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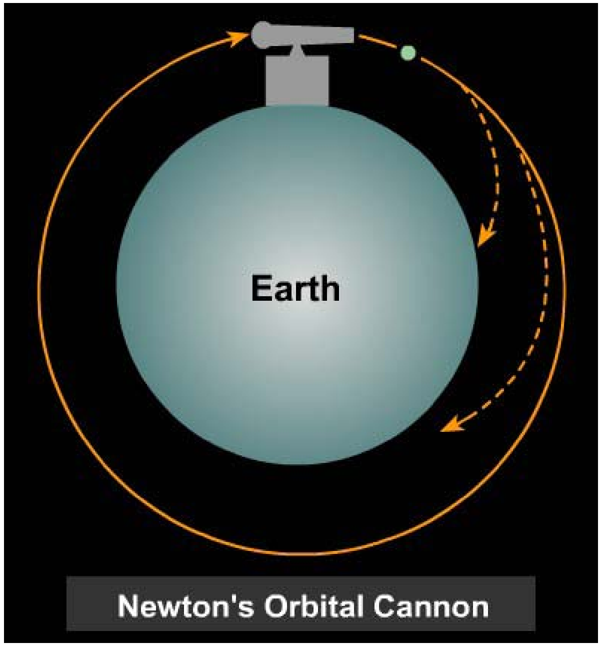
Ballistic Launch to Space



Ed Schmidt and Mark Bundy
Army Research Laboratory
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International Symposium on Ballistics
14-18 Nov 05

Background

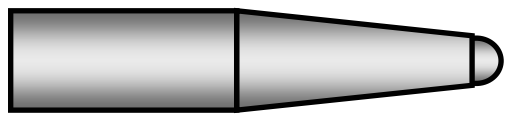
- Rocket based lift to orbit costs between $4000 to $14,000 per pound depending on launcher and payload
- For the Mars mission, NASA anticipates a need for large quantities of supplies and material delivered to earth orbit
- NASA is interested in the possibility of earth launch to space of acceleration tolerant payloads
    - Low Earth Orbit (LEO)
    - 500 kg payload
    - 1000-2000 kg total launch mass
- ARL asked to lead examination of selected launcher technologies:
    - Slingatron
    - Blast Wave Accelerator
    - EM Coil Gun
    - EM Rail Gun

Launch Calculations

Consider orbit of International Space Station (ISS):

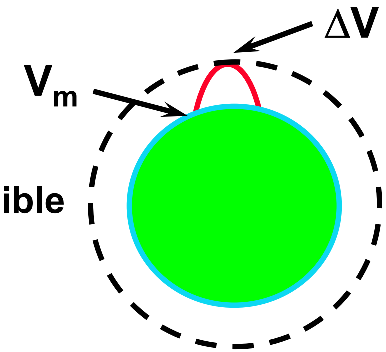
- 359 km at 51.4° inclination to the equator
- Orbital velocity 7.7 km/s

Flight Body:



- 10° half angle blunted conical nose
- Base diameter, D = 0.46 m
- Cylindrical section, L = 2.5 D
- Nose radius, r_n = 0.0575 m
- Total flight mass, m = 1000 kg

Launch Calculations



Assume:

- Projectile just reaches apogee at ISS orbit
- Newtonian flow theory applies => C_D = 0.119
- Use Rice, et al [5] to estimate velocity at exit from sensible atmosphere:

  $$V_e/V_m = \exp[-C_D \rho_o A/2m\beta\sin\theta]$$

  where β is the atmospheric lapse rate = 1.1×10^{-4}/m
- 50% structural mass, 85% rocket mass fraction, I_{sp} = 305 s

Compute muzzle velocity, insertion velocity, and payload mass versus elevation angle for 1000 kg launch mass.

θ (deg)	10	20	30	40	50	60	70	80	90
V_m (km/s)	13.48	7.88	5.74	4.52	3.81	3.35	3.08	2.93	2.88
ΔV (km/s)	1.03	2.62	3.89	4.91	5.66	6.28	6.80	7.28	7.70
m_{pl} (kg)	329	156	72.5	26.3	0.94	Propellant system mass equals or exceeds available non-structural mass			

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High Altitude Research Project

HARP:

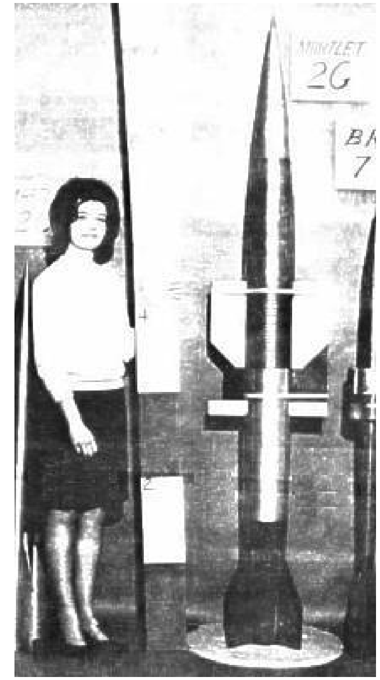
First serious attempt at gun launch to space.

Double length 16” Naval gun.

Achieved altitude of 180 km (V_m = 2.1 km/s) in 1966 firing at Yuma Proving Ground.

