Laser Thermal Propulsion for 6-Month Round-Trip Missions to Mars

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1st Moving to Mars Workshop — November 17, 2022

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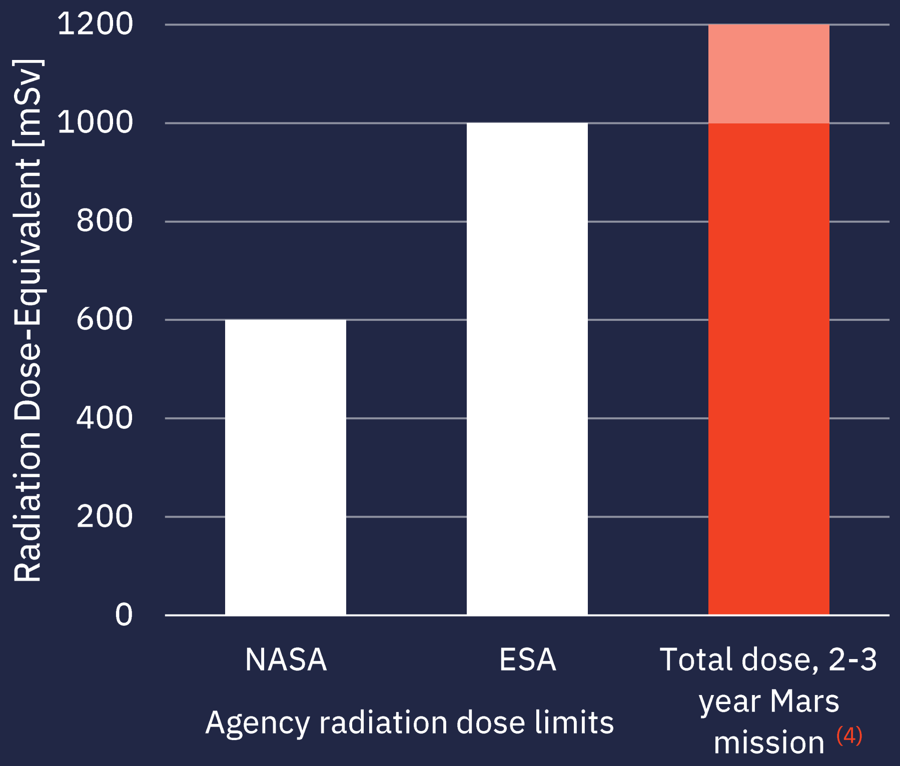
McGill

Why?

- Long duration Mars missions are not possible under current career-long radiation dose limits without heavy shielding
- Harshest environment is interplanetary space(1)
- NASA(2) and ESA(3) standards only allow for short missions with short trips
- Short missions also lower required perishables, life support, etc.



(4) Durante, Marco. "Space Radiation Protection: Destination Mars." *Life Sciences in Space Research* 1 (April 1, 2014): 2–9. https://doi.org/10.1016/j.lssr.2014.01.002.

(1) Berger, Thomas et al. "Long Term Variations of Galactic Cosmic Radiation on Board the International Space Station, on the Moon and on the Surface of Mars." *Journal of Space Weather and Space Climate* 10 (2020): 34. https://doi.org/10.1051/swsc/2020028.

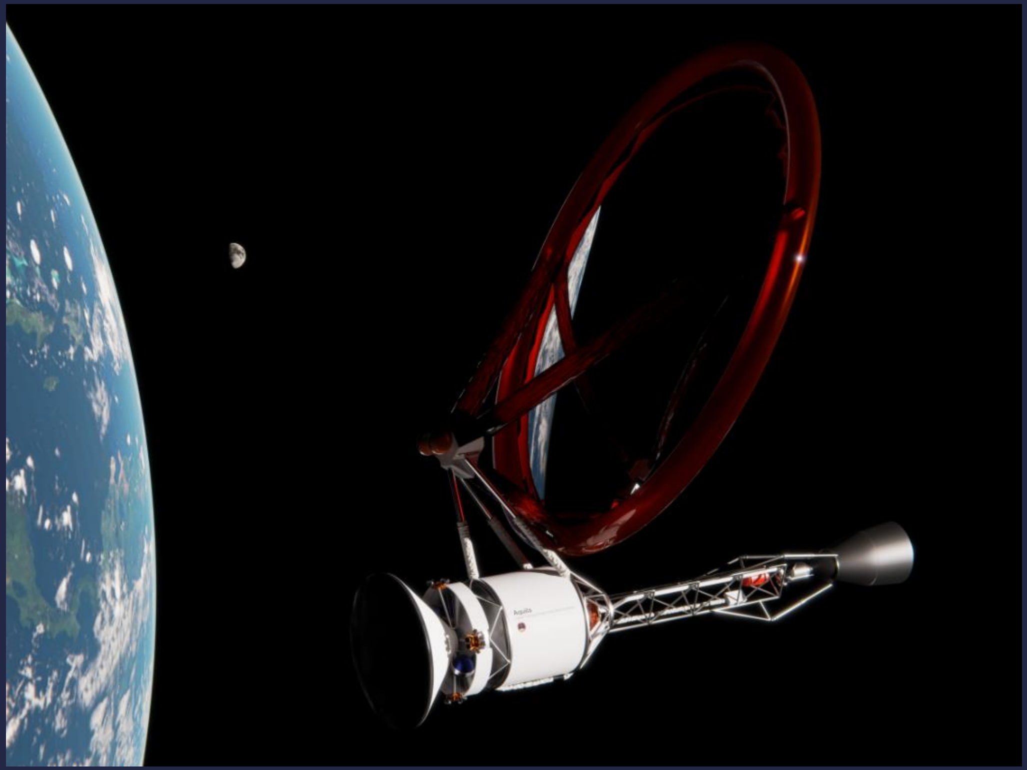
(2) "NASA-STD-3001, VOLUME 1, REVISION B: CREW HEALTH." NASA Technical Standard. NASA SPACE FLIGHT HUMAN-SYSTEM STANDARD. National Aeronautics and Space Administration, January 5, 2022.

