Solar Array Structures for 300 kW-Class Spacecraft

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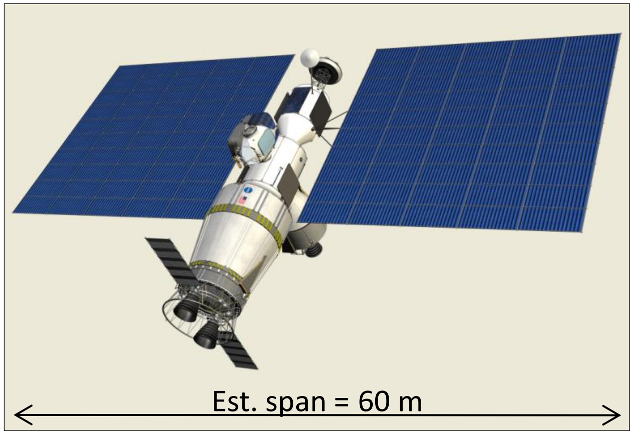
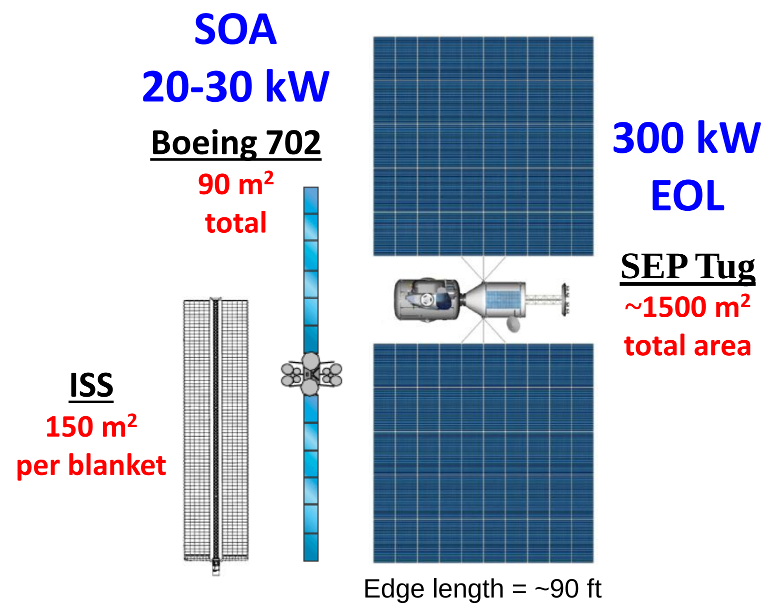
Space Power Workshop, April 24, 2013

Solar Array Structures for 30-300 kW SEP



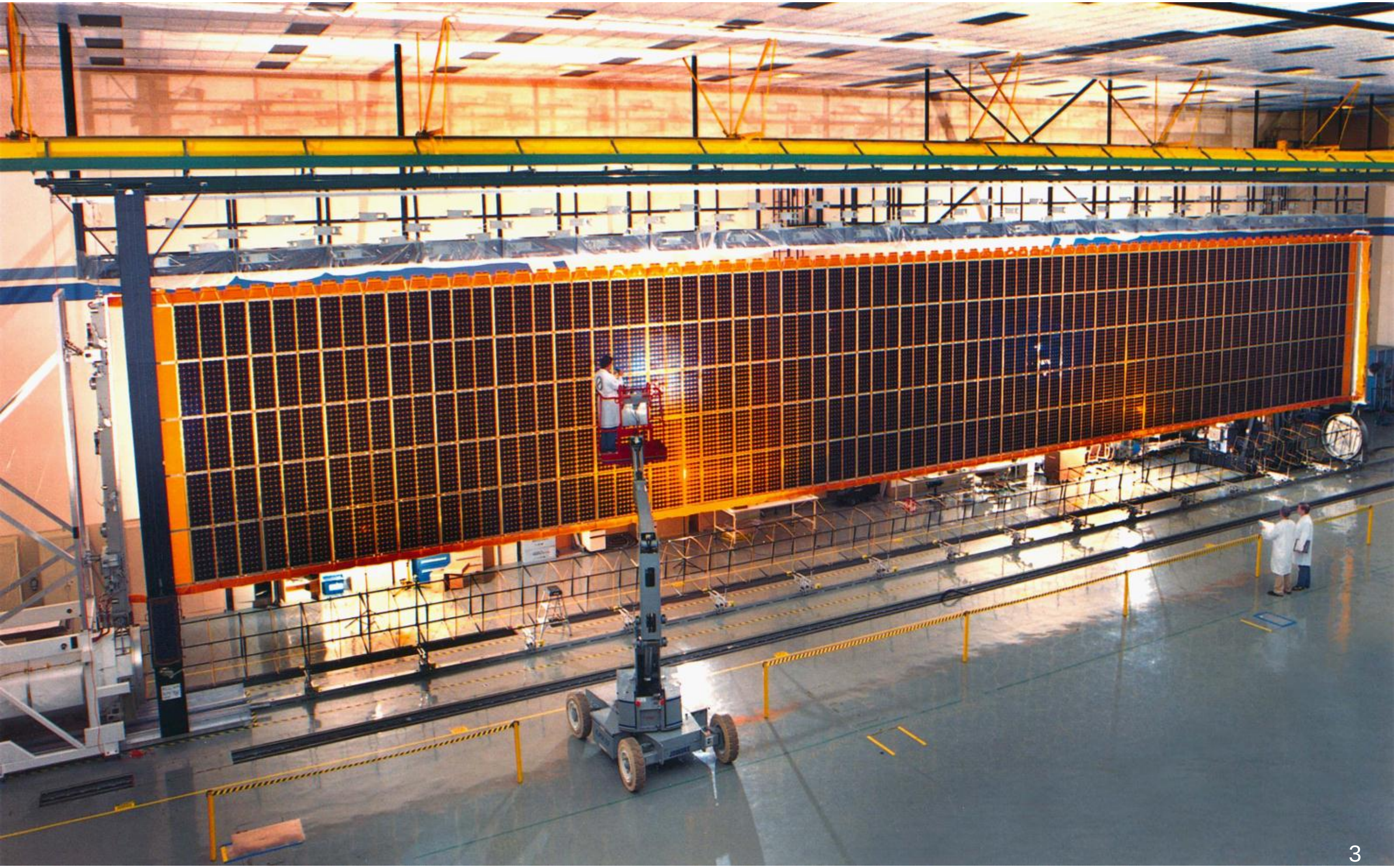
Proposed Mission to NEO using 300-kW SEP Tug (HAT DRM 34B)



Need:	Solar Electric Propulsion (SEP) for cost-effective transfer of cargo (& possibly crew) beyond LEO. SEP is ~10x more fuel-efficient than chemical.
Goal:	Develop mass- and volume-efficient solar array structures >> in size than SOA for proposed exploration and science SEP missions.
Objectives:	Mature key technologies to TRL 5+. In the near term, develop 30-50 kW designs for in-space demonstration by 2018. Far term objective is 300+ kW arrays.

ISS Solar Array Blanket – 150 m^2

A 300 kW solar array needs ~10x this area



Assumptions/Goals for 300 kW-Class Solar Arrays

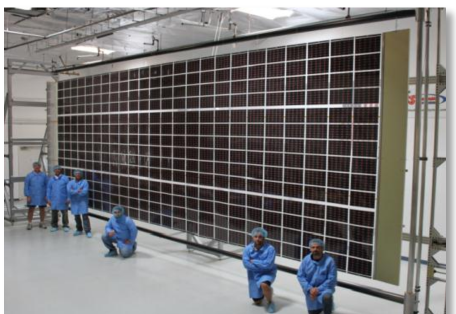
Power	• 450 kW BOL • 300 kW EOL, assuming 33% worst-case degradation
Deployed area (2 wings)	1500 m^2, assuming 300 W/m^2 BOL or 200 W/m^2 EOL
Deployed stiffness	> 0.05 Hz
Deployed strength	> 0.1 g (chemical stage thrusting in some SEP missions)
Specific power	> 120 W/kg BOL (> 100 W/kg EOL), including SADA
Stowed volume	> 40 kW/m^3 BOL
Voltage	160-300+ V
Blanket	Flexible substrate, assuming < 1 kg/m^2 areal density, 0.030" thick
Planar vs concentrators	Assuming planar arrays will be used
Deployment reliability	Goal: "100%" – Deployment is highest perceived project risk

NASA “Game Changing” Activities

for 30-300 kW Solar Array Structures

State-of-the-Art

ATK UltraFlex
14 kW array



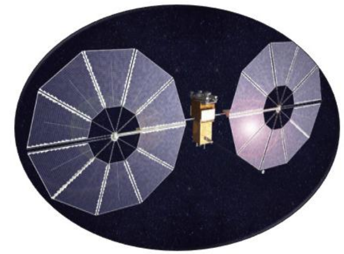
DSS ROSA
20 kW (for 2 wings)

18-month NRA Contracts

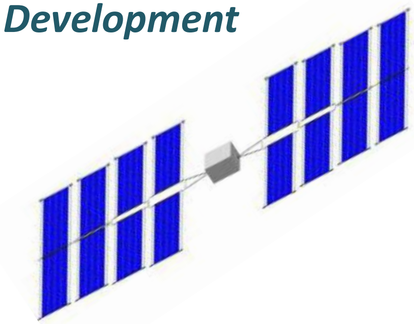
ATK MegaFlex 30-50 kW Prototype →

DSS Mega-ROSA 30-50 kW Prototype →

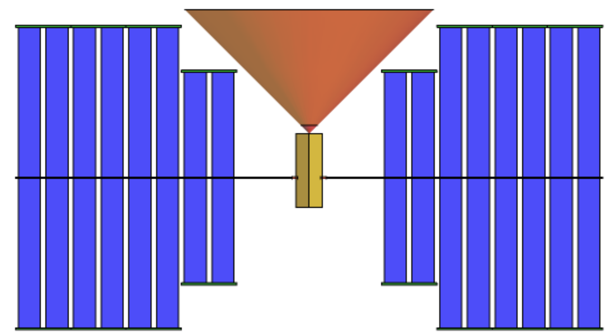
300 kW Solar Arrays (1500 m^2) Technology Development



