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Lunar ^{3}He: Mining Concepts, Extraction Research, and Potential ISRU Synergies

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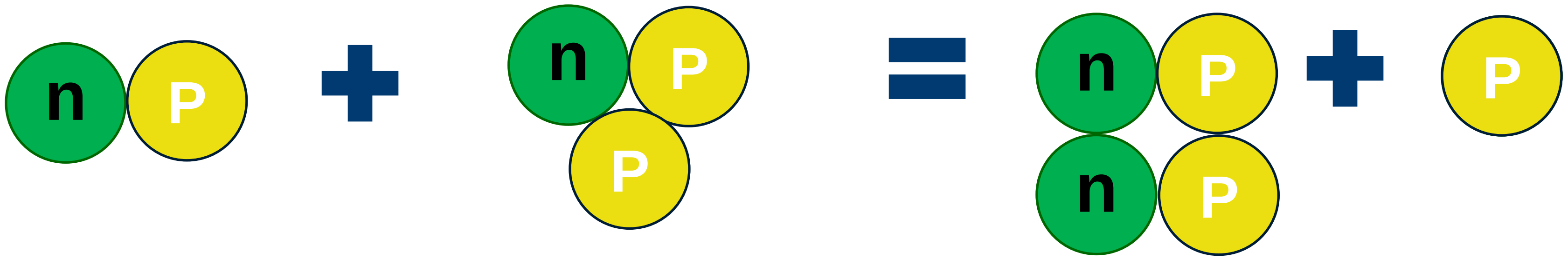
^{3}He Could be a Significant Future Fusion Fuel

Deuterium-Helium-3

$$D + {}^{3}He \rightarrow p\ (14.68\ MeV) + {}^{4}He\ (3.67\ MeV)$$



Deuterium (^{2}H or D) **Helium-3 (^{3}He)** **3.67 MeV** **<u>14.68 MeV</u>**

There has been substantial progress toward ^{3}He fueled reactors

The Moon Could Enable over 700 years of ^{3}He Energy

Solar Wind

96% H^{+}

4% He^{++}

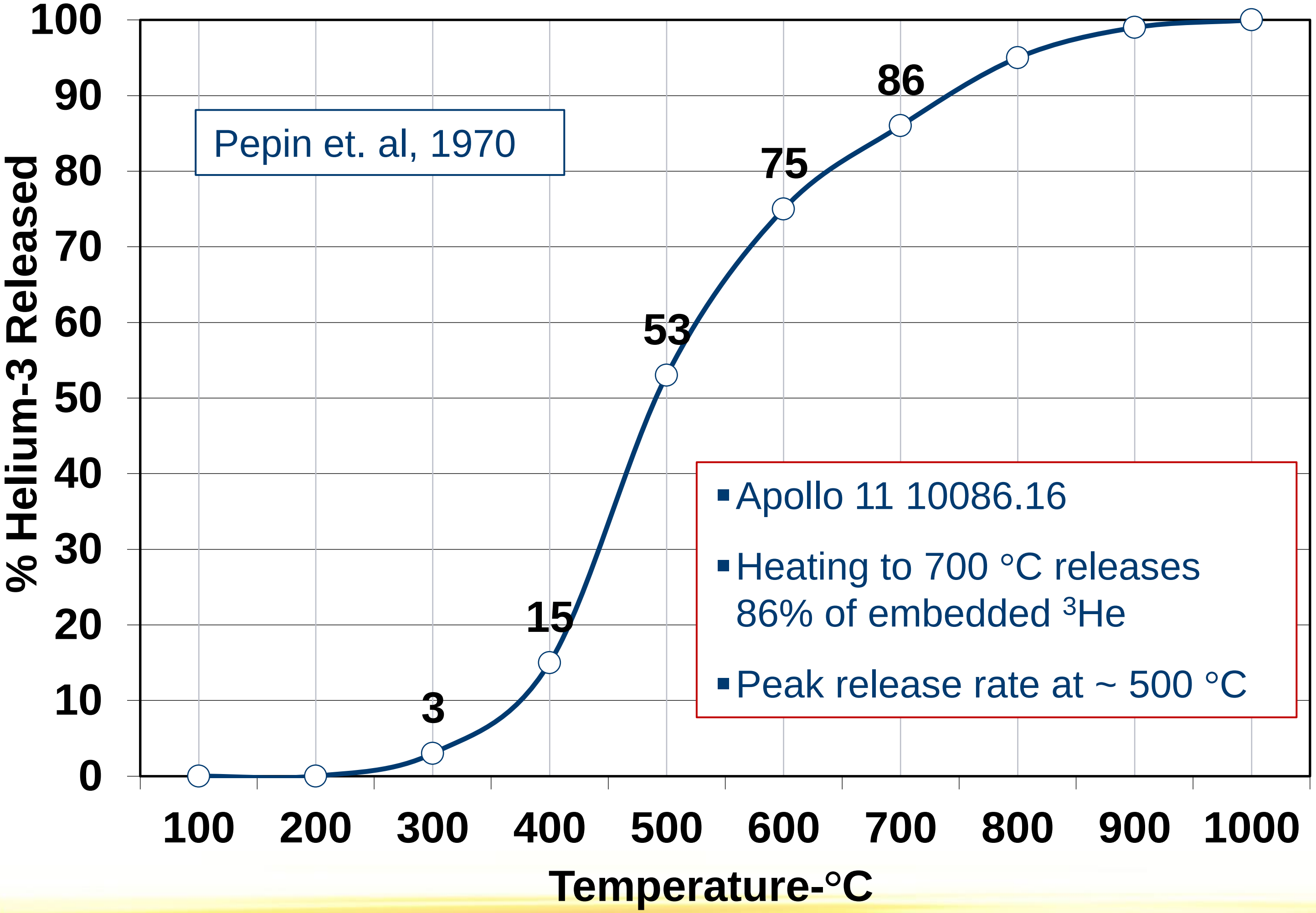
0.002% $^{3}He^{++}$

Total ^{3}He to hit the Moon is about 500 million tonnes over 4.5 billion years

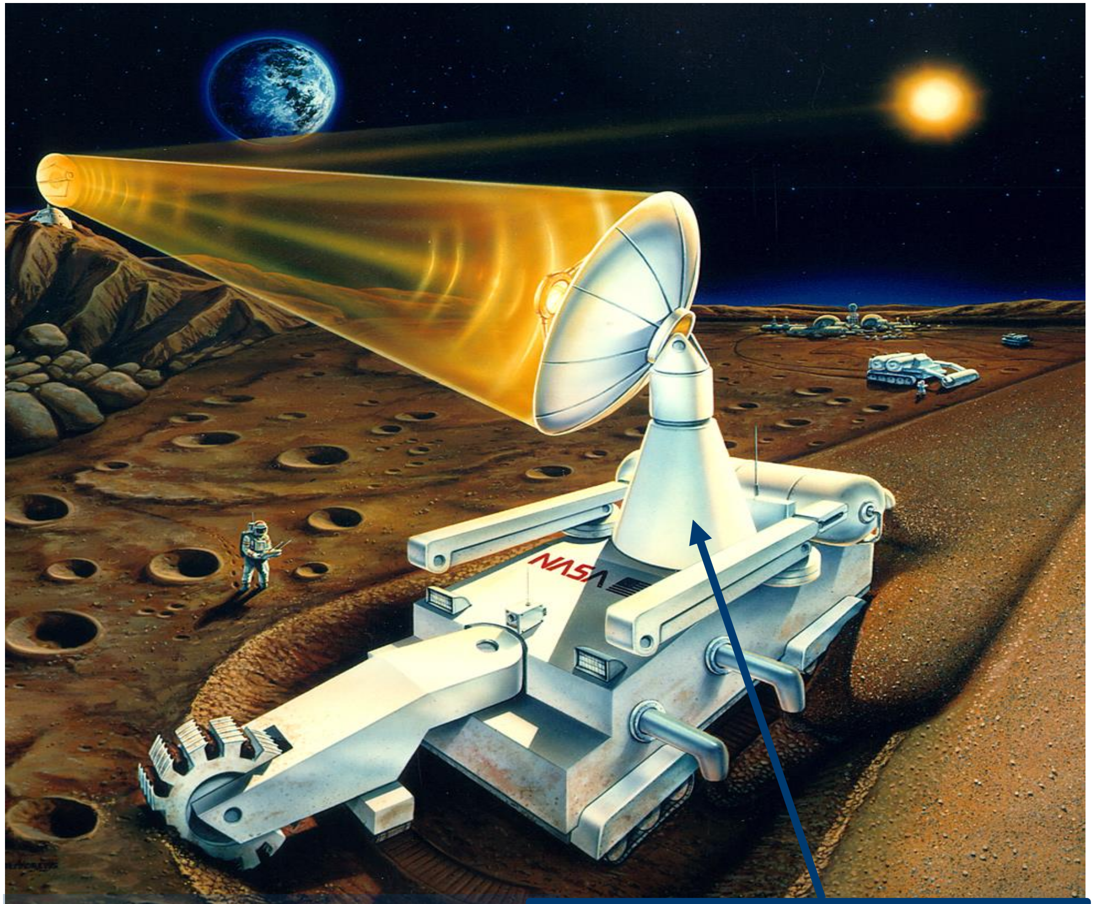
One million tonnes in the top 3 meters

L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski, "Lunar Source of ^{3}He for Commercial Fusion Power," *Fusion Technology* **10**, 167 (1986).

Lunar ^{3}He Miner Designs - Based on Recuperative Heating



- Apollo 11 10086.16
- Heating to 700 °C releases 86% of embedded ^{3}He
- Peak release rate at ~ 500 °C

