Fusion Technology and Charged Particle Research Laboratory
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# APPLICATION OF RAILGUN PRINCIPLE TO HIGH-VELOCITY HYDROGEN PELLET INJECTION FOR MAGNETIC FUSION REACTOR FUELING

PROGRESS REPORT FOR AUGUST 16, 1991 - SEPTEMBER 30, 1992

Prepared

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## 1. Tasks Initiated, Continued, or Completed

a) Trans-augmentation scheme is being tested on a 1.2-m two-stage railgun with Lexan sidewalls, perforated sidewalls, and mullite spacers, respectively. Pellet acceleration extracted from the measured data indicates that trans-augmentation improves the railgun performance by increasing the magnetic field strength inside the railgun bore. See attached plots of hydrogen pellet acceleration with trans-augmentation for the three different sidewalls.

b) The newly designed and tested hydrogen pellet generator-gas gun combination has been employed to produce solid hydrogen pellets for the two-stage, 1.2-m and 2-m railguns. It improves the strength of the frozen hydrogen pellets produced, and reduces the liquid helium consumption. See the attached paper entitled, "Development of a Fuseless Small-Bore Railgun for Injection of High-Speed Hydrogen Pellets into Magnetically Confined Plasmas" presented by K. Kim, et al. at the 6th EML Symposium.

c) Perforated sidewalls have been designed, fabricated, and tested on the railguns to minimize the detrimental effects

of the inertial and viscous drag at high velocities caused by the debris from the projectile and the gun wall trapped in the plasma armature. Because of the reduced viscous and inertial drag, the perforated railgun outperformed the unperforated railgun at high rail currents. A record solid hydrogen pellet velocity of 2.44 km/s has been achieved on a 1.2-m railgun. See attached table and paper entitled, "Study of a New Railgun Configuration with Perforated Sidewalls" presented by J. Zhang, et al. at the 6th EML Symposium.

d) Advanced spacers have been implemented on 1.2-m and 2-m railguns in order to reduce viscous and inertial drag by minimizing pellet and gun-wall ablation .

e) The existing inductors for the pulse-shaping network have been replaced with new ones. These new inductors are easier to wind, and are designed to better maintain their structural integrity.

f) A second photostation has been installed and successfully videotape pellets entering the railgun. The integrity of the pellets at both the gun breech and muzzle can now be compared for the same shot. See the attached pellet pictures.

g) The timing circuit that combines pellet detection with automatic triggering has been completed. It helps prevent pellet disintegration and mistriggering of the arc initiation circuit. See attached paper entitled, "Controls and Diagnostics on a Fuseless Railgun for Solid Hydrogen Pellet Acceleration" presented by T. L. King, et al. at the 6th EML Symposium.

h) B-dot probes have been modified and tested on a 1.2-m railgun with trans-augmentation. Armature currents along the railgun bore have been measured using CAMAC system. Data on B-dot measurements from free arc and pellet acceleration are being analyzed, and will help modify the current pulse shape for optimum pellet acceleration and maintain pellet integrity.

i) A CAMAC system is being assembled to automate and optimize operation of the railgun system. Automation includes:

- charging of the capacitor banks
- freezing of hydrogen pellets
- operating and monitoring of the vacuum system
- logging of pertinent railgun parameters

j) A crude model designed to predict the amount of arc-induced hydrogen pellet erosion during pellet acceleration is being formulated. According to this theory, substantial pellet ablation occurs due to the high density of the plasma armature.

## 2. Status of Major Tasks

a) Based on the measured acceleration of solid hydrogen pellets on the two-stage, 1.2-m and 2-m railguns with Lexan sidewalls, mullite spacers, perforated sidewalls, and transaugmentation (see attached figure), overall performance evaluation of the hitherto tested railgun systems has been carried out. The armature momentum efficiency (i.e., the measured increase in the pellet momentum divided by the total electromagnetic impulse) is found to be as high as 31% on railguns without augmentation, and 20% on railguns with augmentation.

b) The armature momentum efficiency is mainly limited by ablation, viscous and inertial drag, radial rail deflection, pellet balloting, and arc branching. Ablation is the most important factor limiting acceleration of solid hydrogen

pellets. Since the pellet mass is in the milligram range, an increase in the plasma arc armature mass can substantially reduce acceleration. Also, an increase in the viscous drag resulting from ablation drastically reduces armature velocities at high velocities.

c) Analysis of the data obtained to date appears to indicate that the following measures will lead to improved hydrogen pellet acceleration:

- Enhancement of the armature momentum efficiency by
  - employing stiff gun design to reduce radial rail deflection.
  - reducing gun wall ablation by using zero-ablation insulating material.
- Operation of the railgun system at higher currents and lower voltages by employing a current transformer.
- Utilization of a sabot to protect hydrogen and deuterium pellets under high acceleration pressure produced by the high current.

d) A new railgun with low ablation and high stiffness is being designed, and will be utilized to achieve higher pellet acceleration.

e) To protect hydrogen pellets during high current operation, modification of the pellet generator and the first-stage gas gun is under way to allow for implementation of a sabot loading system.

f) B-dot probes have been designed, fabricated, and tested on the 1.2-m and 2-m railguns to measure the railgun and plasma armature currents, and the plasma armature velocities.

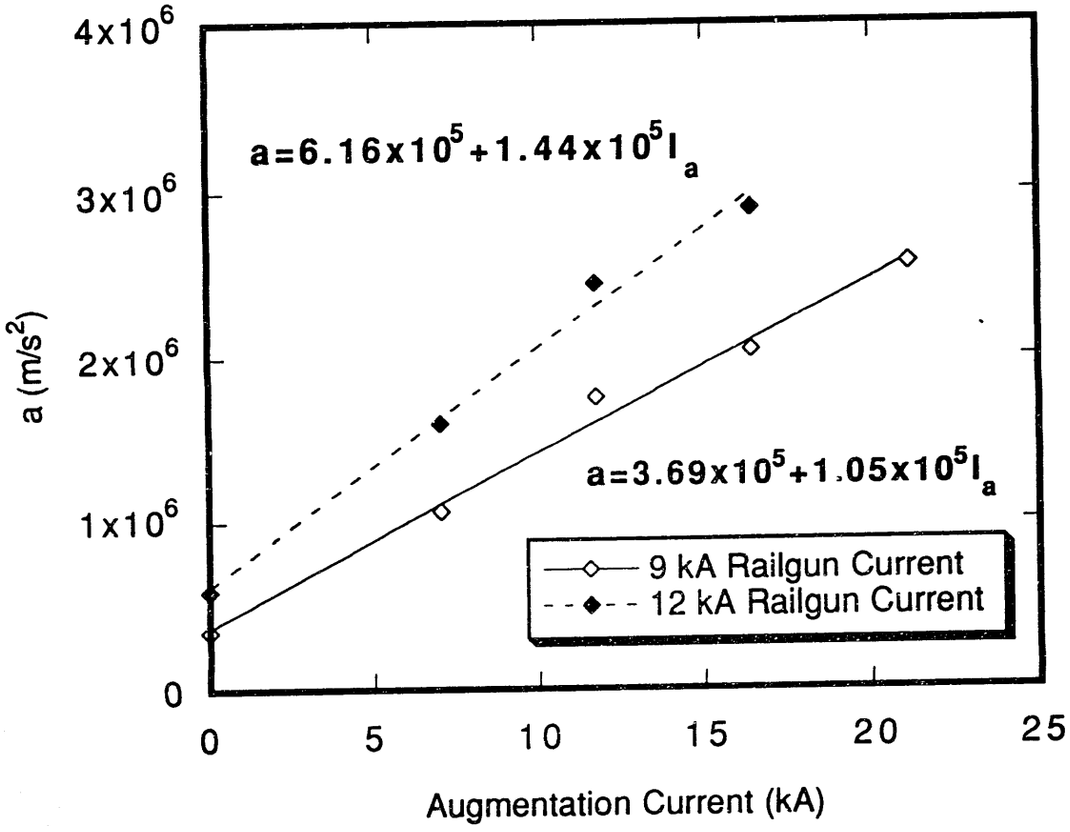
g) Current pulse forming network capable of producing variable rise time, duration, amplitude, and shape is being investigated. Our hope is to employ this network for both rail and augmentation currents to achieve highest acceleration.

h) Better pellet making schemes are being studied to produce hydrogen and deuterium pellets with higher strength while consuming less liquid helium. Automated pellet freezing and implementation of pellet extrusion are under consideration.

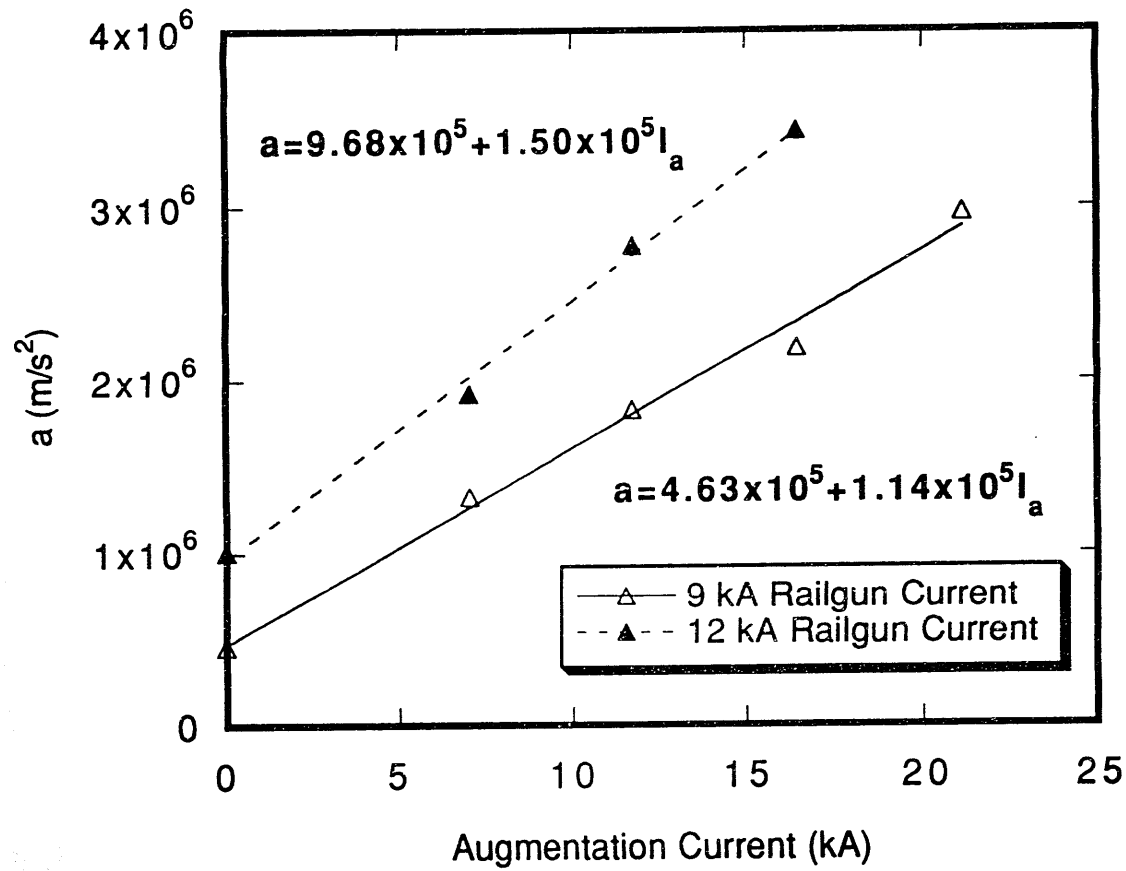
## 3. Research Effort Distribution - Estimated and Actual

See the attached schedule chart on the following pages.

