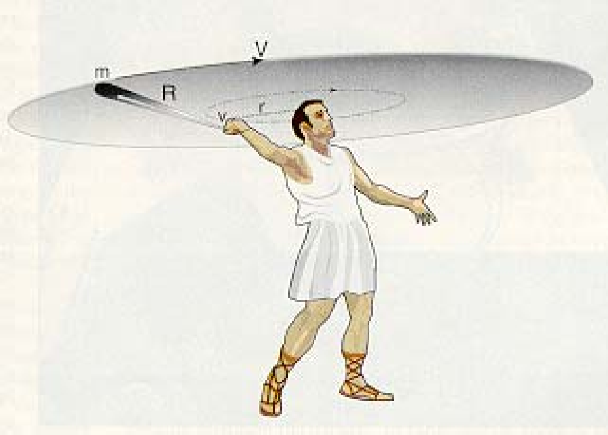
SLINGATRON OVERVIEW

Briefing to Air Force Future Concepts, July 12, 2005



by

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Team: Northrop Grumman, ALCorp, HyperV

Outline

- Dynamics ------------------Spirals, Circles, Hybrids
- Mechanics ------------------Small Test Ring
- Projectiles, Sliding Friction ---- Expt. & Theory
- Defense Machines----Table of Sizes for values of m_{proj},V
- Global Reach Machines and Space Launch

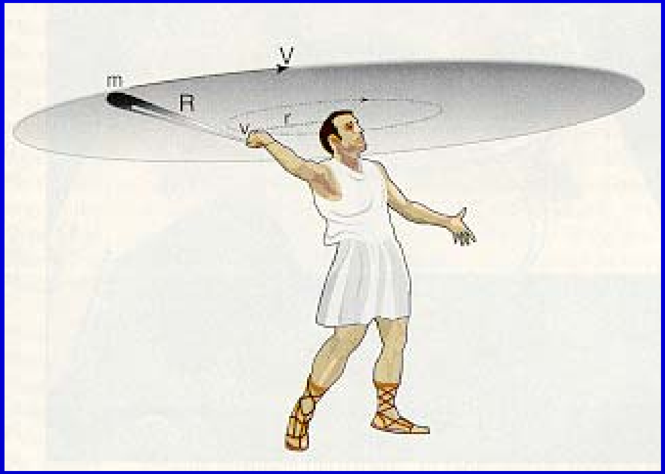
CONSIDER A CLASSICAL SLING

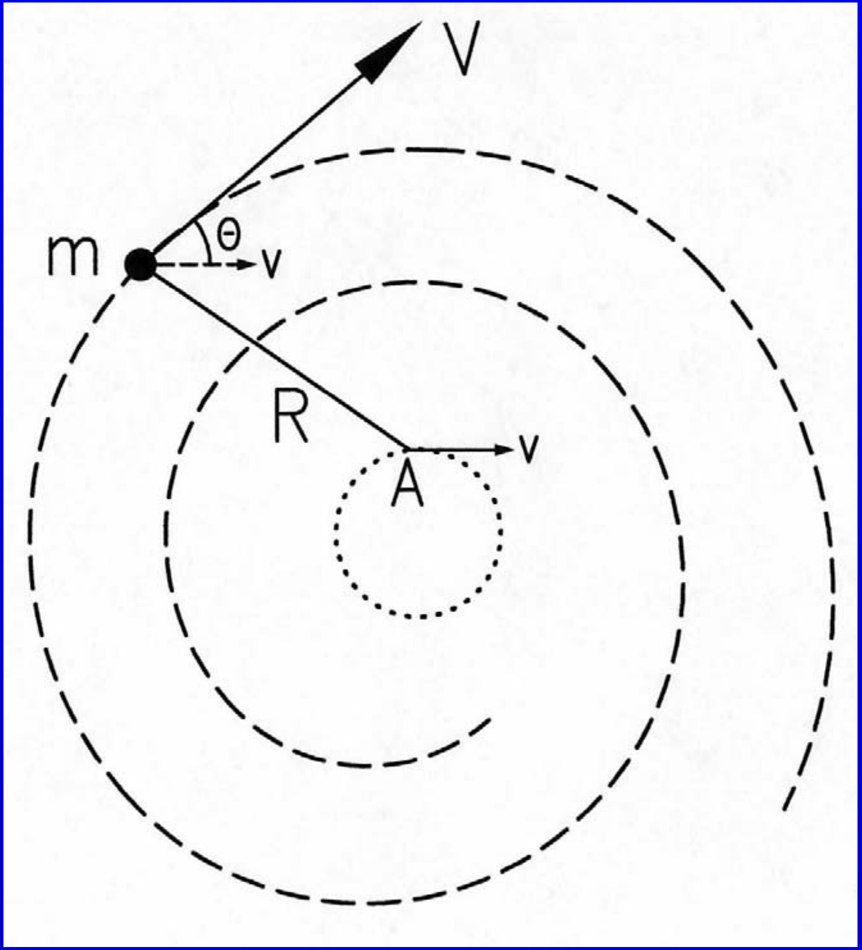
With <u>Constant Frequency f</u> and growing string so $V = 2\pi Rf$

Power $\cong (mV^2/R)v\sin\theta$

It's Phase Stable !

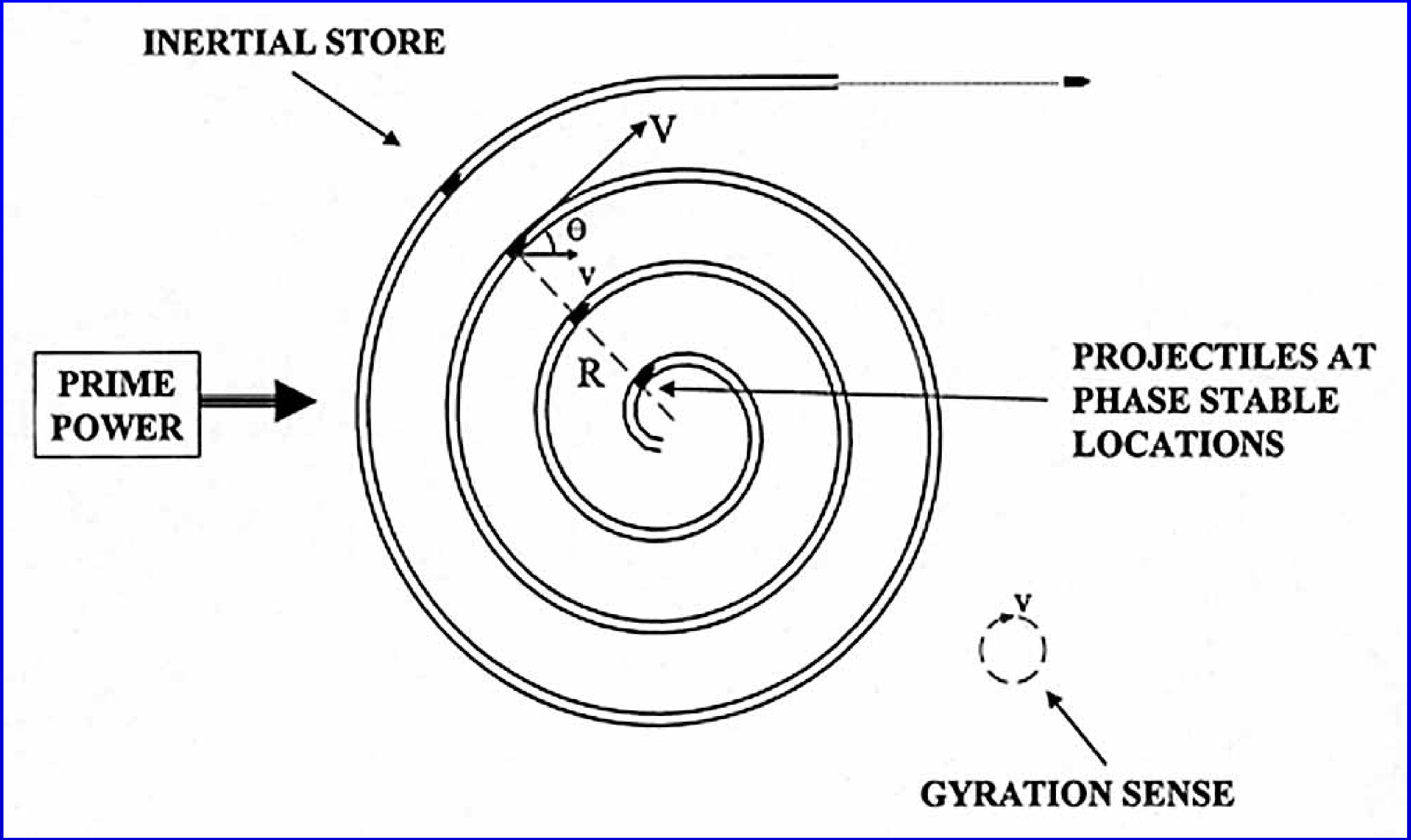
ΔV per turn $\cong 2\pi v\sin\theta$





<u>BUT</u> STRING BREAKS: $mV^2/R = (2\pi mf)V$

SAME SLING DYNAMICS V ~ 2πRf
SWING SPEED v = 2πrf AND PHASE STABLE



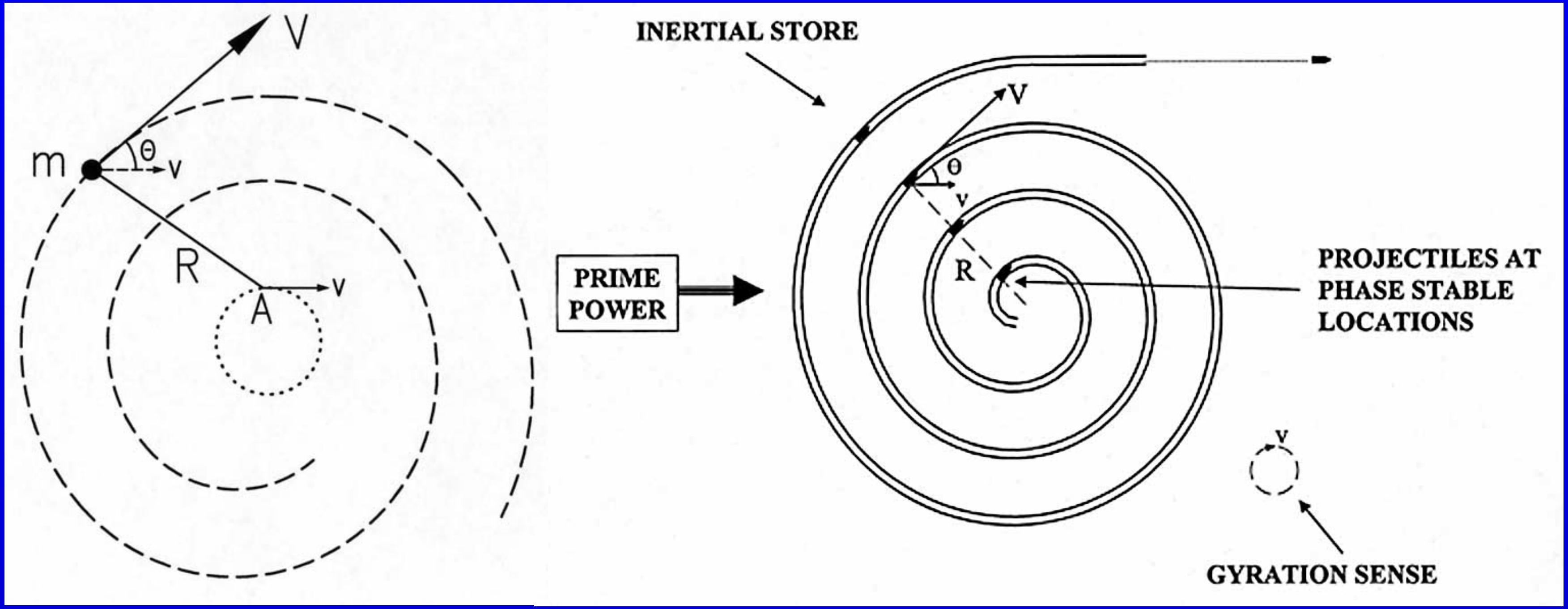
BUT Impulse/Unit Length $\cong (mV^2/R)V^{-1} = 2\pi mf$ = Constant

Tube survives even for constant wall thickness!

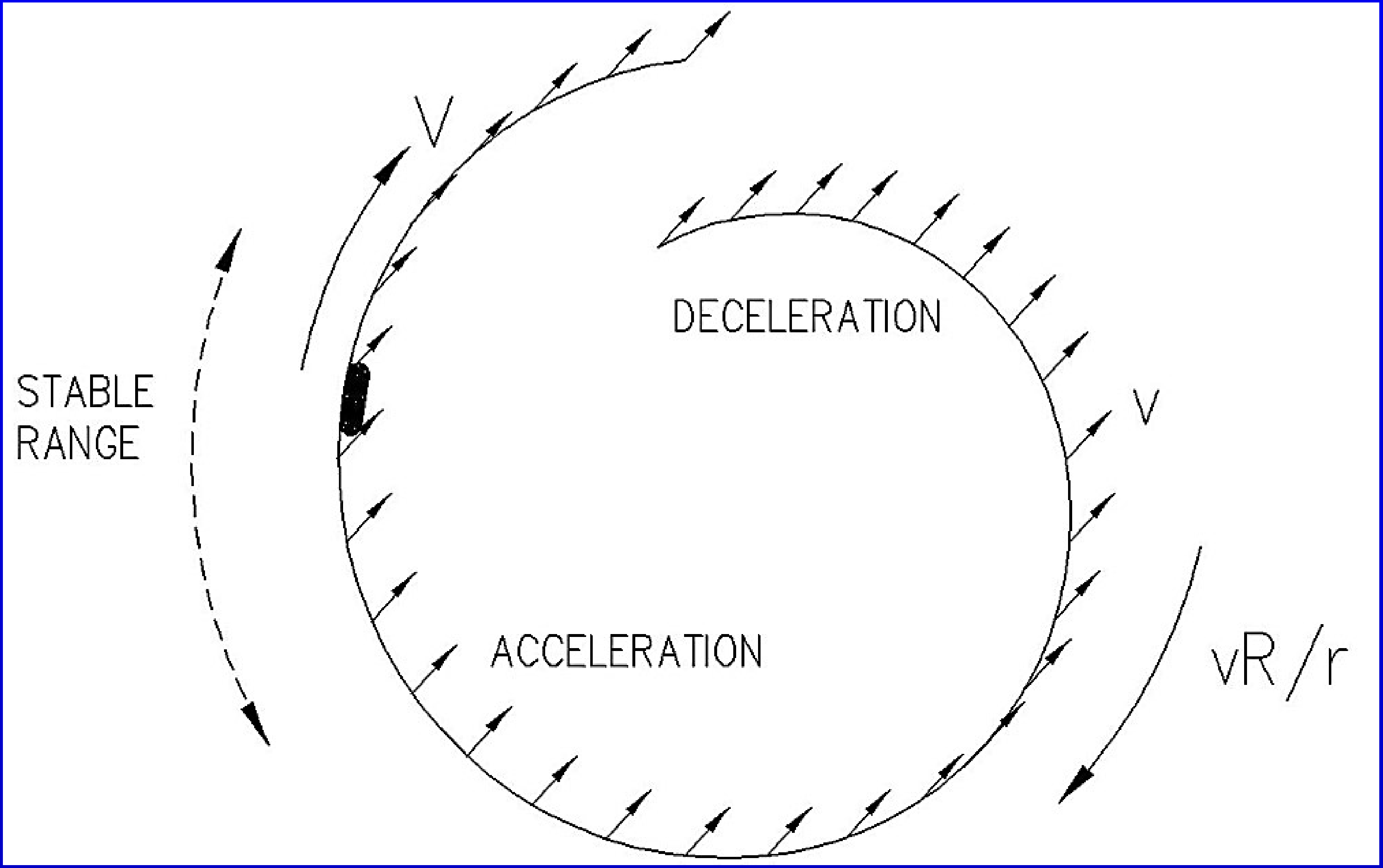
Projectile Stream now possible!

