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CHARACTERISTICS OF AN ELECTRON-BEAM ROCKET PELLET ACCELERATOR*

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ABSTRACT

An electron-beam rocket pellet accelerator has been designed, built, assembled, and tested as a proof-of-principle (POP) apparatus. The main goal of accelerators based on this concept is to use intense electron-beam heating and ablation of a hydrogen propellant stick to accelerate deuterium and/or tritium pellets to ultrahigh speeds (10 to 20 km/s) for plasma fueling of next-generation fusion devices such as the International Thermonuclear Engineering Reactor (ITER). The POP apparatus is described, and initial results of pellet acceleration experiments are presented. Conceptual ultrahigh-speed pellet accelerators are discussed.

I. INTRODUCTION

Pneumatic guns and centrifuge accelerators have been used to accelerate pellets of hydrogen and deuterium, up to 6 mm in diameter and 6 mm long, to velocities of 1 to 2 km/s in plasma fueling experiments in tokamaks.[1-6] Accelerators for injecting pellets at the higher velocities needed in future fusion devices are under development.[7-10]

The development at Oak Ridge National Laboratory (ORNL) of advanced pellet injectors for fusion reactors such as ITER is discussed in Refs. 11–13. For penetration to or near the center of a burning-core plasma, solid deuterium or tritium pellets must be injected at a rate of >10 Hz and at a velocity of 10 to 20 km/s. Injecting such ultrahigh-velocity pellets requires an acceleration technique that can accommodate both the energy levels required and the inherent weakness of solid deuterium and tritium. For example, a 6-mm-diam deuterium pellet traveling at a velocity of 20 km/s has a kinetic energy of 5.6 kJ. Accelerating it over a path length of 20 m in 2 ms would require a pulsed power of 2.8 MW. At 20% efficiency, 14 MW of input power would be required. An average power of 280 kW could accelerate 10 pellets per second. Under these conditions, the acceleration pressure on a 6-mm pellet is about 10 MPa or 100 bar, greatly exceeding the pellet strength limit of 5 bar. However, this acceleration pressure is similar to that now being used safely to accelerate pellets to 1–2 km/s in pneumatic guns and centrifuge accelerators.

Many acceleration techniques (electrothermal gun, rail gun, laser rocket, two-stage pneumatic gun, etc.) have been proposed to accelerate pellets to higher velocities. We are using electron beams to accelerate pellets by means of the rocket effect. Figure 1 shows the basic concept, which is to use an intense electron beam for heating and ablation of a hydrogen propellant stick pellet and to use the rocket effect of the resulting exhaust gas for accelerating deuterium and/or tritium pellets to ultrahigh speeds. This injector is called the electron-beam rocket pellet accelerator.[8,11] We briefly describe the theoretical evaluation, experimental arrangement, and operating characteristics of the pellet accelerator. Conceptual ultrahigh-velocity pellet injectors are also discussed.

II. THEORETICAL EVALUATION

As shown in Fig. 1, a compound pellet consisting of a *hydrogen propellant stick and a deuterium or tritium pellet* is ablated by the intense electron beam to produce a gas cloud. The exhaust gas absorbs some of the electron beam power and shields the pellet. This neutral gas shielding

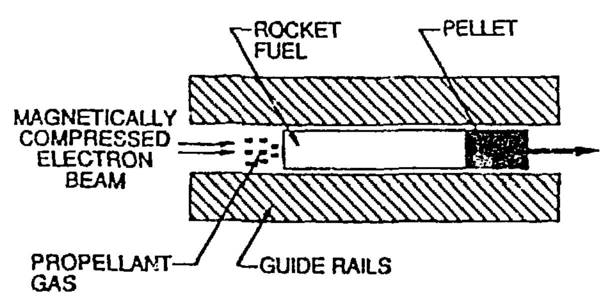

Fig. 1. Electron-beam rocket pellet accelerator concept.

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feature was observed as an evaporation phenomenon for solid hydrogen pellets in fueling experiments on the Oak Ridge Tokamak (ORMAK).[3,14] The resulting high pressure of the heated gas accelerates the compound pellet. The rocket propulsion effect further enhances the speed of the accelerated pellet. The neutral gas shielding model is the basis for the following theoretical evaluation[11] of the electron-beam pellet accelerator.

