Kinetic Space Launch

With Emphasis on SpinLaunch

Bill Gutman January 20, 2023

Kinetic Launch

*** denotes technologies that are in use or are under discussion for application at Spaceport America**

- Definition: a launch in which projectile is imparted very high initial velocity and leaves the apparatus at maximum speed
- Can include
    - Conventional gun*
    - Light gas gun
    - Ram accelerator*
    - Rail gun*
    - Centrifugal accelerator*

Conventional Gun Launch

Notable Achievements

- German Paris guns of the WW I era achieved muzzle velocities of approximately 1600 m/s (5300 ft/s, 3600 mi/hr), 120 km range, apogee of about 40 km
- Gerald Bull and Project HARP achieved 3,048 m/s (10,000 ft/s, 6,818 mi/hr) muzzle velocity and apogee of nearly 170 km
  - Unfortunately, Bull sold his services to Iraq and was assassinated

Light Gas Gun

- Essentially an air rifle
- Low density gas guns have demonstrated exit speeds as high as 8.5 km/s (28,000 ft/s, 19,000 mi/hr, greater than orbital speed)
  - Have generally been used to research high speed impacts using small diameter projectiles
  - One is located at NASA WSTF
  - Concepts for space launch application have been explored

Ram Accelerator

- Resembles a conventional gun
- A projectile moving through a combustible gas mixture in a tube compresses the gas
- Gas mixture ignites behind the projectile
- Projectile accelerates as it rides pressure wave
- This is very similar to the operation of a ram jet engine
- Compared with a gun, tube must be much longer
- But, accelerations are smaller

Ram Accelerator

- Perhaps surprisingly, this technology is already in regular use for an entirely different application
- “Dumb” projectiles (typically concrete castings) are accelerated downward or horizontally to enhance drilling and tunneling
- A Spaceport America customer is the main developer
- The CEO comes from a mining family, but has worked for SpaceX and SeaLaunch

Rail Guns

- Essentially a linear induction motor
- Research by the Navy demonstrated exit velocities comparable to conventional guns

Centrifugal Accelerators

- SpinLaunch has explored the concept for several years
- Current state-of-the-art is the 33-m diameter centrifuge at Spaceport America

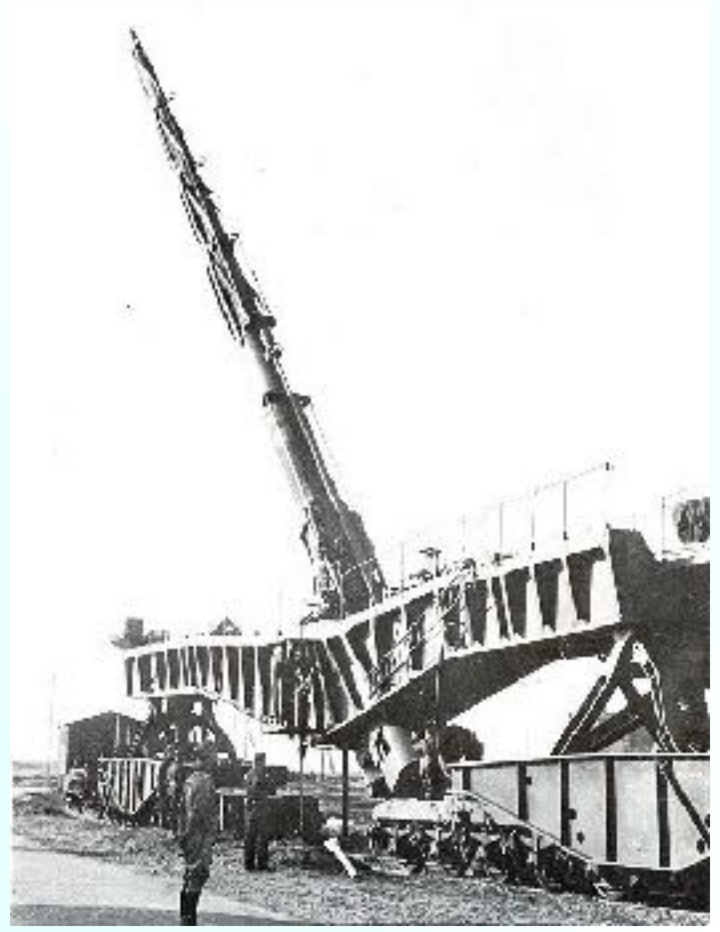
Issue Common to Kinetic Launch Systems

Essentially the definition of kinetic launch

- Highest velocity occurs at exit where air pressure is highest. Therefore
  - Dynamic pressure is highest
  - Drag is highest
  - Aerothermal effects are highest
- To my knowledge, no one expects to reach orbit with a kinetic system
- Companies do expect to exceed the Karman Line and to use the technology as the first stage of an orbital system
- Real payloads will require the protection of an aeroshell

