An RF beam Sweeper for Purifying In-Flight Produced Rare Isotope Beams

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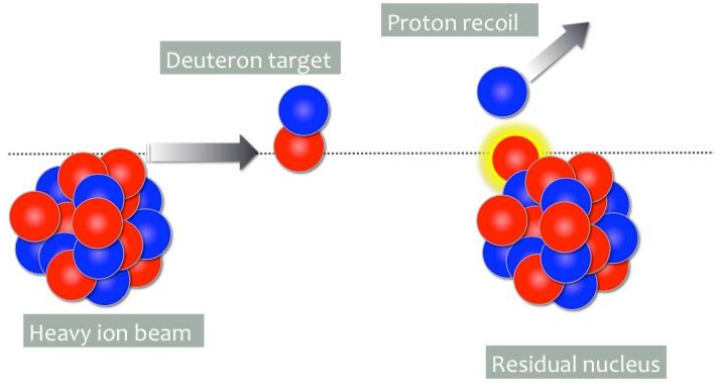
RadiaBeam

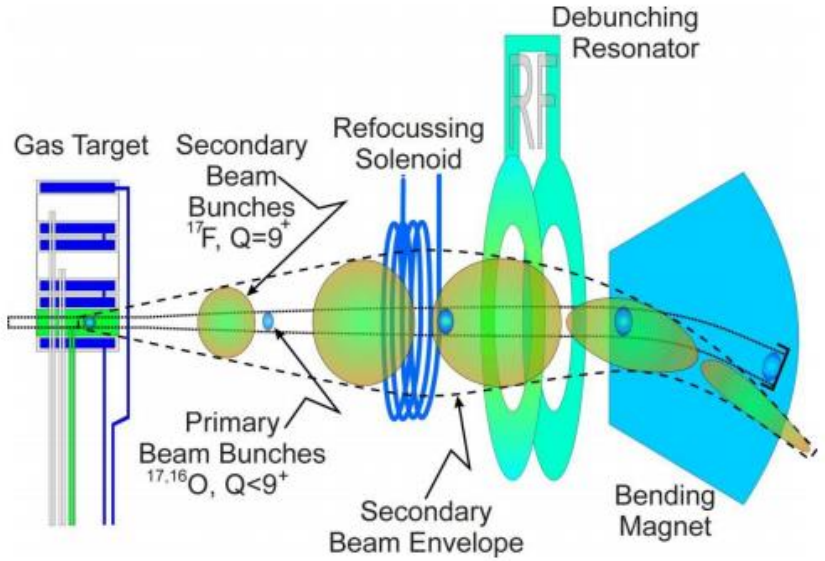
- Founded in 2004
- ~50 employees and growing
- 30,000 ft^2 headquarters in Santa Monica, CA

- Accelerator R&D, design, engineering, manufacturing and testing all under one roof in a dynamic, small-business setting

Background

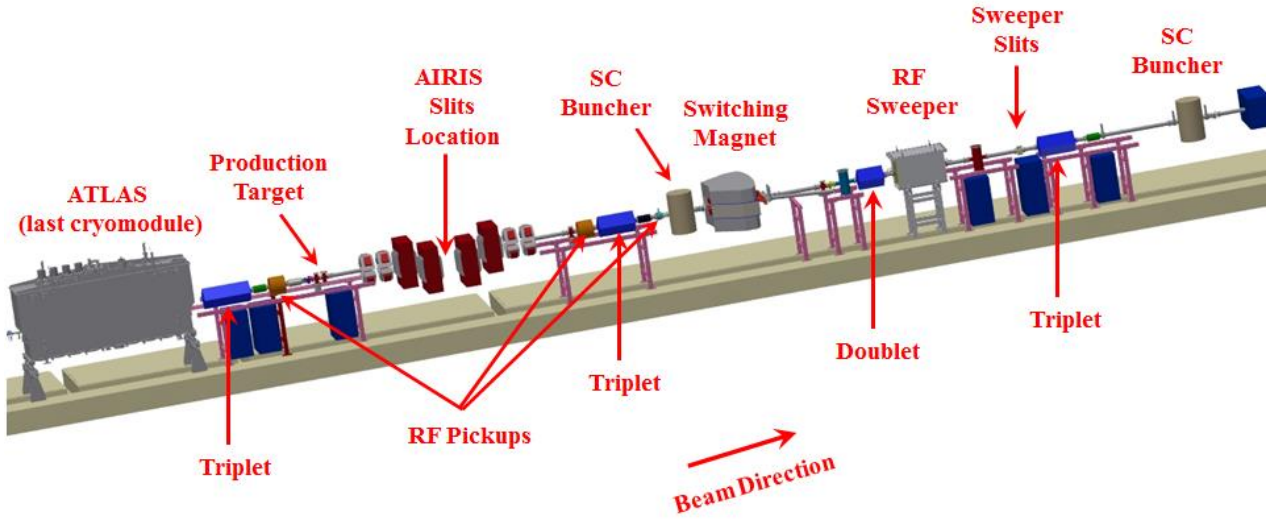
- ATLAS is a major US Nuclear Physics facility
  - 200-400 "single users" per year performing experiments
  - Operating 5000-6500 hrs/yr at about 93% efficiency
  - Provides stable beams at high intensity and energy up to 10-20 MeV/u
- In-flight radioactive beams are produced with poor beam properties
  - Secondary radioactive beams are produced when a primary beam hits the target
  - Other low-energy isotopes are produced during this process
  - The isotopes different from the required isotopes must be filtered

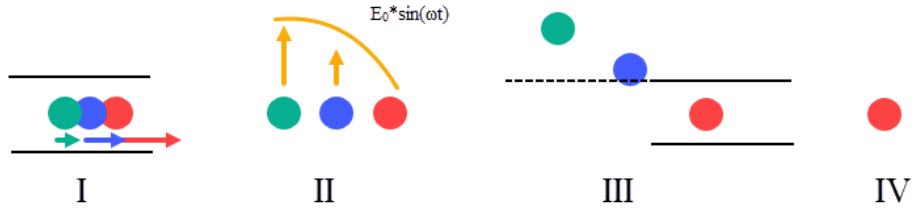




Fragment Separation

- A new inflight radioactive ion separator (AIRIS) will be used to separate and produce secondary radioactive beams from the interaction of ATLAS primary beams in a production target.
  - AIRIS will be at least 10 times more efficient than the existing radioactive
- AIRIS is based on a chicane magnetic fragment separator is to filter the unwanted isotopes,
  - Some isotopes can still pass through this separator
  - Velocity selection criterion is needed





Existing sweeper

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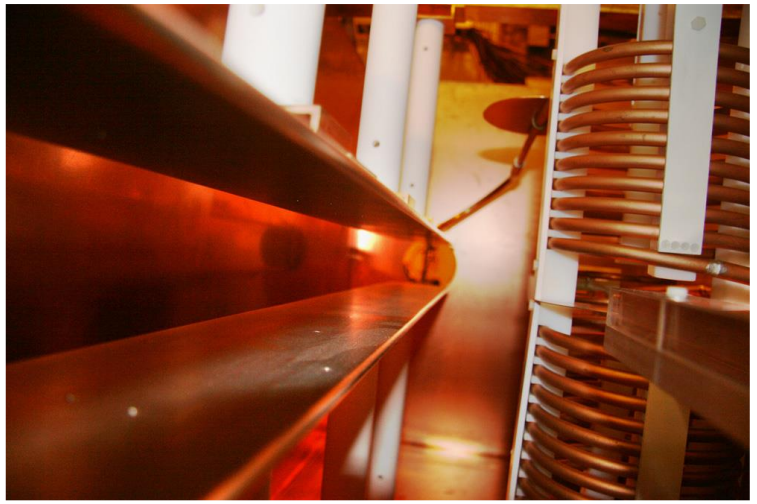
- Currently, ATLAS employs a 6 MHz sweeper that provide 50 kV deflection
  - Many isotopes require higher voltages and frequencies