ATK MegaFlex



DSS Mega-ROSA



300 kW Government Reference Array

Government Team Focus Areas:

- Insight & Oversight of ATK & DSS Tech Work
- IV&V of Contractor 30-50 kW Phase I Designs
- Extensibility of 30-50 kW Designs to 300 kW
- Ground Test Support (Plum Brook & Boeing)
- Structural Concepts
- Scaling and Performance Metrics
- Modeling, Simulation, and Advanced Analysis
- Development of 300 kW Govt Reference Array

Structures for Large Solar Arrays

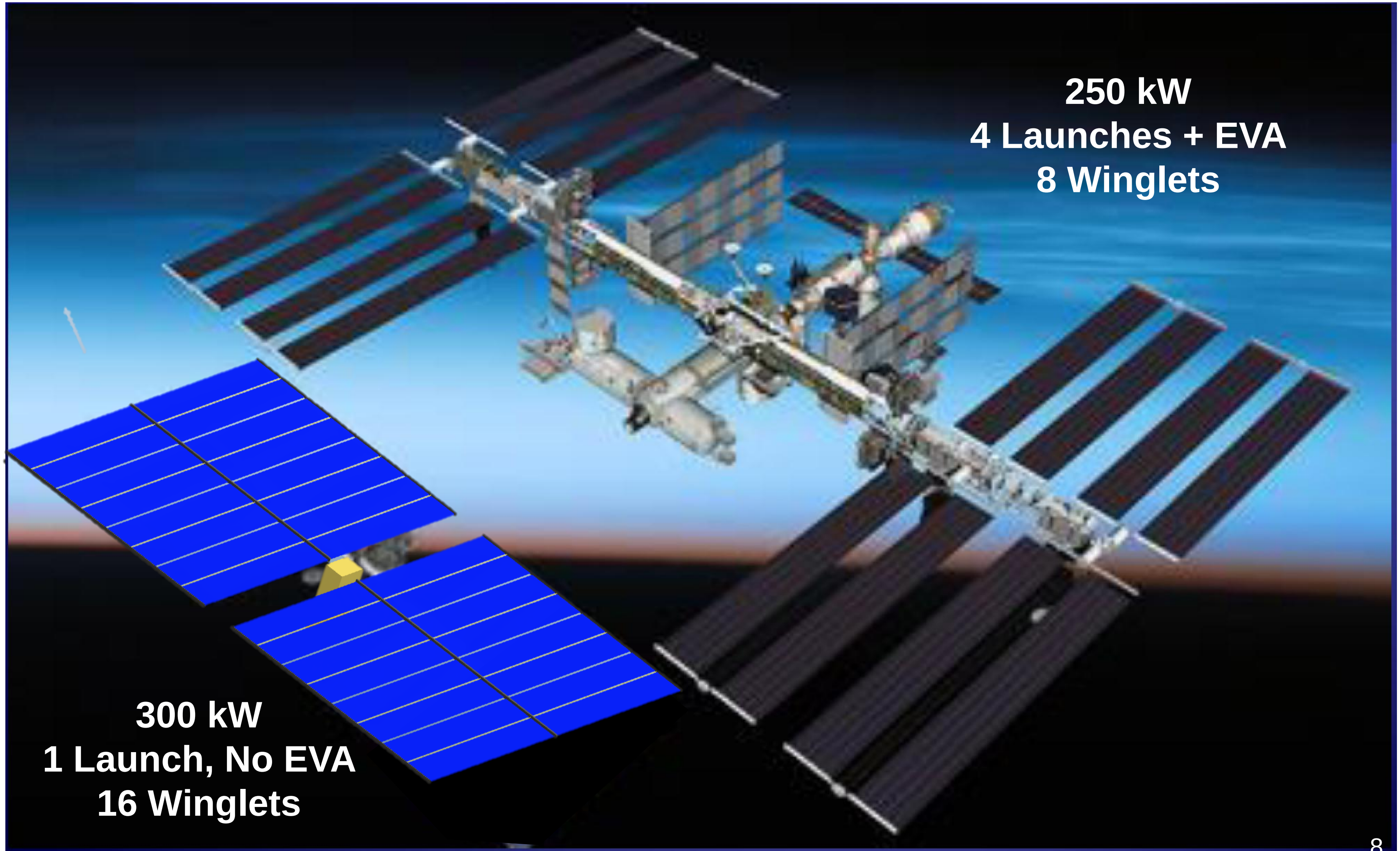
- Challenge - Scaling up solar array power by an order-of-magnitude to ~300 kW requires game changing advances in
  - structural mass fraction
  - packaging, and
  - deployment reliability
- Goal/Objective – Develop and validate array structural concepts with a
  - structural mass fraction of 0.2 or lower and a
  - power/packaging volume ~ 25 to 40 kW/m^3
- Need rational method to compare arrays on a level playing field
- Major question is how reliably results scale

Structures for Large Solar Arrays (Approach)

Develop:

- Performance metrics that enable a rational comparison of array concepts over a wide range of sizes and requirements
  - Mass, volume, deployment reliability
- Government Reference Array (GRA)
  - Intended as a bellwether for very low mass and stowage volume solar arrays
  - Provide comparison with contractors concepts
  - Establish understood array performance limits
- Analytical simulations to substantiate structural and deployment system-level array behavior
- Scaled validation tests of critical array structural characteristics identified in analytical simulations

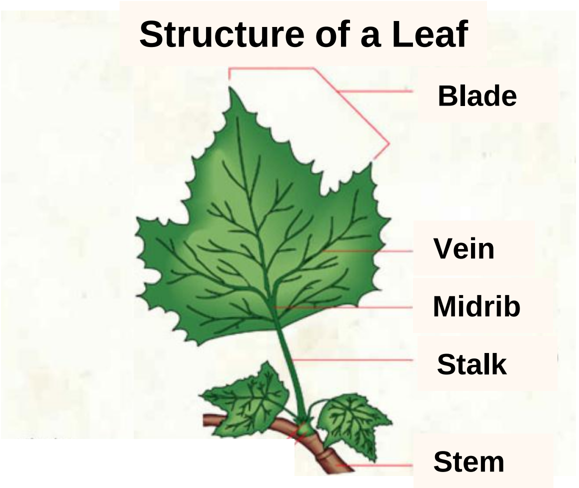
Major Challenge to Achieving High Structural Efficiency is the Compact Packaging Requirement



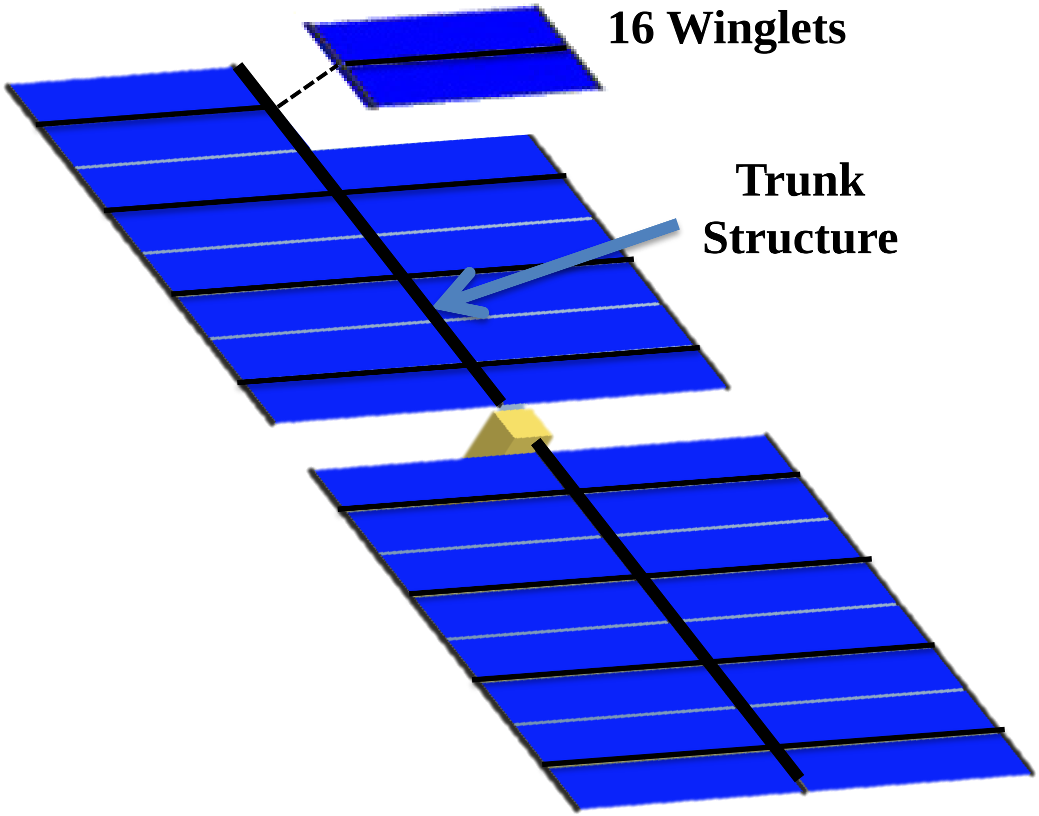
Technologies for Improving Array Structural Mass Fraction and Packaging Volume

- Structural Form
  - Tensioned arrays
  - Concentrated compression loads
  - Modular construction
  - Guy stiffening as needed
- Very high modulus composites
- Trade structures and controls requirements
  - Reduce required natural frequency
  - Allow arrays to feather during periods of high acceleration
- Lightweight deployment mechanisms
- Discard no longer needed hardware (staging)

