



NETS

2022

**NUCLEAR and
EMERGING
TECHNOLOGIES for
SPACE**



Lunar Power Transmission for Fission Surface Power

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Outline

- ❑ **Several trades and assessments were conducted regarding the potential electrical implementation**
 - Stirling power conversion and transmission concept
 - 40 kWe power transmission medium
 - AC vs. DC power transfer

- ❑ **These preliminary results are intended inform future requirements and enhance ability to evaluate contractor designs**



Outline and Takeaways

❑ **Stirling power conversion and transmission concept**

- Two-stage control and boost for maximum reliability

❑ **40 kWe power transmission medium**

- Power beaming
- Superconducting cables
- Carbon nanotube (CNT) cables
- Metallic conductors (copper/aluminum) – Reduces mass and risk

❑ **AC vs. DC power transfer**

- Proposed DC-DC systems need to be evaluated for complexity and demonstrated technical maturity. High part count reduces reliability
- An AC system would reduce component count and allow for higher transmission voltage (reducing losses). Component-level designs and technology demonstration required to validate feasibility.
- Continued development of radiation hardened high-voltage switches is essential for success of a DC architecture



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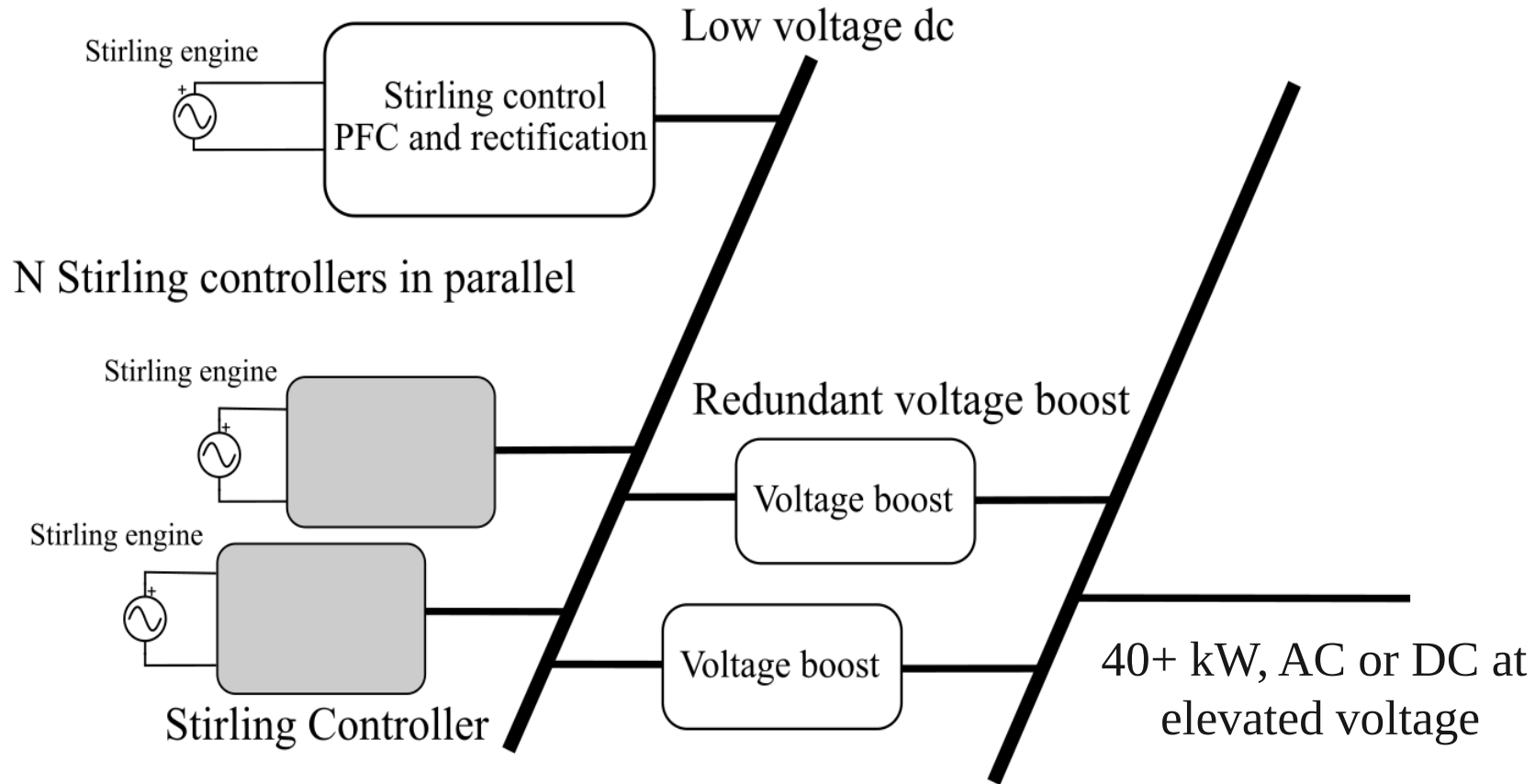
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Proposed Fission Generation System Architecture

