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Abstract

Dielectric wall accelerator (DWA), towards high gradient acceleration field (30 MeV/m–100 MeV/m), is under development at Institute of Modern Physics. A prototype was designed and constructed to prove the principle. This needs a short pulse high current electron source to match the acceleration field generated by the Blumlein-type pulse forming lines (PFLs). In this paper, we report the design and test of a new type short pulse high current electron gun based on principle of vacuum arc discharge. Electron beams of 100 mA with pulse width of 10 ns were obtained.

Full Text

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Development of a High Current Short Pulse Electron Gun∗

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A dielectric wall accelerator (DWA) capable of achieving high acceleration gradients (30–100 MeV/m) is currently under development at the Institute of Modern

Physics. To demonstrate the principle, a prototype has been designed and constructed. This prototype requires a short-pulse, high-current electron source to match the acceleration field generated by the Blumlein-type pulse forming lines (PFLs). In this paper, we report on the design and testing of a novel short-pulse, high-current electron gun based on vacuum arc discharge principles. The device has successfully produced electron beams of 100 mA with a pulse width of 10 ns.

Keywords: Dielectric wall accelerator, Arc discharge, Short pulse high current electron gun, Electric field simulation

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Introduction

The dielectric wall accelerator (DWA) [1, 2] represents a new class of compact induction accelerator that integrates pulse forming lines, switches, and vacuum-insulated walls into a single compact geometry. This design enables high accelerating gradients (30–100 MeV/m) and high beam intensity, making DWA suitable for applications including flash x-ray radiography, heavy ion inertial fusion, and proton therapy [3].

[Figure 1: see original paper] illustrates the basic configuration of a DWA [4]. The system comprises stacked Blumlein-type pulse forming lines (PFLs), high-gradient insulators (HGI), silicon carbide photoconductive switches, an electron source, and a laser triggering system. The laser controls the photoconductive switches, which excite axial accelerating electric fields in the wall structure while the Blumlein lines shape the pulses. Particles emitted from the source are continuously accelerated by these pulsed fields to high energies.

At Lawrence Livermore National Laboratory (LLNL), researchers developed a short-pulse optically switched DWA (see inset of Fig. 1) and achieved accelerating voltages with nominal 3-ns pulse widths [2]. Significant efforts at LLNL have focused on developing DWA components and system architectures for radiography and other applications [5–13].

A prototype DWA is currently under development at the Institute of Modern Physics (IMP), Chinese Academy of Sciences, as shown in [Figure 2: see original paper]. While developing a short-pulse proton source presents considerable complexity and challenges in achieving suitable injection energies, an electron source has been designed and fabricated to test the DWA assembly technology.

The DWA system comprises two main subsystems: the electron gun with its flashboard and pulser, and the Blumlein-type PFLs with their pulse-charging system and laser triggering mechanism. During normal operation, a capacitive discharge unit first pulse-charges the PFLs. The flashboard pulser then applies a high-voltage pulse across the flashboard gaps via resistors, generating plasma that expands into the diode region. Subsequently, each PFL is activated by illuminating its embedded photoconductive solid-state switch with an Nd:YAG laser. Once activated, the PFLs produce a transient voltage across the vacuum insulator, extracting electrons from the plasma and accelerating them toward the anode grid. The relative timing of the pulse-charging system, flashboard pulser, and laser is fully adjustable.

Operating in pulse mode with durations of 3–10 ns and peak currents of several kiloamperes, the DWA requires a new type of high-current pulsed electron gun specifically matched to these parameters. Thermionic cathode sources face limitations due to space charge effects and high-temperature radiation that could damage the gun body's plastic holder. Photocathodes would further complicate the existing laser system already used for photoconductive switching. A plasma cathode, where discharge is excited by a pulsed high-voltage power supply and electrons are extracted by the DWA's electric field, offers a simple solution to these challenges while enabling the production of high-current, short-pulse electron beams.

Principle Design and Flashboard Testing

Vacuum arc electron guns are well-suited for generating high-current electron beams in pulsed mode. A vacuum arc is a discharge between two electrodes in vacuum, where current concentrates at the cathode into numerous tiny, discrete sites known as cathode spots. The formation of these spots is fundamental to vacuum arc discharge, as they produce the plasma that provides the current path between cathode and anode, sustaining the arc [14]. In vacuum arc mode, the cathode itself serves as the sole source of ions and electrons, making arc discharge achievable through cathode spot formation. Key characteristics of arc discharge include: (1) modest voltage requirements, (2) extremely high current density near the cathode, (3) high charged particle concentration in the cathode region, (4) arc extinction below a threshold current, and (5) spontaneous arc current interruption. The plasma exists within cathode spots, but detailed study is challenging due to their small size (diameter 10^{-4} cm) and high velocity (10^{4} cm/s).