Note the Similarities

Constant Frequency Machine



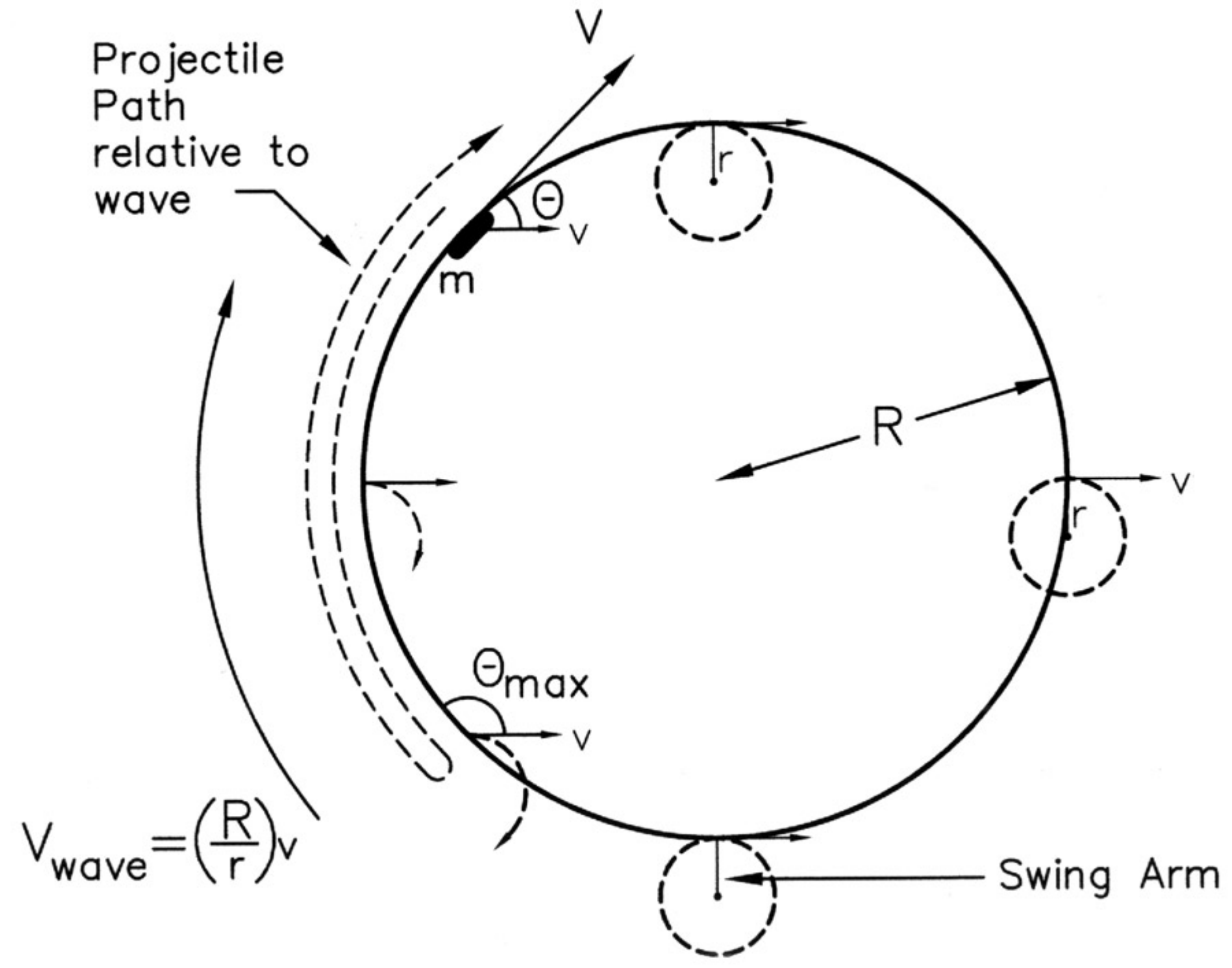
Centripetal Wave Travels Around Spiral at Speed $V = vR/r >> v$. V = speed of constant θ phase point. Can also phase swing.



Phase-Swing like a Surfer

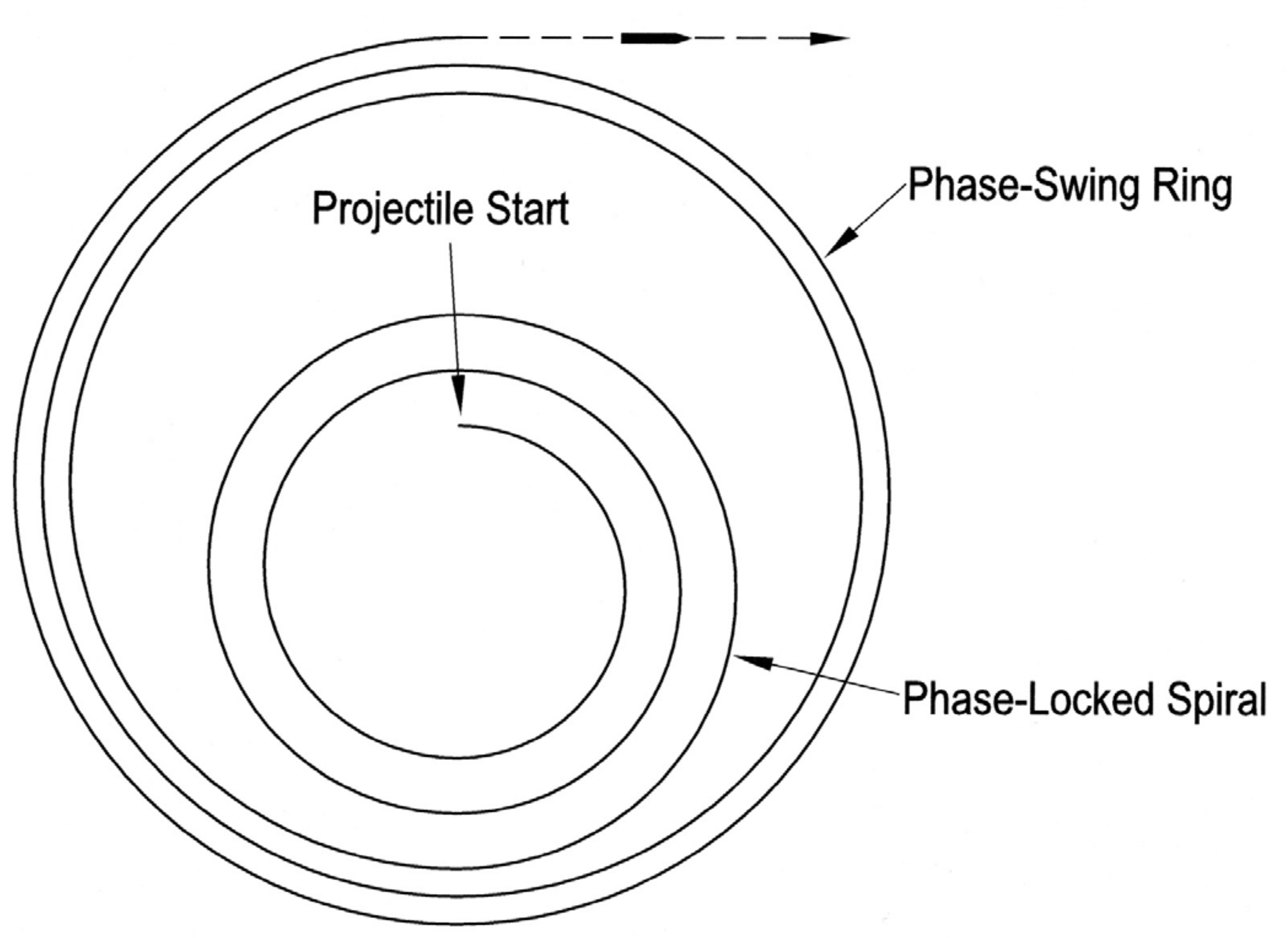
Projectile Phase Swing in a Few Circle Turns.

Up to 50% <u>SMALLER</u> R for given final speed, but needs injection speed. Fast wave "elastic collision" gives $\mathbf{2V_{wave} - V_{inject}}$



Minimize Diameter with Hybrid Design

A Combination consisting of a phase-locked spiral that feeds into an outer phase-swing multi-turn ring. Initial projectile speed at spiral entrance from simple release when breechblock swinging forward.



Approximate Equation for Acceleration

$$\frac{d}{dt}\left(\frac{1}{2}mV^2\right) \cong \frac{mV^2}{R} v\sin\theta - \mu V\frac{mV^2}{R}$$

$i.e.,$

$$\frac{dV}{dt} \cong \frac{V^2}{R}\left(\frac{v}{V}\sin\theta - \mu\right)$$

$$V(\max) = \frac{v\sin\theta}{\mu}$$

$$\mu = \mu(V, m_{projectile})$$

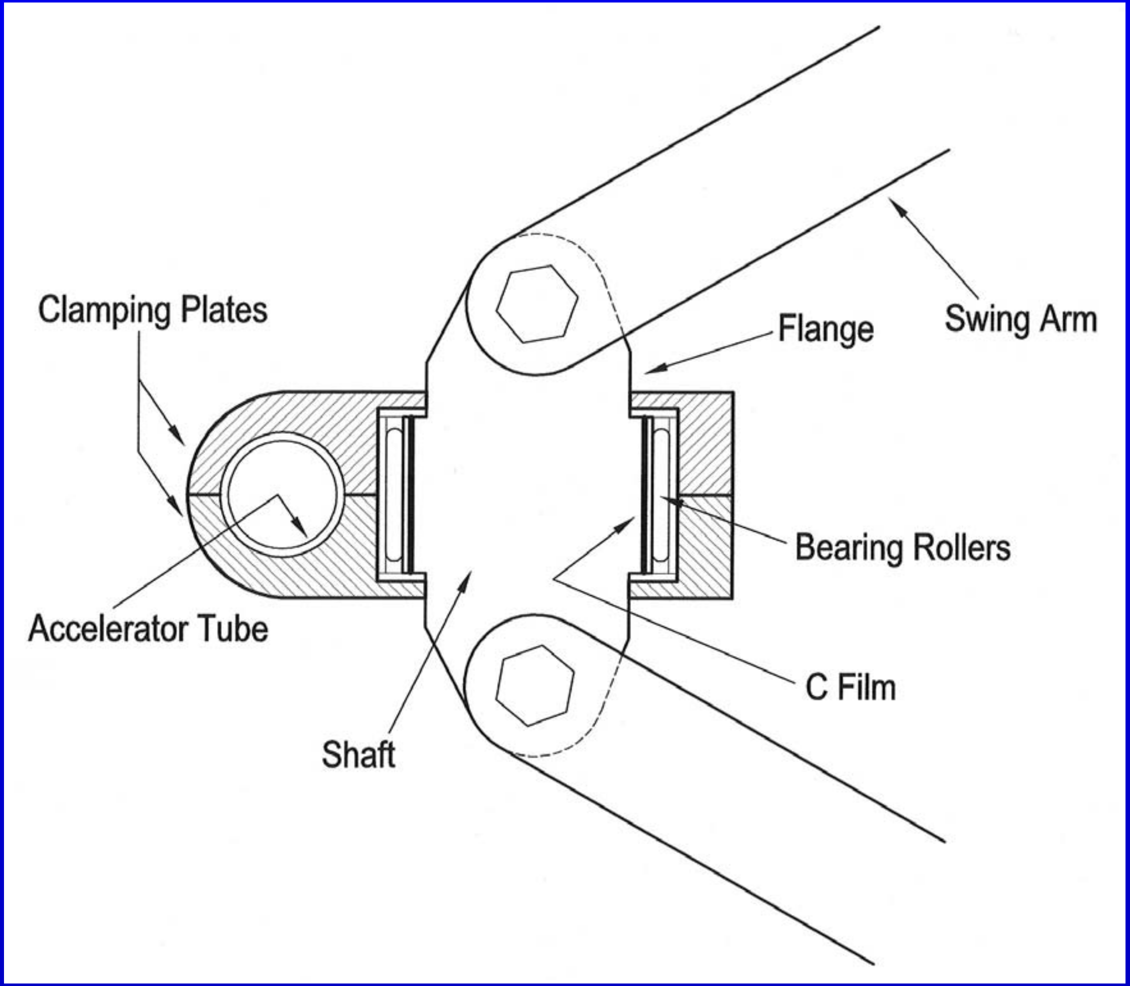
$$E.g., V(\max) = 100m/s \times 0.707/0.004 = 17.7km/s$$

<u>MECHANICS</u>: Must implement a useful gyration speed.
<u>SLIDING FRICTION</u>: Must have low sliding friction.
But Friction decreases for both high V and large m(proj)
due to formation of a gas bearing !

