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CHANGING MASS LINER SYSTEM
FOR GENERATION OF SOFT X- RADIATION.
(Clause F.4.2 of contract 4769M0014-9Y)

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Introduction

This report is issued in compliance with Clause F.4.2 of Contract 4769M0014-9Y "Design study for X-ray generation". In the first report [1] (Clause F.4.1 of Contract) three systems were considered to solve the formulated problem. All of them were designed on the basis of employment of Ø400mm disk explosive-magnetic generators (DEMG) as an energy source using a high-speed (25-30cm/µs) liner converging to the axis. The considered systems differ in modes of current pulse formation.

For further effort the customer has chosen System 3 (in terms of the report [1]) with the changing mass liner¹. In accordance with this fact this report discusses basic theoretic and computational results obtained to date by System 3. Further development of the theory of the considered system is suggested in the context of the series of experiments the ultimate goal of which is to generate soft X-radiation. Section 5 gives principal alternations in making the first experiment being planned as compared to the report [1]. Basic stages of the effort to generate soft X-radiation are discussed on the basis of the schedule given in [1] with consideration of some corrections which occurred when the system type had been selected.

¹ As in the report [1], here and below by the changing mass liner is meant a liner for which mass of its "operational" part changes due to interaction with walls or change in its shape.

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1. Physical scheme of changing mass liner device

The chart of the considered device designed to generate soft X-radiation is shown in Fig. 1.1. Current from DEMG is fed to aluminium liner 2 of $\sim 0.5\text{mm}$ thickness via vacuum transmission line 1. The liner is accelerated by the magnetic field between current-feeding walls 3,4. By the time when maximum current is achieved, liner velocity is $0.5\div 0.7\text{cm}/\mu\text{s}$. At this time one liner edge slides down from the current-feeding wall and flies further opening the annular slot between the wall and the liner. Through the slot enlarging with time magnetic flux of the vacuum transmission line goes to the vacuum chamber 6 where magnetic acceleration and convergence to the axis of the current plasma crosspiece take place. The crosspiece is formed in the process of liner sliding down from the current-feeding wall. Its mass is much less than that of the liner 2 that is substantiated by the results of the experiment [2] with the device similar to the considered as the crosspiece formation is concerned. At the stage of operation of the vacuum chamber 6 the crosspiece plays the role of an independent liner to which acceleration magnetic energy accumulated in the vacuum transmission line is spent. As mentioned in the previous report under this contract [1], an important feature of the considered system is that, besides sharp decrease in liner mass in the process of formation of the crosspiece, smooth decrease in mass per length unity in the process of its acceleration also takes place. This decrease is related to the process of flowing-out of the plasma

"bubble" toroidal in shape. According to the calculation results given in [1], the above processes of decrease in mass being accelerated allow to obtain sufficiently high energies and convergence rates of the plasma liner ($\sim 25\div 30\text{cm}/\mu\text{s}$) without employment of special DEMG current pulse sharpeners.

The process of formation of the current crosspiece and its mass can be considerably impacted by near-wall effects related to liner strength and plasticity properties which show up at the initial stage of liner acceleration. To avoid uncertainties related to the above near-wall effects, the cutoff 5 is placed at the end of the liner flight base (Fig. 1.1).

A similar cutoff was also in the experiment [2]. The main purpose of the cutoff is to cut off and impede the near-wall liner portion to allow the current crosspiece to form on the unperturbed liner portion. Of course, the cutoff serves also as a perturbation source for the sliding-down portion of the liner. However, as we see it, amount of these perturbations is considerably less and predictability of their effect is essentially higher than for near-wall ones.

It is related to the fact that the liner flies against the cutoff in liquid state. The acceleration path of the liner, its thickness and velocity are computationally selected in such a way that by the time of impact on the cutoff the liner were surely molten but not brought to the start of evaporation.