❑ Two-stage approach anticipated

- Stirling controllers operating in parallel followed by redundant voltage boost [3][4]
- Two-stage design increases redundancy and flexibility



System Architecture Concept

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Transmission – Assumptions and Options

- ❑ **Fission Surface Power system must deliver 40 kWe to the load**
- ❑ **The lunar architecture team may find it helpful to situate loads up to 3 km from fission lander. Planning for up to 3 km transmission to primary load reduces uncertainty in conceptual designs.**
- ❑ **Reactor mass (core, shield, radiators, etc.) is relatively proportional to thermal power generation over a differential from the design point**
- ❑ **The fission power source dominates overall power system mass and system-level mass minimization is achieved by minimizing transmission losses [1]**
- ❑ **The concepts evaluated for overall system mass and complexity include:**
 - Power beaming
 - Superconductors
 - Carbon nanotube cables
 - Copper or aluminum wires



Transmission – Power Beaming Technology

☐ Microwave

- Large, higher efficiency systems
- Short distances, where beam spread is less pronounced
- 2-35 GHz

☐ Millimeter Wave

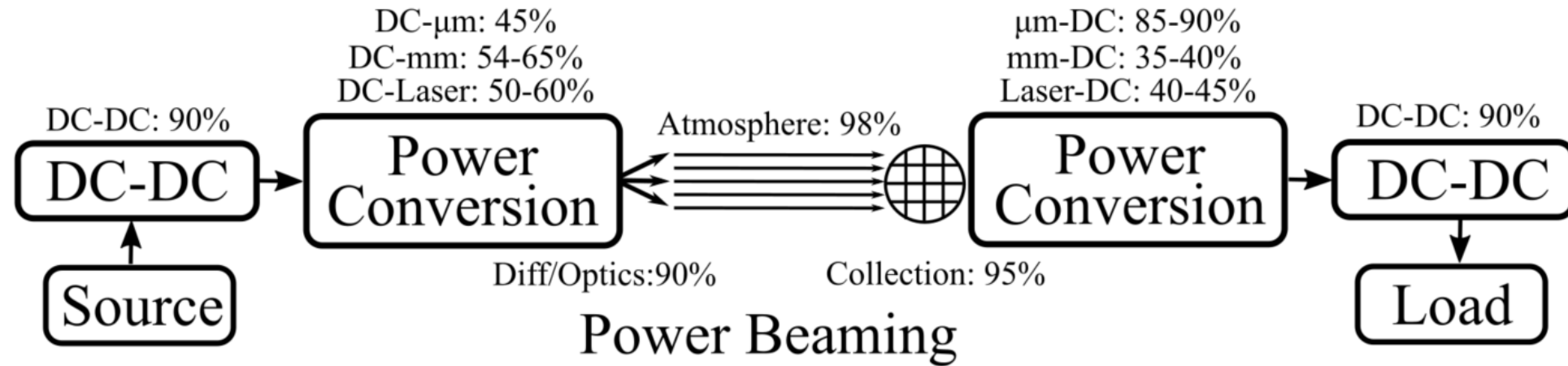
- Possible compromise between size and efficiency, but least developed technology
- 95 GHz

☐ Laser

- Smaller systems
- Long distances, where beam spread is an issue
- 800 nm, 1 μ m etc.