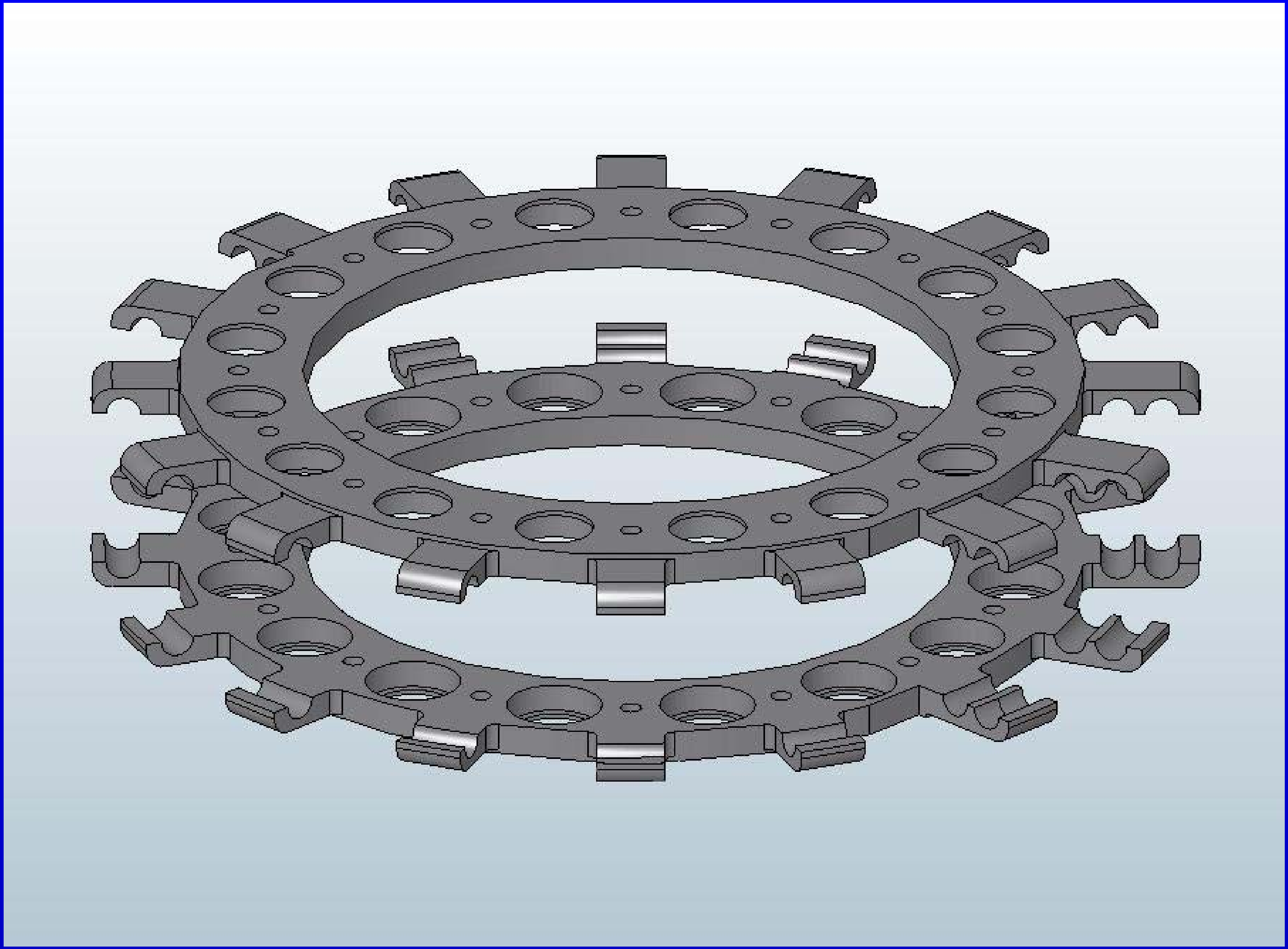
Small Components-Test Slingatron

Al Plates Capture Bearings, Tube, and Shafts. Load on Bearing Rollers = (outer race + rollers + clamping plates + tube segment).

C-Film provides a journal bearing in parallel with needle rollers for backup.