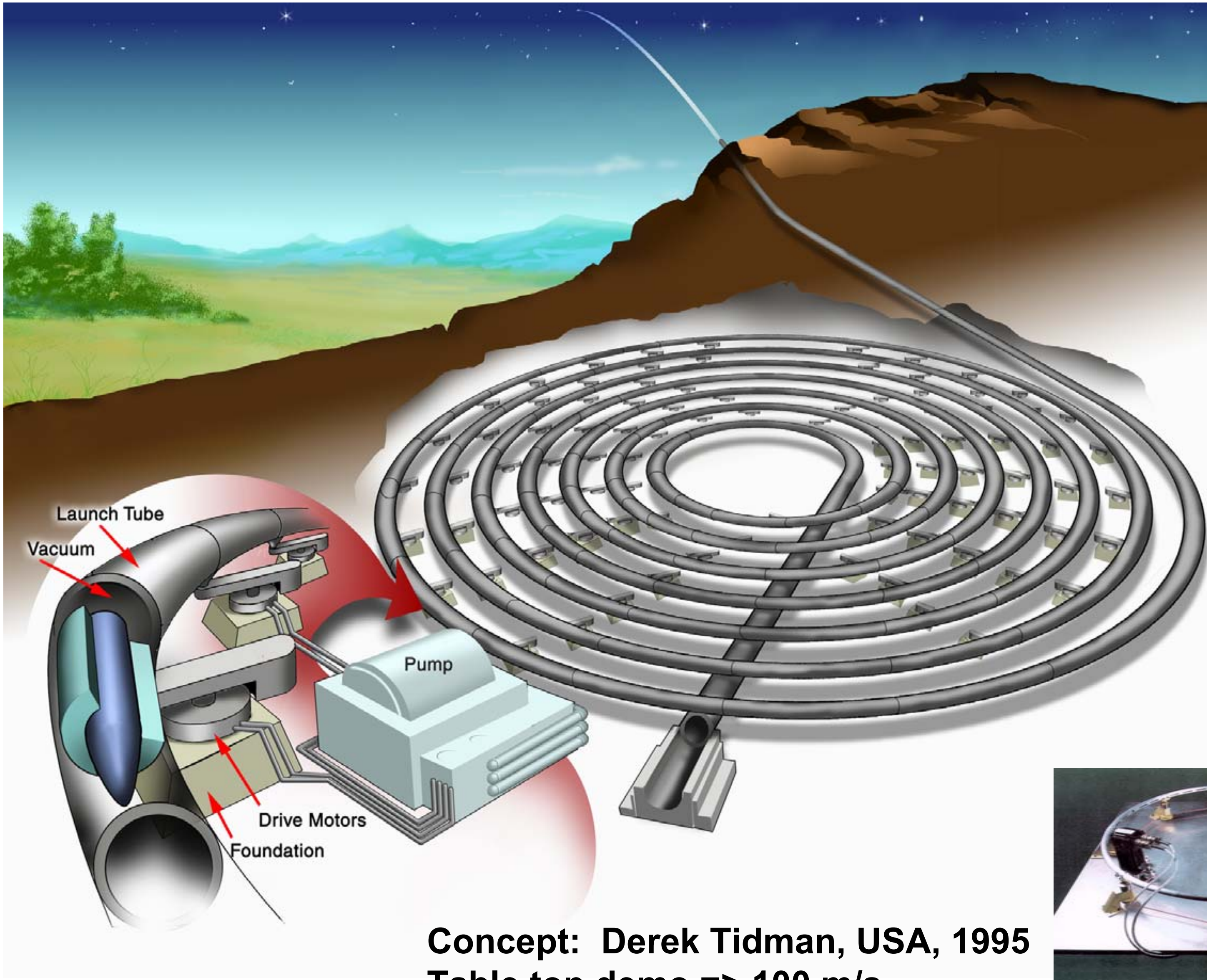
Plans underway for rocket propulsion for orbital insertion.

Project cancelled in 1967.



Martlet 2: launch mass up to 215 kg capable of 25 kGee.
Cost: $3000 each
Launch Interval: 1 per hour

