1. Introduction

The explosion – magnetic generators (EMG) [1], which were developed, are the pulsed energy converters and allow one to get pulses of electric current with the amplitude of $10^4-10^8$ and power of up to $5 \cdot 10^{12}$W. Complete destruction of such devices in each pulse prevents their wide use. This is stipulated not only by the essential device cost, but by particular conditions of usage as well. At the same time EMG has a very high power gain factor $K_w = 30-100$, the value of which is defined as the ratio of the acceleration time of conductors and the time of their slowing down by the pressure generated by a magnetic field in a high–current output electrical circuit. This EMG characteristic is attractive for realisation in a laboratory power amplifier, where it is possible to realise an acceleration of a conducting armature by electromagnetic forces. The inductive store or capacitor bank can be used as primary energy sources for the acceleration. Thus, the electrical pulse generator can be transformed into a pulsed power sharpener – magnetic compressor (MC).

As a basis, the authors of the designed laboratory device have taken the system of flat accelerating liners, launched towards each other. In the paper, the concept of a device is substantiated. According to preliminary estimates it will allow one to get an output current pulse of duration of 3-5μsec and amplitude of 10MA at the voltage of up to 100kV.

The physical and two - dimensional mathematical models of the process of electromagnetic acceleration of a laminar metallic liner have been constructed. The numerical algorithm has been realised in a software code for a PC. The programs developed are for the simulation of versions of the device, with which the experiments on the study of energy compression have been conducted. There were investigated some special features of motion of the liners, which during acceleration and slowing down in a magnetic field change shape from flat one. In the paper, the results of simulations of launches of flat shells are of compared with experimental results, obtained on a small test sharpener model with the liner of 30 mm width and 250mm length.

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2. The geometric concept of the electromagnetic power sharpener

The TRINITI Centre acquired an experience in an electromagnetic launch of heavy cylindrical shells (liners) to velocities of 1-5km/s [2-4] for compressing magnetic field and plasma in thermonuclear Θ-pinches traps. They have some backlog of calculations of stability of shells in different regimes of their loading. However, in this problem, the geometry of liners was chosen to be a strip, under which the area of compressed magnetic flow is limited by plates launched towards each other, these plates being at the same time the conductors of an output current circuit. The geometry of the sharpener is shown in Fig. 1.

In contrast with the cylindrical geometry, where for the output of generated current we have to insert a fixed central conductor, this system has the following advantages:

1. The compression circuit is completely formed by single use elements, which are easily replaced after each operation cycle. It is unlikely that a fixed conductor of output circuit won't be heavily damaged at liner velocities of 1-1.5km/s.

2. The analysis of a pumping system of an initial magnetic flow in the compression circuit has shown that in the case of a strip geometry the initial flow can be delivered by the accelerating circuit itself, saving the device from extra storage and switching circuits.

The magnetic configuration for generating a magnetic flow in the MC output circuit during acceleration of liners, is shown in Fig. 1B. The flow can be captured in the compression circuit at the moment of switching on a load.
3. Special features of power sharpening in the MC system.

In general, the conditions of the process are the following. The liner must be flat. Profiles of liner velocities are unknown. With certain approximation, the stage of compression can be considered as a reverse stage of acceleration with its own transport factors. So there is a need in the numerical simulation of both processes - acceleration and compression.

4. The electromagnetic model for the acceleration of parallel conductors

In MC of this type, there are a motionless inductor and accelerated plate, returning current (see Fig.2). The influence of the second pair (the oncoming accelerated system) can be neglected because of its remoteness. Let us divide the plate into N conductors carrying currents $I_i$ and having masses of $dx\cdot h\cdot r$ each, then find a distribution of currents. Because we don’t know the current distribution in the inductor, we use reflection currents (see Fig.2) and suppose that the conductors with currents $I_i$ and $I_i'$ belong to one of $N$ parallel circuits, connected to a common power source.

