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Finite Element Analysis of the Stress–Strain State of an Electromagnetic Rail Accelerator under Coupled Electrothermal Loading

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Abstract

This article presents a finite element analysis of the stresses and strains arising in an electromagnetic rail accelerator using the ANSYS software package. An elastic model of the device was created and numerical experiments were conducted. Modeling was carried out in the ANSYS Student package using the LS-DYNA module. The optimal shape of the anchor was justified to ensure constant contact between the anchor and the rails. The elastic and elastic-plastic models of the rail accelerator were compared and the use of the elastic model was justified.

Keywords: *ANSYS, finite element method, LS-DYNA, railgun, electrothermal shock.*

INTRODUCTION

An electromagnetic rail accelerator is a device that uses a magnetic field created by a powerful electric discharge to accelerate a metal object along guides (rails). The schematic diagram of this device contains two rectangular copper rails, which act as electrodes to which a current is supplied from a battery of high-voltage capacitors. A projectile (anchor) made of copper, aluminum, or other conductive metal that has a significant contact area with the rails is charged from the breech of the device. It closes an electrical circuit, due to which the current, flowing between the rails, creates a significant electromagnetic field that accelerates the anchor. In practical examples of rail accelerators, the anchor can reach hypersonic speeds when leaving the guide channel. The main advantages of rail accelerators are inertia and, accordingly, low cost of the anchor, since acceleration occurs exclusively due to the Lorentz force, as well as the ability to accelerate the body to high speeds, which, in turn, provide the possibility of delivering a payload in the form of an anchor to extremely long distances (the highest known experimental Mach number of a projectile and the record distance of a body traveling from a rail accelerator are about 10 and 180 km, respectively [1]). Figure 1 shows a schematic diagram of the rail accelerator. Therefore, the purpose of this work is to study the stress-strain state of an electromagnetic rail accelerator under the action of thermal and electrical loads by the finite element method in the ANSYS Student environment using the LS-DYNA module.

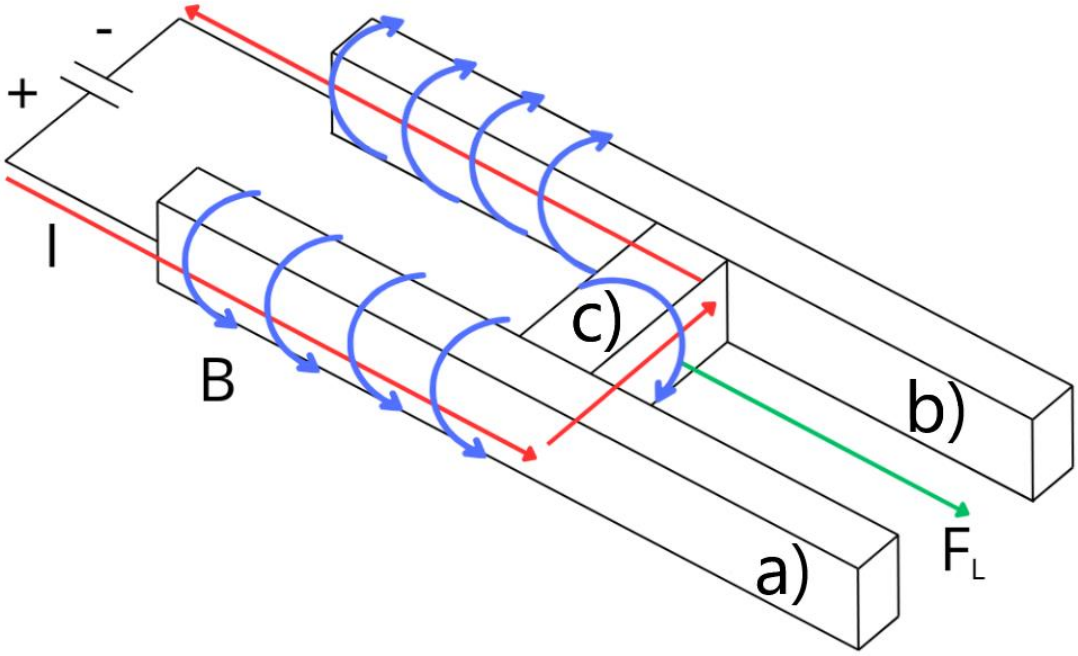


Fig. 1. Schematic diagram of a rail accelerator. I – current direction, B – magnetic field lines, F_L – Lorentz force, a) – right rail, b) – left rail, c) – armature

Theoretical Foundation

The electrical equation of the rail accelerator circuit [2]:

$$\frac{q}{C} + \frac{dL}{dt}\frac{dq}{dt} + L\frac{d^2q}{dt^2} + R\frac{dq}{dt} = 0.$$

Here:
q – electric charge,
C – capacitance of the circuit,
L – inductance of the circuit,
R – total resistance of the circuit.