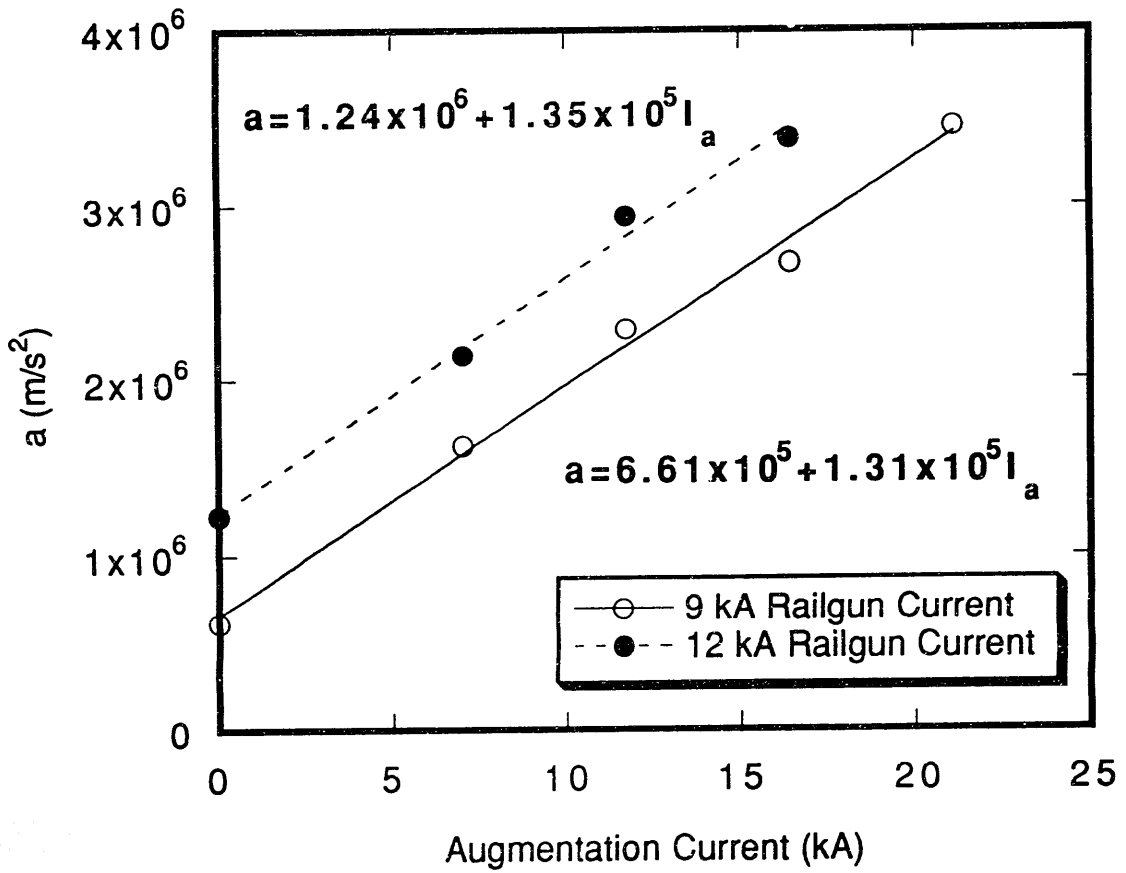
**Hydrogen Pellet Acceleration with Transaugmentation and Lexan Sidewalls on 1.2-m Railgun**



**Hydrogen Pellet Acceleration with Transaugmentation and Mullite Spacers on 1.2-m Railgun**

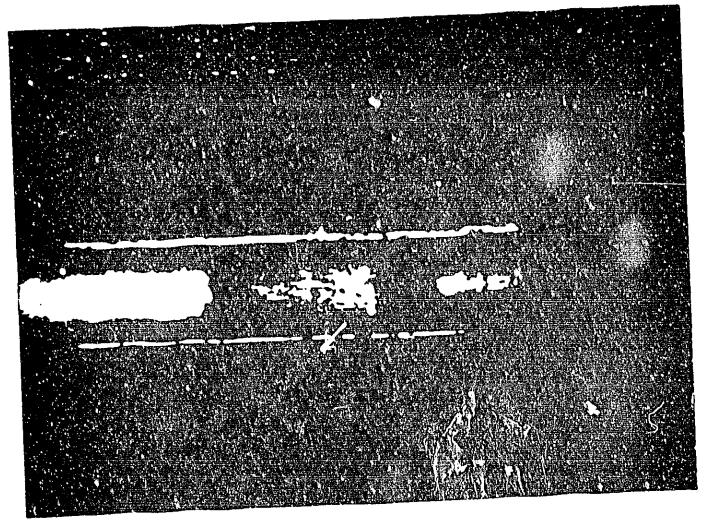


**Hydrogen Pellet Acceleration with Transaugmentation and Perforated Sidewalls on 1.2-m Railgun**

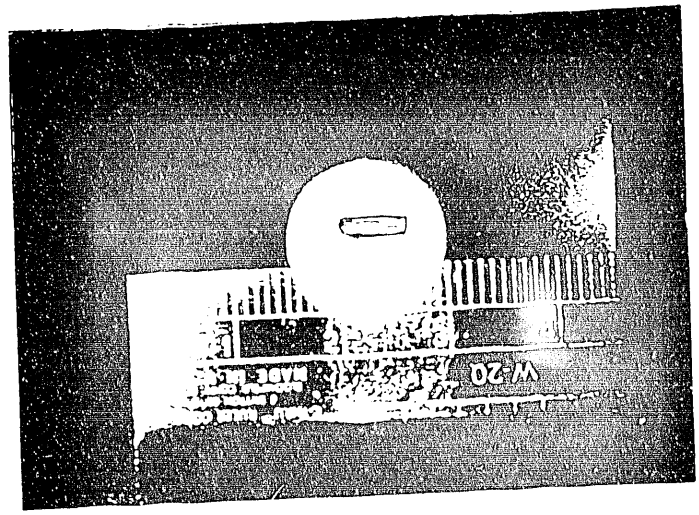


## Hydrogen Pellet Acceleration on a Two-Stage 1.2-m Railgun with Perforated Sidewalls

| Shot # | P (psi) | V (kV) | I (kA) | # of LC | t (μs) | v (in) (m/s) | v (out) (m/s) | dv (m/s) | a (m/s^2) |
|---|---|---|---|---|---|---|---|---|---|
| 91110511 | 600 | 4 | 9.4 | 3 | 615 | 1096 | 1693 | 597 | 9.71E+05 |
| 91110804 | 600 | 4 | 9.4 | 3 | 615 | 1074 | 1675 | 601 | 9.77E+05 |
| 91110805 | 600 | 4 | 9.4 | 3 | 615 | 1119 | 1608 | 489 | 7.95E+05 |
| 91111203 | 600 | 4 | 9.4 | 3 | 615 | 1032 | 1531 | 499 | 8.11E+05 |
| 91111204 | 600 | 4 | 9.4 | 3 | 615 | 952 | 1576 | 624 | 1.01E+06 |
| 92011409 | 600 | 4 | 9.4 | 3 | 600 | 1006 | 1569 | 563 | 9.38E+05 |
| 90091805 | 800 | 5 | 11.75 | 3 | 615 | 833 | 1502 | 669 | 1.09E+06 |
| 91110814 | 600 | 5 | 11.75 | 2 | 438 | 1096 | 1711 | 615 | 1.40E+06 |
| 91111205 | 600 | 5 | 11.75 | 3 | 615 | 982 | 1778 | 796 | 1.29E+06 |
| 91111206 | 600 | 5 | 11.75 | 3 | 615 | 988 | 1905 | 917 | 1.49E+06 |
| 91121315 | 600 | 5 | 11.75 | 2 | 400 | 1212 | 1633 | 421 | 1.05E+06 |
| 91121704 | 600 | 5 | 11.75 | 2 | 400 | 1046 | 1624 | 578 | 1.44E+06 |
| 92011412 | 600 | 5 | 11.75 | 3 | 600 | 1039 | 1658 | 619 | 1.03E+06 |
| 90092110 | 800 | 6 | 14.1 | 3 | 615 | 812 | 1739 | 927 | 1.51E+06 |
| 91110815 | 600 | 6 | 14.1 | 2 | 438 | 1111 | 1893 | 782 | 1.79E+06 |
| 91110816 | 600 | 6 | 14.1 | 2 | 438 | 1081 | 1871 | 790 | 1.80E+06 |
| 91121316 | 600 | 6 | 14.1 | 2 | 400 | 1053 | 1808 | 755 | 1.89E+06 |
| 91121705 | 600 | 6 | 14.1 | 2 | 400 | 1026 | 2012 | 986 | 2.46E+06 |
| 91121706 | 600 | 6 | 14.1 | 2 | 400 | 1006 | 1871 | 865 | 2.16E+06 |
| 92011413 | 600 | 6 | 14.1 | 3 | 600 | 1013 | 1788 | 775 | 1.29E+06 |
| 92011414 | 600 | 6 | 14.1 | 3 | 600 | 1020 | 2000 | 980 | 1.63E+06 |
| 90092111 | 800 | 7 | 16.45 | 3 | 615 | 788 | 2000 | 1212 | 1.97E+06 |
| 90092112 | 800 | 7 | 16.45 | 3 | 615 | 808 | 1768 | 960 | 1.56E+06 |
| 91110817 | 600 | 7 | 16.45 | 2 | 438 | 1111 | 2191 | 1080 | 2.47E+06 |
| 91110818 | 600 | 7 | 16.45 | 2 | 438 | 1103 | 2406 | 1303 | 2.97E+06 |
| 91110820 | 600 | 7 | 16.45 | 2 | 438 | 1126 | 2254 | 1128 | 2.58E+06 |
| 91110821 | 600 | 7 | 16.45 | 2 | 438 | 1126 | 2162 | 1036 | 2.37E+06 |
| 91110823 | 600 | 7 | 16.45 | 2 | 438 | 1126 | 2222 | 1096 | 2.50E+06 |
| 91121707 | 600 | 7 | 16.45 | 2 | 400 | 1060 | 2119 | 1059 | 2.65E+06 |
| 92011416 | 600 | 7 | 16.45 | 2 | 400 | 1053 | 1839 | 786 | 1.96E+06 |
| 92011417 | 600 | 8 | 18.8 | 2 | 400 | 1046 | 2119 | 1073 | 2.68E+06 |
| 92011703 | 600 | 8 | 18.8 | 2 | 400 | 1013 | 1951 | 938 | 2.34E+06 |
| 92011704 | 600 | 8 | 18.8 | 2 | 400 | 1000 | 2133 | 1133 | 2.83E+06 |
| 92011706 | 600 | 9 | 21.15 | 2 | 400 | 1039 | 2443 | 1404 | 3.51E+06 |
| 92011707 | 600 | 9 | 21.15 | 2 | 400 | 1032 | 2012 | 980 | 2.45E+06 |