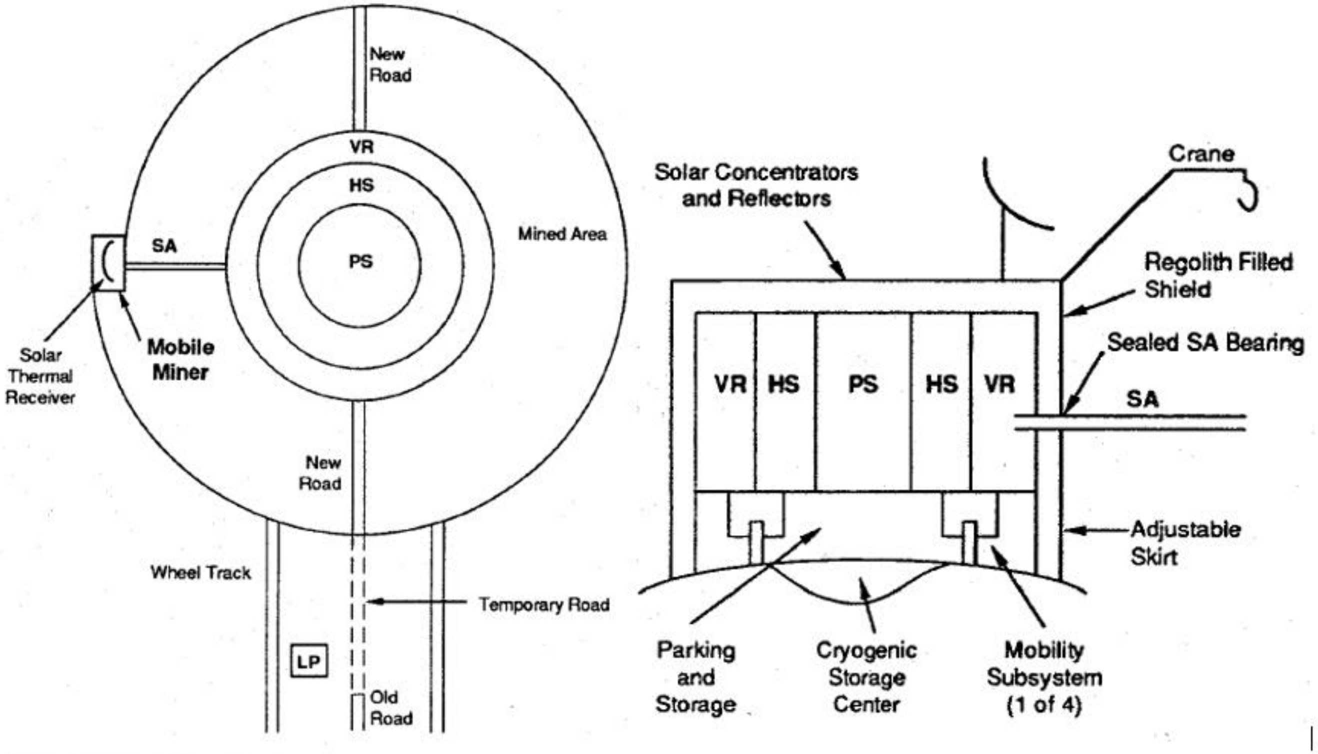


Design: I. Sviatoslavsky
Artwork: J. Andrews

Solar Thermal Heat Pipe Heat Exchanger (HPHX)

Spiral Lunar ^{3}He Miner Concept

- Mobile miner on a support arm or tether
- Centralized volatiles processing
- Spiral mining path
- Complexities of the support arm

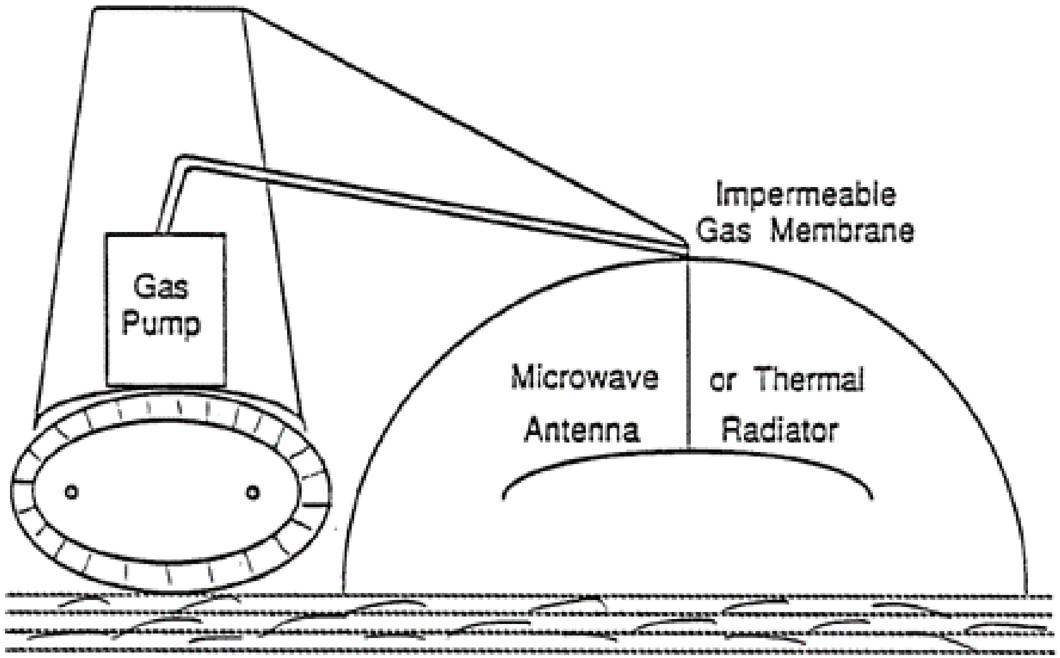


VR: Volatile refining subsystems
HS: Habitat and crew work section
LP: Launch and landing platform
PS: Power subsystems
SA: Mobile Miner support arm

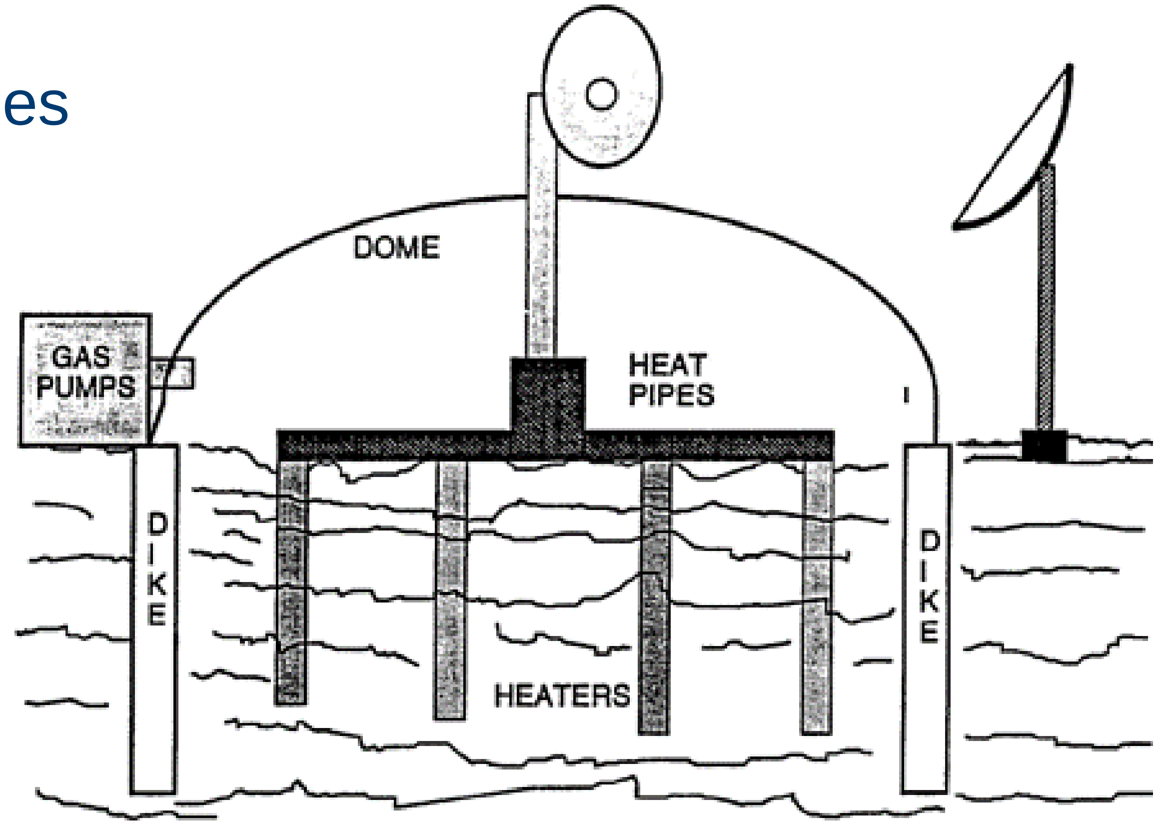
Credit: H.H. Schmitt et al., 1992

In-Situ Extraction & Capture Lunar ^{3}He Miner Concepts

- Impermeable Membrane and diffusion through depth of regolith
- Mobile or "stationary" enclosure approaches



Credit: Y.T. Li et al., 1988



Credit: L.J. Wittenberg, 1993

Helium Extraction Experimental Approach

SWIM

Solar **W**ind **IM**planter (**SWIM**) developed for helium implantation into simulant in 2 kg batches at a time

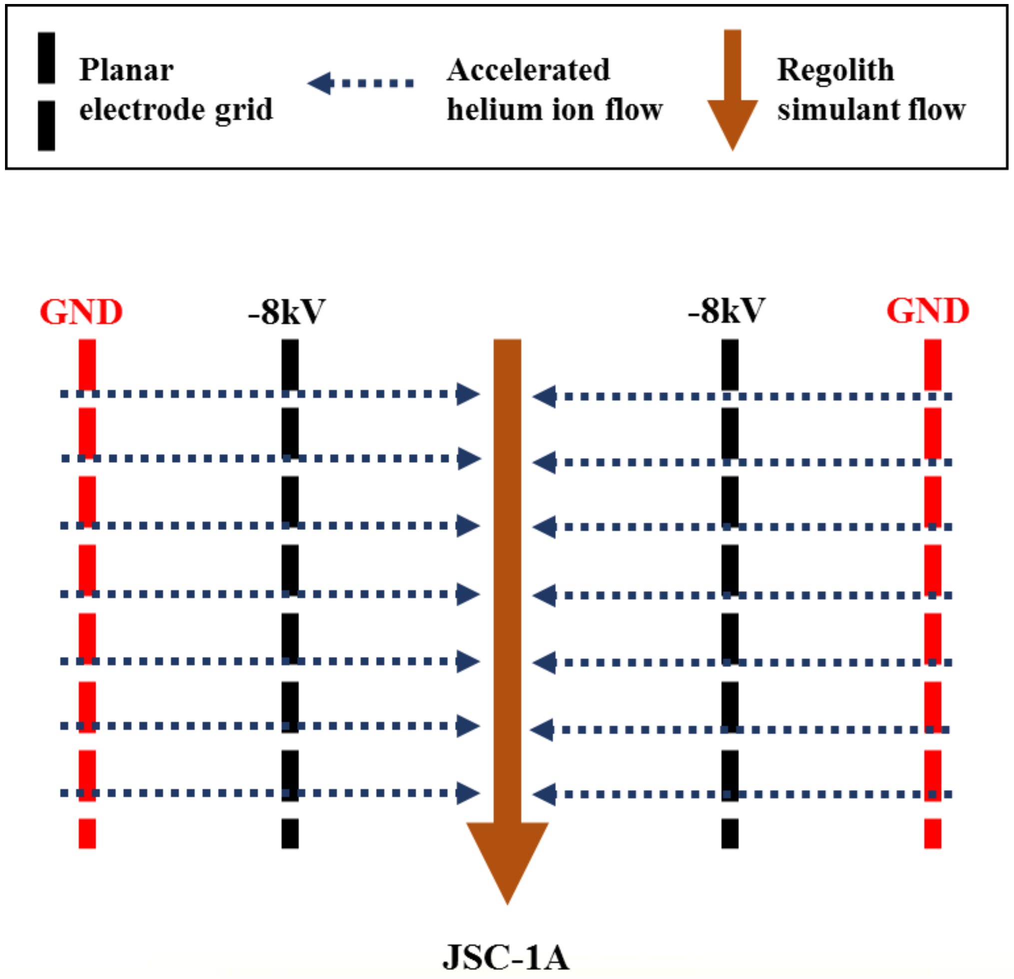
HEAT

Helium **E**xtraction & **A**cquisition **T**estbed (**HEAT**) developed to extract helium from 250 g batches of implanted simulant, at 1.2 - 7.5 mm/s