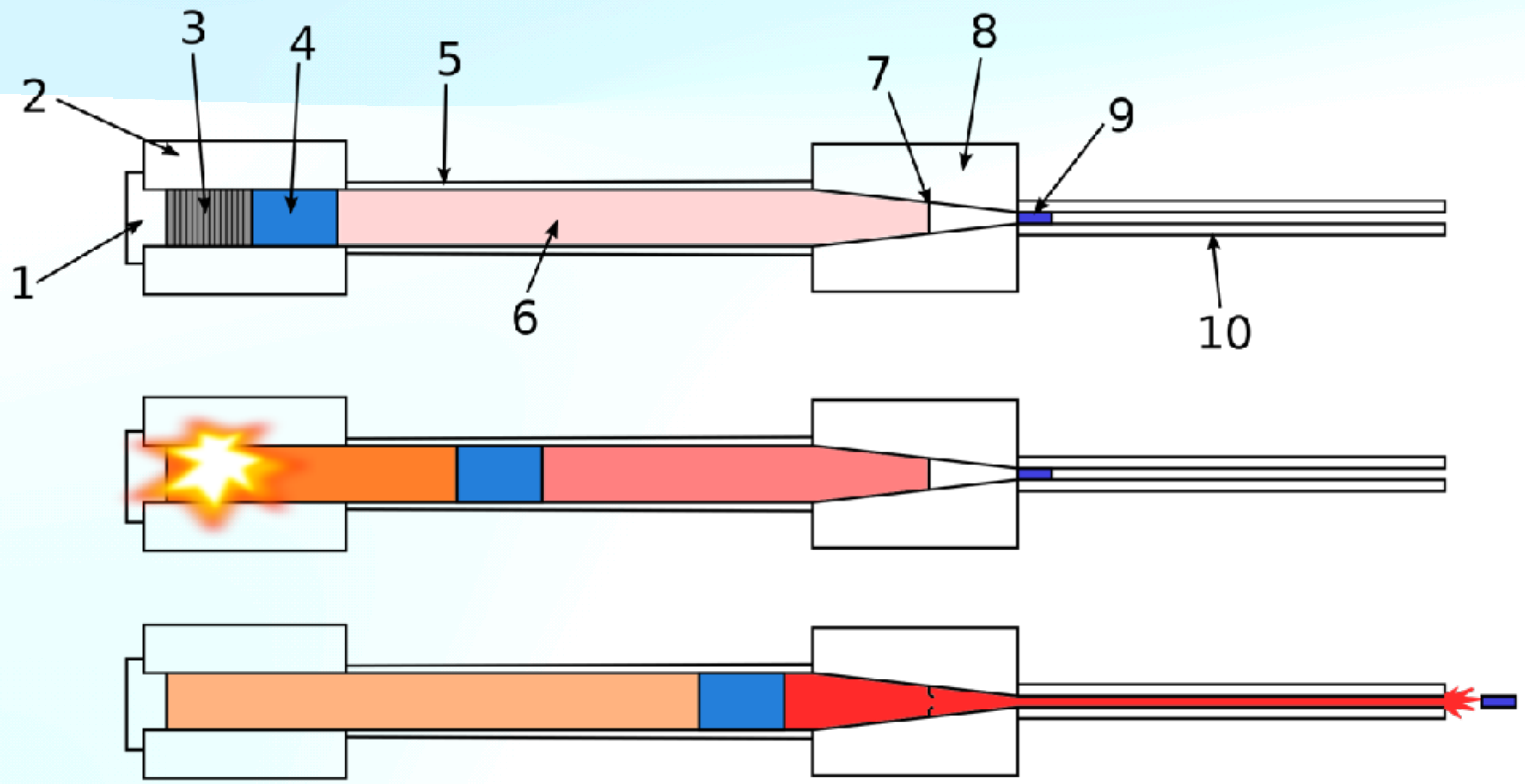
Issues with Conventional Guns

- High exit speed requires long, very heavy barrels
- Supplemental propellant charges may be required along the barrel
- Difficult to alter pointing
- Very high speeds cause rapid barrel erosion



