Overview of the Millimeter-Wave Thermal Launch System (MTLS) Project

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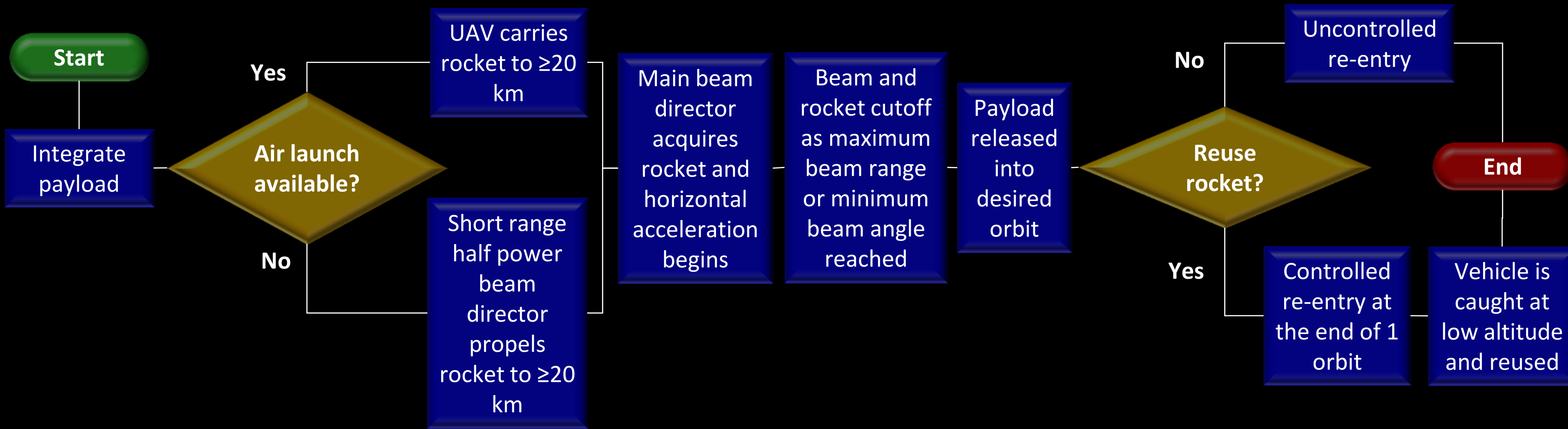
3. NASA Project manager, NASA Ames Research Center
4. DARPA system engineering and technical assistance, CENTRA Technology Inc.

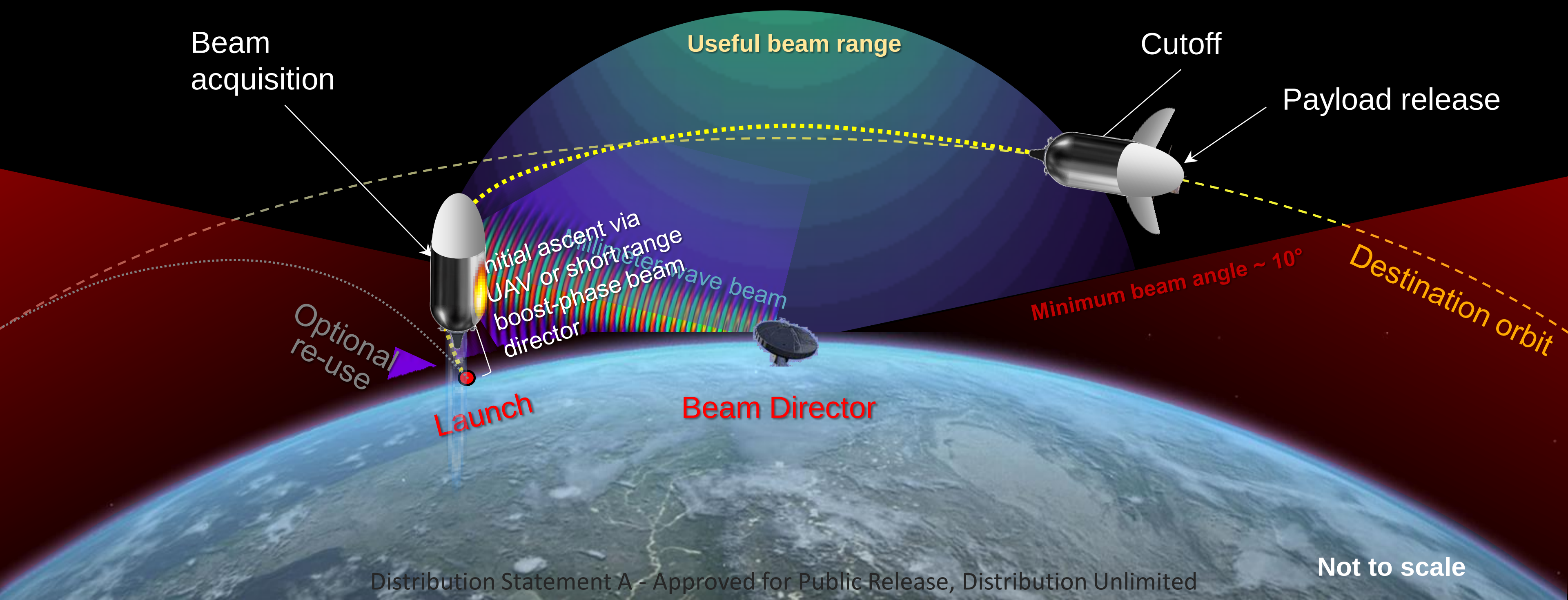
What is the MTLS launch system?

It's a 'thermal' system:

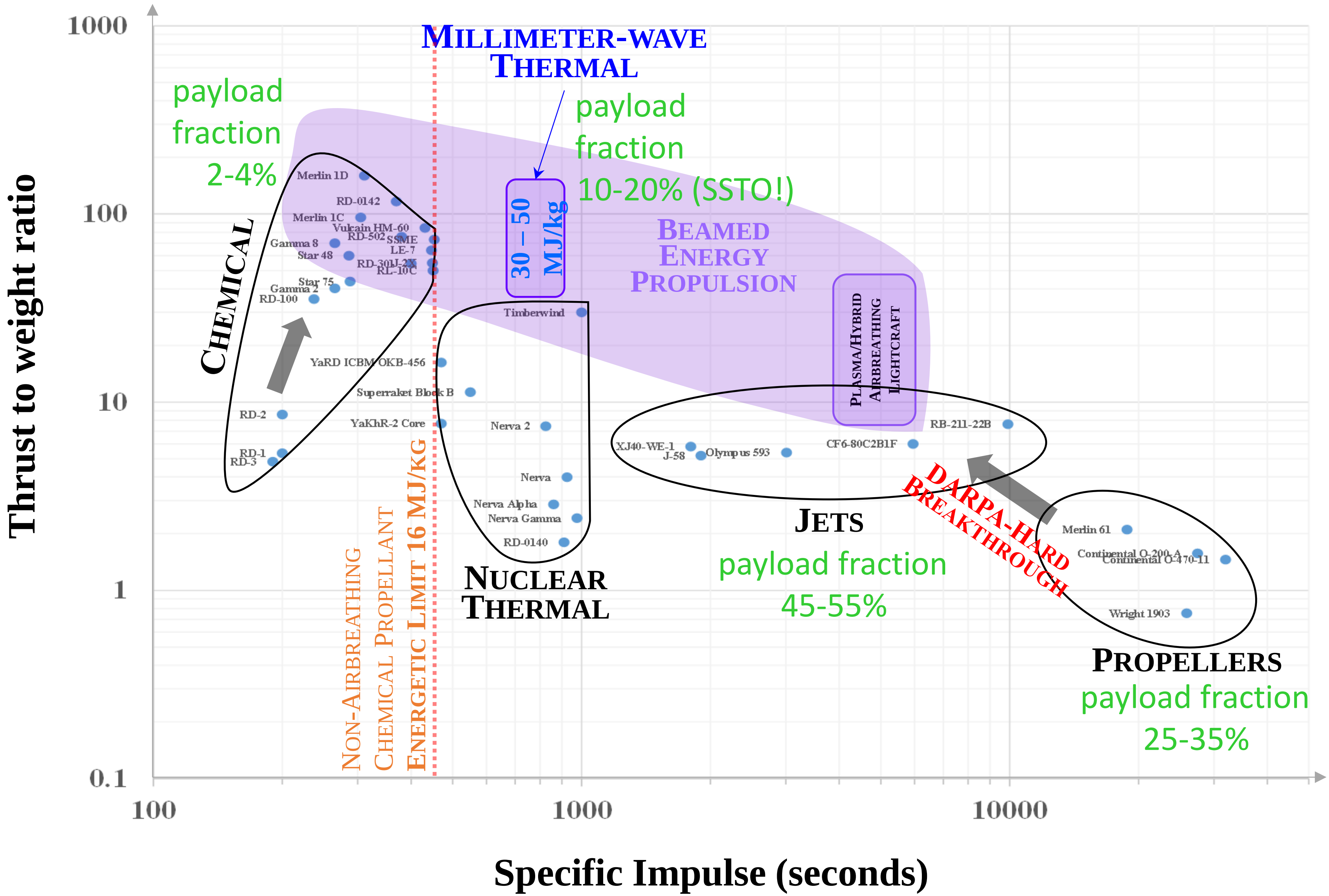
- Beam illuminates heat exchanger
- Heat exchanger absorbs beam
- Heat exchanger gets hot
- Heat is convected into propellant running through heat exchanger
- Propellant is expanded through a nozzle in the conventional way to produce thrust

How would it be used?