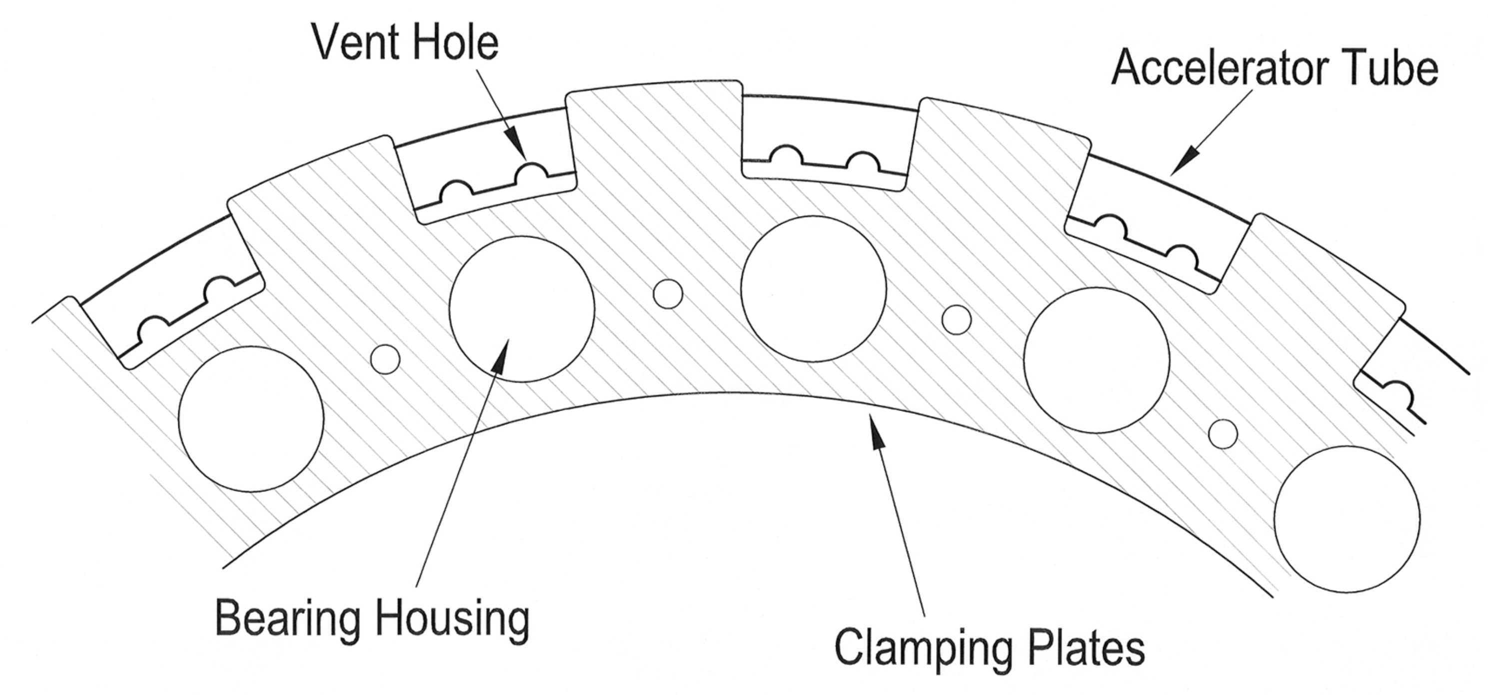


Exploded Clamping Plates for Test Ring

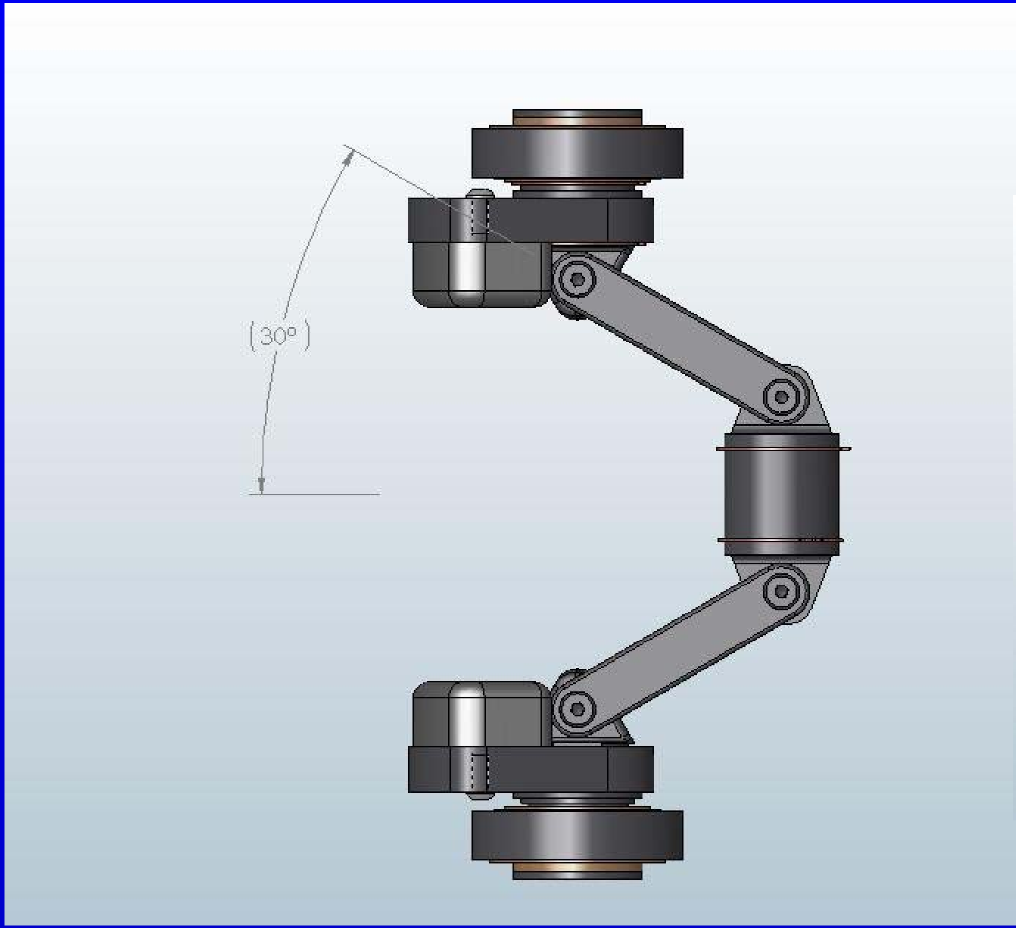


Assembled Test Ring, dia 2 ft

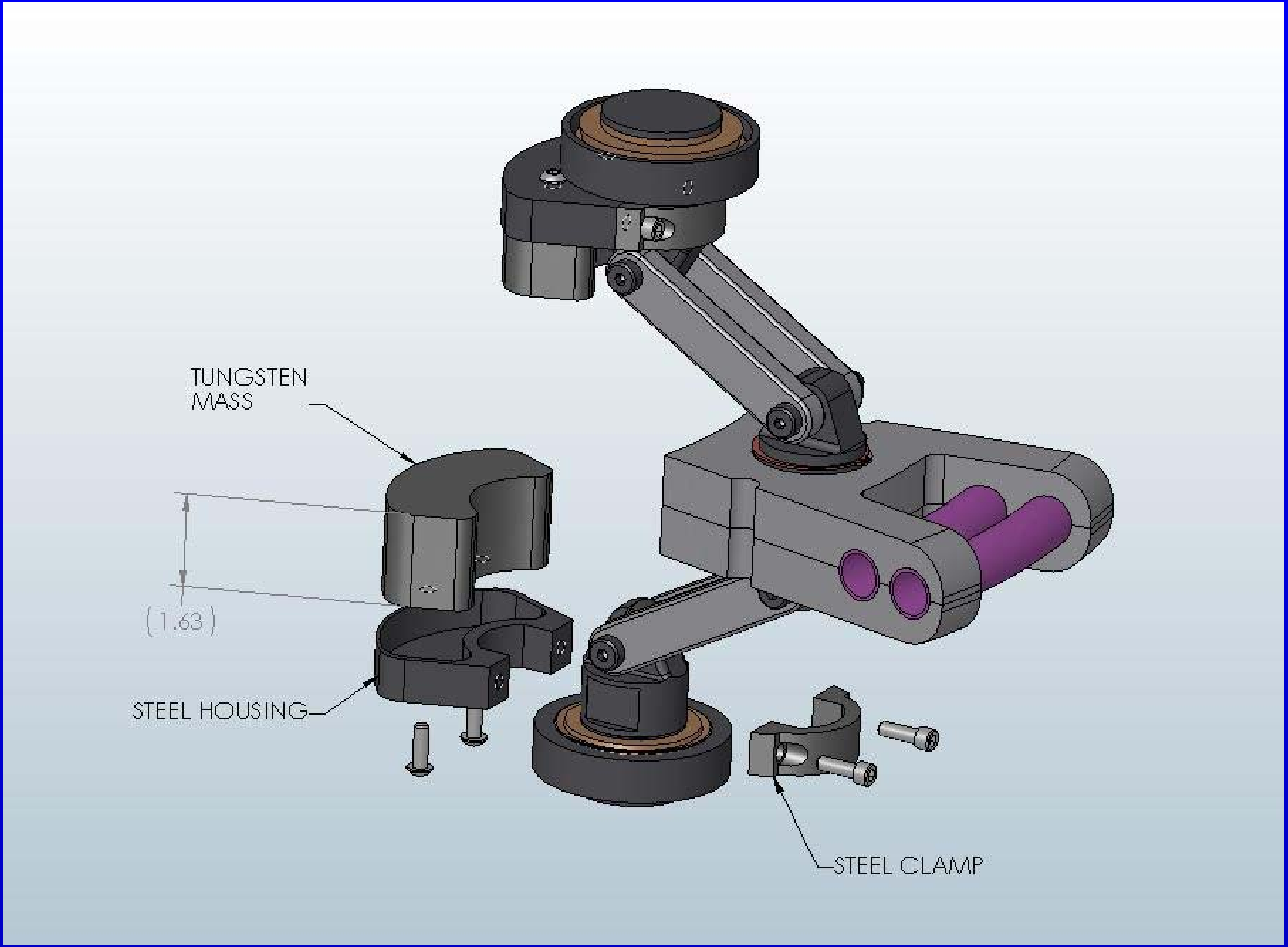
Venting of Projectile Bearing Gas



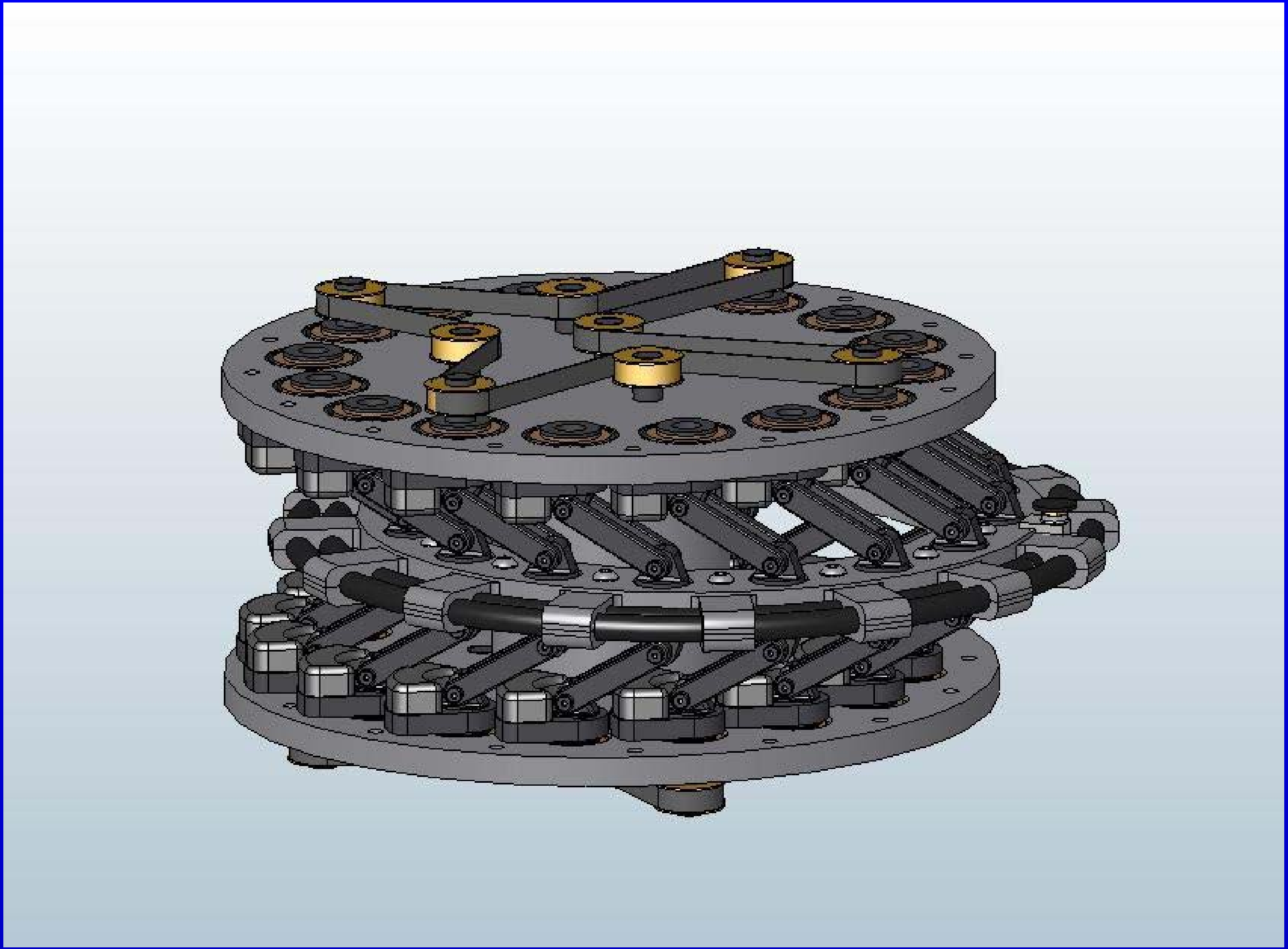
Swing Arm Pair with Counterweights



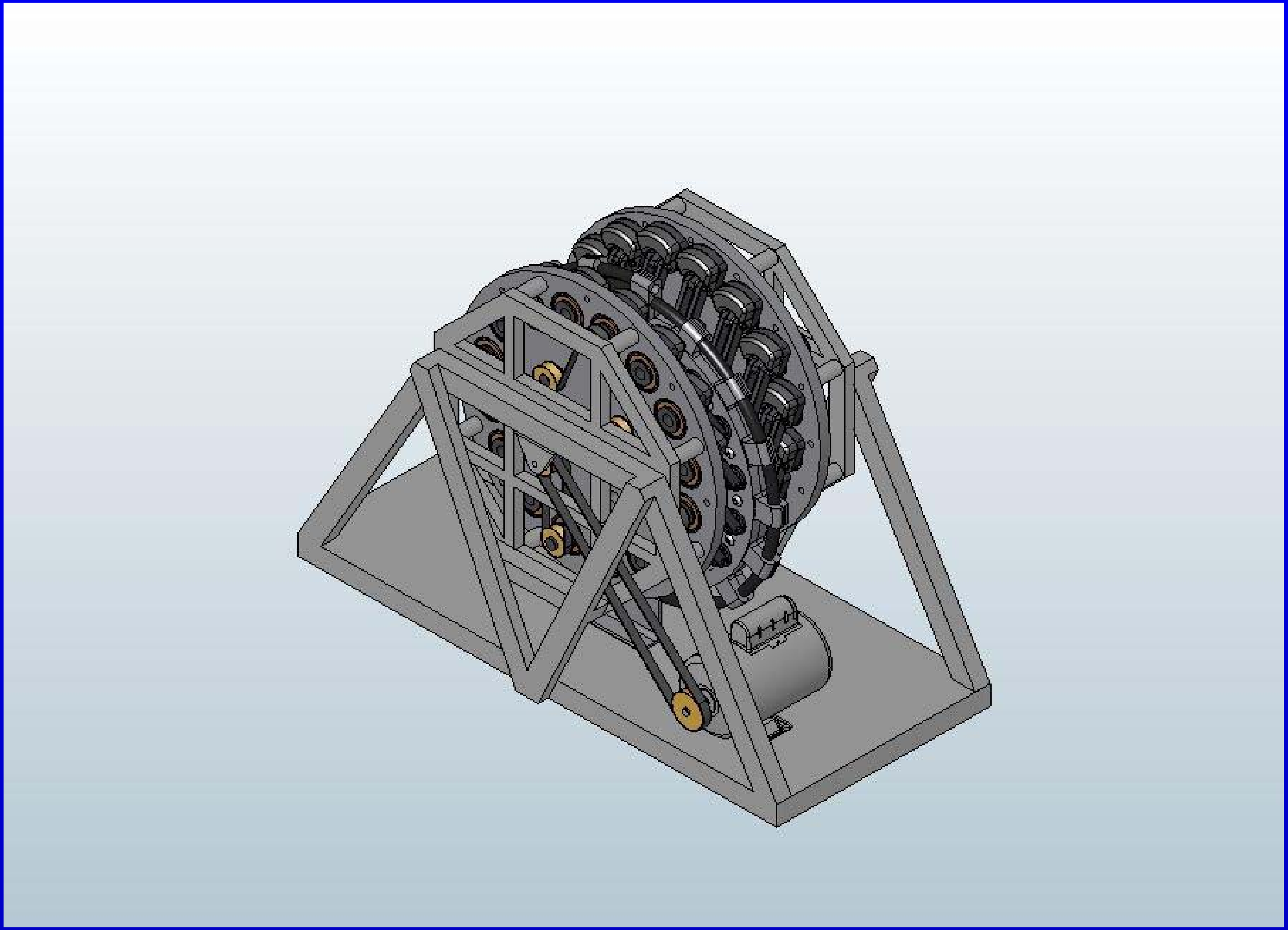
Swing Arm Pair with Counterweights



Components Test Ring

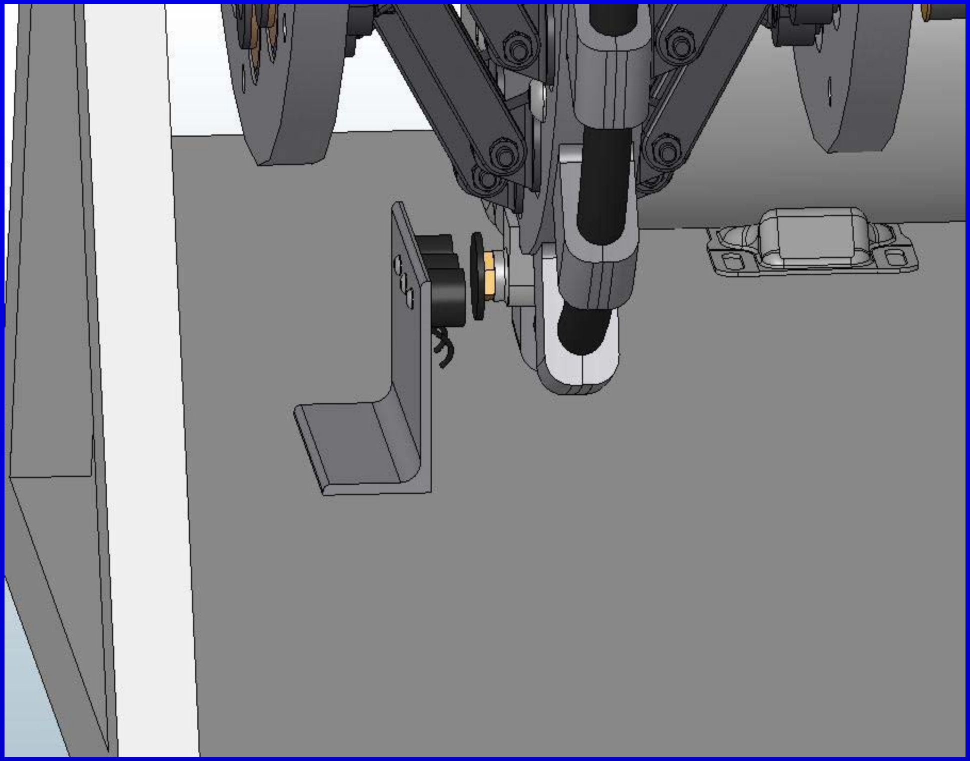


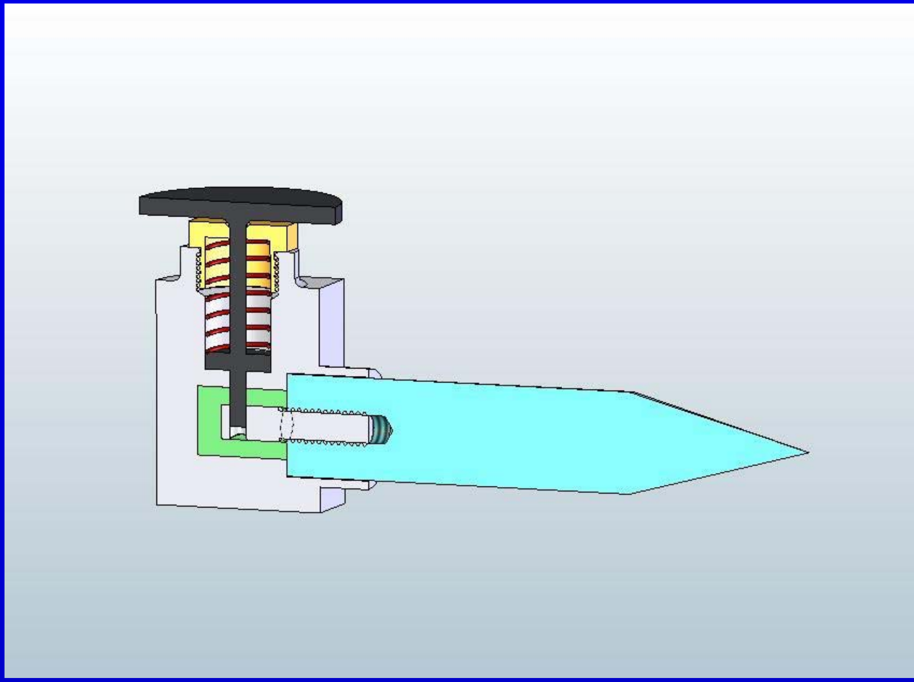
Small (dia = 2 ft) Slingatron Test Machine



Single Shot Projectile-Release

Startup provided by forward motion of breechblock. No other initial V needed. Feeds for Rapid Fire Stream discussed later.





Components Test Machine and a Follow-on Hybrid Machine for 20 lbs to 2.5 k/s

SMALL TEST MACHINE

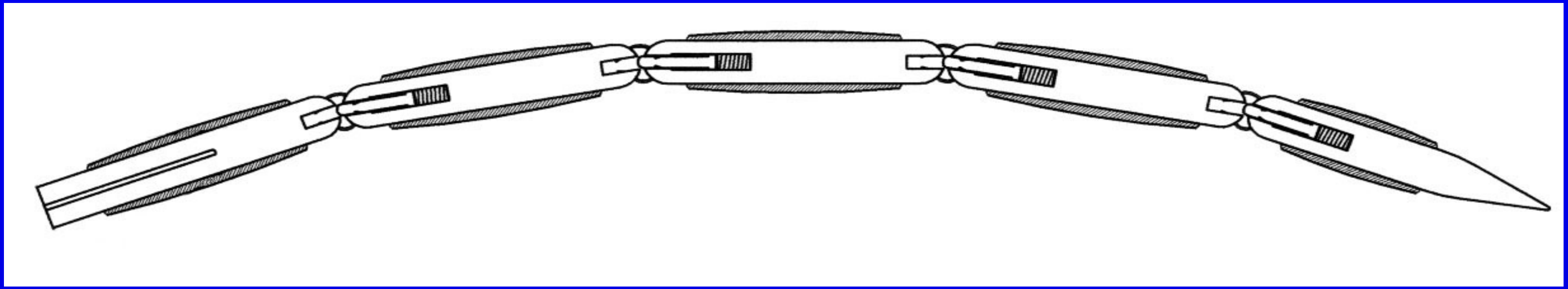
Ring dia 2ft. Projectile mass 0.5 - 1 lb. Swing r = 3.15 in. For Cronidur 30 brgs and Al plates, v(swing) ~ 50 m/s, and V ~ 340 m/s. Projectile tests including moderately large L/D.

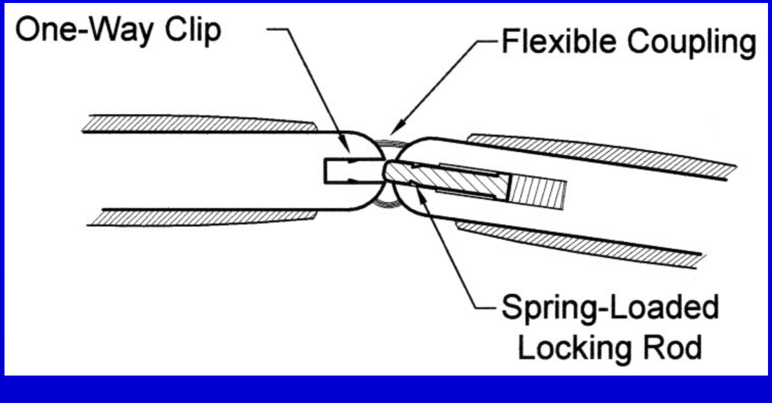
Continuous operation at 4,800 rpm with 50% rated load (assumed life measure L/L_{10}=0.08) gives a zero-failure lifetime of 3 hours (with reliability 90%) for 48 brg assembly. Machine will mostly idle with short visits to high rpm. Life ~ $(1/f)^{20/3}$.