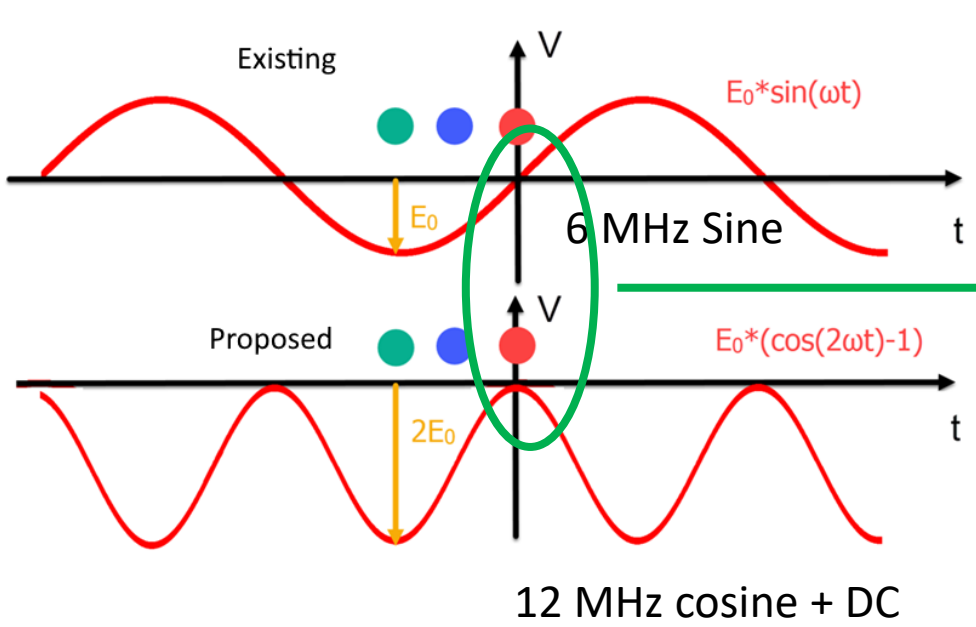


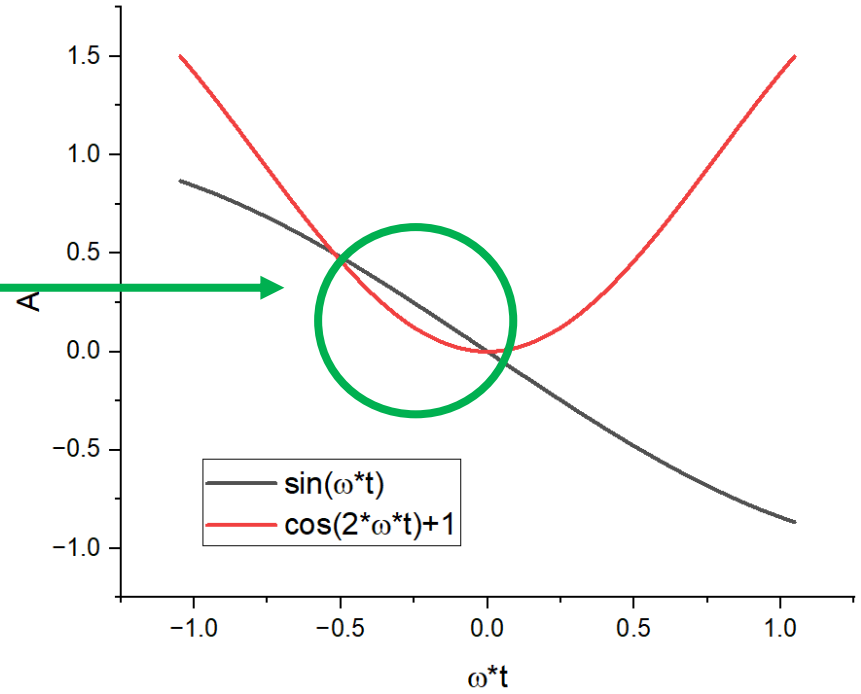
RIB Beam	Energy, MeV	Required voltage, kV
^{6}He	80	59
^{11}C	105	21
^{15}C	200	399
^{15}C	65	61
^{17}F	90	28
^{25}Al	180	30
^{37}K	275	98

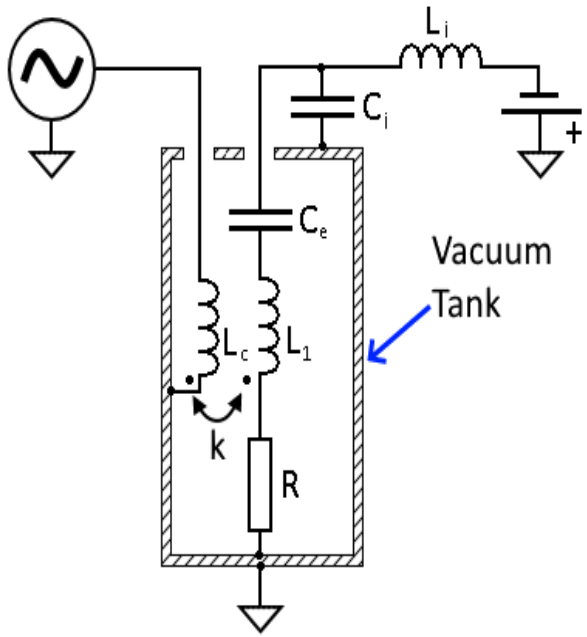
Version	Old	New	
Frequency, MHz	6.0625	6.0625	12.125
Voltage, kV	55	150	150
RF power , kW	1	~10	~11

Original Phase I idea

- We proposed to increase the frequency by factor of 2 and overlap RF deflection with DC bias to achieve the same deflection as pure 150 kV RF kick at 6 MHz
  - Cosine instead of sine
- Unfortunately, since the cosine wave deflector's zero point is at the crest, it is very much non-linear around it and doesn't provide a good separation



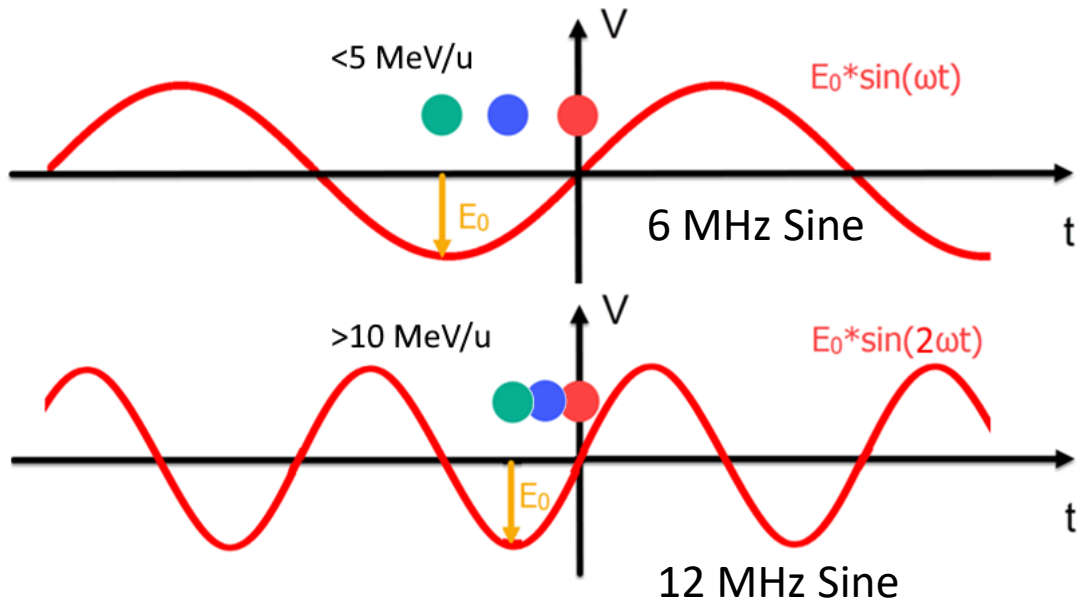




Phase II sweeper design

- We had to redesign the sweeper to provide RF-only kick (no DC bias) of 150 kV that can operate at 2 frequencies: 6 MHz and 12 MHz for different ion species.
- The frequency should be manually switched between the experiments in ~hours timeframe.

Fragment purity improvement	>5 times
Operating frequency	6 and 12 MHz
Deflecting voltage	150 kV
Secondary beam energy	3-10 MeV/u
Charge-to-mass ratio	varies
Aperture	7.5 cm



Main RF Design Challenges

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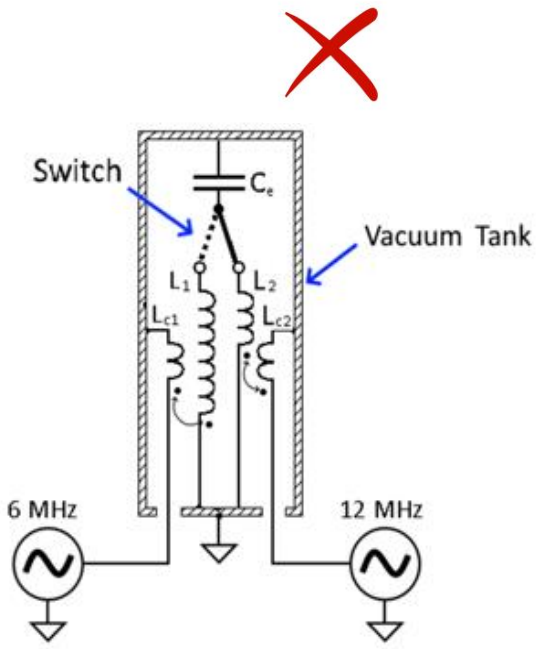
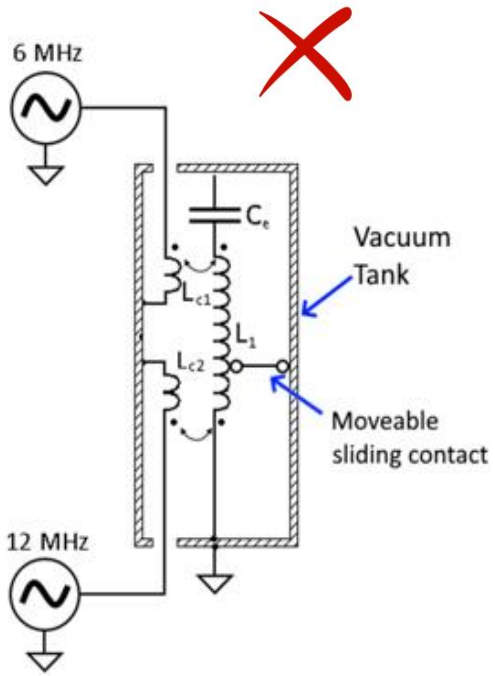
- 1. High peak electric fields
  - Must be kept around 1 Kp at 3x voltage kick
- 2. High RF power losses / heating
  - Scales as ~Voltage^2 (i.e. factor of 10!)
  - Significant enhancement of cooling system
- 3. Two frequencies
  - Two coils
  - Switching mechanism
- 4. Limited footprint
  - Must be fit within the similar-size case to be integrated into ATLAS beamline
  - Must comply with the *existing* space and access restriction for installation
  - Must comply with Argonne safety and reliability requirements

