Implantation of Helium into JSC-1A Lunar Regolith Simulant for Volatile Extraction System Testing

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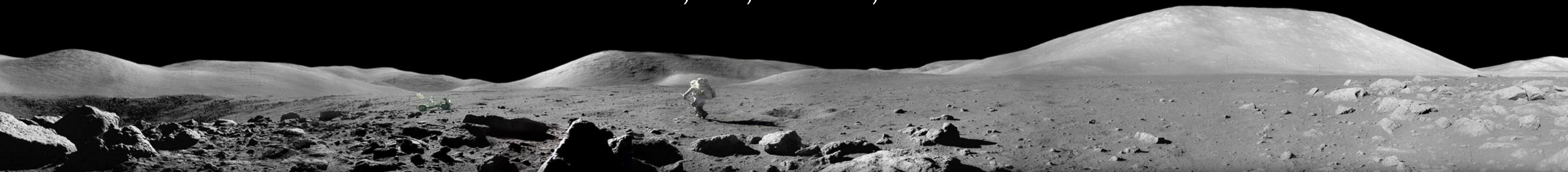
7th SRR/PTMSS
Golden, CO, June 9th, 2016



Outline

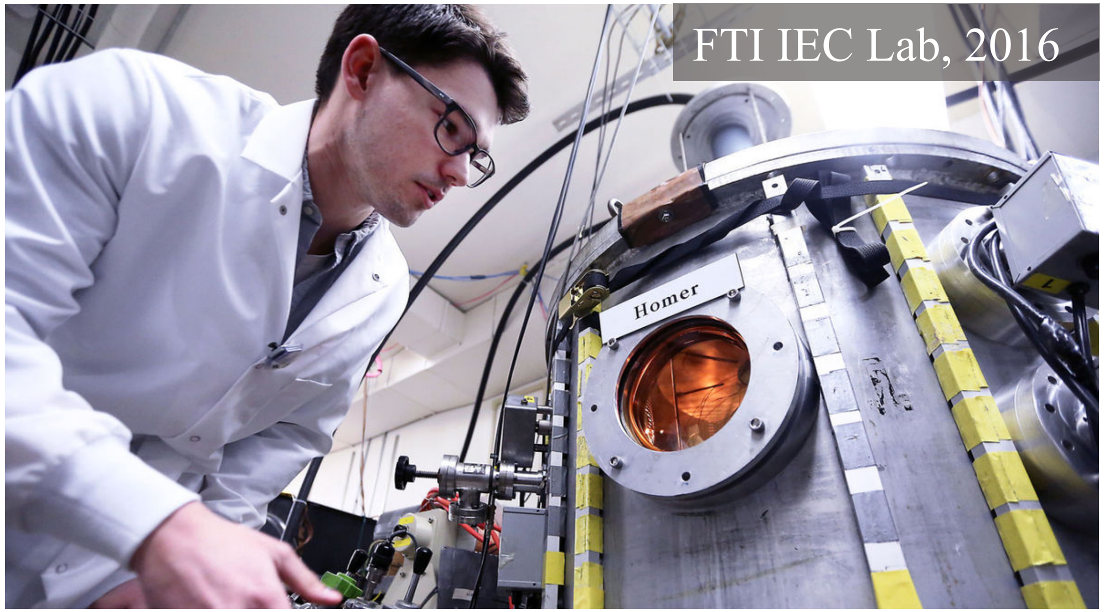
- Motivation and Context for the Presented Research
- Overview of Research to Demonstrate Lunar Volatiles Extraction
- Solar Wind Implanter (SWIM) Design and Operation
- Conclusion: Progress and Future Work

Fusion Technology Institute

- Large government programs: ITER, NIF
- Nearer term applications: neutron sources, medical isotopes
- Commercial fusion companies
- Resources for fusion (Lunar ^{3}He)


Schmitt and Olson, 2013


ITER, 2016

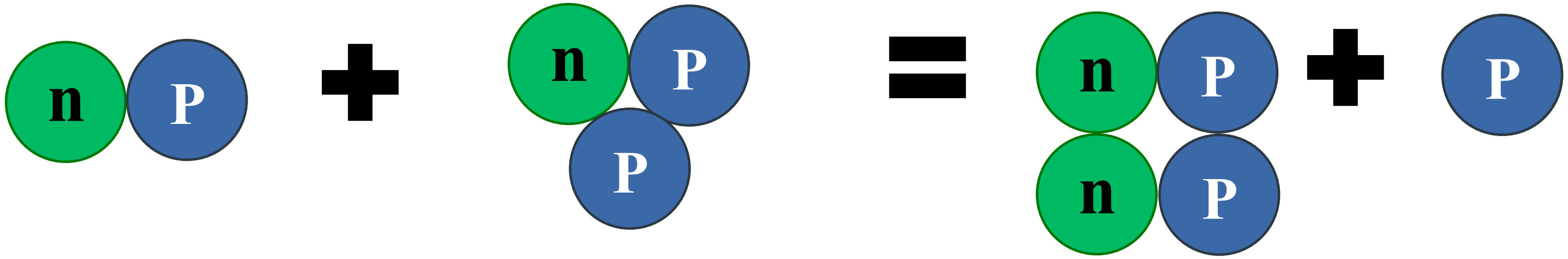


FTI IEC Lab, 2016

^{3}He Fusion Reactors Could Produce Nuclear Power with Little to No Nuclear Waste

Deuterium-Helium-3

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

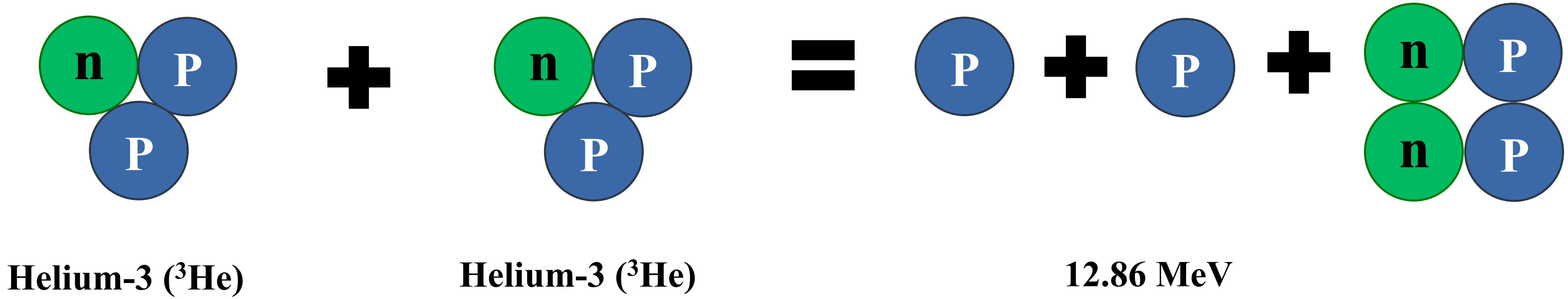


Deuterium (^{2}H or D) **Helium-3 (^{3}He)** **3.67 MeV** **14.68 MeV**

^{3}He Fusion Reactors Could Produce Nuclear Power with Little to No Nuclear Waste

Helium-3 and Helium-3

$$^3He + {}^3He \rightarrow 2p + {}^4He \ (12.86\ MeV)$$



^{3}He Fusion Reactors Could Produce Nuclear Power with Little to No Nuclear Waste

- No Greenhouse or Acid Gas Emissions
- Very High Energy Conversion Efficiencies (>70%)
- Greatly Reduced Radiological Hazard Potential Compared to Fission Reactors (<1/10,000)
- No Possible Offsite Nuclear Fatalities in the Event of Worst Possible Accident
- No Proliferation of Weapons Grade Material

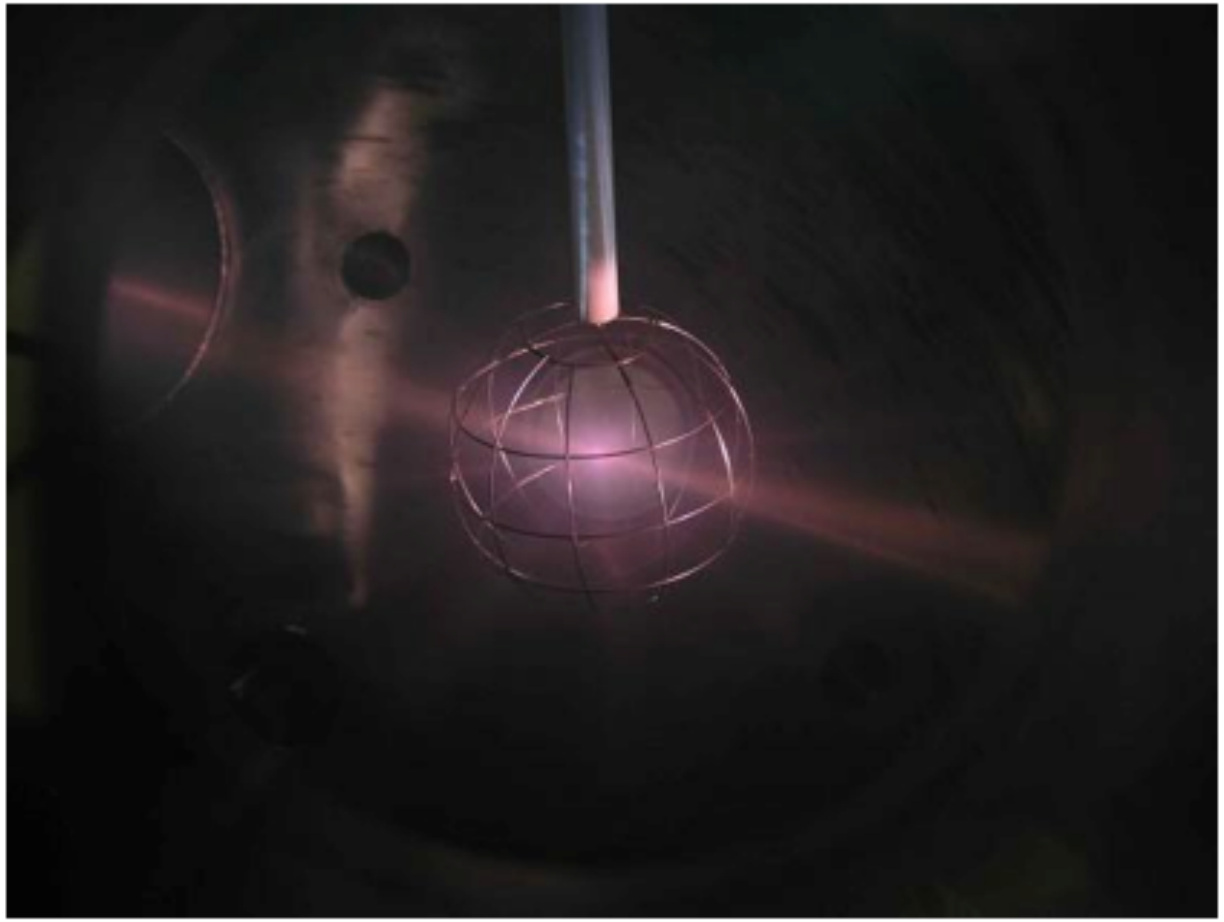
What is Required to Develop ^{3}He Fusion Reactors?

- Continued ^{3}He Fusion Research
- Technology to Access Large Sources of ^{3}He

Progress at Wisconsin Toward ^{3}He Fusion Reactors

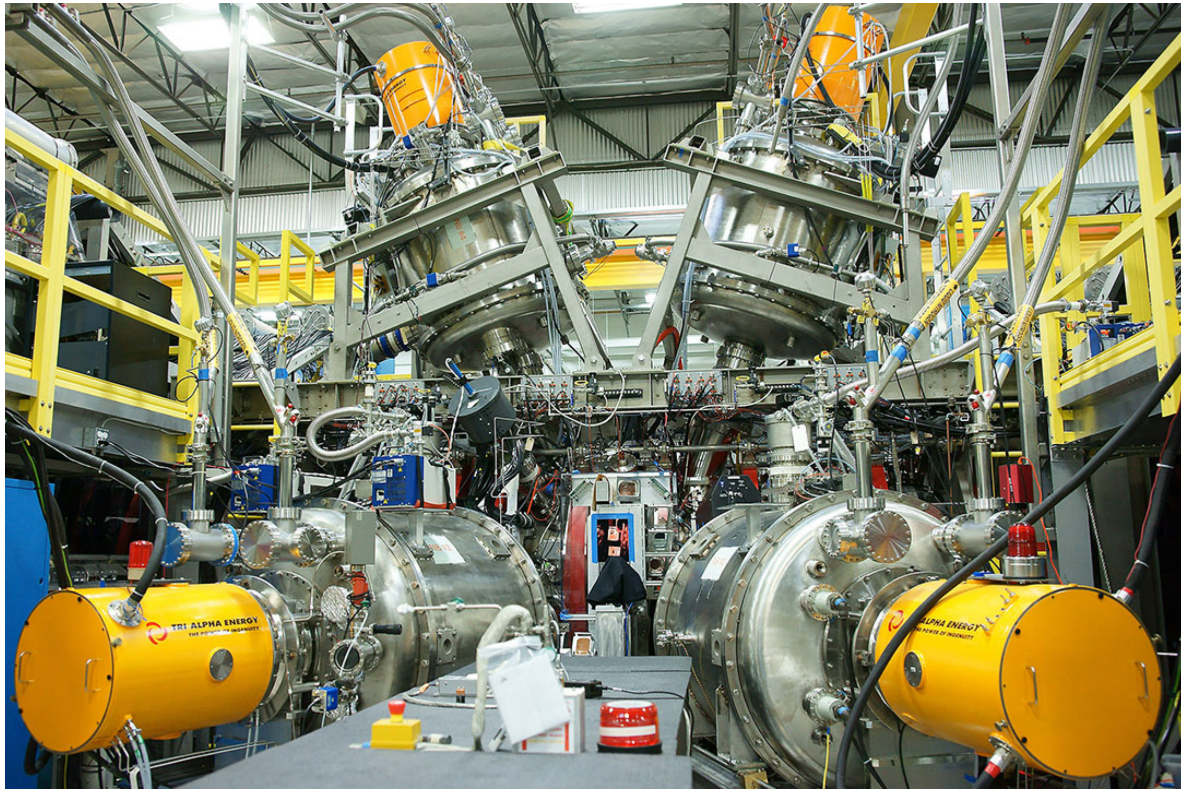
D^{3}He fusion reactions in an IEC device demonstrated in 1999

First demonstration of ^{3}He^{3}He reactions in a plasma in 2005

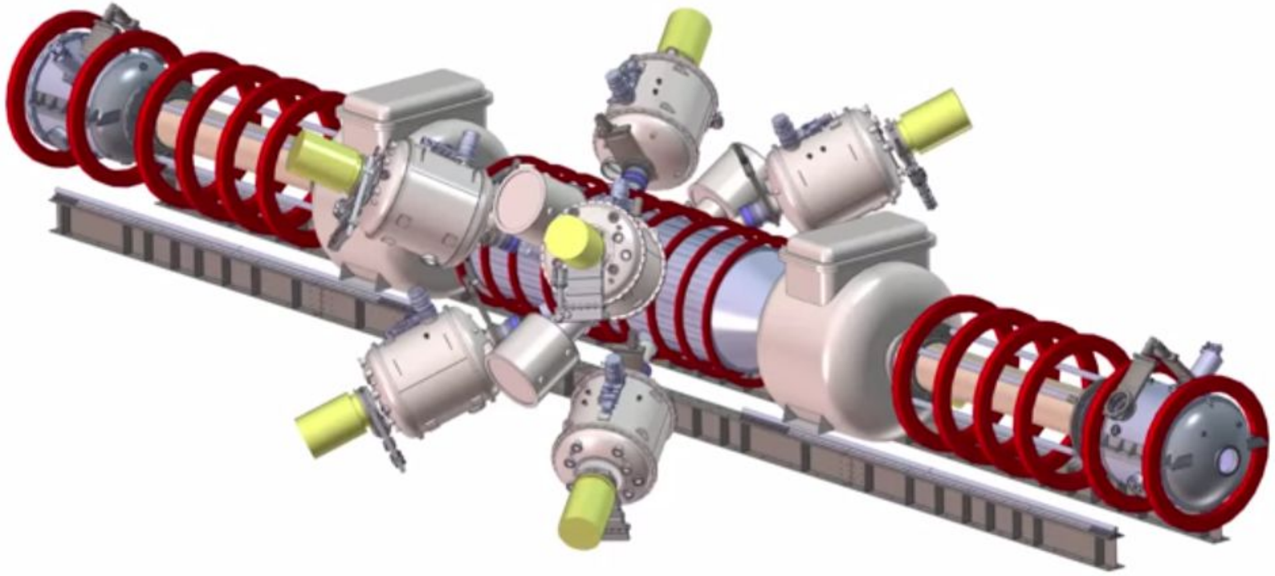


Commercial Progress in Advanced Fuel Fusion Reactors

Tri Alpha Energy, Lockheed Martin, Helion Energy, EMC2



Credit: Tri Alpha Energy, 2015



TRI ALPHA ENERGY
leading the way to the future...

The ^{3}He on Earth is Insufficient to Support Commercial Fusion Power

There is <30 kg of available terrestrial ^{3}He (from Tritium Decay)

*0.6 GWyr of ^{3}He Fusion Energy

Enough for ^{3}He Fusion R&D

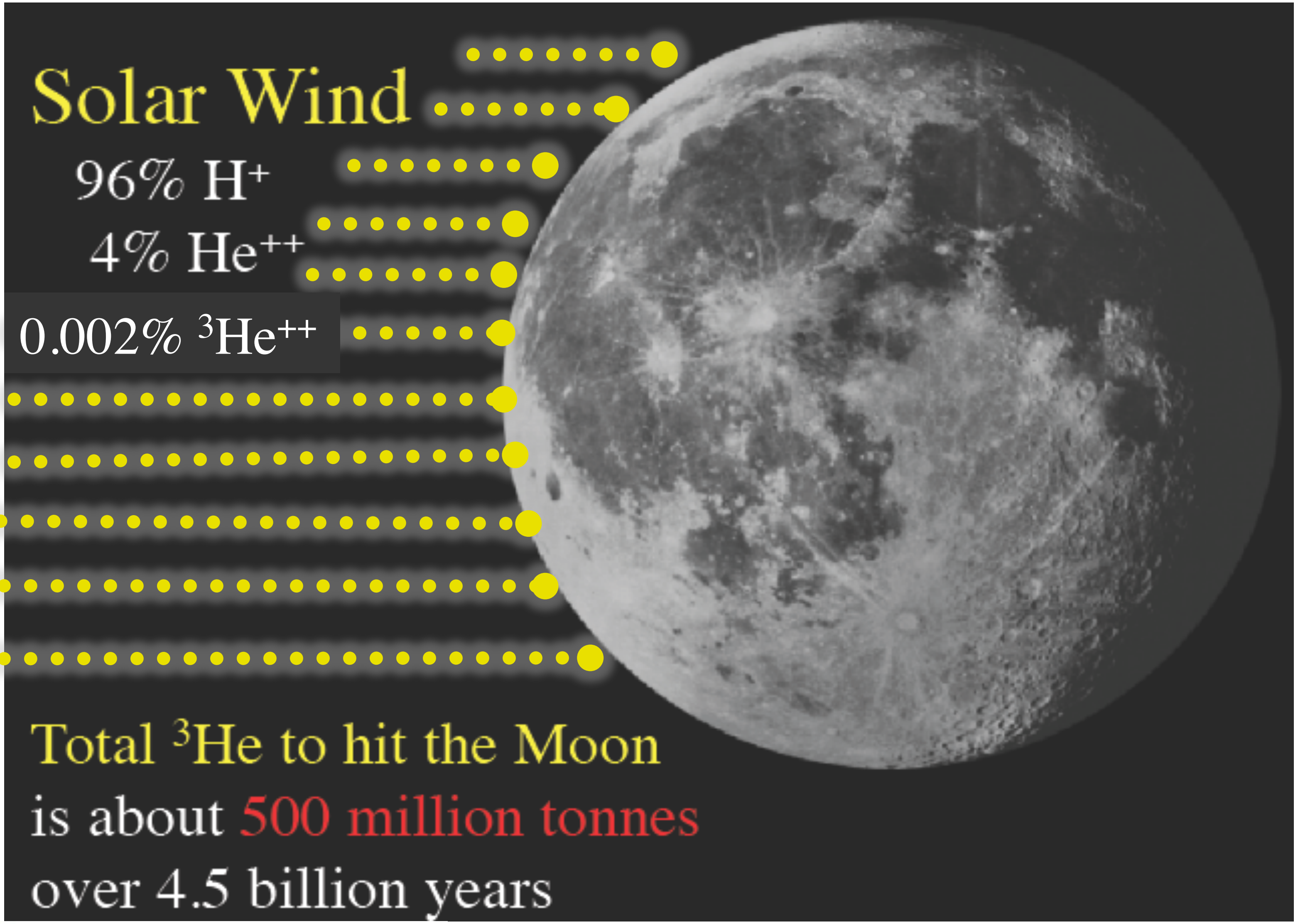
Only enough electricity for 5 weeks in Colorado

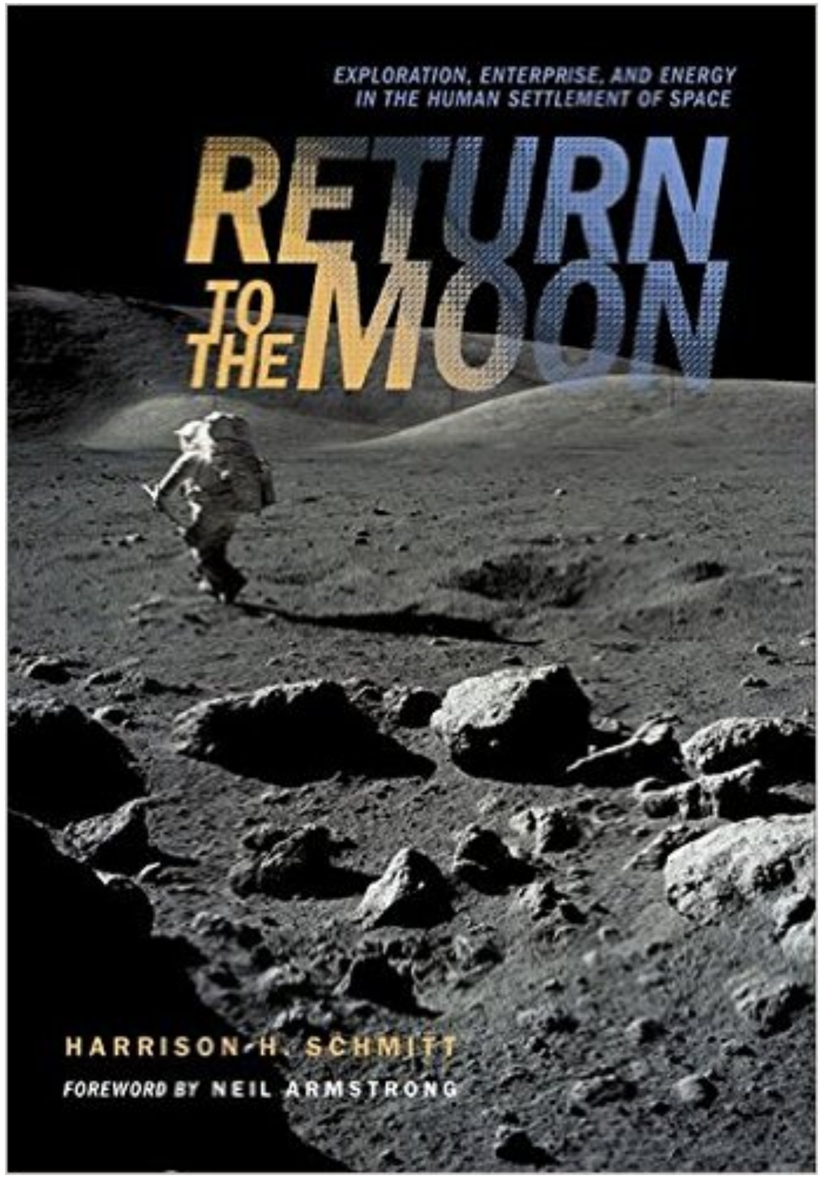
Colorado

~6 GWyr electricity used in 2015

*20 MWyr/kg of fusion energy for ^{3}He

The Moon has retained over 1 million tonnes of ^{3}He

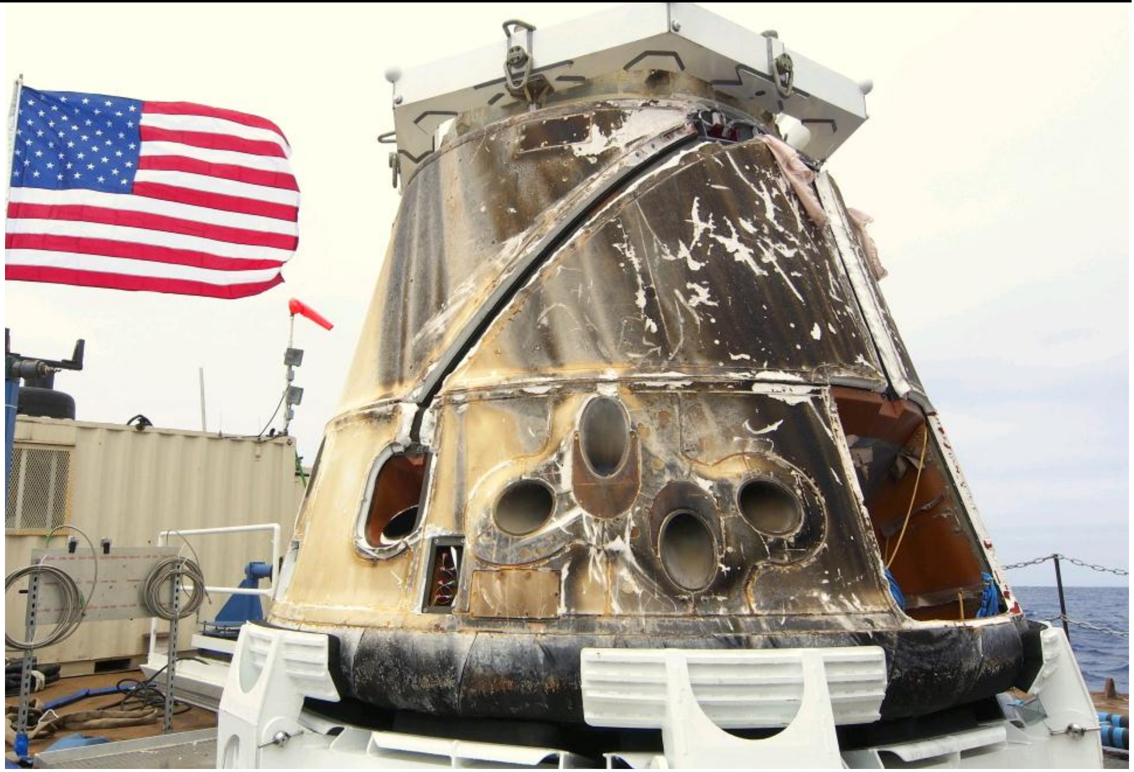




^{3}He on the Moon Could Become Extremely Valuable

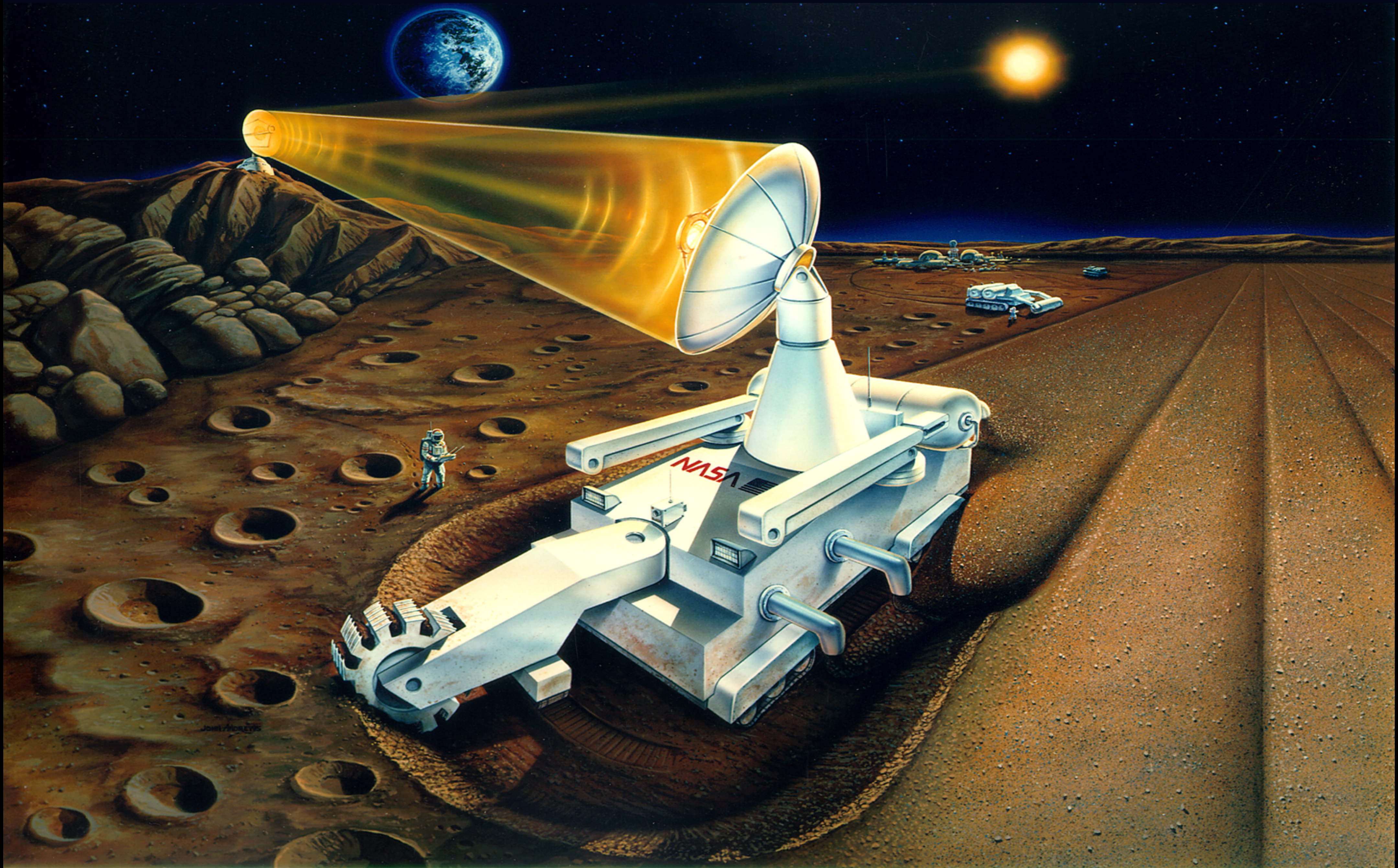
At today's oil prices ($38/barrel) the energy content in one tonne of ^{3}He would be worth $3.7 billion

One of today's SpaceX Dragon capsules could return the volume of a ^{3}He "payload" worth around $15 billion in energy.