Therefore, the electric current is calculated by the formula:

$$i = \frac{dq}{dt},$$

Initial conditions of the problem:

$$q(0) = Q_0,$$
$$\frac{dq(0)}{dt} = 0,$$

here Q_0 is the initial charge of the capacitor.
Then the Lorentz force accelerating the anchor can be given as [3]:

$$F = \frac{1}{2}i^2\frac{dL}{dx}.$$

The energy stored in the capacitor and the energy of the electromagnetic field are, respectively:

$$E_c(t) = \frac{1}{2C}Q^2(t),$$

$$E_{field}(t) = \frac{1}{2}L(t)i^2(t).$$

The kinetic energy of the armature is considered useful. Energy losses are due to heating the rails, plasma formation near the contact surfaces, and deformation of the rails by the magnetic field:

$$E_{loss}(t) = R(t)i^2(t) + E_{plasma} + E_{deform}.$$

The energy losses associated plasma formation were not considered in this problem. In principle, the problem is divided into two components: electromechanical (caused by the Lorentz force) and electrothermal (caused by electrical heating). Accordingly, for total stresses and strains, the following statement is valid:

$$\sigma = \sigma_L + \sigma_t,$$
$$\varepsilon = \varepsilon_L + \varepsilon_t.$$

Here:
σ_L – stresses under the action of the Lorentz force,
σ_t – thermal stresses,
ε_L – strains due to the Lorentz force,
ε_t – thermal strains.

To apply the superposition principle given in the formula above, we will assume that all structural elements are elastic. This essentially simplifies the analytical consideration of the problem and is a first approximation for the study of rail accelerators. For preliminary analytical calculations, we will consider only the first term of the energy equation given above (Ohmic loss) for an approximate calculation of the thermal strains of the rails. Therefore, it is necessary to solve the problem of thermal deformation of the beam.
Under conditions of a discharge with a peak current of the order of several MA at voltages of tens of kV, the phenomenon of electrothermal shock is observed, which is taken into account in the mechanical equation as an inertial term, which is often neglected in the case of slower heating [4]:

$$\nabla \cdot \sigma \neq 0.$$

Accordingly, the mechanical equation takes the form:

$$\rho \frac{\partial^2 u}{\partial t^2} = \nabla \cdot \sigma.$$

The heating mode is an electrothermal shock under the condition $t_{el} \lesssim t_{mech}$, where t_{el} is the duration of the current pulse, t_{mech} is the characteristic mechanical time, estimated from the linear dimension of the conductor L and the elastic wave velocity c in the material:

$$t_{mech} = \frac{L}{c}.$$

Then, the stress tensor has the form [5]:

$$\sigma = C\colon(\varepsilon - \alpha(T - T_0)I).$$

Here:
C=C(T) – tensor of elastic characteristics of the material,
α=α(T) – thermal expansion coefficient,
ε=ε(u(T)) – total strain tensor.

Numerical Modelling Results

To create a computer model, the ANSYS Pre-Post software with the LS-DYNA computational kernel was used due to its wide functionality and the difficulty for the ANSYS Mechanical or ANSYS Electronics environments in providing a complete simulation of a rail accelerator. The task is additionally complicated by the need to simulate the movement of the armature under the action of a magnetic field. The project architecture in the ANSYS LS-DYNA environment is built on a set of separate keyword files. This approach separates the geometric, mechanical, electrical and thermal parts of the project. The analysis includes the calculation of the current strength in the electric circuit, the electromagnetic field strength and the Lorentz force, as well as heating and thermal deformations. Therefore, the resulting strains and stresses are computed within the mechanical and thermal components.