SCAN

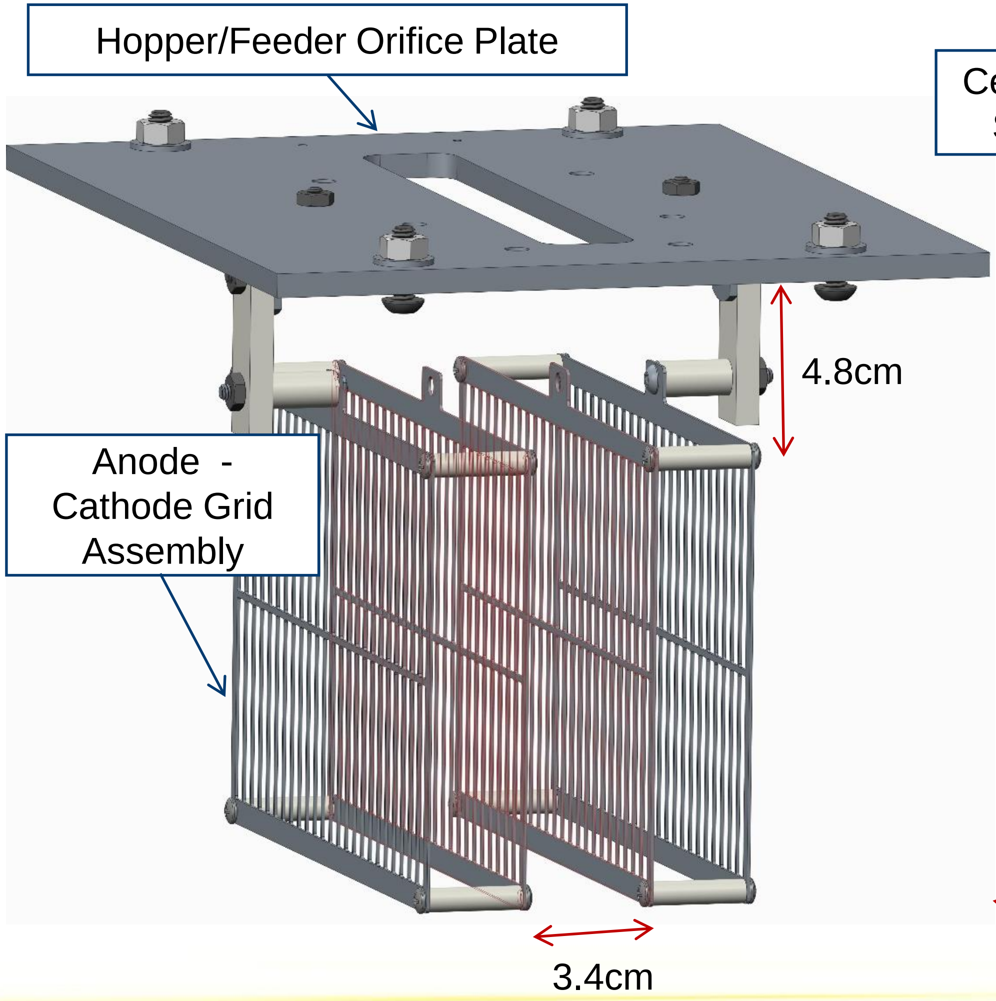
Sample **C**oncentration **AN**alyzer (**SCAN**) by isochronal heating and mass spectroscopy measurements of 20 g samples heated up to 600 °C

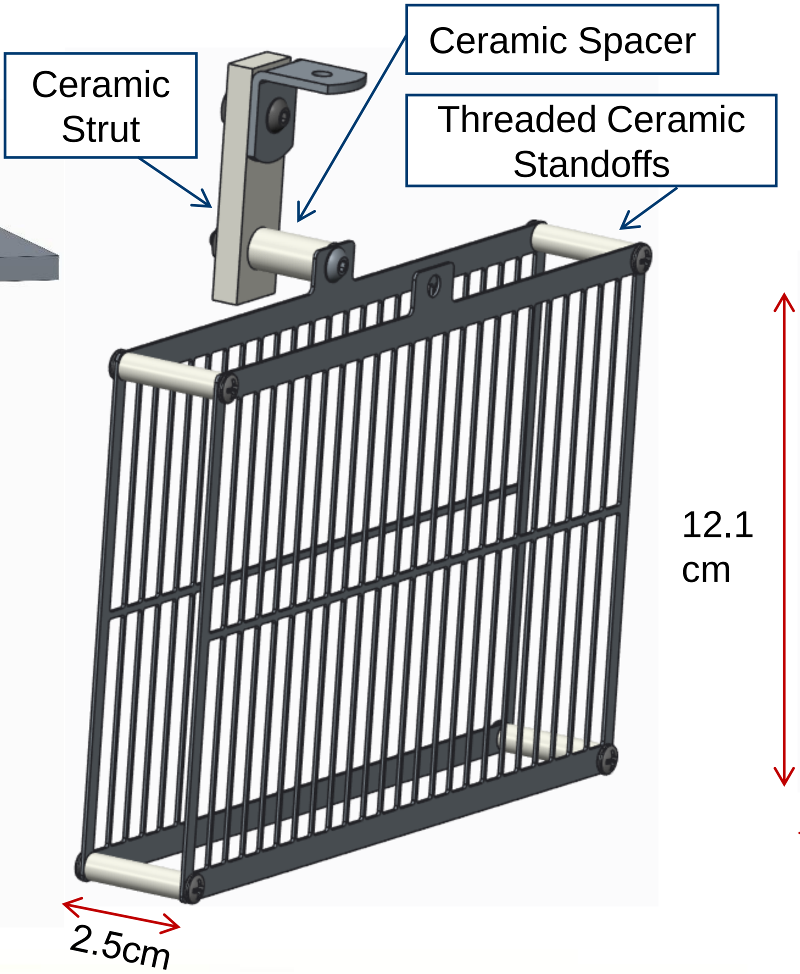
The Solar Wind Implanter (SWIM) Concept

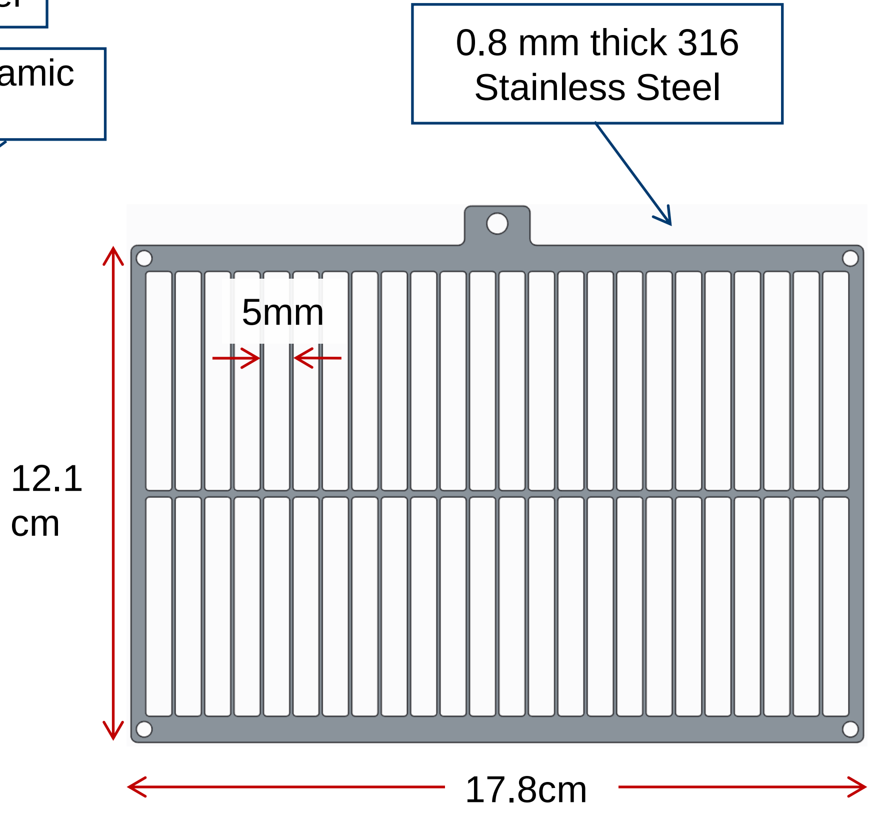


- Implant helium into falling <100 μm JSC-1A lunar simulant
- Replicate solar wind implantation energy at
  ~1 keV/amu with the use of parallel electrode grids
- Use ^{4}He instead of ^{3}He due to cost and availability
  - ^{4}He diffuses out of regolith like ^{3}He