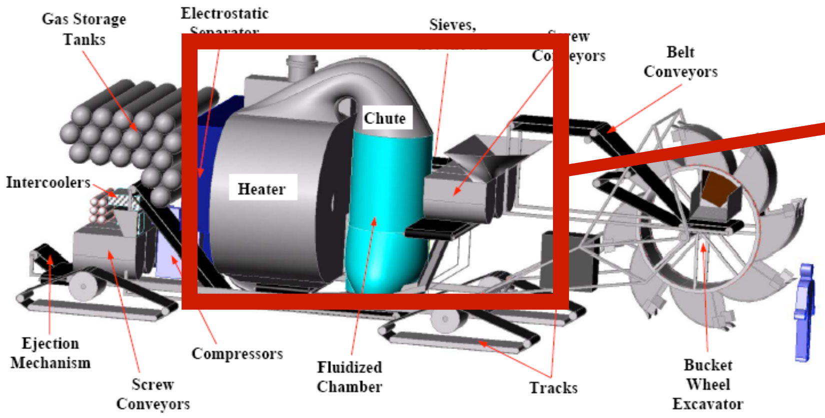
Credit: SpaceX, 2012

Three Iterations of Helium-3 Miners Designed at the UW FTI



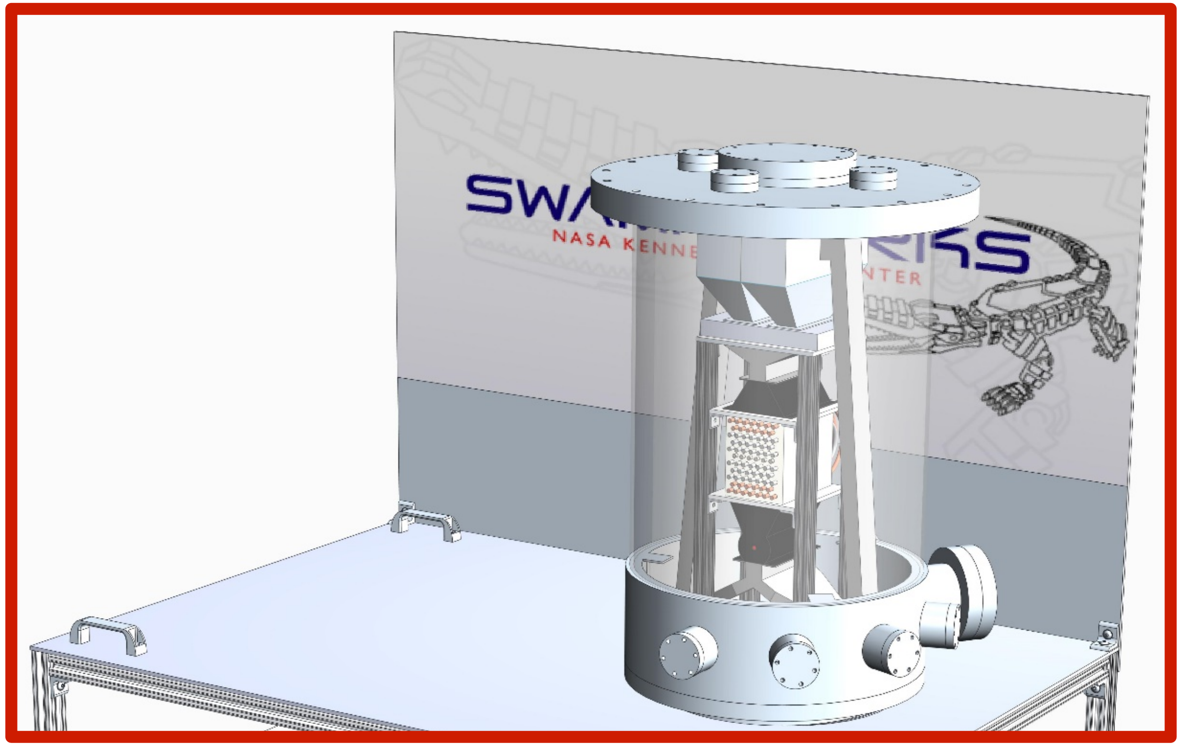
This Research Will Demonstrate ^{3}He Extraction

- First Demonstration of ^{3}He release inside of a heat pipe heat exchanger
- Laboratory scale (TRL 4)



Mark 3 Lunar Miner, Credit: M. Gajda

Helium Extraction and Acquisition Test bed (HEAT)



There are Two Main Aspects of this Work

- Implant He into Simulant
- 1kg Batches of Simulant
- Known Concentrations

Solar Wind Implanter (SWIM)

- Regolith Temperature to 700°C
- Heat Recovery Measurement
- He Release Measurement

Helium Extraction and Acquisition Testbed (HEAT)

Solar Wind Implanter (SWIM) Objectives

Implantation Goals

- Implantation energy: ~1 keV/amu (solar wind)
- Aim for 20 ppb ^4He concentration
- ^4He diffuses out of regolith like ^3He (use ^4He for cost)

Implantation Characterization

- Helium release vs. temperature
- Measure the released helium relative to any background ^4He concentration
- Energy spectrum of implanted ^4He

Past Lunar Regolith Implantation Studies

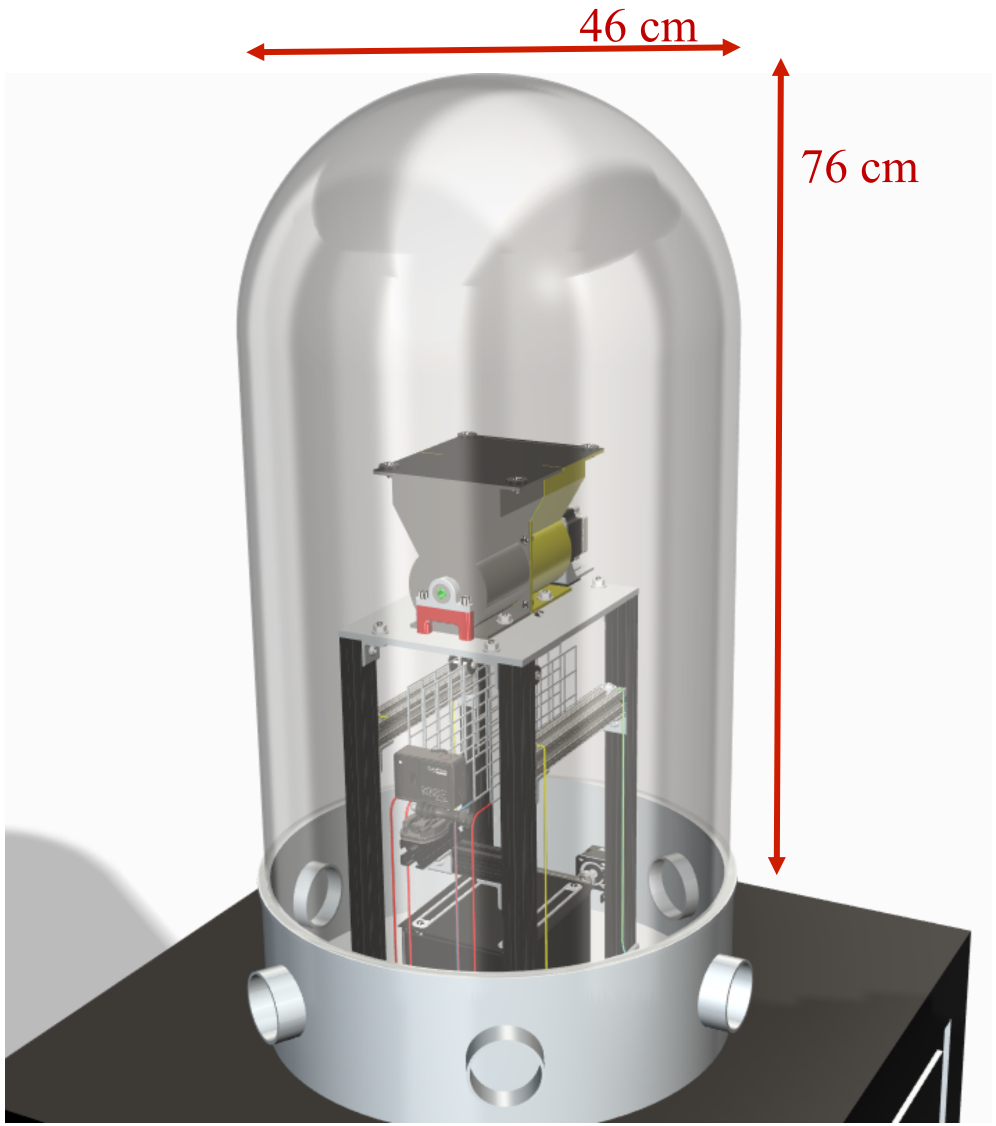
- Plasma Source Ion Implantation (PSII), helium was implanted into regolith simulant at energies between 5-50 keV/amu at the University of Wisconsin (Kuhlman, 1999 and 2012)

- More time consuming means of helium ion implantation into regolith minerals with ion beams have also been done (Futagami et al, 1990)

- An efficient and readily available solar wind implantation device for bulk batches of simulant did not exist to our best knowledge

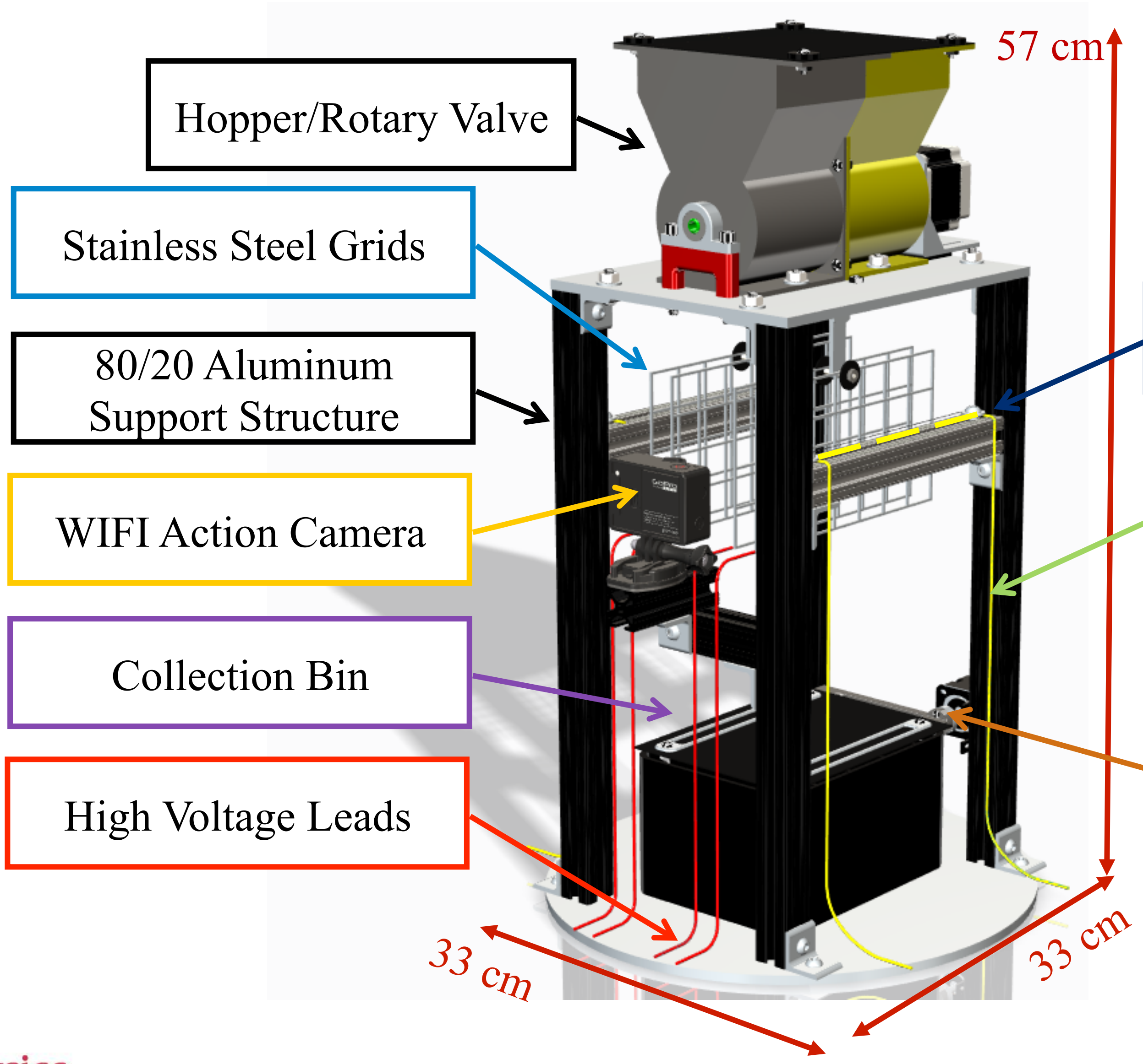
SWIM Current Approach

- Two sets of mesh cathode-anode pairs (implantation into both sides of the falling sheet)
- Use of tungsten filaments to ionize helium gas in vacuum chamber
- Rotary valve (stepper motor driven) to discharge simulant in as thin of falling "sheet" as possible
- Camera to record simulant flow through plasma of inside chamber



Current SWIM CAD Model

SWIM Components



SWIM: Implantation Analysis

Mass of helium to be implanted

$$M_{He}=\left(\frac{c}{1-c}\right)M_{sim}$$

Helium ion flux

$$\Gamma_{He}=\frac{N_A c\dot{M}_{sim}}{2W_{He}(1-c)(1-F_o)L_{grid}h_{grid}}$$

Helium ion current density

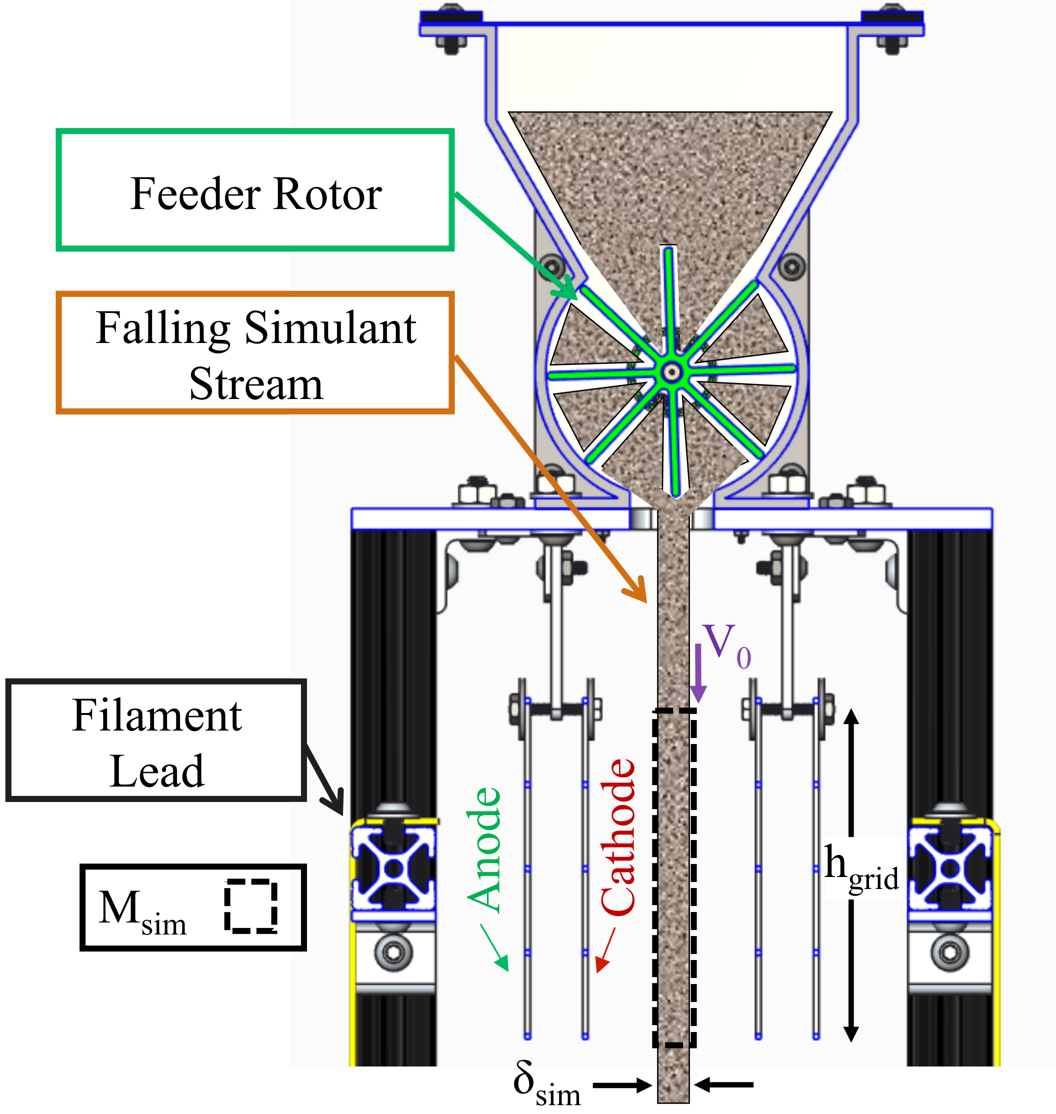
$$J_{imp}=e\Gamma_{He}$$

Measured current

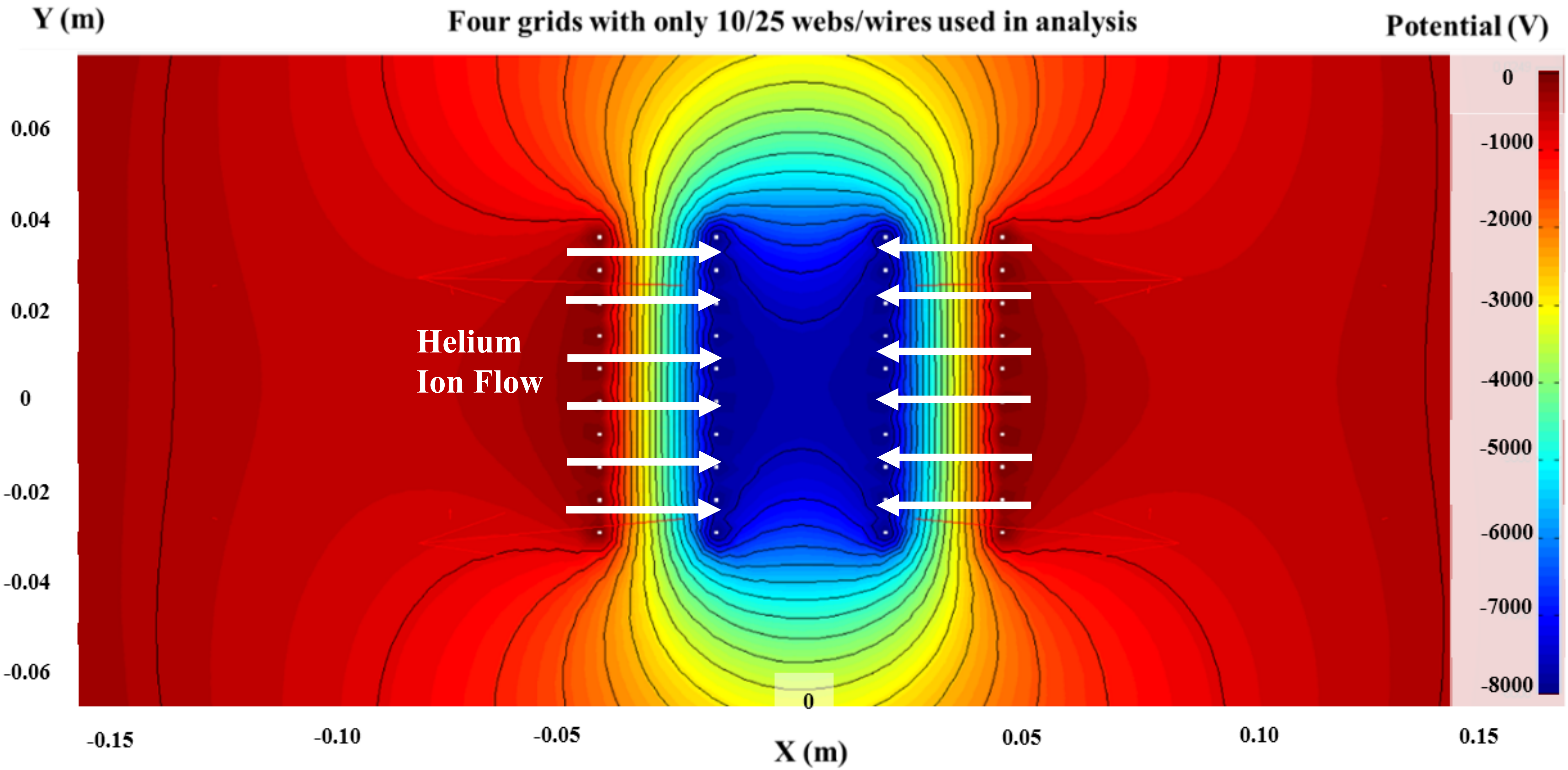
$$I_{meas}=I_{ion}(1+\gamma)$$

Simulant stream thickness

$$\delta_{sim}=\frac{\dot{M}_{sim}\left(-v_0+\sqrt{v_0^2+2gh_{grid}}\right)}{g\rho L_{sim}h_{grid}}$$

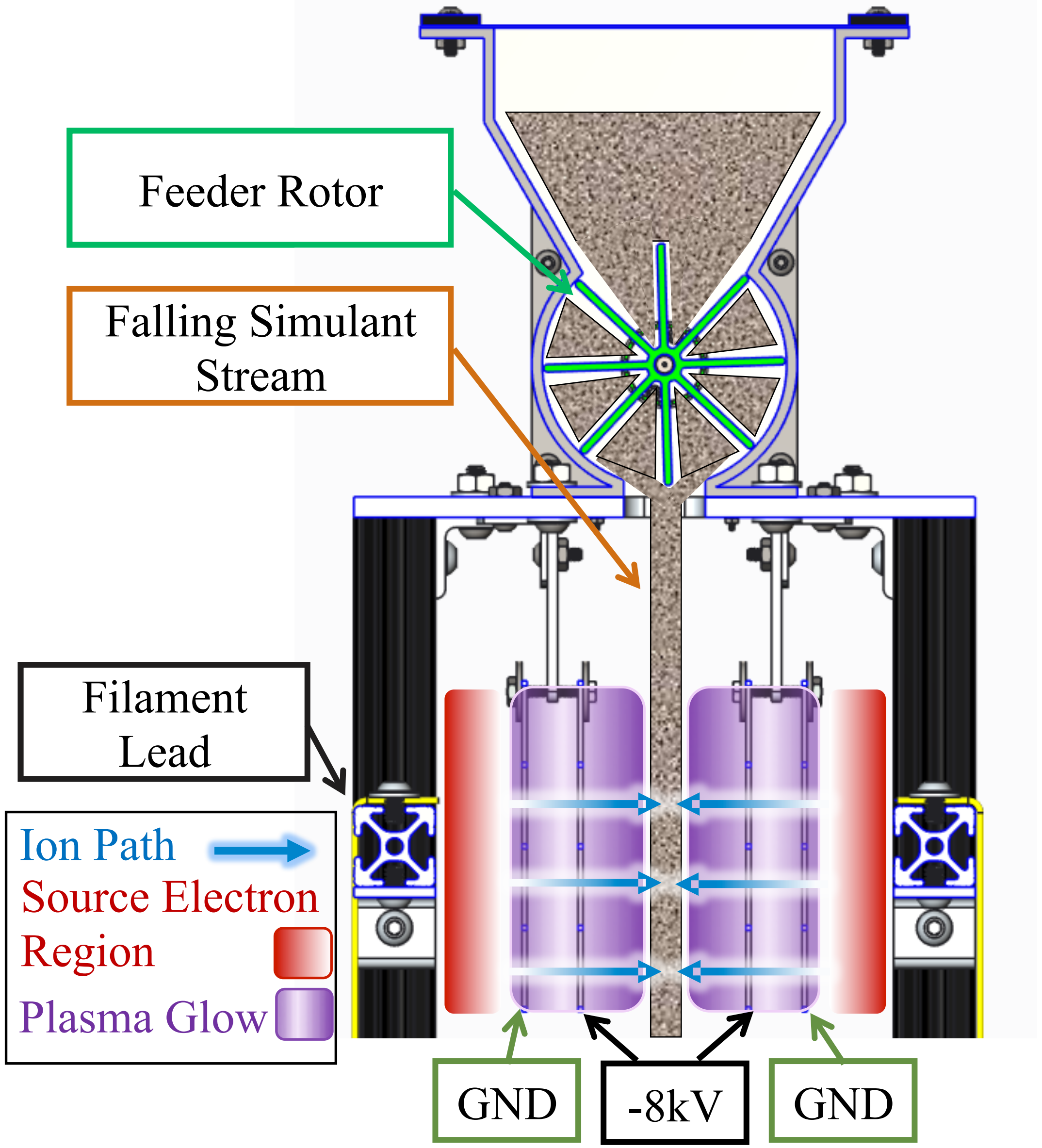


SWIM: Acceleration Grid Assembly



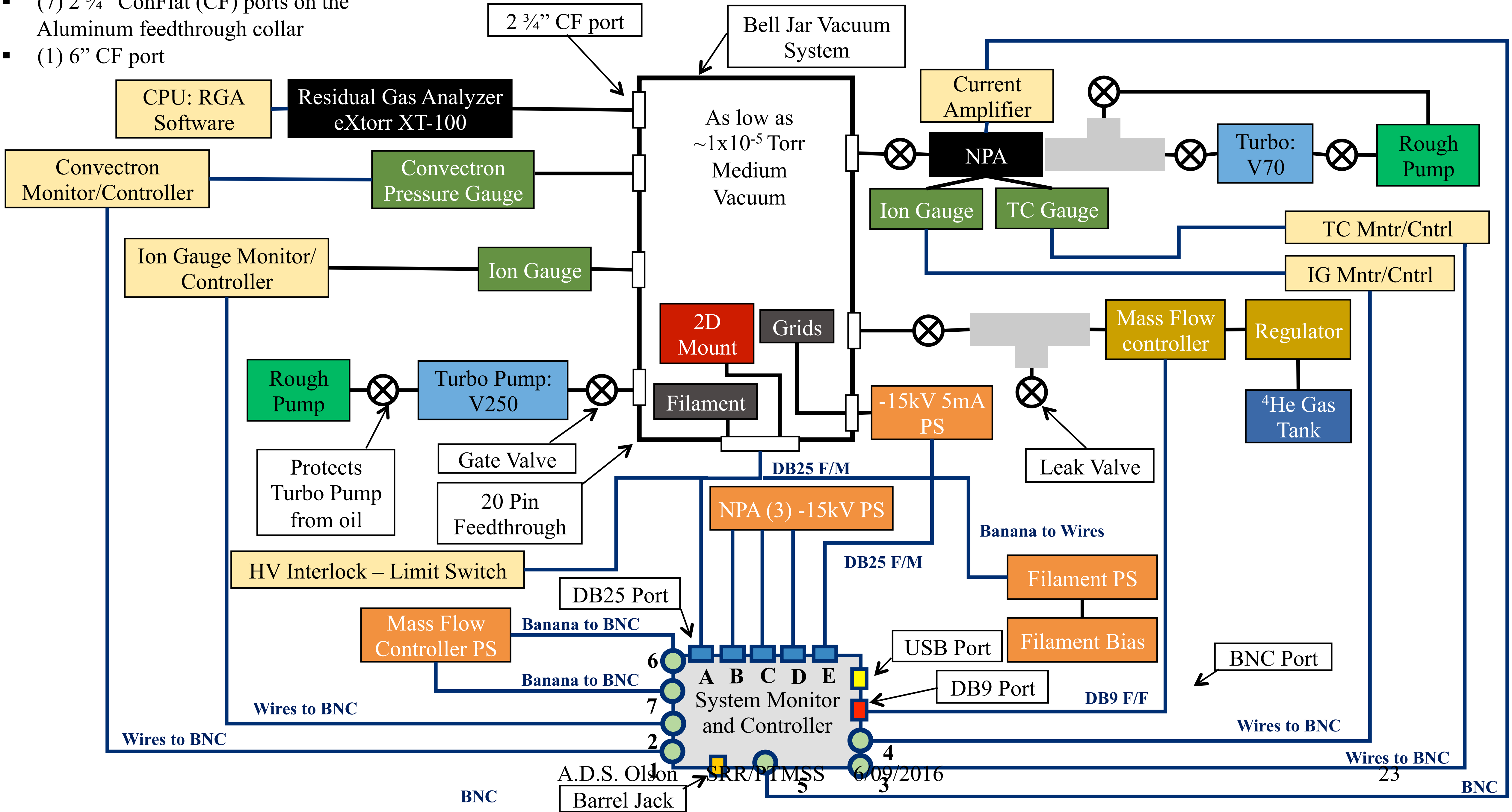
SWIM: Device Operation

- Fill hopper with up to ~2 kg of JSC-1A
  - (<100 micron)
- Pressure: ~1×10^{-4} Torr helium-4
- Grid voltage and current set
- Drive rotor to empty hopper
- Action camera records simulant flow and plasma glow
- Grid and filament voltages and currents recorded