The burn velocity v_b of a solid pellet is essentially determined by the beam energy E and the pellet radius r_p, because the shielding of the ablation gas cloud limits the power flux of the electron beam on the surface of the solid pellet and regulates the pellet evaporation rate. The burn velocity (in meters per second) is proportional to E^2 and can be estimated from

$$v_b = (v_s E^2 m)/(2\alpha\rho r_p), \tag{1}$$

where v_s is the sound velocity of the ablating cryogenic hydrogen gas at the surface of the solid and is assumed to have an effective value of 370 m/s at 20 K, m is the mass of the molecular hydrogen, α is an energy loss constant[2,11] for electrons (>1 keV) diffusing in the cryogenic gas and is about 2×10^{-16} V^2m^2, and ρ is the hydrogen pellet density, which is about 87 kg/m^3. As an example, for E = 20 keV and r_p = 0.002 m, the estimated burn velocity v_b is 7 m/s. However, the intense power fluxes of the electron beam rapidly heat the exhaust gas in a region assumed to lie within one pellet radius. The exhaust velocity v_e (in meters per second) can be estimated from

$$v_e = (4f\alpha I/\pi r_p v_s m E)^{1/2}, \tag{2}$$

where f is the fraction of the beam power being used to heat the exhaust gas and I is the beam current. For this example, if we assume f = 0.6 and I = 20 A, the exhaust velocity v_e is 8000 m/s, and the accelerating pressure p, estimated from

$$p = v_e \rho v_b = [f v_s m I E^3/\pi\rho(r_p)^3]^{1/2}, \tag{3}$$

is about 40 bar. The final velocity of the pellet is the product of the resulting exhaust gas velocity times the log of the ratio of the initial mass to the final mass. For this example, we consider a propellant-hydrogen pellet. If the ablated propellant pellet has a constant cross-sectional area, its mass is proportional to its length. For an initial pellet length L (in meters), the effective length L′ of the pellet during ablation and acceleration is $L' = L - v_b t$. The increased pellet velocity v′ (in meters per second) due to the rocket effect is $v' = v_e \ln(L/L')$. As indicated by Fig. 2, a solid hydrogen pellet that is initially 12 mm long can deliver, after being accelerated for 1.26 ms by a 20-keV, 20-A electron beam, a 3-mm-long pellet at about 11 km/s. The actual performance of a pellet accelerator depends strongly on the efficiency of the beam transmission, the beam ablation, the initial sound velocity of the ablated gas, the heating of the exhaust gas, etc. The mature technology of electron guns and pellet makers has been used to design and build a POP apparatus, which is being operated to study these factors.

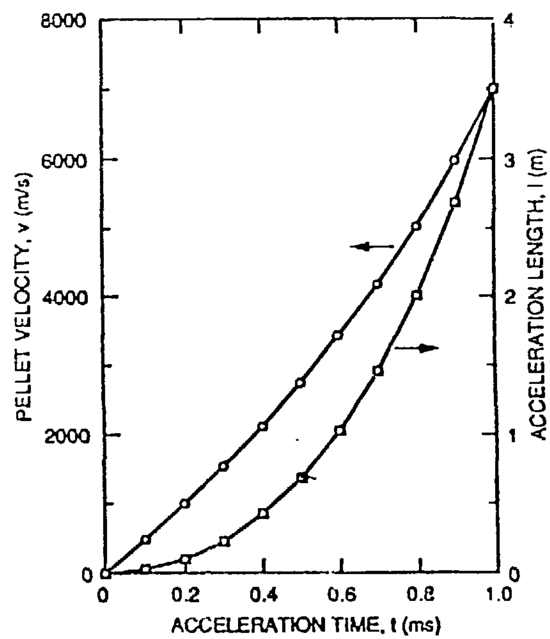

Fig. 2. Velocity of a 12-mm-long, 4-mm-diam, 10-mg pellet accelerated by a 20-keV, 10-A electron beam.

