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**Fusion Technology and Charged Particle Research Laboratory
Report FTCPRL-9302**

**Department of Energy Project
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**APPLICATION OF RAILGUN PRINCIPLE TO
HIGH-VELOCITY HYDROGEN PELLET INJECTION
FOR MAGNETIC FUSION REACTOR FUELING**

PROGRESS REPORT FOR OCTOBER 1, 1992 - SEPTEMBER 30, 1993

Prepared

by

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1. Tasks Initiated, Continued, or Completed

- a) Hydrogen pellet velocities exceeding 1.4 km/s have been achieved with a gas gun by shortening the distance between the fast valve and pellet generator, and by using hydrogen gas as the propellant.
- b) With the improved gas gun and by improving the uniformity of the railgun bore, hydrogen pellet velocities up to 3.3 km/s have been achieved on a 2-m railgun .
- c) Automated pellet-making scheme using LabView has been designed, fabricated, and tested with the existing pellet generator, gas gun, and 1.2-m and 2-m railgun systems. The automation scheme has not only increased the efficiency, but also enhanced the repeatability of pellet making. By varying the various parameters affecting the pellet-making process, an optimal combination has been found, which allows for fabrication of pellets with higher strength while consuming less liquid helium.
- d) To control the power delivery a system that will allow for automated charging of the capacitor banks has been designed and is being assembled using CAMAC and a computer.

- e) Filemaker database has been employed to analyze the 1150+ data measured since 1988, which allows for easy manipulation and processing of the railgun data.
- f) Hydrogen pellet acceleration experiments have been carried out on a 1.2-m augmented railgun with Lexan, perforated, and mullite sidewalls, respectively. Hydrogen pellet acceleration as high as $4.4 \times 10^6 \text{ m/s}^2$ and hydrogen pellet velocity as high as 2.56 km/s have been achieved on the 1.2-m augmented railgun. The measured data show that trans-augmentation improves the railgun performance due to the increased magnetic field strength inside the railgun bore. Work will be underway to implement a similar trans-augmentation system on a 2-m railgun.
- g) Railgun simulation is being carried out to analyze the current density, eddy current, magnetic field, Lorentz force, power loss, and dynamic inductance, with and without trans-augmentation. MSC/EMAS on UIUC CRAY Y-MP and its pre/post processor MSC/XL on an HP-9000 station are employed to do the numerical analysis.
- h) Emission spectroscopy is being implemented to measure the plasma temperature and density along the length of the

railgun. Specifically, Stark broadening and line emission intensities will be measured at different time intervals during the railgun operation.

- i) Pellet acceleration schemes employing higher currents and lower voltages will be investigated to achieve hypervelocities. A current transformer recently acquired from LANL will be modified to produce currents as high as 90 kA.
- j) To enhance armature momentum efficiency of the railguns, a stiff gun that has a uniform bore, and that can minimize radial rail deflection has been designed, and will be manufactured by IAP. Zero-ablation insulating material will be employed to minimize gun wall ablation and thereby, to reduce viscous and inertial drag.
- k) To determine the quality and density of frozen pellets, a pellet mass chamber that can catch the pellet at the gun muzzle and measure its mass has been designed, constructed, and is being tested.
- l) B-dot probes have been improved and employed to measure both armature currents and plasma velocities along the length of a 1.2-m railgun with trans-augmentation.

CAMAC system is used to record the signal from the B-dot probes.

- m) A theoretical model that can predict the amount of arc-induced hydrogen pellet erosion during pellet acceleration has been formulated. According to this theory, substantial pellet ablation occurs due to the high density ($10^{17} - 10^{18}$ cm⁻³) of the plasma armature. Techniques for reducing pellet ablation losses have been evaluated.

2. Status of Major Tasks

- a) Factors limiting the performance of a railgun are, in general, heat dissipation from plasma armature and subsequent rail material ablation, and the resulting viscous and inertial drag, uniformity of the gun bore, radial rail deflection and the resulting pellet balloting, and arc branching. To overcome the difficulties, work is underway to employ advanced materials to minimize the gun wall ablation, to design a stiff gun barrel with a uniform bore so that the radial deflection may be eliminated, and to use trans-augmentation to further increase the magnetic field in the gun bore without increasing the rail current and the rail erosion.