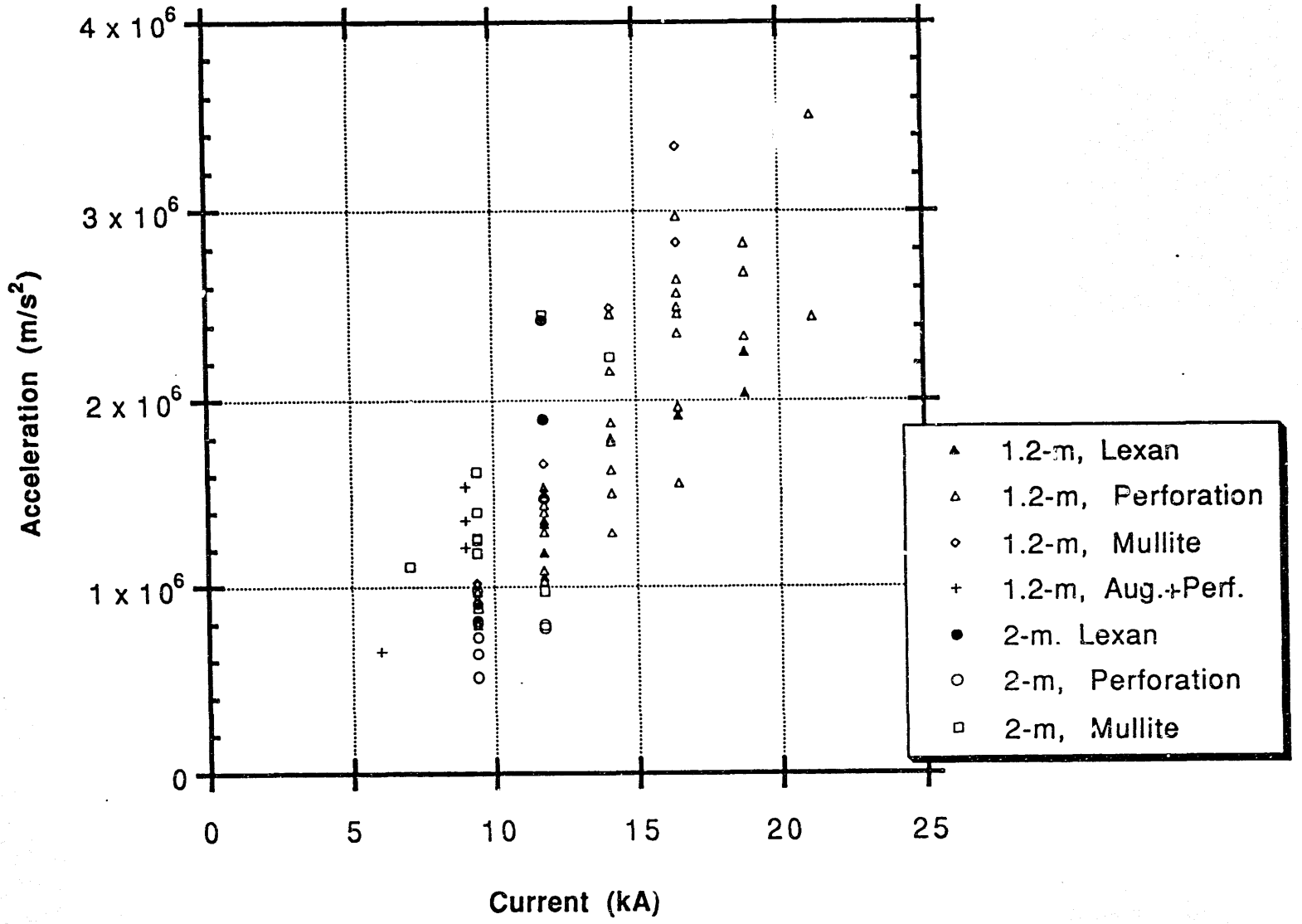


CCD Camera Picture of a Hydrogen Pellet in between Gas Gun and Railgun



Camera Picture of the Same Pellet Exiting Railgun

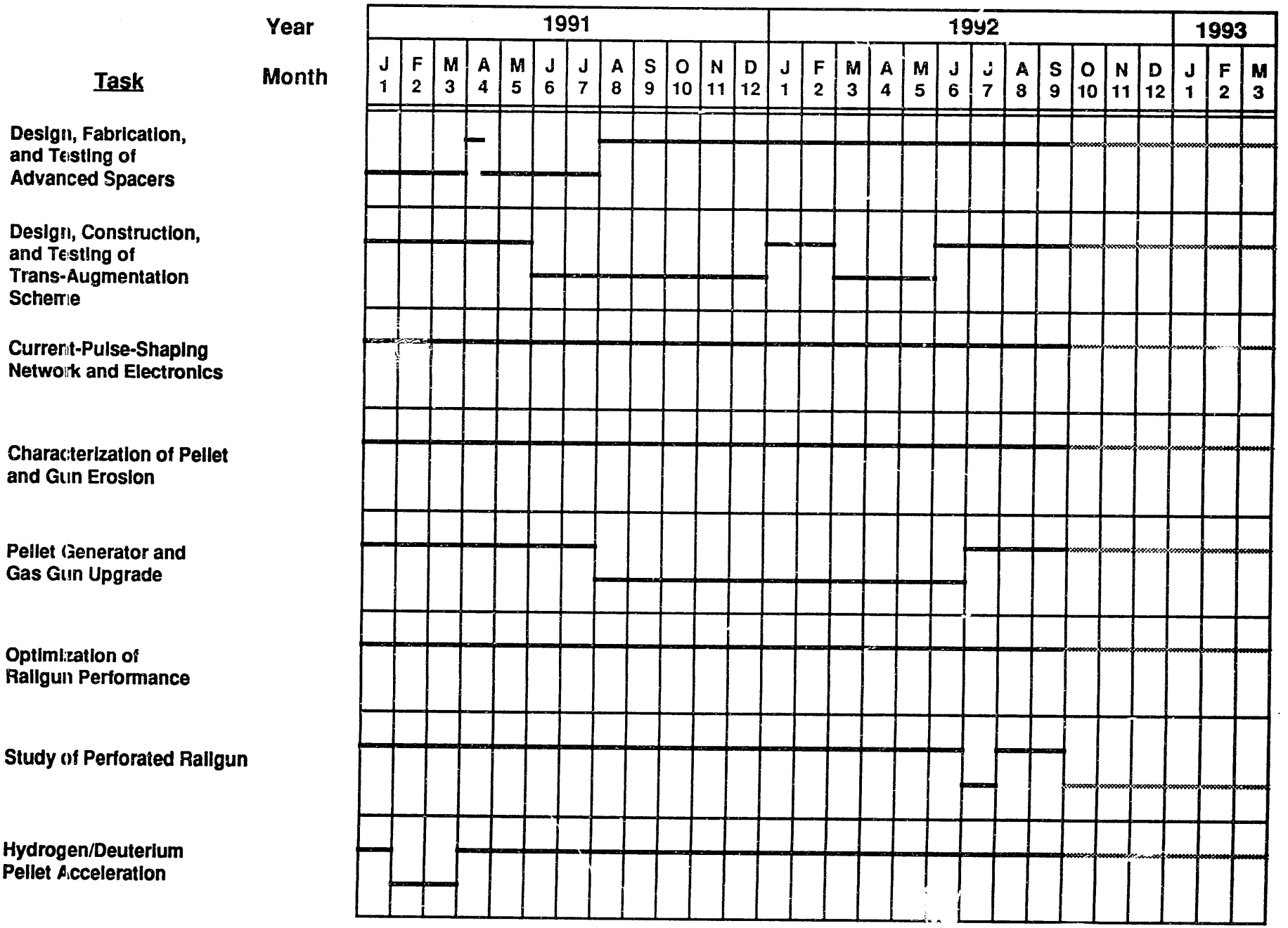
Shot #13, 9/4/1992
Two-Stage Railgun
Vin = 989 m/s
Vout = 1,561 m/s




**Hydrogen Pellet Acceleration on 1.2-m and 2-m Railguns at the UIUC**

# EM RAILGUN PROGRAM - UNIVERSITY OF ILLINOIS

## Schedule of Estimated & Actual Effort Distribution - Page 1



# EM RAILGUN PROGRAM - UNIVERSITY OF ILLINOIS

## Schedule of Estimated & Actual Effort Distribution - Page 2

| Year | 1991 | | | | | | | | | | | | 1992 | | | | | | | | | | | | 1993 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month | J 1 | F 2 | M 3 | A 4 | M 5 | J 6 | J 7 | A 8 | S 9 | O 10 | N 11 | D 12 | J 1 | F 2 | M 3 | A 4 | M 5 | J 6 | J 7 | A 8 | S 9 | O 10 | N 11 | D 12 | J 1 | F 2 | M 3 |
| **Task** | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Diagnostics for Probing Internal Conditions of Plasma-Arc Armature | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Investigation of Saboted Pellet Acceleration using Two-Stage Railgun | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Automation of Railgun Operation and Data Acquisition | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Parametric Study of Pellet Acceleration Scaling | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Study of Pellet-Plasma Interaction | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Travel to Conferences, Workshops, and Cooperating Labs | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Man-Month Actual Effort | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 6 | 6 | 4 | 5 | 5 | | | | | | |

Projected Effort
Actual Effort

Full Height = Major Effort
Half Height = Moderate Effort

# Study of a New Railgun Configuration with Perforated Sidewalls

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***Abstract*—A new railgun configuration with perforated sidewalls is investigated. The motivation for this new configuration is the desire to minimize the detrimental effects of inertial and viscous drag at high velocities caused by the debris from the projectile and the gun wall trapped in the plasma armature. The test has been done on a 1.2-m long railgun with a 3.2-mm-diameter bore. Results for hydrogen pellet acceleration show that at high currents the perforated railgun outperforms the unperforated one. Combined with a newly designed cryogenic pellet generator and the first stage gas gun, a solid hydrogen pellet velocity of 2.46 km/s has been achieved on the 1.2-m railgun.**

## I. INTRODUCTION

Acceleration of solid hydrogen pellets to hypervelocity for tokamak fusion reactor refueling is being investigated at the University of Illinois at Urbana-Champaign (UIUC) [1-3]. Fuseless, plasma-arc-driven electromagnetic railguns of 3.2 mm diameter, and 1.2-m and 2-m lengths have been developed to boost the pellet velocity preaccelerated by the first-stage gas gun which accelerates hydrogen pellet to a speed of around 1 km/s. A unique arc-initiation system was developed at the UIUC to initiate electrical breakdown near the railgun breech which gives a low-resistance path to the railgun current and ensures formation of a plasma-arc armature behind the hydrogen pellet to be accelerated. Figs. 1 and 2 are schematics of the two-stage railgun system, including a cryogenic pellet generator, and a photo station that is employed to record a pellet picture before it enters the railgun.

By utilizing a pressure-relieving coupling scheme between the first-stage gas gun and the second-stage railgun to control the pressure distribution inside the railgun bore, spurious arcing that prevented operation of the railgun at high voltages (and, therefore, high currents) was eliminated [4]. Hydrogen pellet velocities of 2.2 km/s on a 1.2-m two-stage railgun, and of 2.8 km/s on a 2-m two-stage railgun were attained earlier. Acceleration up to $2.9 \times 10^6$ m/s$^2$ has been achieved.

Difficulty, however, was encountered in further increasing the acceleration. It is believed that the acceleration is limited by the following factors:

- Inertial drag proportional to the velocity of the plasma arc armature and the increasing rate of the plasma-arc-armature mass
- Viscous drag proportional to the mass and squared velocity of the plasma arc armature
- Plasma arc blow-by
- Arc branching
- Pellet balloting due to radial deflection of rails because of the repulsion between the high-current-carrying rails

This work was supported by the Office of Fusion Energy of the United States Department of Energy under Grant No. DE-FG02-84ER52111.

To reduce the ablation and viscous drag, we have designed, constructed, and tested a railgun with perforated sidewalls for both solid hydrogen pellet acceleration and free-arc velocity measurements. This paper describes the investigation of perforated sidewalls, their function, and results of hydrogen pellet acceleration on a 1.2-m perforated railgun.

## II. ABLATION AND VISCOUS DRAG

In a railgun, pellets are accelerated by the Lorentz force resulting from the magnetic field produced by the railgun current and the current flowing through the plasma arc armature inside the gun bore. To obtain high acceleration, high currents are utilized. The high current creates a plasma temperature as high as a few eV (1 eV ~ 11,600 K) that ablates, evaporates, and erodes the rails, the sidewalls, and the pellet. The ablated material adds to the plasma mixture, causing inertial drag, viscous drag, and secondary arcs [5, 6]. As a result, the acceleration is much lower than expected.

As an example, we consider a solid hydrogen pellet 3.2 mm in diameter and 4 mm in length accelerated by a railgun current of 11.75 kA, which corresponds to 5 kV on our current pulse forming network. The mass of the pellet is 2.8 mg, and inductance per unit length is around 0.3 μH/m. The **J** x **B** force is as high as 21 N, which could provide an acceleration of $7.5 \times 10^6$ m/s$^2$ to our solid hydrogen pellet. This is much higher than what we have measured.