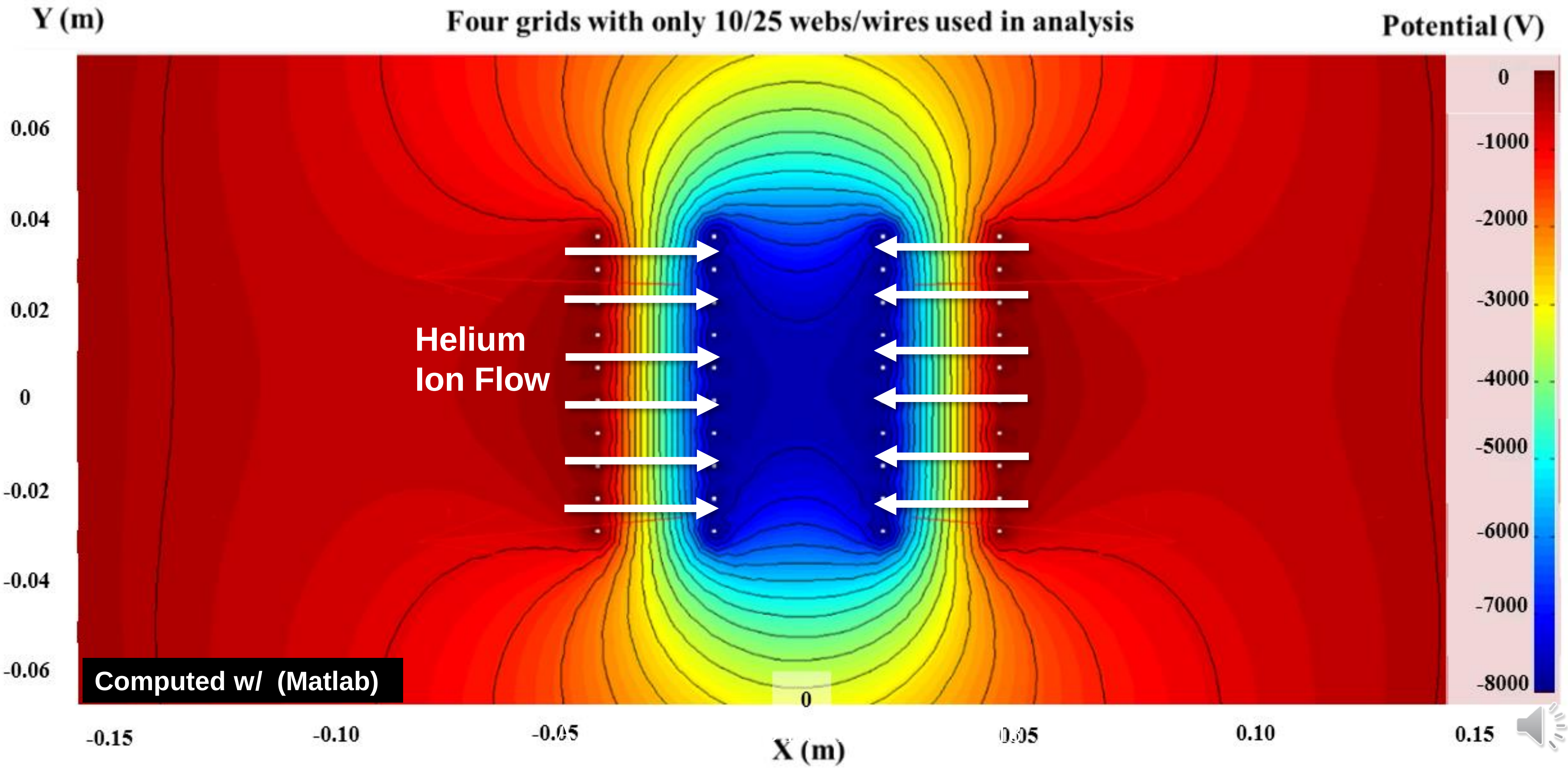
SWIM Design: Acceleration Grid Assembly







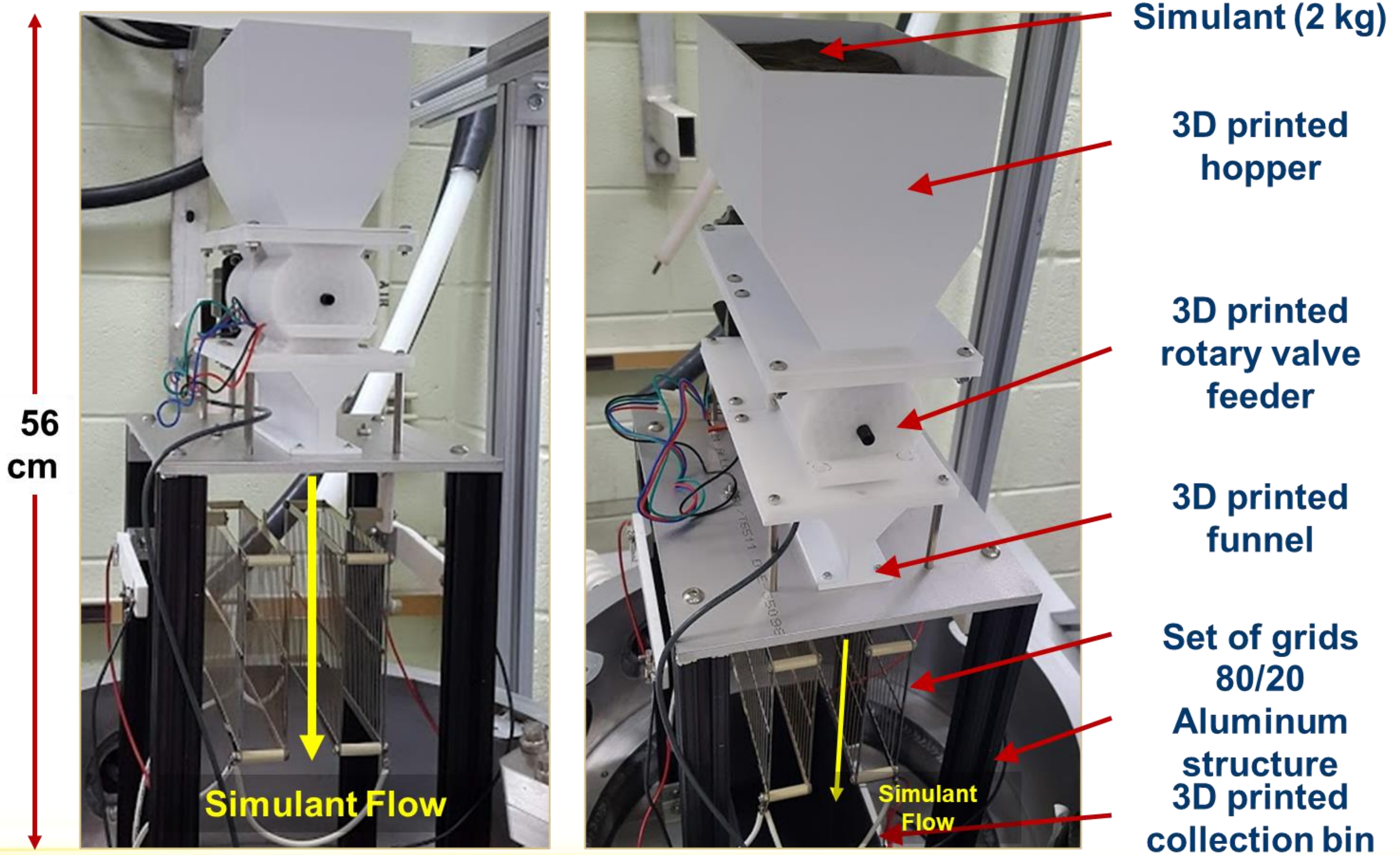
The SWIM Grids Produce a Uniform Electrostatic Potential



