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RESULTS FROM RECENT HYDROGEN PELLET ACCELERATION STUDIES WITH A 2-M RAILGUN

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Abstract

A new 3.2-mm-diameter, two-stage, fuseless, plasma-arc-driven electromagnetic railgun has been designed, constructed, and successfully operated to achieve a record velocity of 2.67 km/s[b] for a 3.2 mmD x 4 mmL solid hydrogen pellet. The first stage of this hydrogen pellet injector is a combination of a hydrogen pellet generator and a gas gun. The second stage is a 2-m-long railgun which serves as a booster accelerator. The gas gun accelerates a frozen hydrogen pellet to a medium velocity and injects it into the railgun through a perforated coupling piece, which also serves as a pressure-relieving mechanism. An electrical breakdown of the propellant gas, which has followed the pellet from the gas gun into the railgun, forms a conducting plasma-arc armature immediately behind the pellet allowing for fuseless operation of the railgun. Study of the pressure profile and the behavior of the plasma-arc armature inside the railgun bore led to elimination of spurious arcing, which prevents operation of the railgun at high voltages (and, therefore, at high currents). A timing circuit that can automatically measure the pellet input velocity and allows for accurate control of arc initiation behind the pellet helps prevent pellet disintegration and mistriggering of the arc initiation circuit. Results from the recent

cryogenic operation of the two-stage pellet acceleration system are reported.

Introduction

A two-stage, fuseless, plasma-arc-driven electromagnetic railgun system consisting of a pneumatic gun (preaccelerator) and a 2-m-long, 3.2-mm-diameter railgun (booster accelerator) has been designed and fabricated in the Fusion Technology and Charged Particle Research Laboratory at the University of Illinois at Urbana-Champaign (UIUC) as an effort to develop a pellet injector that can accelerate hydrogen pellets to high velocities (≥ 3 km/s) and that is, therefore, suitable for refueling high-density high-temperature tokamak plasmas.[1] The two-stage railgun system, as shown in Fig.1, consists of a pellet generator, pressure-relieving coupling piece, railgun, current-pulse-shaping network, arc-initiation circuit, timing circuit, and the diagnostics that are designed to measure pellet velocity at the railgun breech and muzzle, to determine the pellet integrity and momentum, to measure the current, and to take a photographic recording of the plasma-arc motion.

As in our previous work on the electromagnetic railgun[2-8], the first-stage pneumatic gun consists of a solid hydrogen pellet generator and a gas gun, which accelerates a frozen hydrogen pellet to a medium velocity and injects it into the railgun through a coupling piece. As the pellet enters the railgun, a plasma-arc armature is created immediately behind the pellet by an arc-initiation circuit. The J x B force, which is caused by a uniform high current delivered to the rails by the current-pulse-shaping network, accelerates the pellet along the railgun.

Some distinct features of the present system which make it different from the previous systems are as follows:

First, a pressure-relieving perforated coupling piece, which is housed in a large vacuum chamber, is employed in the present system to control the pressure behind the pellet. Based on the measurement of the pressure profile and the investigation of the behavior of the plasma arc armature inside a 1.2-m-long railgun of the same bore size, the 2-m-long railgun was designed to eliminate the spurious arcing which prevents operation of the railgun at high voltages and, therefore, at high currents.

Second, a timing circuit that can automatically measure the pellet input velocity at the railgun entrance and allows for accurate control of arc initiation behind the pellet helps prevent pellet disintegration and mistriggering of the arc initiation circuit.

Third, the longer rails provide longer acceleration time and make full use of the high-current pulses delivered to them by the current-pulse-shaping network.

In this article, we briefly describe the principal components of the most recent version of the UIUC two-stage, fuseless, plasma-arc-driven electromagnetic railgun system and the preliminary results indicating its capability as well as potential.

Pellet Generator

The pellet generator assembly is a combination of a 3.2-mm-diameter hydrogen pellet generator and a gas gun. A straight-tube direct-cooling scheme was adopted to simplify the fabrication and to avoid mechanical problems during the operation. The heart of the new pellet generator is a liquid-helium-cooled OFHC cylinder, which is used as the cryostat. Liquid helium circulates around the cylinder in a helical groove so that the entire copper block can be cooled uniformly to a desired temperature. The solid hydrogen pellet is formed inside a cylindrical hole along the axis of the cylindrical cryostat. The temperature in the cryostat is monitored by a calibrated sensor connected to a temperature controller. A liquid-nitrogen-cooled cylindrical cooling jacket surrounds the center cryostat to reduce liquid helium consumption. On both sides of the gun barrel near the pellet formation site are high-resistance wires wound around the tube which, upon heating, form a steep thermal gradient and control the length of the pellet. A stainless steel vacuum chamber houses all the components described above.

