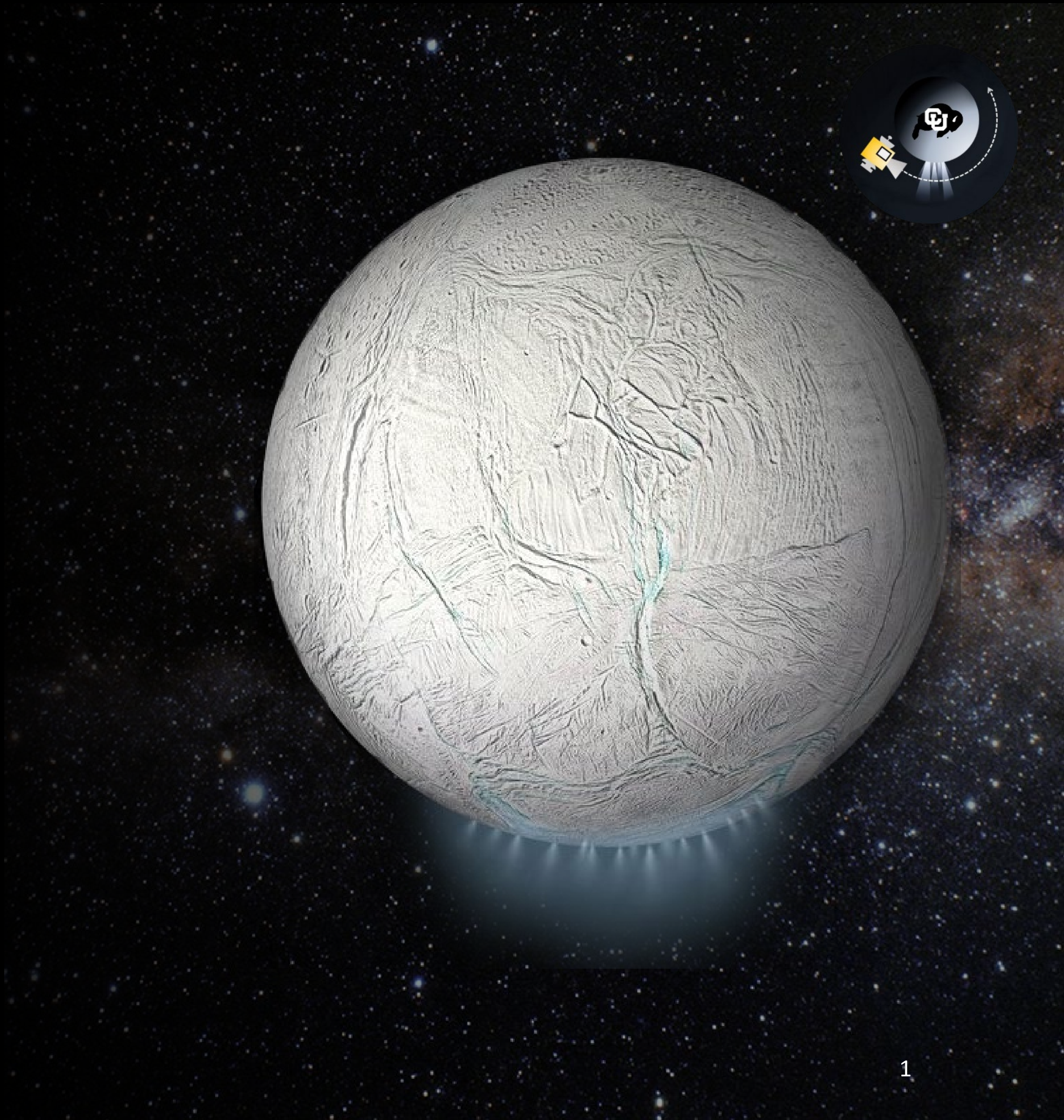
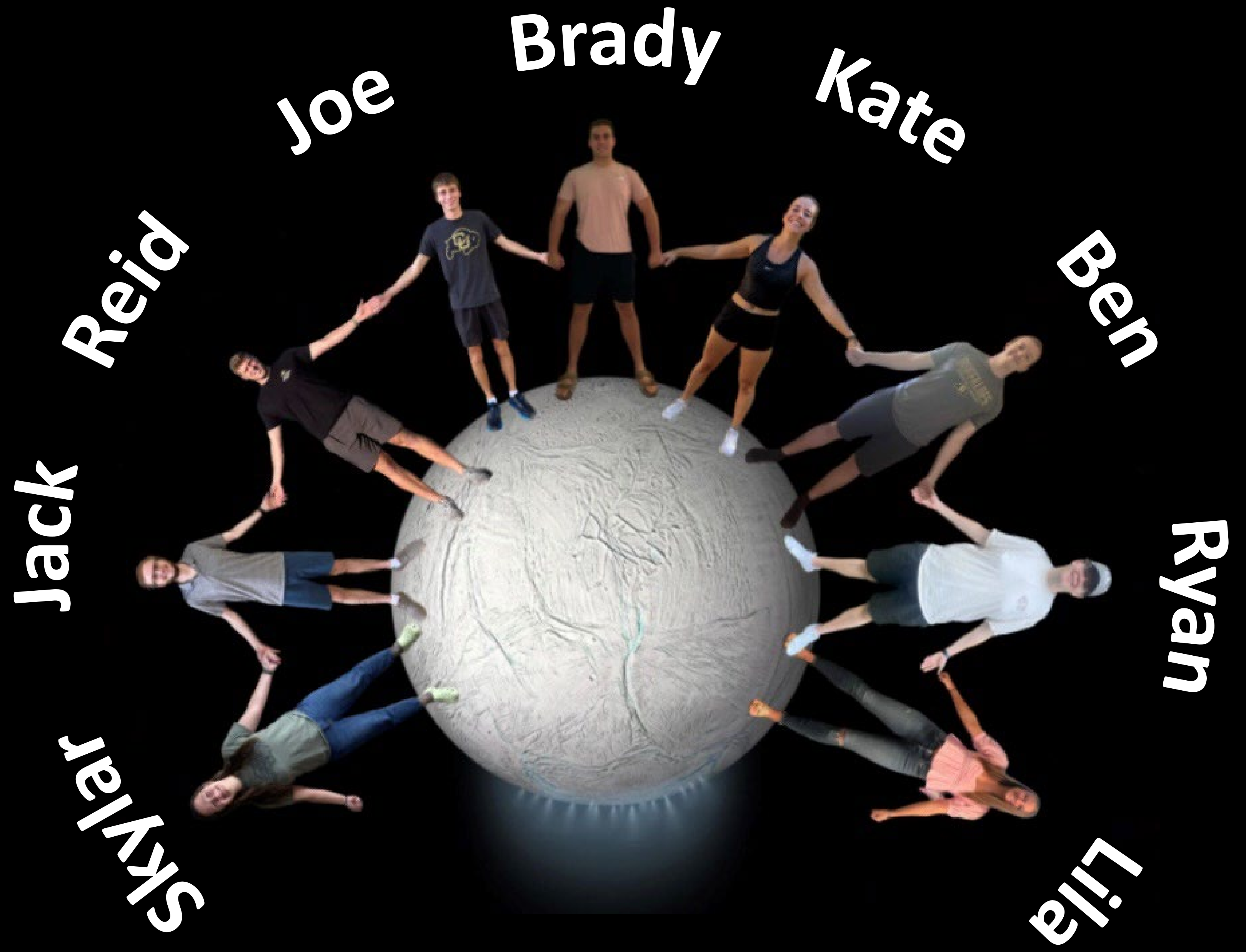
I^{2}CE CDR

Group 12

Sponsored by: ASTROBi

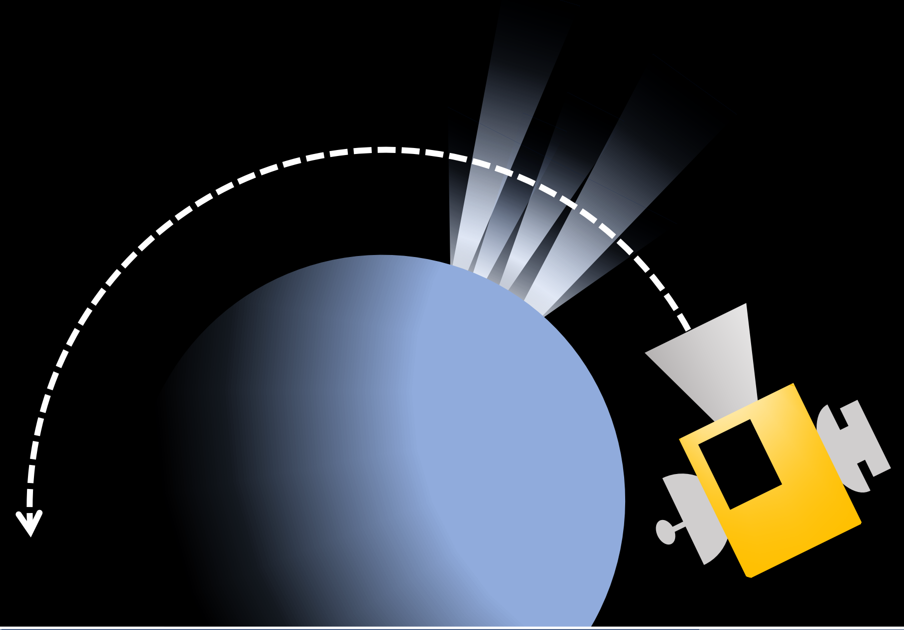


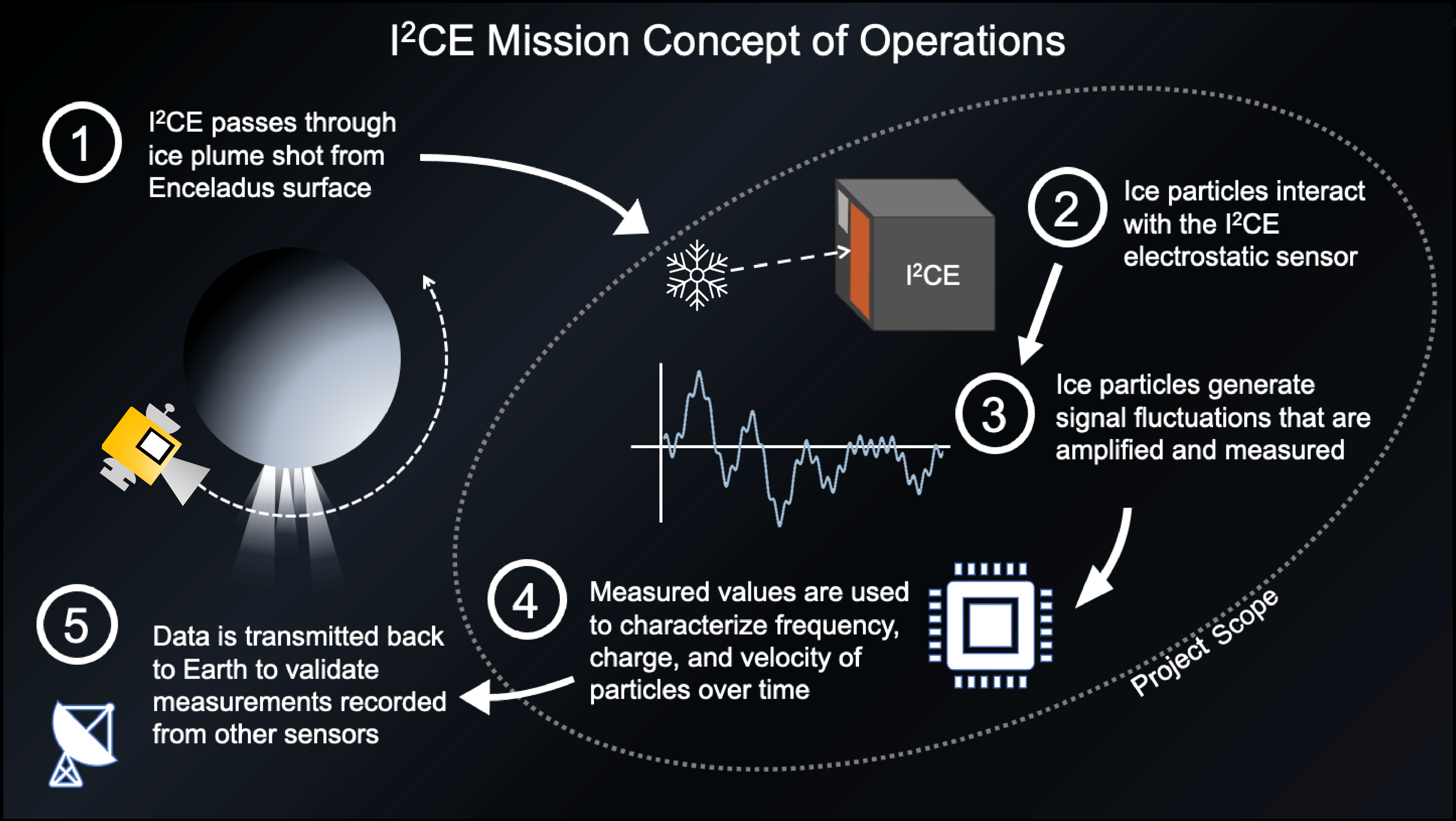

Skylar
Jack
Reid
Joe
Brady
Kate
Ben
Ryan
Lila

Project Purpose and Objectives

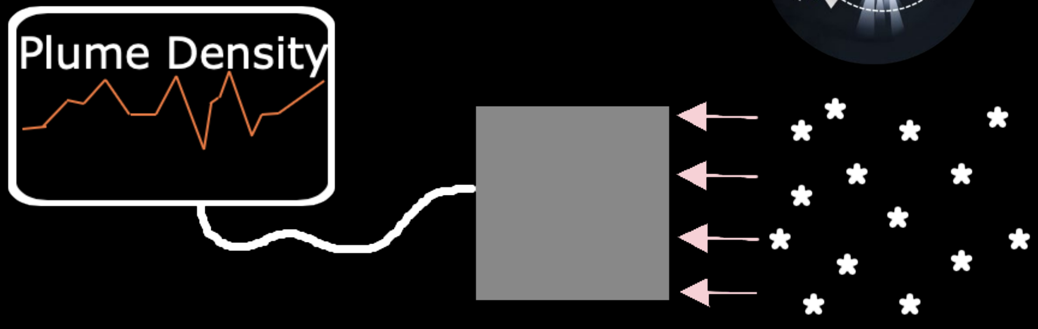
Project Definition

This project is to design and fabricate a proof-of-concept sensor capable of measuring the plume density of ice particles around Enceladus

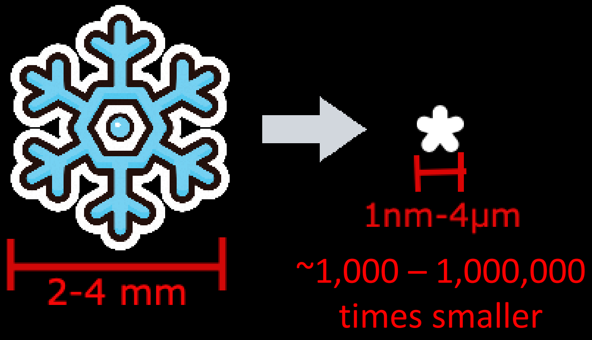



I²CE Mission Concept of Operations
1
I²CE passes through ice plume shot from Enceladus surface
I²CE
2
Ice particles interact with the I²CE electrostatic sensor
3
Ice particles generate signal fluctuations that are amplified and measured
4
Measured values are used to characterize frequency, charge, and velocity of particles over time
5
Data is transmitted back to Earth to validate measurements recorded from other sensors
Project Scope