Good Structural Form is Key to Structural Efficiency

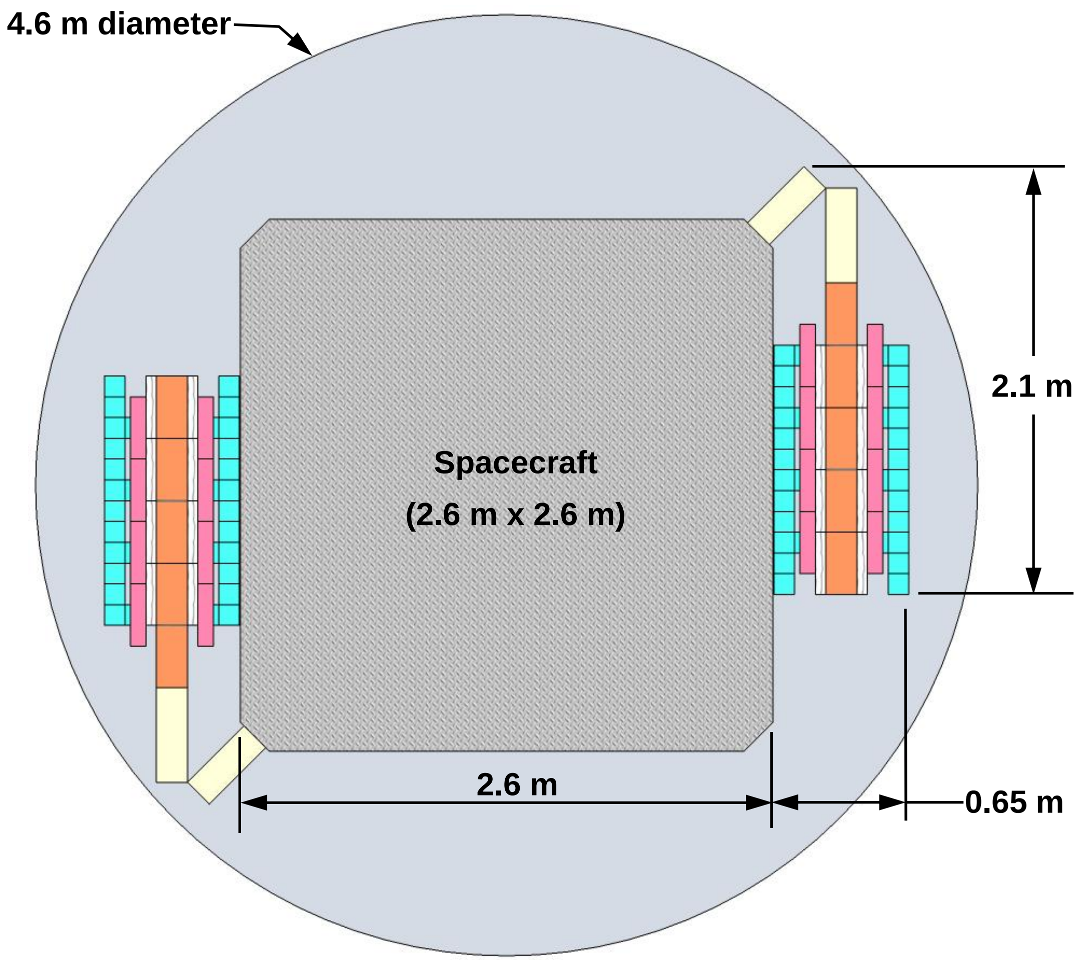


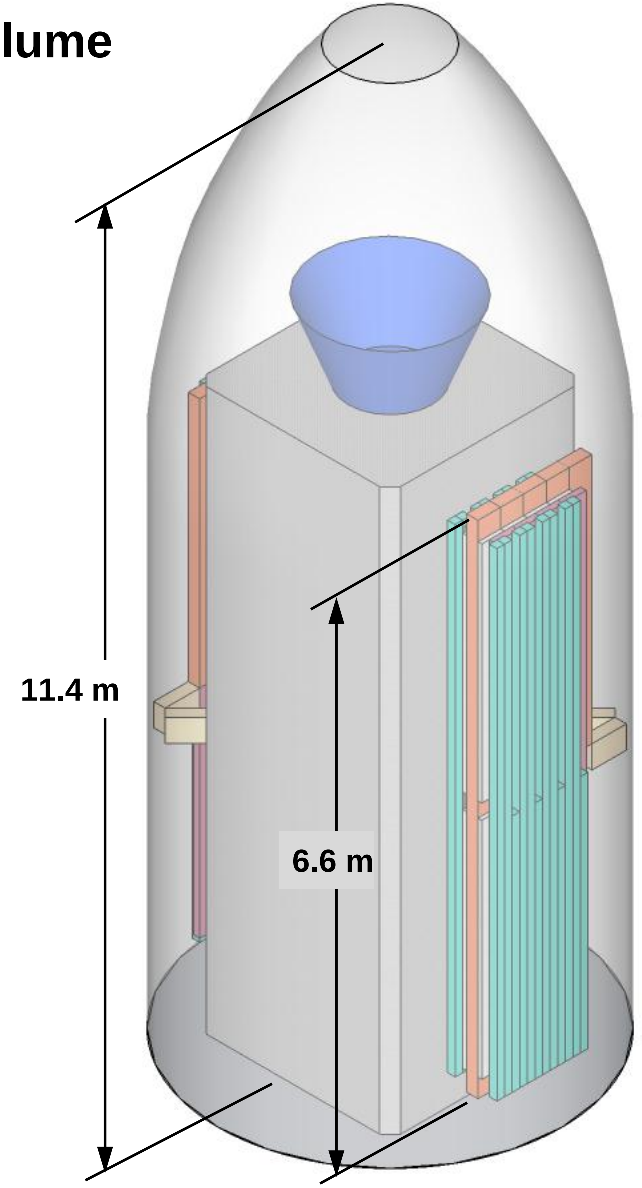
Channel (concentrate) all Loads Into one Major Support Structure



300 kW GRA Stowed Configuration

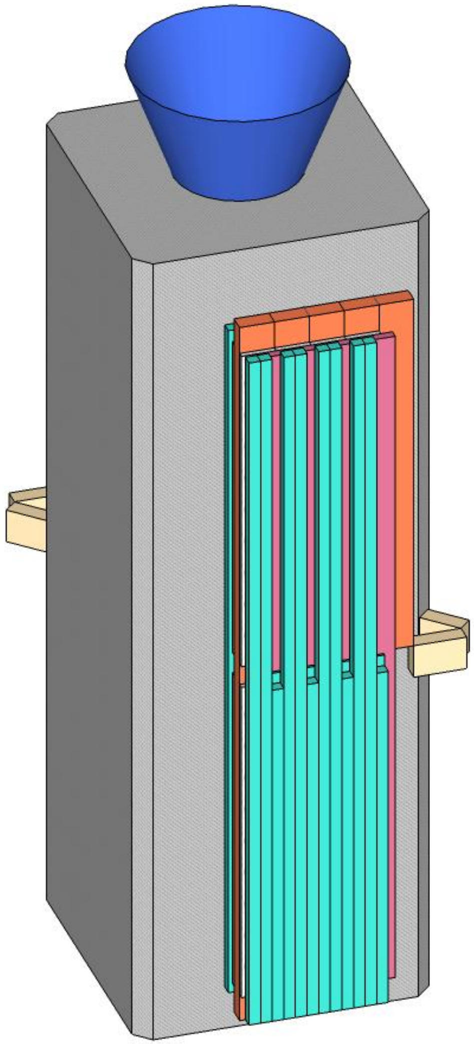
Stowed GRA inside Falcon 9 allowable payload volume