One of negative features of the cutoff being considered is that after the impact of the liner a shock wave arises in it. When the shock wave goes out to the free (rear) surface, splitting-off or

even evaporation of a portion of the cutoff is possible, depending on liner velocity. To reduce shock pressure in the cutoff, liner velocity reduction may be used or other measures which cushion liner impact may be undertaken. According to estimations, when aluminium liner velocity is 10 km/s and other special measures are not taken, evaporation of a part of the cutoff by the shock wave may occur. When liner velocity is reduced down to 5+7km/s, estimations testify for feasibility of a mode where there is no evaporation and the cutoff material velocity after the shock wave has gone out to the free surface is 2+3km/s. Because of this it seems reasonable to reduce liner velocity as compared to the experiment [2] from 10km/s to 5+7km/s. Moreover, it seems reasonable to increase the radius of liner sliding-down from 12cm to ~20cm, maximal current (~70 MA) being retained, in order to reduce maximum value of the magnetic field from 1.2 MOe to ~0.7MOe. It will allow to reduce Joule heating of the surface layer of the current-feeding walls ^{by} a factor of ~3, so that the wall surface will remain even non-molten. In addition, it might allow to avoid aluminium evaporation from the side surface of the liner portion that has slid-down (see Section 2).

2. On mechanism of current crosspiece formation

Consider the process of liquid liner sliding down from the current-feeding wall. Fig. 2.1 gives the chart of mutual arrangement of the liner and the wall during crosspiece formation. The arrow shows the direction of liner motion.

Liner can slide down both in supersonic and subsonic modes, depending on liner velocity. Speed of perturbation propagation under the conditions of concern to us practically coincides with gasodynamical sound speed, since magnetosound speed is much less than gasodynamical. Gasodynamical sound speed in molten aluminium is $\sim 5\text{km/s}$. First consider the supersonic mode.

In this case, if one takes into consideration magnetic field diffusion, the edge of the current-feeding wall begins to considerably influence on the outer liner surface, when the parameter Δ (see Fig. 2.1) becomes of the order of diffusion length $\Delta \sim \alpha/V$, where α -diffusion factor, V -liner velocity. Diffusion factor of magnetic field in liquid aluminium is $\alpha \sim 2.5 \cdot 10^3 \text{cm}^2/\mu\text{s}$, so that $\Delta \sim 2.5 \cdot 10^3 \text{cm}$ with $V = 1 \text{cm}/\mu\text{s}$ and $\Delta \sim 5 \cdot 10^3 \text{cm}$ with $V = 0.5 \text{cm}/\mu\text{s}$. One may expect that since the above mentioned time current manages to level off in the thinning current crosspiece and the crosspiece begins to be intensely accelerated by magnetic pressure and intensely heated by Joule heat.

Estimates show that the crosspiece of α/V thickness explodes practically instantaneously, without further thinning, under the action of current flowing through it. Thus, one can take the

condition $\Delta \sim \frac{x}{V}$ as the criterion for determining the time of current crosspiece formation from the liquid sliding-down liner. Note that obtained characteristic size of the current crosspiece turns out only to depend under the conditions of our concern on liner heat state and liner velocity. The characteristic size Δ turns out to be much less than liner thickness.

Consideration of subsonic mode shows that the criterion of current crosspiece formation time, $\Delta \sim \frac{x}{V}$, remains the same as in supersonic mode. It is related to the fact that squared current density in the crosspiece increases as $\frac{1}{\Delta^2}$ with its thinning, while pressure gradient as $\frac{1}{\Delta}$. For this reason the crosspiece explodes under the action of current earlier than considerable change in its velocity is built up.