Transmission – Power Beaming Efficiency



Transmission	End-to-End Efficiency	Additional Generation	Increased FSP mass (Neglecting beaming hardware mass)
μ m	26%-27%	110 kW	30,000 kg
mm	13%-18%	220 kW	60,000 kg
Laser	14%-18%	210 kW	57,000 kg
Wired System	77%	12 kW	3,200 kg

This mass increase only accounts for increased generation. Full comparison would include mass of beaming system and radiators required to cool beaming transmitter and receiver. These are large because of diode temperature operating limits.

Specific mass of FSP estimated to be 0.27 kg/W



References: [10-16]



Transmission – Beaming Demo (end-to-end)

❑ State of the art Navy beaming demonstration [17]

- Power Transmitted over Laser (PTROL), 2019
- 20% efficiency at 0.33 km – 2 kWe sent and 400 We received

❑ Mass of transmitter/receiver + Additional power generation capability

- 200 kWe generation required for 40 kW system
- Laser & receiver equipment weighed >2500 kg (not minimized)
- Beaming system represents >10 times higher mass penalty than cabled system considering equipment mass, and added generation to compensate for losses

❑ Power beaming is not mass efficient for bulk power transfer in the FSP application

- Line of sight/smooth topography required



2 kW laser [17]



Transmission – Superconducting Cable

❑ Superconducting cable system would increase reliability risks

❑ Significant mass in cryocooling technology (3 km)

- 3+ cryocoolers: ~5500 kg
- Nitrogen coolant: ~600 kg
- Cryo hose mass: ~1500 kg

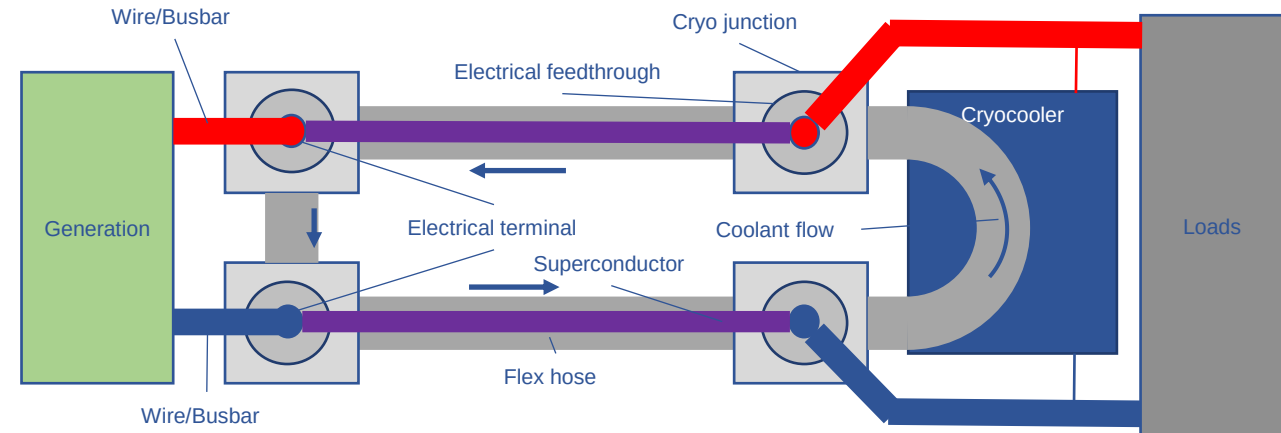
Transmission	End-to-End Efficiency	Additional Generation	Increased FSP generation mass
Superconducting	42%	55 kW	15,000 kg
Wired System	77%	12 kW	3,200 kg

❑ Significant heat removal required to maintain superconductivity

- Heat removal required: ~5500 W [18][19]
- Radiator mass to dissipate heat: ~2300 kg

