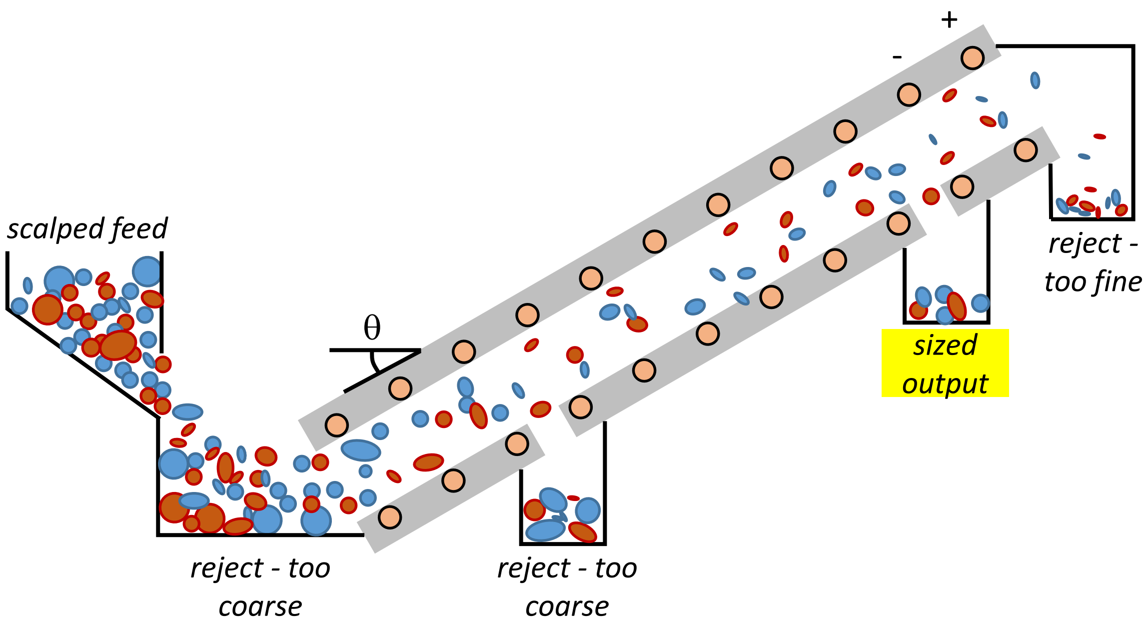
Ground Testing of Electrostatic Transport of Lunar Regolith Simulants with Applications to Electrostatic Sieving

P. Bachle, J. Smith, F. Rezaei, D. Bayless, W. Schonberg, and **D. Han**

On behalf of the LuSTR21 Beneficiation Project Team



Regolith Beneficiation System for Production of Lunar Calcium and Aluminum (LuSTR21)

Outline

- Project Overview
- Year 1 Activities and Achievements
  - Task 1: Materials / Simulants
  - Task 2: Electrostatic Sieve Subsystem
  - Task 3: Particle Size Separation Testing/Modeling
- Planned Year 2 Activities
  - Task 4: Magnetic Separation Subsystem
  - Task 5: Compositional Analysis (Anorthite)
  - Task 6: System Integration
  - Task 7: System Optimization – Size, Weight, and Power (SWaP)

SRR 2023

Regolith Beneficiation System for Production of Lunar Calcium and Aluminum

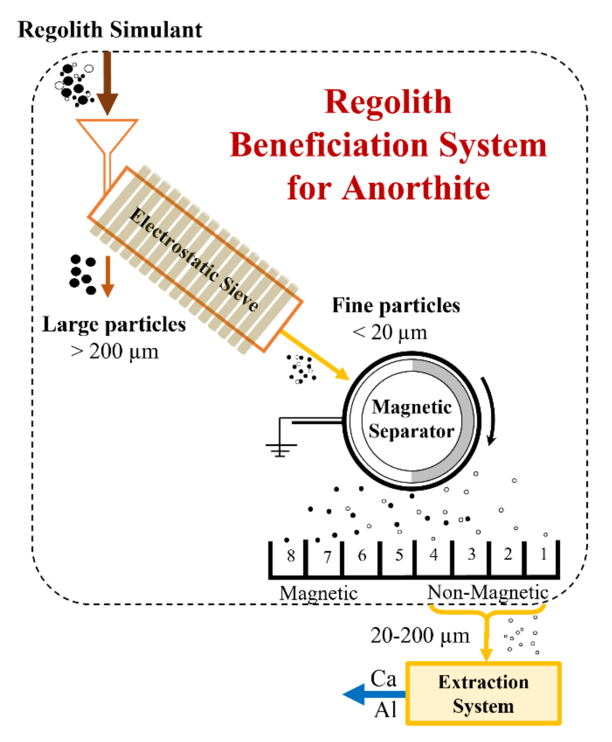
PI: D. Han, Missouri S&T

Team:

F. Rezaei, Missouri S&T
J. Smith, Missouri S&T
W. Schonberg, Missouri S&T
D. Bayless, Missouri S&T
A. Esbeck *et al.*, Bechtel
D. Bergman, Honeybee Robotics
M. Roth, Off Planet Research, LLC

Development Objectives

- Build and demonstrate integrated system for particle size classification and enrichment of anorthite from lunar mare and highland simulants with varying agglutinate fractions.
- TRL4 → TRL5
- Output >70 wt% anorthite, particles 20-200 µm
- Final system <0.51 m^3, 35 kg, 300 watts
- System throughput ≥3 kg/hr



Approach

- Develop and test sub-systems:
  - electrostatic sieve
  - magnetic drum separator
- Under operational conditions:
  - -196°C to 120°C
  - ambient & vacuum pressure
  - representative test materials
- Integrate into complete system, validate vacuum performance
- Optimize size, mass, and power needs of integrated system.

Impact and Infusion

- Enables efficient processing to extract calcium and aluminum from lunar regolith
- Direct application to ISRU and construction materials anywhere on lunar surface
- TRL 6 achievable within 2 years
- TRL 8 achievable within 5 years

Project Deliverables

- As specified in solicitation:
  - System produces particles of 20-200 µm size
  - System product consists of $\geq$ 70 wt% anorthite
- As stated in proposal:
  - System volume $\leq 0.51\ m^3$
  - System mass $\leq$ 35 kg
  - System power requirement $\leq$300 watts
  - System throughput $\geq$3 kg/hr

Top-level Schedule

- Expected task completion dates:

	Task	Status
1.	Prepare simulants and test equipment	Ongoing
2.	Fabricate particle size classifier	Done
3.	Test and model particle size classifier	Ongoing
4.	Fabricate magnetic separator	Aug 2023
5.	Anorthite separation testing and analysis	Oct 2023
6.	Integrate subsystems, develop conops	Jan 2024
7.	Optimize total system and conops	May 2024

- Completion of Task 6 will satisfy TRL 5 exit criteria

Size Classifier Design

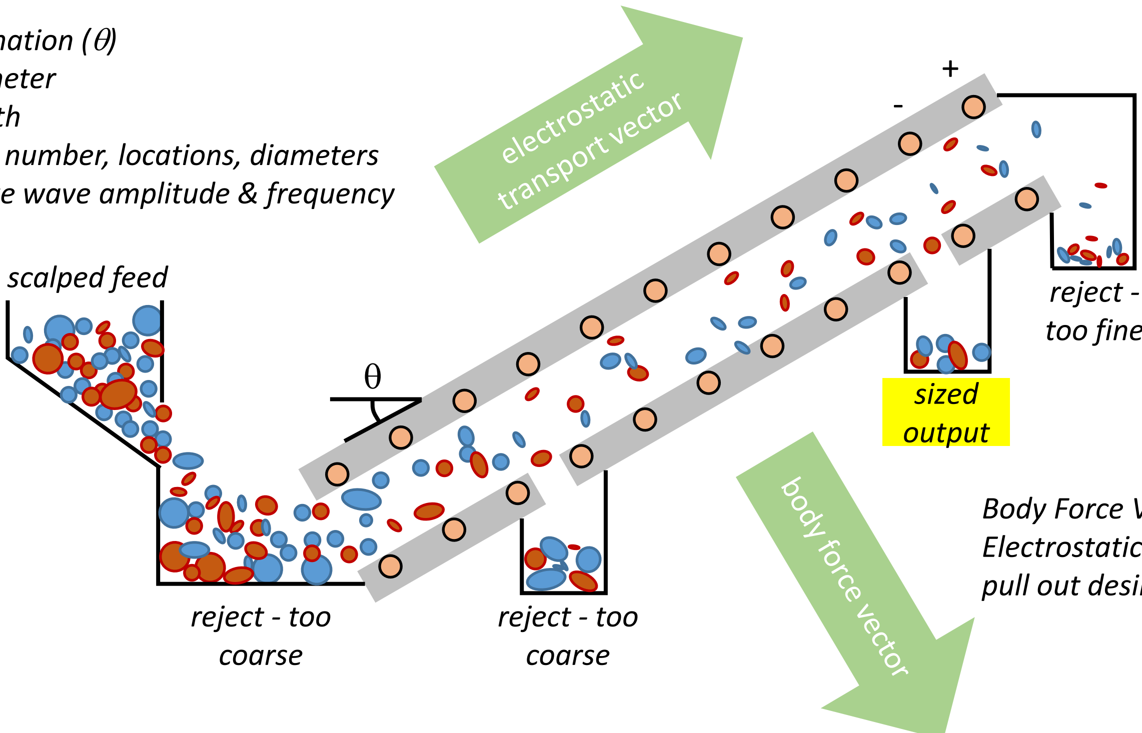
- Recent design sketch for electrostatic sieve, adapted from:

Kawamoto *et al*. (2021) "Vertical transport of lunar regolith & ice particles using electrodynamic traveling wave," ASCE.

Kawamoto *et al*. (2022) "Improved electrodynamic particle-size sorting system for lunar regolith," ASCE.

Control Parameters:

- *feed rate*
- *column inclination (θ)*
- *column diameter*
- *column length*
- *output ports number, locations, diameters*
- *electromotive wave amplitude & frequency*



Body Force Vector interacts with Electrostatic Transport Vector, to pull out desired size fractions

Not Shown:

- *particle charging mechanism*

Magnetic Separator Design

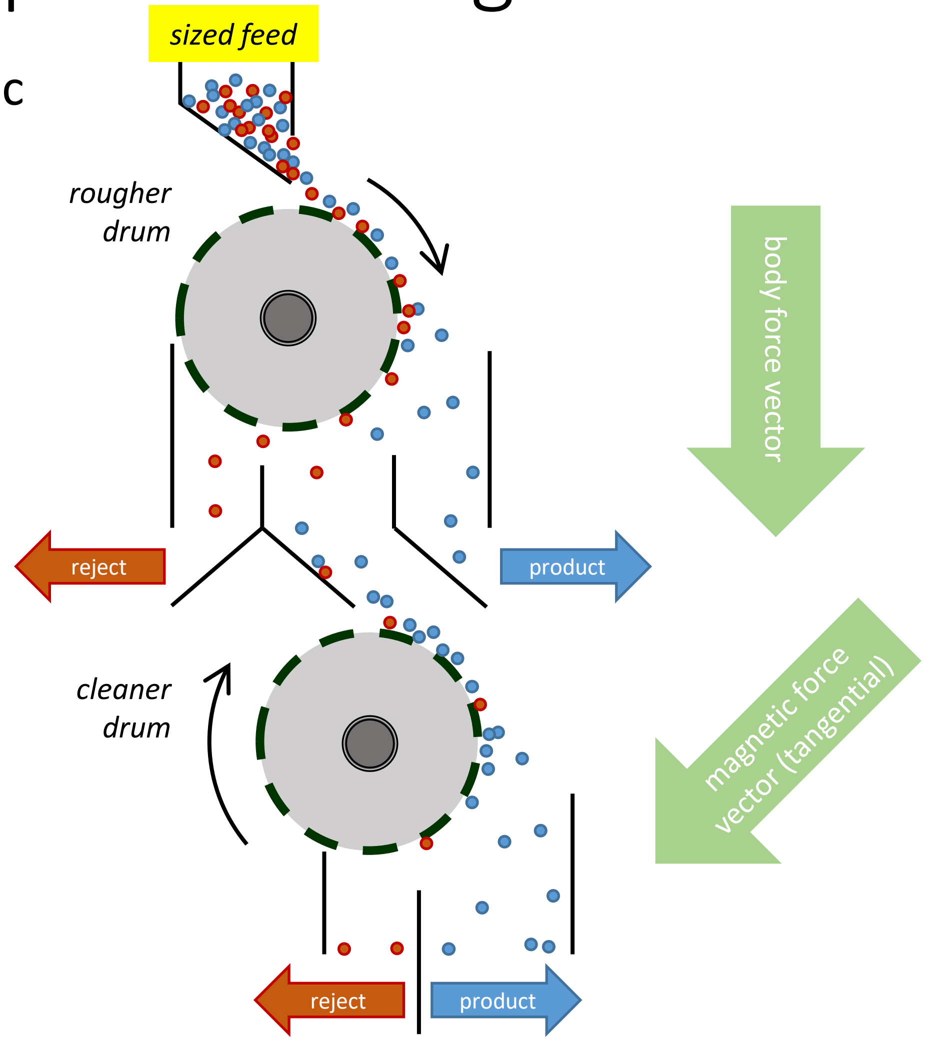
- Recent design sketch for magnetic separator (to be reviewed with Bechtel in Year 2)

Control Parameters:

- *feed rate*
- *absolute & relative drum rotation rates*
- *drum diameters*
- *magnet size, strength, placement in drums*
- *output bins number, locations, threshold geometries*

Magnetic Force Vector (tangential to drum rotation) interacts with Body Force Vector, to separate particles of desired composition – the required number of stages is TBD (this sketch shows two).

"Reject" refers to particles above some level of magnetic susceptibility and "product" refers to less magnetic particles.



Task 1: Preparation of Test Materials

Table 1. Non-Iron-Added Simulants Ordered from Off Planet Research (OPR)

Label Name	Lunar Location		Agglutinates		Size Range		
	Mare	Highland	10%	60%	500-250 µm	250-105 µm	105 µm & finer
L2W10g6	X		X		X		
L2W60g6	X			X	X		
H4W10g6		X	X		X		
H4W60g6		X		X	X		
L2W10g814	X		X			X	
L2W60g814	X			X		X	
H4W10g814		X	X			X	
H4W60g814		X		X		X	
L2W10g17-	X		X				X
L2W60g17-	X			X			X
H4W10g17-		X	X				X
H4W60g17-		X		X			X

Notes:

Mare simulants are 90% basalt, 10% anothosite; PAN Highlands are 10% basalt, 90% anorthosite.

Agglutinates are rock glass (anthropogenic obsidian).

500-250 micron = Mesh #60; 250-105 micron = Mesh #80 to #140; 105 micron & finer = Mesh #170 & finer.

"g" (grain-size Mesh # sans 0) in label is given by MS&T for ease of data entry.

Table 2. Iron-Added Simulants Ordered from Off Planet Research (OPR)

Label Name	Lunar Location		Agglutinates		Size Range		
	Mare	Highland	10%	60%	500-250 µm	250-105 µm	105 µm & finer
L2W10Fg6	X		X		X		
L2W60Fg6	X			X	X		
H4W10Fg6		X	X		X		
H4W60Fg6		X		X	X		
L2W10Fg814	X		X			X	
L2W60Fg814	X			X		X	
H4W10Fg814		X	X			X	
H4W60Fg814		X		X		X	
L2W10Tg814	X		X			X	
L2W60Tg814	X			X		X	
H4W10Tg814		X	X			X	
H4W60Tg814		X		X		X	
L2W10Fg17-	X		X				X
L2W60Fg17-	X			X			X
H4W10Fg17-		X	X				X
H4W60Fg17-		X		X			X

Notes:

Mare simulants are 90% basalt, 10% anothosite; PAN Highlands are 10% basalt, 90% anorthosite.