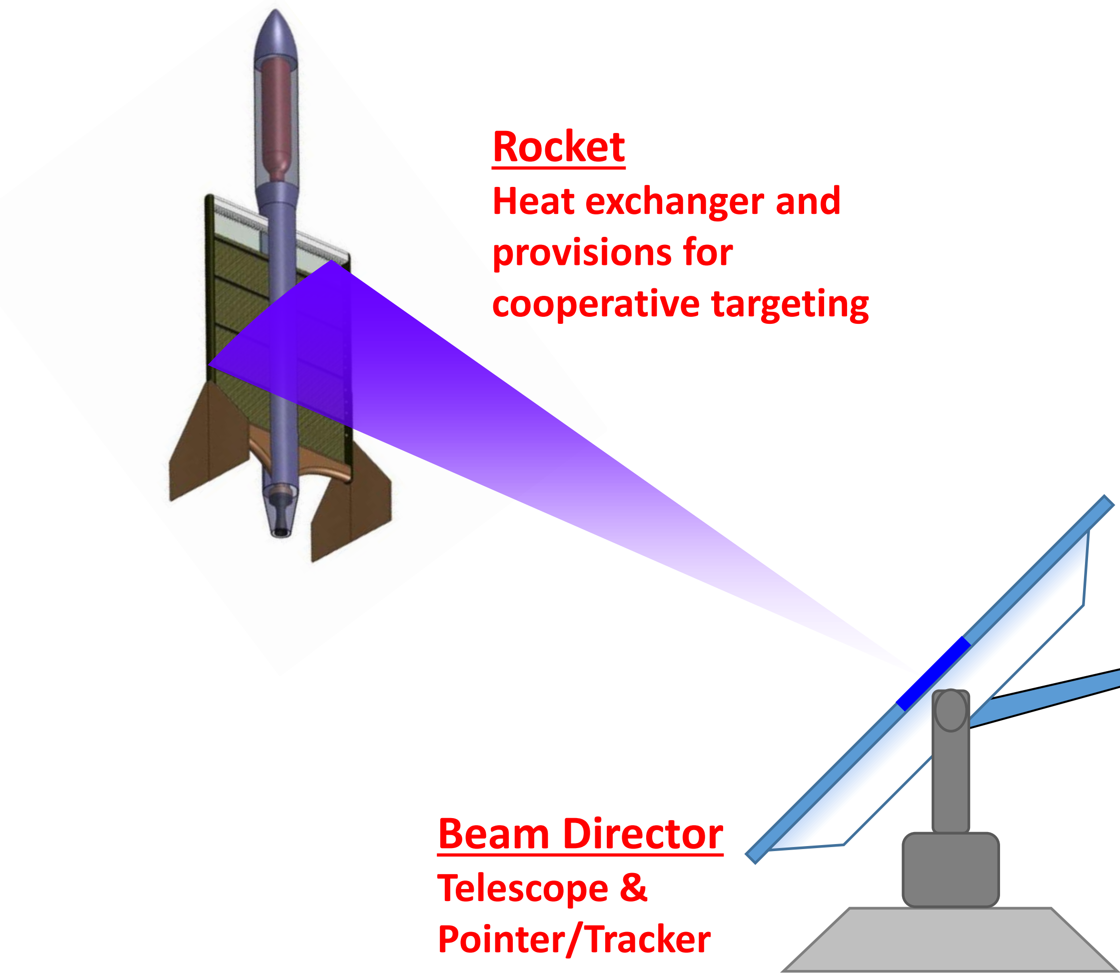
Why is development justified?



How can it be reduced to practice?

DARPA's Challenge:

1) Launch a small thermal rocket into the air, powered by a millimeter-wave beam

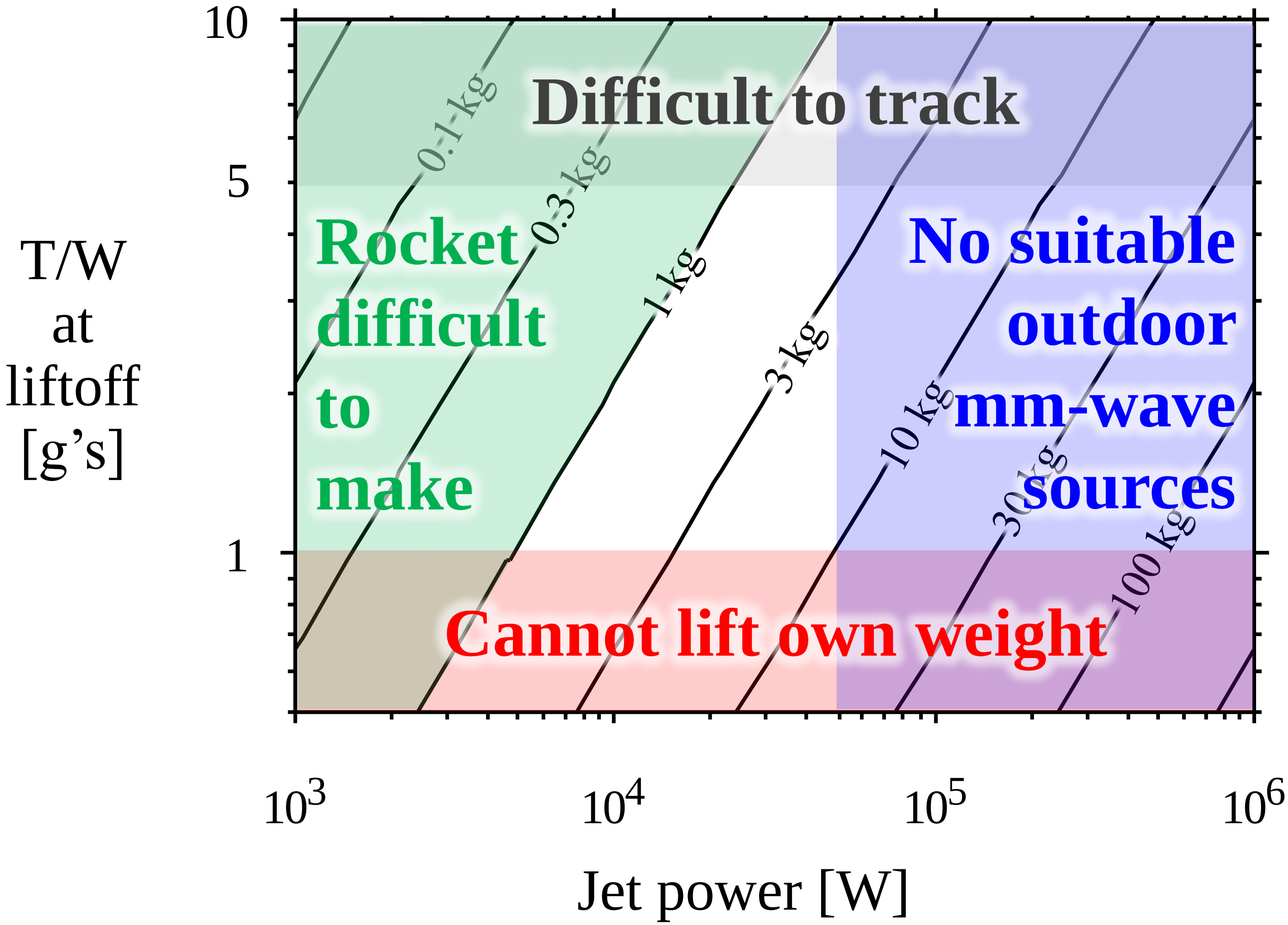


Beam Source

100 kW – 2 MW gyrotron (e.g. Monica Blank and Kevin Felch of CPI shown with 1.2 MW, 110 GHz gyrotron)

Scoping the solution

- $M = \frac{2P_j}{g^2(T/W)I_{sp}}$ is implied by $P_j = \frac{1}{2}\dot{m}v_e^2, T = \dot{m}v_e$ and $v_e = gI_{sp}, W = Mg$
- Contours of liftoff mass are plotted for I_{sp} = 100 seconds



Phases and objectives

Phase I (May 2012 – Aug 2013)

Develop MTLS propulsion system and demonstrate in static test

Heat exchanger

Phase II (Aug 2012 – March 2014)

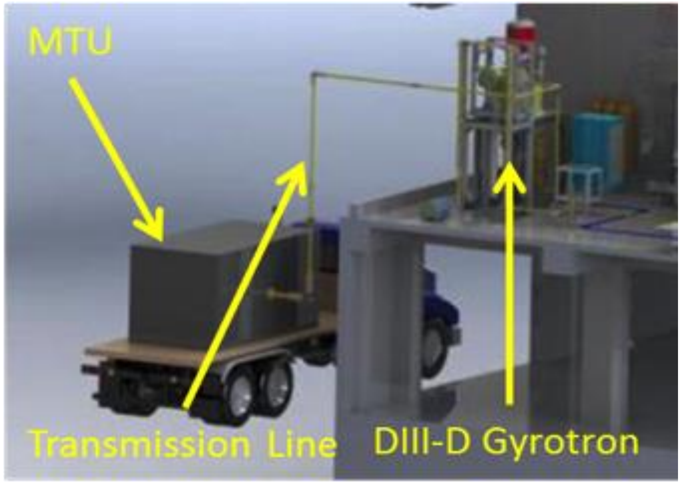
Demonstrate rail-launched flight test of MTLS propulsion system

Beam director

Rocket

Phase I

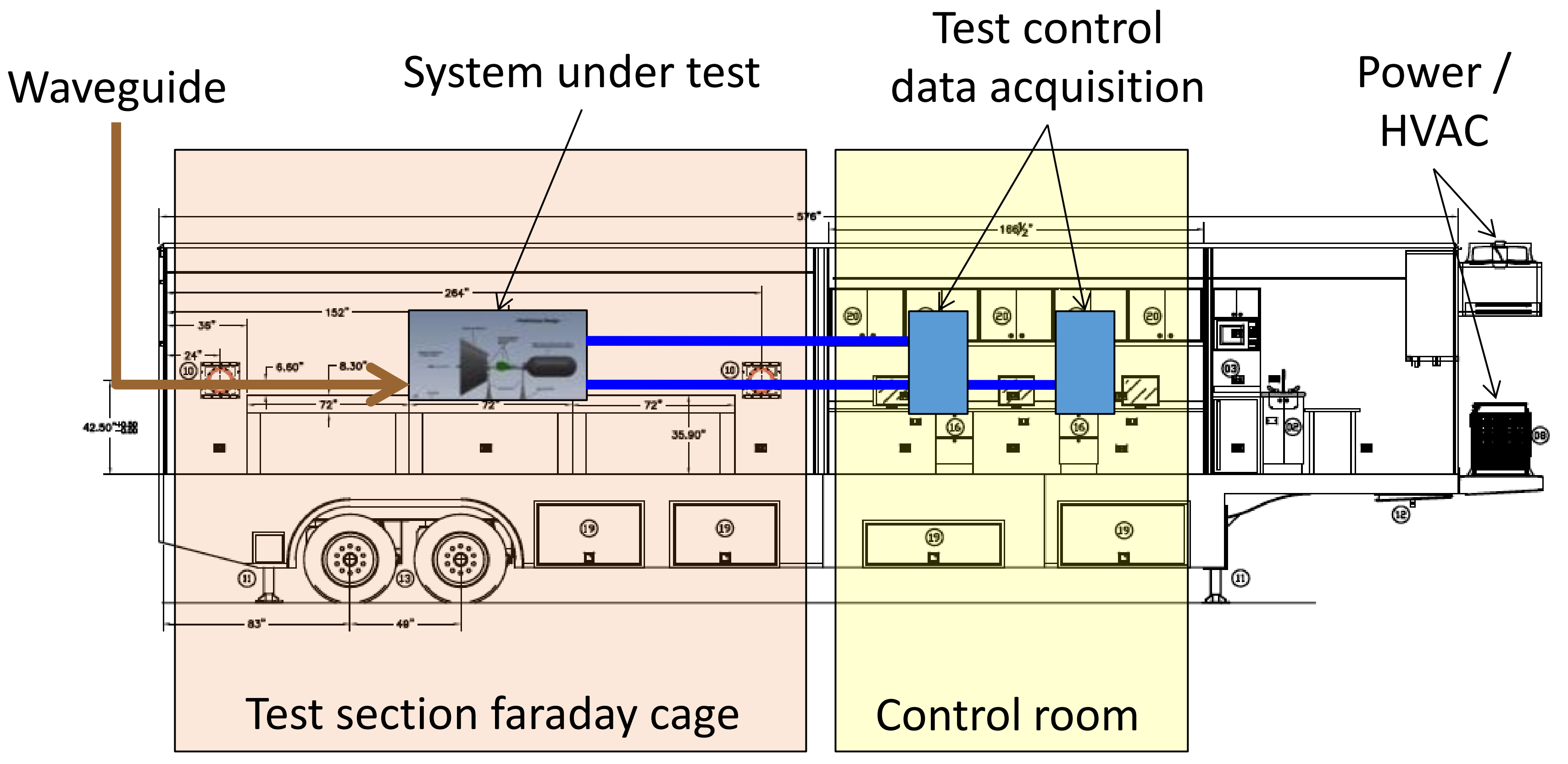
- In partnership with the Department of Energy
  and the General Atomics DIII-D Tokamak Fusion Facility in San Diego
- 6 gyrotrons available
- Any one of which can produce 800 kW at 110 GHz for 5 seconds
- Ongoing uncertainty over millimeter-wave source availability at various candidate sites led to a re-locatable approach for static testing