(3) Walsh, L. et al. "Research Plans in Europe for Radiation Health Hazard Assessment in Exploratory Space Missions." *Life Sciences in Space Research* 21 (May 1, 2019): 73–82. https://doi.org/10.1016/j.lssr.2019.04.002.

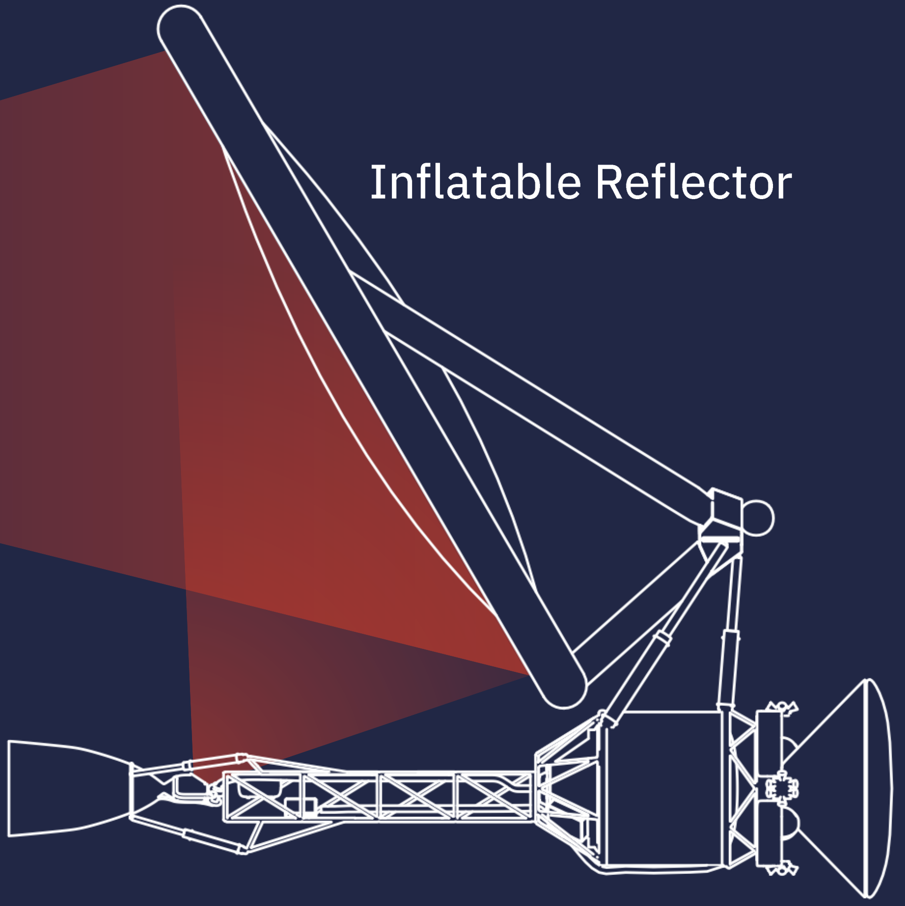
Background

- One-way 45-day trips are possible with laser-thermal propulsion (LTP)[5]
- I_{sp} of 2500—3000 s
- ~1-hour propulsive maneuver
- 15—30 km/s missions

(5) Duplay, Emmanuel, Zhuo Fan Bao, Sebastian Rodriguez Rosero, Arnab Sinha, and Andrew Higgins. “Design of a Rapid Transit to Mars Mission Using Laser-Thermal Propulsion.” *Acta Astronautica* 192 (March 1, 2022): 143–56. https://doi.org/10.1016/j.actaastro.2021.11.032.