Primary Objectives

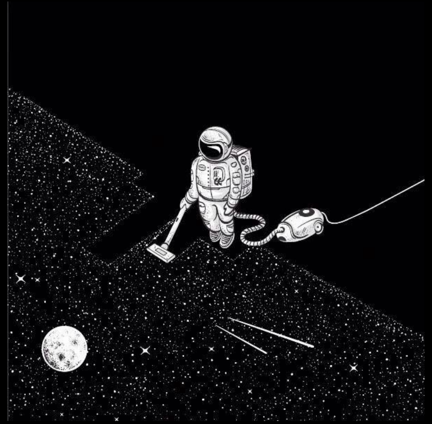


1) Measure incident particle flux over time



2) Detect particles from 0.5 µm to 4 µm in radius

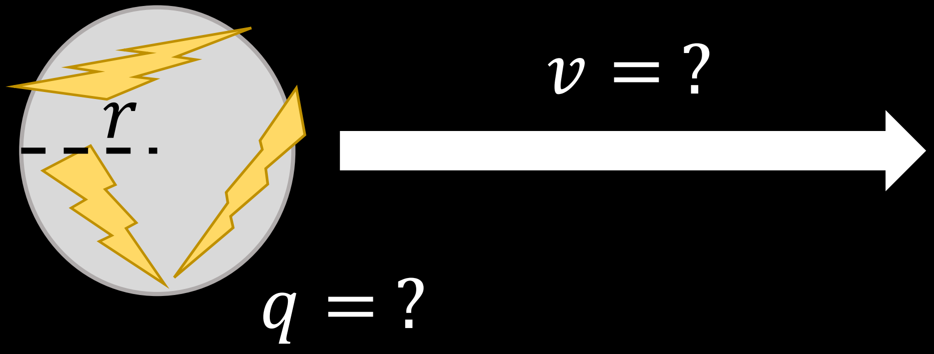
3) Operate in vacuum conditions

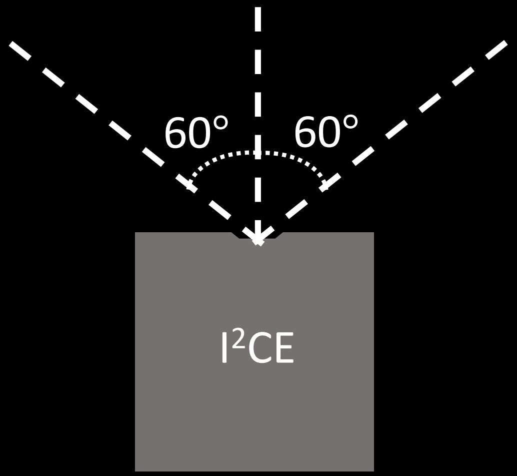


4) Develop Parametric Model to predict sensor performance

Higher Level Objectives

1) Measure the speed and charge of particles of radius > 0.5 µm

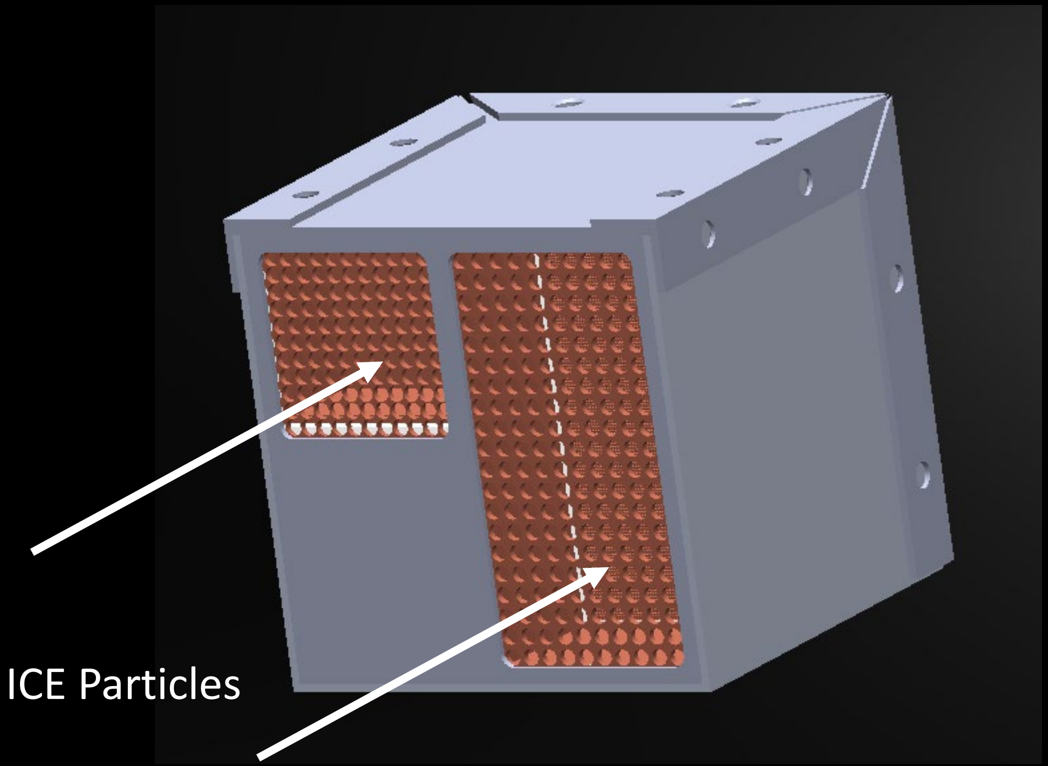


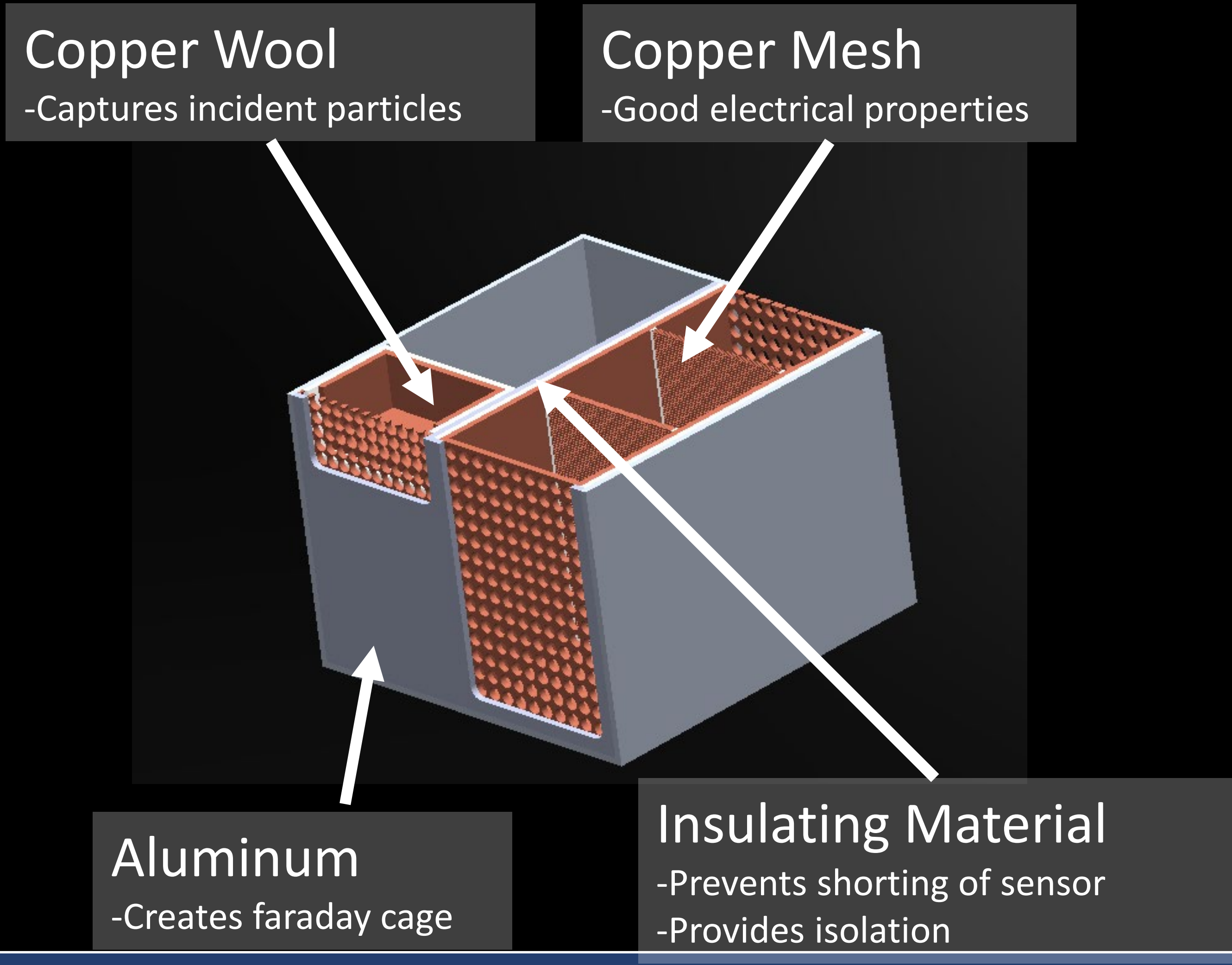


2) Measure particles with an incidence angle of 60° from sensor opening (120° total FOV)

Design Solution

Final Design Solution





Charge Based Sensing

- Particles have an inherent, measurable charge
- Combination of two charge detection methods:

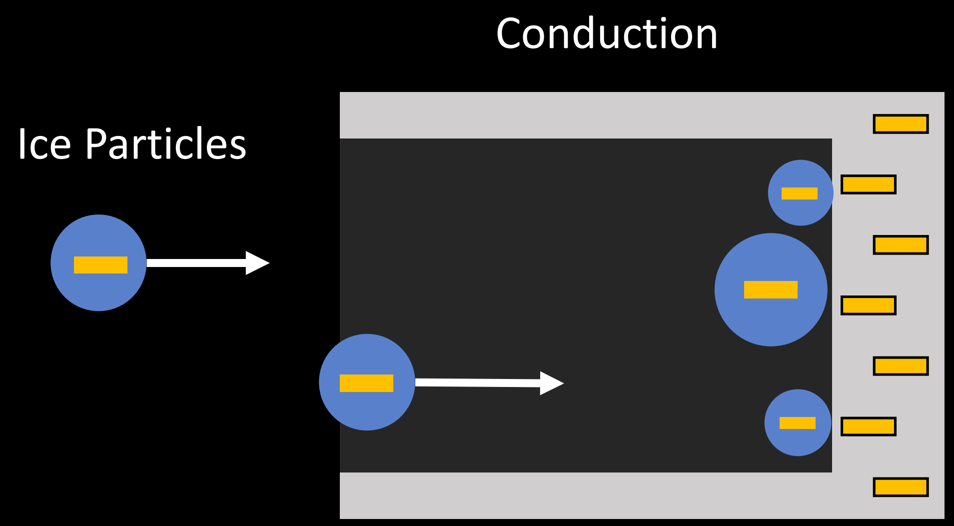
Electrostatic Conduction	Induction
• Best for bulk charge • Heritage: Parker Solar Probe, Cassini	• Best for large, individual particles • Heritage: Cassini

Charge Based Sensing - Conduction

Conduction Based – Faraday's Cup

1. Incident particles impact sensor face, some charge is transferred
2. Sensor face is discharged periodically

- Cannot measure individual particles
- Measures total charge density



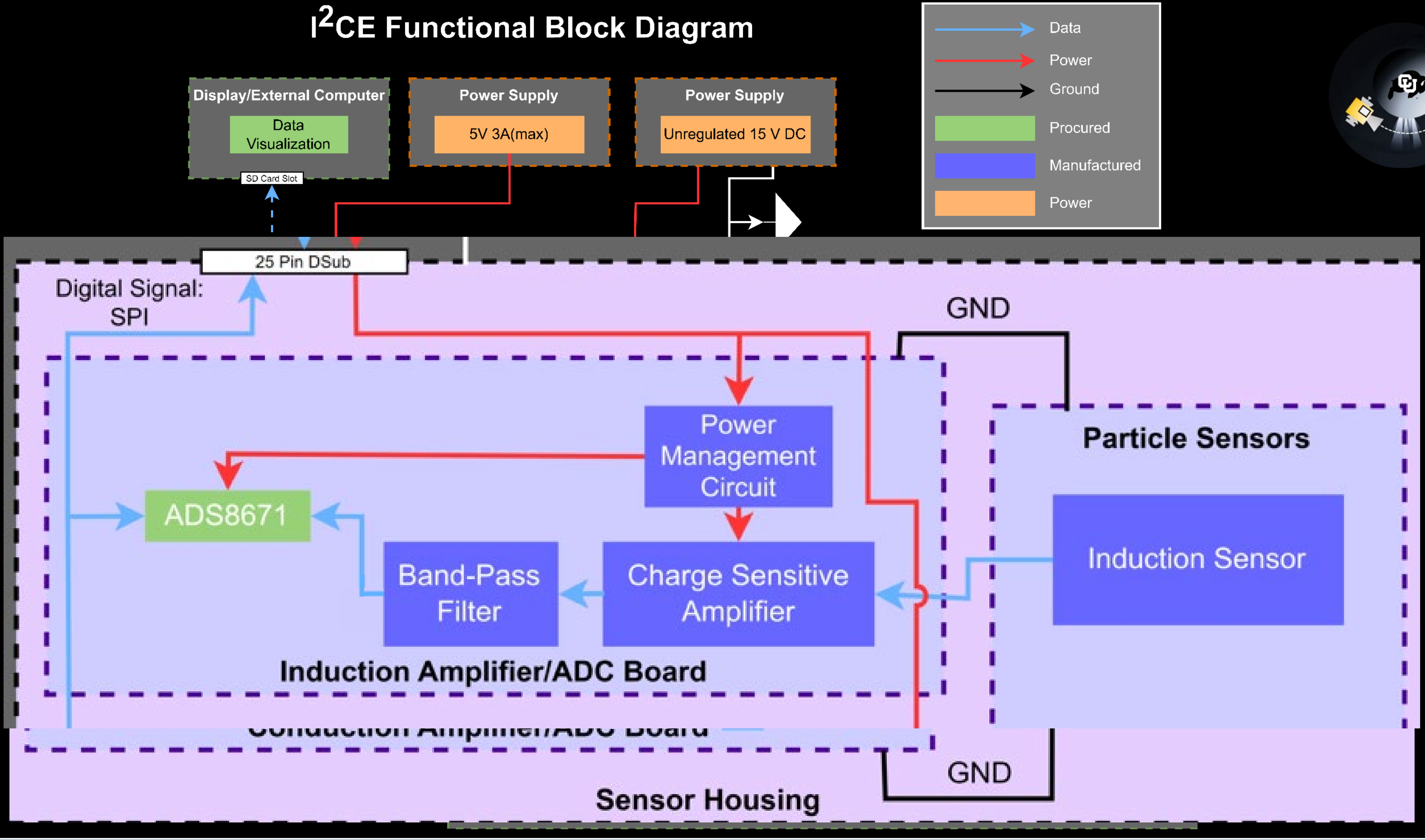
Charge Based Sensing - Induction

Induction Based – Mesh Grid

1. Negatively charged particles fly through a conductive wire grid
2. Particles induce a charge in the grid
3. Measurements of integrated electrons show particle charge

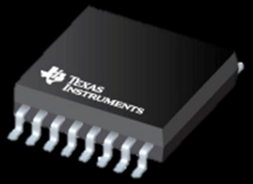
- Measures speed

I^{2}CE Functional Block Diagram

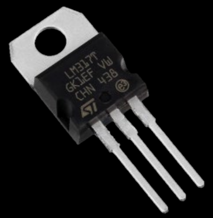


Chosen Components

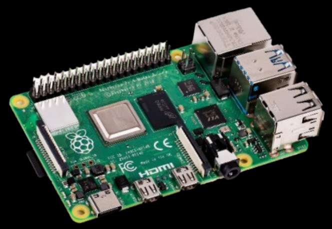
ADC – TI ADS8671:
- 1 MSPS
- Configurable analog input



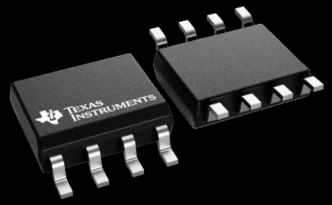
Power Management – LM317,LM337:
- Accurately produce ±Voltage



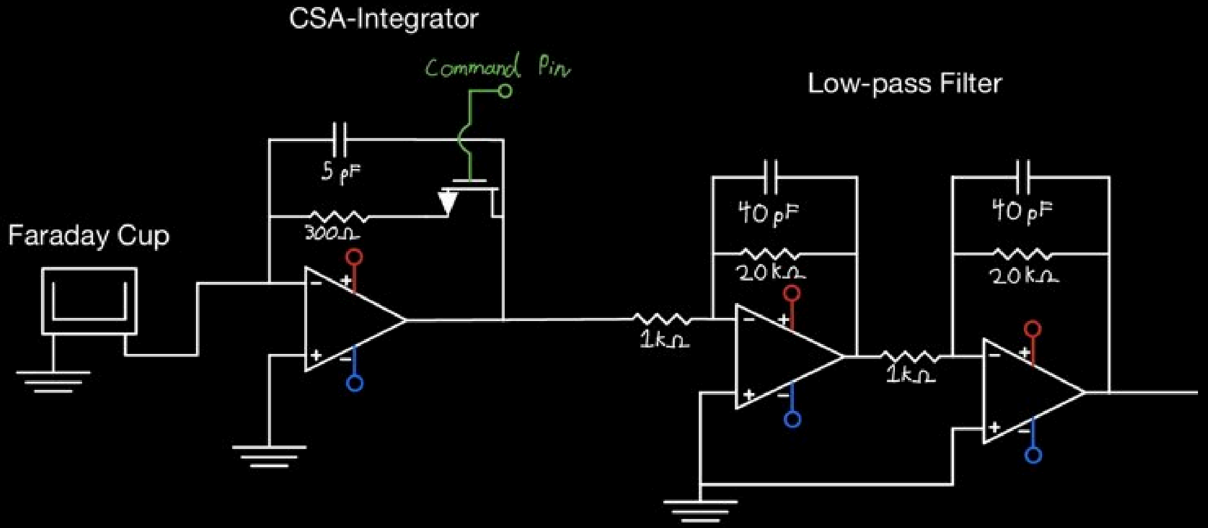
Computer – Raspberry Pi 4 model B:
- Provides needed computational power
- Supports 1 MSPS ADC



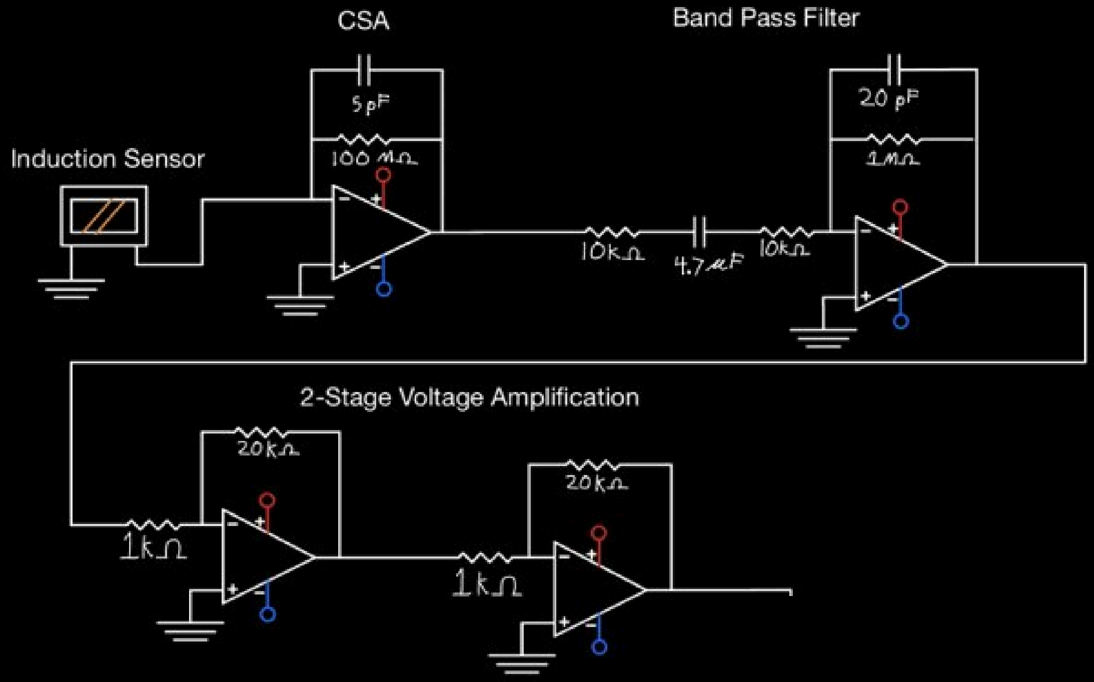
Op Amps:
- Charge to Voltage (CSA) - LTC 6240
- Filtering – OP27
- Voltage Gain - OPA2182
    - dual stage amplification
    - low voltage offset