Our concerns are supported by the equation of motion of plasma-arc armature and pellet [5]

$$(m_p + m_a)\dot{v} = \frac{1}{2}L'I^2 - F_a - F_d \ ,$$

where $m_p$ is the pellet mass, $m_a$ is the arc armature mass, v is the plasma velocity, L' is the railgun inductance per unit length, and I is the railgun current. The inertial drag force $F_a$ and the viscous drag force $F_d$ between the fast-moving, hot plasma and the railgun wall are

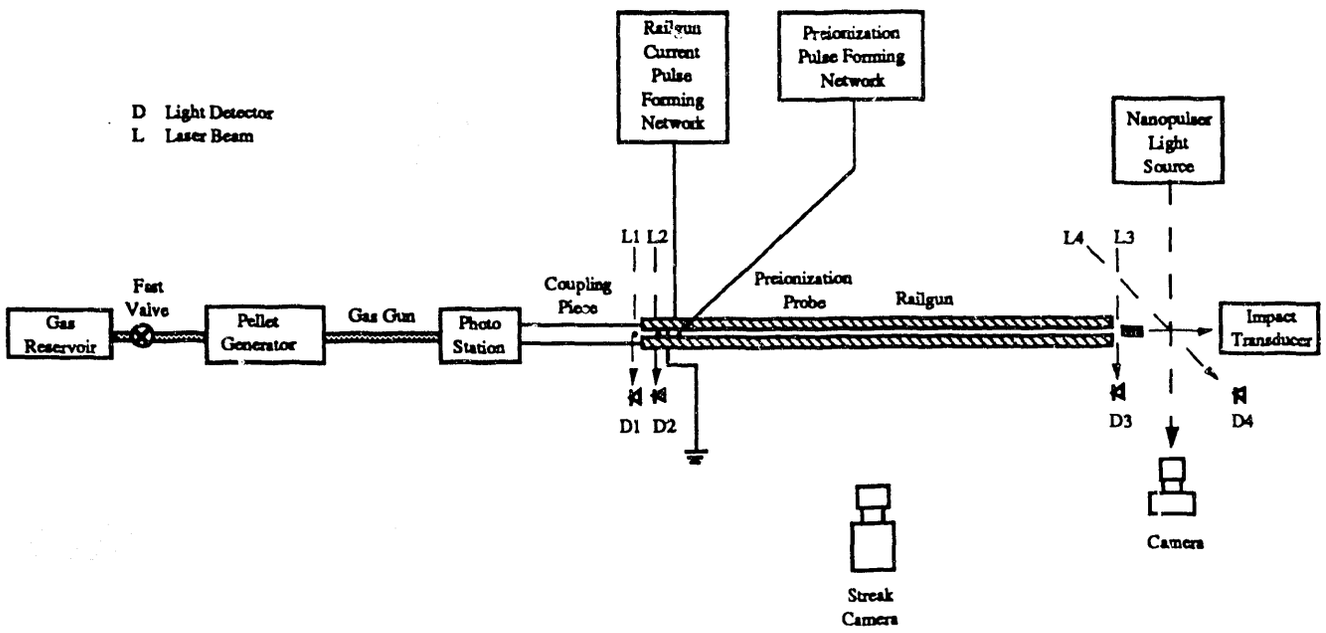


Fig. 1. Schematic of the University of Illinois two-stage-railgun hydrogen pellet acceleration system

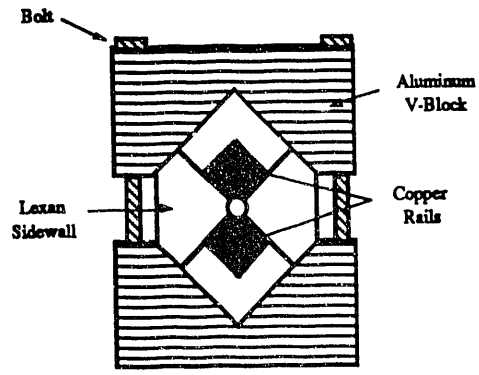


Fig. 2. Cross section of electromagnetic railgun

$$F_a = \dot{m}_a v$$

and

$$F_d = \frac{C_d m_a v^2}{r} .$$

Here r is the radius of the railgun bore, and $C_d$ is the dimensionless drag coefficient ($0.0015 \leq C_d \leq 0.006$). Going back to the earlier example, for the given current and an armature voltage of 50 V, the ablated mass from the Lexan sidewalls can become as high as 1.5 mg within 1 millisecond, comparable to the pellet mass. This results in an inertial drag force of 3.6 N, and a viscous drag force as high as 11 N at a pellet speed of 2.46 km/s. The net force on the plasma arc armature and the pellet is as low as 6.4 N, which produces an acceleration of only $1.5 \times 10^6$ m/s$^2$ toward the end of the acceleration. Since the inertial drag term is proportional to the plasma velocity, and the viscous drag term to the squared velocity, there is an acceleration and velocity limitation to the railgun launcher due to the plasma-bore interaction.

## III. PERFORATED SIDEWALLS

As indicated in the previous section, the pellet acceleration is limited due to the effect of ablation and viscous drag. The viscous drag dominates, especially at high arc-armature velocities. The techniques for achieving higher acceleration are: reduction of ablation, and elimination of neutral gas ablated from the gun wall and the pellet.

Measurements of the pressure in the railgun bore and the free arc velocity were carried out on a 1.2-m railgun. The pressure measurement showed that the pressure of the propellant gas behind the pellet inside the railgun bore could be as high as 50 torr for the propellant pressure of 600 psi, which was needed to accelerate the pellet to 1 km/s in the gas gun. According to the free-arc velocity measurements made at different gas pressures in the gun bore, the free arc velocity is higher at a lower pressure. The higher arc velocities that occur at lower pressures are the motivations for using perforations to release the pressure behind the pellet. In an earlier paper R. A. Marshall introduced holes in both the rails and sidewalls of a rectangular-bore railgun to allow plasma to escape from the armature, which enabled him to measure armature length and plasma temperature [7]. Perforations at the UIUC are used to remove the ablated material from the railgun.

Several railgun configurations and different wall materials can be utilized to reduce inertial and viscous drag:

- Low-ablation material can be employed to directly reduce the gun wall ablation.
- Transaugmentation can provide higher magnetic fields in the railgun bore so that lower rail currents may be used to achieve high acceleration. As a result, the ablation is reduced.
- Perforations through railgun sidewalls remove particles from the armature, thus reducing the inertial and viscous drag.

To create perforations we designed a railgun with many parallel holes drilled through the Lexan sidewalls as shown in Fig. 3. The holes are small, and spaced so that hydrogen pellets are not damaged during acceleration. A wide groove is milled from the outside of the sidewalls to assure that the material being removed travels only a very short distance in the small holes, resulting in a high throughput of material removal.

## IV. EXPERIMENTAL RESULTS

Measurements of solid-hydrogen-pellet velocities have been carried out on a 1.2-m two-stage railgun with and without perforations. As shown in Fig. 1, He-Ne lasers and fiber optics are used at D1 and D2 to measure the breech velocity of the pellet provided by the first stage gas gun, and at D3 and D4 to measure the pellet velocity at the railgun muzzle. Plasma motion with respect to time is recorded by a streak camera. Streak pictures provide not only information on plasma motion vs. time, from which velocity and acceleration can be extracted, but also information on the plasma structure, such as plasma arc blow-by, arc branching, and spurious arcing. Solid hydrogen pellets are also recorded using a combination of a camera and a nano-pulser.

Results from free-arc velocity measurements on a 1.2-m railgun with and without perforations are shown in Figs. 4 and 5. The free arc velocities at different hydrogen and helium pressures, and at different railgun voltages are measured using a streak camera calibrated with a pulsed diode laser. The following observations can be made from the measured free arc velocities:

- Although free arc velocities on a gun with perforations are slightly lower than those without perforations at low railgun voltages, the velocities obtained from the perforated gun exceed those of the unperforated gun at higher voltages. Free arc velocity measurements were carried out at voltages below 5 kV since higher railgun voltages could create substantial damage to the small-bore railgun. However, it is our belief that at higher voltages the perforated railgun will outperform the unperforated one.
- At higher hydrogen or helium pressures, the perforated railgun fares better than the unperforated one since perforation is more effective at higher gas pressures.

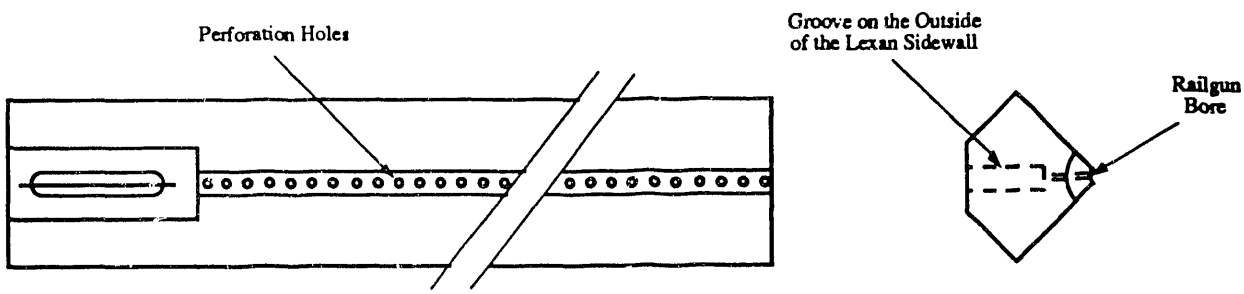


Fig. 3. Schematic of perforated sidewall

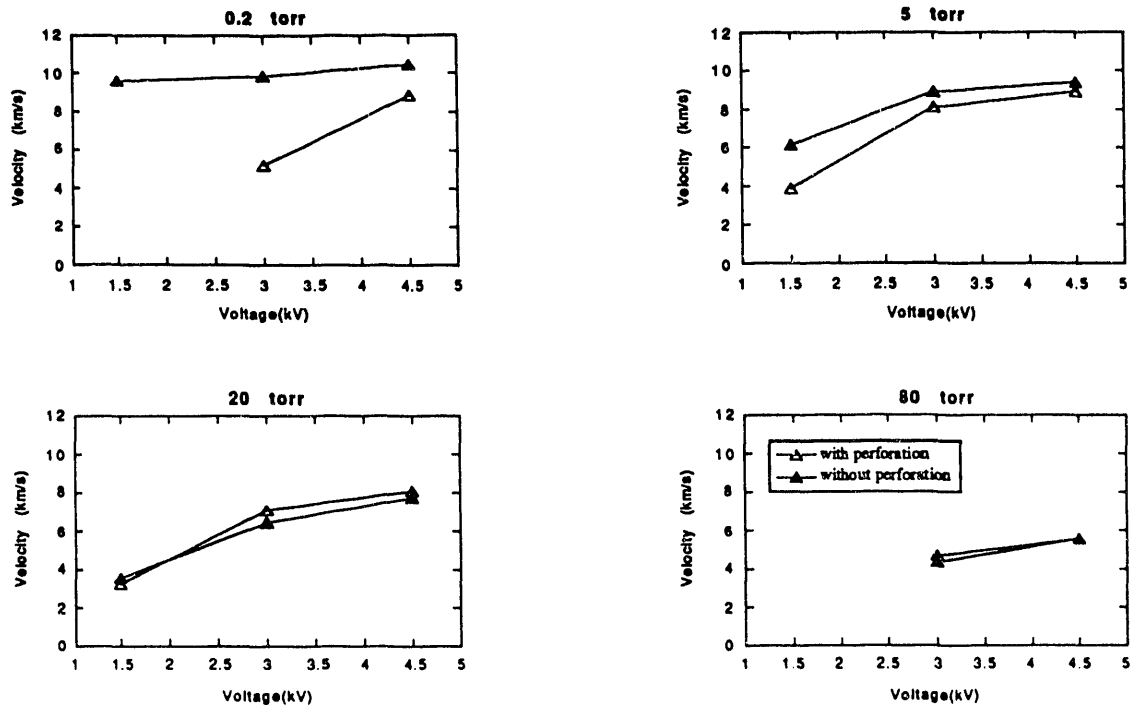


Fig. 4. Free arc velocity with helium on a 1.2-m railgun with and without perforations