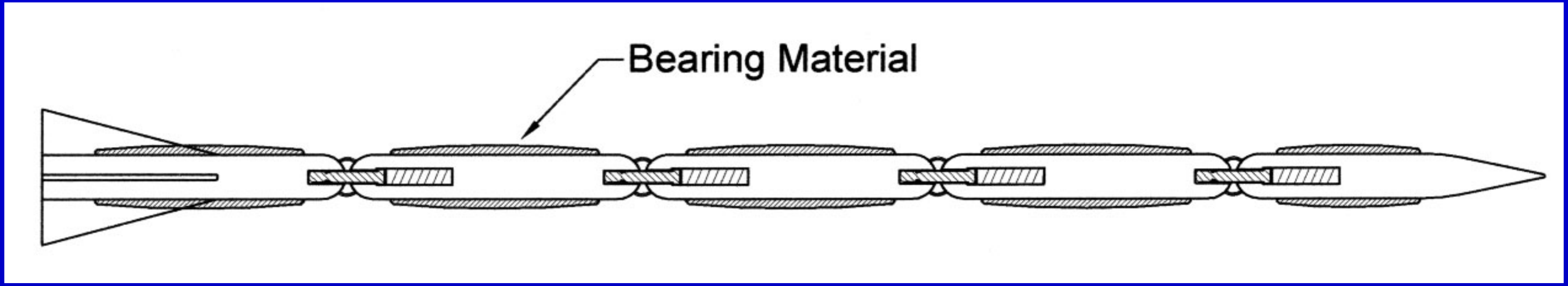
FOLLOW-ON MACHINE: Add turns in stages using modularized components. E.G., Choose bore so **m = 20 lbs**. Then **V = 2 km/sec** when **Dia = 8.7 meters**, and continue to add turns for more V.

WHAT ABOUT LARGE L/D PROJECTILES ?

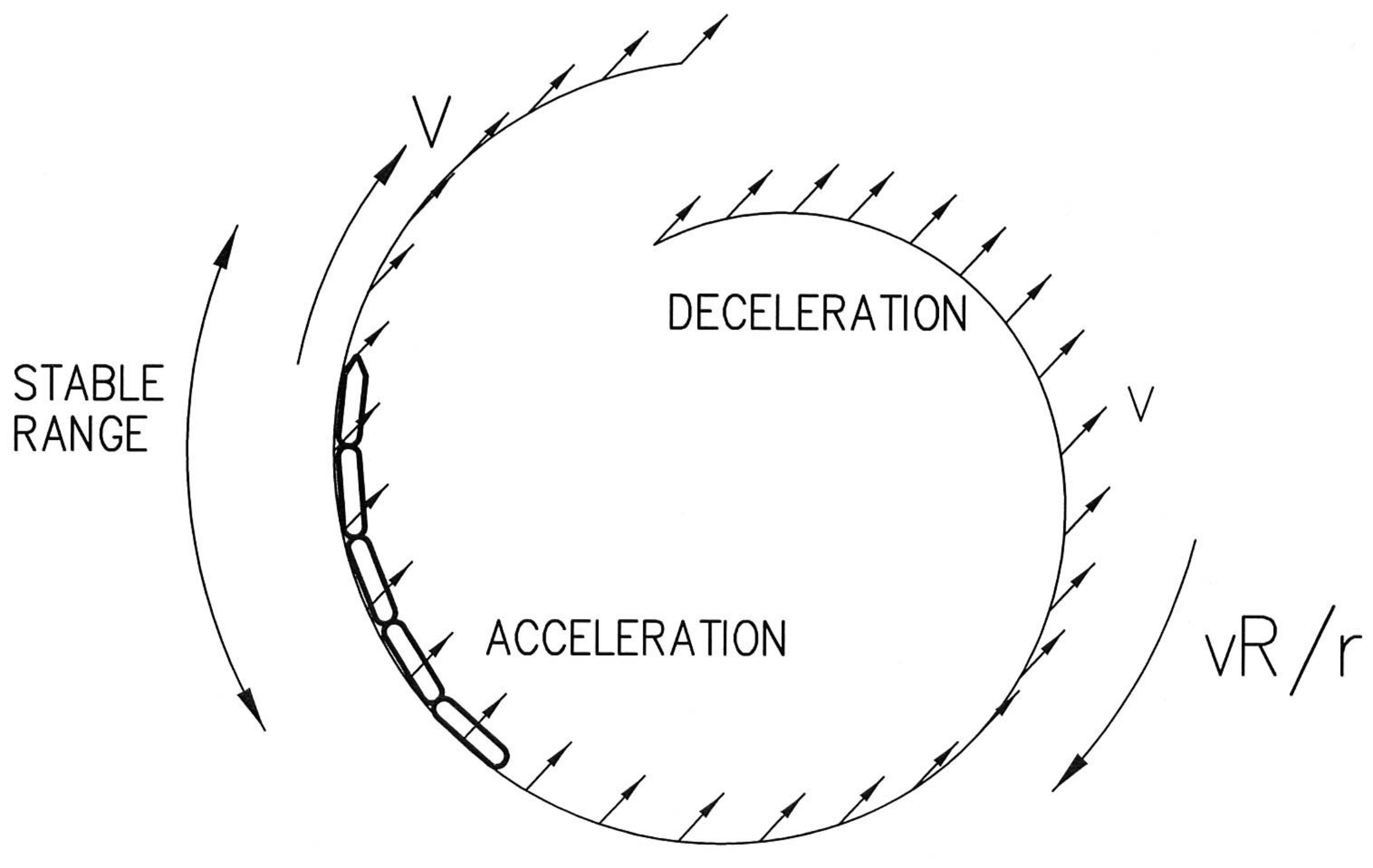
Spring-Loaded Rods Lock Segments into Straight Position as Traverse Straight Section of Tube at Exit. Large L/D stability tolerates some radial asymmetry as combustible bearing burns off in air flight.







A Large L/D Projectile in an inner turn. Accelerating Force is Distributed along Projectile. Equivalent to Sliding Downhill in Strong g. Can use a Smaller Bore Tube for a given Projectile Mass.



Exit Angular Dispersion

- Assume Projectile traverses a straight segment at exit equal to projectile length L_{proj} in a time $t_{exit} = L_{proj}/V$.
- Fraction of gyration period is,

$$\frac{t_{exit}}{t_{period}} = \left(\frac{L_{proj}}{V}\right)\left(\frac{v}{2\pi r}\right) \cong \frac{L_{proj}}{2\pi R_{exit}} \ll 1$$

- Design so exits when swing v parallel to projectile V so perpendicular kick proportional to

$$\left(t_{exit}/t_{period}\right)^2 \ll 1$$

High-V gyration dispersion < 10^{-3} rads.

BUT ALL LONG RANGE MISSIONS (GUNS OR SLINGATRONS) REQUIRE SMART PROJECTILES

Projectile Sliding Friction

Gas Film Provided by Evaporation of a Low Thermal Conductivity Projectile Surface Layer

Theoretical Model shows Larger Geometrically Similar Projectiles have:

(1) smaller High-V Sliding Friction Coefficient

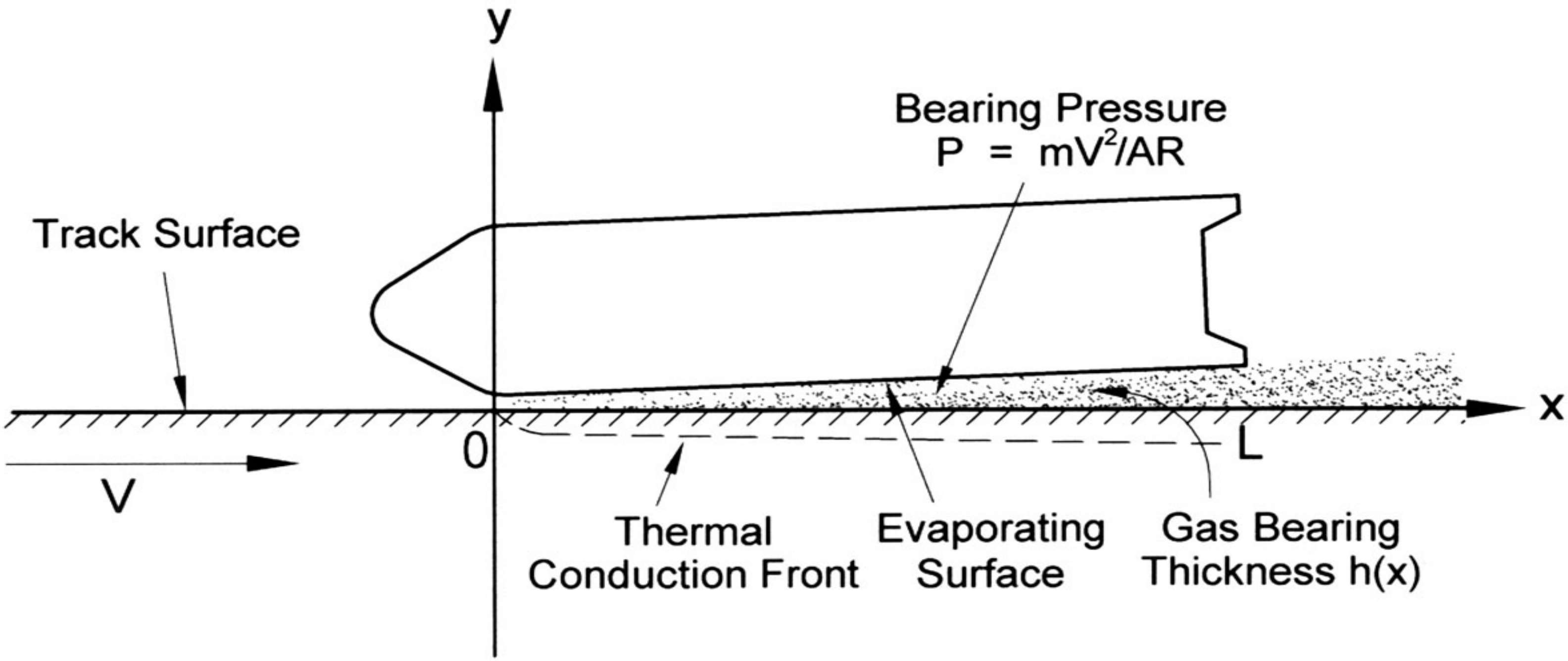
(2) smaller Fractional Mass Loss

(3) same track T increase immediately behind projectile

Sled Evaporation Supplies Gas Film for Low Friction at High V

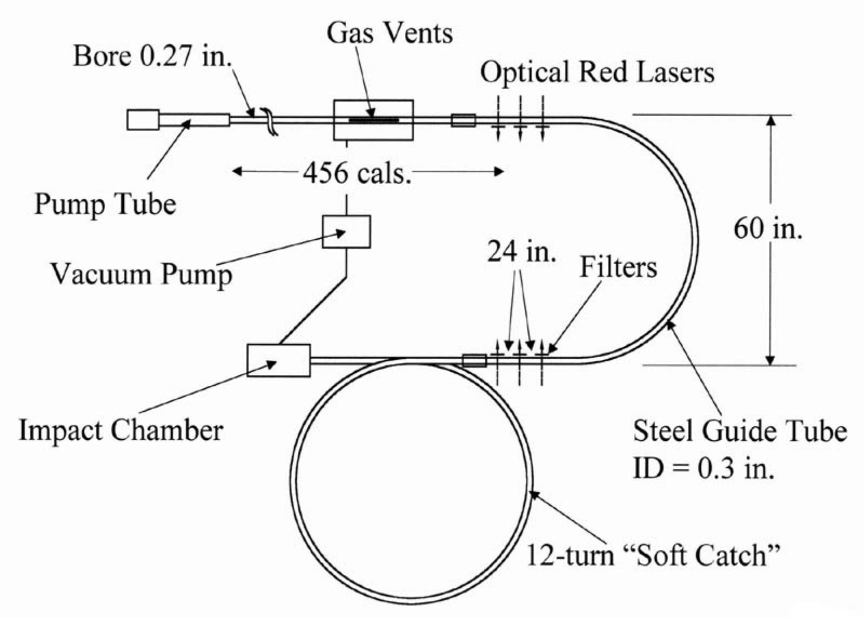
Larger projectiles →Smaller Friction (Thicker gas film)

Faster projectile → Smaller Friction (Hotter lower density gas film)



$$\mu = \left\{ \frac{\eta V \left(W + P \right)}{LP^2 (1 - f_{track})} \right\}^{1/2} \equiv \frac{1}{\sqrt{VLd\rho_{proj}}} \left\{ \frac{\eta R}{\left(1 - f_{track}\right)} \left[\frac{\gamma \left(\varepsilon_{evap} + \varepsilon_{dissoc} \right)}{c_s{}^2} + \frac{\gamma}{\left(\gamma - 1\right)} \right] \right\}^{1/2}$$