The test results show that the pellet generator is capable of making a pellet 3.2 mm in diameter and 7 mm in length, and that pellet acceleration can produce a maximum pellet speed of 1.1 km/s at a propellant helium-gas pressure of 800 psi. On the average, about 15 pellet shots can be made with 30 liters of liquid helium. A vacuum on the order of 10^{-7} torr is maintained in the main vacuum chamber of the pellet generator to ensure thermal insulation.

Electromagnetic Railgun

As indicated by Fig.1, the UIUC railgun consists of two parallel rails, 2 meters in length, which form an acceleration path. Together with the plasma-arc armature created by the arc-initiation circuitry, the rails provide an electrical path. A J x B force is created by the high current that flows through the rails and the plasma-arc armature and by the magnetic field that is induced by the current, driving and accelerating the pellet downstream from the railgun breech to the muzzle.

The rails are made of square copper rods with one quarter of a circle removed from one corner. Copper was chosen as the rail material because of its excellent thermal characteristics. The two copper rails and two Lexan sidewalls form a 3.2-mm-diameter circular bore. Lexan was chosen as the insulating material because of its higher melting temperature and transparency, which allows viewing of the plasma-arc motion in the bore. The top and bottom Lexan covers provide electrical insulation and hold the rails to maintain the correct shape for the bore. The entire structure is clamped between two aluminum V-blocks which are held together by screws.[6] The railgun is housed in a vacuum chamber which has windows for the optical diagnostics and to view the plasma motion.

Railgun currents as high as 23.5 kA are produced by the current-pulse-shaping network. The network consists of 5 capacitors of 500 μF each, 5 inductors of about 12 μH each, and a load resistor of 0.16 Ω. The current-pulse-shaping network generates a uniform current pulse of 985-μs duration at a current-to-voltage ratio of 2.35 A/V. The high current is delivered to the rails through an ignitron, which is triggered by an SCR.

Fuseless pellet acceleration using a plasma-arc armature is employed to avoid the friction produced by a sliding metal armature and, in particular, to prevent high-Z impurities from entering the fusion plasma during pellet injection. The plasma-arc armature is created by a sharp tungsten needle located at the railgun breech. Having been triggered by the delayed signal from a photodiode at the breech, an arc-initiation pulse-shaping network delivers a high voltage pulse of 5 kV to the preionization probe, which produces an electrical breakdown and creates a high-charge-density plasma in the propellant gas behind the pellet. The high current is then delivered from the current-pulse-shaping network to the rails at the moment when the arc-initiation current reaches its maximum. The current finds a lower-resistance path, provided by the plasma, forming a plasma-arc-armature behind the pellet. Arc initiation and main currents are monitored through the use of Rogowski coils and an oscilloscope. To ensure that the plasma-arc-armature is formed behind the pellet with no spurious arcing elsewhere, the pressure distribution inside the railgun bore has been measured, and a pressure-relieving perforated coupling piece housed in a separate vacuum chamber is employed to reduce the gas pressure behind the pellet.[9]

Diagnostics and Timing Circuit

The pellet position is monitored at five locations along the trajectory of the pellet in order to measure initial and final pellet velocities. Four laser beams, one pair at the coupling piece and another pair at the railgun muzzle, cross the bore at fixed distances and illuminate four photodetectors. These photodetectors are labeled D1 to D4 in Fig.1. When the pellet breaks the laser beams, the photodetectors transmit pulses to the oscilloscopes. By measuring the time between pulses, the velocity may be calculated before and after pellet acceleration. A fifth position measurement is provided by an impact transducer located at the end of the vacuum chamber.

Timing for most system functions is provided by a special automatic timing circuit. This circuit insures that the plasma is formed a proper distance behind the pellet. When the pellet passes D1, the circuit counts up. When the pellet passes D2, it counts down. The ratio of clock frequencies for counting down and up is equal to the ratio of the distances from D1 to D2 and D2 to the tungsten needle. When the count returns to zero, the pellet has reached the needle and the timing circuit triggers the arc initiation circuit. The count can be adjusted to introduce an advance or delay in this trigger. A streak camera is triggered at the same time as the arc initiation circuit. The main rail current is applied after arc initiation with an adjustable delay of a few microseconds.