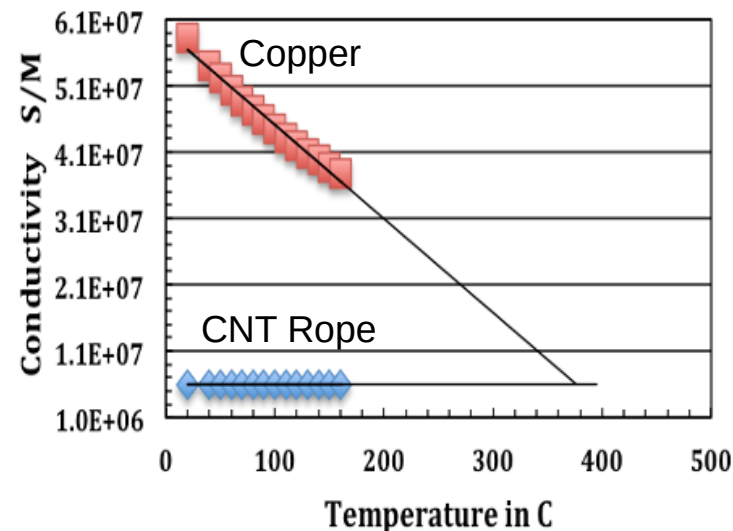
❑ Dedicated power system/backup required for cryocoolers

- Cryocooler power required: ~55 kW
- Additional generation mass: 15,000 kg
- **Total Mass: 25,000 kg**



Transmission – Carbon Nanotube (CNT) Rope

- ❑ **CNT offers advantages over metallic conductors in the correct application**
 - Nearly indefinite wire fatigue, acid and corrosion resistance, 4 times the tensile strength of copper.
- ❑ **CNT can withstand much higher temperatures than copper**
 - Beneficial in high temperature environments and high-peak current applications
- ❑ **CNT volumetric conductivity is 6-10 times lower than copper**
 - Lower conductivity increases mass of CNT cable when high efficiency is a requirement



Comparison of conductivity for
CNT rope (blue) and copper (red)

Transmission – Carbon Nanotube (CNT) Rope

- ❑ DexMat of Houston, TX and BORONITE of Burlington, MA are both producing prototype carbon nanotube (CNT) cables



- ❑ The US is lagging in the equipment needed to effectively produce larger cable diameters. China has formed a 100-person company around a US graduate student to work on the problem.



- ❑ Mass Comparison
 - 10 AWG Copper: 47 kg/km
 - Equivalent conductivity CNT cable: 34 kg/km – 57 kg/km [21][22]

- ❑ Mass benefit from switching to CNT is minimal or not existent because high transmission efficiency is needed