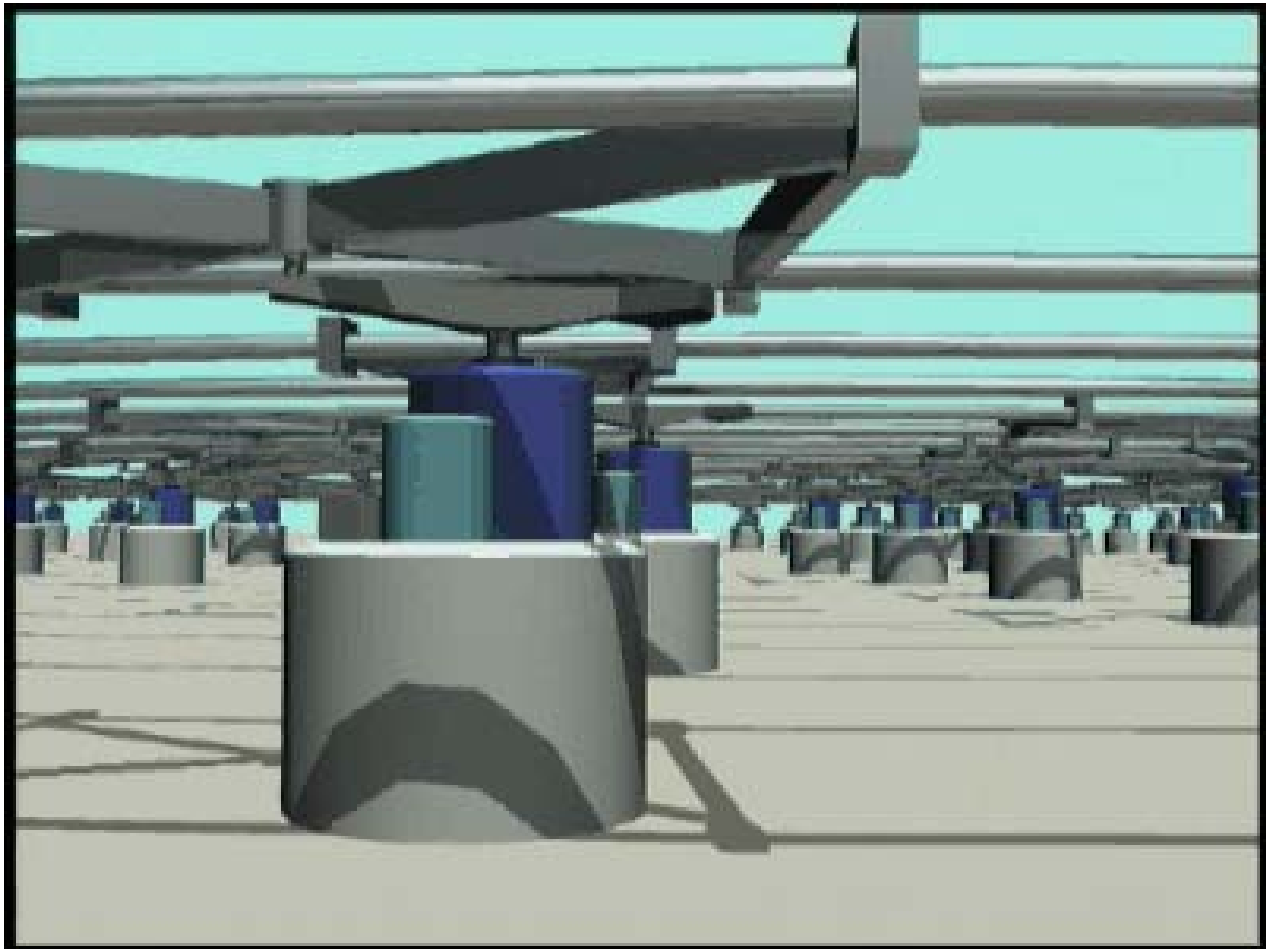
Slingatron



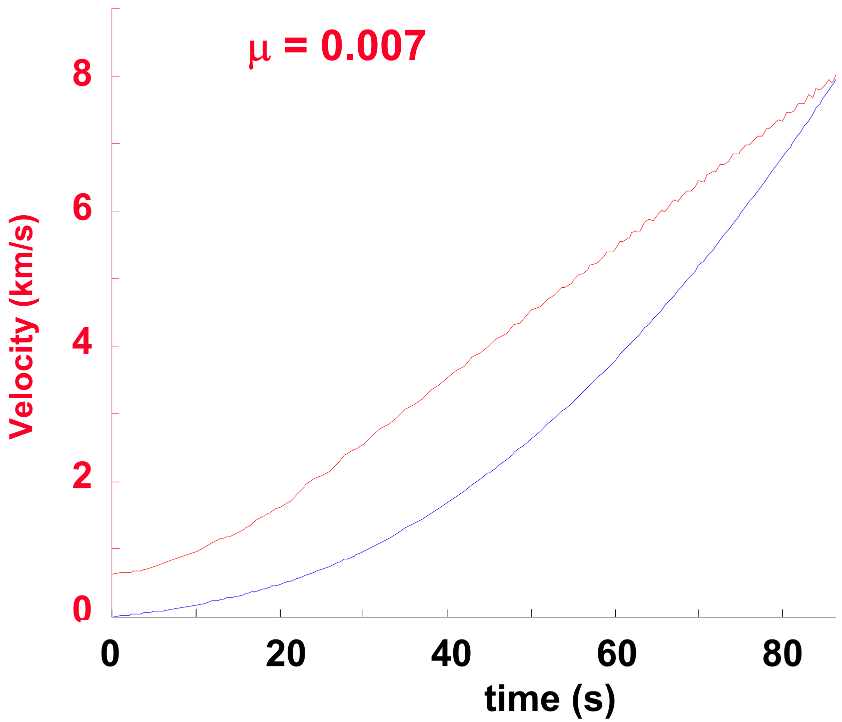
Concept: Derek Tidman, USA, 1995
Table top demo => 100 m/s

Graphics courtesy of J. Jones, NASA

Slingatron Functioning



ARL MATLAB Simulation



ARL simulation agreed with Tidman's analysis. Slingatron can in theory accelerate a body to high velocity, but there are significant unknowns – one of which is high speed friction.