The time-dependent position of the arc along the railgun is recorded using a streak camera, which is triggered by the timing circuit. The arc may be seen by the camera through the Lexan spacers. The arc position and velocity for the entire run may be obtained from an analysis of the resulting picture. In addition, any malfunction such as arcing at the end of the railgun may be diagnosed.

It is possible to take a picture of the actual frozen hydrogen pellet as it exits the railgun. This is done by having D4 trigger a nanopulser light source placed right after the laser beam which illuminates D4. The nanopulser illuminates the pellet, and the image is captured by a camera whose shutter is left open during the run. With this technique, clear pictures may be taken of the pellet in flight.

Results from Cryogenic Two-Stage Operation

The 3.2-mm-diameter, 2-m-long, two-stage electromagnetic railgun system described in the foregoing was successfully operated using frozen hydrogen pellets. The highest output pellet velocity was 2.67 km/s which was achieved for a solid hydrogen pellet of 3.2 mmD x 4 mmL. A propellant gas pressure of 800 psi was employed at the gas gun to produce an input pellet velocity of 750 m/s at the railgun breech. The railgun current was 11.75 kA which was obtained at a rail voltage of 5 kV. Because of the limited duration of the current pulse used for this run, the pellet was accelerated over an effective railgun length of 1.4 m, with an average acceleration of 2.44×10^6 m/s^2. The full capability of the present railgun system could, however, not be fully tested since shortly after achieving the record velocity of 2.67 km/s, the hydrogen pellet generator developed a vacuum leak preventing further experimentation with hydrogen pellets. Repair of the pellet generator is under way and should be completed soon. We are also considering the possibility of constructing a new pellet generator that can more precisely and consistently control the size, density, and strength of the solid hydrogen pellets being fabricated.

Table I indicates the highest velocities achieved to date on our various railgun systems: a 1.5-mm-diameter, 1.2-m-long railgun; a 3.2-mm-diameter, 1.2-m-long railgun; and the present 3.2-mm-diameter, 2-m-long railgun. The velocities are 1.71 km/s, 2.20 km/s, and 2.67 km/s, respectively. In the table, v_{in} and v_{out} are the pellet velocities at the railgun breech and muzzle, Δv is the velocity increase achieved by the railgun, τ is the acceleration time, and ℓ is the acceleration distance. The three guns used to obtain the data in Table I represent, in a nutshell, our efforts to date toward developing a railgun system which will be most suitable for achieving hypervelocity solid hydrogen pellets. Note that there has been continuous improvement in the achieved velocity increase, ΔV.

The pellet accelerations achieved with the 1.5 mmD x 1.2 mL, 3.2 mmD x 1.2 mL, and 3.2 mmD x 2.0 mL railguns are plotted against rail currents in Fig.2. The best acceleration achieved so far is 2.92×10^6 m/s^2, which was obtained at a rail current of 18.8 kA on the 3.2 mmD x 1.2 mL railgun. If used as a booster accelerator, our railgun with some modifications should, therefore, be able to accelerate a 2.8-km/s hydrogen pellet injected from an existing two-stage pneumatic gun[10,11] to a velocity of 4.4 km/s. To improve the railgun acceleration one must do the following: to increase the dynamic inductance of the rails, to increase the strength of the magnetic field inside the railgun bore, and, in particular, to minimize the viscous drag inside the railgun bore during pellet acceleration by reducing sidewall ablation. Accurate measurement of the temperature and density of the plasma-arc-armature that is being carried out will also facilitate further understanding and optimization of the railgun performance.

Summary and Future Work

A 3.2-mm-diameter, 2-m-long, fuseless, plasma-arc-driven, two-stage electromagnetic railgun system has been designed, constructed, and tested. A record output pellet velocity of 2.67 km/s was achieved for a solid hydrogen pellet of 3.2 mmD x 4 mmL, which was injected into the railgun with a gas gun at a velocity of 750 m/s. The operating voltage of the railgun was 5 kV and the actual length of the railgun used for the acceleration was 1.4 m. The unique features of the present railgun system are that it can achieve uniform acceleration because of the uniform current provided by the current-pulse-shaping network, that it has a reliable arc-initiation scheme which ensures creation of a plasma-arc-armature immediately behind the pellet by combining a pressure-controlling perforated coupling piece and a timing circuit, and that the acceleration scheme employs a fuseless plasma-arc-armature to prevent high-Z impurities from entering the tokamak plasma during pellet injection.

