

Design and preliminary experiment of electromagnetically driven high-speed moving target

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Flash photography is developing in the direction of multiframe and high precision, requiring accelerators to provide multipulse and small-spot electron beams. This imposes increasingly higher demands on the design of conversion targets. High-speed moving targets offer an effective solution to the problem of beam-target damage. Among them, electromagnetically driven high-speed moving targets represent the most promising technical approach. This paper first introduces the conceptual design of the electromagnetically driven target, then uses dynamics software to analyze the stress conditions of the target under strong impact, provides the maximum acceleration of the electromagnetic rail gun limited by the mechanical properties of the target material, and finally presents the preliminary experimental results. Under the drive of the existing electromagnetic rail gun in the laboratory, the target sheet achieved a motion speed of 1.7 km/s. The novel high-speed moving target technology introduced in this paper is expected to completely solve the beam-target interaction damage problem in multipulsed conversion targets and meet the new demands of flash photography development.

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I. INTRODUCTION

Flash x-ray photography can image the dynamic process of rapidly moving objects and has been widely applied in fields such as explosion physics and high-speed penetration. In order to adapt to the development trends of high-precision and multiframe flash photography, linear induction accelerators are also evolving toward smaller focal spots and multipulsed operation. This has made the issue of beam-target damage increasingly prominent [1–3]. The high-energy, high-current pulsed electron beams interact with the conversion target, depositing an extremely high energy density on the target (up to tens of thousands of J/cm²). The energy deposited in the target heats the target, causing it to melt and vaporize, converting it into a warm dense state and plasma state, seriously reducing the density of the target in a single pulse. In the long-interval multipulse mode, subsequent electron beams will face the dilemma of having no target to interact with [4]. Damage to targets by high-energy, high-current electron beams has become an urgent problem to be solved in the development of multipulsed flash photography technology.

High-speed moving targets can quickly refresh the target material, ensuring that each pulse beam interacts with a fresh target. This can effectively solve the problem of damage to targets by high-current pulsed electron beams, which leads to a decrease in the dose of subsequent pulses. For multipulsed flash photography, the linear motion speed of the target is about 2 km/s. Currently, the relatively mature driving methods mainly include light gas gun, rotating target, and electromagnetic rail gun [5–10]. A light gas gun can meet the acceleration requirements but cannot be used in a vacuum. Rotating targets require achieving an ultrahigh linear speed of 2 mm/μs. For commonly used target materials like Ta and W, the pressure generated by high-speed rotation is approximately 1 GPa, which is difficult to achieve in engineering. The electromagnetic rail gun-driven target has a high acceleration gradient, a compact device footprint, and can be equipped with targets by slightly modifying the armature. This is currently a relatively feasible technical approach.

This paper first introduces the conceptual design of the electromagnetically driven high-speed moving target, then analyzes the stress conditions of the target under strong impact, and finally presents the preliminary experimental results.

II. CONCEPTUAL DESIGN

The conceptual design of the electromagnetically driven high-speed moving target is shown in Fig. 1. The target

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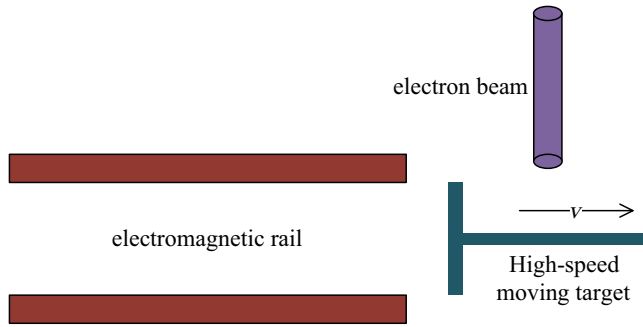


FIG. 1. Conceptual design of electromagnetically driven high-speed moving target.

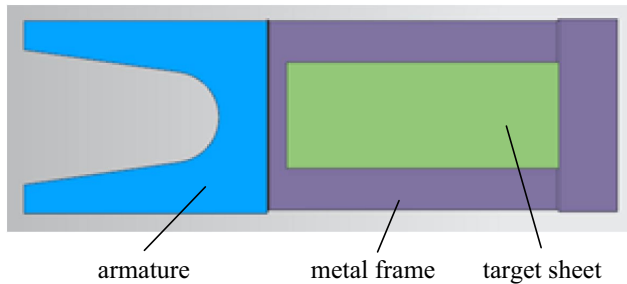


FIG. 2. Conceptual design of the integrated projectile.

sheet is first accelerated to the target speed in the electromagnetic rail gun, then its flight attitude is adjusted through the flight guidance section, and finally launched. Through timing control, the target and the electron beam reach the shooting position at the same time, generating high-dose x-rays.