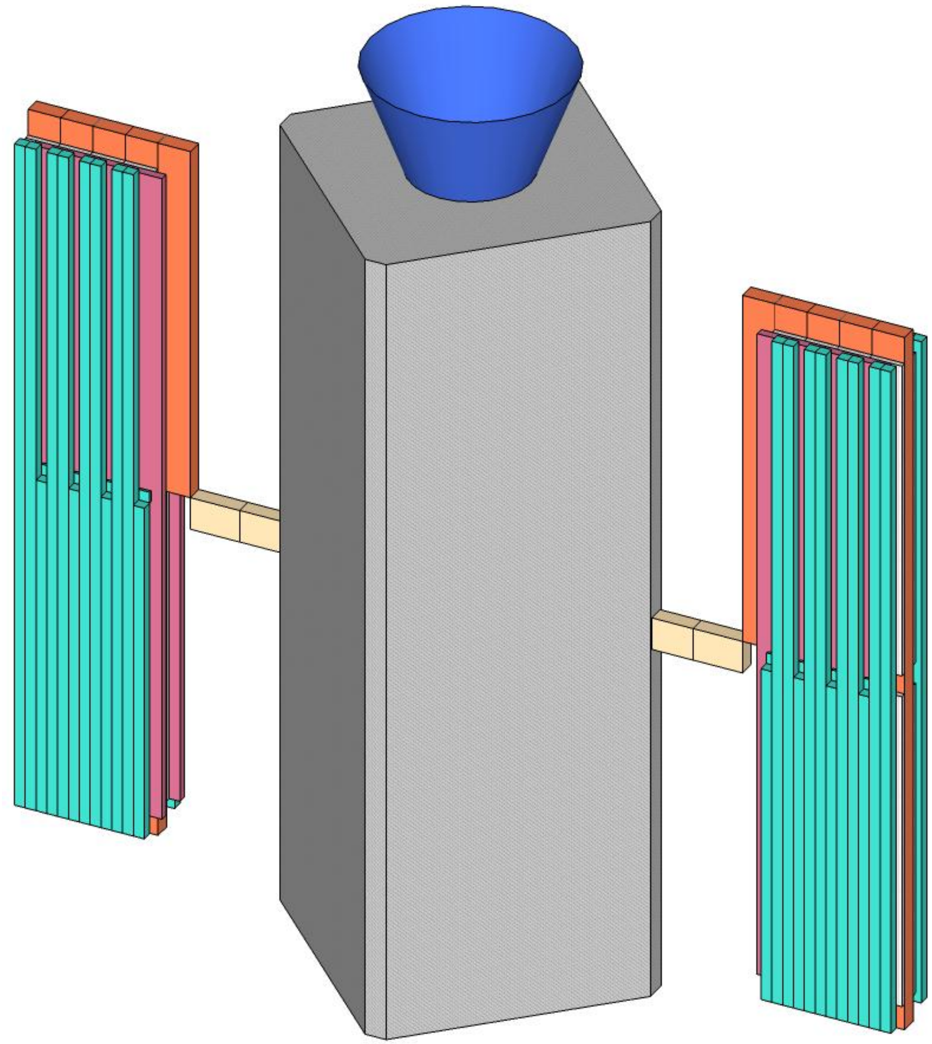


300 kW GRA Deployment Sequence

Stowed Configuration

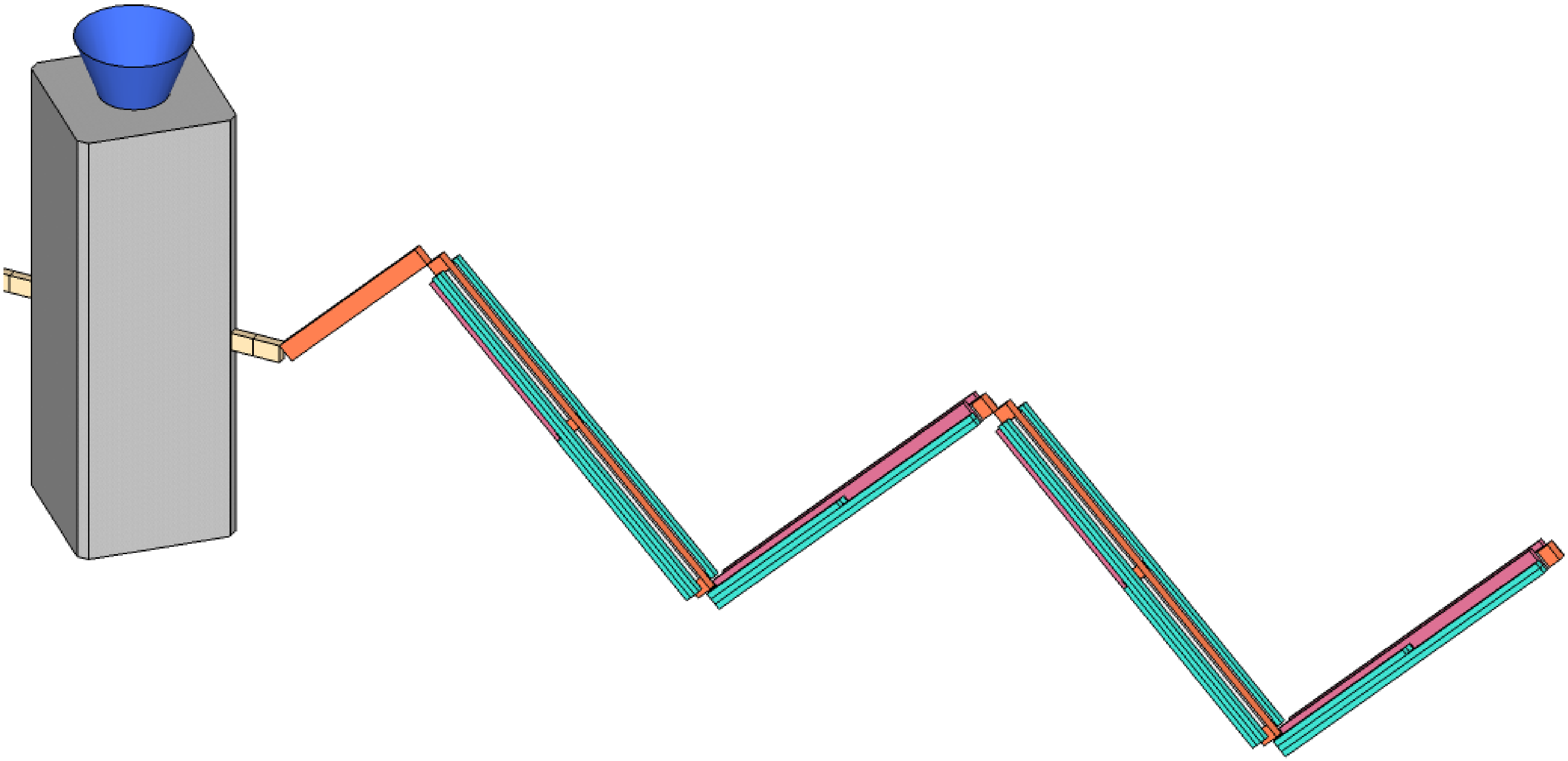


Wings Unfolded



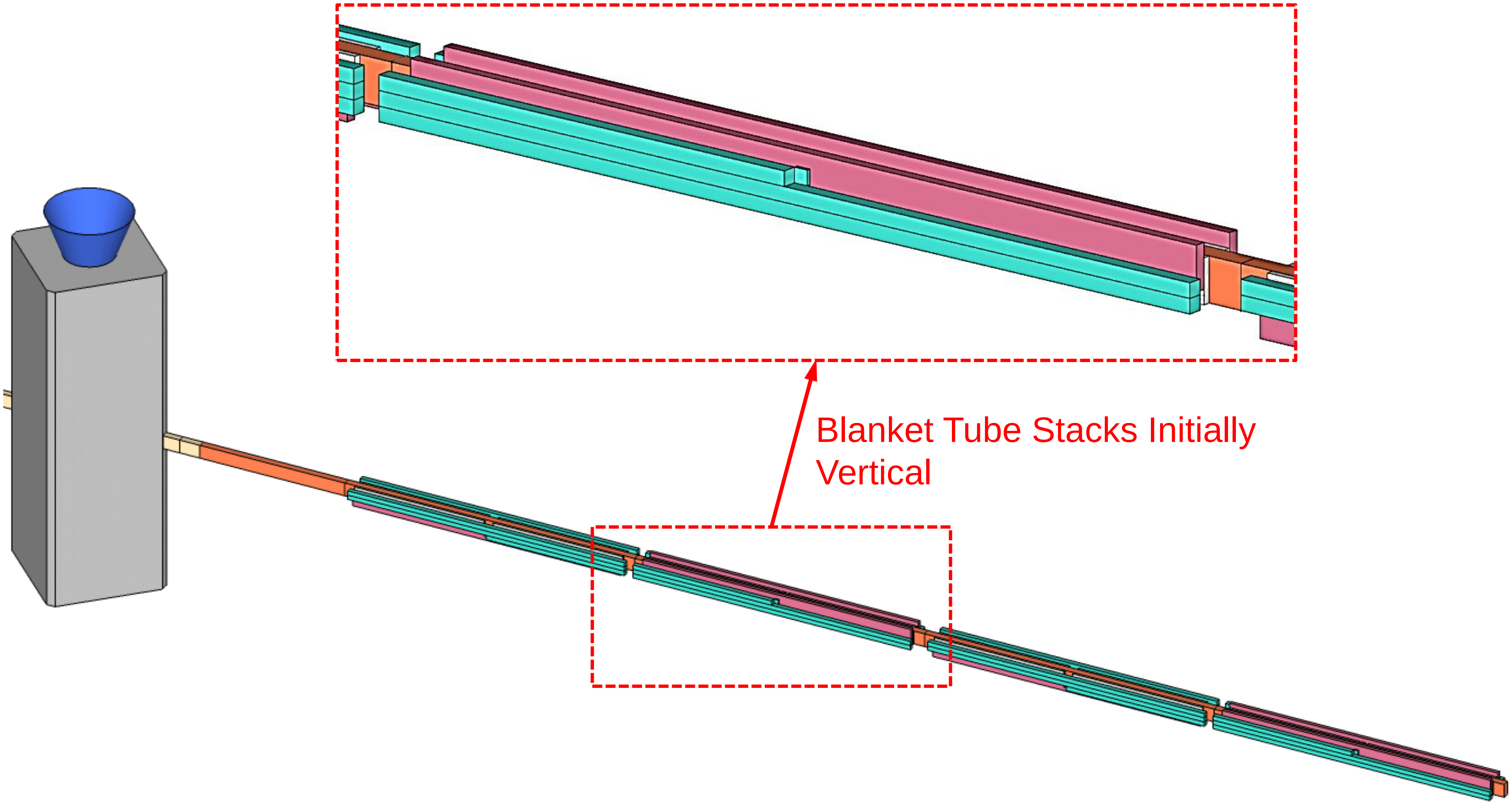
300 kW GRA Deployment Sequence

Trunk Beam Partially Extended



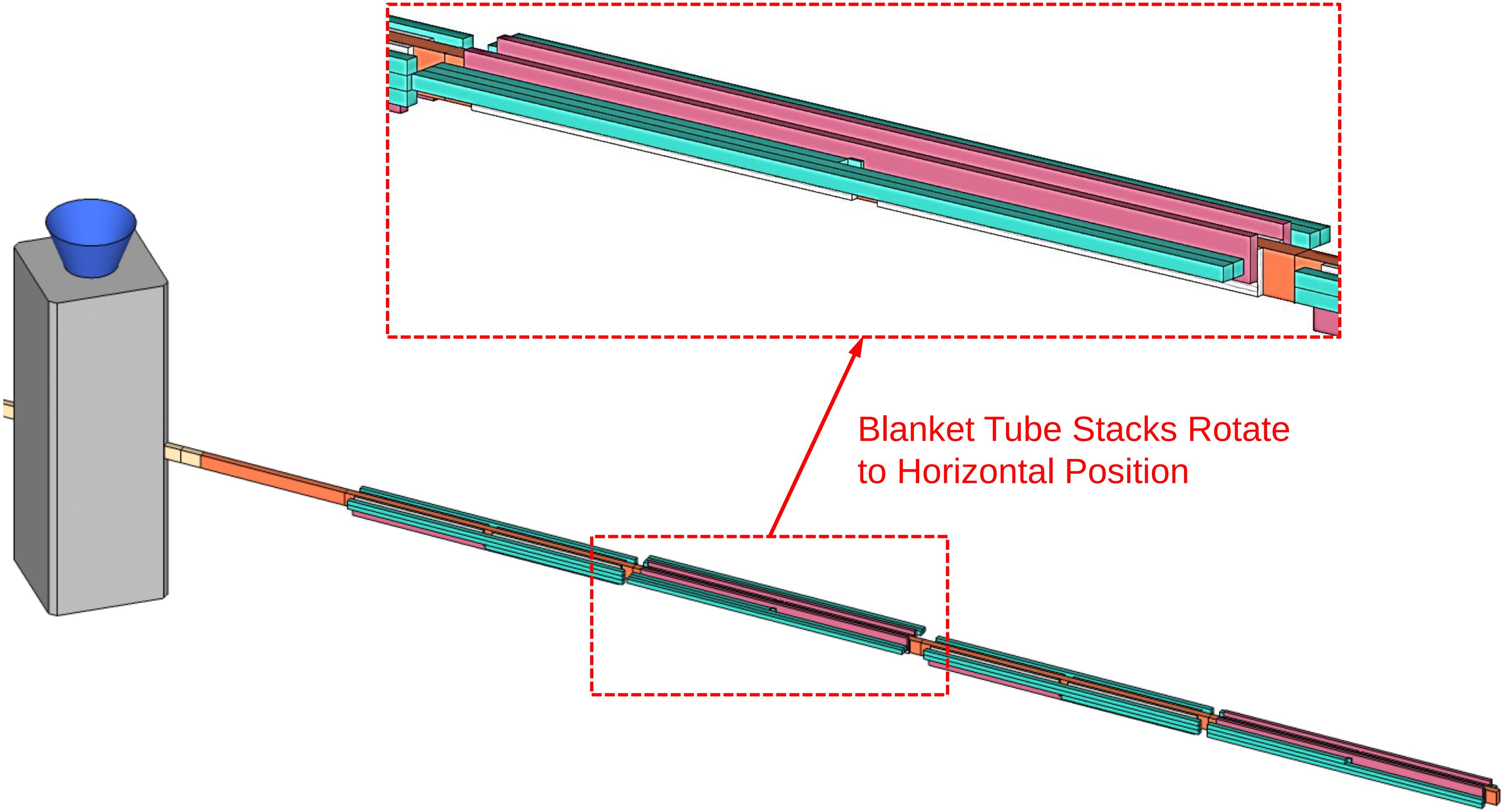
300 kW GRA Deployment Sequence

Trunk Beam Fully Extended



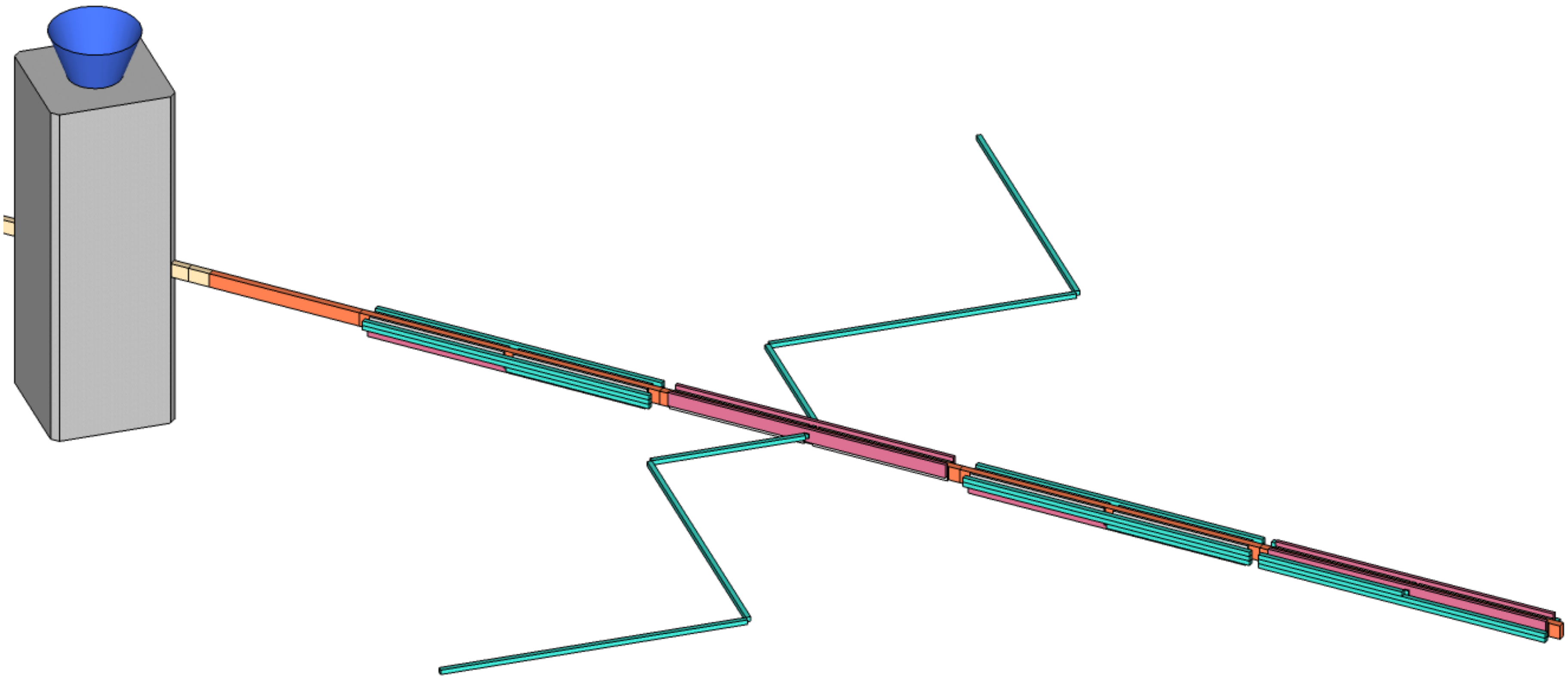
300 kW GRA Deployment Sequence

Begin Winglet Deployment



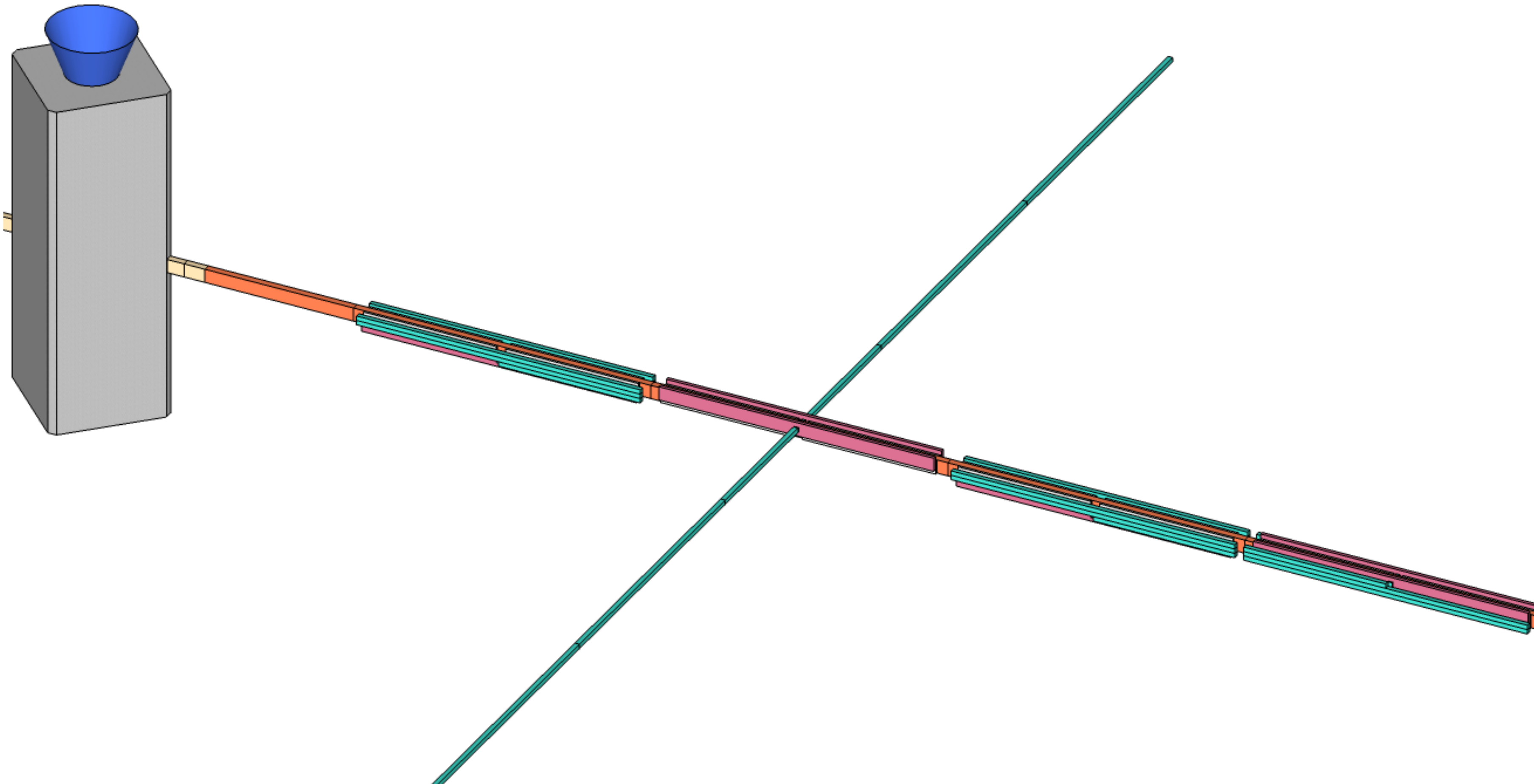
300 kW GRA Deployment Sequence

Blanket Tube Partially Extended



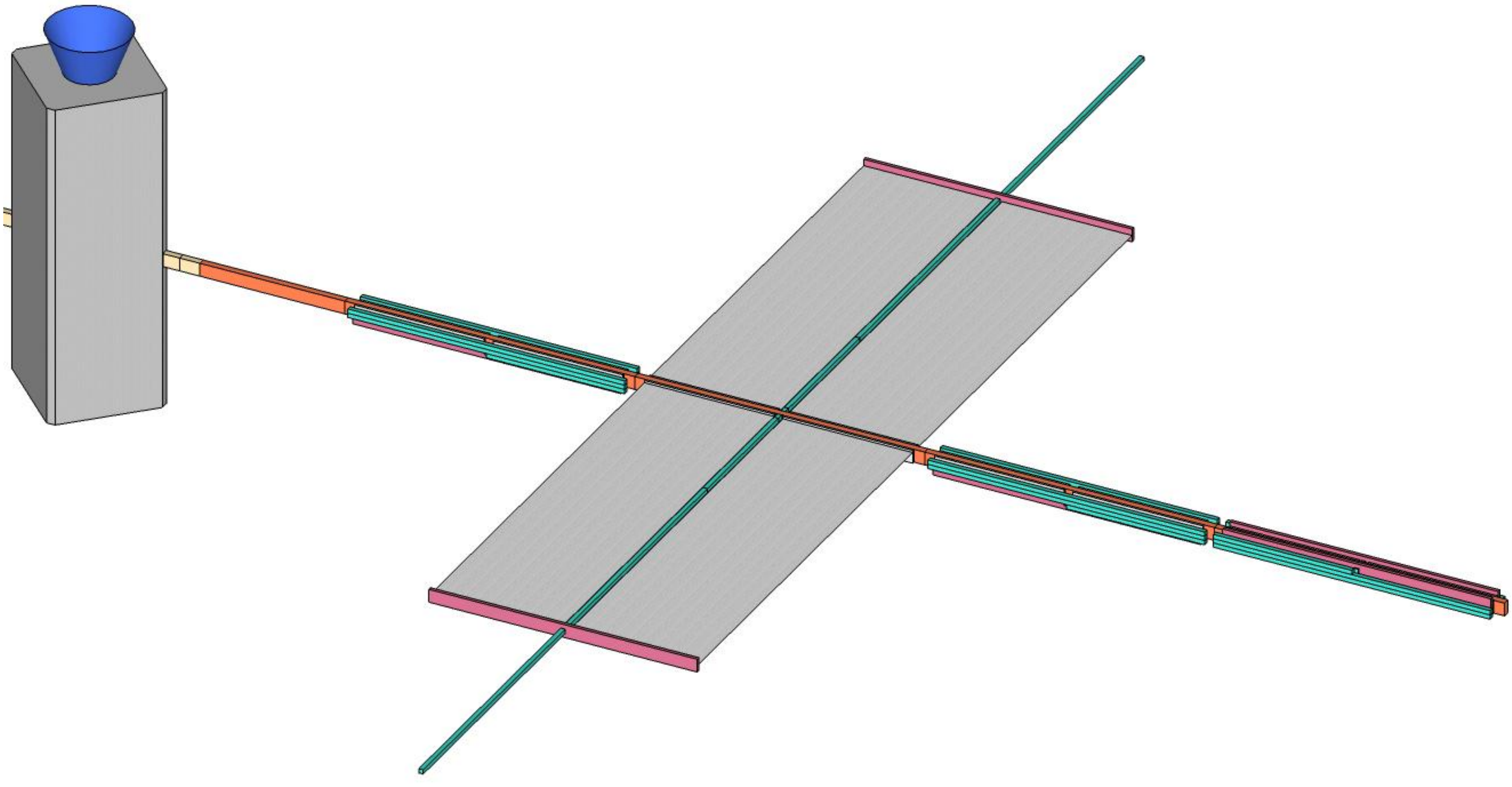
300 kW GRA Deployment Sequence

Blanket Tube Fully Extended