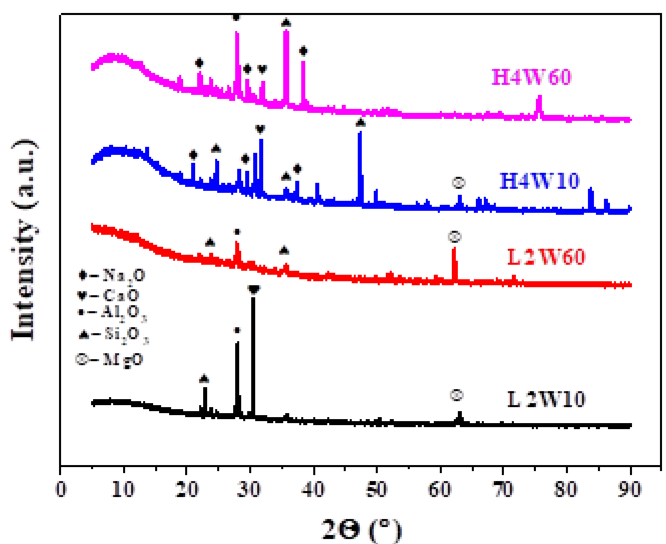
Agglutinates are rock glass (anthropogenic obsidian).

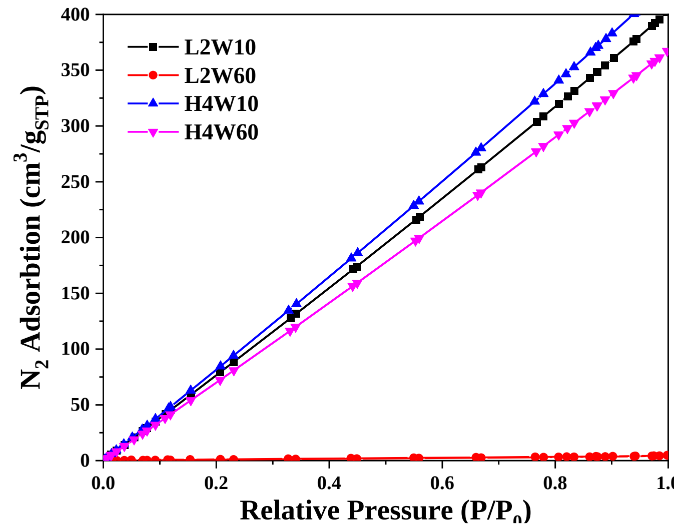
500-250 micron = Mesh #60; 250-105 micron = Mesh #80 to #140; 105 micron & finer = Mesh #170 & finer.

"F" simulants have 10% added iron. "T" simulants have 10% added ilmenite.

"g" (grain-size Mesh # sans 0) in label is given by MS&T for ease of data entry.

Initial testing results of samples





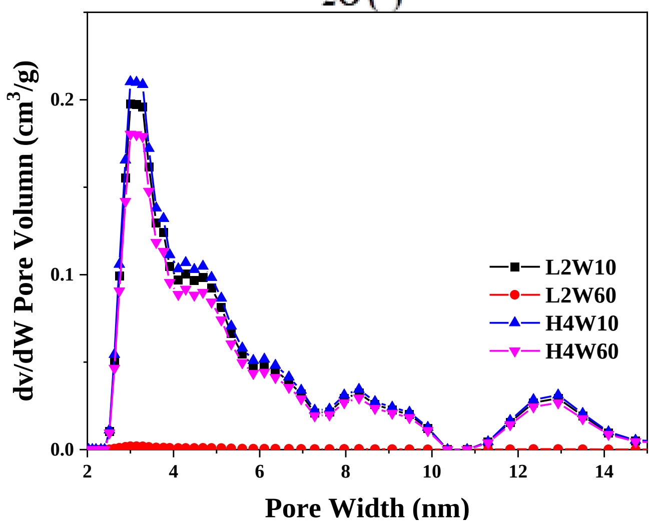
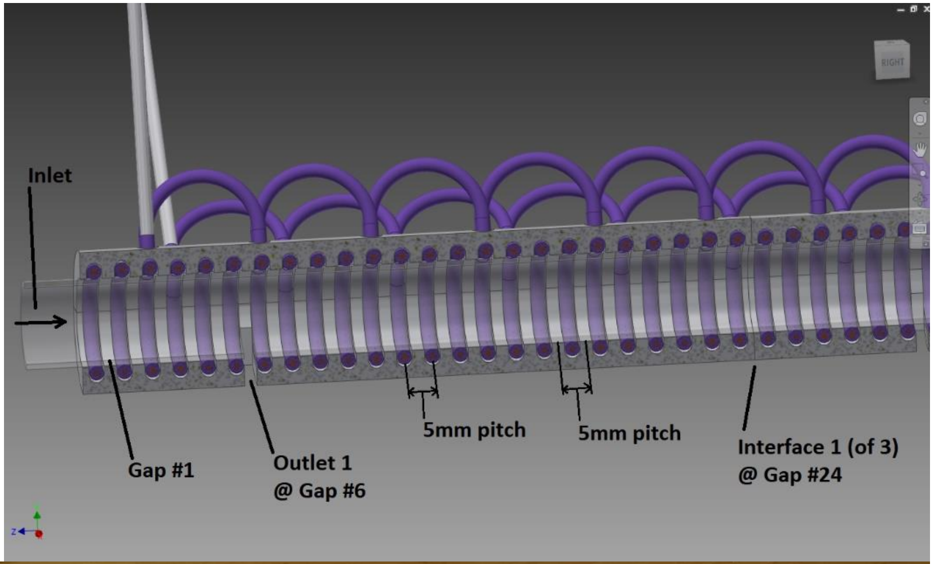
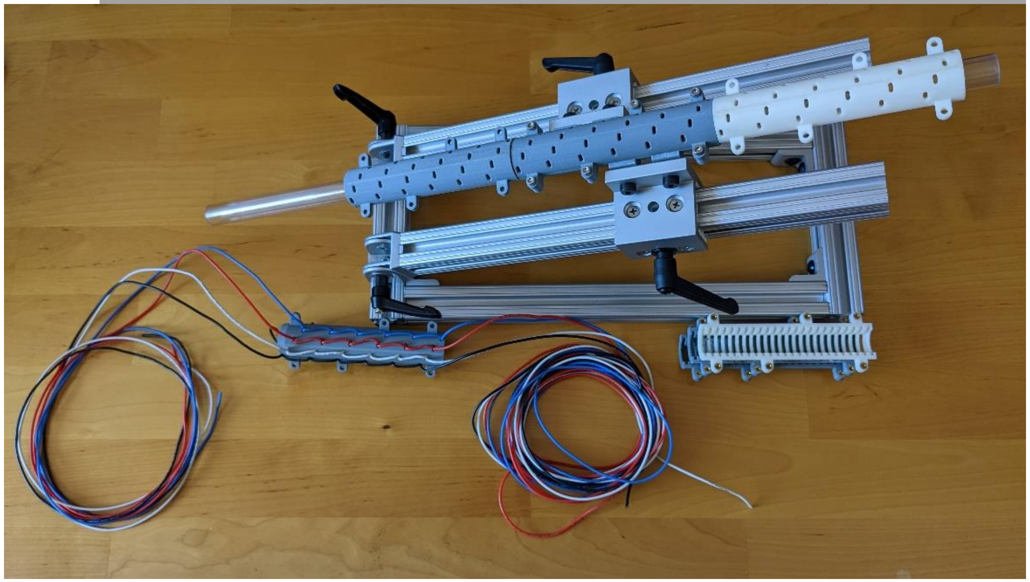


Fig. 1. Characterization of raw simulant samples.
Top Left: XRD patterns.
Top Right: N_2 physisorption isotherms.
Bottom: pore size distribution profiles of the raw simulants.

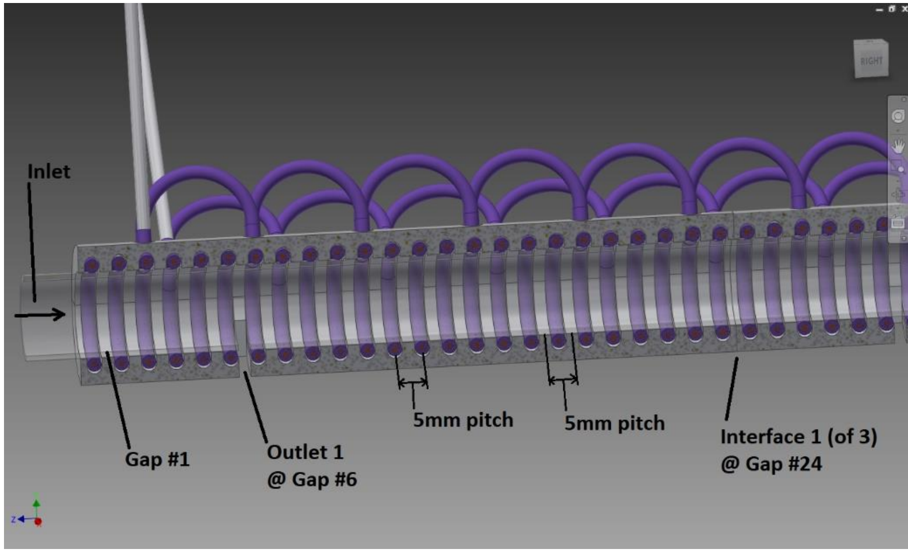
Task 2: Design/Fab of Electrostatic Sieve Subsystem

Fig. 2. Overview of the design/fab of electrostatic sieve prototype.





Design of Electrostatic Sieve Prototype



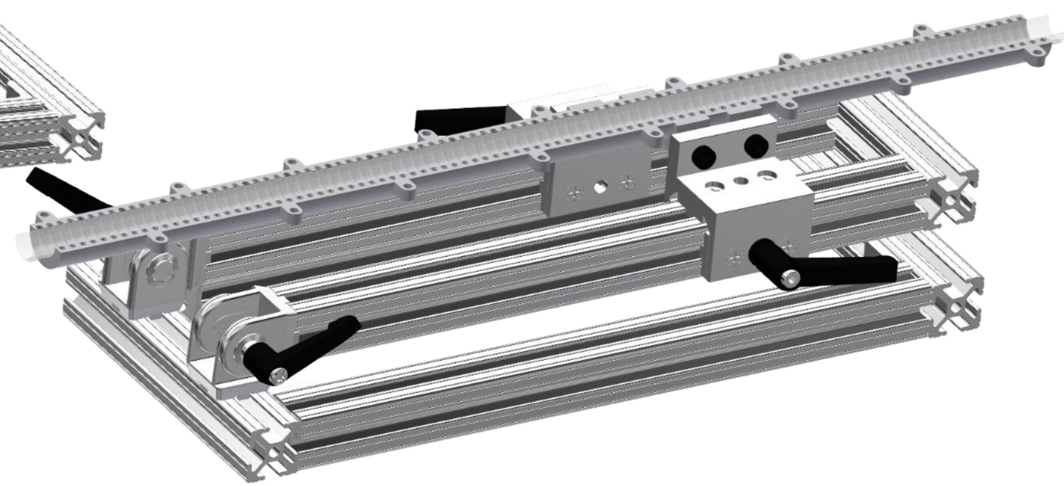


Fig. 3. CAD rendering of the prototype

Fabrication of Electrostatic Sieve Prototype

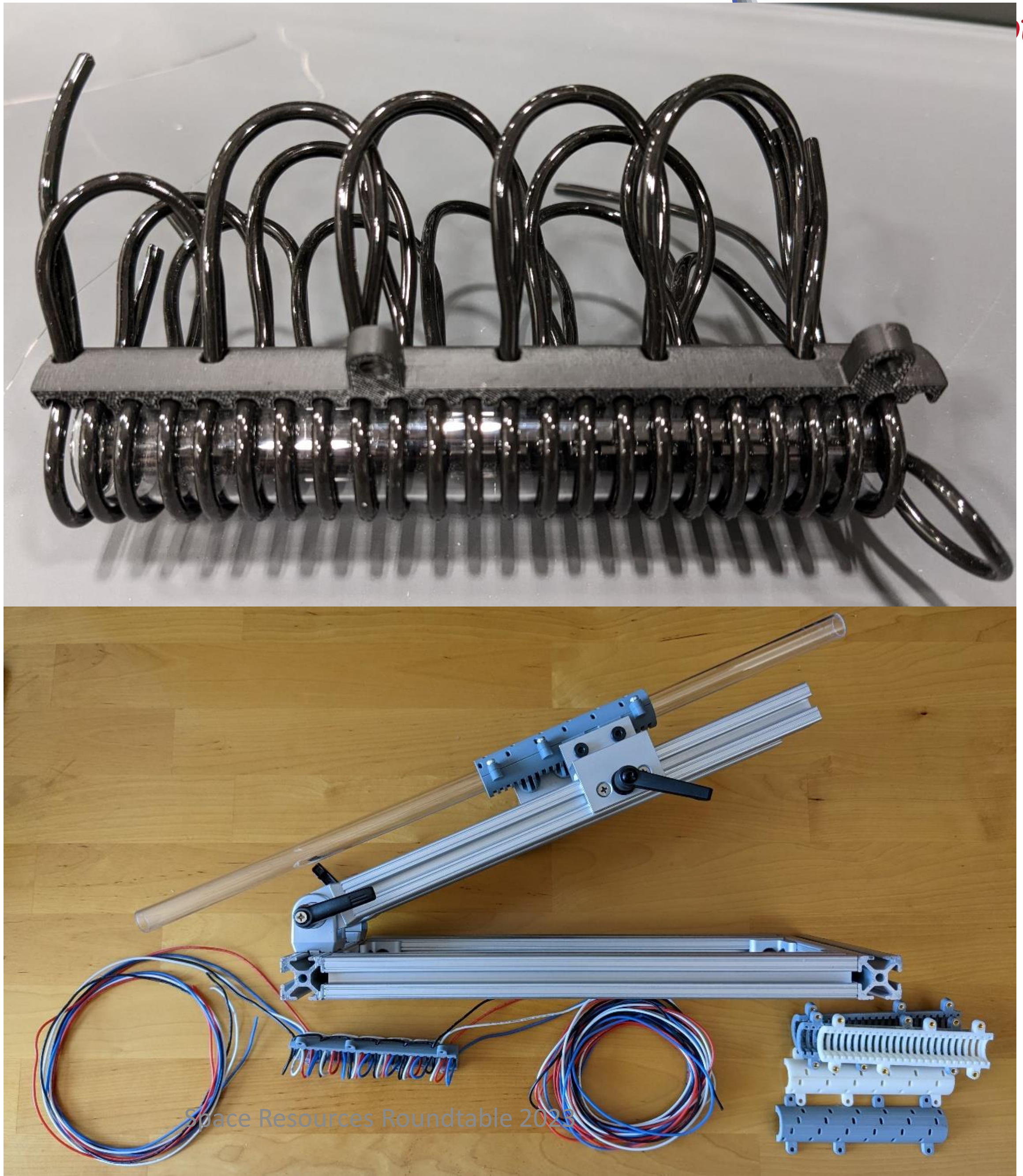
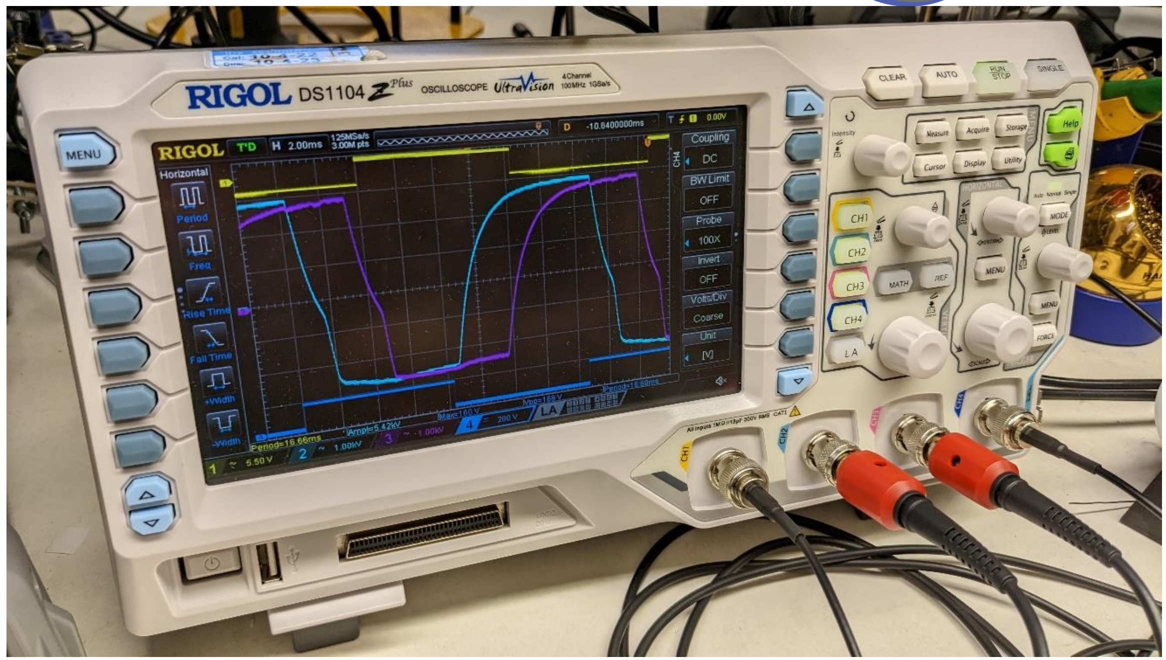
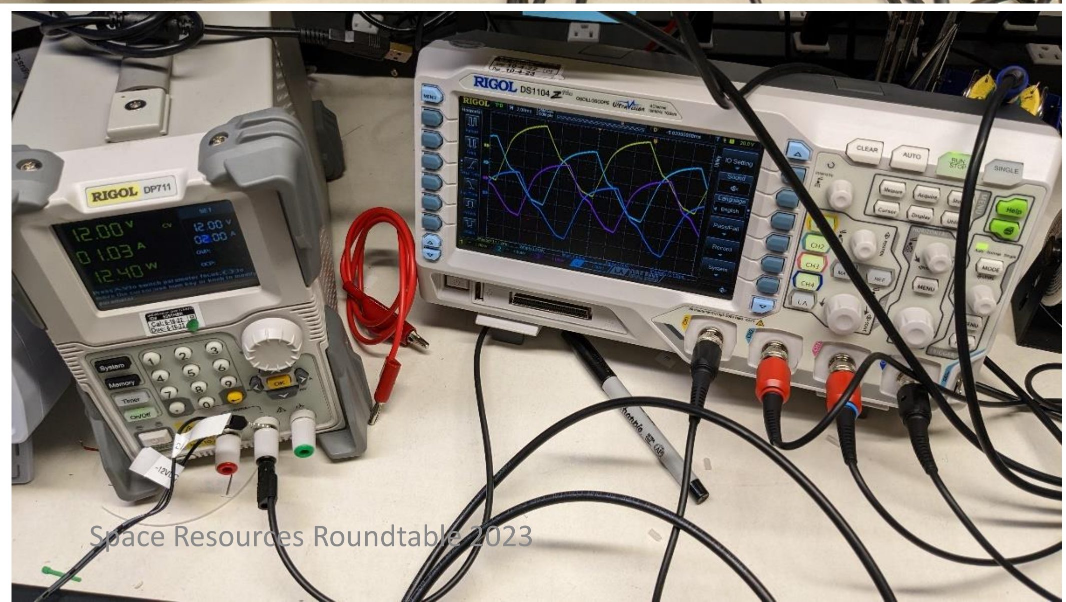