LTP background



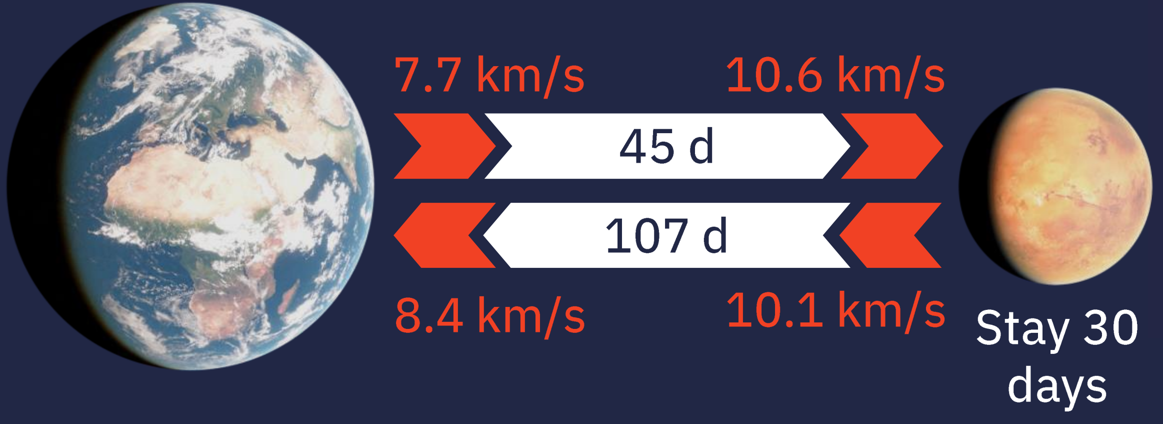
Propulsion system dry mass: ~2.5 tons

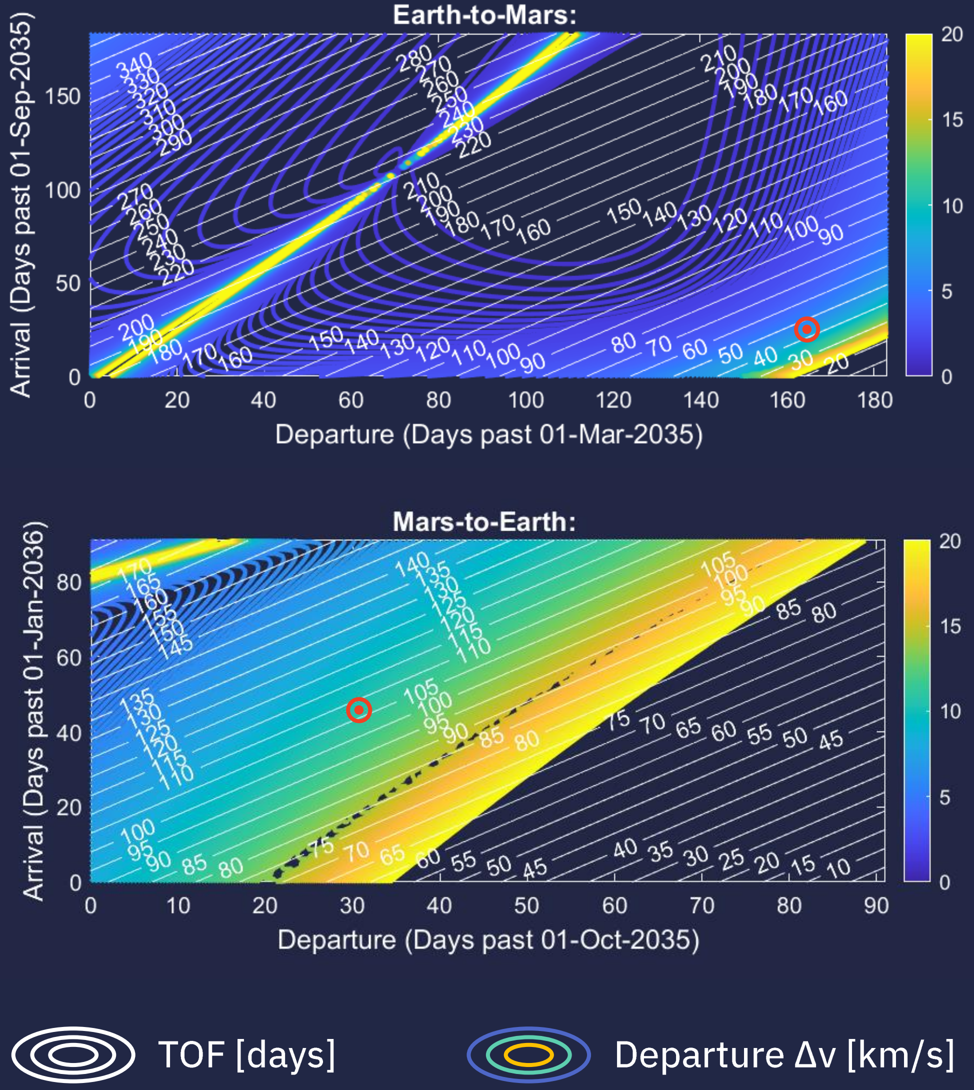
(5) Duplay, Emmanuel, Zhuo Fan Bao, Sebastian Rodriguez Rosero, Arnab Sinha, and Andrew Higgins. "Design of a Rapid Transit to Mars Mission Using Laser-Thermal Propulsion." *Acta Astronautica* 192 (March 1, 2022): 143–56. https://doi.org/10.1016/j.actaastro.2021.11.032.

