizes of two walls and co-ordinated them with the sizes of the measuring unit and the outer casing 5 of the transmission line. The distance between the PU lateral walls at the diameter 120mm was 60 ± 0.2 mm, the length of the initial liner portion was 97 mm.

Maximum misalignment of the lateral walls 2 and 3 relatively to the inner liner surface did not exceed 0.3 mm. After that the measuring unit 4, consisting of two portions (LANL+VNIEF) was installed. Maximum shift from parallelism of measuring unit bore surfaces at the distance 150 mm did not exceed 0.1 mm.

Sealing of the chamber volume, when installing the measuring unit was made by the sealing rings 14, 15 and partially by the current carrying rings 16, 17 made of annealed copper tube.

Electric contact of two portions of the measuring unit was provided by a gasket method. Degassing of the chamber was made through the special connection, located in the lateral wall 3, the residual pressure in the PU working chamber did not exceed 100 Pa.

1.2. MEASUREMENTS OF CURRENTS AND CURRENT DERIVATIVES IN HEL-1

The facility and the measuring system are shown in Fig.1.6.

Fig.1.7 shows trigger timing scheme of the powering and explosive equipment with the times measured in HEL-1.

1.2.1 Helical EMG features

To power disk generator with the seed energy helical EMG of the POTOK type (12 MA x 110 nH) was used in the experiment. This generator has inner diameter of turns 24 cm, the length of the helix is 120 cm. Central armature is made of copper, it expands towards the load. HE mass in the generator is 21.5 kg. Initial helix inductance is 122 μ H.

Experimental data of DEMG "POTOK 12 MA x 110 nH" with two-, three-, five-module disk EMG 100 cm in diameter are given in [2]. Generator is able to form up to 15 MA of current in the inductive load with characteristic time 30-40 μ s for current rise, the maximum magnetic field over the helix turns does not exceed 1 MG.

In HEL-1 HEMG was initially powered by a "flux capture" method, when the capacitor bank KB-0.5 discharged into the coupling coil.

The coupling coil is turned above HEMG by a high voltage wire. Its inner diameter is about 28 cm, its length is 102 cm. Coupling coil inductance is 110 μ H.

The capacitor bank of 480 μ F was charged in the experiment up to 23.6 kV. Coupling coil maximum current with the capacitor bank discharge was 36.9 kA, the magnetic energy was up to 75 kJ. Hence, keeping in mind the coupling factor between the coupling coil and the EMG helix, which is 0.68, the seed magnetic energy of HEMG is about 34.5 kJ, the magnetic flux is about 2.9 Wb (the expected value of the flux is 3 Wb).

Oscillogram of a current in the coupling coil is given in Fig.1.8.

Measurements of HEMG current derivative was done by ten inductive probes, located in a coaxial path between HEMG and a disk generator. Signals from inductive probes were made by oscilloscopes C1-24 and C1-27 with the sweep from 80 to 120 μ s.

Current derivatives obtained by averaging the signals from all the probes and HEMG current are given in the Table 1.4. Fig1.9 and 1.10 give the plots of HEMG current and current derivative as a function of time. Maximum value dI/dt is about 2×10^{11} A/s, maximum current is about 9.1 MA.

As it is seen from Fig. 1.9, HEMG current derivative has its own specific features: starting from $t=172.5 \mu$ s sharp drop dI/dt is observed. As our experience shows these drops dI/dt are determined by active resistance changes of HEMG load electric contour affected by the passing current. Up to the first drop of current derivative ($t=172.5 \mu$ s) HEMG current amplitude is equal to the expected value i.e 2.9 MA, which is a factor of 1.2 higher than in the preliminary experiment HEL-1P with the similar facility, which took place on 30.05.96.

1.2.2 Measurement of current derivative in HEMG of 1000mm diameter at the input to the coaxial transmission line

Table 1.5 presents data from inductive probes, used to measure current derivative at the input to the horizontal transmission line. Fig 1.11 shows probe location. Fig. 1.12 shows current derivatives of disk EMG at the input.

Table 1.6 gives experimental data obtained upon the measuring results of DEMG current derivative at the input. The same Table presents the current values, obtained by integrating of derivatives, and average values of $I(t)$ and $\bar{I}(t)$.

Plot 1.13 illustrates the experimental data, obtained, when measuring current derivatives at the input to the horizontal transmission line of DIMG, plot 1.14 shows the average value of current derivative.

The measurements showed that:

- maximum current derivative at the input to DEMG was $5,5 \times 10^{12}$ A/s,
- at the 55 μ s the current was equal to 104 MA,
- current derivative on plots and oscillograms does not have pockets (rise curve $\dot{I}(t)$ is smooth),
- after 55 μ s derivative drops are recorded, which is associated with the impact on the transmission line and shock probes, when copper disks fly up to the locations of the probes.

1.2.3 Measurement of current derivatives at the input to the load radial transmission line

Table 1.7 shows inductive probe data, used to measure current derivative at the input to the radial transmission line. FIG.1.15 shows probe location. Fig. 1.6 shows the traces of DEMG current derivative in the radial transmission line.

Table 1.8 shows experimental data upon the results of DEMG current derivative measurements in the radial transmission line. The same table provides the currents obtained by integrating of the derivatives, and average values $\dot{I}(t)$ and $I(t)$.

Plot 1.17 illustrates the experimental data, obtained, when measuring current derivatives at the input to the radial transmission line of DEMG, plot 1.18 shows the average value of the current derivative.

The measurements showed that:

- maximum value of the current derivative in DEMG radial transmission line was $5.5 \times 10^{12} \text{A/s}$.

- at the $55.5 \mu\text{s}$ from the beginning of DEMG operation (derivative crosses 0) the current was equal 106 MA.

- plots and oscillograms do not show features testifying about flux pocketing.

Table 1.9 shows the average current and current derivative values at the DEMG input and also in the radial transmission line, it also shows general average values $\dot{I}(t)$ and $I(t)$.

Fig. 1.19 shows the average values of current derivative at the input and in the radial transmission line, Fig. 1.20 shows the curve of average values.

Fig.1.21 and 1.22 show the average values $\dot{I}(t)$ and $I(t)$, resulted from measurements of current derivative in DIMG.

Comparison of the curves at the input and in the radial transmission line showed that:

- current derivatives $\dot{I}(t)$ up to the $53 \mu\text{s}$ practically coincide,
- derivative maximum value was $5.5 \times 10^{12} \text{A/s}$,
- maximum current value in disk EMG was 105 MA,
- when PU liner imploded the current in the load dropped up to 19.7 MA at the 88

μs .

HEMG-CLOSING SWITCH-DEMG-LPU,
MOUNTED ON A STAND

Fig.1.1

SCHEME OF THE EXPERIMENTAL DEVICE AND
CABLE LINES DISPOSITION

Fig.1.2

Fig.1.3

Fig.1.4

Fig. 1.5

PRINCIPAL SCHEME OF THE HEL-1 FACILITY

Fig.1.6

SEQUENCE OF WORK DIFFERENT PARTS OF HEL-1 FACILITY

Fig.1.7

Fig.1.8

Fig.1.9

Fig.1.10

PROBES LOCATION (INPUT DEMG)

Fig.1.11

EXPERIMENTAL OSCILLOGRAMS (INPUT DEMG)

OK-17
N11

$1 \mu\text{sec} = 4 \text{ MKC}$

OK-17
N12

$1 \mu\text{sec} = 4 \text{ MKC}$

OK-17
N13

$1 \mu\text{sec} = 4 \text{ MKC}$

Fig.1.12

Table 1.4

Current derivative and current in HEMG

$t, \mu\text{s}$	$dI/dt, 10^{11} \text{ A/s}$	I, MA
55	0	0
65	0.00256	0.00128
75	0.00497	0.00504
85	0.0114	0.0132
92.5	0.0199	0.025
100	0.0281	0.043
107.5	0.0496	0.0721
115	0.0718	0.118
122.5	0.11	0.186
130	0.151	0.284
137.5	0.23	0.427
145	0.356	0.646
152.5	0.562	0.991
160	0.772	1.491
167.5	1.12	2.2
172.5	1.64	2.89
175	1.21	3.247
180	1.39	3.897
185	1.65	4.657
189	1.8	5.347
191	1.7	5.697
195	1.92	6.421
196	1.99	6.616
198	1.73	6.988
200	1.79	7.34
205	1.43	8.146
208	1.18	8.537
215	0.218	9.026
217	0.0984	9.058

Table 1.5

PARAMETERS OF PROBES AND DEVICES, USED TO MEASURE A CURRENT
DERIVATIVE ON THE ENTRANCE OF THE HORIZONTAL
TRANSMISSION LINE

Device	Device number	Measured interval, μs	Marks, MHz	Initiating facility	Delay of the start working, μs	Type of the measuring	Initial data	Sensitivity, V/mm
OK-25	31	100	0,1	BY-19 ₂	0	$I_{\ln\text{DEMG}}$	$i = 0,6032 \cdot 10^{10} \cdot U$ $i = 1,5078 \cdot 10^{10} \cdot U$	10,94 10,01
OK-17	5	60	0,25	BY-19 ₂	20	$I_{\ln\text{DEMG}}$	$i = 1,2098 \cdot 10^{10} \cdot U$ $i = 2,022 \cdot 10^{10} \cdot U$	17,16 16,56
OK-17	11	60	0,25	BY-19 ₂	40	$I_{\ln\text{DEMG}}$	$i = 7,540 \cdot 10^{10} \cdot U$ $i = 4,464 \cdot 10^{10} \cdot U$	14,79 15,53
OK-17	12	60	0,25	BY-19 ₂	50	$I_{\ln\text{DEMG}}$	$i = 0,60 \cdot 10^{11} \cdot U$ $i = 4,340 \cdot 10^{10} \cdot U$	15,81 14,90
OK-17	13	50	0,25	BY-19 ₂	60	$I_{\ln\text{DEMG}}$	$i = 2,8911 \cdot 10^{10} \cdot U$ $i = 9,0522 \cdot 10^{10} \cdot U$	16,05 16,25

Table 1.6

DISK EMG EXPERIMENTAL DATA (ENTRANCE OF THE
HORIZONTAL TRANSMISSION LINE)

T, us	$I, 10^{12} \text{ A/s}$ dev 31/1 D N 66	$I, 10^{12} \text{ A/s}$ dev 31/2 D N 68	$I, 10^{12} \text{ A/s}$ dev 5/1 D N 65	$I, 10^{12} \text{ A/s}$ dev 5/2 D N 72	$I, 10^{12} \text{ A/s}$ dev 11/1 D N 31	$I, 10^{12} \text{ A/s}$ dev 11/2 D N 74	$I, 10^{12} \text{ A/s}$ dev 12/1 D N 22	$I, 10^{12} \text{ A/s}$ dev 12/2 D N 15	$I, 10^{12} \text{ A/s}$ dev 13/1 D N 32	$I, 10^{12} \text{ A/s}$ dev 13/2 D N 73	$I_{av}, 10^{12} \text{ A/s}$	$I_{av}, 10^6 \text{ A}$
0	0	0	0,012								0	9,27
2	0,068	0,076	0,065								0,070	9,34
4			0,083								0,083	9,49
6			0,131								0,130	9,71
7	0,213	0,180									0,197	9,87
8			0,196								0,196	10,07
10			0,214	0,220							0,217	10,48
12	0,445	0,379	0,344	0,325		0,297	0,352	0,335			0,352	11,05
14			0,439	0,402		0,416	0,434	0,414			0,425	11,83
16			0,558	0,593	0,479	0,535	0,488	0,552			0,534	12,78
18			0,694	0,698	0,542	0,753	0,678	0,690			0,676	14,18
20			0,872	0,880	0,702	0,931	0,867	0,888			0,857	15,87
22	0,954	0,863	0,967	1,014	0,861	1,07	0,976	1,026	0,841	0,955	0,953	17,64
24			0,991	0,966	0,766	1,03	0,949	0,986	0,841	0,955	0,936	19,53
26			1,026	1,053	0,893	1,13	1,007	1,105	1,009	1,008	1,029	21,50
27	1,17	1,04									1,105	22,56
28			1,139	1,100	1,02	1,13	1,030	1,144	1,009	1,061	1,079	23,65
30			1,234	1,244	1,12	1,347	1,139	1,263	1,177	1,154	1,208	25,94
32		1,35	1,382	1,282	1,40	1,446	1,274	1,341	1,220	1,26	1,328	28,47
34			1,542	1,598	1,47	1,64	1,52	1,48	1,345	1,485	1,51	31,31
36			1,821	1,664	1,85	1,84	1,68	1,716	1,598	1,645	1,727	34,55
38			2,03	2,105	2,04	2,20	2,033	2,05	1,849	1,923	2,029	38,31
40		2,58		2,411	2,65	2,52	2,30		2,228	2,321	2,43	42,76
42				2,870	2,93	3,03	2,85	2,505	2,522	2,692	2,771	47,97
44				3,300	3,79	3,586	3,31	3,41	3,069	3,183	3,378	54,11
46					4,33	4,36	4,01	4,06	3,70	3,778	4,040	61,53
48					5,10	4,87	4,72	4,79	4,245	4,536	4,710	70,28
50					5,51	5,47	5,21	5,13	5,262	5,357	5,323	80,32
51					5,35	5,59				5,516	5,485	85,72
52					4,84	5,428	5,422	5,23	5,34	5,504	5,294	91,11
53					0	5,29	5,15	4,93		5,331	5,175	96,34
54					0	4,64	4,88		4,876	5,066	3,892	100,88
55					2,07	3,88			0	4,416	2,592	104,14
56					3,19	3,88			1,26	5,503	3,458	107,14
57					0	2,44				0	1,22	109,48
58						2,44			7,99	4,31	4,913	112,55
59						1,07					1,07	115,54
60					0				7,57	0	3,785	117,97
61									0		0	119,86

CURRENT DERIVATIVE EXPERIMENTAL DATA ON THE
ENTRANCE DEMG

Fig.1.13

CURRENT DERIVATIVE EXPERIMENTAL DATA ON THE ENTRANCE
OF DEMG AND THEIR MEAN VALUE OF $\dot{i}(t)$

Fig.1.14

PROBE LOCATION
(RADIAL TRANSMISSION LINE)

Fig.1.15

EXPERIMENTAL OSCILLOGRAMS (RADIAL TRANSMISSION LINE)