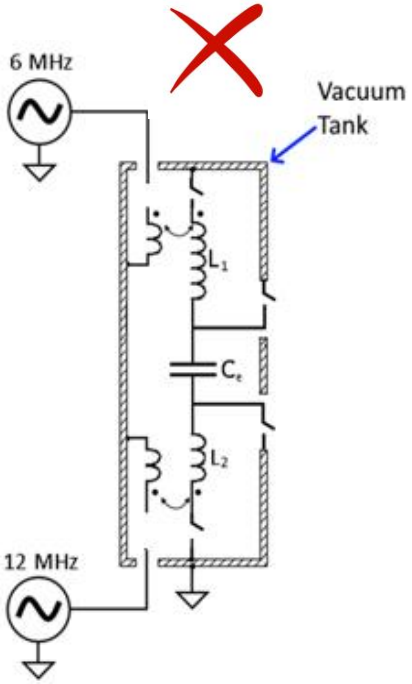
Dual-frequency operation



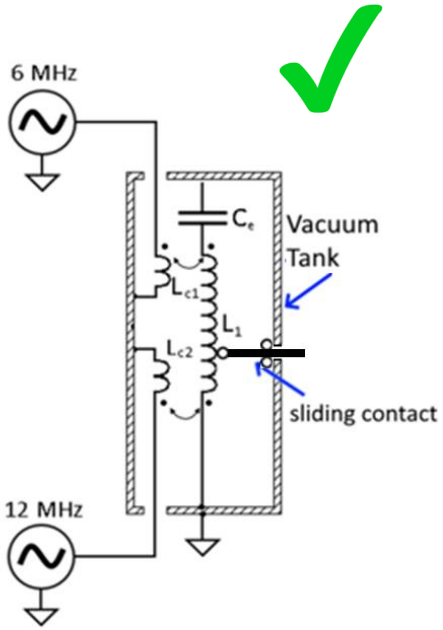
- In-vacuum switch:
  - Problem to connect RF and water inside vacuum volume



- Sliding contact:
  - Problem to connect RF and water inside vacuum volume
  - Very large coil



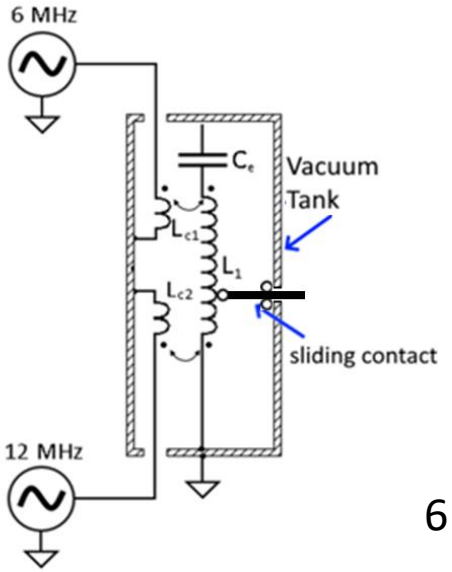
- Ground switches:
  - Allows water flow thru both electrodes
  - RF leakage

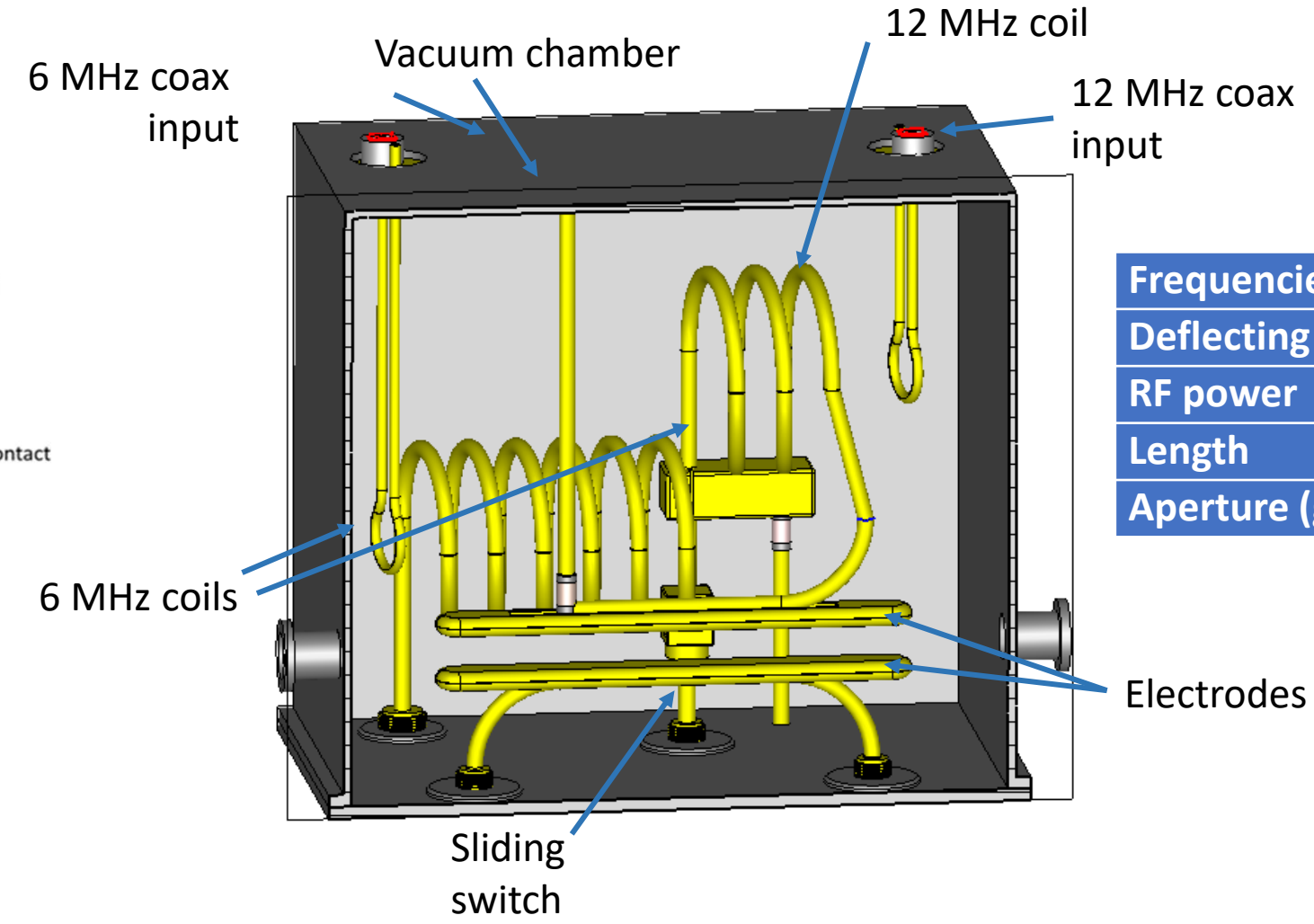


- Sliding GND switch:
  - Two separate coils
  - Vacuum, water, mechanical problems are mild

Baseline RF design of the New Sweeper

- We designed a new sweeper based on 'lumped' elements that allows two operation regimes each providing with 150 kV kick





Frequencies	6 + 12 MHz
Deflecting voltage	150 kV
RF power	~11.5 kW
Length	1 m
Aperture (gap)	7.5 cm

Mode Selector (RF Switch)