Fig. 4. Prototype as built.

Misc. of Electrostatic Sieve Prototype

Fig. 5. Checking out the power supply and output for traveling-wave pattern at HBR.





Prototype in S&T Glovebox

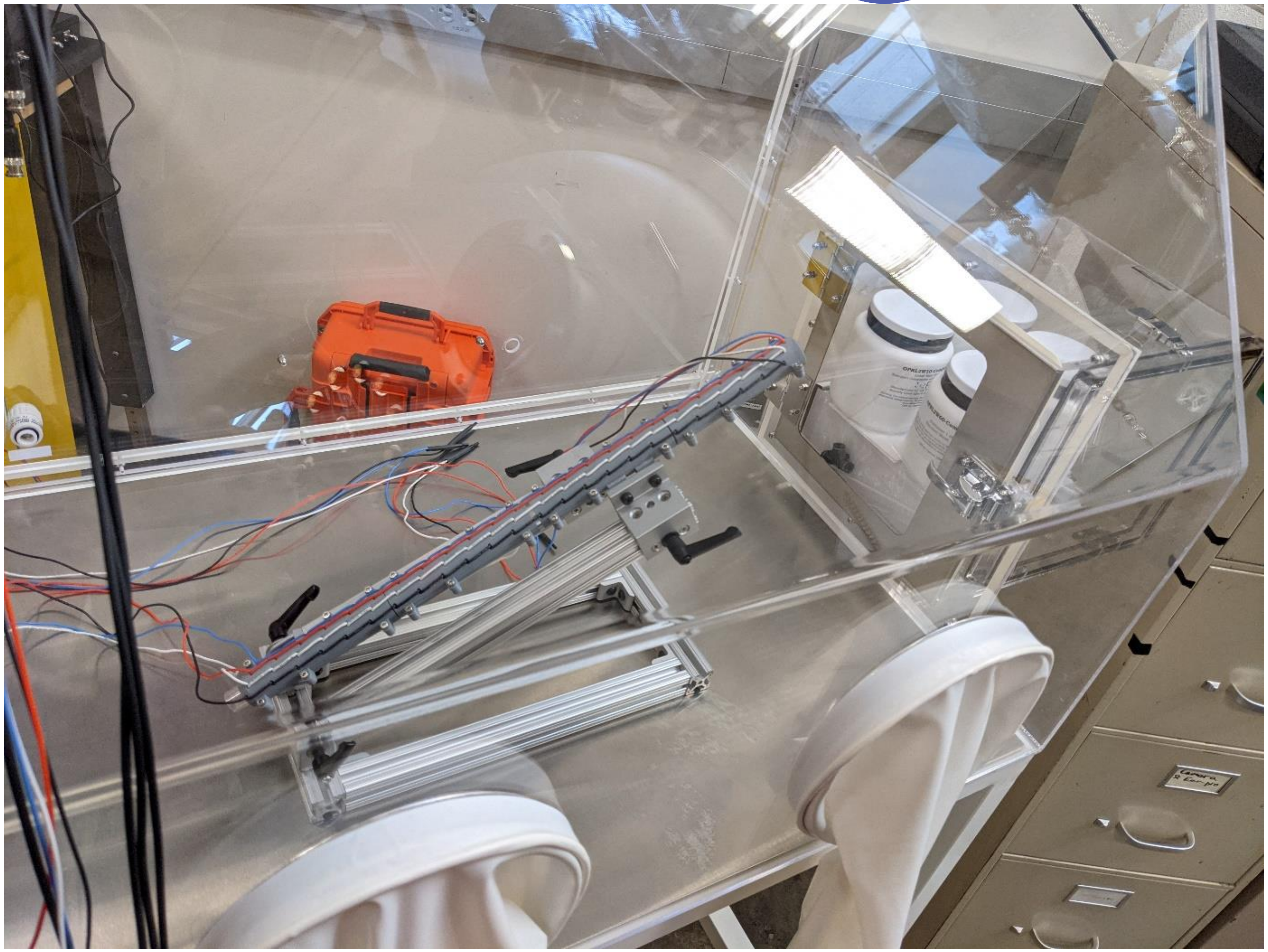
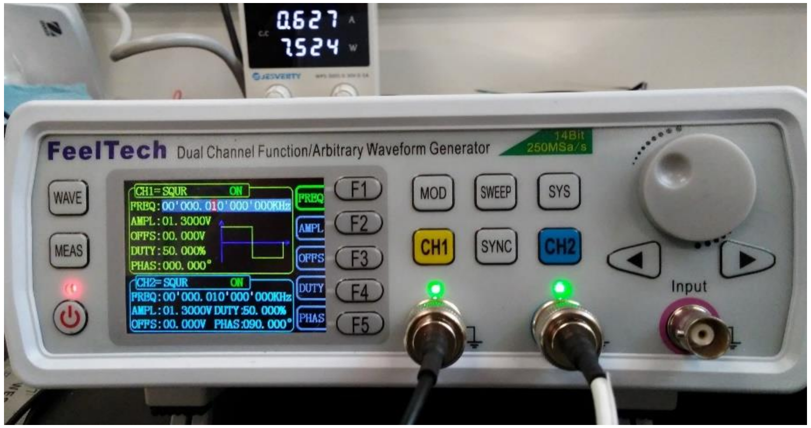
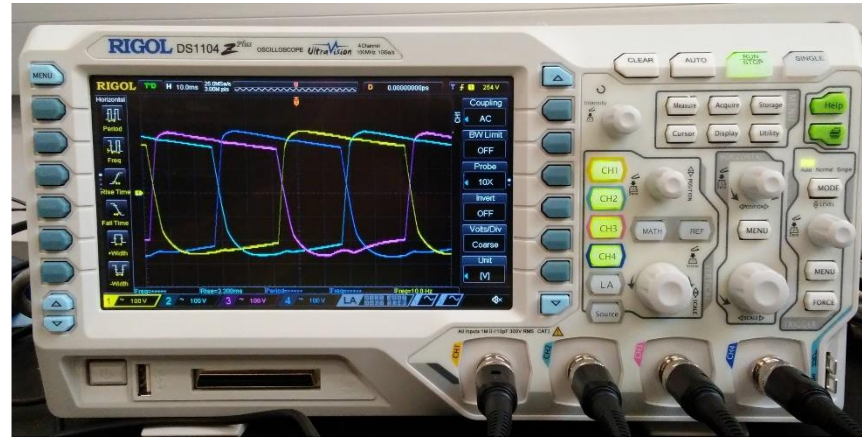


Fig. 6. Prototype in the glovebox.

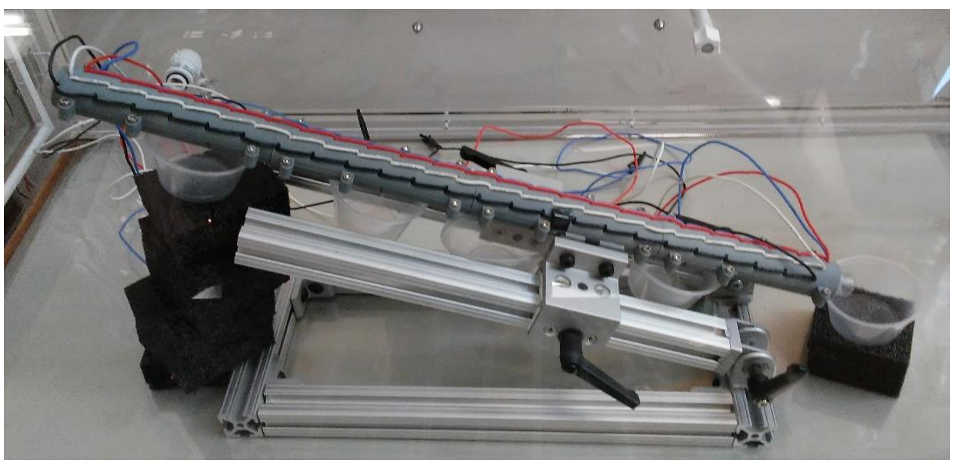
Task 3: Electrostatic Sieve Testing (Glovebox)



Waveform generator # 1 operating at 10 Hz, 1.3 Amps, Square wave, 50% duty cycle.



The 4-phase oscilloscope with four channels offset 90° and signal strength of 256V. Waveforms staggered at 0°, 90°, 180°, and 270°.

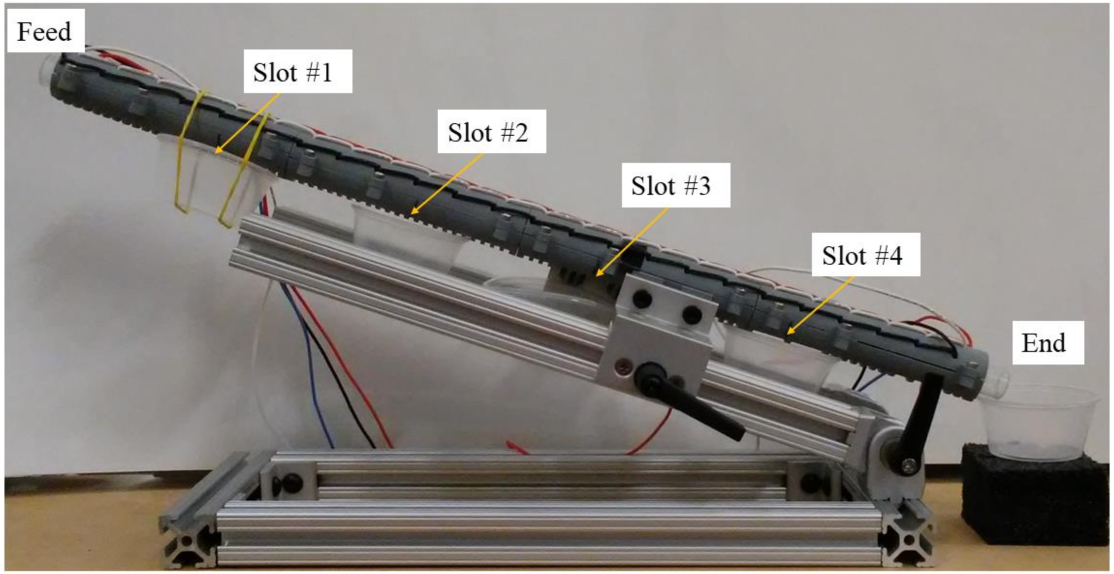


Electrostatic sieve tube with collection cups every 10 cm.

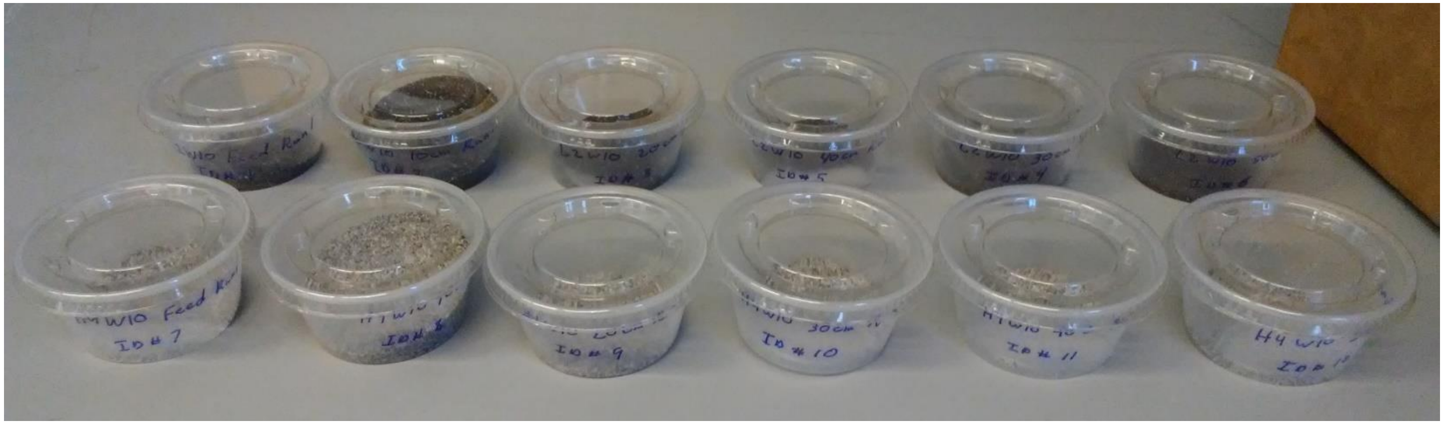
Fig. 7. Checking out power control and setup in the glovebox at MST.

Electrostatic Sieve Testing Config.

Fig. 8. Testing configuration.



Electrostatic sieve slots. Sieve set-up for -20° run.



Samples collected from first run for L2W10 and H4W10. Labeled and delivered to Chemical Engineering for analysis.

Electrostatic Sieve Testing – A video

Electrostatic Sieve Testing - Analysis

- Microtrac S3500 particle analyzer (MS&T McNutt Room 264).