OK-17
N14

1 gen = 4 MKC

OK-17
N15

1 gen = 4 MKC

OK-17
N23

1 gen = 4 MKC

OK-17
N24

1 gen = 4 MKC

Fig.1.16

Table 1.7

PARAMETERS OF PROBES AND DEVICES, USED TO MEASURE A CURRENT
DERIVATIVE IN THE LPU RADIAL TRANSMISSION LINE

Type of devices	Device number	Time interval, μs	Marks, MHz	Initiation from	Time delay of initiation, μs	Measuring	Initial data	Sensitivity, V/mm
OK-17	14	60	0,1	BY-19 ₂	40	I_{LPU}	$\dot{I} = 3,0456 \cdot 10^{10} \cdot U$ $\dot{I} = 0,5839 \cdot 10^{11} \cdot U$	16,67 15,58
OK-17	15	60	0,25	BY-19 ₂	50	I_{LPU}	$\dot{I} = 3,8926 \cdot 10^{10} \cdot U$ $\dot{I} = 1,1678 \cdot 10^{10} \cdot U$	16,36 16,36
OK-17	23	50	0,25	BY-19 ₂	70	I_{LPU}	$\dot{I} = 0,6632 \cdot 10^{11} \cdot U$ $\dot{I} = 1,3150 \cdot 10^{11} \cdot U$	15,44 14,96
OK-17	24	50	0,25	BY-19 ₂	60	I_{LPU}	$\dot{I} = 1,8975 \cdot 10^{11} \cdot U$ —	15,91 —

Table 1.8

DISK EMG EXPERIMENTAL DATA (ENTRANCE OF THE RADIAL
LPU TRANSMISSION LINE)

T, μ s	I_r 10^{12} A/s dev 14/1 D N 23	I_r 10^{12} A/s dev 14/2 D N 69	I_r 10^{12} A/s dev 15/1 D N 70	I_r 10^{12} A/s dev 15/2 D N 18	I_r 10^{12} A/s dev 23/1 D N 21	I_r 10^{12} A/s dev 23/2 D N 17	I_r 10^{12} A/s dev 24/1 D N 15	I_{av} 10^{12} A/s	I_{av} 10^6 A
12			0,327					0,327	11,05
14	0,366		0,400					0,383	11,76
16	0,537		0,564					0,550	12,69
18	0,653		0,691					0,672	13,92
20	0,841	0,858	0,855					0,851	15,44
22	0,899	0,883	0,981					0,921	17,21
24	0,899	0,858	0,982					0,913	19,04
26	0,951	0,942	1,037					0,976	20,93
28	1,044	1,091	1,092					1,075	22,98
30	1,146	1,195	1,164					1,168	25,23
32	1,334	1,352	1,346		1,492	1,518	1,467	1,418	27,81
34	1,537	1,508	1,582	1,746	1,551	1,760	1,579	1,609	30,84
36	1,760	1,767	1,819	1,801	1,873	1,854	1,898	1,824	34,27
38	2,074	2,157	2,074	2,019	2,165	2,304	2,070	2,123	38,22
40	2,437	2,547	2,474	2,619	2,513	2,642	2,759	2,570	42,91
42	3,002	2,885	2,911	3,056	2,984	2,978	2,932	2,964	48,45
44	3,368	3,430	3,456	3,711	3,570	3,485	3,708	3,532	54,89
46	4,177	4,080	4,184	4,097	4,184	4,271	4,484	4,211	62,63
48	5,120	4,886	4,911	4,638	4,916	5,059	5,002	4,933	71,77
50	5,569	5,666	5,457	5,090	5,325	5,452	5,350	5,415	82,12
51	5,772		5,639	5,294			5,400	5,526	87,59
52	5,453	5,536	5,603		5,380	5,680	5,35	5,500	93,10
53	4,743	4,964	5,184	4,530	4,974	5,339	4,66	4,913	98,31
54	3,118	3,717	3,638	3,454	3,450	4,50	3,104	3,569	102,55
55			1,200	2,946		2,249	0	2,132	105,40
55,5	0	0	0	0	0	0	0	0	105,94
56	-1,813	-2,209	-1,746	-2,838	-2,692	-0,890	-2,416	-2,086	105,48
57				-4,693			-3,80	-4,247	102,25
58	-4,931	-4,958	-4,422	-4,475	-5,062	-4,384	-4,656	-4,698	97,77
59	-4,641		-5,020		-4,242	-4,664	-4,571	-4,628	93,11
60	-4,495	-4,808	-4,675	-4,447	-4,331	-4,609	-4,571	-4,562	88,52
62	-4,352	-4,366	-4,675	-3,983	-4,242	-4,495	-4,140	-4,432	79,52
64	-3,988	-3,768	-4,275	-3,711	-5,950	-4,384	-3,708	-3,969	71,12
66	-3,554	-3,378	-3,711	-3,220	-3,570	-3,821	-3,192	-3,492	63,66
68	-3,046	-3,119	-3,383	-3,001	-3,101	-3,541	-2,846	-3,148	57,02
70	-2,610	-2,729	-2,983		-2,780	-2,978	-2,742	-2,804	51,07
72	-2,408	-2,339	-2,419		-2,429	-2,698	-1,983	-2,380	45,88
74		-2,079	-2,201		-2,153	-2,360	-1,983	-2,155	41,35
76			-1,910		-1,990	-2,360		-2,087	37,11
78			-1,637		-1,580	-2,250		-1,822	33,20
80			-1,455		-1,785	-1,799		-1,680	29,70
82			-1,455		-1,260	-1,236		-1,317	26,70
84			-1,273		-1,32	-1,293		-1,295	24,09
86			-0,819					-0,819	21,97
88			-0,364					-0,364	20,79

CURRENT DERIVATIVE EXPERIMENTAL DATA IN THE LPU

RADIAL TRANSMISSION LINE

Fig.1.17

CURRENT DERIVATIVE EXPERIMENTAL DATA IN THE LPU
RADIAL TRANSMISSION LINE AND THEIR MEAN VALUE IN
LPU RADIAL TRANSMISSION LINE

Fig.1.18

Table 1.9

AVERAGE VALUE OF THE CURRENT AND CURRENT
DERIVATIVE ON THE ENTRANCE OF DEMG AND
IN RADIAL TRANSMISSION LINE

T, μ s	$I_{mvDn},$ 10^{12} A/s	$I_{mvLpu},$ 10^{12} A/s	$Imv,$ 10^{12} A/s	$Imv,$ 10^6 A
0	0		0	9,27
2	0,070		0,070	9,34
4	0,083		0,083	9,49
6	0,130		0,130	9,71
7	0,197		0,197	9,87
8	0,196		0,196	10,07
10	0,217		0,217	10,44
12	0,352	0,327	0,340	11,00
14	0,425	0,383	0,404	11,74
16	0,534	0,550	0,542	12,69
18	0,676	0,672	0,674	13,90
20	0,857	0,851	0,854	15,43
22	0,953	0,921	0,937	17,22
24	0,936	0,913	0,925	19,08
26	1,029	0,976	1,003	21,01
28	1,079	1,075	1,077	23,09
30	1,208	1,168	1,188	25,36
32	1,328	1,418	1,373	27,92
34	1,51	1,609	1,560	30,85
36	1,727	1,824	1,776	34,19
38	2,029	2,123	2,076	38,04
40	2,43	2,570	2,5	42,62
42	2,771	2,964	2,867	47,98
44	3,378	3,532	3,455	54,30
46	4,040	4,211	4,126	61,89
48	4,710	4,933	4,822	70,83
50	5,323	5,415	5,369	81,02
51	5,485	5,526	5,506	86,46
52	5,294	5,500	5,397	91,91
53	5,175	4,913	5,044	97,13
54		3,569	3,569	101,44
55		2,132	2,132	104,29
55,5		0	0	104,82
56		-2,086	-2,086	104,30
57		-4,247	-4,247	101,14
58		-4,698	-4,698	96,66
59		-4,628	-4,628	92,00
60		-4,562	-4,562	87,41
62		-4,432	-4,432	78,41
64		-3,969	-3,969	70,01
66		-3,492	-3,492	62,55
68		-3,148	-3,148	55,91
70		-2,804	-2,804	49,96
72		-2,380	-2,380	44,77
74		-2,155	-2,155	40,24
76		-2,087	-2,087	36,00
78		-1,822	-1,822	32,09
80		-1,680	-1,680	28,59
82		-1,317	-1,317	25,59
84		-1,295	-1,295	22,98
86		-0,819	-0,819	20,86
88		-0,364	-0,364	19,68

CURRENT DERIVATIVE MEAN VALUE ON THE ENTRANCE AND
IN LPU RADIAL TRANSMISSION LINE

Fig.1.19

MEAN VALUE OF THE CURRENT DERIVATIVE IN DEMG

Fig.1.20

CURRENT DERIVATIVE EXPERIMENTAL DATA ON THE EXTRANCE
OF DEMG AND IN RADIAL TRANSMISSION LINE AND
THEIR MEAN VALUE

Fig. 1.21

MEAN VALUE OF THE CURRENT IN DEMG

Fig.1.22

2. THE RESULTS OF ADDITIONAL MEASUREMENTS OF DEMG PARAMETERS AND LOAD CHARACTERISTICS

In this paper VNIIEF presents the analysed data on recording of the load parameters on 15 measuring facilities:

- 8 channels of "Tektronix" digitizers,
- 19 oscillographic channels,
- 49 channels on ГСИ recorder,
- 42 channels on MAPTA recorder,
- 23 channels on СУПИ-23 recorder,
- 22 channels on ВФУ recorder.

The data is obtained using the signals recorded by these measuring facilities from inductive, piezoelectric, light, manganine, electrocontact and resistive probes and from divider.

Table #2.1 presents the data on the types of recording devices, types of trigger signals, additional time of their delay, sweep duration and input channel resistance. probe types and channel numbers are given. The Table #2.1 provides the sensitivities of inductive probes, expected maximum voltage values from inductive and piezo probes, signal attenuation coefficients and intervals of time marks.

Data got by recorders ГСИ-100, MAPTA, СУПИ-23, ВФУ, are given in Tables #2.2 - #2.5.

All the plots in the report are given in a time scale with the onset ($t=0$) from the time, when the signal goes from ВУ-19-1.

Timing of data recorded by ГСИ-100, MAPTA, ВФУ and Tektronix was made using the auxiliary signal (from the high-voltage facility ИСКРА - 06, see Table #2.1), enabling time of signal passing through the cable to be ignored. This signal was applied to ГСИ-100 (see Table #2.2, line 49), MAPTA (see Table #2.3, line 22) and Tektronix 540 (see Table #2.1). Fig. 2.1 shows the signal from ИСКРА-06 recorded by Tektronix 540. The time between the signal from ВУ-19-1 and the signal from ИСКРА-06 was 261.7 μ s, the time was measured by an additional control device. According to the signal from ИСКРА-06, recorded by Tektronix, it is clear that the time scale for all the signals recorded by Tektronix should be shifted by 0.22 μ s. The correction of the time scale is given in Fig.2.2. Time correction by 0.22 μ s has been done for the signals from Tektronix channels, which are compared with the signals from ГСИ-100, MAPTA, СУПИ, ВФУ. For other channels of Tektronix time correction has not been done.

2.1 MEASUREMENTS OF CURRENT DERIVATIVE IN THE LOAD BY "TEKTRONIX" RECORDERS AND "СУП" OSCILLOSCOPES

The previous sections of the paper gave the data on measurements of the current derivative in the beginning of a coaxial transmission line and at the input to the radial ПЛ, obtained from recorders aiming to measure exactly EMG current characteristics. A part of signals from the load inductive probes (see Fig.2.3) ПЛ-1, ПЛ-2, ПЛ-3, ПЛ-4, ПЛ-5, ПЛ-6 was used for timing with the measured characteristics of the load. The data on how the signals from these probes were used is given in the Table

#2.1. The Table #2.1 also gives the data on the types of recording devices type of trigger signals, their additional delay time, sweep duration and channel input resistance. Probes and channel numbers are also indicated. The Table #2.1 also shows the sensitivities of inductive probes, the expected maximum voltage values and intervals between time marks.

Fig. 2.4, 2.5 present the current derivative pulses, recorded from the probes of ПЛ-1 and ПЛ-2 by Tektronix. The maximum current derivative according to the ПЛ-1 probe was $5.32 \text{ MA}/\mu\text{s}$, according to ПЛ-2 probe - $5.37 \text{ MA}/\mu\text{s}$. Fig. 2.6, 2.7 show the current pulses, flowing through the liner, corresponding to these current derivatives. The maximum current according to ПЛ-1 probe was 104 MA, according to ПЛ-2 it was 103 MA. All the plots are given in a time scale with the beginning of the counting ($t=0$) from the time of the signal going from BY-19-1.

Fig. 2.8 gives the dependencies of the current derivative in DEMG, obtained by the signals from ПЛ-3, ПЛ-4, ПЛ-5 probes, recorded by oscilloscopes CYP and OK-17 (Table #2.1). Signal oscillogramms from the probes ПЛ-3, ПЛ-4, ПЛ-5 are given in the section "Load parameter measurement data" in Fig. 2.9, 2.11, 2.12.

2.2 MEASUREMENT OF THE MOTION OF TRANSMISSION LINE OUTER BOUNDARIES AND OF THE DIFFERENCE IN TIME OF DEMG DISK OPERATION

In the experiment the shift of coaxial and radial transmission line (CTL and RTL) outer boundaries was measured, using electric contact pins. The shift of CTL and RTL outer boundaries was measured by two groups of electrocontact pins (5 probes in each group). The probes on DEMG casing (ЭК-СКПЛ 0.2, 0.5, 0.8, 1.1, 1.4) were located close to LANL V-dot probes, on the RTL (ЭК-СРПЛ 0.2, 0.5, 0.8, 1.1, 1.4) were located close to VNIIEF attenuator ЕД-2. The numbers denoting probes correspond to the distance between the probe and the transmission line outer boundary in mm.

Casing thickness of the CTL at the probe location was about $\sim 17 \text{ mm}$, RTL casing thickness was about 37 mm .