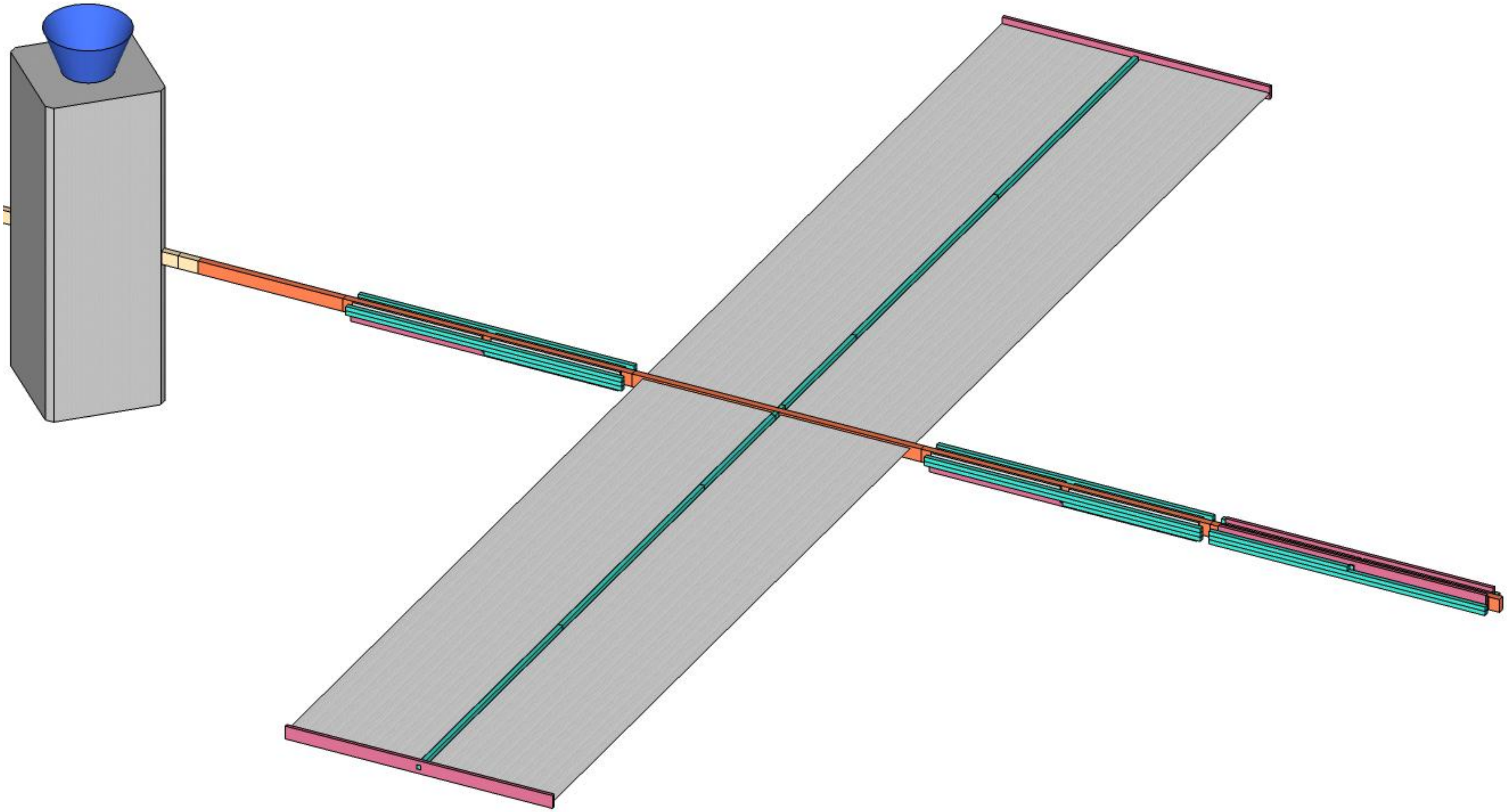
300 kW GRA Deployment Sequence

Blanket Deployment

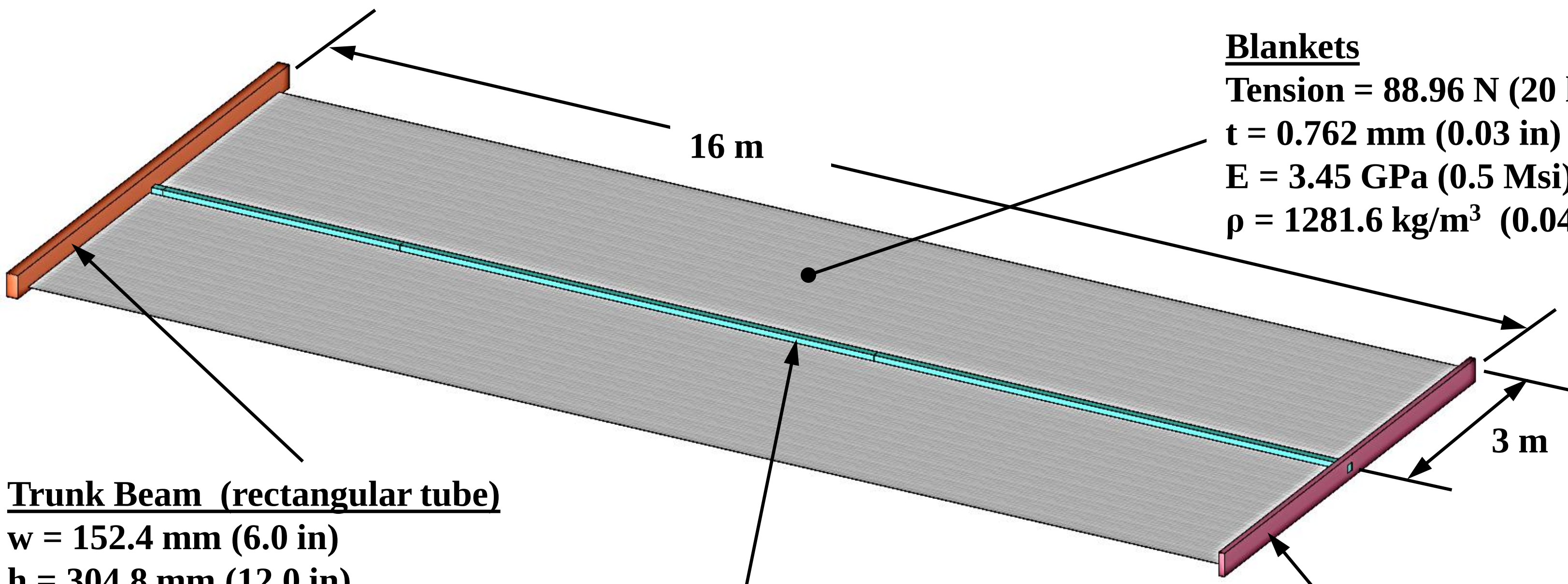


300 kW GRA Deployment Sequence

Blanket Fully Deployed



Single Winglet Physical Properties



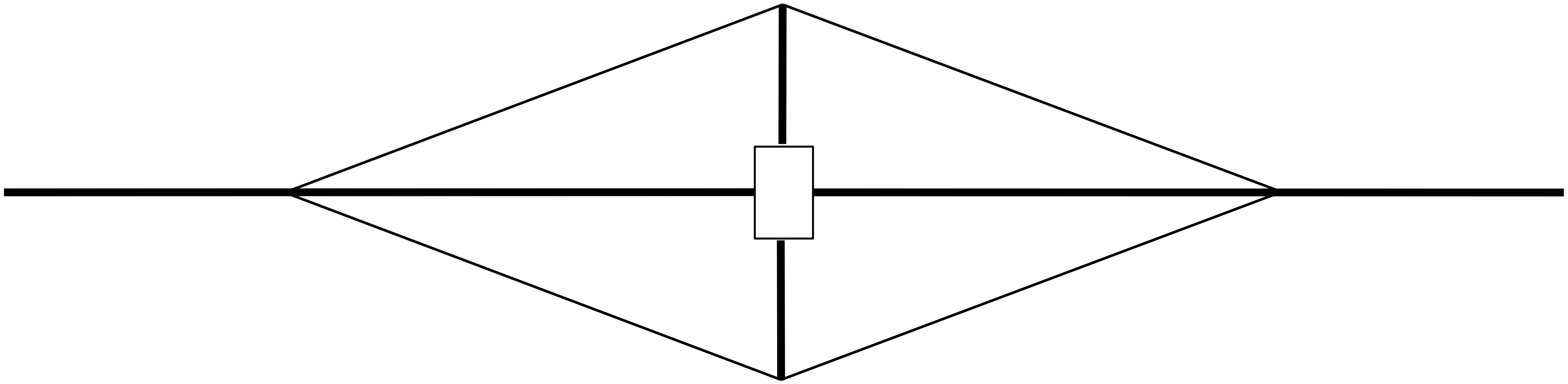
Blankets
Tension = 88.96 N (20 lbs)
t = 0.762 mm (0.03 in)
E = 3.45 GPa (0.5 Msi)
ρ = 1281.6 kg/m^3 (0.0463 lb/in^3)

Trunk Beam (rectangular tube)
w = 152.4 mm (6.0 in)
h = 304.8 mm (12.0 in)
t = 1.524 mm (0.06 in)
E = 140 GPa (20.3 Msi)
ρ = 1993.0 kg/m^3 (0.072 lb/in^3)

Blanket Tube (square tube)
w = 101.6 mm (4.0 in)
h = 101.6 mm (4.0 in)
t = 1.27 mm (0.05 in)
E = 140 GPa (20.3 Msi)