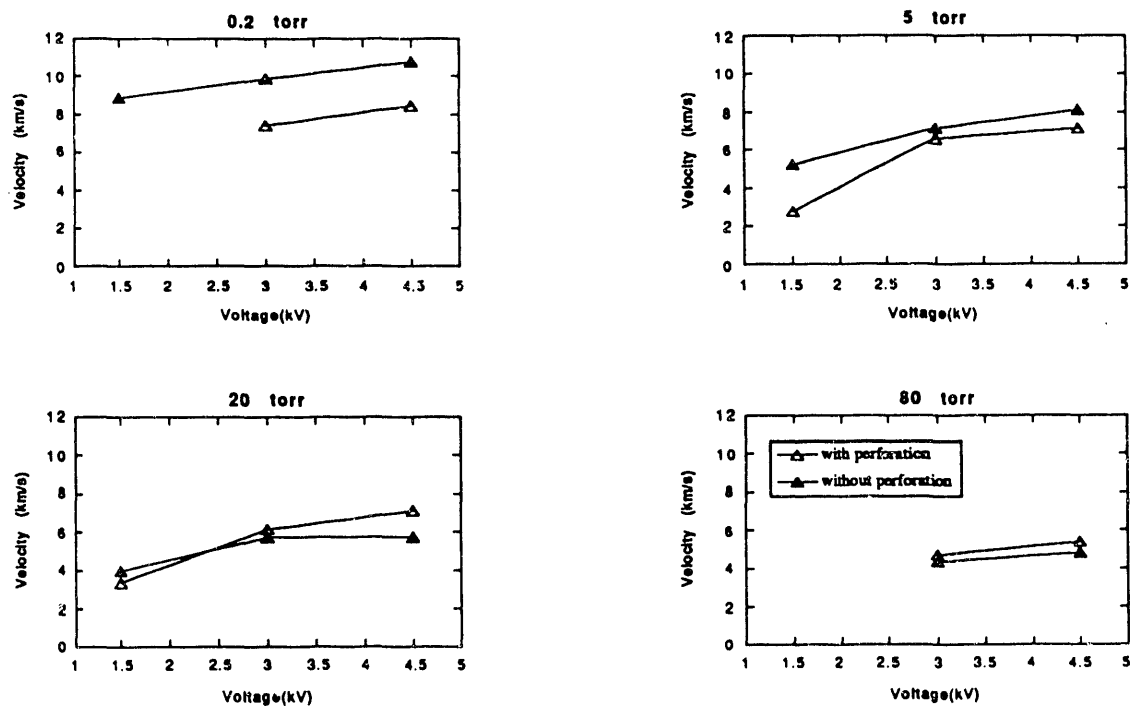


Fig. 5. Free arc velocity with hydrogen on a 1.2-m railgun with and without perforations

- With heavier gas (helium), the perforated gun gives better performance than the unperforated one at high voltages due to the fact that perforations play a more important role with heavier plasma media. One may predict that the perforation configuration would be more effective on guns with metallic fuses in which high-Z plasmas are present.

Fig. 6 plots the velocity increase vs. railgun current. Increase in the hydrogen pellet velocity on a perforated railgun is lower than that on a unperforated railgun at railgun currents below 12 kA. However, at currents higher than 16 kA, the perforated railgun overwhelmingly outperforms the railgun without perforations. There is no pellet acceleration data from unperforated railgun at currents higher than 21 kA mainly due to the erosion of hydrogen pellet and plasma blow-by, which is partially eliminated by using a perforated railgun. An analysis based on the experimental data indicates that ablated material is responsible for limited acceleration on the plasma arc armature and the pellet at high currents. Because of the added mass to the plasma arc armature, the inertial and viscous drag forces dominate the plasma motion at high armature velocities. With the ablated material removed, higher acceleration can therefore be expected at higher plasma velocities.

Inspection of the bore surfaces of the rails and Lexan sidewalls of the perforated railgun reveals less wall contamination than those of a unperforated railgun. This may be an indication that with the removal of ablated material, heat loading on the gun wall is also reduced, thus resulting in less ablation and reduced drag forces.

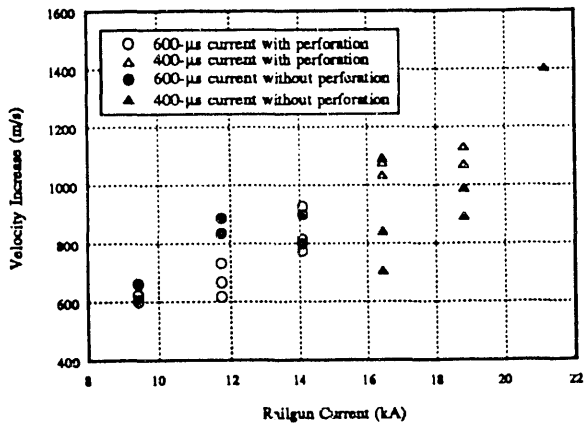


Fig. 6. Velocity increase of hydrogen pellets on a 1.2-m railgun

Using perforations, secondary arcing is also expected to be reduced since neutral particles evaporated from the wall are removed more efficiently from behind the hot plasma in the bore.

## V. SUMMARY

Ablation is one of the most critical limiting factors in the performance of a plasma-arc-driven electromagnetic railgun at high currents. A new railgun with perforated sidewalls was designed, fabricated, and tested at the UIUC for possible application to pellet fueling of magnetically confined plasmas. By

creating perforations on the sidewalls, ablated material is continuously vented out from the railgun bore, minimizing inertial and viscous drag. Solid-hydrogen-pellet velocities up to 2.46 km/s were achieved on a 1.2-m two-stage perforated railgun. Owing to the reduced viscous drag at high plasma-armature velocities, the perforated railgun outperformed the unperforated one at high rail currents.

To achieve higher pellet velocities, higher rail currents are used, creating more radial deflection of the rails, and increasing the plasma pressures and temperatures behind the pellet. Consequently, maintaining pellet integrity becomes a matter of increasing concern. One possible solution is to employ a sabot to protect hydrogen pellets from fracture. Transaugmented and low-ablation railguns are being investigated in an attempt to further reduce ablation and viscous drag. Efforts are also being made to reduce radial deflection by designing a compact railgun system with more rigid rails and sidewalls.

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# Development of a Fuseless Small-Bore Railgun for Injection of High-Speed Hydrogen Pellets into Magnetically Confined Plasmas

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***Abstract*** **— The most effective known way of refueling a tokamak fusion reactor is to inject high-speed pellets composed of fusion fuel (i.e., isotopes of hydrogen) at a controlled rate and velocity. To effect such a fueling scheme, in particular for contemporary and future large tokamaks, pellet speeds as high as 10 km/s and injection rates as high a 10 Hz may very well be required. Also, to prevent the onset of plasma instabilities pellet sizes need to be maintained below 3 to 4 mm in diameter. These requirements, plus the fact that the yield strength of frozen hydrogen is extremely low (~2 atmospheres) make the task of developing an ideal pellet injection scheme a challenge. In an attempt to meet this challenge, a fuseless small-bore railgun has been under development at the University of Illinois during the past several years. Some of the unique features of this railgun system are: 1) it is a two-stage accelerator with the first stage consisting of a combination of a hydrogen pellet generator and a gas gun, and the second stage a railgun, 2) it is a fuseless railgun in that the plasma armature is formed by electrically breaking down the propellant gas immediately behind the pellet, 3) it is a small-bore railgun with the bore size in the range of a few millimeters in diameter. Perforated sidewalls and transaugmentation schemes have also been employed in an effort to improve the railgun performance. The principal diagnostics are the magnetic probes, laser interferometry, optical emission spectroscopy, and a streak camera which are designed to determine the plasma arc length, the electron density distribution along the length of the arc, the line-averaged plasma density and temperature, and the plasma velocity change during acceleration, respectively. Using a prototype system hydrogen pellet velocities exceeding 2.8 km/s have been achieved on a 2-m-long railgun for a cylindrical pellet of 3.2-mm diameter and 4-mm length. This report presents a brief review of some of the existing hydrogen pellet acceleration techniques, an overview of the University of Illinois railgun program, the results to date, and the future plan.**

## I. INTRODUCTION

Ever since the first such fueling experiment was successfully carried out on the ORMAK tokamak in 1976 at the Oak Ridge National Laboratory [1], injection of high-speed frozen pellets of hydrogen isotopes has become the most widely accepted method for fueling magnetically confined plasmas for controlled thermonuclear research. The effectiveness of such a fueling scheme has proven to be practical not only for tokamaks, of which there are many worldwide, but also for other toroidal devices such as stellarators and reversed-field pinches. The benefits of this pellet injection scheme are not limited to plasma fueling only, but also include improvements in energy confinement properties of those devices due to modifications in the plasma density and/or temperature profiles as a result of the fueling or particle deposition profiles. For an excellent review of this subject on pellet fueling of magnetic confinement devices the reader is referred to a recent article by S. L. Milora [2].

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As for the pellet injection speed, it is desirable that the pellet has sufficient speed so that it may penetrate the plasma a significant fraction of the distance to the magnetic axis. Large (millimeter-size) pellets can be used to overcome the difficulty of achieving high pellet velocities. However, due to plasma stability considerations, pellets cannot be made arbitrarily large; their size must be limited so as to contribute only a small fraction (≤ 30%) to the ions already present in the plasma. This places a burden on increased pellet velocity. The actual pellet fueling requirements vary in accordance with the specific plasma parameters and the physical and operating charateristics of the devices since the pellet evaporation rate depends on the electron temperatures and densities of the plasmas and since the detailed fueling scenarios must be determined based on the plasma volume, the type of plasma limiter, the experiment's pulse length, etc. For example, for the ITER (International Thermonuclear Experimental Reactor) tokamak, a 5-mm-radius spherical pellet would represent about 30% of the total particle inventory, and a pellet injection speed of 5 km/s would enable the pellet to reach less than one half the distance to the center of the tokamak [3].

To produce the high-speed hydrogen pellets that are required for pellet fueling, several high-speed driver concepts have been under development. These drivers include mechanical devices such as light gas guns (both single- and two-stage) [4-7] and centrifugal injectors [8, 9], electrothermal guns [10, 11], an electron-beam-heated rocket accelerator [12], and electromagnetic railguns [13-19]. This work reviews the railgun research program at the University of Illinois at Urbana-Champaign (UIUC) which, since its inception in 1984, has been dedicated to the task of evaluating and demonstrating the feasibility of applying the railgun principle to high-velocity hydrogen pellet injection for magnetic fusion reactor refueling. The main components and distinctive features of the UIUC railgun system will be described along with the program's chronology and major achievements. The work in progress and future plans will be presented.

## II. HYDROGEN-PELLET-INJECTOR RAILGUN AT UIUC

A schematic of the UIUC hydrogen-pellet-injector railgun system, which is a two-stage accelerator, is shown in Fig. 1. The first stage is a preaccelerator combining a hydrogen pellet generator with a gas gun. Liquid helium is used in the pellet generator to liquefy and freeze ultrahigh-purity hydrogen gas into a cylindrical pellet at temperatures in the range of 6 to 10 K. This hydrogen pellet is then accelerated to a medium speed (≤ 1 km/s) using a high-pressure light gas (either hydrogen or helium) and injected into the second-stage railgun via a coupling piece. The coupling piece is perforated, and serves two important functions: to provide guided, continuous pellet motion between the gas gun and the railgun and to vent out the propellant gas coming from the gas gun so that the pressure inside the railgun bore can be controlled to a level that will suppress spurious arcing.

Once the hydrogen pellet enters the railgun, a unique arc-initiating tungsten needle installed at the gun breech is activated so that the propellant gas immediately behind the pellet (which has followed the pellet from the gas gun into the railgun) may be electrically broken down forming a plasma-arc armature, and therefore a conducting path between the rails. At the peak of this electrical breakdown the main rail current is pulsed into the rail. Fig. 2 shows the relative timing between the arc-initiation current and the rail current. While this current is flowing, the plasma armature becomes more fully ionized due to ohmic heating, and the resulting **J** x **B** force propels the pellet to a high velocity. The fact that no "conventional" fuse is employed to run this railgun (i.e., it does not rely on the usual metallic fuse to effect the railgun operation) is important since high-Z impurities introduced into the fusion plasma during pellet fueling will contribute to lowering of the plasma temperature, which is undesirable.

Unique to hydrogen pellet acceleration is that one must pay close attention to the physical properties of hydrogen ice since they play an important role, especially in determining the operating parameters (amplitude and shape of the current pulse) for the achievement of velocities in the range of 10 km/s which might be needed for future reactor-grade fusion plasmas. Solid hydrogen isotopes have low densities (0.09, 0.20, and 0.31 g/cm$^3$ for $H_2$, $D_2$, and $T_2$, respectively), which is certainly an advantage in choosing the

acceleration forces. However, the yield strength of the solid is also small (~ 5 bar) placing a limit on the tolerable acceleration forces. In spite of this, acceleration pressures equivalent to 60 to 108 bar have been used to accelerate 6-mm deuterium pellets using a two-stage light gas gun [5].