Charge Sensitive Amplifier (CSA) Circuitry



Conduction Sensor



Induction Sensor

Critical Project Elements & Risks

CPE's

1. Geyser Density Detection
    - Measure particles per second incident to the spacecraft
    - Used to prove that the spacecraft is flying through ice plume

2. Noise Mitigation
    - Must reduce external noise
    - Maximizes usable data

3. Simulation
    - Must quantitatively model the sensor response to incident ice particles

Risk Matrix

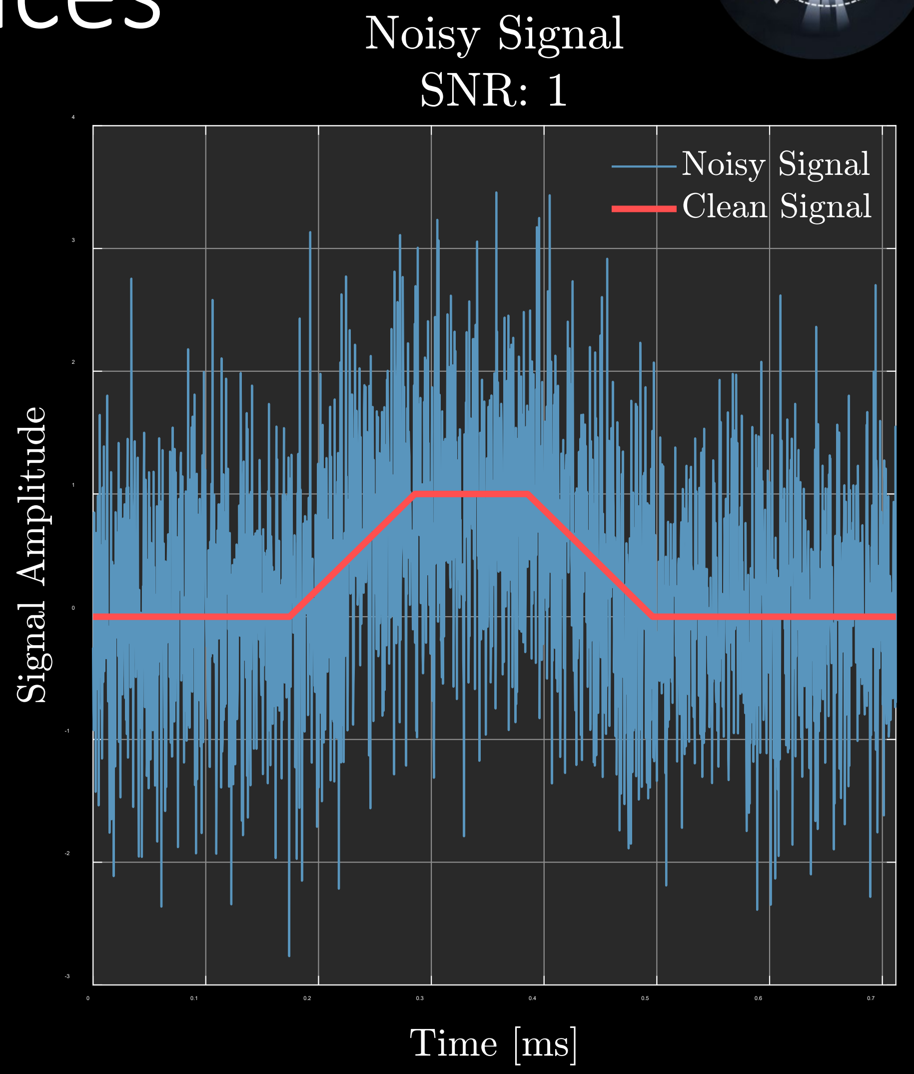
IICE Risk Management Matrix

Probability \ Impact/Consequence	1	2	3	4	5
5					
4					Signal to noise ratio too small
3		Cannot sense individual particles	Faraday cup overfills with ice		% charge induced/conducted too small
2					
1		Component temperatures outside of acceptable range	Sensor damaged in transit		

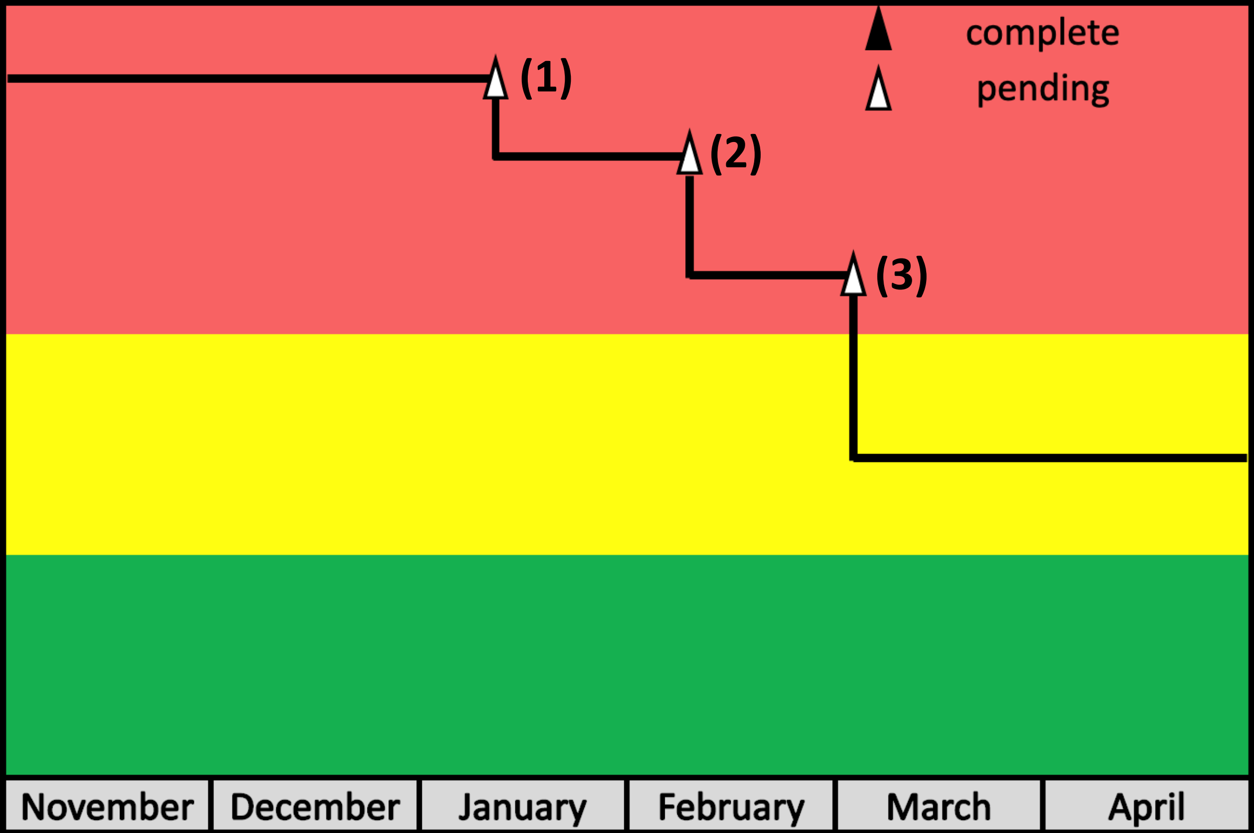
Primary Risks and Consequences

1. Signal to noise ratio is too small
   - Intermediate: Inaccurate speed measurements
   - Worst Case: Cannot detect individual particles

2. % charge induced/conducted too small
   - Intermediate: Inaccurate charge measurements
   - Worst Case: Cannot detect plume density

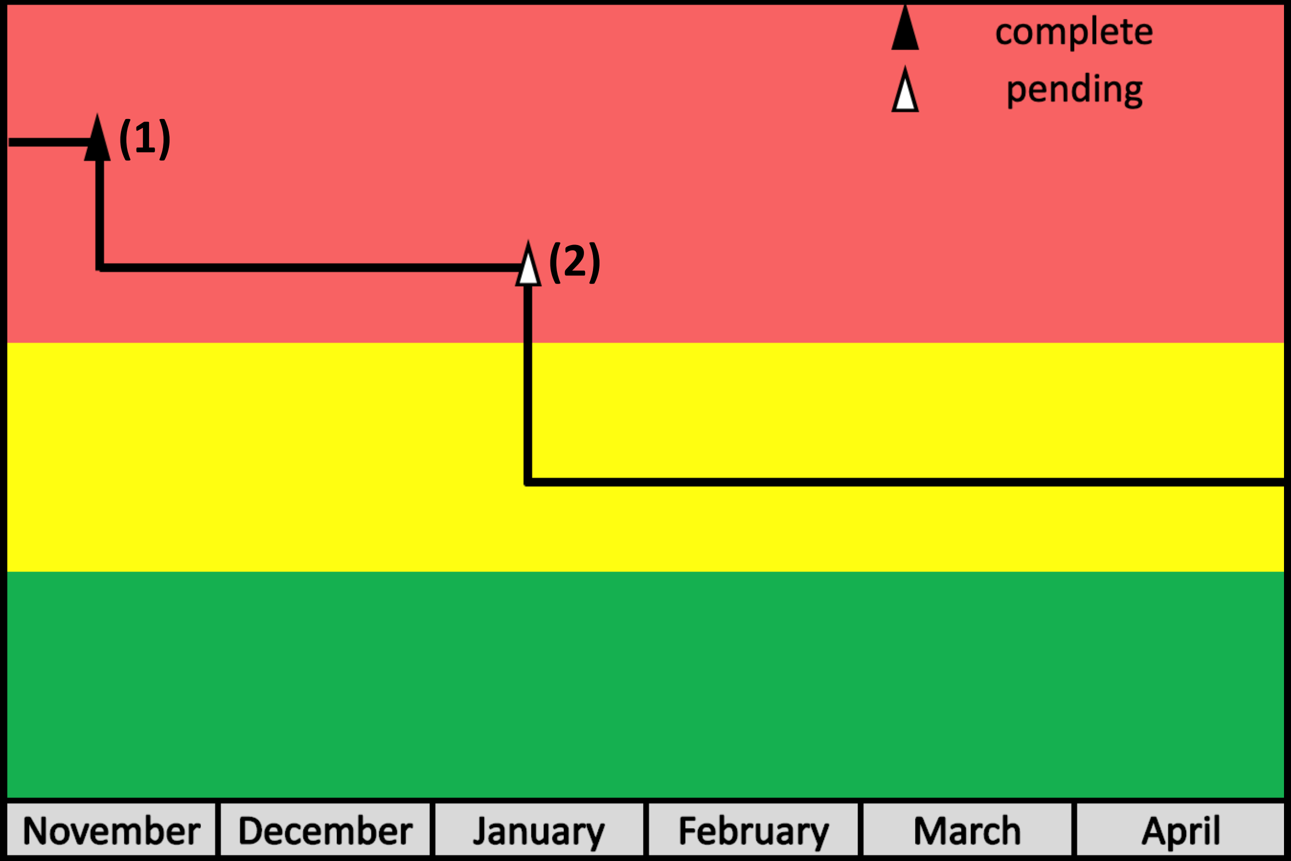


SNR Risk Mitigation Plan



1. Implement connector techniques
   - twisted, shielded wire
2. Digitize as quickly as possible
   - place ADC within vacuum chamber
3. Implement convolution filter
   - frequency pattern matching

Electronics Risk Mitigation Plan



1. Implement Faraday Cage
   - aluminum foil
   - metal box

2. Grounding techniques
   - single point grounding
   - eliminate ground loop

Design Requirements & Their Satisfaction

Model Development: Particle Detection

1. Particle Charge Modeling

2. Charge Sensitive Amplifiers

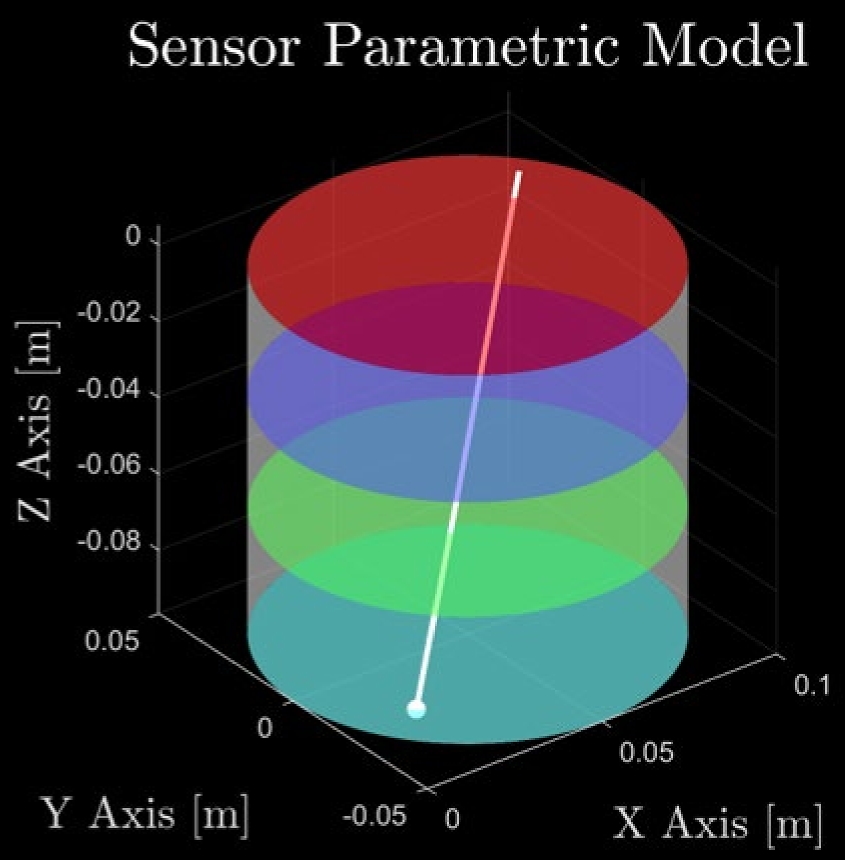
3. Matched Filtering

General Requirements	
Radius	0.5 – 4 µm
Speed	100 – 300 m/s
Charge	0.05 – 0.5 fC
Electrons	312 – 3120

Charge Modeling

Simulation

1. Parametric model of sensor design
2. Calculate charge induced on grid versus time given particle parameters
3. Assumes infinite plane grids