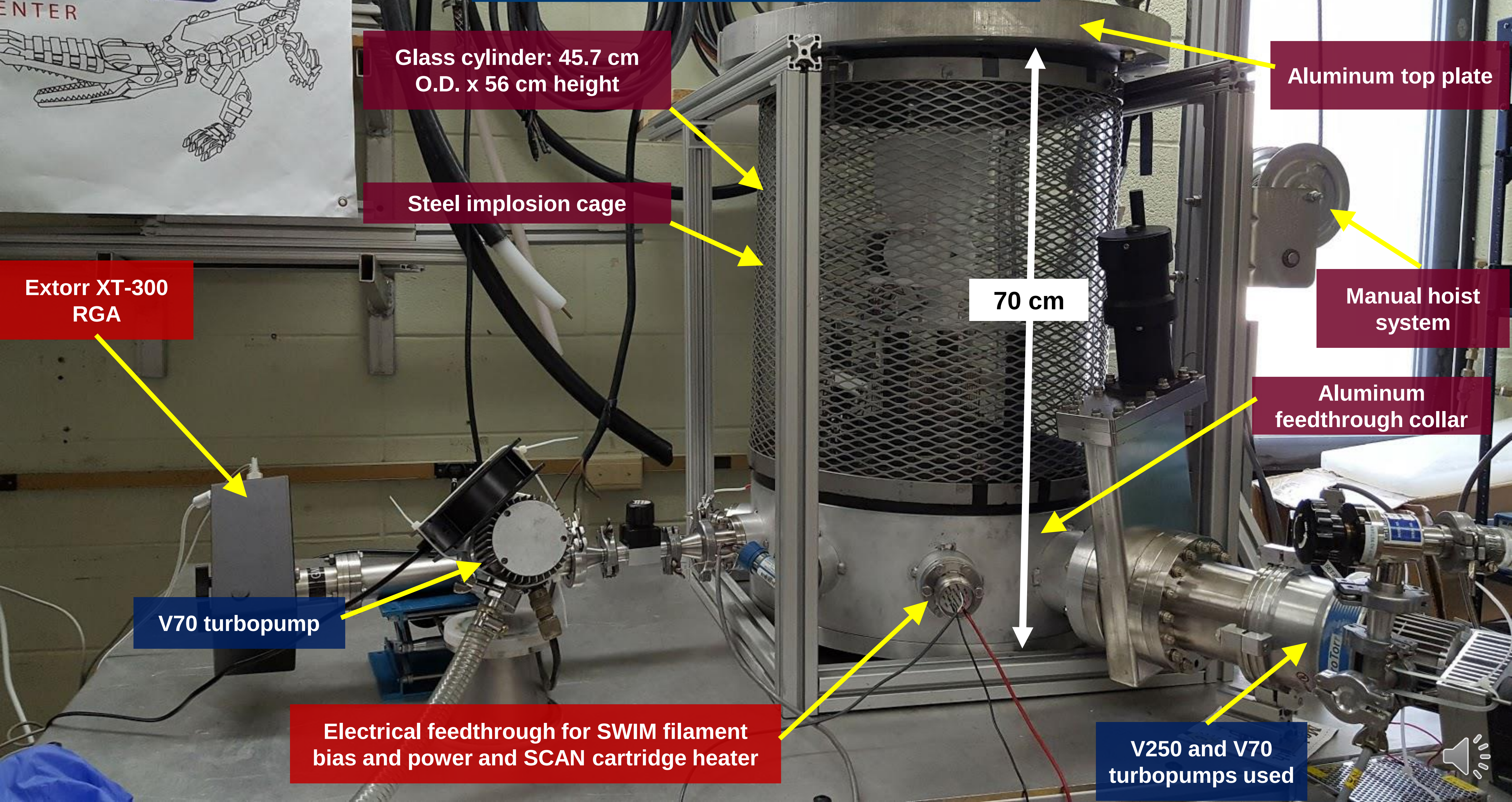
SWIM Design : Principal Components

Power supplies

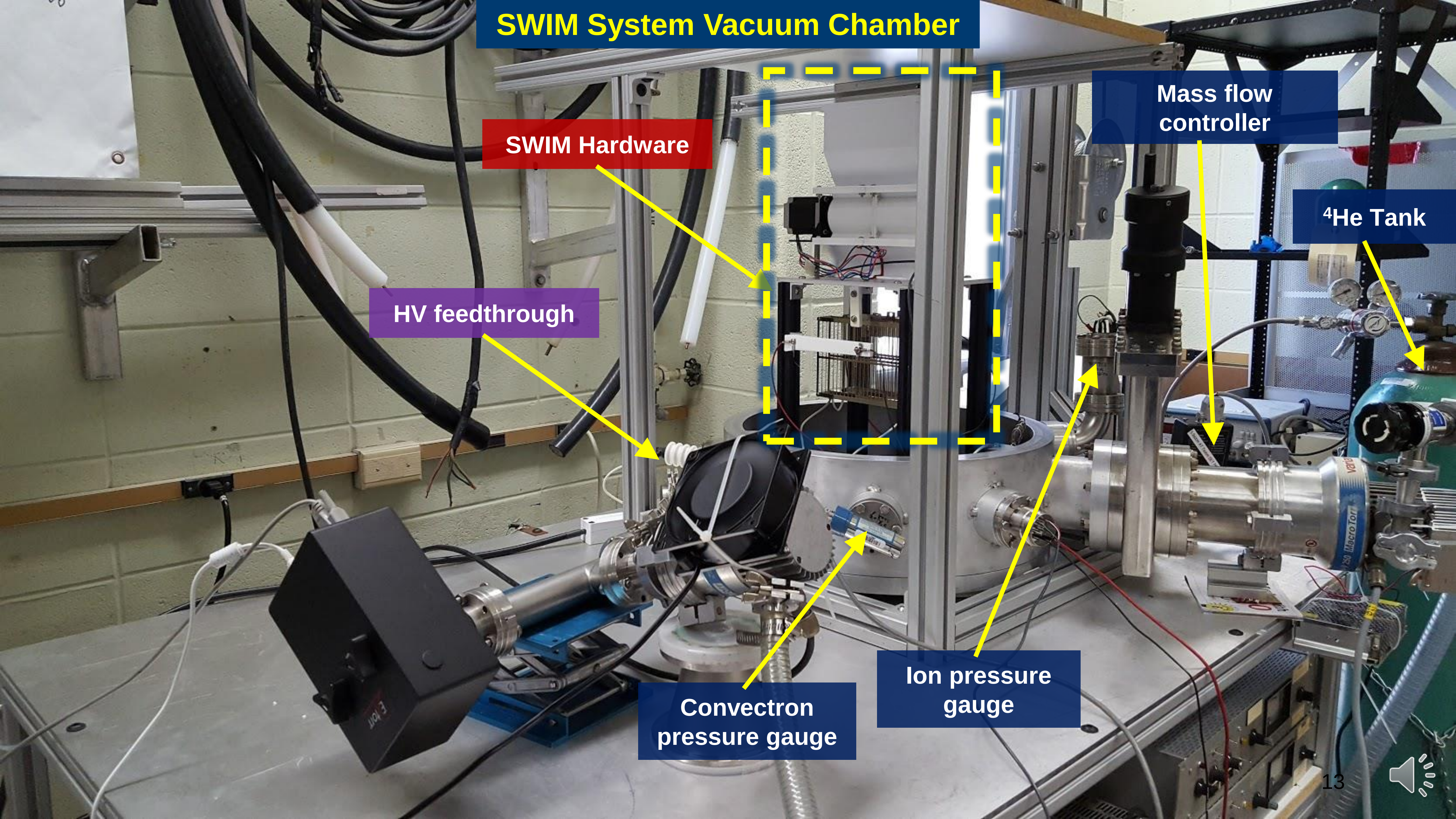
- -20 kV, 15 mA high voltage
- -500 V, 5 A filament bias
- 30 V, 5 A filament heating



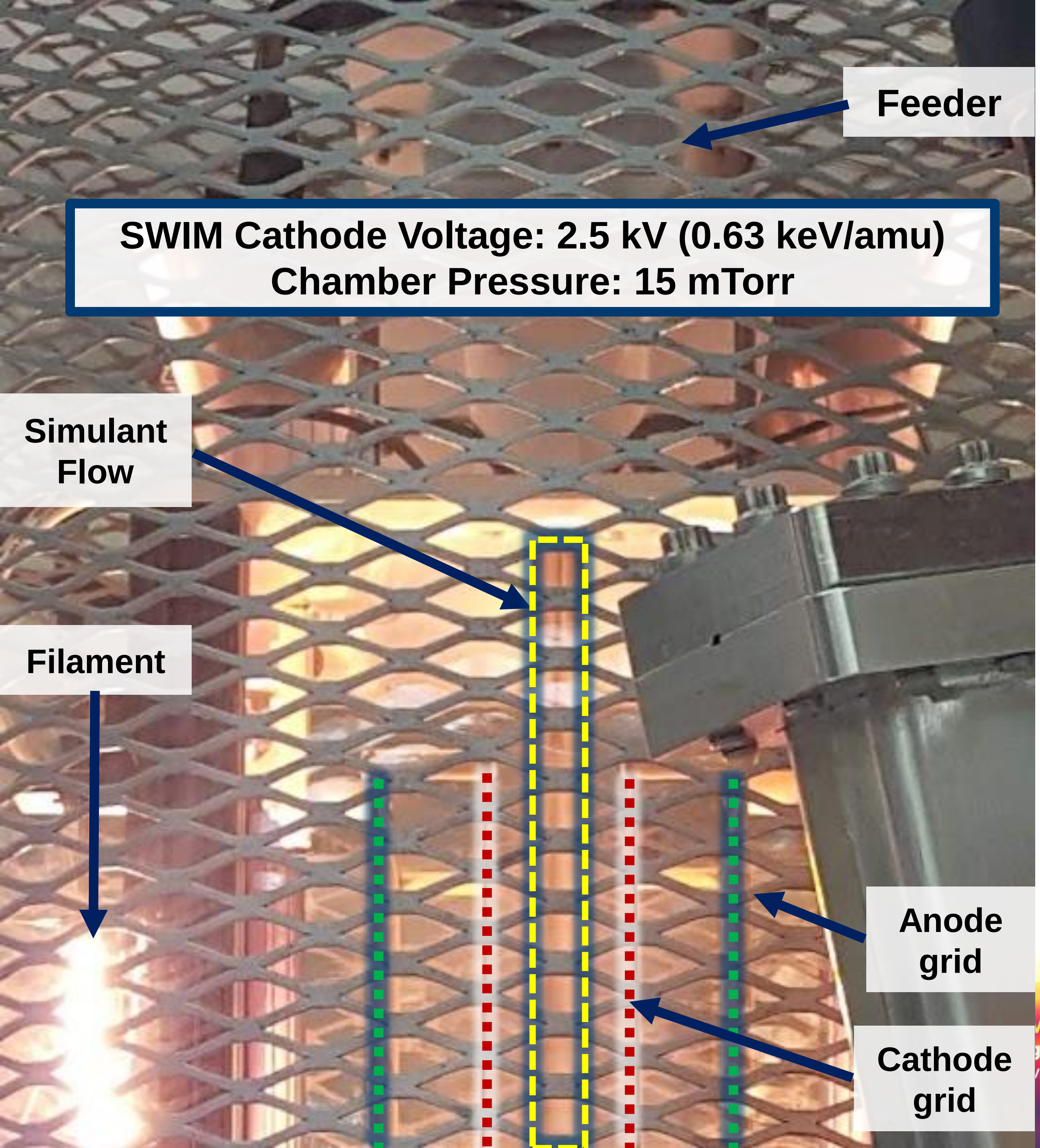
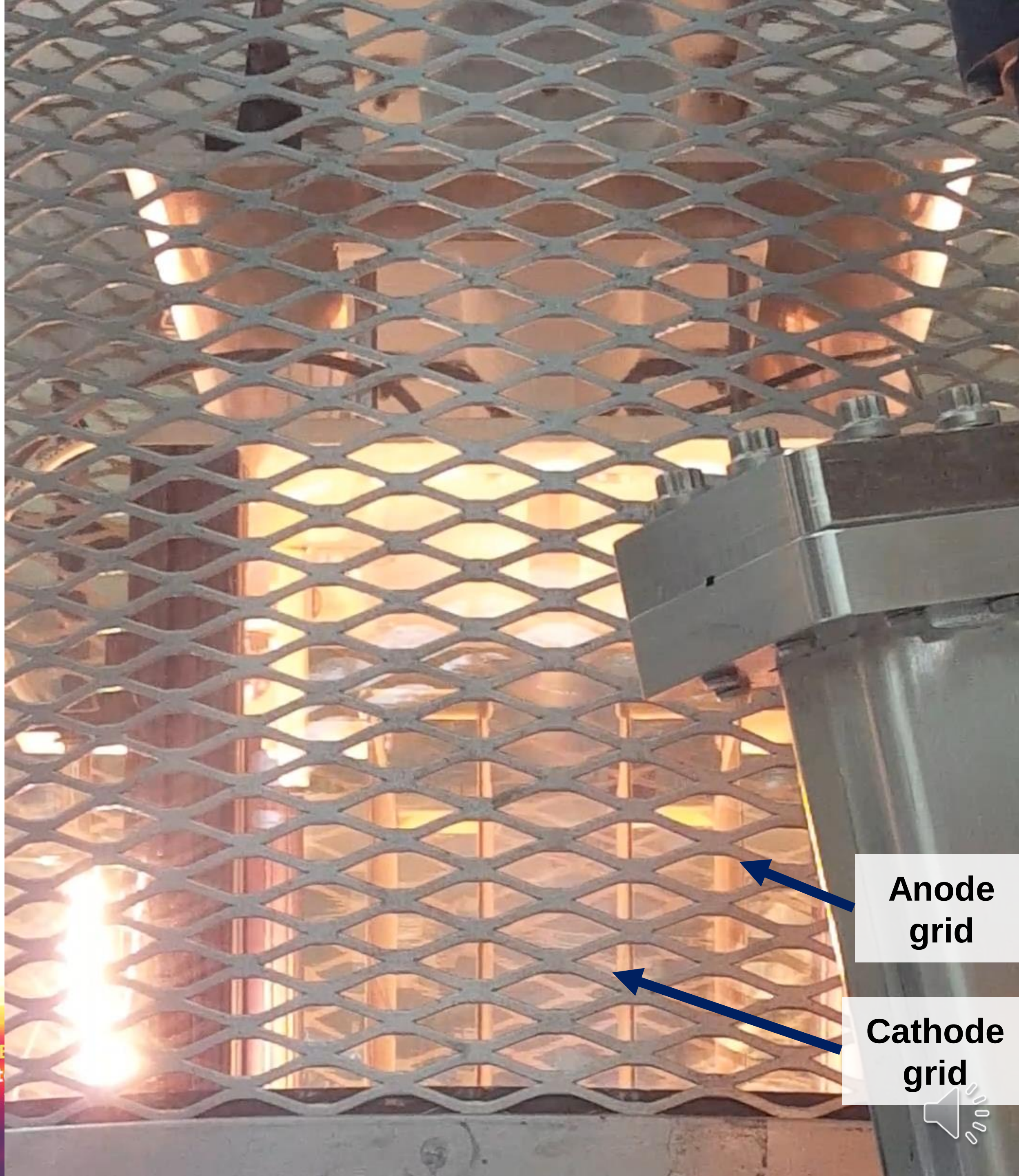
SWIM System Vacuum Chamber