Issues with Light Gas Guns

- Similar issues with conventional guns
- Typically use an explosively driven piston to compress the working gas



1 — Breech block
2 — Chamber
3 — Propellant charge (gunpowder)
4 — Piston
5 — Pump tube
6 — Light gas (helium or hydrogen)
7 — Rupture disk
8 — High pressure coupling
9 — Projectile
0 — Gun barrel

Issues with Ram Accelerators

- A means must be provided to inject the gas mixture into the tube
    - For optimum performance, gas mixture must vary along the tube
    - Projectiles must be placed at the bottom of the tube
        - For tunneling and drilling, tube can be breech loaded
        - For space launch, it’s hard to see how muzzle loading can be avoided
        - A means is required for initial acceleration to achieve ram ignition
- Typically, tube would be recessed into the ground—think well casing
    - Repointing not feasible
    - A separate tube likely would be required for each desired trajectory.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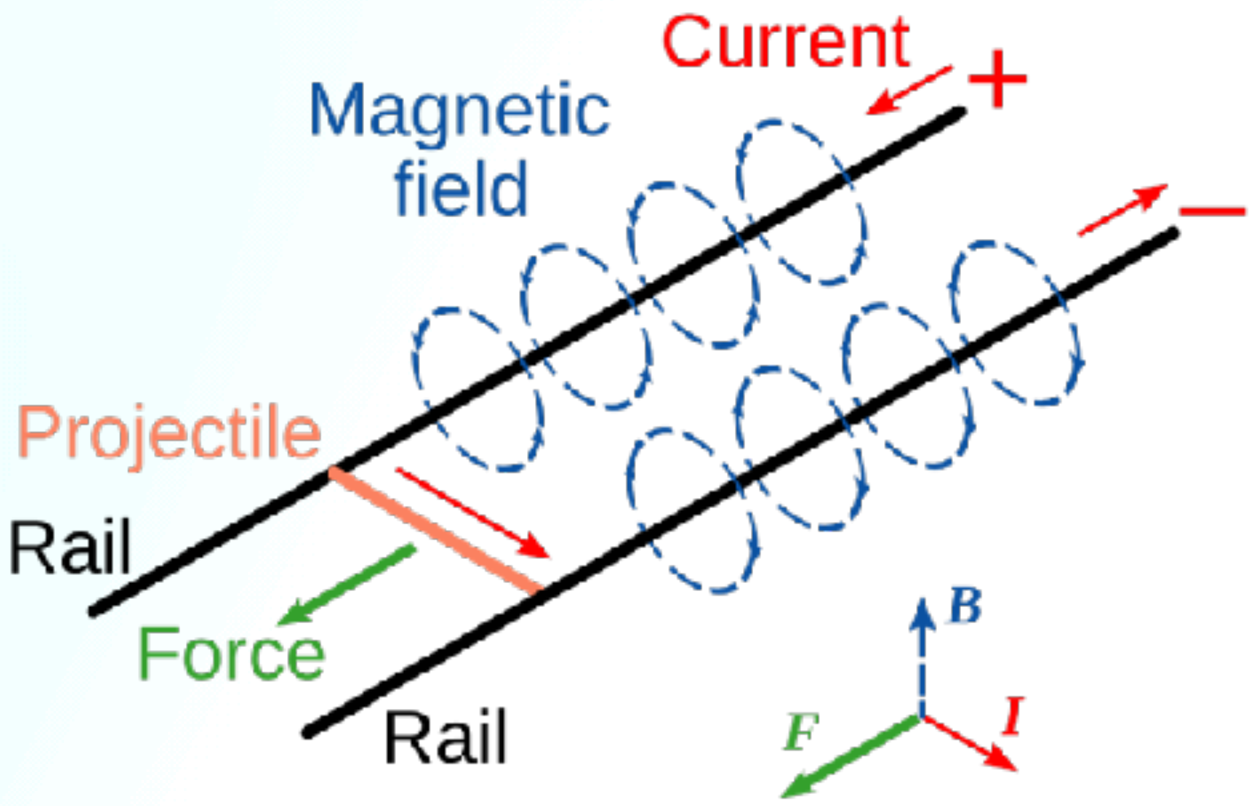
Issues with Rail Guns