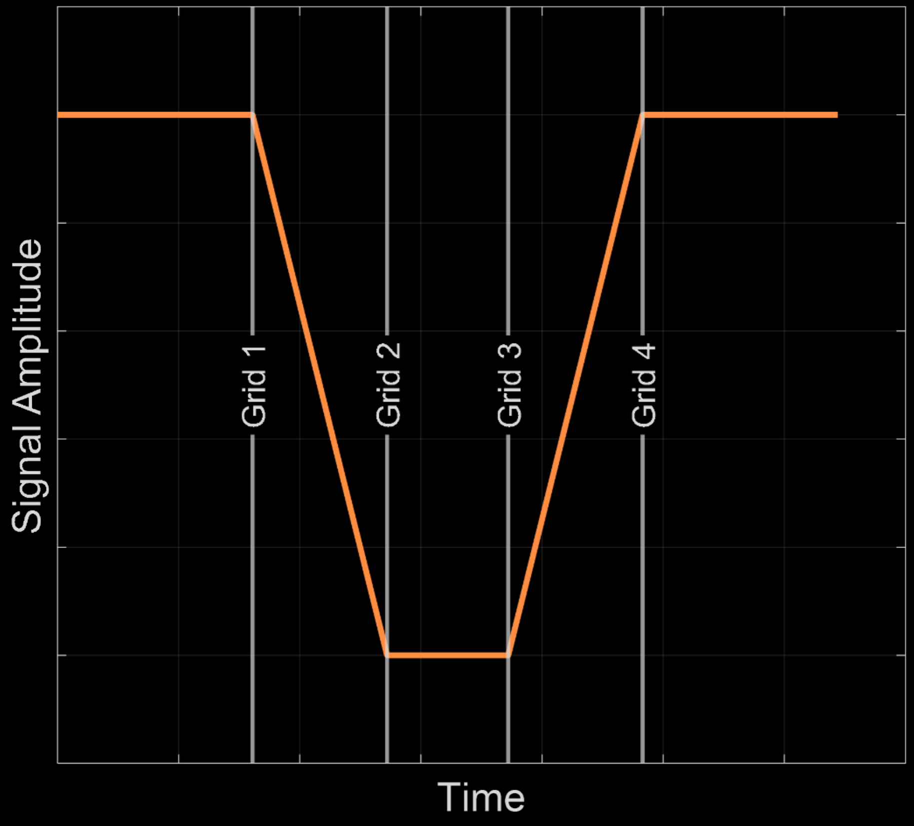


Requirements Satisfied

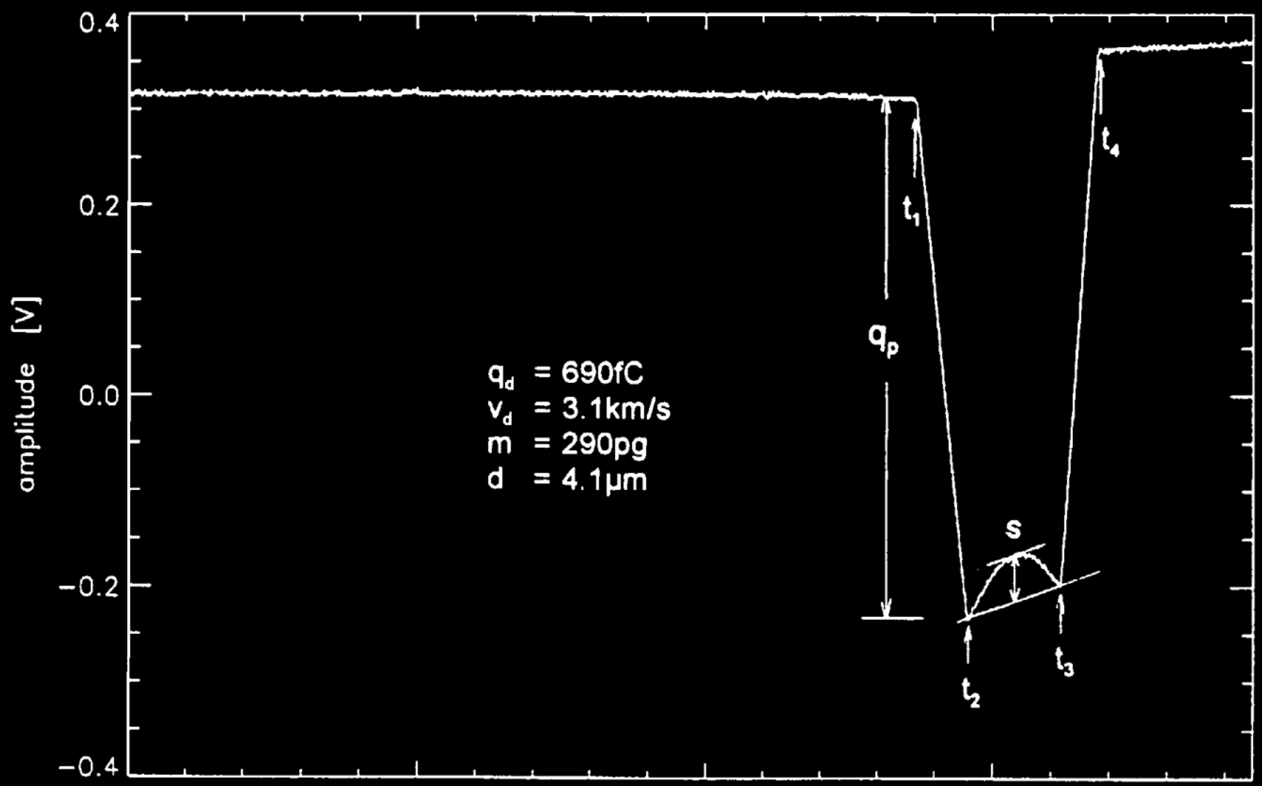
- ☑ 1.3.1
- ☑ 1.3.2

Charge Modeling

Modeled Charge Particle Signal



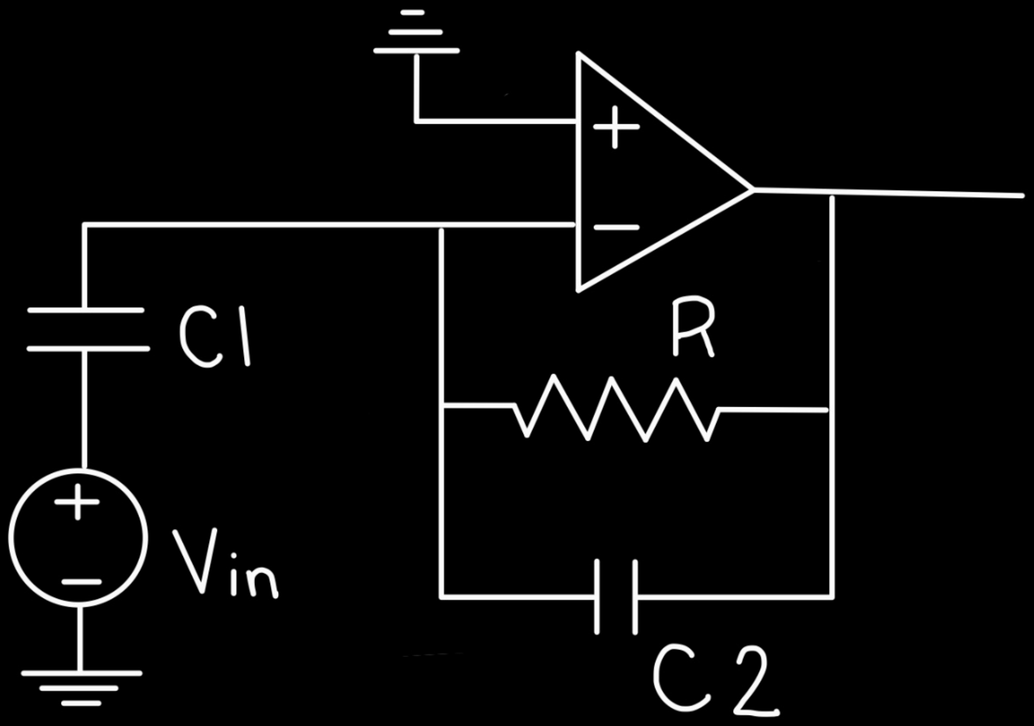
Cassini Charged Particle Data



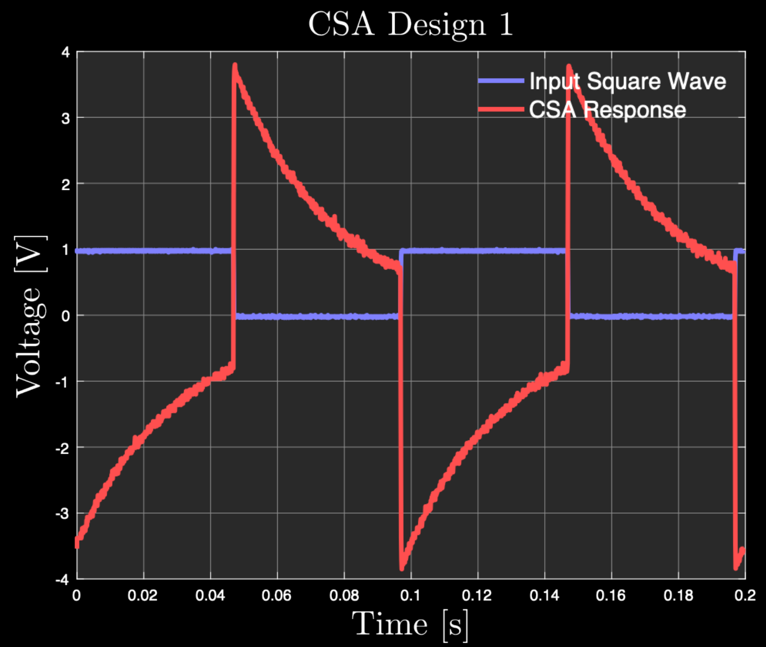
CSA – Design for Initial Testing

DR 1.1.1.1: Sensor shall detect presence of incident charged particles

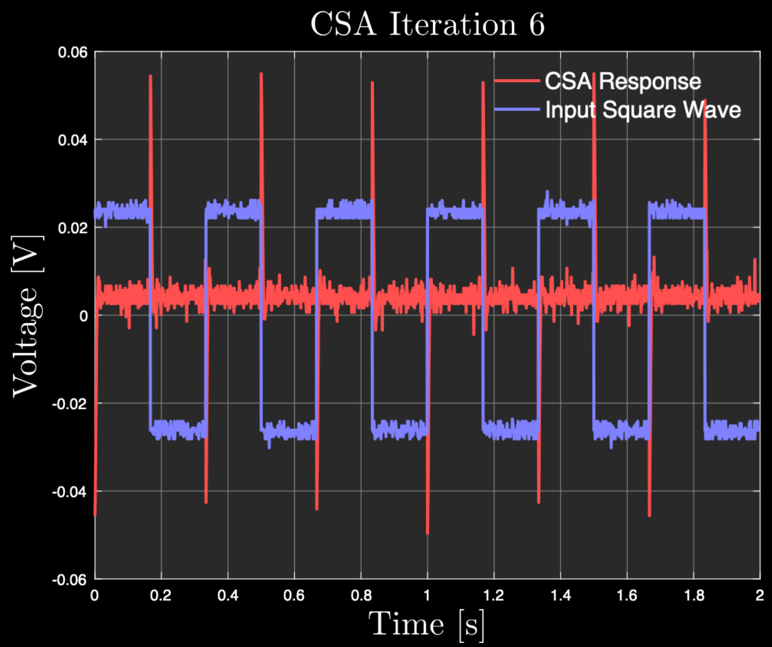
- Begin with basic CSA circuit
- Iterate component values
  - Determine smallest recognizable charge



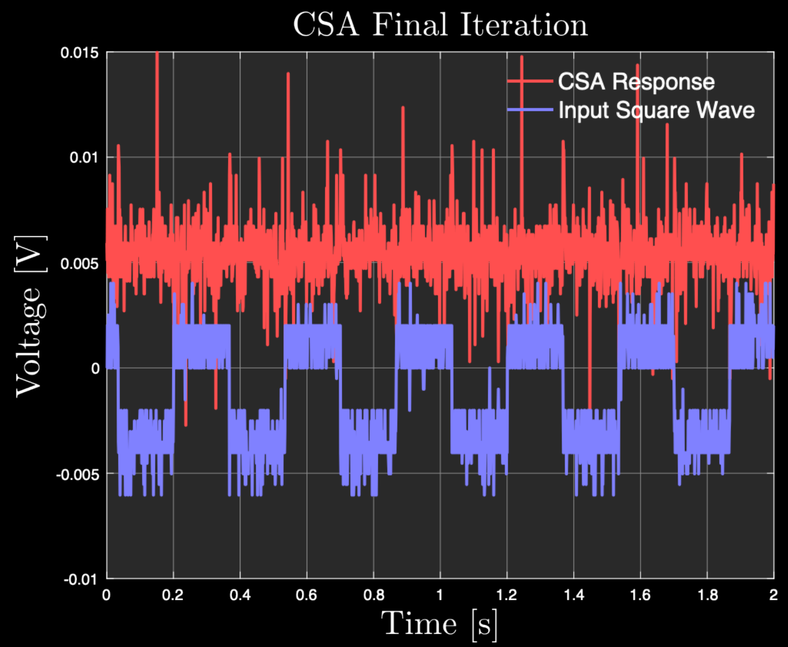
CSA – Design Results



1 μC detected

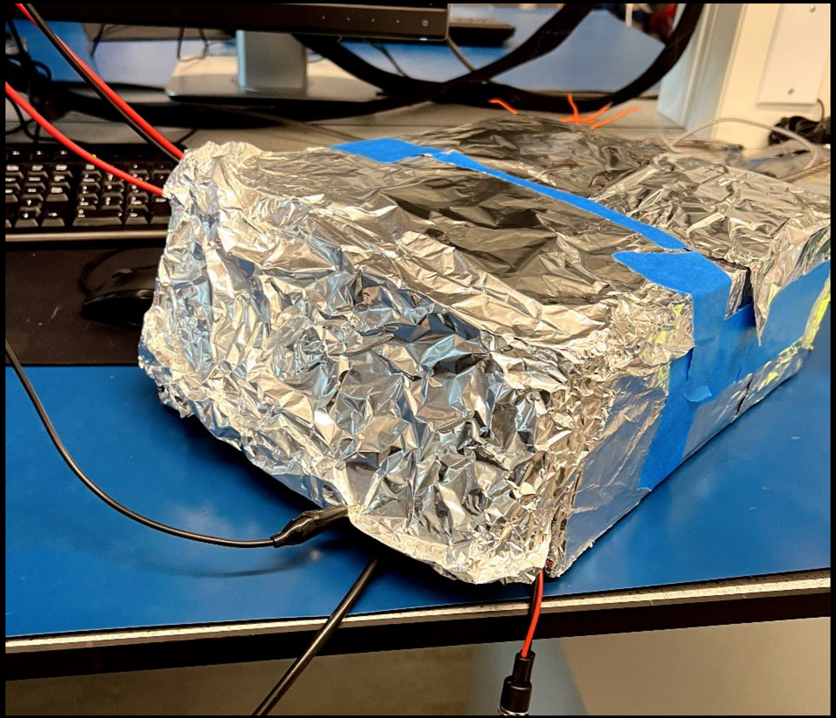


0.5 pC detected

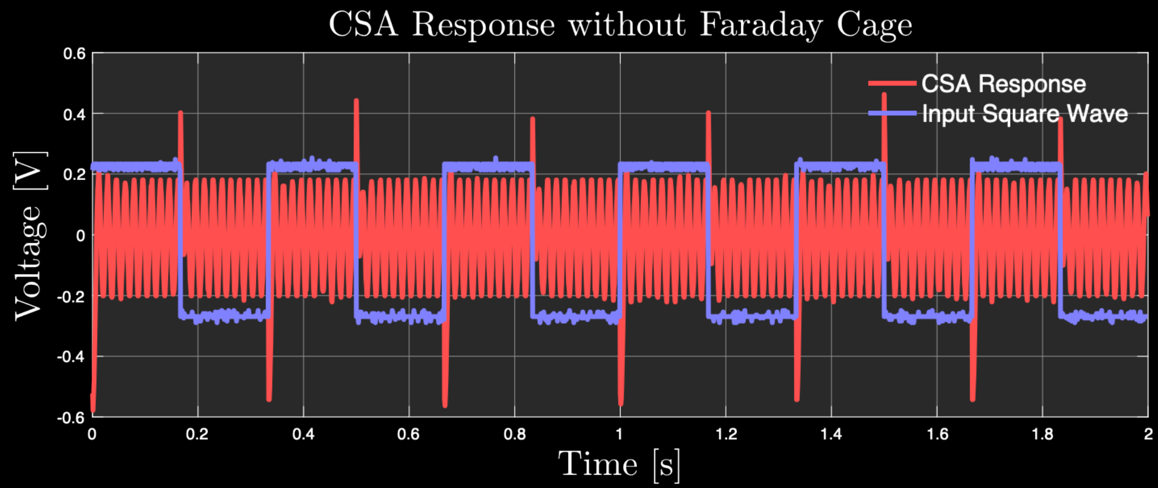


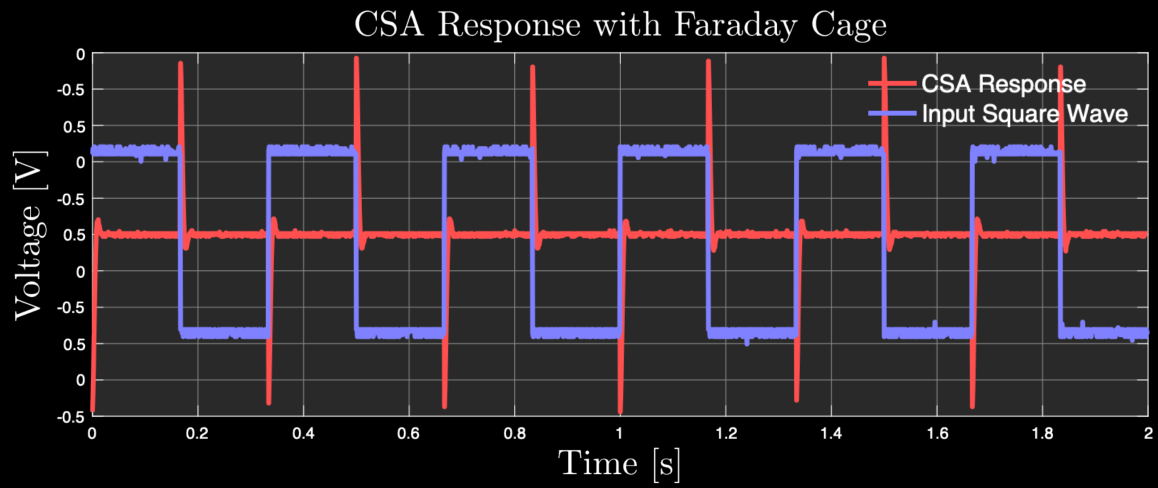
50 fC detected

CSA – Impact of Faraday Cage



Noise Mitigation Implementation

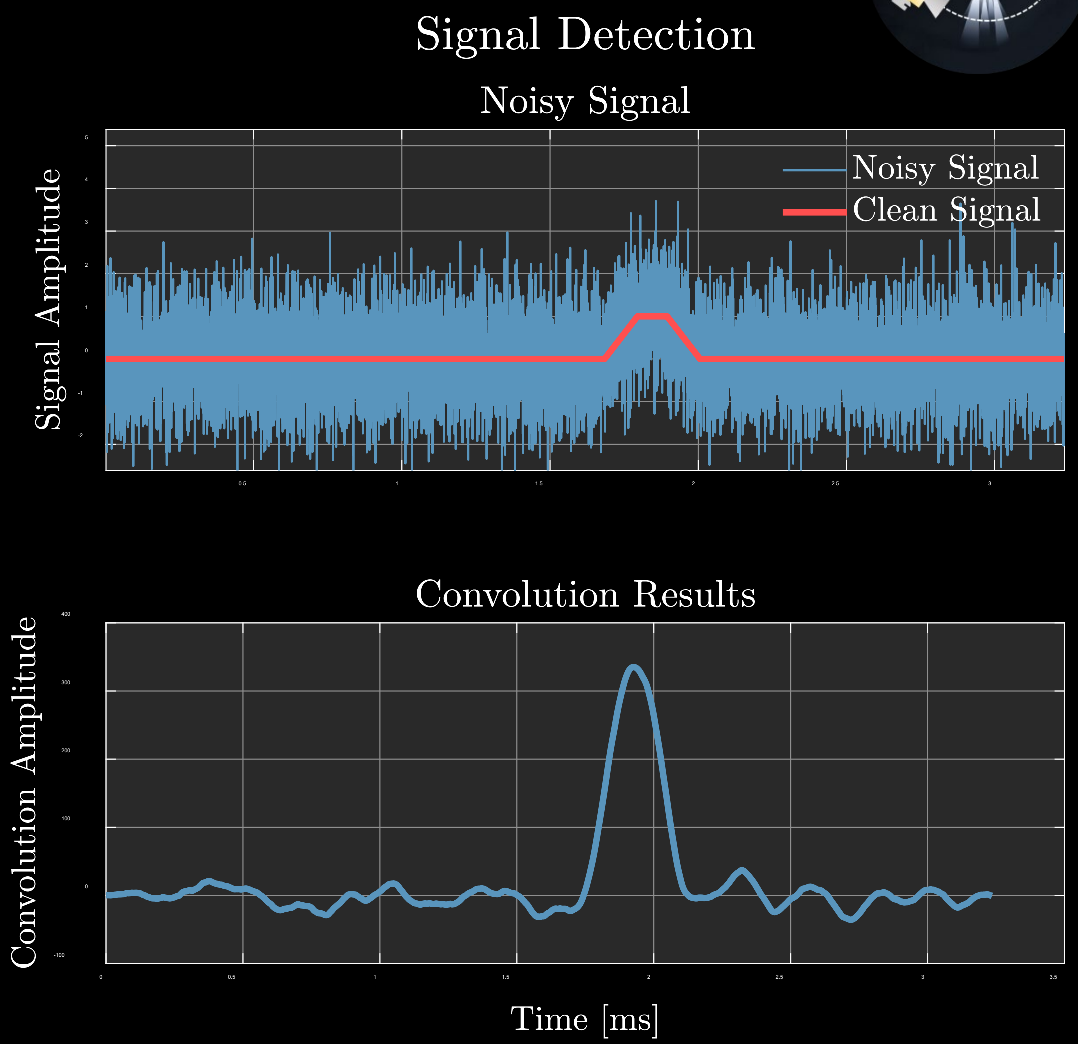




Matched Filtering

DR 2.4.1: Shall use matched filtering on induction line to detect signals with particles in the range of 100-300 m/s with charges between 0.05 - 0.5 fC