III. POP APPARATUS

The POP apparatus, shown in Fig. 3, consists of a pellet maker, an electron gun, a pellet accelerating column that includes guide rails, and a set of axial magnets for beam compression and confinement. The innovative design of the pellet feed ramp guides the pellet into the guide rails, where the intense electron beam is focused on it. The apparatus is equipped with a diagnostic system, also shown in Fig. 3, that includes a television (TV) camera (at PD7) for imaging the accelerated pellet and light trip detectors (PD1 to PD6), a microwave mass detector (MD), and a shock

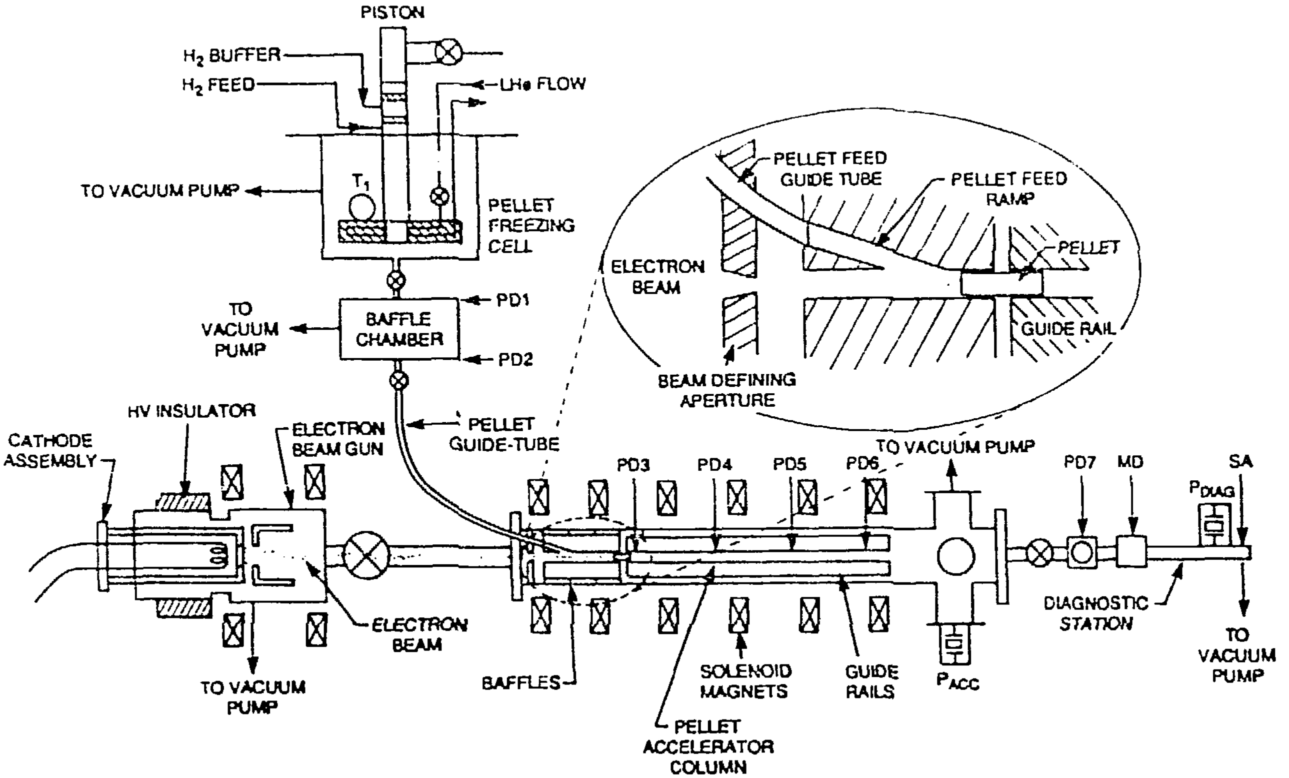

Fig. 3. Proof-of-principle apparatus.

accelerometer (SA) for measuring the pellet speed. The distances of these monitors from PD1 are as follows: PD2, 78 cm; PD3, 165 cm; PD4, 185.3 cm; PD5, 200.6 cm; PD6, 221 cm; PD7, 320 cm; MD, 355.6 cm; and SA, 475 cm.