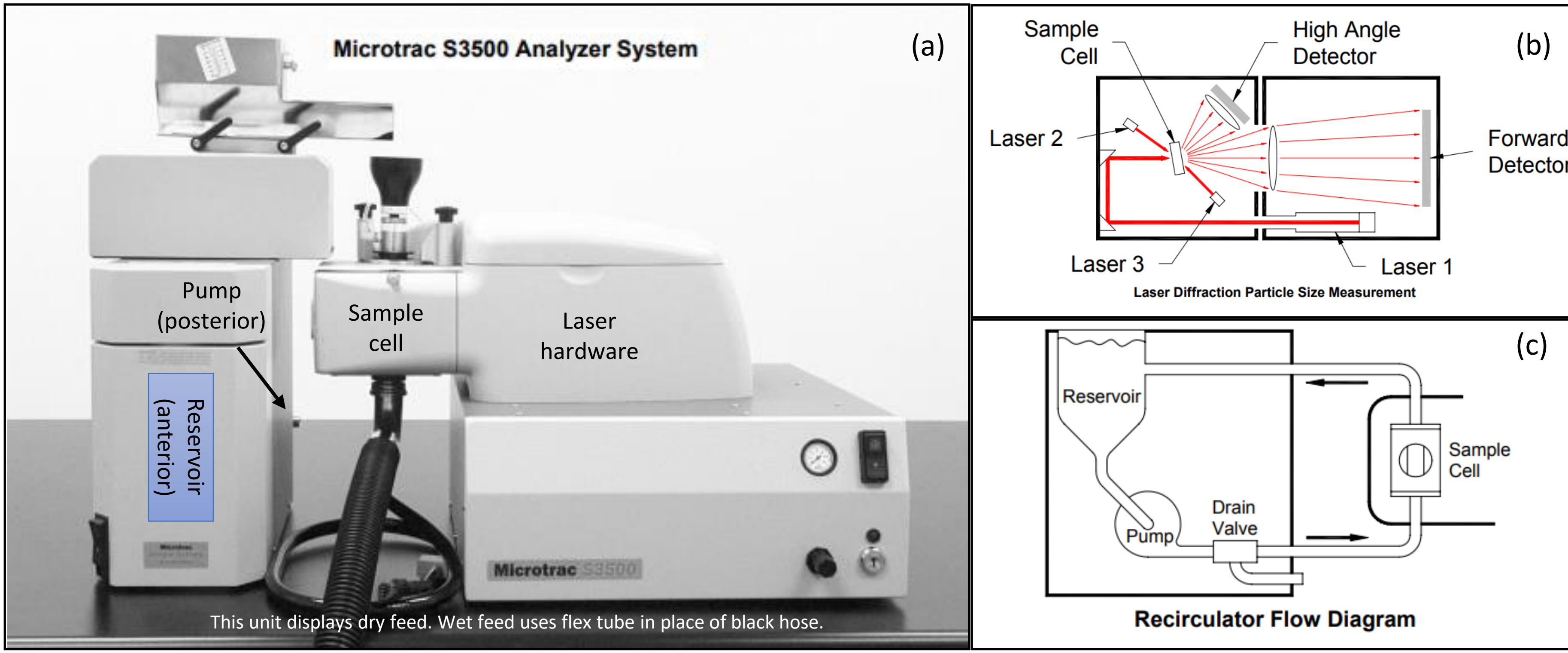


Fig. 9. Microtrac S3500 particle analyzer and schematic.

Flowchart of Electrostatic Sieve Testing

Space Resources Roundtable

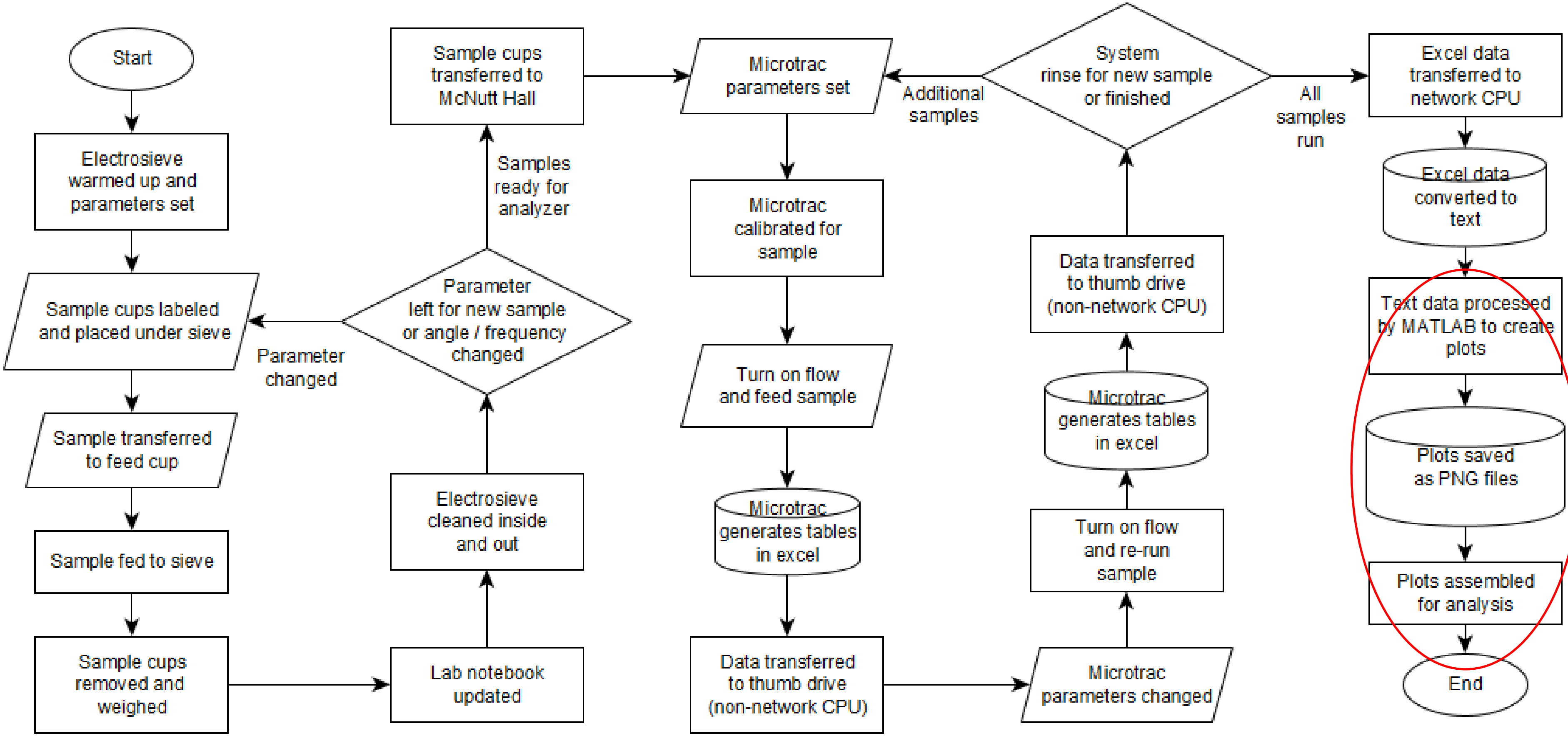


Fig. 10. Flowchart of the testing process. Red oval shows data processing steps.

Missouri S&T

An example of size separation analysis

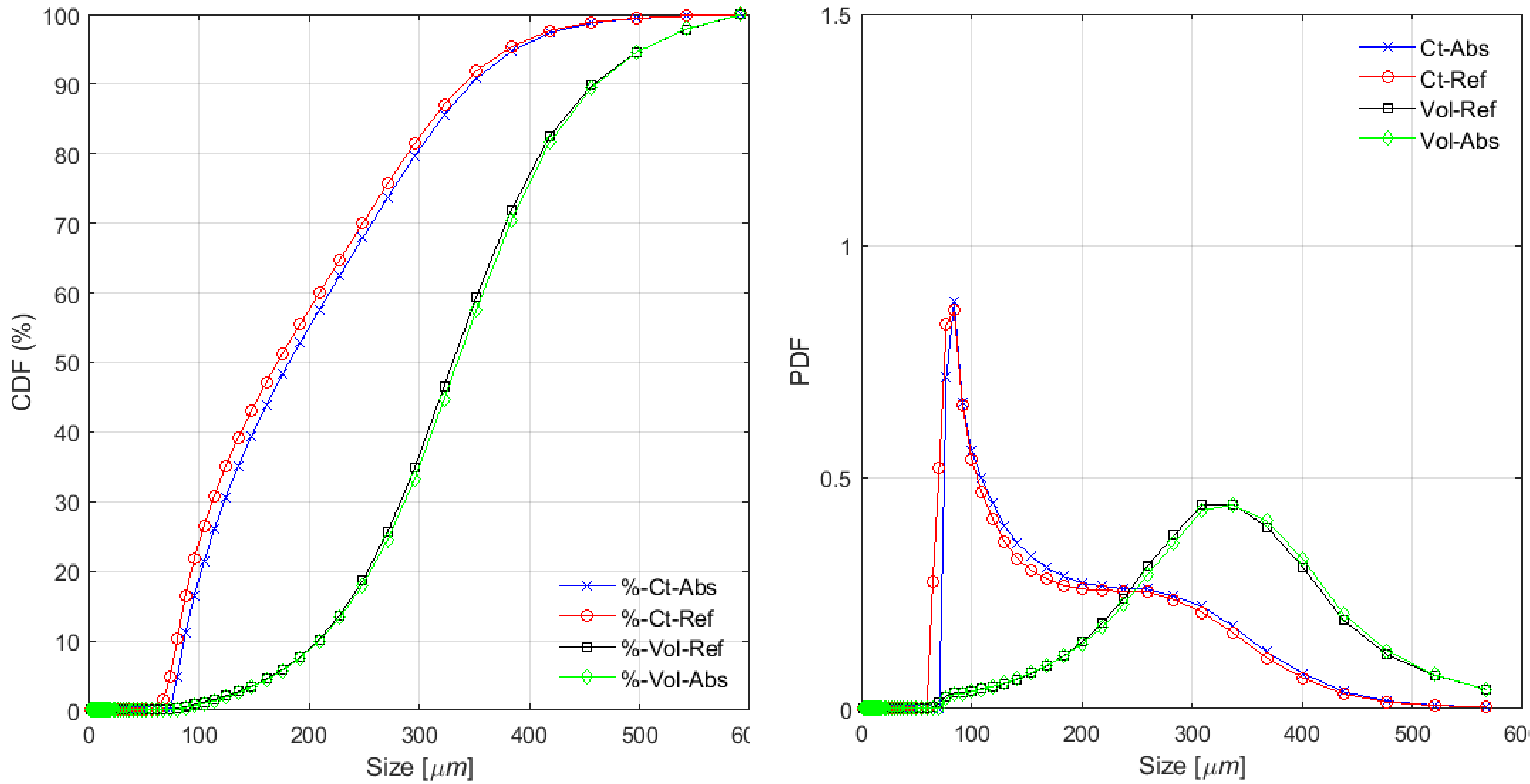


Fig. 11. An example of size separation analysis - particle size cumulative and probability density function curves for L2W60 feed stock.

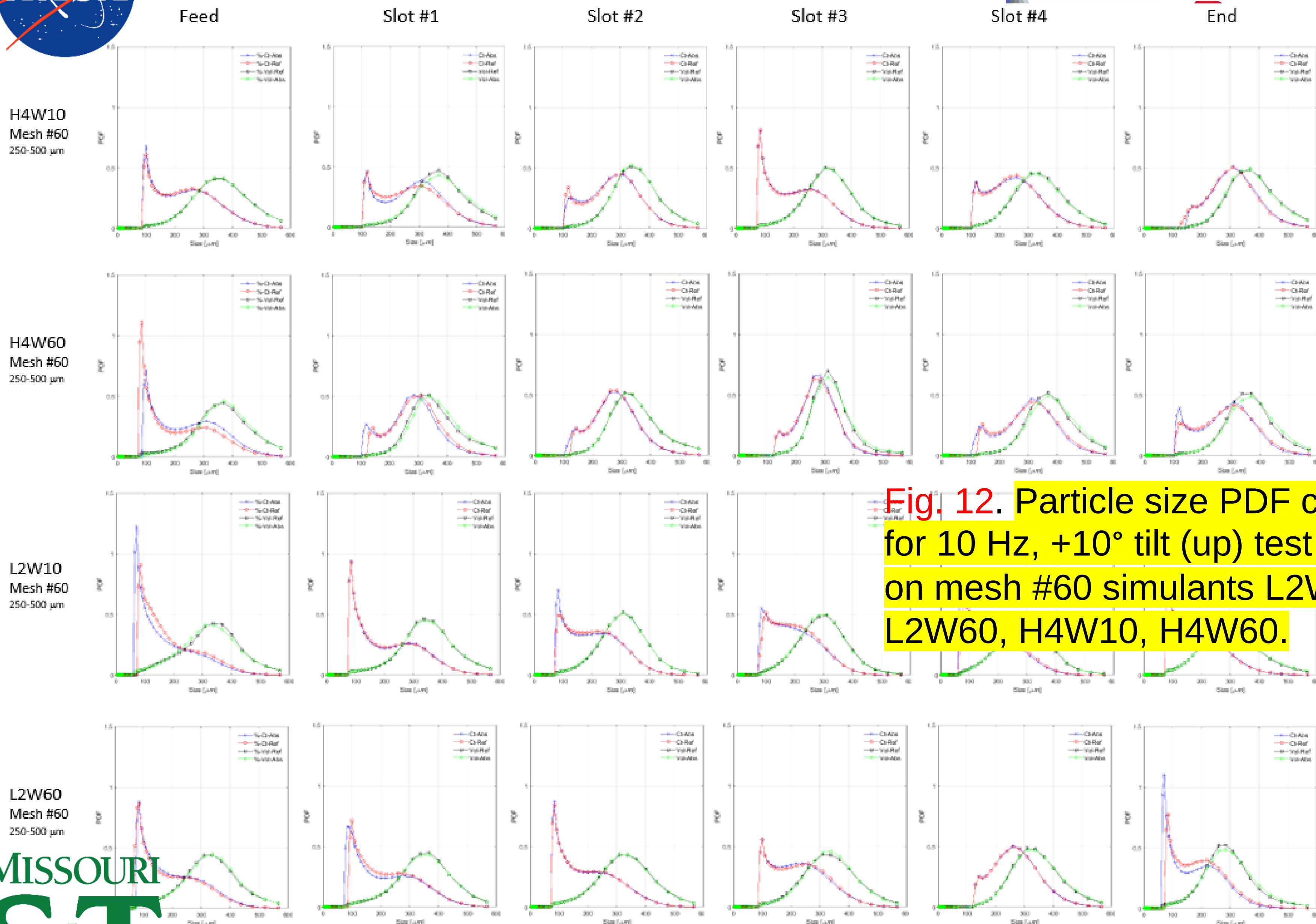


Fig. 12. Particle size PDF curves for 10 Hz, +10° tilt (up) test run on mesh #60 simulants L2W10, L2W60, H4W10, H4W60.