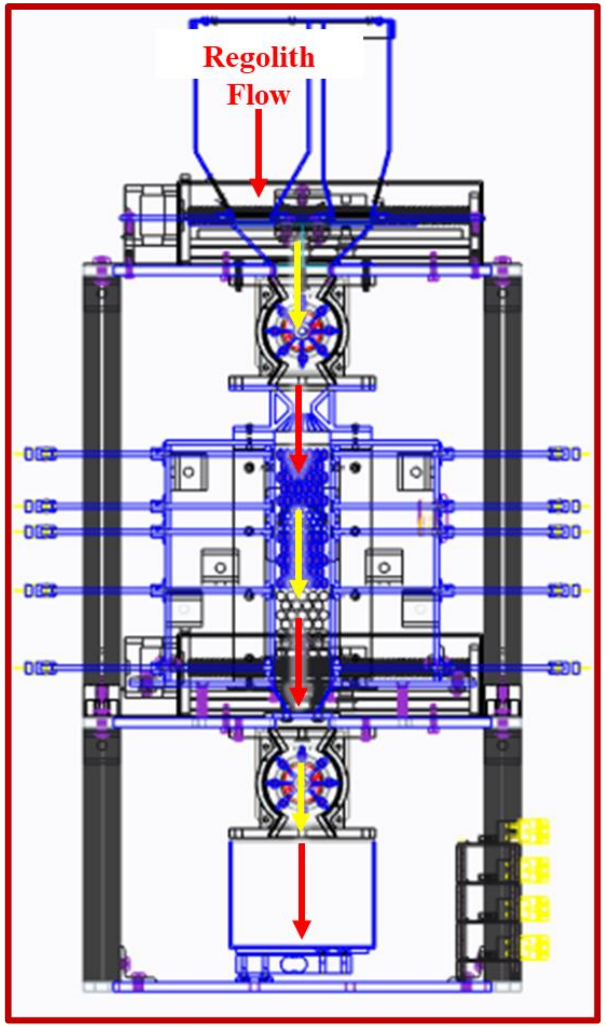
SWIM System Vacuum Chamber

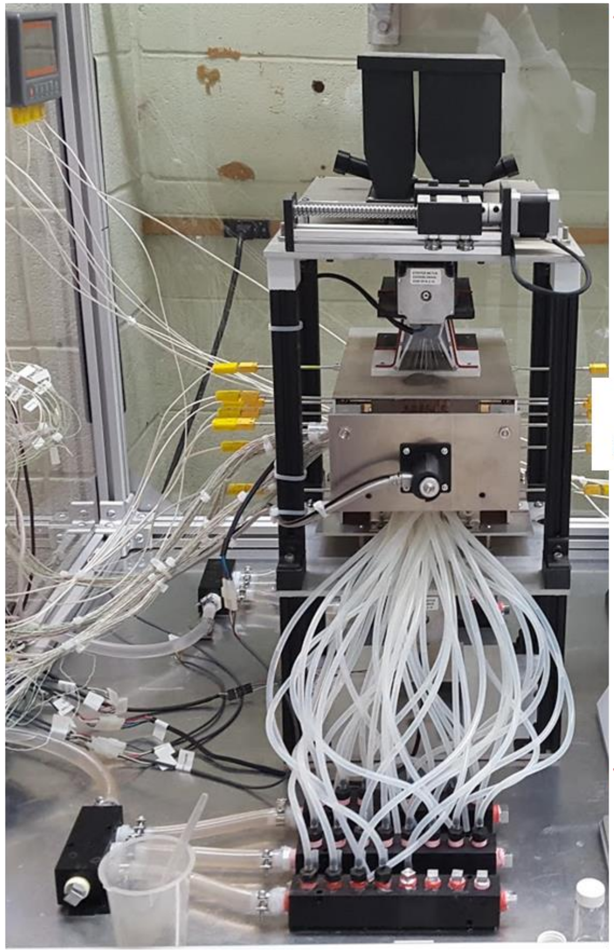


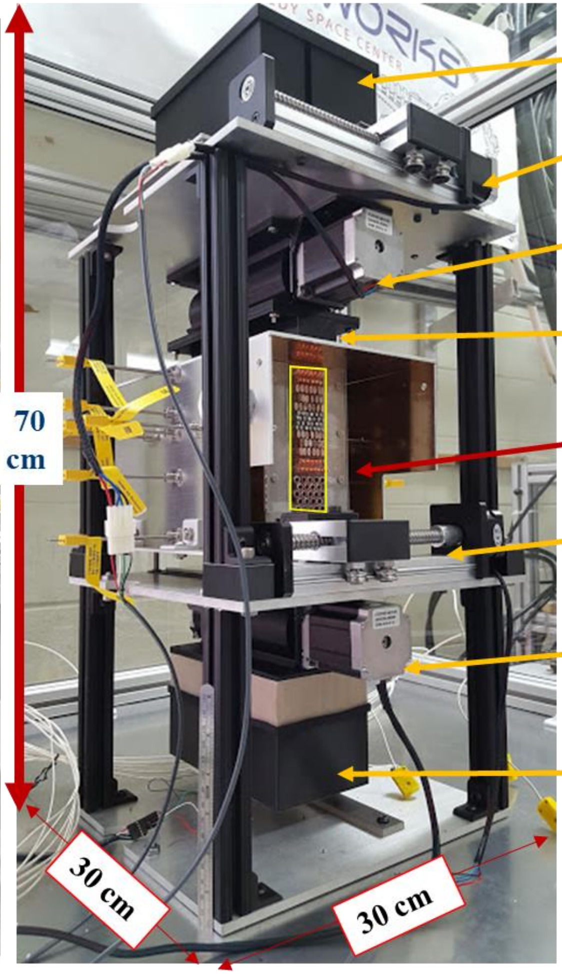

Pressure = 0.56 mTorr ^4He
Grid Voltage = 8kV
Grid Current= 4.96mA
Filament Voltage = 19.9V
Filament Bias = -300V
72.3 g of <100 micron
JSC-1A simulant
implanted – Dec. 2015
2.5cm
Simulant Flow
5 mil diameter wire
Tungsten Filament
Anode
Cathodes
Anode


Feeder
SWIM Cathode Voltage: 2.5 kV (0.63 keV/amu)
Chamber Pressure: 15 mTorr
Simulant Flow
Filament
Anode grid
Cathode grid

Anode grid
Cathode grid

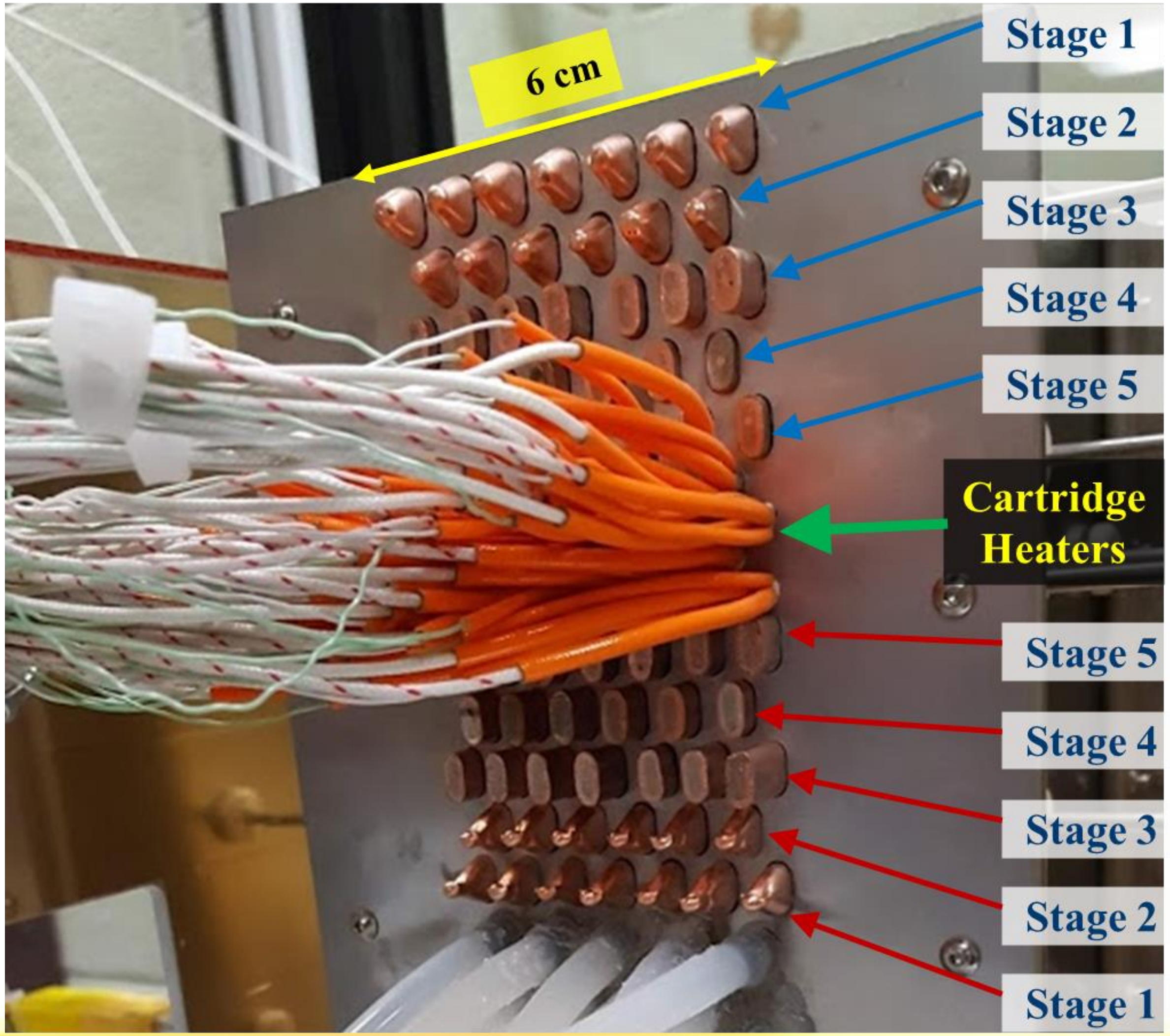
HEAT was Designed to Test Agitation and Thermal Extraction