Table #2.3 (lines 33-42) shows recorded times of probe operation ЭК-КПЛ 0.5, 1.1, 1.4 and ЭК-СРПЛ 0.5, 1.1, 1.4. Not a single group of probes did not record operation of the probe, located at the distance of 0.2 or 0.8 mm. Fig. 2.13 shows time dependencies of the shift in CTL casing outer surface and in the outer surface of RTL external current conductor. The velocity of the outer shell expansion, obtained by linear approximation of experimental points from the probes ЭК-СКПЛ is about $0.1 \text{ mm}/\mu\text{s}$ and is close to calculated velocity after its acceleration ($0.09 \text{ mm}/\mu\text{s}$). If to keep in mind the signal propagation over the casing $17 \text{ mm} / 5.8 \text{ mm}/\mu\text{s} \approx 3 \mu\text{s}$, then the linear approximation of experimental points gives the crossing of a time scale at the time of $267 \mu\text{s}$, which corresponds to the maximum current in EMG about 104 MA, which also agrees with the calculation. The magnetic field value in CTL at this time is 0.24 MH, the pressure on the walls is about 7 kbar.

The expansion velocity of the outer shell in RTL is about $0.05 \text{ mm}/\mu\text{s}$ and also is closed to the calculated one after it was accelerated ($0.06 \text{ mm}/\mu\text{s}$).

The motion of the inner boundary in RTL had to begin a bit earlier than in CTL because of the high magnetic field at each time. However, the experimental points from

the probes ЭК-СРПЛ 0.5 and 1.1 are ahead of similar probe operation at CTL ЭК-СКПЛ 0.5 and 1.1 in a relatively large time about 10 ns. For other channels of Tektronix time correction has not been done. It is also unclear that the expansion velocity of a casing outer boundary in RTL is recorded to decrease (see Fig.2.13, curve Z, point with shifts 1.4 mm), whereas in CTL it is recorded to increase in time (see the curve R).

Fig.2.14 provides the locations of piezoelectric probes (ПД-ДВМГ-1,2,3,4,5) and electrocontact pins (ЭК-ДВМГ-1,2,3,4,5), using which the operation of each five modules of DEMG was recorded. The probes were attached to the plate, which was not rigidly fastened to EMG casing. The distance between the casing surface and probe ends was 2 mm. Table #2.3 (lines 23-32) show the recorded operation times for those probes.

Fig. 2.15 shows time dependencies of shock wave coming into the outer surface of DEMG casing. It is obvious that the signals from piezoelectric and electrocontact probes are close, which proves the reliability of the measurements.

To determine non-uniformity in time of EMG module operation it is possible to use only time of probe operation above the charges #1,3,4,5. Later times in operations of the probes above the charge #2 (see Fig.2.14) are resulted from the protrusion on the casing (steel ring) about 34 mm thick. It is difficult to account accurately for delay of shock propagation through the protrusion (the ring) as a result of the effect of the release wave from lateral ring surfaces on the shock wave attenuation and because of the air gap between the ring and the main casing. Difference in time of shock wave appearance above module #1,2,3,4,5 is less than $\sim 2 \mu\text{s}$. The real difference in time of module operation is even less because shock waves from modules pass through the transmission line with a multilayer insulator and air gaps.

2.3 MEASUREMENT OF ELECTRIC VOLTAGE IN RADIAL TRANSMISSION LINE

During the experiment voltage in radial transmitting line (RTL) was measured with the help of three capacitive dividers (ЕД). Signals from the two dividers (ЕД #1 and 2) were recorded on VNIIEF oscillographs and a signal from the 3rd was measured on LANL recorder.

The scheme of voltage capacitive divider is shown in Fig.2.16. High voltage branch of each of dividers was the capacitor C_1^0 between the inside current lead and copper foil made in the form of sector part of the ring with radiuses 440 and 390 mm and sector angle of 55 deg. Three foil ring sectors were mounted on the outside RTL insulator surface. It was made by means of gluing of mylar film with thickness of 50 μm (dielectric constant of mylar is 3,15). General thickness of insulator was 2 mm. Foil thickness was 25 μm .

The foil of each divider was separated from outside RTL current lead with mylar film with thickness of 175 μm . Low voltage branch of capacitive divider consisted of capacitor C_2^0 , foil relative to outside RTL body and two, parallel connected to it additional radiotechnical capacitors C_{add} . The scheme of C_{add} capacitors connection together with two matching resistors of 75 Ohm to the input and output of measuring cable (with wave resistance of 75 Ohm) along which the signal was transmitted from VNIIEF dividers to CYP oscillograph is shown in Fig.2.16. Such a scheme of capacitive divider connection to measuring cable is offered for a signal transmittance to

oscilloscope with minimal distortion. 500 Ohm resistance was damping one in the input circuit of CYP oscilloscope.

After foils mounting on RTL insulator that was carried out in high voltage laboratory building all capacitive dividers were calibrated together with measuring cables and CYP oscilloscopes with impulse voltage of 30 kV amplitude, with duration of leading edge $\sim 20 \mu\text{sec}$, and impulse duration's - $\sim 40 \mu\text{sec}$. Calibrating impulse amplitude was set with the help of measuring balls air gap break-down, connected parallel to divider being calibrated. The distance between measuring balls was set according to MOK tables (accuracy $\pm 5\%$).

To protect measuring lines from electric stray pick-up the measuring VNIIEF cables were placed into copper braiding shields. The shields were connected to experimental device body and to "ground" of the bank.

CYP oscilloscopes and outside current leads of measuring cables were disconnected from the "ground" of the room and all parasite currents came through shields but not through measuring cables conductors.

Feeding circuit decoupling was done by the use of decoupling transformers. Oscilloscopes starts were made with electric signal transformation into interval light impulse.

For voltage divider it is necessary to stipulate the condition that time constant of capacitive divider output network $3RC$ is to be much more than characteristic time of voltage increase in RTL ($\sim 10\text{-}15 \mu\text{sec}$). Measuring network parameters do not satisfy the condition "much more", so there exists measuring scheme transmittance factor dependence on frequency. For precise restoration of the signal recorded on the oscilloscope it is necessary to take into account this frequency dependence. Because of technologic features of load elements mounting in this experiment the foil together with mylar insulator of 175 mkm. (see Fig.2.16) were cemented together and stuck on RTL current lead outside surface, i.e. in HEL-1 experiment measures to prevent rigid mechanic restrain of foil with RTL body were not undertaken (as it was in X-RAY-I experiment). The foil can shift together with the body under the influence of magnet field of the current flowing through RTL. Between the inside current lead and RTL insulator (which was not stuck to it) and also between the foil and RTL insulator during RTL current leads under the influence of magnet field vacuum clearances are formed. Capacitance of these clearances will exert some effect on the divider factor. However clearances "vacuumness" is useful for them to have large enough conductance in the strong electric field, so we didn't take into account these clearances effect. The scheme of capacitive dividers orientation relatively inductive probes placed on RTL input is shown in Fig.2.17 (view from HEMG side) Fig.2.11 presents voltage oscillograms of RTL from capacitive divider ЕД1 and current derivative in TL (ПЛ-3 probe) and Fig.2.12 presents voltage oscillograms in PTL from capacitive divider ЕД2 and current derivative in TL (TL - 4 probe). In Fig.2.18 voltage oscillograms calculation results from ЕД 1,2 probes and current derivative from TL1 probe. Signals amplitude is given in relative values. One can see that because of oscillographs scanning non-linearity and referencing inaccuracy of signals from different oscillographs in Fig.2.18 is observed temporal mismatch of voltage impulses trailing edges. Specific signals changes are observed on voltage impulses and on current derivative impulse and they can be referred to certain processes in EMG or liner load. Such changes include the rise of

derivative up to 272 μsec , connected with shock waves outlet into coaxial TL, and to this derivative rise corresponds the voltage outlet to quasi-flat sections. Derivative rise to $\sim 298 \mu\text{sec}$ is connected with liner outside surface turn after it's impact against CMU. The increase of voltage velocity drop at impulse trailing edges of voltages must correspond to this time movement. All this special features are observed on voltage impulses. Assuming that the feature corresponding to liner outside surface turn on voltage impulse and current derivative impulse is to be observed at one and the same time, voltage impulses were adjusted in time. Adjusted signals are shown in Fig.2.19. Signal amplitude from ED1 divider was $\sim 37 \text{ kV}$, and from ED2 was 42 kV . Amplitudes definition accuracy was about $\pm 10\%$.

2.4 DESIGN SCHEME IF CENTRAL MEASURING UNIT (CMU) VNIIEF

General view scheme of liner load together with central measuring unit (CMU) is shown in Fig.2.20. CMU VNIIEF design scheme and the scheme of its mating to LANL CMU.

VNIIEF CMU was made of alloyed steel with mechanic features $\sigma_r > 130 \text{ kg/mm}^2$ and $\sigma_t > 150 \text{ kg/mm}^2$.

CMU VNIIEF was mated to CMU LANL along the left surface of CMU VNIIEF body (see Fig.2.21). For this purpose an annular tooth was made on VNIIEF CMU body surface and a groove was made on LANL CMU body mating surface. For vacuum sealing of PU acceleration chamber the rubber ring 7 was installed into the slot. VNIIEF and LANL bodies electric contact is made with the help of indium ring 8 which is deformed by bracing screws 9. On the upper part of VNIIEF CMU body the annular groove is done in which the ring with 1-4 inductance probes is installed ИДЦИБ1-4. For vacuum sealing 2 rubber rings 2 were prearranged which were pressed by tightening the ring 1 to VNIIEF CMU body by means of screws 16.

In VNIIEF CMU body the seats for measuring probes were done. Probes seats schemes for $z=5, 10, 16$ and 20 mm are shown in Fig.2.22-2.25. Spigot 11 made of alloyed steel with the same characteristics as the body were hermetically vacuumly cemented into the seats.

After VNIIEF and LANL units joining, the tube 17 were screwed into threaded hole in CMU VNIIEF body (see Fig.2.20). At the left end of the tube there was a flange (17) with 16 mm diameter for installation of joint VNIIEF and LANL CMU bodies into the seat of liner load along the guide tube 12, screwed into threaded hole in the load body. Three recess holes were also made in the left flange of tube 17 for the outlet of measuring cables from LANL CMU through annular space between tubes 12 and 17.

Electric contact of CMU body with current conducting side walls 14,15 of acceleration chamber was conducted by means of empty copper rings 6,7 deformation. Vacuum sealing of acceleration chamber PU to the liner was done by means of rubber rings 10,11. Light pipes from light probes VNIIEF installed on the left side wall (14) were brought out through inner hole of tube 12. Measuring cables and wires from VNIIEF CMU probes were brought out through the space between CMU and tube 17 to the 4 connectors (19) and 2 connectors (20).

Vacuum in the chamber was produced by pumping out with the pump provided by LANL, through pipe connection 16 with inner hole diameter of 6 mm. To the second pipe connection placed exactly opposite to the first one the sampling vacuummeter was connected. Before the experiment, vacuum not less than 0,1 mm mercury column was provided in acceleration chamber PU.

2.5 LINER ACCELERATION AND TO CMU FLIGHT CHARACTERISTICS MEASUREMENTS

The scheme of probes position on the PU side wall is given in Fig.2.26. Detailed drawings of each probe type (the information of their signal is being considered in this section) corresponding to the legend of Fig.2.26 are presented in Fig.2.27-2.31. The information of recording devices types, modes of starting signals and additional time of their delay, scanning duration, input resistance channels are presented in measurements Table #2.1.

Probes types and numbers of channels recording their signals are shown as well. Sensibilities of inducing probes, expected maximum voltages values from inductive and piezo-probes signal deviding factors, periods of time marking are also presented.

The numbers of light probes (their signals were recorded on ВФУ) on the right side wall of PU acceleration chamber and their spatial parameters (azimuth angle and radius) are presented in Table #2.5 in lines from 16 to 21 (columns 1,3,4).

2.5.1 Information from inductive probes

On the side wall inductive probes were situated

on azimuth $\varphi=340$ deg, ИДБС (R=130,8 mm) ИДБС2 (R=105,8 mm)¹
on azimuth $\varphi=160$ deg, ИДБС3 (R=130,8 mm), ИДБС 4 (R=105,8 mm).

Pairs of these probes placed after 180 deg were intended for recording time internals between liner pass moments of radiuses R=130,8 mm and R=105,5 mm at azimuth angles $\varphi=340$ and $\varphi=160$ deg. signals oscillograms from inductive probes ИДБС 3 and ИДБС 4 received from oscillograph ОК-17(#32 see Table #2.1) are shown in Fig.2.32. For suitable comparison of signals from two groups of inductive probes ИДБС1, ИДБС2, and ИДБС3, ИДБС4 recorded on Tektronix channels and ОК-17 oscillograph (see Fig.2.32 and Table #2.1), they are presented in a common time scale in Fig.2.33.

Signals from probes ИДБС-3 and ИДБС-4 are alike, but signals from probes ИДБС-1 and ИДБС-2 differ from each other and from ИДБС-3 and ИДБС-4 probes signals. Significant signals difference on $\varphi=340$ deg. is related, perhaps, with different

¹ Radiuses 130,8 and 105,8 mm correspond to co-ordinates of probe axis crossing with inner surface of acceleration chamber PU.

character of contact phenomenon of passing liner with current conducting wall in each of probes situation fields.

One can assume, that the beginning of signals corresponds to time moment when liner outer surface coincides with maximum radius of dielectric probe shell (corresponding, 130.8+4mm and 105.8+4mm see Fig.2.29). Then from the relationships given in Fig.2.33 it follows that liner outer surface on azimuth $\varphi=340$ deg. flies to radius 130.8+4 mm at a moment $t=284$ μ s and to radius 105.8+4 mm at a moment $t=287$ μ s. Analogically the outer liner surface on azimuths $\varphi=160$ deg flies up to radius 130+4 mm at a moment $t=282$ μ s, and to radius 105.8+4 mm at a moment $t=287.1$ μ s.

Note, that signals mating precision from probes ИДБС-1 and ИДБС-2 recorded on Tektronix is < 0.1 μ s, while signals mating precision from probes ИДБС-3 and ИДБС-4, recorded on oscillograph OK-17 is only ~ 1 μ s.