- ❑ CNT cable could be integrated later as technology advances



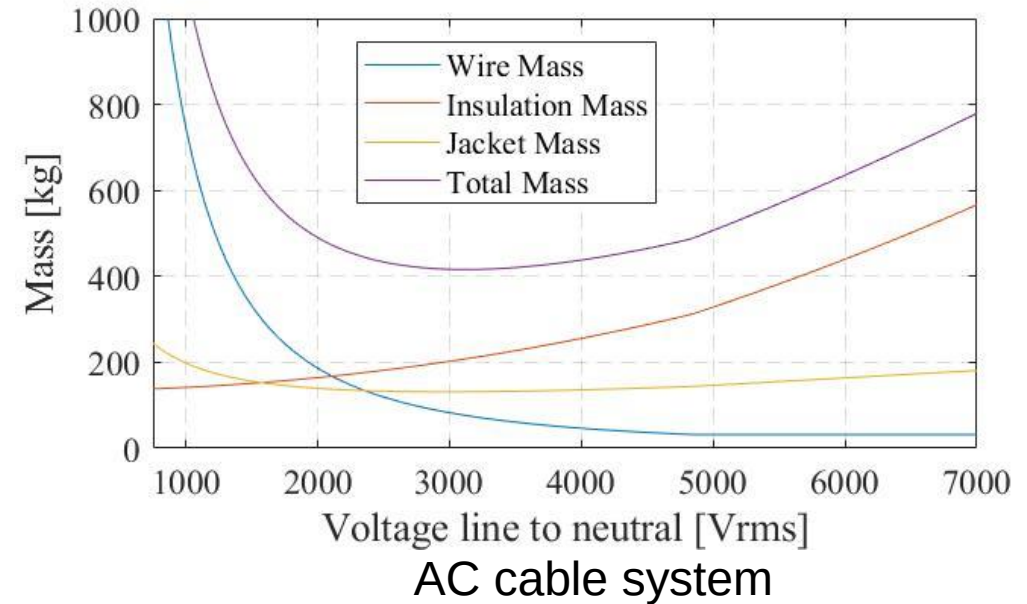
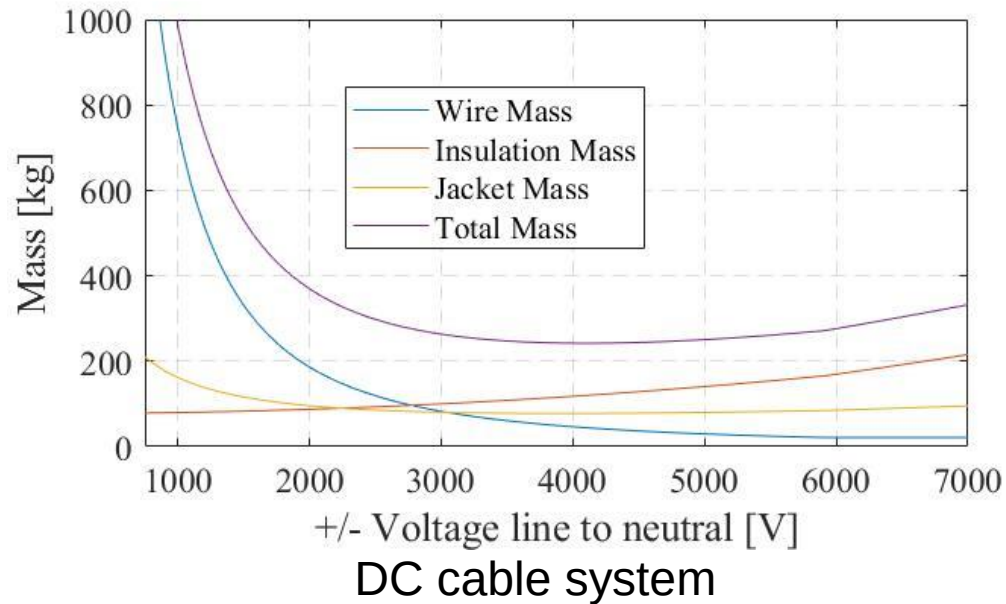
Transmission – Metal Conductors

❑ Technology well understood and minimizes program risk

- Cable mass dependent on transmission voltage

❑ Assumptions:

- Cable sized for transmission of 43 kW a distance of 3 km with 95% efficiency
- Cable power loss limited to 0.7 W/m