H4W10

Mesh #60

250-500 µm

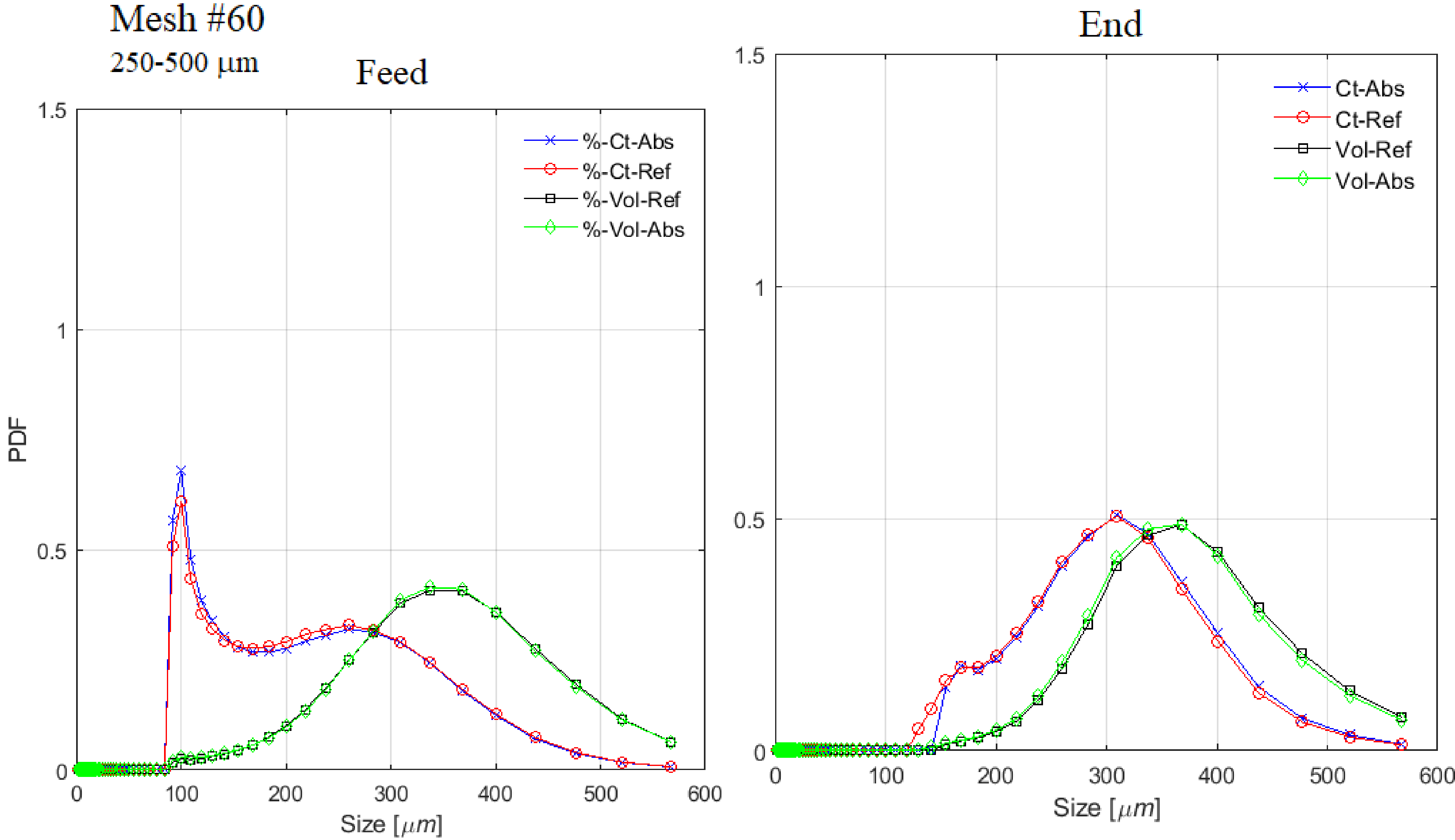


Fig. 13. Zoom in for a part of Fig. 12.

Compositional analysis (Task 5)

Table 3. Compositional analysis of separated samples (XPS)

Samples	Cl2p(%)	O1s(%)	Si2p(%)	Al2p(%)	C1s(%)	Ca2p(%)	Na1s(%)	Mg1s(%)	Fe2p(%)	Ti(%)
H4W60 S0	-	54.23	16.6	12.82	9.59	3.48	1.35	0.7	1.22	-
H4W60 S3	0.15	53.56	15.97	12.12	12.23	2.73	1.69	0.94	0.61	-
H4W10 S0	0.38	56.24	17.46	12.65	8.67	1.8	1.11	0.62	0.96	-
H4W10 S3	0.19	53.18	15.86	12.39	12.61	2.05	1.73	0.84	1.15	-
H4W10 814 S0	-	49.94	15.66	11.58	17.53	3.01	1.14	0.58	0.56	-
H4W10 814 S3	-	53.06	15.59	11.7	13.8	2.99	1.52	-	0.82	-
L2W10 S0	-	56.7	16.94	6.64	9.93	2.83	1.86	1.95	2.53	0.6
L2W10 S3	0.2	61.35	19.3	-	10.05	2.62	2.7	1.41	-	0.52
L2W60 S0	-	57.27	17.77	12.85	5.52	2.84	1.99	0.78	0.98	-
L2W60 S3	-	49.24	15.2	6.27	20.94	2.55	1.88	1.38	1.72	0.62
H4W60 814 S0	-	50.76	16.5	12.1	16.52	2.16	1.34	0.49	0.14	-
H4W60 814S3	-	52.01	16.12	11.25	14.74	3.14	1.42	0.53	0.79	-

S0 is the ‘feed’ sample and S3 is the third slot along the separator.

Exploring a large parameter space

Currently we are exploring a large parameter space, varying:

- Frequency of duty cycle of the 4-phased electrodes,
- Tilt angle of the sieve,
- Samples,
- Plus 6 cups of collected samples for each configuration
- …
- And that's … (next page)

Exploring a large parameter space

SPACE RESOURCES ROUNDTABLE

10Hz, -20°				30Hz, -20°				50Hz, -20°				70Hz, -20°				10Hz, -15°				30Hz, -15°				50Hz, -15°				70Hz, -15°			
Sample	Angle (deg)	Freq. (Hz)	Slot	Sample	Angle (deg)	Freq. (Hz)	Slot	Sample	Angle (deg)	Freq. (Hz)	Slot	Sample	Angle (deg)	Freq. (Hz)	Slot	Sample	Angle (deg)	Freq. (Hz)	Slot	Sample	Angle (deg)	Freq. (Hz)	Slot	Sample	Angle (deg)	Freq. (Hz)	Slot	Sample	Angle (deg)	Freq. (Hz)	Slot
2w10g6	-20	10	feed 1 2 3 4 end	2w10g6	-20	30	feed 1 2 3 4 end	2w10g6	-20	50	feed 1 2 3 4 end	2w10g6	-20	70	feed 1 2 3 4 end	2w10g6	-15	10	feed 1 2 3 4 end	2w10g6	-15	30	feed 1 2 3 4 end	2w10g6	-15	[illegible]	feed 1 [illegible]	[illegible]	[illegible]	[illegible]	feed 1 [illegible]
2w60g6	-20	10	feed 1 2 3 4 end	2w60g6	-20	30	feed 1 2 3 4 end	2w60g6	-20	50	feed 1 2 3 4 end	2w60g6	-20	70	feed 1 2 3 4 end	2w60g6	-15	10	feed 1 2 3 4 end	2w60g6	-15	30	feed 1 2 3 4 end	2w60g6	-15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
h4w10g6	-20	10	feed 1 2 3 4 end	h4w10g6	-20	30	feed 1 2 3 4 end	h4w10g6	-20	50	feed 1 2 3 4 end	h4w10g6	-20	70	feed 1 2 3 4 end	h4w10g6	-15	10	feed 1 2 3 4 end	h4w10g6	-15	30	feed 1 2 3 4 end	h4w10g6	-15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
h4w60g6	-20	10	feed 1 2 3 4 end	h4w60g6	-20	30	feed 1 2 3 4 end	h4w60g6	-20	50	feed 1 2 3 4 end	h4w60g6	-20	70	feed 1 2 3 4 end	h4w60g6	-15	10	feed 1 2 3 4 end	h4w60g6	-15	30	feed 1 2 3 4 end	h4w60g6	-15	50	1 2 3 4 end	h4w60g6	-15	70	1 2 3 4 end
2w10g814	-20	10	feed 1 2 3 4 end	2w10g814	-20	30	feed 1 2 3 4 end	2w10g814	-20	50	feed 1 2 3 4 end	2w10g814	-20	70	feed 1 2 3 4 end	2w10g814	-15	10	feed 1 2 3 4 end	2w10g814	-15	30	feed 1 2 3 4 end	2w10g814	-15	50	feed 1 2 3 4 end	2w10g814	-15	70	feed 1 2 3 4 end
2w60g814	-20	10	feed 1 2 3 4 end	2w60g814	-20	30	feed 1 2 3 4 end	2w60g814	-20	50	feed 1 2 3 4 end	2w60g814	-20	70	feed 1 2 3 4 end	2w60g814	-15	10	feed 1 2 3 4 end	2w60g814	-15	30	feed 1 2 3 4 end	2w60g814	-15	50	feed 1 2 3 4 end	2w60g814	-15	70	feed 1 2 3 4 end
h4w10g814	-20	10	feed 1 2 3 4 end	h4w10g814	-20	30	feed 1 2 3 4 end	h4w10g814	-20	50	feed 1 2 3 4 end	h4w10g814	-20	70	feed 1 2 3 4 end	h4w10g814	-15	10	feed 1 2 3 4 end	h4w10g814	-15	30	feed 1 2 3 4 end	h4w10g814	-15	50	feed 1 2 3 4 end	h4w10g814	-15	70	feed 1 2 3 4 end
h4w60g814	-20	10	feed 1 2 3 4 end	h4w60g814	-20	30	feed 1 2 3 4 end	h4w60g814	-20	50	feed 1 2 3 4 end	h4w60g814	-20	70	feed 1 2 3 4 end	h4w60g814	-15	10	feed 1 2 3 4 end	h4w60g814	-15	30	feed 1 2 3 4 end	h4w60g814	-15	50	feed 1 2 3 4 end	h4w60g814	-15	70	feed 1 2 3 4 end
2w10g17-	-20	10	feed 1 2 3 4 end	2w10g17-	-20	30	feed 1 2 3 4 end	2w10g17-	-20	50	feed 1 2 3 4 end	2w10g17-	-20	70	feed 1 2 3 4 end	2w10g17-	-15	10	feed 1 2 3 4 end	2w10g17-	-15	30	feed 1 2 3 4 end	2w10g17-	-15	50	feed 1 2 3 4 end	2w10g17-	-15	70	feed 1 2 3 4 end
2w60g17-	-20	10	feed 1 2 3 4 end	#10	-20	30	feed 1 2 3 4 end	#10	-20	50	feed 1 2 3 4 end	#10	-20	70	feed 1 2 3 4 end	#10	-15	10	feed 1 2 3 4 end	#10	-15	30	feed 1 2 3 4 end	#10	-15	50	feed 1 2 3 4 end	#10	-15	70	feed 1 2 3 4 end
h4w10g17-	-20	10	feed 1 2 3 4 end	#10	-20	30	feed 1 2 3 4 end	#10	-20	50	feed 1 2 3 4 end	#10	-20	70	feed 1 2 3 4 end	#10	-15	10	feed 1 2 3 4 end	#10	-15	30	feed 1 2 3 4 end	#10	-15	50	feed 1 2 3 4 end	#10	-15	70	feed 1 2 3 4 end
h4w60g17-	-20	10	feed 1 2 3 4 end	#10	-20	30	feed 1 2 3 4 end	#10	-20	50	feed 1 2 3 4 end	#10	-20	70	feed 1 2 3 4 end	#10	-15	10	feed 1 2 3 4 end	#10	-15	30	feed 1 2 3 4 end	#10	-15	50	feed 1 2 3 4 end	#10	-15	70	feed 1 2 3 4 end

= Completed sample run   = No simulant movement

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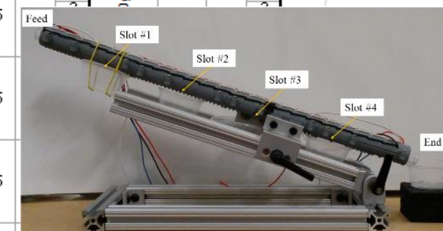


Estimated 384 test runs - >2,300 samples/cups for particle analyzer runs!

Table 4. Part of the tabulated parameter space.

MISSOURI S&T

Task 3: Electrostatic Sieve Modeling

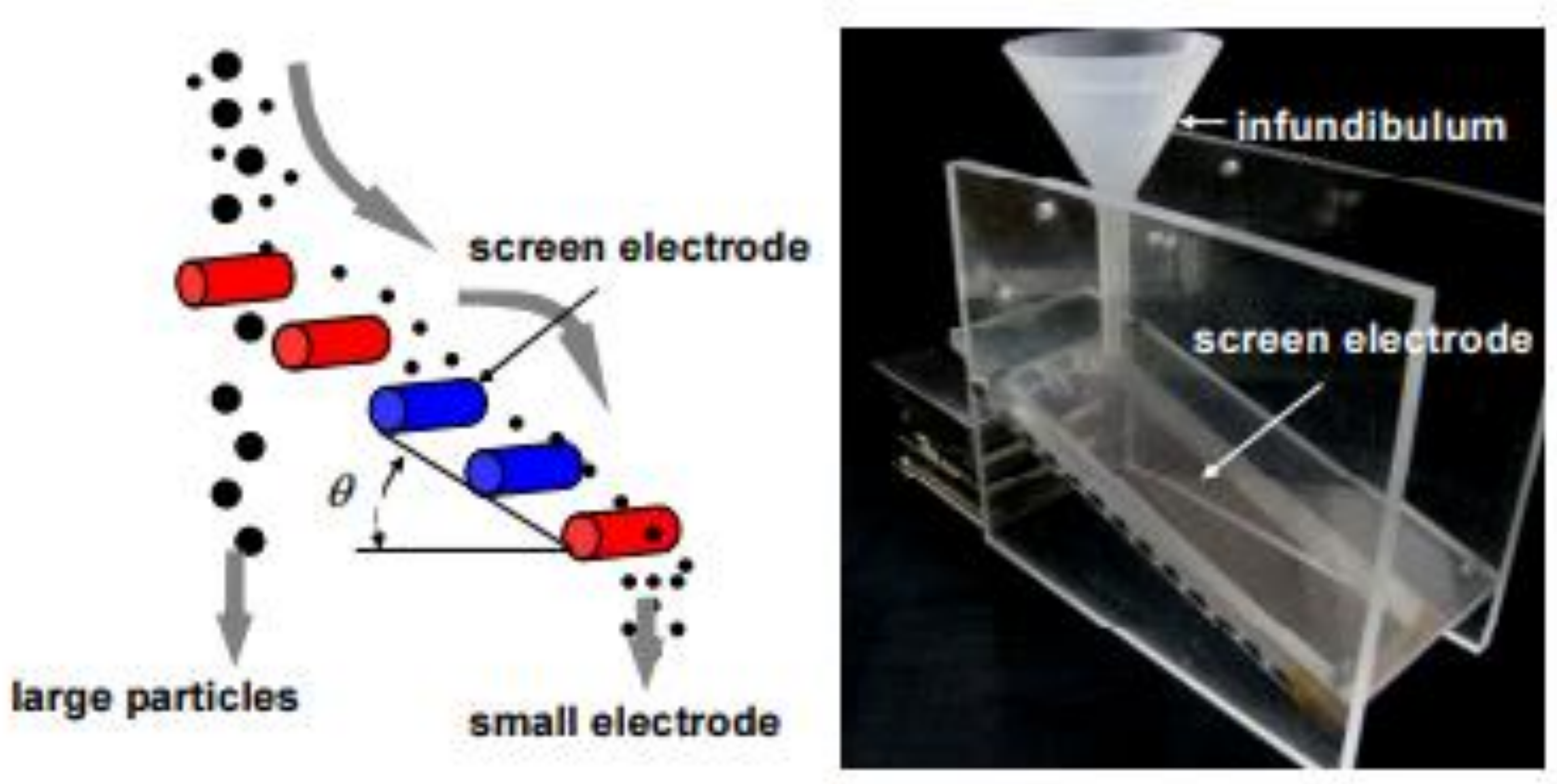


Fig. 14. Image from Kawamoto, H. and Adachi, M. (2014). “Electrostatic particle-size classification of lunar regolith for in-situ resource utilization."