Thus sufficiently reliable experimental points on R-t liner flight diagram can be obtained only from Tektronix device signals. In Fig. 2.34 these points (liner outer surface position as it follows from above assumption) correspond to starting points on ИДБС-1 and ИДБС-2 probes. Signals from probes pairs ИДБС-1, ИДБС-2 and ИДБС-3, ИДБС-4 can be used for estimation of liner outer surface average speed on the flight base from radius $R=130.8$ mm to radius $R=105.8$ mm:

On azimuth $\varphi=340$ deg. $V=(130.8-105.8)\text{mm}/3.1\mu\text{s}=8.1\text{mm}/\mu\text{s}$

On azimuth $\varphi=160$ deg. $V=(130.8-105.8)\text{mm}/3.5\mu\text{s}=7.1\text{mm}/\mu\text{s}$

2.5.2 Information from piezoelectric probes.

On the side wall piezoelectric probes were situated (see Fig. 2.28):

on azimuth $\varphi=25$ deg. ПД-1 ($R=130.8$ mm), ПД-2 ($R=105.8$ mm),

on azimuth $\varphi=205$ deg. ПД-3 ($R=130.8$ mm), ПД-4 ($R=105.8$ mm).

These probes pairs placed after 180 deg. were intended to record time interval between liner pass moments radiuses $R=130.8$ mm and $R=105.8$ mm on azimuth angles $\varphi=25$ and $\varphi=205$ deg.

Oscillograms of signals from piezoprobes ПД-3 and ПД-4 obtained from oscillograph OK-17 (N33 see Table #2.1) are shown in Fig.2.35.

For comparison of signals from two groups of piezoelectric probes ПД-1, ПД-2 and ПД-3 and ПД-4, recorded on Tektronix channels and oscillograph OK-17 (see Fig. 2.35 and Table #2.1) they are shown in uniform time scale in Fig. 2.36. Signals from probes ПД-1 and ПД-2 are cut by recording device Tektronix, signals from probes ПД-3 and ПД-4 are cut visually to oscillograms (along distinguished level).

One can assume, that signals starting corresponds to time moment, when shock wave, caused in current conducting wall by liner inner surface movement, get the probe sensitive element.

Shock wave propagation time along the shortest way of current conducting wall of acceleration chamber is a sum of its time of propagation through steel the distance of

2 mm (sound speed $V_{st} \approx 5.8 \text{ mm}/\mu\text{s}$) and to polyamide of distance 3 mm (sound speed $V_{pol} \approx 2.5 \text{ mm}/\mu\text{s}$). General delay time will be

$$t_{del} = 2\text{mm}/(5.8\text{mm}/\mu\text{s}) + 3\text{mm}/(2.5\text{mm}/\mu\text{s}) \approx 1.5 \mu\text{s}$$

Everything told in previous section about signals mating precision from inductive probe also refers to piezoelectric probes signals. Signals mating precision from ПД-1 and ПД-2 probes, recorded on Tectronix device is $0.02\mu\text{s}$, and signals mating precision from ПД-3 and ПД-4 probes, recorded on oscilograph OK-17 is $\sim 1\mu\text{s}$. So sufficiently reliable experimental movement points of liner inner boundary on R-t diagram can be obtained for azimuth $\varphi = 25 \text{ deg.}$ under the signals from ПД-1 and ПД-2 probes.

At $R = 130.8 \text{ mm}$ the inner liner surface flies up at a moment $285.7\mu\text{s}$ - $t_{del} = 284.2\mu\text{s}$

At $R = 105.8 \text{ mm}$ the inner liner surface flies up at a moment $289.7\mu\text{s}$ - $t_{del} = 288.2\mu\text{s}$

These points are put down on R-t diagram shown in Fig. 2.34.

All signals from probe pairs ПД-1, ПД-2 and ПД-3, ПД-4 can be used to estimate liner inner surface mean speed on flight base from radius $R = 130.8 \text{ mm}$ to radius $R = 105.8 \text{ mm}$.

On azimuth $\varphi = 25 \text{ deg.}$ $V = (130.8 - 105.8) \text{ mm} / 3.9\mu\text{s} = 6.4 \text{ mm}/\mu\text{s}$

On azimuth $\varphi = 205 \text{ deg.}$ $V = (130.8 - 105.8) \text{ mm} / 3.7\mu\text{s} = 6.8 \text{ mm}/\mu\text{s}$

2.5.3 Light probes information

Light measurements scheme of liner movement in acceleration chamber is presented in Fig. 2.27.

It was supposed, that narrow light beams incoming into acceleration chamber through multifiber light guides 7 and collimation holes 2 mm in diameter from impulse argon source, will be broken by pass flying liner and this light break, with the help of light guides - receivers will be registered on photochronograph БФУ.

Impulse source was plastic vessel filled with argon, in which shock wave was produced due to detonation of blasting cartridge being in contact with a vessel.

Light probes (see Fig. 2.26) were placed on azimuth angles $\varphi = 115 \text{ deg.}$ and $\varphi = 295 \text{ deg.}$ on radiuses 150, 125 and 100 mm.

In Table #2.5 in lines from 16 to 21 (columns 1,3,4) light probes numbers on the right side wall of PU acceleration chamber (CD27-CD32) are presented and their spacial parameters (azimuth angle and radius). Their signals were registered on БФУ photochronograph.

Unfortunately, the light from argon source was not registered by БФУ photochronograph. However, on 5 (CD27, CD28, CD30, CD31, CD37) out of 6 light guides-receivers measurements channels on БФУ photochronograph - light flashes were registered.

Photochronogram from БФУ registrator with designations to beams corresponding light probes is presented in Fig.2.37. On some light lines sharp rising

in intensity flashes are observed, on others before flashes less intensive glows-forerunners.

Flashes moments are presented in the last column of Table #2.5 (see lines from 16 to 21). On both azimuth angles first operated the probes at $R=150$ mm and then at $R=125$ mm.

Of probes at $R=100$ mm only the signal from probe CD32 was registered.

To the moments of flashes from probes, placed on one azimuth angle but on different radiuses, one can estimate disturbance propagation average speed on the base between these radiuses. These estimates are the following:

$\varphi=295$ deg., flight base from $R=150$ mm to $R=125$ mm , $V=25/2.63 = 9.5$ mm/ μ s

$\varphi=115$ deg, flight base from $R=150$ mm to $R=100$ mm , $V=25/2.45=10.2$ mm/ μ s.

It seems likely that light flash formation process at each measuring channel was one and the same.

Flash time moments, registered by light probes are late in relation to calculated moment of liner flight up to this radius for 3-4 μ s on radius 150 mm and for 2-3 μ s on radius 125 mm.

One can assume, that after liner passing the collimation hole leading to probe (see Fig. 2.27), it shut by magnet field. Along the hole axis cumulative jet spreading from current conducting wall. It effects the window made of acrylic plastic and causes glow (mayby of air on the outer surface of the window). Since magnet field pressure increeses square-like with radius reduction, then holes shutting speed will rise and probe operation delay speed will decrease. Thus disturbance propagation speed, to which light probes operated is significantly higher than liner movement speed obtained on inductive and piezoelectric probes.

Unfortunately light probes operation moments can not be used for obtaining experimental points on R-t diagram because of uncertainty of delay time between liner fly up moment to probe installation radius and a moment of probe light flash generation.

2.5.4 Information from manganin probes.

Manganin probes were placed on the side wall (see Fig. 2.26 and Fig. 2.31):

on azimuth $\varphi=70$ deg. M-1 ($R=130.8$ mm) M-2 ($R=105.8$ mm),

on azimuth $\varphi=250$ deg. M-3 ($R=130.8$ mm) M-4 ($R=105.8$ mm).

These probes pairs, placed after 180 deg. were intended to record time intervals between moments of liner pass flight by radiuses $R=130.8$ mm and $R=105.8$ mm on azimuth angles $\varphi=70$ and $\varphi=250$ deg., and pressure produced by liner in current conducting wall.

Manganin probes installation scheme in side wall is shown in Fig. 2.31.

The sensitivity of each of 4 measuring channels were chosen regarding the expected maximum pressure 5 GPa.

The signal from Rogowski coil, placed near experimental assembly on exploding cable from BY-19-2 was applied to synchro-impulses formation unit

(BIC-10) from which pressure recording devices C9-8 and C9-4A were started with delay of 50 μ s.

Pressure recording in the experiment was conducted only on the radius $R=130.8$ mm on C9-8 device.

The oscillogram of signals from probes M-1 and M-3 is presented in Fig. 2.38. Signals starting corresponds to 61.1 μ s from oscillograph scanning beginning and time moment 286.6 μ s-t del. from BY-19-1. This time is obtained by summation of the following times intervals:

$$175.5 \text{ (time between BY-19-1.2)} + 50 \text{ (delay)} + 61.1 - t \text{ del.} = 286.6 \mu\text{s} - t \text{ del.}$$

Delay time t del. is defined the following way.

Since we use everywhere the time scale from BY-19-1 operation time in the bank, and pressure recording devices were put into operation from supplying to the DEMG site signal from BY-19-2, then from the time of 286.6 μ s one shall abstract signal along cables propagation time (length about 90 m) t del.1 ~ 0.5 μ s. Furthermore out of time of 286.6 μ s it is necessary to abstract also t del.2, corresponding to disturbance propagation time from current conducting wall to manganin wire. This time is a sum (see Fig.2.31) of its propagation time though steel distance 2mm (sound speed $V_{st} \sim 5.8$ mm/ μ s) and though acrylic plastic distance 1.5mm (sound speed $V_{ap} \sim 2.5$ mm/ μ s):

$$t \text{ del.2} = 2\text{mm}/(5.8\text{mm}/\mu\text{s}) + 1.5 \text{ mm}/(2.5 \text{ mm}/\mu\text{s}) = \sim 1\mu\text{s}$$

Thus $t \text{ del.} = t \text{ del.1} + t \text{ del.2} = \sim 1.5 \mu\text{s}$ and signals starting will correspond to $286.6 \mu\text{s} - 1.5 \mu\text{s} = 285.1 \mu\text{s}$ from BY-19-1. This time moment is put down on R-t diagram, shown in Fig.2.34.

Pressure signals have two maximums in 1.3 μ s from each other for a signal on upper beam and 0.8 μ s for a signal on lower beam. First maximums amplitude for both signals are the same and equal to ~ 0.53 GPa. Second maximum amplitude of the first signal is a little more than second maximum amplitude and the other signal's second maximum is higher than the first nearly 2 times (0.9 GPa).

Pressure curves with two maximums seem to reflect pressure impulse superposition against shock interaction of liner with the wall and magnet field pressure impulse propagated through current conducting wall together with current layer. 285 th μ s magnet field pressure impulse on manganin probe installation radius has amplitude just a little more than 0.5 GPa. Differing pressure impulses forms on opposed positions of probes seem to reflect azimuth asymmetry of liner to wall interaction.

2.5.5 About the signals from inductive probes over CMU.

For current recording over liner in CMU body in the area of right side acceleration chamber wall prolongation a ring grooving was made in which 4 inductive probes ИДЦИБ 1, 2, 3, 4 (see Fig.2.20) were installed. The rough drawing of

inductive probe is shown in Fig.2.30. Azimuth situation of ИДЦИБ 1-4 probes is shown in Fig.2.26.

Signal from ИДЦИБ-1 was recorded on Tektronix 420, signals from other probes ИДЦИБ-2, 3, 4 were recorded on oscillographs ОК-17 (see Measurements Table 2.1).

Characteristic oscillograms obtained during the experiment are presented in Fig. 2.9, 2.10. In Fig. 2.9 there is oscillogram of current derivative under the liner to the signal from ИДЦИБ-2 probe (on the other beam is the oscillogram of current derivative in TL to signal of probe ПЛ-5). In Fig. 2.10 there is oscillograms of current derivative under the liner to the signals from ИДЦИБ-3 and ИДЦИБ-4.

In Fig. 2.39 probe ИДЦИБ-1 signal diagram (Tektronix-420) and in Fig.2.40 current derivative dependences under the liner obtained to signal of probes ИДЦИБ-2, ИДЦИБ-3, ИДЦИБ-4 are presented. First at consideration of oscillograms in Fig. 2.9 one can conclude that there was no penetration of magnet field under the liner during the whole DEMG work and larger part of liner flight.

Signals from ИДЦИБ-2, 3, 4 probes (see Fig.2.40) begin in the time range from 290 μ s (probe ИДЦИБ-3) up to 297 μ s (probe ИДЦИБ-2) as signals were recorded at the end of oscillographs scannings, so the precision of time referencing of signals beginning is very low. The spread of 7 μ s is connected with signals referencing precision but not with liner flight to coil with inductive probes asymmetry.

Calculated moment of liner outer surface flight to maximum radius of probes dielectric shell $R=69$ mm (see Fig.2.30) is ~ 294 μ s and corresponds to average time of probes ИДЦИБ-2, 3, 4 signals beginning spread interval.

To the signal from probe ИДЦИБ-1, recorded on Tektronix-420 was possibly superimposed with a signal of transmission line noise. A large signal of negative amplitude in time range from 100 μ s to 180 μ s (i.e. on the stage of HEMG) is observed.

There are two confirmations that this signal is not connected with magnet field penetration under the liner: first-the signal has opposite polarity of basic signal polarity (in time range from ~ 290 μ s up to ~ 300 μ s), and if magnet flow penetrated under the liner through liner contact with current conducting walls so signals polarities must coincide; the second- probe sensitivity is very low to give a signal of such a large amplitude on the stage of HEMG operation, even if there were no contact of liner with current conducting wall.

2.6. MEASUREMENT OF LINER IMPACT AGAINST CMU CHARACTERISTICS.

In Fig. 2.41-2.44 the schemes of probes positions in Central Measuring Unit (CMU) in four planes perpendicular to CMU axis for distances from mating plate with CMU LANL $z = 5, 10, 16, 20$ mm are presented. Such rough drawings of each probe type, corresponding to the legend of Fig. 2.41-2.44 are shown in Fig. 2.45-2.52.

Information of CMU probes signals recording is shown in Table of measurement # 2.1. In the first four columns of Table #2.2 (lines 1-48), Table #2.3 (lines 1-21), Table #2.4, Table #2.5 (lines 1-15) are shown probes types in CMU and their spatial parameters (distance from mating plate z , azimuth angle and radius). Their signals were recorded correspondingly on devices ГСИ-100, МАРТА, СУПИ-23, ВФУ.

In Fig.2.53 and 2.54 signals oscillograms from resistive probes RD and RA are shown.