Mission

» Send a small crew (2-4) to Mars and back within 6 months

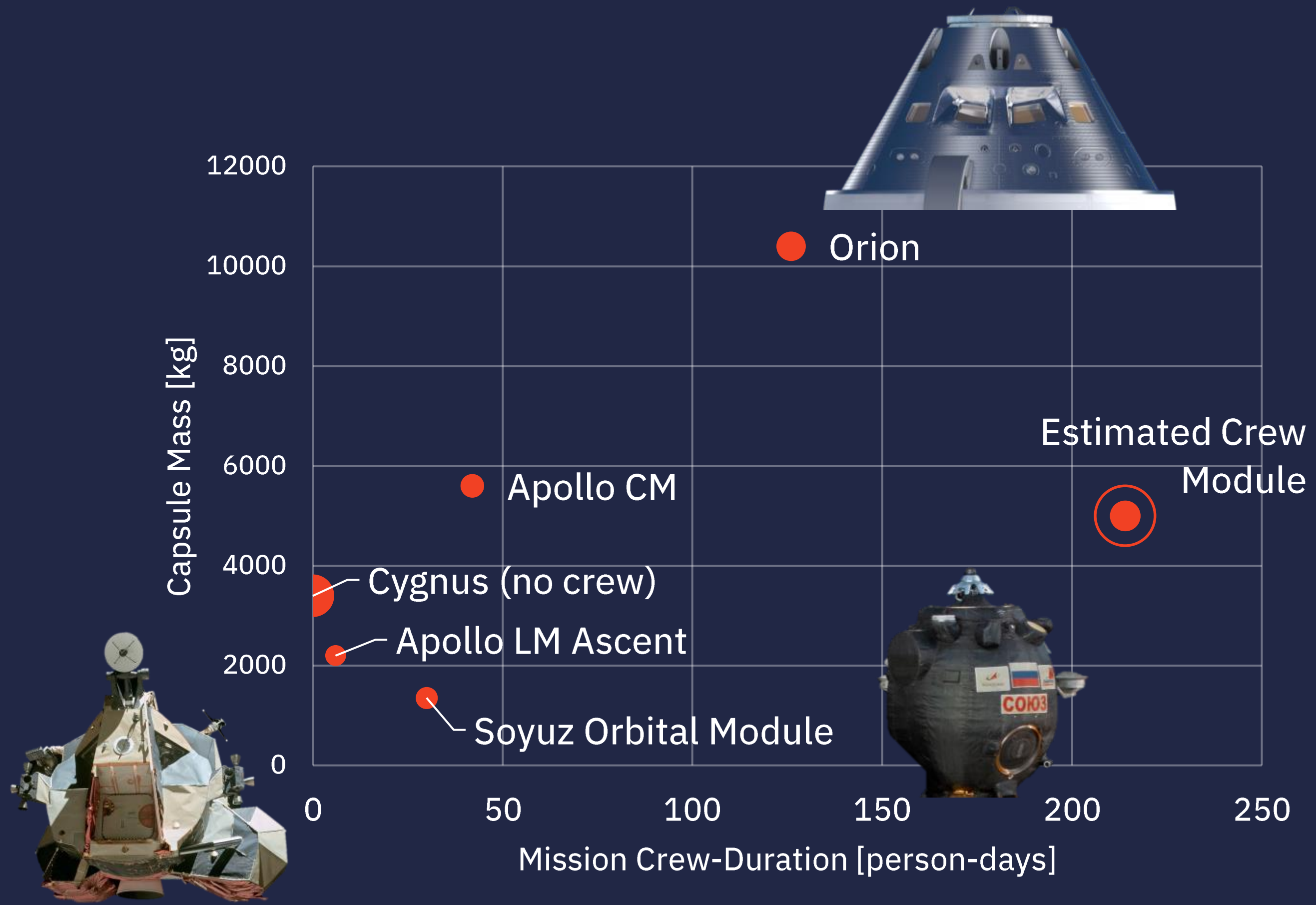
2035 launch window





Mission

- Crew capsule mass estimated to 5 tons
  - No re-entry system
  - No propulsion
  - Less MMOD shielding needed
  - Inflatable technologies allow for large habitable volume



One small problem

There is no laser array on Mars.

One small problem

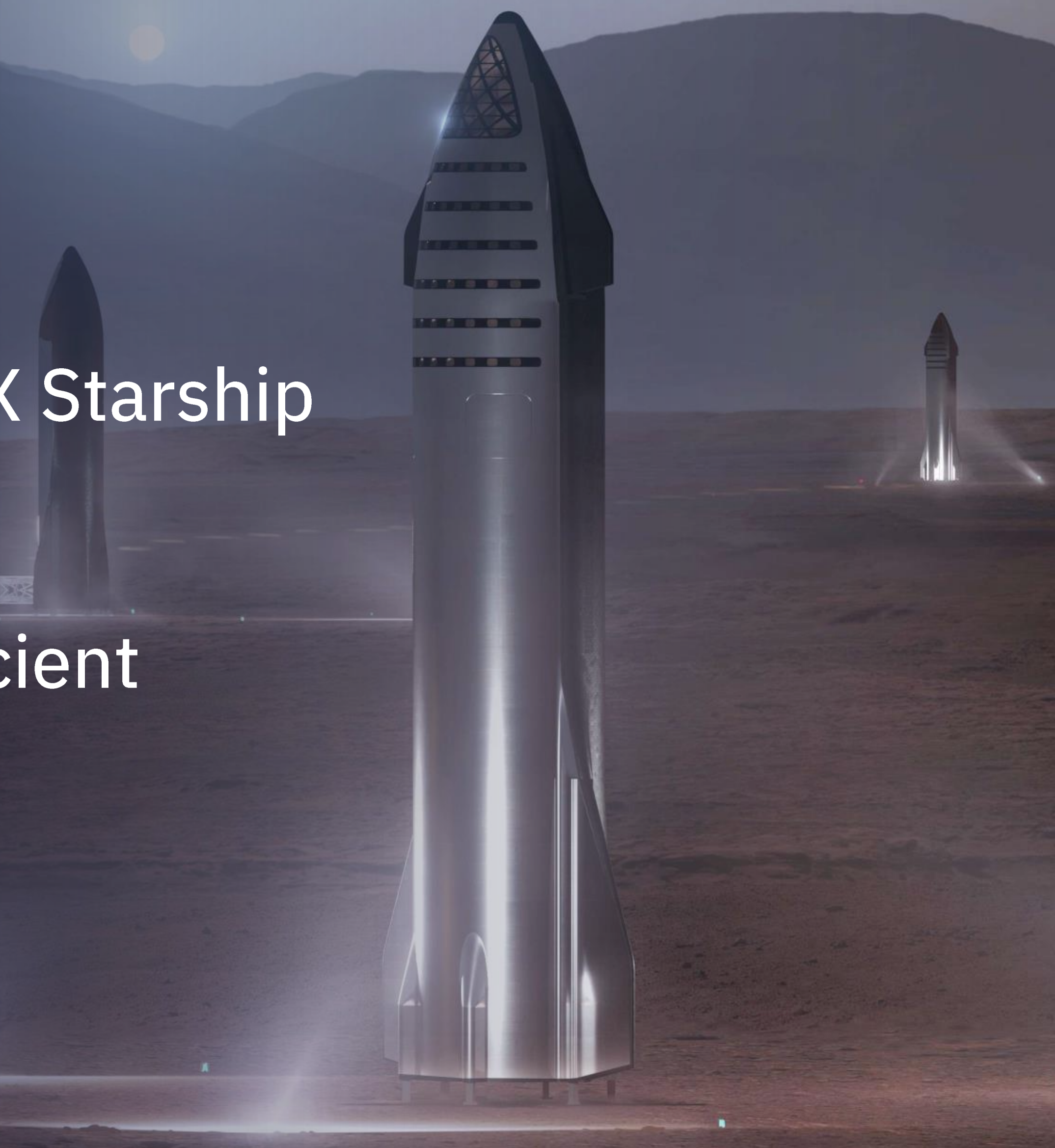
There is no laser array on Mars.

