Low-Pressure IMS Construction

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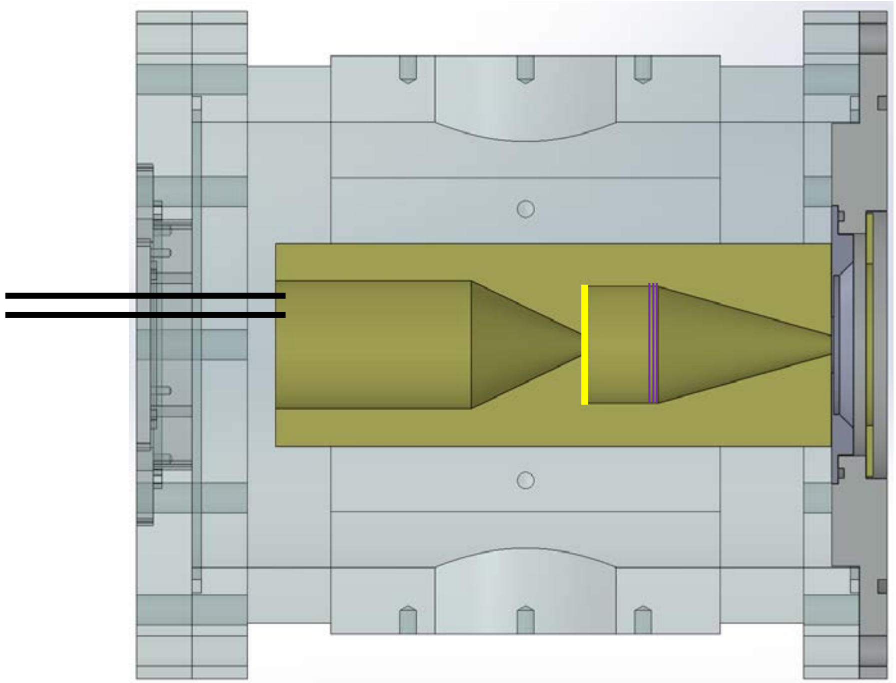
Table of Content

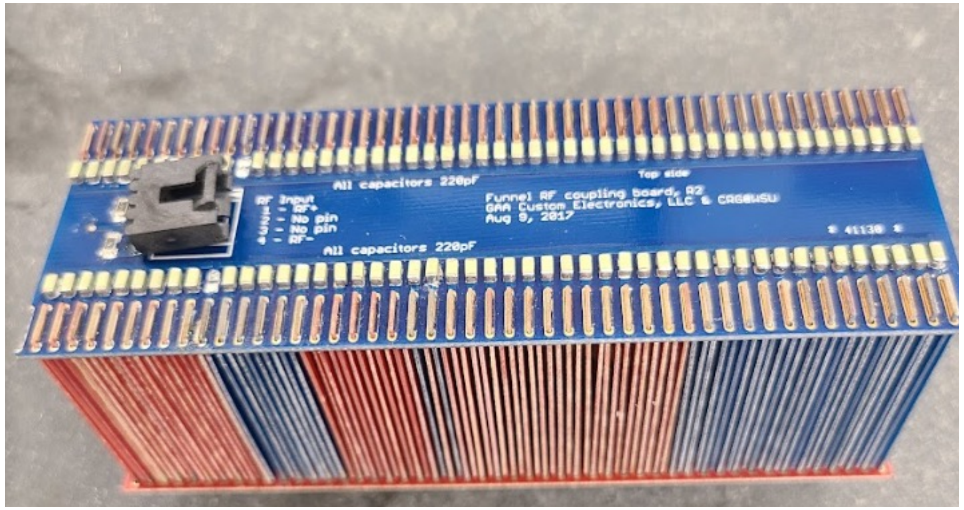
Low-Pressure IMS Construction: Front Ion Funnel

Front Funnel

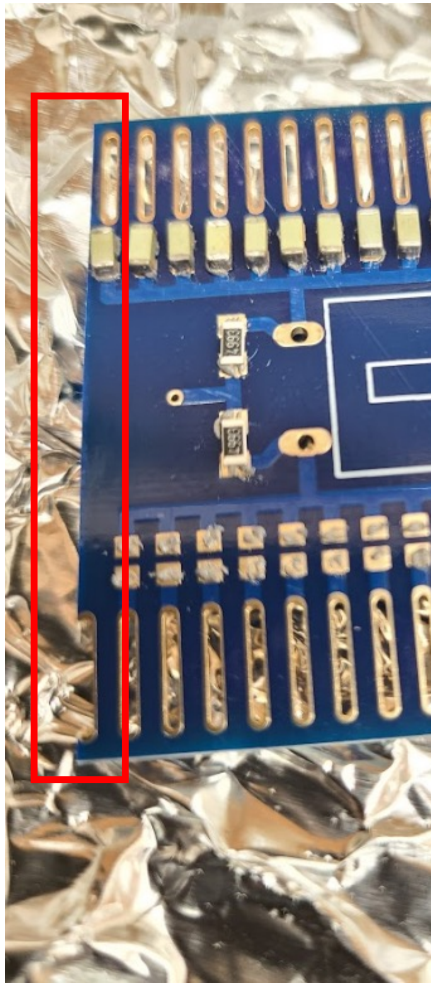
- Entirely comprised of PCB electrodes
  - Relatively low-cost
  - Reproducible
  - Ease of assembly and *maintenance*

700 – 900 kHz and up to 250 V_{P2P}



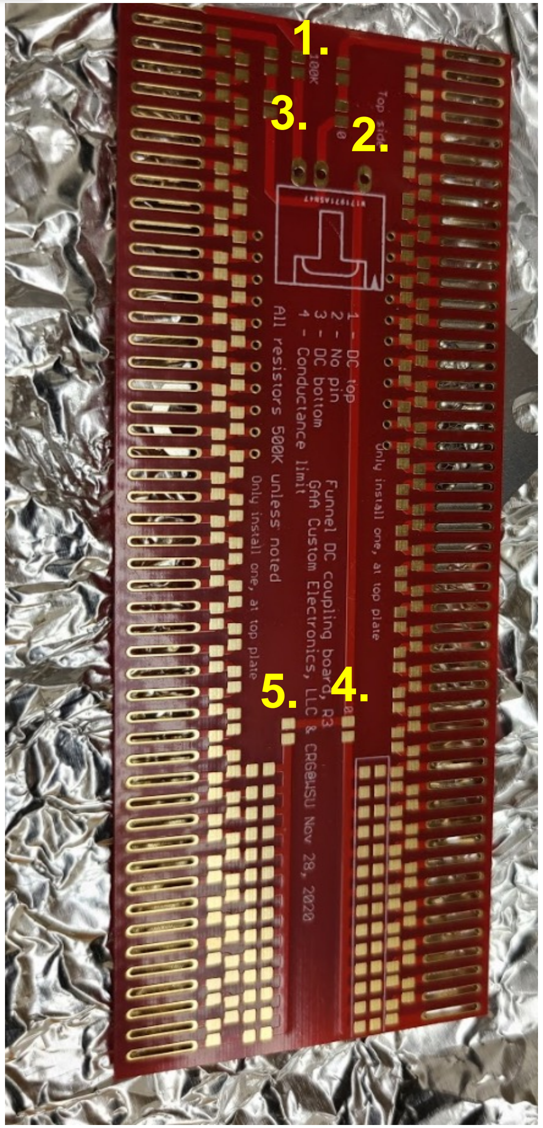


Trim PCB Boards



- When ordered, both PCBs are slightly oversized, and must be trimmed to size.
- Shown is the ready to use RF board with the last electrode partially removed.
- Our lab uses a gravity shear to remove the excess.

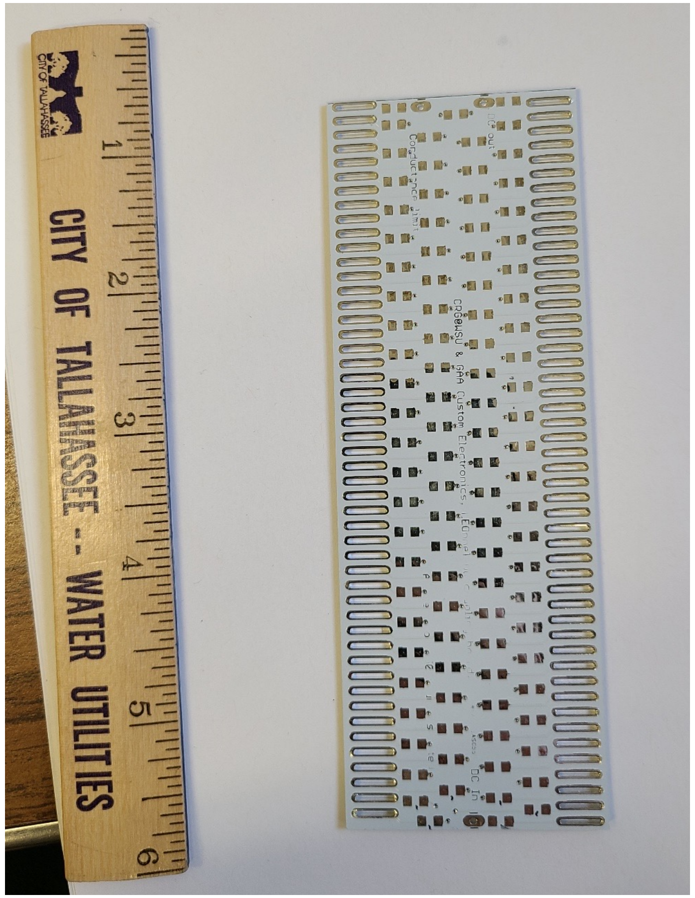
Front Funnel DC Board



Gen 1

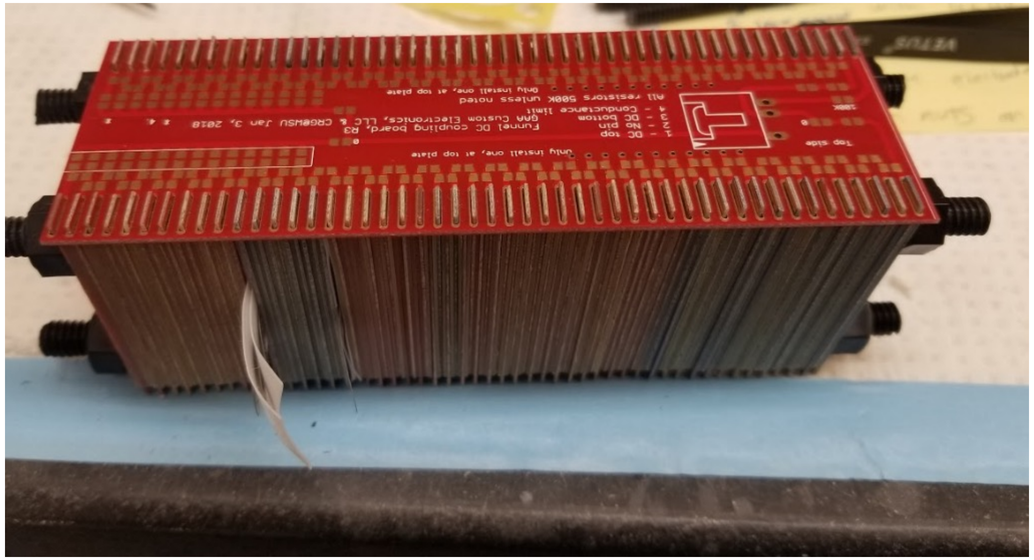
- Gen 1 board requires resistors of variable values to maintain correct voltages on both sides at marked locations.
- **1**.= 100 kΩ
- **2**.= 0 Ω
- **3**.= 250 kΩ
- **4**.= 0 Ω
- **5**.= 250 kΩ

- Gen 2 board all resistors are the same.



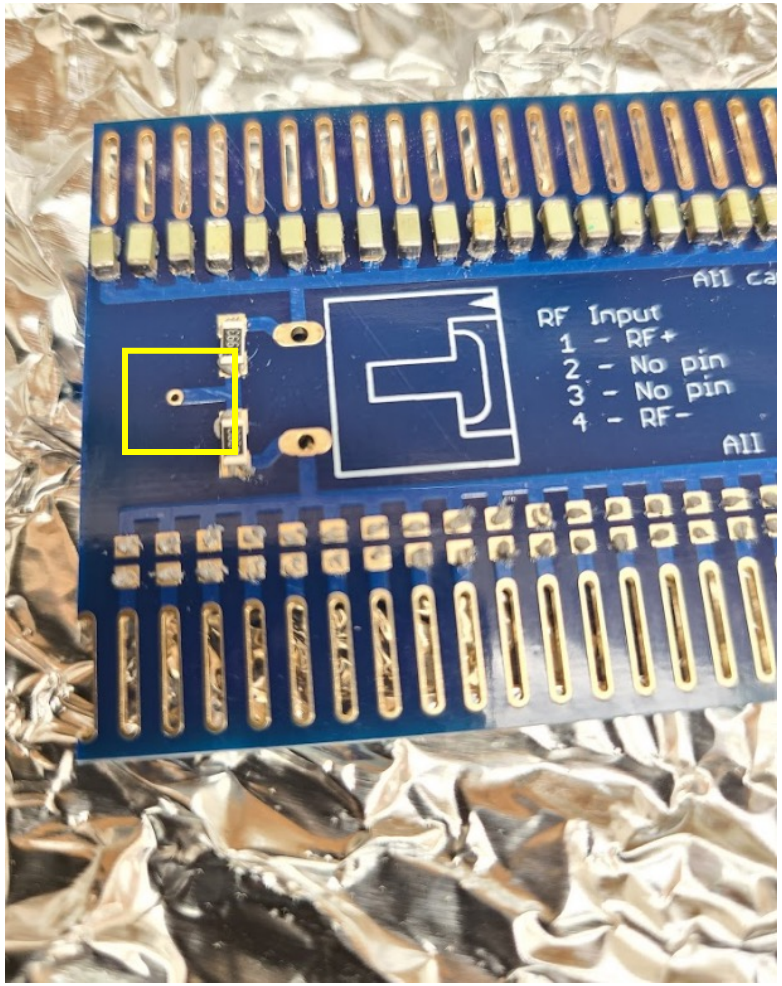
Gen 2

Front Funnel



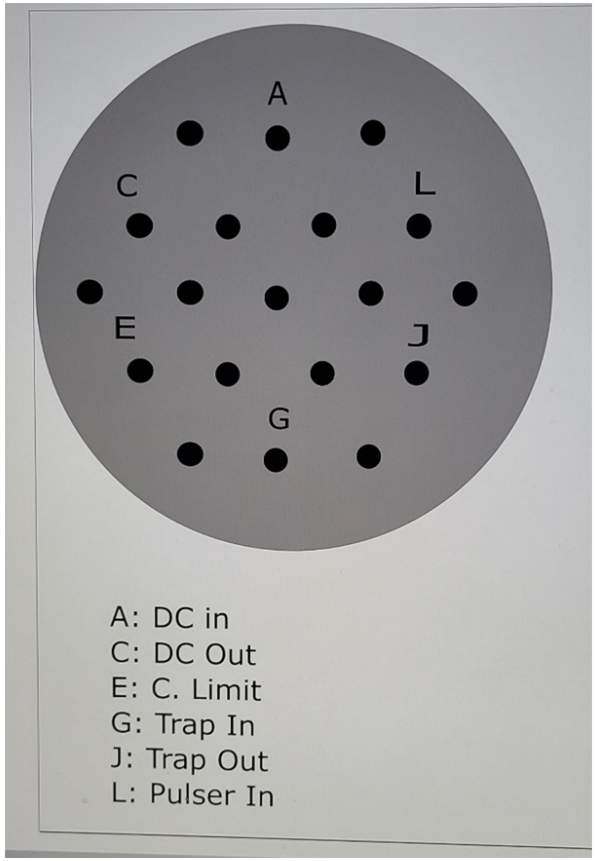
- Resistors are soldered into place
- Electrodes are soldered into place after careful alignment. (A 3d printed cone helps maintain exact alignment of electrodes)
- Ensure any ion gates are in line (grid pattern overlaps cleanly)
- Adding spacers (~3) on either end of funnel helps to not compress the electrodes during soldering assembly.
- When applying Molex connectors for DC voltages, remove any unused pins from the connector.

Front Funnel RF Board



- Place capacitors carefully, solder electrodes at same time as DC board
- Ensure the two resistors are in place (resistors are of same resistance as DC board)
- If funnel is floated, connect a wire from middle of the DC board to the marked spot on the photo
- When applying the Molex in for RF in and RF out, remove any unused pins from the connector.

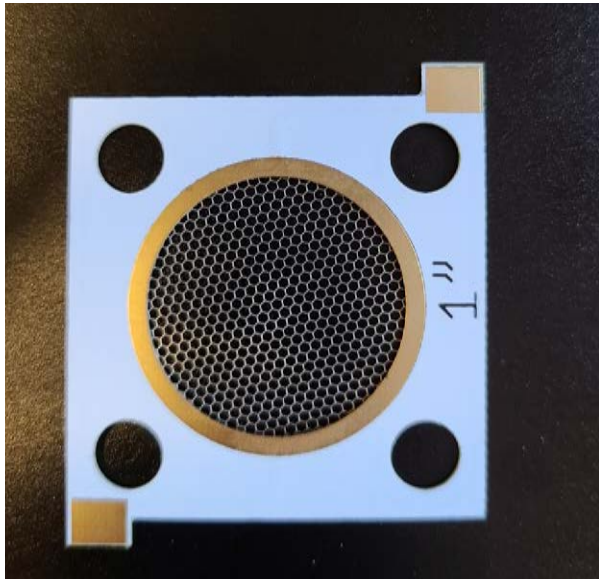
Front Funnel Electrical Connections



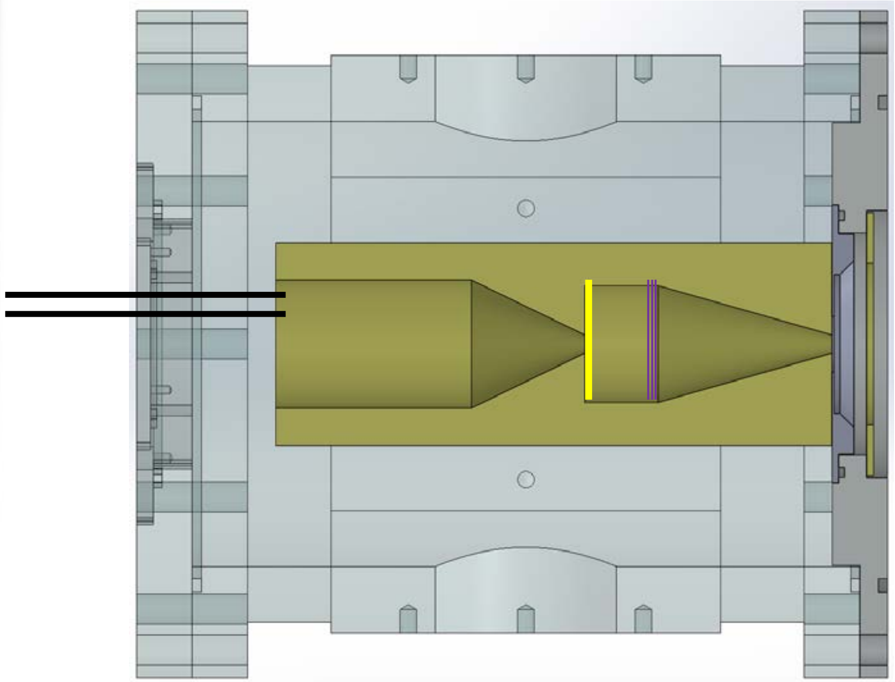
- Representative connections will change depending on electrical connectors used.
- This schematic was for the original ion trap funnel using a 19-pin feedthrough.
- Utilization of different configurations will change electrical connections, ensure proper documentation during assemble of electrical components.

Front Funnel

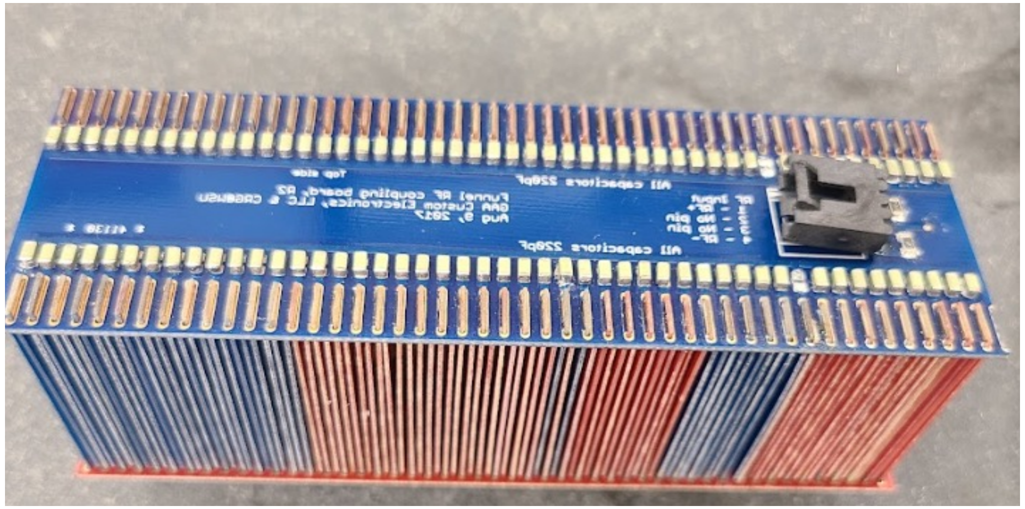
- Ion gates are comprised of stainless-steel mesh spot welded onto a PCB electrode
- Ensure that electrical connections are maintained as intended, and no secondary path is created.



Ion Gate



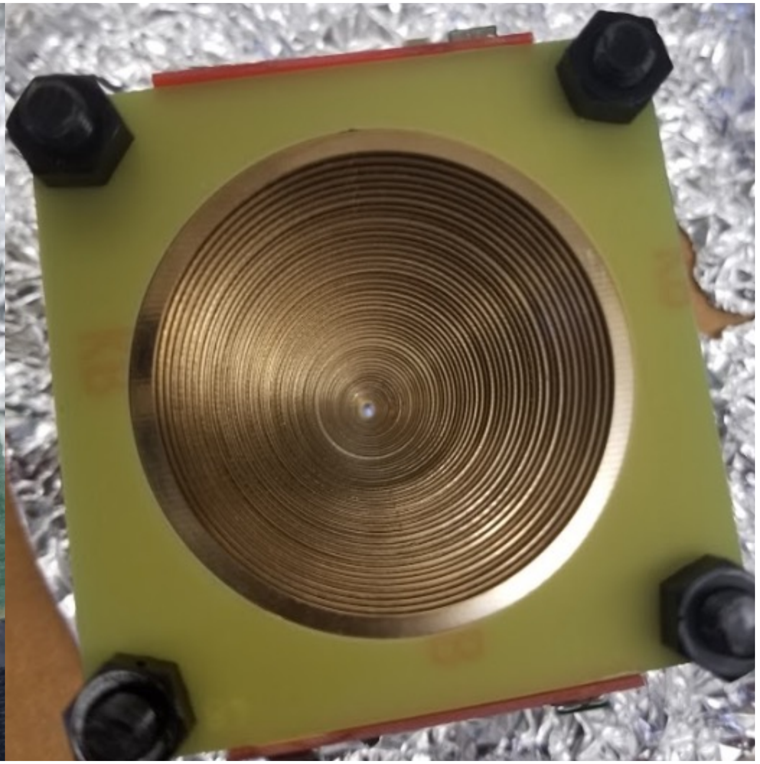
Ion Gate locations



Front Funnel

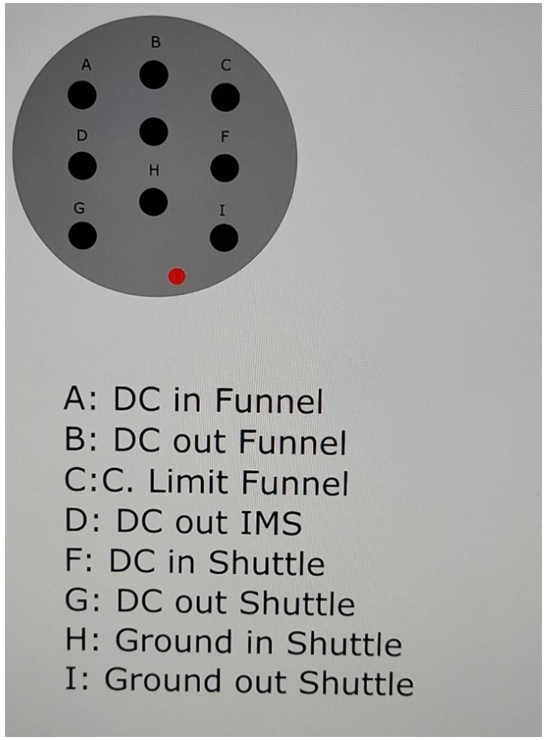
Low-Pressure IMS Construction: Rear Ion Funnel

Rear Funnel Construction



- Assemble the rear ion funnel the same way as the front ion funnel
- Note that the DC board has the same resistor configuration as the Gen 1 front funnel DC
- Test the same as front funnel

Rear Funnel Electrical Connections



- Representative connections will change depending on electrical connectors used
- This schematic was for the original rear ion funnel and Ion Shuttle configuration.