A particle-kinetic approach

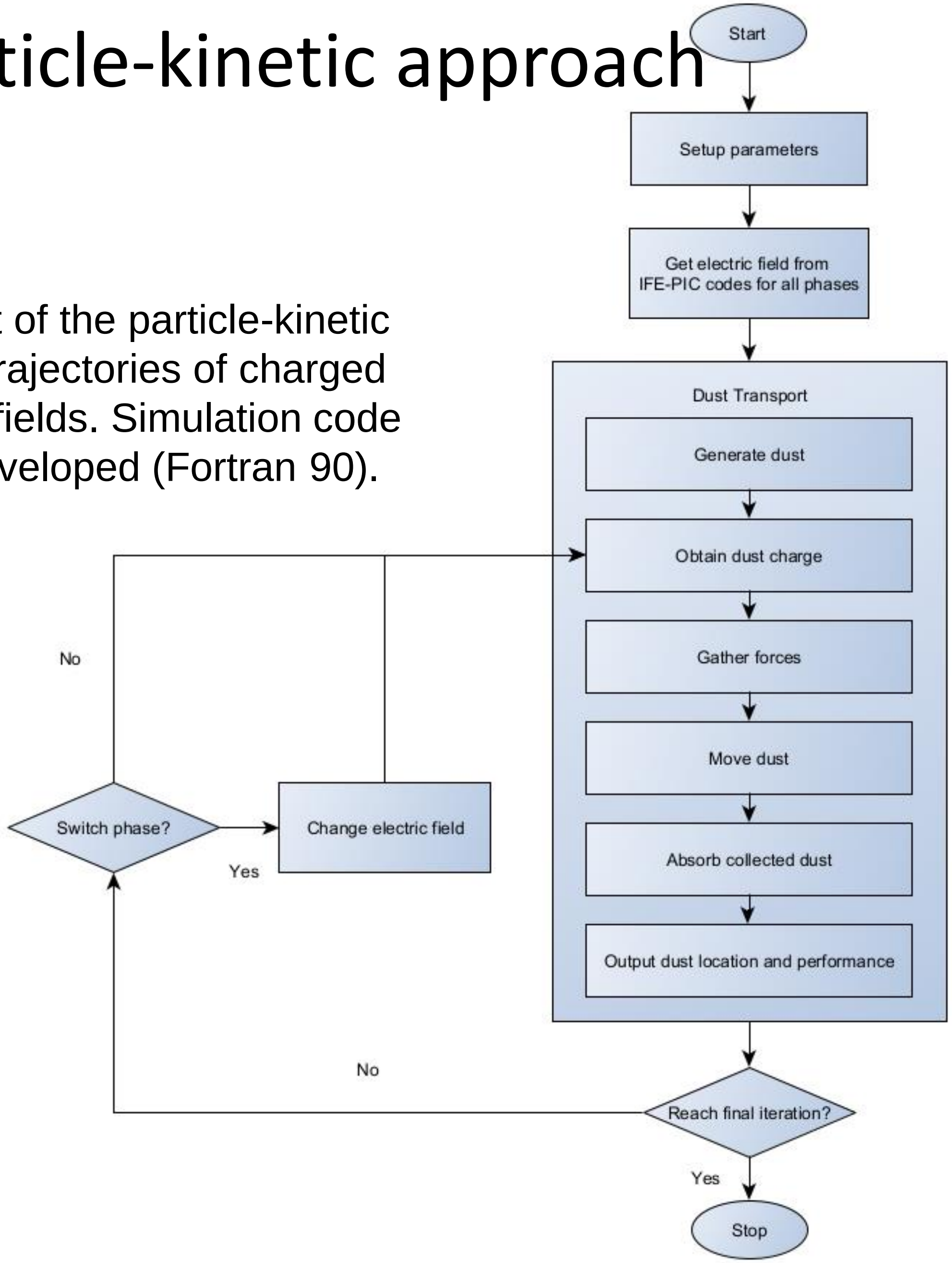
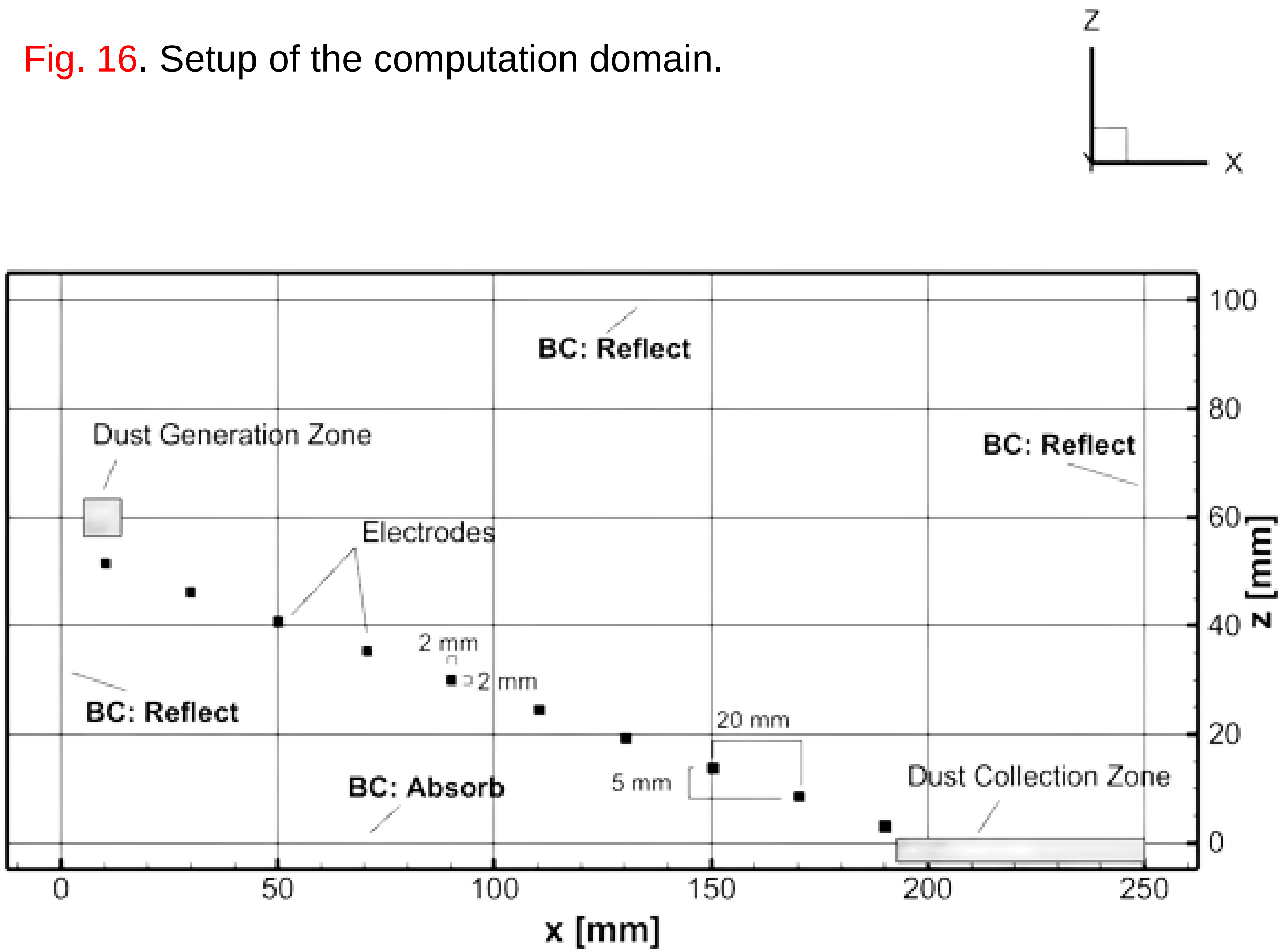


Fig. 15. A flow chart of the particle-kinetic approach tracking trajectories of charged particles in electric fields. Simulation code suite is in-house developed (Fortran 90).

Computation domain setup

Fig. 16. Setup of the computation domain.



Sample the particle size distribution

- Lunar particles follow a logarithmic normal distribution
- Using the accept-reject method, specific particle distributions can be modeled.
- The simulated particle size distribution (PSD) is then loaded into the sieve model.

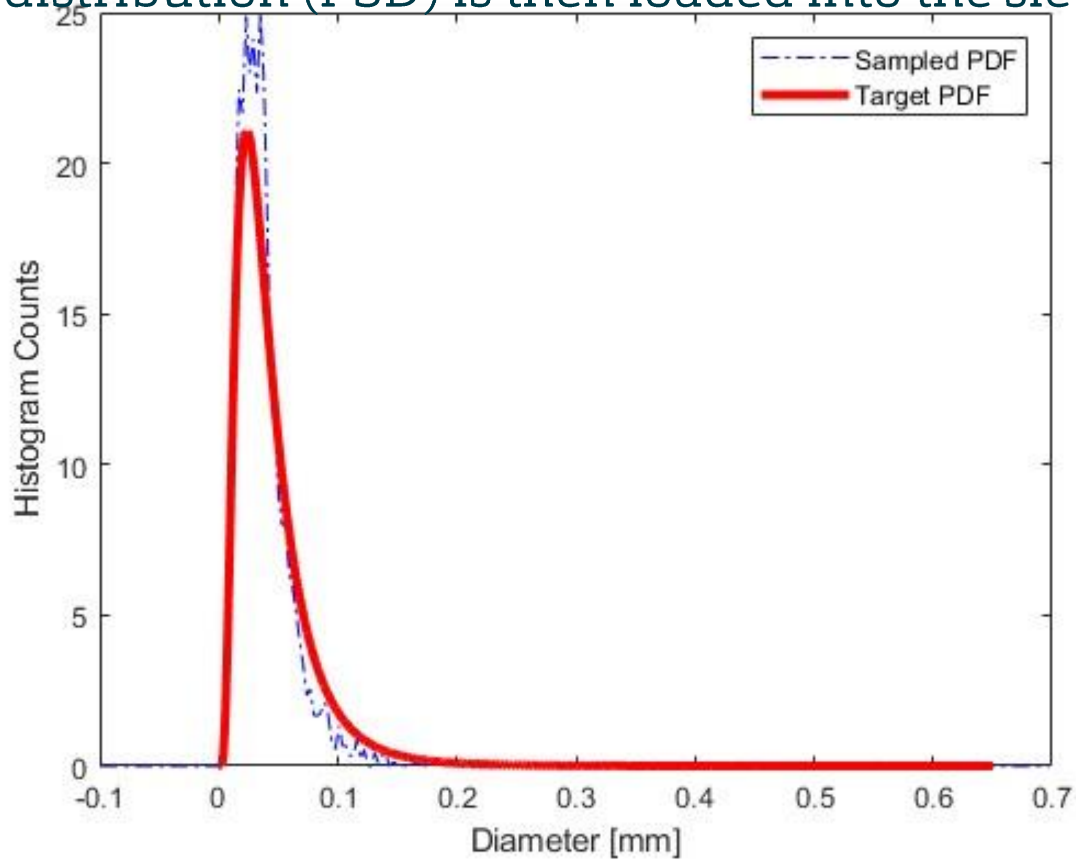
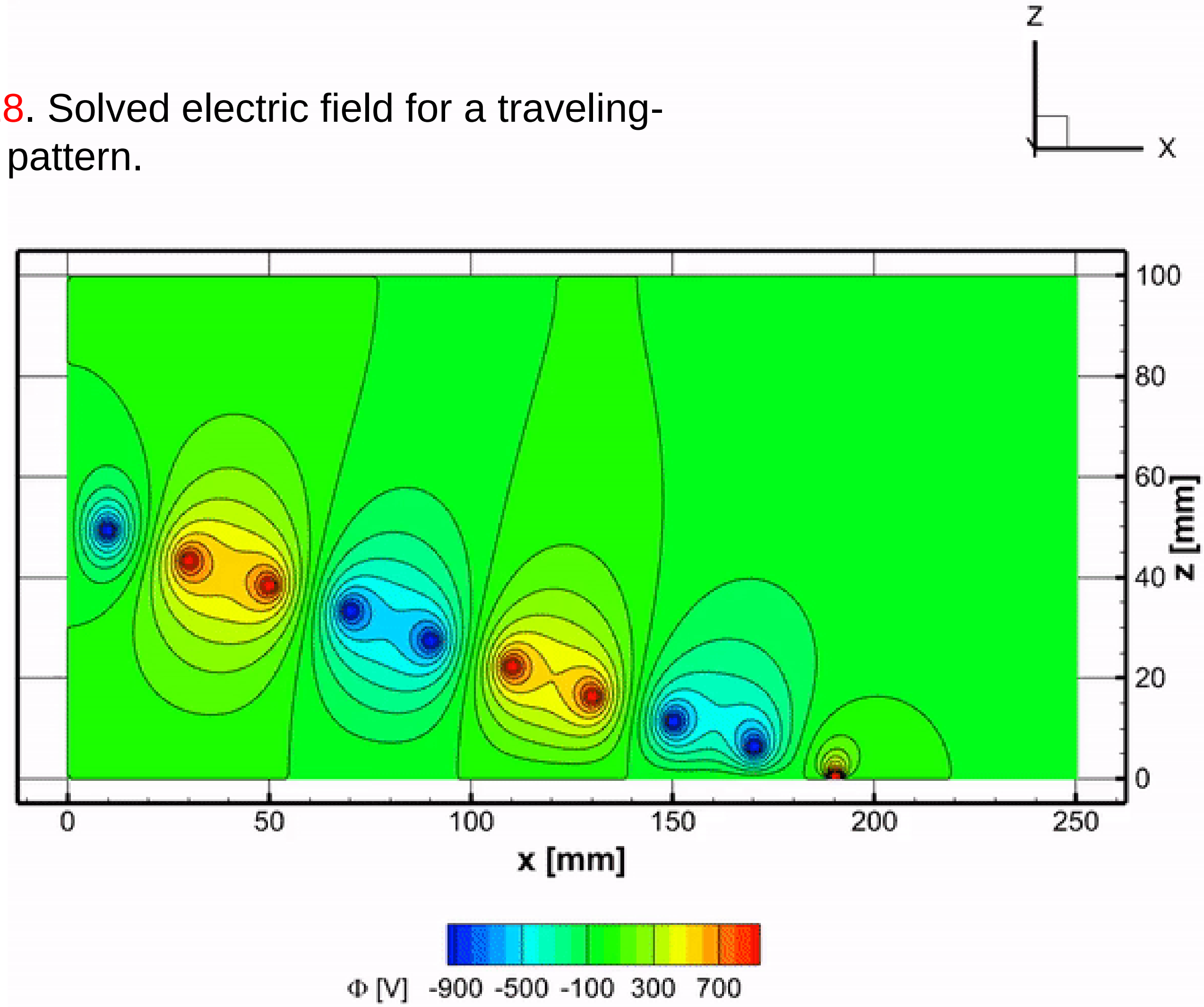


Fig. 17. Sampling the PSD curve.

Solving for electric potential - Animation

Fig. 18. Solved electric field for a traveling-wave pattern.



Particle trajectories in sieve - Animation

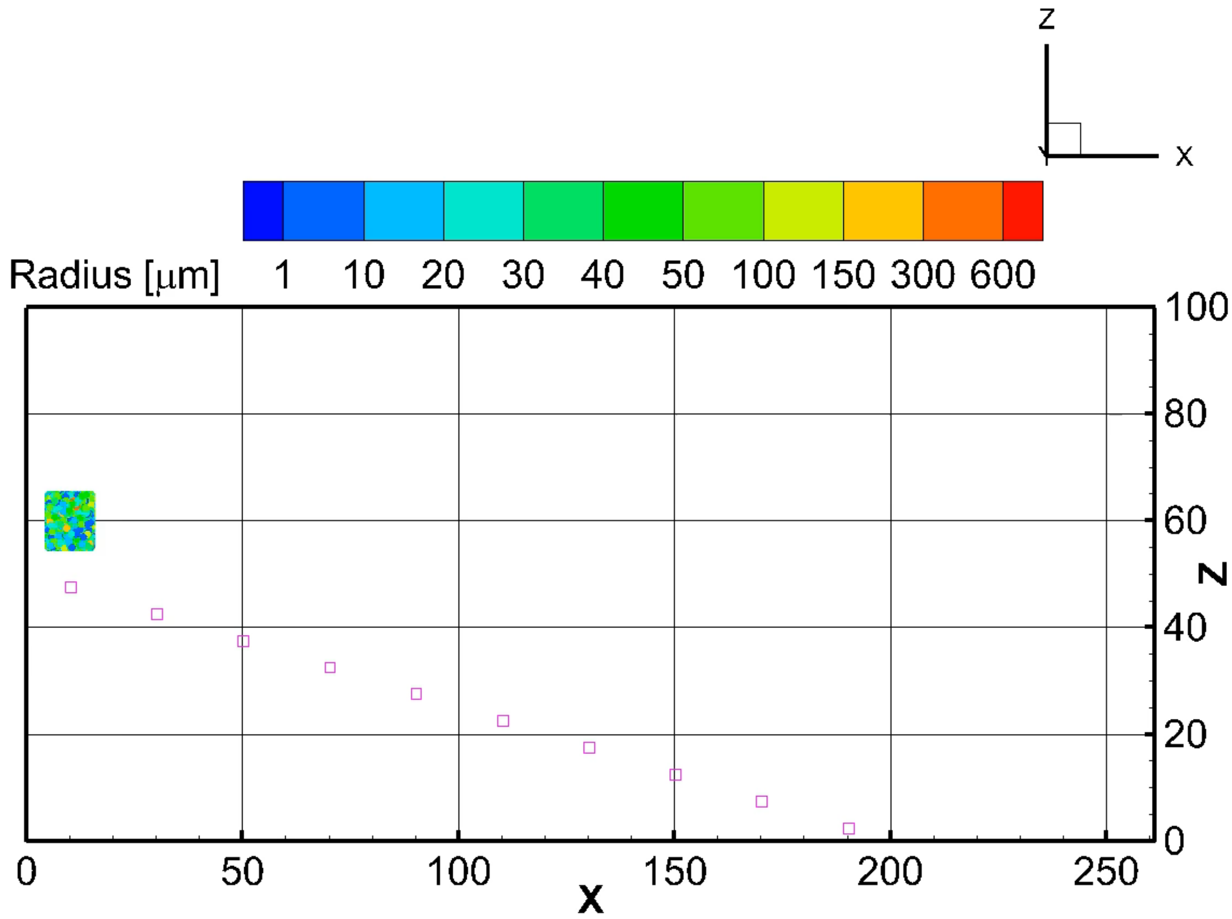


Fig. 19. Animation of particle trajectories.