- b) To achieve higher acceleration, higher currents provided by a current transformer will be utilized. Due to the high pressure in high-current operation, use of a sabot could very well be necessary to protect the hydrogen and deuterium pellets. A sabot loader that attaches to the present pellet generator has been designed, so that it may be used in conjunction with the high-current operation.
- c) Lack of control on the current pulse shape results in less-than-optimal pellet acceleration. Current-pulse-forming network capable of producing variable rise time, duration, amplitude, and shape is being investigated. Utilization of this network for both rail and augmentation currents will help achieve highest acceleration.
- d) A CAMAC system has been assembled to automate and optimize the operation of the railgun system. It includes:
- freezing hydrogen pellets under controlled temperature, pressure, and time,
 - operating and monitoring the vacuum system,
 - logging pertinent railgun parameters, and
 - charging capacitor banks.

Automation of the pellet-making process has improved the quality of the frozen hydrogen and deuterium pellets. Pellets of variable sizes and higher strength have been produced with less liquid helium consumption.

- e) Diagnostics for probing the internal conditions of the plasma-arc armature have been developed using laser interferometric and spectroscopic techniques. These diagnostics will help us develop better understanding of the behavior of the electromagnetic railgun.
- f) Numerical simulation of the railgun behavior is being carried out and will help improve the design of a 2-m railgun with trans-augmentation, and help configure the railgun for practical application to fusion reactor refueling. Simulations of a compact gun and a gun with square bore are being carried out.

3. Research Effort Distribution - Estimated and Actual

See the attached schedule chart on the following pages.

EM RAILGUN PROGRAM - UNIVERSITY OF ILLINOIS

Schedule of Estimated & Actual Effort Distribution - Page 1

[illegible]

EM RAILGUN PROGRAM - UNIVERSITY OF ILLINOIS

Schedule of Estimated & Actual Effort Distribution - Page 2

Task	Year	1992												1993												1994		
	Month	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
		1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
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	6	6	4	5	5	5	5	5	5	5	5	5	5	5	5	4	5						

Projected Effort
Actual Effort

Full Height = Major Effort
Half Height = Moderate Effort

Achievements on Hydrogen Pellet Acceleration

Highest Hydrogen Pellet 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
Initial Pellet Length	2.2 mm	6 mm	6 mm
P (psi)	360	600	1100
V (kV)	2.00	4.50	7.00
I (kA)	3.20	13.50	16.45
v_{in} (m/s)	941	1006	1227
v_{out} (km/s)	1.71^a	2.56^b	3.30^a
Δv (m/s)	770	1554	2073
τ (μ s)	800	420	800
a (m/s^2)	9.66×10^5	3.70×10^6	2.59×10^6
L (cm)	102	75	181

a. without transaugmentation

b. with transaugmentation

RAILGUN SYSTEM OPTIMIZATION

- Pellet Freezing
 - Pellet making process fully automated
 - Chamber added to precisely measure pellet mass
 - Automation consistently produces high quality pellets
- Gas Gun
 - Hydrogen propellant gas instead of helium
 - Modified gas gun layout
 - Improved gas gun produces significantly higher initial pellet velocities

- Railgun
 - Current railgun designs modelled
 - New railgun being designed that maintains bore uniformity
 - Bore uniformity testing has led to highest railgun pellet velocities

- Result: > 61% of all pellet velocities > 2 km/s achieved in first half of 1993

Old gas gun layout

Total length = 18.75" (48 cm)

New gas gun layout

Pellet velocity vs. propellant gas pressure

DATA ANALYSIS

- Data presented for the period 1988 to 1992 prior to system optimization
- Simple Railguns
 - 1.2 m: Mullite performed best
 - 2 m: Lexan performed best
 - Lexan: 2 m outperformed 1.2 m
 - Mullite: 1.2 m outperformed 2 m
 - Perforated Lexan: 1.2 m performed slightly better than 2 m

-
- Transaugmented Railguns
 - Performance improves as augmentation voltage increases
 - 0 kV: Perforated Lexan performed best
 - 3 kV: Perforated Lexan performed best
 - 5 kV: Perforated Lexan performed best
 - 7 kV: Perforated Lexan performed best
 - 9 kV: Perforated Lexan performed best
 - Overall Comparison: 2 m Lexan had highest Δv