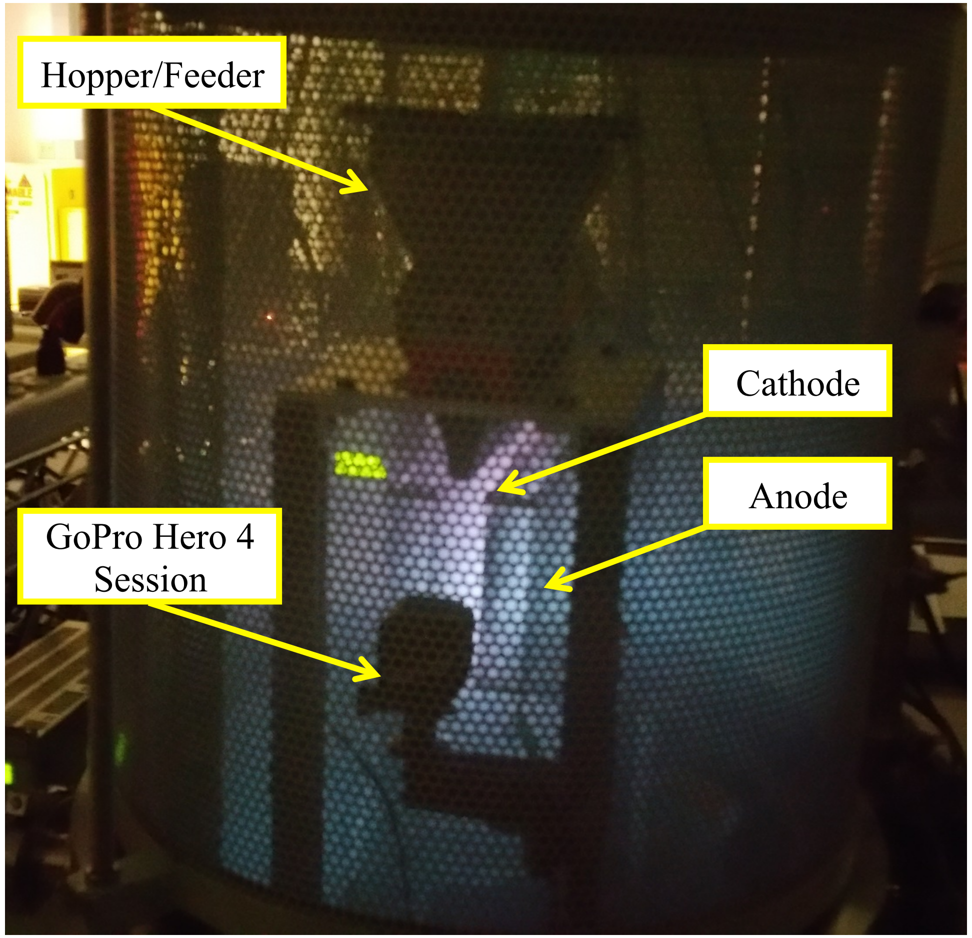


SWIM NPA Layout A.D.S. Olson (FTI, Univ. of Wisconsin) 04/28/2016

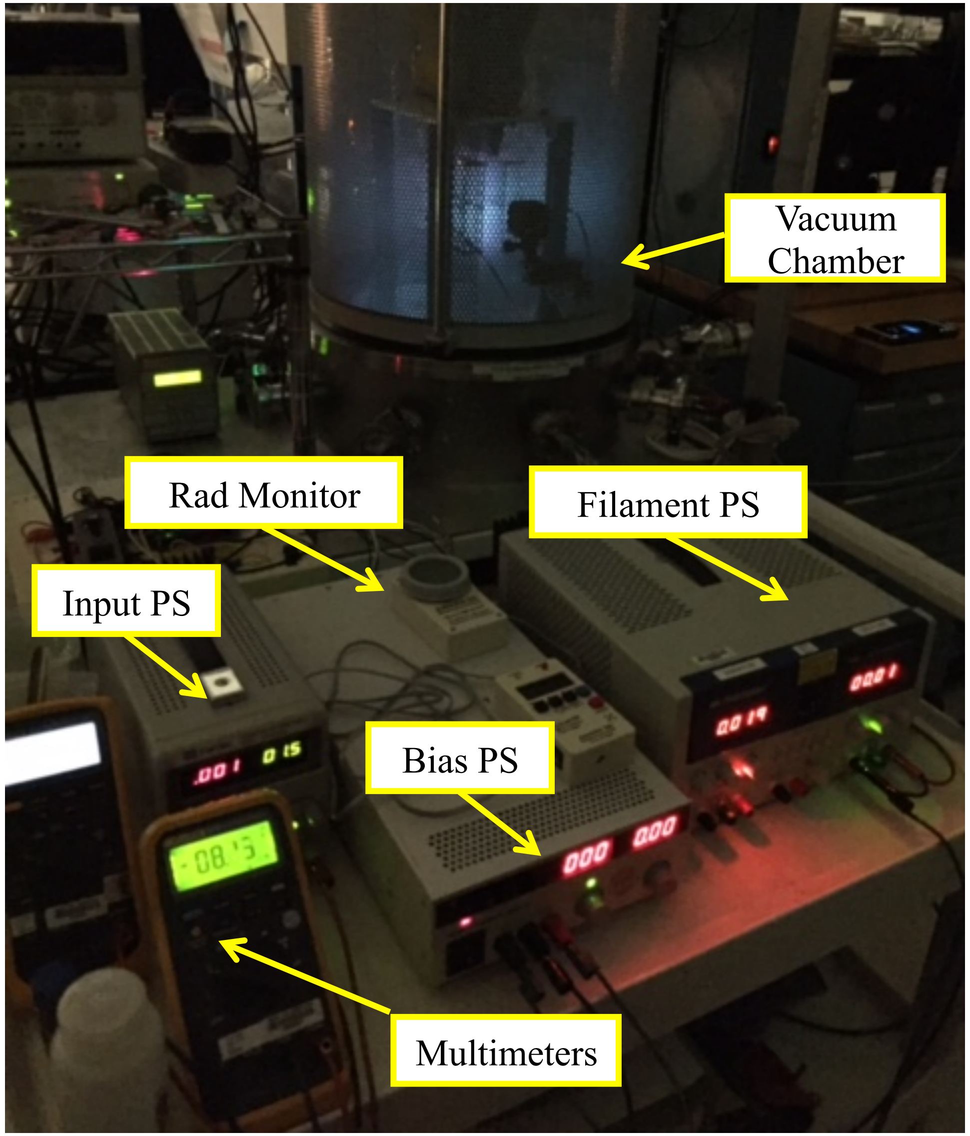
- 18” OD, 22” tall glass cylinder
- (7) 2 ¾” ConFlat (CF) ports on the Aluminum feedthrough collar
- (1) 6” CF port

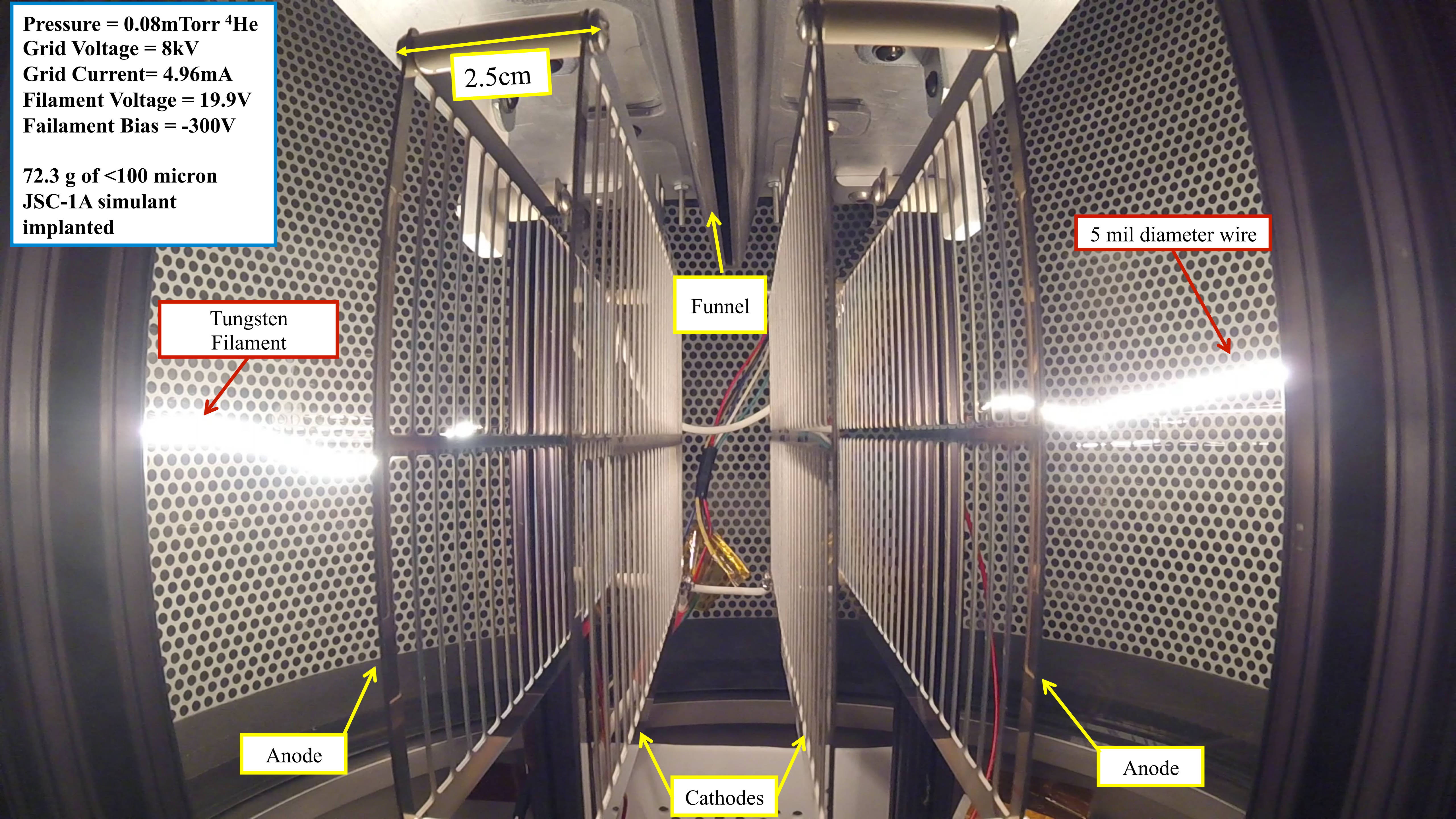


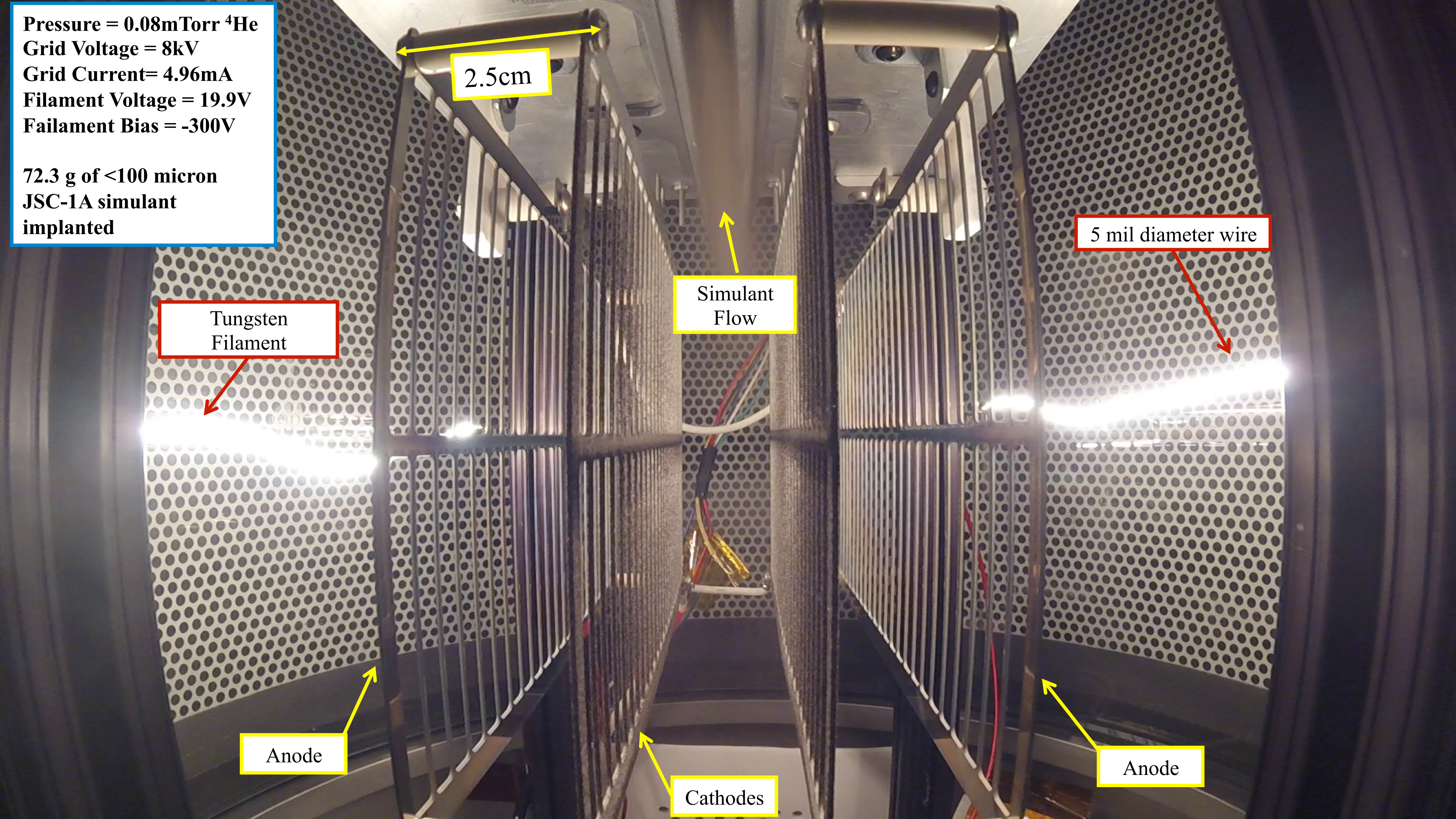
SWIM: Setup at NASA KSC ESPL



- HV amplifier (±10kV,10mA)
- HV input power supply
- Filament bias power supply (600V, 1.7A)
- Filament power supply (30V, 4A)
- Multimeters to measure output voltage and current
- AdAware radiation monitor
- Varian 301 turbo pump, gate valve, and controller
- Scroll pump
- Extorr 300 RGA
- 18”x30” bell jar and 8-port feed through collar
- Helium K bottle
- Baratron gauges
- Ion gauge




Pressure = 0.08mTorr ^{4}He
Grid Voltage = 8kV
Grid Current= 4.96mA
Filament Voltage = 19.9V
Failament Bias = -300V
72.3 g of <100 micron
JSC-1A simulant
implanted
2.5cm
Tungsten Filament
Funnel
5 mil diameter wire
Anode
Cathodes
Anode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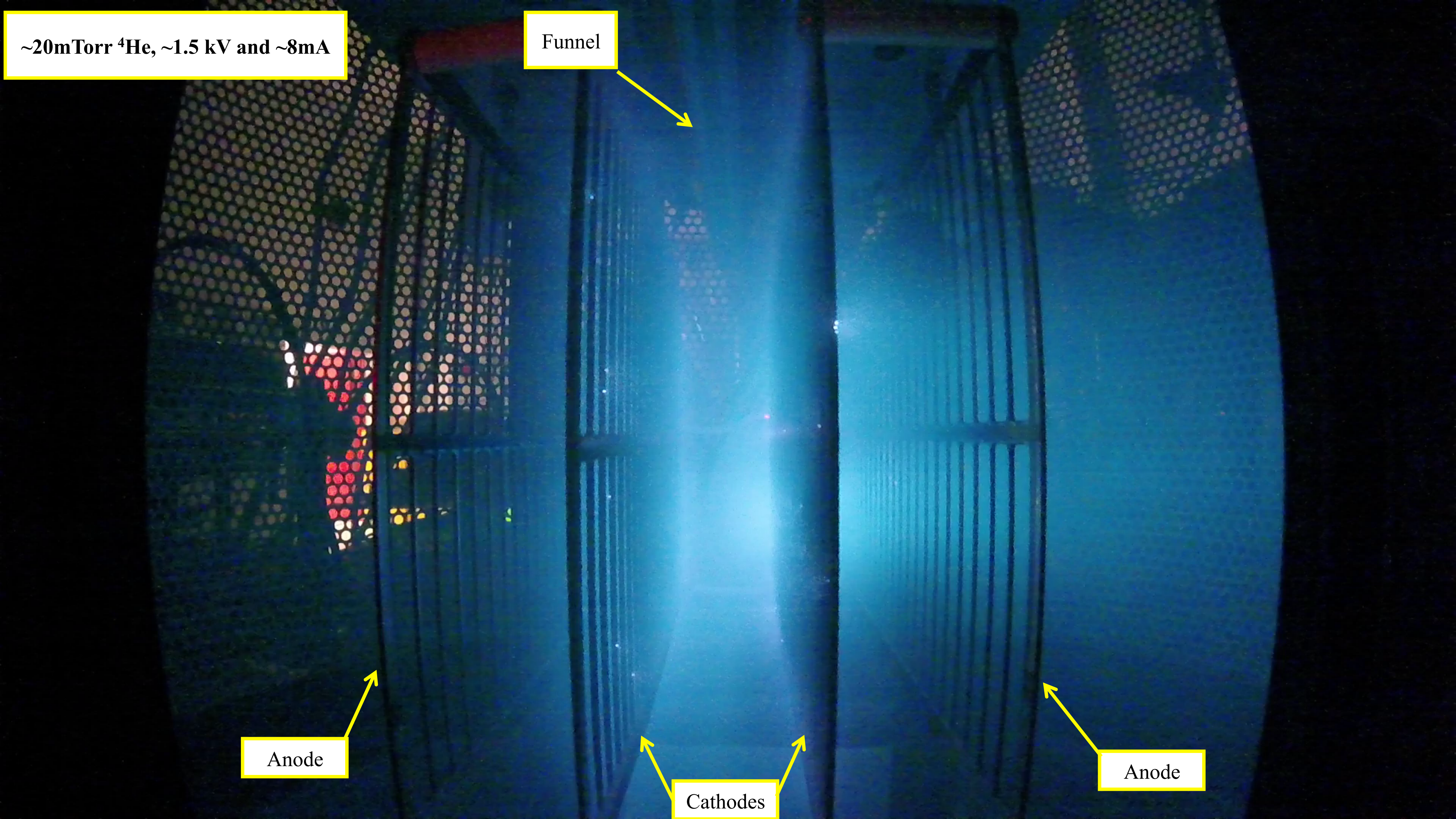
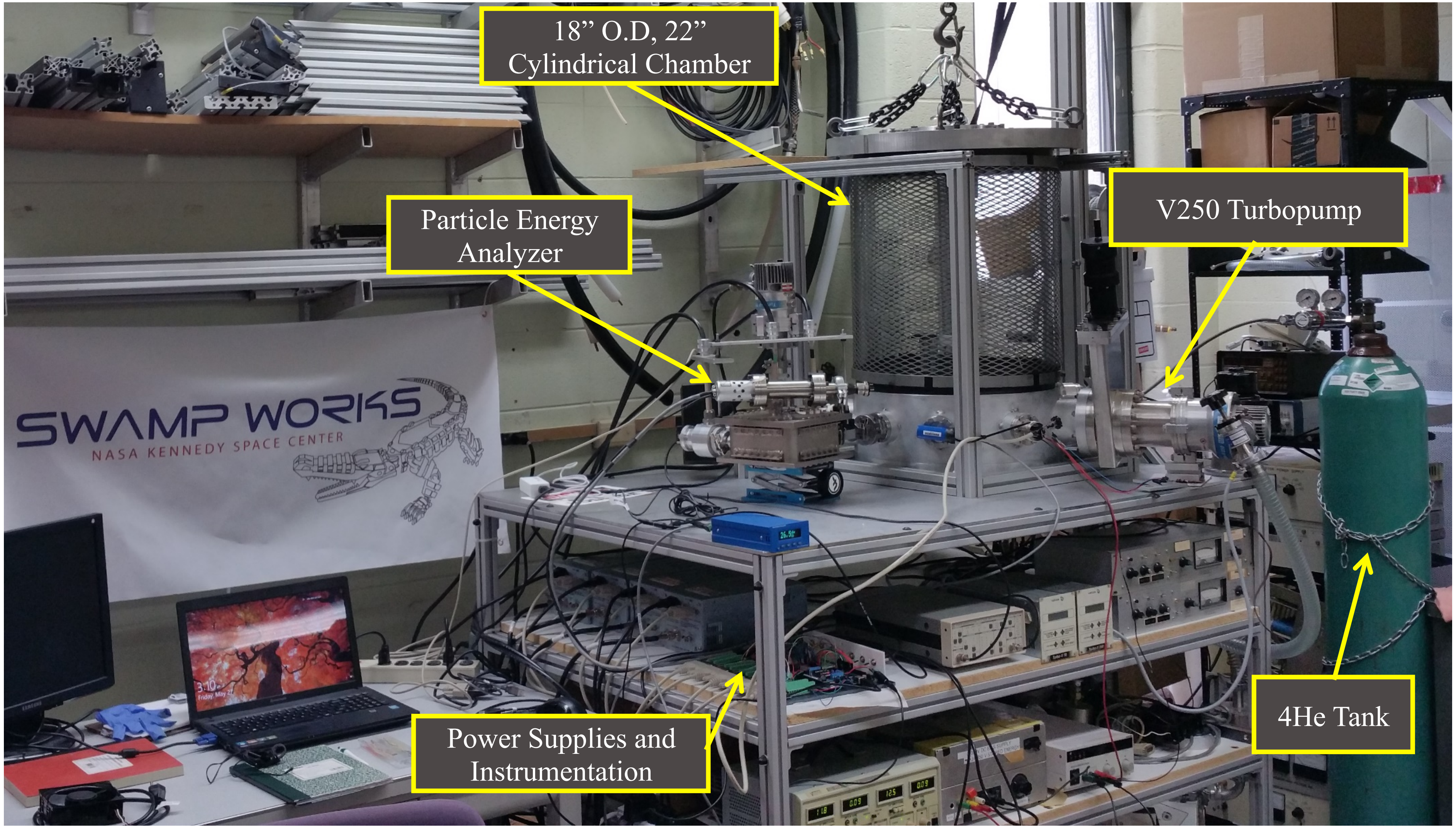
72.3 g of <100 micron
JSC-1A simulant
implanted
2.5cm
Simulant
Flow
Tungsten
Filament
5 mil diameter wire
Anode
Cathodes
Anode

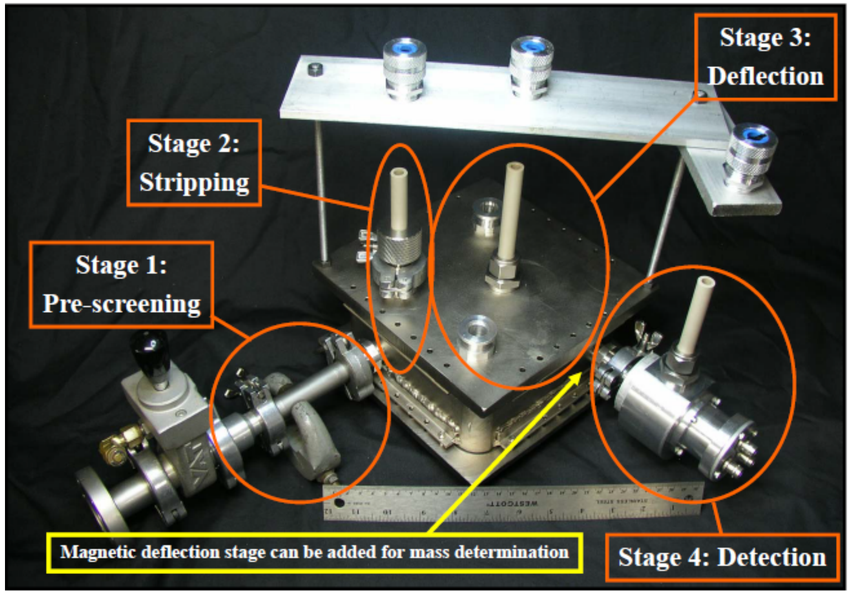

~20mTorr ⁴He, ~1.5 kV and ~8mA
Funnel
Anode
Cathodes
Anode

SWIM Setup Replicated in FTI Lab for Continued Testing

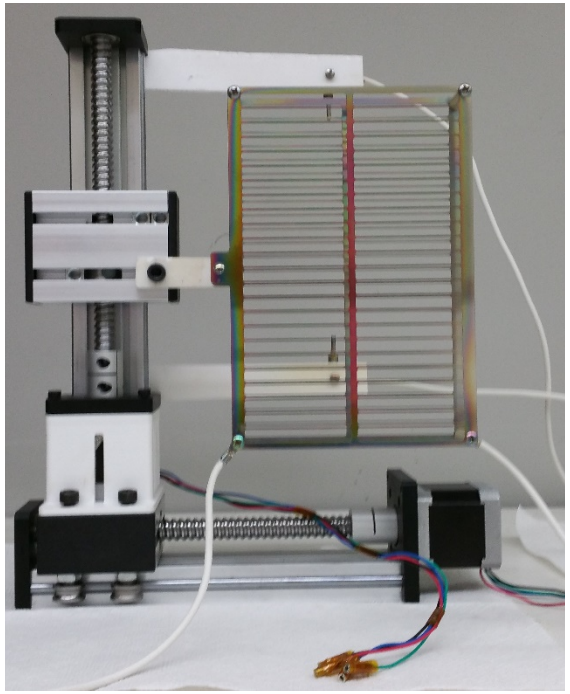


Helium Ion Energy Spectrum Testing

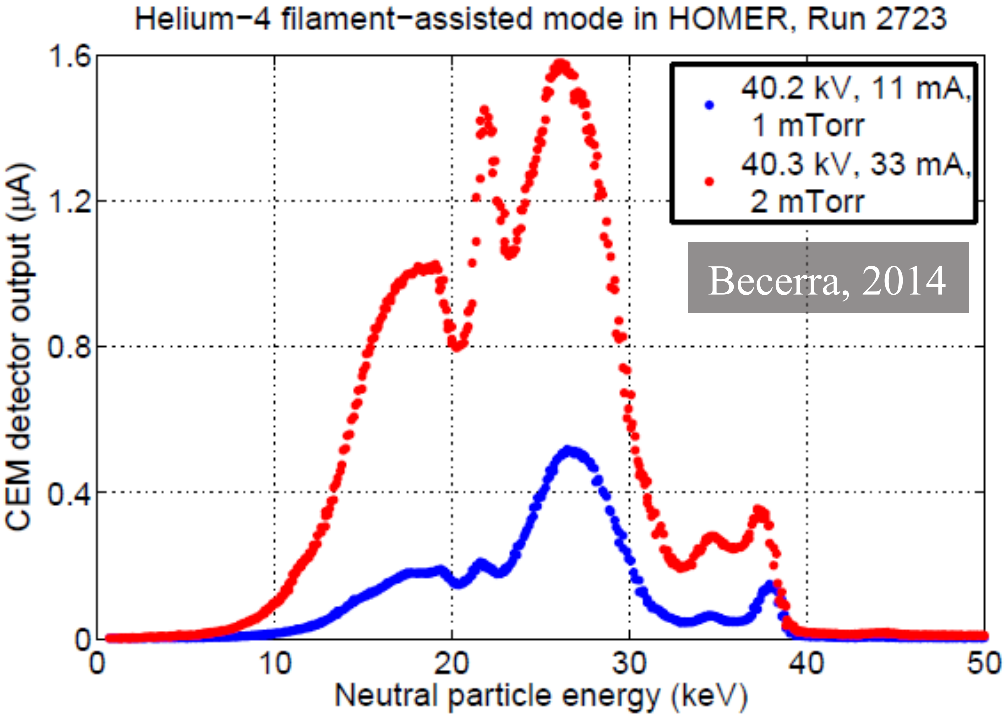
- Attach particle energy analyzer to SWIM chamber
- Mount SWIM grid assembly onto a moveable (2 DOF) platform
- Measure $^4He^+$ energy spectrum: vary pressure, grid voltage, filament settings