The integrated design of the armature and target is the key to the electromagnetically driven high-speed moving

target. Under strong impact, the projectile is very easy to disintegrate. The projectile design is shown in Fig. 2. The armature is made of a saddle-shaped aluminum alloy, lightweight, with high mechanical strength and good electrical conductivity. The target sheet is the load of the armature, generally made of high-Z materials such as Ta or W. The energy of the flash x-ray accelerator is approximately 20 MeV, and the optimal thickness for bremsstrahlung x-ray production is about 1.2 mm when the target is made of Ta [11]. To reduce the effect of electron scattering on the x-ray focus spot and decrease the projectile mass, the target thickness is designed to be 1 mm. The projectile is accelerated to a speed of 2 km/s in a 2-m-long track. Currently, the acceleration time of the electromagnetic rail gun in our laboratory is 2 ms, with an average acceleration of 1×10^5 G. The target will withstand the strong stress caused by the high overload. To prevent the target from breaking or deforming, the projectile is fixed within a metal frame, distributing the stress across the entire frame to reduce stress concentration.

The mass of the projectile is approximately 20 g. Based on an estimated 20% firing efficiency, an electric energy source of approximately 200 kJ is required to accelerate the target sheet to 2 km/s. The structure of the electromagnetic rail gun is shown in Fig. 3. The current input segment is connected to the power supply. The acceleration segment plans to adopt a serial dual-track enhanced structure to ensure a firing efficiency of over 20%. Additionally, to prevent the strong muzzle flash caused by the high-temperature fiberglass in the traditional structure from affecting the measurement of the target's state, high-temperature and wear-resistant special ceramic materials are used for side insulation. Finally, there is the flight guidance section, where the target sheet continues to

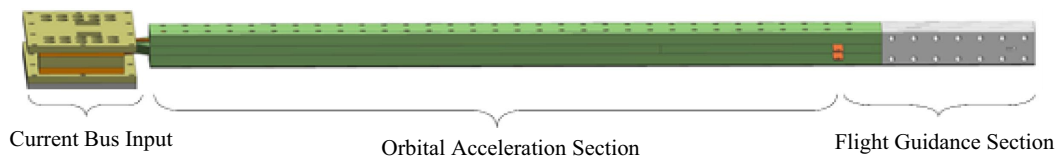


FIG. 3. Structure diagram of electromagnetic rail gun.

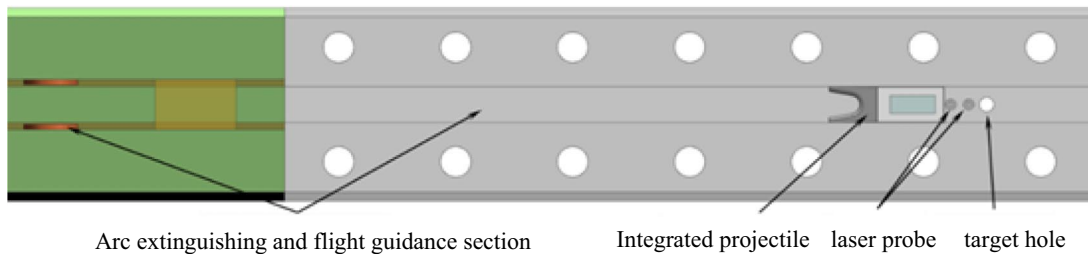


FIG. 4. Flight guidance section.

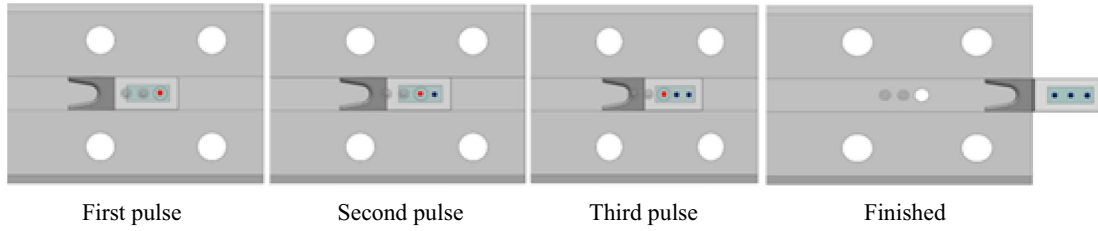


FIG. 5. Process of three pulsed photography.

fly, maintaining its flight attitude and preventing it from deviating from the direction of the electron beam motion.