MTU = Mobile Testing Unit

Phase I Test Configuration

- Uncertainty over which millimeter-wave sources would be available led to a re-locatable approach for static testing



An MRI trailer was re-purposed

Built by Advanced Mobility Specialty Vehicles of Monee, IL

Shielded laboratory section

Control room

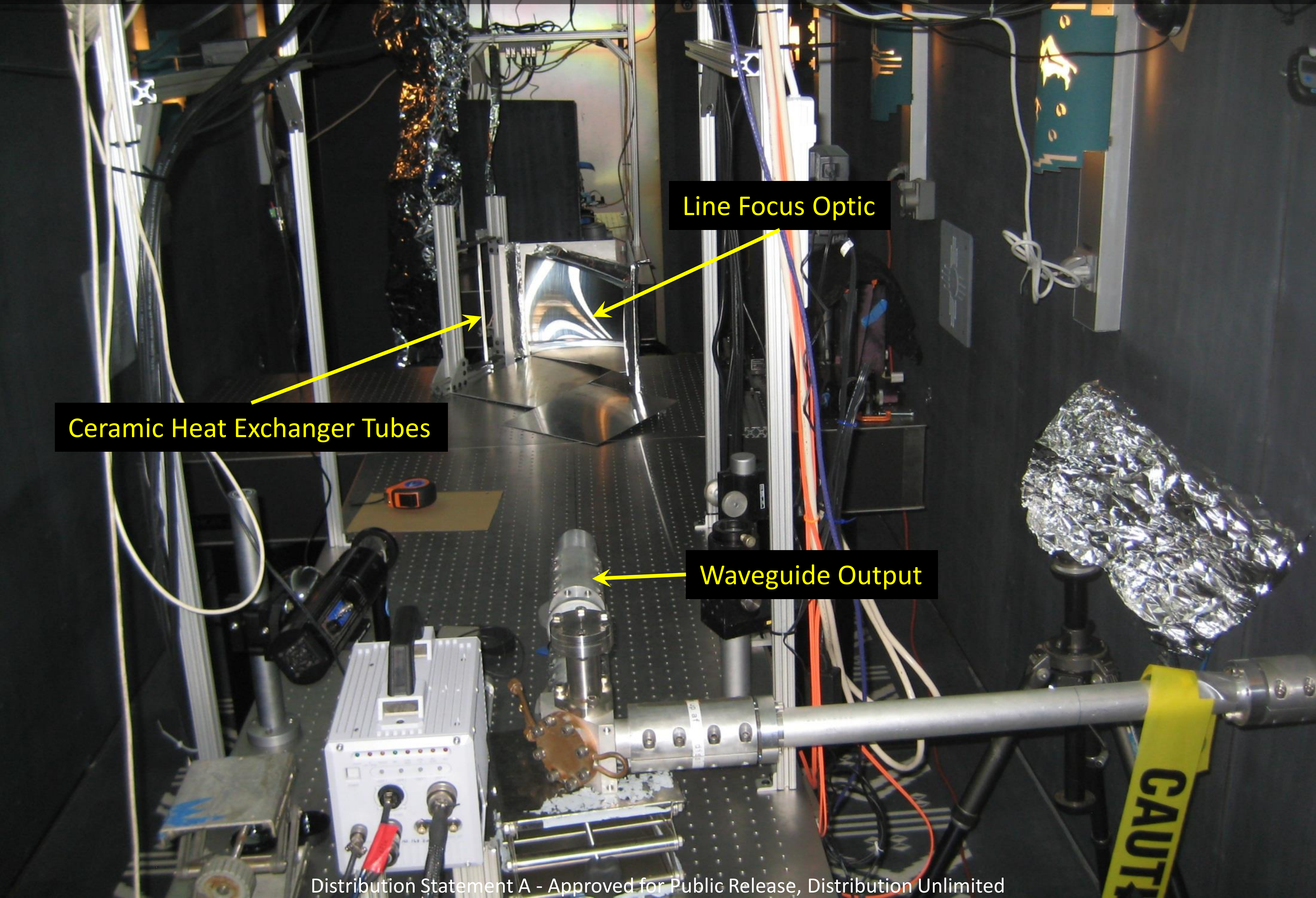
Fiber optic feed-through
(cameras and instrumentation
run via fiber bridges)

Beam ports

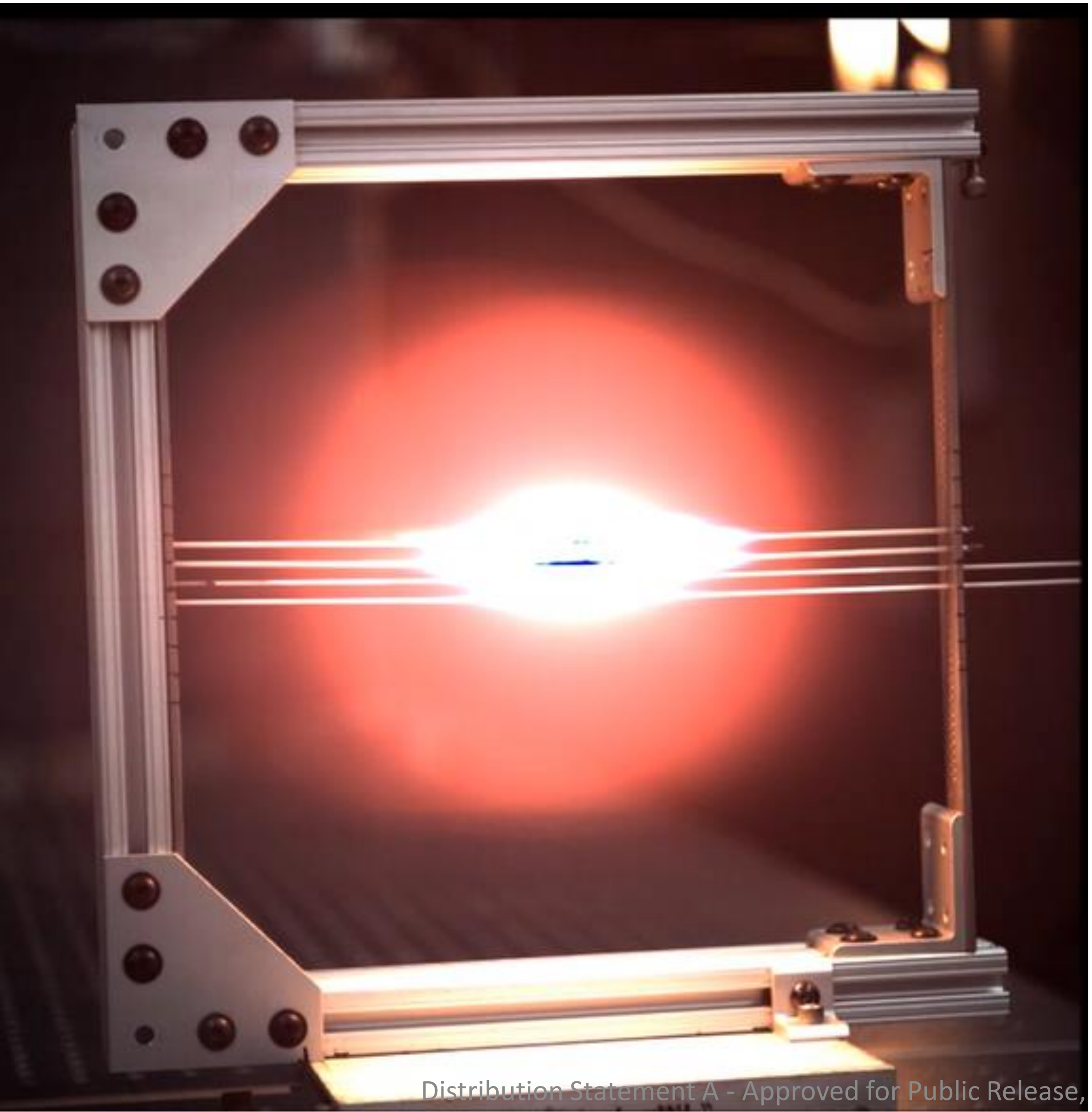
Experiment bench

TiO_2-coated steel walls
(for mm-wave absorption,
thermal mass)

An early experimental configuration



13th August 2013: First demonstration of millimeter-wave absorption by ceramic heat exchanger tube



- 20 kW
- 110 GHz
- Free-space propagation (incident Gaussian Beam)
- Mullite and alumina tubes
- >1,800 K wall temperature achieved (no flow)
- By Parkin, Lambot, Myrabo, and Murakami at General Atomics DIII-D Facility

Phase II

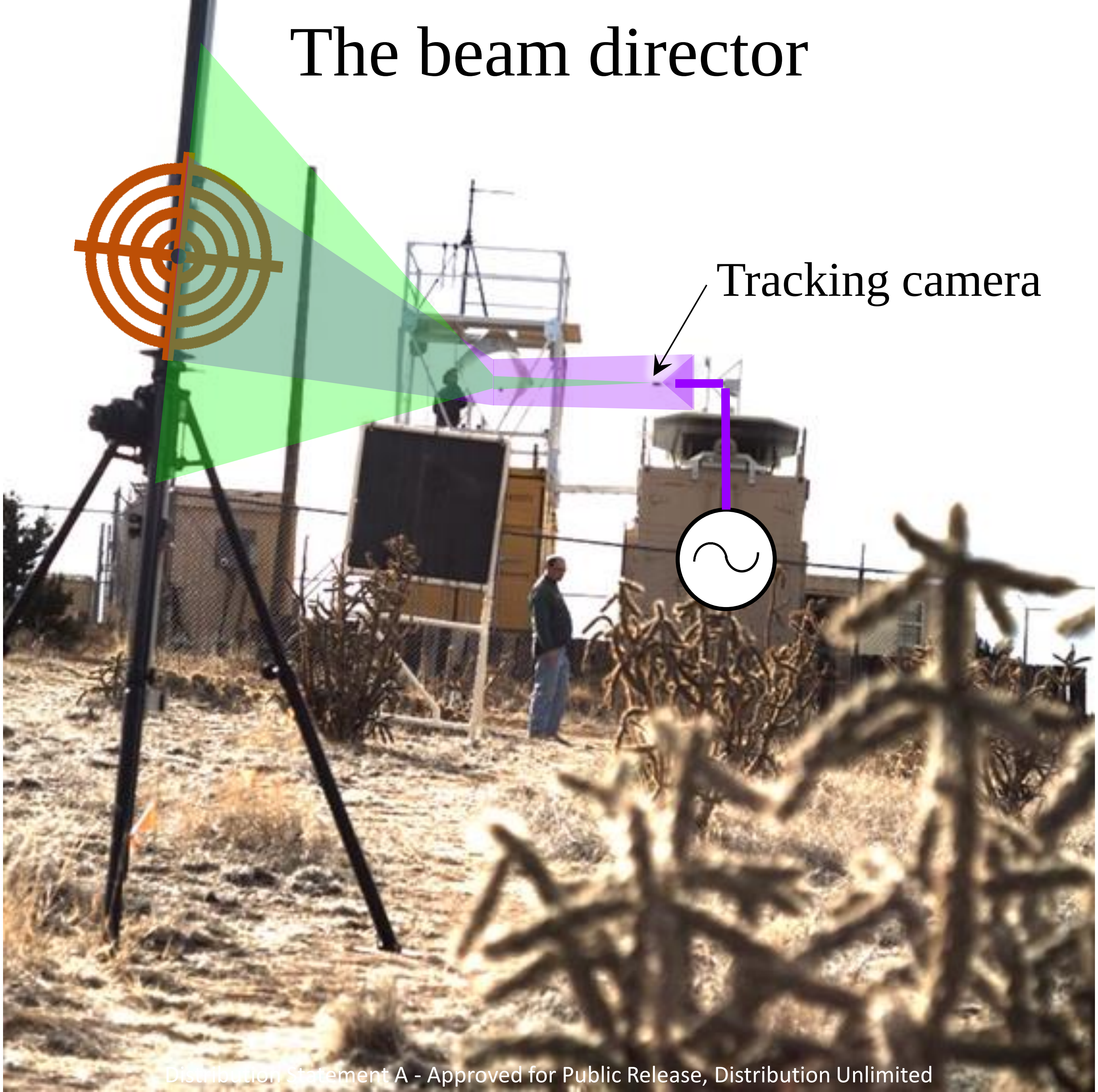
- In partnership with the Air Force Research Laboratory (AFRL) and the Army High Energy Laser Test Facility (HELSTF)