Δ Velocity vs. action for 1.2 m railguns

Δ Velocity vs. action for 2 m guns

Δ Velocity comparison for simple Lexan guns

Δ Velocity comparison for simple mullite guns

Δ Velocity vs. action for transaugmented Lexan gun

Δ Velocity vs. action for transaugmented mullite gun

Δ Velocity vs. action for transaugmented perforated Lexan gun

Δ Velocity comparison with no augmentation voltage

Δ Velocity comparison with 3 kV augmentation voltage

Δ Velocity comparison with 5 kV augmentation voltage

Δ Velocity comparison with 7 kV augmentation voltage

Δ Velocity comparison with 9 kV augmentation voltage

Highest Δ velocity comparison for various railguns

Railgun Automation

Railgun Automation

- **Pellet Generation**

Labview

Pressure Transducer

Camac

Relays & Manual Switchboard

- **Diagnostics**

Temperature Controller

Pellet Camera

- **Firing**

Pellet Generation

▪ Labview Program

Visual Programming using virtual instruments (vi's)

Driver modules and Task modules

Scopes Panel as an Example:

- Oscilloscopes read Laser pulse data**
- Display is sent to Labview and replotted**
- Data is manipulated for Leading Edge Points**
- Velocity/Acceleration are Determined and sent to front panel**

Front Panels

Front Panel

TOTAL TIME IT TOOK
TO MAKE THE PELLET
(SEC)

0

Fire fast valve +1sec

Temperature and pressure record

Time since start (sec)

0

pressure (torr)

0.00

Pellet making
time in min.

2.00

Pellet making
pressure

110

Temperature setpoint

5.00

delay after
setpoint sec.

10.00

Current sub vi's

Set Pressure2.vi
pressure.vi
Temperature1.vi

pressure

Temperature

0.00

Temperature vs time in seconds

Temperature (K) vs Time (sec)

Pellet Generation

- **Other Systems peripheral to Labview include**

- Manual/Automatic Switch**
Manual Switchboard-Relays controlled
by operator

- **Diagnostics**

- Temperature controller**
Direct GPIB hookup to Labview
Future Improvements could include
manipulation of pellet size and freeze
time

- Pellet Camera**
Electropneumatic switch hooked up
through relay board to Labview

- Labview triggers camera before AI -**
eliminating human error

- **Summary**

Results Of Automation

- Increased Efficiency**
- A Superior Quality Pellet**
- Enhanced Repeatability**
- Mistake-Free Pellet Generation and Firing**

2+ km/s Hydrogen Pellet Velocities On 2-m Railgun Since 1991 By Date

Database

Database benefits

1150+ Railgun Shots From 1988-Present-Imagine selecting all the data which involves transaugmentation!

Filemaker Databasing allows for easy manipulation and processing of Railgun Data

Benefits include fast and virtually limitless trend analyses, exclusion, omission or collection of specific data groups, and, with numerous layouts, the accentuation of different parameters.

Transaugmentation

WHY TRANSAUGMENTATION

- **Higher rail currents have to be used on a conventional railgun in order to get higher acceleration.**
- **Higher currents on rails result in more ablation of gun bore and pellet.**
- **The more the ablation, the larger the viscous drag and inertial drag, and the lower the acceleration.**
- **Transaugmentation provides a way to increase magnetic field in the gun bore without increasing the rail current and the resulting ablation.**
- **Transaugmentation allows one to minimize inertial drag and viscous drag at high pellet velocities.**
- **Higher acceleration can be achieved with transaugmentation.**

CONFIGURATIONS OF AUGMENTATION

CONVENTIONAL AUGMENTATION

TRANSAUGMENTATION

LORENTZ FORCE

- **Conventional railgun**

$$F = \frac{1}{2} L' I_r^2$$

- **Transaugmentation**

$$F = \frac{1}{2} L' I_r^2 + M' I_r I_a$$

where

L' Inductance per unit length
of rails

M' Mutual inductance per unit
length between rails and
augmented rails

I_r Current on rails

I_a Current on augmented rails

CHARACTERISTIC FEATURES OF THE UIUC TRANSAUGMENTATION SYSTEM

- **Compact configuration of rails for augmented currents to produce high magnetic field in the railgun bore**
- **Kapton film as insulating material between the two sets of rails**
- **Copper sulphate resistors as impedance-matching resistors and bank short resistors**
- **Newly designed current-pulse-shaping networks:**

	Augmentation	Railgun
C_t (μF)	2,500	2,000
V_{max} (kV)	10	5
t_p (μs)	1,000	700
R (Ω)	0.173	0.159
I/V (A/V)	2.35	3.00

- **Optimum overlap of the two currents**
- **Combination of transaugmentation and ablation-free sidewall and perforated sidewall**