ρ = 1993.0 kg/m^3 (0.072 lb/in^3)

End Support Beam (circular solid)
R = 76.2 mm (3.0 in)
E = 140 GPa (20.3 Msi)
ρ = 64.0 kg/m^3 (0.0023 lb/in^3)

Tension Stiffening Could be Added to Winglets or Trunk Beam as Necessary

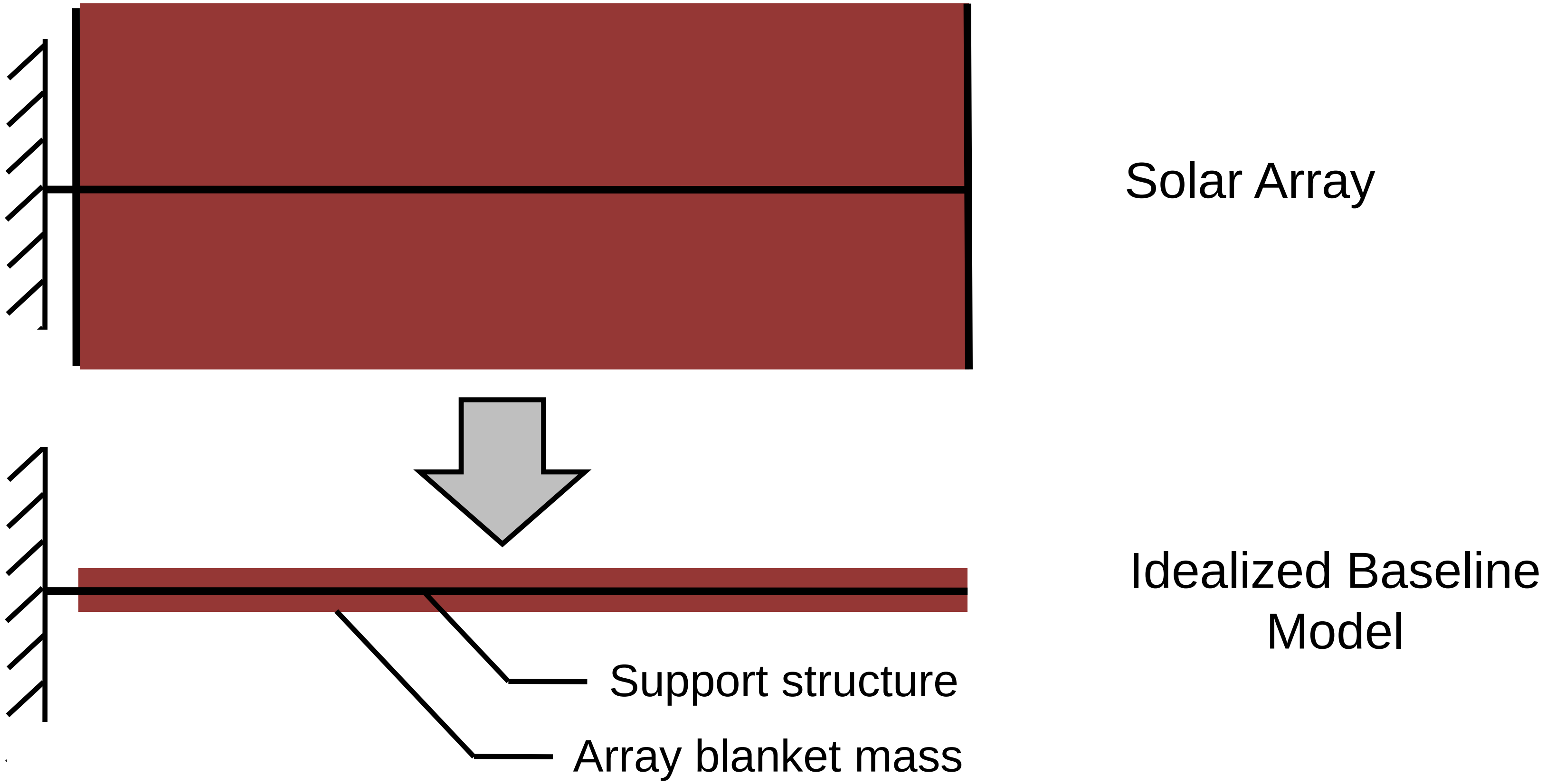


Portable Tension Supported Video Camera Support Cranes

Summary of 300 kW Government Reference Array Design Features

- Folded box beam members
- High-modulus composites
- No restrictions on beam wall thickness (not rolled)
- Trunk beam doubles as winglet base
- Dual blanket/single-boom winglet configuration (like ISS)
- Cable stiffening of winglets and/or trunk beam as needed
- 300 kW EOL / 450 kW BOL "easily" fits on Falcon 9
- Configurable to meet requirements
- Intended as a bellwether for very low mass and stowage volume solar arrays

Idealized Solar Array Structure Selected as a Baseline for Performance Comparison



- Assume array blanket mass is distributed along the beam
- Provide baseline against which other arrays can be compared

Baseline Solar Array Four Governing Equations and Four Unknowns

Solve[{

$$Ms == n\,2\,\pi\,R\,t\,L\,\rho,$$

$$m == \frac{\frac{Ms+Ma}{L}\,a\,g\,osf\,L^2}{2},$$

$$\frac{\gamma}{FS}\,\frac{Ec\,t}{R} == \frac{m\,R}{n\,\pi\,R^3\,t},$$

$$f == \frac{cf}{2\,\pi}\sqrt{\frac{Ec\,n\,\pi\,R^3\,t}{(Ms+Ma)\,L^3}}$$

}, {Ms, m, R, t}]

1 - Structural mass eq.