In Fig.2.55 there is a photochronogram from ГСИ-100 with marking, to beams, of corresponding electrocontact and resistive probes.

In Fig.2.37 there is photochronogram from ВФУ device with marking to beams of corresponding light beams.

Operation moments of corresponding electrocontact CMU probes or light signals emergence moments recorded on ГСИ-100, МАРТА, СУПИ-23, ВФУ devices are presented in column 4 of Table #2.2 - #2.5.

The same time scale was used with a start of reading ($t=0$) from the moment of BY-19-1 signal generation.

In the space over CMU up to radius ~ 66 - 67 mm on the three bases the probes were situated with the help of which it was intended to measure the speed and symmetry of liner flight to CMU. These probes were placed in cross section $z=5$ mm and 20 mm (see Fig.2.41, 2.44, 2.52).

On the angles $\varphi=0$ and 180 deg. three light protected probes CD1,2,3, CD4,5,6 (see Fig.2.52) were placed. On the angle $\varphi=205$ deg. the resistive probe RA was installed (see Fig.2.51), the rest probes were electrocontact ones (see Fig.2.51). Two electrocontact probes on $\varphi=205$ deg. were used for registering devices putting into operation.

Probes protection against shock waves in the air which are generated during the process of liner flight between it and CMU were carried out by means of air pumping out to the pressure of about 0.1 mm mercury column.

Operation time of these probes is presented in the last column of Tables #2.2-#2.5. In Fig.2.56 the results obtained on ГСИ-100, СУПИ, МАРТА and ВФУ devices situated in the radiuses range $66.24\text{mm} < R < 66.95\text{mm}$ and $49.95\text{mm} < R < 50.73\text{mm}$ shown in dependence of azimuth angle. Upper radiuses range relates to measurement of shock wave coming to probes moments. The shock wave propagated along CMU after the liner impact against it.

Sufficiently good measurements results coincidence in the lower radiuses range is seen (in Fig.2.56 experimental points, related to this range are marked with R50) and less coincidence is observed in upper range i.e. at the distance ~ 12 mm from CMU body (in Fig.2.56 these experimental points are marked with R67).

The largest divergence is observed on two pairs of electrocontact probes: on the angle $\varphi=75$ deg.; their signals were recorded on МАРТА and ГСИ-100 devices (difference $\sim 3\mu\text{s}$) and on $\varphi=255$ deg. for signals recorded on СУПИ and ГСИ-100 (difference $\sim 4\mu\text{s}$).

Probes operation moments over CMU in the form of R-t diagrams are presented in Fig.2.57 (see Tables #2.2 - #2.5).

Note that some groups of protruding over CMU surface electrocontact probes, situated in one tube but at different bases operated nearly at one time (see, e.g. Table #2.2, probes on $\varphi=135$ deg.: 1A1N2-Г, 2A1N2-Г, 3A1N2-Г). The same picture is observed also for probes in angle sector $\varphi=75$ deg.

Because of some effect, metal tube (probe body) pinch took place and also its shorting with probes wires near CMU surface.

Azimuth distribution of liner flight moments to radius ~ 67 mm is difficult to present due to inconsistency of signals protruding over CMU probes.

It's natural to assume that probes moments operation azimuth distribution in the lower radii range (which react to shock wave) will also reflect azimuth distribution moments of liner flight to probes protruding over CMU.

Liner speed measurements results (at his flight up to CMU) given below present average speed value $8.1 \text{ mm}/\mu\text{s}$. As the base separating the upper range from the lower one is $\sim 17 \text{ mm}$, so we for signals (R50) shifted the curve for $2 \mu\text{s}$ to the area of (R67) signals from probes situated in the upper radii range. This curve is shown by the thick line in Fig. 2.56. Note, times coincidence on boundary points of the curve (at $\varphi \sim 30$ degree and at $\varphi \sim 340$ degree).

Experimental points of R67 signals in Fig. 2.56 is sufficiently well correlated with this curve, that attests the reality of obtained azimuth picture of liner flight to CMU assymetry. Liner parts flight advance is observed near the angle ~ 150 degree and $\sim$ in angles range 240-250.

Together with probes, placed over CMU for liner flight up to CMU speed measurement also were used two probes groups placed in cross section $z=10 \text{ mm}$ (see Fig. 2.42, 2.46, 2.47).

The first group in angles range $\varphi=35-65$ degree are electrocontact probes E1-E3 and light ones - CD9-11.

The second group in angles range $\varphi=215-245$ degree are electrocontact probes E4-E6 and light ones - CD18-20.

All of them were placed at the same distance from CMU surface, but central spigots with probes in each group (E2, CD10 and E5, CD19) were installed into the seats with deeper grooving (see Fig. 2.42) that made measuring base 3 mm (see Tables #2.2, #2.3, #2.5).

These probes operation time is presented in the last column of Tables #2.2, #2.3, #2.5 and in Fig. 2.58 the results are shown that were obtained on ГСИ-100 and MAPTA. One can see, that in the 1st probes group the information on ГСИ-100 and MAPTA coincides. The extreme probes (E1, E3) operated practically at the same time. E1-E3 probes give the following liner speed values: $7.24, 8.36, 8.36, 8.44 \text{ mm}/\mu\text{s}$ (to MAPTA and ГСИ devices). Liner speed value, obtained by averaging, will be $8.1 \text{ mm}/\mu\text{s}$.

From the first light probes group a signal was recorded only from CD9 probe, from which the light flash ($297.3 \mu\text{s}$) occurred $\sim 0.5 \mu\text{s}$ later than E1 probe signal ($296.76 \mu\text{s}$). In the 2nd probes group sufficiently earlier operation of E6 probe ($293.9 \mu\text{s}$) was observed in comparison with E4 probe ($296.36 \mu\text{s}$) installed on the same radius. Liner speed to probes E4, E5 is $\sim 20.8 \text{ mm}/\mu\text{s}$. The information from light probes in this group is not obtained. Possibly in this angles range local narrow directed release of substance from the liner was formed.

Shock wave speed in CMU body was measured according to probes installed in CMU body in $z=10 \text{ mm}$ cross section on azimuth angles $\varphi=115$ and 295 degree (see Fig. 2.42 and 2.49). On the angle $\varphi=295$ degree except electrocontact probes a resistive probe RD was installed. Installation parameters of electrocontact probes are presented in Tables #2.2, #2.3.

Electrocontact probes operation times recorded on ГСИ-100 and MAPTA are presented in the last column of Tables #2.2, #2.3 and in Fig.2.59 R-t diagrams, obtained to them are presented. In the same Fig.2.59 R-t diagram obtained as a result of signal processing from resistive probe RD, is shown.

In $z=16\text{mm}$ cross section on the angles $\varphi=0$ and 180 degree two opened noncollimated light probes CD25 and CD26 were installed (see Fig. 2.43). The beginning of glow from the probe at $\varphi=180$ degree (CD26) is observed from $\sim 284\mu\text{s}$ (see photochronogram in Fig.2.37), when the liner, according to calculation, was on the radius $\sim 130\text{mm}$. This glow possibly came from the area of liner contact with the wall. Glow intensity continuously increased in time. At $288.5\mu\text{s}$ much larger rise of light flaming speed with achievement of its maximum intensity at $289\mu\text{s}$. Further one can see continuous decrease of intensity. Light termination is observed at $\sim 292.7\mu\text{s}$ i.e. approximately in $3\mu\text{s}$ before calculated liner impact against CMU.

The next sharp light appearance starts in $\sim 3\mu\text{s}$ at a time of $\sim 295.7\mu\text{s}$, which corresponds to the calculated time of the impact between the liner and the probe. Further a short light break is observed.

Another picture is observed at the opposite azimuthal angle $\varphi=0$. There is no glow up to the time $\sim 297.2\mu\text{s}$, which is close to the calculated time of the impact between the liner and the probe. Apparently, in this region of azimuthal angles the contact between the liner and the walls was good. The difference between light flashes at the $295.7\mu\text{s}$ ($\varphi=180$ degree) and $297.2\mu\text{s}$, probably, reflects asymmetry of liners flight up to CMU. At the region of the angle $\varphi=180$ the $\sim 1.5\mu\text{s}$ advance is observed as compared to the region close to the angle $\varphi=0$ degree. This conclusion is confirmed by the results, given in Fig. 2.56.

It was assumed to measure the value of shock wave pressure, propagating over CMU casing. For that purpose manganine probes were located in CMU casing at the azimuthal angles $\varphi=90$ and 270 degrees (see Fig. 2.43). Unfortunately, we failed to record pressure pulse (see oscillogram in Fig. 2.60).

To estimate pressure at the front of the 1-st shock wave close to the CMU surface after it passed over steel the distance $\sim 16\text{mm}$, the velocities of free surface release were measured. For that purpose light and electrocontact probes were located in CMU casing at the cross section $z=10\text{mm}$ at azimuthal angles of $\varphi=165$ and 345 degree at $R=\sim 50$ and $R=\sim 48\text{mm}$ and at the angles 15 , 135 , 195 and 315 degree at $R=\sim 34$ and $R=\sim 32\text{mm}$ (see Fig. 2.42, 2.48 and 2.50). The recorded data from probes is given in Fig. 2.61 and 2.62 (see Tables #2.2 - #2.5).

The additional information about the release velocity of CMU inner boundary free surface was obtained from the probe RD (see Fig. 2.59, R-t diagram with $R<35\text{mm}$).

The detailed analysis of the data is given in section 3.

Fig.2.63 provides all the experimental data, characterizing the liner flight, when it hits the measuring unit, to have a better understanding about number of signals from TL probes and about time distribution of those points relatively to the current derivative.

The table of measurements #2.1

Type Device	Start-up	Delay. Start-up,	Duration display. μ s	N channel	Probe	Sensitivity.	Expected voltage	R, Ohm	The notes
Tektronix 420	ВУ-19-1	1	540	0008	ПЛ-1	0.00816	114	75	Кдел=11.26
				0009	ИДБС-2	0.033	100	75	Кдел=11.41
				0010	ИДБС-1	0.027	100	75	Кдел=10.48
				0011	ИДЦИБ-1	0.028	100	75	Кдел=11.04
Tektronix 540	ВУ-19-1	1	380	0008	ПЛ-2	0.01234	173	75	Кдел=10.56
				0009	ПД-1		200	75	Кдел=10.68
				0010	ПД-2		200	75	Кдел=10.68
				0011	Метка ИСКРА-06		350	75	Кдел=10.75
СУР N1	ВУ-19-2	70	50	1	Емк. дел. N1				Метки-2 мкс
СУР N2	ВУ-19-2	70	50	2	ПЛ-3	0.00816	114	75	
				1	ПЛ-4	0.01249	175	75	Метки-2 мкс
СУР N3	ВУ-19-2	100	25	2	Емк. дел. N2				
				1	РА				Метки-2 мкс
СУР N4	от эл. контакта ЦИБ	0	4	2	RD				
				1	РА				Метки-0.5 мкс
ОК-17 N25	ВУ-19-2	35	120	2	RD				
				1	ПЛ-5	0.01633	230	75	Метки-10 мкс
ОК-17 N4	ВУ-19-2	60	60	2	ИДЦИБ-2	0.055	200	75	
				1	ИДЦИБ-3	0.028	100	75	Метки-10 мкс
ОК-17 N32	ВУ-19-2	90	30	2	ИДЦИБ-4	0.055	200	75	
				1	ИДБС-3	0.027	100	75	Метки-4 мкс
ОК-17 N33	ВУ-19-2	90	30	2	ИДБС-4	0.033	100	75	
				1	ПД-3		200	75	Метки-4 мкс
Марта	ВУ-19-2	60	80	2	ПД-4		200	75	
					Эл. контакты				
СУПИ-23	от эл. контакта ЦИБ	0	5		Эл. контакты				
ВФУ			125		Световые				
ГСИ-100			125		Эл. контакты				
ФЭР	от эл. контакта ЦИБ	0	33		Световые				

Device ГСН

Time from BY-19-1

Table #2.2

N probe	Z, mm	azimuth angle	Radius, mm	Time, μ s
1A3-Г	5	25	66.945	296.00
2A3-Г	5	25	62.495	296.35
3A3-Г	5	25	57.995	296.29
4A3-Г	5	25	55.595	296.35
1A1N1-Г	5	75	66.945	293.10
2A1N1-Г	5	75	61.545	296.12
3A1N1-Г	5	75	56.195	296.10
1A1N2-Г	5	135	66.945	292.94
2A1N2-Г	5	135	61.195	292.68
3A1N2-Г	5	135	55.695	292.62
1A-Г	5	205	68.945	295.30
2A-Г	5	205	65.045	296.02
3A-Г	5	205	61.245	296.02
4A-Г	5	205	56.145	295.95
RA	5	205	66.945	294.90
1A1N3-Г	5	255	66.945	291.15
2A1N3-Г	5	255	61.495	293.66
3A1N3-Г	5	255	55.945	294.99
1CN1-Г	10	15	34.05	298.80
2CN1-Г	10	15	32	299.28
E1-Г	10	35	50.725	296.76
E2-Г	10	50	47.685	297.12
E3-Г	10	65	50.695	296.76
1D1*-Г	10	115	50.485	296.36
2D1*-Г	10	115	45.535	296.70
3D1*-Г	10	115	40.535	297.20
4D1*-Г	10	115	35.435	297.76
1CN2-Г	10	135	34.05	
2CN2-Г	10	135	31.8	298.55
1BN1-Г	10	165	49.945	295.15
2BN1-Г	10	165	47.695	295.75
1CN3-Г	10	195	34.05	
2CN3-Г	10	195	31.85	
E4-Г	10	215	50.635	296.36
E5-Г	10	230	47.725	296.50
E6-Г	10	245	50.735	293.90
RD	10	295	50.435	296.29
1D-Г	10	295	50.635	296.16
2D-Г	10	295	45.885	
3D-Г	10	295	40.585	297.22
4D-Г	10	295	35.385	297.85
1CN4-Г	10	315	34.05	298.28
2CN4-Г	10	315	32.05	298.55
1BN2-Г	10	345	50.145	296.85
2BN2-Г	10	345	47.995	296.96
1A2N1-Г	20	135	66.945	291.87
2A2N1-Г	20	135	61.485	293.18
3A2N1-Г	20	135	55.985	294.10
Искра-06				261.70

