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Electrostatic cumulation: a convenient research instrument to obtain Mbar pressures in solids

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Abstract. Magnetic cumulation is not the sole phenomenon capable to produce high-dense electron beams in relativistic vacuum diodes. Electrostatic cumulation phenomenon also exists and reveals at much lower accelerating voltages in relativistic diodes with a ring-type cathode. A distinctive feature of electrostatic cumulation is quite low spread of electron energies in the produced high-dense beam. These circumstances give advantages to electrostatic cumulation phenomenon if the latter is considered as a convenient research instrument for high energy density physics. Electrostatically cumulated electron beam with energy of 400 keV is capable of exciting a shock wave with an amplitude of 0.25 Mbar in a tungsten plate, which can be used to compress a target. Research can be carried out using one high-current beam or several.

Keywords: electrostatic cumulation, high energy density, shock waves.

1. Introduction

For several decades, cumulation phenomena have been the main research tool in high energy density physics [1, 2]. With the help of cumulation in a small volume of matter, it is possible to achieve energy densities significantly exceeding 104 J/cm3 and pressures over 100 kbar, which provides a unique opportunity for studying matter in extreme conditions. The essence of cumulation is the creation of a converging high-energy flow of directed energy. The latter can be a substance accelerated by an explosion, powerful laser radiation, relativistic ion or high-current electron beams. Electrostatic cumulation associated with high-current electron beams is the subject of this paper.

The pioneer research into high-current electron beams dates back to the 30ies of the past century [3]. For the lack of equipment and tools affording the generation of high-power charged-particle beams under terrestrial conditions, the researchers mainly focused their attention on theoretical consideration of astrophysical problems [4].

The first high-current electron beams with the power from several of gigawatts to several of terawatts [5–10] obtained three decades later made a revolution in the cumulation research. This became possible primarily through two remarkable achievements in experimental physics: First, current densities were obtained as high as 10^8 A/cm^2 from the microprotrusions of the metal cathode placed in a strong electric field [11–14]; second, the investigation of dielectric breakdown strength provided the potential for developing high-voltage pulse generators [15–16].

Self-focusing of high-current electron beams with their own magnetic fields [17, 18] provided the charged-particle beam intensities as high as ~1 TW/cm^2, thus enabling the laboratory investigation of the extreme state of matter. The expectation was that by cumulation of high-current beams, the deuterium-tritium targets would be compressed and heated to ignition so as to initiate thermonuclear reactions and thus accomplish pellet fusion.

Though the goal of developing a pellet fusion was not achieved [19, 20], high-current electron beams found successful applications in other fields of physics [21, 22]. They are used for research in radiation physics [23], generation of high-power microwaves [24, 25], collective acceleration of ions [26, 27], and pumping gas lasers [28].

This paper considers an alternative mechanism of high-power electron beam cumulation, namely, electrostatic cumulation [29–31]. This mechanism occurs in relativistic vacuum diodes with a ring-type cathode. Our main task here is to provide a theoretical description of this cumulation mechanism and investigate the interaction of a cumulated electron beam with matter.

This paper is arranged as follows. First, we give quite a detailed description of electrostatic cumulation. Then we report the experimental results that confirm the considered phenomenon at 400 kV. In conclusion, we investigate the interaction of cumulated electron beam with a tungsten target to archive pressures over 100 kbar.

2. The phenomenon of electrostatic cumulation

Electrostatic cumulation was revealed during modeling of high-current accelerators [29] and confirmed experimentally [30]. The qualitative picture of electrostatic cumulation can be described as follows. In a relativistic vacuum diode, electron emission is most intense from the cathode's edges (Fig.1). Let us consider electrons emitted from the inner edge. The Coulomb repulsion causes the charged particles to rush to the region free from the beam. As a result, the accelerated motion of electrons toward the anode comes alongside the radial motion to the cathode's symmetry axis. As a result, the high-current beam density increases multifold on the axis as compared to the average current density in the cathode-anode gap [30, 31].