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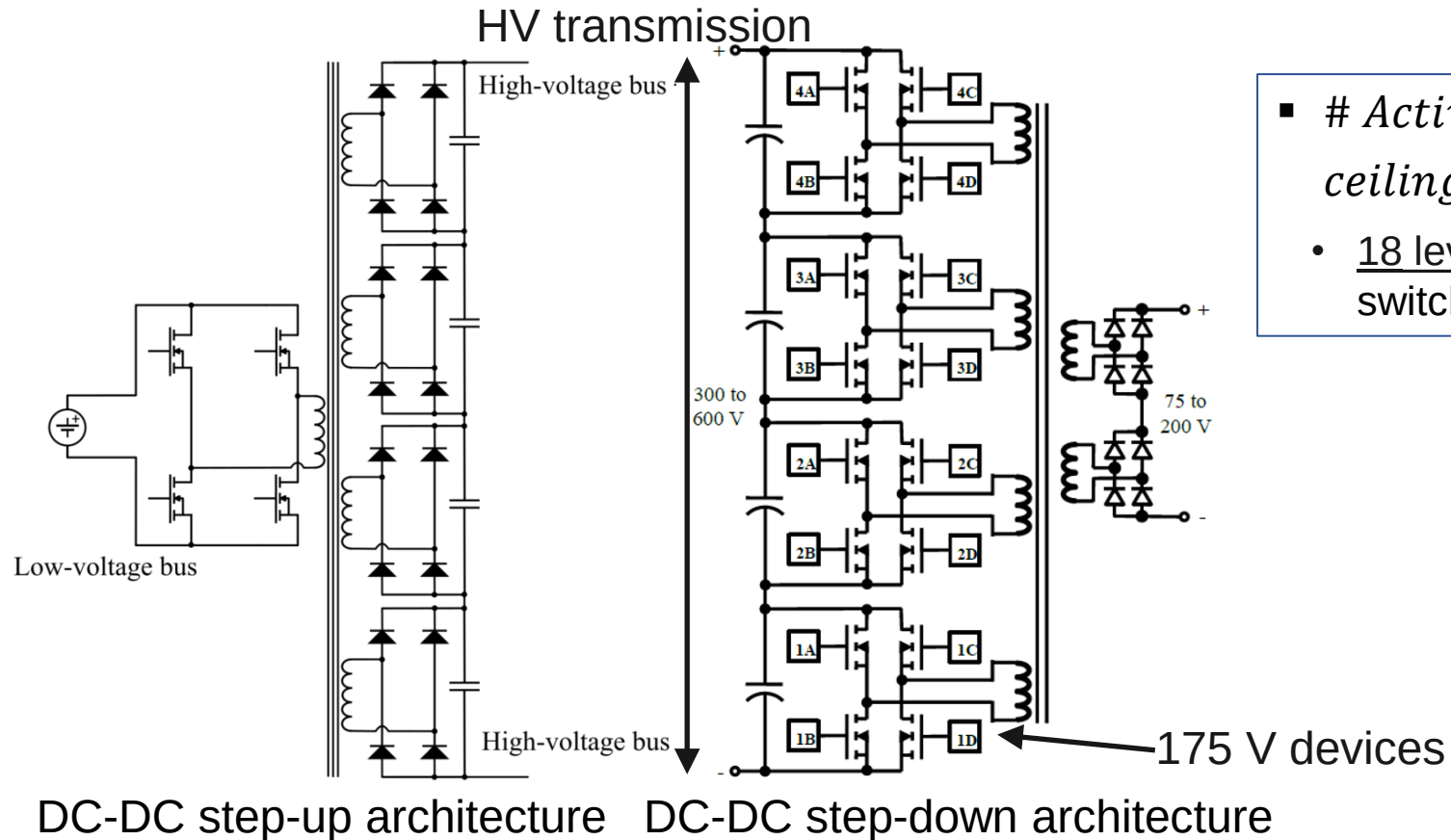
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AC vs. DC – DC Architecture

❑ Limited high-voltage switches necessitate a complex stacked architecture

- Accessible flight-rated switching devices are limited to 175 V operation
- Cable mass is minimized at 3-6 kV
- Development of higher voltage (400 V – 1200 V) radiation hardened switching is crucial



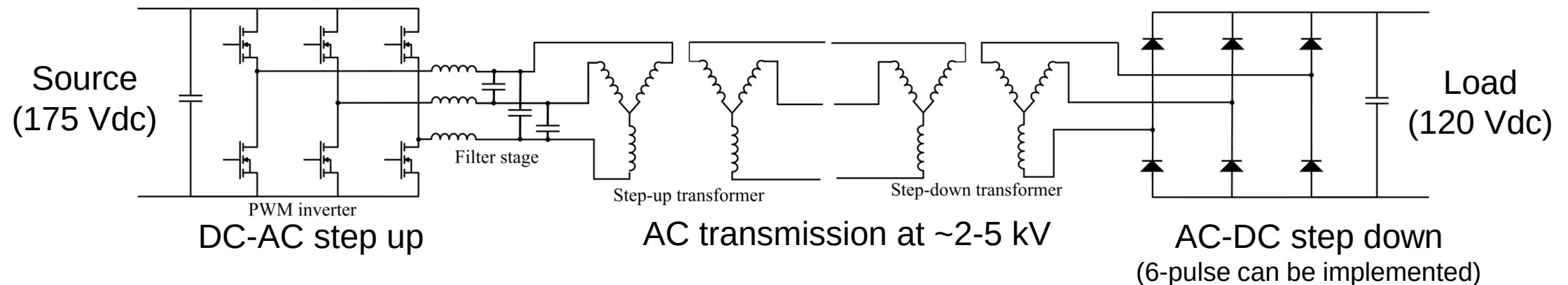
- # Active Switches = $4 * \text{ceiling} \left[\frac{\text{Transmission voltage}}{\text{Switch voltage}} \right]$
- 18 levels, 72 switches required to use 175 V switches on a 3 kV transmission system