- Very long “barrels” would be required, but feasible
    - Very large currents are required
        - Energy would be measured in MJ over times in ms
    - Very precise current control is required
    - Support structure (“barrel”) must be constructed of non-conductive, non-magnetic materials, but must be very strong



Issues with Centrifugal Accelerators

- Projectile is continuously subjected to centripetal acceleration from spin up to release
- The tether requires very high tensile strength
- High tangential speeds with acceptable aerothermal heating levels can only be achieved in a reasonably hard vacuum
- There must be some type of seal between the atmosphere and the chamber
- Inrushing air after release must be dealt with
- To avoid destroying the internal mechanism on every shot, there must be a counter weight that is released simultaneously with the payload
- The release mechanism must have very precise timing
- The plane of rotation of the centrifuge constrains the launch azimuth

Centripetal Acceleration Issue

- A local know-it-all claimed in a Facebook post that this is impossible because only solid materials would be able to withstand the g-forces
- The centripetal acceleration for a body in uniform circular motion at radius r moving with tangential speed v is given by
- $a_c = v^2/r$
- For the SpinLaunch accelerator at Spaceport America, the goal is to reach at least Mach 5 (about 1650 m/s) and r is 16.5 m
- Therefore, $a_c = 1.65 \times 10^5$ m/s^2 = 16.8 k-gs
- This g-level is fairly easy to harden against
  - By the end of WWII, the Allies were using antiaircraft and artillery shells with vacuum tube electronic proximity fuzes which survived linear and centripetal accelerations on the order of 40 k-gs

Centripetal Acceleration Issue

The other part

- At 16.8 k-gs, at the end of the tether, the tensile force on the tether, assuming a 100-kg projectile, is
- F = ma = 100 kg x 1.65×10^5 m/s^2 = 1.65×10^7 Nt = 3.71×10^6 pounds
- This would require a steel bar of about 10-inch diameter, and does not even include the contribution of the tether itself. Strength-to-weight ratio requirement is a challenge.
- Therefore, high tech materials are required
- As of late 2022, the carbon fiber composite tether in use was good for about Mach 2, and improved tether was under development
- To achieve higher speeds, the radius of the accelerator can be increased as the only practical method to help with tether tensile strength requirements. Hence the 100-m orbital launch system.

Aerothermal Heating and Drag Issue inside Centrifuge

- For current experiments, pressures of 1-3 millibars are acceptable
- As tangential speeds increase, better vacuum will be required
  - A very good vacuum certainly will be needed for an orbital system

Atmospheric Seal and Inrushing Air Issues

- During spin-up and up to release, vacuum integrity of centrifuge chamber must be maintained
- SpinLaunch accomplishes this with a breakable membrane
- Once seal is broken, air rushes in
  - This subjects the still turning tether to drag and aerothermal effects
- Rapid acting baffles deploy in the exit tunnel to impede air inrush
- Simultaneously, a fast acting braking system is activated
- Both the sudden drag and the braking subject the tether to shear forces, which much be designed for as well as tensile forces