Effects of particle size separation

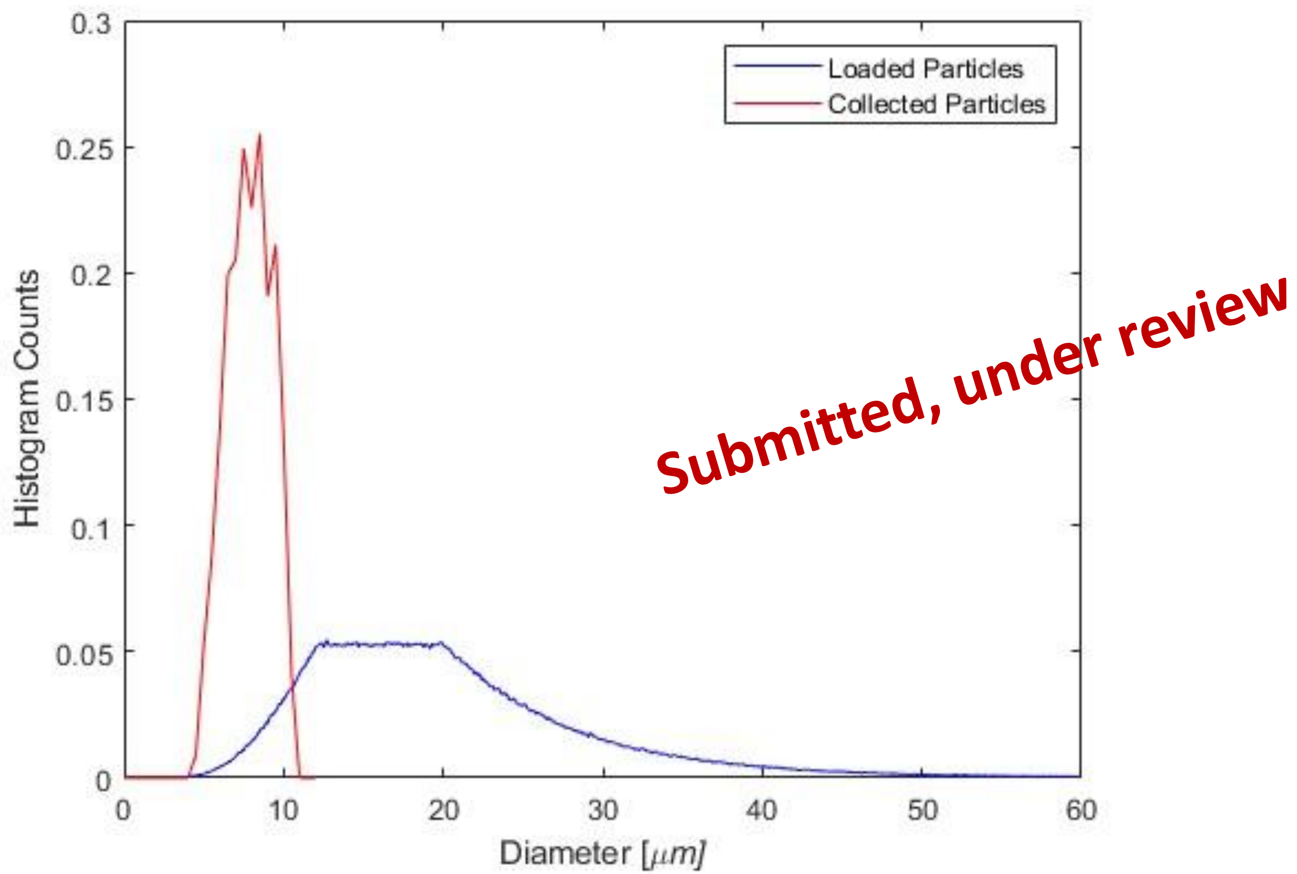


Fig. 20. Effects of size separation: loaded vs. collected.

Simulation as a design tool

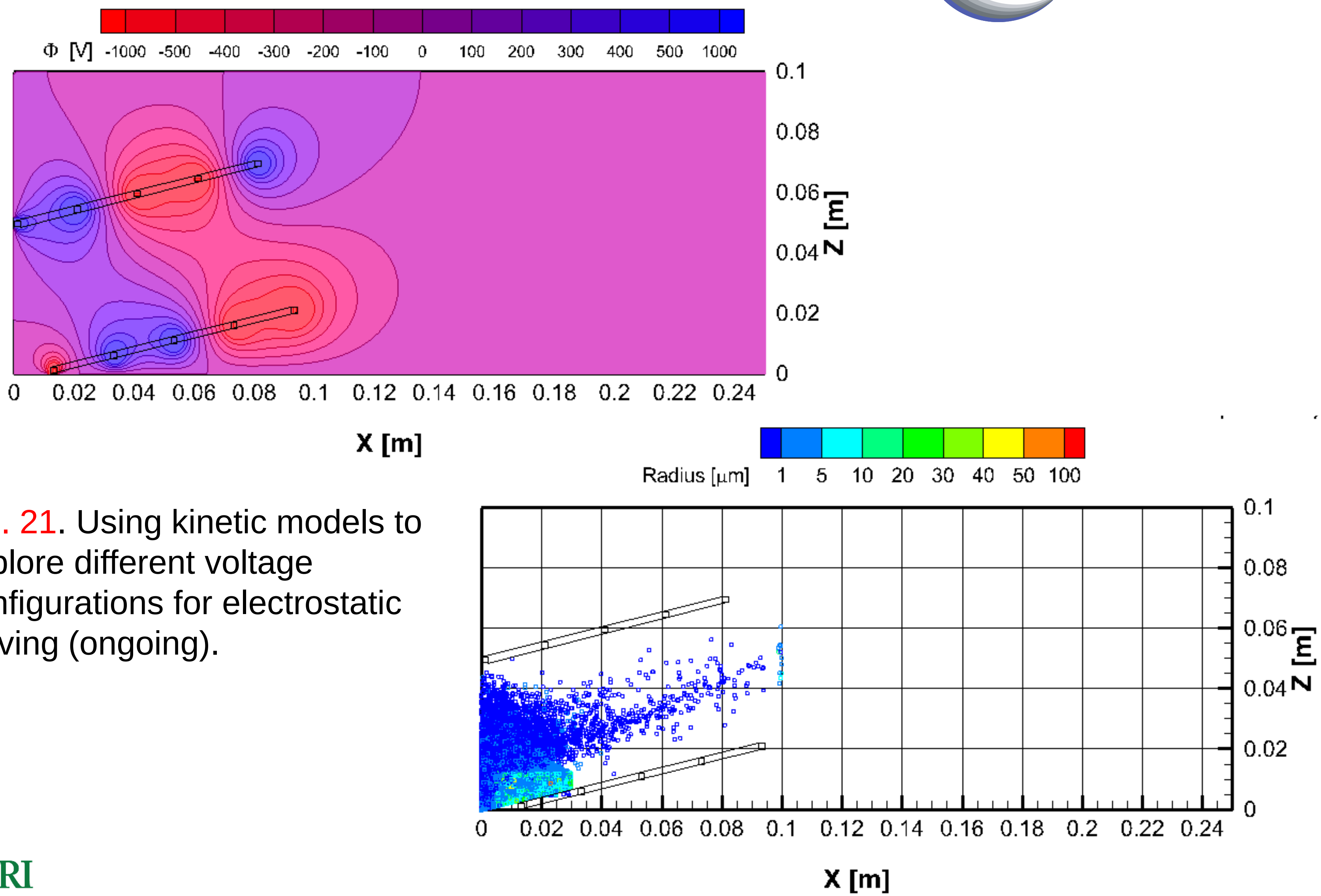
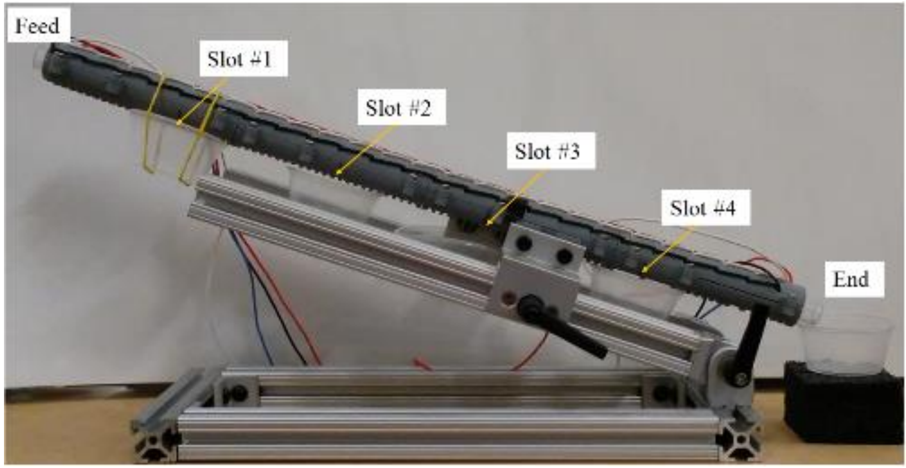
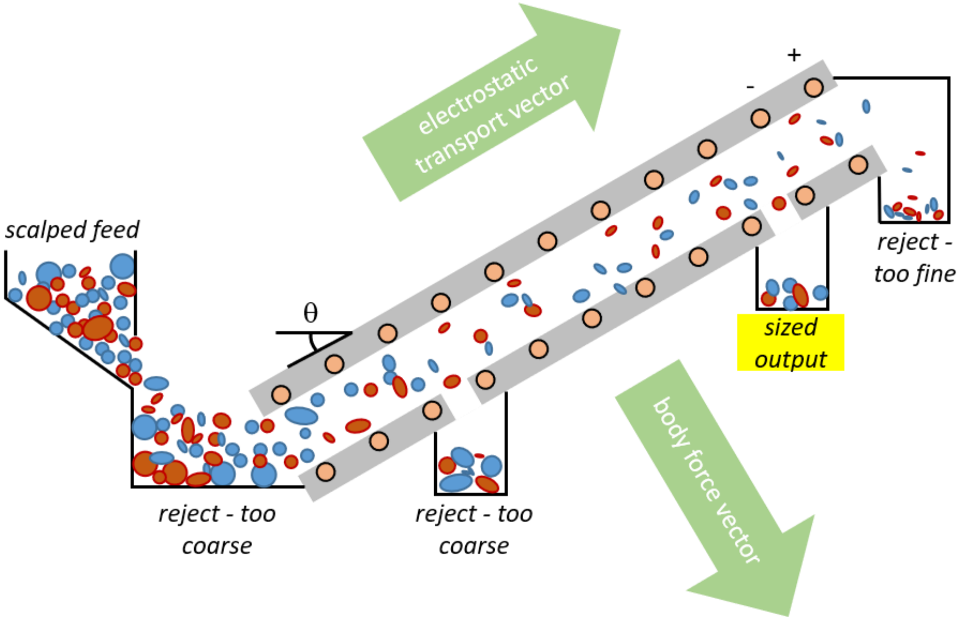


Fig. 21. Using kinetic models to explore different voltage configurations for electrostatic sieving (ongoing).

Hybrid *kinetic-fluid* modeling

Fig. 22. Prototype configurations to be modeled using hybrid kinetic-fluid approach (ongoing).





Manuscript in preparation

Thanks to the team at S&T:

<u>Research Specialist/Associate/Technician</u>: Todd Sander, Mitchell Cottrell, Peter Bachle

<u>Graduate Students</u>: Jacob Ortega, Kolawole Adesina, Emmanuel Wie-Addo, Amen Eze, Kyle Newport

<u>Undergraduate Students</u>: Aaron Berkhoff, Easton Ingram, Prakash Kovvuri, Christopher Schneider, Mason Phillips, Selena Allen, Mercedes Lane, Grant Baer, Keaton Painter, Nicholas Graham, Matthew Sherman, Katelynn Timmons, Rachel Adcock

Ground Testing of Electrostatic Transport of Lunar Regolith Simulants with Applications to Electrostatic Sieving

MISSOURI S&T
D. Han (PI, handao@mst.edu), F. Rezaei, J. Smith, W. Schonberg, D. Bayless, P. Bachle

HONEYBEE ROBOTICS
D. Bergman, J. Hernandez, B. Yen, H. Jung

BECHTEL
A. Esbeck, K. Churchill, B. Pletcher, D. Meadows, P. Carrato

OFF PLANET RESEARCH
M. Roth

BACK UP SLIDES

Task 4: Magnetic Drum Separator (Bechtel)

Control Parameters:

- *feed rate*
- *absolute & relative drum rotation rates*
- *drum diameters*
- *magnet size, strength, placement in drums*
- *output bins number, locations, threshold geometries*

Magnetic Force Vector (tangential to drum rotation) interacts with Body Force Vector, to separate particles of desired composition – the required number of stages is TBD (this sketch shows two).

"Reject" refers to particles above some level of magnetic susceptibility and "product" refers to less magnetic particles.

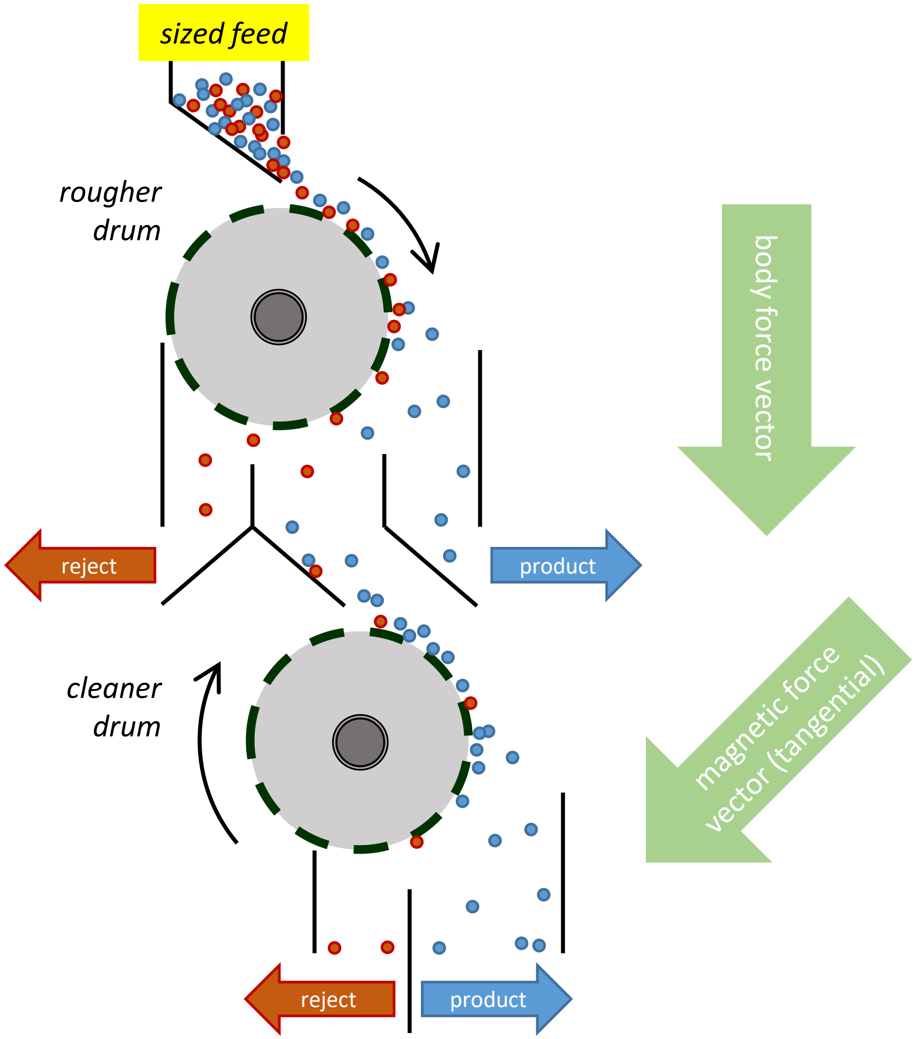


Fig. 23. Prototype design of the magnetic drum separator.