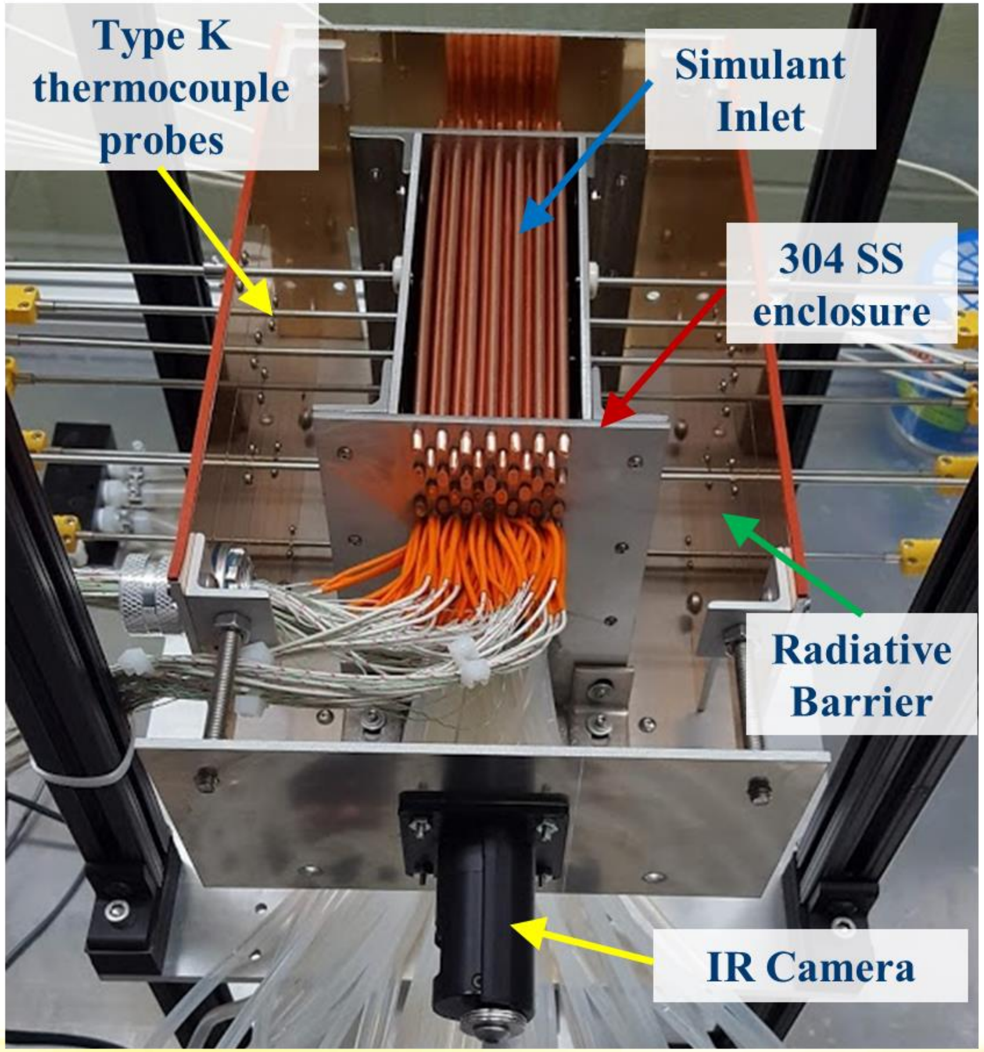






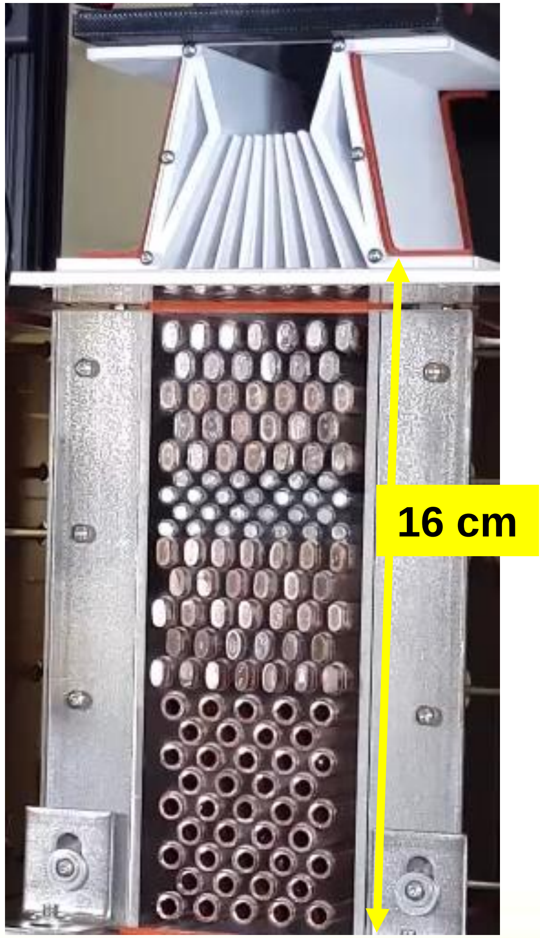
Simulant Flows Around Copper & Steel Tubes in HEAT