- Filter incoming data in software
- Detect events using matched filter (convolution)



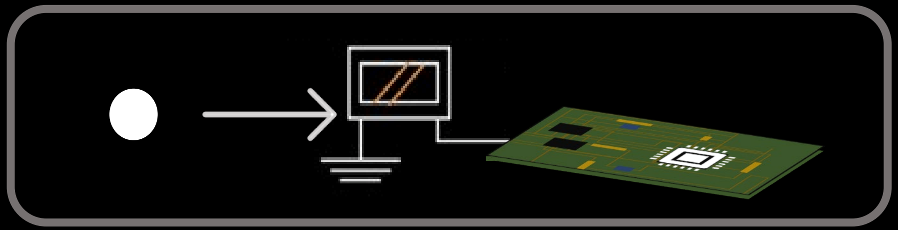
Verification & Validation

Verification & Validation

3 main tests:

1. Charge applied directly to electronics board
2. Physical particle detection in open-air conditions
3. Physical particle detection in vacuum chamber

Induction/Conduction Sensor

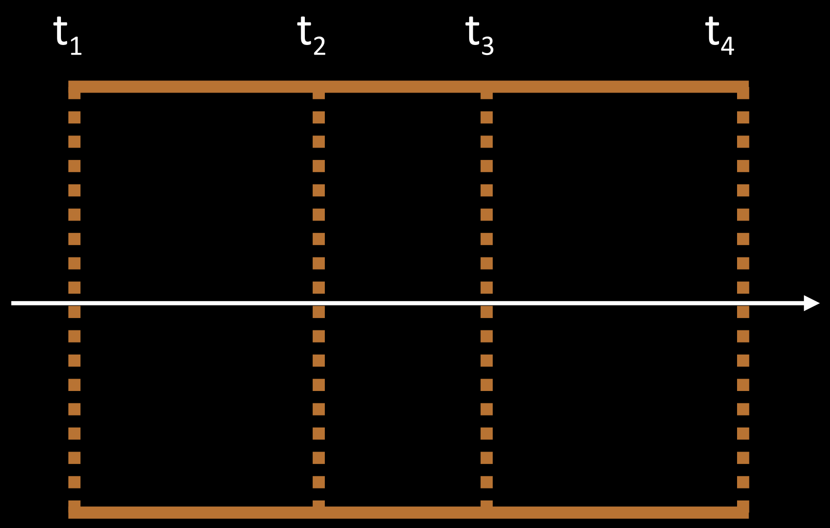


Vacuum Chamber

Direct Charge Application - Overview

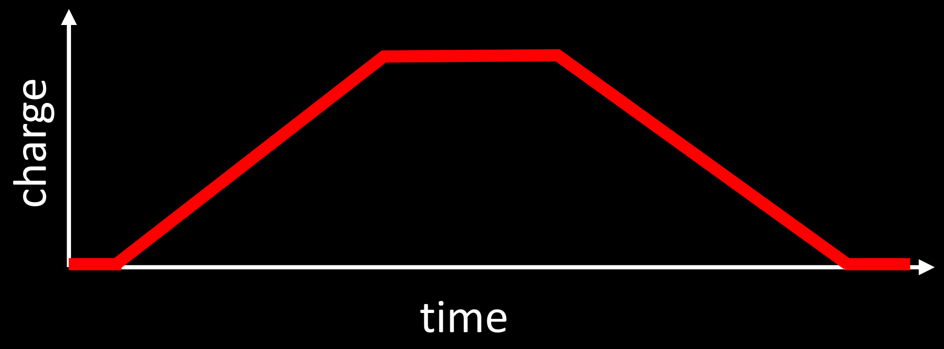
Purpose:

Demonstrate that system can detect particles of same size and speed as those around Enceladus



Requirements Satisfied:

- ☑ 1.2.1
- ☑ 1.2.2
- ☑ 1.2.4
- ☑ 2.2.2



Direct Charge Application - Validation

Process:

Use function generator to apply expected charge signal to simulate actual testing conditions

Success Criteria:

- Conduction circuit and software must correctly calculate charge given a known charge flux with a ±1% margin

- Induction circuit and software must correctly calculate charge and speed given a known injected charge with a ±1% margin

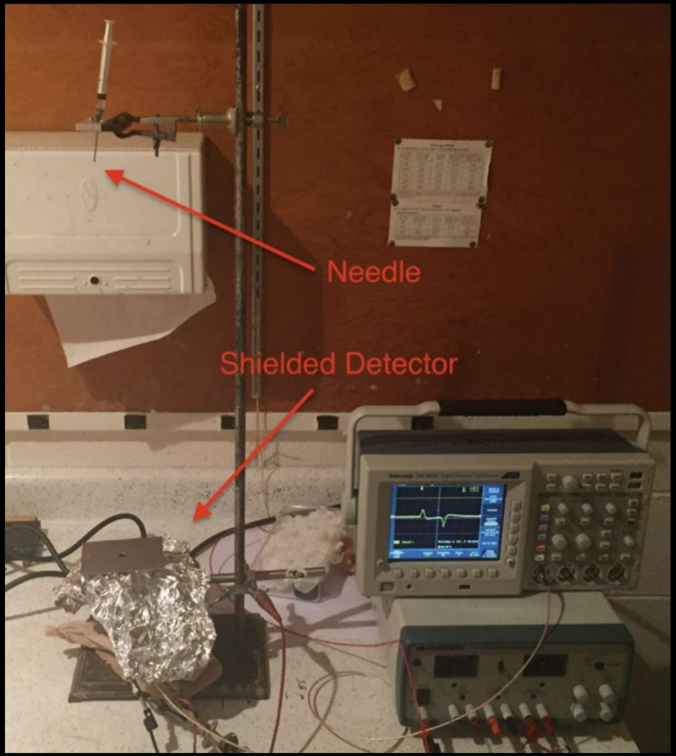
Open Air Physical Particle – Overview

Purpose:

Demonstrate that the system can detect the correct order of magnitude for the charge of a physical object

Requirements Satisfied:

- ☑ 1.1.1.1
- ☑ 3.1.1
- ☑ 3.5.1



Previous Experimental Setup

Phys. Teach. 58, 200 (2020);
https://doi.org/10.1119/1.5145417

Open Air Physical Particle – Validation

Process:

Apply charged water droplets to sensor surfaces using a needle and syringe

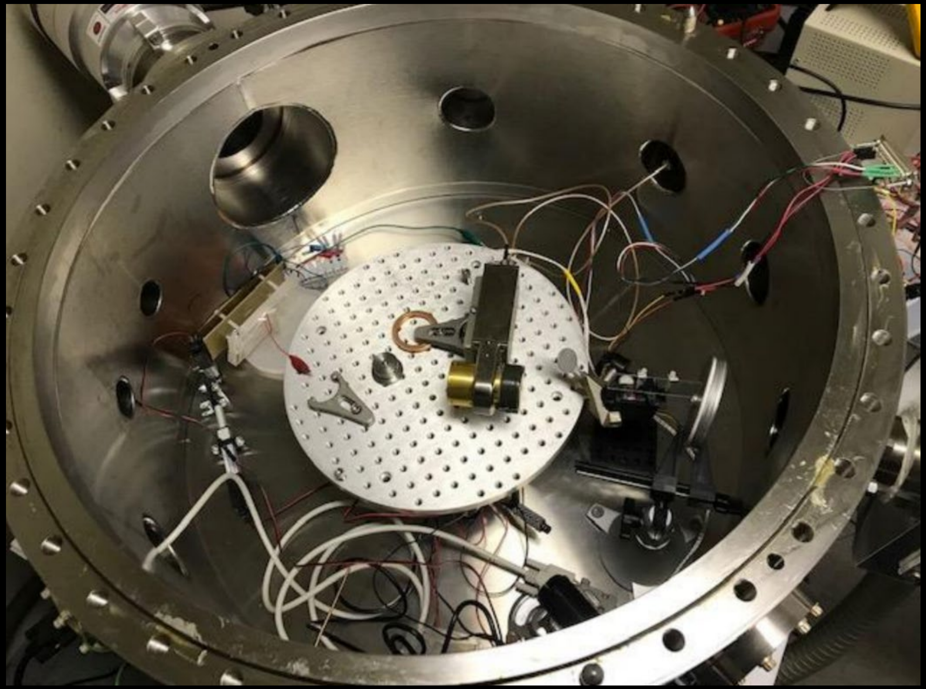
Success Criteria:

- Calculate a charge with ±1% variation using induction and conduction sensors
  - 18pC is experimental value found in previous experimentation
- Calculate speed of particle with ±1% margin using induction sensor

Vacuum Chamber - Overview

Purpose:

Demonstrate that sensor, under vacuum conditions, can detect particle size and speed using particles similar to those around Enceladus



Requirements Satisfied:

- ☑ MO.4
- ☑ 1.1.3
- ☑ 1.1.4
- ☑ 1.1.5

Vacuum Chamber - Validation

Process:

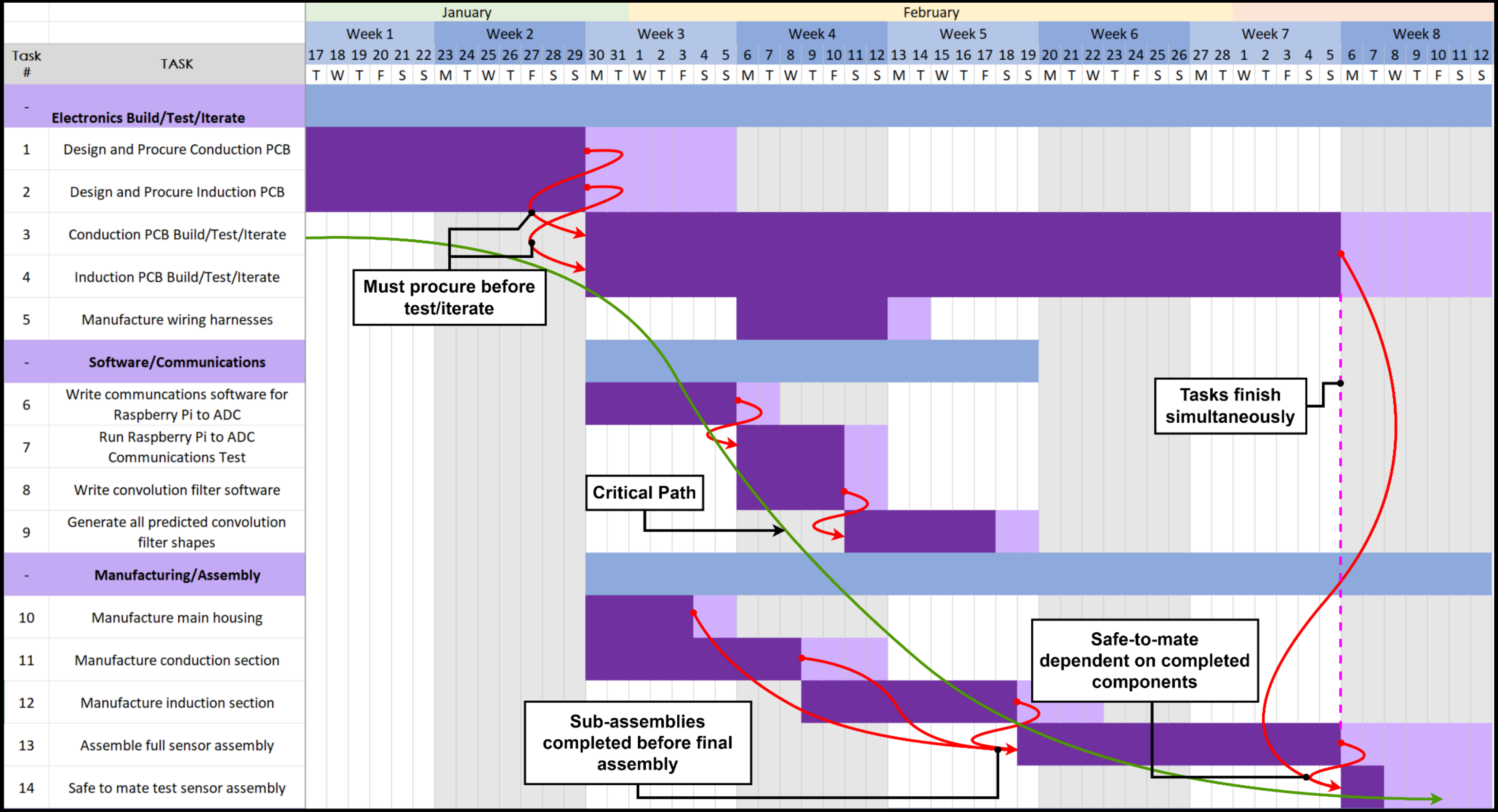
1. The sensor shall be placed within a vacuum chamber equipped with a particle launcher
2. Particles of 2-4 micron radius are accelerated towards the sensor at speeds of 100-300 m/s

Success Criteria:

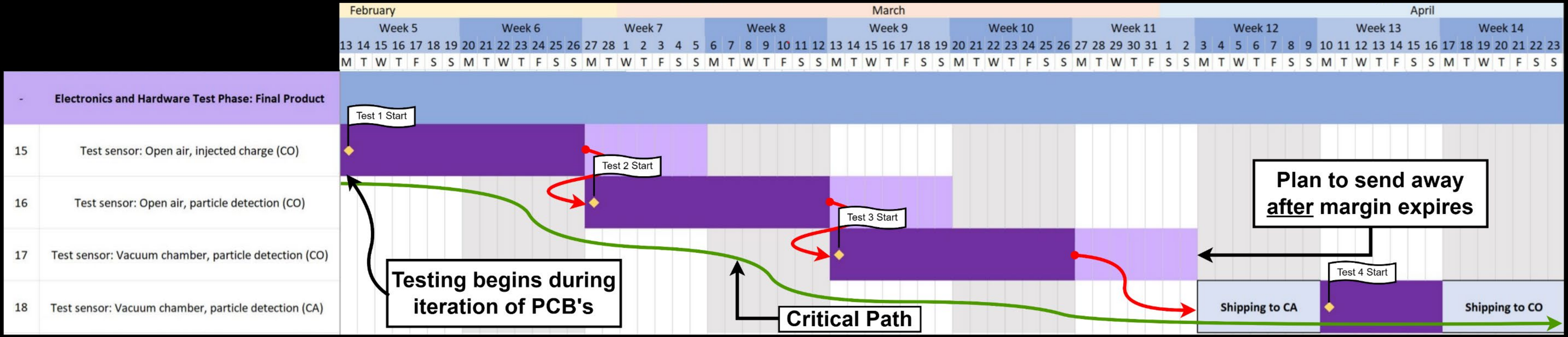
- Calculate charge of particle ±1% using induction and conduction sensors
- Calculate speed of individual particles ±1% using induction sensor
- The sensor is accurate up to ±60 degrees incident angle
- All heat is dissipated to surroundings

Project Planning

Work Plan: Manufacture/Assemble



Work Plan: Testing

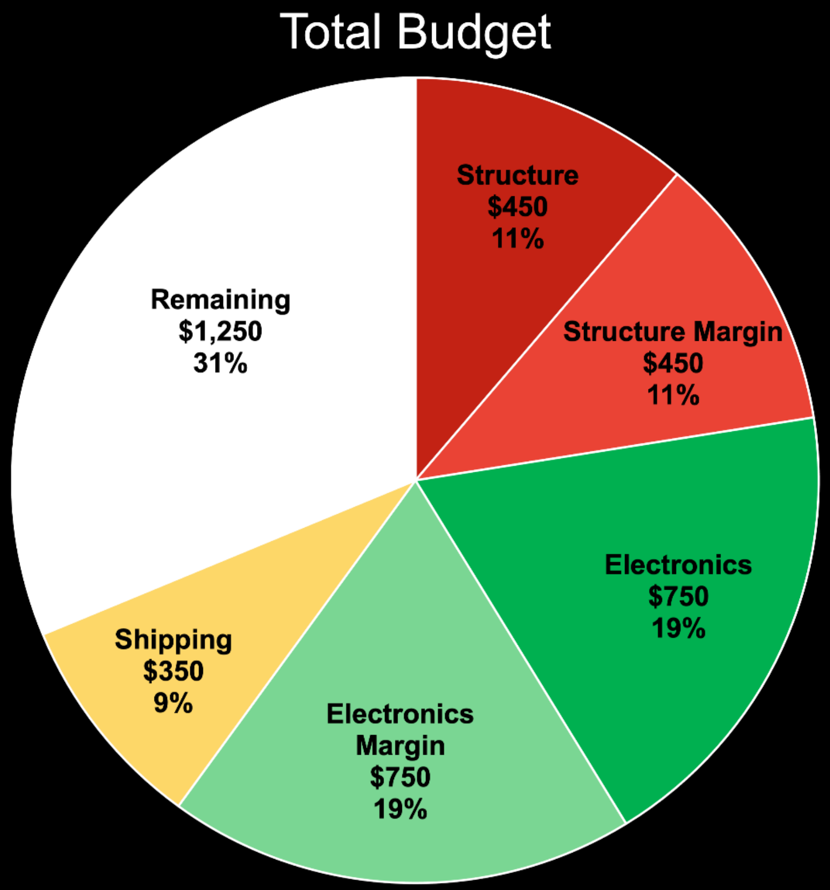


Testing Plan

Test	Date	Location	Notes
Direct Charge Application	February 13	Electronics Shop	-
Open-Air Physical Particle	February 27	Electronics Shop	-
Local Vacuum Chamber Test	March 13	LASP/Sternovsky	Pending approval
Vacuum Chamber Test	Shipping: April 3 Test: April 10	RadMet, San Mateo, CA	-

Cost Plan: Overview

Total Budget	$4000
Structures (Margin)	-$450 (-$450)
Electronics (Margin)	-$750 (-$750)
Shipping	-$350
Remaining	**$1250**



Cost Plan: Major Expenses

Major Electronics	Cost
Raspberry Pi 4	$180
4 Conduction PCBs	$80
4 Induction PCBs	$80
ADCs and Op Amps	$150
Misc. Capacitors and Resistors	$100

Major Structures	Cost
Aluminum Housing	$75
Copper Housing	$75
Copper Mesh	$30
Delrin Insulation	$25
Shielded Wire	$30

Thank you for listening!