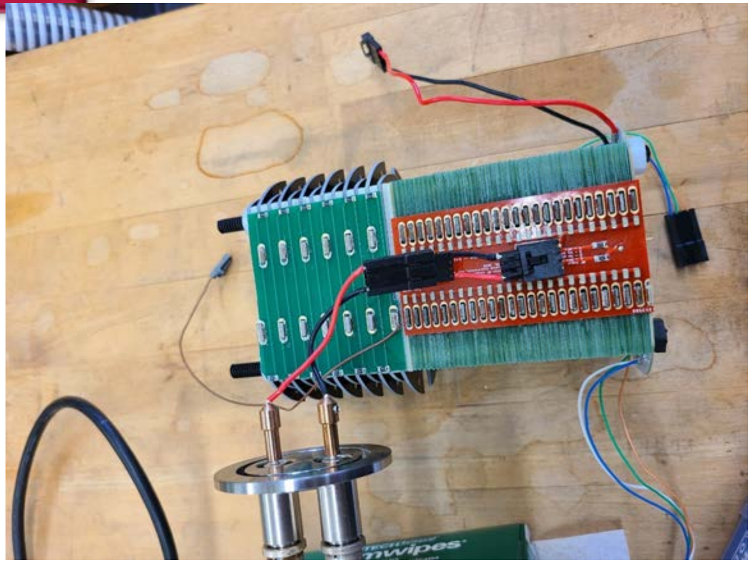
NEED TO ADD A SLIDE ABOUT THE FINAL ELCTRODE AND HOW TO BUILD IT

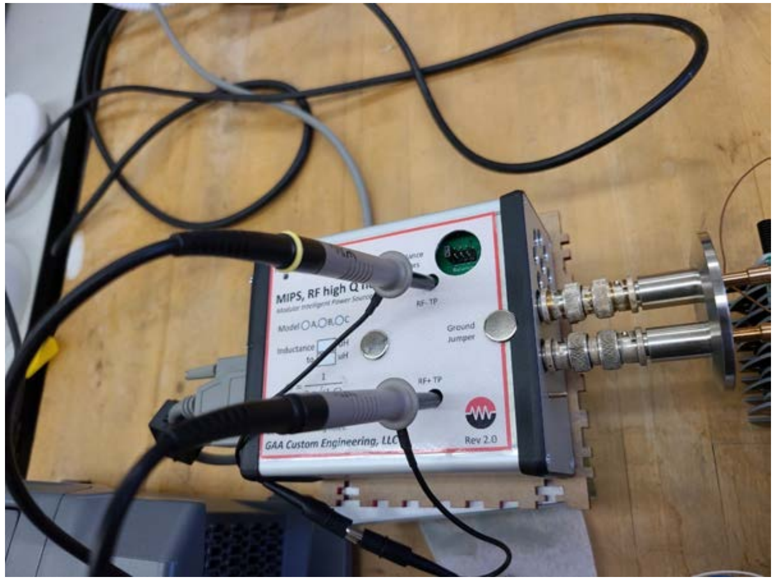
Rear Funnel

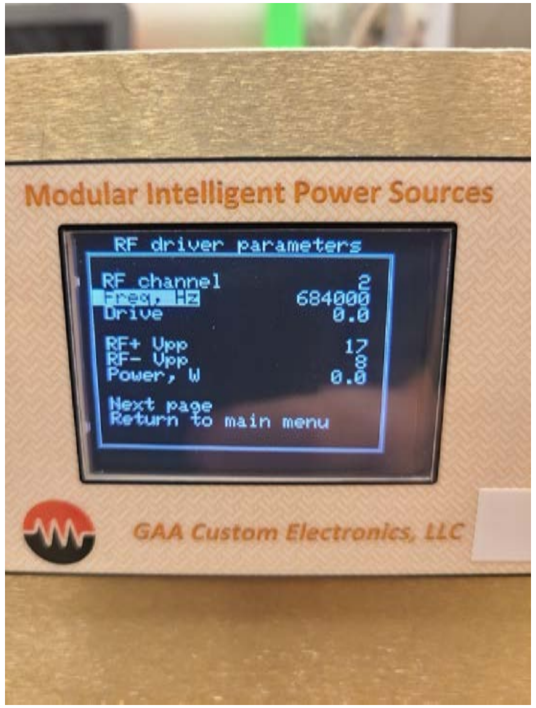
- The Rear ion funnel used with a Faraday plate is **NOT** compatible with the ion shuttle.
- The ion shuttle voltages are applied through the PCB electrode via pins (shown on image)
- We built a second rear ion funnel which does not have these pins to collect Faraday plate data.
- When we utilized the ion shuttle, we switched funnels for the ones with these connectors.

Low-Pressure IMS Construction: Ion Funnel Testing

Ion Funnel Testing

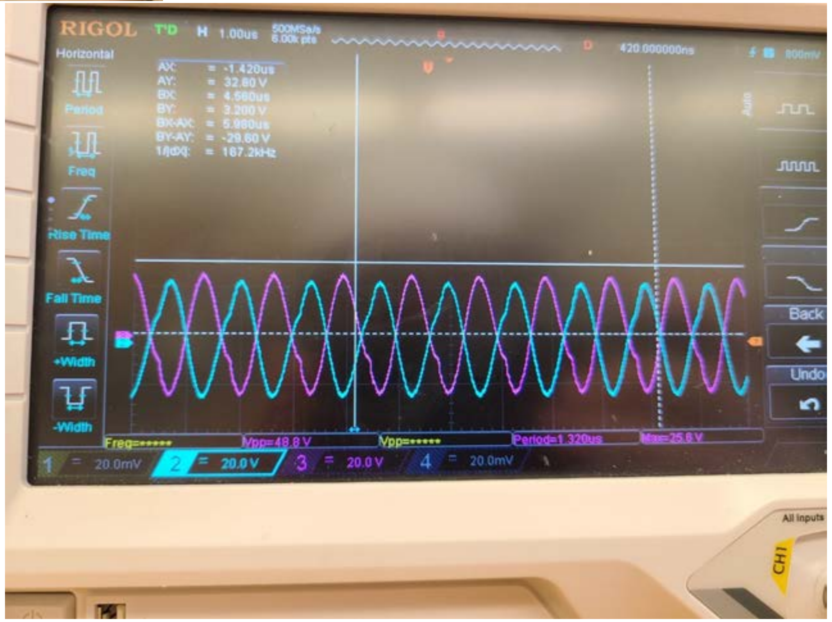






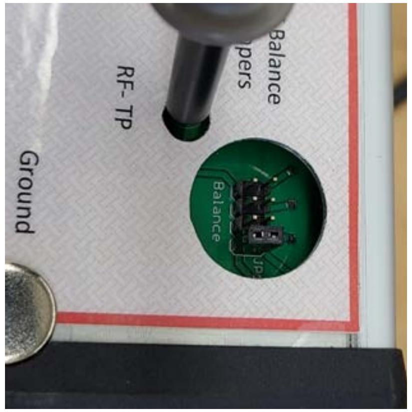
- Rear and Front ion funnel tested the same way
- Using a MIPS RF channel readout, ensure the drive is zero before connecting anything.
- On Benchtop, connect the RF power feeds to the RF quad driver (High Q head)
- Connect oscilloscope probes (10x attenuation ONLY) to testing points. Scale trigger levels and ensure voltage scale for the two channels are identical.

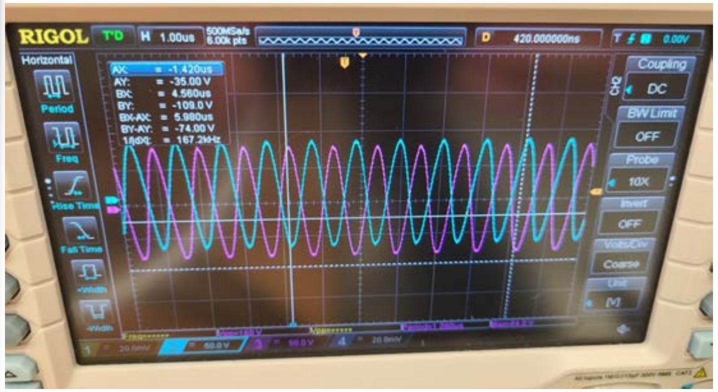
Ion Funnel Testing



- Using the MIPS RF channel readout, apply a drive of about 20, which should be about 150 V_{P2P}
- Change the frequency of the system until the two traces are in relative alignment. Most likely between 750 kHz to 1 MHz
- Upper photo is at low RF and non resonant frequency.
- Lower photo is at correct frequency and RF voltage

Ion Funnel Testing



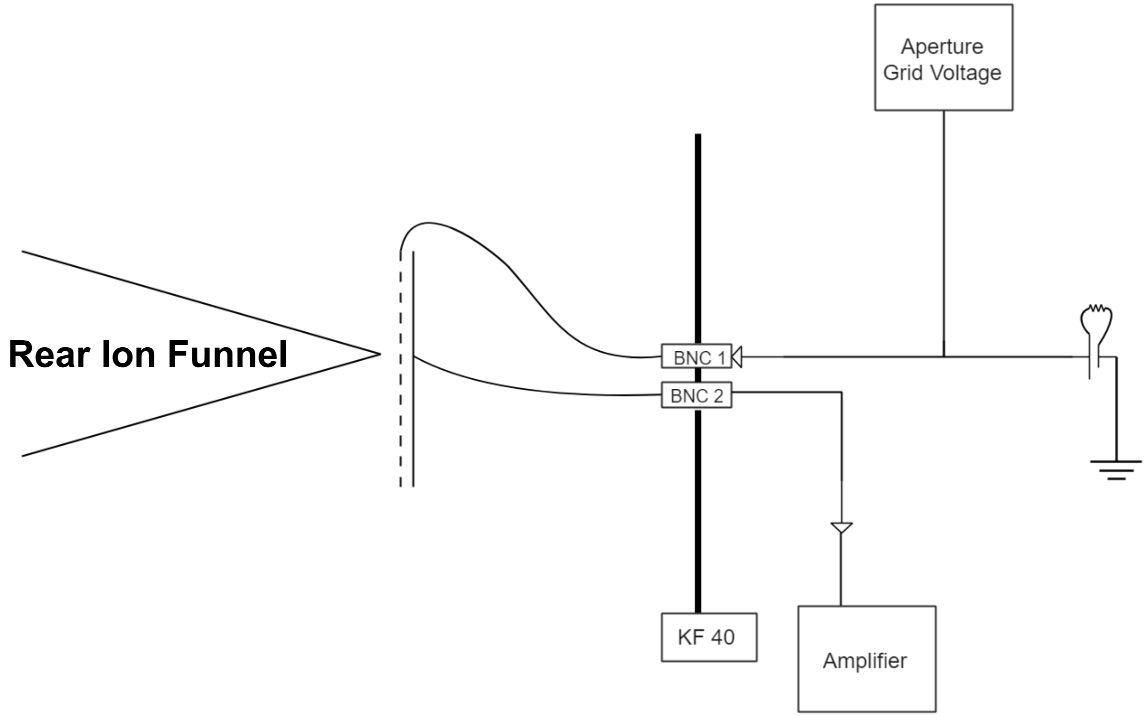


- After finding a resonant frequency, turn off RF power and adjust the jumper to a different spot as needed
- Location of jumper might change resonant frequency slightly. Adjust frequency and jumper until the two traces are near identical
- If traces are unable to be in alignment, check wire connectors, BNC connectors, RF feedthrough ports, and all connections on funnel

Low-Pressure IMS Construction: Faraday Plate

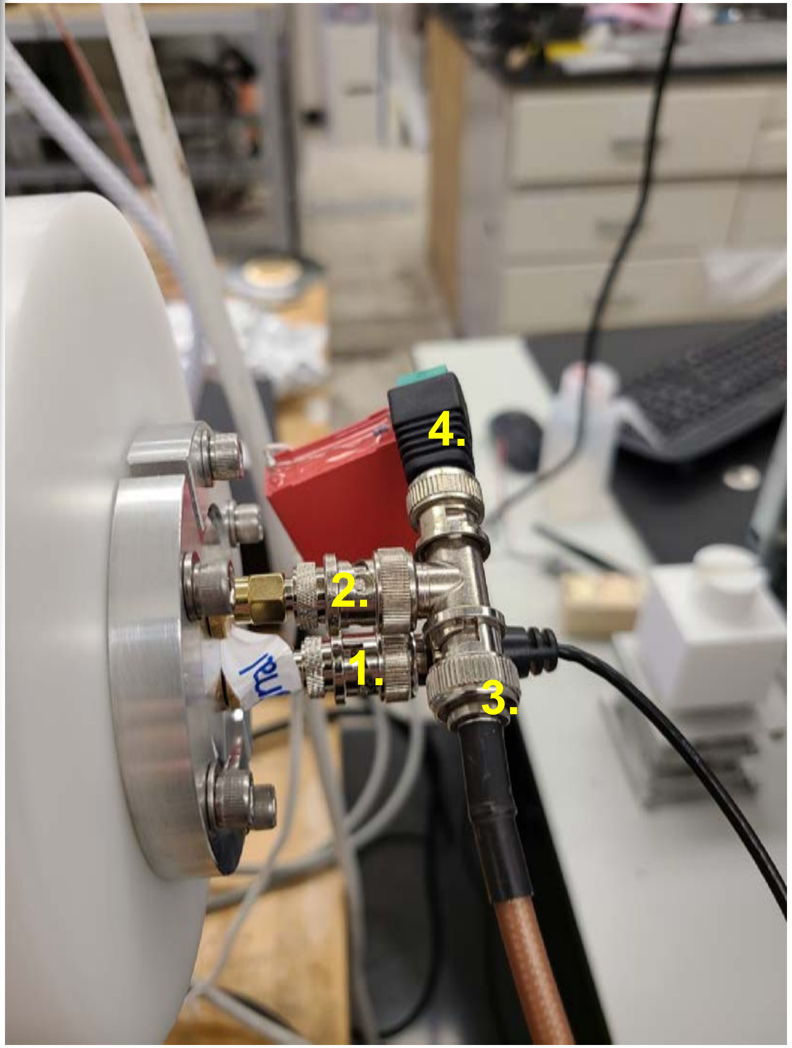
Before connecting to our mass analyzer, we utilized the IMS as a standalone system to ensure it was fully operational and to troubleshoot the system. To do so, we used a Faraday plate as our detector housed inside a Teflon enclosure and mounted to the back of the system.

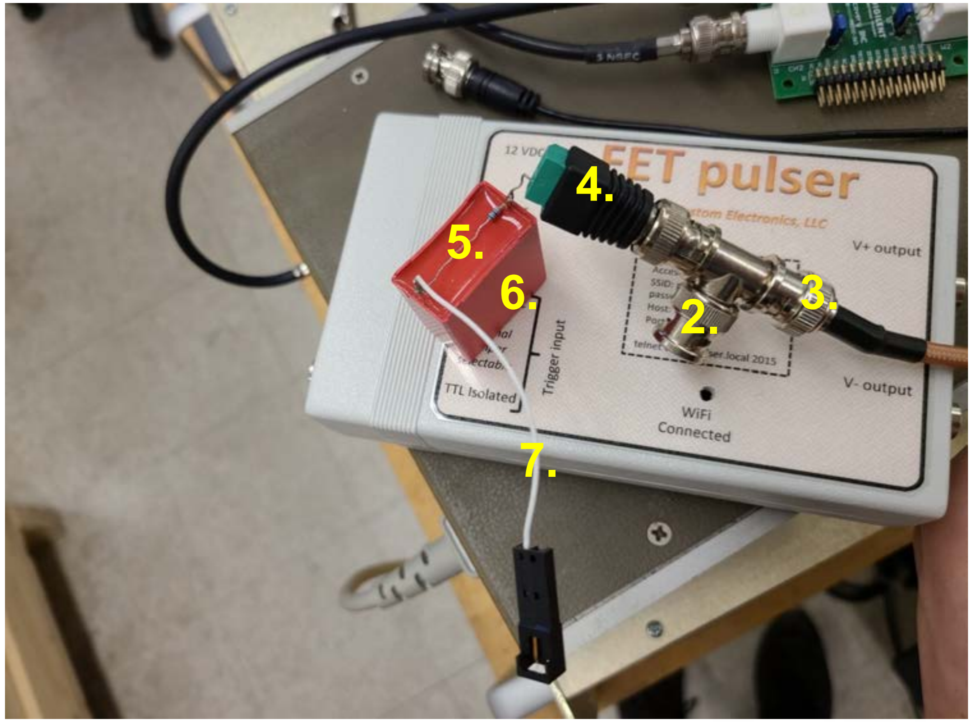
Faraday Plate Schematic



- Ensure that a Teflon spacer is placed between aperture grid and Faraday plate

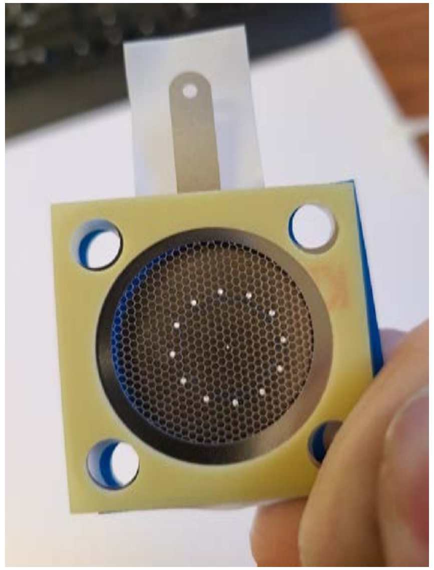
Faraday Plate Connections

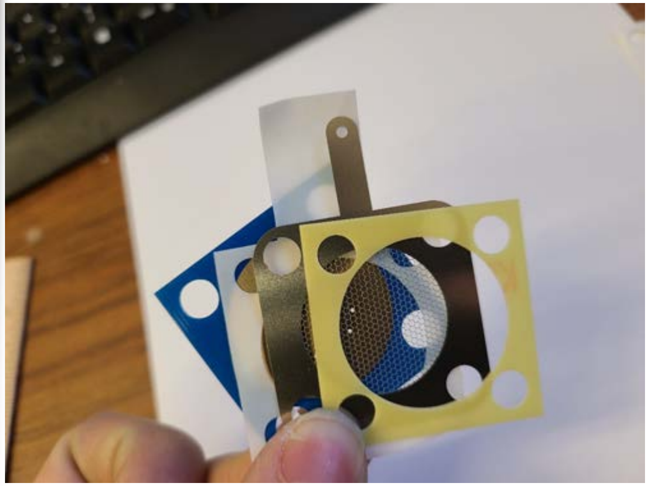


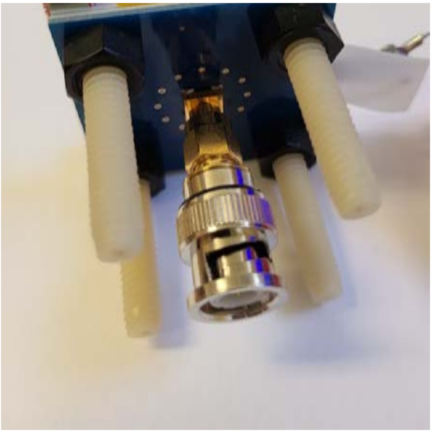


1.= Signal out to Amplifier. From SMA connector on Faraday plate
2.= To aperture grid
3.= aperture grid voltage from MIPS
4.= Capacitor to ground path
5.= 330 kΩ resistor
6.= 250 nF capacitor
7.= Molex path to ground

Faraday Plate Construction

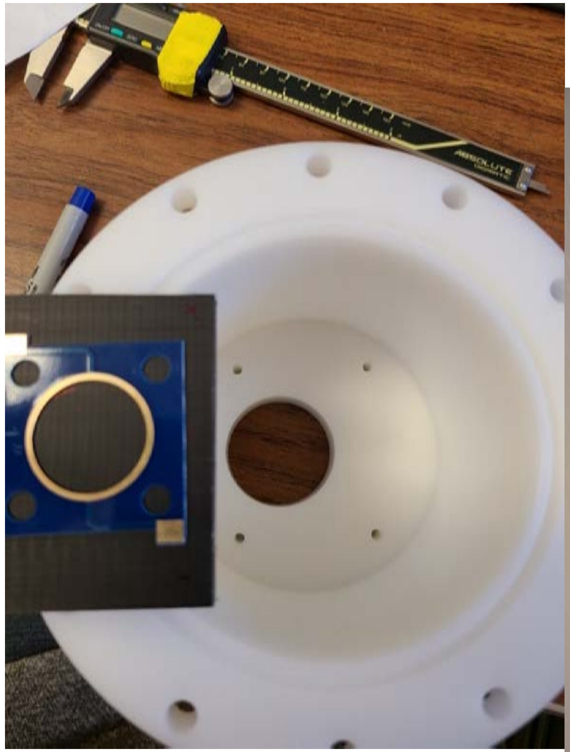


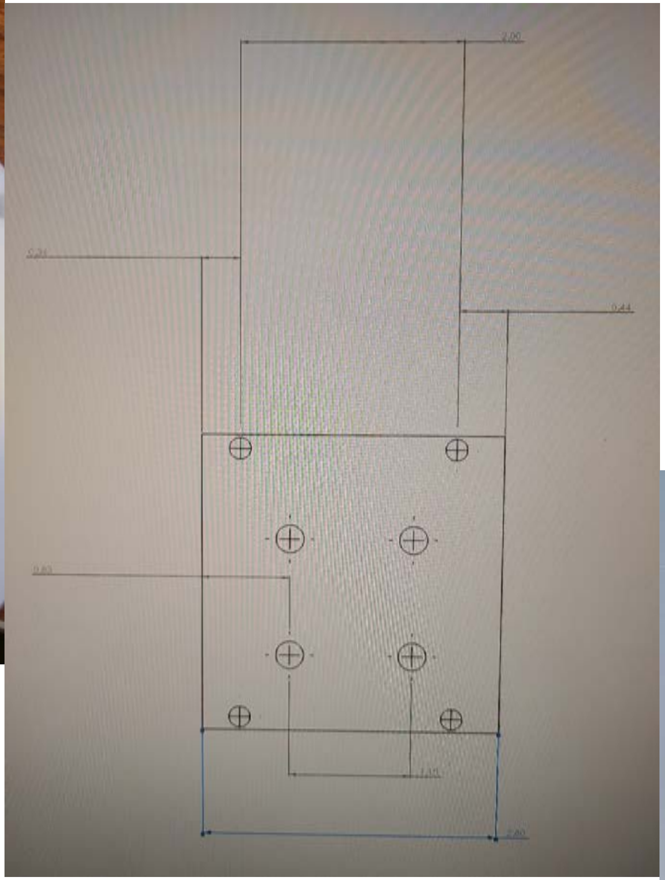


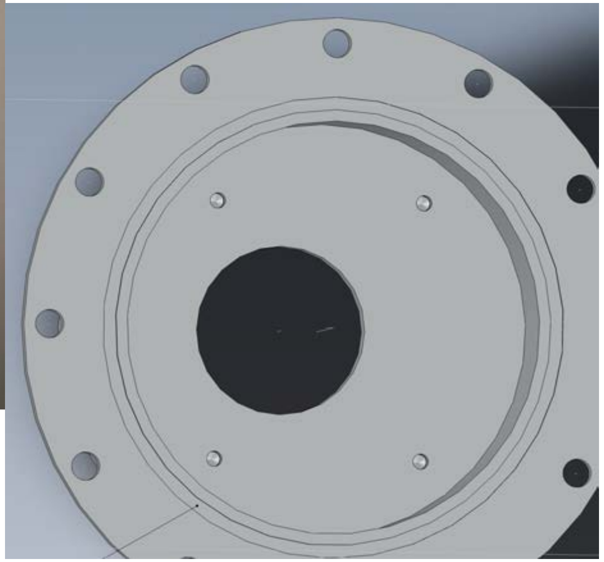


- A SMA connector to BNC needs to be connected to the rear of the Faraday detector (Alternatively a SMA to other connector can be used depending on the output of the MIPS)
- A wire will be needed to connect the Aperture Grid to the MIPS readout. A No. 2 screw and nut can be used to securely attach a wire connector
- A Teflon spacer is placed between the Faraday detector and the aperture grid.
- ¼" x 20 nylon rods and nuts can be used to secure the Faraday plate assembly in conjunction with the custom designed mount.
- Ensure Faraday plate does not make electrical contact with aperture grid.

Faraday Plate Construction





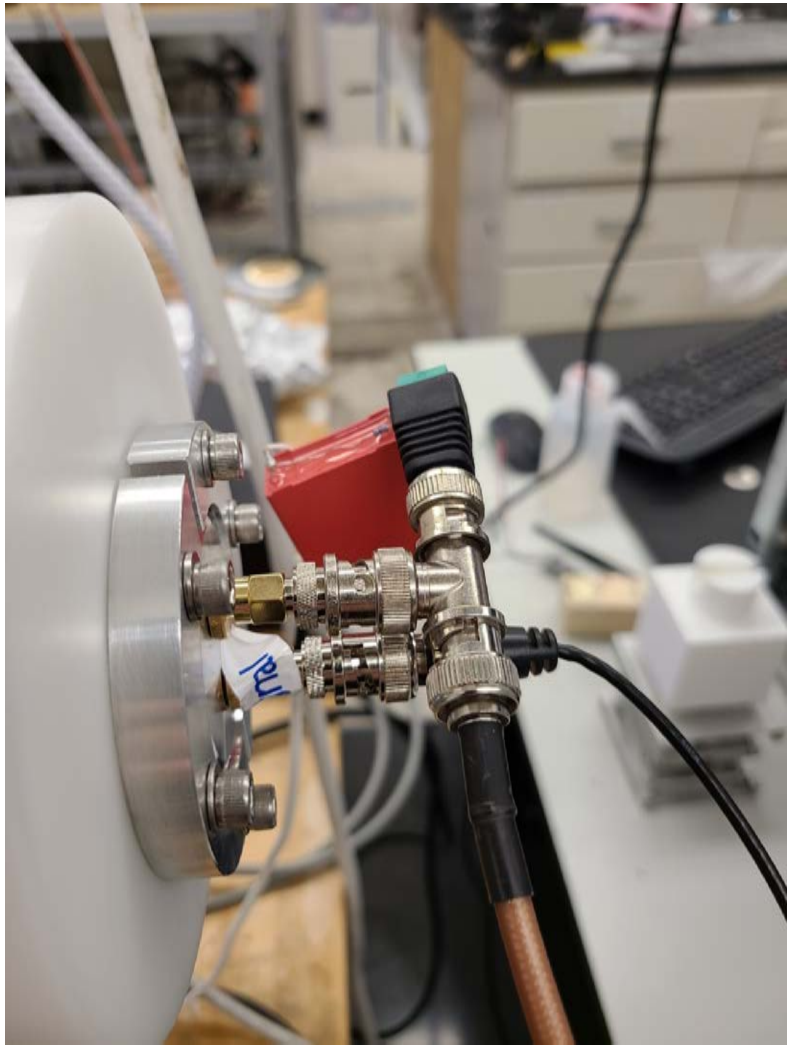


- The solution we used for mounting the Faraday plate as close to the rear funnel was utilizing a square of Delrin and machining it to have clearance holes for No. 4 screws and clearance holes for ¼ x 20 nylon rods. Appropriately sized nuts were used to secure everything in place at the desired height.
- Note that the Teflon chamber we used had asymmetrically placed threaded holes.

Faraday Plate Construction

- Connect the Faraday plate output to an adaptor from low pressure to atmospheric. We used SMA to SMA cable on the vacuum side, and then had an SMA to BNC vacuum adaptor for making connection to the MIPS.
- Ensure connections are made before placing system under vacuum.

Faraday Plate Operation

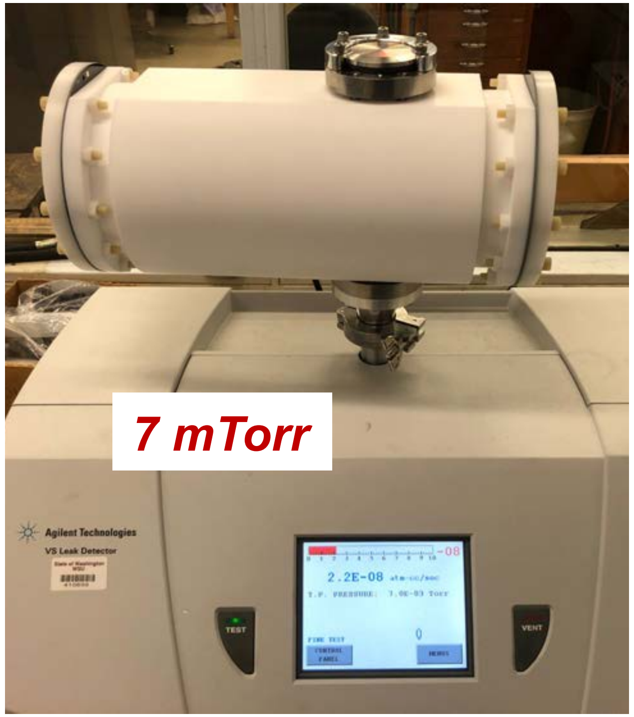


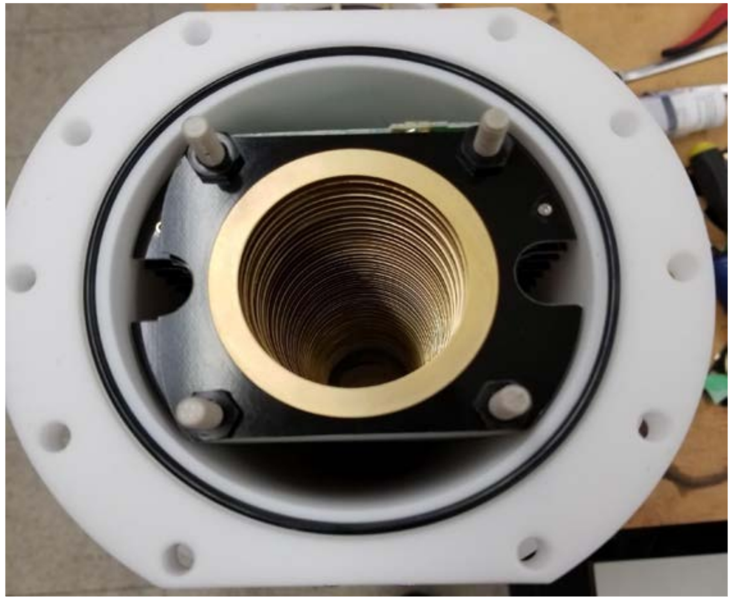
- Applying a positive voltage to the aperture grid will induce a negative current on the signal output which can be observed on an Oscilloscope.
- If not observed, recheck connections and that the Faraday plate is not touching the aperture grid and appropriate path to ground through resistor/capacitor set up.

