Generation of intense radiation fluxes and megabar pressures in liner systems

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The generation of pulses of soft x radiation and pressure in the collision of a strongly radiating plasma liner with a coaxial solid rod is examined. The interaction of the liner with the plasma corona, which arises during the ablation of the rod, increases the density of the liner plasma, the radiation intensity, and the pressure amplitude in the rod.

Sources of soft x radiation based on the use of strongly radiating liners as the loads of electrical generators are capable of producing intense radiation pulses.[1,2] Pulses of soft x radiation with a duration $\Delta t = 20$–30 ns and an output energy of more than 100 kJ have been produced at the Angara-5-1 installation with a maximum current $I_0 \simeq 4$ MA (Ref. 1). At the Saturn installation in the USA, the output energy increased to 0.5 MJ, with a soft x-ray pulse lasting $\Delta t = 20$ ns, as the current was raised to 11 MA (Ref. 2).

The soft x radiation is emitted as a result of the heating of a multicharge plasma during the randomization of the kinetic energy of the liner compressed by a magnetic field and the Joule heating of the plasma in its compressed state—in a pinch. The duration of the radiation pulse and thus the power are determined by the liner thickness. A lower limit is set on the characteristic thickness of the shell by the size of the skin layer;[3] this thickness may increase as the result of a Rayleigh-Taylor instability. In addition, during the compression of a liner of a heavy-ion plasma, with a large atomic number $A \gg 1$, it is difficult for the energy acquired in the shock wave to be transferred from the ions to the electrons. The duration of the ion–electron exchange, which is proportional to the ratio of the ion and electron masses and inversely proportional to the plasma density, may thus also determine the duration of the radiation pulse, as in the nonisothermal compression of a xenon liner.[4]

The megampere currents developed in electrical generators are also capable of producing magnetic pressures in the megabar range. A pressure of 20 Mbar has been achieved at the Saturn insulation in a metal crowbar 0.2 cm in diameter.[5]

In this letter we propose a liner system which is capable of generating a short, intense radiation pulse and a pulsed multimegabar pressure. The system consists of a strongly radiating liner and a central solid rod. The diameter of this rod is roughly a tenth that of the liner.

The liner, accelerated by the magnetic pressure to a velocity $V = (3$–$5) \times 10^7$ cm/s, and compressed by a factor of about ten, collides with the central rod. As it is decelerated, its kinetic energy converts into radiation; the momentum creates a pressure pulse in addition to the magnetic pressure. The ultimate degree of liner compression (before the collision), $R_0/r_k \sim 10$, limits the amplitude of the Rayleigh–Taylor instability. The compression of the radiating liner in the interaction of the liner shell with the plasma corona of the rod leads to an increase in the density of the liner plasma and a reduction of its thickness. As a result, the pulse of soft x radiation is shortened, and the amplitude of the radiation power and the pressure amplitude increase.

The following processes govern the mechanism for the liner compression. As a layer of a multicharge ($Z \gg 1$), strongly radiating plasma is accelerated, the electron temperature reaches several tens of electron volts as a result of a balance between the radiative loss from the plasma and the heating of the electrons by the conduction current[3] or in a collisional transfer of energy from ions behind the front of the first shock wave.[4] The radiation from the liner in the acceleration stage causes an ablation of the solid central rod and the formation of a plasma corona with a density profile similar to the isothermal (exponential) profile. Before the collision with the dense rod, the liner is decelerated in the low-density corona plasma. This interaction leads to a compression of the magnetic shell to the point that a liner-deceleration shock wave forms.