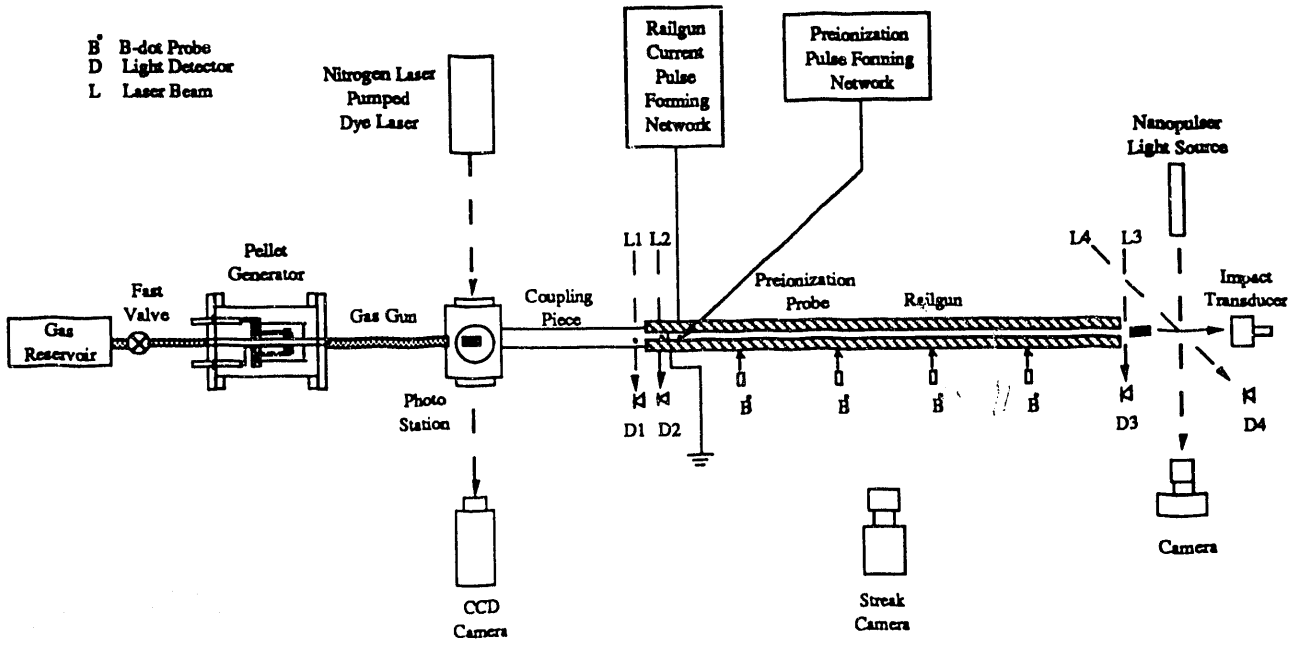


Fig. 1. Schematic of the University of Illinois two-stage-railgun hydrogen pellet acceleration system

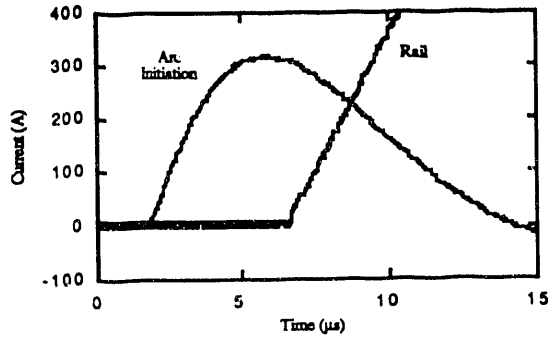


Fig. 2. Oscillogram showing the timing between arc initiation and rail current

The diagnostics employed are mainly to determine the pellet velocities at the breech and muzzle of the railgun, to measure the various current and voltage components, to probe the plasma-arc behavior and characteristics inside the gun bore, and to record the picture of the pellet exiting the gun muzzle. Two pairs of laser-photodetector combinations installed on the coupling piece measure the pellet velocity and, with a predetermined time delay, triggers the arc-initiation circuit so that plasma arc will form behind, not in front of, the pellet. B-dot probes installed along the length of the railgun measure the plasma-armature currents at different locations. A streak camera with a field of view covering the entire gun length records the distance-vs.-time signature of the plasma motion inside the gun bore. This is possible by using a Lexan sidewall which is semitransparent to the plasma luminescence. By using a combination of a nanolamp with a 10-nsec light pulse and a camera, a still picture of the pellet exiting the railgun is recorded. This picture allows one to determine the amount of pellet erosion during acceleration. By using a detection mechanism similar to that on the coupling piece the pellet velocity is also measured just outside the gun muzzle. The pellet is finally led to impinge upon an impact transducer so that the momentum carried by it can be determined.

Probing of the internal conditions of the plasma-arc armature is achieved by using a Mach-Zehnder interferometer (Fig. 3) combined with a streak camera which measures the line-averaged plasma densities along the length of the arc, and by using an optical multichannel analyzer system (Fig. 4) which spectroscopically determines the change in the density and temperature of the plasma arc while it travels along the length of the railgun. This information plus the information on the current and voltage and the pellet velocity and erosion is valuable in evaluating the gun performance and establishing a theoretical model that can correctly describe plasma-arc-driven pellet acceleration (See the companion paper by King et al. for further information on diagnostics and controls).

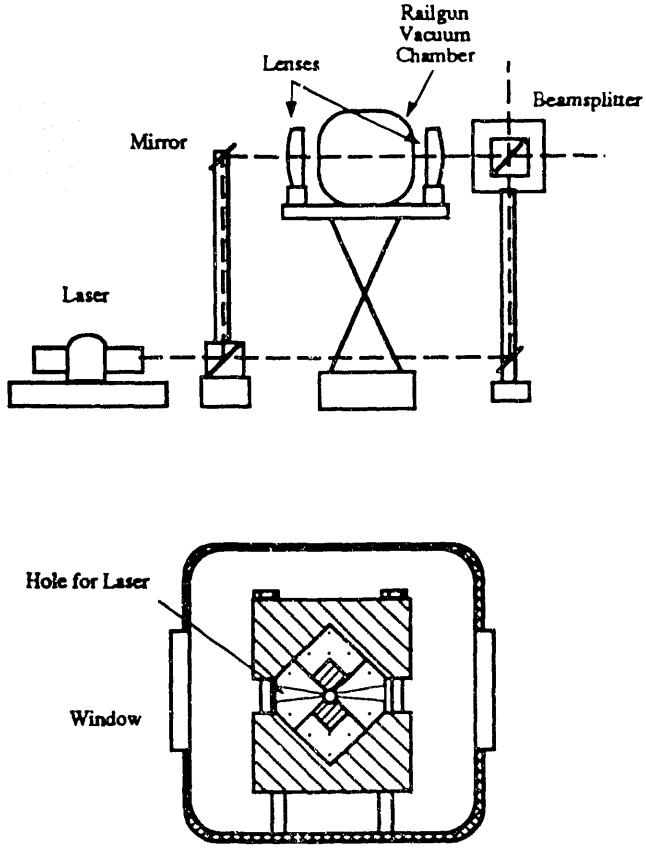


Fig.3. Mach-Zehnder interferometer setup for measurement of electron density of plasma-arc armature

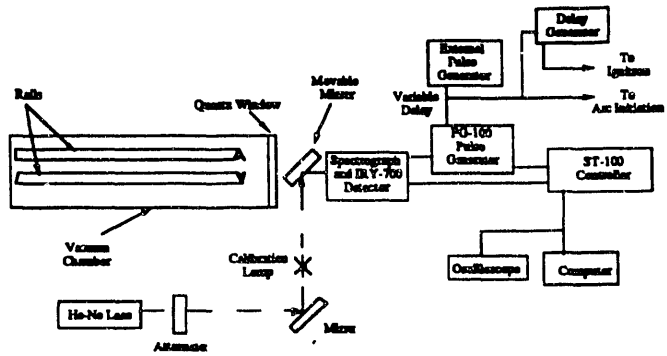


Fig.4. Experimental arrangement for spectroscopic measurement of electron density and temperature of plasma-arc armature

## III. HIGHLIGHTS OF RESULTS FROM UIUC RAILGUNS

Being a pioneering project, our research activities at the beginning, after its inception in 1984, centered around resolving two major issues: (1) can a railgun with a small circular-bore (~1.5 mmD) and reasonable length (~1 m) be built and operated to accelerate a projectile, and (2) can such a railgun accelerate a frozen hydrogen pellet without melting the pellet completely due to arc heating. In addition, a clever mechanism had to be developed to make sure that the use of a metallic fuse could be avoided since it would introduce high-Z impurities into the tokamak, subsequently quenching the plasma.

Since then, the program has steadily identified a number of critical technical problems unique to the acceleration of frozen hydrogen pellets in a railgun and successfully developed practical engineering solutions to the problems. These problems are associated, in one way or another, with the operation of the railgun in a high vacuum and with the use of a cryogenic projectile which has extremely low mechanical strength. Some of the major problems and their solutions are summarized as follows:

(a) The problem of initiating a plasma arc in a debris-free manner: solved by the innovative development of fuseless technique for the initiation of the plasma arc.
(b) The problem of coupling a pneumatic gun preaccelerator with the railgun in a manner which provides control over the pressure distribution inside the highly evacuated ($10^{-3}$ Torr) railgun to prevent spurious arcing: the solution involves the invention of a ventilated coupling piece.
(c) The problem of operating an extremely small-bore railgun with a large length-to-diameter (L/D) ratio.
(d) The problem of obtaining sufficient mechanical strength and compactness in the hydrogen pellet produced by the pellet generator.
(e) The problem of diagnosing the size and shape of the cryogenic pellet before and after the plasma acceleration, etc.

Having solved these problems of an operational nature and demonstrated the practicality of using the railgun to accelerate cryogenic pellets to high velocities ($\geq$ 2.8 km/s) without sabot (1989) (see Table I for the velocity records and railgun parameters), we began to turn our attention to the principal task of exploring the velocity potential of the railgun for refueling fusion plasmas. To this end, we conducted a total of 101 experiments and accumulated a significant database using a 2-m-long, 3.2-mm-diameter railgun from which we were able to develop a working picture of the interior ballistics occurring in our railgun. Our experimental data showed that the occurrence of ablation and the resulting inertial and viscous drag from the

ablation products is a major inhibitor to the attainment of velocities significantly higher than 2.8 km/s. However, if ablation can be drastically reduced, velocities in excess of 10 km/s should be quite possible as clearly shown by our recent free-arc experiments in which a free-arc velocity of 36 km/s was obtained.