Low-Pressure IMS Construction: Teflon Enclosure

PTFE Enclosure

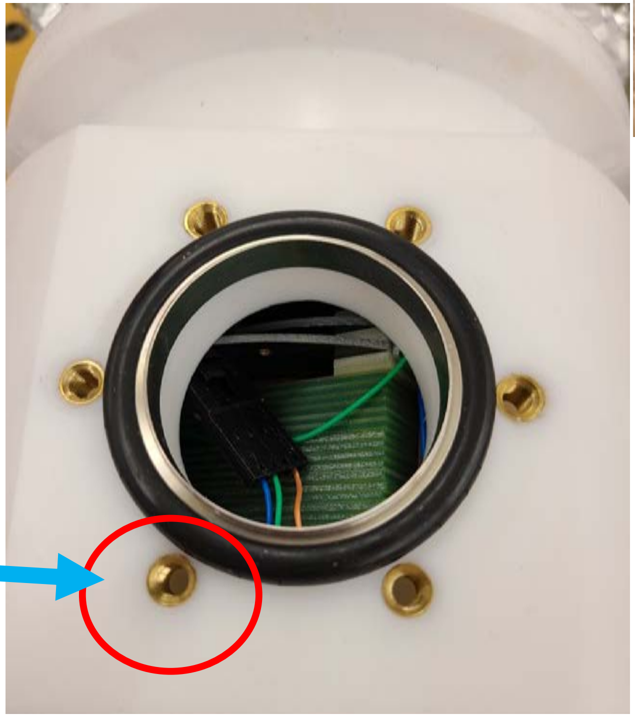
- 6” OD Teflon housing
  - Insulating material
  - Inert
  - Minimal machining
- PCB flanges
  - Sealed with O-rings





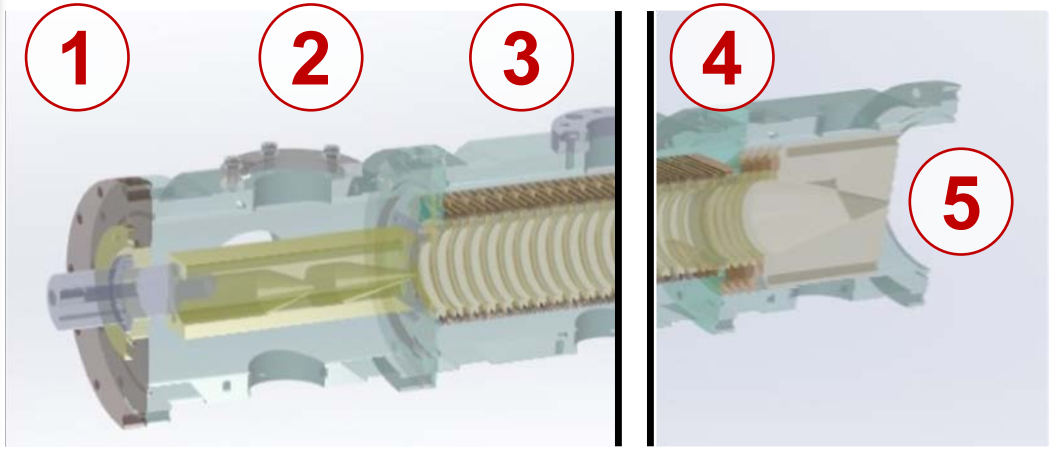
Brass Threaded Inserts

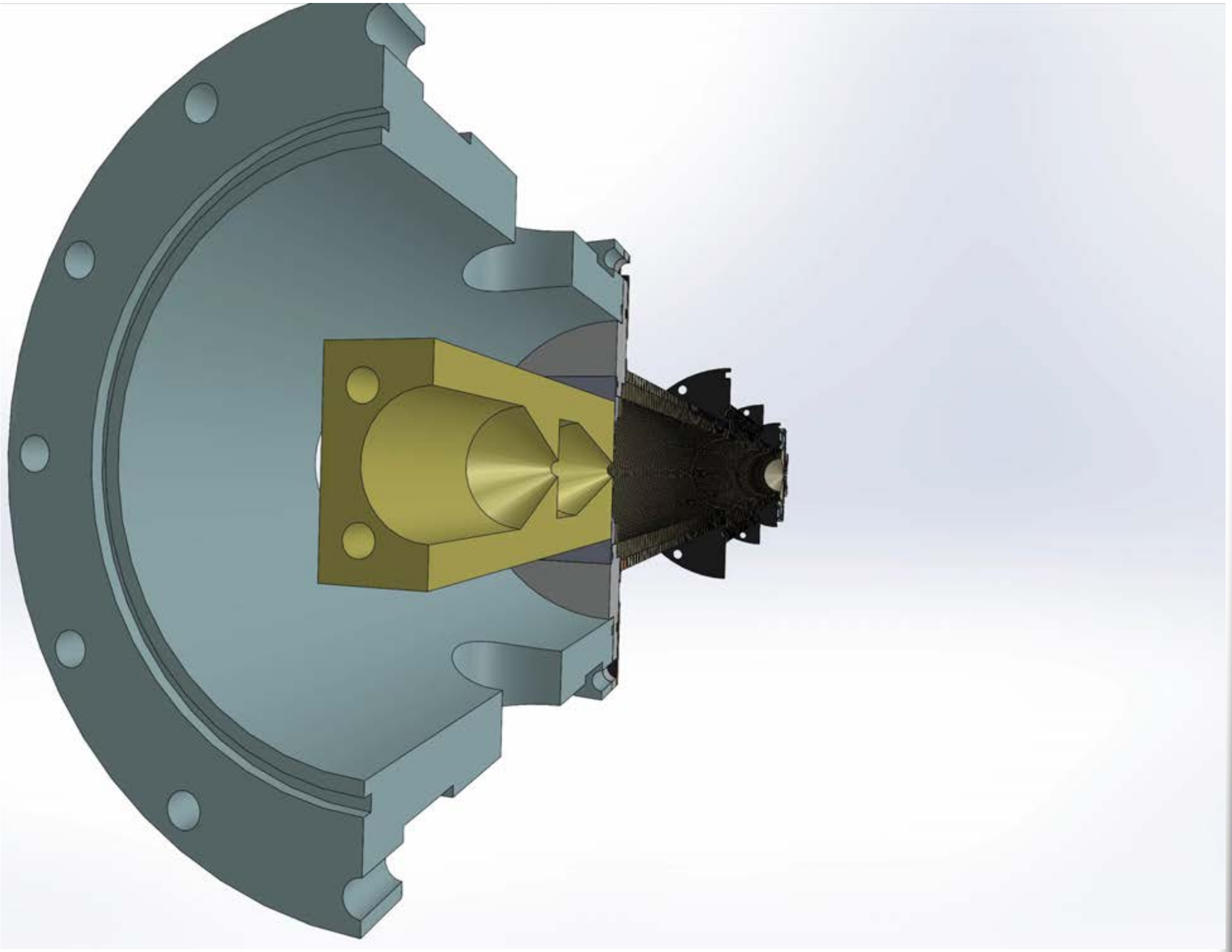
- Brass threaded inserts
  - KF-40 coupling
  - ~99 in/oz Torque tightened to PTFE housing



Low-Pressure IMS Construction: Drift Region Assembly

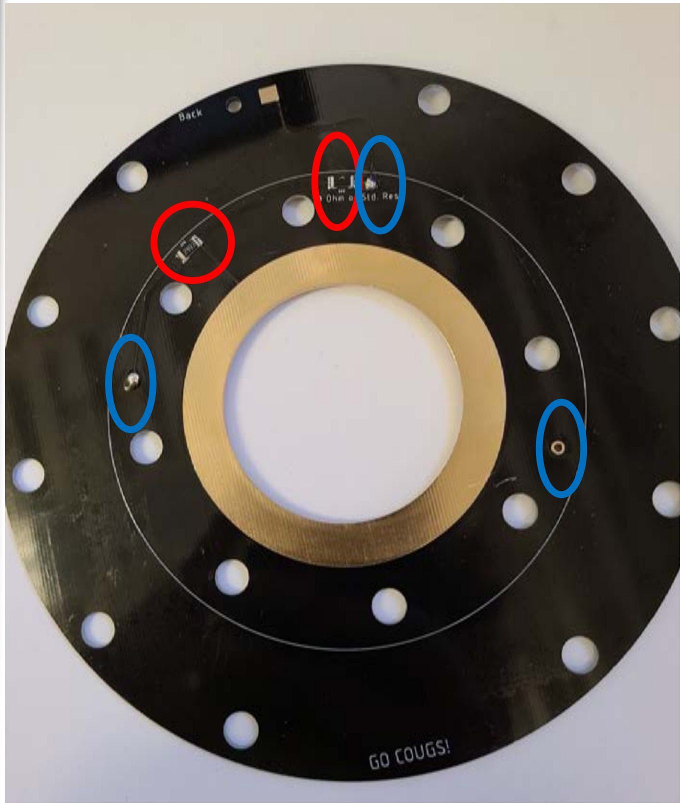
Low-Pressure IMS Sections





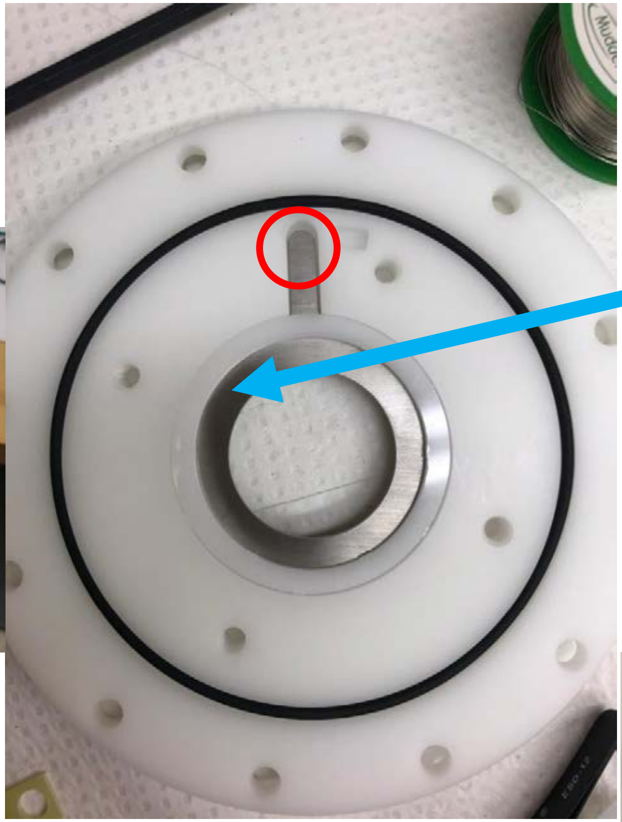
1. Heated capillary inlet
2. Front ion funnel, ~3.95 Torr,
3. Drift region (~102 cm), ~4 Torr,
4. Rear ion funnel
5. Ion Shuttle (not shown)

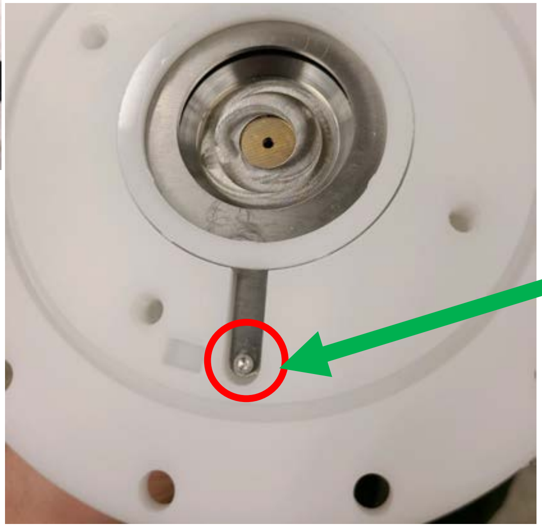
PCB Flange Construction



- Two resistors are 250 kΩ and the labeled spot is for a 0 Ω resistor (red circles)
- POGO pins are used to connect the drift regions. Ensure proper electrical connection. (blue circles)
- PCB flange may need to be reversed depending on orientations of drift regions. Ensure that 500 kΩ is measured from POGO pin in to POGO pin out if changing orientations.

Drift Region 1



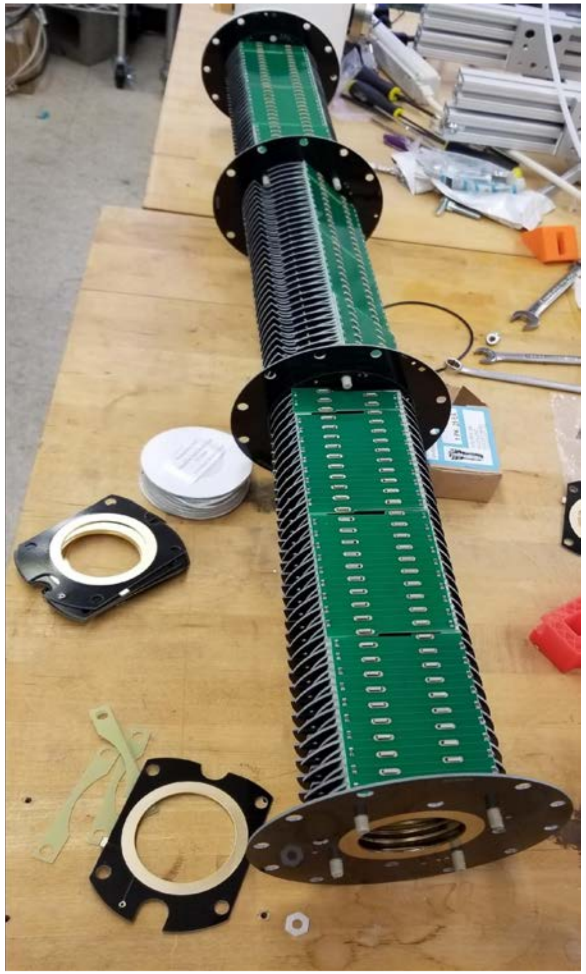


- The first drift region is distinct because of the mounting plate for utilization with front ion funnel.
- A Delrin insert was machined to lay flush with the metal ring to keep it in place.
- The PCB ion flange has a pogo pin which is not long enough to connect with the metal ring. A hole (No. 2) must be bored and tapped through this metal ring tab, and after tightening the screw, a grinder was used to make it flush with the metal ring to ensure it lay flat.

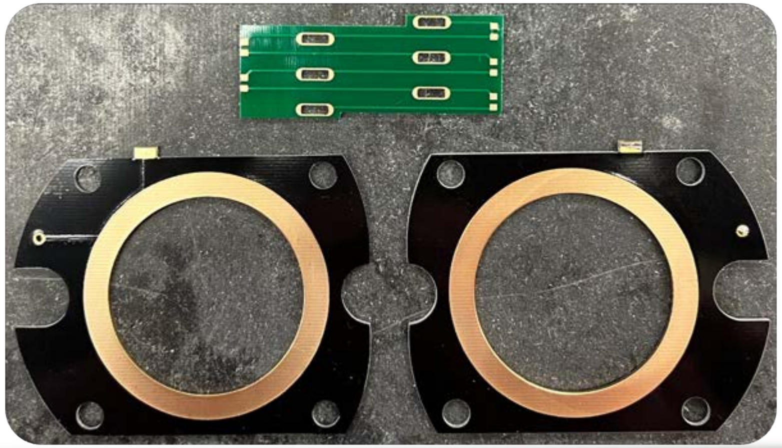
Drift Region Construction

- 200 Electrodes
  - ~104 cm drift length
  - 3 mm spacer distance
- PCB flanges
  - Sealed with O-Rings
  - Contact via pogo pins

PCB Flange



Drift Ring Electrodes

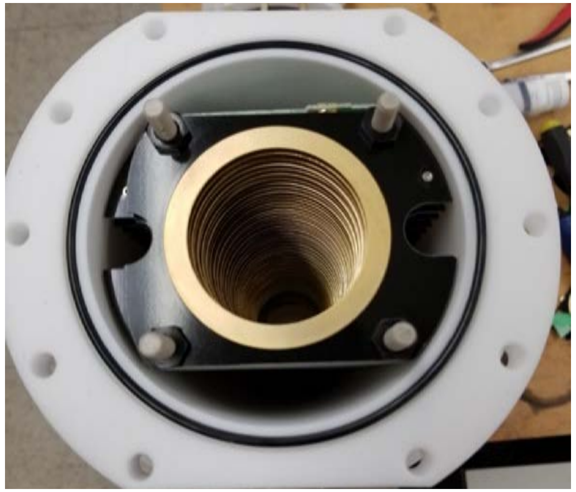


Drift Tube PCB Construction

- Resistors are all 250 kΩ surface mount
- Solder in place and ensure connectivity
- PCB boards are bridged with 250 kΩ wire resistors
- Ensure that electrodes are soldered into place cleanly, and that the solder is free of any unwanted solder spikes or burrs.
- Each drift region is composed of three full size top boards, one half size top board, and then **ONE** extra electrode to make connection with the PCB flange via POGO pin

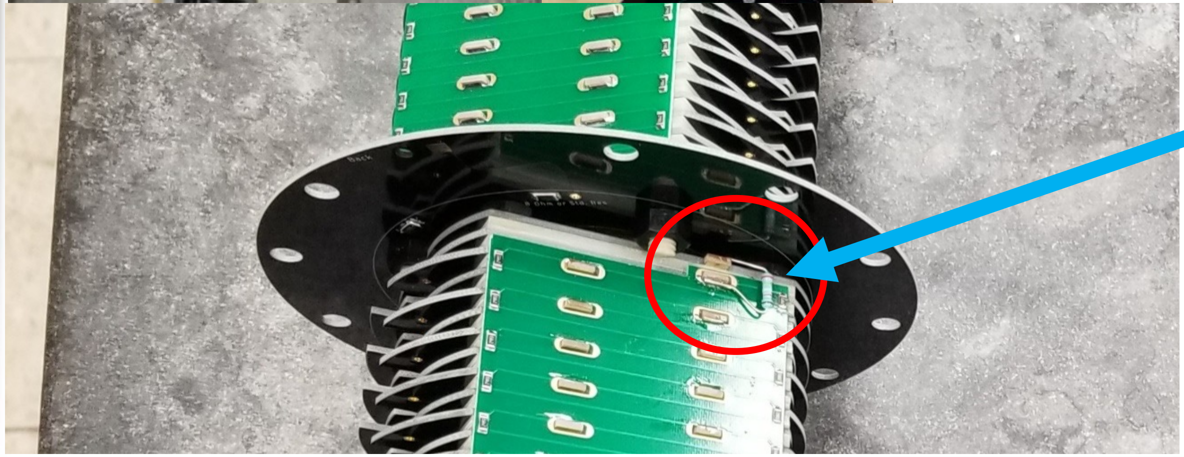
Drift Region 1





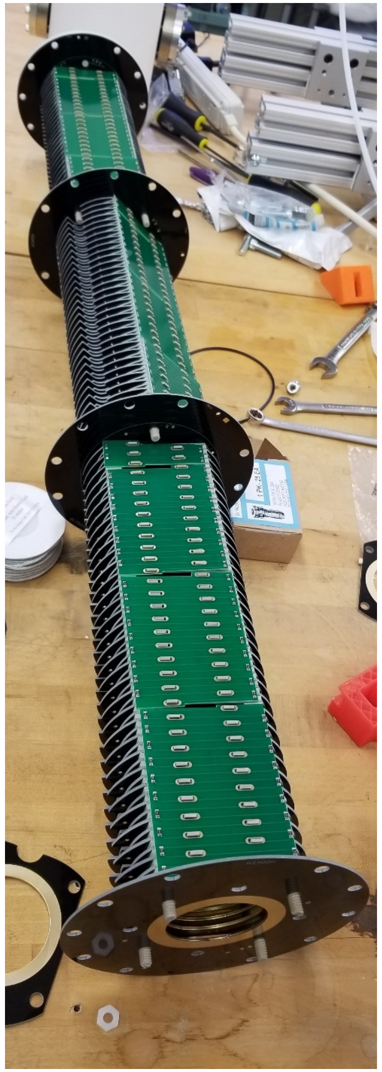
- The first drift region is distinct because of the mounting plate for utilization with front ion funnel.
- **Ensure connection with metal ring via POGO pin**
- Loosen or tighten thin nylon nuts (3mm) after placing electrodes to ensure drift region fits within Teflon chamber.

Drift Regions 1 to 2



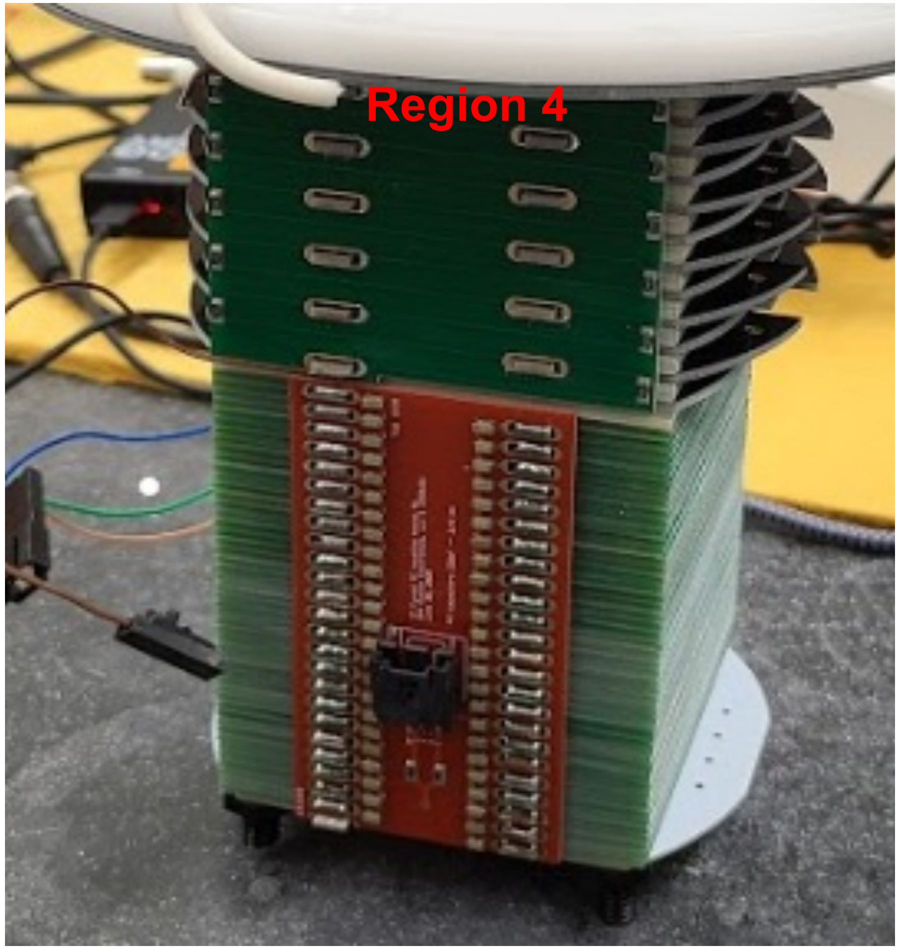
- Drift region 2 is offset 45 degrees from drift regions 1 and 3 to ensure electrical connection
- **Ensure connection via POGO pins from region 1 to region 2** (Each flange contributes 500 kΩ)
- Loosen or tighten thin nylon nuts (3mm) after placing electrodes to ensure drift region fits within Teflon chamber as before
- **NOTE** that there is a deliberate reversal of the **LAST electrode of region 2** which is connected via wire resistor. This is to allow for connection via POGO pin to the PCB flange

Drift Region 2 to 3



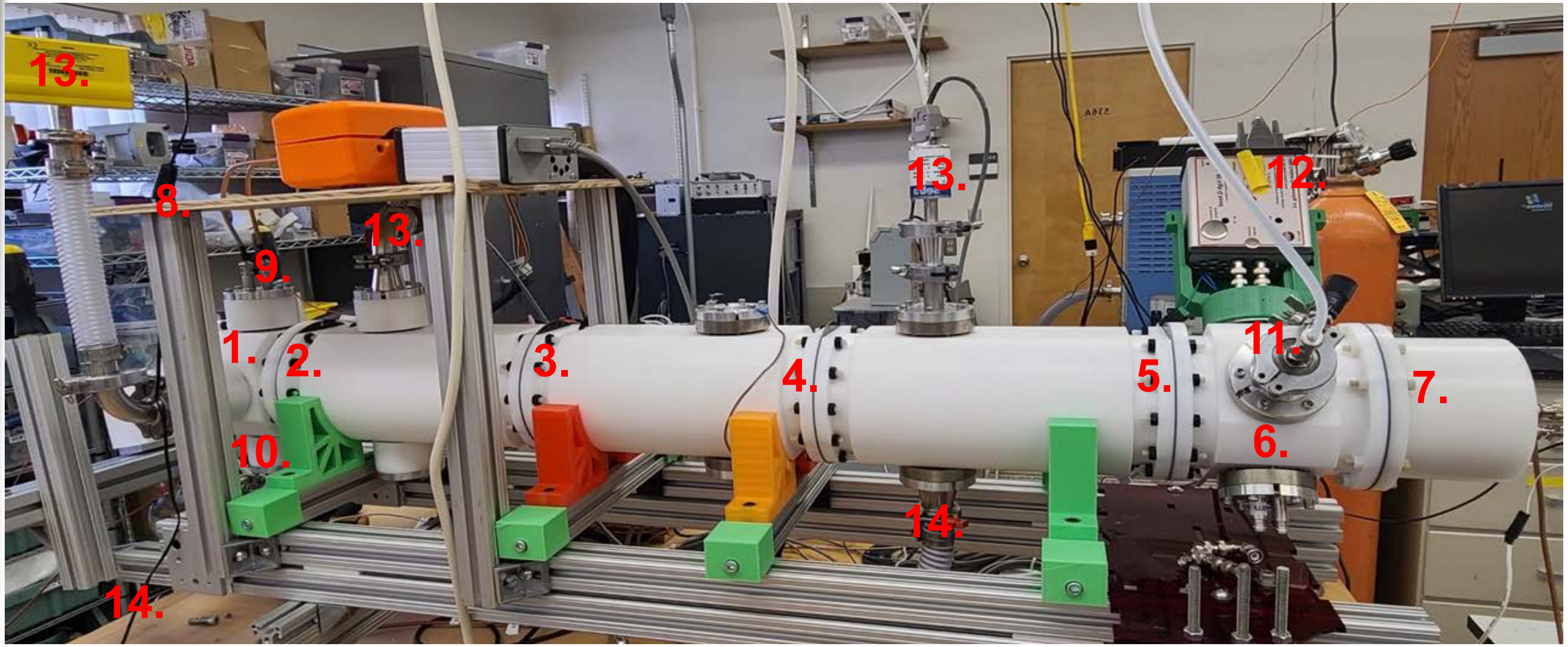
- Drift region 2 is offset 45 degrees from drift regions 1 and 3 to ensure electrical connection
- **Ensure connection via POGO pins from region 2 to region 3** (Each flange contributes 500 kΩ)
- Loosen or tighten thin nylon nuts (3mm) after placing electrodes to ensure drift region fits within Teflon chamber as before
- **NOTE** that there is a deliberate reversal of the **FIRST** **electrode of region 3** which is connected via wire resistor to the next electrode. This is to allow for connection via POGO pin to the PCB flange