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Slingatron Launcher

- For 1,000 kg launch mass at 8,000 m/s, a Slingatron solution:
  - Circuit Diameter = 300 m
  - Tube Diameter = 0.4 m
  - Tube Wall Thickness up to 0.25 m
  - Gyrational Frequency = 9 cycles/sec
  - Weight = 20,000 tons
- Issues:
  - Structural integrity
  - Friction and surface wear
  - In-Bore stability
  - Fabrication of curved guide tube
  - Drive and support system design integrity
  - Synchronization of multiple drives
  - Power to bring to speed and maintain during firing
  - Reacting the acceleration and centrifugal recoil load

Blast Wave Accelerator

Graphics courtesy of J. Jones, NASA

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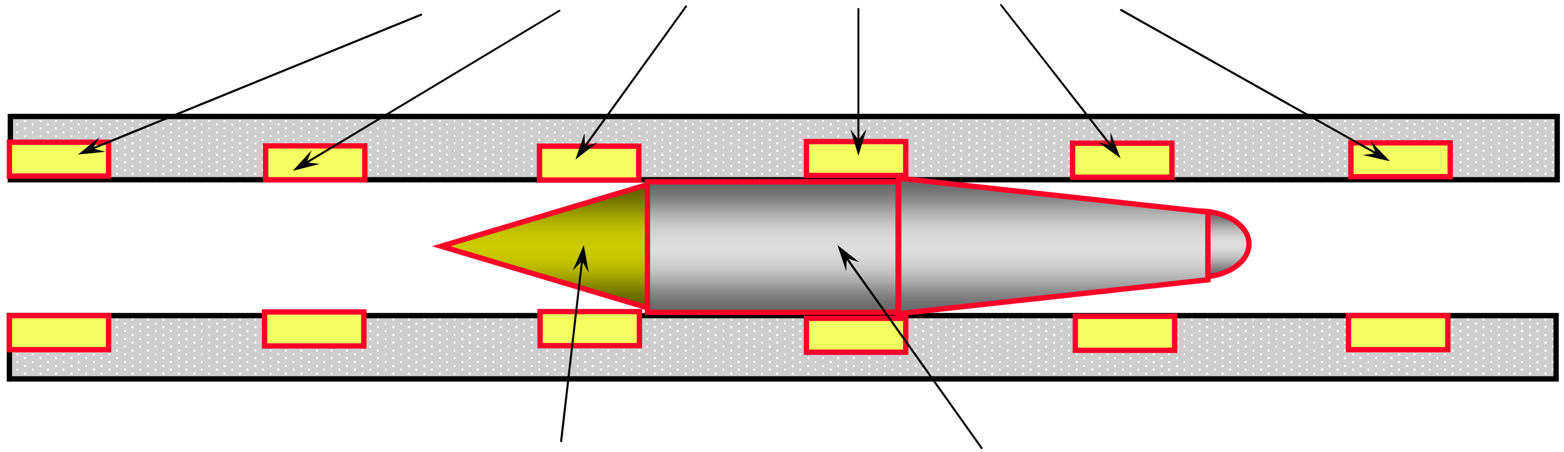
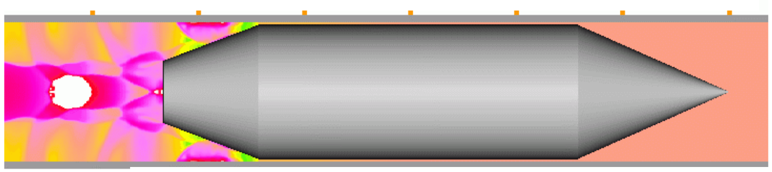
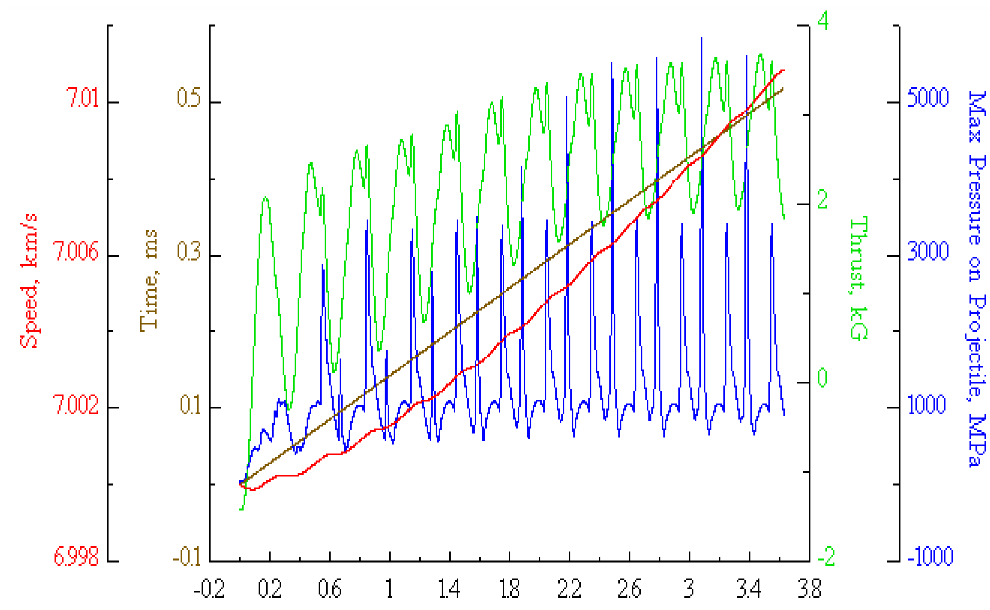
Blast Wave Accelerator Concept