FRICTION EXPERIMENTS, 1999-2000



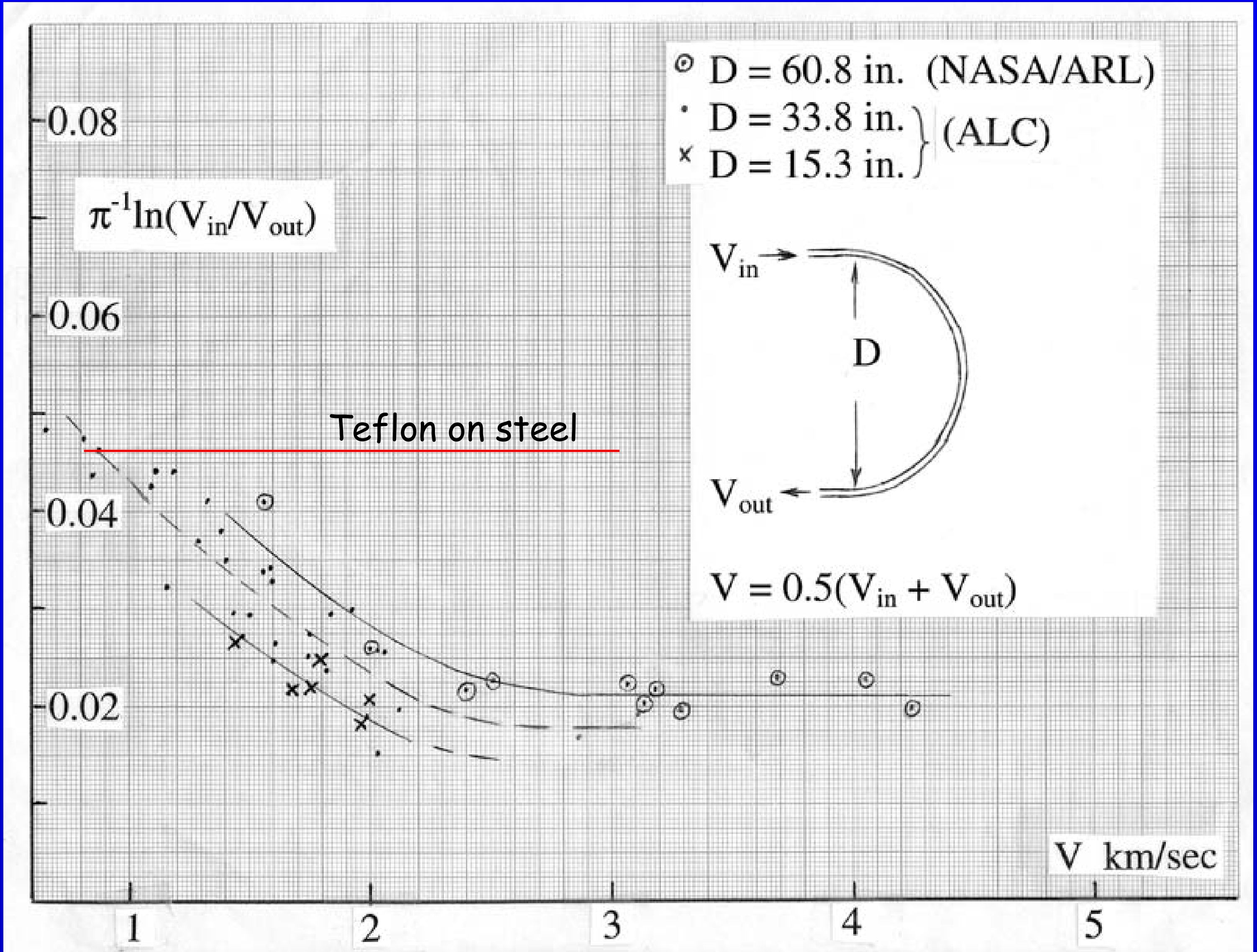
Two Stage
Light Gas Gun

Projectile Sliding Friction to ~ 2.5 km/s
Containment Data for ΔV ~ 10 km/s

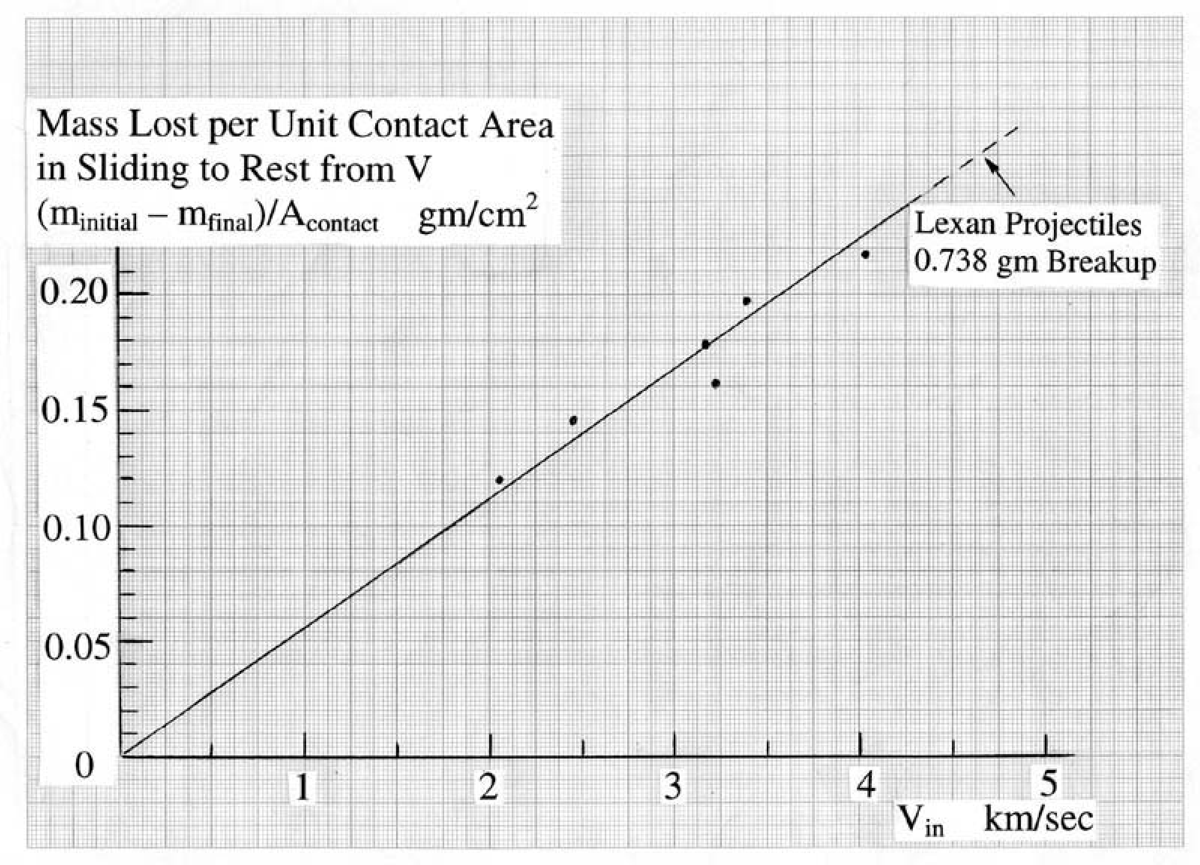
0.74 gm Lexan Projectile
slid to rest from 2.06 k/s

Sliding Friction Coefficient for <u>Small</u> 0.8 gm Lexan Projectiles

$\mu = \pi^{-1} \ln(V_{in}/V_{out})$

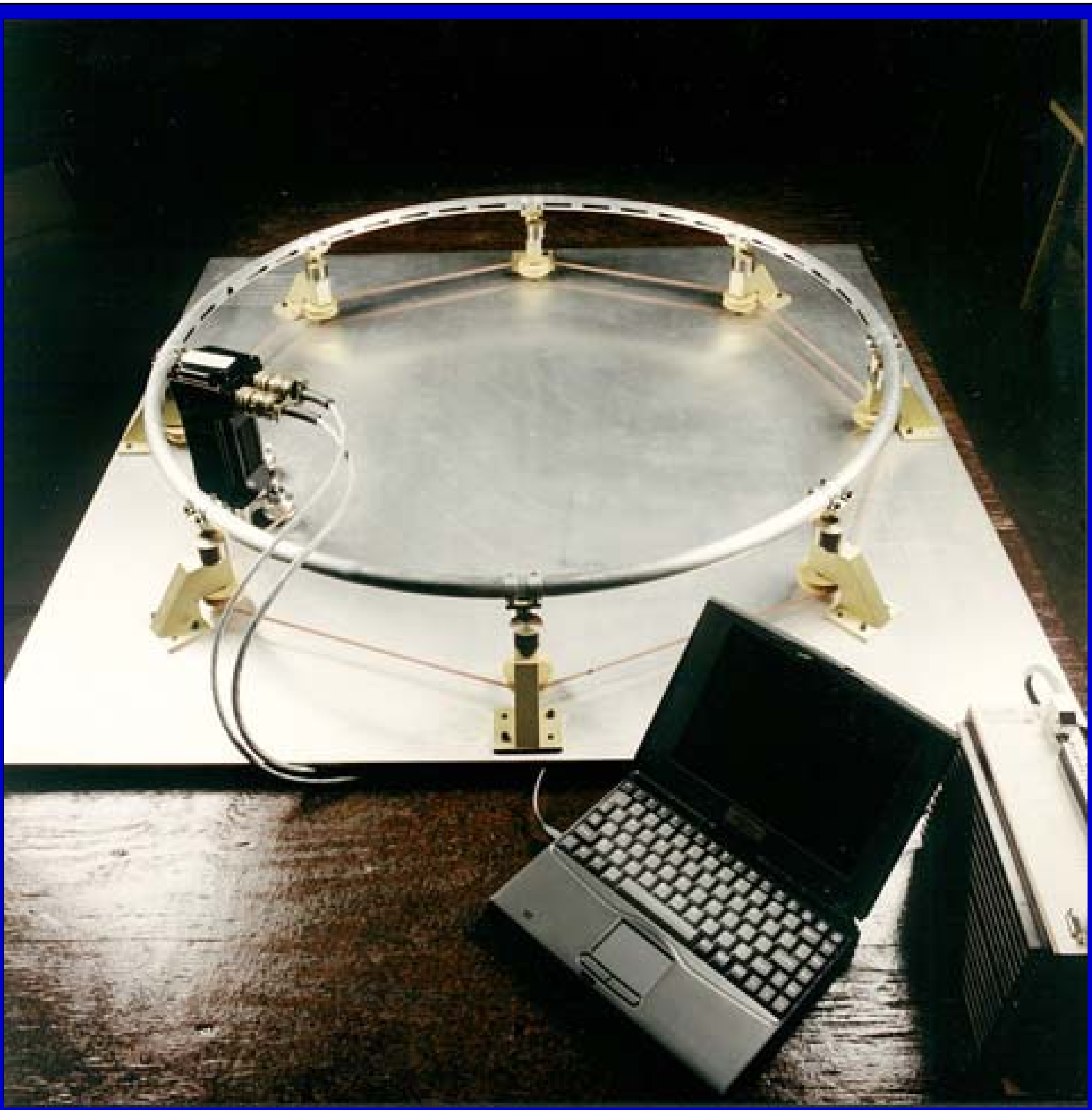


Mass Loss of Small Lexan Projectiles



Mass Loss Data for 0.738 gram Lexan Projectiles that Slide to Rest in a Multi-Turn "Soft Catch". For V_{in} = 3.4 km/sec about 50% of the 0.738 gram projectile had Ablated Away, and above 4 km/sec the Projectiles Broke Up so data could not be obtained. For a Slingatron Accelerating Similar 0.738 gram Lexan Projectiles with a Net Force equal to 3 times the Frictional Drag, one expects ~ 0.33 times the above Mass Loss. <u>Less for larger projectiles.</u>

Small Ring Demonstrated Phase Stability, 1995.



Scaling for Constant Load on Swing Arm Pair

Hold swing g_v and m_{load} per orbiting plate brg constant, so bearing life constant. Then machine size decreases for a given V if r and swing speed v *are decreased.* But this requires lower projectile friction, i.e., larger projectiles.