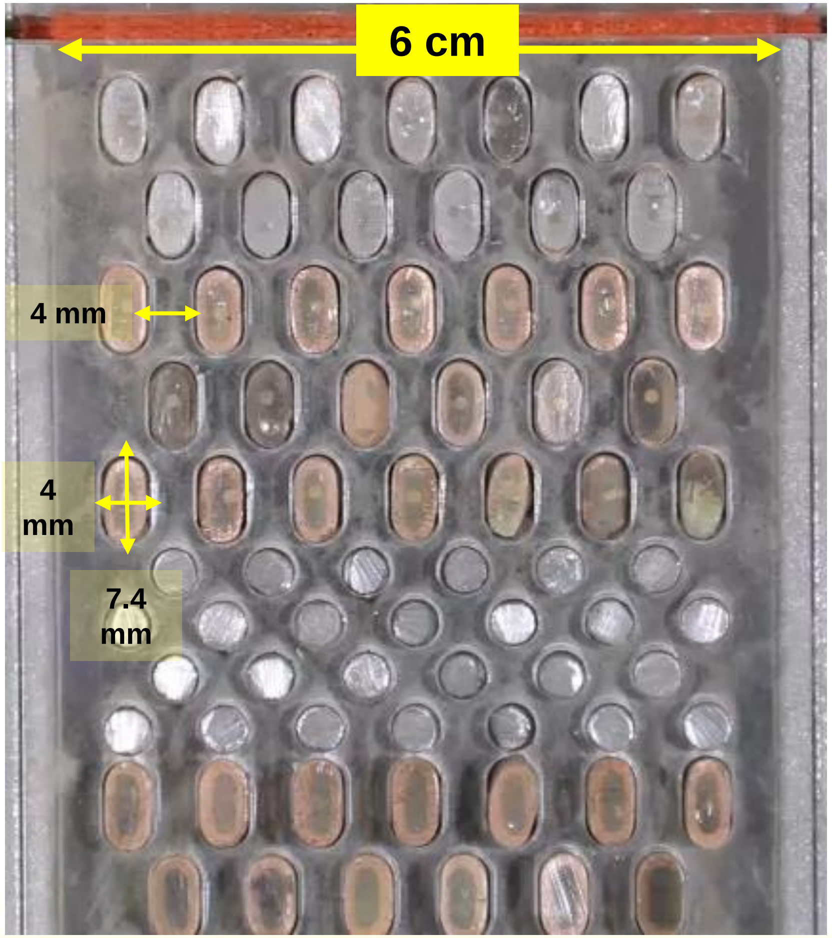


Filling and Discharging the HEAT HPHX - 16x Speed

Flow into Diffuser

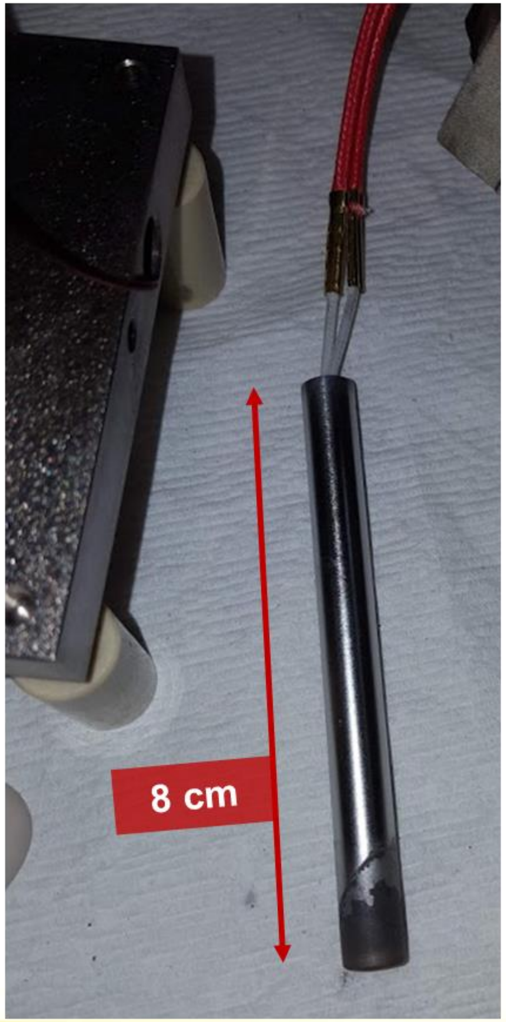


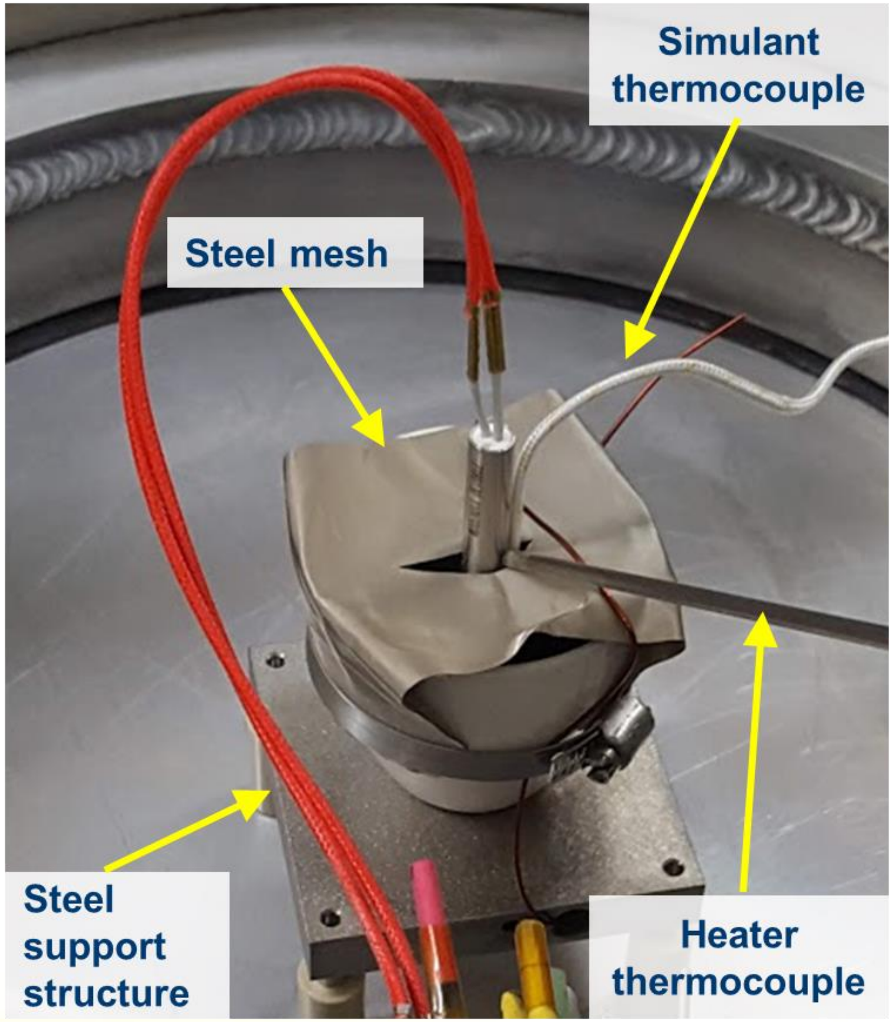
Flow into HPHX



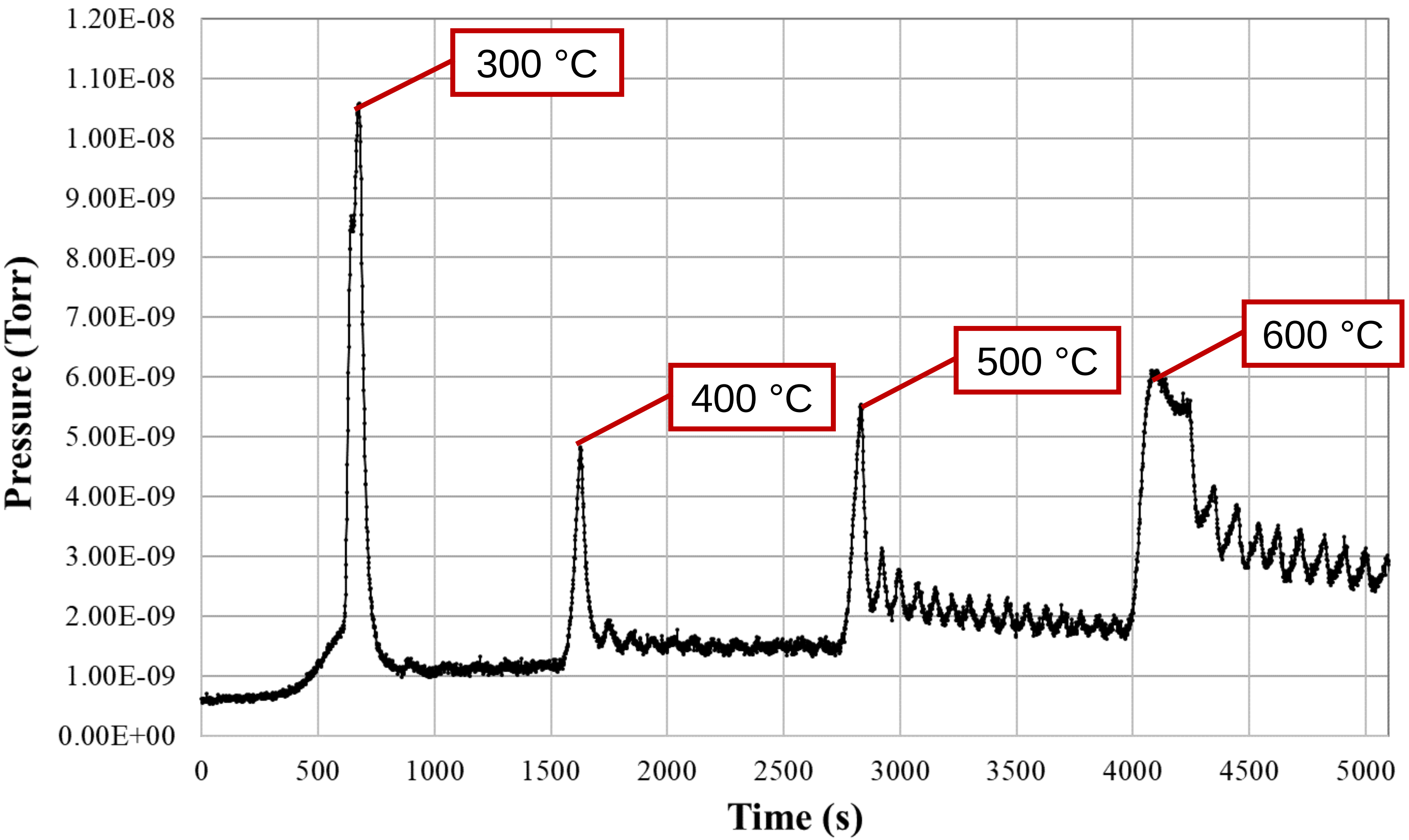
Flow out of HPHX

Sample Concentration Analyzer (SCAN) Components

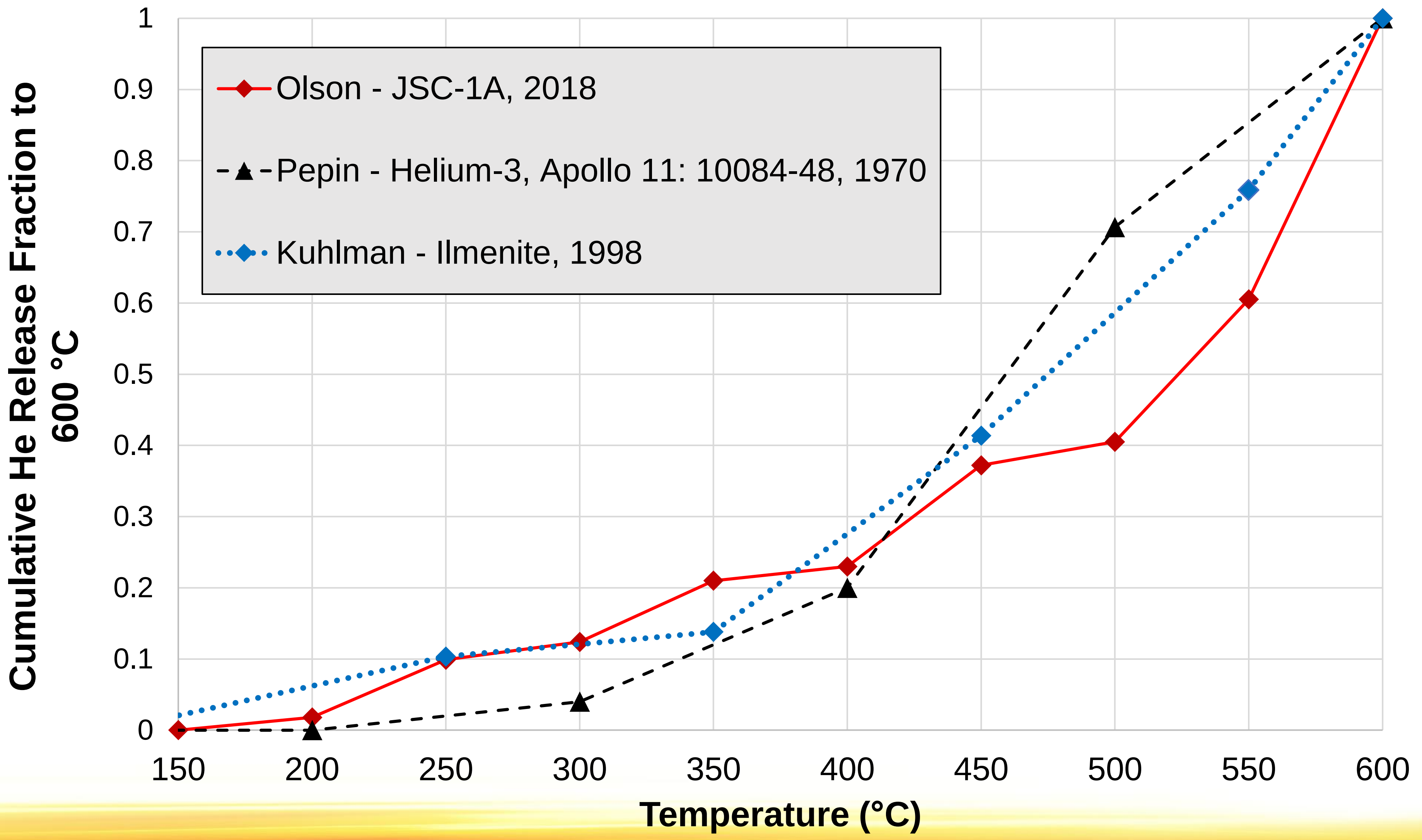




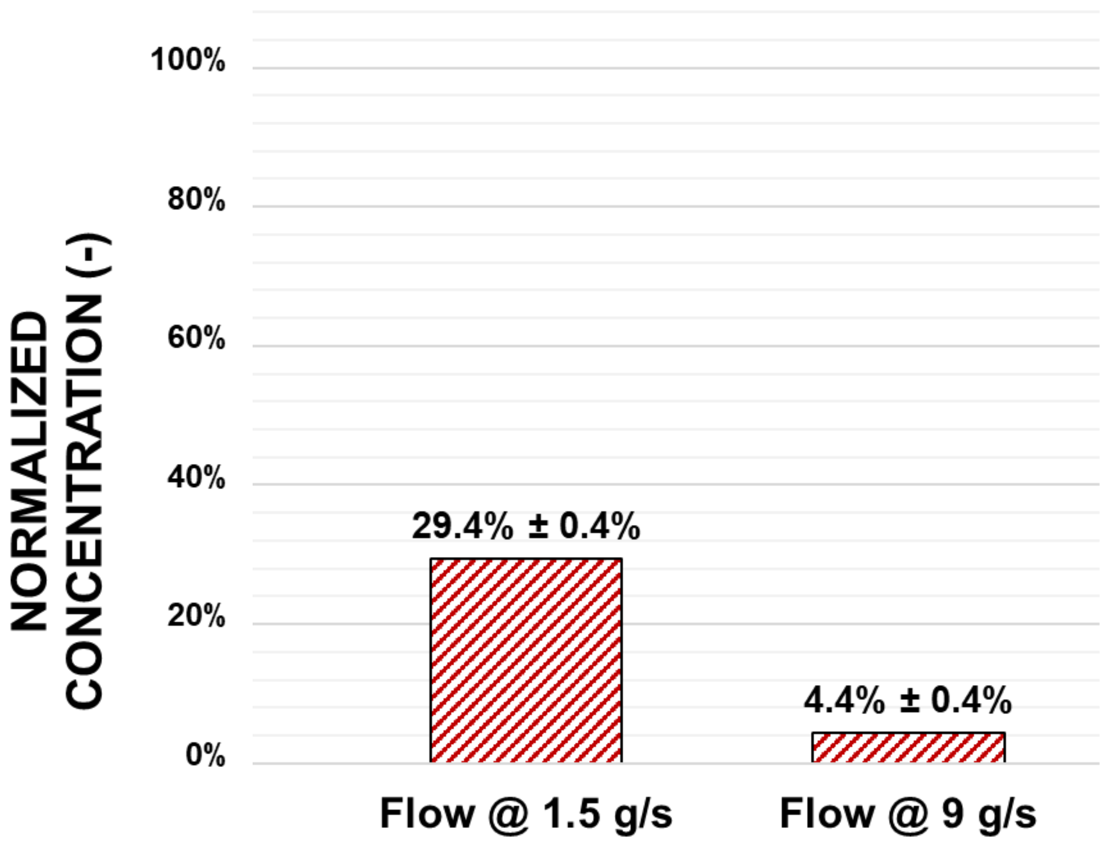
^{4}He Release from an Implanted Simulant Sample



^{4}He Release from SWIM Implanted Simulant & Lunar Regolith



Flow Induced Agitation Reduces Retained ^{4}He in Simulant



Sample(s)	Retained ^{4}He Concentration (ppb)
After SWIM Implantation	2.4
HEAT – 1.5 g/s flow rate	0.7
HEAT – 9 g/s flow rate	0.1

Experimental Limitations

- < 1 keV/amu average helium implantation energy likely resulted in shallower ion implantation compared to lunar soil
- Samples were only heated to 600 °C – potentially up to 25% of the implanted ^{4}He remained, i.e., 100% released at 1000 °C for Apollo samples

Potential In-Situ Resource Utilization Synergies

- Utility scale ^3He mining produces tonnes of valuable by product volatiles
- Artemis – NASA and its partners are going to the Moon to stay
- 400+ tonnes to be excavated to refuel a lander needing 10 tonnes of O_2 (from 15 tonnes of ISRU derived water)
  - Up to 6 g of ^3He could be released and collected
- Passive agitation release of ^3He in ISRU and construction activities could be leveraged to demonstrate feasibility of ^3He lunar processing

Thank You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