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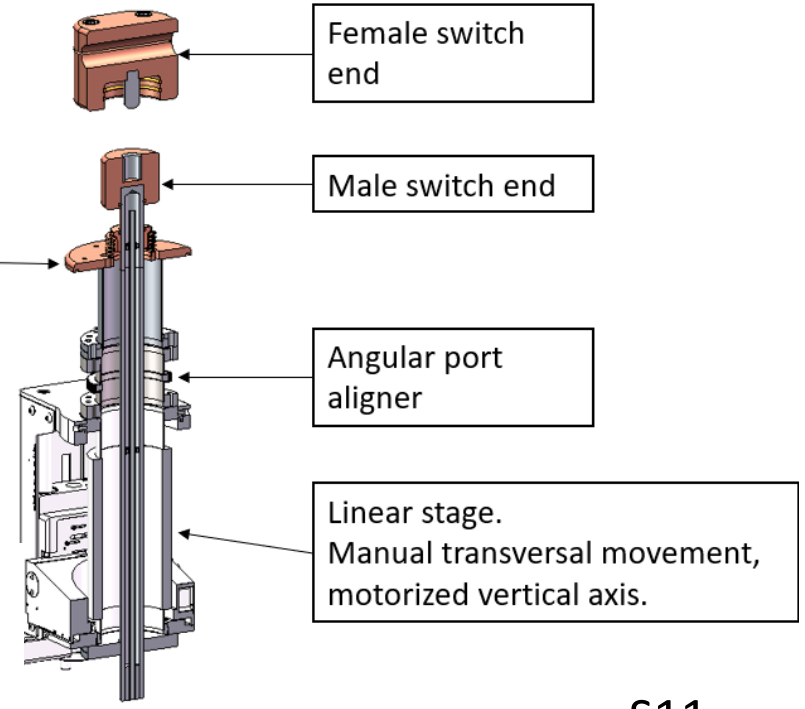
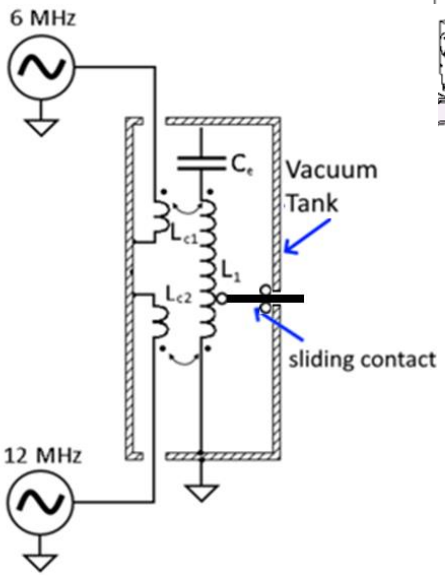
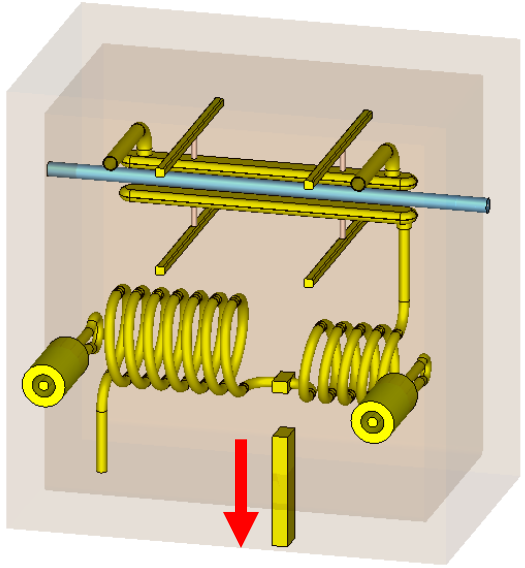
Sliding switch

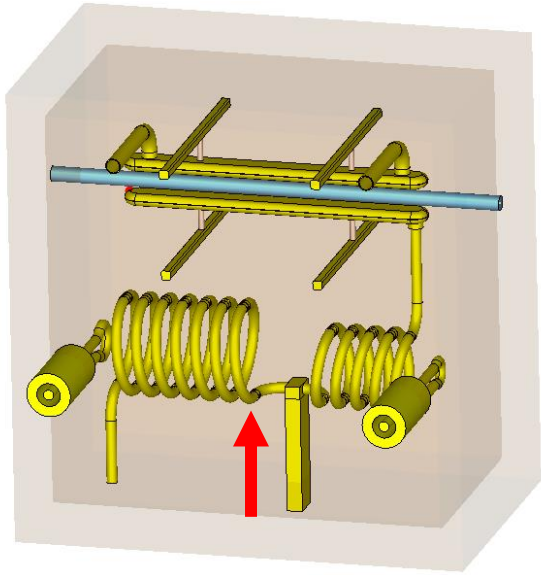




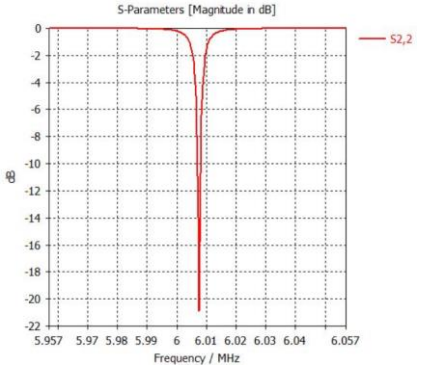
6 MHz mode



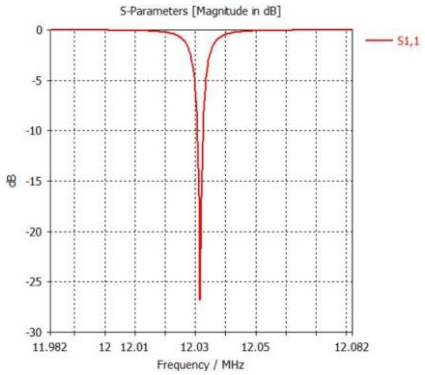
12 MHz mode



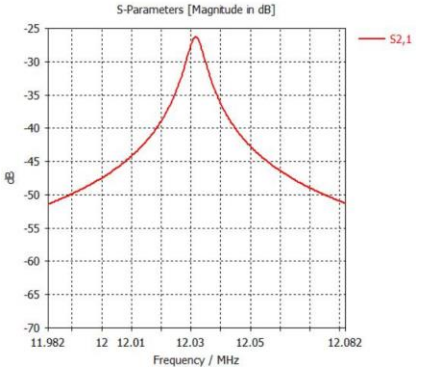
S11



S22



S21



Resonator design considerations

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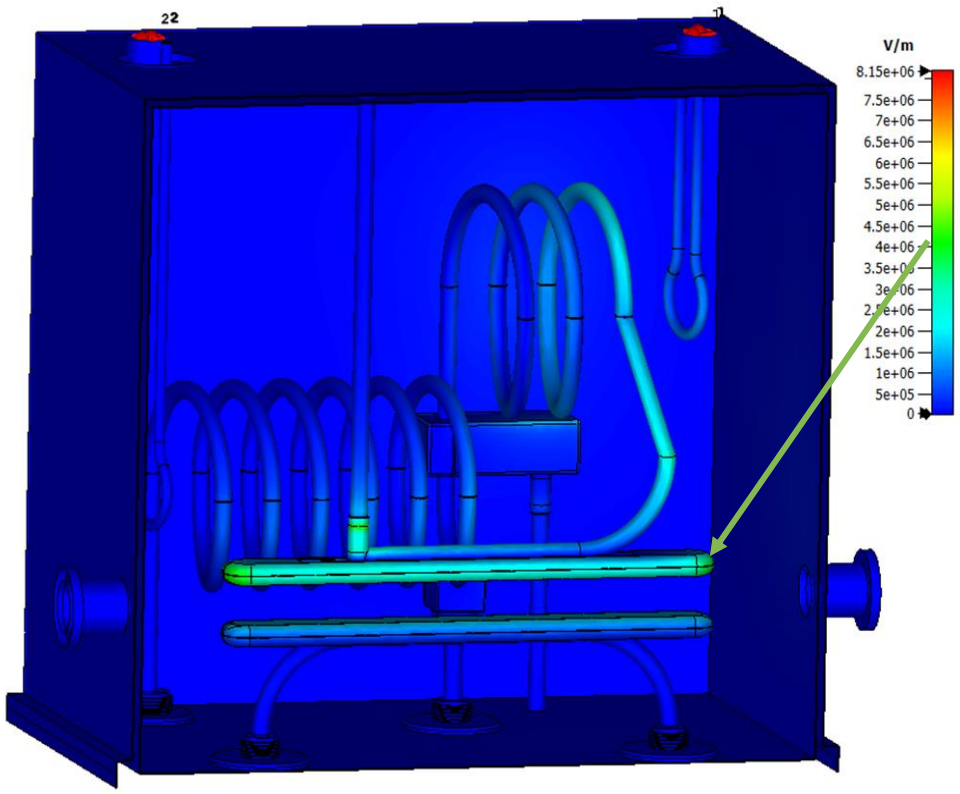
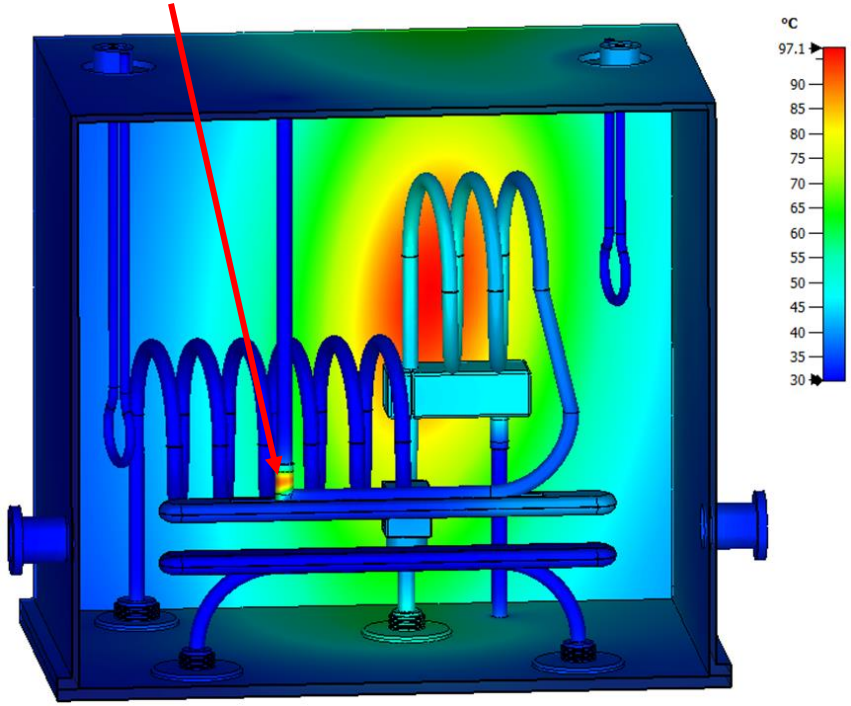
- RF: 3 x higher required voltage = 9 x higher power and RF dissipation in all components: coils (90%), chamber walls (5%) and electrodes (5%)
  - Water must be run through all current conductors
  - Electrodes must have blended shapes to minimize peak E-field on the tips
  - Coils dimensions (pipe OD, winding period, major diameter) must be optimized to increase Q
- Mechanical: Large heavy coils and electrodes must be mechanically stable
  - +/- 1mm tolerance on electrode-to-electrode gap
  - Dielectric supports must be introduced to ensure stable electrodes alignment under RF heat load. Alumina is the only option due to low loss and the highest thermal conductivity. MACOR and PEEK have 10x and 100x worse thermal properties.
  - Sliding switch must not deform the coils (and electrode) position during engaging/disengaging
- Vacuum: Avoiding water-to-vacuum braze joints as ATLAS requirement implies making the coils from a single pipe.