Special thanks to:

Advisor: Dr. Erik Knudsen

Sponsor: Erik Buehler & ASTROBi Foundation

Course Coordinators: Dr. Kathryn Wingate & Chris Muldrow

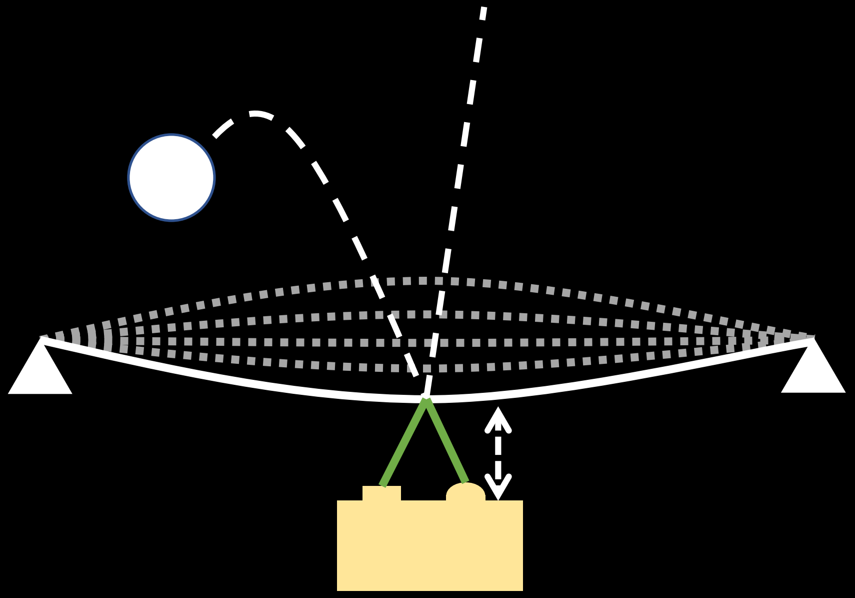
The Senior Project Advisory Board

Backup Slides and Slide Links

Charge Detection Versus Plate Deflection

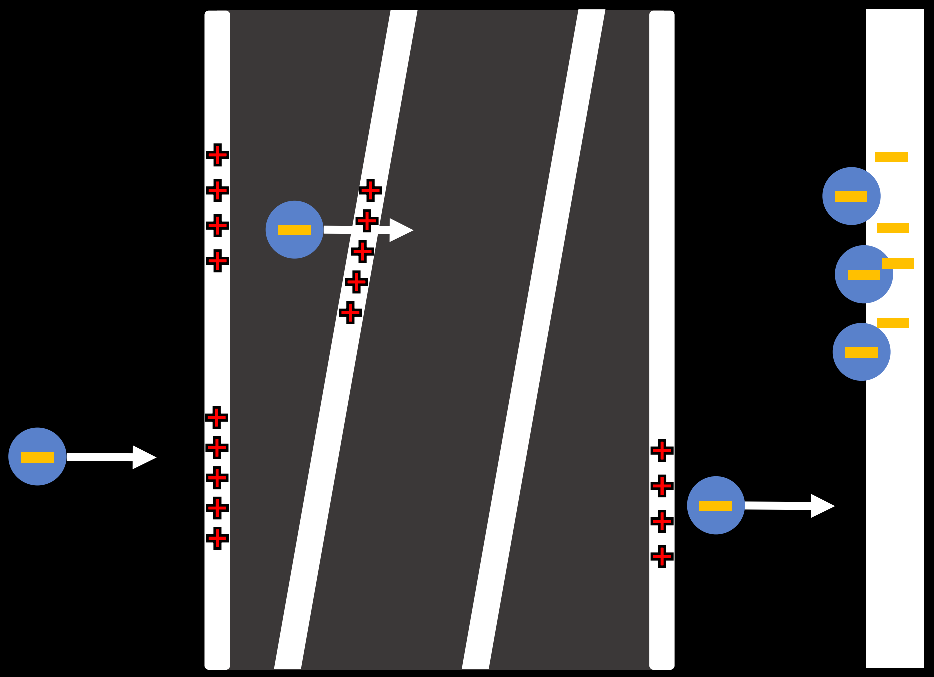
Deflection Based Detection

- Model impact surface deflection as particle collides with surface



Charge Based Detection

- Model induced charge as ice particle passes through the device



Impact Modeling

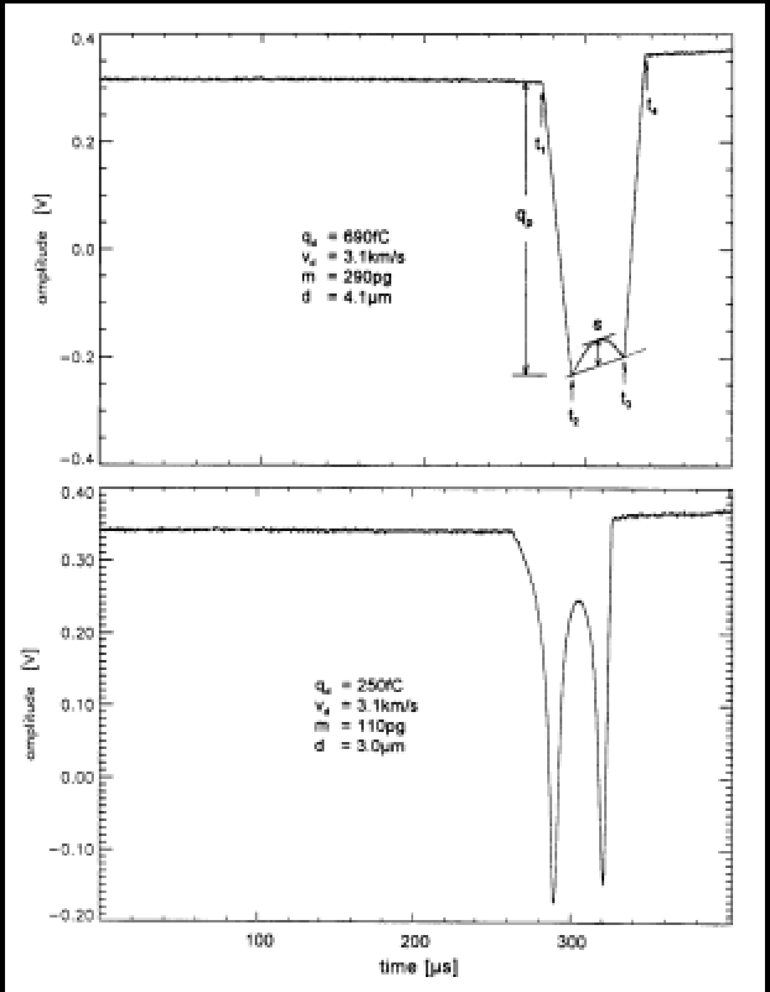
- Simulation
  1. Model impact surface as spring mass grid
  2. Center node is given a downward velocity such that momentum is conserved in an elastic collision
  3. Propagate system with ODE 45
- Results
  - Maximum deflection of +/- 0.55 microns
  - Occurs immediately after impact
    - Suggests boundary effects are of little importance

Acoustic Model Limitations

- Speed of propagation limited by number of points
  - Each simulation only propagates signal to neighboring nodes
  - More nodes = slower propagation
- Particle movement limited to vertical axis only
  - Found no significant lateral deflection during initial impact so was deemed unnecessary to allow simulation simplicity

Charge Model Limitations

- Charge model assumes infinite sensing planes
- Particle charge is completed inducted into planes, no charge is lost to grounded sensor box
- Will see dip in charge signal
  - Only important component of signal is max peak value which is not affected by this sag as this value is the particle charge



Cassini Cosmic Dust Analyzer Results[1]

[1] The charge and velocity detector of the cosmic dust analyzer on Cassini. Planetary and Space Science 50 (2002) 773 – 779 S. Auer et. Al.

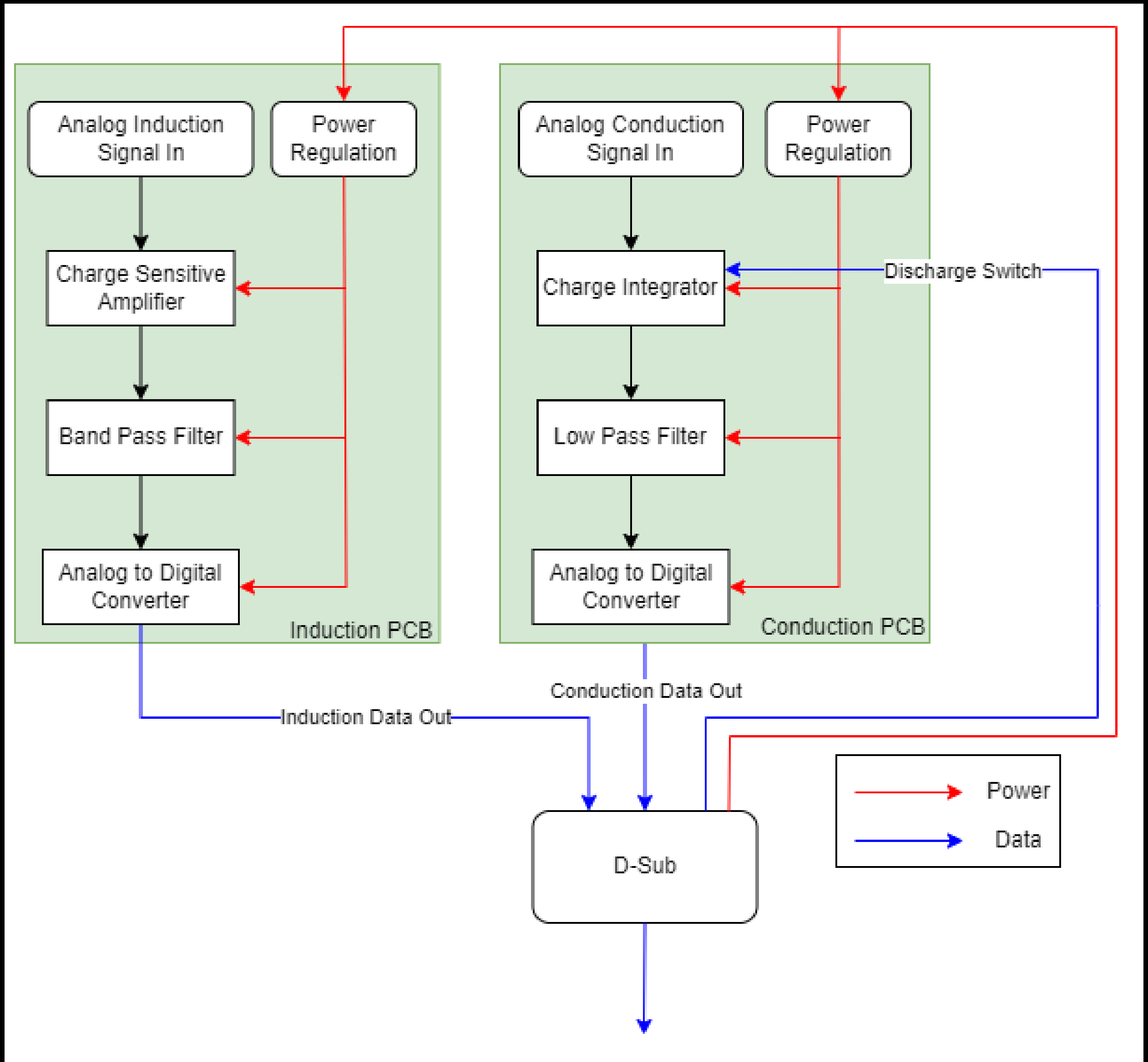
Electronics Design

Circuit Specifications

	Open Air - Conduction	Open Air - Induction	Vacuum - Conduction	Vacuum - Induction
Input Charge	50 18pC particles (0.9nC)	18pC	100 0.5fC particles (50fC)	0.5fC
Stages	1) Charge Sensitive Amplifier (CSA) 2) Low Pass Filter	1) CSA 2) Low Pass Filter	1) CSA 2) Low Pass Filter	1) CSA 2) Band Pass Filter 3) Voltage Amplification
Filter + Voltage Amplification	2 Stage $f_c = 200kHz$ Gain = 0	1 Stage $f_c = 60Hz$ Gain = 0	2 Stage $f_c = 200kHz$ Gain = 400	1 Stage $f_1 = 350$ Hz $f_2 = 8.5kHz$ Gain = 100 + Secondary Gain of 400
Voltage Output	4.09V	2V	4 V	4V

PCB Functional Block Diagram

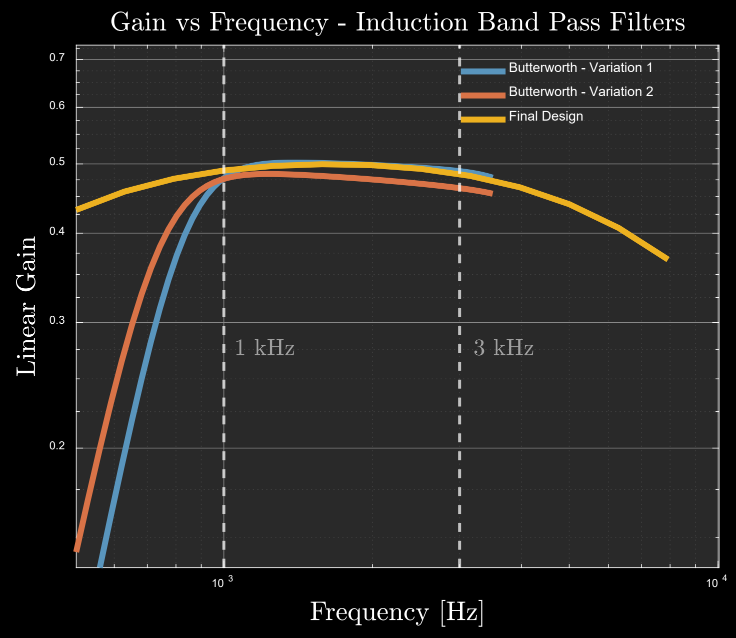
- Two PCBs inside the vacuum chamber
- D-Sub leads to and from the Raspberry Pi
- Each PCB will have a Vacuum and Open-Air Design
    - 4 total PCBs designed

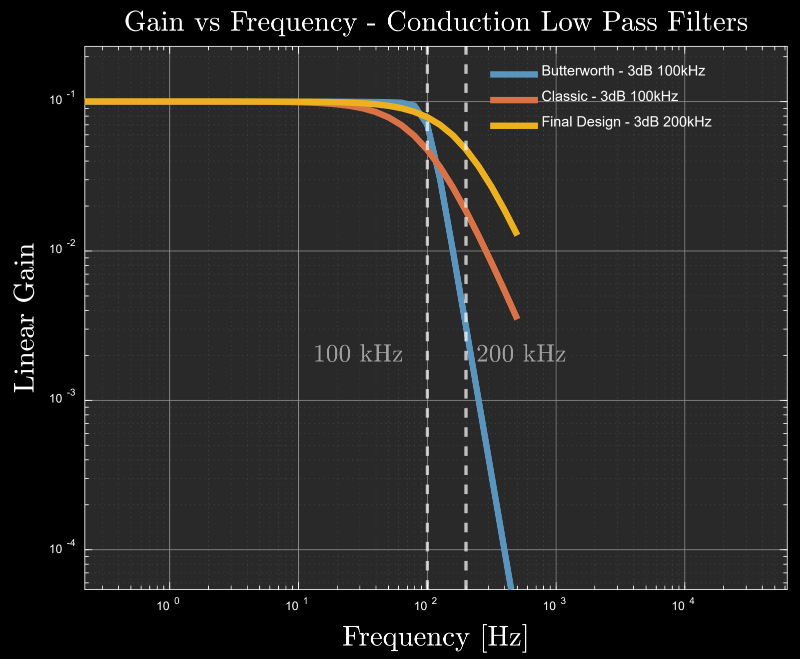


Filter Creation

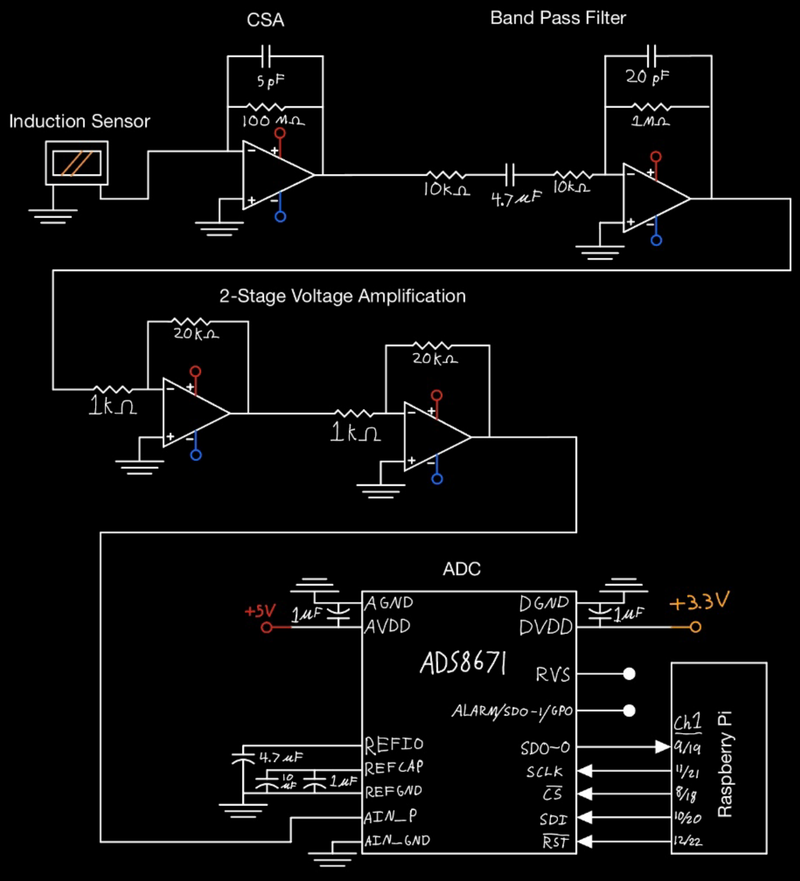
- Anti-Aliasing / Lab Noise filtering

Final Design	Open Air	Vacuum
Induction	Low Pass 1 Stage Gain = 0 $f_c = 60Hz$	Band Pass 1 Stage Gain = 100 $f_1 = 350\ Hz$ $f_2 = 8kHz$
Conduction	Low Pass 2 Stages Gain = 0 $f_C = 200kHz$	Low Pass 2 Stages Gain/Stage = 20 $f_c = 200kHz$