Drift Region 3 to 4



- The connection between drift region 3 and drift region 4 is distinct as drift region 4 is directly preceding the rear ion funnel
- **Ensure connection via POGO pins from region 3 to region 4** (Each flange contributes 500 kΩ)
- DC IMS out is connected to last electrode of IMS
- The length of drift region 4 is however many electrodes it takes to have the rear ion funnel be flush with the exit of the Teflon chamber (our system is 13 electrodes)
- A PCB top board was cut to the correct length using a gravity shear (careful application of wire cutters also works, do not break electrical connection or leave any floating voltages).
- Loosen or tighten thin nylon nuts (3mm) after placing electrodes to ensure drift region fits within Teflon chamber as before

Low-Pressure IMS System



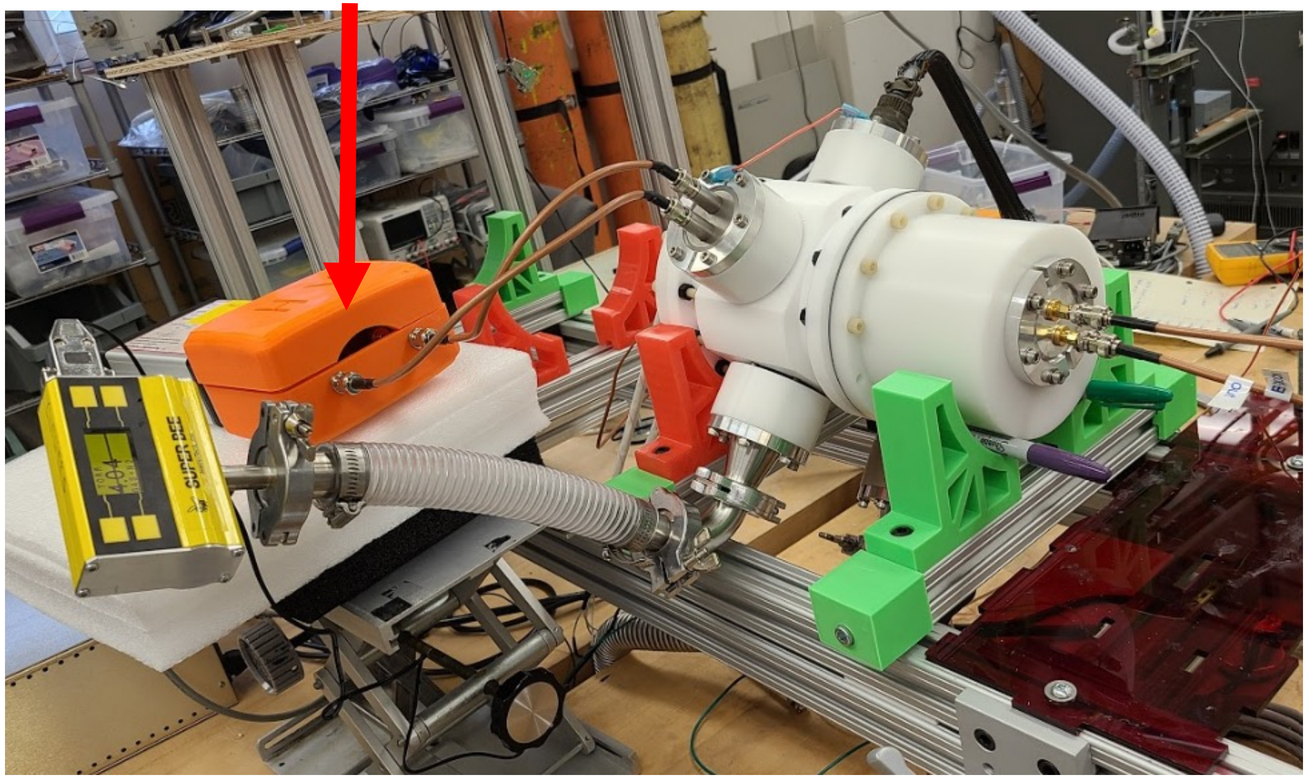
1. Front Ion Funnel
2. Start of Drift Region 1
3. Start of Drift Region 2
4. Start of Drift Region 3
5. Start of Drift Region 4
6. Start of Rear Ion Funnel
7. Faraday Plate Chamber
8. Custom support shelf
9. RF in Front Ion Funnel
10. DC In Front Funnel
11. Drift Gas in
12. RF in Rear Funnel
13. Pressure Gauges
14. Vacuum Lines (behind IMS)

Low-Pressure IMS Construction: Current Testing

Before assembling our full system, we iteratively tested every segment. Starting with only the front funnel, then rear funnel with front funnel. Once signal was recorded, we added drift segments until the full system was operational.

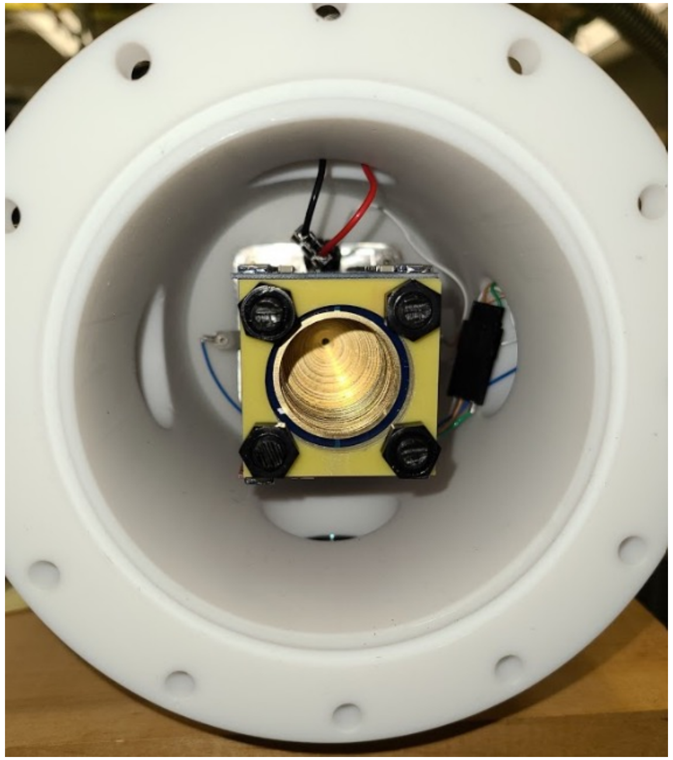
Front Funnel

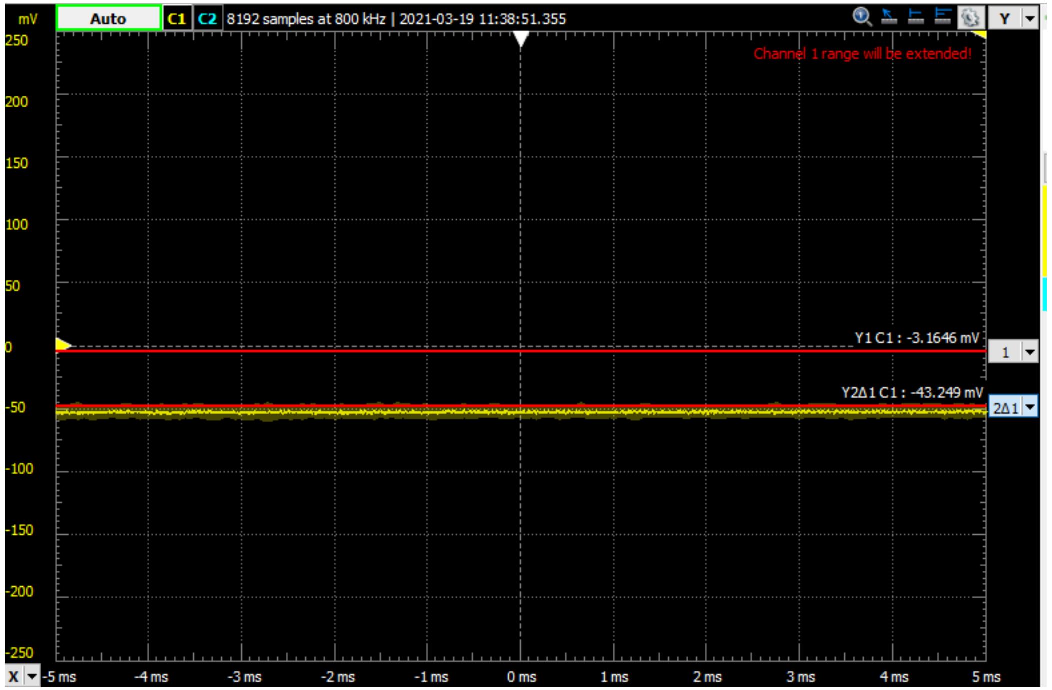
Capacitors to account for applied HV



- Testing the ion current with just the front ion funnel on the faraday plate. (Modifications to the supports and vacuum attachments may be required).
- An ESI needle was placed at the inlet capillary and total ion current was measured.

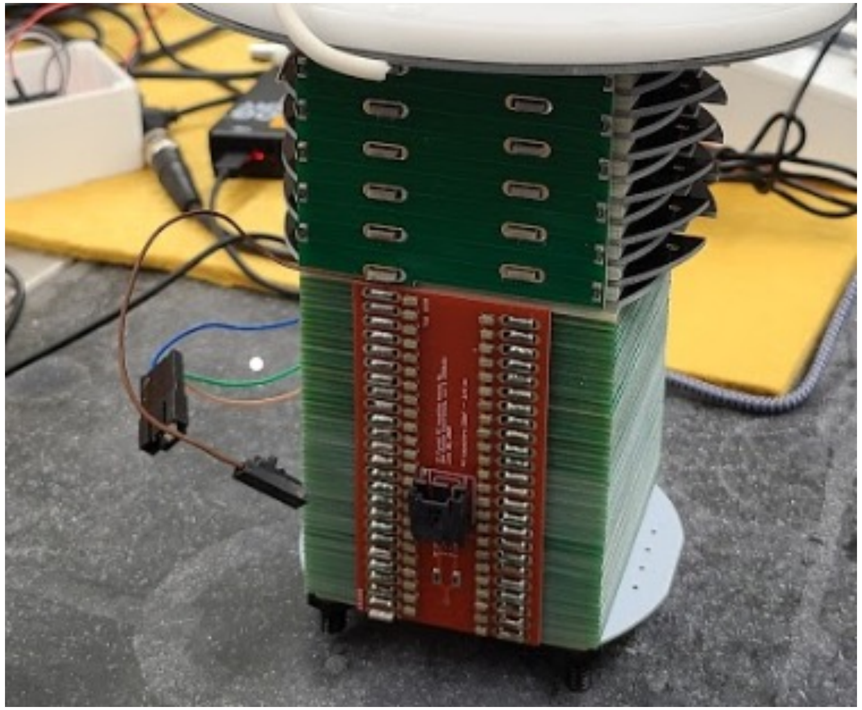
Front Funnel Ion Current



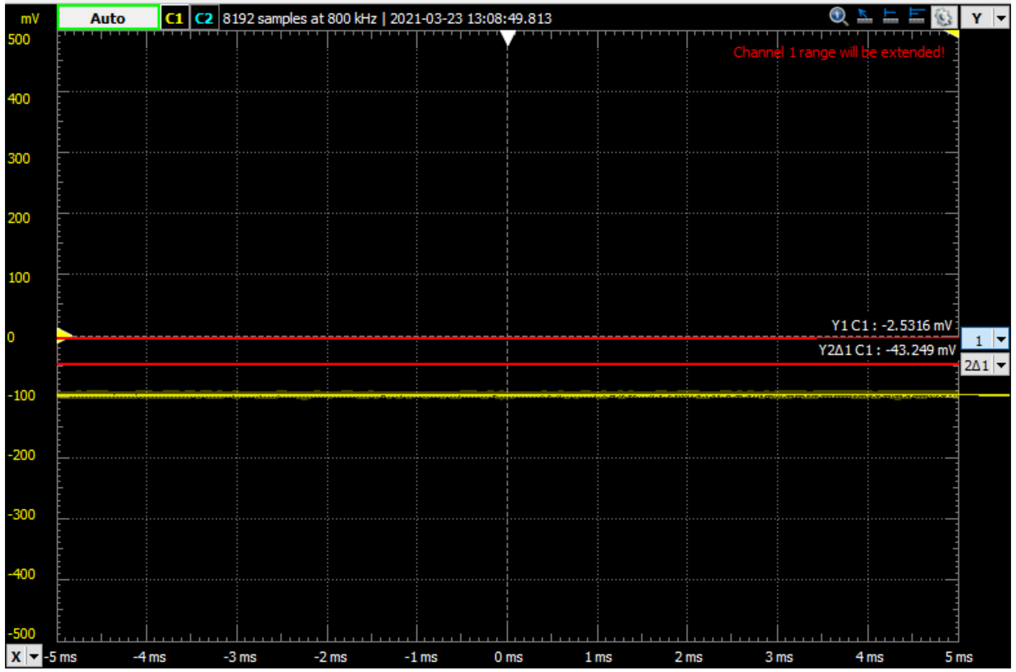


- T4A in ESI solvent (80:20:0.1% MeOH, water, formic acid) was electrosprayed.
- Faraday plate was placed at the end of ion funnel.
- Positive ions induce a negative recorded current.

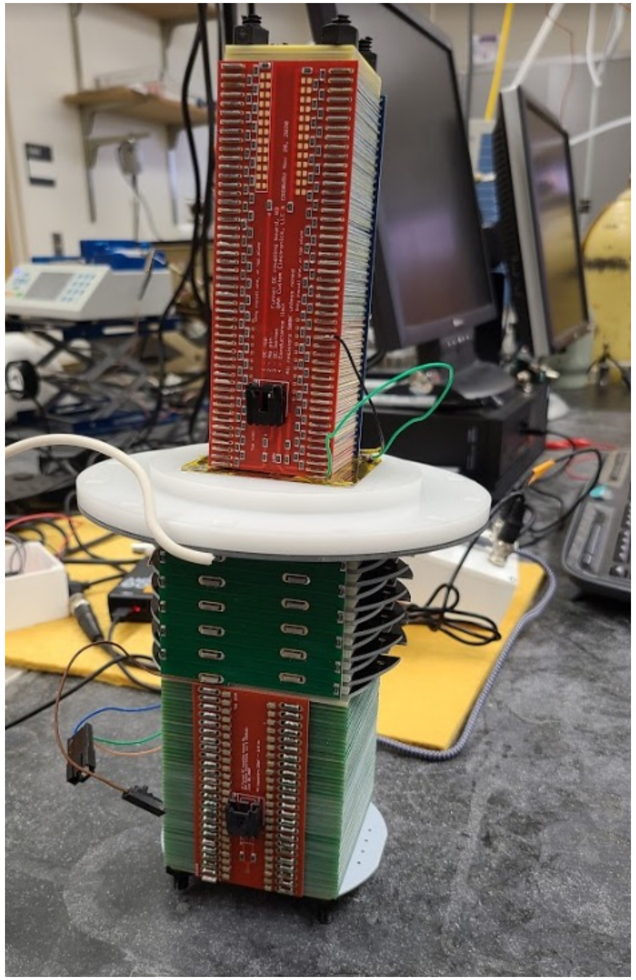
Rear Funnel

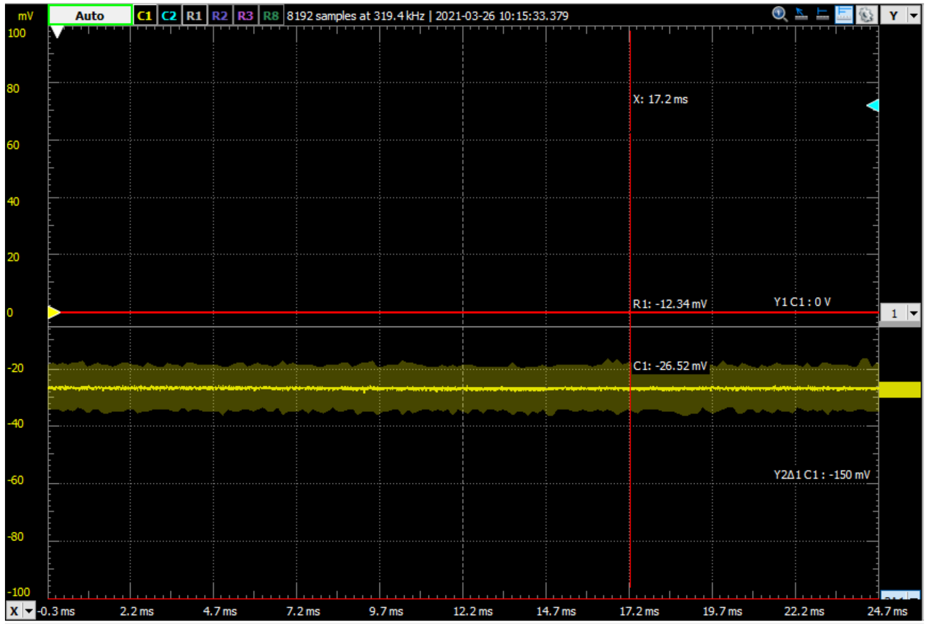


- Add ~16 V cm^{-1} DC field to IMS portion by applying DC in and DC out to IMS
- Test the rear ion funnel the same as the front ion funnel. Set DC in Funnel to be about 10 volts lower than IMS DC out for testing purposes.



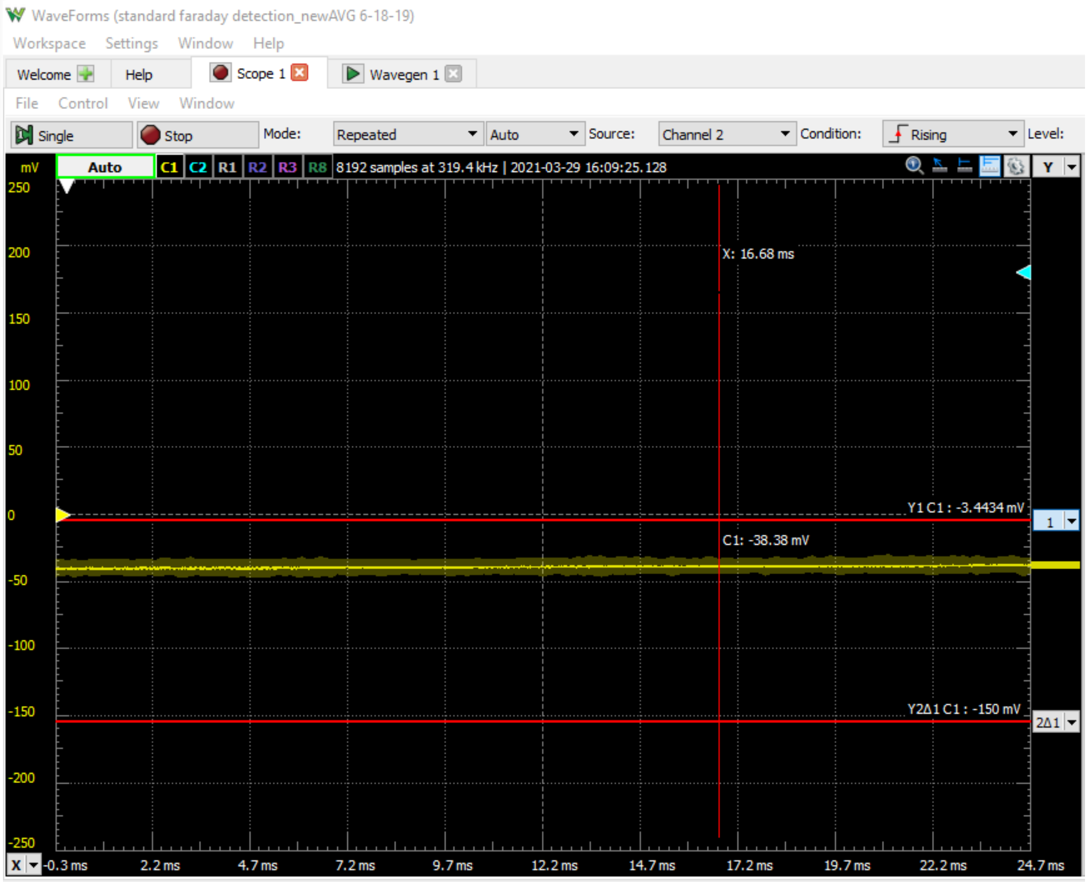
Testing Funnel Ion Current





- Both ion funnels were used in tandem to ensure ion current.
- Creative modifications to vacuum lines, pressure gauges, and electrical connections are required to ensure connections and successful operation
- Ensure that the front chamber has a slightly higher (~0.1 Torr) than the rear chamber or ion current will not be observed.

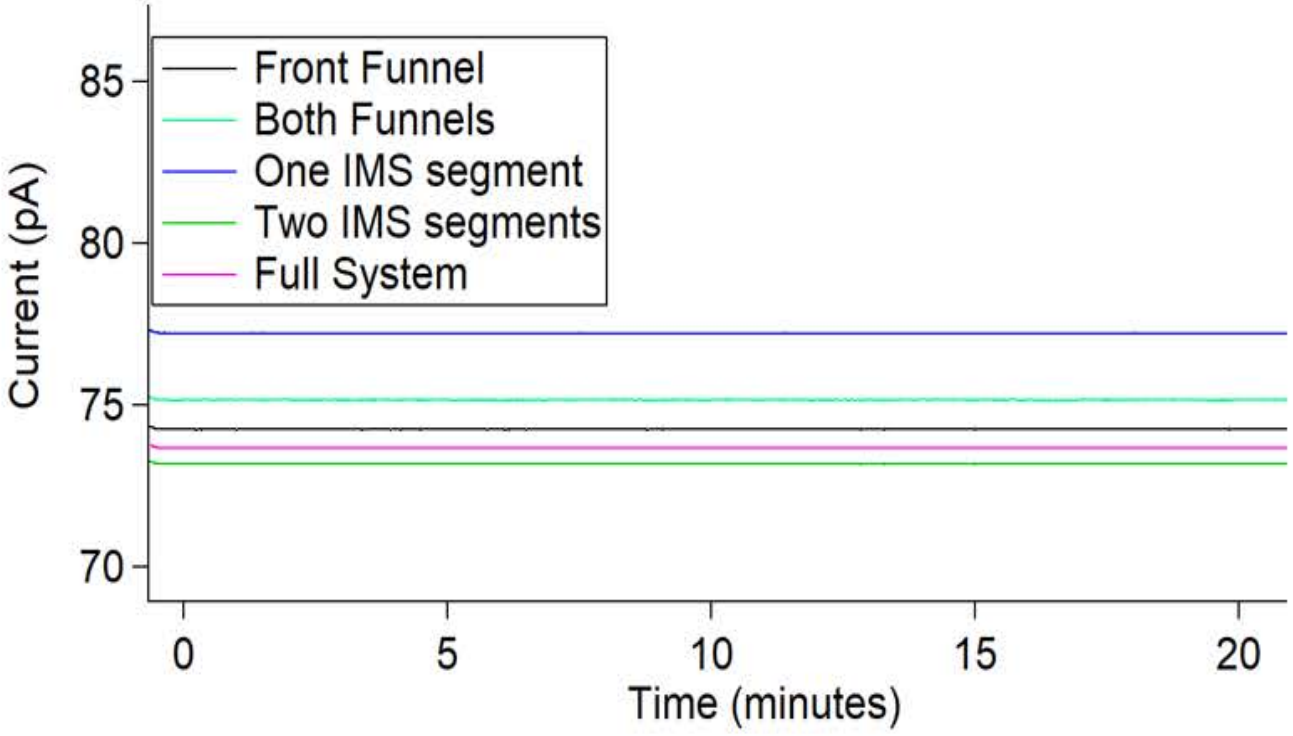
Drift Region Ion Current



- **Before running full system, iteratively test each drift region**
- With both ion funnels in place, add drift region 1 and test for successful ion current.
  - Front funnel is capacitively coupled to drift region 1 voltage
- Creative modifications to vacuum lines, pressure gauges, and electrical connections are required to ensure connections and successful operation
- Ensure that the front chamber has a slightly higher (~0.1 Torr) than the first drift region chamber or ion current will not be observed.
- Same testing parameters as for individual funnel

Total Ion Current from Different Configurations

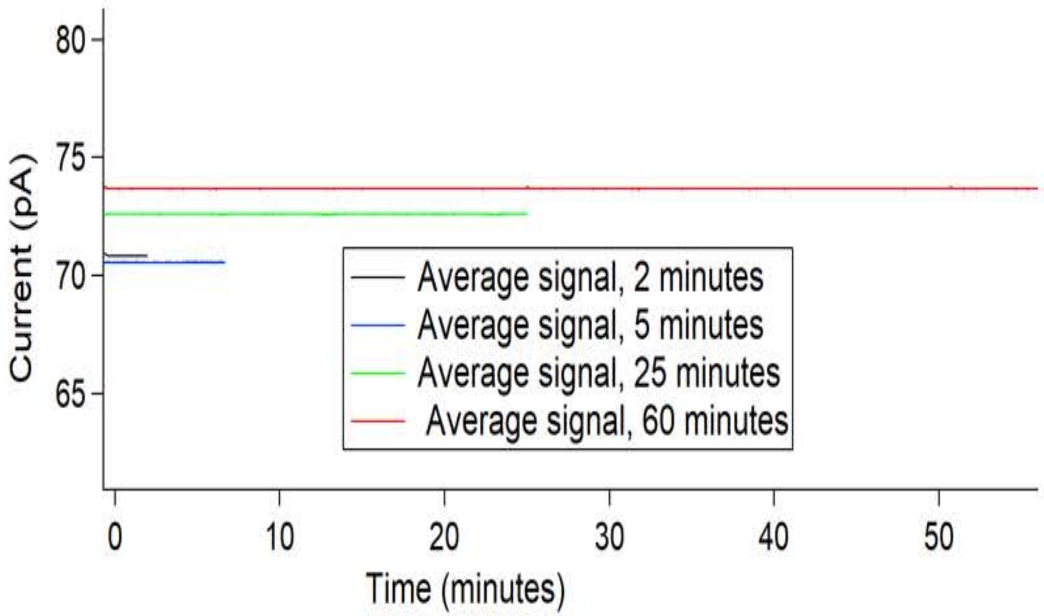
- Drift length = Variable
- Field strength = 17 V cm^{-1}
- Pressure = ~4 ± 10% Torr
- Temperature = 300.5 K



- If the same solution is used for all ion current measurements, observed values should be in close agreement

Stability of Total Ion Current

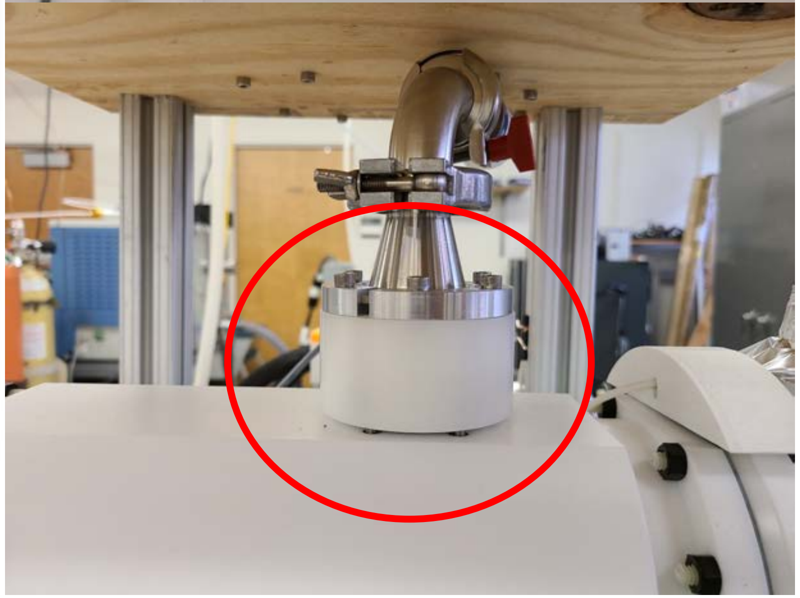
- Drift length = ~104 cm
- Field strength = 17 V cm^{-1}
- Pressure = ~4 ± 10% Torr
- Temperature = 297 K



- To ensure that the system is not charging, measure total ion current at different time increments
- The longest time increment should have approximately same signal as the shortest. If it is significantly higher, system is building charge. If the signal goes to zero most likely there was an electrical discharge that took out the electrical supply.