According to the simulation results, numerical values of the main physical characteristics of the device were obtained, which allows the validity of the model to be assessed. The maximum value of kinetic energy at the moment the armature leaves the rails ($t = 4.12*10^{-4}$ s) is 19.79 kJ (Fig. 2). The graphical representation of the dependence of the armature acceleration (Fig. 3) on time is closely correlated with the current strength curve given earlier. Since the Lorentz force and, accordingly, the armature acceleration are proportional to the square of the current strength, the acceleration graph given below shows an increase in the current strength until the moment $t = 2*10^{-4}$ s, when the current strength and acceleration reach their maxima, and a gradual decrease in the acceleration to 0 until the moment $t = 4.12*10^{-4}$ s, when the armature completely leaves the rails. At the same time, the leading edge of the anchor reaches the end of the rails at the time $t = 3.76*10^{-4}$ s, which causes a short-term acceleration.

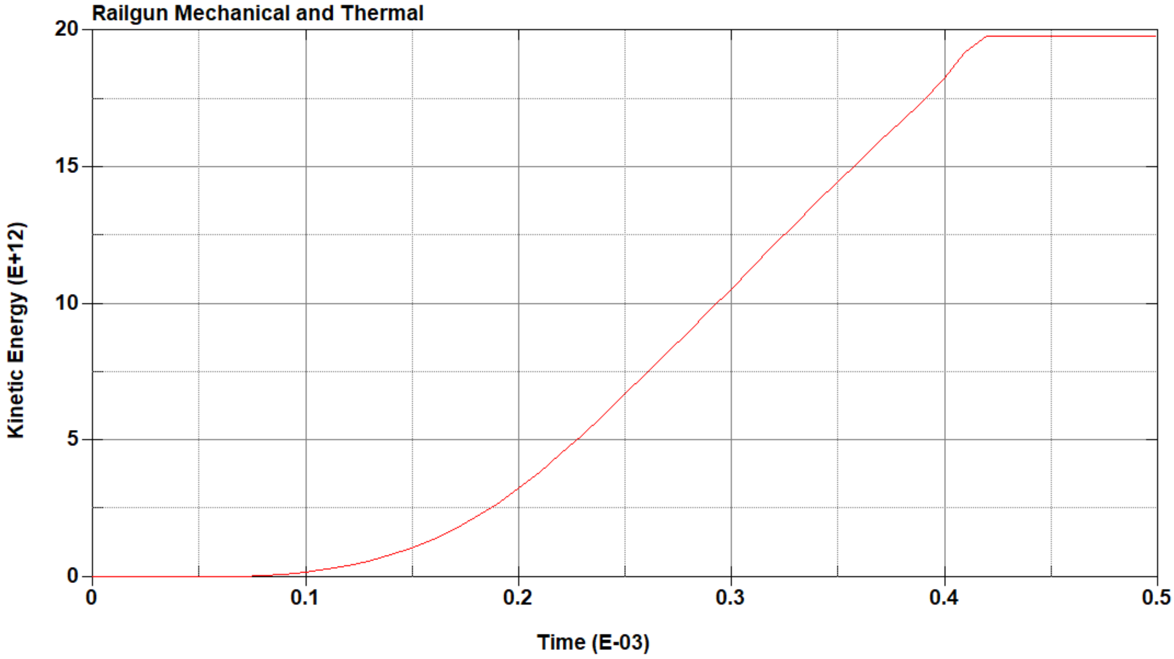


Fig. 2. Kinetic energy of the armature as a function of time

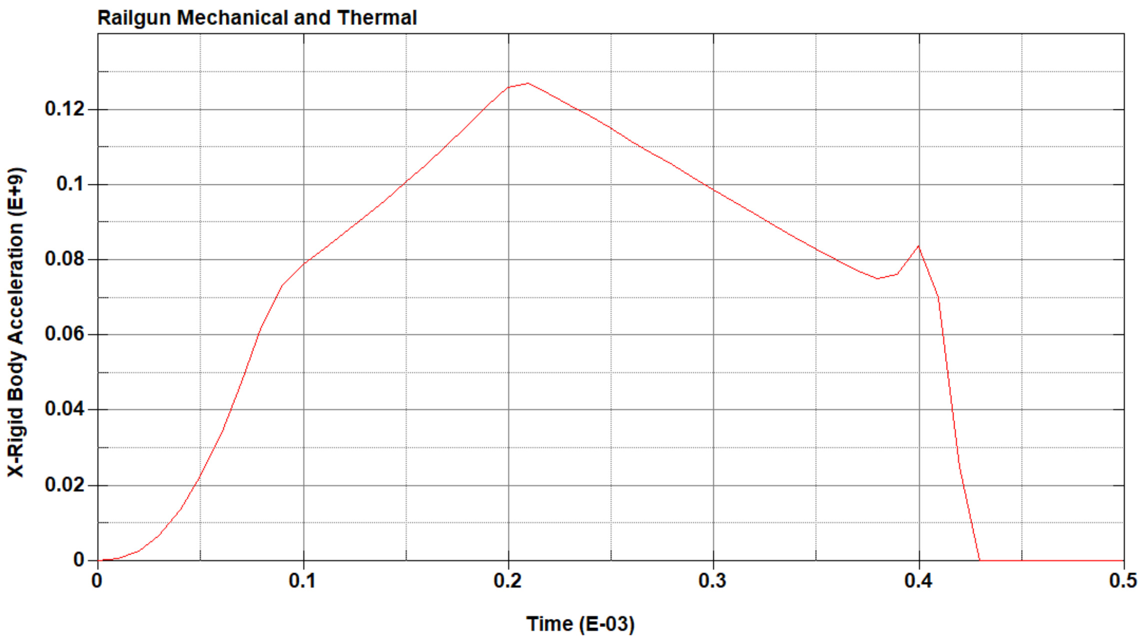
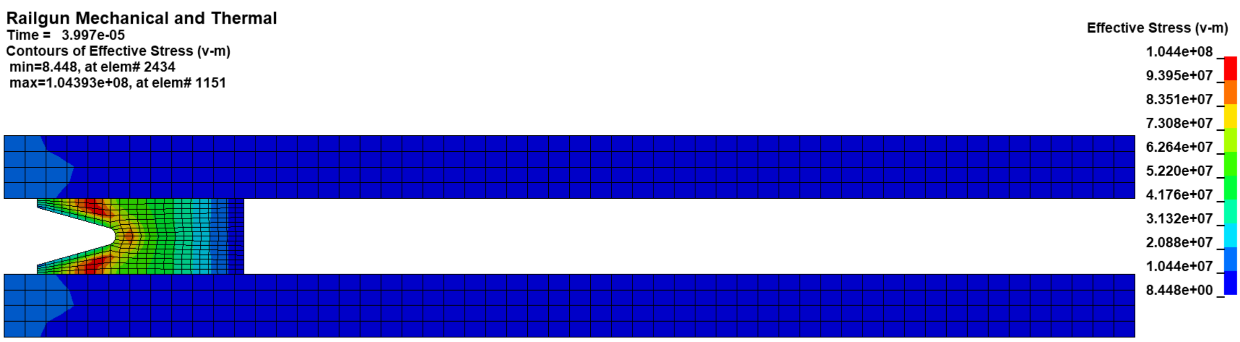
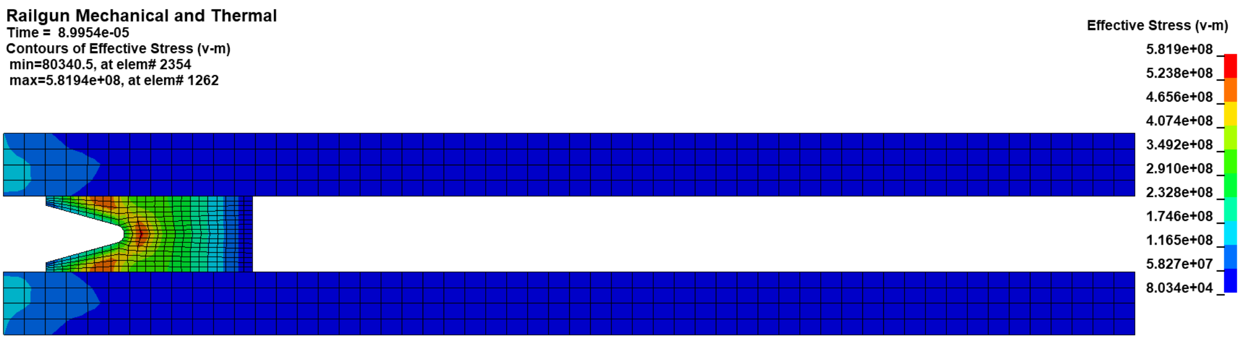