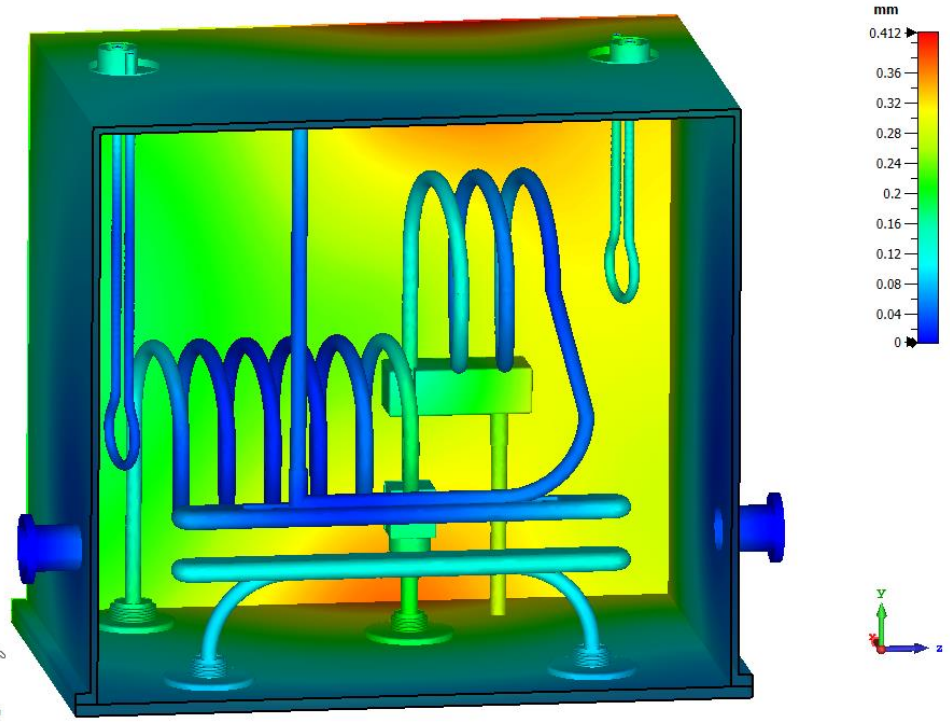


Electrode support

Alumina support
<100 C

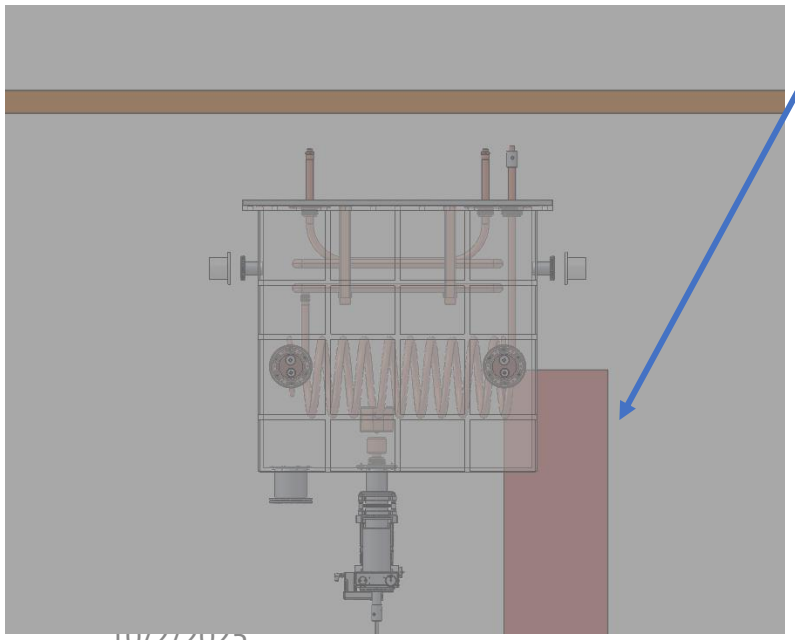


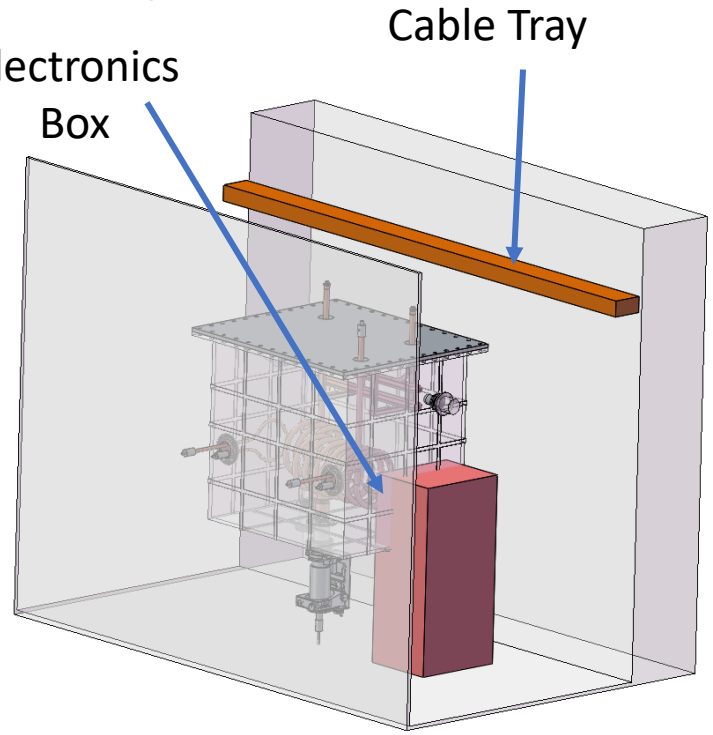
~150 microns
deformation

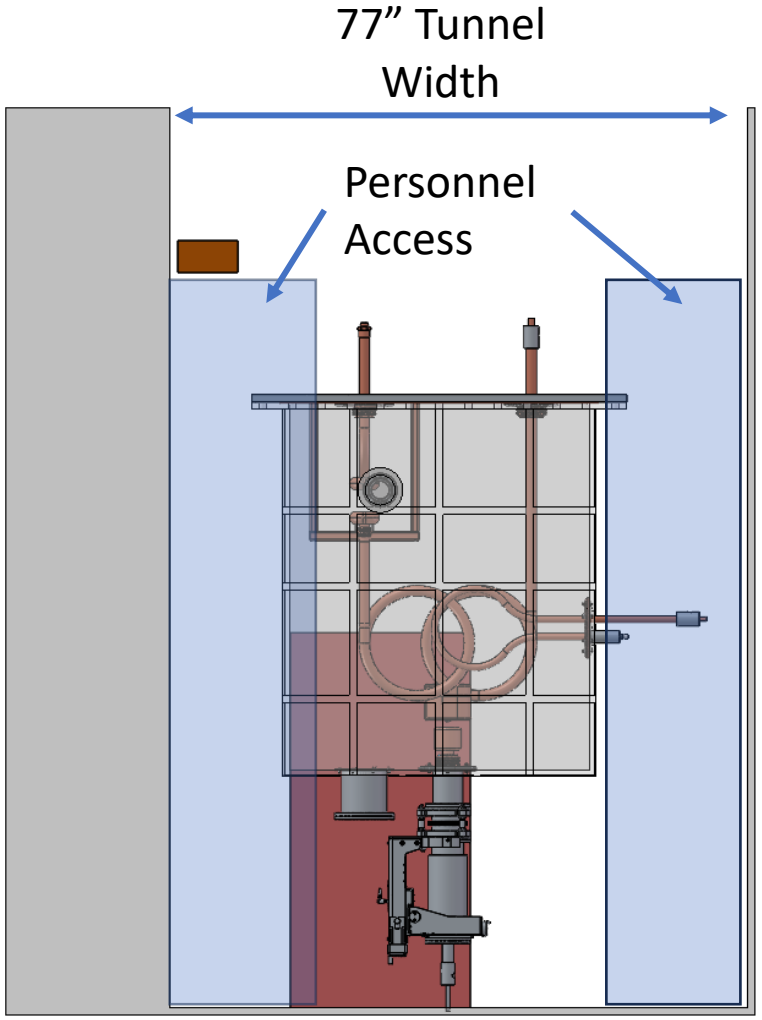


Engineering model – version 1

- V1 Engineering design was ready in 2022, demonstrated good performance, but didn't fit ATLAS tunnel
  - Significant redesign required due to previously unknown / unspecified ANL restrictions
- Interferences
  - Electronics box
  - Cable tray
- Beamline tunnel size