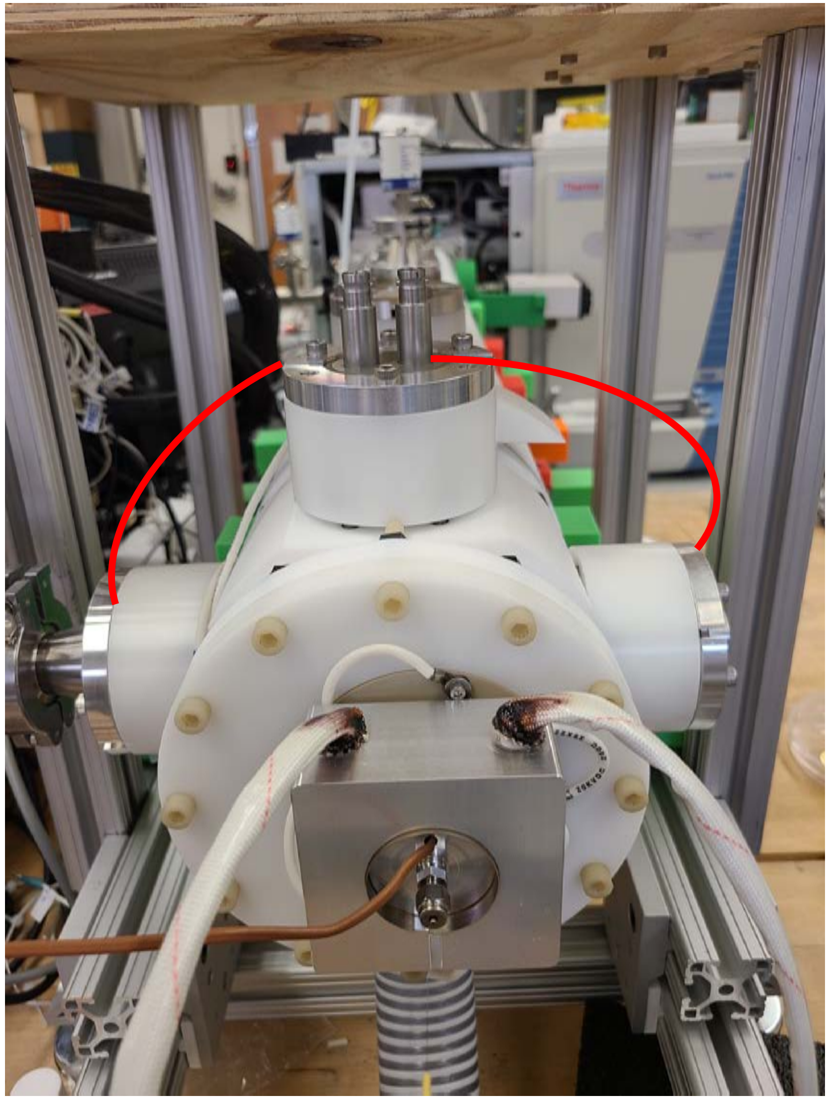
Low-Pressure IMS Construction: Charging Concerns

Electrical Discharge Management



- Before addition of these custom Delrin spacers, arcing would occur when trying to bring system up to operational voltage
- Delrin spacers were added on all 6 locations for the front funnel chamber (4 locations) and the first drift region (2 locations) to prevent electrical discharge.
- Also, we used POM centering rings on the high voltage in to reduce arcing. (This step may not be needed).

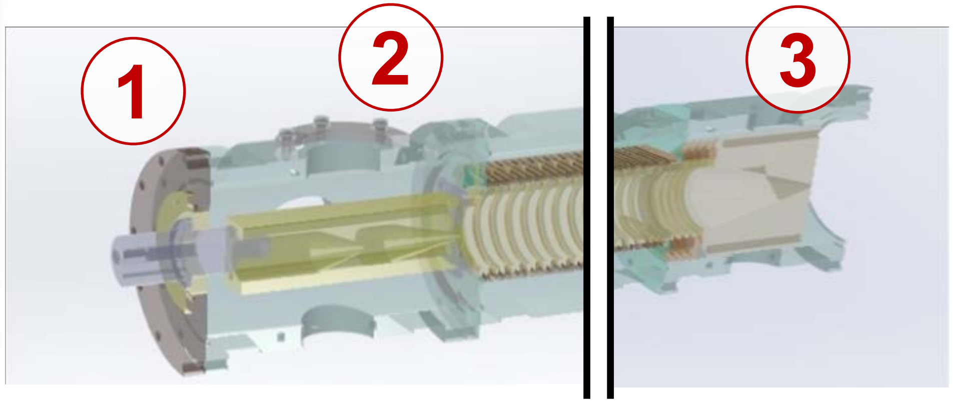
Electrical Discharge Management

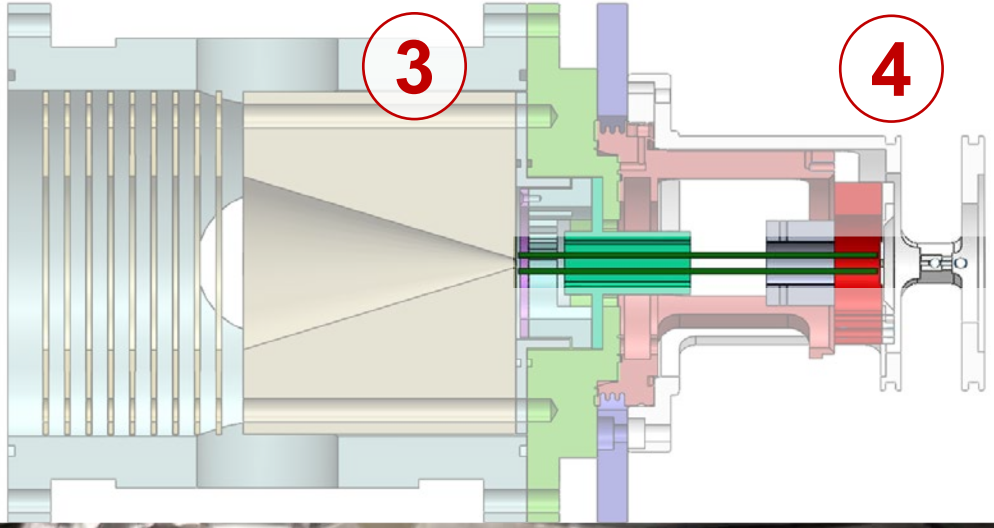


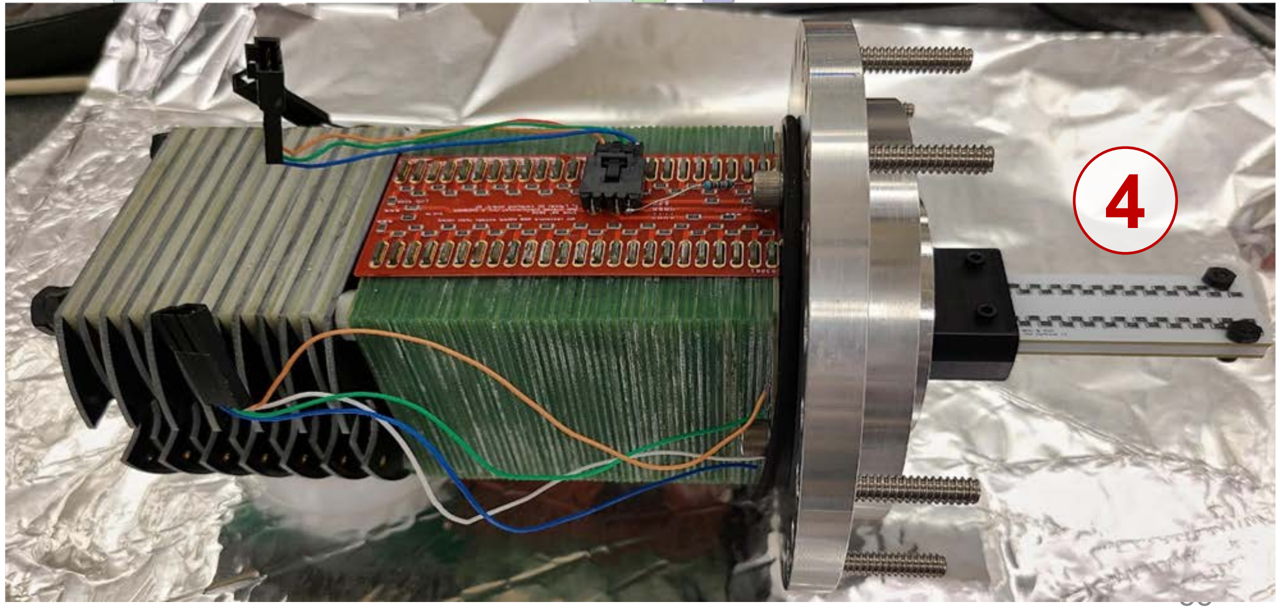
- The KF 40 plates for the RF in and DC in of the front ion funnel both need to be electrically connected to prevent arcing. We have all front-end components floating on drift voltage.
- The voltage applied to the drift region also needs to be connected to the KF 40 inlet for DC in of the front funnel to prevent arcing.
- The front capillary voltage has a secondary DC voltage applied on it as well, so it must be isolated from the other four floated KF 40 plates.

Low-Pressure IMS Construction: Ion Shuttle

Ion Shuttle Implementation





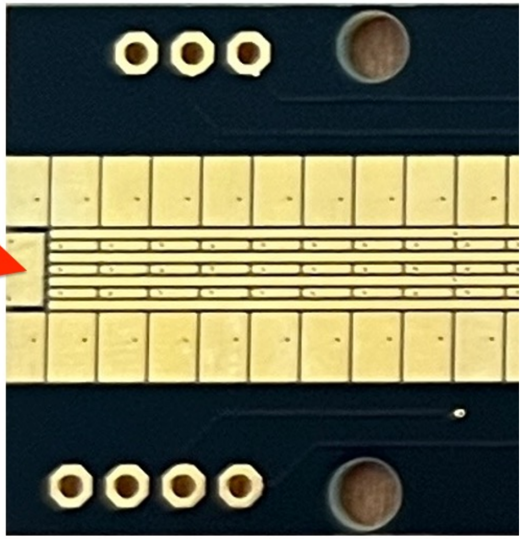


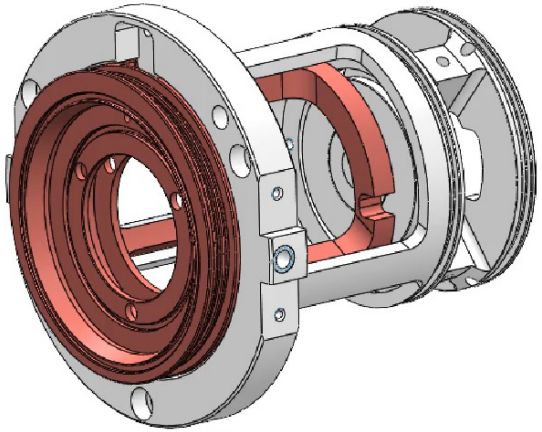
1. Heated capillary inlet
2. Front ion funnel
3. Rear Ion funnel
4. Ion Shuttle

Ion Shuttle Interface Design

- Modeled after SLIM 1.0
- Replaces the inlet capillary to bridge exit of the IMS to the entrance of the ion optics.

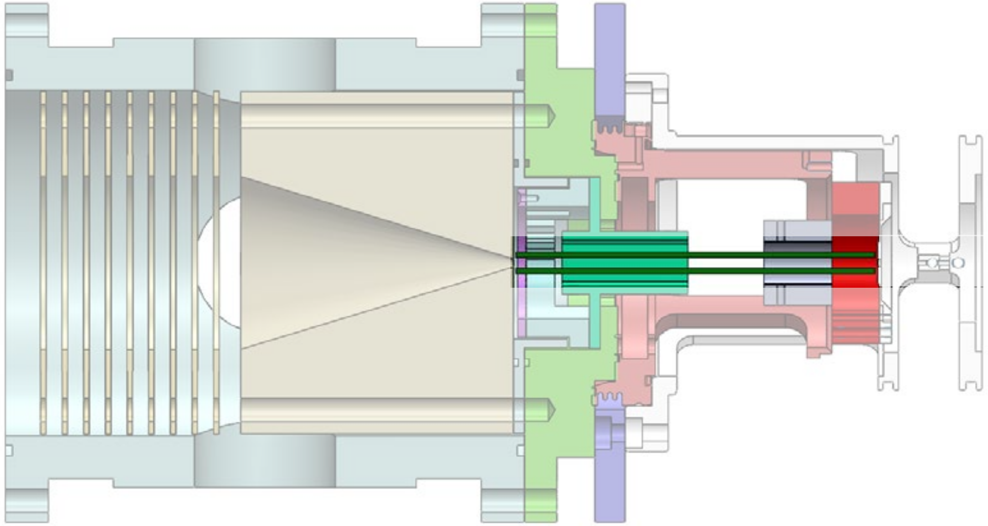
"2nd Gate" Modulation Electrode

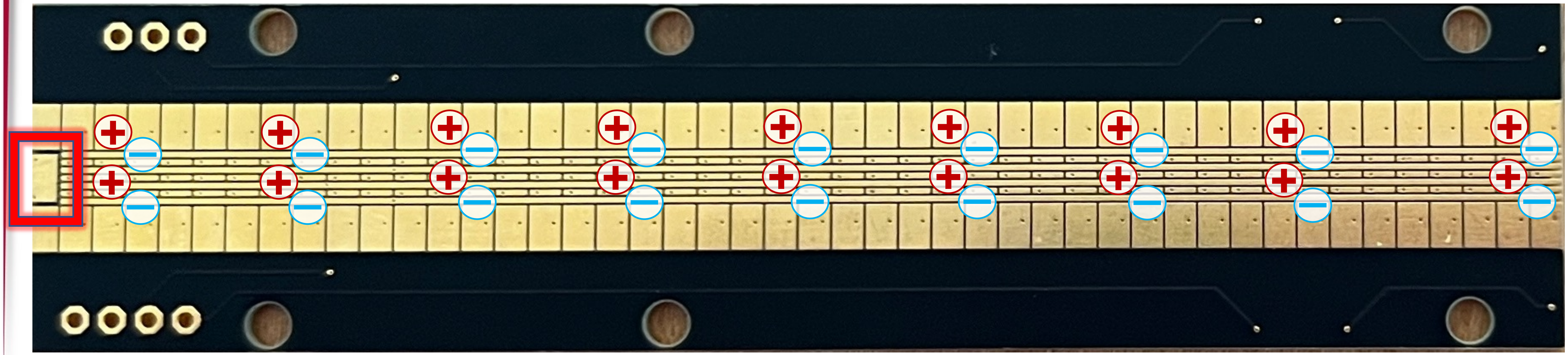




Ion Shuttle Interface Design

- Electrodes located at the entrance of the ion shuttle serve to modulate the incoming ion beam.
- Two RF tracks to radially confine ions.
- Small DC gradient to transfer ions

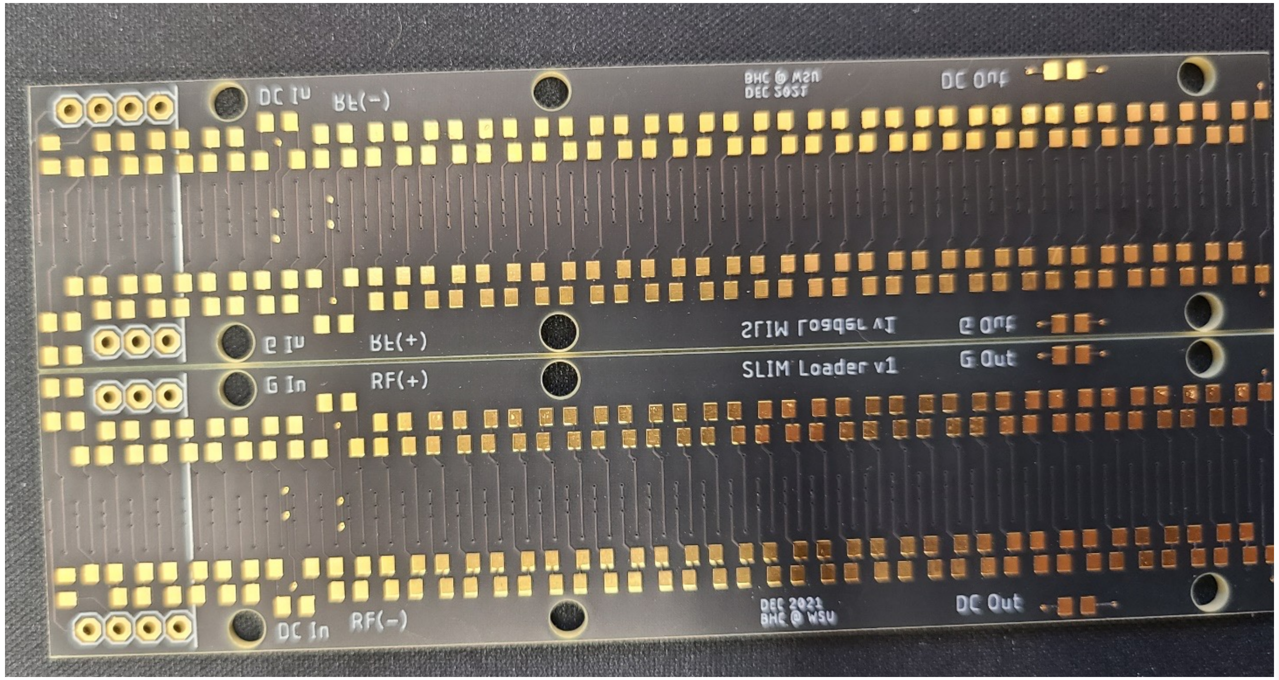


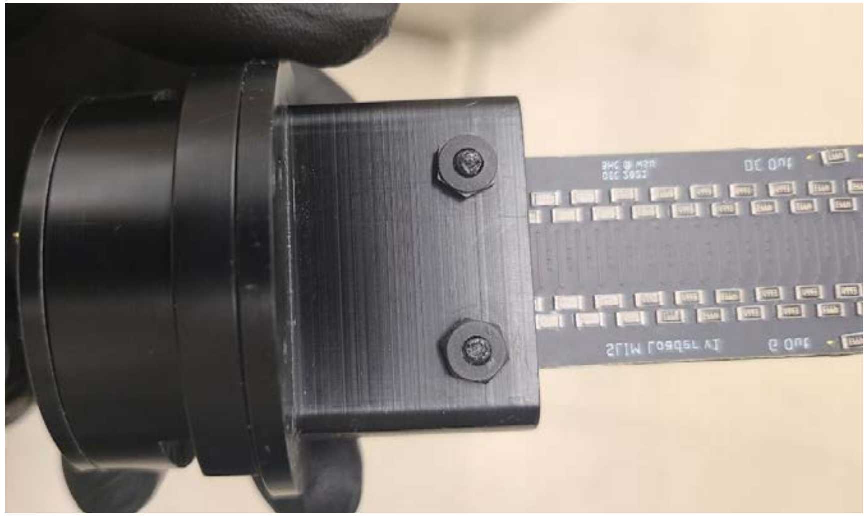


Ion Shuttle Assembly

Ion Shuttle Assembly

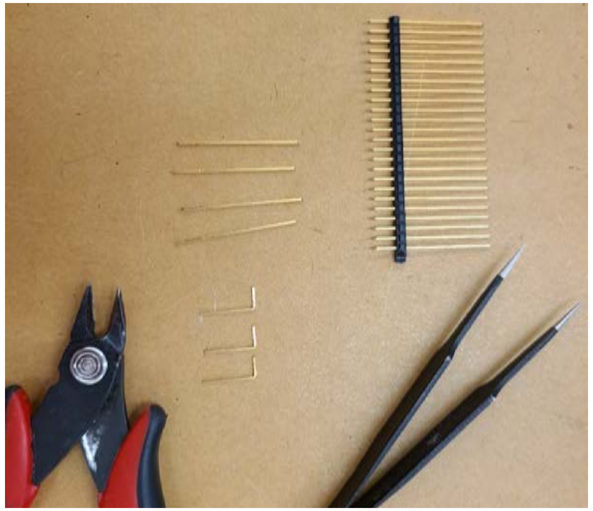
- Solder the surface mounted 250 kOhm resistors as was done for the IMS and ion funnels
- To assemble the shuttle, use the two Delrin spacers and 4-40 screws/nuts and the Delrin ion shuttle holder.





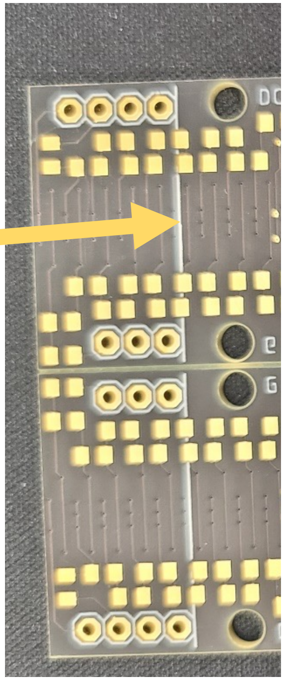
Electrical Connections

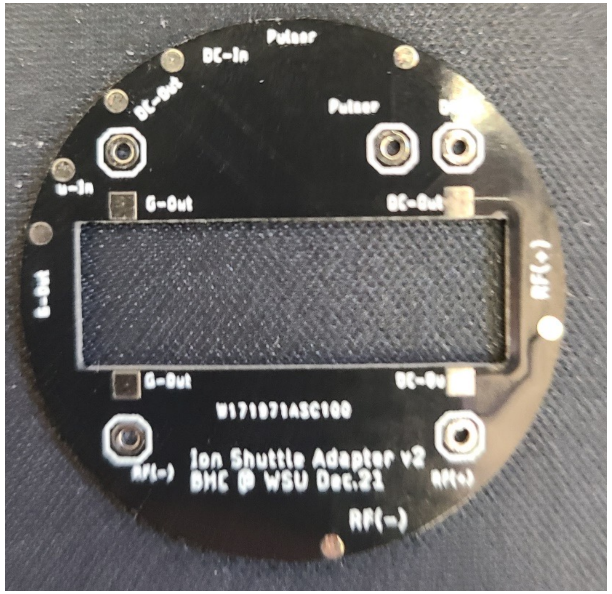
- For the ion shuttle electrical connection to the PCB connector electrode as well as the ion funnel/ion shuttle connector electrode, metal conn pins are cut and bent into the required geometries.
- Trial and error may be required to ensure correct lengths and angles are present.
- Ensure that no accidental connections are made and solder joints are clean and fully connected.



Ion Shuttle Assembly

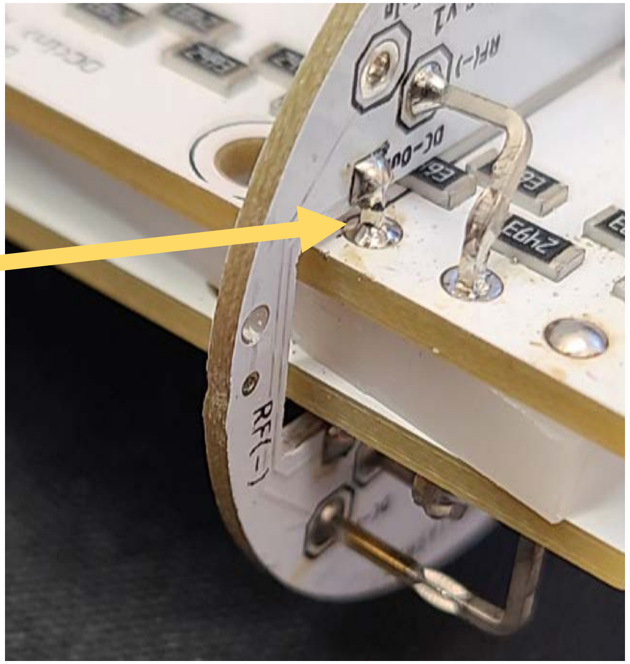
- The PCB connector electrode must be soldered on at the indicated line. Correct alignment is of **CRITICAL IMPORTANCE**
- The connector electrode is directional so be careful in aligning with the ion shuttle.