$$g_v = \frac{v^2}{r} = const.$$

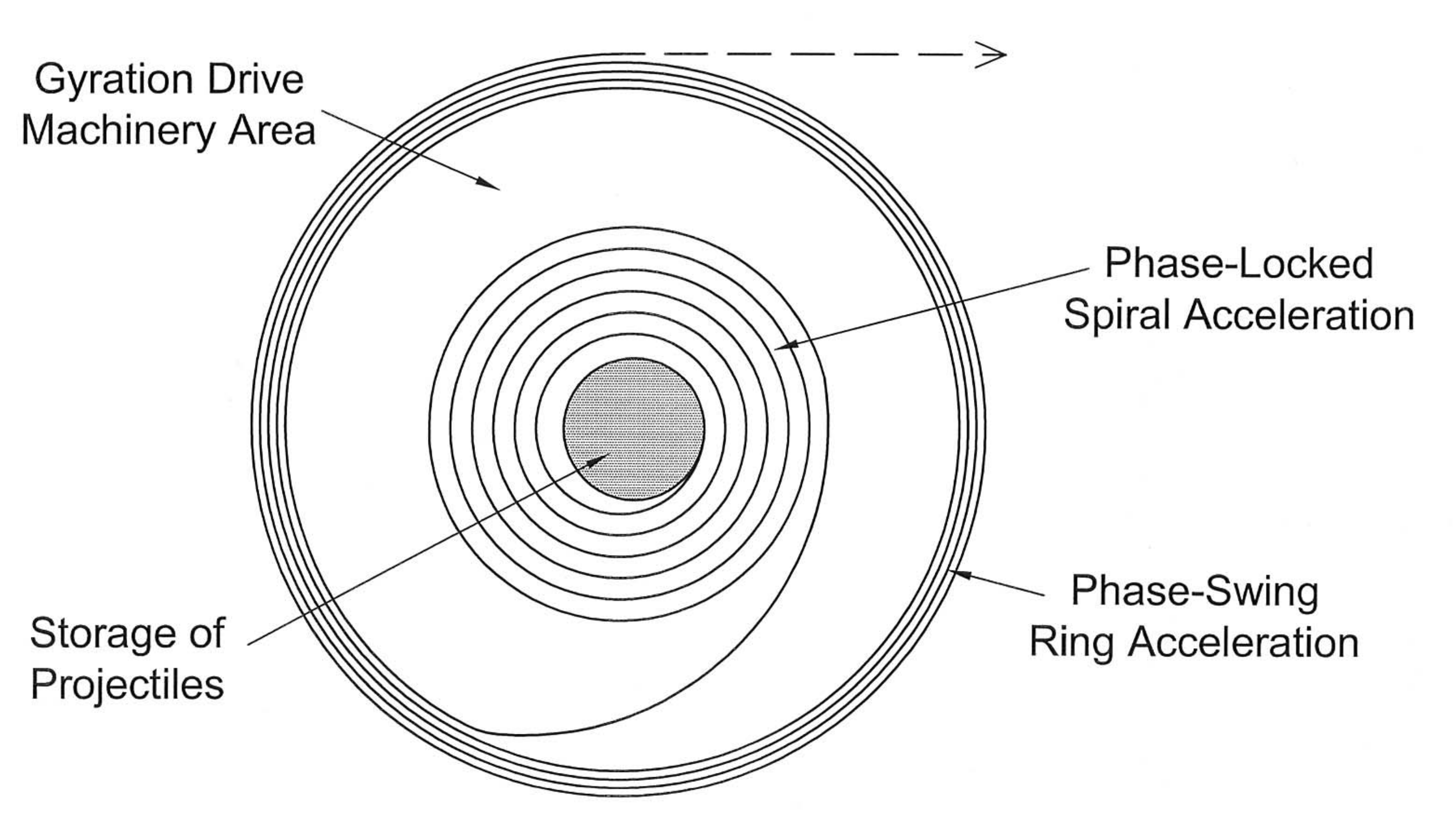
$$v = \sqrt{g_v r} = const.\sqrt{r}$$

$$Spiral: R \approx r\left(\frac{V}{v}\right) = V\sqrt{\frac{r}{g_v}}$$

High Performance Hybrid Slingatrons

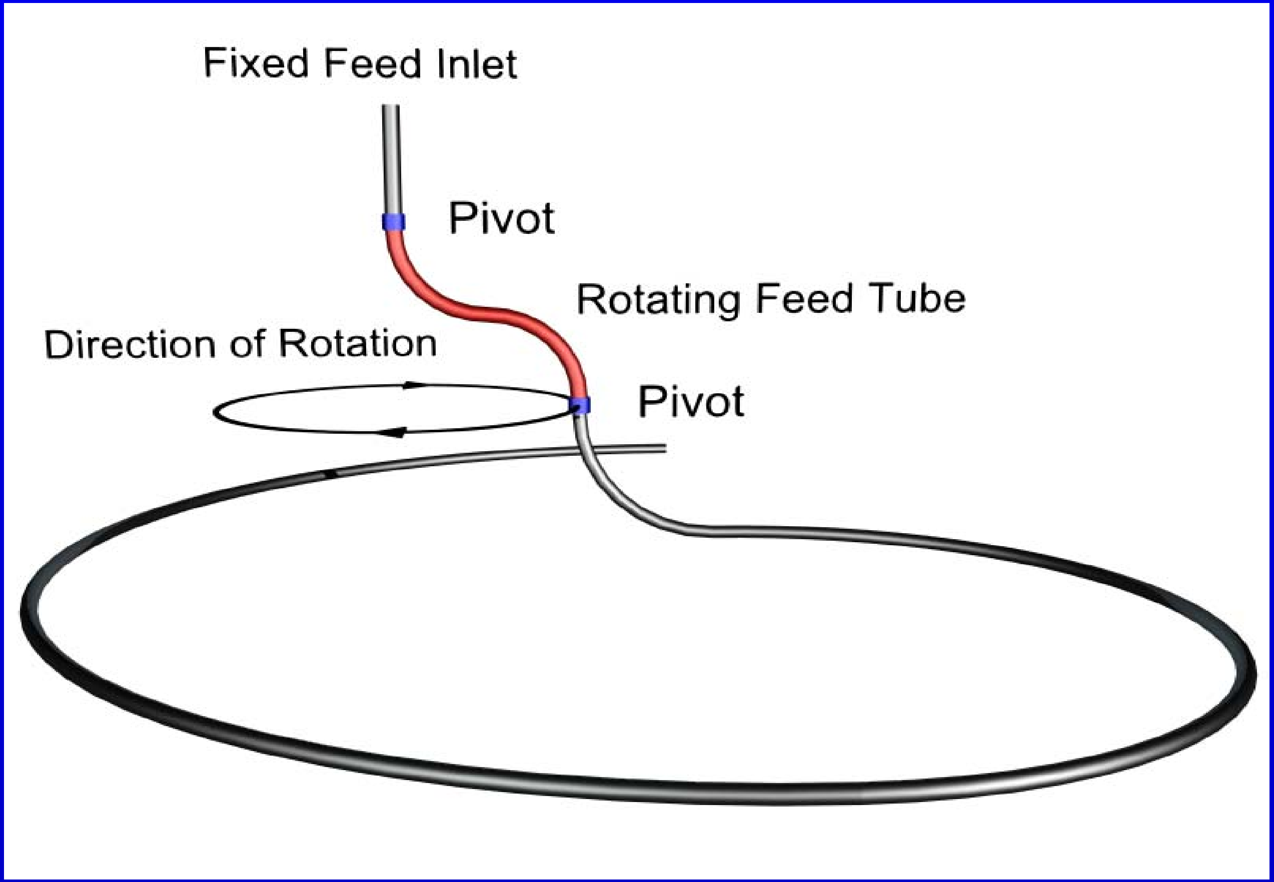
Separate Locations on Swing Plate for Swing-Arm-Bearings and Tube.

Projectiles fed from center region.

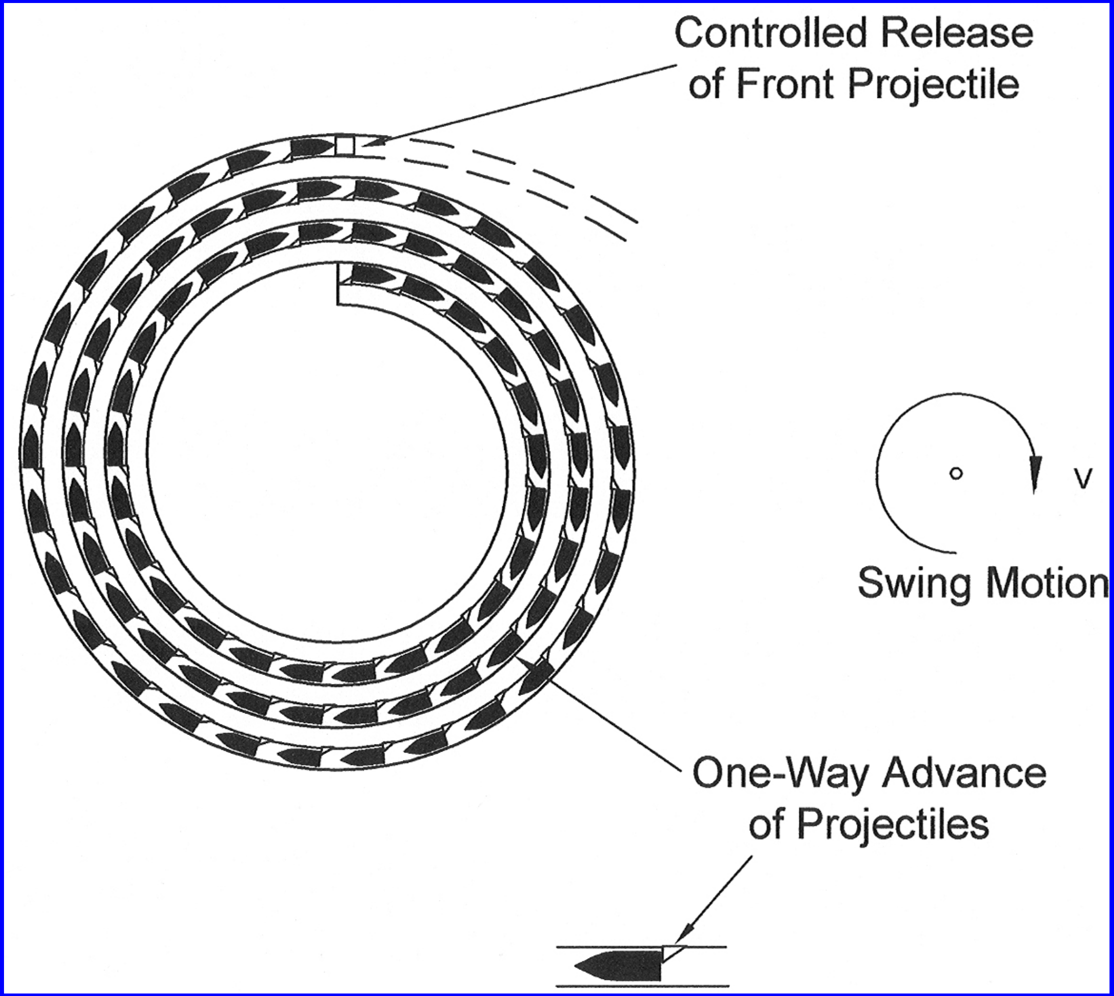


Centripetal Feed of Projectiles

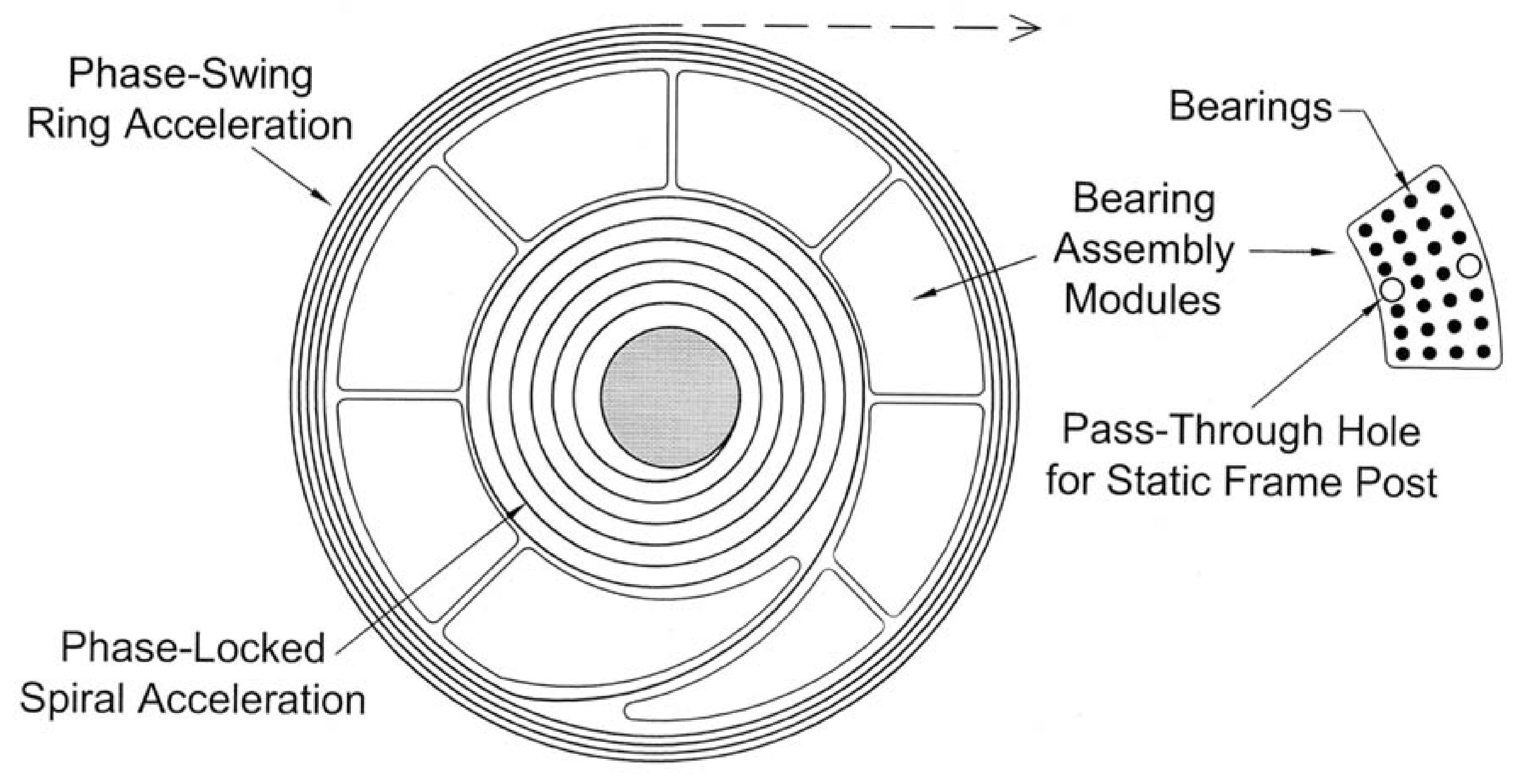
Swing arms do not clutter the entrance end of slingatron when bearing space is separated from spiral tube. Can feed a stream of moderate L/D Projectiles.



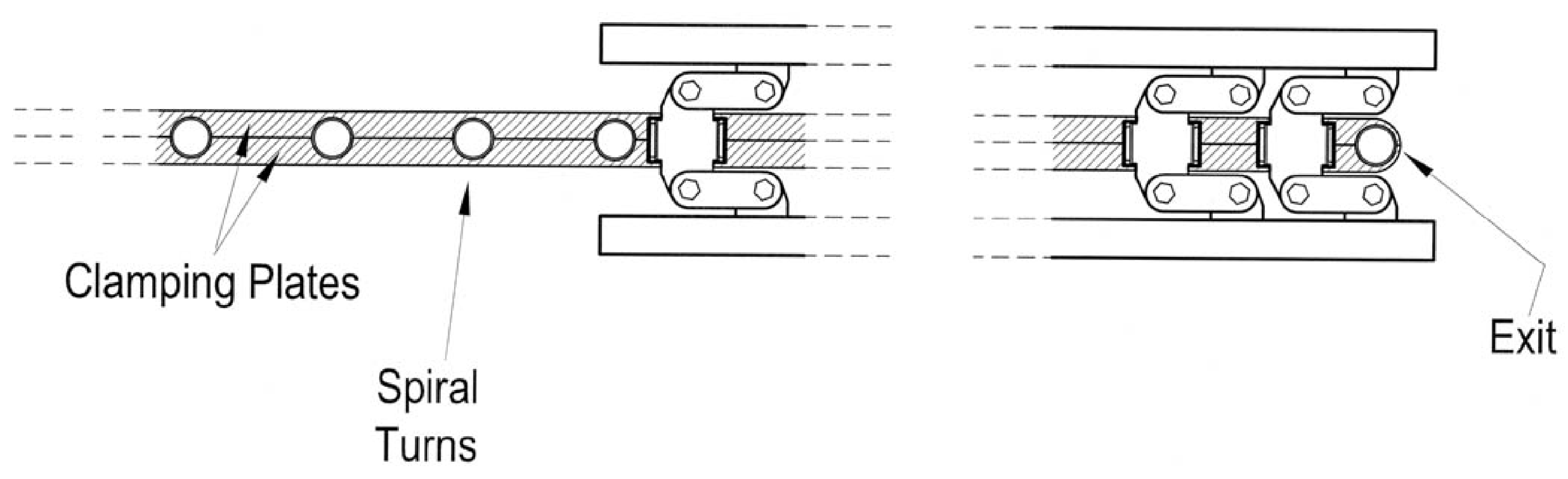
Alternative Projectile Feed System using inner turns as a Storage "Magazine" on Swing Plate. Magazine participates in orbital motion that feeds projectiles forward via one-way valves. Also works for large L/D.



Hybrid Spiral-Ring System with Bearing Assembly Modules. C-Film on shaft for bearing backup. Replace a tray when it shows more friction (C-coated shaft "journal" backup). Projectile impulse per unit length absorbed by disc.



Side View. Arms could be Horizontal for Large m_{proj} because smaller μ allows smaller r, v.



Mechanical Improvements ?