What would it take to build one?

Mission

- We assume the availability of SpaceX Starship
  - ~100 tons to Martian surface
  - 1200 tons of propellant storage
- Array net power ~500 MW, 50% efficient
- Propulsion duration ~2 hours

→ **1 GWh out**
2 GWh input



(SpaceX)

Power generation & storage

- » Use the Martian atmosphere and ice as a chemical “battery”
- » Direct solar PV is bulky
  - » 1200 tons, 2.2 km^2 (specific power ~0.8 kW/kg[6])
- » SpaceX will produce propellant in-situ for Starship

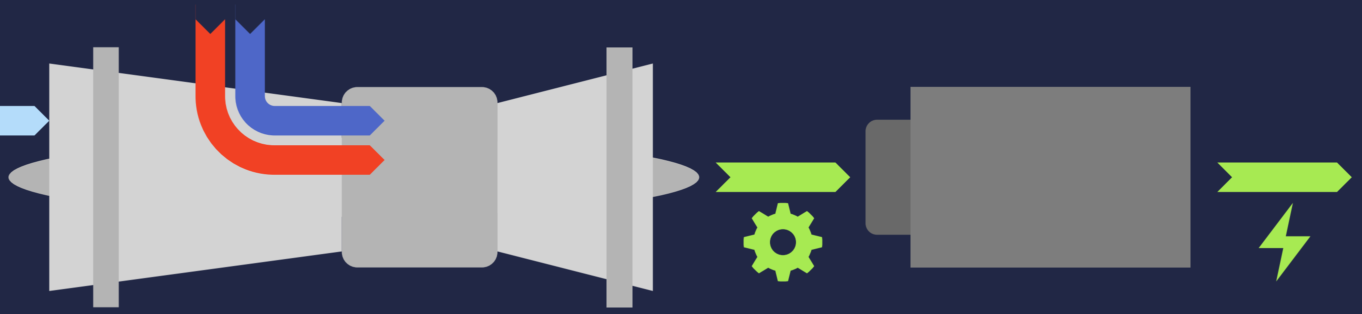
Options	Specific Energy [kWh/kg]	Efficiency	Total Mass [kg]	
Li-ion Battery	0.27		7 400 000	
Fuel cells	3.70	~70%[7]	772 000	⚠ Specific power too low
Methalox	3.02	~41%[8]	1 608 000	Produce it in-situ

(6) Peter Entwistle et al. “Study on Cost-Benefit Analysis of Space-Based Solar Power (SBSP) Generation for Terrestrial Energy Needs.” Frazer-Nash Consultancy Limited, August 2022. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS/Cost_vs._benefits_studies.

(7) Kenneth A. Burke. “Fuel Cells for Space Science Applications.” Technical Memorandum. NASA STI Report Series. National Aeronautics and Space Administration, August 2003. https://ntrs.nasa.gov/citations/20040010319.

(8) “LM6000 Marine Gas Turbine.” GE Aviation, 2018. https://www.ge.com/gas-power/products/gas-turbines/lm6000.