Intended launch area for side-engaged rocket 30-100 meters downrange (photo in next slide is taken from this area)

Intended launch area for axial-engaged rocket, introduced shortly

100 kW class W-band source

The beam director



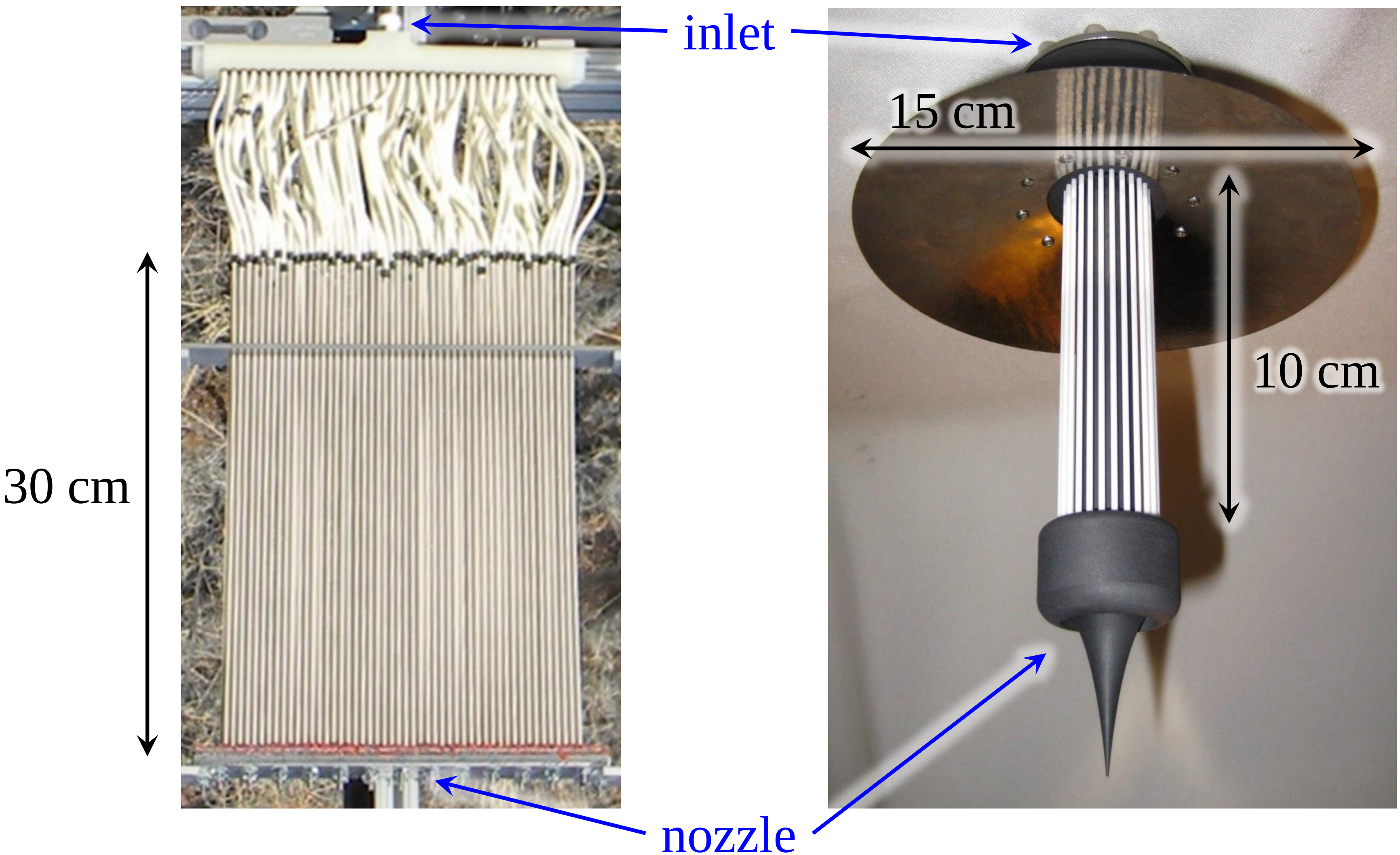
The rockets

Dr. Bruccoleri with the side engagement rocket

Dr. Myrabo with the axial engagement rocket

	Side	Axial
Beam pointing	Hard	Easy
Beam focusing	Easy	Hard

The engines



side

axial

First launch (side-engage, without beam)

- Cold gas only. Milestone to test correct operation of rocket and tracking/pointing

First launch (axial-engage, without beam)

- Cold gas only. Milestone to test correct operation of rocket and tracking/pointing

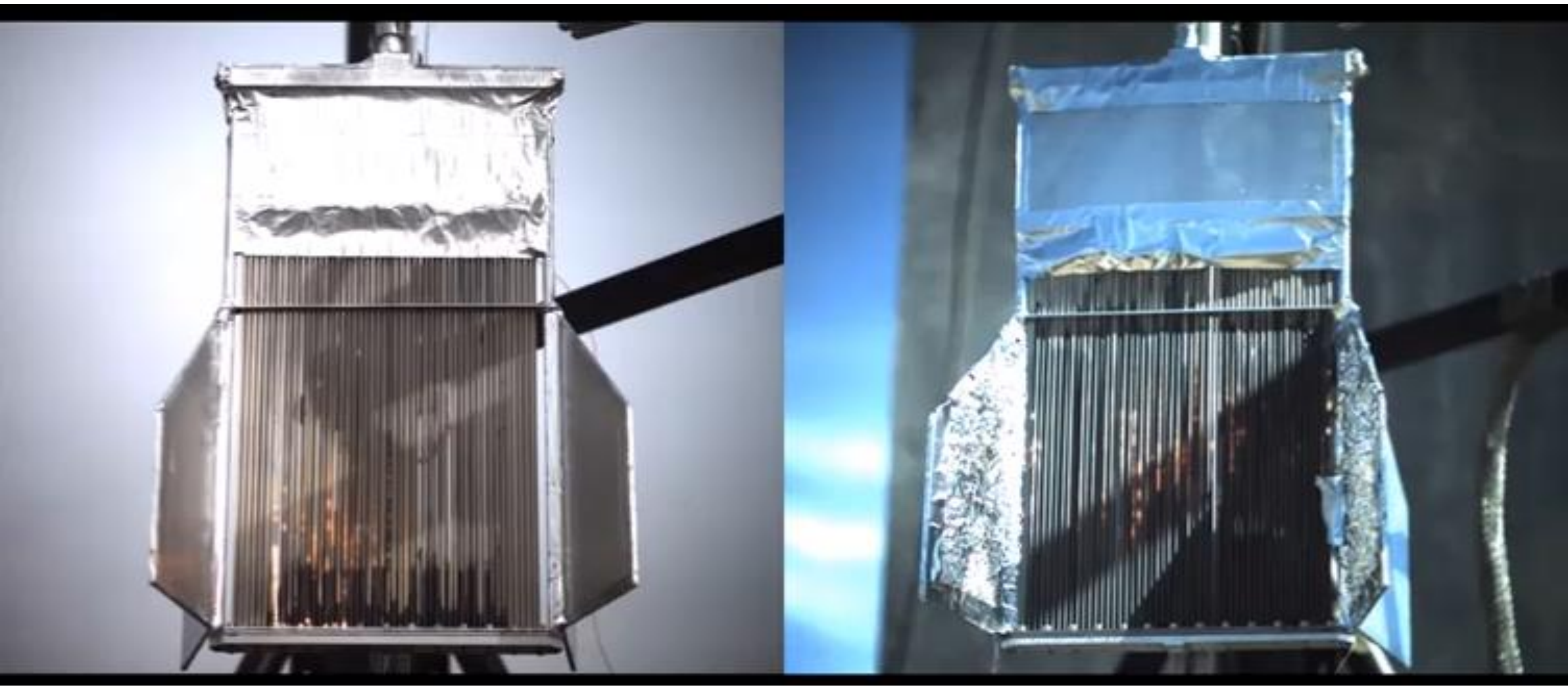
Co-operative tracking

- High brightness green LEDs (527 nm)
- Clustered toward top and bottom of rocket
- Tracking camera uses 527 nm filter with 20 nm bandwidth.
  - Optical path bounces off the turning flat and is co-aligned with the beam
- Software processes ~24 fps to produce steering signal for pan-tilt unit of turning flat

Top left: A scene taken through the green filter. The LEDs saturate the CMOS sensor of a Basler ACE acA2040-180kc camera (not the tracking camera used). Bottom left: The same scene taken at minimum exposure time of 24 μs. The sensor is still saturated and background clutter reduced to essentially none.