Energy analyzer detached from vacuum chamber

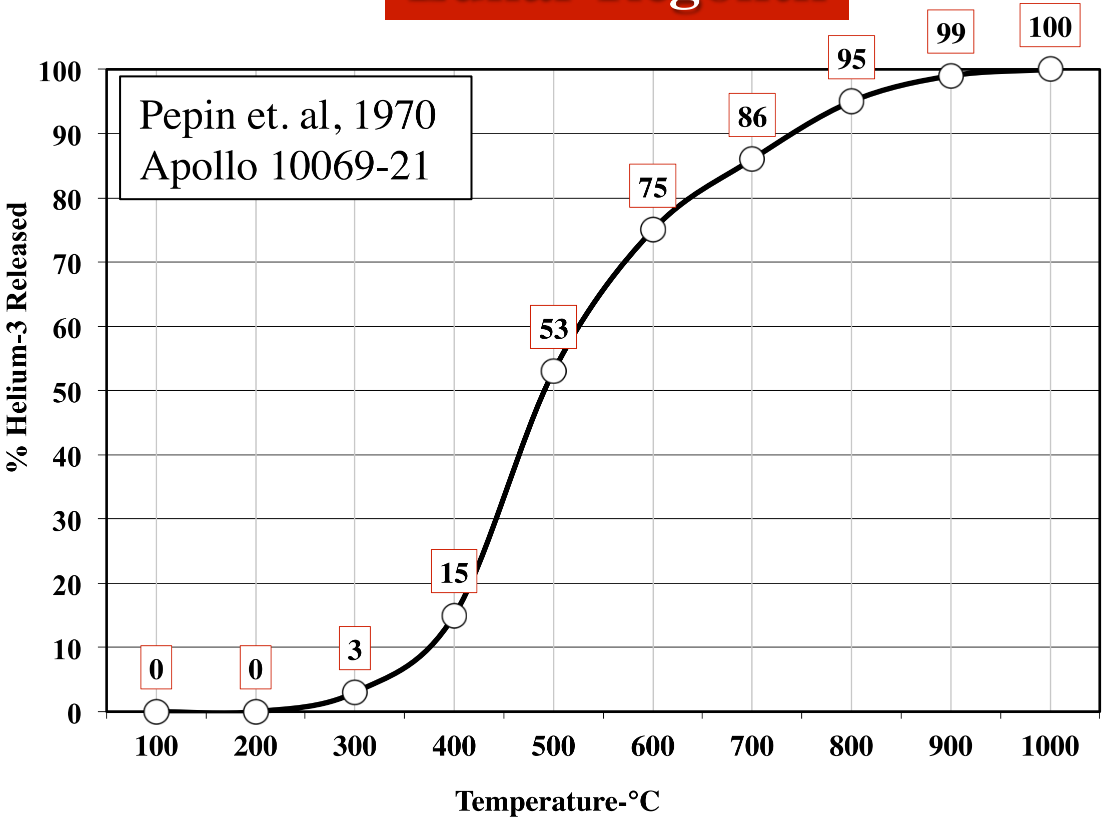


SWIM grids on 2D platform

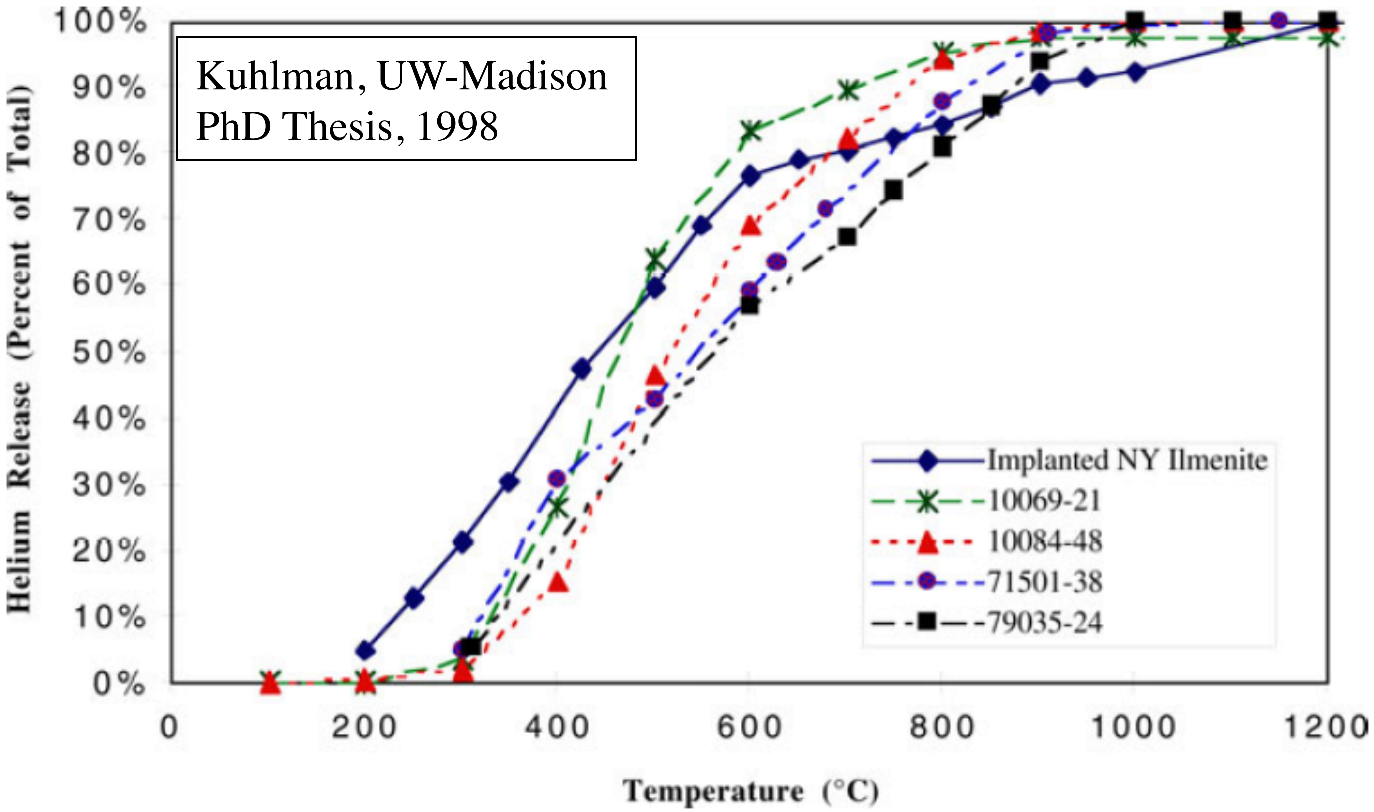


Helium Release vs. Temp: Dr. Pepin at U. Minnesota

Lunar Regolith



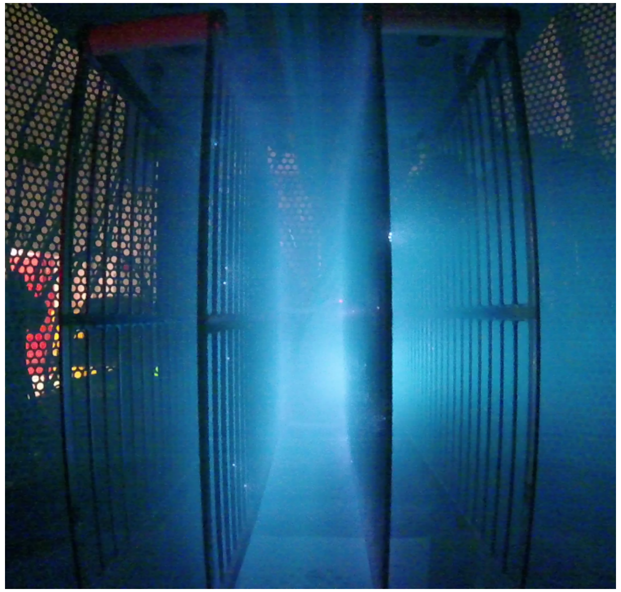
Analog Regolith



Application to General Space Resources Field

SWIM

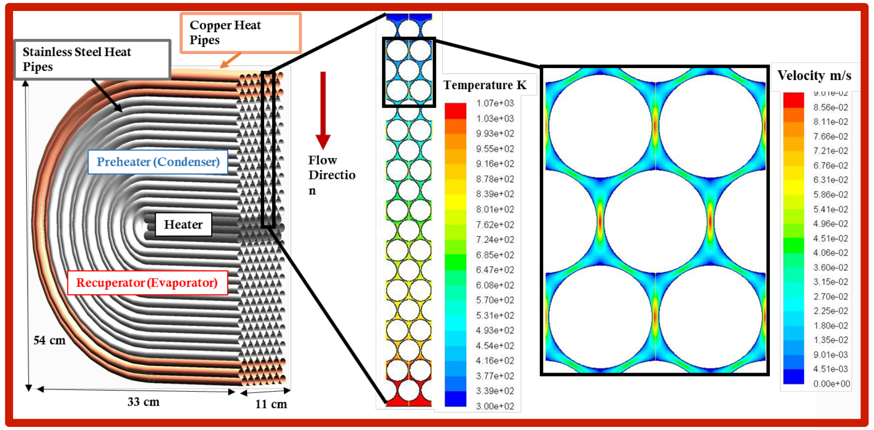
- Implantation of other volatiles
- Simulation of space weathering effects

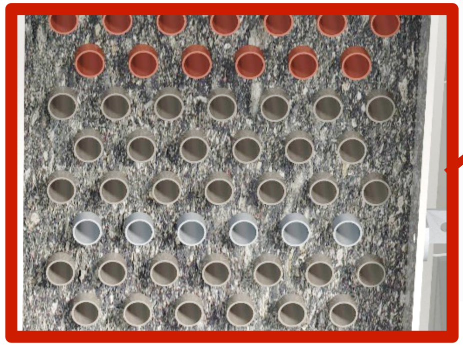


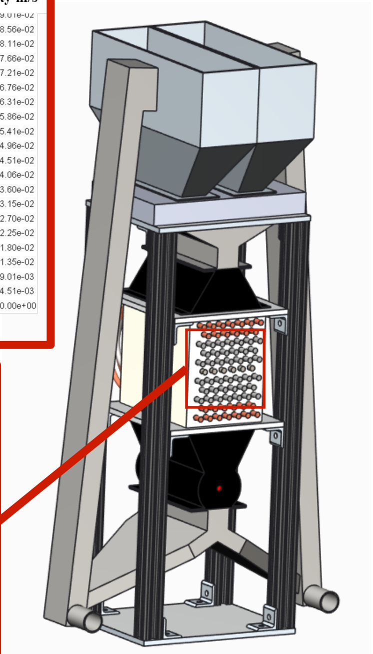
JSC-1A (Orbitec)

HEAT

- Heat recuperation with heat pipes
- Granular flow in heat exchangers
- Volatile gas release measurement with residual gas analyzers







Conclusion: Progress and Future Work

- Conclusions
  - SWIM designed and can produce implanted simulant
  - More work to go to better characterize the implantation

- Up Next:
  - Complete ion energy spectrum tests
  - Sample testing at Univ. of Minnesota
  - More batches created for use in the HEAT system
  - Possible implantation of other gases for future work

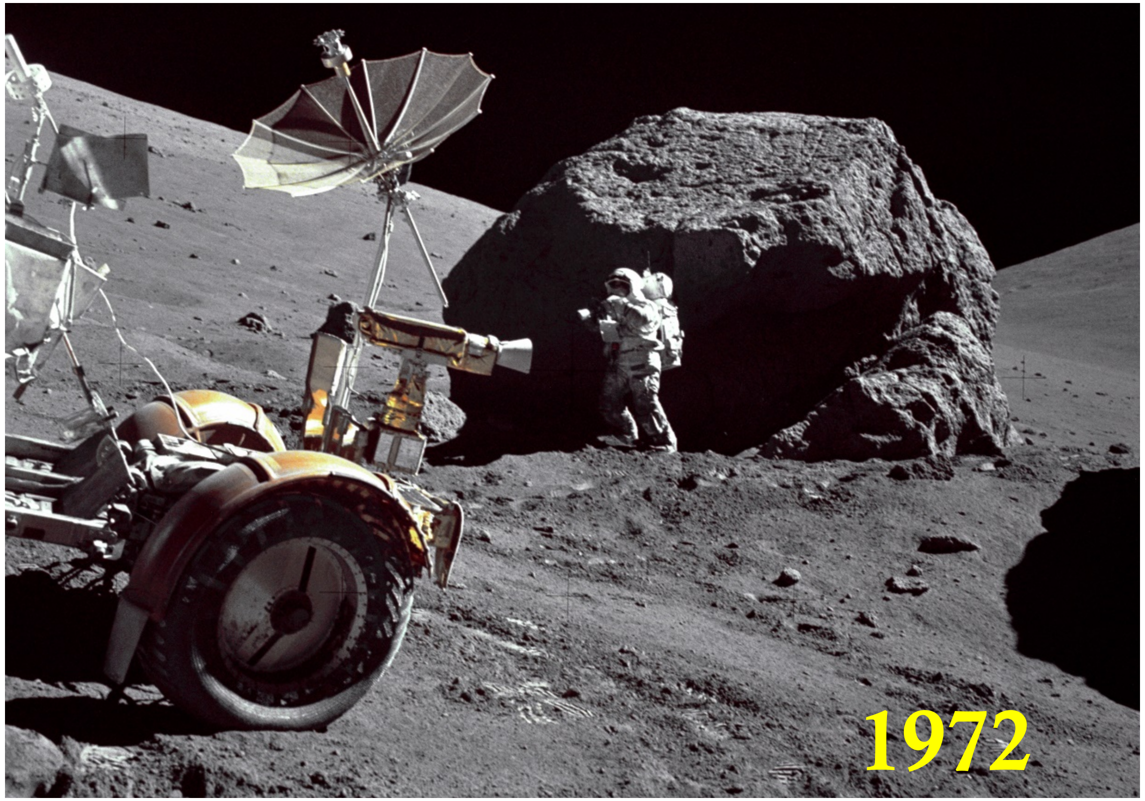
This Research is Supported by a NASA Fellowship

- Space Technology Research Fellowship (NSTRF)
- Class of 2014
- Collaboration with Kennedy Space Center

SWAMP WORKS
NASA KENNEDY SPACE CENTER

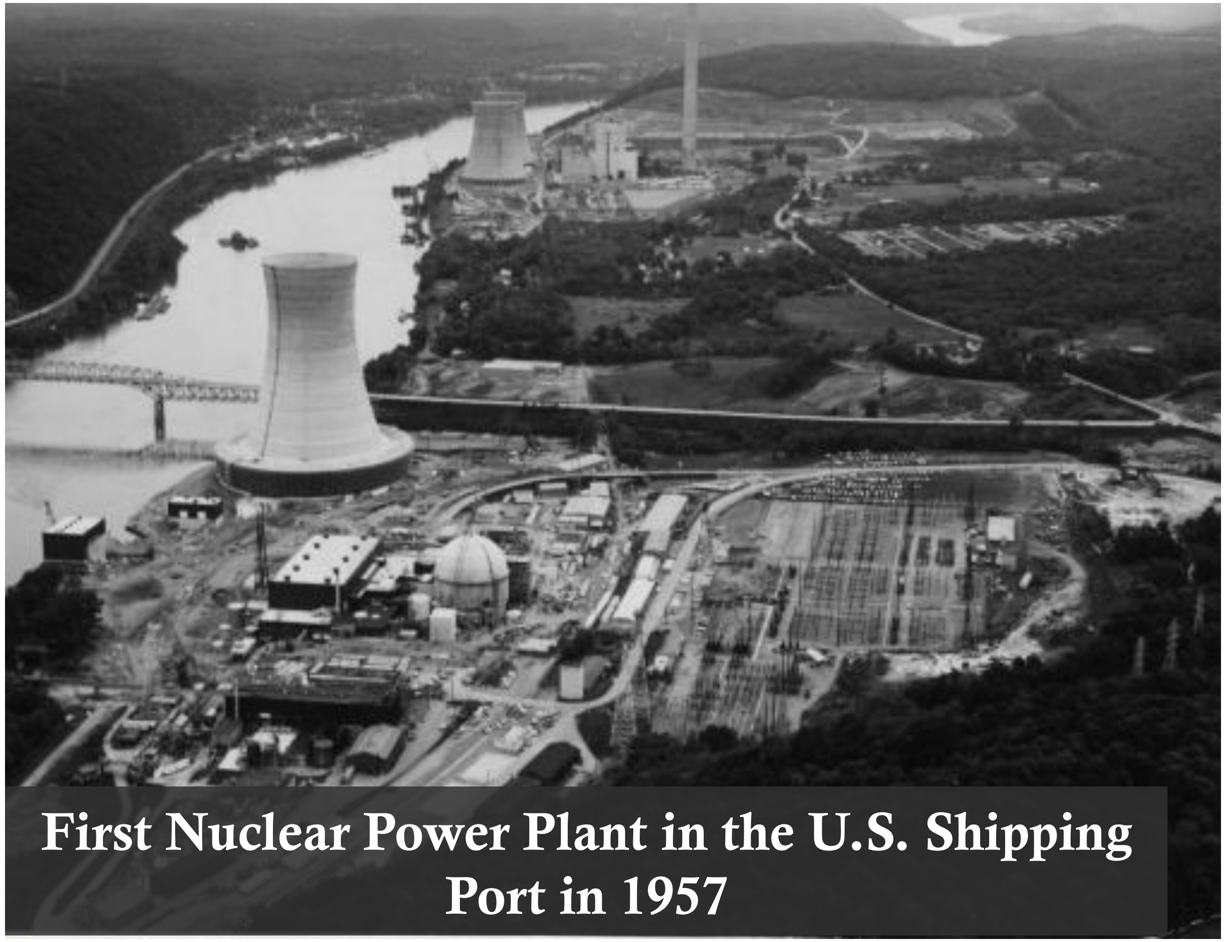
Mining ^{3}He Could Happen Sooner than you Think

"Space travel is utter bilge." –Dr. Richard Wooley, Astronomer Royal, space advisor to the British government, 1956

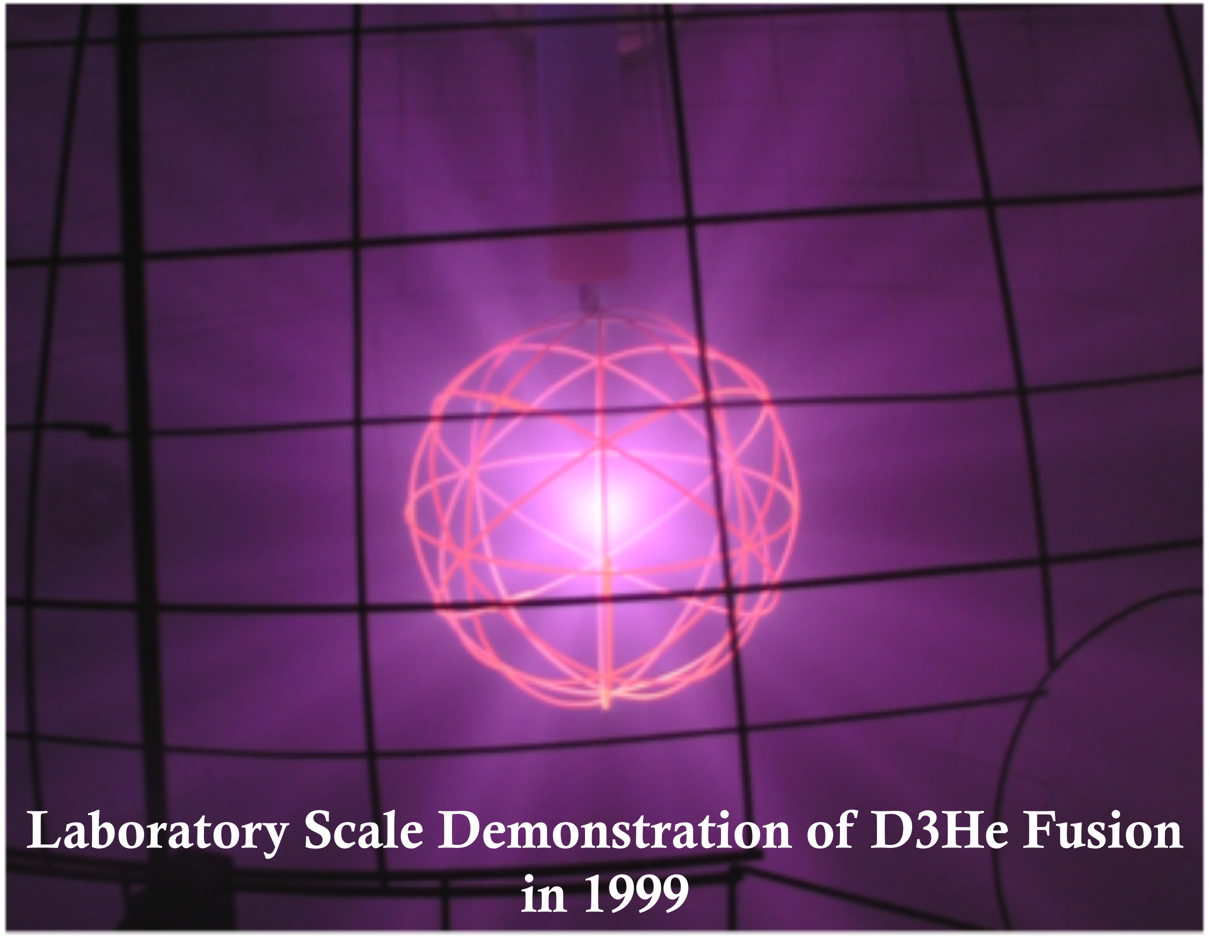


Fusion Could Happen Sooner than you Think

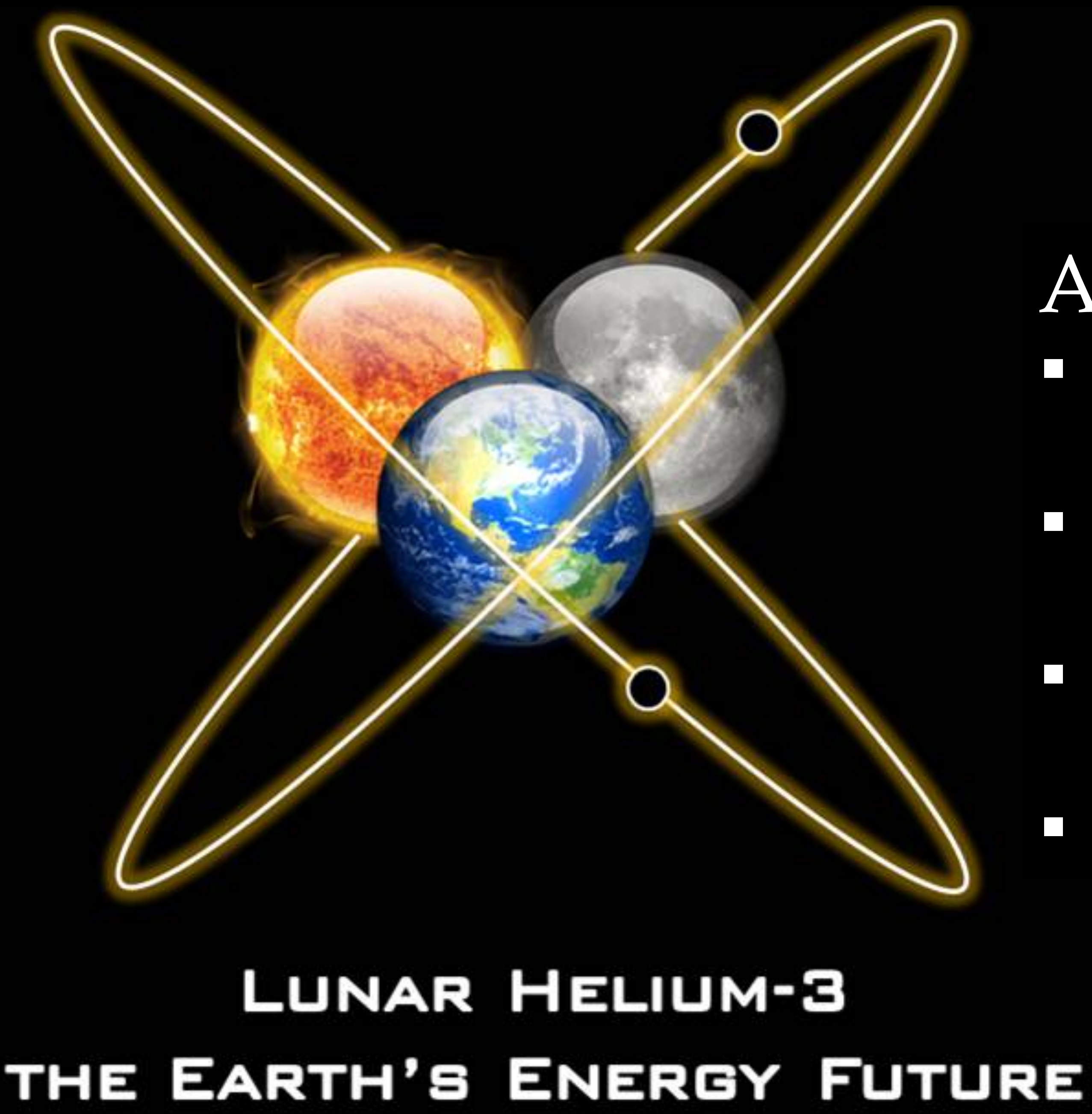
"Anyone who looks for a source of power in the transformation of the [nucleus of the] atom is talking moonshine." –Ernest Rutherford, 1933



First Nuclear Power Plant in the U.S. Shipping Port in 1957



Laboratory Scale Demonstration of D3He Fusion in 1999



Questions?

Acknowledgments

- NASA Space Technology Research Fellowship Program
- NASA Kennedy Space Center Swamp Works Labs
- Wisconsin Space Grant Consortium
- Alex Strange, Tashi Atruktsang

Key References

- Fusion Related:

Wittenberg, L. J., Santarius, J. F., and Kulcinski, G. L. (1986). “Lunar Source of 3He For Commercial Fusion Power.” *Fusion Technology*, 10(September), 167–178.

Wittenberg, L. J. (1989). “Terrestrial Sources of Helium-3 Fusion Fuel- A Trip to the Center of the Earth.” *Fusion Technology*, 15(1108).

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Kulcinski, G. L. (2012). “Fusion Fuel Resources.” *UW-Madison, NEEP-536 Course Lecture 6, Sept. 20, 2012*, 20.

- Lunar ^{3}He Extraction Related:

Sviatoslavsky, I. N., and Jacobs, M. K. (1988). “Mobile Helium-3 Mining and Extraction System and Its Benefits Toward Lunar Base Self-Sufficiency

Sviatoslavsky, I. N. (1993). “The Challenge of Mining He-3 on the Lunar Surface: How All the Parts Fit Together.” *Space 94.”Wisconsin Center for Space Automation and Robotics Technical Report (WCSAR-TR)AR3-8808-1*

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Olson, A. D. S. (2013). “The Mark IV: A Scalable Lunar Miner Prototype.” *International Astronautical Congress 2013, Beijing, China, IAC-13.A3.2B.7*.

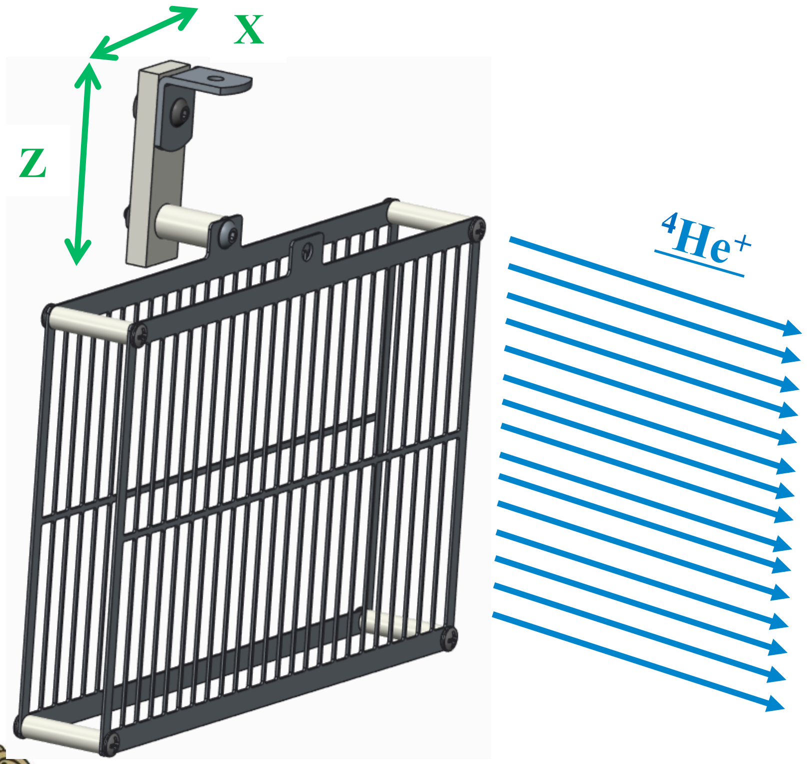
Olson, A. D. S., Santarius, J. F., and Kulcinski, G. L. (2014). “Design of a Lunar Solar Wind Volatiles Extraction System.” *AIAA SPACE 2014 Conference and Exposition*.