In this stage of the collisionless deceleration of the strongly radiating liner as a result of the radiative loss, the pressure in the liner is due primarily to the magnetic pressure, and the compression of the shell can be described by the MHD model of a strongly radiating plasma.[3] It follows from this model that in the collisionless stage of the deceleration of a liner in the expanding plasma, with an exponential density profile and a characteristic dimension $d = c_s t$ (c_s is the sound velocity, and t is the rod ablation time), the liner is compressed to a density

$$\rho \sim \frac{M}{2\pi r_k} \left(\frac{\sigma V}{c^2 d} \right)^{1/2}, \tag{1}$$

where M is the mass per unit length of the liner, r_k is the liner radius at the end of the compression, and σ is the conductivity of the liner plasma in the stage of the collisionless deceleration. An increase in the liner density in the course of the compression leads to an increase in the radiation power and in the pressure in the final stage of the deceleration in the shock wave that is formed:

$$W_{rad} \sim \frac{\rho V^3}{2}, \qquad P \simeq \rho V^2. \tag{2}$$

Let us take a brief look at the results of calculations carried out with the help of the RAZRYaD software[6] on the acceleration of a xenon liner with an initial dimension $R = 1.65$ cm and a mass per unit length $M = 140$ μg/cm, at a current amplitude $I = 2.5$ MA, and on a collision with a molybdenum rod 2 mm in diameter. The liner is accelerated to a velocity $V = 4 \times 10^7$ cm/s. In the acceleration stage, the liner plasma is not isothermal. The electrons are heated to 40 eV. The radiation from the liner causes an ablation of the rod, and the velocity of the expanding plasma corona reaches 3×10^6 cm/s. The expansion of the strongly radiating plasma as a result of the ablation due to the thermal radiation occurs in a nearly isothermal fashion. The density

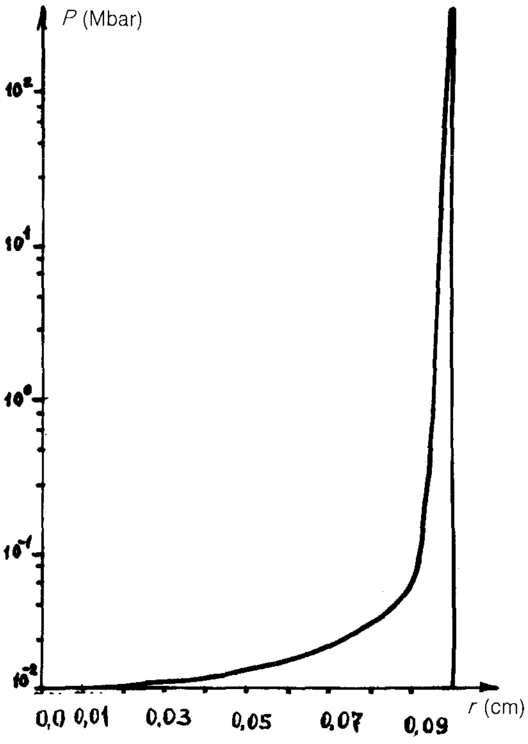

FIG. 1. Radial profile of the pressure at the time at which the pressure maximum is reached, at $t = 134.44$ ns. The arrow shows the position of the contact surface between the liner plasma and the rod.

profile of the expanding plasma is thus approximately exponential. The deceleration of the liner in the plasma with increasing density leads to a compression of the liner along its thickness. In the first stage of the deceleration, the magnetic pressure in the liner leads to a collisionless deceleration (the thermal pressure is low because of the radiative cooling of the plasma). At the time at which the MHD shock wave forms, the liner density reaches 0.3 g/cm^3. As the liner decelerates in the shock wave, the radiation and pressure reach their maximum values $W|_{t=134.44\text{ns}} = 7.7\times10^{13}$ W/cm^2 and $P|_{t=134.44\text{ns}} \approx 350$ Mbar. The region in which the radiation and the pressure are generated is at this time concentrated near the contact boundary of the liner plasma and the rod (Fig. 1). Because of the small thickness of the liner, the radiation pulse (Fig. 2) and the pressure pulse decay over a time ~ 0.2 ns. About 90% of the kinetic energy of the liner, $E_{\text{kin}} = 10$ kJ/cm, is radiated. The liner then radiates for a long time, along with the rod, as a result of Joule heating. The total amount of radiated energy is 20 kJ/cm.

After the pressure pulse ends, a shock wave with a pressure $P \approx 0.5$ Mbar propagates inside the rod. As the shock wave converges on the rod axis due to "implosion," the pressure increases again. At the time 590 ns, the pressure reaches its maximum, 6.3 Mbar, at the axis. As a result of rarefaction of the shock wave after the implosion, the rod expands.