AC vs. DC – AC Architecture

□ Simplifies voltage step-up and step-down

- AC transmission allows use of existing flight-rated switches without stacking (175 Vdc)
- Eliminates the need for high voltage capacitors
- Additional wire insulation stress imposed by AC systems must be considered

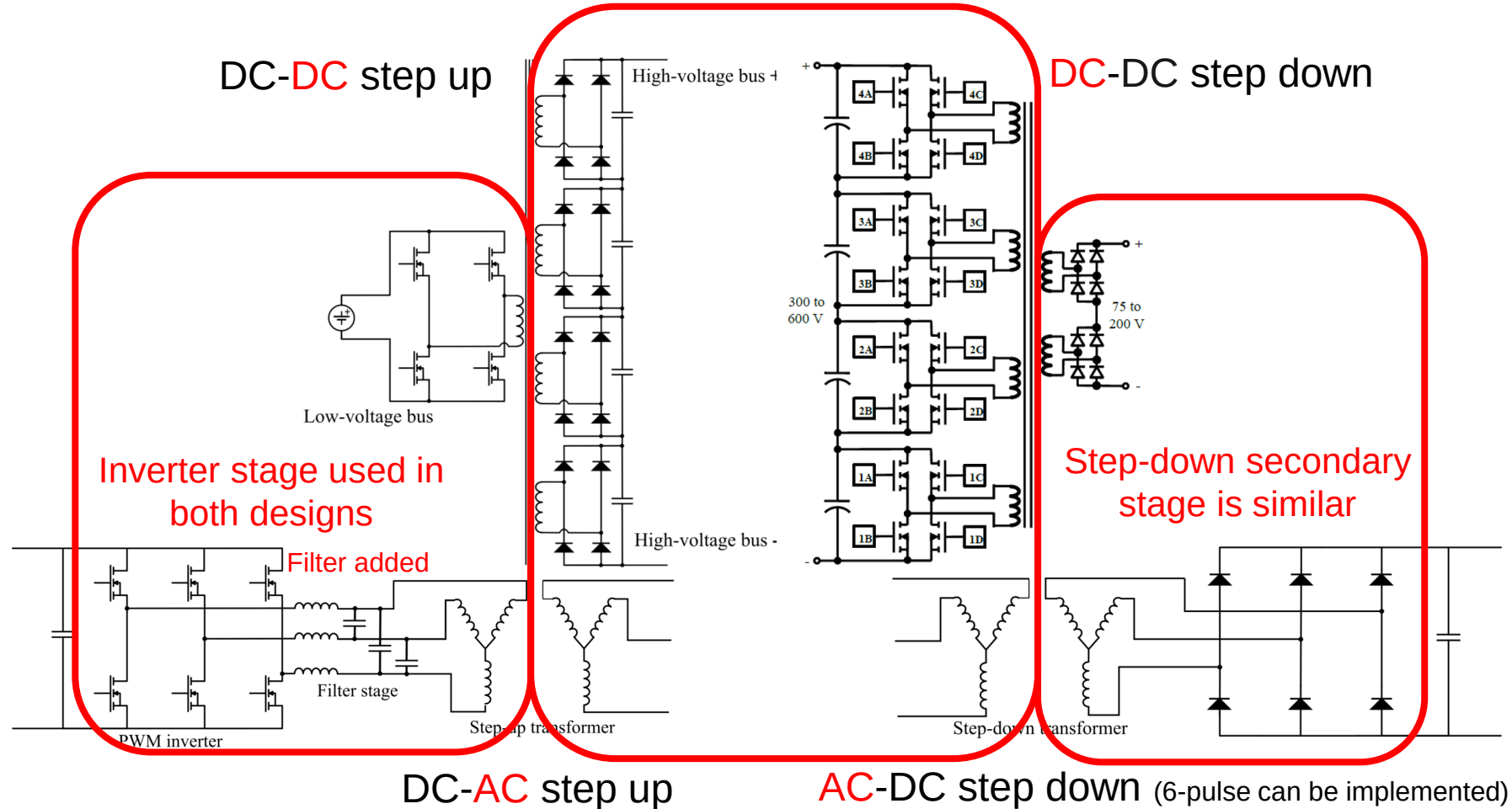
□ Modest frequency (1-5 kHz) AC transmission options have been proposed and preliminarily evaluated. AC and DC system masses are comparable[1,24,25].