Fig. 3. Acceleration of the armature as a function of time

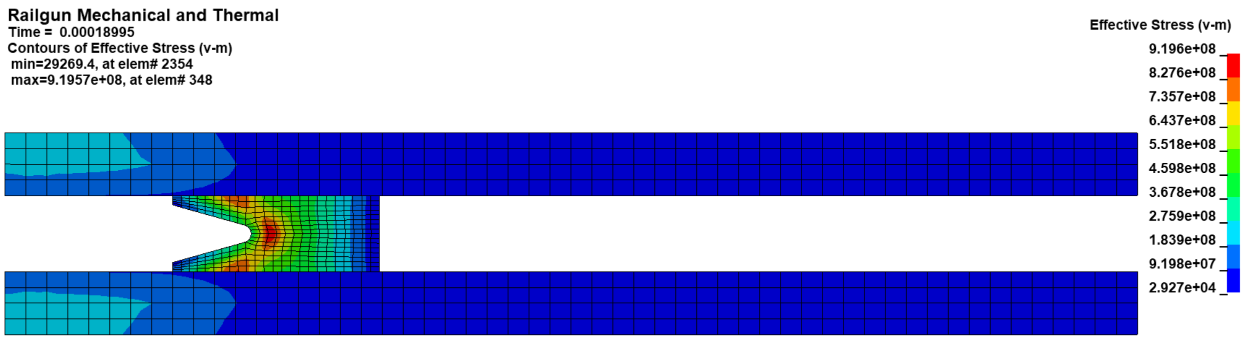
In addition to the general physical data, a numerical solution for the deformation field was obtained. The stress and deformation distribution of the rails and the anchor is given below (Fig. 4, 5). It is important to note that the yield strength of the materials was exceeded only at the anchor nodes, while the rails remained elastic. The maximum value of the von Mises stress during the simulation is 1591 MPa and is reached in the anchor. The images below are frames of the animation of the movement of the anchor, showing the distribution of stresses and deformations at different times.



a)



b)

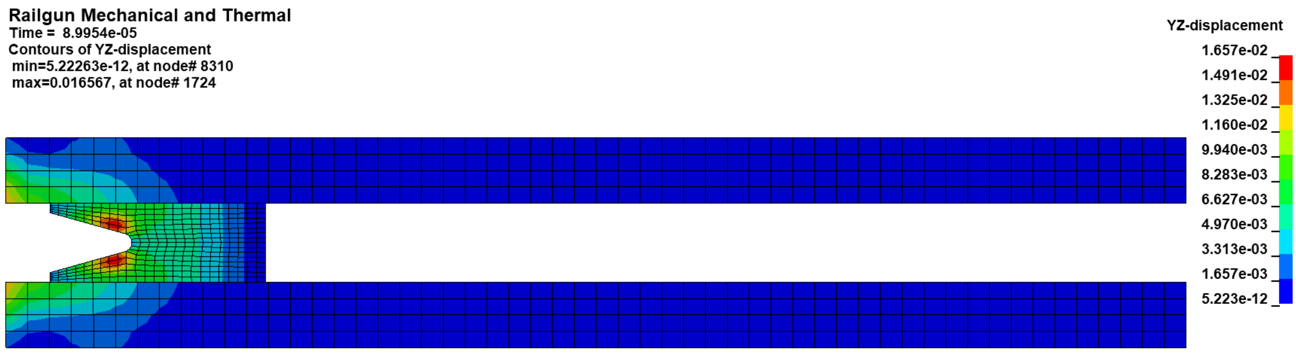


c)