(1) Better Roller Bearings, Cronidur 30. Kevlar Clamping Plates to reduce orbiting mass.

(2) Journal Bearings: NFC (Near Frictionless Carbon) Films on steel. Data at Argonne Labs. In clean environment of dry N_2 or Argon, $\mu = 0.001$ or less. Low wear rates. Potential for Higher Loads. Dry N_2 gas would be a burden, but perhaps acceptable for increased performance. Journals could at least share rpm's via some inner race rotation for longer life for rollers.

(3) Advanced Fibers, e.g., Spectra, for low-ρ reinforcement of steel arms (for longer high v-swing arms).

DEFENSE

A Simple Mechanical System with Motors

Outer Ring Diameters D(meters) for Various Projectile Masses lbs and Velocities k/s. Large L/D Projectiles. <u>Numbers based on design including only item (1) in preceding viewgraph, i.e., ***potentially smaller***.</u>

	m = 1 lb	20 lb	100 lbs	2000lbs
V = 2 k/s	D = 3.2 meters	D =8.7	D =14.9	D =40.3
V = 4 k/s	D = 7.2	D = 19.5	D = 33.4	D = 90.7
V = 6 k/s	D = 11.2 Close to friction limit for this "low mass" case.	D = 30.4	D = 52	D = 141 meters

Extreme L/D Projectiles can be Accelerated and have Advantages

- Smaller Slingatron Bore

  for a Given Projectile Mass. Impulse distributed over wider arc of clamping plates.

- Smaller Air Drag

  potential low cost Multiple Shots with Global Reach from CONUS.

- Negligible Air Mass Snowplowed

  inside long Accelerator Tube (vent holes anyway).

- Can Penetrate Atmosphere to Space

  Low Elevation Angle Launch (e.g., 15°) for apogee kick into orbit.

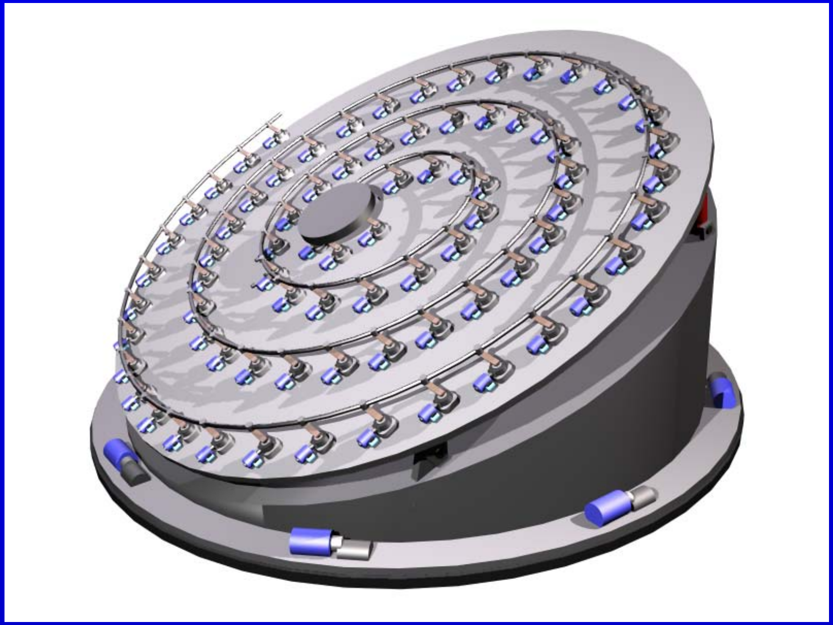
Scaling to Geometrically Similar Systems

Multiply all dimensions by β, while holding velocities v, V, constant.

Quantity		Scaling
Masses		$\sim \beta^3$
Swing radius & period (= 1/f)		$\sim \beta$
Centripetal force, Structure Cross-Sections	$\sim \beta^3/\beta$	$\sim \beta^2$
Bearings rated load and rpm's	side area $\sim \beta^2$	rpm's $\sim \beta^{-1}$
Bearing pressure of projectile	$\frac{mV^2/R}{A}$	const.
Projectile impulse/length Tube mass/length		const.
Projectile sliding friction		decreasesfaster than $\beta^{-0.5}$
Track Heating behind projectile		const.
Projectile Fractional Mass Loss $\Delta m/m$		$\sim \beta^{-1/2}$
Mechanical rolling friction coefficient		$\sim \beta^{-1}$

Global or Space Launch

Low Cost Launch of *numerous* Hypervelocity Large L/D Projectiles through the Atmosphere for Global Access, Space, Asteroid Defense.



Impact Physics Experiments
Staging unique to inertial fusion. Use Magnetized DT Impact Fusion to Ignite Larger Advanced Fuel for Power Production

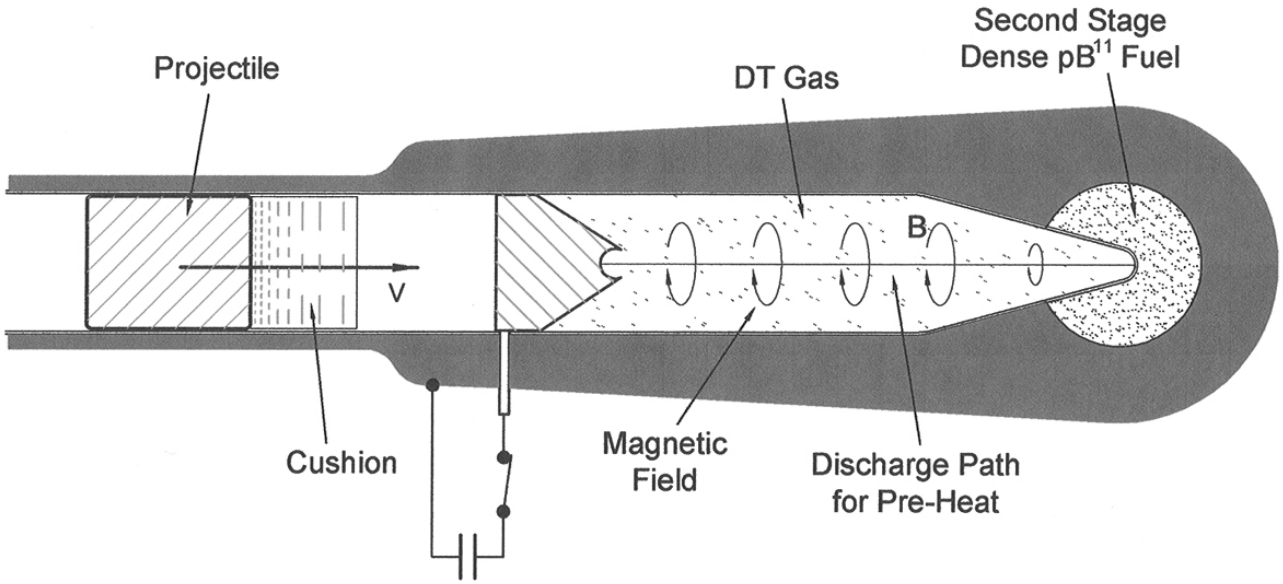
DT magnetized fuel target ignites Second Stage pB^{11}. Large reduction in neutrons and radioactive products per energy. Benign He product.

$B^{11}(5p,6n) + p = 3\alpha + 8.7$ MeV

B^{11} is 80% of natural Boron. Broad cross-section centered at ~ 675 kev.

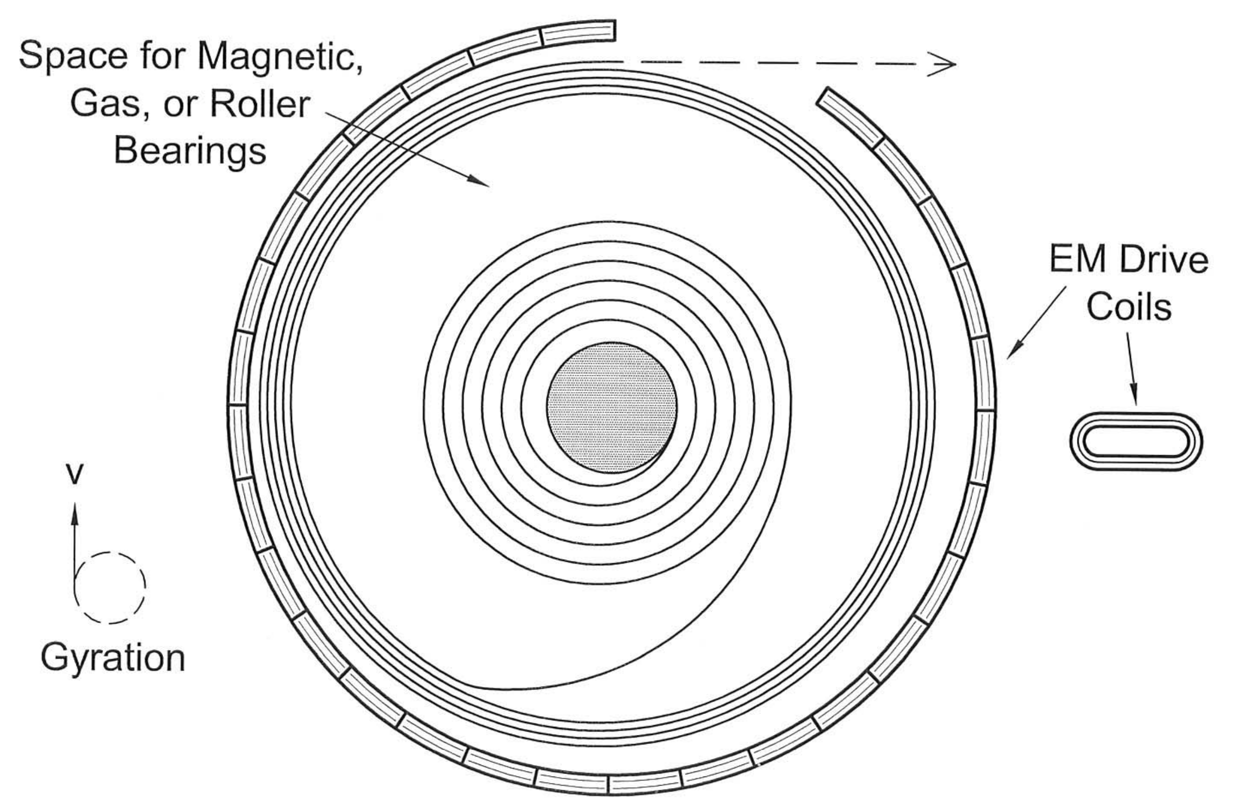
Hydride, decaborane $B_{10}H_{14}$ ~ 1 gm/cc (boils at 213°C).

DT explosion must heat pB to ~ 100 keV. Yield ~ 72 GJ/gm of pB.



Is there a Potential Role for Direct EM Drive ?

Magnetic-Field could push on receding half of ring and pull on approaching half, i.e., push-pull propulsion power with a larger torque-arm than motor shafts. Potential for alleviating loads on roller bearings for more lifetime.



Slingatron Advantages

- Purely Mechanical Approach to Hypervelocity
- Off-the-Shelf Drive Motors (Combustion or Electric)
- Steel Tubes with Long Lifetime and Rapid Fire
- Inertial Energy Storage in the Swing Machinery
- No High Voltage, Tube Arc Damage, or Pulsed Power
- Projectiles with very Large Mass and L/D possible. Sliding friction decreases with increasing projectile size.
- A Rugged Machine that can be Maintained with Replacement Parts.

Potential Applications: defense, industry, space, energy.

Slingatron Disadvantages

- Exit Dispersion is higher than conventional guns

  But at long ranges *need smart projectiles anyway*

- Physically large with different "footprint".

  But, *Recent Designs are smaller* due to hybrid designs, and lower friction for larger mass projectiles allows lower swing v that translates into lower r and R for given swing $g = v^2/r$. Advanced materials and designs expected to allow further size reduction.

Summary

- Strong theoretical foundation
- Friction data and theory……… hypervelocity is achievable
- Mechanical designs………… can build and further improve with designs and advanced materials.
- Wide Range of Potential Applications

1.“Sling Launch of a Mass Using Super-conducting Levitation”, D. A. Tidman, IEEE Trans. Magnetics, Vol. 32, No. 1, pages 240-247, January, 1996 (Submitted Oct. 30, 1994)

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5. “Slingatron Dynamics and Launch to LEO”, D. A. Tidman, Proceedings of the 13th SSI/Princeton Conference on Space Manufacturing, May 8-11, 1997, edited by B. Faughnan, Space Studies Institute, Princeton, NJ, pp.139-141.

6. “Slingatron Engineering and Early Experiments”, D. A. Tidman and J. R. Greig, Proceedings of the 14th SSI/Princeton Conference on Space Manufacturing, May 6-9, 1999, pages 306-312, edited by B. Faughnan, Space Studies Institute, Princeton, NJ.

7. “A Scientific Study on Sliding Friction Related to Slingatrons”, D. A. Tidman, UTRON Inc., Final Report for U. S. Army Contract No. DAAD17-00-P-0710, February 20, 2001.

8. “The Spiral Slingatron Mass Launcher,” D. A. Tidman, CP552, Space Technology and Applications International Forum-2001, edited by M. S. El-Genk, published by the American Institute of Physics, 2001. 1-56396-980-7/01

9. “Sizing a Slingatron-Based Space Launcher,” AIAA Journal of Propulsion and Power, M. L. Bundy, D. A. Tidman, and G. R. Cooper, Vol. 18, No. 2, March -April, 2002, p330-337. (Presented earlier at 10th U.S. Army Gun Dynamics Symposium, April 23-26, Austin, TX).

10. “Numerical Simulations of the Slingatron,” G. R. Cooper, D. A. Tidman, and M. L. Bundy, AIAA Journal of Propulsion and Power, Vol.18, No. 2, March-April, 2002, p.338-343. (Presented earlier at 10th U.S. Army Gun Dynamics Symposium, April 23-26, Austin, TX).

11. “Slingatron: A High Velocity Rapid Fire Sling,” D. A. Tidman, AIAA Journal of Propulsion and Power, Vol.18, No. 2, March-April 2002, p322 - 329. (Presented earlier at 10th U.S. Army Gun Dynamics Symposium, April 23-26, Austin, TX).

12. “Study of the Phase-Lock Phenomenon for a Circular Slingatron,” G. R. Cooper and D. A. Tidman, AIAA Journal of Propulsion and Power, Vol. 18, No. 3, May-June, 2002, p 505-508.

13. “Constant-Frequency Hypervelocity Slings”, D. A. Tidman, AIAA J. Propulsion and Power, Vol. 19, No. 4, July-August, 2003, pp 581-587.