III.A. Pellet Maker

In the pellet maker, long compound pellets are produced by *in situ* condensation of hydrogen and its isotope on the walls of a hole in the liquid-helium-cooled copper block. The resulting pellet is punched out by a mechanical piston or plunger. The pellet length is a function of the amount of gas fed into the freezing cell. Pellets of hydrogen and deuterium, 4 mm in diameter by 12 mm long, have been made and launched into the pellet accelerator. During launching, the piston converts a fraction of the pellet ice into high-pressure gas, which accelerates the pellet. The initial pellet speed, which can be influenced by the piston temperature and by the gas pressure applied to the piston, is typically betweeen 50 and 100 m/s.

III.B. Pellet Accelerator

A baffle chamber immediately following the pellet maker limits the flow of gas (created during pellet launching) into the pellet accelerator. After passing through the baffle chamber, the pellet is transported into the accelerator through a guide tube. As shown in Fig. 3, a pellet feed ramp/ funnel loads the pellet from an off-axis trajectory in the guide tube into the accelerator guide rails. The pellet is constrained to travel down a set of three 0.6-m-long graphite guide rails. In this acceleration column, the pellet is ablated and accelerated by the electron beam. Along the guide rails, baffle plates with proper spacing localize the exhaust gas and enhance the pellet acceleration. Figure 4 shows the accelerator assembly, including the feed ramp. All components are made of graphite to ensure reliable operation of the pellet accelerator.

A solenoid magnet installed on the acceleration column produces an axial field of 1 T. This strong axial magnetic field is used to compress and contain the intense electron

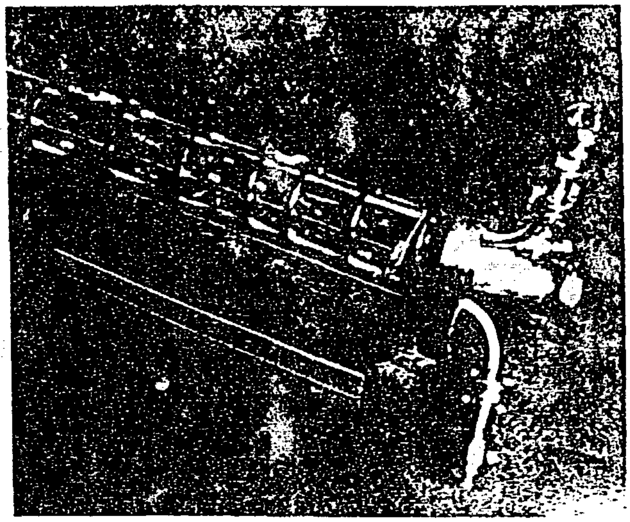

Fig. 4. The accelerator assembly.

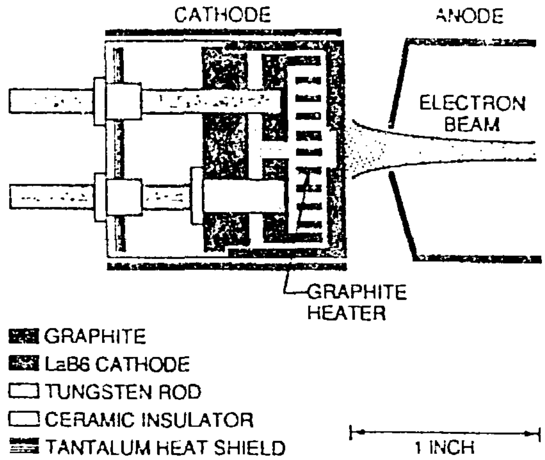

Fig. 6. The 30-keV electron gun.

beam. The electron gun is located in the throat of the solenoid, at a field of 0.0833 T. The magnets in the acceleration column have successfully compressed the electron beam to one-twelfth of the cathode size, as demonstrated by using a compressed beam to burn a 3-mm hole in a graphite paper sensor disk located in the region of the guide rails. As shown in Fig. 5, the triangular shape of the burned hole images that of the cathode.