To achieve higher pellet velocites, concentrated efforts are being expended to increase the dynamic inductance of the rails, to increase the magnetic field inside the rail bore, and to reduce the sidewall ablation which increases viscous drag. A new pellet generator that can more precisely and consistently control the size, density, and strength of the solid hydrogen pellets may turn out to be essential in reducing pellet disintegration and, if so, will be designed and constructed. The idea of constructing a two-stage pneumatic gun will also be explored to increase the initial pellet velocities at the railgun breech. The temperature and density of the plasma-arc-armature will be measured as an effort to facilitate understanding as well as optimization of the railgun performance.

Acknowledgment

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a) Person to whom correspondence should be addressed.

b) Using the same railgun, a new record velocity of 2.82 km/s was achieved for a solid hydrogen pellet on Oct. 6, 1989, one day after the presentation of this paper at the 13th IEEE Symposium on Fusion Engineering, Knoxville, TN.

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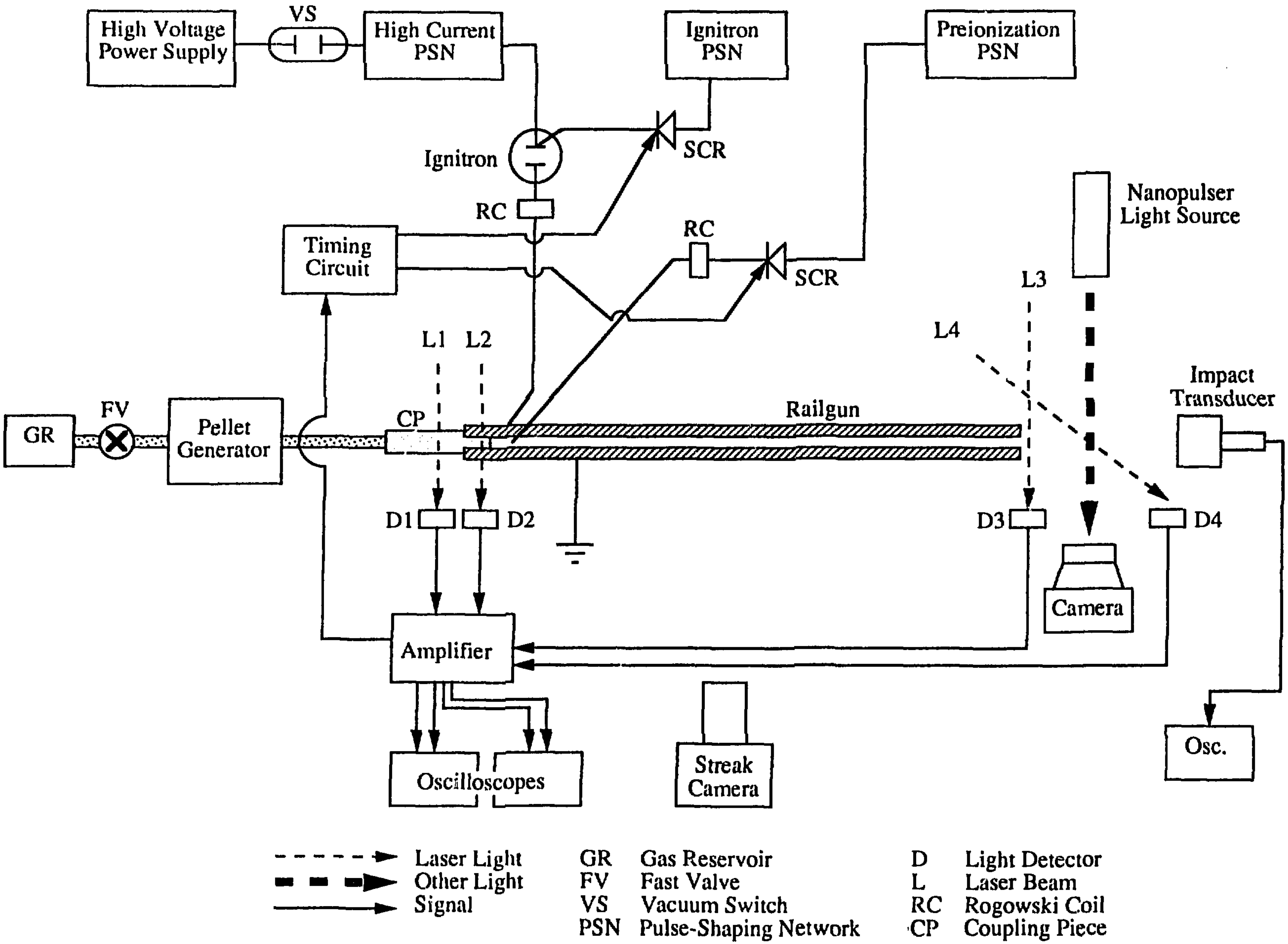