Atmospheric Seal Issue and Inrushing Air Issues

Continued

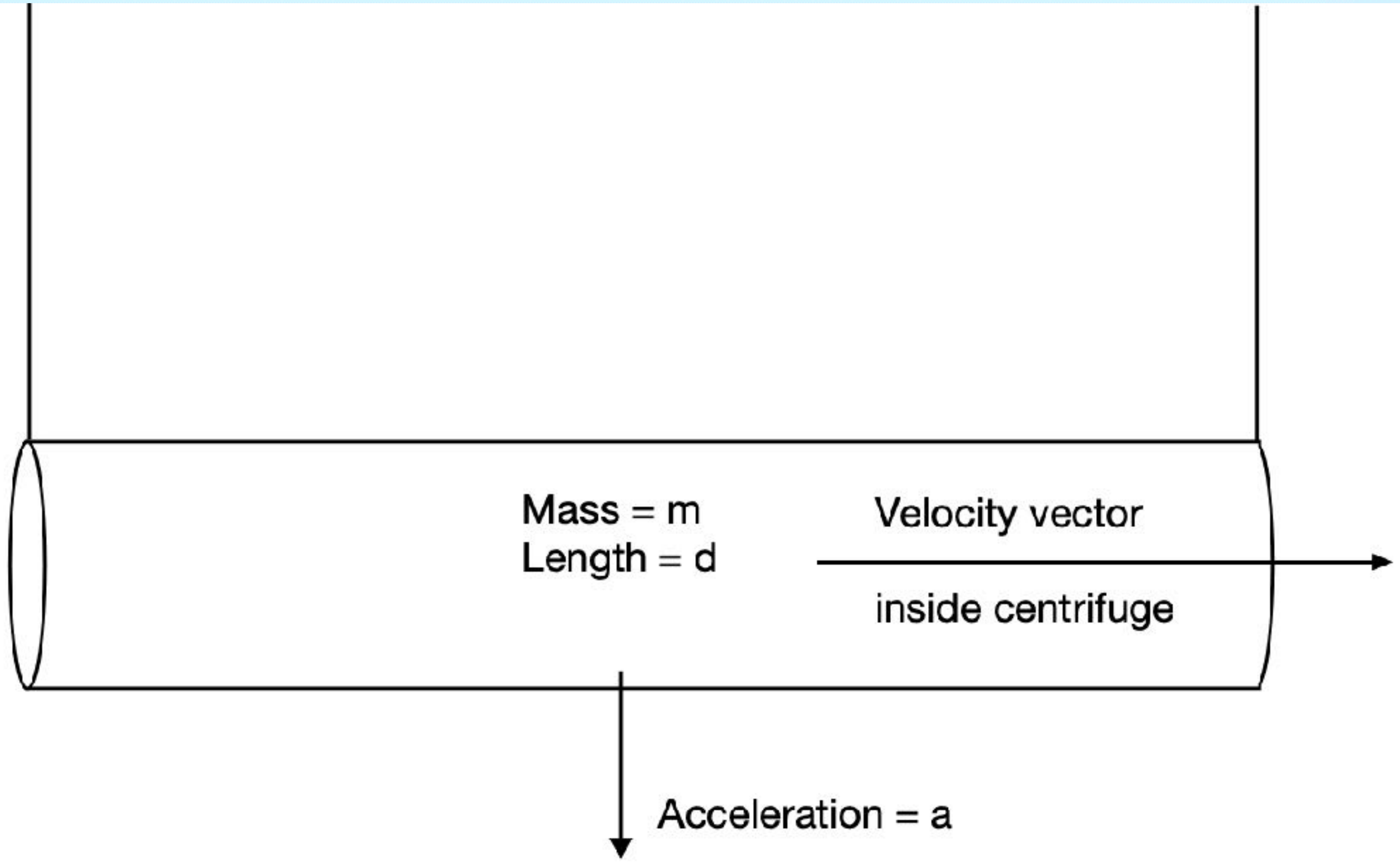
- SpinLaunch uses a polymer material that is attached to the end of the exit tunnel via a flange
- The details are proprietary, but the material resembles several layers of thick polyester (Mylar) film
- After a flight, there is a snow storm of plastic shards

Counterweight Requirement

- To maintain balance, and thereby keep the system from shaking itself apart, a counterweight must be released simultaneously with the projectile
- Consequently, there must be a robust catchment fixture internal to the chamber
- The nature of this fixture is among the more protected proprietary information

Release Mechanism Timing Issue

- To me, this appears to be one of the most difficult problems to solve
- To maintain orientation of the projectile within the centrifuge, it must be suspended at at least tow points
- Suppose a uniform metal bar is being accelerated via a force applied with a simple two-point suspension at the ends



The angular acceleration is given by

$\tau = I_c \times \alpha$

or $\alpha = \tau / I_c$

For the case shown, I_c is approximately 1/3 md^2
The torque is approximately amd/2

Suppose a = 5000 gs = 4.9×10^4 m/s^2, d = 3 m, and m = 100 kg
Then, $\alpha = (4.9 \times 10^4 \text{ m/s}^2 \times 50 \text{ kg} \times 1.5 \text{ m})/[1/3 \times 50 \text{ kg} \times (1.5 \text{ m})^2]$
$= 8.2 \times 10^4$ rad/s^2

Suppose there is a 1 ms delay from the release of the first tether connection to the second