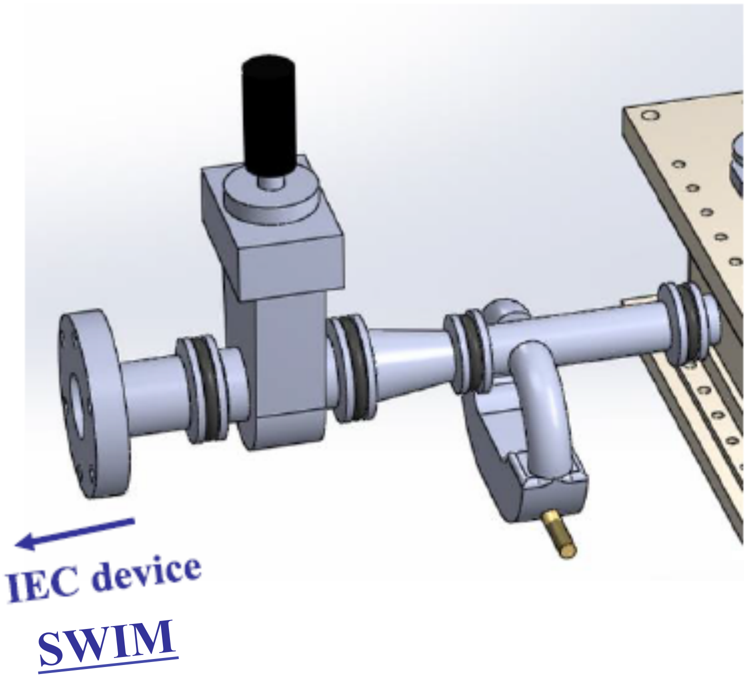
Backup/Reference Slides

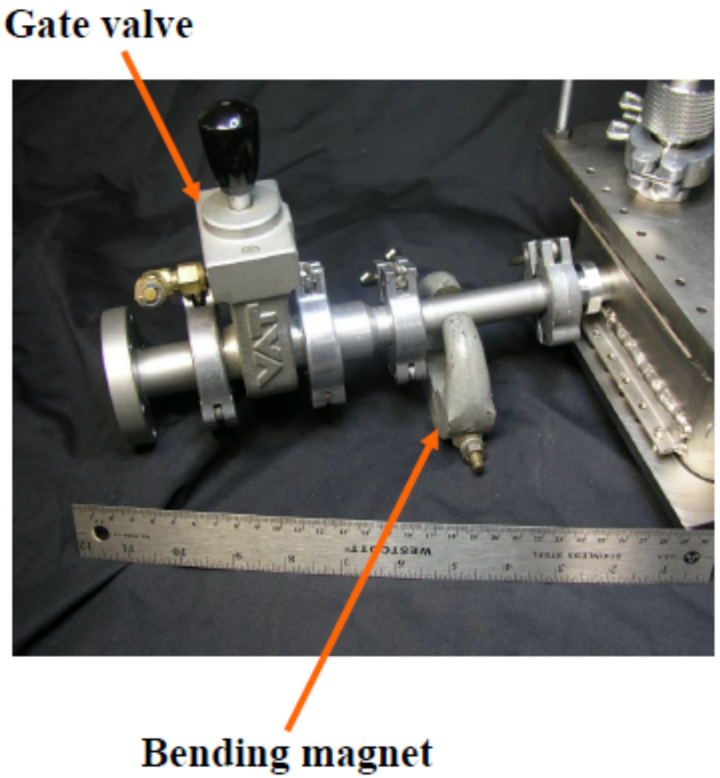
Helium Ion Energy Testing

Energy spectrum testing concept:

- Attach particle energy analyzer to SWIM chamber
- Mount SWIM grid assembly onto a moveable (2 DOF) platform
- Measure $^4He^+$ energy: vary pressure, grid voltage, and filament settings

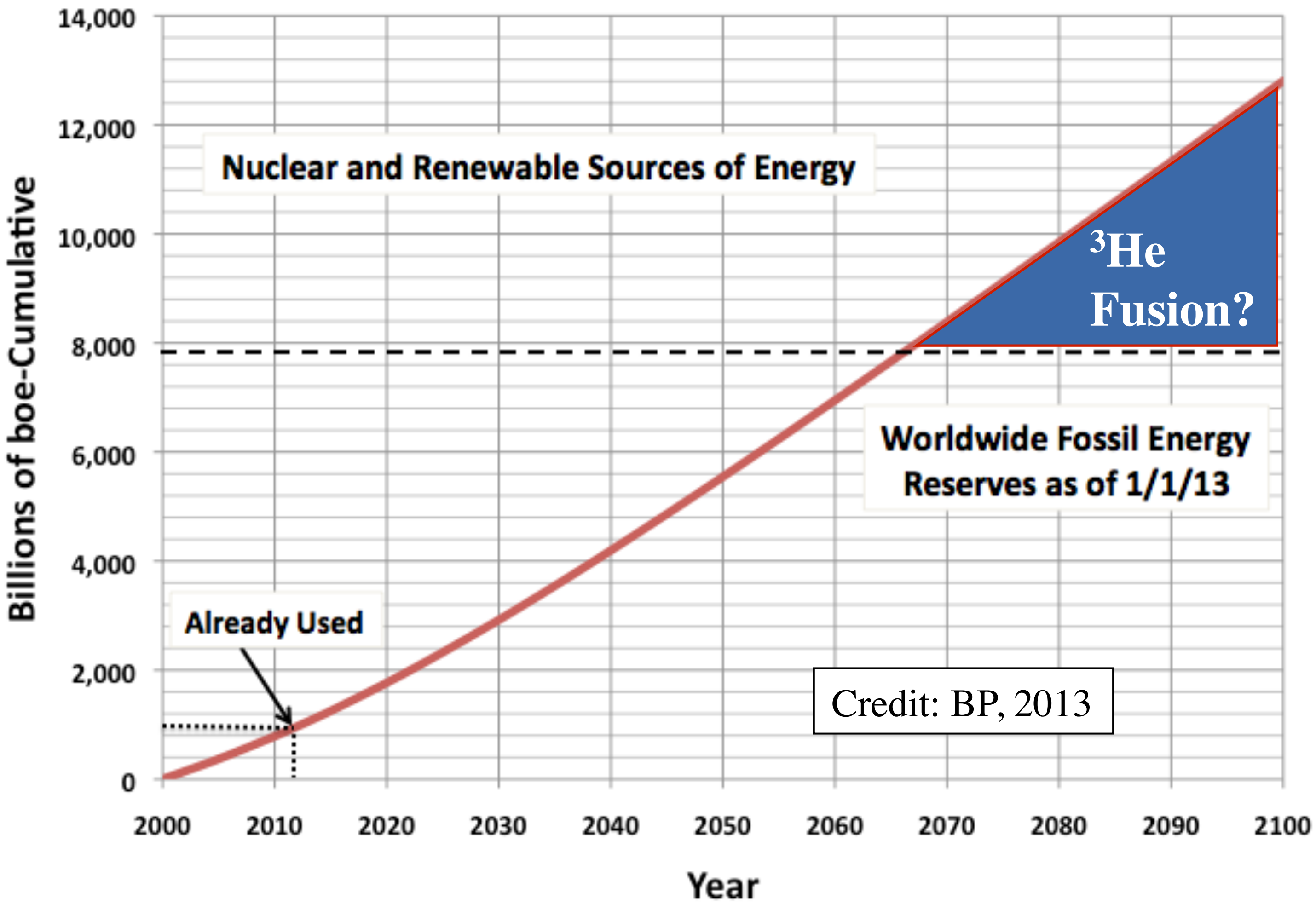






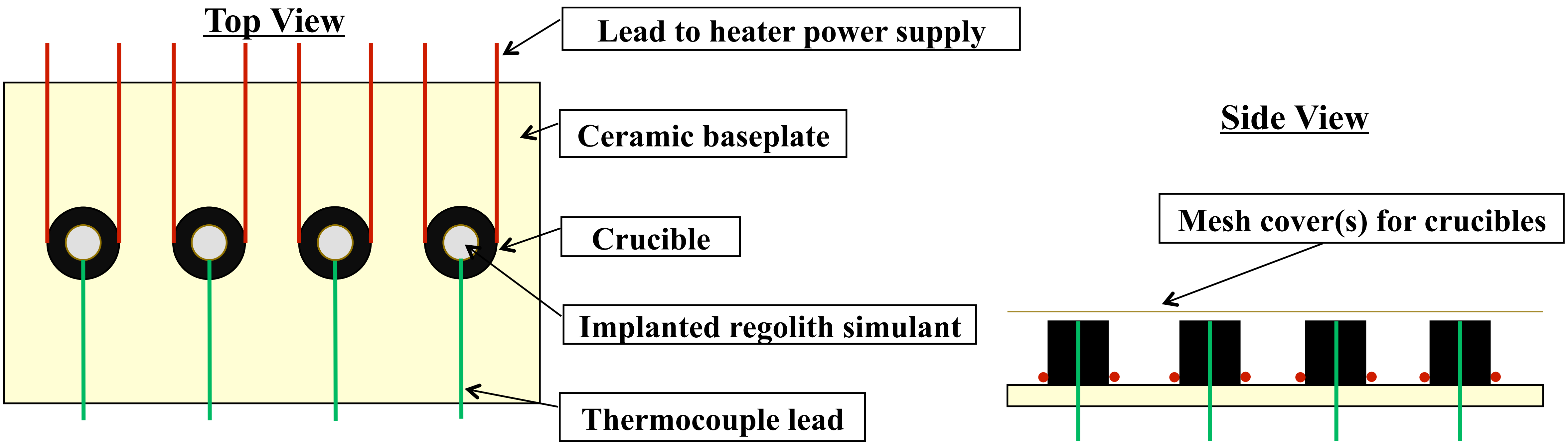
^{3}He Fusion Can Help Satisfy Future Energy Needs

- Energy usage is increasing
- Nuclear and renewable energy will be key in meeting our future needs
- Helium-3 fusion can be a part of the energy solution and enables unique space applications



Sample Concentration Analysis (SCAN) Concept

- Within a vacuum system with a turbo pump and RGA
- Ceramic crucibles with specialized insulating heaters and a ceramic baseplate
- Heat implanted simulant in the crucibles to ~1000ºC (step-wise heating)
- Use thermocouples to record regolith temperature



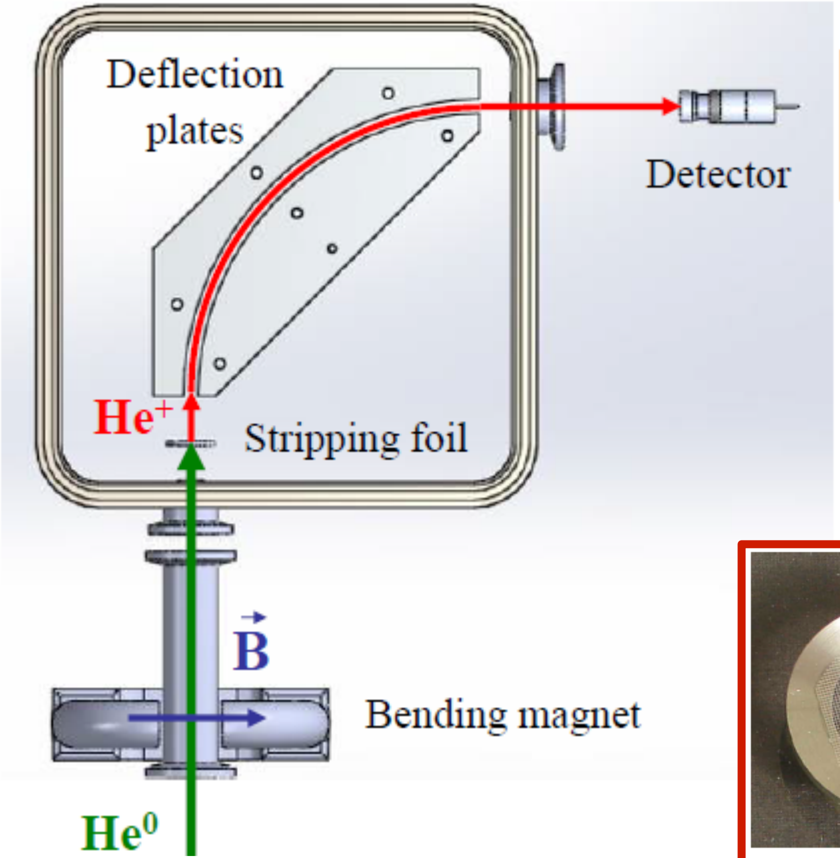
Neutral Particle Analyzer

Use the NPA as an Ion Energy Diagnostic: Remove stripping/screening foil

Stage 3: Deflection

Stage 2: Stripping

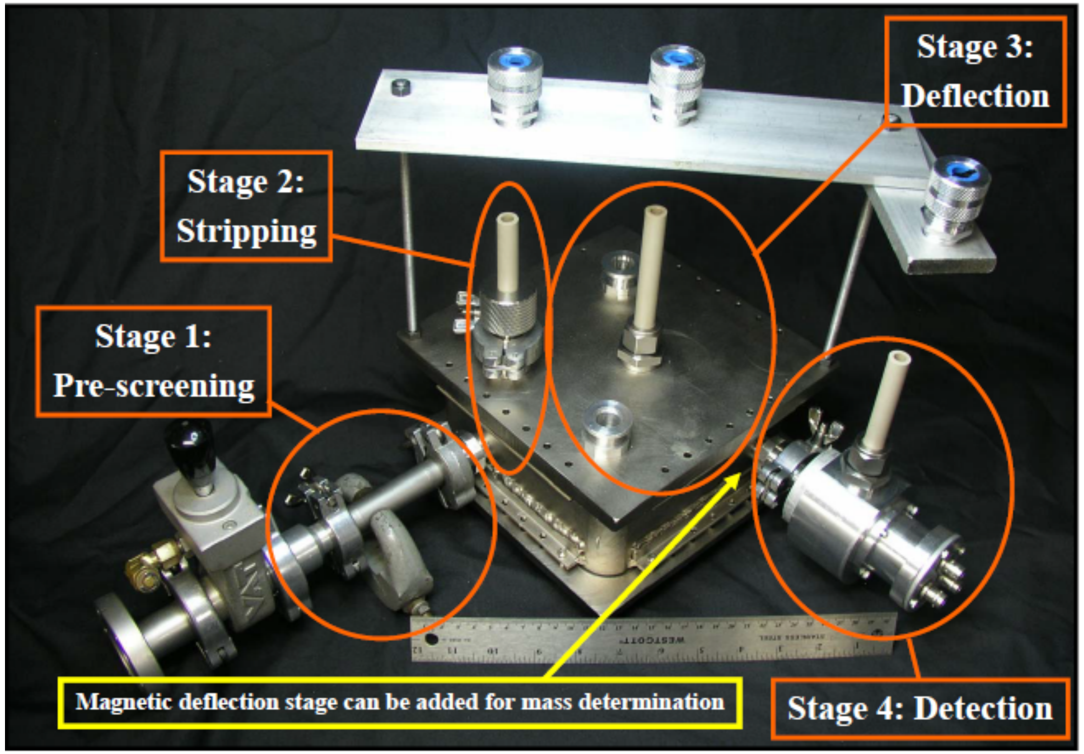
Stage 1: Pre-screening



Stage 4: Detection

Credit: Becerra et. al, 2014

Thin Carbon foil (~10nm thickness)



System Monitor and Controller

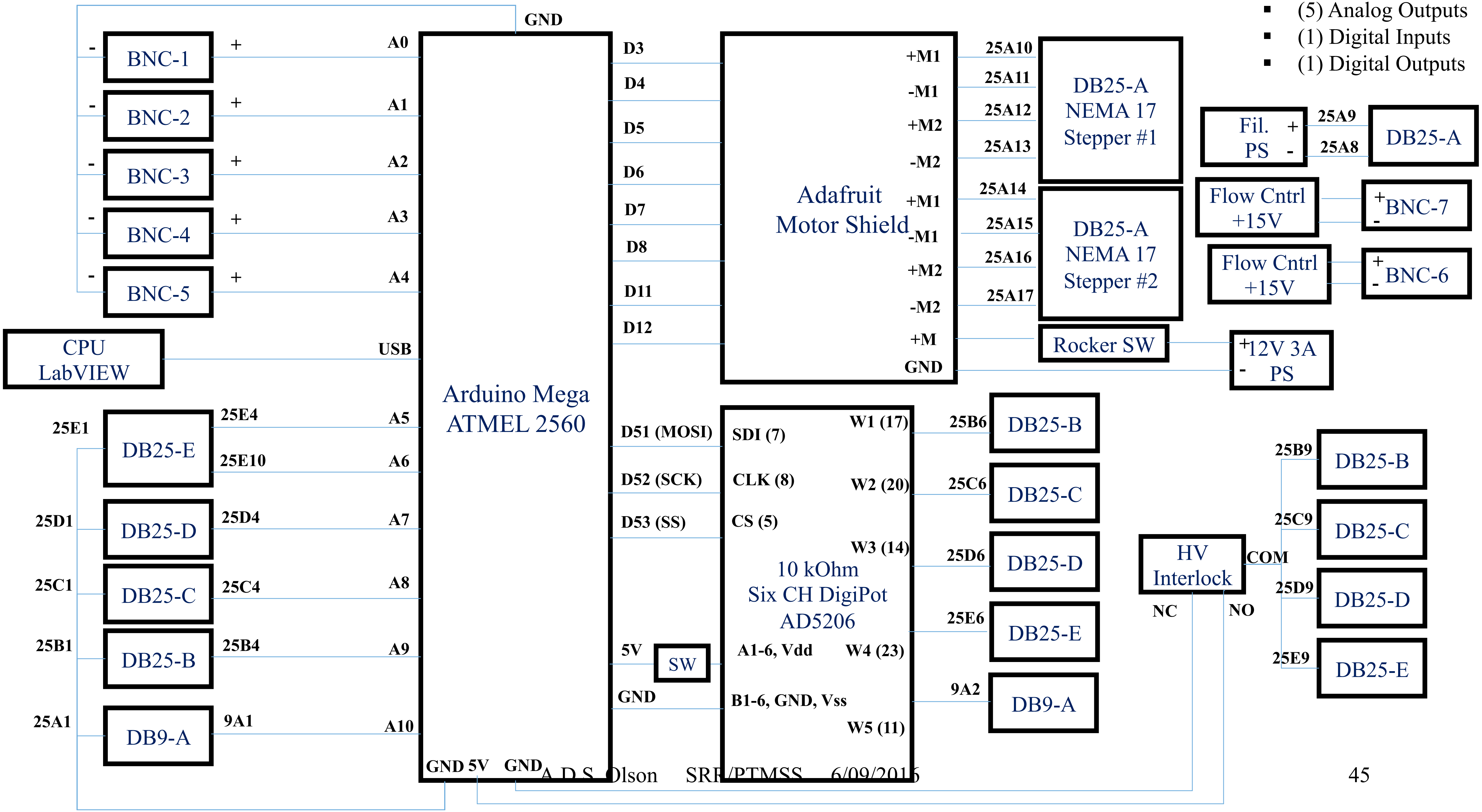
Input		Connection
Pressure	Chamber Convectron	BNC-1
	Chamber Ion	BNC-2
	NPA TC	BNC-3
	NPA Ion	BNC-4
Grid High Voltage	Voltage Monitor	DB25-E
	Current Monitor	DB25-E
NPA High Voltage	Voltage Monitor (3)	DB25-B,C,D
		DB25-B,C,D
NPA Measurement	Energy Signal	BNC-5
Flow Controller PS	-15 V	BNC-6
	+15 V	BNC-7
	Flow Signal	DB9-A
Filament PS	Filament Power Supply	DB25-A
HV Interlock	High/Low Signal	DB25-A
Motor PS	Motor Power Supply	Barrel Jack

Output		Connection
2D Mount	(8) Leads	DB25-A
Filament PS	(2) Leads	DB25-A
Grid HV PS	Voltage Control	DB25-E
NPA HV PS	Voltage Control (3)	DB25-B,C,D
Flow Controller	Control Signal	DB9-A
CPU	LabVIEW	USB-1

- (11) Analog Inputs
- (5) Analog Outputs
- (1) Digital Inputs
- (0) Digital Outputs

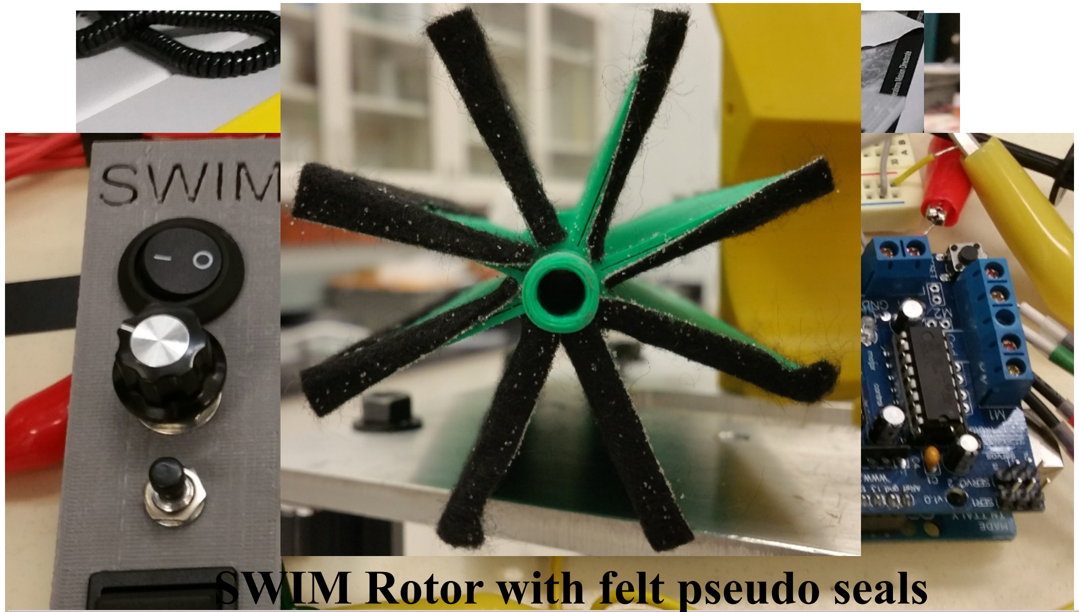
- (9) BNC Ports
- (5) DB25 Ports
- (1) DB9 Port
- (1) USB Type B Port

- (11) Analog Inputs
- (5) Analog Outputs
- (1) Digital Inputs
- (1) Digital Outputs

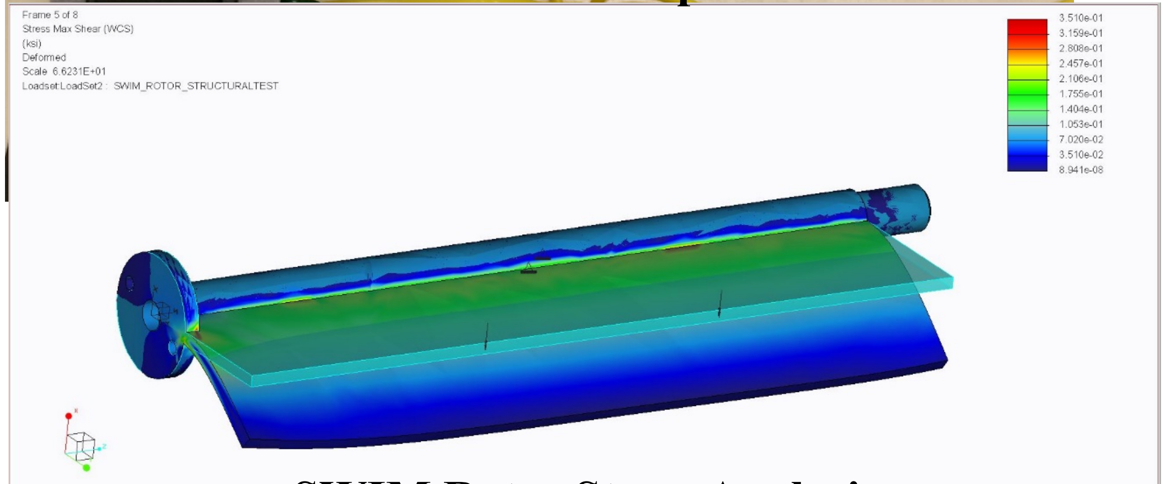


SWIM: Hopper/Feeder

- Almost completely 3D printed PLA plastic
- Rotor made thick enough for motor torque
- Inside surfaces lined with adhesive backed aluminum to bleed off static charge
- Arduino Mega (Atmel 2560) microcontroller and Adafruit motor shield for rotor control



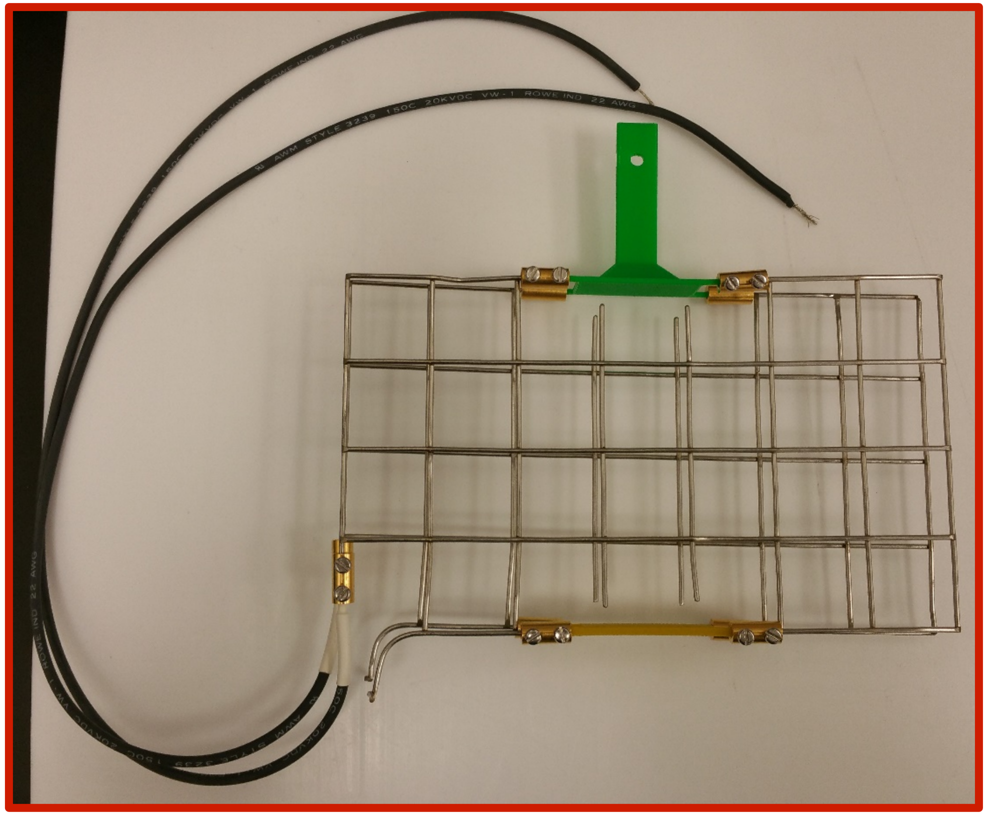
SWIM Rotor with felt pseudo seals



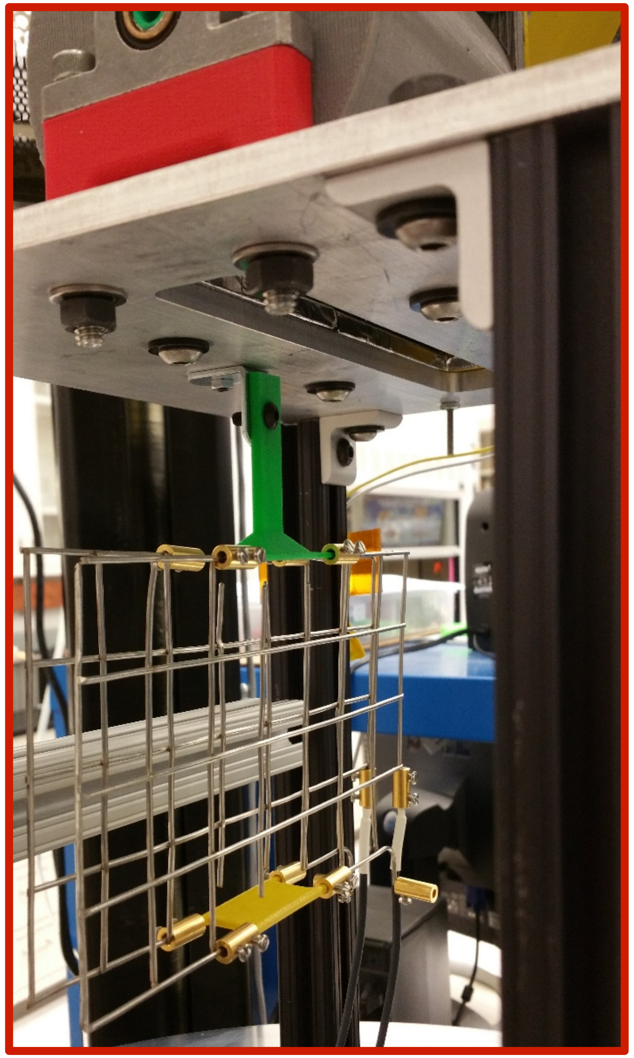
SWIM Rotor Stress Analysis

SWIM: Ion Acceleration Grids

- 90% Open Stainless Steel Welded Wire Mesh (1/16” diameter wire)
- 5/8” grid separation
- PLA Support struts (stable to ~60 ºC)
- Brass wire connectors
- High voltage wire (up to 30kV, 150 ºC)