Device MAPTA

Time from BY-19-1

Table #2.3

N probe	Z, mm	azimuth angle	Radius, mm	Time, μ s
1A3-M	5	25	66.245	296.16
2A3-M	5	25	60.395	296.36
1A1N1-M	5	75	66.945	296.04
2A1N1-M	5	75	61.645	296.06
3A1N1-M	5	75	56.445	295.94
1A1N2-M	5	135	66.945	292.74
1CN1-M	10	15	34.05	298.76
2CN1-M	10	15	31.95	299.56
E1-M	10	35	50.725	296.72
E2-M	10	50	47.685	297.14
E3-M	10	65	50.695	296.78
1D1*-M	10	115	50.485	296.38
2D1*-M	10	115	43.185	296.96
3D1*-M	10	115	35.435	297.78
1CN4-M	10	315	34.05	
2CN4-M	10	315	32.05	298.8
1BN2-M	10	345	50.095	296.96
2BN2-M	10	345	48.195	297.04
1A2N2-M	20	315	66.945	293.64
2A2N2-M	20	315	61.695	294.52
3A2N2-M	20	315	56.695	294.98
Искра-06				261.7
ПД-ДВМГ-1				277.58
ПД-ДВМГ-2				293.66
ПД-ДВМГ-3				276.38
ПД-ДВМГ-4				278.08
ПД-ДВМГ-5				276.98
ЭК-ДВМГ-1				277.38
ЭК-ДВМГ-2				291.18
ЭК-ДВМГ-3				279.96
ЭК-ДВМГ-4				277.96
ЭК-ДВМГ-5				278.6
ЭК-СРПЛ-0.2				
ЭК-СРПЛ-0.5				266.38
ЭК-СРПЛ-0.8				
ЭК-СРПЛ-1.1				277
ЭК-СРПЛ-1.4				285.1
ЭК-СКПЛ-0.2				
ЭК-СКПЛ-0.5				276.74
ЭК-СКПЛ-0.8				
ЭК-СКПЛ-1.1				284.06
ЭК-СКПЛ-1.4				285.4

Device СУПИ

Time from BY-19-1

Table #2.4

N probe	Z, мм	azimuth angle	Radius, mm	Time, μ s
2A1N2-C	5	135	61.445	
3A1N2-C	5	135	56.045	
1A-C	5	205	66.995	
2A-C	5	205	61.495	
3A-C	5	205	56.195	
1A1N3-C	5	255	66.345	294.99
2A1N3-C	5	255	60.995	295.51
3A1N3-C	5	255	55.695	295.50
1A1N4-C	5	315	66.945	295.35
2A1N4-C	5	315	61.845	296.08
3A1N4-C	5	315	56.545	296.96
1CN2-C	10	135	34.050	
2CN2-C	10	135	31.800	
1CN3-C	10	195	34.050	295.15
2CN3-C	10	195	31.850	295.14
E4-C	10	215	50.635	
E5-C	10	230	47.725	
E6-C	10	245	50.735	
1D-C	10	295	50.535	
2D-C	10	295	42.635	
3D-C	10	295	35.235	
1BN1-C	10	345	50.165	
2BN1-C	10	345	47.965	294.84

Device ВФУ

Time from BY-19-1

Table #2.5

N probe	Z, mm	azimuth angle	Radius, mm	Time, μ s
CD1	5	0	66.945	296.65
CD2	5	0	61.045	297.47
CD3	5	0	55.345	297.88
CD7	10	15	35	300.12
CD8	10	15	33.4	
CD9	10	35	50.725	297.30
CD10	10	50	47.685	
CD11	10	65	50.695	
CD18	10	215	50.635	
CD21	10	315	35	299.95
CD22	10	315	33.4	299.78
CD23	10	345	50.045	297.59
CD24	10	345	48.045	297.73
CD25	16	0	55.055	297.16
CD26	16	180	55.055	284.07
CD27		295	150	284.93
CD28		295	125	287.56
CD29		295	100	
CD30		115	150	284.55
CD31		115	125	287.00
CD32		115	100	287.40

Fig.2.1

Fig.2.2

Probe situation scheme at the input into radial TL

Fig. 2.3

Fig.2.4

Fig.2.5

Fig.2.6

Fig.2.7

Fig.2.9 Oscillograph OK-17 N 25
 Upper beam - Current derivative in TL. Probe ПЛ-5
 Lower beam - Current derivative under liner. Probe ИДЦИБ-2
 Time marks 10 μ s

Fig.2.10 Oscillograph OK-17 N 4
 Upper beam - Current derivative under liner. Probe ИДЦИБ-3
 Lower beam - Current derivative under liner. Probe ИДЦИБ-4
 Time marks 10 μ s

Fig.2.11 Oscillograph CYP N 1
 Upper beam - Voltage in TL. Probe - capacitive divider N1
 Lower beam - Current derivative in TL. Probe ПЛ-3
 Time marks $2 \mu\text{s}$

Fig.2.12 Oscillograph CYP N 2
 Upper beam - Current derivative in TL. Probe ПЛ-4
 Lower beam - Voltage in TL. Probe - capacitive divider N 2
 Time marks $2 \mu\text{s}$

Fig.2.13

Fig.2.14

Fig.2.15

Fig.2.16 Capacitive divider scheme for voltage measurements in RTL. $C_{10} = 280\text{pF}$; $C_{20} = 3.2\text{nF}$; $C_{add} = 56\text{nF}$

Fig.2.17 Scheme of voltage devices referencing to inductive probes, view from EMG

Fig.2.18

Fig.2.19

Fig.2.20 General view of liner load with central measuring unit (CMU)

Fig.2.21 CMU VNIIEF design scheme and its mating to CMU LANL

Fig.2.22 Probes installation seats scheme in CMU VNIIEF
for $Z=5$ mm

Fig.2.23 Probes installation seats scheme in CMU VNIIEF for $Z=10$ mm

Fig.2.25 Probes installation seats scheme in CMU VNIIEF
for Z=20 mm

Probes situation scheme on the side outer PU wall

Fig.2.26

Fig.2.27 Scheme of light measurements with probes on the side wall of PU. 1-light guide receiver $\varnothing 1.25$ mm; 2-window of acrylic plastic; 3-sealing ring of fluoroplastic; 4-epoxy compound; 5-steel tube $\varnothing 0.4 \times \varnothing 0.3$ mm; 6-PU side wall; 7-multi-fiber radiating light guide $\varnothing 2$ mm; 8-light guide tag; 9-kaprondevee; 10-inner side PU wall

Radius

R=150 mm for probes CA27 and CA30

R=125 mm for probes CA28 and CA31

R=100 mm for probes CA29 and CA32

Fig.2.28 Rough drawing of piezoelectric transducer installed in side PU wall. 1-piezoelement; 2-body made of polyamid; 3-PU side wall made of steel; 4-epoxy compound; 5-cable.

Radius $R=105.8\text{mm}$ for probes ПД2, ПД4,
 $R=130.8\text{mm}$ for probes ПД1, ПД3.

Fig.2.29 Rough drawing of inductive probe, installed in PU side wall. 1-inductive probe of rectangular form (frame 8x4 mm); 2-probe body (acrylic plastic); 3-epoxy compound; 4-kapron tube; 5-cable PK-75-2-11; 6-sealing ring of fluoroplastic; 7-PU side wall.

Radius $R=130.8\text{mm}$ for ИДБС1 and ИДБС3,
 $R=105.8\text{mm}$ for ИДБС2 and ИДБС4.

Fig.2.30 Rough drawing of inductive probe in CMU (ИДЦИБ1-ИДЦИБ4). 1-inductive probe; 2-frame; 3-body; 4-insulating tube; 5-epoxy compound; 6-cable; 7-CMU body; 8-PU side wall; 9,10-sealing rings

Fig.2.31 Rough drawing of manganine pressure probe;
 1-manganine wire; 2-PU side wall; 3-probe body of acrylic plastic;
 4-acrylic plastic rod; 5-current lead wires; 6-acrylic plastic cap

Fig.2.32 Oscillograph OK-17 N 32
Upper beam - Signal from inductive probe ИДБС-3
Lower beam - Signal from inductive probe ИДБС-4
Time marks 4 μ s

Fig.2.33

Fig.2.34

Fig.2.35 Oscilloscope OK-17 N 33

Upper beam - Signal from piezoprobe ПД-3

Lower beam - Signal from piezoprobe ПД-4

Time marks 4 μ s

Fig.2.36

Fig.2.37 Signal from light probes

Fig.2.38 Signals from manganine probe

Fig.2.39

Fig.2.40

Scheme of probes situation in CMU

Fig.2.41

Scheme of probe situation in CMU

Fig.2.42

Scheme of probes situation in CMU

Scheme of probes situation in CMU

Fig. 2.44

Fig.2.45 Rough drawing of light open probes CD25 and CD26 in CMU for $z=16\text{mm}$.
 1-light guide $\varnothing 0.125$; 2-tube $\varnothing 1.75 \times \varnothing 1.55 \times 20\text{mm}$; 3-epoxy compound; 4-air gaps; 5-spigot $\varnothing 8 \times \varnothing 1.8 \times 10\text{ mm}$; 6-glass

Fig.2.46 1-tube $\varnothing 1.75$; 2-solder; 3-air gap ($h=1\text{mm}$); 4-spigot; 5-base; 6-foam plastic($=0.27\text{g/cm}^3$); 7-light guide; 8-contacts; 9-adhesive
 $Z=10\text{ mm}$ $\varphi=35, 65, 215, 245$

Fig.2.47 1-tube $\varnothing 1.75$; 2-solder; 3-air gap ($h=1\text{mm}$); 4-spigot; 5-base; 6-foam plastic($=0.27\text{ g/cm}^3$); 7-light guide; 8-contacts; 9-adhesive;
 $Z=10\text{ mm}$ $\varphi=50, 230$

Fig.2.48 1-adhesive; 2-light guides; 3-tube $\varnothing 1.25$; 4-kapron clamp; 5-base; 6-copper foil ($h=0.03\text{mm}$); 7-metal tube $\varnothing 0.4$; 8-air gap ($h=1\text{mm}$); 9-contacts;
 $Z=10\text{ mm } \varphi=15, 135, 195, 315$

Fig.2.49 1-foam plastic($\rho=0.27\text{g/cm}^3$); 2-tube $\phi 1.75$; 3-solder; 4-air gap ($h=1\text{mm}$); 5-spigot; 6-base; 7-contacts; 8-adhesive;
 $Z=10\text{ mm } \phi=115, 295$

Fig.2.50 1-kaprolon sleeve; 2-foam plastic ($\rho=0.27\text{g/cm}^3$); 3-tube $\varnothing 1.75\text{ mm}$; 4-solder; 5-tube $\varnothing 1.25$; 6-adhesive; 7-light guide; 8-base; 9-spigot; 10-copper foil ($h=0.1\text{mm}$); 11-contacts; 12-metal cap; 13-copper foil ($h=0.03\text{mm}$); 14-air gap ($h=1\text{mm}$); $Z=10\text{ mm}$ $\varphi=165, 345$

Fig 2.51 1-tube $\phi 0.3$ (about 1...3 pieces); 2-adhesive; 3-base; 4-spigot; 5-foam plastic ($\approx 0.27\text{g/cm}^3$); 6-solder; 7-tube $\phi 1.75$; 8-copper foil ($h=0.1\text{mm}$); 9-contacts

Fig.2.52 1,3-solder; 2-tube $\phi 1.75$; 4-tube $\phi 1.25$; 5-adhesive; 6-spigot; 7-base; 8-adhesive; 9-light guides; 10-air gap; $Z=5$ mm $\varphi=0, 180$

Fig.2.53 Oscillograph CYP N 3
Upper beam - Signal from resistive probe RD
Lower beam - Signal from resistive probe RA
Time marks $2 \mu\text{s}$

Fig.2.54 Oscillograph CYP N 4
Upper beam - Signal from resistive probe RD
Lower beam - Signal from resistive probe RA
Time marks $0.5 \mu\text{s}$

Fig.2.55 Experiment photochronogram ГСИ-100
Time marking 0.1 μ s

Fig.2.56

Fig.2.57

Fig.2.58

CMU probes operation diagram at azimuths 115 and 295 degrees

Fig.2.59

Fig.2.60 Oscillogram of the signal from manganine probe placed in CMU. Time marks $0.2 \mu\text{s}$

Fig.2.61

CMU probes operation R-t diagram (Z=10mm)

Fig.2.62

Fig.2.63

3. Theoretic and computational analysis of the results of physical measurements in experiment HEL-1. Comparison with expected results.

Report [1] presents the theoretic and computational justification of the physical scheme and principal parameters of the DEMG-PU system and central measuring unit (CMU), setting-up and computed results for various computation types are given which were used as a basis for prediction of the principal expected experimental results. This section is mainly devoted to comparison of the experimental data with these expected results for two basic systems of the experimental device: for the DEMG - PU and PU - CMU systems. Other results of the VNIIEF and LANL physical measurements [7] and computed results for these systems regarding the currents obtained in the experiments are also discussed.

3.1. DEMG - PU system operation

Figs. 3.9 - 3.11 of report [1] present three versions of temporal dependencies for the following characteristics of the DEMG - PU system measured in the experiment: current derivative with respect to time $\dot{I}(t)$, current $I(t)$, voltages in the coaxial $U_h(t)$ and radial $U_r(t)$ transmission lines, displacements of the outer boundaries of the body of these transmission lines $\Delta_h(t)$ and $\Delta_r(t)$. These three versions differ in the values unknown before the experiment of the DEMG initial current I_0 and magnetic flux losses in the DEMG - PU system additional to model [3]. The values $I_0 = 10 \text{ MA}$ and 11 MA are correspondent with the expected rated value ($I_0 = 10 \text{ MA}$) and upper estimate. The version with the value $I_0 = 9 \text{ MA}$ was considered as the lower estimate of the expected results. It is this version that the experimental data is compared with below, as $I_0^{(\text{exp})} \cong 9.1 \text{ MA}$; besides, this is compared with the new computations for $I \cong 9.1 \text{ MA}$ where the liner was computed in the 1D MHD approximation in contrast to the above-mentioned computations.