Launch with beam

- Pan-tilt platform had insufficient control authority to keep the beam on the HX
- Grossly non-uniform coating led to tube fracture (seen in bottom left video)
- Achieving a uniform coating evidently needs further work
- Central tubes fractured on earlier static tests with beam – hammer shock suspected
- Concentrating back-reflector planned for next iteration of HX



Summary

- We built a refractory ceramic heat exchanger
  - Worked out how to make it absorb millimeter waves and heated it to > 1,500 K
  - Integrated it into 2 types of rocket
  - Showed that the rocket produces 25% more thrust with beam heating, which indicates surprisingly poor heat transfer to argon that needs further investigation and modeling

- We simplified a beam director so it could be built within cost and schedule
  - Built a cooperative tracking system that could accurately determine where the beam should be steered as the rocket ascended

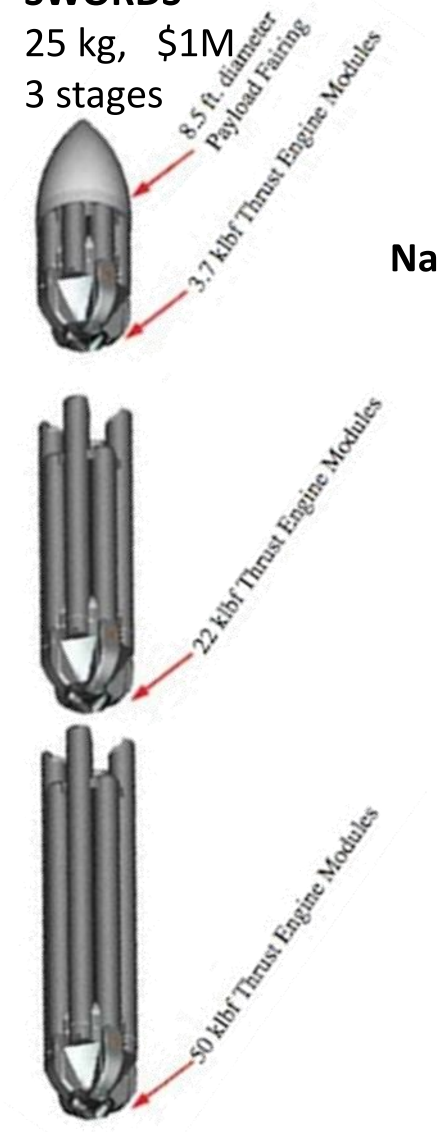
- We launched a rocket which was beam-heated as it began its ascent up the launch rail
  - Weren't able to keep the beam on the heat exchanger as the rocket ascended due to inadequate control authority from the pan-tilt unit and lack of time to calibrate and troubleshoot the system

- In all, we were asked to do something hard with limited time and resources
  - A coalition of superb teams rose to the challenge
  - Got 90% of way to a fully-tracked launch. With refinement would likely have achieved it
  - In keeping with DARPA's request, ran far ahead of the usual scope and pace of an incremental research-led program, retiring early concerns and gaining important insights
  - Now have an excellent justification to go back and fill in the missing research
  - Flight test capability and competitions can motivate, focus and measure research progress

Why is development justified?

- Lighter rocket for given payload
- Complementary to reusables

SWORDS
25 kg, $1M
3 stages

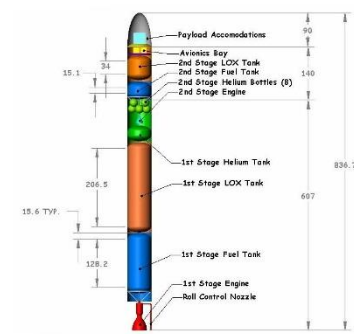


Nammo North Star LV
10 kg, $TBD
3 stages

Virgin Galactic LauncherOne
225 kg, $10M
1 stage

TO RELATIVE SCALE

Garvey 10/250 NLV
10 kg, $TBD
2 stages



Millimeter-wave thermal
3 kg, <$50k
1 stage


MTLS
MMXIII
LTI
NO Whining
Visitor


Safety First


Safety First


MOBILE TEST UNIT
by Lightcraft Technologies
MTLS

Comparative Advantage of Thermal Propulsion

The rocket equation is conventionally written,

$$\frac{m_{wet}}{m_{dry}} = e^{\frac{\Delta v}{g I_{sp}}}$$

Introducing propellant mass,

$$m_{wet} = m_{dry} + m_{pro}$$

The rocket equation can be expressed,

$$\frac{m_{pro}}{m_{dry}} = e^{\frac{\Delta v}{g I_{sp}}} - 1$$

Hence, for rockets of *equal dry mass*,

$$\frac{m_{pro,1}}{m_{pro,2}} = \frac{e^{\frac{\Delta v}{g I_{sp,1}}} - 1}{e^{\frac{\Delta v}{g I_{sp,2}}} - 1} \qquad \frac{m_{wet,1}}{m_{wet,2}} = \frac{e^{\frac{\Delta v}{g I_{sp,1}}}}{e^{\frac{\Delta v}{g I_{sp,2}}}}$$

Example: LH_2 thermal vs. LOX/LH_2:

$I_{sp,1}$=900 seconds, $I_{sp,2}$=450 seconds, Δv=10 km/s

$$\frac{m_{pro,1}}{m_{pro,2}} = \frac{e^{\frac{10000}{9.81\times900}} - 1}{e^{\frac{10000}{9.81\times450}} - 1} = 0.24 \qquad \frac{m_{wet,1}}{m_{wet,2}} = \frac{e^{\frac{10000}{9.81\times900}}}{e^{\frac{10000}{9.81\times450}}} = 0.32$$

LH_2 thermal requires a quarter the mass of propellant than LOX/LH_2 for rockets of equal dry mass. Overall, the rocket is a third of the wet mass.

Comparative Advantage of Thermal Propulsion

LH_2 Thermal vs. LOX/LH_2 Example Continued

Not all components get lighter. A more careful scaling analysis is needed.

Tank mass

- Scales in inverse proportion to propellant density (lower density means heavier tank).
- The ratio of average densities for LOX/LH_2 vs. LH_2 is $$\frac{361.14\frac{kg}{m^3}}{70.8\frac{kg}{m^3}} = 5.1$$
- For monopropellant there is no inter-tank structure, which is roughly 25% of $LOX+LH_2$ tank mass.
- Net effect is that LH_2 thermal tank is 5.1*0.24*0.75 = 0.92x heavier.

Engine mass

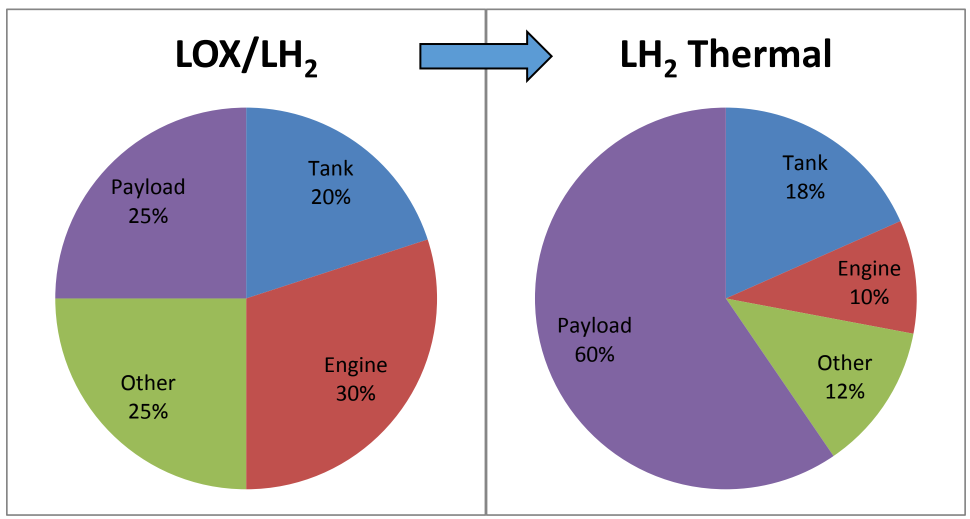
- Scales in proportion to thrust, or wet if mass initial acceleration and engine T/W are held constant
- In such a case LH_2 thermal engine mass = 0.32x LOX/LH_2 engine mass

Other mass

- Is a combination of structure that scales with thrust, and relatively fixed masses such as avionics. For the purposes of this example we'll use 0.5x

Implications

- (1) Using the above multipliers and
  (2) Assuming these dry mass proportions for LOX/LH_2,



- **2.4x more payload per unit dry mass**
- **9.8x less propellant per unit payload**

Comparative Advantage of Thermal Propulsion

Dense Propellant Scoreboard (as of 6/19/2013)

Propellant	Price ($/kg)	Phase	O/F Ratio	Oxid. Density (kg/m3)	Fuel Density (kg/m3)	Average propellant density (kg/m3)	Specific volume normalized to LOX/RP-1	Density relative to LOX/LH2	ISP (s)	CEA2 Isp @ 1500K	CEA2 Isp @ 2000K	CEA2 Isp @ 2500K	CEA2 Isp @ 3000K	CEA2 Isp @ 4000K
LOX/LH2		l	6	1141	70.8	361.1	2.85	1.00	452					
LOX/RP-1		l	2.56	1141	820	1028.0	1.00	2.85	350					
LH2-NBP	$ 6.7	l				70.8	14.52	0.20			769	873	975	1182
Slush LH2 @?K		l+s				85.0	12.09	0.24			769	873	975	1182
Be(BH4)2 (beryllium borohydride)		s				609.0	1.69	1.69			436	538	597	710
LiBH4 (lithium borohydride)	$ 300.0	s				666.0	1.54	1.84			468	536	587	780
NH3BH3 (borozane, ammonia borane)						780.0	1.32	2.16					586	
B2H6 (diborane)						481.8	2.13	1.33					567	
Methane (or LNG)	$ 0.4	l				415.0	2.48	1.15			432	490	562	722
SLCH4		l+s				482.0	2.13	1.33			432	490	562	722
Li3AlH6	$ 200.0	s				1130.0	0.91	3.13			417	462	554	682
LHe	$ 5.0	l				145.0	7.09	0.40		389	453	509	551	636
BeH2		s				650.0	1.58	1.80			413	485	544	653
(NH4+BH4-) Ammonium borohydride		s				642.0	1.60	1.78			412	482	534	655
LiH	$ 100.0	s				820.0	1.25	2.27			364	482	532	644
Al(BH4)3 (aluminum borohydride)						787.0	1.31	2.18					526	
LiAlH4 (LAH)	$ 180.0	s				917.0	1.12	2.54			356	398	522	624
Lithium	$ 95.0	s				534.0	1.93	1.48				470	496	
Ethane						546.5	1.88	1.51			361	435	486	586
Ethane (C2H6) @ 90 K						652.0	1.58	1.81			361	435	486	586
NH3 (ammonia)		l				618.9	1.66	1.71					476	
NH3-Solid		s				817.0	1.26	2.26					476	
NBP Propane, 231.04K,101350kPa		l				581.2	1.77	1.61			344	429	467	563
Propane (C3H8) @91.5K,0.7kPa						726.8	1.41	2.01			344	429	467	563
C20H42 (Icosane)		s				770.0	1.34	2.13					460	
Butane (C4H10)						600.0	1.71	1.66			334		457	551
NaBH4 (sodium borohydride)	$ 20.0	s				1070.0	0.96	2.96					444	
N2H4	$ 177.8					1004.5	1.02	2.78			337	382	425	512
Methanol* (C3OH) @20degC						792.0	1.30	2.19				382	425	
RP-1*	$ 1.0					820.0	1.25	2.27					420	
SiH4 (silane) - NBP	$ 300.0					556.0	1.85	1.54				370	402	511
KBH4 (potassium borohydride)	$ 1.5					1110.0	0.93	3.07					372	
H2O		l				1000.0	1.03	2.77			289	331	371	458
AlH3 (aluminum hydride)		s				1486.0	0.69	4.11			288	322	367	526
MgH2	$ 630.1	s				1450.0	0.71	4.02			246	314	353	425
NaH		s				1390.0		3.85					337	
H2O2		l				1463.0	0.70	4.05			252	288	322	392
C12H10		s				1222.0		3.38					321	
N2		l				808.0	1.27	2.24			211	238	263	306
CO2		l				770.0	1.34	2.13			195	222	248	304
Ne						1207.0	0.85	3.34			200	227	248	287
Mn	$ 2.3	s				7470.0	0.14	20.68					209	
Ar		l				1400.0	0.73	3.88			142	161	177	204
I2 (Iodine)		s				4933.0	0.21	13.66			79	93	103	118