SWIM Grid Assembly

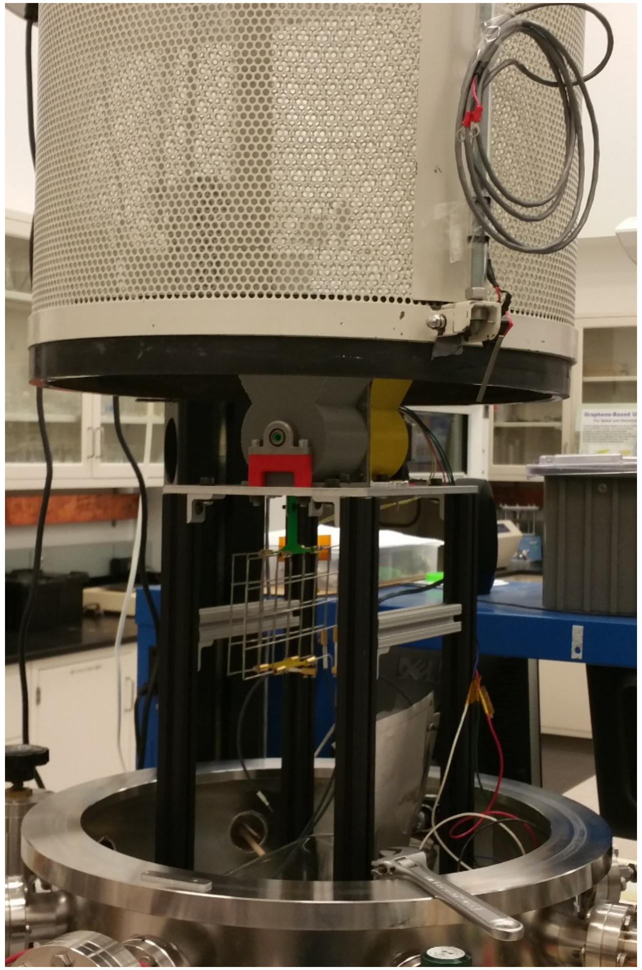


SWIM Grid Installed

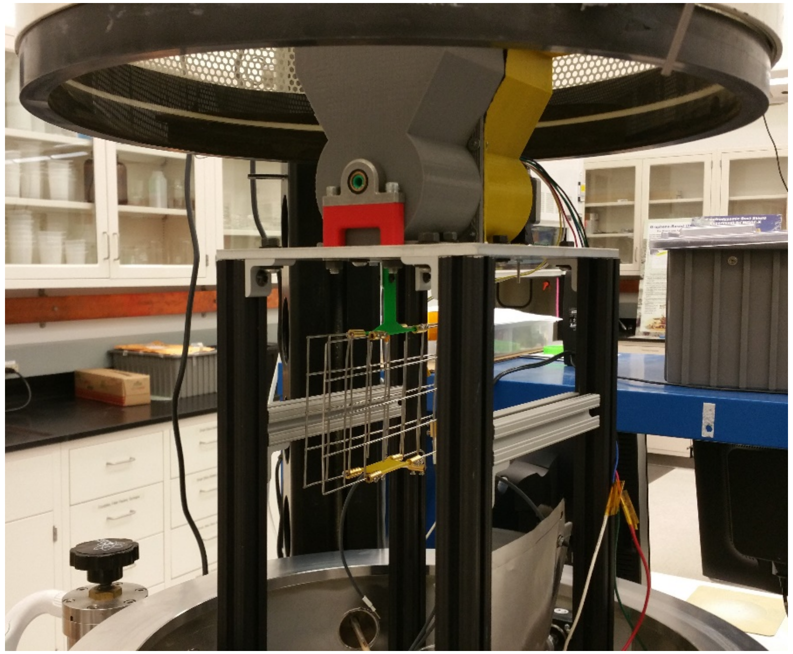
SWIM: Vacuum Chamber at NASA KSC

- Bell jar vacuum system in Electrostatics and Surface Physics Lab (ESPL)

SWIM System in ESPL

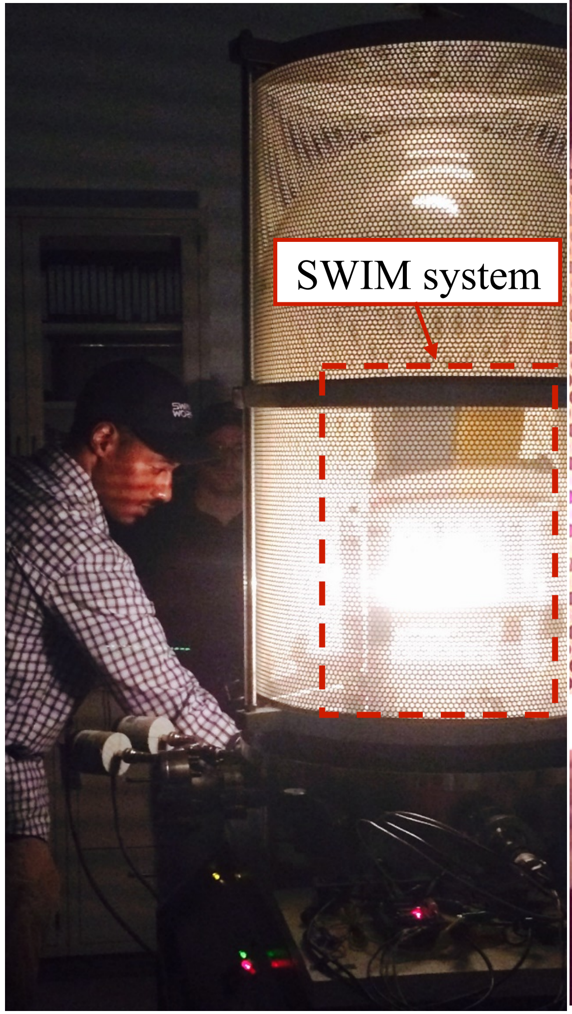


SWIM Vacuum System Open

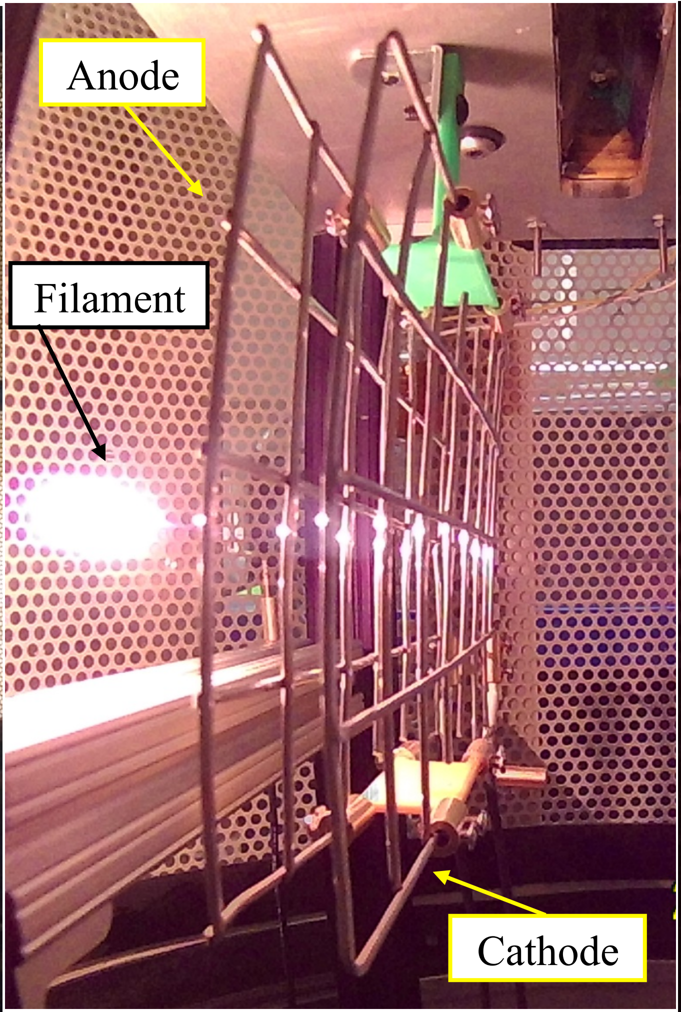


Pressure Monitor

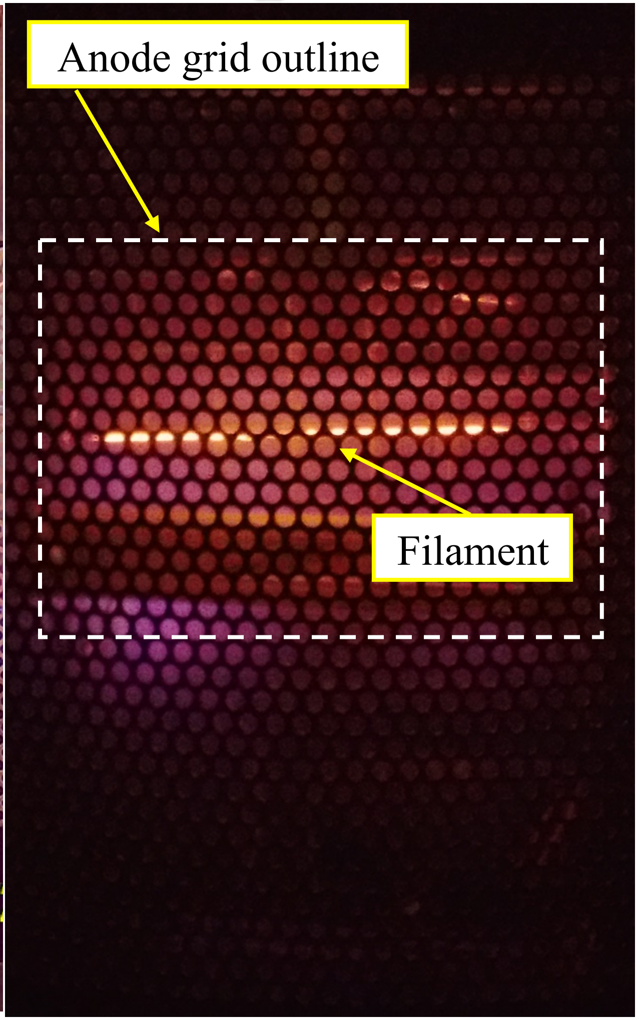
SWIM: Device Operation



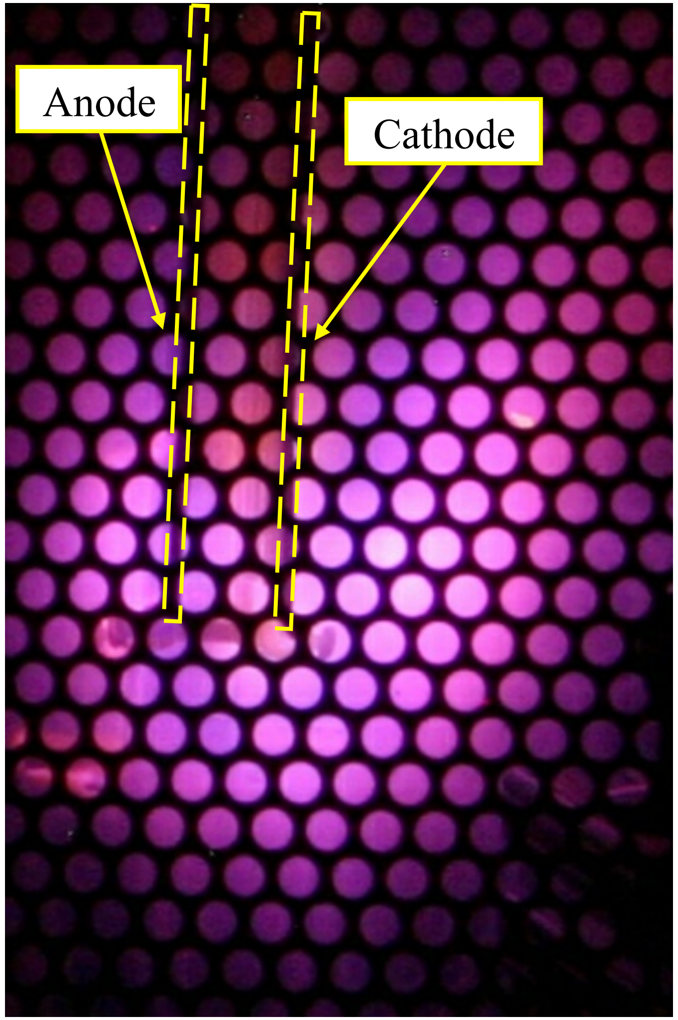
Filament on only



Action cam image



Filament on and discharge (side view)

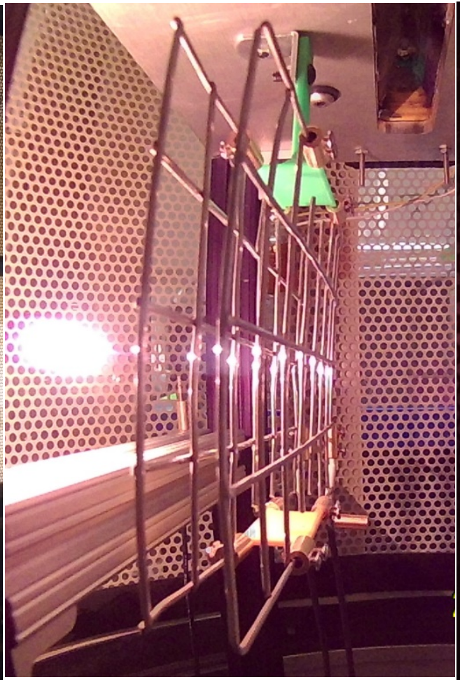


Discharge (front view)

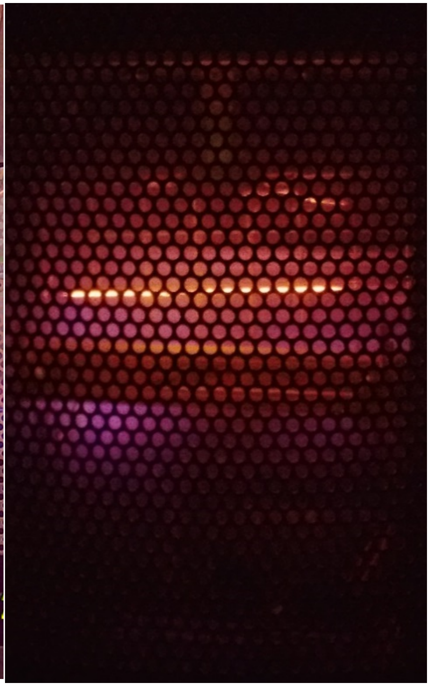
SWIM: Issues from Initial Device Operation

- Grids
  - Eliminate “sharp” points
  - Increase the ratio of the inter-grid spacing to mesh gap width
  - Potentially ceramic support pieces instead of PLA
- Filaments:
  - Increase bias voltage to ~200V range
- Instrumentation
  - Current measurement: LabView VI and DAQ (or microcontroller)
- Camera Issues
  - More reliable method needed

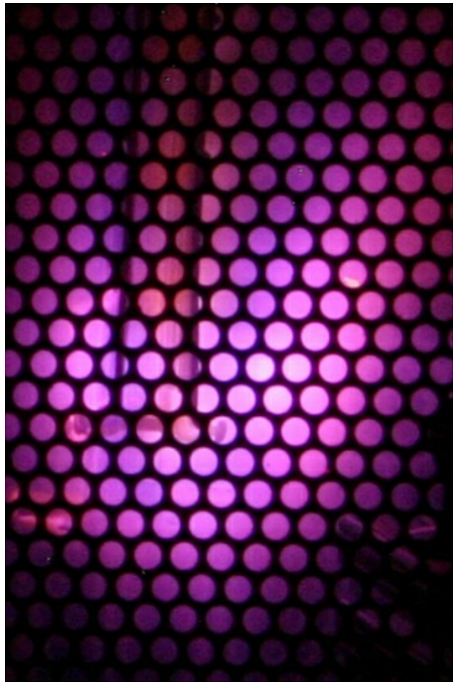
Filament on only



Action cam image

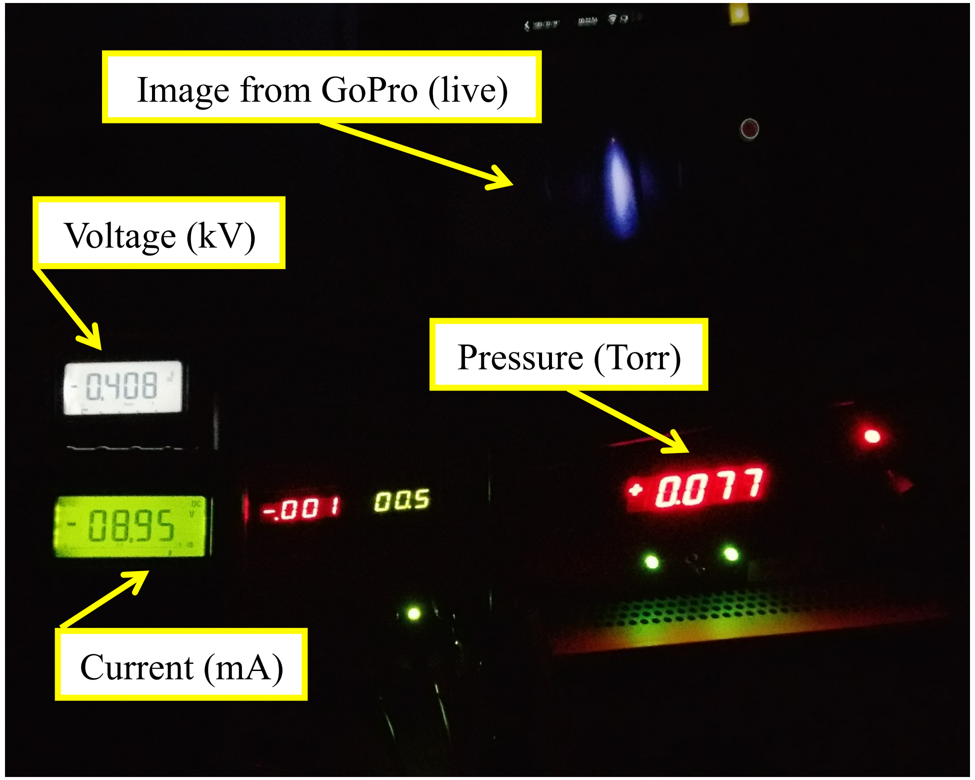


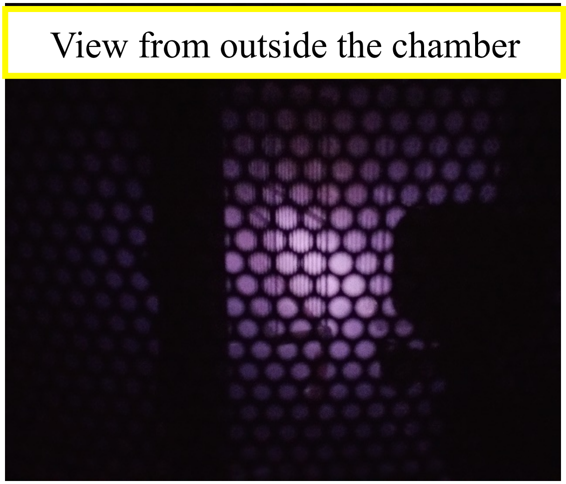
Filament on and discharge (side view)



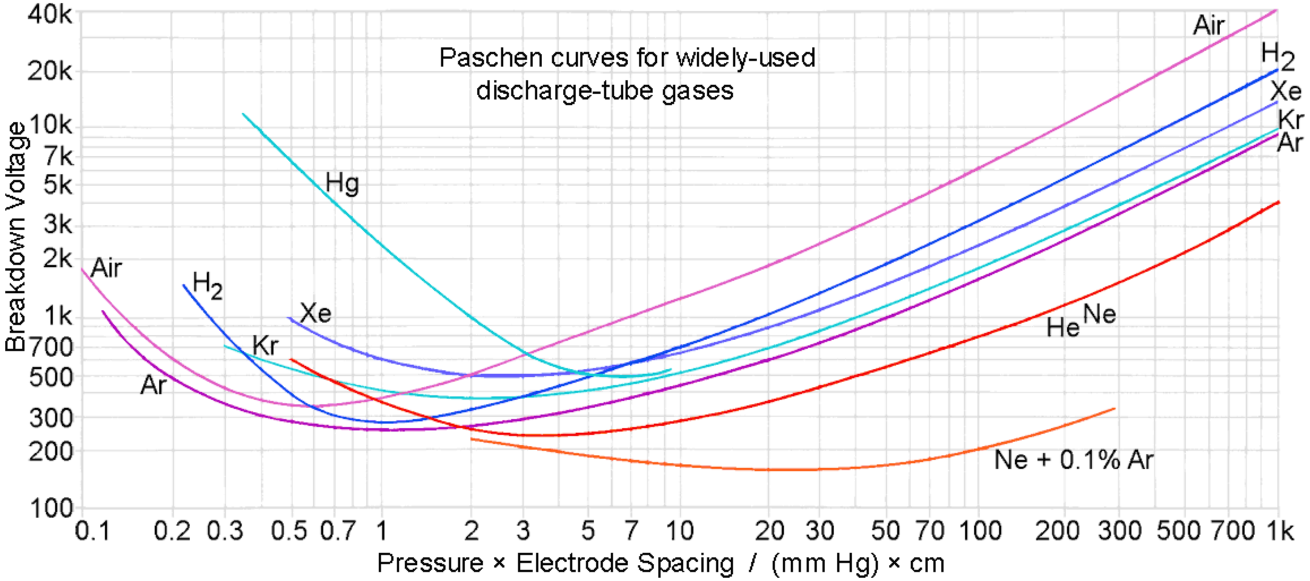
Discharge (front view)

SWIM: Tests with New Grids





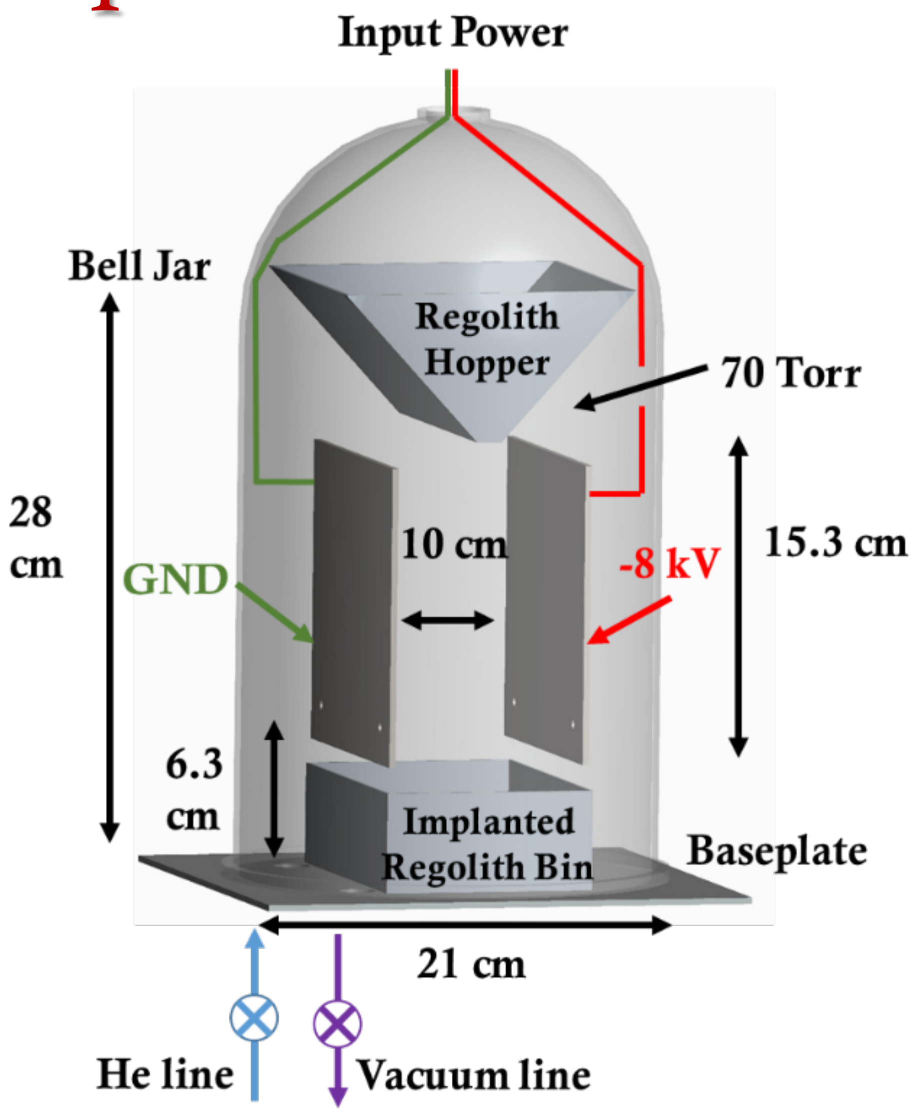
Discharge occurs approximately where the Paschen curve suggests for the same pressure-distance product of 0.2Torr-cm at ~400V for **air**



DEPARTMENT OF Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

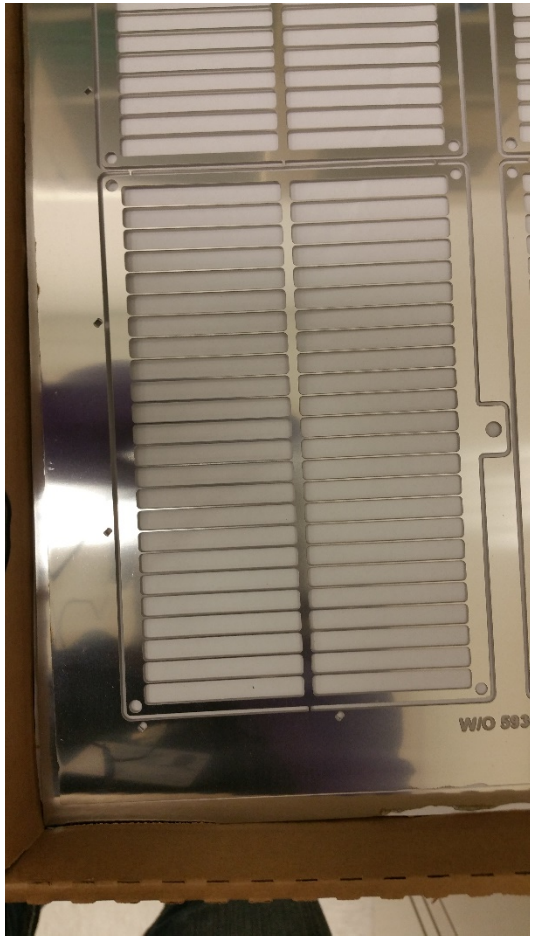
SWIM Initial Concept

- Drop simulant downward between a dc parallel electrode discharge
- Cathode held ~8kV below anode to accelerate positively charged helium ions toward the cathode
- Accelerated ions moving between the electrodes impact the falling simulant particles and are thus implanted
- Process done in a bell jar vacuum chamber filled with low pressure helium-4

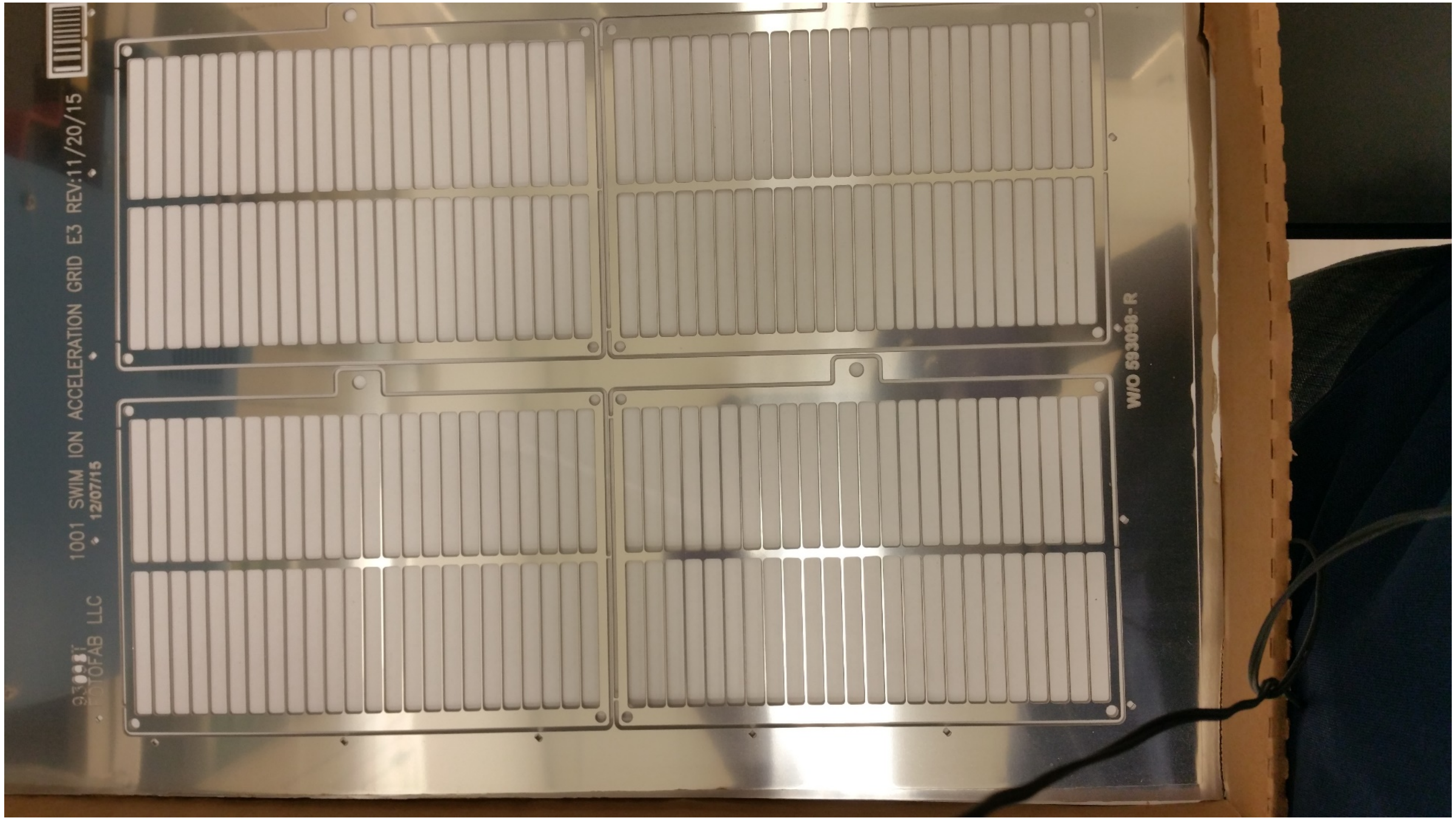


Original SWIM Concept

SWIM: New Grids from Fotofab, Inc.