3.1.1. Temporal dependency of current derivative with respect to time.

This most important experimental dependency proved practically identical at various points of the DEMG-PU current circuit, namely, in the DEMG TL on the HEMG side and in the load up to the time when the main maximum was reached $\dot{I}_{\text{max}} \cong 5.5 \text{ MA}/\mu\text{s}$ (cf. the curve families in Figs. 1.13 and 1.14). This testifies, in contrast to the HEL - 1P experiment [1], for normal operation of the DEMG TL.

The difference between the above families of the experimental curves, as it should be, begins later, from time t_* when the shock waves leave DEMG explosive for DEMG TL. However, a considerable time difference of this process was observed

in the experiment, $\Delta t_s^{(11)} \sim 7 \mu s$, judging by the times when the values I_{max-1} recorded by inductive sensors 11/1 and 11/2 were reached (see Fig. 1.10). The actual value $\Delta t_s^{(exp)}$ was, undoubtedly, considerably less than the above value, probably, relating to the sensor 11/1 readings "spike" and coarse timing of the oscillographic measurements.

Figs. 3.1, 3.1a compare the computed results, predicted and specified, for the current derivative in the load and measured results for this value obtained from various inductive sensors. The subscript "exp" denotes the averaged oscillographic curve, subscripts "TL1" and "TL2" correspond to the results recorded from the TL-1 and TL-2 sensors with the "Tektonix" device. The last two reliable timing curves are used for timing other curves on the time scale originating from the time of VU - 19 - 1 actuation.

Mention two features of the curves being compared. First, there is a local non-monotonicity on the curves near I_{min} caused by termination of DEMG operation at $t \sim t_*$. Second, an abrupt growth in $I(t)$ is observed at $t > t_f \approx 297.7 \mu s$ due to the turn of the outer surface of the liner after its impact on CMU. In the 1D computation $\Delta t_f \rightarrow 0$, as here the process depends on the one-dimensional (cylindrical) diverging shock wave. The experimental values are $\Delta t_s^{(exp)} \approx 3.5 \mu s$ and $\Delta t_f^{(exp)} \approx 3 \mu s$.

Figs. 3.2, 3.2a compare the computed and experimental curves of the load currents similar to the comparison of the current derivative curves in Figs. 3.1, 3.1a.

The results of this computed and experimental data comparison are quite satisfactory:

This means that in the HEL - 1 experiment the DEMG - PU system operated close to the lower estimate made before the test. In the system magnetic flux losses additional to our model DISL - L [3] took place which are taken into account better through introduction of additional resistance $\Omega_{eff} \approx 0.13 m\Omega$ to the DEMG - PU current circuit than the values $L_{eff} \approx 1.4 nH$.

Precisely the same loss estimation provides the best description of the results of experiments with the same DEMG on the inductive load: the experiment of 1988 and experiment HEL - 1P, see Table 3.1 in report [1].

The magnetic flux losses in the HEL-1 experiment were less than in the similar liner experiment of 1988 [4] analyzed in report [1]. According to the computation of the DEMG - PU system for this experiment, the value $\Omega_{eff} = 0.13 m\Omega$ would have been correspondent with the maximum current $\sim 84 MA$ which is by $\sim 20\%$ higher than the experimental value of maximum current.

Thus, one may state the usefulness of some constructive measures taken before the HEL - 1 experiment to improve the electrical contacts between the current-carrying elements of the DEMG - PU current circuit [1], though these measures may have not resolved all the problems existing here.

Fig.3.1. Comparison of the averaged experimental curve for the load current derivative with computed curves [1] for $I_0=9.1$ MA (dotted line).

Fig.3.2. Comparison of the averaged experimental curve for the load current $I_{exp}(t)$ with computed curves [1] for $I_0=9$ MA (dotted line).

Fig.3.1a. Comparison of the experimental curves for the load current derivative obtained by sensors TL1 and TL2 with the specified computed curves for $I_0 = 9.1\text{MA}$ (dotted line).

Fig.3.2a. Comparison of the experimental curves for the load current obtained by sensor TL1 and $I_{exp}(t)$ with the specified computed curves for $I_0 = 9.1\text{MA}$ (dotted line).

3.1.2. DEMG - PU system voltages and TL wall displacements.

Figs. 3.3, 3.3a present the computed voltages $U_r(t)$ in the radial TL [1] compared to the experimental data obtained from two capacitance sensors. Here the comparison results are somewhat worse than in the previous section, especially when the main maximum on the curves compared has been reached. The causes of some voltage underestimation in the computation are known: the process of the DEMG "cutting-off" from the load is taken into account roughly and the magnetic field diffusion into the PU end walls opening at the liner implosion is not completely taken into consideration. The experimental data can be also specified more exactly after the frequency dependence of the measuring scheme has been taken into account and the data from the third capacitance sensor in the radial TL and measured results for voltage in the coaxial TL have been received from LANL.

Therefore, the results of the comparison of the experimental and computed voltages in the TL presented in Figs. 3.3, 3.3a do not allow to judge confidently about presence or absence in the experiment of additional magnetic flux losses at the joints of the TL current-carrying elements.

Note that the preliminary results of measurement of some of these additional voltages taken by LANL experts outside the DEMG-PU current circuit [7] also give no grounds to speak about any noticeable additional magnetic flux losses on the examined segments of this current circuit.

Fig. 3.4 presents the computed [1] displacements of the outer boundaries of the coaxial $\Delta_h(t)$ and radial $\Delta_r(t)$ transmission line walls compared to the experimental data.

The comparison results for these experimental and computed data improve if one assumes certain errors of the experimental data timing, see Fig. 3.4a.

The sensors for measuring the time difference Δt_D of DEMG module operation put at a distance of 2 mm from the DEMG body recorded the DEMG body scattering just under the action of the shock wave from the DEMG explosive charges, as the DEMG body displacement under magnetic pressure (see Fig. 3.4a) was considerably less. The late time of actuation of the sensors for charge No. 2 may be accounted for by presence of a thick steel flange (~ 27 mm) with an air gap (~ 7 mm) on the body, as this provides the shock wave time delay close to the experiment (by ~ 5 μ s and ~ 7 μ s, respectively).

Thus, the measured results for the time difference in the DEMG module operation may be considered satisfactory. The maximum time difference in operation of two neighboring modules was, most probably, for modules No. 4 and No. 5 and was no higher than 2 μ s. According to 2D DEMG computations [1], such a nonsynchronous operation of the DEMG modules could not lead to considerable additional magnetic flux losses in DEMG.

Fig.3.3. Comparison of experimental voltages in the radial TL with computed voltages for $I_0 = 9\text{MA}$ [1] (dotted line).

Fig.3.4. Computed displacements of coaxial Δ_h and radial Δ_r TL outer boundaries [1] compared to the experimental data (dotted line).

Fig.3.3a . Comparison of experimental voltages in the radial TL with specified computed voltages (dotted line).

Fig.3.4a. Computed displacements of coaxial Δt_h and radial Δt_r TL outer boundaries [1] compared to the experimental data modified for $\Delta t_h = -5 \mu s$ and $\Delta t_r = 7 \mu s$ (dotted line).

3.2. PU - CMU system operation.

3.2.1. Liner motion before impact on CMU.

Figs. 3.5, 3.5a present the computed ($R-t$) and ($v-t$) plots of the liner's inner and outer boundaries obtained from the liner MHD computations with setting the current curves shown in Figs. 3.2, 3.2a. The time dependencies of the liner's kinetic energy obtained in these computations are given in Figs. 3.6, 3.6a. According to these computations, the maximum values of liner velocity and kinetic energy are $v_l = (7.7 - 8.0) \text{ km}/\mu\text{s}$ and $E_{kin} = (23 - 26) \text{ MJ}$, and the impact begins at time $t_l \approx 295 \mu\text{s}$.

Computed ($R-t$) plots of the liner inner boundary are presented in Fig. 3.7 compared to some experimental data. The latter are obtained using inductive and piezoelectric sensors put on the PU end wall at angles $\varphi = 295^\circ$ and 115° (see Fig. 2.40), and using electric contact and light sensors put above CMU close to the PU ends in the angular sectors closest to the above ($z = 20 \text{ mm}$, $\varphi = 315^\circ$ и 135° ; $z = -15 \text{ mm}$, $\varphi \sim 0^\circ$) [7]) and near the PU symmetry plane ($z = 5 \text{ mm}$, $\varphi = 75^\circ$ and 255°). The experimental ($R-t$) plots in the five angular sectors under consideration are considerably spread (the complete time scatter in the data obtained over all the sensors is also shown: $\sim 5 \mu\text{s}$ for $R \approx 67 \text{ mm}$ and for $R \approx 56 \text{ mm}$).

Figs. 3.8, 3.8a^{*)} present the angular distribution of the time of appearance of signals from all the sensors put above CMU at radii from $R \approx 67 \text{ mm}$ to $\sim 56 \text{ mm}$. The data for $R = 67 \text{ mm}$ from various sensors to practically coincide in the angular sectors $\varphi = 25^\circ$, 135° and 205° but differ considerably at $\varphi = 75^\circ$ (ГЧИ and МАПТА) and at $\varphi = 255^\circ$ (ГЧИ and СУПН). This testifies for different actuation mechanisms of sensors of identical design. For example, 5 of 6 contact sensors positioned in the angular sector $\varphi = 75^\circ$ from $R = 67 \text{ mm}$ to $R = 56 \text{ mm}$ gave their signals practically simultaneously at $t \approx 296 \mu\text{s}$; probably, the electric contact between the cylindric case of the sensors and wires running from the contacts at $R = 67 \text{ mm}$ and 62 mm and positioned inside this case occurred at the radius $R \leq 56 \text{ mm}$. A similar pattern also took place in some other angular sectors (see below).

The velocity v_l of the processes responsible for the contact closing or light sensor actuation at the 1st measuring base (from $R = 67 \text{ mm}$ to $R = 62 \text{ mm}$) can be estimated basing on the available data in ~ 10 cases; a wide spread in the values of v_l is observed:

$$1.2 \leq v_l \leq 29 \text{ [km/s]}$$

^{*)} $\theta = \begin{cases} \varphi + 158, & \varphi < 202^\circ; \\ \varphi - 202^\circ, & \varphi \geq 202^\circ. \end{cases}$

Fig.3.5. Computed (R-t) and (v-t) plots of liner's inner and outer boundaries for $I_{\text{HJI}}(t)$.

Fig.3.6. Computed temporal dependencies of liner's kinetic energy for $I_{\text{HJI}}(t)$ and $I_0 = 9 \text{ MA}$ (dotted line).

Fig.3.5a. Specified computed (R-t) and (v-t) plots of liner's inner and outer boundaries for $I_0 = 9.1 \text{ MA}$.

Fig.3.6a. Computed temporal dependencies of liner's kinetic energy for $I_{\text{III}}(t)$ and $I_0 = 9.1 \text{ MA}$ (dotted line).

As a rule, it was impossible to obtain similar velocities v_2 and v_3 at the 2nd and 3d measuring bases due to practically simultaneous appearance of signals from the sensors located at deeper radii (like at $\varphi = 75^\circ$, see above). This is testified for by the data from 6 sensor sets: A3 ($\varphi = 25^\circ$), A1N1 ($\varphi = 75^\circ$, ГСН, MAPTA), A1N2 ($\varphi = 135^\circ$), A ($\varphi = 135^\circ$) and A1N3 ($\varphi = 255^\circ$). Only in three cases it is possible to estimate the values v_2 ($\varphi = 135^\circ$, 255° and 315°):

$$v_2 \cong 6 \text{ km/s}, 4.2 \text{ km/s} \text{ and } (6-11) \text{ km/s},$$

with $v_2 < v_1$ in one case ($\varphi = 135^\circ$, where the contact which actuated earlier than the others was that located at the minimum radius $\sim 56 \text{ mm}$). A similar pattern also took place at $\varphi = 75^\circ$ (ГСН, MARTA) and $\varphi = 255^\circ$ (СУП).

The spread under discussion and some contradictions of the available experimental data, as it was already mentioned above, testify for a different actuation mechanism of the sensors. This mechanism depends not only on the liner velocity and state, but also on actual sensor manufacture details deteriorating the electric contact at the design point R_c and improving the electric contact at the off-design point $R < R_c$ (for example, some sensors might be without shielding with Cu foil at $R_c \cong 67 \text{ mm}$; glue thickness might be different between the Cu foil and contact at $R_c \cong 67 \text{ mm}$ or between the sensor case and wires inside the case; the wires might have its insulation defective, etc.).

The liner state, namely, "the degree of liner condensedness" is a determining factor for the design hydrodynamical mechanism of spent sensor actuation (the cylindric nickel sensor cases are 0.3 mm in outer diameter, 0.2 mm in inner diameter, insulated copper or nichrome wires inside these cases are $0.05 - 0.07 \text{ mm}$ in diameter depending on their number). Off-design operation of the resistive sensor RA, in contrast to similar sensor RD positioned inside CMU, testifies for unreliability of the electric contact maintenance by the actual mechanism of the liner-sensor coupling (the lower the liner density, the more reliable the electric contact). In addition, the actual asymmetry of the liner motion might have considerably upset the design mechanism of sensor operation providing for only a small liner asymmetry.

Therefore the pattern of the angular time difference of the signals from the sensors positioned at radii $R = 67 \text{ mm}$ and 56 mm presented in Figs. 3.8, 3.8a should be considered but as the estimate of the angular asymmetry of the liner motion.

The longitudinal asymmetry of the liner motion may be estimated similarly by comparing the measured results discussed for $z = 5 \text{ mm}$ and results for $z = 20 \text{ mm}$ ($\varphi = 135^\circ$ and 315° , see Figs. 3.7, 3.8, 3.7a, 3.8a). On the $z = 5 + 20 \text{ mm}$ measurement base the near-wall liner part is seen to be ahead no more than $\sim 2 \mu\text{s}$, that is $\Delta R \leq \Delta z$, which agrees with 2D computations taking into account liner's interaction with PU end walls (see, for example, the figure 2.2.29 in report [1]).

Note that a close and more detailed pattern of the longitudinal time difference is provided by signals from LANL light sensors positioned at $R = 65 \text{ mm}$, $\varphi = 22^\circ$ ($z = 5-15-20-25 \text{ mm}$, sensors A8-C7-D2-E2): $t \cong 296.25 - 295.0 - 294.55 - 294.15 \mu\text{s}$,

respectively^{*)}. So one may expect that in the angular sector $\varphi = 315^\circ - 22^\circ$ liner's motion was symmetric about the plane $z = 0$.