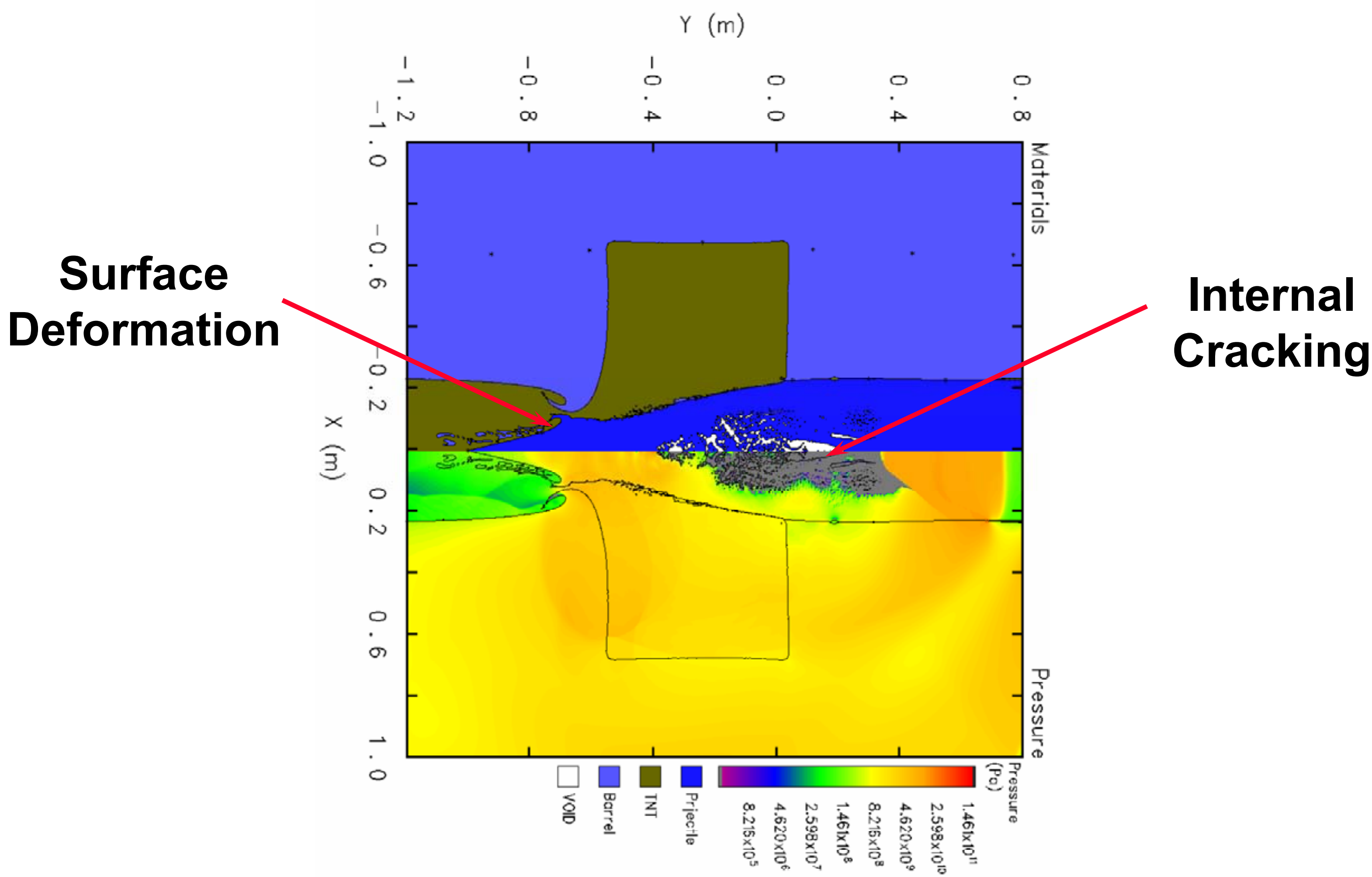




CFD calculation of D. Wilson.

ARL calculations in agreement.

ARL CTH Results



Simulations showed structural damage to mild steel projectile.

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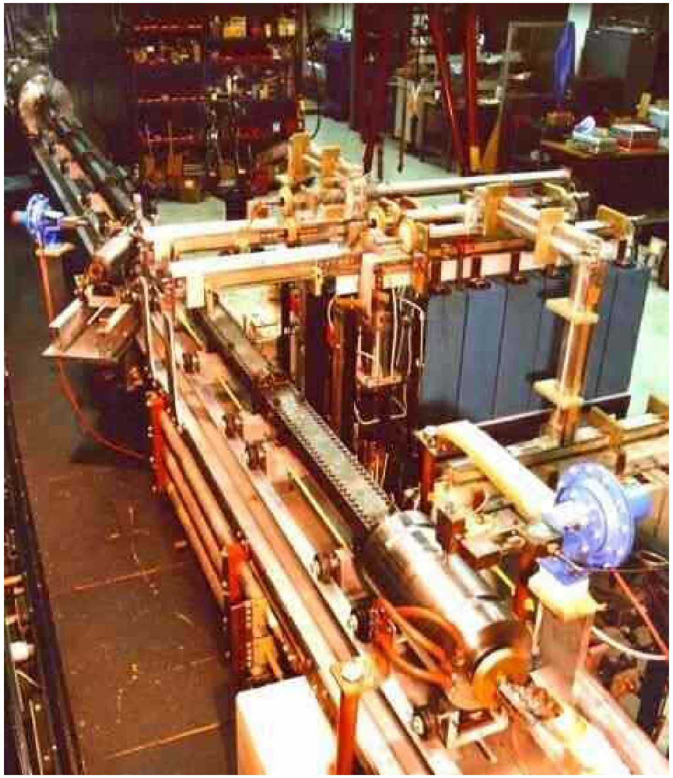
Blast Wave Launcher