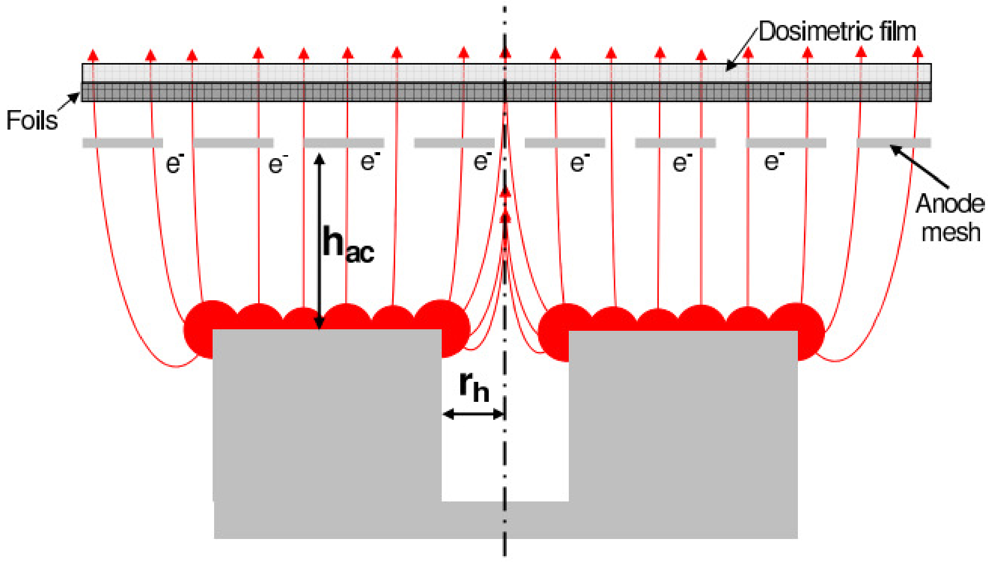

Fig.1. Cumulation mechanism.

Fig.2 shows the results of simulations: the dose absorbed by the anode. The assumed parameters of the cathode are as follows: cathode radius 30 mm, cathode-anode gap 16 mm, and the radius of the inner hole 10 mm. The maximum value of the accelerating voltage pulse is taken equal to 360 kV and its duration is 130 ns. The simulated current density in the region of the central spot on the anode at the moment corresponding to the maximum accelerating voltage is as large as 10 A/mm^2, being 5 times greater than the average current density of the high-current diode. A typical radius of the spot is about 1 mm. Thus, the simulation result indicates the electron-beam cumulation on the axis of a high-current diode with a ring-type cathode. Moreover, if we consider a tiny region of $3\cdot10^{-4}$ cm^2 on axis the current density and beam intensity reach values equal to 100 kA/cm^2 and 40 GW/cm^2, respectively. However, it is difficult to make measurements with such spatial resolution.

The undeniable advantage of electrostatic cumulation is a very low energy spread of particles due to the stationary flow of charged particles. In contrast, self-focusing of a beam by its own magnetic field leads to a turbulent flow, and the charged particles acquire a significant energy spread. In this case, the electron flow is like a compressed relativistic gas with the electron temperature T_e determined by the accelerating voltage, $T_e \sim q_eU/k_B$ [32]. (Symbols q_e and k_B denote the elementary charge and the Boltzman constant, respectively.)

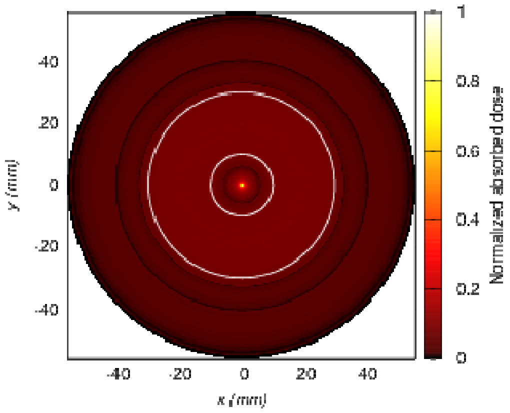

Fig.2. Electrostatic cumulation: simulation results.