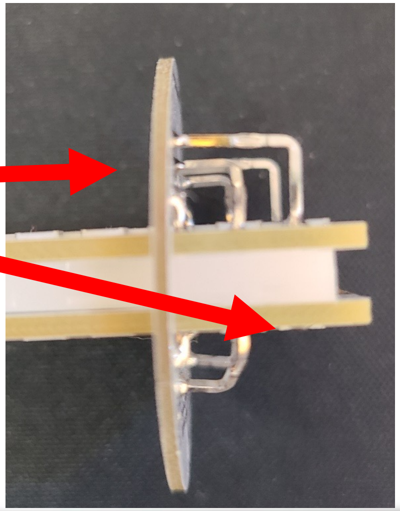




Ion Shuttle Assembly

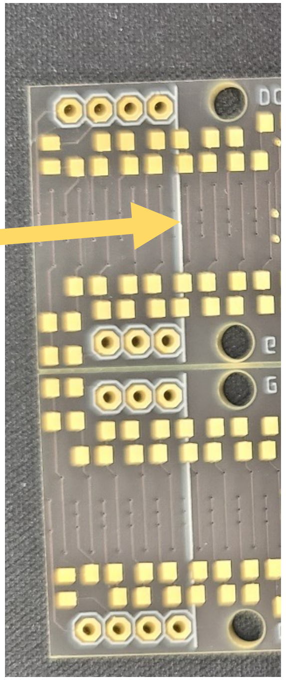
- Using the metal conn pins, carefully bend and solder pins to all seven electrical points.
- Before soldering, slide two pins through the DC and ground out locations as placing these first help prevent the electrode from misalignment. Solder these pins first.
- When soldering, be aware that the Delrin piece can melt under prolonged heating.
- After all connections are made ensure that the excess is cut flush to the electrode and the shuttle and carefully soldered to avoid burrs and spikes

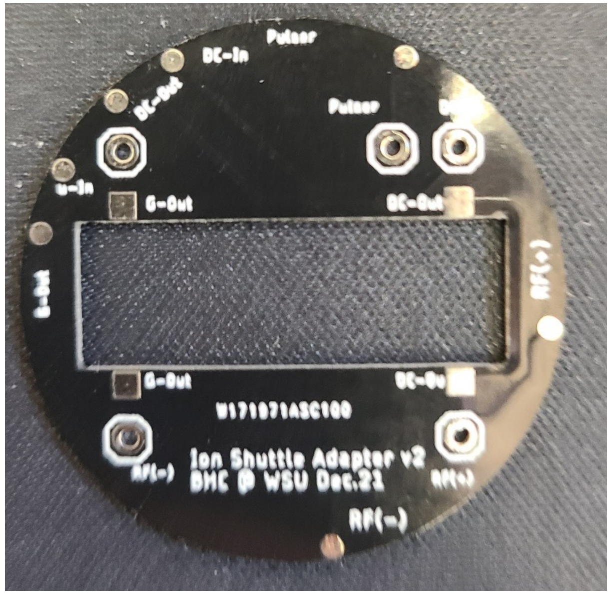




Ion Shuttle Assembly

- The PCB connector electrode must be soldered on at the indicated line. Correct alignment is of **CRITICAL IMPORTANCE**
- The connector electrode is directional so be careful in aligning with the ion shuttle.



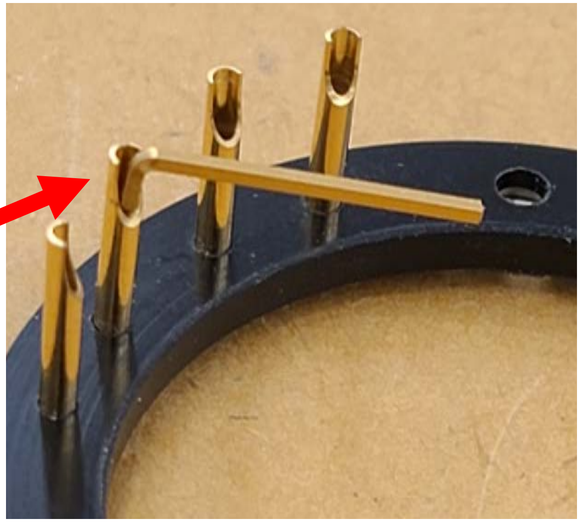


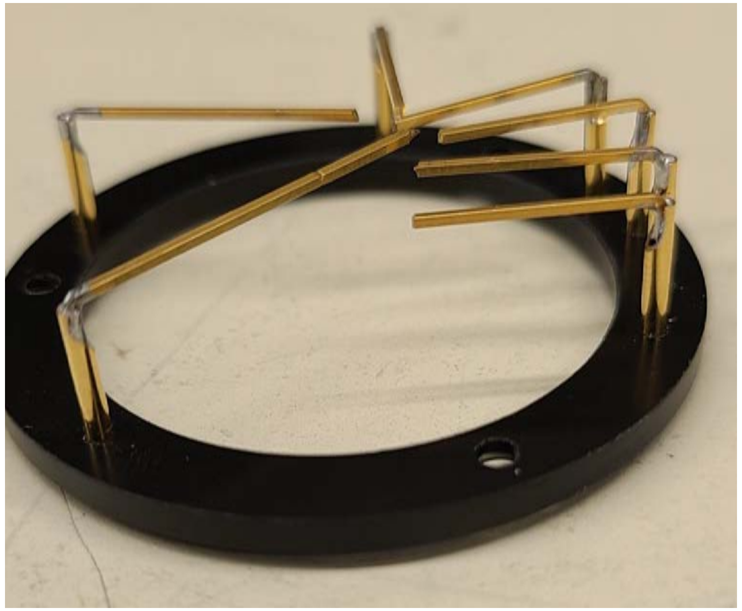
Ion Shuttle Assembly

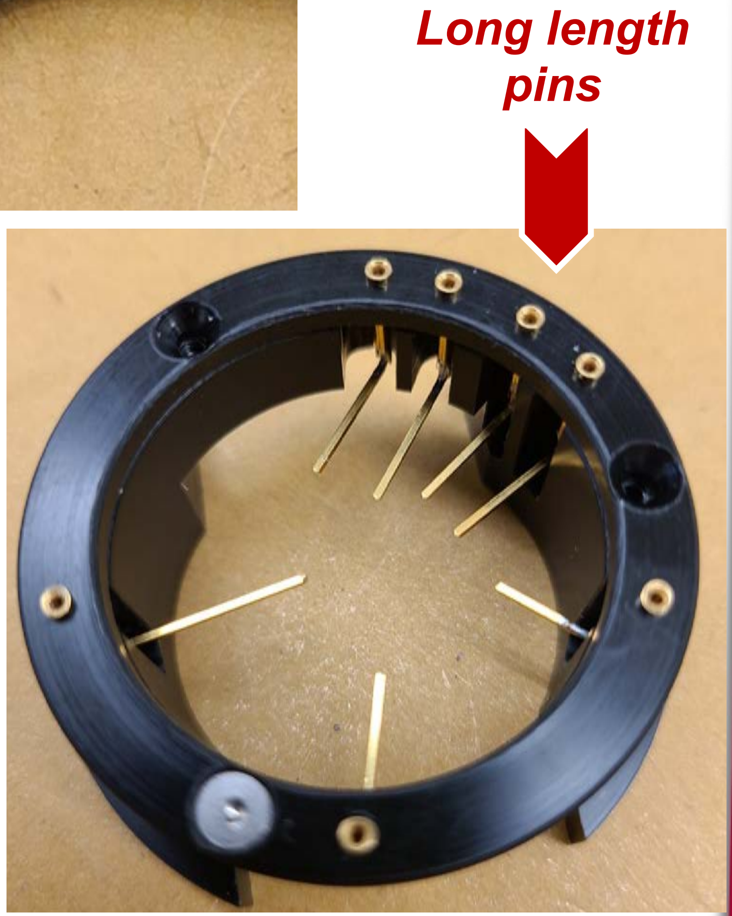
- Push connect the seven pressfit conn pin into the Delrin ring.
- Note that both the conn pins and the Delrin ring are directional.

Ion Shuttle Assembly

- Invert the Delrin ring and place bent metal conn pins as shown.
- The height of the pin is most critical dimension, and should be equal to the height of the press fit connector.
- Solder all pins into place. Be aware that prolonged heating will damage the Delrin piece and require replacement.
- *During original assembly, the pins were deliberately left long so the next step would be easier, as we could cut the pins to the exact length required, as it is distinct for each pin, due to the positioning around the PCB connector electrode.*

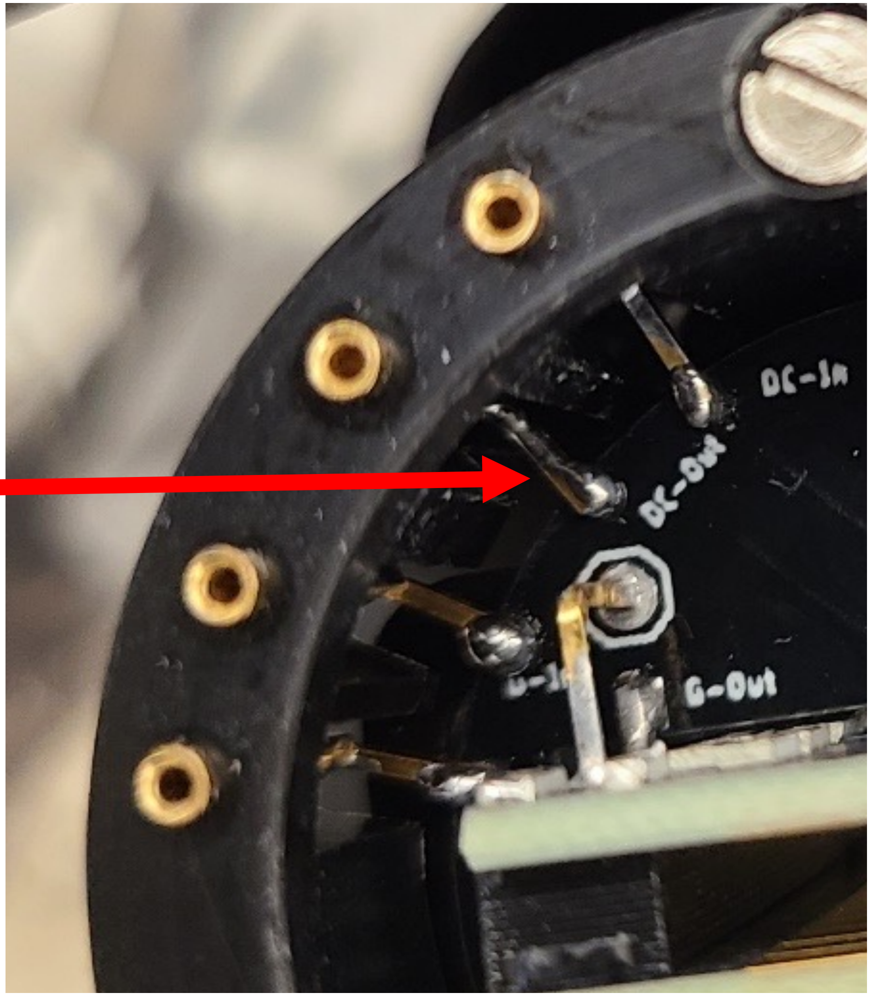






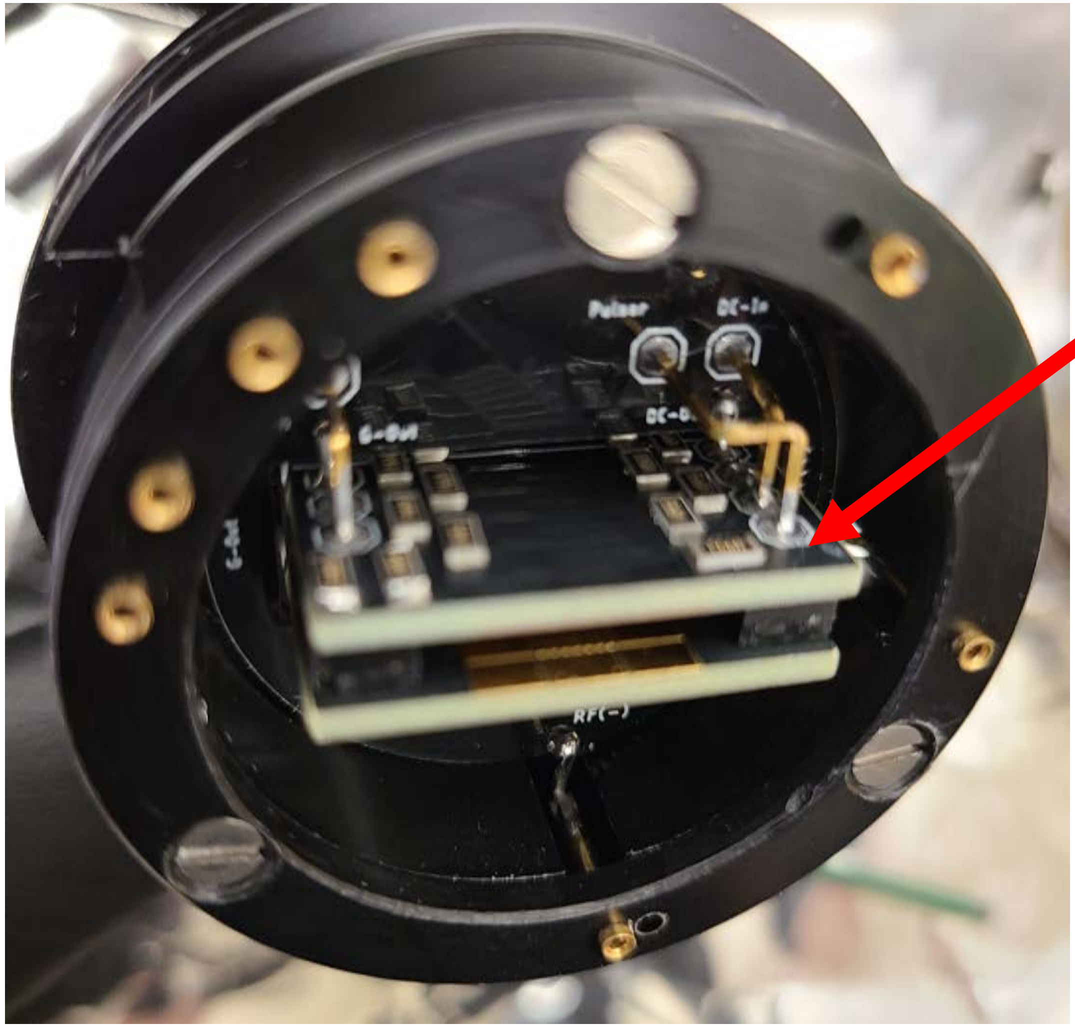
Ion Shuttle Assembly

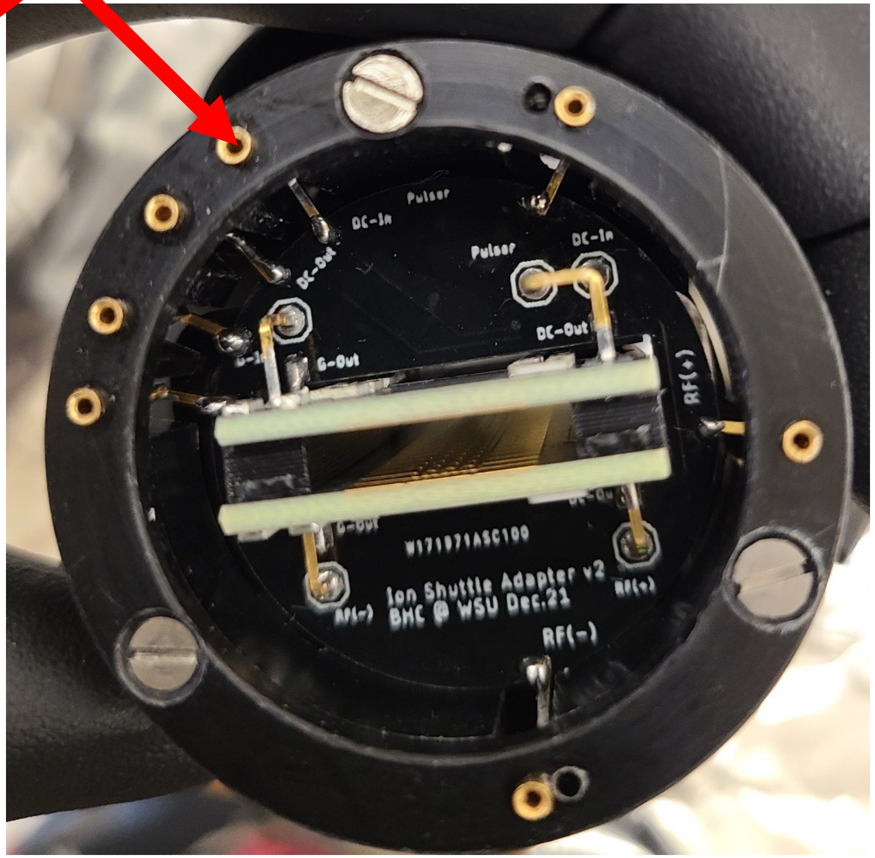
- Combine the Delrin ring and Delrin ion shuttle and align the pins with the appropriate solder connection point.
- Carefully trim the pin length to the correct length and solder pins to PCB connector electrode.



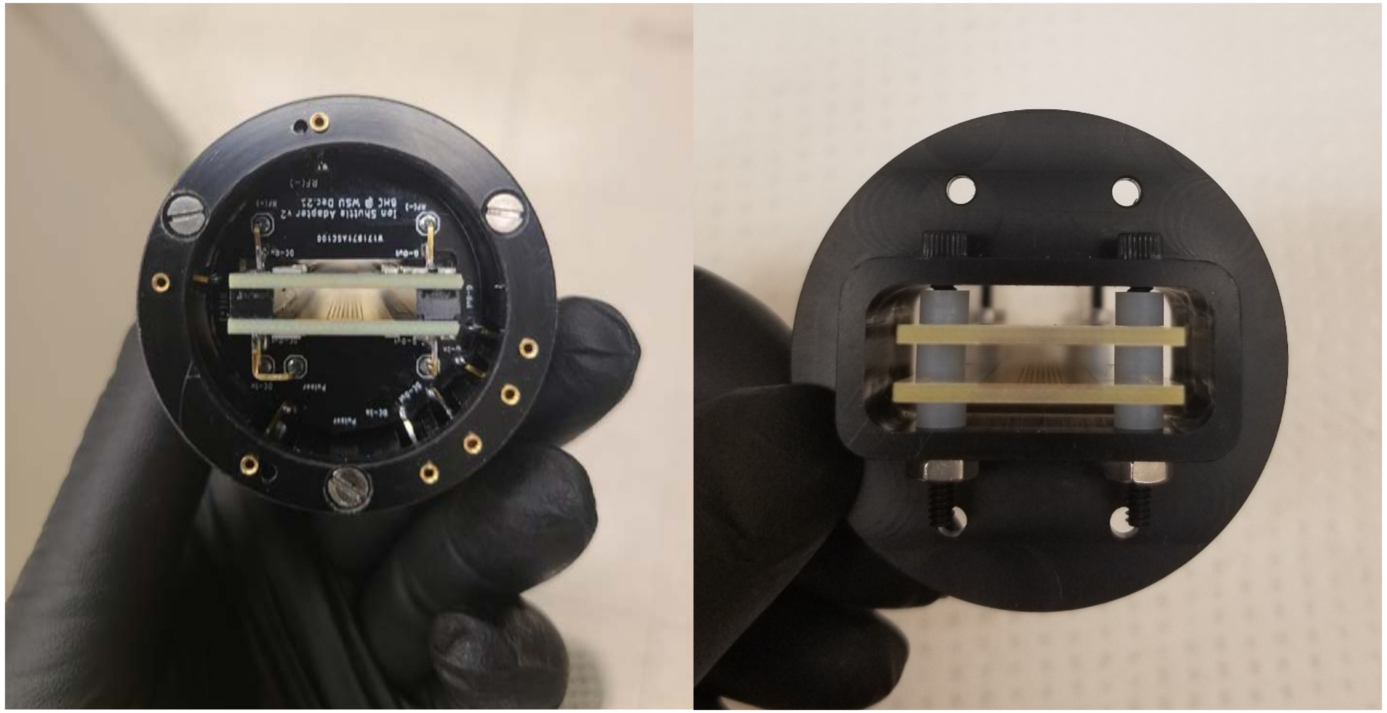
Completed Shuttle

After soldering, ensure electrical connection is made to the PCB from the socket head for all seven voltages and the shuttle connections match the rear funnel final electrode





Completed Shuttle

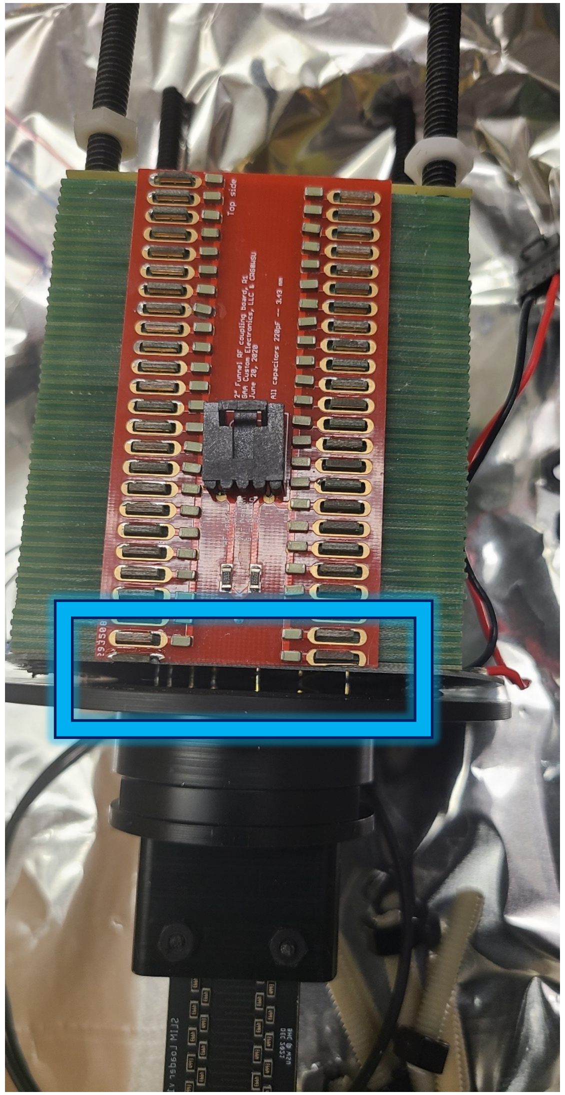


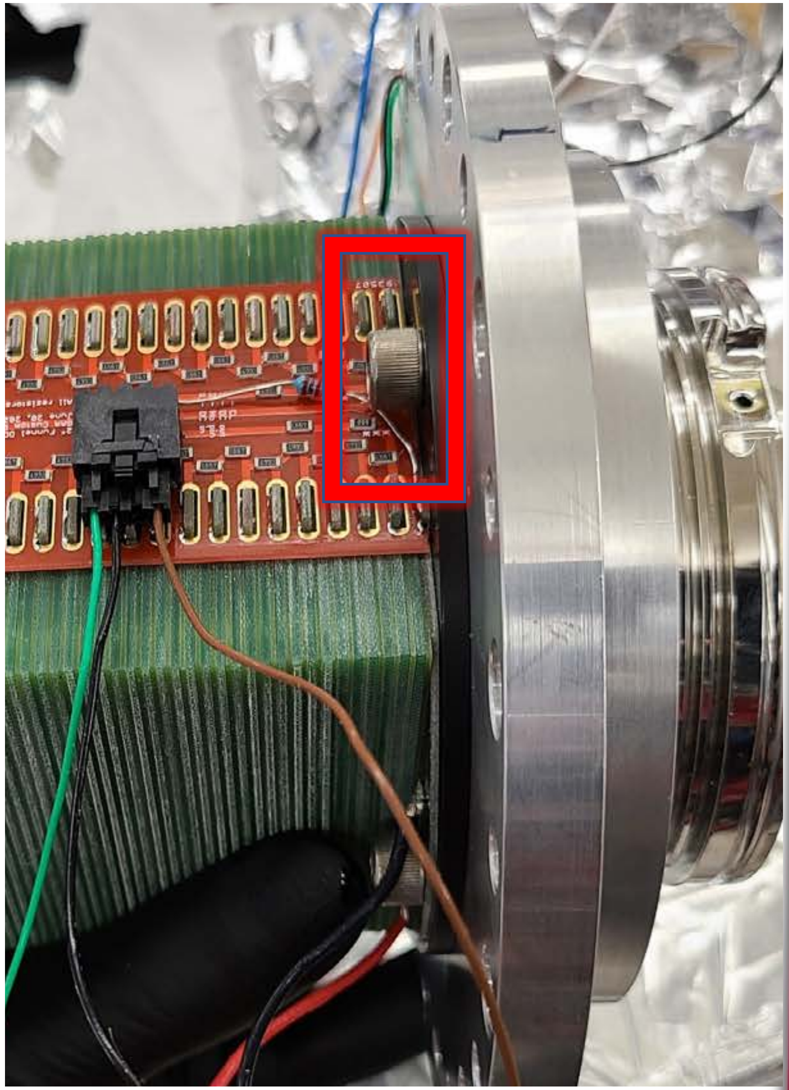
- The completed shuttle should have the pins as compact as possible, to minimize the chance of errant connections.
- There should be 14 total spacers used. 12 within the Delrin holder, and 2 at the shuttle end.
- Ensure that the pins are fully connected before assembly and that nothing is errantly connected

Ion Shuttle Implementation

Ion Shuttle Assembly

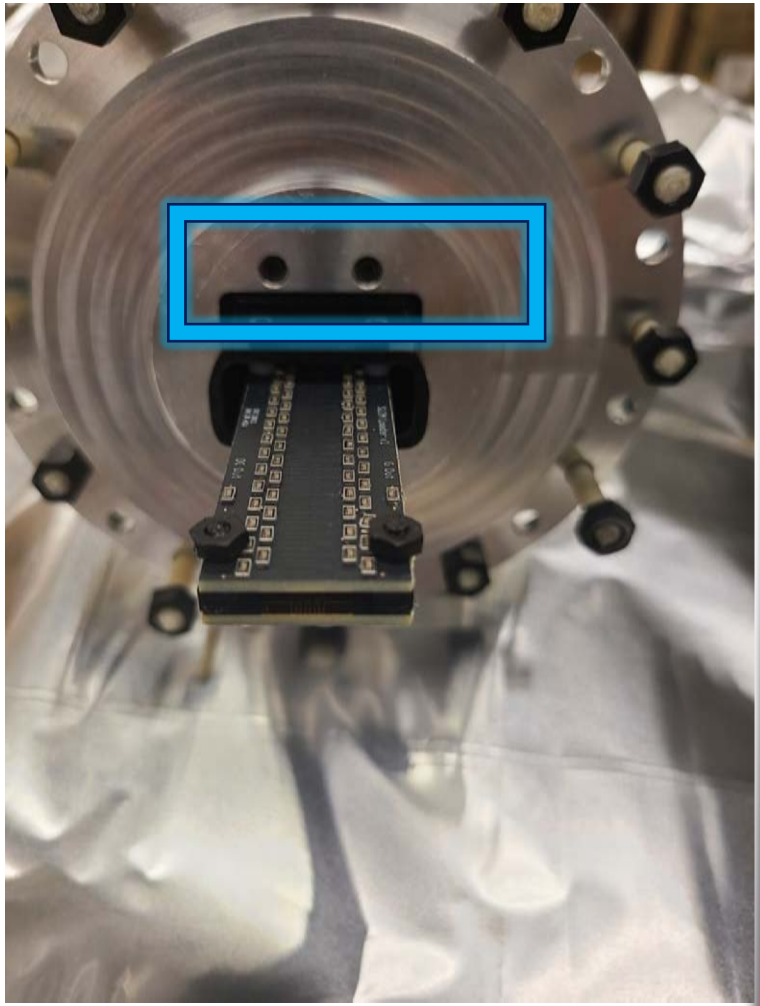
- The completed shuttle should be thoroughly tested and cleaned before installation into the MS analyzer.
- Carefully align the pins on the Rear funnel final electrode and press into the sockets in the Delrin ring.
  - *If the final electrode is not soldered onto the ion funnel do so and ensure that all connections are made as they should, and that the rods holding the funnel together are fully tightened into the metal plate.*
- After securing the four nylon rods, screw on the four metal bolts to hold the funnel to the metal plate.