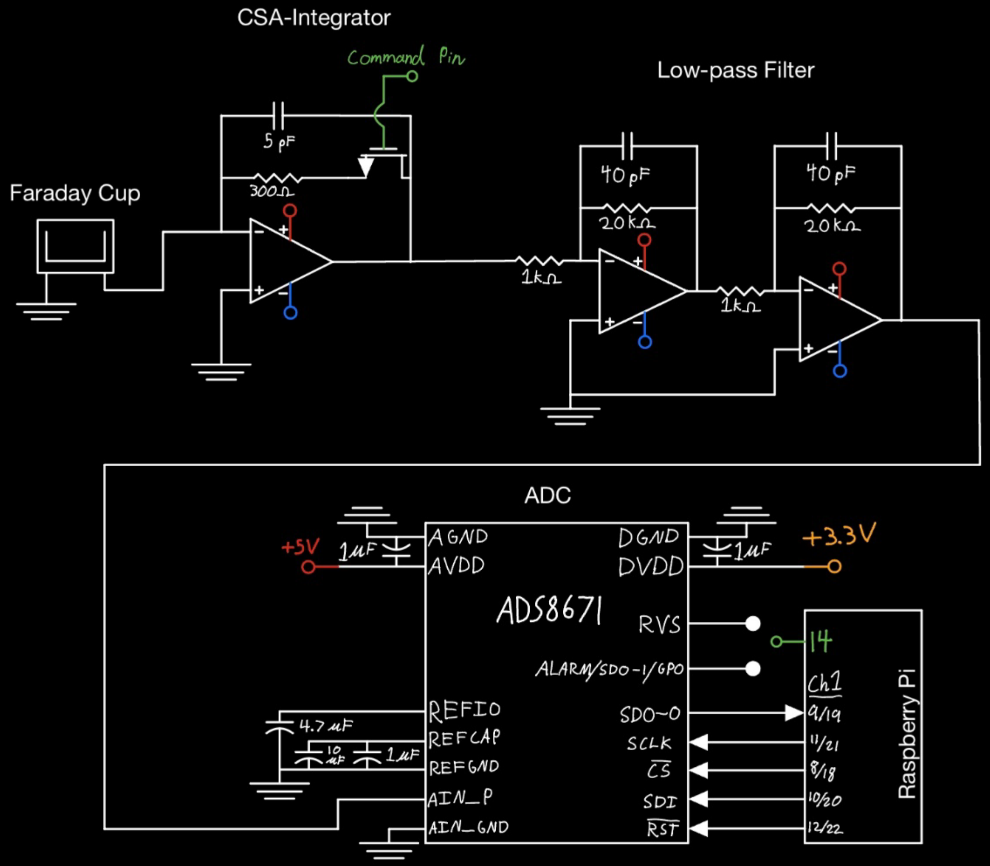




Vacuum Circuit Schematics



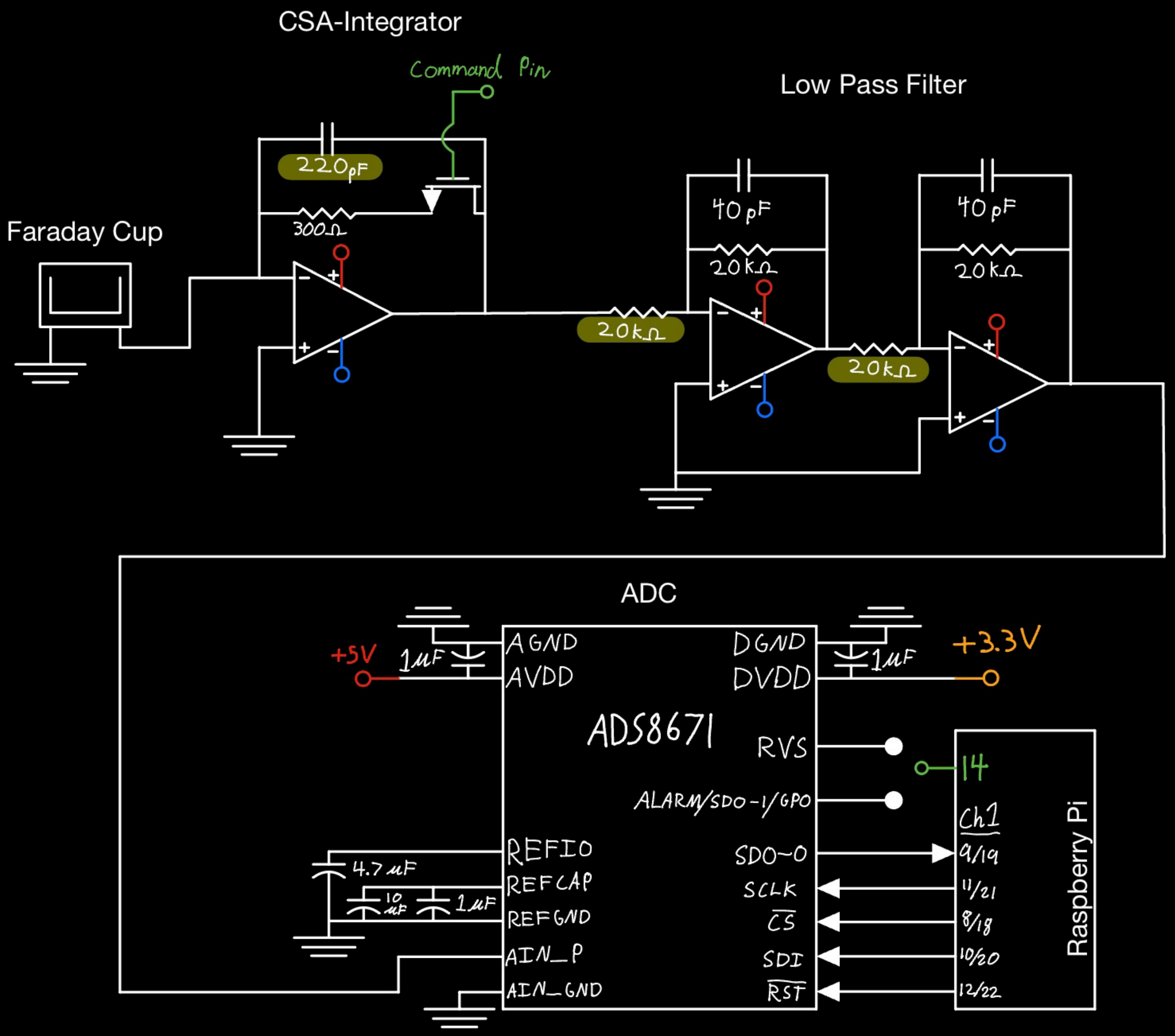
Induction Circuit



Conduction Circuit

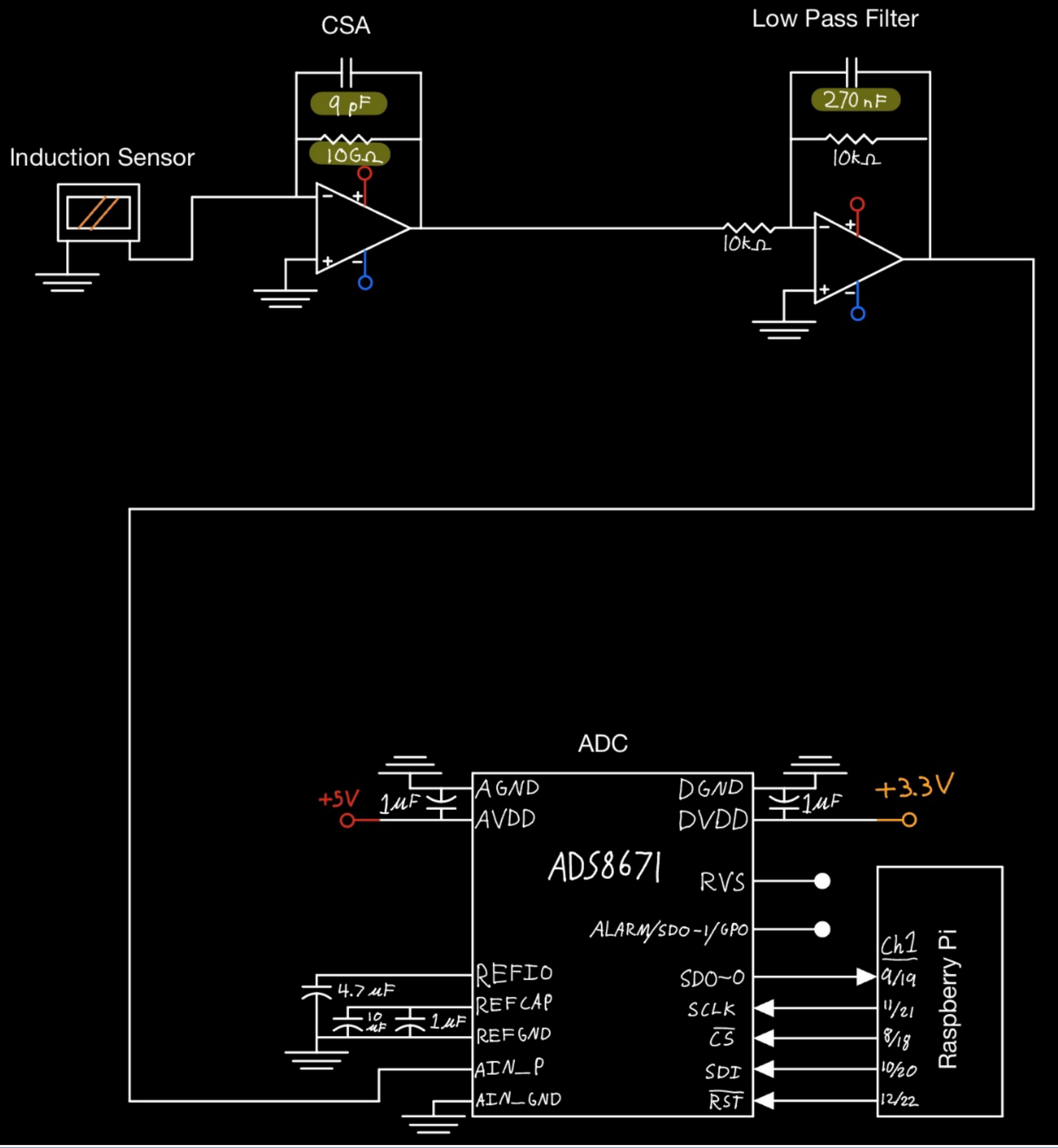
Note: All grounds are tied

Open Air Test - Conduction Circuit



Note: All grounds are tied

Open Air Test - Induction Circuit

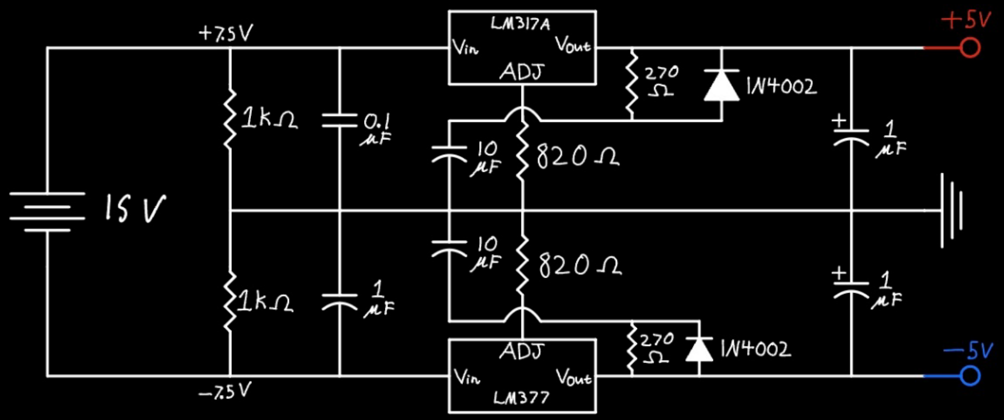


Note: All grounds are tied

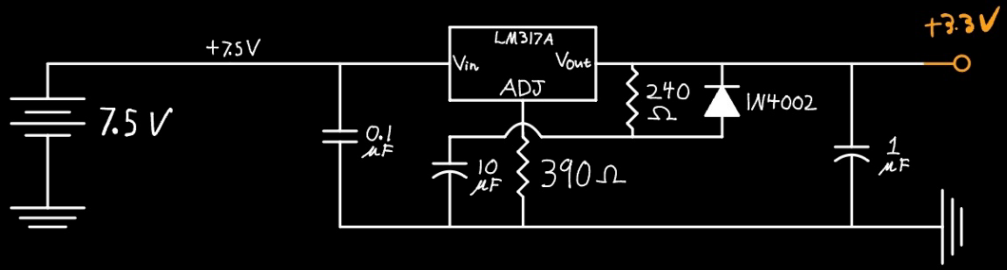
Power Regulation Circuits

- Identical Power Regulation on all PCBs
- 3.3V Regulator
    - 7.5V input from voltage divider stage of ±5V regulator

5V Regulator



3.3V Regulator



Electronics Testing

CSA Testing- Component Information

Circuit Values	
Vin	1 V
R	120 kΩ
C1	1 µF
C2	22.5 µF

Trial 1 - 1 µC

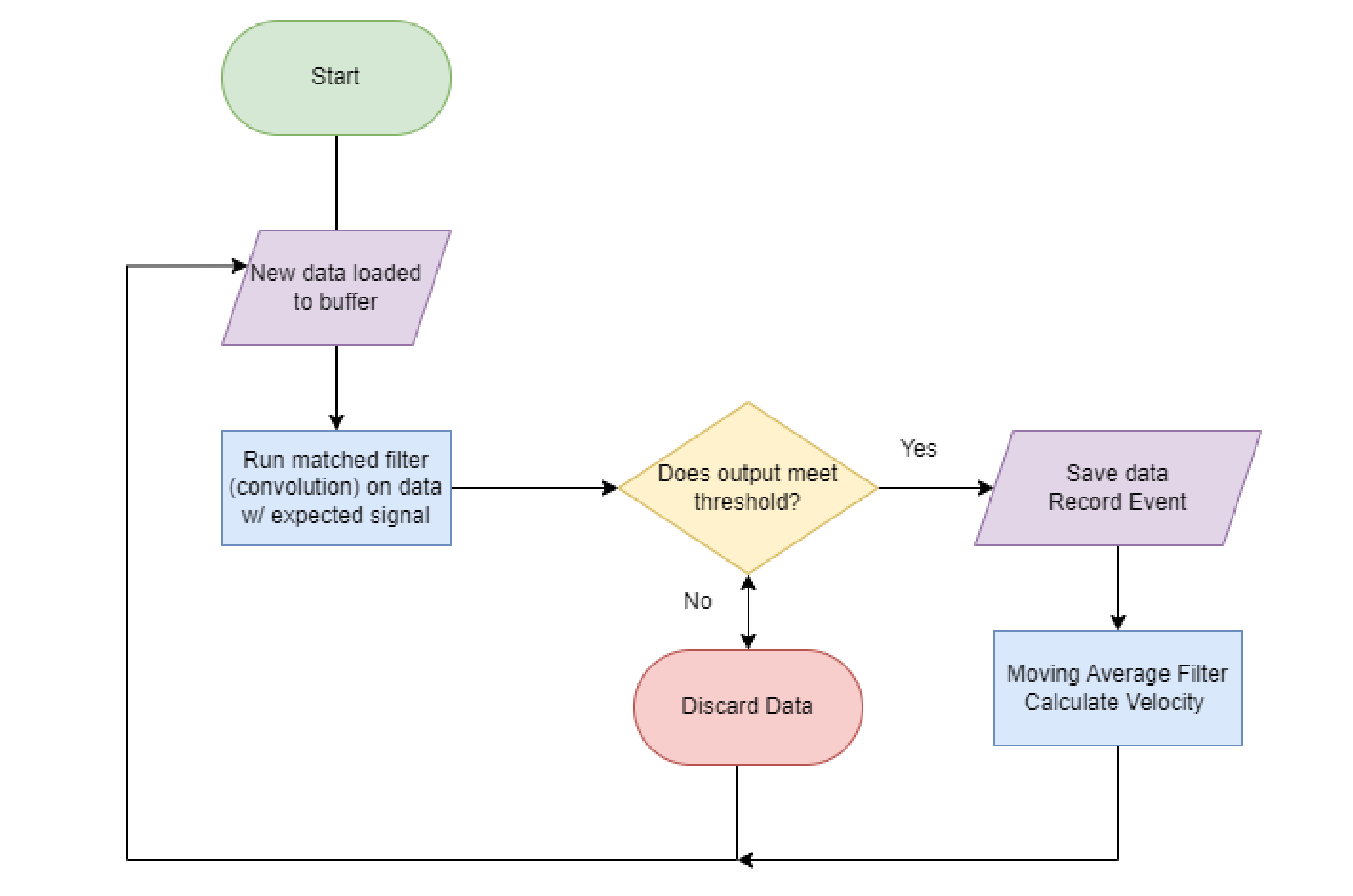
Circuit Values	
Vin	50 mV
R	220 MΩ
C1	10pF
C2	10pF