As shown in [Figure 3: see original paper], vacuum arc mode enables high current generation without requiring high voltage. Therefore, our plasma cathode employs vacuum arc discharge technology, generating plasma on a dielectric surface through vacuum arc. Electrons are then extracted by the PFLs, delivering a high-current, short-pulse electron beam into the DWA for acceleration mechanism testing.

Preliminary flashboard testing focused on determining optimal cathode geometry and verifying reliability. The first step involved designing the vacuum arc discharge structure. As illustrated in [Figure 4: see original paper], a cathode structure (or flashboard) was developed using a printed circuit board with narrow gaps machined into the copper layer. Since discharge initiates more readily at sharp corners, triangular islands with 0.3-mm gap width were adopted as the discharge configuration.

To verify reliability, the flashboard discharge was tested in atmospheric conditions. [Figure 5: see original paper] (x-axis scaled at 4 µs) shows the arc discharge voltage across the gap. Measurements using a high-voltage probe indicated an arc discharge voltage of 600 V, demonstrating that the flashboard readily generates arc discharge at low voltage, confirming its suitability as a plasma cathode.

The electron beam optics were simulated using the EGUN code [15], which confirmed that the designed structure produces good laminar flow. [Figure 6: see original paper] presents the simulation results for electric potential distribution and electron beam transport. A 45° Pierce electrode was employed to limit transverse emittance.

Experimental Result and Discussion

[Figure 7: see original paper] presents the experimental results for the electron gun installed in the prototype DWA. At a pulse voltage of 20 kV with approximately 10 ns pulse width, the measured beam current was 100 mA under vacuum conditions of 1×10^{-4} Pa or better. The electron gun has essentially met its design requirements.

The current waveform exhibits a delay relative to the voltage pulse, primarily due to the approximately 3-ns drift time required for electrons to travel from the cathode to the fast current transformer. Because the DWA power supply's nanosecond pulse output has voltage limitations, a microsecond pulse power supply was used as a substitute to test cathode emission capability at higher pulse voltages. This configuration delivered over 2 A of beam current at 4.5 kV, with the relationship between beam current and pulse voltage shown in [Figure 8: see original paper].

The peak beam current of our electron gun is lower than the 8 A achieved by the vacuum arc high-current short-pulse electron gun at LLNL [2]. This difference is attributed to machining accuracy limitations that prevent simultaneous discharge from all triangular islands. A solution involves employing etching technology to fabricate the flashboard gaps, which would enable 0.1-mm gaps instead of the current 0.3-mm width. This modification would reduce the flashboard's operating voltage while increasing the number of triangular islands, thereby increasing beam current. Additionally, discharge stability depends on the flashboard's mechanical structure, and etching can improve mechanical stability.

Conclusion

A prototype DWA with a vacuum arc plasma cathode has been successfully demonstrated. The pulsed electron gun achieves currents exceeding 100 mA at a pulse width of 10 ns, with the cathode discharging continuously and stably for over 20 minutes. Peak perveance measurements exceed 7.2×10^{-6} A/V^{3}/^{2}, satisfying the definition of a high-current pulsed electron gun and meeting DWA requirements.

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References

[1] Caporaso G J, Sampayan S, Chen Y J, et al. in Proc. Particle Accelerator Conf., 2007, 857–861.
[2] Harris J R, Hickman B, Anaya R, et al. IEEE T Plasma Sci, 2009, 37: 1069–1077.
[3] Chen Y J and Paul A C. IEEE, PAC. 2007, 1787–1789.
[4] Zhao Q T, Zhang Z M, Yuan P, et al. Nucl Instrum Meth A, 2013, 729, 227–232.
[5] Harris J R, Caporaso G J, Blackfield, et al. Appl Phys Lett, 2007, 91: 121–504.
[6] Harris J R, Blackfield D, Caporaso G J, et al. J Appl Phys, 2008, 104: 23–301.
[7] Rhodes M A, Watson J, Sanders D, et al. in Proc. IEEE Pulsed Power Conference, 2007, 538–543.
[8] Sanders D, Cook E, Anaya R, et al. in Proc. IEEE Pulsed Power Conference, 2007, 1826–1830.
[9] Sullivan J S and Stanley J R. IEEE T Plasma Sci, 2008, 36:
[10] Nelson S D, Poole B R, Caporaso G J. in Proc. Particle Accelerator Conference, 2007, 1784–1786.
[11] Chen Y J and Paul A C. in Proc. Particle Accelerator Conference, 2007, 1787–1789.
[12] Sampayan S, Caporaso G, Chen Y J, et al. IEEE T Plasma Sci, 2007, 857–861.
[13] Harris J R, Kendig M, Poole B, et al. Appl Phys Lett, 2008, 93:
[14] Brown I G. (Ed) The Physics and Technology of Ion Sources Second, Revised and Extended Edition [M] WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 2004, 259–260.
[15] Herrmannsfeldt W B. EGUN: An Electron Optics and Gun Design Program, SLAC-033.

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