III.C. Electron Gun

The electron gun, shown in Fig. 6, has been designed with the goal of forming 30-keV, 30-A electron beams lasting 1 to 5 ms. It consists of an indirectly heated cathode and an anode. The cathode can be heated to 2000 K by a graphite heater, which is operated at a power of 1 kW (or 30 V and 33.3 A). Proper heat shielding minimizes the heating power requirements. The thermal time constant is about 5 min. The continuous wave (cw) graphite heater can heat a 2.5-cm-diam cathode to above 2000 K; such a cathode has the potential to produce electron beams with currents above 100 A.

The electron emitter is made of 6-mm disks of single crystals of lanthanum hexaboride, which are fastened to the graphite holder with graphite glue. The preliminary results are very encouraging. For example, the beam current density of the single-crystal emitter is about twice that of a polycrystal emitter. With a single disk, the gun has been used to form intense 12-keV, 15.6-A electron beams with a current density above 70 A/cm^2, even without magnetic compression.

In studies of beam compression and transmission along the pellet acceleration column, the electron gun has been operated to form intense beams of 14 keV, 11 A, and 300 μs. As shown in Fig. 5, the magnetically compressed electron beam is about 3 mm in diameter. Thus, the beam current density is above 100 A/cm^2. The magnetic coils beside the electron gun are used both to compress the beam and to align it along the accelerator axis. The beam-defining plates at top, bottom, left, and right align the beam and protect the guide rails.

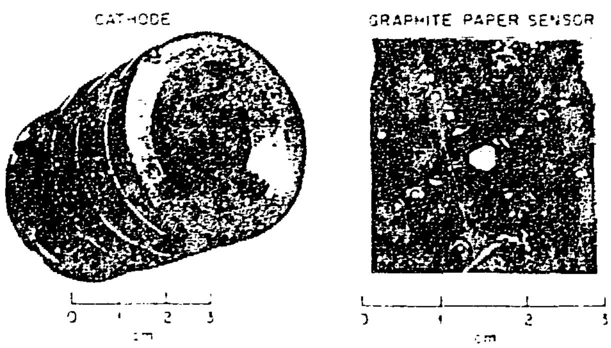

Fig. 5. The electron gun cathode and a graphite paper sensor disk on which the electron beam was focused.

III.D. Diagnostics

The basic diagnostics of the POP apparatus measure the current and voltage associated with formation and transmission of the electron beam and characterize the size and speed of the pellets. The signals from these diagnostics are used to study the actual performance of the accelerator, which strongly depends on the efficiency of beam transmission, beam ablation, gas heating, etc. The current and voltage measurements are used to characterize the performance of the electron gun, the beam compression, and the beam transmission. From these measurements, the pulsed beam energy (including power and pulse duration) available for accelerating the pellet can be estimated.

Light trip detectors and light-emitting diodes installed at the entrance and the exit of the baffle chamber and along the pellet accelerator guide rails are used to detect pellet speed before and during electron-beam acceleration. Figure 3 shows the locations of these monitors. Other diagnostics are installed in the diagnostic station next to the pellet accelerator chamber. The light trip detector labeled PD7 in Fig. 3 triggers a nitrogen laser to illuminate the accelerated pellet. The TV camera then records the pellet shadow and measures the size of the accelerated pellet. The microwave mass detector and the target impact shock transducer are also used to measure the pellet speed and size. The gate valves between chambers are closed to isolate the chambers after the pellet passes through. The measured pressures in the accelerator chamber and the diagnostic chamber can be used to determine the amount of the pellet ablated during acceleration and the size of the accelerated pellet, respectively.