Power delivery



- Benefit from power & propulsion systems for airborne applications with high specific power

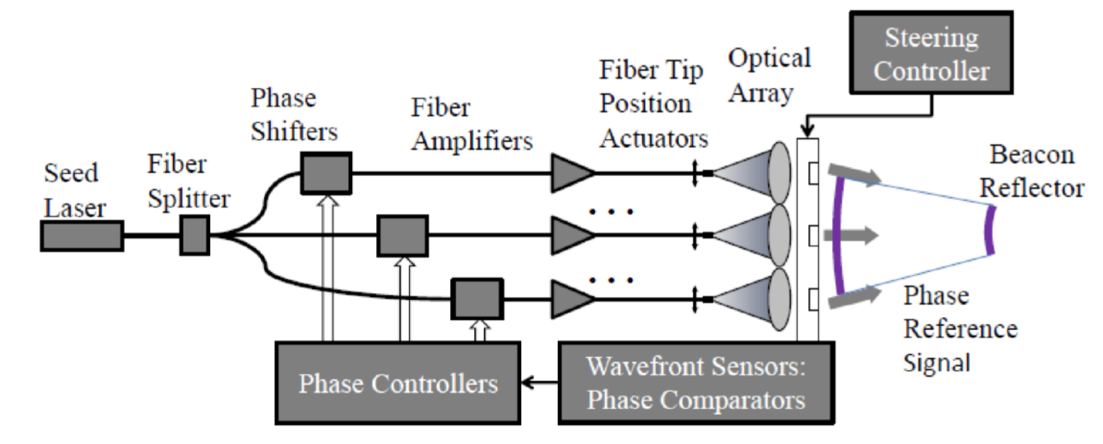
Component	Specific Power [kW/kg]	Total Mass [kg]
Gas Turbine[8]	7.00	144 000
Generator[9]	65.00	7720

(9) Mykhaylo Filipenko et al. “Concept Design of a High Power Superconducting Generator for Future Hybrid-Electric Aircraft.” *Superconductor Science and Technology* 33, no. 5 (March 2020): 054002. https://doi.org/10.1088/1361-6668/ab695a.

Laser array

- » Master Oscillator Power Amplifier (MOPA) architecture, as considered for Breakthrough Starshot initiative
- » Key mass contributors are amplifiers, optical fiber, and the optomechanical system

P. Lubin, 2016(10)

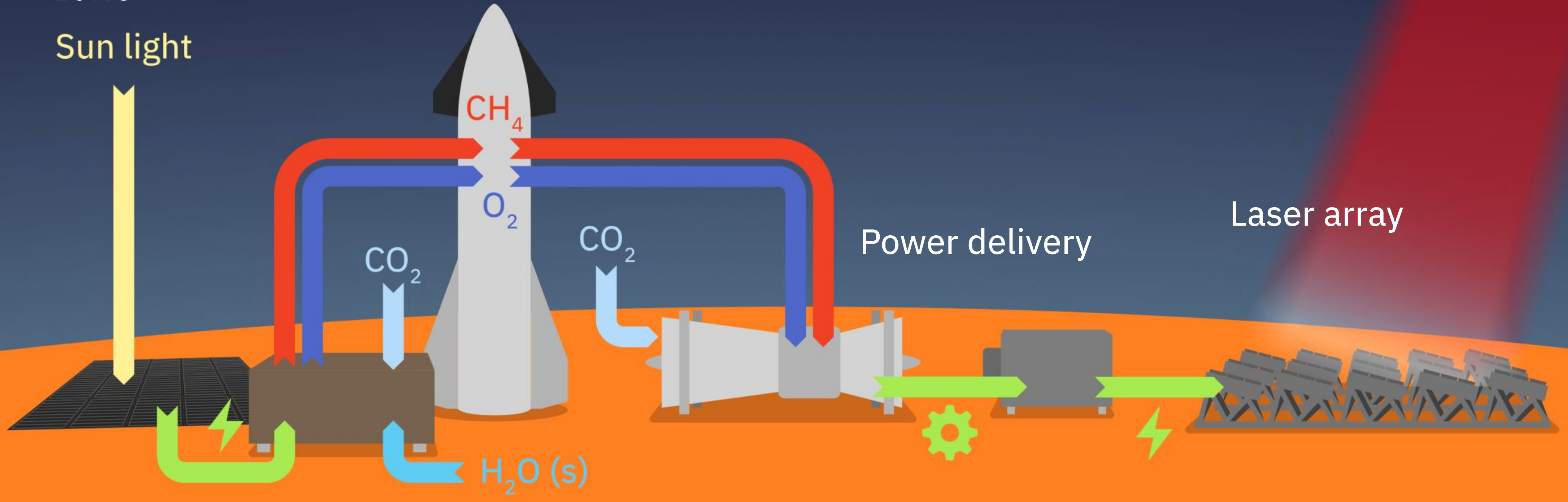


Component	Specific Power [kW/kg]	Total Mass [kg]
Fiber Amplifier(10)	0.60	833 000
Optomechanics	3.10	161 000
Optical Fiber	0.74	675 000