**Augmented Current (5-LC, 10 kV)
and Rail Current (5-LC, 5kV)**

Cross Section of Transaugmentation

Trans-Augmentation Assembly of the 1.2-M-Long Railgun

ACHIEVEMENTS

- **Designed, fabricated and tested a 1.2-m-long, two-stage electromagnetic railgun system with transaugmentation.**
- **Designed, constructed, and tested current-pulse-shaping networks for transaugmentation system.**
- **Free arc velocity exceeding 13 km/s has been measured on the 1.2-m augmented railgun.**
- **Hydrogen pellet acceleration as high as 4.4×10^6 m/s² has been achieved on the 1.2-m augmented railgun.**
- **Hydrogen pellet velocity as high as 2.56 km/s has been achieved on the 1.2-m augmented railgun.**

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 1.2-m Railgun without Transaugmentation Since September 1992

Hydrogen Pellet Acceleration on a 1.2-m Railgun with Transaugmentation Since September 1992

Hydrogen Pellet Acceleration on a 2-m Railgun without Transaugmentation Since September 1992

Railgun Simulation with EMAS

MSC/EMAS

- **MSC/EMAS is a general purpose 2-D and 3-D program for simulating static, frequency-dependent, transient and resonant electric and magnetic fields by using FEM to solve Maxwell's equations.**

MSC/XL

- **MSC/XL is the preprocessor and postprocessor of EMAS. It**
 - **plots geometry of the model;**
 - **generates mesh best suited for the model;**
 - **assigns material properties to the model;**
 - **applies boundary conditions and excitations to the model;**
 - **generates arrow and contour plots; and**
 - **calculates electromagnetic quantities.**

SIMULATIONS USING EMAS

- **Conventional railgun (UIUC configuration)**
- **Railgun with transaugmentation**
- **Compact gun configuration:**
 - **IAP design**
 - **MER design**
- **Square-bore railgun configuration**

SIMULATION RESULTS

- **Contour and arrow plots of magnetic field B**
- **Contour and arrow plots of current density J**
- **Lorentz force on plasma armature**
- **Inductance per unit length L' of the railgun**
- **Mutual inductance per unit length M' of the railgun with transaugmentation**
- **Resistance of plasma armature**
- **Repelling force on the rails that results in radial deflection**

SIMULATION RESULTS

	Railgun	Augmentation
Current	$I_r = 20 \text{ kA}$	$I_r = 10 \text{ kA}$ $I_a = 20 \text{ kA}$
Inductance	$L' = 0.292 \text{ } \mu\text{H/m}$	$L' = 0.301 \text{ } \mu\text{H/m}$ $M' = 0.210 \text{ } \mu\text{H/m}$
Resistance	$R = 0.0061 \text{ } \Omega$	$R = 0.0061 \text{ } \Omega$
Lorentz Force	$F_z = 90.50 \text{ N}$	$F_z = 91.02 \text{ N}$
Repelling Force	$F_{ry} = 9,558 \text{ N/m}$	$F_{ry} = 17,880 \text{ N/m}$ $F_{ay} = 3,078 \text{ N/m}$

1.0e-15	6.6e+07	1.3e+08	2.0e+08	2.6e+08	3.3e+08	3.9e+08	5.3e+08	5.9e+08
6.6e+07	1.3e+08	2.0e+08	2.6e+08	3.3e+08	3.9e+08	4.6e+08	5.9e+08	6.6e+08

RT 1: ResultsCalculator
 Statics Analysis
 MagneticVectorPotential Magnitude
 ConductionCurrentDensity Magnitude
 Subcase 1

Plasma Diagnostics

Side-On Railgun Optical Spectrometry with H₂ pellet in situ

- **Experimental Setup**
- **Results Expected**
- **Correlation with Theoretical Modeling**

Experimental Setup

- **Optical Triggering/Pulse
Generator W/Delay**

- **IRY-700**

- Cooling
Gating
Diode Readout**

- **TurboC Program/Osma**

- **Apple File Sharing Allows Manipulation
of data to be controlled by programs
available in the lab**

Experimental
Setup Block
Diagram

Xenon Spectrum vs. Wavelength

Anticipated Results:

- **FWHM of Stark Broadened H₂ Beta line and Ratio of Relative Broadening between H₂ Alpha and Beta line will lead to Plasma Electron Density and Temperature values**
- **Values should correspond roughly to experimental results of end-on free arc spectrometric testing from 1991. Density values may be higher than 10¹⁷ cm⁻³ range previously detected.**
- **Experimental Data can be correlated to modeling & simulation work done by theoretician M. Grapperhaus**
- **Also Planned For Fall are Side-on in situ Laser Interferometric Density Measurements**