Propellant	P chamber (bar)	Flow freeze point	Expansion ratio	Dsp @ 3000 K	Payload fraction relative to LOX/LH2 baseline @2000K	Payload fraction relative to LOX/LH2 baseline @2500K	Payload fraction relative to LOX/LH2 baseline @3000K	Payload fraction relative to LOX/LH2 baseline @4000K	(pay. mass)/(propellant mass) rel. to LOX/LH2 @2000K	(pay. mass)/(propellant mass) rel. to LOX/LH2 @2500K	(pay. mass)/(propellant mass) rel. to LOX/LH2 @3000K	(pay. mass)/(propellant mass) rel. to LOX/LH2 @4000K
LOX/LH2	100	throat	100	163								
LOX/RP-1	100	throat	100	360								
LH2-NBP	100	throat	100	69	1.7	2.1	2.4	2.8	5.3	8.2	11.2	17.3
Slush LH2 @?K	100	throat	100	83	2.0	2.3	2.6	2.9	6.1	9.0	12.0	18.1
Be(BH4)2 (beryllium borohydride)	100	throat	100	363	1.5	2.4	2.7	3.0	1.4	3.7	5.1	8.1
LiBH4 (lithium borohydride)	10	None (eqm)	100	391	1.9	2.5	2.7	3.2	2.1	3.7	4.9	10.0
NH3BH3 (borozane, ammonia borane)	10	None (eqm)	100	457			2.7				5.0	
B2H6 (diborane)	10	None (eqm)	100	273			2.5				4.2	
Methane (or LNG)	100	throat	100	233	1.2	1.9	2.4	3.0	1.0	2.3	4.0	8.1
SLCH4	100	throat	100	271	1.3	2.0	2.5	3.0	1.1	2.4	4.1	8.2
Li3AlH6	10	None (eqm)	100	626	1.6	2.1	2.7	3.1	1.3	2.2	4.3	7.6
LHe	100	throat	100	80	-0.1	0.9	1.3	2.0	-0.1	1.1	2.1	4.3
BeH2	100	throat	100	354	1.2	2.1	2.5	2.9	0.9	2.5	3.8	6.6
(NH4+BH4-) Ammonium borohydride	100	throat	100	343	1.2	2.1	2.4	2.9	0.9	2.4	3.6	6.6
LiH	100	throat	100	437	0.3	2.2	2.5	2.9	0.2	2.5	3.7	6.5
Al(BH4)3 (aluminum borohydride)	10	None (eqm)	100	414			2.5				3.5	
LiAlH4 (LAH)	10	None (eqm)	100	479	0.1	1.2	2.5	2.9	0.1	0.8	3.5	6.0
Lithium	10	None (eqm)	100	265		1.8	2.1			2.0	2.6	
Ethane	100	throat	100	265	-0.2	1.4	2.0	2.6	-0.1	1.3	2.4	4.8
Ethane (C2H6) @ 90 K	100	throat	100	317	0.0	1.5	2.1	2.7	0.0	1.4	2.5	4.9
NH3 (ammonia)	100	throat	100	294			2.0				2.2	
NH3-Solid	100	throat	100	389			2.1				2.4	
NBP Propane, 231.04K,101350kPa	100	throat	100	272	-0.8	1.4	1.9	2.5	-0.4	1.2	2.0	4.2
Propane (C3H8) @91.5K,0.7kPa	100	throat	100	340	-0.5	1.5	2.0	2.6	-0.2	1.3	2.1	4.4
C20H42 (Icosane)	10	None (eqm)	100	354			1.9				2.0	
Butane (C4H10)	100	throat	100	274	-1.1		1.8	2.5	-0.5		1.8	4.0
NaBH4 (sodium borohydride)	10	None (eqm)	100	475			1.9				1.8	
N2H4	100	throat	100	427	-0.5	0.9	1.6	2.4	-0.2	0.5	1.4	3.3
Methanol* (C3OH) @20degC	100	throat	100	337		0.7	1.5			0.5	1.3	
RP-1*	100	throat	100	345			1.5				1.2	
SiH4 (silane) - NBP	100	throat	100	224		0.1	0.9	2.2		0.1	0.7	3.0
KBH4 (potassium borohydride)	10	None (eqm)	100	413			0.7				0.4	
H2O	100	throat	100	371	-3.5	-0.7	0.6	2.0	-0.9	-0.3	0.4	2.1
AlH3 (aluminum hydride)	100	throat	100	545	-3.1	-0.8	0.7	2.6	-0.8	-0.3	0.4	3.7
MgH2	100	throat	100	512	-9.1	-1.3	0.3	1.8	-1.2	-0.4	0.2	1.5
NaH	10	None (eqm)	100	469			-0.2				-0.1	
H2O2	100	throat	100	471	-7.8	-3.1	-0.9	1.3	-1.2	-0.8	-0.3	0.9
C12H10	10	None (eqm)	100	392			-1.0				-0.4	
N2	100	throat	100	212	-24.8	-12.5	-7.1	-2.4	-1.7	-1.5	-1.3	-0.7
CO2	100	throat	100	191	-38.7	-19.0	-10.1	-2.6	-1.8	-1.6	-1.4	-0.8
Ne	100	throat	10,20,20,20	300	-30.5	-15.0	-8.8	-3.4	-1.6	-1.4	-1.3	-0.9
Mn	10	None (eqm)	100	1560			-20.3				-1.3	
Ar	100	throat	10,20,20,20	247	-263.7	-112.1	-62.9	-26.8	-1.7	-1.7	-1.7	-1.6
I2 (Iodine)	100	throat	100	506	-7E+04	-1E+04	-4E+03	-1E+03	-1.6	-1.6	-1.6	-1.6

HEAT EXCHANGER WEIGHT WILL NOT NEGATE THE PERFORMANCE ADVANTAGE

- This year: 5-10 kg/m^2, 1700 K. Ceramic tubes; metal tubes but not roll-bonded
- In 2-5 years: 1-5 kg/m^2, 2500 K. Roll-bonded and graphite tubes
- In 5-15 years: <0.1 kg/m^2, 3500 K. rGO paper or similar

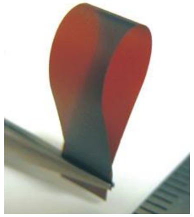
- Final heat exchanger will combine roll-bonded, ceramic and graphite in different areas of the beam to produce max. temperature for minimum weight
- Graphene heat exchangers (e.g. rGO), whenever they happen, will enable very large area, lightweight, heat exchangers that could substantially shrink beam facility size and cost

Roll-bonded
0.1-5 kg/m^2
<1 MW/m^2
<1200 K
(Artal Italiana panels shown)

Ceramic tubes
1-10 kg/m^2
<10 MW/m^2
<2500 K

Graphite tubes
1-5 kg/m^2
<1 MW/m^2
<3500 K

rGO paper
~0.003 kg/m^2
<1 GW/m^2
<4900 K

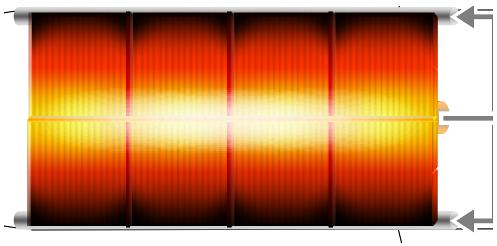


Comparative Advantage of Thermal Rockets

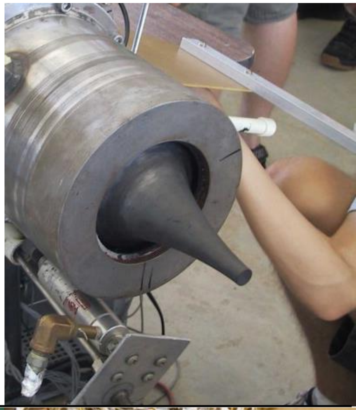
Complexity

Added

Heat exchanger
(final form and areal density TBD)



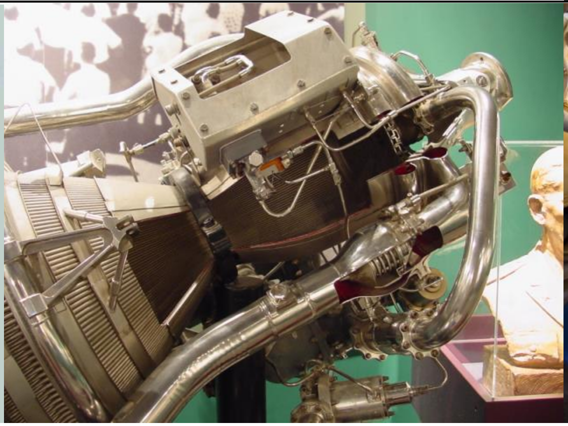
Uncooled graphite plug nozzle
(CSULB P-2 shown)



Subtracted

Intertank structure
(Delta upper stage shown)

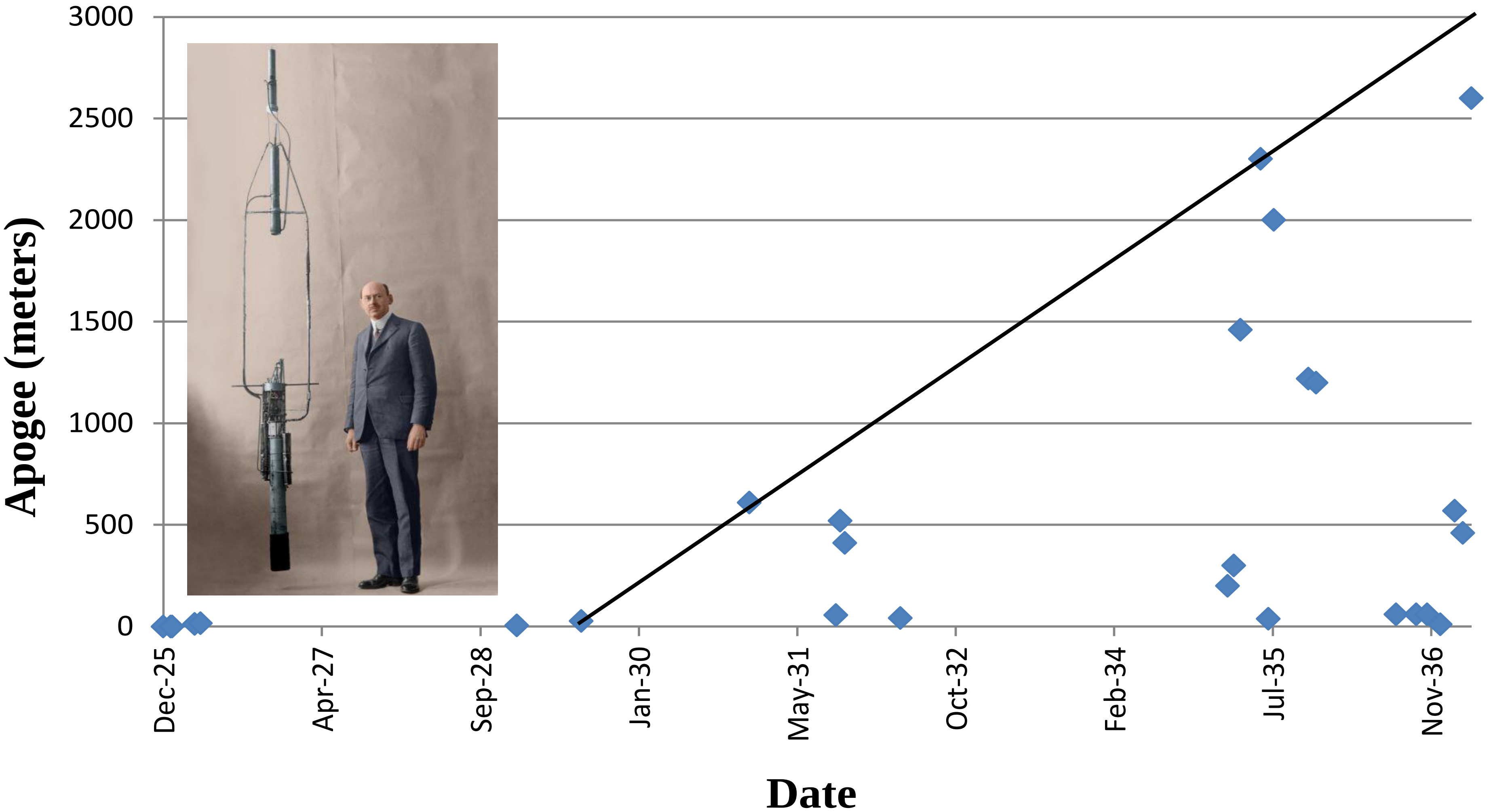
All LOX components (shown in blue)
(RD-0146 shown)