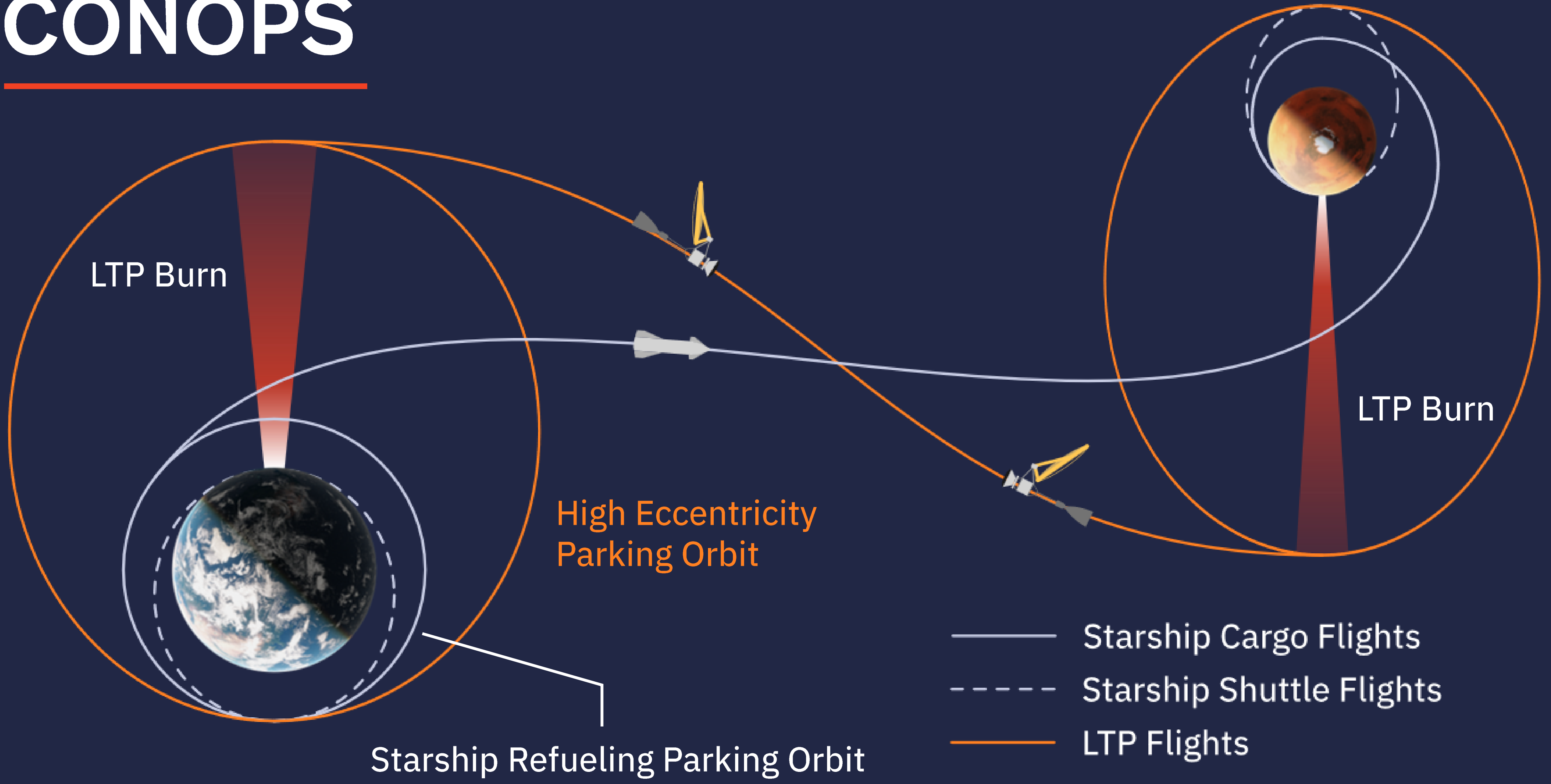
(10) Lubin, Philip. “A Roadmap to Interstellar Flight.” *Journal of the British Interplanetary Society* 69 (2016): 40–72.

Infrastructure

Power generation and storage with Starship ISRU



CONOPS


LTP Burn
LTP Burn
High Eccentricity
Parking Orbit
Starship Refueling Parking Orbit
Starship Cargo Flights
Starship Shuttle Flights
LTP Flights

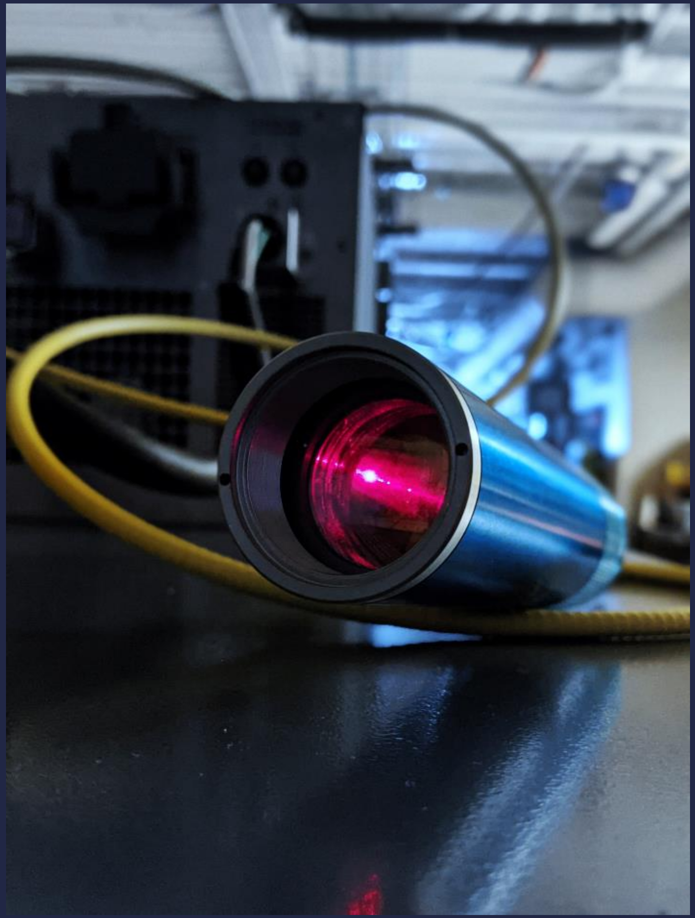
Conclusion

Subsystem	Total Mass [kg]	Starships
Laser array	1 670 000	16.7
Gas turbines	144 000	1.4
Generators	7720	0.1
TOTAL	1 820 000	19.0