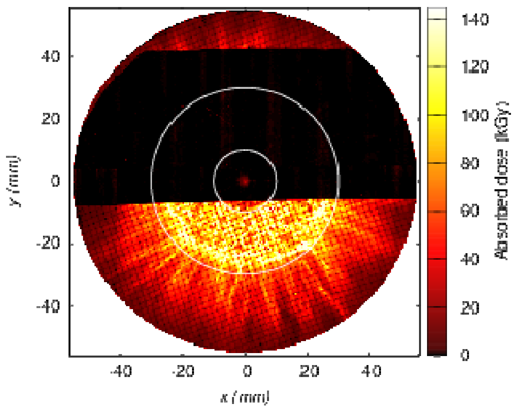

Fig.3. Electrostatic cumulation: experimental results.

To obtain information about electron beam parameters, we use a nanosecond pulse-periodic electron accelerator with a compact SF6-insulated high-voltage generator providing pulsed voltage up to 400 kV in 30 Ohm resistive load with a full width at half maximum of 130 ns and rise time of 30 ns [30]. To obtain full-sized imprints of electron beams, we use a radiochromic dosimetry film placed 3 mm behind the anode mesh made of stainless steel (the geometrical transparency of the mesh is 0.77); the cathode-anode gap is 16 mm. The dosimetry film enables to obtain information about the total absorbed dose over the beam cross section, caused by passage of charged particles.

Our first experiments had shown that the intense flow of charged particles on the axis had burned the film through. For this reason, in further experiments we placed 70 μm-thick aluminium foil in front of the dosimetry film to decrease the absorbed dose (see Fig.3) [30]. This enables us to cut off the flows of both the cathode plasma and the weakly-relativistic electrons produced at the voltage pulse decay. The experiments conducted with one, two, and three foils demonstrated that a sharp increase in the absorbed dose remains in the center. This means that the particle flow consists of high-energy electrons at the beam axis. In the experiments with three foil layers cutting off all electrons whose energy was less than 250 keV, the absorbed dose in the center was almost four times as large as the average dose across the beam cross section, showing a good agreement with the simulation results.

It should be noted that, most likely, the phenomenon of electrostatic cumulation was also observed in [33, 34] for high current pulses with a duration of 0.1–10 ns. However, no detailed description of the cumulation mechanism was given in the articles.

3. Irradiation of a tungsten target

The high intensity of cumulated electron beams makes it possible to achieve high energy densities during target irradiation. As a target, materials with a high density and consisting of atoms with a large charge number Z are best suited. High density protects targets from premature expansion. A large charge Z leads to an increase in the specific energy losses during electron motion inside the target. These two circumstances lead to the fact that electrons lose their energy in a smaller volume. This means that with the same initial energy of particles, the loss of kinetic energy per unit volume will be higher in dense substances with a large charge number. Tungsten ($Z = 74$), which has a density of 19.25 g/cm^3, is a reasonable choice.

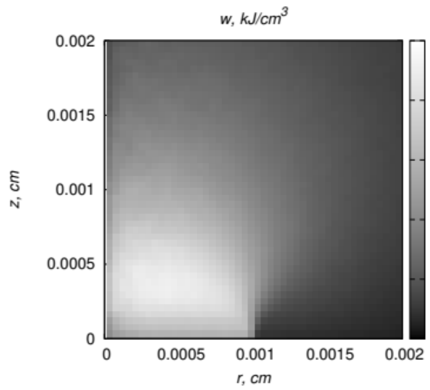

Fig.4. The distribution of energy density in a tungsten plate.