Injector
Combustion chamber
(RL-10 shown)

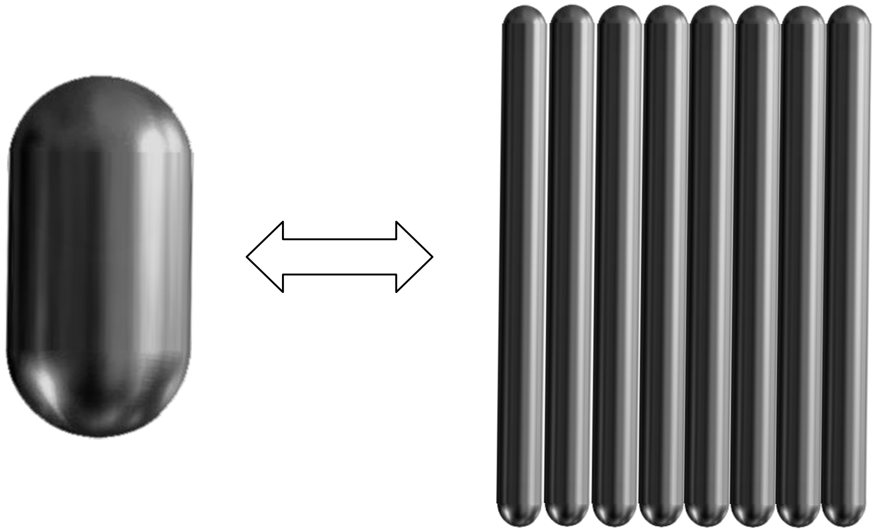
Regeneratively-cooled bell nozzle
(RL-10 shown)

The world record apogee for a beamed energy launch is currently 71 meters. It was set in the year 2000 at HELSTF by Leik Myrabo.

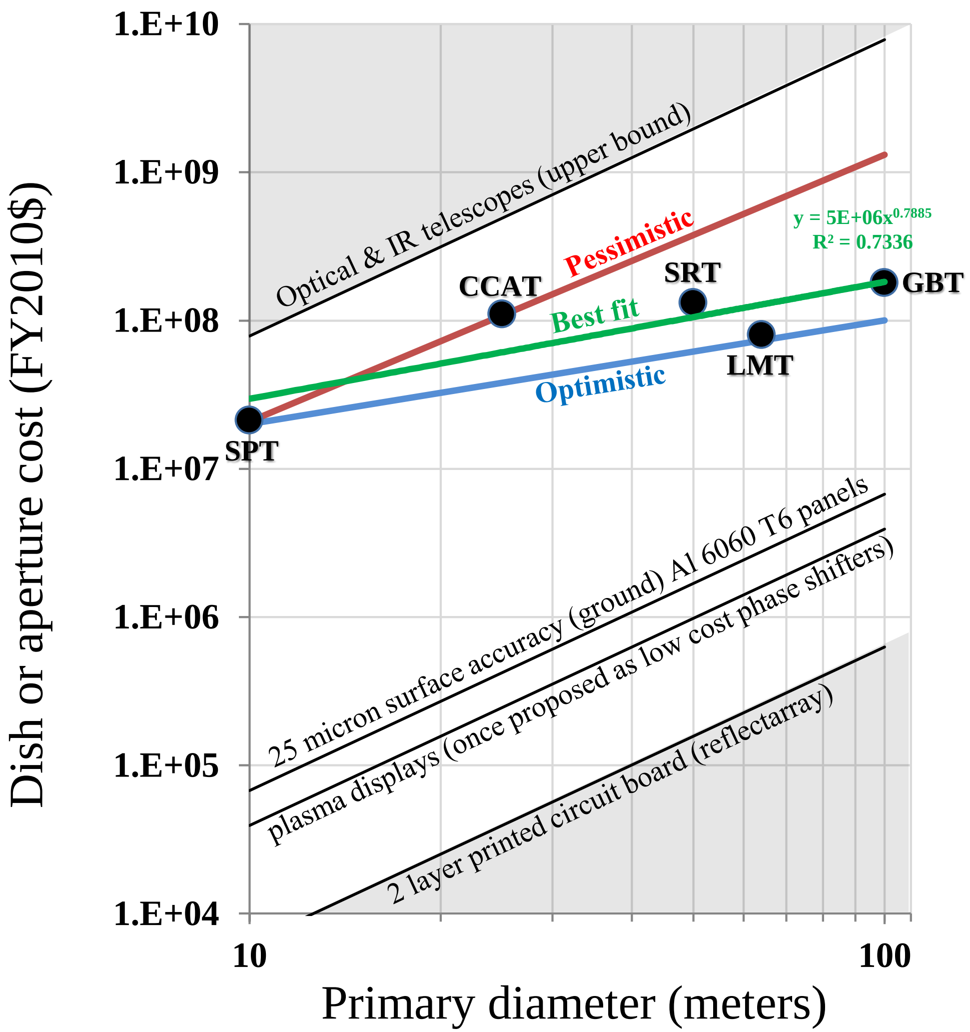


WANTED PHASE III TECHNOLOGIES: FOIL BALLOON TANKS

- Attractiveness of LH_2 thermal rockets increases as tank technology gets lighter
- Using pre-launch helium tent, insulation is not needed (air density at 20 km is 14x lower)
- At LH_2 temperatures, 15-3-3-3 titanium has UTS of > 1.9 GPa (280 ksi)
  - Excluding end-caps, longitudinal forces, weld efficiencies and safety factors
  - Assuming 2 bar pressure and SD kitchen foil thickness of 16.5 microns (0.65 mil):
    - $\mathrm{D} = 2 \times \frac{\sigma t}{P} = 2 \times \frac{1.9E9 \times 16.5E-6}{2E5} = 0.31\ meters$
    - $\frac{m_{LH2}}{m_{tank}} = \frac{\frac{\pi}{4} D^2 L \rho_{LH2}}{\pi D L t \rho_{Ti}} = \frac{D}{4t} \frac{\rho_{LH2}}{\rho_{Ti}} = \frac{0.31}{4 \times 16.5E-6} \frac{70.8}{4780} = 70\ kg/kg$
    - Tank could be split into many standard diameter tubes
      - Mass is unchanged because thickness varies. Less slosh. Higher heating. Higher drag. Higher lift.
      - Potentially very cheap and easy to make
      - Doubling target diameter halves dish diameter (e.g. 100 m -> 50 m)



WANTED TECHNOLOGIES: CHEAPER APERTURE



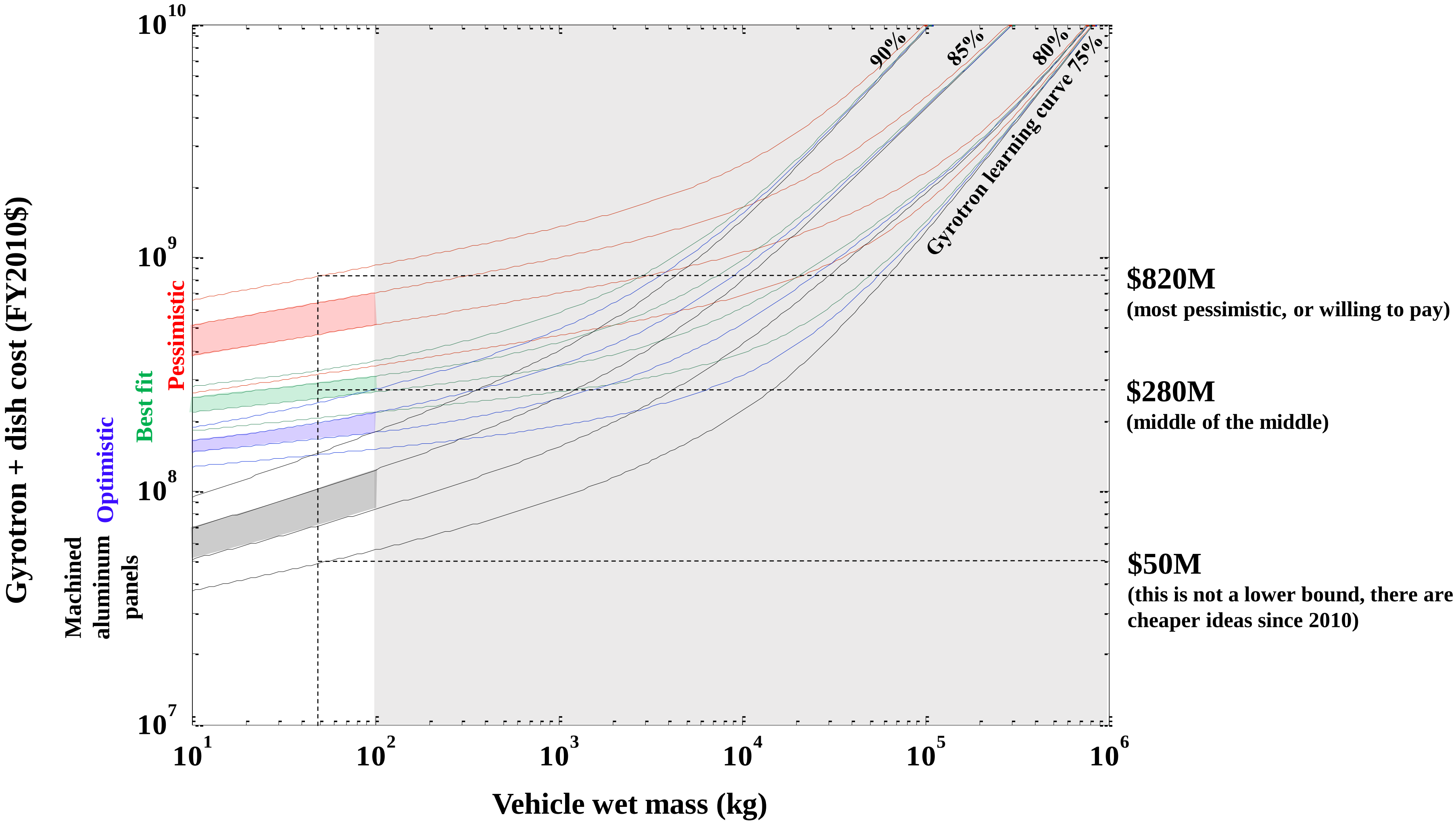
A mm-wave rocket beam facility is now affordable to governments. However, reduced aperture cost would make it more affordable for DARPA.