Then the angular rotation between releases is

$\varphi = 1/2\ \alpha t^2 = 0.041$ rad = 2.3 degrees

This would be a very large angle of attack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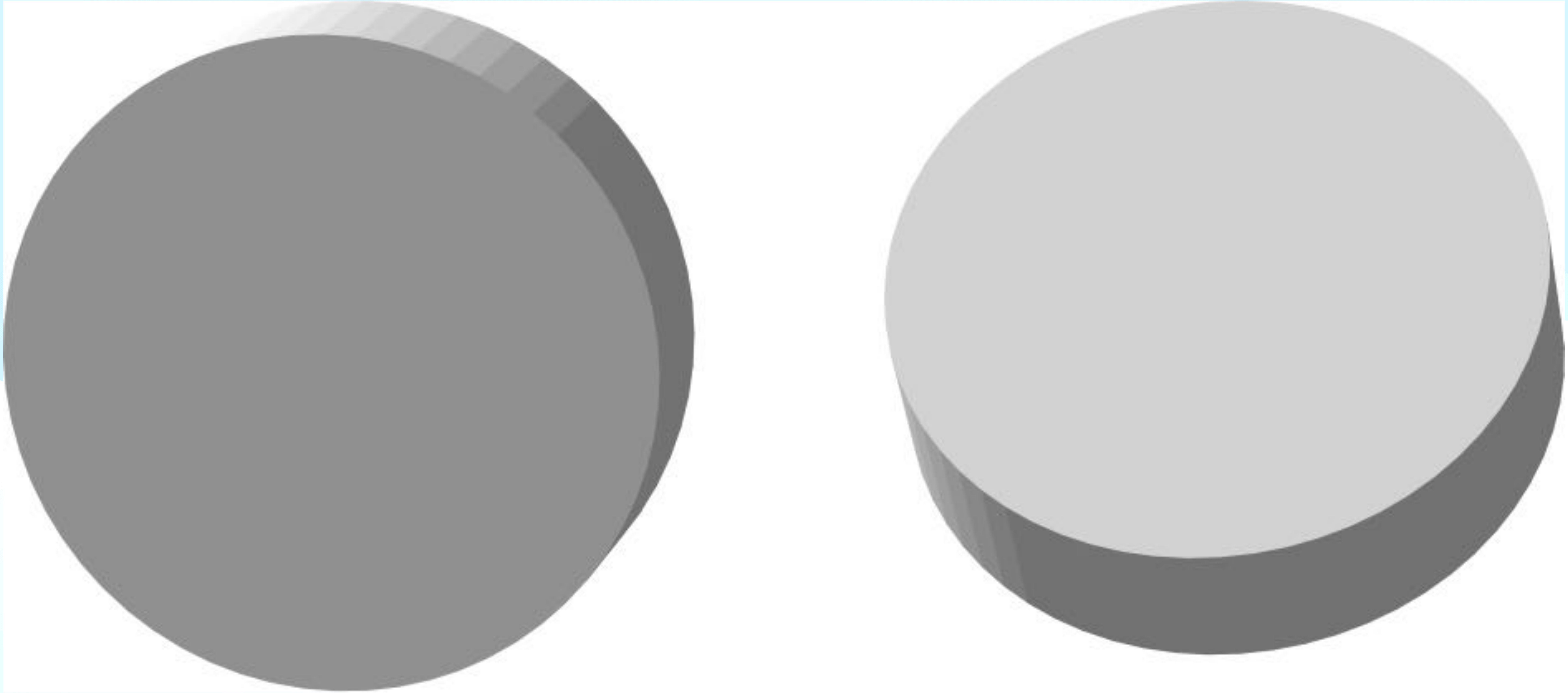
FLIGHT TEST #8
First on-board footage

Angle of Attack

- A substantial angle of attack can clearly be seen in the preceding videos
- In the second video, angular oscillations damp fairly quickly
  - But by then, substantial loss of energy has occurred
- The angle of attack problem must be dealt with

Constrained Launch Azimuth Issue

- As installed at Spaceport America, the centrifuge can be rotated about its horizontal axis to vary the exit elevation angle
  - Most shots have been conducted at about 88°
  - One shot was conducted horizontally
- The azimuth angle is fixed
- For an orbital system, the orbital inclination could potentially be adjusted by rotating the centrifuge about its rotational axis if the rotational axis is tilted
  - This would also affect the elevation angle of the initial trajectory, leading to complex orbital mechanics calculations and trade-offs
- The most straightforward (but expensive) solution would be to have a centrifuge for each desired inclination



Fun Facts about SpinLaunch's SA Facility

- The centrifuge weighs about 2.5 million pounds
- The total weight of the centrifuge and support is about 3.5 million pounds
- The steel is mostly 3 inches thick, but up to 6 inches think in crucial areas
- It requires 4 MW to power the centrifuge and pumping system
- It can spin up to Mach 1.5 in 10-15 minutes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FLIGHT TEST #7
An inside look


#10
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