  - Personnel access
  - Ceiling limited lifting height
- Underwent several iterations of design changes

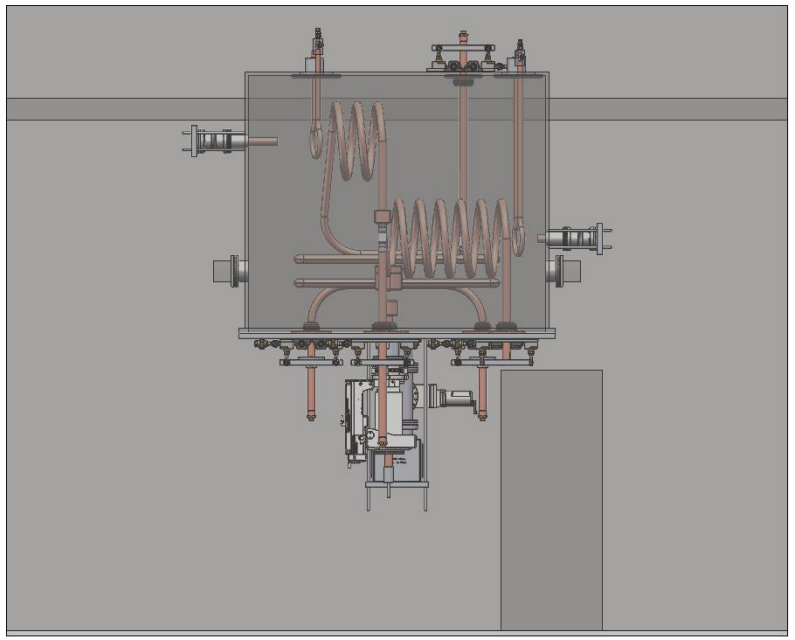


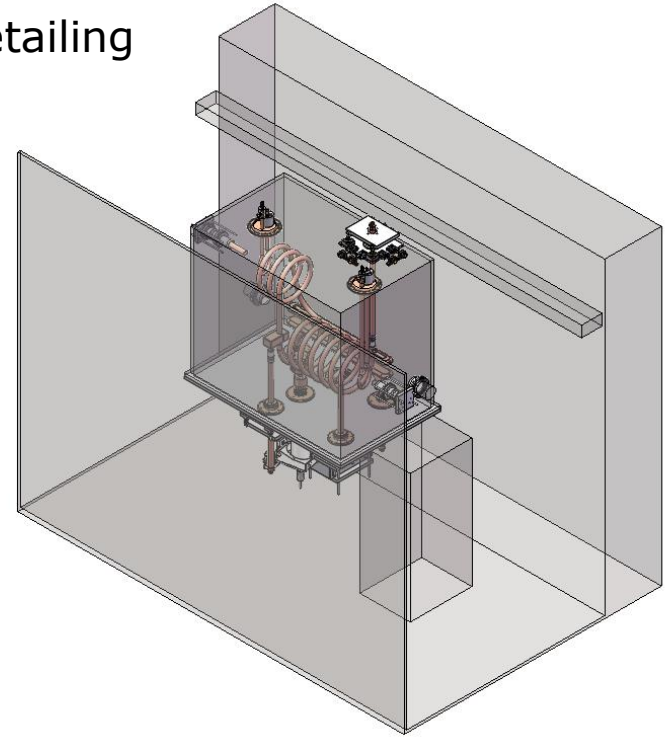


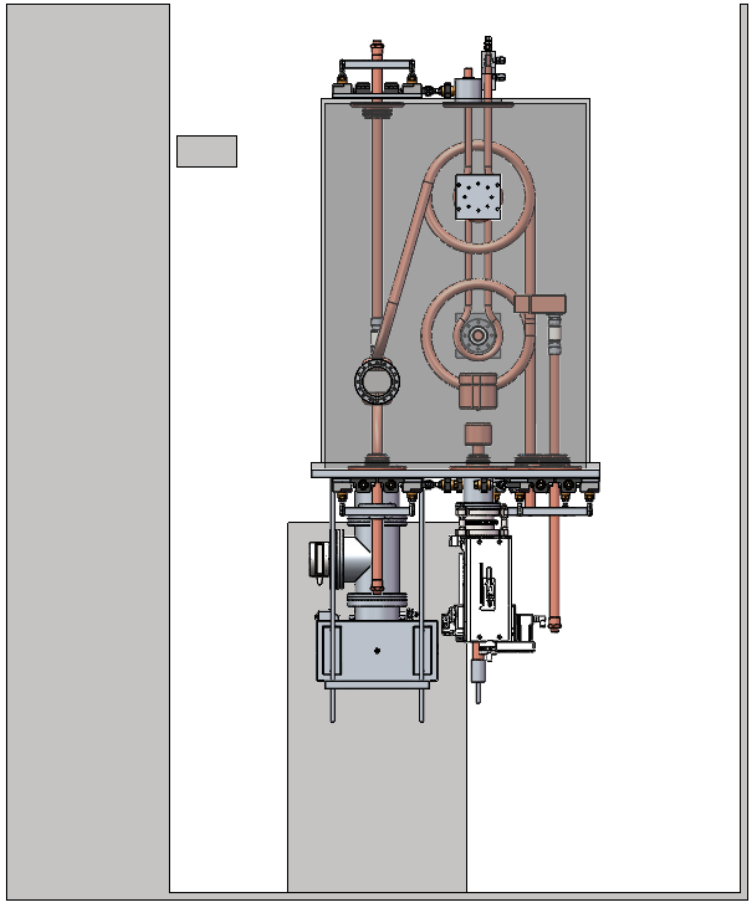


Engineering model – version 2

- Significantly more compact
  - Even higher power density
- Reviewed by ANL and sufficient personnel access reserved
- All interferences resolved
- Conceptual installation plan reviewed
- Tuning and Cooling not designed
- Required significant mechanical detailing