Current crosspiece formation can be effected by the slid-down liner portion. In the slid-down liner portion, from its side, the rarefaction wave must propagate (see Fig. 2.1). If the value of magnetic field frozen in the liner is higher than some critical value, then magnetic field diffusion near the liner side must lead to liner material evaporation. According to our estimates² the above value of the magnetic field in the liner is $\sim 1.2 \text{ MOe}$. If the magnetic field in the liner is less than critical, then side unloading can be without evaporation. In this case liner side surface velocity equals double magnetosound speed in the liner and is $0.14 \text{ cm}/\mu\text{s}$ when $H=0.7 \text{ MOe}$. For magnetic fields higher than the critical value,

²The estimates are made under the assumption that volume density of Joule energy released with unloading is approximately equal to initial density of magnetic energy. This assumption has to be verified.

i.e. in the mode of unloading with evaporation, surface velocity must be higher, therefore such a mode is not desirable.

After electric explosion of the current crosspiece one portion of evaporated aluminium must propagate into the area under the liner, while the other-into the area above the liner, since heat pressure at the crosspiece explosion is much higher than magnetic pressure above the liner. After a time, after expanding vapors above the liner have stopped by magnetic field, the process of reverse flow of vapors into the gap between the slid-down liner and the current-feeding wall starts. The process of plasma current shell formation may be basically considered completed when all evaporated material from the area above the liner is pushed by the magnetic field into the area under the liner. To make quantitative description of the processes considered here it is hard to do^{it} with some simple estimations. Quite complex two-dimensional MHD-computations are needed. These computations will be performed for specific experimental systems.

3. Quasi-two-dimensional calculations of plasma shell motion with account of reflection from side walls.

The quasi-two-dimensional computer program (in the approximation of infinitesimally small thickness) which was used to compute the plasma shell as given in [1], was extended to account reflection of the plasma shell from side walls when it impacts on them. Shell reflection was assumed elastic, though the impact on the wall may be not quite elastic due to energy losses to radiation. Shell motion after reflection from the wall was considered in two variants. In the first variant the fact was taken into account that the shell continues to interact with the magnetic field after the impact in the same way as before the impact and it leads to its deceleration by the magnetic field after the impact.

In the second variant it was assumed that the shell after the impact flies by inertia, not being decelerated by the magnetic field (rough account of Rayleigh-Taylor instability).

The results of the computations with and without account of shell deceleration are given in Figs.3.1 and 3.2, respectively. The results with account of deceleration provide a more favourable situation. During all the time of plasma shell motion a sufficiently wide channel remains free for the magnetic flux to flow to the shell portion converging towards the axis. Such a situation is also favourable from the energetic standpoint, since when a shell portion

reflects from the walls, system inductance decreases and current increases.

Computations without account of deceleration, as it is seen from Fig. 3.2, give an unfavourable result. Shell portions reflected from the walls manage to impact with each other before the time of central shell portion focusing.

The results obtained testify for the fact that the issues pertaining to shell reflection from walls need to be studied further. Possibly, the distance between walls will have to be increased. Computation results for increased distance between walls are given in Fig. 3.3. The results are favourable.

4. One-dimensional MHD-calculation of liner implosion with account of decrease in liner mass per length unity.

In paper [1] liner thickness was estimated using quasi-stationary solution. To take into account the effect of the non-stationary problem, the one-dimensional MHD-calculation of liner implosion with account of decrease in liner mass per length unity was performed. Total liner mass (0.09g) is constant in time. In this calculation the liner remains cylindrical, but being between conical walls. The distance between the walls increases linearly from 0.0025cm to 2cm as the radius decreases from 20cm to zero. The initial (mean) liner radius was set to be 19.975cm. Radiant heat transfer was taken into account in the calculation in the "to-and-fro" approximation. Current in the liner was given as the function of its outer radius. This function was taken from the quasi-two-dimensional calculation similar to that given in [1]. To increase liner kinetic energy up to 4MJ accumulative inductance was increased from 10 to 15nH and initial current in the inductance was increased from 60 to 70MA. As we see it, owing to development of instabilities the internal liner boundary should not cumulate exactly to the axis. The stagnation of liner particles will take place in the region of the characteristic radius of the order of one centimetre. To take into account this circumstance in some way and limit the growth of liner mass per square centimetre, a rigid wall was put at the radius of $R=1\text{cm}$ in the one-dimensional calculation.