- For 1,000 kg launch mass at 8,000 m/s:
  - Charge mass per Stage = 10 kg
  - Number of Stages = 2870
  - Gun Length = 861 m

- Issues:
  - Projectile integrity
  - Launcher integrity (repetitive firings)
  - Timing of sequential detonation
  - Explosive detonation uniformity
  - In-bore stability
  - Detonation of 30,000 kg of explosive

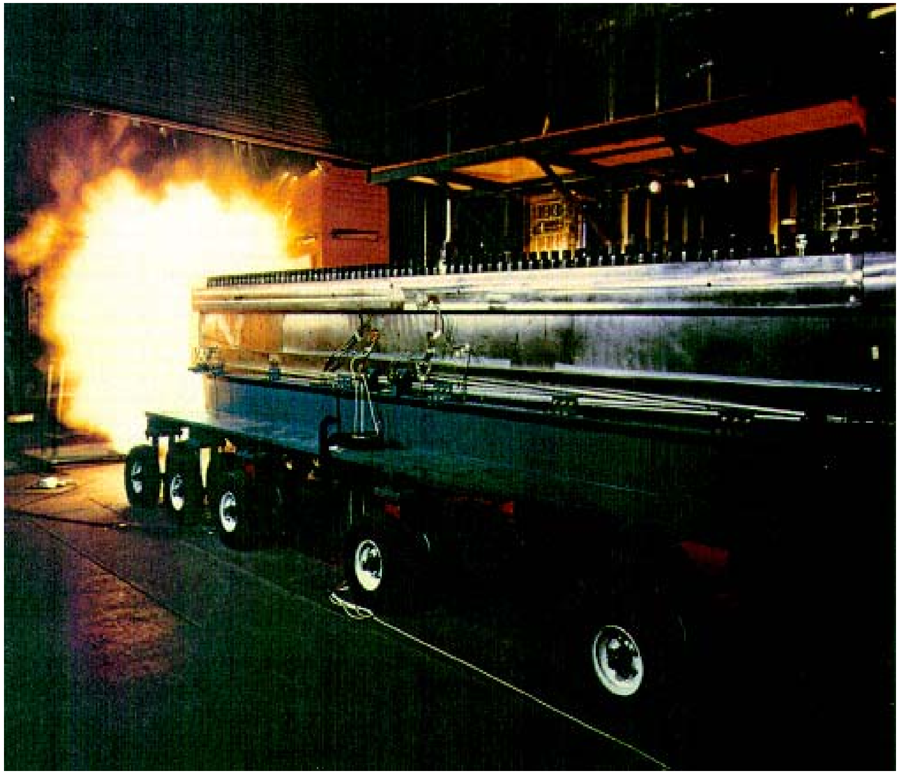
Electromagnetic Guns

Sandia Electromagnetic Coilgun



Coilgun has launched 230 g to 1000 m/s

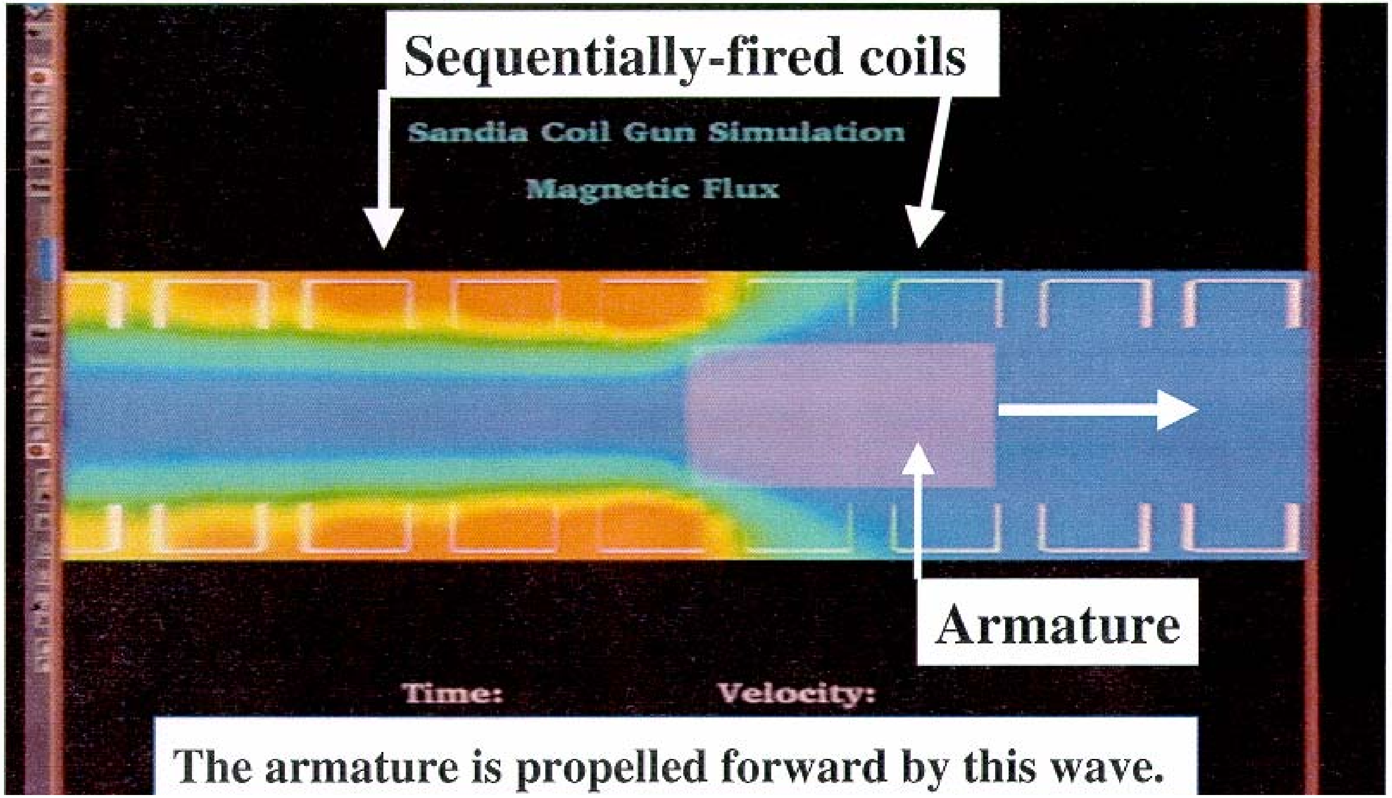
Greenfarm Electromagnetic Railgun



Railguns have launched ~2 kg to 3000 m/s (1 g to 7000^{+} m/s)