The specific structure of the flight guidance section is shown in Fig. 4. There is an arc extinguishing device at the muzzle, which absorbs the residual current in the track at the end of launch and reduces the intensity of the muzzle arc. The flight guidance section can make the shooting position far away from the electromagnetic rail gun and reduce the influence of muzzle flame on the accelerator.

There are two laser interruption probes installed at the end of the guidance section to obtain the velocity and position information of the projectile. Based on this information and the shooting position, the trigger delay time of the accelerator is set to ensure that the target sheet passes through the shooting position and achieves

photography by three pulsed beams, as shown in Fig. 5 [12,13].

III. SIMULATION OF TARGET MECHANICAL ANALYSIS

The material strength of the target is a key parameter for the electromagnetically driven high-speed moving target. For this purpose, the stress intensity of the Ta target material under different impact accelerations is initially calculated using mechanical analysis software. The simulation model is shown in Fig. 6, with the target size being $30 \times 15 \times 1$ mm and the impact acceleration loaded on the smallest area surface.

When the impact acceleration is 10^5 G, the maximum deformation of the target sheet is in the length direction, approximately 50 μ m, and the maximum stress is at both sides of the impact acceleration surface, approximately 1 GPa, as shown in Fig. 7. For Ta material, the fracture strength is approximately 300 MPa, far lower than the impact stress. Ta-W alloy is a common method to improve the mechanical strength of Ta material, and the higher the W content, the higher the mechanical strength [14,15]. Currently, industrial W content can reach around 10%, with a tensile strength of approximately 600 MPa. Additionally, microcrystalline tantalum is another method to enhance the tensile strength of Ta material, which is currently under research, and it is reported that its tensile

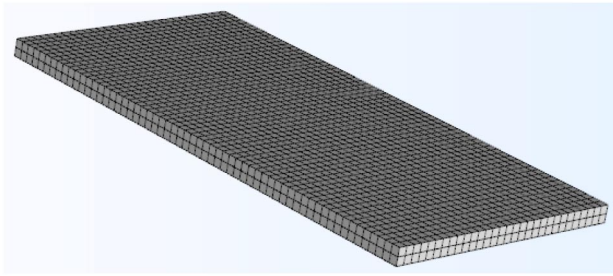
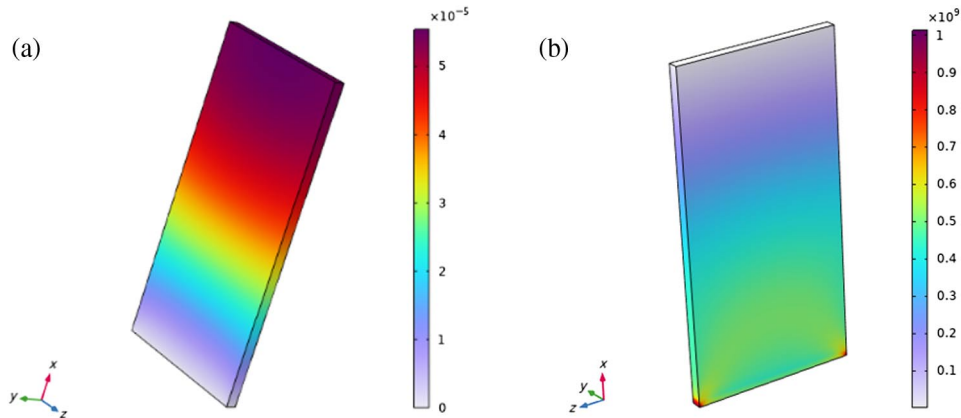


FIG. 6. Simulation model of stress intensity of target material under impact acceleration.

FIG. 7. Deformation map (a) and stress map (b) of the target under the impact acceleration of 10^5 G.

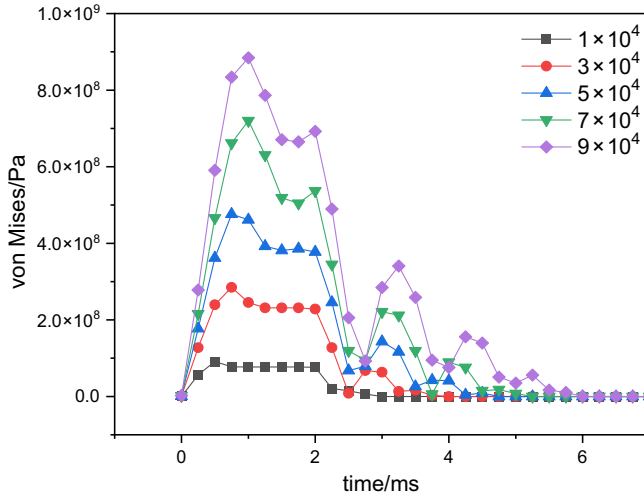


FIG. 8. Stress of the target under different impact accelerations.

strength can reach over 1 GPa, but the process is not yet mature [16–18].

