A Standoff Driver for Solid Implosion of Magnetized Target Plasma

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For fusion, high velocity is an advantage

3D array of dense plasma jets/beam
Jets merged to form a quasi-spherical plasma shell
Particle beams used to drive currents and generate seed magnetic fields to be imploded

Electron beam
Ion beam
Alternate targets: Dynamic merging of multiple CTs (FRC-like)

A 2D or 3D arrays of super-Alfvénic FRCs is launched and timed to arrive at the same time as the projectile.

The converging shell of the merged FRCs gets hotter. The plasma becomes even more conductive, freezing and conserving the flux as it compresses itself towards the center.

The projectiles further compresses and confines the target to fusion conditions.

Issue: The FRCs might bounce back if the ram pressure and Alfvén Mach number is not sufficiently high.
For economical electrical power generation, the primary source of driver power cannot be chemical

- Chemical propellants or explosives are simply too expensive
  - It will require the fusion cycle to have enormous fusion yield and gain to break even financially.
- Projectile velocity from chemically propelled guns are too limited.

The gun must be electrified

Railgun is an option
Outline of the talk

• What is a railgun? How does it work? Its key parameters.
• The main physics impediments to achieving high velocity.
• What have been done about it, and what else can be done about it that could make a quantum leap in this field.
• Issues and challenges
What is a Railgun? How Does it Work?

Simple Railgun (A Linear D.C. Motor)

Current

Conducting rails

Magnetic field

Armature

Lorentz Force = \( \frac{1}{2} L' I^2 \)

Series Augmented Railgun

Augmentation rail
Independently powered augmentation

Augmentation rail

Distributed Energy Store (DES) Railgun
An example of a cross section of a railgun
Key parameters of plasma armature railguns

- Bore size: 1 - 2 cm square bore
- Current: ~ 200 kA per cm of rail height.
- Magnetic field: 20 - 30 T
- Bore effective inductance gradient:
  - 0.3 µH/m (un-augmented),
  - 0.7 - 1 µH/m (augmented)
- Plasma or magnetic pressure: 1 - 3 kbars
- Plasma temperature: ~ 20,000 deg K
- Plasma density: \(10^{25} - 27\) per m³
- Plasma is strongly coupled.
  - Coupling coefficient ~ 0.1 - 1.
- Plasma resistivity ~ 0.04 - 0.1 milliohm-m
The plasma armature is vulnerable to several undesirable effects

- Diffusion across the magnetic field
  - $\delta \sim 25$ cm in 100 $\mu$s
- Filamentation instabilities
  - Growth of longitudinal disturbance in the armature
  - Amplitude e-folding time is the transit time of an Alfven or acoustic wave over the length of the armature
- Ablation, restrike and secondary arcs
  - Ablation drag
  - Ablated material is vulnerable to restrike
- Viscous drag
  - Ultimate limit on velocity
As a result of the afore-mentioned effects, the plasma armature have a tendency to evolve into the following structure.
Concepts and approaches for mitigating ablation

- To avoid ablation, the wall temperature rise needs to be kept below the ablation temperature of the wall material.

Wall temperature rise:

$$\Delta T = \frac{2VI}{s\sqrt{\pi \rho c_v \kappa / a \ell}}$$

- $V, I, v_a, \ell$ - armature voltage, current, velocity, length
- $\rho, c_v, \kappa$ - wall density, specific heat, thermal conductivity
- $s$ – bore perimeter

Use low armature current → Apply field augmentation to maintain reasonable acceleration

Use material with high ablation temperature → Advanced ceramics with high thermal conductivity and capacity

Armature voltage, length → Plasma species, generation technique

Armature velocity → Pre-injection
## A few landmark plasma-armature experiments

<table>
<thead>
<tr>
<th>Year</th>
<th>Inst.</th>
<th>PI</th>
<th>Mass</th>
<th>Velocity km/s</th>
<th># of stages</th>
<th>Features</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1976</td>
<td>ANU</td>
<td>Marshall</td>
<td>3 g</td>
<td>5.9</td>
<td>1</td>
<td>HPG, opening switch</td>
<td>Sparked worldwide interest</td>
</tr>
<tr>
<td>1979</td>
<td>LLNL</td>
<td>Hawke &amp; Fowler</td>
<td>1 g</td>
<td>5.5 (10.1)</td>
<td>1</td>
<td>Flux compression generator</td>
<td>EOS, impact fusion</td>
</tr>
<tr>
<td>1985</td>
<td>LANL</td>
<td>Parker</td>
<td>1 g</td>
<td>3.6</td>
<td>1</td>
<td>Physics studies.</td>
<td>First to Quantify performance loss due to ablation</td>
</tr>
<tr>
<td>1986</td>
<td>W</td>
<td>Thio</td>
<td>1 g</td>
<td>8.2</td>
<td>2</td>
<td>Augmentation, novel plasma initiation, multi-stage</td>
<td>First systematic attack on ablation, sec arcs, restrike</td>
</tr>
<tr>
<td>1988</td>
<td>GTD</td>
<td>Witherspoon</td>
<td>1 g</td>
<td>5.6</td>
<td>1</td>
<td>Ceramic insulators, pre-injection</td>
<td>Another attack on ablation</td>
</tr>
<tr>
<td>2009</td>
<td>IAT</td>
<td>McNab</td>
<td>7 g</td>
<td>5.2</td>
<td>1</td>
<td>Augmentation, ceramic insulator, pre-injection</td>
<td>Bore ablation practically eliminated</td>
</tr>
</tbody>
</table>
The IAT 7-m Plasma-Armature Railgun