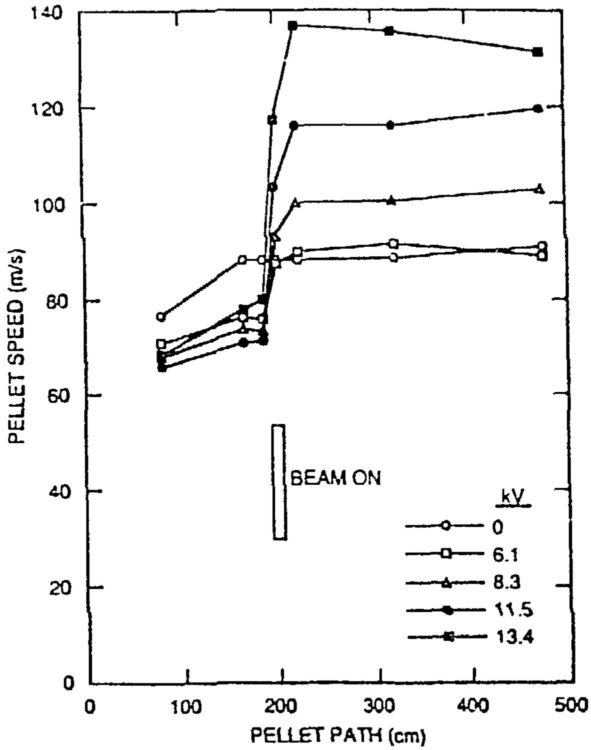

Fig. 7. Results of electron beam rocket pellet acceleration.

IV. RESULTS

Pellets can be accelerated by means of electron-beam heating, as demonstrated by the preliminary results of the experimental study (Fig. 7). The POP apparatus has been operated to demonstrate pellet acceleration. Cryogenic cylindrical pellets of frozen hydrogen, up to 4 mm in diameter and 12 mm long, were reliably injected into the accelerator guide rails and detected by pellet monitors. Pellets are accelerated by partially ablating the back of the pellet with high-power pulsed electron beams at various electron energies, beam currents, and pulse lengths. The typical speed increment of the accelerated pellets is up to 300 m/s and increases with the beam power. The speed of the pellets was diagnosed by time of flight along the pellet trajectory using light trip detectors, a microwave mass detector, and a target impact shock transducer. The locations of the pellet detectors are used to estimate pellet speeds; the time difference in the signals from PD1 and PD2 is used to estimate the initial pellet speed, and the time differences among signals from PD6, PD7, MD, and SA are used to estimate the final pellet speed. With the present experimental arrangement, pellet speeds can be measured accurately. We observed that electron-beam pellet acceleration can be done efficiently when pellets are 15 cm into the guide rails. The preliminary results of the experimental study reveal an estimated burn velocity consistent with theoretical estimates. The exhaust velocity and the acceleration efficiency are being studied in the ongoing experiments.

V. CONCEPTUAL ULTRAHIGH-SPEED INJECTORS

The reliable operation of the POP apparatus results from the following factors. The intense electron beam can accelerate pellets efficiently. The solenoid magnet can compress, confine, and guide the electron beam during pellet acceleration. All electrodes adjacent to the trajectory of the intense electron beam are made of graphite, the appropriate material for this application. The baffle chamber between the pellet maker and the guide tube enhances the operational reliability of the electron gun. The innovative pellet feed ramp is suitable for repetitive pellet acceleration.

The preliminary results of these POP experiments demonstrate the viability of electron-beam rocket pellet acceleration. This acceleration technique can be scaled up for injecting ultrahigh-speed (10- to 20-km/s) pellets. Figure 8 shows a conceptual ultrahigh-speed pellet injector that could use either a single-stage or a multiple-stage electron-beam acceleration scheme. The axial pellet feed scheme in this injector is an improvement on that in Fig. 3; it provides the flexibility of accelerating pellets with different lengths and reduces the transverse scattering angles of the accelerated pellets. The electron gun can be designed to form hollow electron beams with high currents in high vacuum. A single-stage pellet injector can be built by lengthening the accelerator column and its solenoid magnet, the beam pulse, and the propellant pellet. A multiple-stage pellet injector can be built with multiple sets of electron guns and pellet accelerators. With continuous cryopump modules distributed along the accelerator path, an electron beam dump, and a differentially pumped drift tube, ultrahigh-speed injectors could be developed and used for continuous fueling of reactor plasmas.

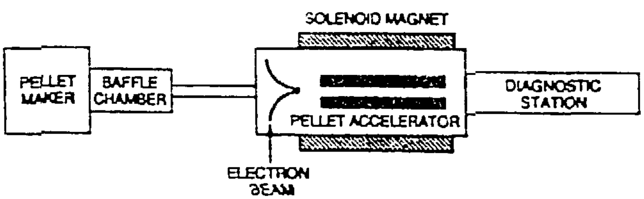

Fig. 8. Conceptual design for an ultrahigh-speed pellet injector.

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