Pellet Mass Measurement

Pellet Mass Chamber

Pellet Ablation Modeling

The Model

- Flow of ablated material from the pellet attenuates the incoming energy flux such that energy flux reaching the pellet surface is exactly enough to continue the ablation at a constant rate
- System is in a quasi-steady state
- Ablatant flow behaves as a one dimensional ideal gas
- Heat flux from the plasma is carried by the electrons
- Ionization and dissociation occur by thermodynamic processes rather than by electron impact

Governing Equations

Fluid:

$$\rho v = -G \quad \text{Continuity}$$

$$v = v_i + \left(\frac{P - P_i}{G} \right) \quad \text{Momentum}$$

$$\left(h + \frac{v^2}{2} \right) - \left(h + \frac{v_i^2}{2} \right) = \frac{q - q_i}{G} \quad \text{Energy}$$

Electrons:

- Continuous slowing down limit

$$\frac{dE}{dx} = -\frac{2pL(E)}{m_{H_2}} \quad \text{Linear electron}$$

energy loss function

- Neglect backscattering, assume electrons maintain Maxwellian distribution

$$\frac{dT_e}{dx} = -\frac{4p\bar{L}(T_e)}{3m_{H_2}}, \quad q = \frac{q_i}{T_{e_i}} T_e$$

Boundary Conditions

Plasma-Cloud interface:

$$h_o = h_i + \frac{v_i^2}{2} = h_{\text{plasma}} \quad 1^{\text{st}} \text{ Law}$$

$$Tds = du + Pd\left(\frac{1}{\rho}\right) - \sum_j \mu_j dn_j = 0 \quad 2^{\text{nd}} \text{ Law}$$

Global energy balance:

$$q_{\text{plasma}} = G(h_{\text{plasma}} - h_{\text{pellet}})$$

Pellet-Cloud interface:

$$h_p + \frac{v_p^2}{2} = h_{\text{pellet,s}} + E_{\text{sublimation}} \quad 1^{\text{st}} \text{ Law}$$

$$\frac{G}{m_{\text{H}_2}} = \frac{P_v(T_s)\alpha(T_s)}{\sqrt{2m_{\text{H}_2}kT_s}} \quad \begin{array}{l} \text{Sublimation} \\ \text{kinetics} \end{array}$$

Ablation Rate

- For a hydrogen plasma, the global energy balance gives

$$G = \sqrt{\frac{2}{\pi m_e}} \frac{\alpha \rho (kT_e)^{3/2}}{\frac{\gamma kT_e}{(\gamma - 1)} (1 + \alpha_i) + 2E_D + \alpha_i E_i}$$

- This relation holds for the above assumptions regardless of the energy deposition profile and of the flow characteristics
- Determination of the range of validity for the model requires the solution of the flow field

Analytical Solution

- Assumes that the flow is composed entirely of monatomic hydrogen
- Dissociation and Ionization energy are supplied by:
 - a) Discontinuity in the electron energy flux
 - b) Allowing the temperature to exceed the required value
- Division of energy balance is determined by the additional restriction that pressure remain continuous across the interface
- Gives the same ablation rate as the full solution since global energy balance is maintained
- Allows an estimate of the thermal choking regime in which the flow is no longer quasi-steady state

Plasma-Cloud Mach Number Squared

- Temperature scaling is very strong, since increases in temperature increase not only the average electron energy, but also the fraction ionized
- Density scaling is weak, since it only influences the Mach number through the fraction ionized
- Changes in boundary conditions, fluid model, and electron energy deposition will shift the thermal choking limit

Electron Number Density

- Calculated using Saha's equation assuming that the plasma arc consists of pure hydrogen

Surface Regression Rate

- Temperature dependence

- a) at low temperatures the scaling is strong, since the fraction ionized depends strongly on the temperature
- b) at higher temperatures the scaling becomes weaker, since the plasma becomes nearly fully ionized

- Density dependence

- a) linear for a fully ionized plasma
- b) is weakly dependent on density at lower temperature, since the dependence of the fraction ionized nearly offsets the linear dependence

Comparison with Experiment

- Requires

- a) simultaneous measurement of temperature, density and the surface regression rate

- or-

- b) an armature model which can relate these quantities to experimental input parameters

- Results compare in magnitude to experimentally observed ablation rates

- Experimentally observed thermal choking is difficult to determine, since when no pellet exists no data will be available (average acceleration etc.)

Experimental Results

- Large error bars occur since measurements are made using exit photographs of pellets
- Augmentation and perforated sidewalls show marked improvement over the standard rail configuration

DATE

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END