Augmentation Current (peak) 15 modules~850 kA
Primary Rail Current (peak) 3 modules ~190 kA
Preinjection Velocity 0.5 - 1 km /s
Inductance Gradient 0.40 µH/m
Mutual Gradient 0.29 µH/m
Bore Pressure 100 MPa (15 ksi)

Projectile Mass 5.4 g
Bore 17 mm × 17 mm
Gun Length 7 m

Institution: U. Texas at Austin
Team: Wetz, Stefani, Parker, McNab
The SUVAC Railgun Launch Facility

2-stage DES augmented railgun experimental facility

Stage 1: 8.2 mF
Stage 2: 11.88 mF
Max charging voltage: 10 kV

Institution: Westinghouse
Team: Thio, McNab, Condit, Ometz, Stefani, Frost, Subramanian, Sucov
The SUVAC-II Railgun Barrel

For the 8.2 km/s shot:

Stage 1: 6.04 kV,  
150 kJ,  
198 kA,  
L’ = 0.34 μH/m  
M’ = 0.17 μH/m

Stage 2: 4.74 kV,  
133 kJ,  
280 kA,  
L’ = 0.32 μH/m  
M’ = 0.16 μH/m

Projectile: 1.024 gram

Bore: 9.09 mm x 9.80 mm
Mitigation of armature growth, secondary arcs, and restrike

- Eliminate ablation
- Use DES railgun

In 1989, Parker pointed out that distributed current injection in a DES gun may prevent restrike.

Demonstrated in two-stage SUVAC in 1986: Experimental data was consistent with the shedding of armature mass shortly after the switching-on of the second stage capacitor module. Normal projectile acceleration was achieved in the second stage. This allows SUVAC to achieve its velocity of 8.2 km/s.
Path forward for railgun development towards higher V

Synchronous DES as a Traveling-wave Railgun

- The primary rails and the augmentation rails are configured as a pair of transmission lines, for an electromagnetic (near-square) pulse of voltage and current down the rails.
- A distributed array of capacitors, wrapped around the gun, is used to slow down the EM wave, so that its wave speed matches the average speed of the projectile around a given capacitor module. Each capacitor also adds to the current and energy of the traveling pulse.
- A new way to think about an old concept

One way to defeat the tri-factor: magnetic diffusion, filamentation instability, and restrike.
How much would a railgun cost launching 128 g to 10-km/s?

- Bore: 4 cm x 4 cm square
- Projectile: 4-cm cube with hemispherical cup, 130 g
- Projectile kinetic energy: 6.4 MJ.
- Gun electric-kinetic (wall-plug) efficiency: 50%
- Total stored pulsed power energy per shot: 12.8 MJ, $15M
- Length: 50 m, 50 stages, 1 m per stage (80% piezo-kinetic)
- Inner rail: thoriated tungsten, 141 kg; 400 kA, 0.4 μH/m
- Augmentation rail: copper, 0.2 μH/m, 1.6 MA, water cooled
- Acceleration: $10^6$ m/s$^2$ ~ 100 kG
- Gun capital cost: $5M
- Acceleration time: 10 ms
- Charge transfer between rails and plasma armature per shot: 4000 C
Cost per MJ delivered over lifetime of drivers

- Data for electrode erosion for slow moving arcs (<100 m/s) indicates an erosion rate of ~ 50 ng/C
- Nominal electrode erosion: 0.2 mg/shot/rail (based on data on low-velocity arcs)
- Recycle rails when 1% of its mass is eroded: ~ 7 million shots
- Rep-rate: 1 Hz -> Recycle rails every 3 months.
- Cost of recycling: $0.1M
- Cost of delivering 1MJ per recycling: $0.002/MJ
- Total cost of pulsed power supply and gun over lifetime ($10^8$ shots): $0.03/MJ
- Projectile cost: ?
- Capital cost of driver: ~ $40M for delivering 2 projectiles of 128 g each at 10 km/s
Attractive features of railgun as a standoff driver for fusion

• Mechanically robust
• Reactor embodiment can be easily adapted to thick liquid wall
• Projectile travel is insensitive to chamber conditions
• Low capital cost (~ $5/J) compared to lasers or particle beams ($1000/J)
• Being low capital cost, multiple pair of guns may share one reactor chamber, lowering the rep-rate required per gun.
• Many other applications – opportunities for multi-agency collaborations and private-equity funding
  – Ground-to-space launch (NASA, DOD, commercial)
  – Tactical and strategic defense (DOD)
  – Planetary defense against asteroids
  – Logistics support (DOD, commercial)
Issues and Challenges

- Lifetime, operational stability and reliability
- Diagnostic access during R&D is challenging
- Precision of targeting (launch trajectories)
- The hydrodynamics of the projectile collision, leading possibly to jetting of material into the target plasma
- The availability of suitable magnetized targets in size and having the required magnetic fields
- Stiff containment of a number of pieces to provide a tight fitting bore and stable bore dimensions
- Cost of projectile per shot
- Solid debris
- The range of velocity available is limited (<20 km/s)
  - Limited headspace for defeating thermal transport
References

References