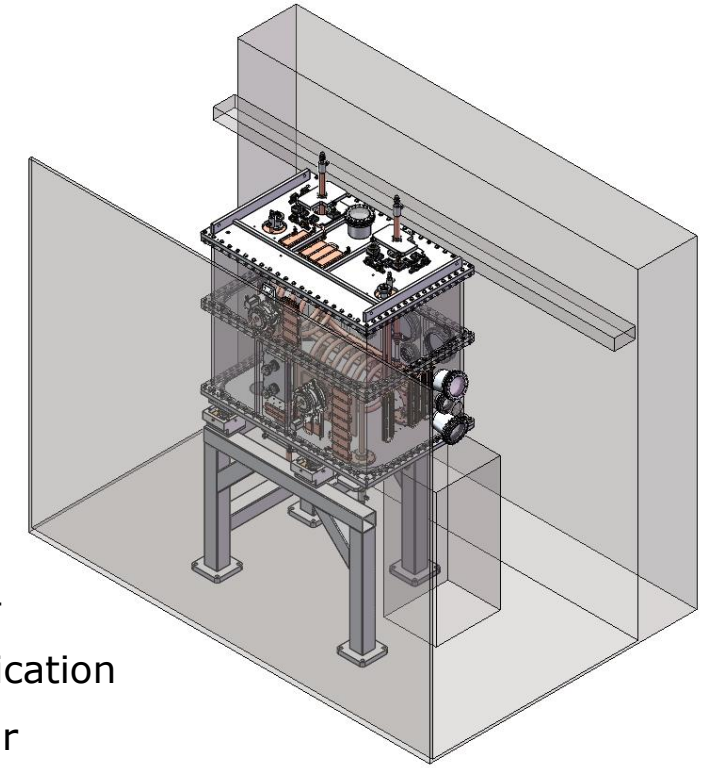


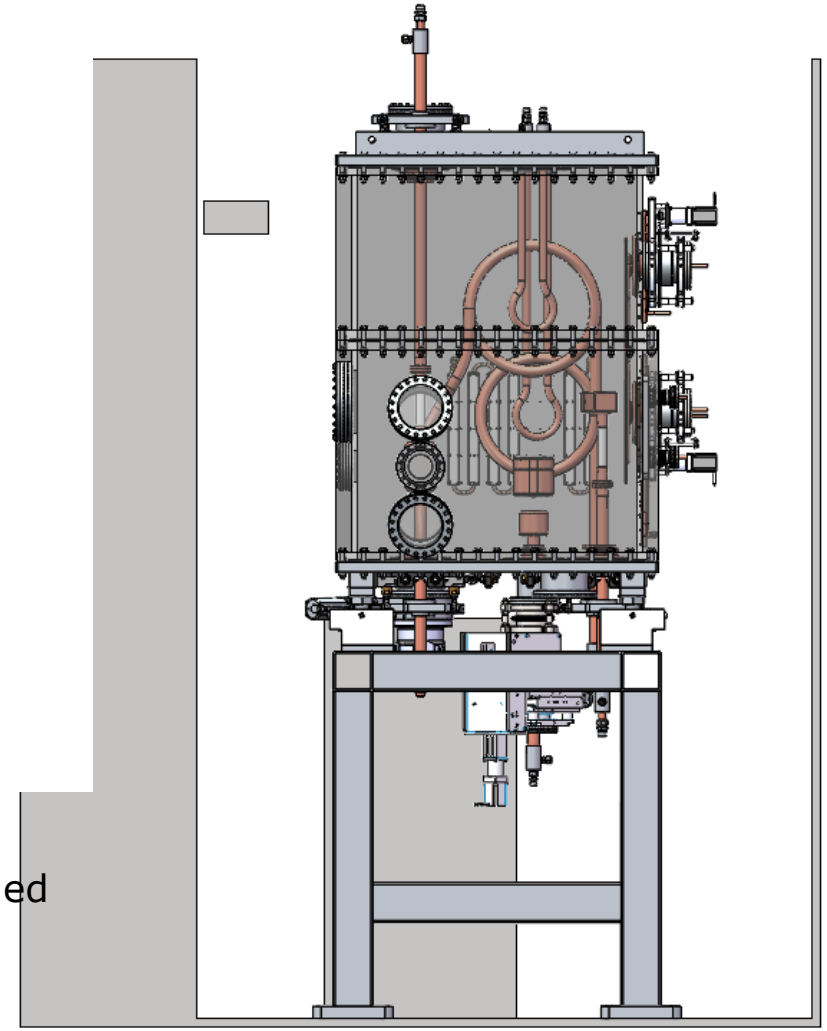




Final Model (2024)

- Split Chamber to allow for assembly in tunnel with low head clearance
- Upper and lower lids to ease asse
- Hand/Assembly access ports add
- All clearances maintained
- Lifting provisions added
- Stand and kinematics added
- Maintained personnel access





- Dual build plate design eases assembly
- Coupling loops adjusted to better match + RF simulation and meet EIA specification
- Switch detailed to match lower coil contour
- Custom alumina ceramic breaks designed for coupler and supports
- Line of sight ports, RF tuning plates, and extra ceramic support for electrode added
- External cooling blocks added

Fabrication Status

Completed:

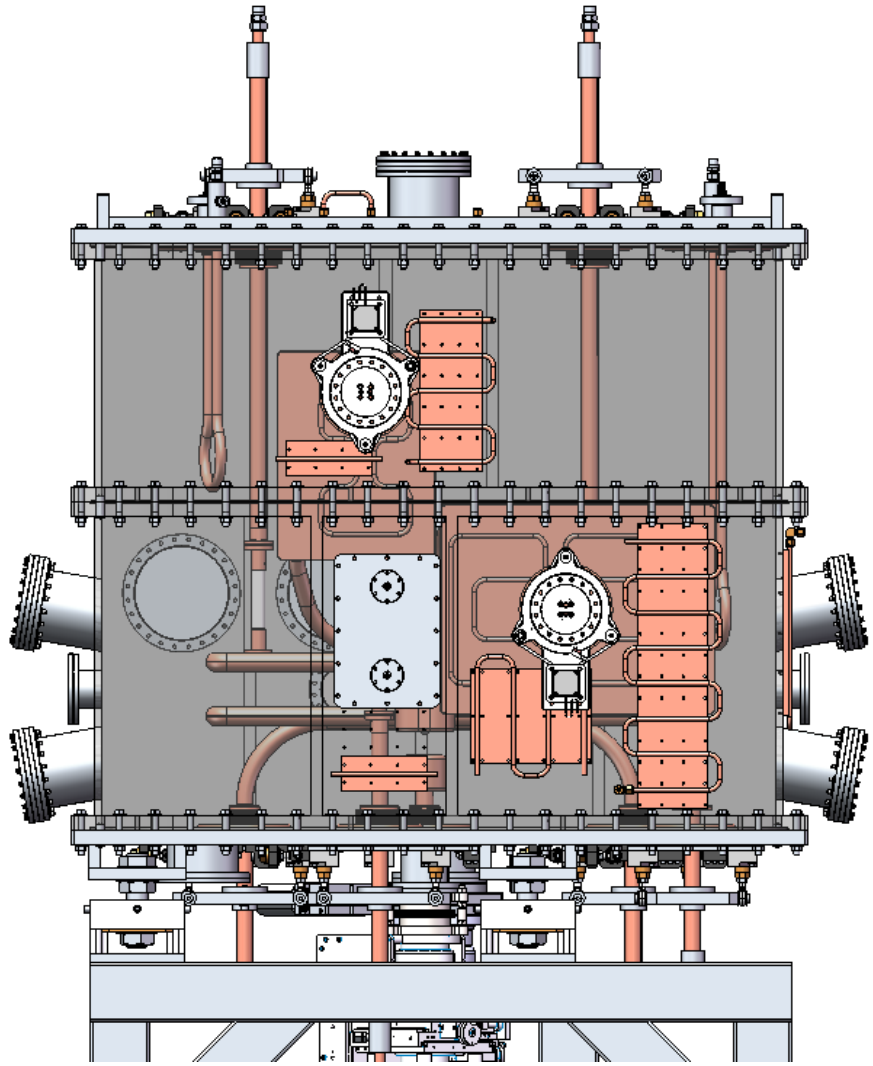
- Chamber
- Ceramic Break Support Bellows
- Ceramic Break Support Ceramics
- Power Coupler Test Braze Components
- Frequency Switch Linear stage
- Frequency Switch Bellows
- Tuner Bellows complete
- Tuner Linear stages complete

In Manufacturing

- Power Coupler Ceramic Interfaces
- Main Coils

In Drafting/Manufacturing Approval

- Ground Switch Components
- Electrode Components
- Tuner Components
- Chamber Support Kinematics
- Chamber Stand
- External Cooling