Fig.1. Schematic of the University of Illinois two-stage railgun hydrogen pellet acceleration system

Table I. Highest velocities achieved on the UIUC railgun systems

Railgun Length	1.2 m	1.2 m	2.0 m
Pellet Diameter	1.5 mm	3.2 mm	3.2 mm
Pellet Length	2.2 mm	4 mm	4 mm
P (psi)	360	800	800
V (kV)	2.00	5.00	5.00
I (kA)	3.20	11.75	11.75
v_{in} (m/s)	941	1000	750
v_{out} (km/s)	1.71	2.20	2.67
Δv (m/s)	770	1200	1920
τ (μs)	800	615	788
a (m/s^2)	9.66×10^5	1.95×10^6	2.44×10^6
D (cm)	102	99	140

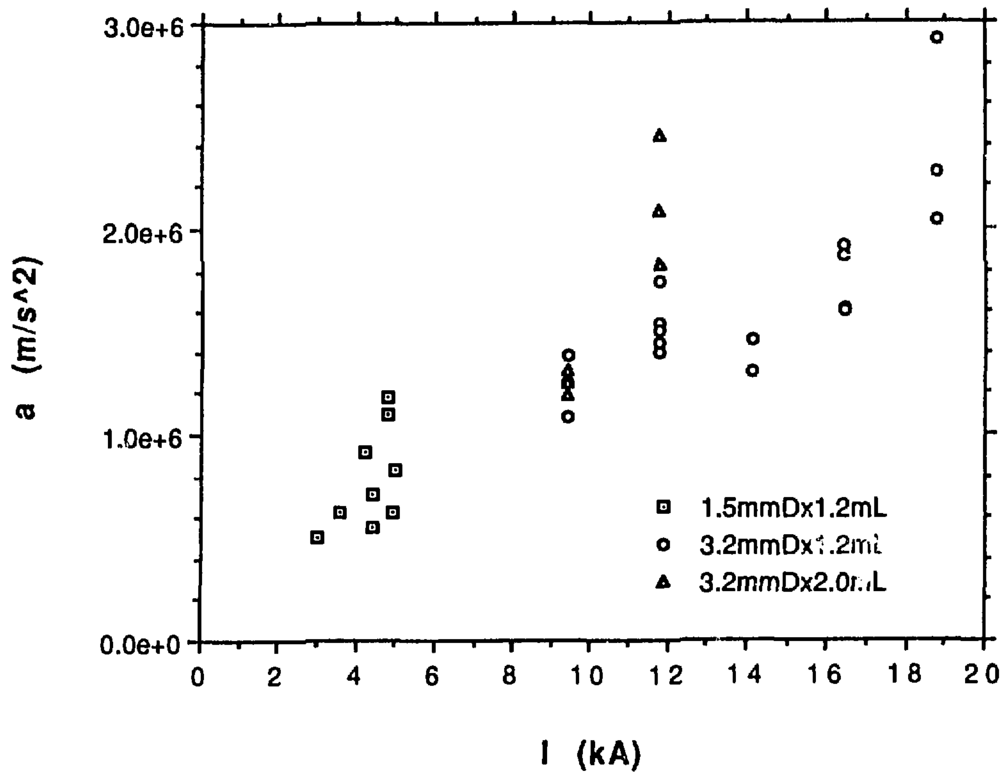

Fig. 2. Hydrogen pellet acceleration on the UIUC railgun systems