The calculation results are as follows. Fig. 4.1 shows dependence of liner thickness on its outer radius. It also gives the results of quasi-stationary estimations (dashed curve) by the formulas from [1]. Fig. 4.2 gives time dependence of outer and inner liner radii. Maximum value of average liner velocity is $31\text{cm}/\mu\text{s}$ (before the impact). Maximum value of liner kinetic energy is 4MJ . Energy released by the liner in the course of its impact on the wall is 2.7MJ . In the calculation the characteristic radiation time is $\sim 1\text{ns}$. The obtained calculational parameters are considered satisfactory at this stage.

5. On making the first experiment.

The design of the device intended for the first experiment remained basically the same to date, as in report [1]. The changes which took place are as follows.

1. The number of disks in DEMG decreases from 10 to 5 owing to shortage of funding. It leads to the fact that in the process of liner motion in the model experiment current will reduce much faster owing to small accumulative inductance than in a large-scale experiment. Current reduction (as compared to a large-scale experiment) will also take place at the initial stage. Calculations show that this reduction seems to be relatively small ($I_0 \sim 40 \div 50 \text{ MA}$ instead of $I_0 \sim 70 \text{ MA}$ in a large-scale system).
2. In the model test, as well as in the test [2], a cutoff is put on the path of the liner.
3. The radius of liner sliding point is suggested to somewhat increase as compared to the experiment [2] in order to reduce the operational value of the magnetic field in the zone of current crosspiece formation in accordance with some conclusions of Section 2. Moreover, it is suggested to decrease liner velocity at the time of crosspiece formation from 10 km/s to $5\text{-}7 \text{ km/s}$ with retaining the liner thickness-velocity ratio, i.e. with keeping its molten state. Decrease in liner velocity is needed to attenuate intensity of the shock wave in the cutoff and to improve cutoff operation which was discussed in Section 1.

Conclusion. Basic stages of works on designing the system for generation of soft X-radiation of about 2MJ total energy.

1. Performance of 2 or 3 model experiments.

1.1. In the first 1 or 2 experiments without the vacuum transmission line parameters of the flying liner formed from the plasma crosspiece at the initial stage are measured. The number of DEMG disks is $N=5$.

The term of performance - the year 1995.

1.2. Performance of 1 or 2 experiments with the vacuum transmission line. The number of disks is 5-10.

The term - the year 1996.

1.3. Performance of the experiment with 15-disk DEMG (with the vacuum transmission line) in order to obtain soft X-radiation with measurement of radiation amount and spectrum.

The term - the years 1996-1997.

2. If it is needed to increase amount or hardness of X-radiation, 2 or 3 experiments with 25-disk DEMG is performed.

2.1. Designing and testing of spiral EMG capable to energize 25-disk DEMG with 6-7MA current

The term - the year 1996.

2.2. Performance of 1 or 2 experiments with 25-disk DEMG in order to measure the parameters of the imploding liner.

The term-the year 1997.

2.3. Performance of the experiment with 25-disk DEMG in order to obtain soft X-radiation of about 2MJ energy.

The term-the year 1998.

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Fig . 1 . 1

Chart of the device with the changing mass liner

- 1 - Vacuum transmission line
- 2 - Al- liner
- 3 , 4 - current - feeding wall
- 5 - cutoff
- 6 - vacuum chamber.

Fig . 2 .1

Liner and current - feeding wall configuration.

- 1 - Liner in liquid state
- 2 - Current - feeding wall
- 3 - Rarefaction wave front
- 4 - Liner motion direction.

Geometry of the liner converging to
the axis in successive times
(with account of liner deceleration
by the magnetic field after reflection
from the walls)

Fig. 3.1.

Fig. 4.1. Liner thickness vs its radius

Fig. 4.2. Liner boundaries vs time

Geometry of the liner converging to
the axis in successive times
(without account of liner deceleration
after reflection from the walls).
The distance between the walls
is increased (see Fig.3.2.).

Fig. 3.3.