Vacuum Chamber

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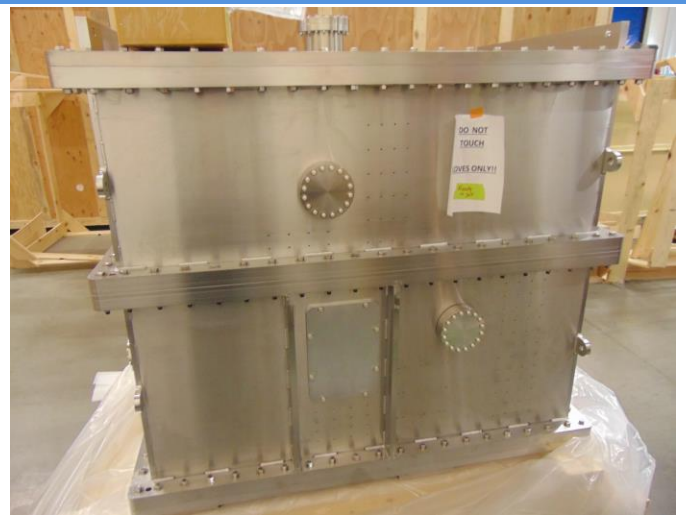
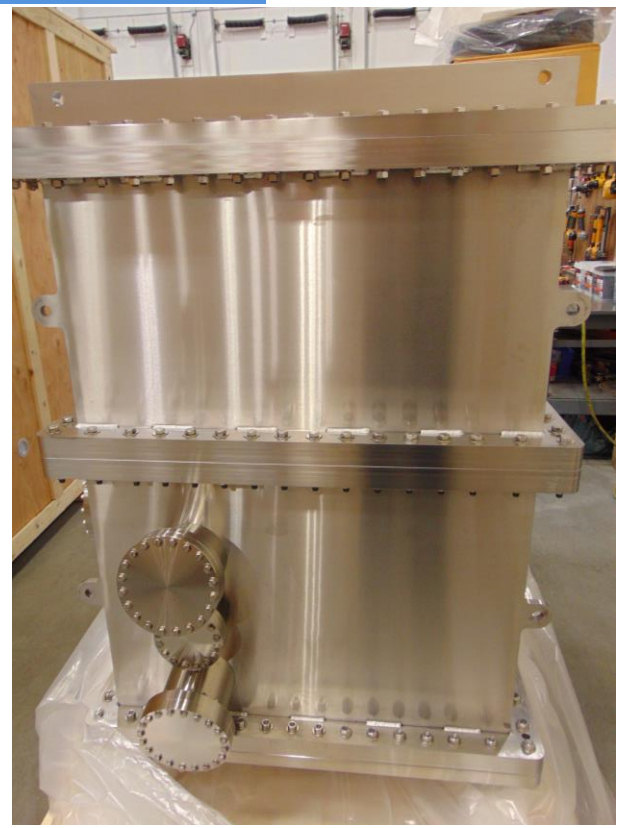
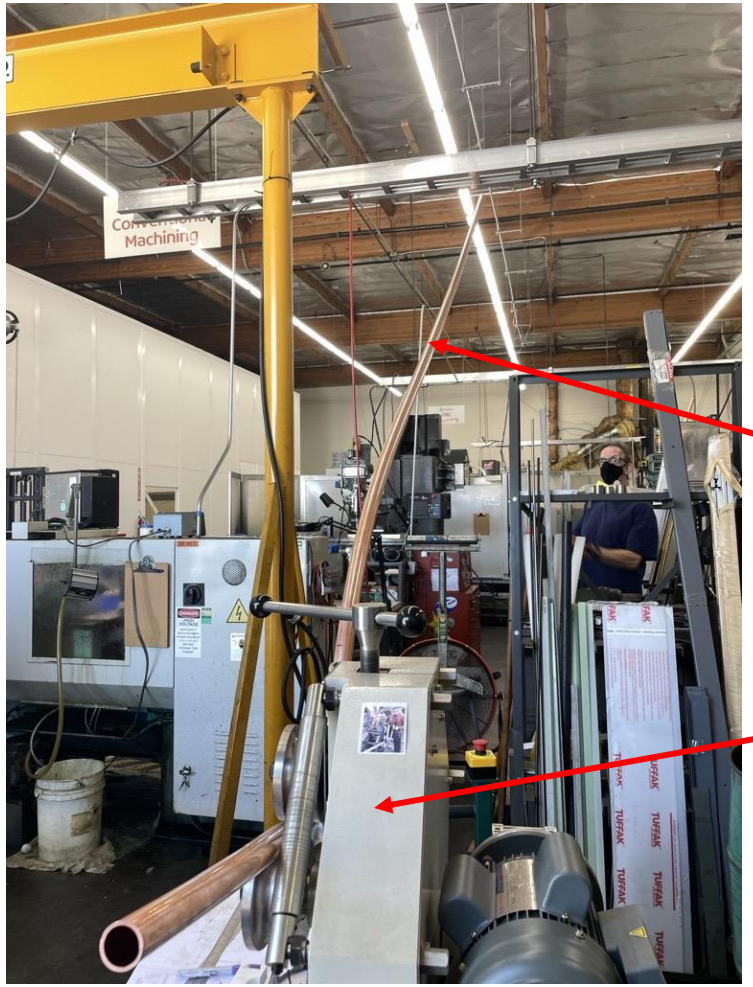
Chamber construction is complete





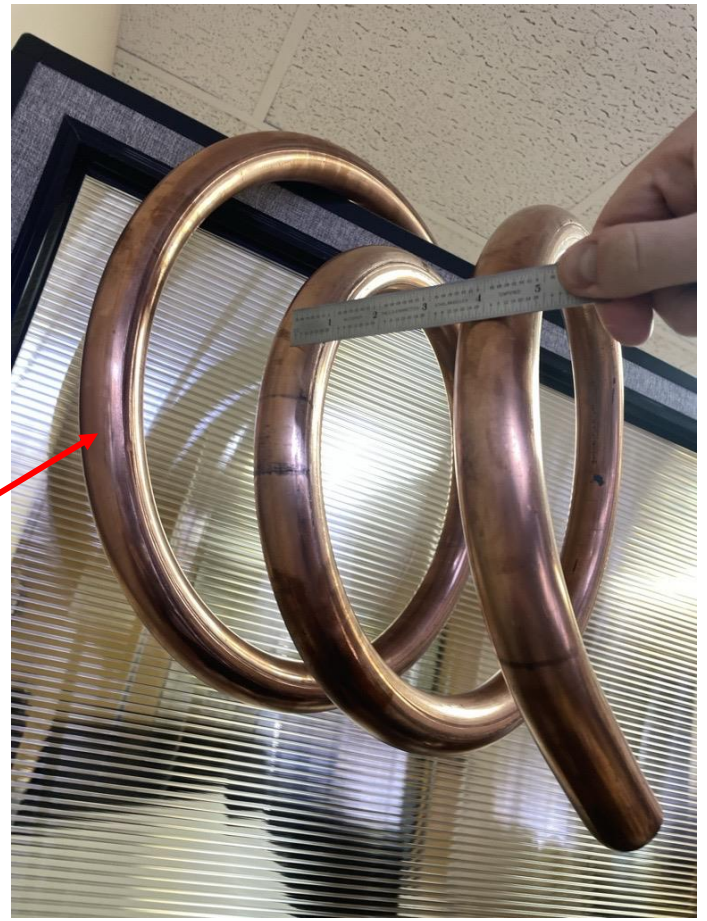
Main Coil Progress



Successfully Coiled Coil With Pitch Similar To Required

~4” Pitch

Tube Length to make this coil



3 Roll Bender, can be flipped horizontal

Longer lengths we will coil upwards and use more horizontal space to reduce the height copper sticks out

Tuner and Frequency Switch Stages

Tuner Linear Stage Complete

Frequency Switch Linear Stage Complete

Ordered Items Arrival

Power Coupler Ceramic

Tuner Bellows

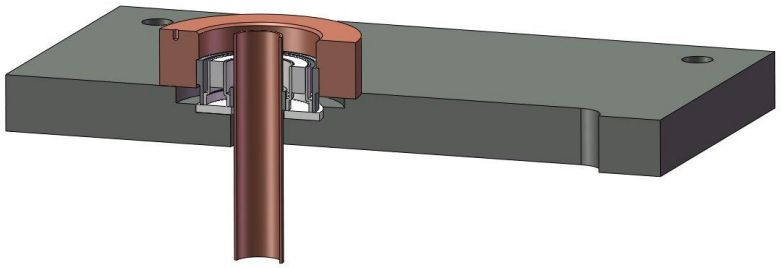
Inline Ceramic

Manufacturing Update

Power Coupler Ceramic Break Test Cu Tubes

Power Coupler Ceramic Break Flange Blanks

Kovar Pieces In Progress



Power Coupler Ceramic Break SS Rings

Power Coupler Braze Tooling Complete

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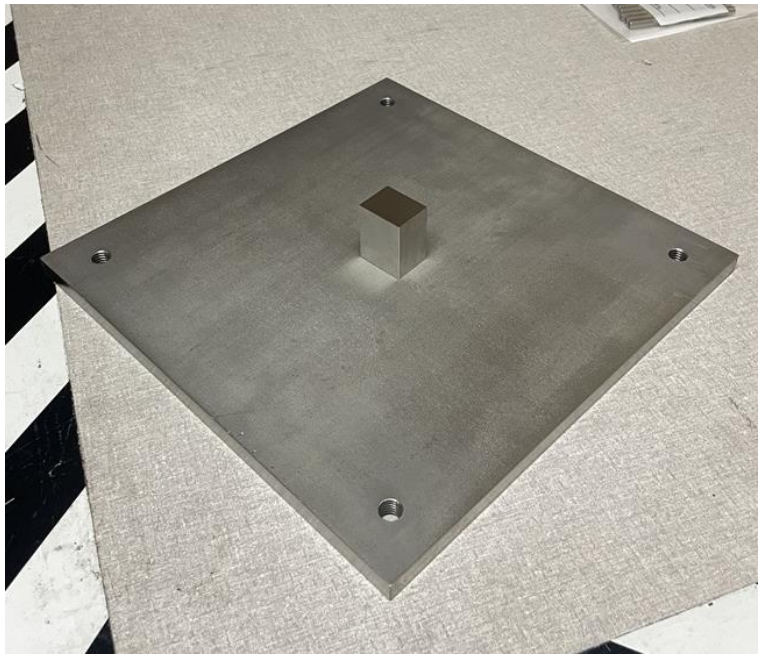

Conclusions

- The most challenging and ambitious cavity design so far
- Many unexpected obstacles were encountered = delayed progress
- The latest iteration design resolves all problems and been accepted by ANL engineers
- Simulation results are very promising
- Fabrication in progress

- Project Team:
  - Alexander Smirnov, Ronald Agustsson, Aurora Araujo, Evgeny Ivanov and Sergey Kutsaev
- Special acknowledgements:
  - ANL (Brahim Mustapha, Al Barcikowski)
  - DOE NP (Michelle Shinn, Manouchehr Farkhondeh)