AC vs. DC – Comparison

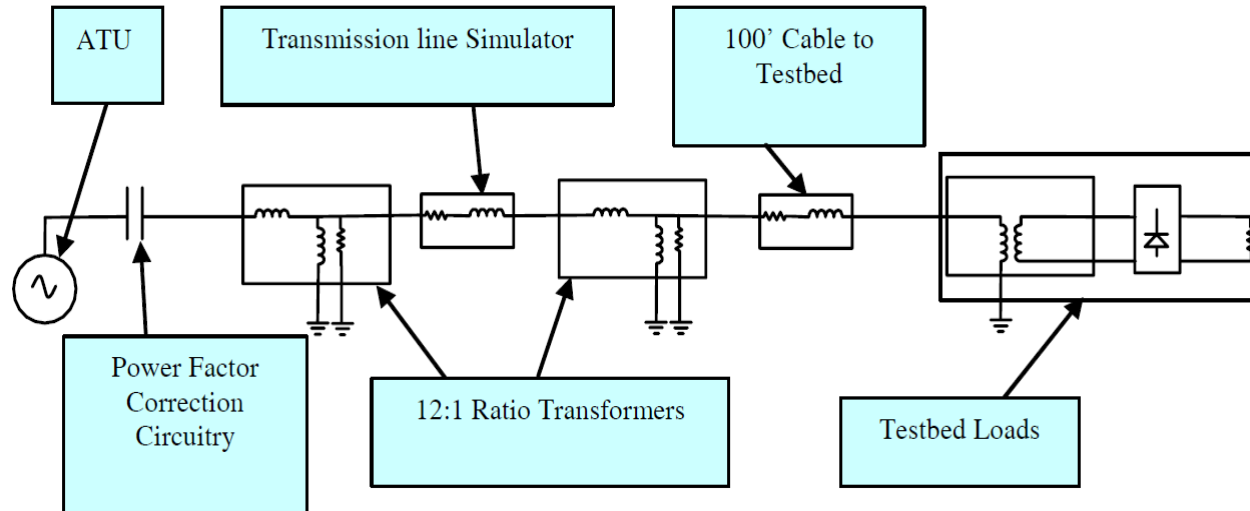
- ❑ Input and output stages are similar for both designs
- ❑ AC system is significantly simpler than DC
- ❑ **Details of mass trade will depend on rad-hard switch availability**

Intermediate rectification and inversion removed



AC vs. DC - Past AC Transmission Demonstration

- ❑ Elevated frequency AC power transmission has already been demonstrated successfully at GRC [28]
- ❑ 1 km, AC power transmission demonstrated in 2008 as part of the Lunar Power System Facility (LPSF) during the 2007-2016 Fission Surface Power project
- ❑ 1 km, 14 AWG, 1/8" spaced transmission line designed for 50 kWe
 - 3-phase, 1750 Hz fundamental frequency
 - Line impedance represented by 500 μ H inductors and 4 Ω resistors



Schematic of LPSF 1 km line model at GRC



Lunar Power System Facility at GRC

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Questions and discussion

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