Trial 2 – 0.5pC

Circuit Values	
Vin	5 mV
R	220 MΩ
C1	10 pF
C2	10 pF

Trial 3 – 50fC

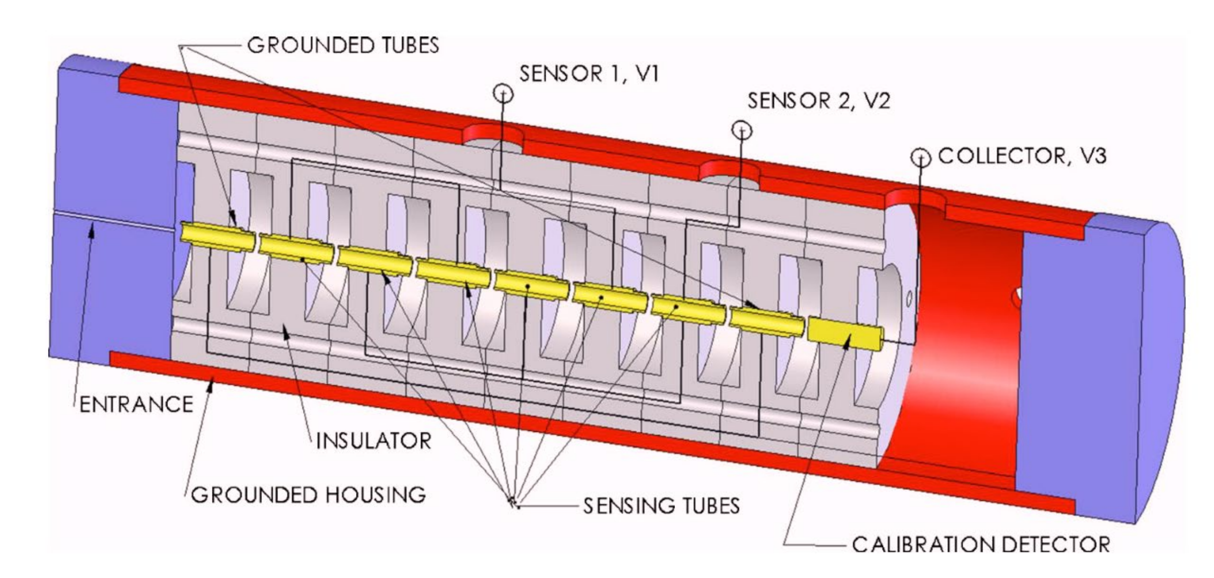
Code Flow Chart



Induction Type Trade

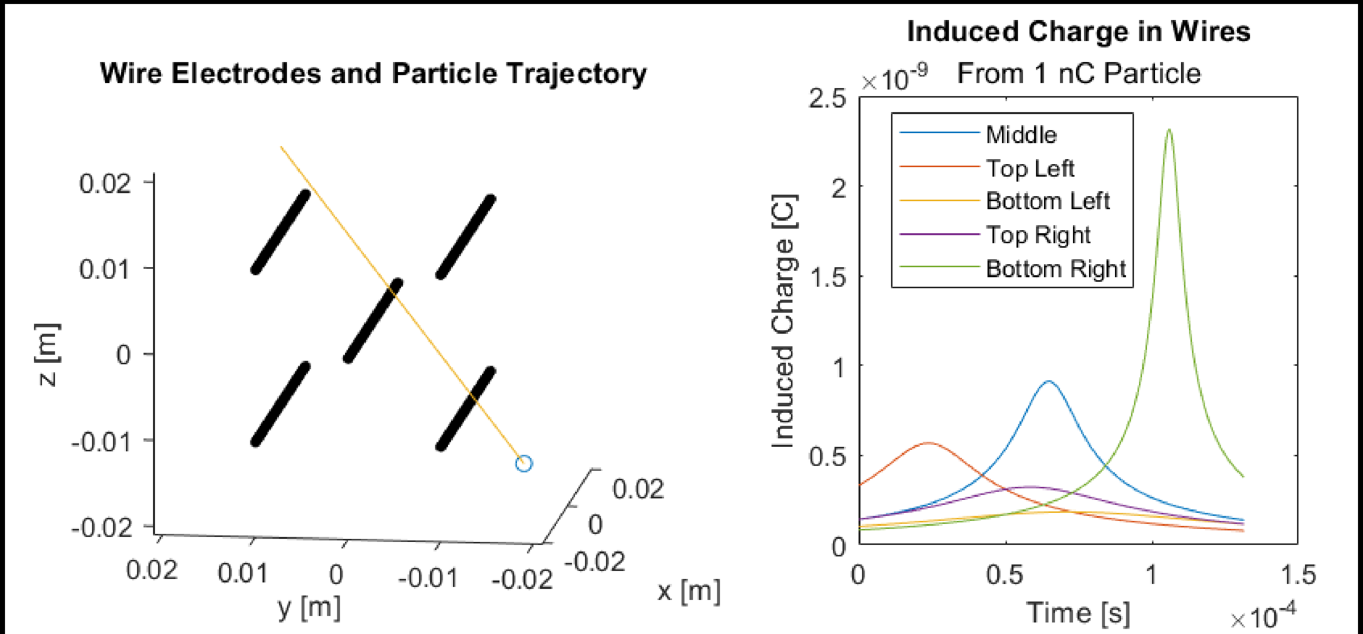
Induction Tube

- High sensitivity
- Particles must have almost entirely axial velocity



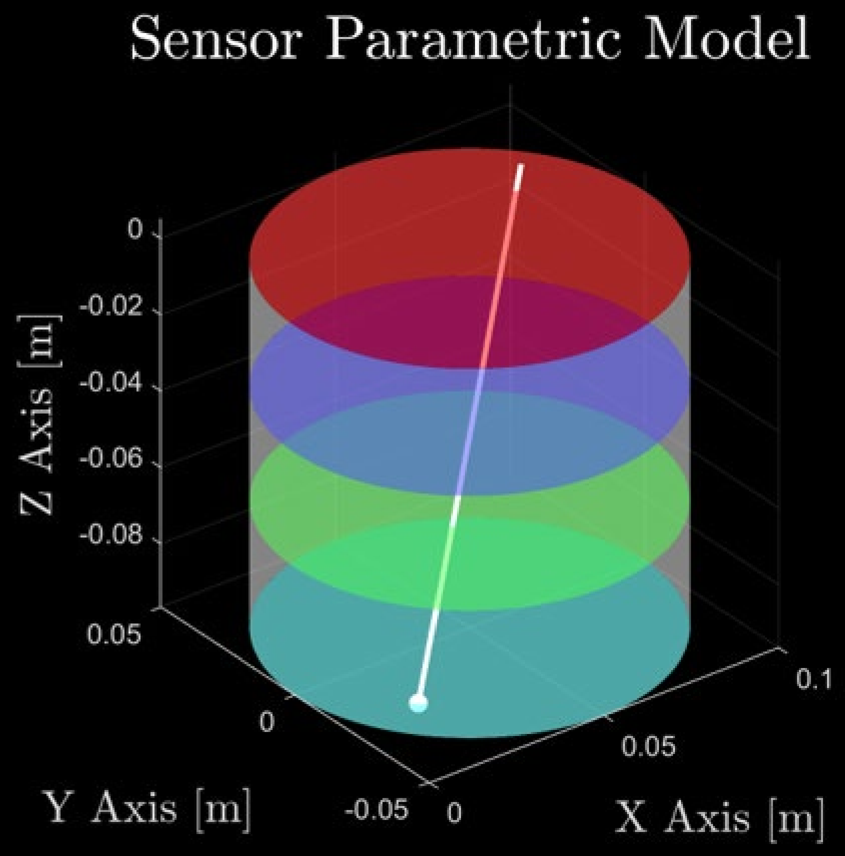
Wire Electrode Array

- Individual Wires
- Can calculate trajectory
- Less sensitive
- Wide range of impact angles
- Heritage – Dust BUSTER



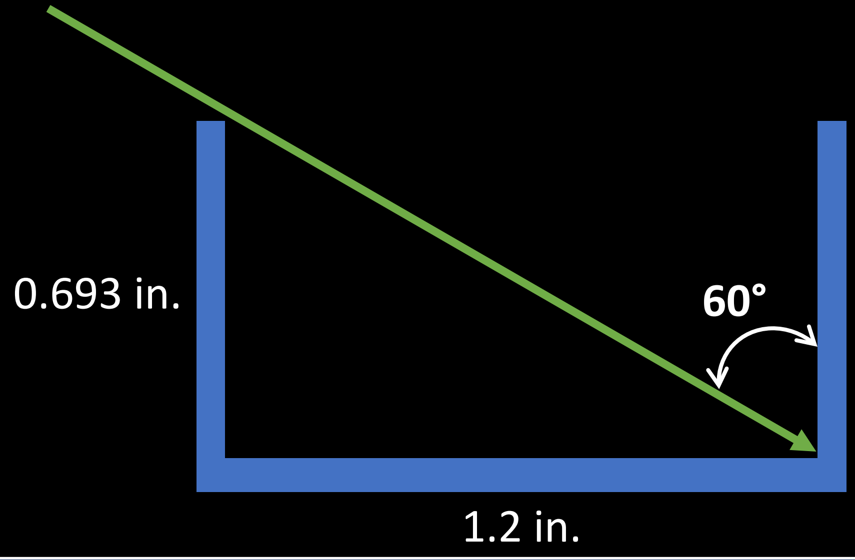
Mesh Grid

- More sensitive to smaller particles than individual electrodes
  - Less sensitive than tube
- Wide range of impact angles
- Flight Heritage - Cassini

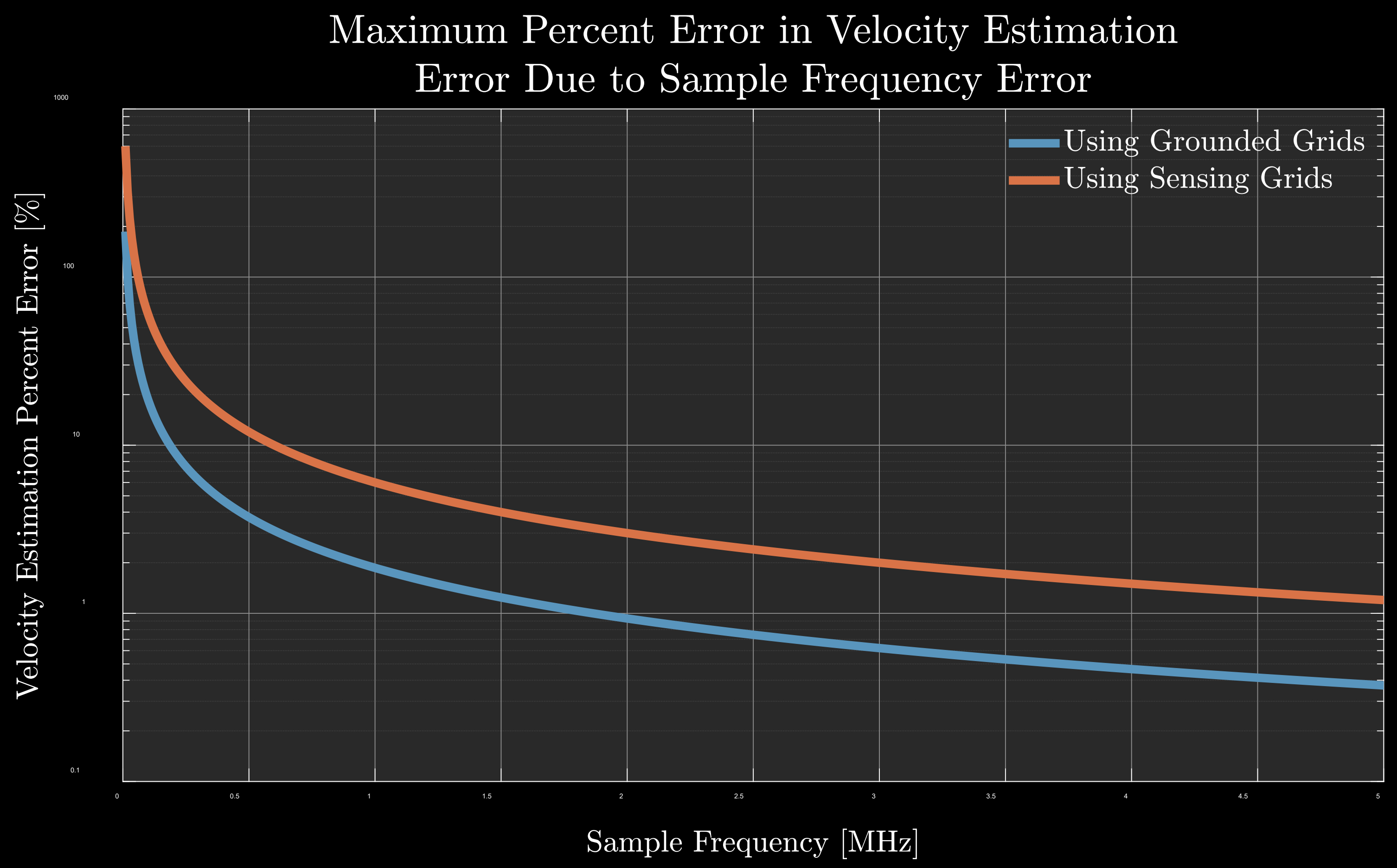


Key Requirement: Incident Angle

- Sensor shall detect particles with incident angles between 0 and 60 degrees
  - 0 degrees is defined as perpendicular to the sensor plate
- Conduction section geometry will capture all particles in this range



Sampling Frequency Models

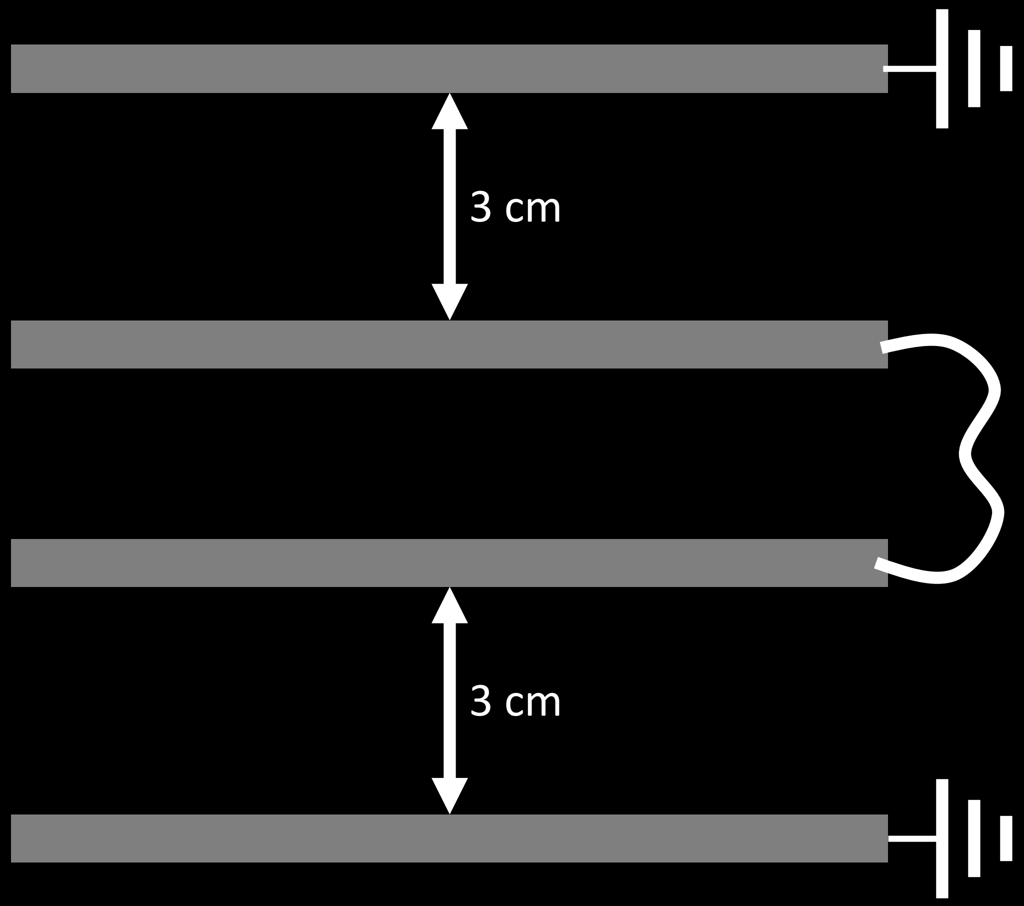


Sensor Stray Capacitance

- Capacitance of sensor relates to sensor noise
  - Should be less than 8 pF according to Dr. Zoltan Sternovsky who has designed similar detectors
- Sensor acts as two capacitors in parallel
- Due to Miller Effect this capacitance is virtually grounded and does not affect measurement, just contributes to noise

Per Sensing Plane: $C_i = \frac{\epsilon_0 \cdot A}{d} = 1.474 \cdot 10^{-12}\ F = 1.47pF$

Total: $C_t = 2 \cdot C_i = 2.95\ pF < 8\ \text{pF}$



Risk Matrix Criteria - Probability

What is the Probability the Risk Will Happen?		
Level 1	Not Likely	Avoid or mitigate risk with standard practices
Level 2	Low Likelihood	Create plan to mitigate risk with minimal oversight
Level 3	Likely	Workarounds must be applied to mitigate associated risk
Level 4	Highly Likely	Cannot mitigate this type of risk, different approach may be successful
Level 5	Near Certainty	Cannot mitigate this type of risk, no workarounds available

Risk Matrix Criteria - Impact

Given the Risk is Realized, what would be the Magnitude of Impact?			
Level	Technical	Schedule	Cost
1	Minimal or no impact	Minimal or no impact	Minimal or no impact
2	Slight alterations required	Minor slip in schedule, remains within margin	Slight increase in budget
3	Components must be altered or added	Additional activities required to recover	Serious impact on budget plans
4	Unacceptable, but workarounds available	Impact on program critical path	Little to no margin remaining in budget
5	Unacceptable, no alternatives exist	Cannot meet major program milestone	Budget exceeds allowable amount

Component Selection

ADC Selection Trade

Name	Sample Rate (0.35)	Resolution (0.2)	SNR (0.15)	Programmable (0.3)	Score (Out of 5)
ADS 7028	4	3	2	1	2.6
ADS 7951	4	3	3	5	3.95
ADS 8671	4	3	4	5	4.06

ADC Selection Trade Scoring

Score	Sample Rate	Resolution	SNR	Programmable
1	< 1 MSPS	8 Bits	< 60	NO
2	-	10 Bits	60 - 70	-
3	-	12 Bits	70 - 80	-
4	1 MSPS	14 Bits	80 - 90	-
5	> 1 MSPS	16 Bits	90+	YES

MOSFET Selection

- BSS123 MOSFET
- Low leakage current MOSFET
- Keeps maximum amount of charge across capacitor to minimize charge dissipation
- 50 nA leakeage current

Manufacturing

Insulating Bracket for Copper Mesh