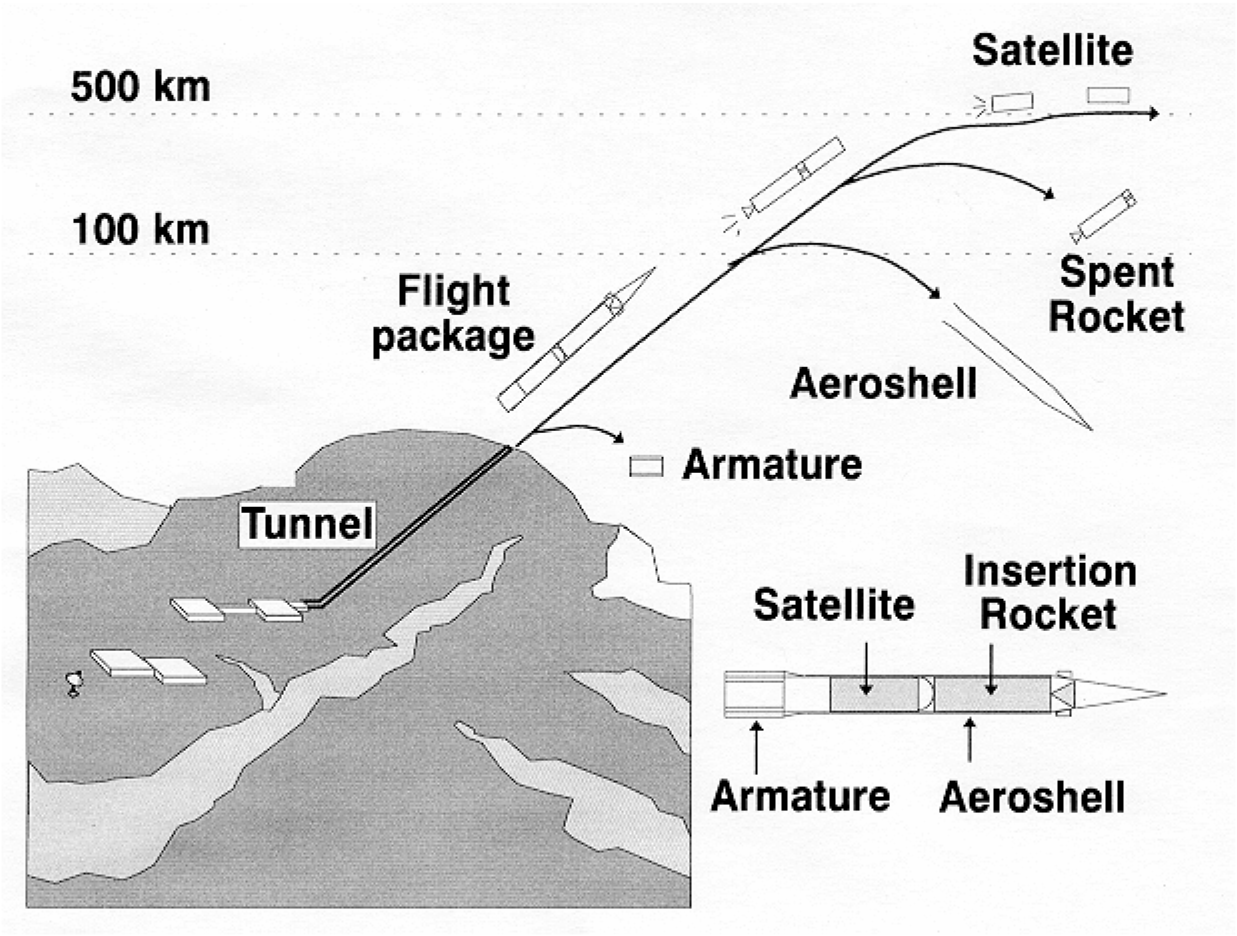
EM Coilgun

A magnetic travelling wave is created by synchronized sequential switching of individual coils.
Strong centering force "levitates" projectile for minimal wall contact



Graphics courtesy of Sandia

Sandia Coilgun Concept



Graphics courtesy of Sandia

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Coilgun Launcher

- For 837 kg launch mass at 7,000 m/s:
  - Launcher Length = 400 m
  - Tube Diameter = 1.0 m

- Issues:
  - Structural integrity of projectile and launcher
  - Pulsed power supply
  - Switching
  - In-bore stability of levitating projectile

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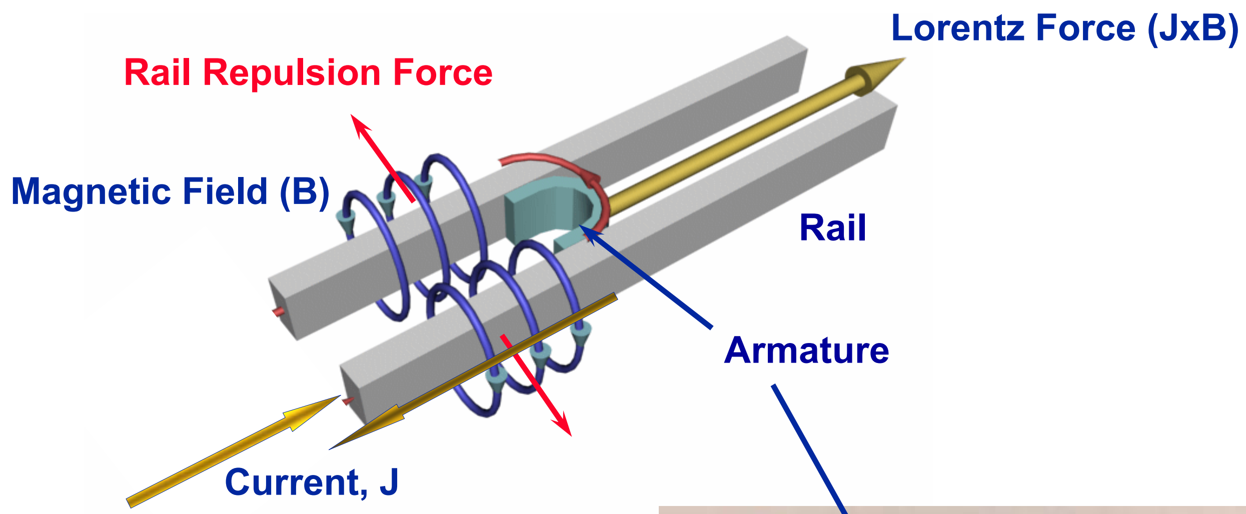
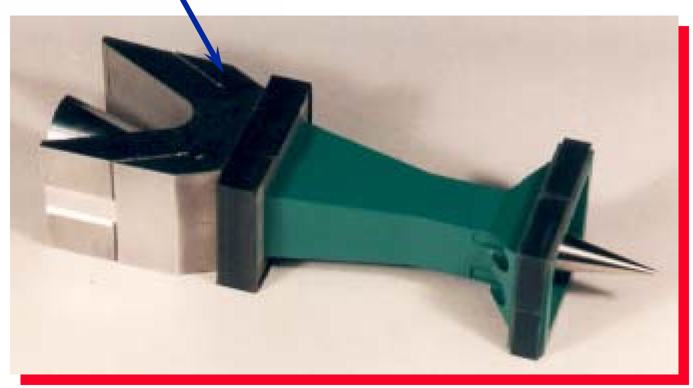
EM Railgun





For velocity > 3 km/s a plasma armature is used.

Firing similar to coilgun – near equator, at high altitude, and from an evacuated launch tube.

Graphics courtesy of IAT

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Railgun Launcher

- **For 1,250 kg launch mass at 7,500 m/s:**
  Launcher Length = 1600 m
  Tube Diameter = 1.1 m

- **Issues:**
  Structural integrity projectile and launcher
  Rail life
  Pulsed power supply
  Switching
  Plasma armature performance

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Summary

Comparison of launchers:

	V_m (m/s)	M_{proj} (kg)	E_m (GJ)	L_{tube} (m)	A_{max} (kG)
Slingatron	8000	1000	32	D = 300 m	43
BWA	8000	1000	32	861	55
Coil Gun	7000	837	21	400	7
Railgun	7500	1250	35	1600	2

Conclusions:

- Achieving an 8 km/s muzzle velocity did not violate any laws of physics
- All had serious engineering and materials issues
- Significant research is required
- Facilitization costs would be high
- All are high risk