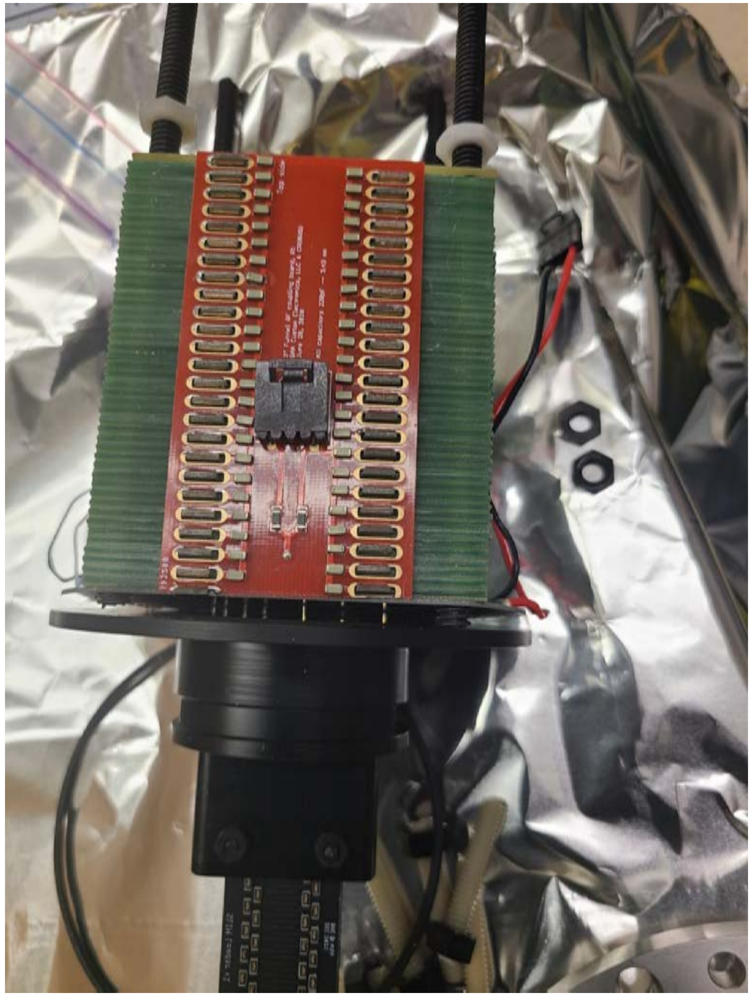




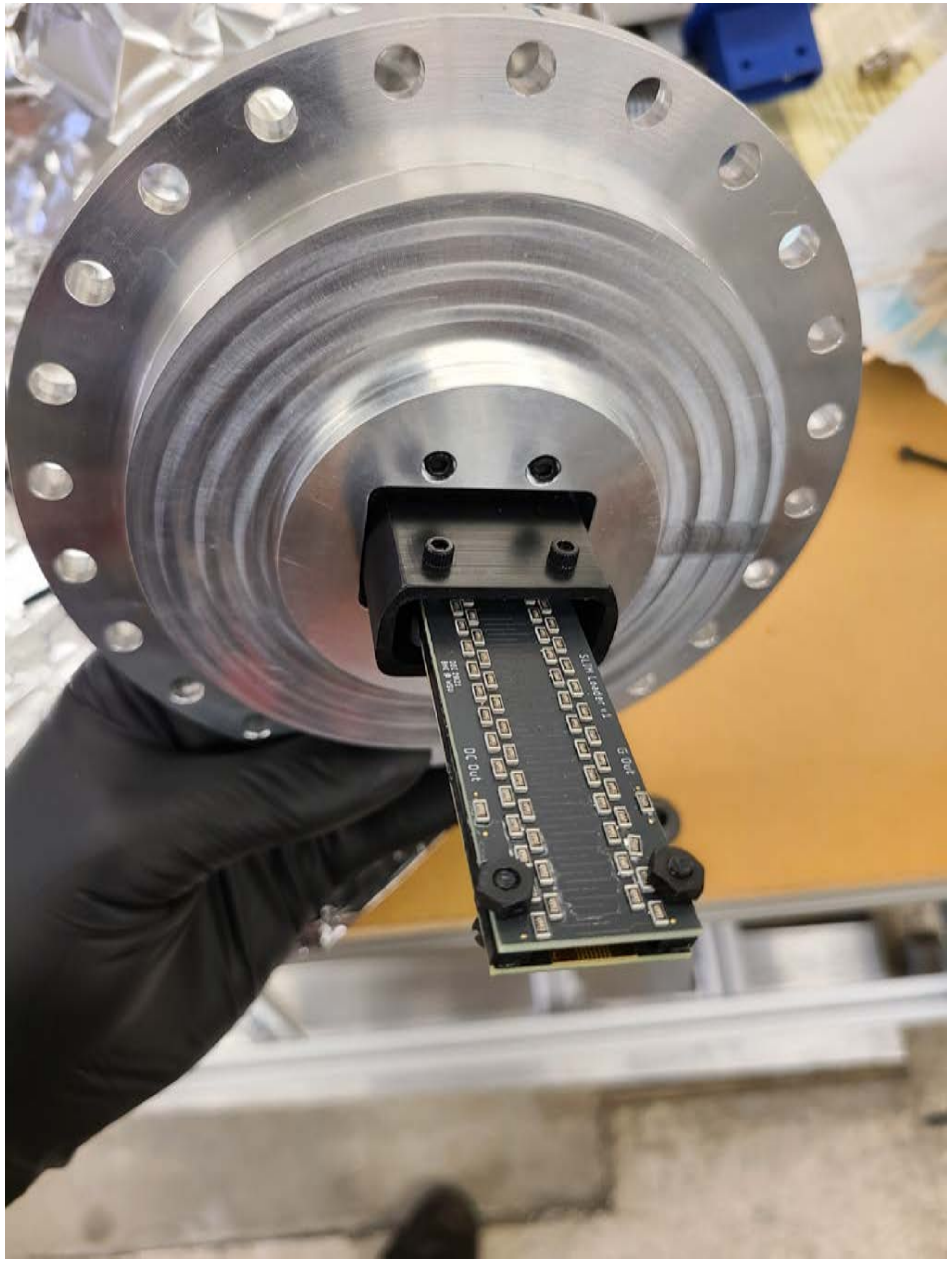
Ion Shuttle Assembly

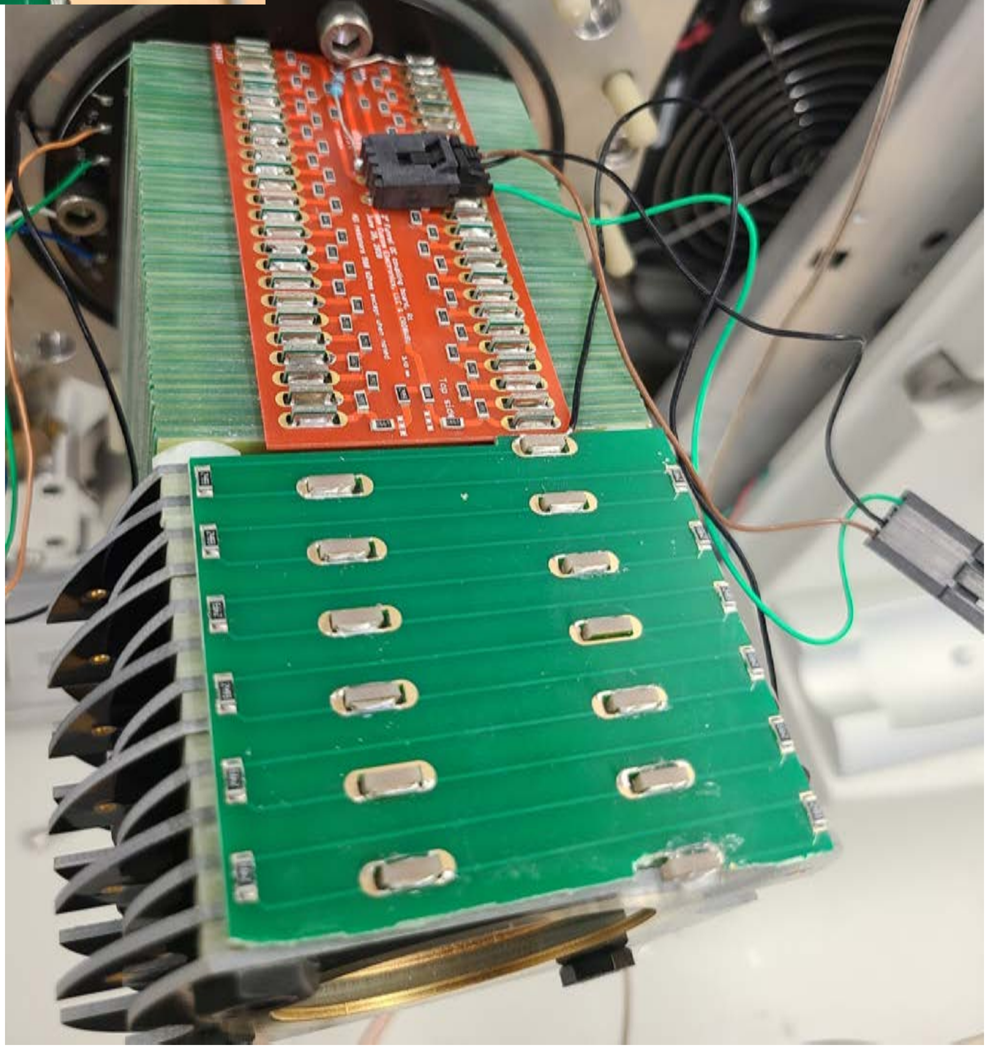
- Flip the assembly around and tighten the four screws on the back of the shuttle to hold the Delrin shuttle holder to the metal plate.



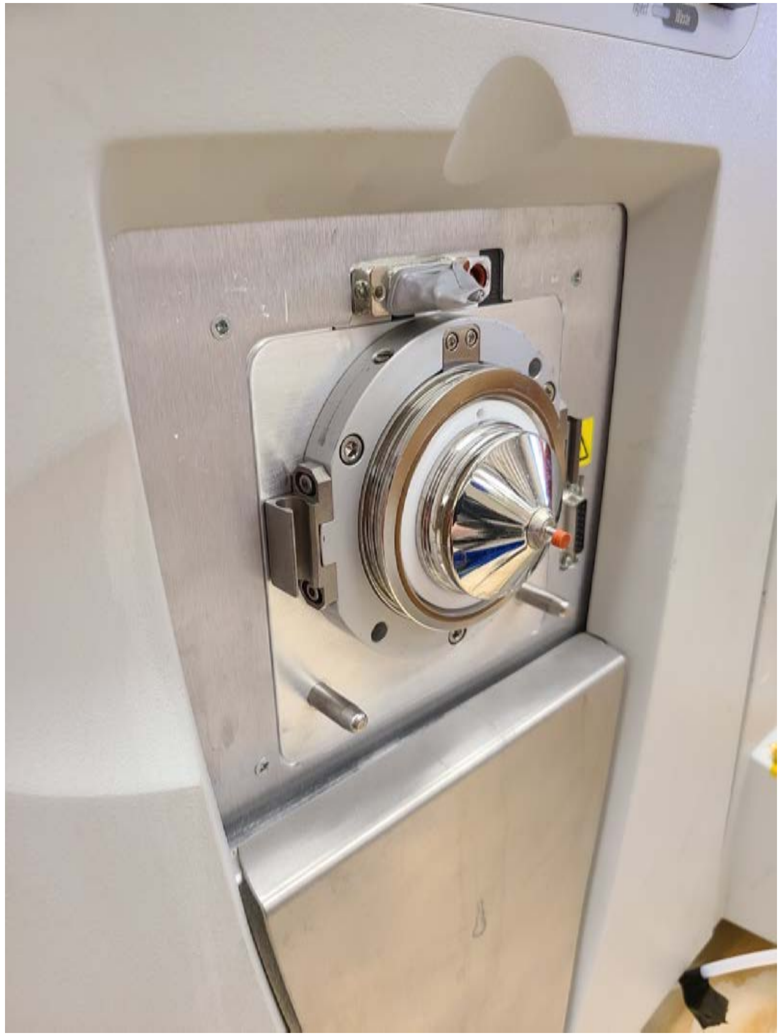


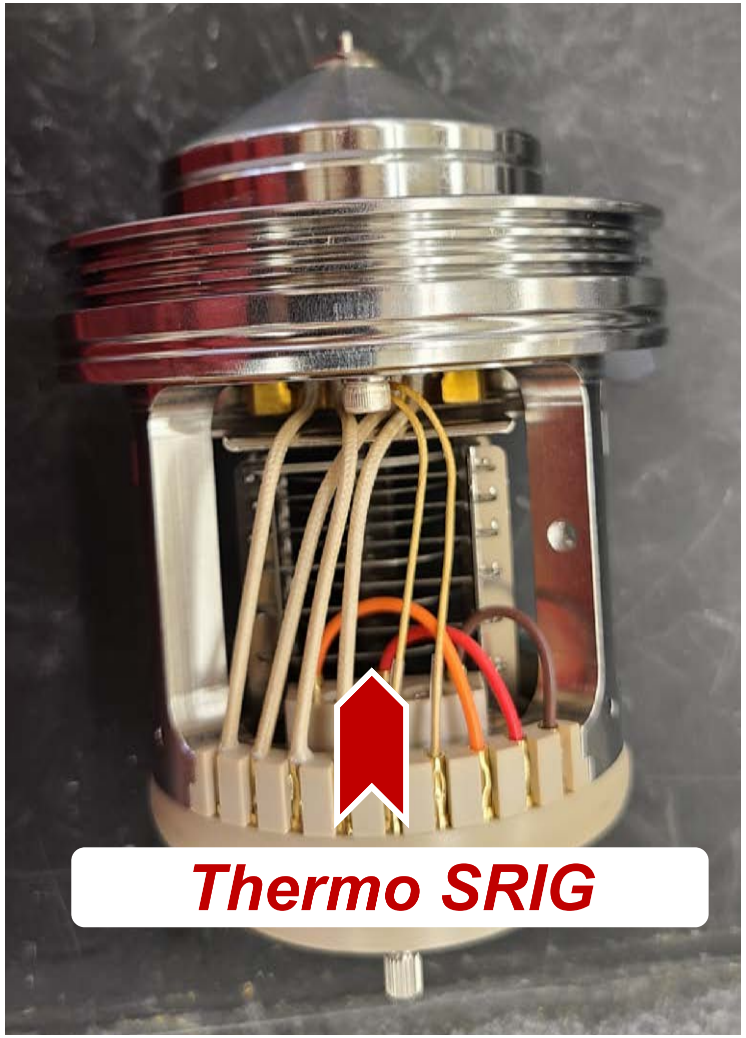

Ion Shuttle

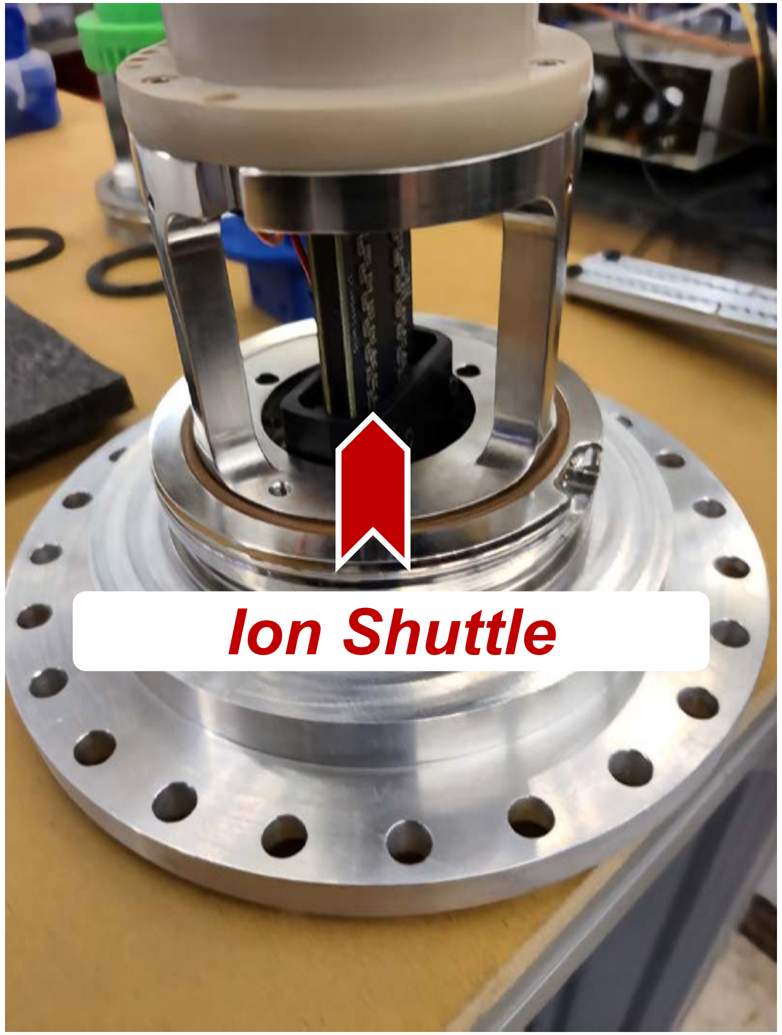

DC Out
G Out



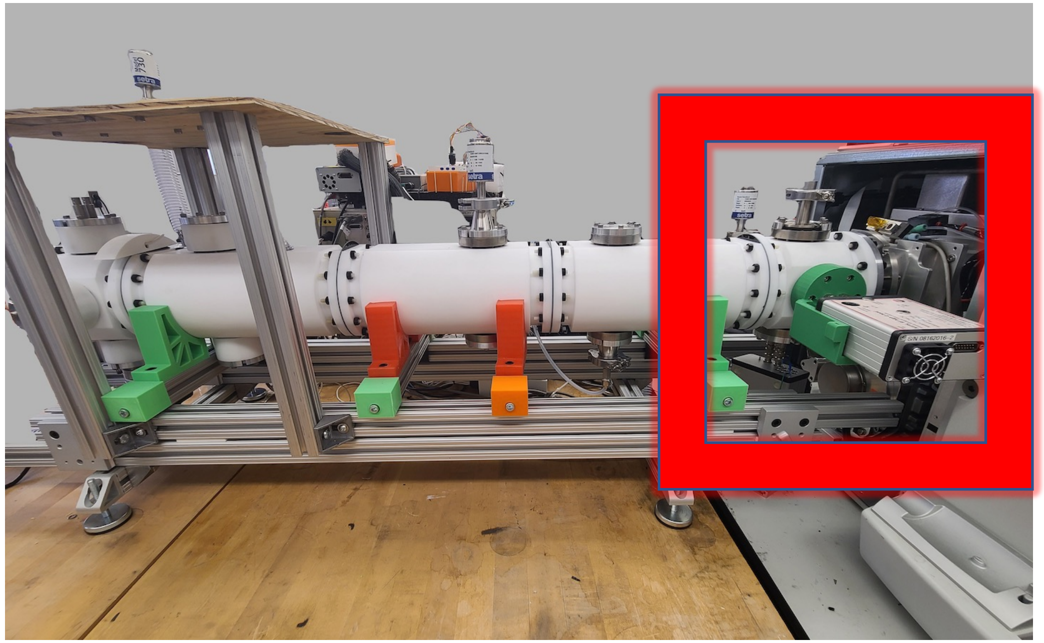
Ion Trap Coupling

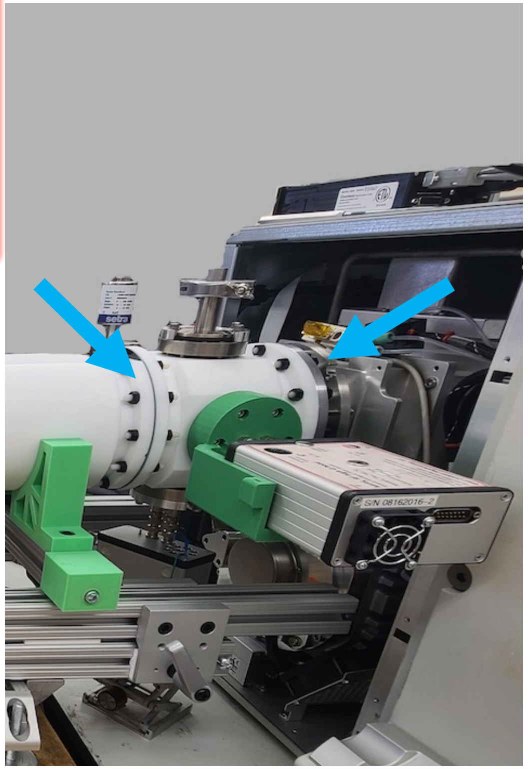






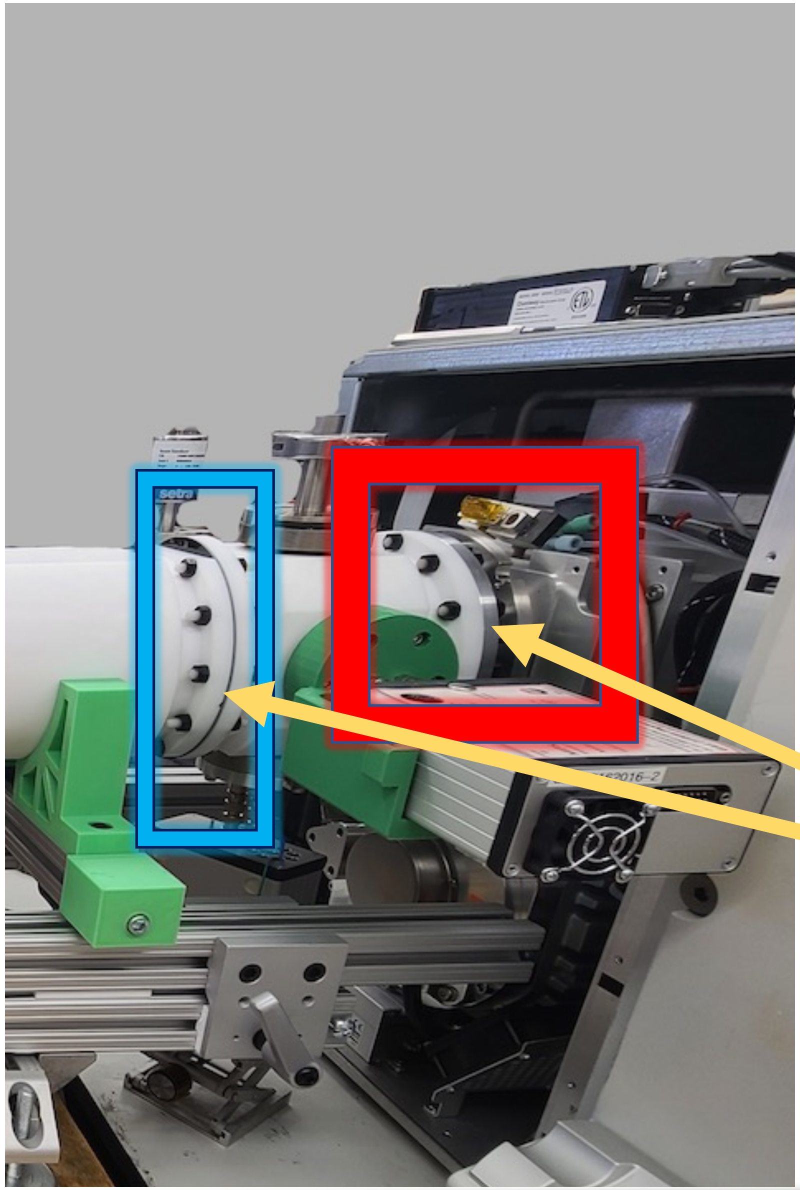
Ion Shuttle Disassembly





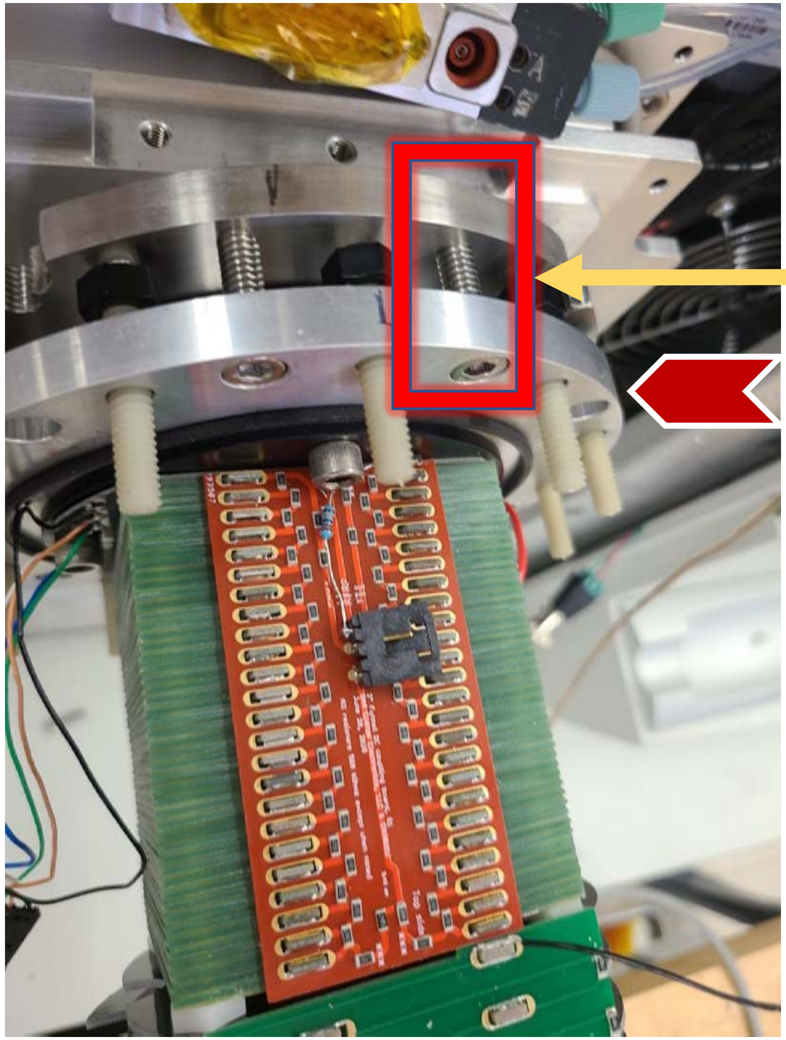
To replace the ion shuttle, you first need to loosen and remove the bolts connecting the final PTFE enclosure on both sides. This will allow you to separate the rest of the IM system and access the ion shuttle.

Ion Shuttle Disassembly



To replace the ion shuttle, you first need to disconnect all the DC and RF feedthroughs connecting the Teflon enclosure from the rear ion funnel/shuttle connection. Then you must loosen and remove these bolts. This will allow you to separate the Teflon enclosure from the rear ion funnel. **HOWEVER**, if you have a wired connection between the drift region and the flange you must remove these bolts and disconnect the wired connection as well before removing the Teflon enclosure.