Arrived 12/10/2015 at KSC



2 sets of (4) 1/32" thick 316 stainless steel grids ($750 for 8 grids)

Testing in Minnesota

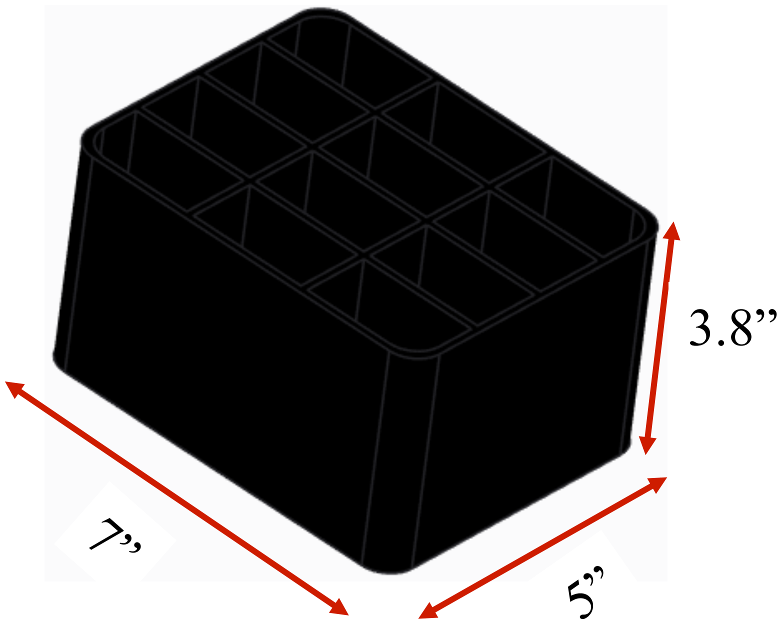
- Dr. Pepin can test samples of helium implanted simulant in the degassing system in the Physics dept. at the University of Minnesota
- Sample requirements
  - Wrapped in 5mm x 7mm Pt foil (provided by the lab)
  - Heated up to 1400ºC by direct resistance heating
  - ~1 hr/test
  - ~10 samples/week can be tested
  - There are samples already in line for testing
  - Lab will close in mid July at the latest

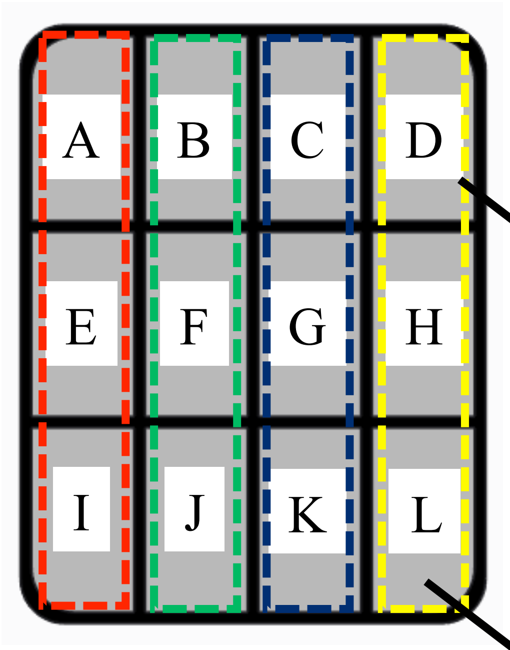
SWIM Sampling Strategy

- Objectives
  - Obtain a helium concentration vs. (helium flux/simulant mass flow rate) curve
  - Obtain some info the variability of helium dose into the simulant stream

- Setup
  - Load hopper with 240 g of <100 micron JSC-1A simulant
    - Each rotor scoop holds ~60 g of simulant
  - Drop rotor scoops at 4 different helium flux levels corresponding to an estimated 10, 20, 40, 80 ppb concentration into a 12 section partitioned bin
  - Take three ~15 mg samples per section at random for 36 total samples
    - Sample foil enclosures can hold ~15 mg of <100 micron JSC-1A

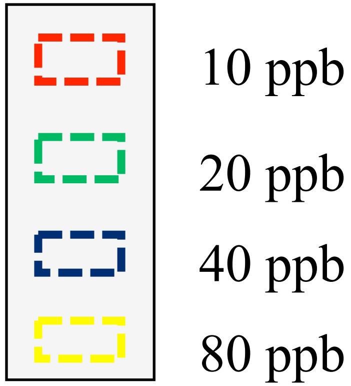
SWIM Sample Bin



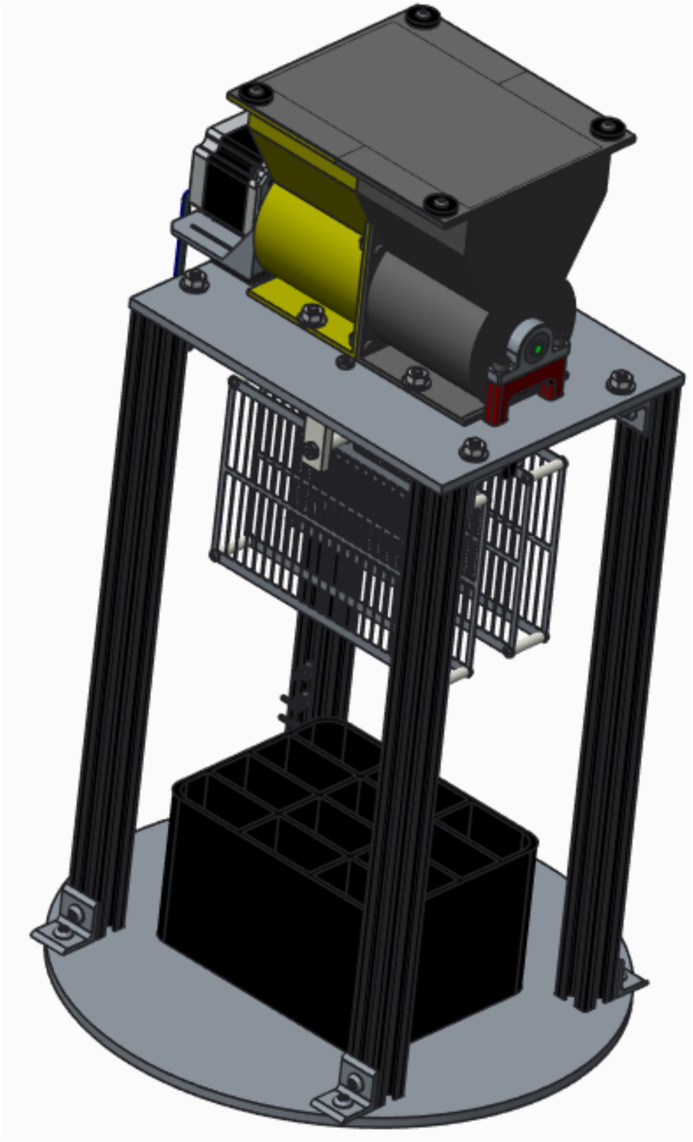


20 g/section

Three 15 mg samples



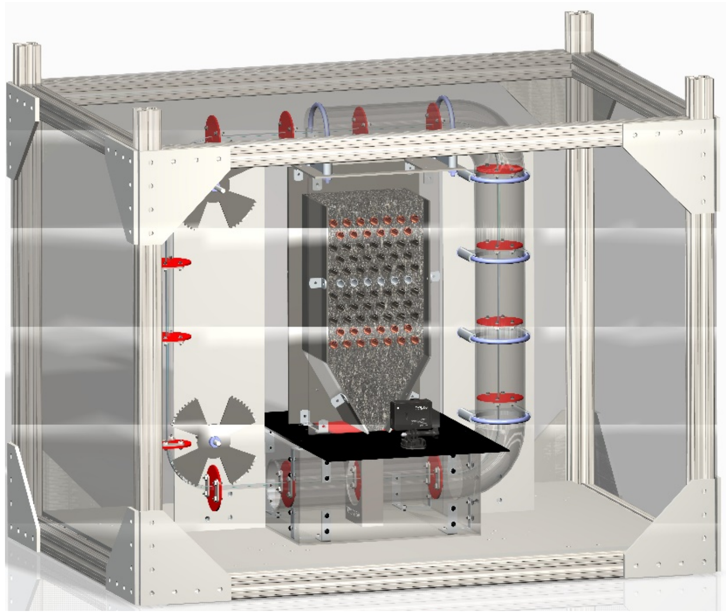
60 g per implantation level



Follow-On Wisconsin ^{3}He Extraction Research Roadmap

Lab Prototypes

- Heating System Optimization
- ^{3}He Release Measurement



(UW HEAT GFX)

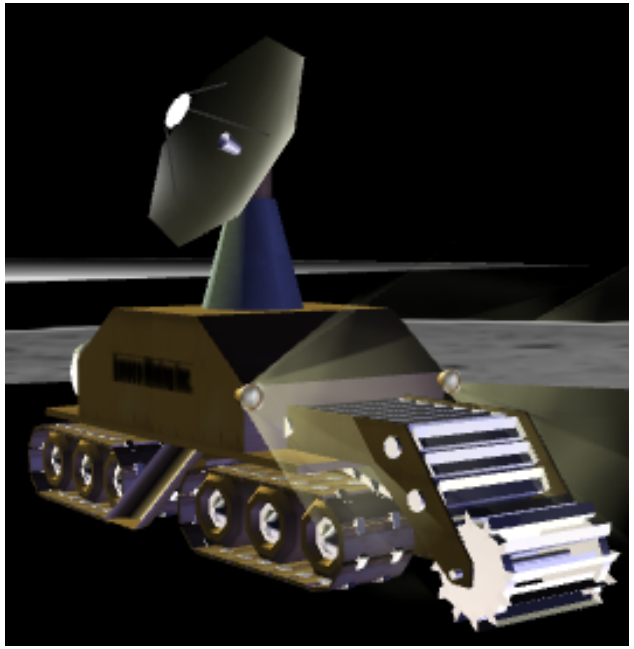
Lunar Gravity Testing

- Regolith Flow through Heating System in Lunar Gravity

(Lunar G HEAT)

Small Scale Lunar Mission

- INTERLUNE 1 Concept
- Use of GLXP Provider(s)?



(Micro ^{3}He Miner)

The ^{3}He on Earth is Insufficient to Support Fusion Power

Three sources of helium-3 on the Earth

- **Atmosphere:**
  - helium-3 concentration in atmosphere is ≈ 7×10^{-12} by volume.
  - total amount in the entire atmosphere is ≈ 4,000 tonnes

- **Natural Gas**: potentially as much as 280 kg in reserves and speculative sources that are not being tapped

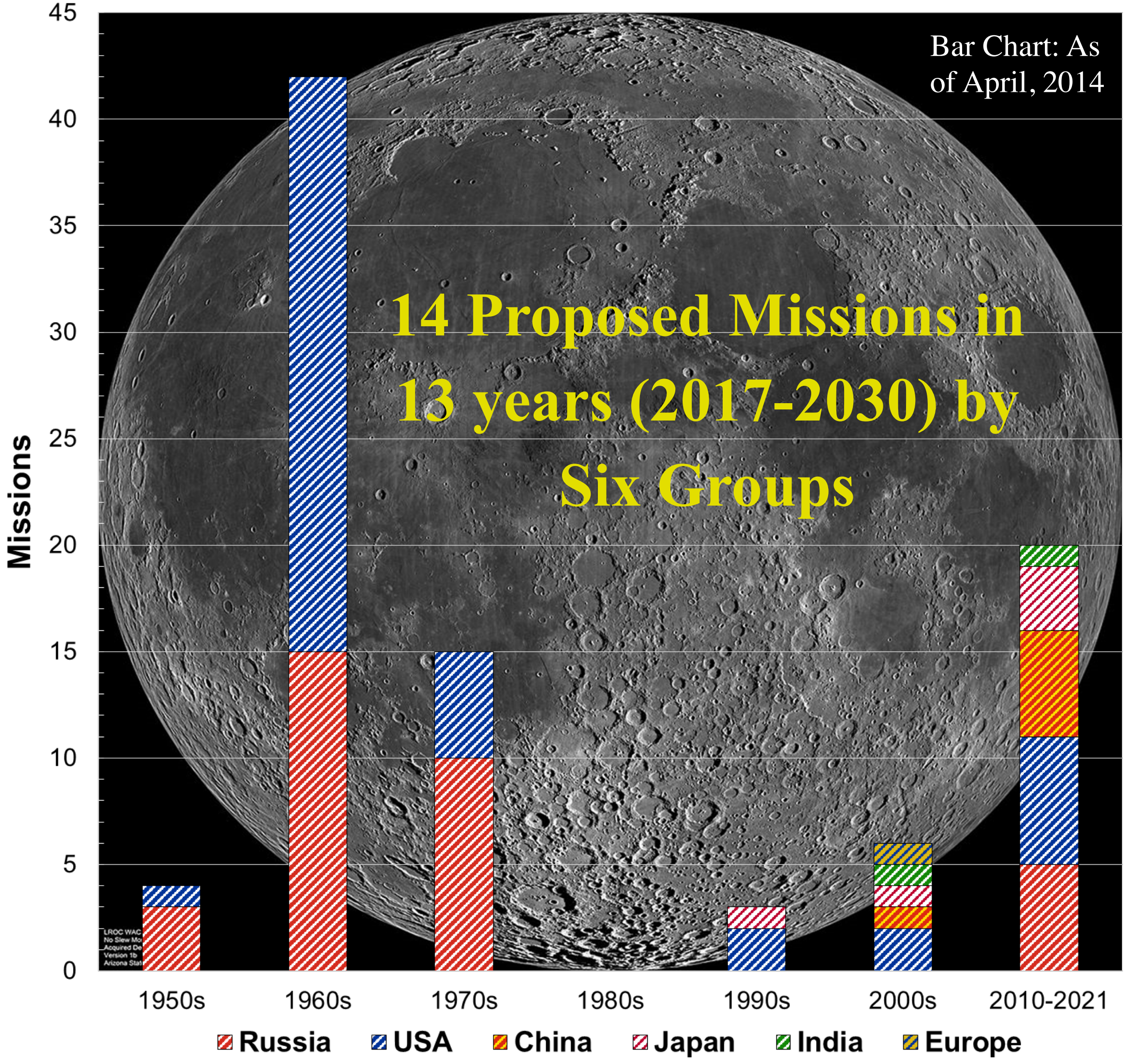
- **Decay of Tritium**: tritium decays into helium-3 with a 12.3 year half life and 2-4 kg/yr of helium-3 is produced from tritium in the U.S. and Canada

Shortage

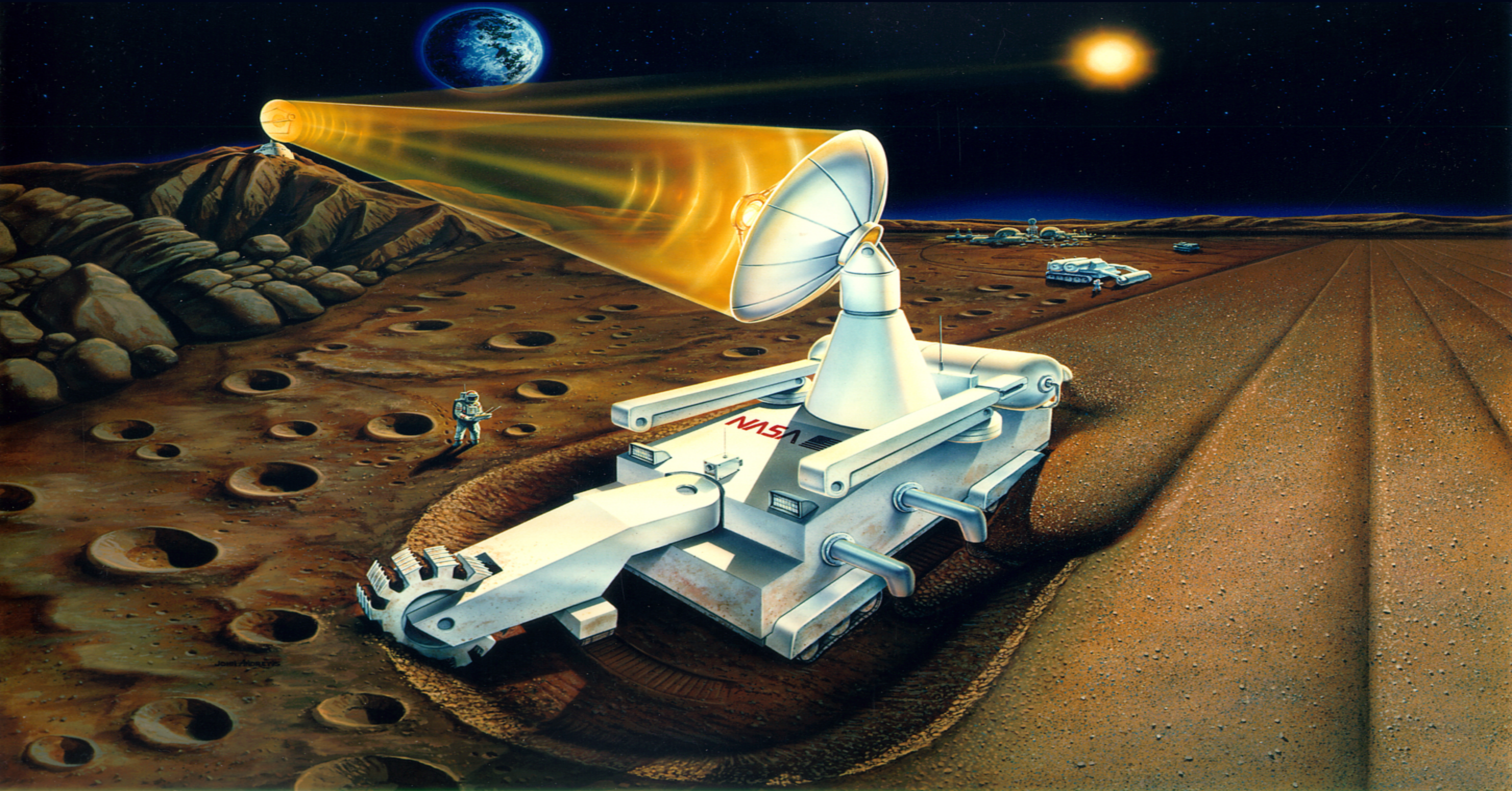
- **Increased Usage:** supply depleted of helium-3 from tritium decay (down to < 10 kg in the U.S. as of 2010)
- **Increased Price:** from (~\$1,000,000/kg) to (> \$30,000,000/kg)
- **Available for Fusion R&D:** only ~10 kg ^{3}He (200 MW-y fusion energy) is accessible on Earth

Interest in Lunar Exploration is Ramping Up

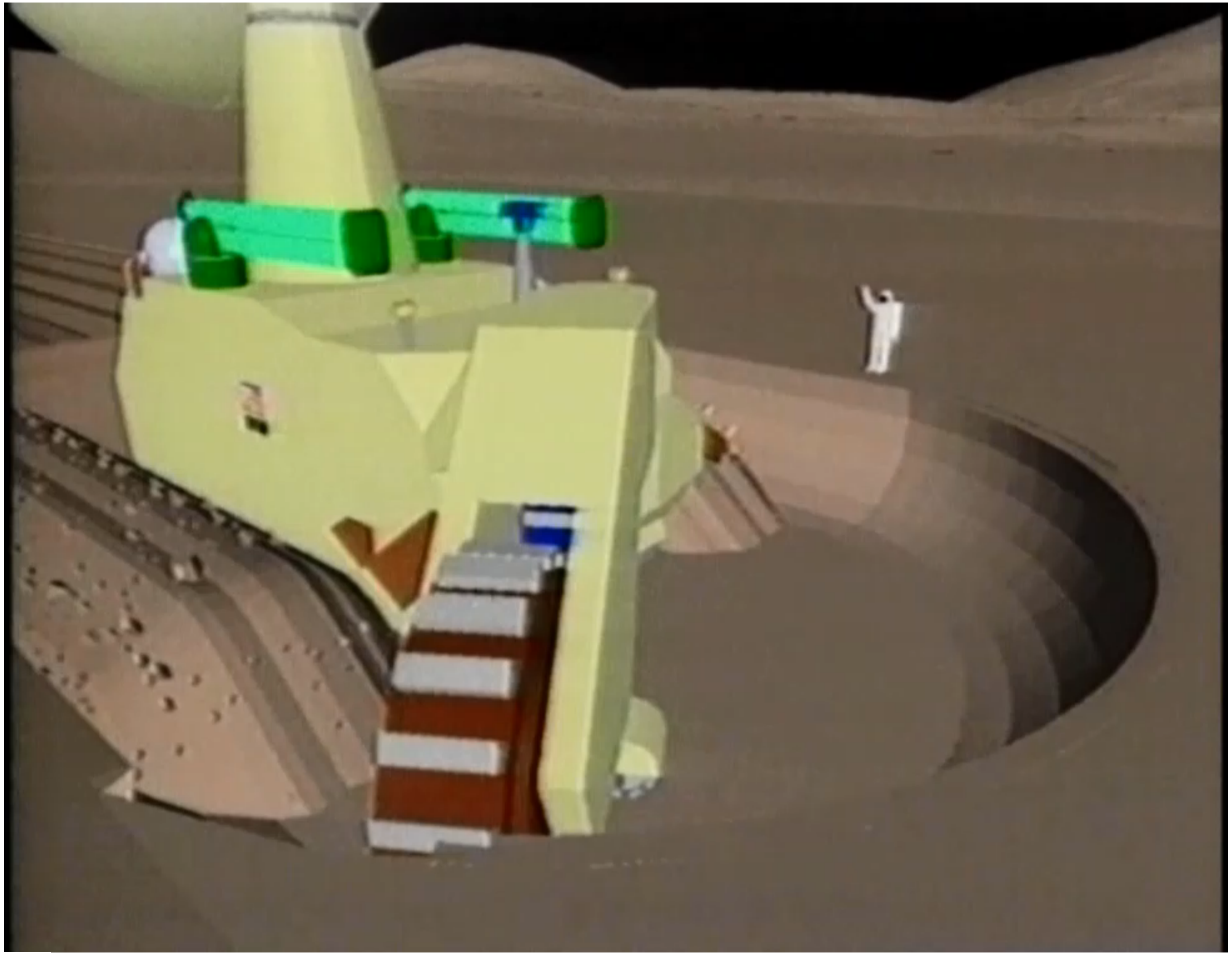
Lunar Mission Manifest			
Launch Date	**Organization**	**Country**	**Mission**
2015-2018	Google Lunar XPrize (GLXP)		GLXP
2017	CNSA	China	Chang'e-5
2017	JAXA	Japan	SELENE-2
2018	ISRO	India	Chandrayaan-2
2018	NASA	USA	RP
2018	NASA	USA	EM-1
2020	CNSA	China	Chang'e-6
2021	NASA	USA	EM-2
2020s	Roscosmos	Russia	Luna-25
			Luna-26
			Luna-27
			Luna-28
			Luna-29
	JAXA	Japan	SELENE-3



Lunar Helium-3 for Clean Fusion Power on Earth or in Space



There are Three Main Processes in a ^{3}He Miner

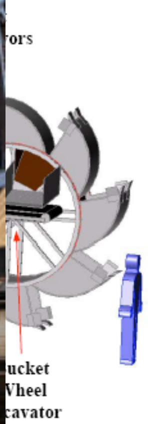


There are Three Wisconsin Lunar ^{3}He Miner Designs

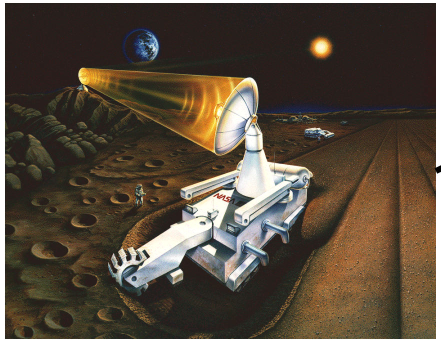
Excavation rate (tonnes/hr)	1258
Processing rate (tonnes/hr)	556
Thermal process power (MW)	
^{3}He extraction (kg/yr)	66

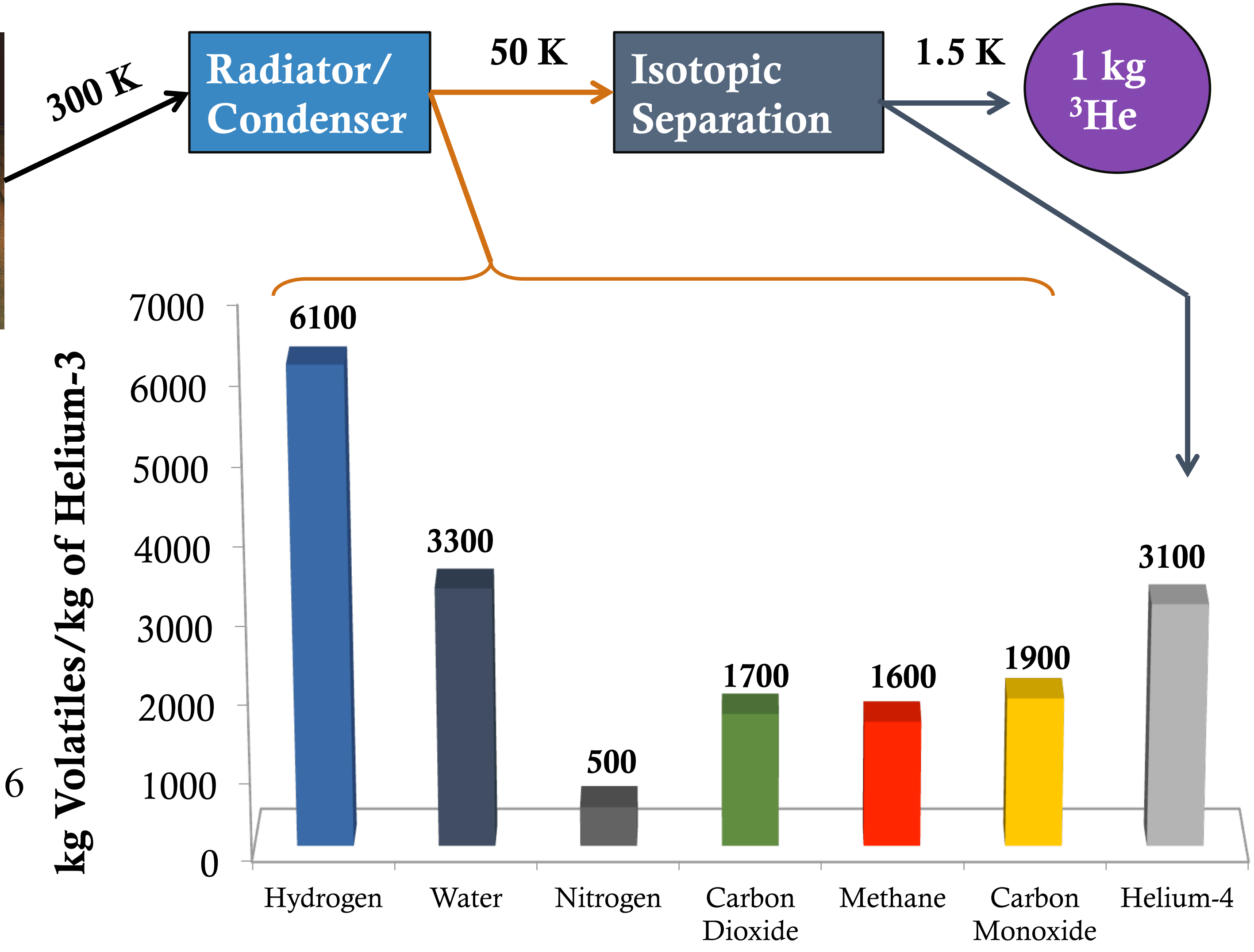
TAKRAF SR 8000 bucket-wheel excavator can excavate > 16,000 tonnes/hr of bituminous coal and has a mass of 14,200 tonnes