2 - Structural moment due to inertial loading

3 - Wall buckling due to moment

4 - Array natural frequency

Solve in Mathematica

Array Structural Mass Equation Showing Functional Dependence on Major Parameters

$$M_{Structure} = \frac{2\ a^{2/5}\ f^{2/5}\ g^{2/5}\ n^{2/5}\ p^{4/5}}{cf^{2/5}\ E^{3/5}\ g^{2/5}}\ r\ L^{2}\ M_{Blanket}^{3/5}$$

Re-arrange equation to obtain the structural performance metric, M_S/M_{Bl}

$$\frac{M_{Structure}}{M_{Blanket}} = \frac{2\ g^{2/5}\ n^{2/5}\ p^{4/5}}{cf^{2/5}\ g^{2/5}}\ \frac{r}{E^{3/5}}\ \left(\left(\frac{a\ f}{M_{Blanket}} \right)^{1/5} L \right)^{2}$$

Shape parameter	Material parameter	Loading parameter

Select Solar Array Parameters for a Baseline Mass Curve

Composite Tube

E_c = 68.9x10^9 Pa (10x10^6 psi)
r_c = 1660 kg/m^3

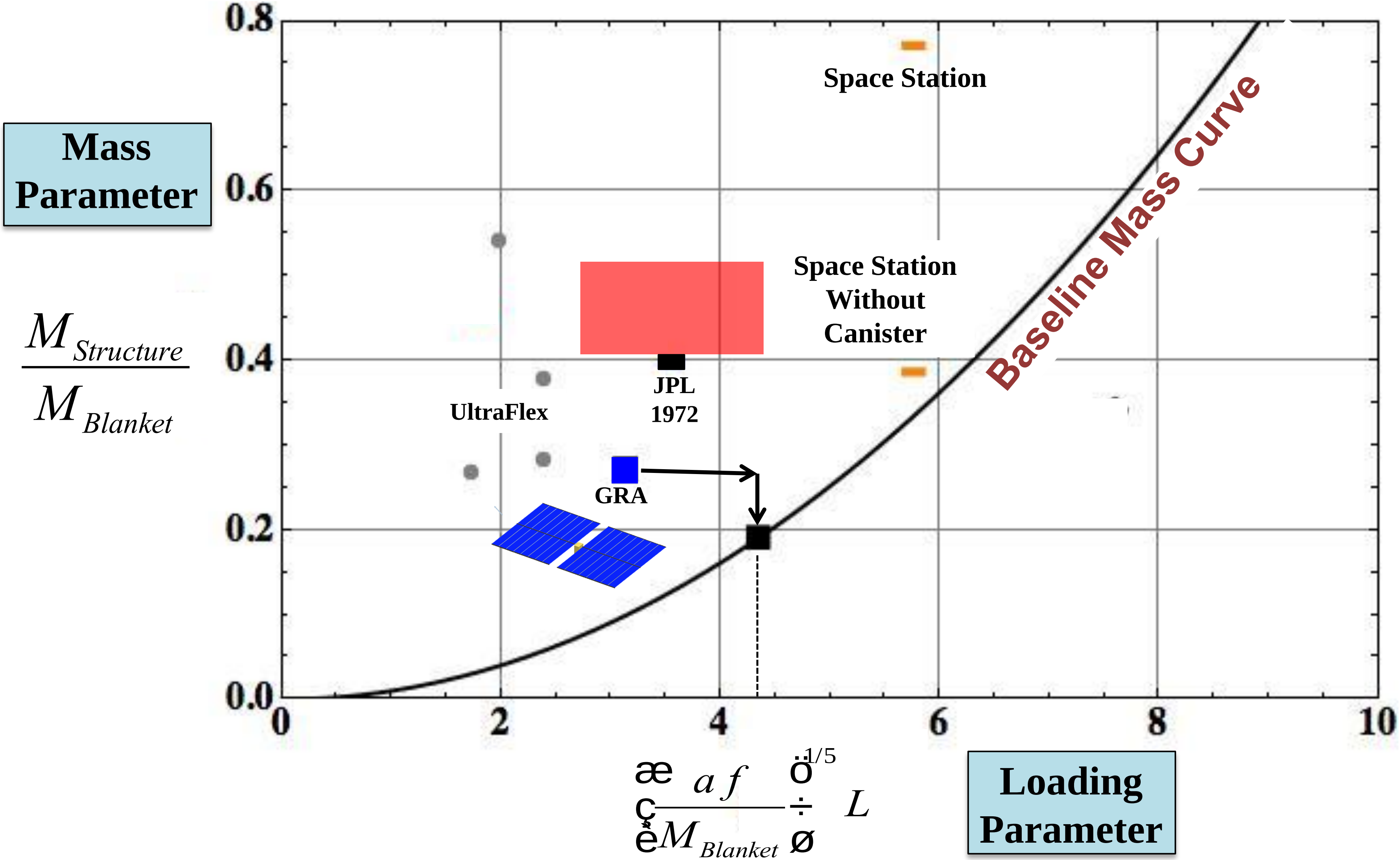
Frequency = 0.1 Hz

Acceleration = 0.2

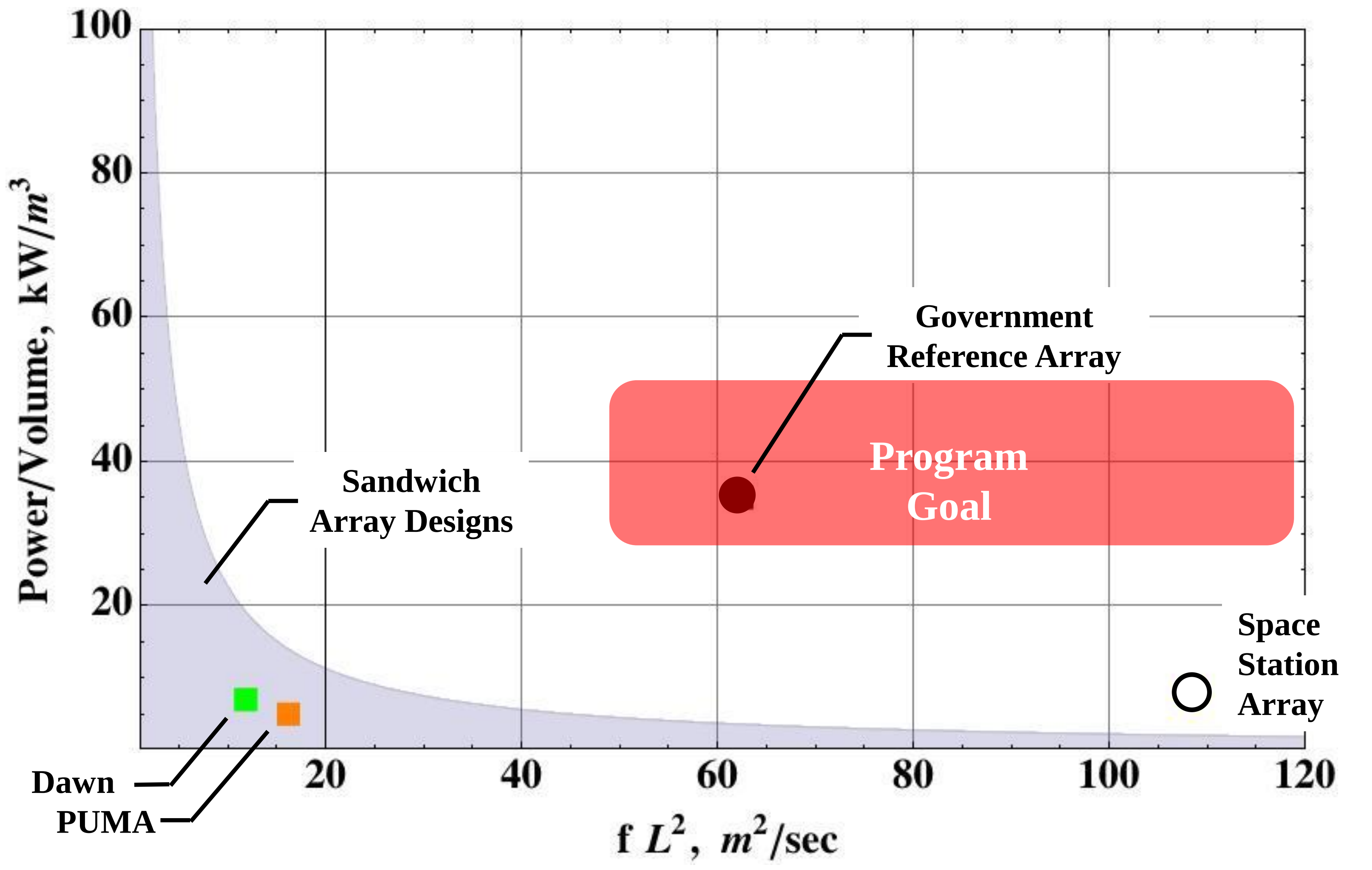
FS = 1.5

Dynamic overshoot factor = 2

Solar Array Structure Mass Fraction Trend is to Increase With Acceleration and Frequency



Current Program Goal Provides Game Changing Increases in Solar Array Power per Unit Volume



Concluding Remarks

- Mass performance metrics established
- Array data needed for level playing field comparison:*
  - Natural frequency
  - Acceleration capability
  - Overshoot factor used if any
  - Structural factor-of-safety
  - Blanket mass and dimensions
  - Array packaging volume

**It would be desirable if this data were not proprietary*

- 300 kW government reference array developed
  - Bellwether for structural mass fraction & packaging volume
  - Major effort remaining to develop and validate a viable reliable deployment system