Ion Shuttle Disassembly



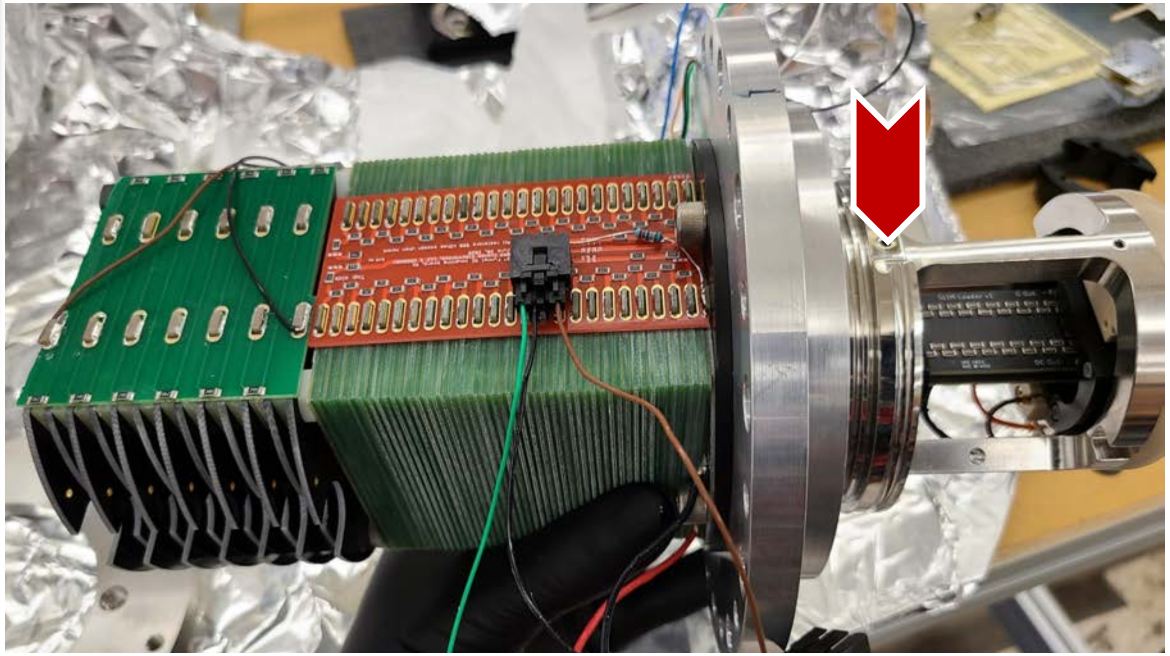
First Plate

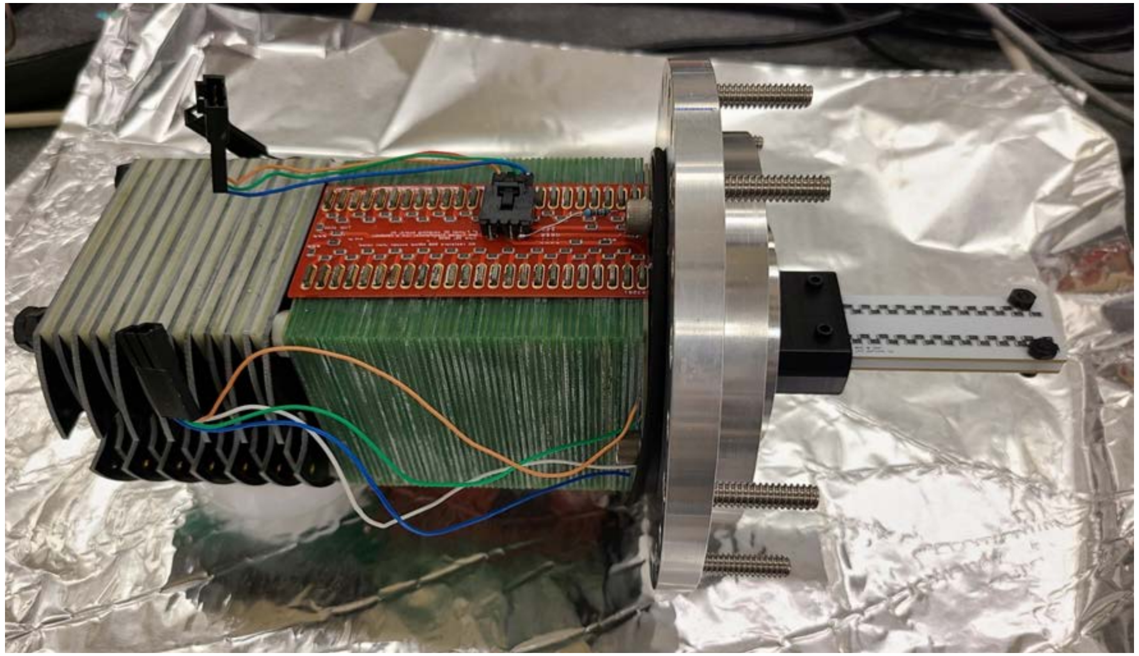
Once all the connections surrounding the rear ion funnel have been removed, these metal screws connecting the two vacuum plates need to be undone. Once the last bolt is undone the whole rear ion funnel/ion shuttle along with the first of the metal plates. will be able to be pulled out.

Ion Shuttle Disassembly

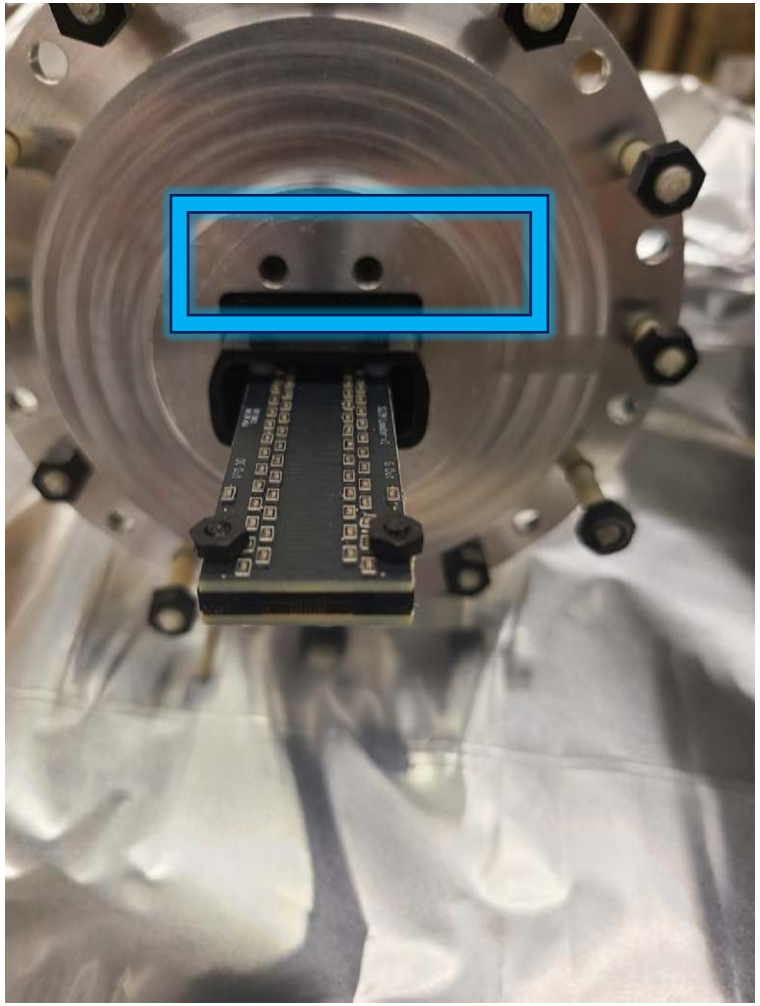
The Thermo ion cage and rear plate will most likely not be removed when this assembly is pulled out. To remove the Thermo ion cage, a small lever can break the seal to the mass spec and remove the Thermo Ion cage if needed.

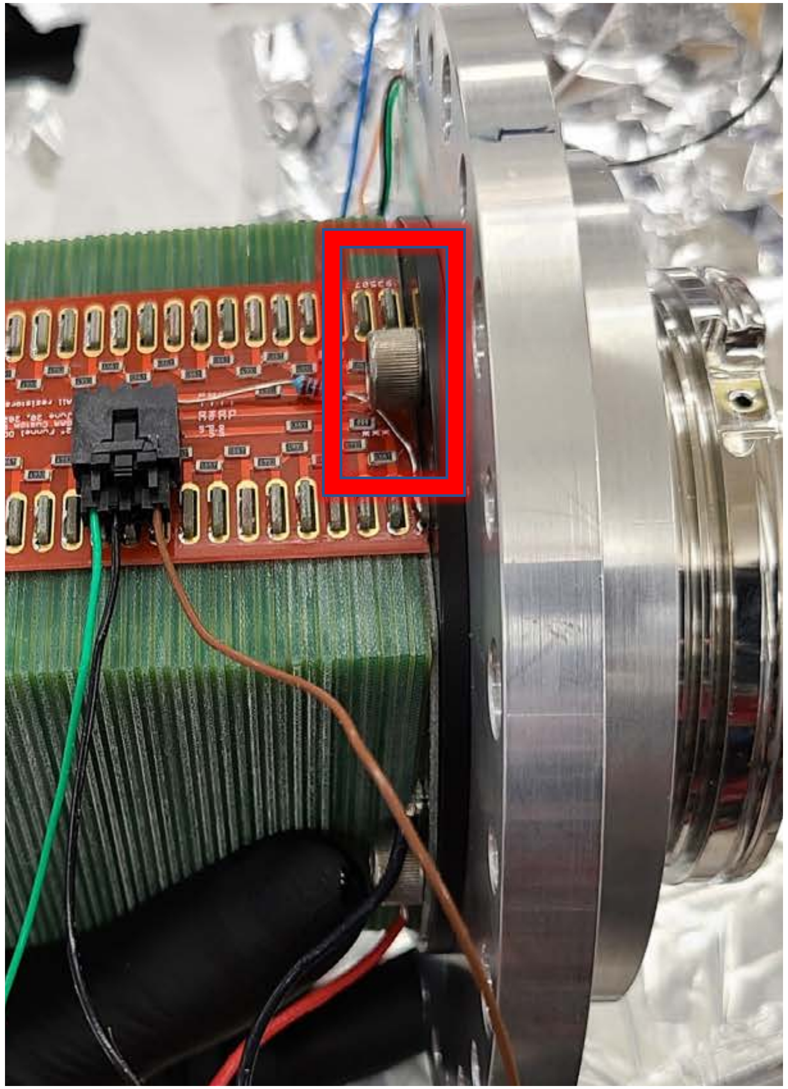
Thermo Ion Cage





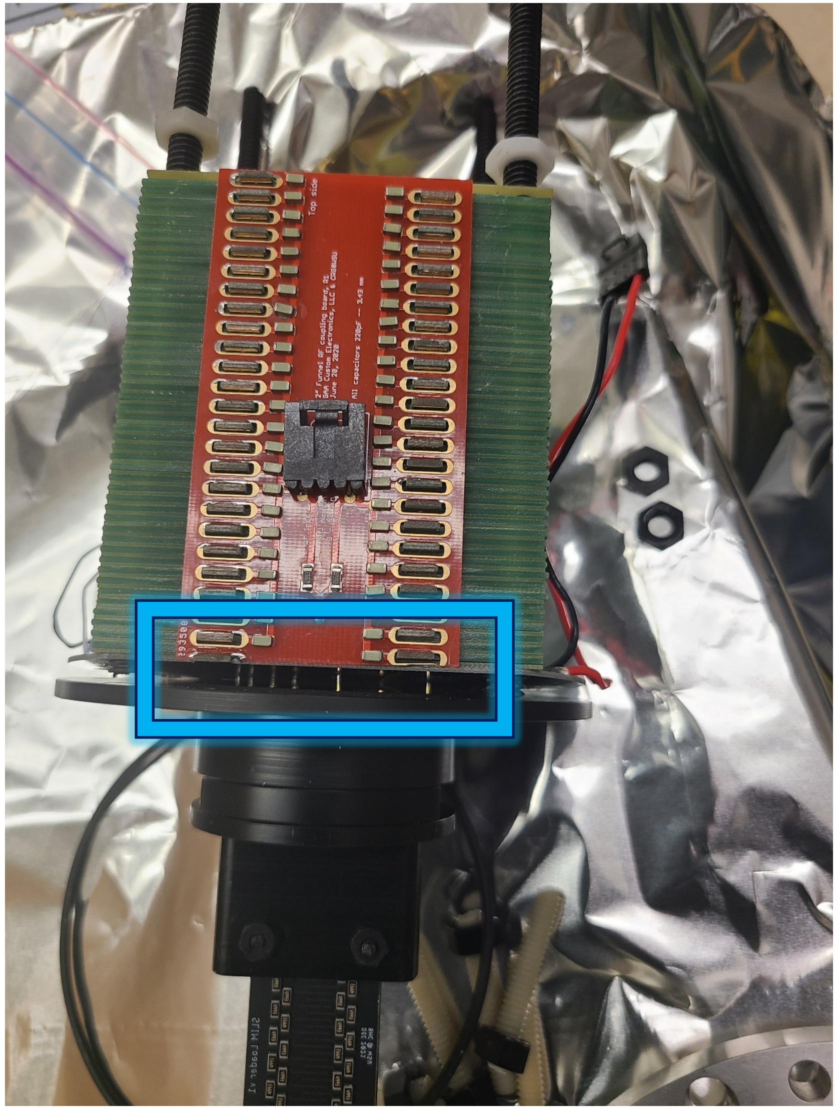
Ion Shuttle Disassembly





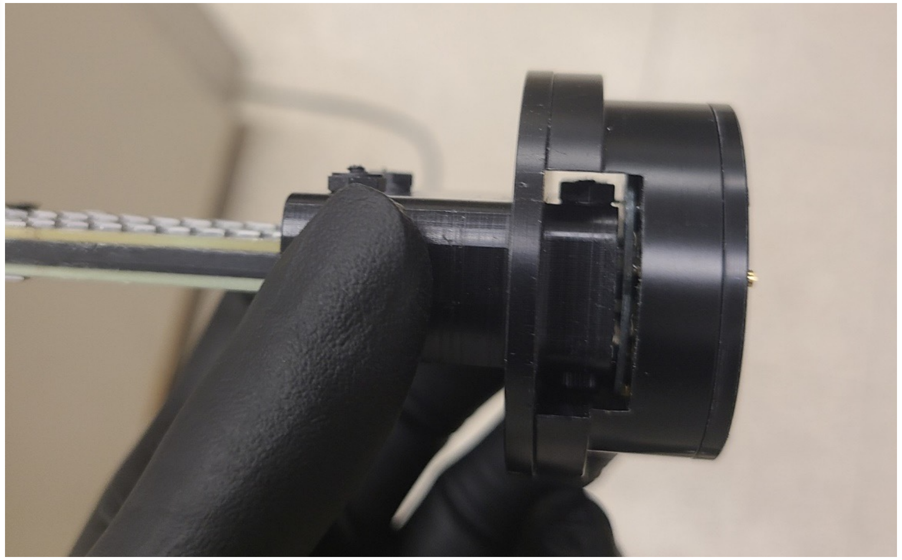
On the back side of the metal plate, unscrew the four bolts connecting the metal plate to the rear ion funnel board. Then unscrew the 4 bolts on the front of the plate and carefully pull the ion shuttle through the metal plate.

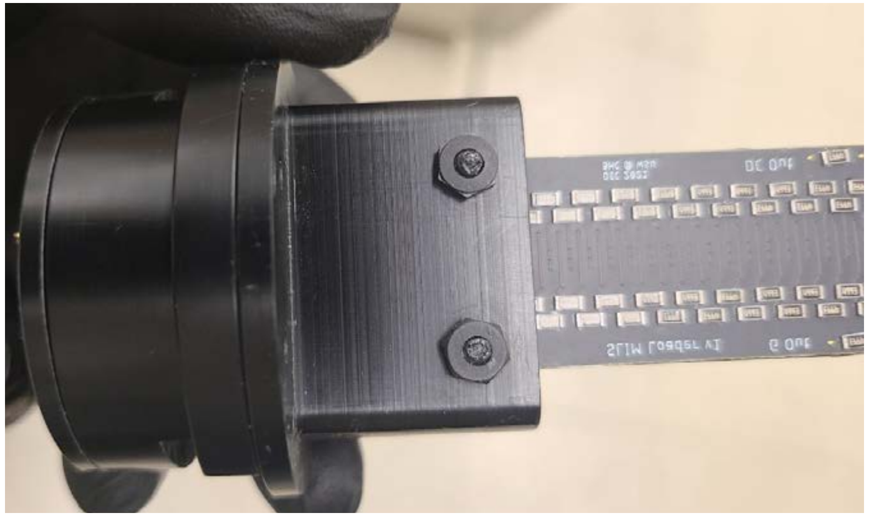
Ion Shuttle Disassembly



Carefully unscrew the rods connecting the rear ion funnel to the Delrin insert. If the rods are not long enough to fully be able to turn, the last segment of the drift tube can be removed for additional clearance (be careful not to have the spacers fall out). Once all four rods are unscrewed, carefully separate the two pieces without damaging the pins.

Completed Shuttle





Lift out the entire ion shuttle and Delrin and replace with the new one. Be careful to not damage O-Rings or the metal connectors.

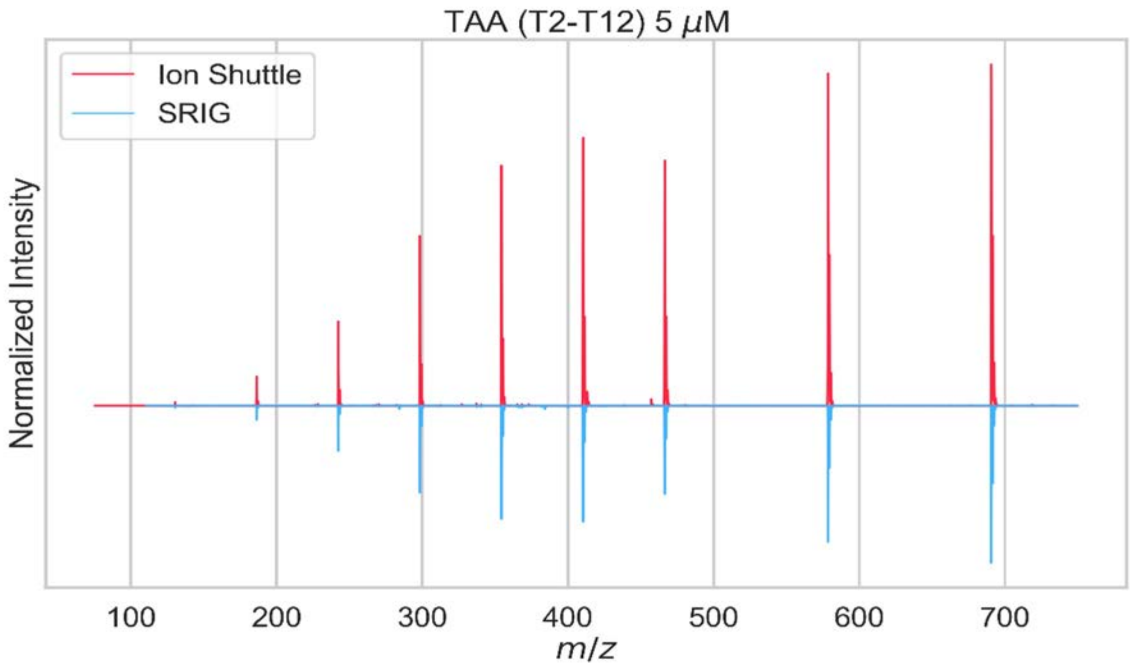
Clean all Components with IPA/Methanol and reassemble. If the ion shuttle is not going to be installed day of, reinstall the original Thermo components and place mass spec under vacuum.

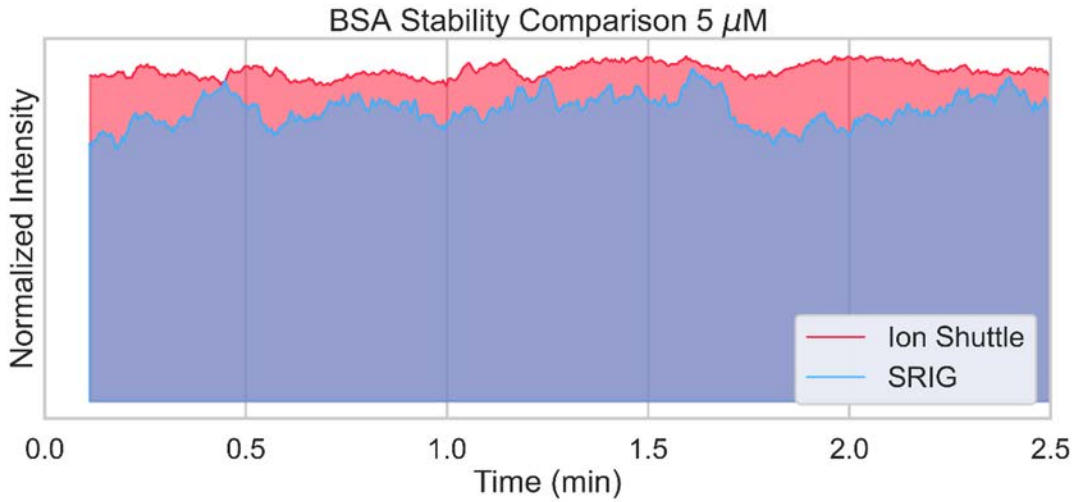
Ion Shuttle Evaluation

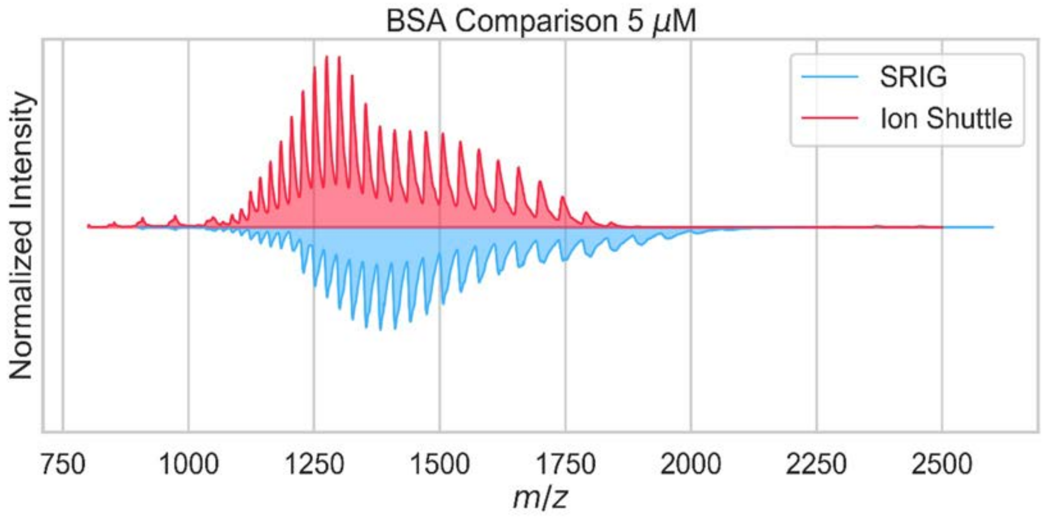
Should see approximately equal performance when comparing ion shuttle directly to the Thermo SRIG or ion optics. We tested the ion shuttle before assembly with the full IM system by using just the rear ion funnel. This step is not necessarily needed if the full system works, but it was beneficial to ensure the ion shuttle works as intended before connecting the ion mobility drift cell. The following slide shows the comparison between the Thermo SRIG and our ion shuttle/ rear ion funnel for the same electrosprayed sample.

Ion Shuttle Evaluation

- Ion shuttle replaces Thermo SRIG
- “Equivalent” performance
- Transmission characteristics largely dependent upon RF_{P2P} and frequency.



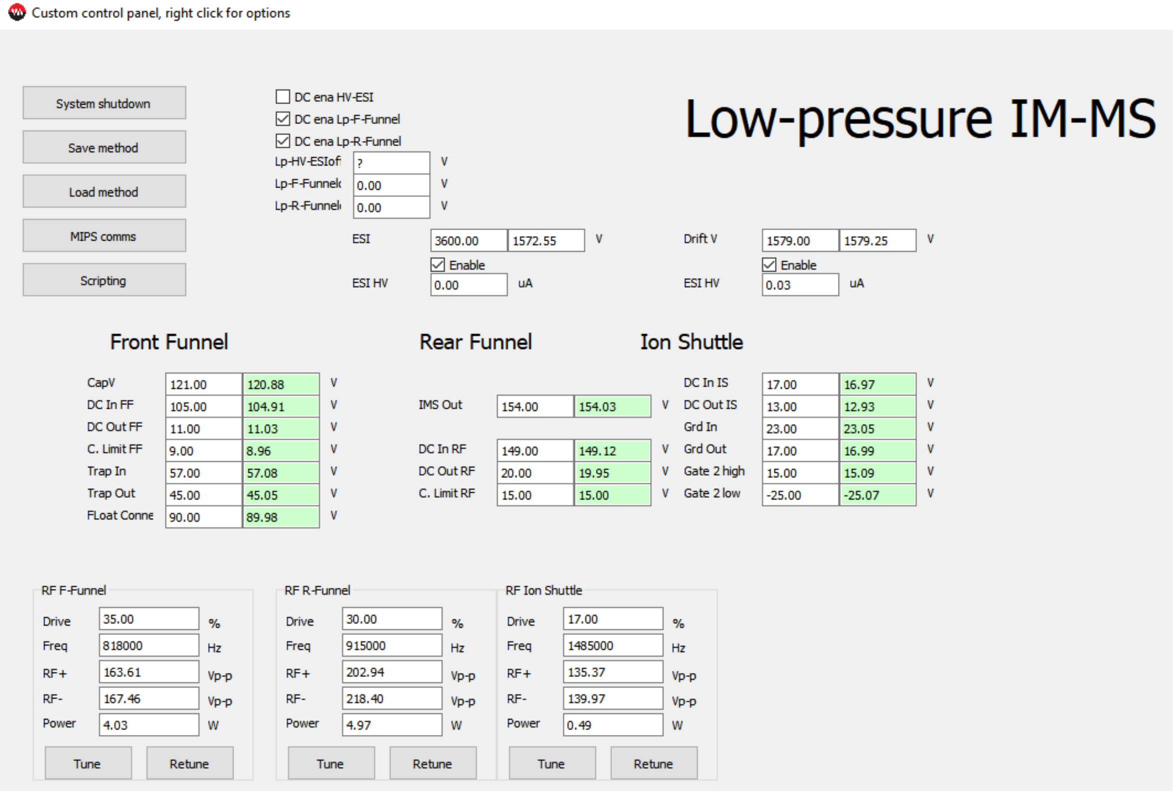




Electronic Control

We use 3 MIPS systems purchased from GAA Custom Electronics. One MIPS controls the heated inlet and the floated front ion funnel and capillary voltage. One is utilized as a high voltage power source and controls electrospray and drift voltage (and floats the first MIPS). The final MIPS controls the ion shuttle and the rear ion funnel, as well as the drift voltage out. We built a GUI (shown on next slide) to control all the voltages through the computer as well as to save the different voltage settings for a variety of field strengths.

MIPS Control



MIPS Control Settings

MIPS Systems