This high velocity was achieved using a low-ablation sidewall fabricated out of mullite, and is certainly a substantial improvement over the previous record of 10 km/s obtained with a Lexan sidewall (see Figs. 5 and 6). The high velocity is also a direct demonstration that the inertial and viscous drag which is enhanced by wall ablation is the major inhibitor to the attainment of high velocities. In addition to the new record free-arc velocity, our recent research achievements include the following:

(a) Transaugmentation rails that boost the magnetic field strength inside the railgun have been designed, fabricated, and partially tested producing encouraging results. Additional detailed experimentation is required, and will be undertaken.
(b) Pulse-shaping networks that provide lower current to the main rail and higher current to the transaugmentation rail, respectively, have been fabricated, installed, and successfully tested.
(c) A new hydrogen pellet generator-gas gun combination that allows one to fabricate frozen hydrogen (and isotope) pellets of variable diameters and lengths has been designed, constructed, and successfully tested. This hydrogen pellet generator not only improves the strength of the frozen hydrogen pellets produced, but it also substantially reduces the liquid helium consumption.
(d) In an effort to vent out the ablation debris and neutral particles from the railgun (so that inertial and viscous drag will be minimized), a new railgun with a perforated sidewall has been designed, built and tested. The preliminary results indicate that hydrogen pellet acceleration continuously increases with increasing rail current, and that the manner in which the hydrogen pellet velocity increases appears

TABLE I
HIGHEST VELOCITIES FOR VARIOUS RAILGUNS

| 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 | 600 | 800 |
| V (kV) | 2.00 | 7.00 | 5.00 |
| I (kA) | 3.20 | 16.45 | 11.75 |
| $v_{in}$ (m/s) | 941 | 1159 | 947 |
| $v_{out}$ (km/s) | 1.71 | 2.46 | 2.82 |
| $\Delta v$ (m/s) | 770 | 1301 | 1870 |
| $\tau$ ($\mu$s) | 800 | 400 | 985 |
| a (m/s $^2$) | $9.66 \times 10^5$ | $3.25 \times 10^6$ | $1.90 \times 10^6$ |
| D (cm) | 102 | 90 | 186 |

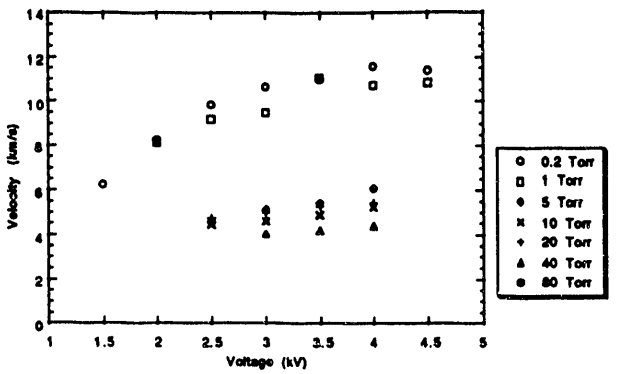


Fig. 5. Free hydrogen-arc velocity with Lexan spacer on a 2-m railgun

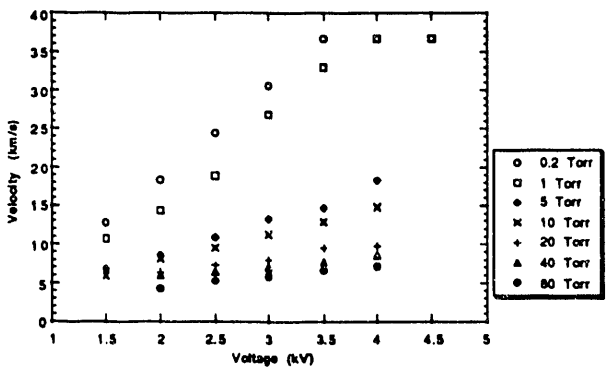


Fig. 6. Free hydrogen-arc velocity with mullite spacer on a 2-m railgun

more promising with the perforated railgun than with the nonperforated railgun at higher currents (see the companion paper by J. Zhang et al. for detailed information). Further experimentation is required, and will be done.

(e) By combining a laser interferometer with a streak camera, detailed density profiles of the plasma arc armatures along the gun axis have been measured for the first time under different operating conditions (Figs. 7 and 8). These data indicate that at high voltages (or currents) the density profiles are no longer smooth but choppy and irregular, possibly indicating the presence of an increasing amount of ablation (Fig. 9). We hope that these measurements will eventually help us to understand and eliminate the factors giving rise to secondary arcs, which are an energy loss mechanism detrimental to efficient railgun operation.

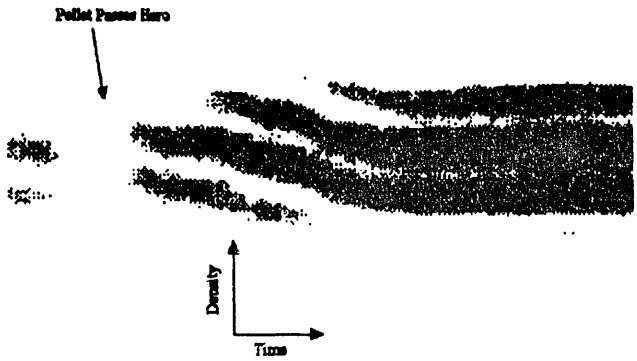


Fig. 7. Recorded fringes at 3 kV

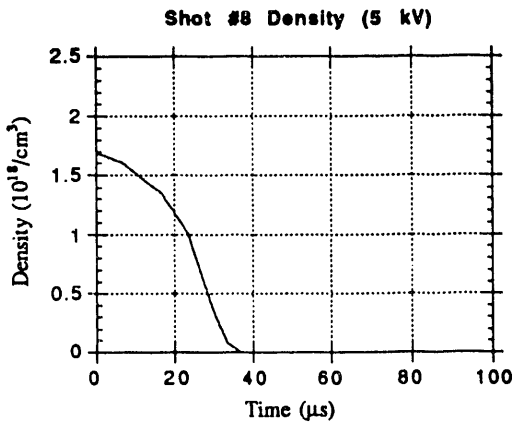


Fig. 8. Electron density distribution of plasma arc with Lexan pellet

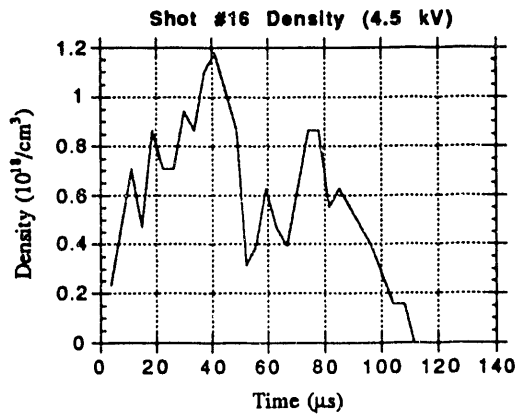


Fig. 9. Electron density distribution of plasma arc with foam pellet

(f) By measuring Stark broadening and line emission intensities at different time intervals during the railgun operation, we have been able to determine the change in the density and temperature of a free arc as it travels toward the gun muzzle under a variety of operating conditions (Fig. 10 and 11). This and other similar studies will allow us to more thoroughly understand and improve the railgun behavior.

(g) Numerous pellet acceleration runs have been performed with both room-temperature pellets and frozen hydrogen pellets with an advanced railgun of 1.2-m length (which combines low-ablation sidewalls and transaugmentation rails), demonstrating that the advanced railgun outperforms the old guns by a substantial margin. Further experimentation is still needed on the 1.2-m gun, which will later be extended to a 2-m gun to maximize the attainable hydrogen pellet velocities.

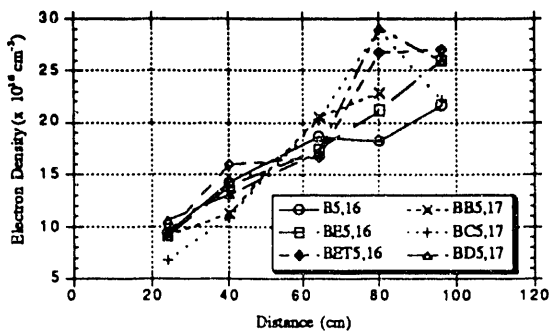


Fig. 10. Electron density vs. distance for 5 kV and 20 torr

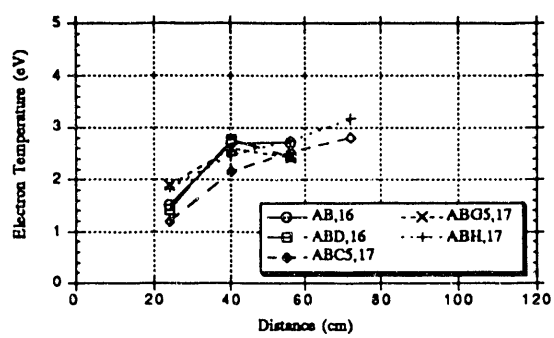


Fig. 11. Electron temperature vs. distance for 5 kV and 20 torr

## IV. CONCLUDING REMARKS

A fuseless, small-bore, two-stage railgun system particularly suited to accelerating frozen hydrogen pellets for fueling magnetically confined plasmas was described. Results were presented on hydrogen pellet acceleration indicating that it is feasible to employ a railgun to accelerate hydrogen pellets to high velocities; however, to achieve the highest hydrogen pellet velocity, one must reduce gun wall ablation (to minimize inertial and viscous drag) and deterioration of pellet integrity. Capitalizing upon the achievements we have made so far, our very next step in the continuation of this program is the development of some very innovative technologies to overcome ablation, with a goal of achieving velocities exceeding 5 km/s in the short term, and laying the foundation for even higher pellet injection velocities (exceeding 10 km/s) in the longer term.

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# Controls and Diagnostics on a Fuseless Railgun for Solid Hydrogen Pellet Acceleration

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***Abstract*-A two-stage railgun system has been built incorporating several controls and diagnostics, some including unique features to account for the fact that the projectile is a frozen hydrogen pellet for fusion reactor refueling. A timing circuit has been developed to monitor projectile breech and muzzle velocities and to automatically trigger a sequence of events critical for effective plasma armature railgun operation. This circuit can initiate electrical breakdown of the propellant gas directly behind an incoming projectile, thus enabling fuseless operation. It also triggers a streak camera and a flashlamp for photographing the arc and the outgoing projectile, respectively. The automatic timing circuit is expandable and has been extended to incorporate a trigger for transaugmentation. The timing circuit is immune to mistriggering due to electromagnetic interference or fragmentation of the fragile hydrogen pellets. Railgun diagnostics also include Pearson coils and B-dot probes for monitoring rail and armature currents, respectively. Laser interferometry and optical spectroscopy are also employed to measure plasma density and temperature. Digitizing oscilloscopes are used to acquire data. The data is transferred to a computer via GPIB.**

## INTRODUCTION

The Fusion Technology and Charged Particle Research Laboratory of the University of Illinois at Urbana-Champaign (UIUC) is investigating the feasibility of fusion reactor refueling using railgun technology. Electromagnetic railguns may be used to inject high-speed (> 5 km/s) frozen fuel pellets into the hot plasma core of tokamak reactors. The UIUC has been developing railgun systems to accelerate solid hydrogen pellets since 1984 [1-9].

The current system, shown in Fig. 1, consists of a newly designed pellet generator for freezing hydrogen gas inside the gun bore. A gas gun injects the pellet into the railgun at about 1 km/s. When the pellet enters the railgun breech, an arc is formed in the propellant gas behind the pellet and the railgun is fired. The gas is ionized by applying high voltage to a tungsten needle inserted through the railgun sidewall. This fuseless operation eliminates potential contamination of the tokamak plasma by high-Z fuse material.

Pellet velocities of 2.46 and 2.8 km/s have been achieved using 1.2-m and 2-m long railguns, respectively. New designs, including novel sidewalls and transaugmentation are being investigated to improve railgun performance.

Accelerating fragile hydrogen pellets presents several challenges. Small fragments preceding the main projectile may cause premature triggering of functions that are dependent upon pellet location. Also, the initial impact of the approaching armature may damage the pellet and result in plasma blowby. This paper describes the diagnostics and controls that have been and are being implemented on the railgun system, some of which include unique features to account for the fact that the projectile is a frozen hydrogen pellet.

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## DIAGNOSTICS

The projectile velocity is determined by shining a pair of laser beams across the bore onto a pair of 1 mm optical fibers. The light is transmitted to an automatic timing circuit located in the screen room. The circuit converts optical signals into electrical ones and sends them to a digitizing oscilloscope. When the pellet intercepts the laser beams, the pulses are stored on the scope and the velocity can be measured. Both the breech and muzzle velocities of the projectile are measured in this fashion.

The pellet size is measured by photographing the projectile as it flies over a transparent ruler located at the muzzle. (See Fig. 2.) A xenon flashlamp illuminates the pellet for 10 ns, freezing the image on film. A nanopulser inside the screen room flashes the lamp when triggered by the automatic timing circuit.

An impact transducer is mounted to a stopping plate at the end of the railgun chamber. When the pellet strikes the plate, the transducer sends a signal to its power supply located in the screen room. This signal is captured on a digitizing oscilloscope. The transducer signal can then be interpreted to provide pellet mass information.

The ionization, railgun and transaugmentation currents are measured with Pearson coils. The output signals are displayed on digitizing oscilloscopes.

Pulse-shaping network (PSN) voltages are measured across voltage dividers with digital voltmeters. The meters are mounted on a voltage control panel.