Credit: Tenova TAKRAF



^{3}He Mining Produces Valuable ISRU Volatile By-Products





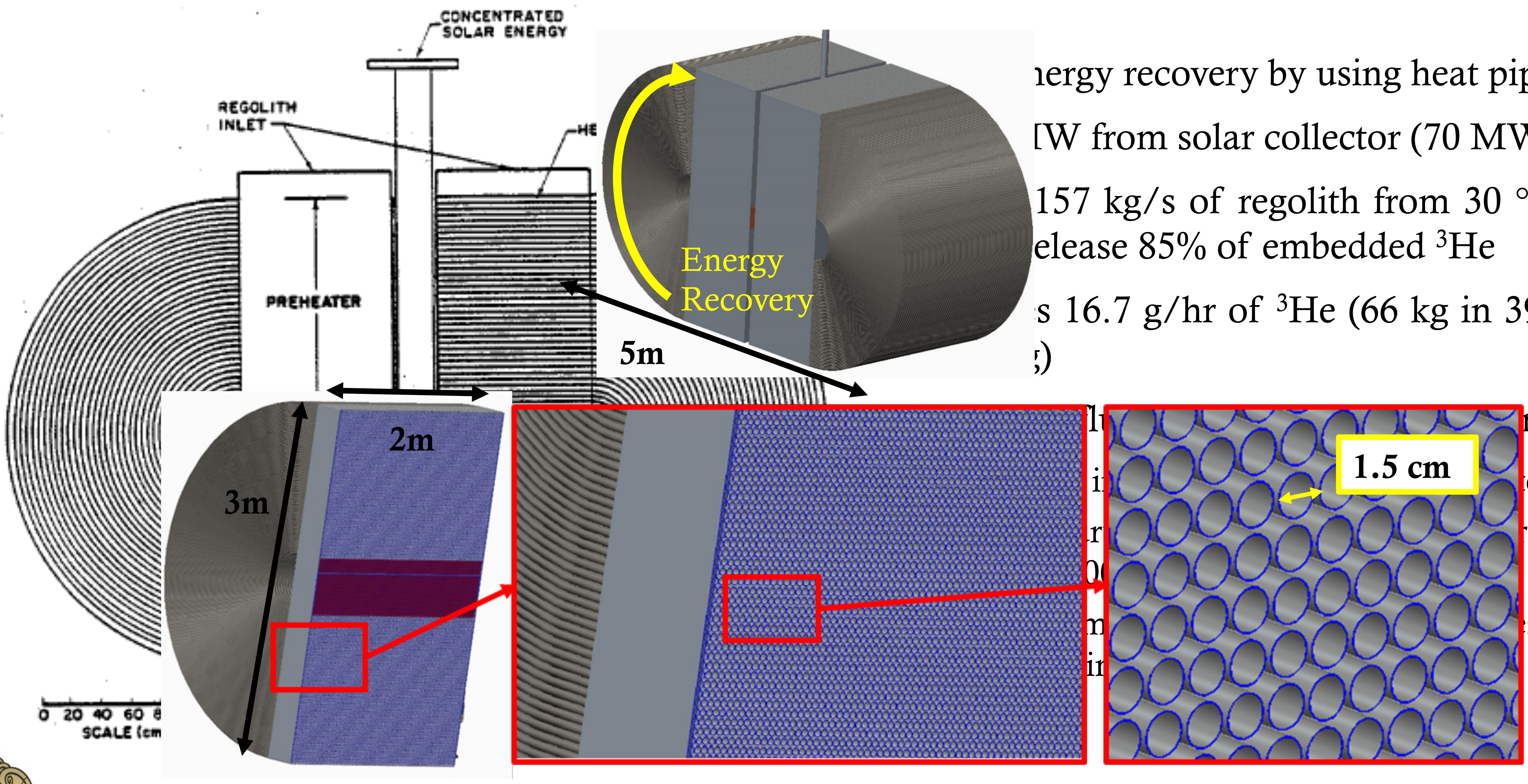
- Fuel: H_2, CH_4, H_2O
- Life support:

CO_2, CH_4, N_2, H_2O

- Cryogenics: ^4He

Results from Apollo 11 sample 10086.16

The Heat Pipe Heat Exchanger is a Key Part of the Miner



ergy recovery by using heat pipes

W from solar collector (70 MW reduction)

157 kg/s of regolith from 30 °C up to 700
elease 85% of embedded ^{3}He

s 16.7 g/hr of ^{3}He (66 kg in 3942 hours of
)

mbinations

o ~250 °C

ating between

ss steel pipes:

JSC-1A Lunar Regolith Simulant Will be Used

JSC-1A Merriam Crater Cinders (left) and ground regolith simulant (right). Credit: ORBITEC

Thanks to Dr. James Mantovani for 8kg of JSC-1A from NASA KSC

Den		0 [k
Mea		μm
Mea		μm
Specific heat	700- 1400 [J/kg-K]	1047.41 log(Temp) – 1848.15 [J/kg-K]
Thermal Conductivity @20 kPa	0.15 - 0.40 [W/m-K]	$3.9e^{-4}$(Temp) + 0.1588 [W/m-K]
Cohesion	1 kPa	1 kPa
Angle of Internal Friction	40-55 degrees	45 degrees

Minerals	JSC-1A
Plagioclase	37.83
Clinopyroxene	18.77
Orthopyroxene	0.66
Olivine	12.44
Glass	26.67
Magnetite	0.01
Chromite	0.00
Ilmenite	0.11
Sulphides	0.17
Iron	0.00
MgFeAl Silicate	3.06
K Feldspar	0.07
Quartz	0.01
Calcite	0.11
Others	0.07
Total	100.00

The ^{3}He on Earth is Insufficient to Support Fusion Power

Three sources of ^{3}He on the Earth

- **Atmosphere:**
  - helium-3 concentration in atmosphere is ≈ 7×10^{-12} by volume.
  - total amount in the entire atmosphere is ≈ 4,000 tonnes
- **Natural Gas:** potentially as much as 280 kg in reserves and speculative sources that are not being tapped
- **Decay of Tritium**: tritium decays into helium-3 with a 12.3 year half life and 2-4 kg/yr of helium-3 is produced from tritium in the U.S. and Canada

There is enough ^{3}He on Earth for Fusion R&D

- **Available for Fusion R&D:** ~100 kg ^{3}He (2000 MW-y fusion energy) is accessible on Earth

A Potential Roadmap for Lunar Helium-3

Prospecting and Research ~2015-2025

- Government missions
- **Research at UW-Madison**
- Google Lunar X-Prize

(NASA RESOLVE)

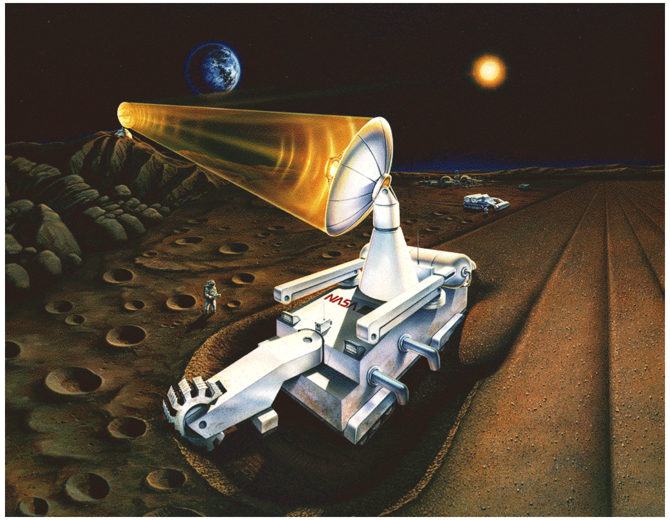
Small Scale Mining ~2025-2035

- First small test lunar miners
- Start of lunar outposts
- Other mining activities starting

(Small scale concept)

Established Mining Industry ~Post 2035

- Large lunar miners
- Established Moon-Earth shipping
- **^{3}He Fusion Reactors**



(UW Mark-II concept)

Upcoming Lunar ^{3}He Fusion Book

Lunar Helium-3 Fusion: The Earth's Energy Future

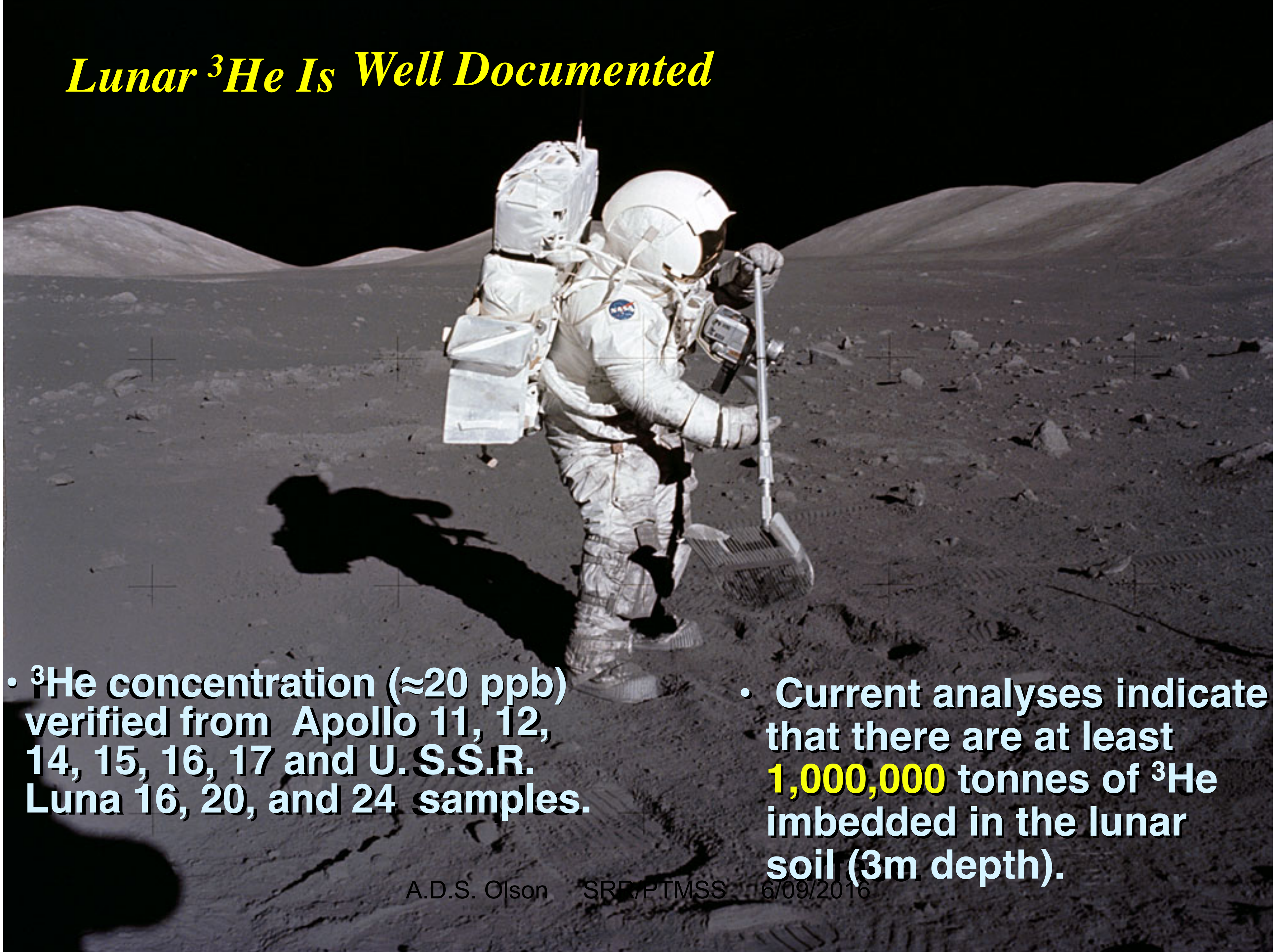
Follow-on to *Return to the Moon* by Dr. Harrison Schmitt, to be published in 2017

Discusses

- Increasing need for power worldwide
- Potential role of ^{3}He fusion technology
- Lunar bases and resources
- Legal regimes for lunar mining
- Economics of ^{3}He procurement
- Terrestrial fusion power plants
- Space applications of ^{3}He fusion
- Current lunar initiatives around the world

Authors: Dr. Harrison Schmitt, Dr. Gerald Kulcinski,
Dr. John Santarius, Aaron Olson

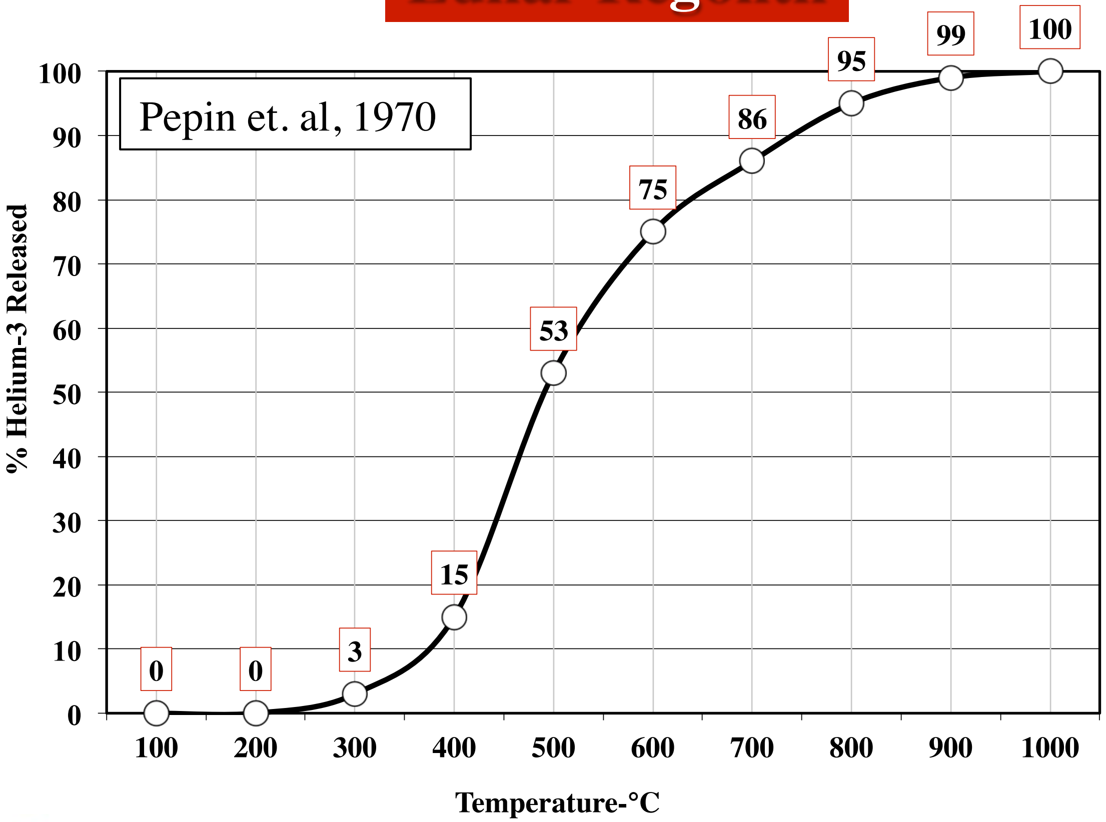
Lunar ^{3}He Is Well Documented



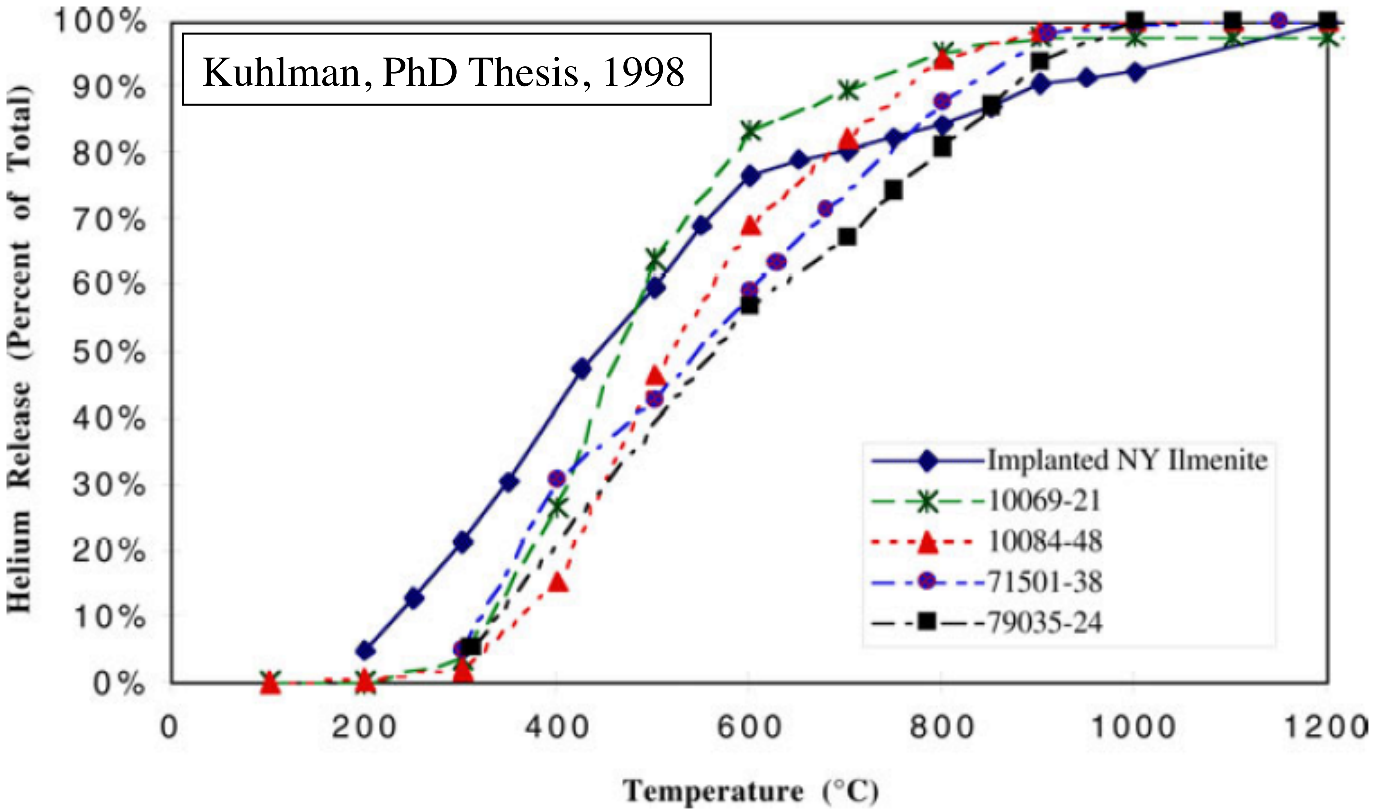
- ^{3}He concentration (≈20 ppb) verified from Apollo 11, 12, 14, 15, 16, 17 and U. S.S.R. Luna 16, 20, and 24 samples.
- Current analyses indicate that there are at least 1,000,000 tonnes of ^{3}He imbedded in the lunar soil (3m depth).

^{3}He Diffusion out of Lunar Regolith has been Studied

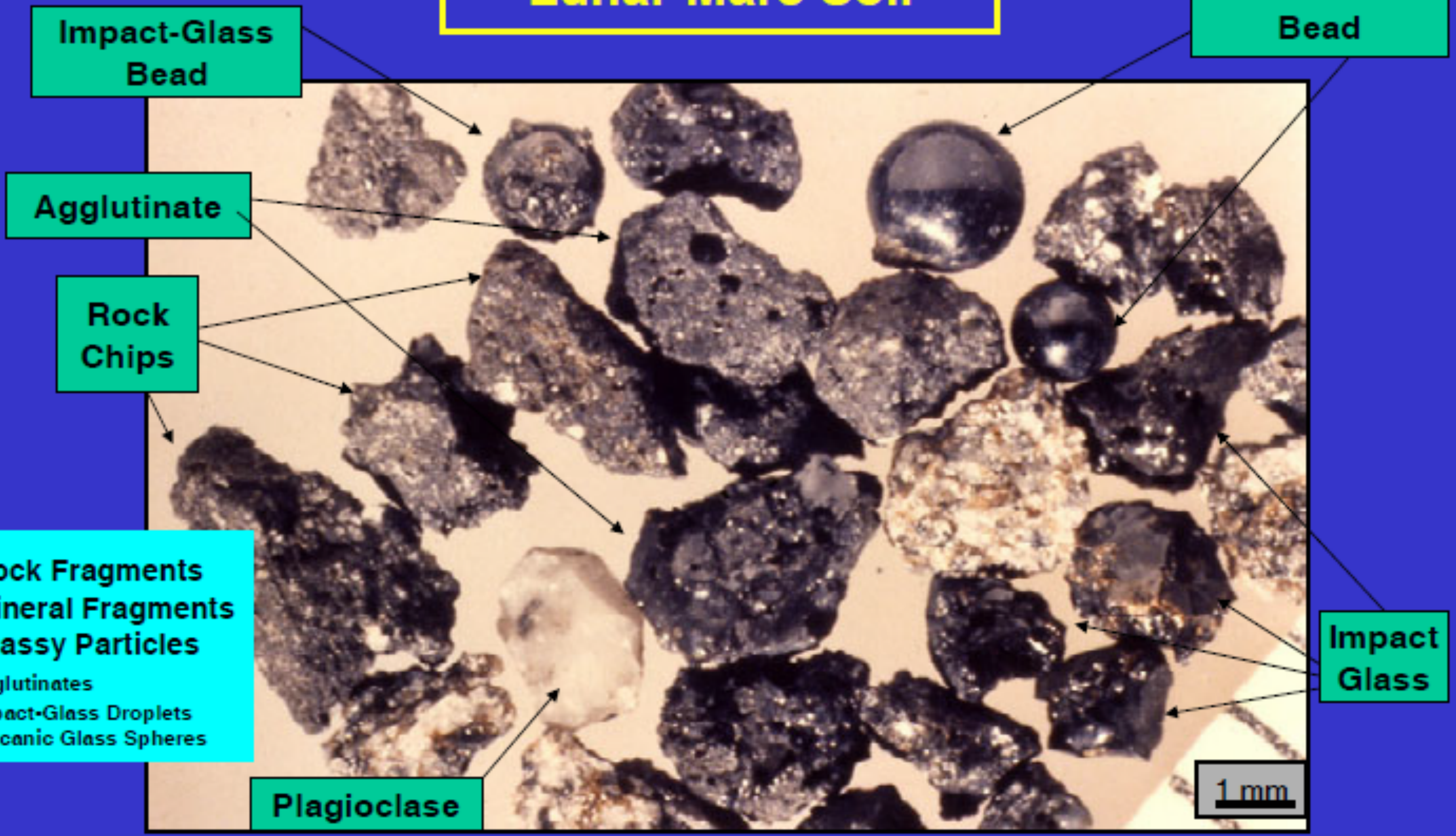
Lunar Regolith



Analog Regolith



Lunar Mare Soil

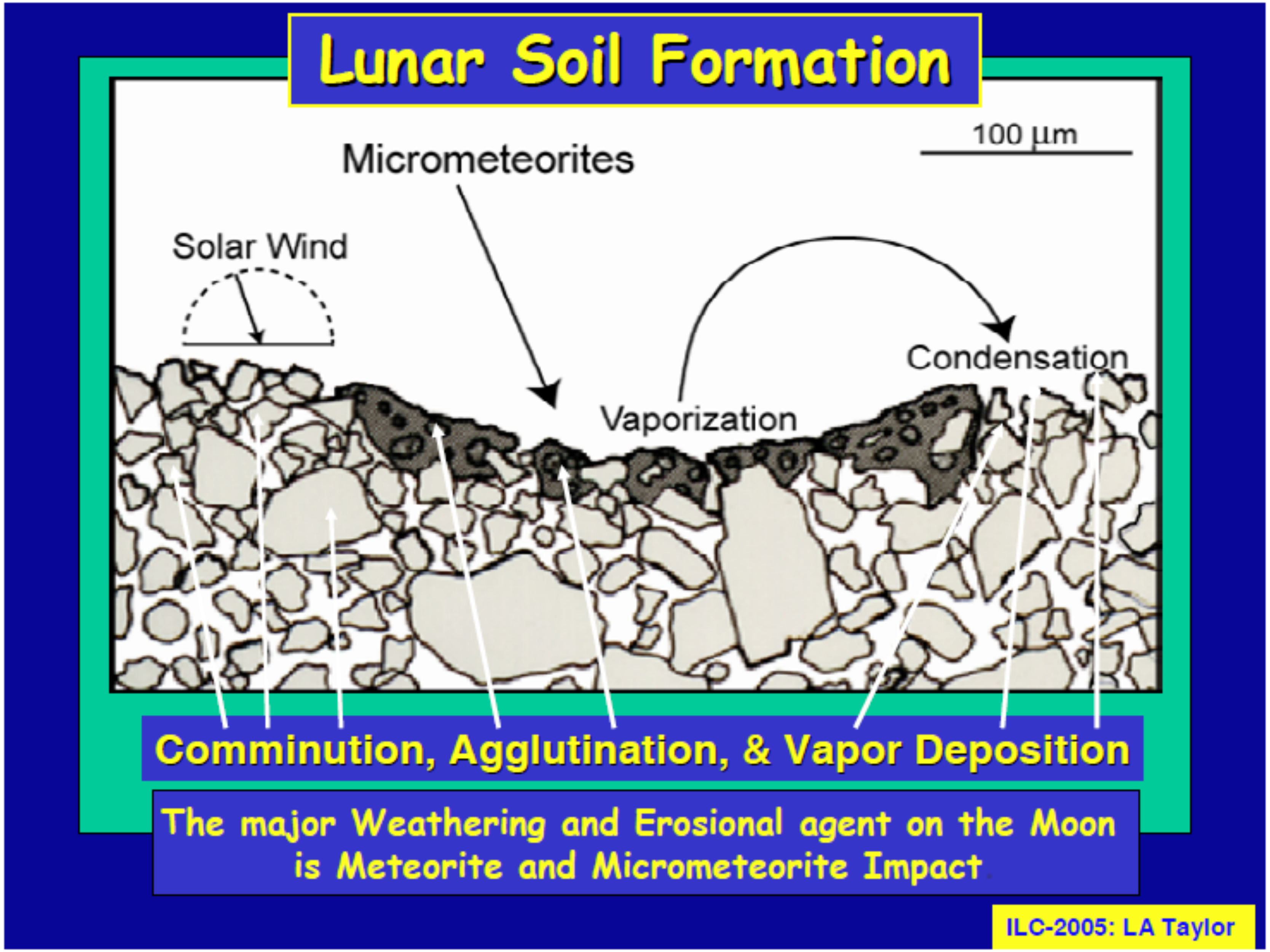


- Rock Fragments
- Mineral Fragments
- Glassy Particles
  - Agglutinates
  - Impact-Glass Droplets
  - Volcanic Glass Spheres

Regolith: broken up rock material; '**Soil**': <1 cm portion of the Regolith

Dust: < 50 µm portion of the Soil

ILC-2005: LA Taylor


Lunar Soil Formation
100 µm
Micrometeorites
Solar Wind
Condensation
Vaporization
Comminution, Agglutination, & Vapor Deposition
The major Weathering and Erosional agent on the Moon is Meteorite and Micrometeorite Impact
ILC-2005: LA Taylor


Production of JSC-1A
Mining of Lunar Soil Simulant at Flagstaff, Arizona
ILC-2005: LA Taylor

Regolith for the Heat Exchanger Must be Implanted with ^3He

- JSC-1A lunar regolith simulant will be used for the HEAT demonstration system
- JSC-1A does not contain any measurable amount of helium-3
- The simulant must be implanted with helium-3
- A dc glow discharge implantation system has been proposed to address this issue
- Simulant from a hopper will fall between parallel electrode plates inside of a vacuum chamber
  - Voltage between plates selected to simulate the energy helium ions have in the solar wind
  - Chamber pressure and distance between plates determined by the Paschen curve for helium

$$A' Pd \exp(-B' Pd/V_b) = \ln(1+(1/\gamma_{se}))$$

$$A' = 2.1 \;Pa^{-1}m^{-1}$$

$$B' = 57.75 \;\frac{V}{Pa - m}$$

$$\gamma_{se} = 0.109$$