- Deployment of a minimum viable laser array on Mars appears feasible with only 19 additional Starships sent to Mars
- Required propellant equivalent to 2 Starships worth of production and storage

Further work

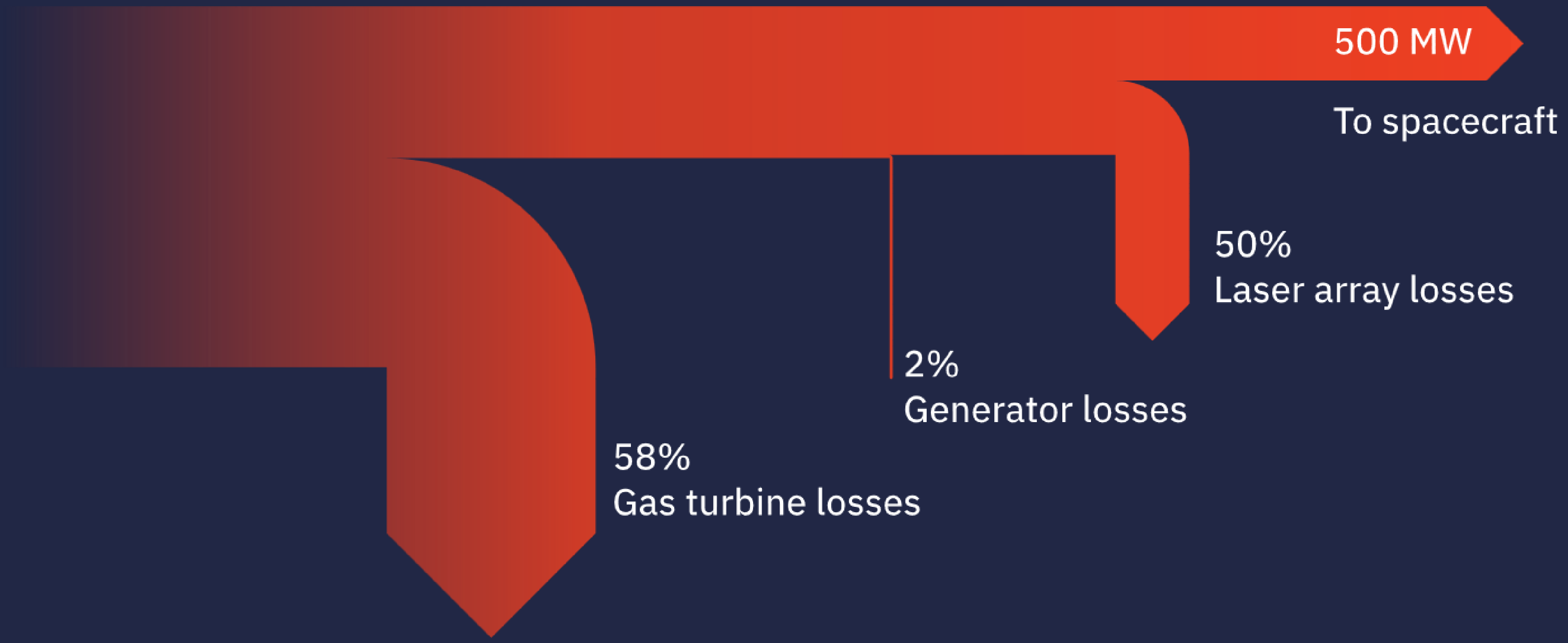
- Development of a 3-kW-class laboratory-scale LTP experiment at McGill University
- Further optimizations may be possible
  - Turbopump modification
  - Space-based arrays
- Convince Elon to sell Twitter



Thank you

Supplementary Slides

Efficiency


500 MW
To spacecraft
50%
Laser array losses
2%
Generator losses
58%
Gas turbine losses

References

1) Berger, Thomas, Daniel Matthiä, Sönke Burmeister, Cary Zeitlin, Ryan Rios, Nicholas Stoffle, Nathan A. Schwadron, et al. “Long Term Variations of Galactic Cosmic Radiation on Board the International Space Station, on the Moon and on the Surface of Mars.” *Journal of Space Weather and Space Climate* 10 (2020): 34. https://doi.org/10.1051/swsc/2020028.

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3) Walsh, L., U. Schneider, A. Fogtman, C. Kausch, S. McKenna-Lawlor, L. Narici, J. Ngo-Anh, et al. “Research Plans in Europe for Radiation Health Hazard Assessment in Exploratory Space Missions.” *Life Sciences in Space Research* 21 (May 1, 2019): 73–82. https://doi.org/10.1016/j.lssr.2019.04.002.

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8) “LM6000 Marine Gas Turbine.” GE Aviation, 2018. https://www.ge.com/gas-power/products/gas-turbines/lm6000.

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