The plasma armature position versus time is photographed using a streak camera. Fig. 3 shows the free arc moving from left to right at 4.7 km/s. The breaks in the streak correspond to the window frames of the railgun chamber and serve as a

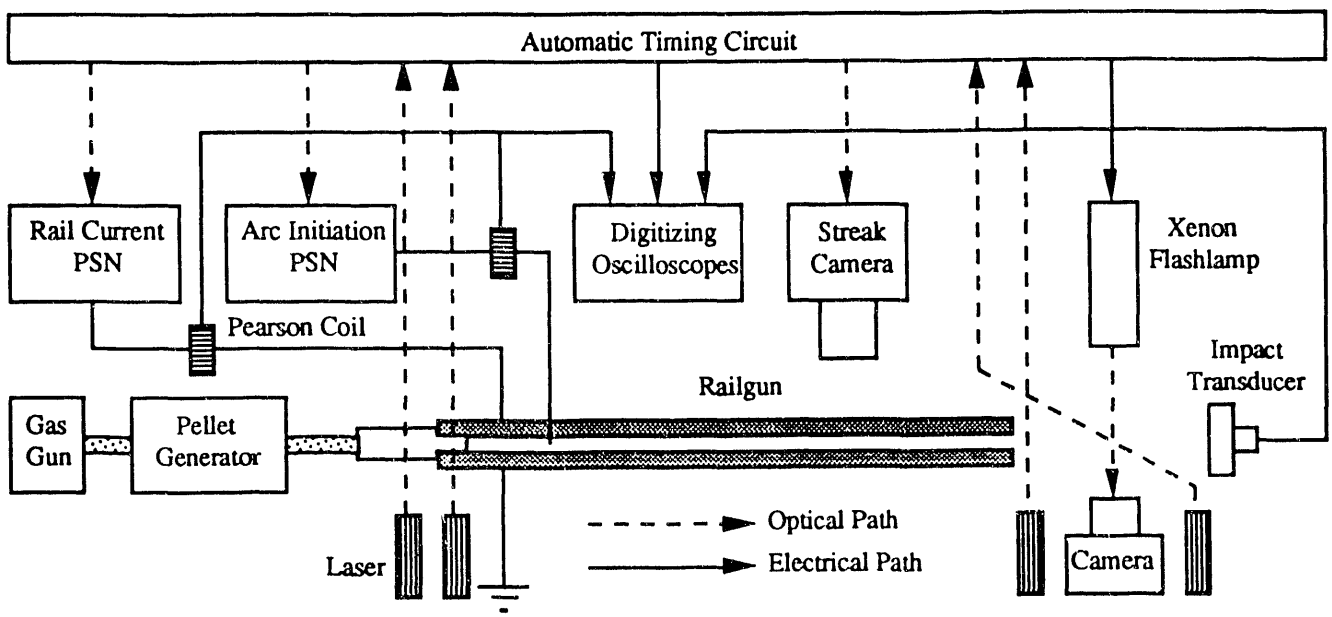


Fig. 1. Schematic of the University of Illinois two-stage railgun.

convenient measure of distance. Forward motion stops when the arc reaches the muzzle, as shown in the upper left corner of the picture. A pulsed laser diode module is used to calibrate the vertical time scale on the right by placing dots on the film at 10-μs intervals. These pictures provide a wealth of information. Arc speed, secondary arcing, plasma blowby and arc stalling can all be identified using this technique. B-dot probes have also been used on the railgun to detect plasma position versus time. B-dot probe signals are displayed on digitizing oscilloscopes.

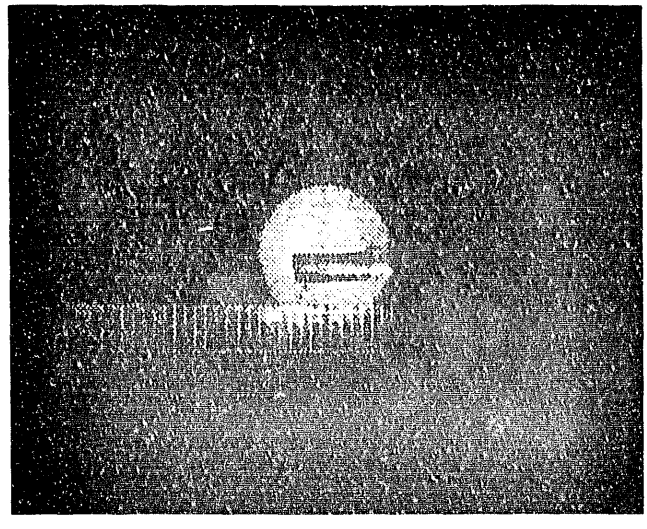

Fig. 2. Photograph of frozen hydrogen pellet.

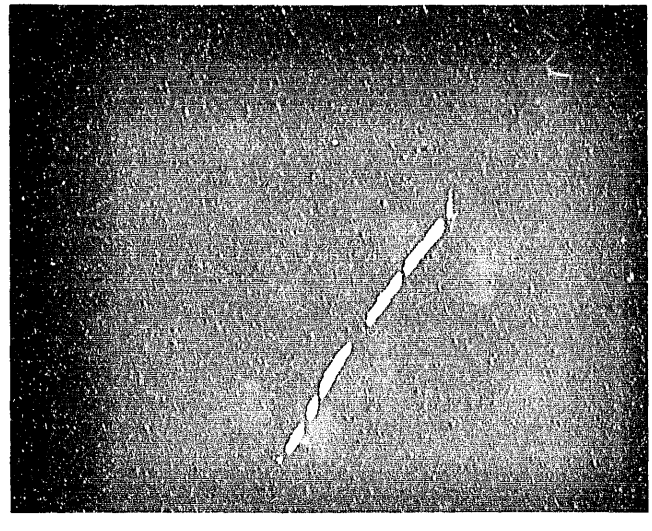

Fig. 3. Photograph of plasma position versus time

The muzzle voltage is measured by monitoring the current flowing through a resistor connected to the ends of the rails. The resistor current is measured with a Pearson coil and stored on a digitizing oscilloscope. The breech voltage is determined in like manner.

Laser interferometry is used to measure the time-resolved, line average electron density profile of the plasma [10]. A 10-mW helium-neon laser is used in a Mach-Zehnder configuration, as shown in Fig. 4. The laser beam goes to a cube-type beam splitter. The reference beam passes under the railgun. The object beam travels across the bore through small holes in the Lexan sidewalls. The beams are then combined in a second beam splitter cube. The beams are both projected onto the streak camera with a small angle between them, thus forming linear interference fringes. A slit is placed in front of the camera to convert the fringe lines to dots. An arc detecting circuit triggers the streak camera as the arc approaches the object beam. The streak camera then photographs the fringe positions versus time. A fringe shift corresponds to a density change of $1.1 \times 10^{18}$ $cm^{-3}$. Density measurements have been made at different rail currents using 16 mg Lexan and 3-7 mg foam pellets.

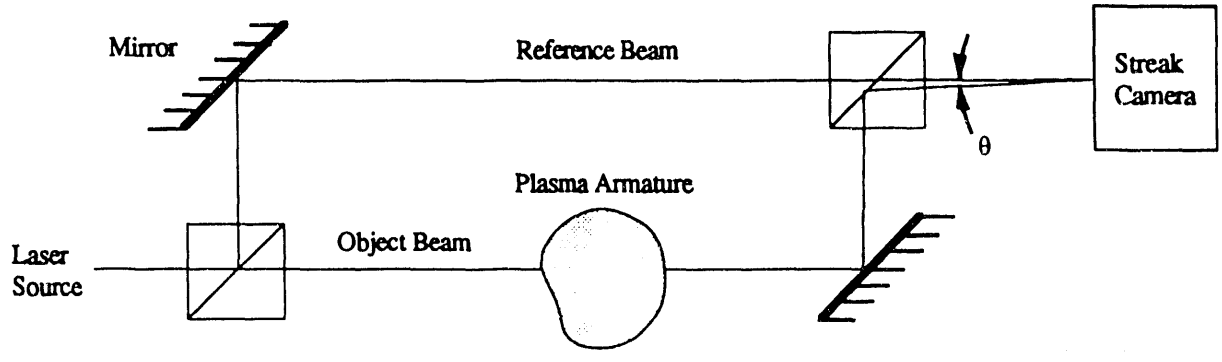


Fig. 4. Schematic of laser interferometer.

Optical spectroscopy is used to make free arc electron density and temperature measurements [11]. The electron density is determined by measuring the half-width of the Stark-broadened hydrogen beta line. The electron temperature is determined from the relative intensities of the hydrogen alpha and beta lines. For this measurement, the stopping plate at the end of the railgun chamber is replaced by a quartz window, as shown in Fig. 5. An optical spectrometric multichannel analyzer (OSMA) is set up facing the railgun muzzle through the window. When the OSMA is ready to acquire a spectrum, the railgun is fired with a pulse generator. The rising edge of the positive pulse triggers the gun. The falling edge triggers the OSMA. By varying the pulse width, spectra for the plasma at different locations along the gun are measured. B-dot probes are used to check for consistent plasma speeds from shot to shot. Density and temperature measurements for various rail currents are shown in Fig. 6.

Data captured on the digitizing oscilloscopes is transferred via GPIB to a Macintosh IIfx. The computer uses LabVIEW software to perform data acquisition and control.

The railgun is videotaped during operation. This provides a visual record that may prove vital whenever troubleshooting becomes necessary.

## CONTROLS

High voltage power supplies charge up the PSN's via vacuum switches. These switches are operated from the voltage control panel. The control panel can also rapidly discharge the capacitor banks when necessary. This is done by connecting the PSN's to resistors grounded through solenoid switches.

Because the timing circuit uses optical signals, it is immune to mistriggering due to electromagnetic interference. The circuit also filters out small pulses in the pellet detection signals to prevent mistriggering on pellet fragments.

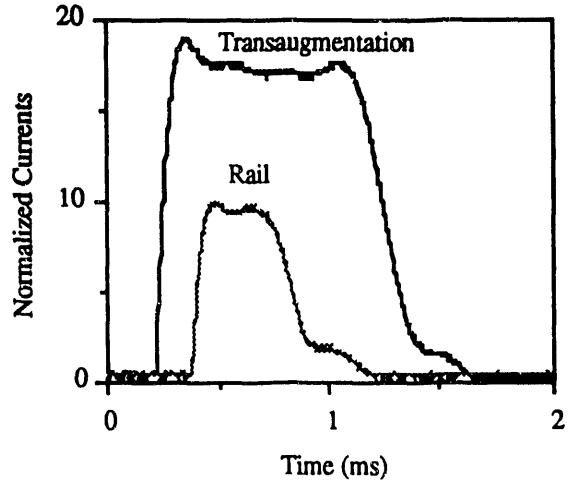


Fig. 7. Normalized transaugmentation and rail currents.

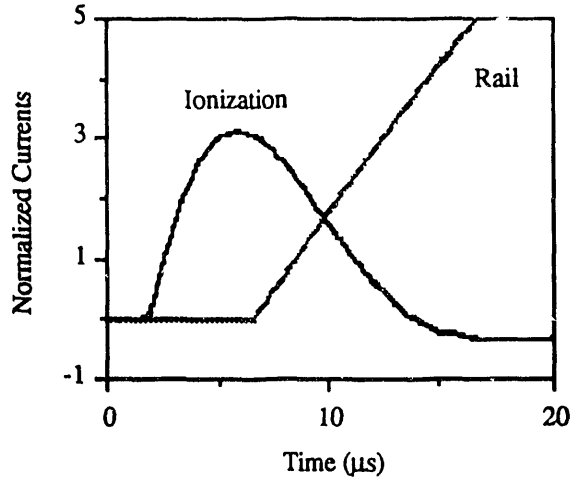


Fig. 8. Normalized ionization and rail currents.

## FUTURE PLANS

Diagnostic and control capabilities on the two-stage railgun system are currently being expanded. A pulsed nitrogen laser and video equipment are being installed to videotape the pellet entering the railgun breech. The equipment consists of a CCD camera, monitor, VCR, video printer and time-date generator.

A CAMAC system is being assembled to automate operation of the railgun system and digitize B-dot probe signals. The CAMAC controller interfaces with the microcomputer via GPIB.

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