Since on a surface of an ideal conducting inductor the normal component of a magnetic flux density vector $B_n = 0$, this picture adequately reflects the distribution of inductance between parallel conductors of the liner connected to the
common source. Knowing dimensions \( dx \cdot (j-i) \) and using arbitrary \( R_i \) and \( R_j \), which are not equal to each other, one can calculate a mutual inductance for any pair of conductors, and after that obtain all \( L_{ij} (R_i, R_j) \). Their determination means that the problem of finding a distribution of currents is solved, and, consequently, the magnetic field in the accelerating gap at the moment of a switching on of a source of accelerating current becomes known. Then it isn’t hard to find forces \( F_{yi} \), acting on conductors, and acceleration of the plate element at the initial stage of a launch. The acceleration of the liner and the change of \( R_i \) later on lead to the change of \( L_{ij} \) and necessity to take into account their derivatives in an electrical circuit. At this stage we can neglect forces \( F_{xi} \), assuming a thin plate to be flexible, but non-stretched and incompressible.

The results of calculations of currents, acting forces and velocity profiles of \( N=20 \) conductors and profiles of a liner plate at different moments of time \( t=10-50\mu \text{sec} \) are presented on Fig.3. The transverse dimensions (20×1mm) of Al plate correspond to dimensions of a small specially made test device (the length of a strip system is 300mm), fed with current of 300kA amplitude.

It is well seen in Figures that the motion of the plate begins from edges, departing from the motionless surface of an inductor. The edges gain an essential velocity before the observable displacement of the central part of plates. With the further motion of the whole plate, the edges "run away" forward and get into the zone of a weak action of the force \( F_{y1N} \) generated by the magnetic field. The maximum of the velocity profile starts to move from the edge to the middle of the plate, until the clearly distinctive central maximum of the velocity profile at 30μsec is formed.

From this moment, the originally formed deflection of the plate begins to straighten, the plate of the liner restores a flat shape at \( t=30\mu \text{sec} \), and to the moment \( t=50\mu \text{sec} \) the direction of sagging changes. It should be noted that the changing of a direction of sagging is accompanied not only by a reduction of acceleration, but also by a weak slowing down of the central conductors. This is well seen by the decrease of the absolute velocity. The described above picture of plate oscillations was observed experimentally in the device with the above mentioned dimensions.

Photos of the accelerating plate were taken by SPR in the mode of "magnifying glasses of time". Two distinctive frames corresponding to different moments of time in one cycle of acceleration are shown in Fig.4. In the first frame at \( t=20\mu \text{sec} \) from the beginning of current input, there is observed the spreading of a "shade" of a plate profile, which gets thin (~ 1mm) in the second frame at \( t=40\mu \text{sec} \).

So, both calculations and experiment show the waves of the plate oscillations in the transverse direction, along the magnetic field. The natural explanation of this effect is the development of Alfven magnetohydrodynamic waves [5], in which the role of restoring forces is played by inertia forces \( mdV/dt \). An initial disturbances here are the "running away" edges in the cross - section. The estimation of the Alfven velocity at characteristic parameters of the experimental device (used in the calculation) gives a value \( V_a = H/\sqrt{\mu_0 \rho} = 400 \text{m/s} \).

![Fig.3. The field of velocities of the point conductors of the liner and the profile of the plate.](image)
When at the beginning of the launch calculations give the first maximum of the velocity profile in the middle of the plate at \( t = 40 \mu \text{sec} \), there is a good agreement with the Alfven velocity: \( V_{\text{calc}} = \frac{(dx \cdot N/2)}{t} \approx 500 \text{m/s} \). In Fig.3, at \( t = 80\mu \text{sec} \) one can see the development of the second harmonics of the Alfven waves, which is marked as a "darkness" (overcrowding of spots) on the diagram of velocities field in the area \( X = (dx \cdot N)/4 \) and \( X = (dx \cdot N)/3/4 \). It should be noted that the marginal area of the slot is a permanent disturbance source for the generation of Alfven waves, ending when the value of the opening slot becomes equal to the half – width of the plate. The results of the calculations show that in the phase of acceleration the relatively low calculated value of the plate deflection is provided, if the Alfven wave has the time to pass the whole width of the plate.