Future work should look into:

- CCAT 10 μm active surface on GBT-size dish
- Multiple smaller dishes (adds beam splitting stage)
- Radar-style (non-circular) dishes
- 1D,2D Fresnel reflectors; beam steering options
- Holographic reflectors; beam steering options
- Low-cost reflectarrays; beam steering options
- Tactile or plasma displays as spatial modulator (*enables fixed primary to be laid out flat on the ground*)
- Hollow beams e.g. Bessel-Gauss (*reduces area, mass and cost of primary aperture*)
- Negative refractive index techniques (*e.g. Wee, W. H., and J. B. Pendry. "Super phase array." New Journal of Physics 12.3 (2010): 033047*)
- Artificially generating ionospheric plasma lens in D-region using HAARP or similar

Each data point is the construction cost of a millimeter wave telescope which uses an active surface primary. The best fit curve to the data is a power law where dish cost varies with diameter to the power of about 0.8. Historical dish costs are inflation-adjusted on a Production Worker Compensation basis.

Power vs. aperture tradeoff for minimum cost



- **A beam facility is in the price range of typical government rocket development programs ($0.1-$40Bn)**
  - It may soon be affordable to wealthy individuals – a middle estimate for 50 kg beam facility is $280M
  - Cost scaling as mass increases is very favorable – a middle estimate for 500 kg is $600M
    - This scaling is even more favorable for the pessimistic case – 50 kg for $820M vs. 500 kg for $2Bn
- Low areal density heat exchangers e.g. graphene are substantially cheapen these cost estimates due to larger target size

Point design for orbital launch

Inputs

Wet mass	50 kg
Dry Mass Margin	30%
Delta V	9.7 km/s
LH2 initial tank state	1.5 bar, 16 K
Tank L/D ratio	2
Nose fineness ratio	2
Tank overall factor of safety	1.25*2.0 = 2.5
Nozzle factor of safety	2.0
Max. T/W0	5.4
Overhead for structural mounts	10% of propulsion subsystem mass
Stagnation pressure at nozzle	10 bar
Nozzle expansion ratio	100
HX channel	Roughness = 0.002, Wall thickness = $D_h/20$
HX channel outlet	Re = 15,000, M = 0.7, static T = 1,750 K

Point design for orbital launch
Outputs: Mass breakdown

Tank	1.5 kg (0.62 m diameter, 42 µm thick 15-3 Ti)
Turbopump	1.9 kg
Heat exchanger	2.0 kg (622 alumina channels, D_h = 1.9 mm, peak wall T = 1,900 K, inlet P = 45 bar, avg. intensity at surface = 6 MW/m^2)
Nozzle	0.1 kg (I_{sp} = 724 sec, length = 28 cm, Nb-alloy)
Nosecone	0.63 kg
Payload adapter	0.25 kg
Reaction control system	8.5 g (this looks low and will be revisited)
Structural mounts	0.4 kg
Avionics	1.0 kg
Dry mass margin	2.9 kg
Payload	2.0 kg (subject to further change)
Propellant	37 kg

Point design for orbital launch
Outputs: Figures of merit

Payload fraction	4.1 %
Payload	2.0 kg
Vacuum I_{sp}	721 sec
Propulsion T/W	67
Absorbed power	10 MW
Thrust	2.6 kN
Mass flow rate	0.37 kg/sec of H_2
Reminder from inputs:	
Wet mass	50 kg
Dry mass margin	30%

- Zero payload reached at wet mass of ~ 30 kg
- Could increase delta V to 11 km/sec and still preserve positive payload (0.2 kg)

Caveats:

- This is minimal scale and there is much to refine in the models, including the ascent trajectory. These numbers *will* change.

Launch Cost Estimate Breakdown

- Based on current point design for 2 kg payload launcher (50 kg wet mass)
- **The very low weight and cost is enabled by millimeter-wave thermal propulsion**
- Little more than a rough cost estimate makes sense at this early stage
- Costs will decrease further with volume production and as the system becomes reusable
  - Cars cost $7/kg as a rule of thumb

Component	Mass (kg)	Cost	Cost justification
Tank	1.5	$ 1,800	Complex short run aircraft rule of thumb: $1,200/kg
Pump	1.9	$ 3,948	JetCat turbines cost $2078/kg. Assuming similar.
Heat exchanger	2	$ 6,220	622 alumina channels, Dh = 1.9 mm, $10 per tube in bulk
Nozzle	0.1	$ 120	Complex short run aircraft rule of thumb: $1,200/kg
Nosecone	0.63	$ 756	Complex short run aircraft rule of thumb: $1,200/kg
Payload adapter	0.25	$ 300	Complex short run aircraft rule of thumb: $1,200/kg
Reaction control system	0.008	$ 10	Complex short run aircraft rule of thumb: $1,200/kg
Structural mounts	0.4	$ 480	Complex short run aircraft rule of thumb: $1,200/kg
Avionics	1	$ 1,200	Complex short run aircraft rule of thumb: $1,200/kg
30% dry mass margin	2.9	-	
Payload	2	-	
Propellant	37	$ 248	Based on $6.7/kg for LH2
		$ 15,082	
Integration		$ 15,082	Assumed equal to component cost
Electricity		$ 264	Based on 30 MW for 300 sec. and industrial grid rate of $0.1055/kWh for California on May 1, 2013
Total	49.688	**$ 45,509**	Excludes operational personnel cost and initial R&D + beam facility cost

Vision: Reliable same-day cubesat launch to LEO for $50k

Use beamed energy propulsion to reduce the size, complexity and cost of the rocket

Initially 1-3 kg cubesats to orbit

- Nanosats and cubesats – NASA, University, DoD STP, AF RDT&E, ORS, disaggregated payloads
- Water for life support and future propellant requirements
- Raw material for near-future 3-D printer needs

Growing to larger payloads as beam power is increased

Aircraft-like approach

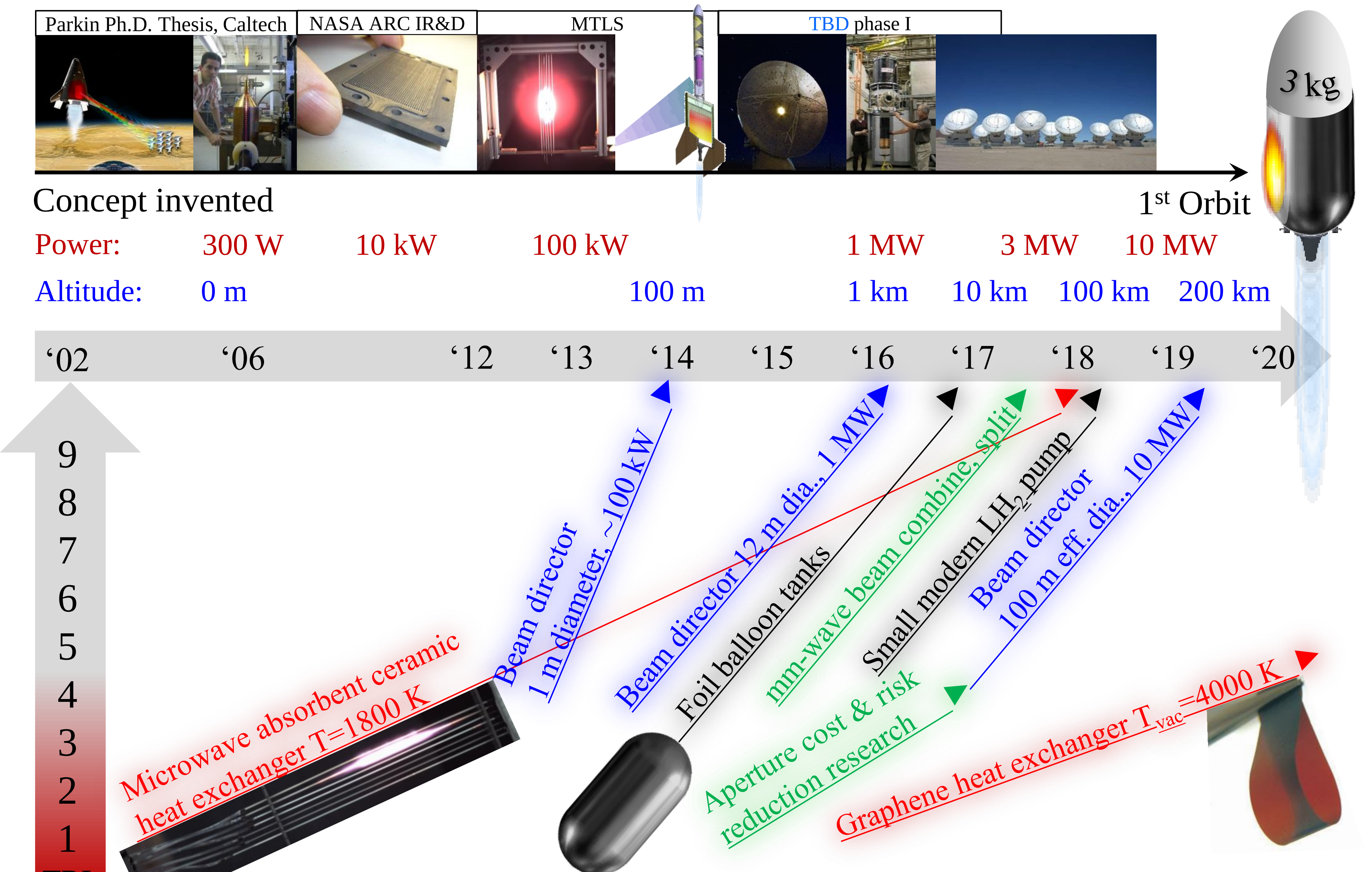
- Dispense with the expensive big rocket mindset. Minimal ceremony. Greater risk tolerance.
- Baseline traffic: Launch 1 rocket every 3 days (cubesat demand forecast >100/year by 2020)
- Surge capability: Launch 1 rocket every 4 minutes per beam director (no fundamental reason this cannot be so. 4 minutes is the duration of an ascent trajectory. The Mk 29 NATO Sea Sparrow launcher can launch 1 rocket every 2 seconds.)

Each cubesat-class beam director is capable of putting 300,000 kg into orbit per year

- Transform the economics of space access from low-rate high-cost, to high-rate low-cost

Increasing to a daily stream of mass to orbit and eventual payload costs of <$100/kg to LEO

Notional Schedule



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