3.2.2. Velocity and angular asymmetry of liner impact on CMU.

The experimental value of the maximum velocity v_l^{exp} of liner impact on CMU, if it had been estimated only by sensors outside CMU, would have had a larger error and would have been actually estimated "experimentally and computationally", through comparison of the experimental and computed (R - t) plots (see it.3.2.1: $v_l^{(exp)} \sim v_l^{(calc)}$). However, straightforward measurement of this velocity [1] on the base from $R = 56 \text{ mm}$ to $R = 53 \text{ mm}$ was also provided specifically for [1] using two sets of contact sensors positioned inside CMU at $z = 10 \text{ mm}$, i.e. the set of sensors E1-E3 ($\varphi = 50^\circ \pm 15^\circ$) and E4-E6 ($\varphi = 230^\circ \pm 15^\circ$). The former of these sensor sets provided the following values of $v_l^{(exp)}$ (ГЧН-МАРТА):

$$\begin{cases} (8.44 - 7.24) \text{ km/s}, & \varphi = 50^\circ - 65^\circ, \\ (8.36 - 8.36) \text{ km/s}, & \varphi = 35^\circ - 50^\circ. \end{cases}$$

Here the spread in the results is, most probably, due to the liner's angular asymmetry increasing with φ at $\varphi \geq 60^\circ$, see Fig. 3.8. For a similar reason the second sensor set provided even a wider spread in the data which did not allow to estimate $v_l^{(exp)}$ (20.8 km/s and 1.16 km/s).

Thus, in the angular sector $\varphi = 35^\circ - 50^\circ$ the value $v_l^{(exp)} \cong 8.4 \text{ km/s}$ is recorded which is higher than the maximum computed value (see Fig. 3.5). This experimental liner velocity value is correspondent with the computed liner kinetic energy $\sim 30 \text{ MJ}$.

The angular time difference in the process of the liner impact on CMU is seen from Figs. 3.9, 3.9a which present the measured times of recording the first shock wave in CMU ($z = 10 \text{ mm}$): near the outer surface of the CMU case ($R \approx 51 \text{ mm}$) and after passage of this wave onto the inner free surface of the CMU case ($R = R_{min} \cong 32 \text{ mm}$ and $R = 34 \text{ mm}$). LANL results for $R = 50 \text{ mm}$ are also presented here.

The comparison of Figs. 3.9 and 3.8 shows that the shock wave angular time difference at $R = 51 \text{ mm}$ is quantitatively close to the angular time difference in the

^{*)} Signals from similar LANL sensors positioned at $\varphi = 202^\circ$ (A1, B1, C1, D1, E1) appear practically simultaneously at $t \cong 287 \mu\text{s}$ and may be of off-design character [2.3]. There is their correlation with the ГЧН data providing earlier signals in the close angular sectors $\varphi = 135^\circ$ and 255° and especially with the data from the light sensors CD25 and CD26 ($\varphi = 0^\circ$ and 180° , $z = 16 \text{ mm}$) which provide the maximum angular time difference of the signal appearance beginning on the order of $12 \mu\text{s}$ ($t|_{\varphi=0^\circ} = 297.2 \mu\text{s}$ and $t|_{\varphi=180^\circ} \leq 285 \mu\text{s}$).

Fig.3.7. Comparison of computed (R - t) plots of liner's inner boundary (see Figs.3.5 and 3.5a) with the experimental data ((z, ϕ) - dotted line).

Fig.3.8. Experimental data for the angular (ϕ) and longitudinal (z) time difference of liner's approach to CMU.

Fig.3.9. Experimental data for the angular (ϕ) and longitudinal propagation of the shock wave in CMU.

Fig.3.8a. Some experimental data for the angular (θ) and longitudinal (z) time difference of liner's approach to CMU.

Fig.3.9a. Experimental data for the angular (θ) and longitudinal propagation of the shock wave in CMU.

liner's approach to CMU, but the total time difference value is lower: $\Delta t_{\varphi}^{(max)} \cong 4 \mu s$. At $R \cong 51 \text{ mm}$ advancing areas remain in two angular sectors ($\varphi \cong 245^\circ$ and 165° , the data of ΓCH only). Outside these relatively narrow angular sectors the shock wave angular time difference is not larger than $1 \mu s$, with the data from various sensors agreeing with each other: ΓCH and MAPTA ($\varphi = 345^\circ, 35^\circ, 65^\circ, 115^\circ$), electric-contact and resistive ($\varphi = 295^\circ$). The signals from the light sensors provide a close shock wave angular time difference, but are delayed by $\sim 1 \mu s$ relative to the signals from electric contact sensors ($\varphi = 345^\circ$ and 35°).

Note that the shock wave angular time difference in CMU recorded by four LANL light sensors at $z = -15 \text{ mm}$ and $R = 50 \text{ mm}$ (C2, C5, C8, C11) [7] was not larger than $0.7 \mu s$. The angular dependence of this time difference is close to the VNIIEF data, excluding two above-mentioned narrow angular sectors $\varphi = 165^\circ$ and 245° (where the ΓCH results give advancement by $\sim 1 \mu s$ and $\sim 2 \mu s$, respectively).

The angular time difference of shock wave escape from CMU is measured in smaller angular intervals: at $R \cong 34 \text{ mm}$ 4 measurements are taken ($\varphi = 295^\circ - 315^\circ - 15^\circ, \Delta\varphi = 80^\circ$), at $R \cong 32 \text{ mm}$ there are 6 measurements ($\varphi = 295^\circ - 315^\circ - 15^\circ - 135^\circ, \Delta\varphi = 200^\circ$). This angular time difference in the measured angular intervals is close in its character and quantity to the shock wave time difference near the outer CMU surface,

3.2.3. Parameters of shock wave in CMU

Fig.3.10 compares the experimental ($R-t$) plots of the shock wave in the CMU steel case measured using the electric contact and resistive sensors at $z = 10 \text{ mm}$, $\varphi = 115^\circ$ and 295° with the computations. Two computed ($R-t$) plots correspond to the rated 1D MHD computation and model computation which differs from the rated computation in the fact that it imitates preservation of the liner's condensed state only in some liner part $m_{eff}/m \sim 1/3$ [1], where m is the initial linear mass of the liner (the absolute times are conventional here). The computed profiles of the MHD values in the liner before the impact on CMU and of HD values in CMU obtained in these computations are presented in Figs. 3.11 - 3.12.

The preliminary analysis of the results presented in Fig. 3.10 - 3.12 allow to draw the following basic conclusions.

1. The rated computed ($R-t$) plots can be considered close to the experimental ($R-t$) plots, if possible errors of the measured results, especially at the first measurement base^{*)}, are taken into account.

2. Most probably, in the angular sector $\varphi = 115^\circ$ a stronger shock wave realized than in the angular sector $\varphi = 295^\circ$. Here the data from both the sensor sets (D1*-I and D-I, $\varphi = 115^\circ$) are in good agreement providing an identical value

^{*)} The mechanism of the sensor actuation at the ends of the first measuring base may be different, so the first measured time interval may depend not only on the shock wave velocity.

Fig.3.10. Comparison of the experimental ($R-t$) plots for the shock wave in CMU with two computations ($\Delta t \approx 1.5 \mu s$), in one of which the liner's effective linear mass is reduced by a factor of 3.

Fig.3.11. Computed profiles of MHD values in the liner before impact on CMU ($m_{eff} = 1/3m$ - dotted line).

Fig.3.12. Computed shock wave profiles near the outer and inner CMU surfaces, $\Delta t = 1.8 \mu\text{s}$. ($m_{eff} = 1/3m$ - dotted line).

of the average shock wave velocity $\bar{D} = 10.75 \text{ km/s}$ and close values of the shock wave velocity estimated (at the last measuring base): $D_f = 9.45 \text{ km/s}$ and 9.1 km/s . Similar data for $\varphi = 295^\circ$ from the sensors D1*-M and RD are $\bar{D} = 9.0 \text{ km/s}$ and 9.5 km/s , $D_f = 8.25 \text{ km/s}$ and 8.8 km/s , respectively. In both the cases a noticeable shock wave attenuation may have taken place.

3. It should not be ruled out that at least in the angular sector $\varphi \approx 295^\circ$ the shock wave was more intensive than in the rated computations, but was generated by a lower effective mass of the liner remaining in the condensed state (according to the estimations, $v_l \approx 10 \text{ km/s}$, but $m_{\text{eff}}/m \leq 1/3$).

These conclusions might be verified if it were possible to measure the pressure attenuation in the shock wave propagating over the CMU case. Unfortunately, only some data is obtained for the mass velocities arising after the shock wave passage to the steel free surface near the outer CMU boundary (u_0 , $R = 50 - 48 \text{ mm}$) and near the inner CMU boundary (u_f , $R = 34 - 32 \text{ mm}$):

$$u_{0|\varphi=165} \approx 3.75 \text{ km/s (ГЧИ)}; \quad u_{0|\varphi=345} \approx \begin{cases} 19.5 \text{ km/s (ГЧИ)}, \\ 23.4 \text{ km/s (МАРТА)}; \end{cases}$$

$$u_{f|\varphi=295} \approx 4 \text{ km/s (RD)}; \quad u_{f|\varphi=315} \approx 7.4 \text{ km/s (ГЧИ)};$$

$$u_{f|\varphi=15} \approx 1.75 \text{ km/s (МАРТА)},$$

The shock wave parameters corresponding to this data which was obtained with the method of (P-u) plots for steel are presented in Table 3.1 (P, u - pressure and mass velocity at the shock wave front, D - velocity of the shock wave front).

Table 3.1

φ	u_0, u_f km/s	u km/s	D km/s	P Mbar
15°	2 (u_f)	1	5.4	0.42
$\begin{Bmatrix} 295^\circ \\ 165^\circ \end{Bmatrix}$	4 $\begin{Bmatrix} u_f \\ u_0 \end{Bmatrix}$	2	7.0	1.1
315°	7.4 (u_f)	3.5	9.5	2.6
345°	20 (u_0)	8	16	10

Basing on this data, it should not be ruled out that in the angular sector $\varphi = 345^\circ$ the shock wave was most intensive, but also was attenuated most

severely during its propagation through the CMU thickness, i.e. was generated by a very low liner mass $m_{eff} \ll m$ remaining in the condensed state and additionally accelerated before the liner failure due to severe growth in the liner initial perturbations (see Sections 2.3 and A.1 in report [1]). The quantitative characteristics of this wave presented in Table 3.1 seem highly improbable in the experiment as in the nearest angular sector $\varphi = 295^\circ$ the shock wave was relatively weak. Besides, the shock wave of even less intensity leads to evaporation of the near-boundary steel mass, in doing so the design hydrodynamic mechanism of the sensor contact closing may be violated and measurement errors may increase. The design mechanism of operation of some sensors can also be upset due to the shock wave asymmetry in CMU, for example, due to the angular asymmetry near $\varphi = 245^\circ$, $z = 10 \text{ mm}$.

CONCLUSION

The report presents a large amount of the experimental data characterizing operation of all principal units of the experimental device: helical EMG, disk EMG, transmission lines, PU, CMU.

The principal PU and CMU parameters are as follows: the cylindrical liner was 9.7 cm in height, 24 cm in radius, 4 mm in thickness, no more than 6 μm in thickness on the 8 mm base, its material was Amg-6 alloy, the inclination angles of the PU end walls were 6° ; the cylindrical body of CMU was 55 mm and 25 mm in outer and inner radii and made of type 30X13 high-strength steel (VNIIEF's share).

In the transmission lines inductive and capacitance sensors were put which were used to obtain the temporal dependencies of the current derivative and voltage. On the PU end walls inductive and piezoelectric sensors were put which recorded the liner motion on the base $R = 150\text{-}100 \text{ mm}$. The electric contact, resistive and light sensors of CMU recorded the velocity and symmetry of the liner's approach to CMU and the shock wave parameters in the CMU material.

The results of the preliminary incomplete analysis of the experimental data allow to draw the following basic conclusions.

1. The DEMG had generated a current pulse $\sim 105 \text{ MA}$ in amplitude close to the norm in the load which had been expected according to the computations for the initial current $I_0 \sim 9.1 \text{ MA}$ obtained in the experiment. The latter proved near the lower limit of the expected values. The principal computed liner characteristics corresponding to this current are as follows: kinetic energy $\sim 26 \text{ MJ}$, maximum velocity $\sim 8.0 \text{ km/s}$.
2. The experimental and computed characteristics of the liner motion before the impact on CMU taking into account their errors are in a good agreement. The velocity, as well as angular and longitudinal time difference in the liner's approach to CMU are measured. The experimental value of the maximum velocity equals 8.4 km/s which is close to the computation and corresponds to the liner's kinetic energy $\sim 30 \text{ MJ}$. This reliably measured value of the liner velocity corresponds to the retarding part of the liner ($\varphi = 35^\circ\text{-}65^\circ$). The liner velocity of the advancing part ($\varphi = 295^\circ\text{-}315^\circ$) exceeded 10 km/s .

3. The longitudinal asymmetry of the liner is close to the expected according to the computations: the recorded maximum time difference is $\sim 1.5 \mu s$. The angular time difference in the liner's approach to CMU is $\sim 1 \mu s$, excluding a small portion of the angular sector $\sim 20\%$ where a considerable advance of the signals obtained from the sensors and requiring an additional analysis was observed.
4. The shock wave angular time difference in CMU was measured that was not higher than $1 \mu s$ which corresponds to the shock wave angular asymmetry of no more than 20% (as a minimum, in the major fraction of the angular sector this was $\sim 80\%$). The $(R-t)$ plots of the CMU shock wave were measured which were close to the computed $(R-t)$ plots. The characteristic shock wave parameters are as follows: front velocity $\sim 9 \text{ km/s}$, mass velocity $\sim 3 \text{ km/s}$ (pressure $\sim 2 \text{ Mbar}$).
5. The experimental indications are obtained that at the impact on CMU not the whole liner thickness remained in the condensed state, as it was expected according to the 2D computations of the growth in small initial perturbations of the liner.

The conclusions about the symmetry of the liner's approach to CMU, about the symmetry of the shock wave in CMU and about the liner state before the impact on CMU are of a tentative character and will be specified more exactly upon the additional analysis of the VNIIEF and LANL experimental data.

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