The figure Fig.4 shows the distribution of specific energy in a tungsten plate irradiated with an electron beam ($j \approx 100$ kA/cm^2) in the $3 \cdot 10^{-4}$ cm^2 area for 20 ns. The maximum specific energy (~ $2.5 \cdot 10^4$ J/cm^3) is observed at a depth of ~ 4 μm. The pressure in this region is about 0.25 Mbar.

When a pressure jump occurs in the medium, a shock wave begins to propagate. If we now place a target in the path of the shock wave, then we should expect the significant compression of the target. Compression can be increased by irradiating the tungsten plate with electron beams from different directions (Fig.5).

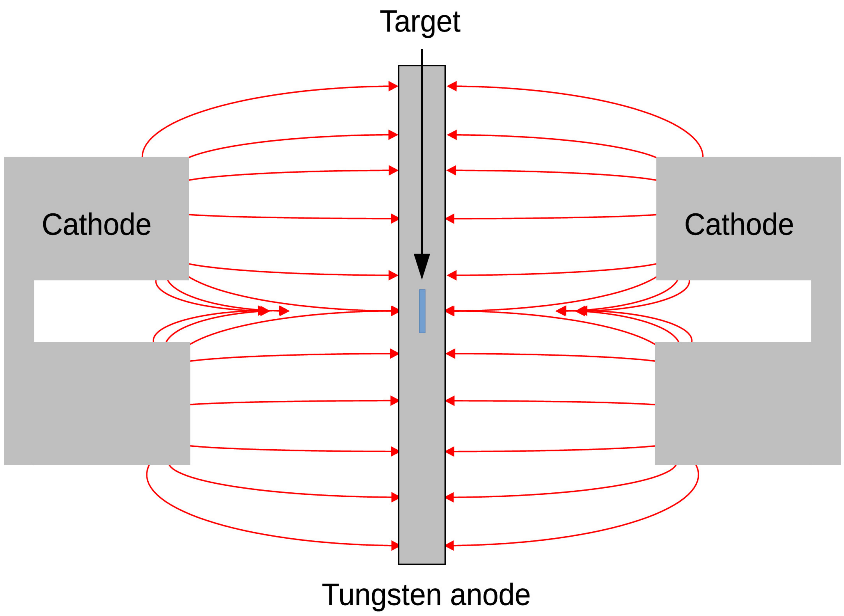

Fig.5. Target irradiation with two electrostatically cumulated beams.

Let us now pay attention to a significant difference in the interaction of electron beams obtained as a result of magnetic and electrostatic cumulation. A beam magnetized by its own field has a significant spread in energy, which leads to different path lengths of particles in matter. Thus, under conditions of magnetic cumulation, the region in which the most intense energy release occurs turns out to be much wider than in the case of electrostatic cumulation. The disadvantage of electrostatic cumulation is the too small size of the region in which the current density reaches $j \approx 100$ kA/cm². However, as estimates show, an increase in the accelerating voltage in a vacuum diode by an order of magnitude can significantly increase the intensity of a high-current beam (by 1–2 orders of magnitude) and, as a consequence, increase the pressure up to 10 Mbar.

4. Conclusion

In this paper we describe a new cumulation mechanism for high-current beams in relativistic vacuum diodes with a ring-type cathode. The basis of the cumulation mechanism is electrostatic repulsion of electrons emitted from the inner edge of the cathode. At several hundred kilovolts, the electrostatic cumulation is verified experimentally. The current density and beam intensity equal to 100 kA/cm^2 and 40 GW/cm^2, respectively, are obtained in simulations at 400 kV in the $3\cdot10^{-4}$ cm^2 area.

A beam with such characteristics is capable of exciting a shock wave with an amplitude of 0.25 Mbar in a tungsten plate, which can be used to compress a target. Research can be carried out using one high-current beam or several. An increase in the accelerating potential up to 4 MV makes it possible to significantly rise the intensity of the electron beam. As a consequence, the amplitude of the shock wave in the substance will increase by 1–2 orders of magnitude and will amount to 10 Mbar.

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