Task 4: Magnetic Drum Separator (J. Smith)

We did observe magnetic response of the simulant samples

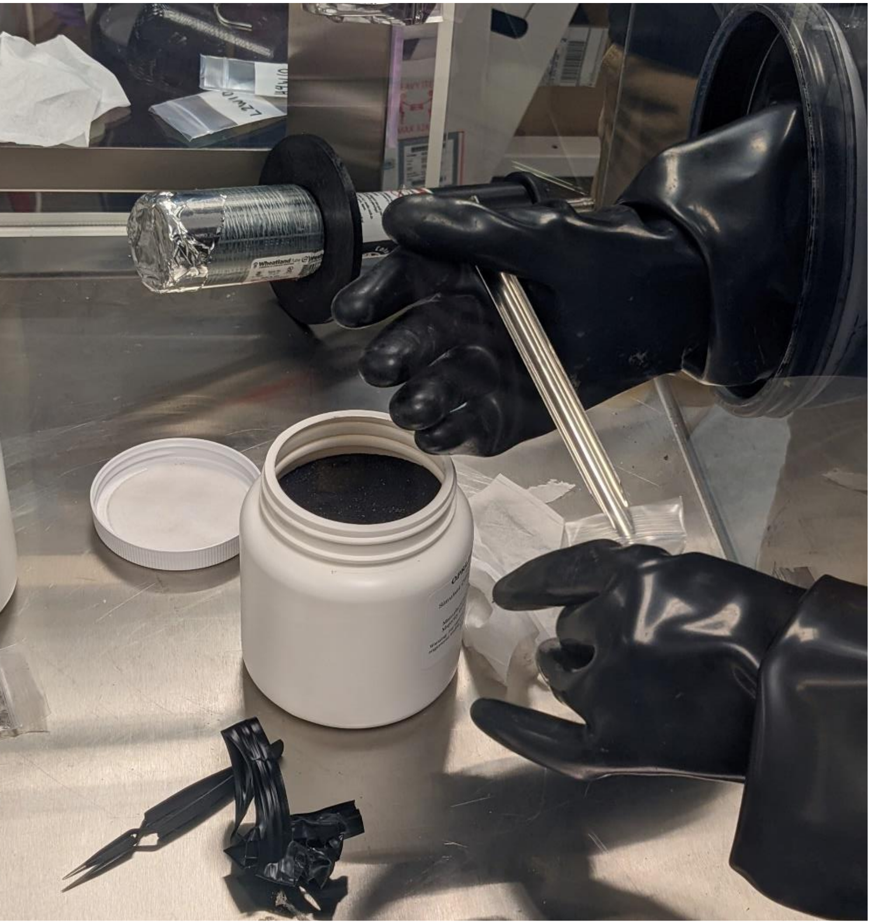
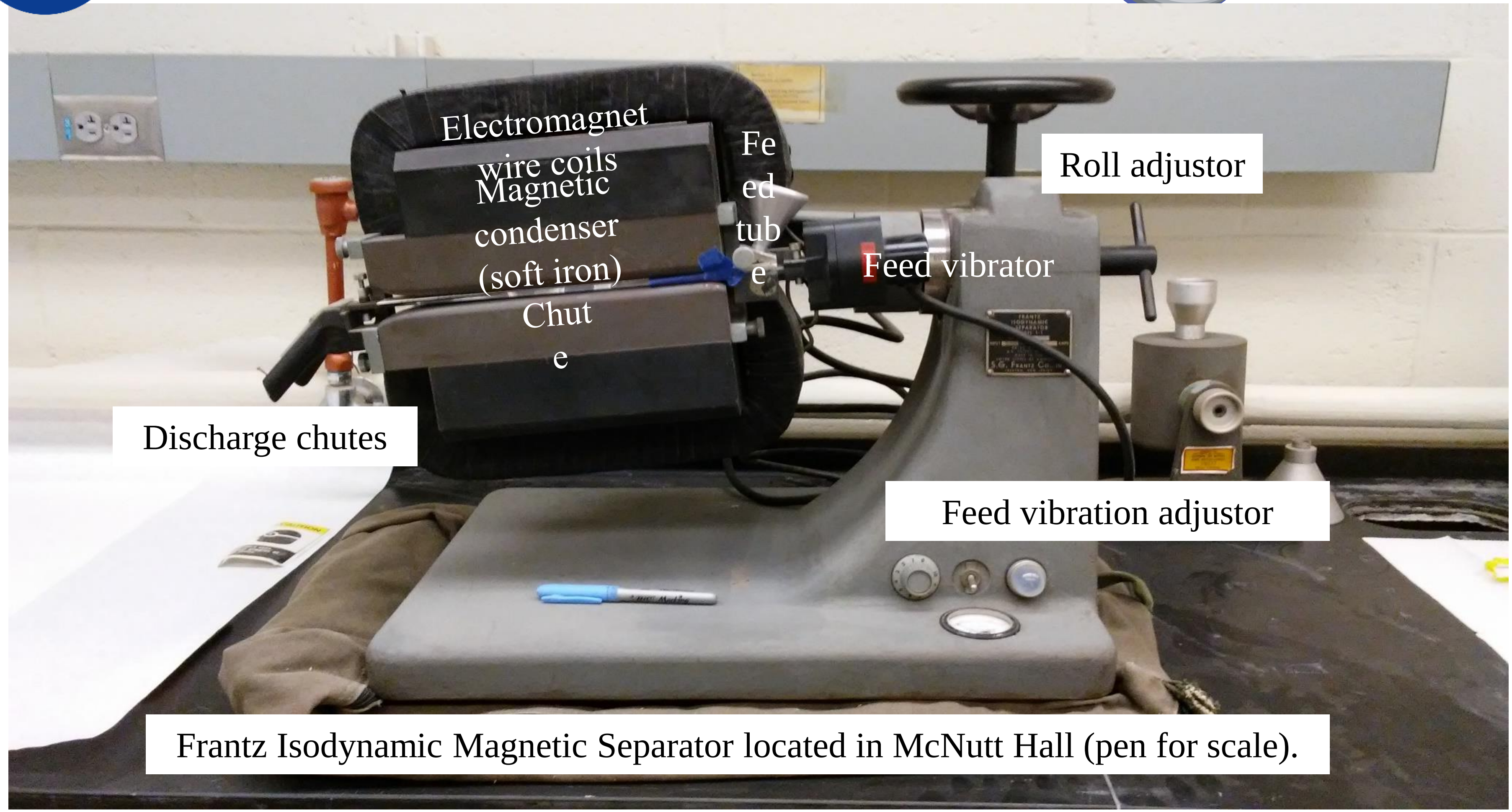


Fig. 24. Checking magnetic response of the simulant samples.

Task 4: Magnetic Drum Separator (J. Smith)



Frantz Isodynamic Magnetic Separator located in McNutt Hall (pen for scale).

Fig. 25. A magnetic drum separator at MST as a reference.

Task 4: Magnetic Drum Separator (J. Smith)

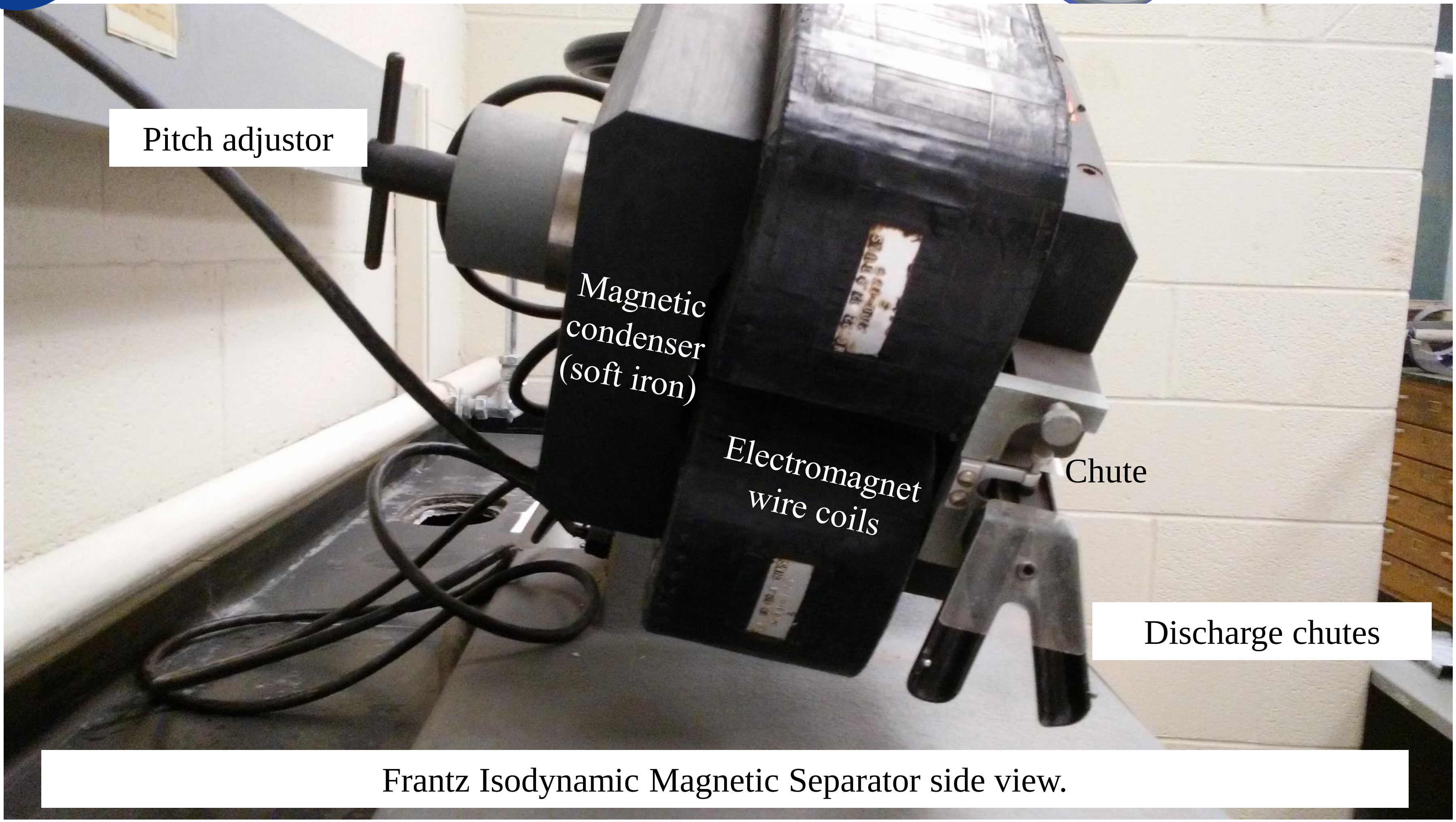
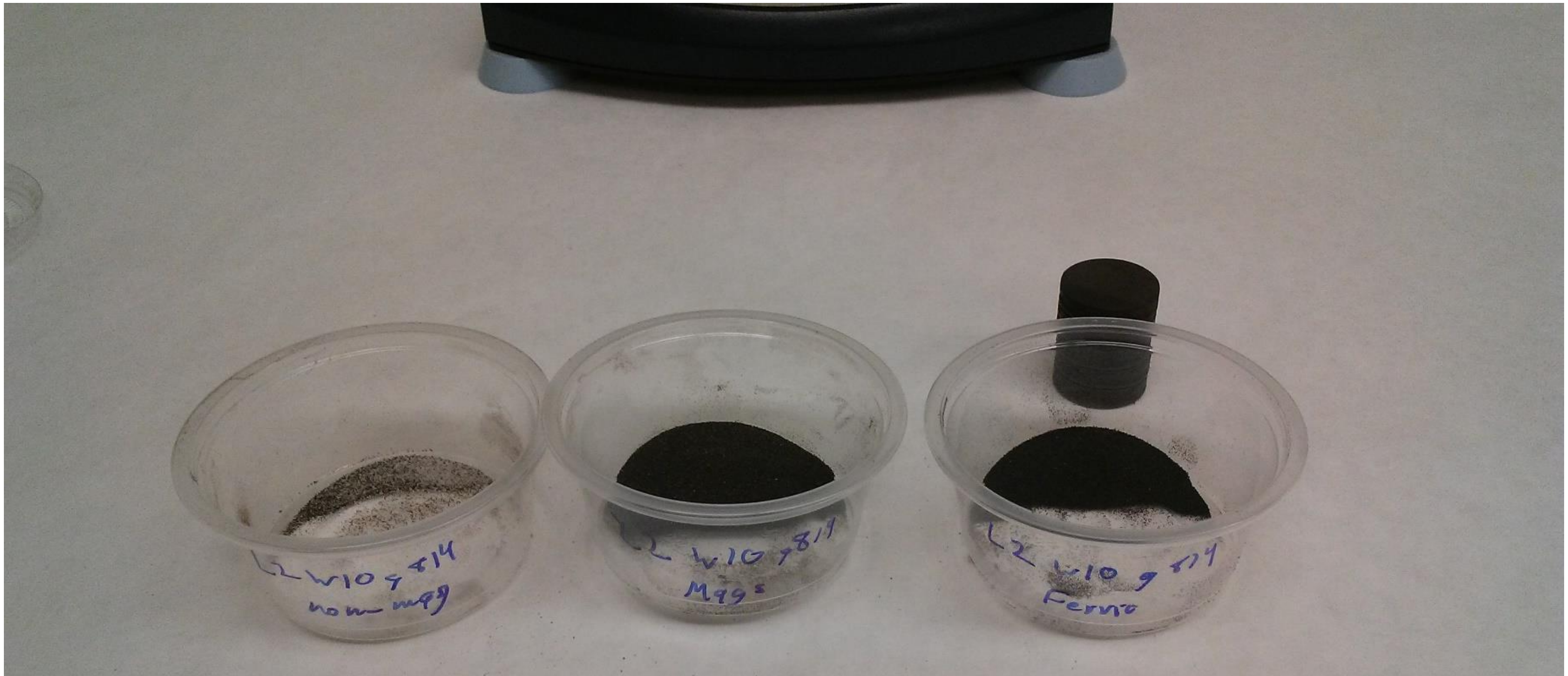


Fig. 26. A magnetic drum separator at MST as a reference (cont'd).

It does separate particles – A video

…after the recorded run



from left to right: mostly anorthosite (diamagnetic),
basalt (paramagnetic),
and ferro-magnetics (removed with magnet sweep prior to separator).

Fig. 27. Separated samples out of the magnetic separator.

Task 6: System Integration and Testing (MS&T and Bechtel)

MS&T chamber – Video tour (chamber and pumps)

Task 6: System Integration and Testing (MS&T and Bechtel)

MS&T chamber – DURIP and LuSTR21 upgrade to TVAC (ongoing)

Fig. 28. A screenshot of the time lapse of chamber facility upgrade.

Task 6: System Integration and Testing (MS&T and Bechtel)

Fig. 29. More equipment/hardware on chamber facility upgrade (LN2 shroud and tanks, and crane).

Task 7: Optimize total system SWaP and Develop ConOps (All)

- Output >70 wt% anorthite, particles 20-200 µm
- Final system <0.51 m^3, 35 kg, 300 watts
- System throughput >3 kg/hr