In order to determine the maximum impact acceleration allowed by the mechanical strength of Ta-W alloys, the von Mises stress of the target at different impact accelerations is calculated, as shown in Fig. 8. The stress is nearly proportional to the impact acceleration, and the smaller the impact acceleration, the easier it is for the target to transition from oscillation to equilibrium. When the tensile strength exceeds 500 MPa, the corresponding maximum impact acceleration is 5×10^4 G, requiring the acceleration time of the target to be increased from 2 to 4 ms.

IV. PRELIMINARY EXPERIMENT

A preliminary target acceleration experiment was carried out by using an electromagnetic rail gun device that was readily available in the laboratory. The experimental layout is shown in Fig. 9. Outside the electromagnetic rail, a high-speed camera was installed to measure the shape of the accelerated projectile. The minimum exposure time was 6.6 μ s. Two laser interruption probes were arranged to detect the projectile velocity. The lasers emitted two beams

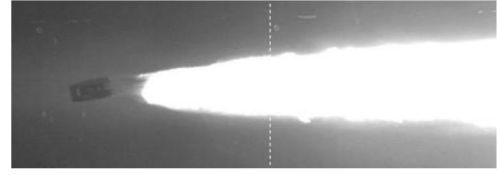


FIG. 10. Preliminary results of the projectile for the electromagnetic rail gun.

of laser light. When the projectile passed through the beams, it blocked the light from reaching the photo-detectors and generated two attenuation signals. The velocity of the projectile can be calculated based on the distance between the two beams and the time difference of the attenuation signals. The target material was a Ta-10 W alloy, which is relatively mature in industry. The acceleration time of the electromagnetic rail gun was 4 ms, and the peak current was 360 kA.

The results are shown in Fig. 10. The experiment was conducted in an atmospheric environment, and the muzzle flame behind the projectile was particularly intense. According to the measurements of the laser probes, the flight speed of the projectile was about 1.7 km/s, and the integrated projectile remained intact. Due to the effect of air resistance, the flight angle of the projectile appeared inclined after exiting the rail gun. In a vacuum, the projectile's flight attitude will be more stable.

V. CONCLUSION

Electromagnetically driven high-speed moving targets offer an effective solution to the problem of damage to targets in multipulse flash x-ray photography. This paper presents a preliminary conceptual design for such targets and analyzes the stress on the target under high-impact conditions. Based on the mechanical properties of the material, an appropriate electromagnetic rail gun acceleration was selected, and preliminary experiments were conducted. The target remained intact, verifying the feasibility of this method. In the next phase, the electromagnetic rail gun will be placed in a vacuum chamber to eliminate the effects of air resistance.

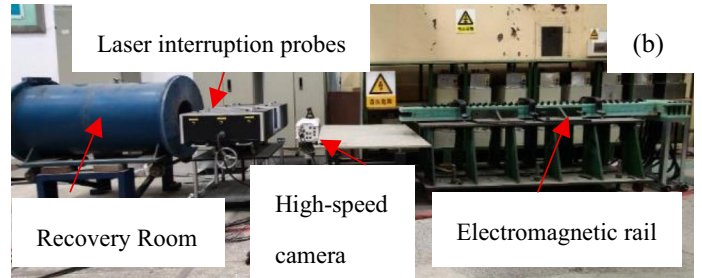
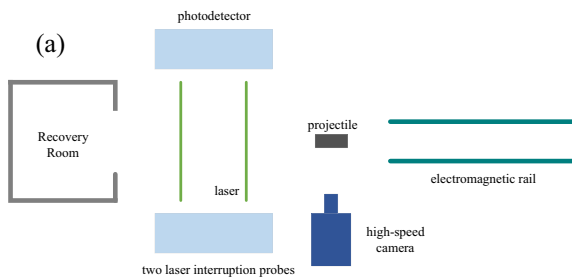


FIG. 9. (a) Schematic diagram and (b) photograph of the experimental setup.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this article are openly available [1].

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