4. The two - dimensional electromagnetic model of the plate launch taking into account non - linear field diffusion

The 200mm liner plate acceleration in a big machine is different to the above considered in the next three things: 1. a comparatively small length of the acceleration length, thus the Alfven wave does not manage to run the whole width of the plate; 2. an aspect ratio d/h in this case reaches 100 thus intensifying the role of marginal effects; 3. a special emphasis should be placed on the simulation of the compression process, resulting in high current density and magnetic flux density \( B_{\text{max}} \approx 100 \text{Tl} \).

Due to non – uniformity of the currents distribution and the accelerating field typical for strip line edges, there is no warranty that the accelerated plates will move in a plane – parallel way at this choice of a flat geometry. The achievement of high output power at the compression of the flow requires small distortions of the liner flat geometry, since the transformation of the liner kinetic energy into the magnetic energy must occur as simultaneously as possible on all surfaces of a closing slot. The value of deflections from a plane, \( \Delta x \), must be smaller than the characteristic length \( X_{\text{ref}} \) of the plate slowing down by the compressed magnetic flow. Supposing the launch length of the plate is \( X \) and the gain factor of power for device is \( K_p = 50 \), we obtain \( \Delta x < X_{\text{ref}} = X/K_p = 2 \text{mm} \). Seemingly, it is possible to reduce distortions of the plate shape by profiling an inductor plane, making it convex, as shown in Fig.1 (or with the inverse curvature), and make an initially non – uniform slot. Other measures could be undertaken.

On the other hand, due to the same reasons the liner shape perturbations, which occur during acceleration, will have the tendency to restore a shape in the slowing down phase. However, the joule heating of conductors renders the significant influence on these processes, and effects of joule heating are different in the acceleration and the slowing down phases.

That is why there was stated the problem, and specified the task of the software development for the numerical simulation of electromagnetic launch of flat plates and compression of magnetic flux in the output circuit of pulsed power amplifier before the fabrication of an experimental device.
In model [6] it is assumed that the liner material is incompressible conducting liquid. On each liner particle the Lorentz force, hydrodynamic and viscous pressures act. Thus, in connection with characteristic phenomena of transport, the calculation grid is taken to be changing its shape in accordance with the viscous liquid flow. The self-consistent problem for finding magnetic fields and currents distribution in conductors and in space (see also [7,8]) was solved, taking into account the non-linear resistance caused by the joule heating by the currents in an inductor and in a liner.

The calculation grid in the zone of the liner, presenting its shape at the respective moment of time at low assumed viscosity (kinematic viscosity 0.01), is shown in Fig.5. It is seen that there is an essential distortion of the initial rectangular shape of the liner. Such a distortion is accompanied by the transport of the liner material together with the magnetic field diffused in there. In Fig.6, the level lines of \( H_y \) component show the presence of areas with the increased strain in the liner.

It should be noted that the real ratio of the liner dimensions for better graphic presentation is changed in the figures. True liner sizes on abscissas and ordinates axis are distinguished approximately in 50 times.

When the viscosity is increased to 0.1, the characteristic shape of ends of the accelerating plate changes. This is shown in Fig. 7.

While in the previous two cases the widths of an inductor and liner were equal, and that led to the higher acceleration of the ends, the increase of the liner width to 1 cm resulted in the fact that the direction of deflection had a reversal in flight. It is clearly seen in Fig. 8, where the density of the Lorentz force distribution is shown as well.

In general, the presented results realistically agree with an expected qualitative picture of flat liners acceleration up to the moment of full stop of converging parts (edges or middles).

This stage of the software development, which is connected with the fact of the reversal of a velocity vector is currently under testing and adjustment.

5. Conclusion

The results of the studies of special features of acceleration of flat plates with the current are presented. The qualitative picture of processes for the duration of acceleration of 50-100μsec and the nature of the plates deformation on edges of the equivalent strip line are determined. Further works will concentrate on the actual experimenting with acceleration of broad plates (200mm) and the analysis of special features of fast (2-3μsec) compression of a magnetic flux at the magnetic flux density about 80 Tesla, at which case the processes of diffusion of the field play the main role.
References