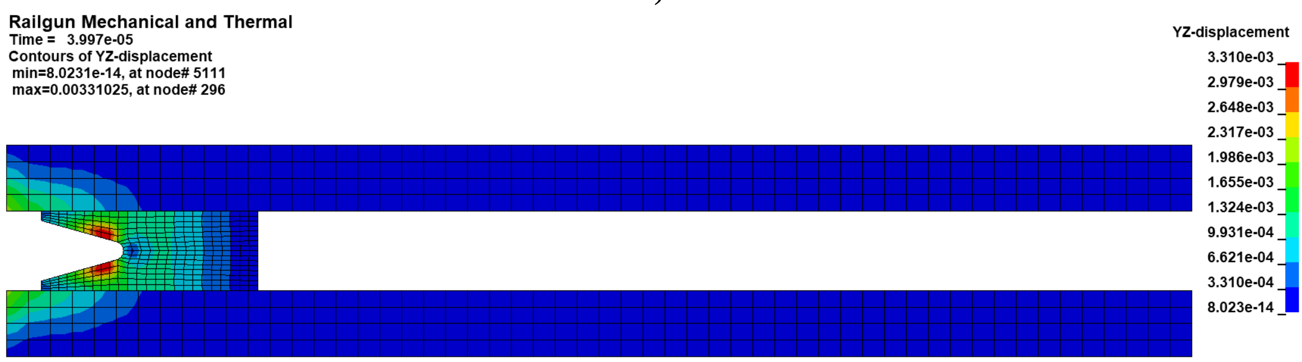
Fig. 4. Von Mises stress at simulation step: a) 5; b) 10; c) 20

The maximum value of the amplitude of displacement in the YZ plane was reached in the armature and was 0.0962 mm, while the maximum displacement of the rails was 0.0180 mm. As can be seen from the figures, the displacement in the armature in the YZ plane continue to increase during the movement of the armature along the rails. The maximum displacement along the Y axis was 0.0962 mm for the armature and 0.0153 mm for the rails. It is worth noting that in real rail accelerators there are plastic deformation occurs in the rails, but in this simulation they were not taken into account, since the processes of melting and ionization of the upper layers of copper are not considered.

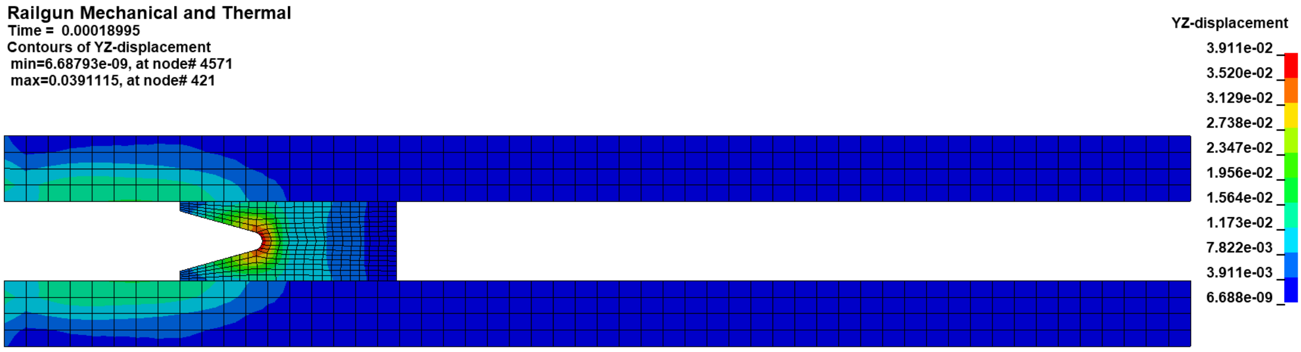
Thus, a visual representation of the key physical quantities, as well as the parameters of the stress-strain state of the structural elements of the rail accelerator, was obtained, and their numerical values were calculated.



a)



b)



c)

Fig. 5. Displacement in the YZ plane at simulation step: a) 5; b) 10; c) 20

Practical Importance

Electromagnetic railgun technology has numerous potential applications, including in the military as extra-long-range artillery systems or air defense systems, due to the high initial velocity and range of the payload, as well as the low launch cost. Railguns are also considered a promising technology in the aerospace industry, in particular as one of the possible alternative methods of launching payloads into low Earth orbit, which could significantly reduce the cost of accessing space in the future.

CONCLUSION

As a result of numerical modeling in the ANSYS Student environment using the LS-DYNA module to study the stress-strain state of a rail electromagnetic accelerator under the action of thermal and electrical loads, numerical values of stresses and deformations of various structural elements, as well as general physical parameters of the system, in particular the kinetic energy and armature velocity as functions of time were obtained. The maximum values of these quantities (about 20 kJ and Mach 3) are realistic for such devices.

The constructed model demonstrates the possibility of using numerical methods to study complex processes occurring in rail accelerators, in particular the distribution of forces, rail deformations and dynamic interaction between structural elements. This confirms the feasibility of using modern software packages to predict the behavior of such systems at the design stage.

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