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

DOE SBIR Award DE-SC0019719

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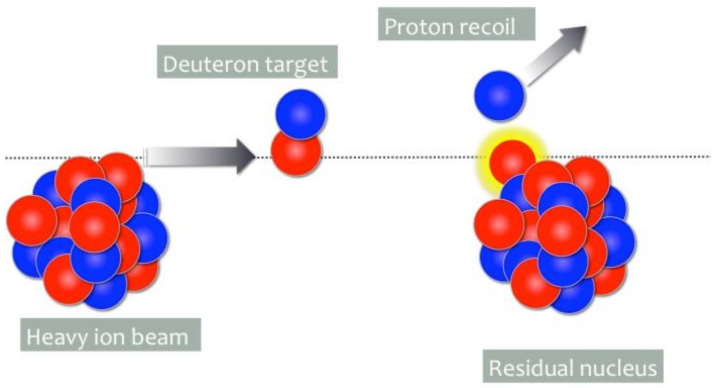
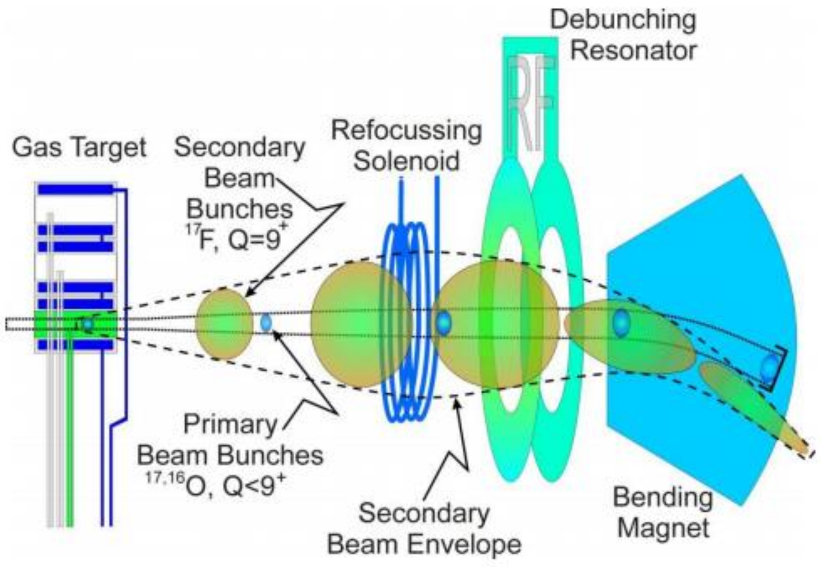
Background

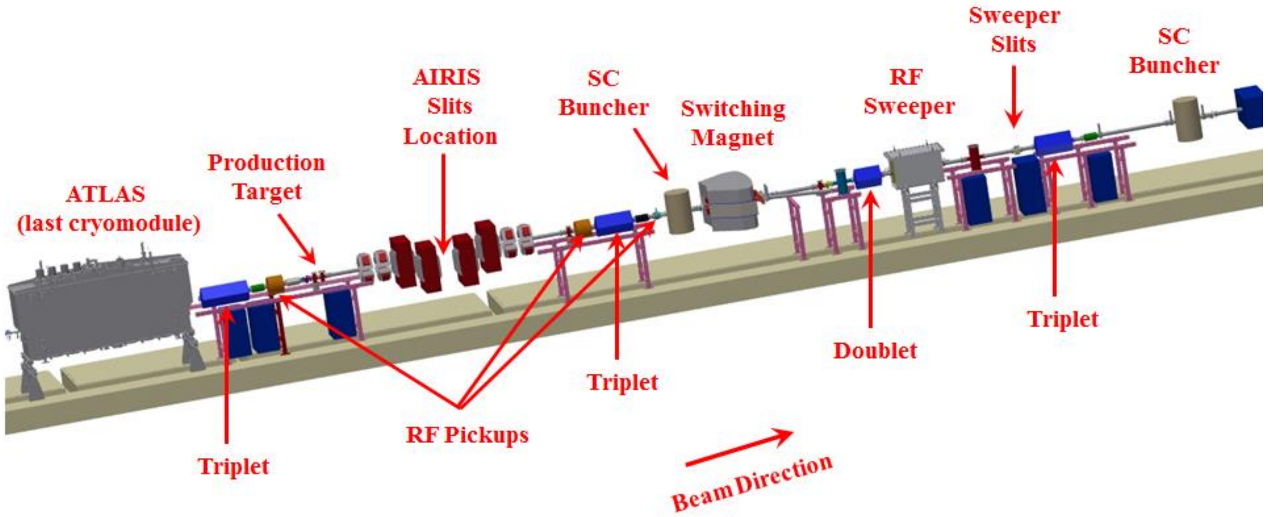
- ATLAS is a major US Nuclear Physics facility
  - 200-400 “single users” per year performing experiments
  - Operating 5000-6500 hrs/yr at about 93% efficiency
  - Provides stable beams at high intensity and energy up to 10-20 MeV/u
- In-flight radioactive beams are produced with poor beam properties
  - 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

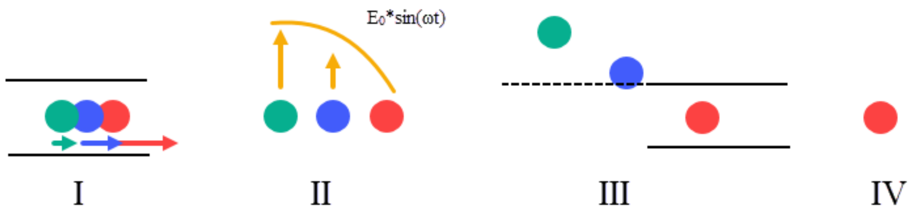




Fragment Separation

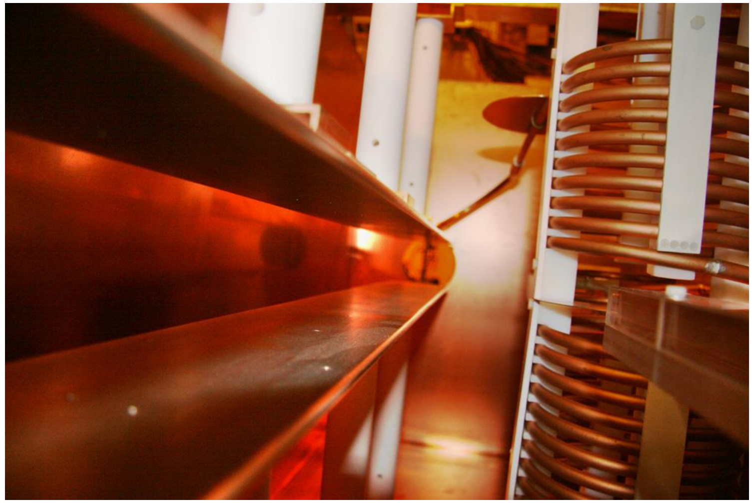
- A new inflight radioactive ion separator (AIRIS) will be used to separate and produce secondary radioactive beams from the interaction of ATLAS primary beams in a production target.
  - AIRIS will be at least 10 times more efficient than the existing radioactive
- AIRIS is based on a chicane magnetic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





Existing sweeper

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

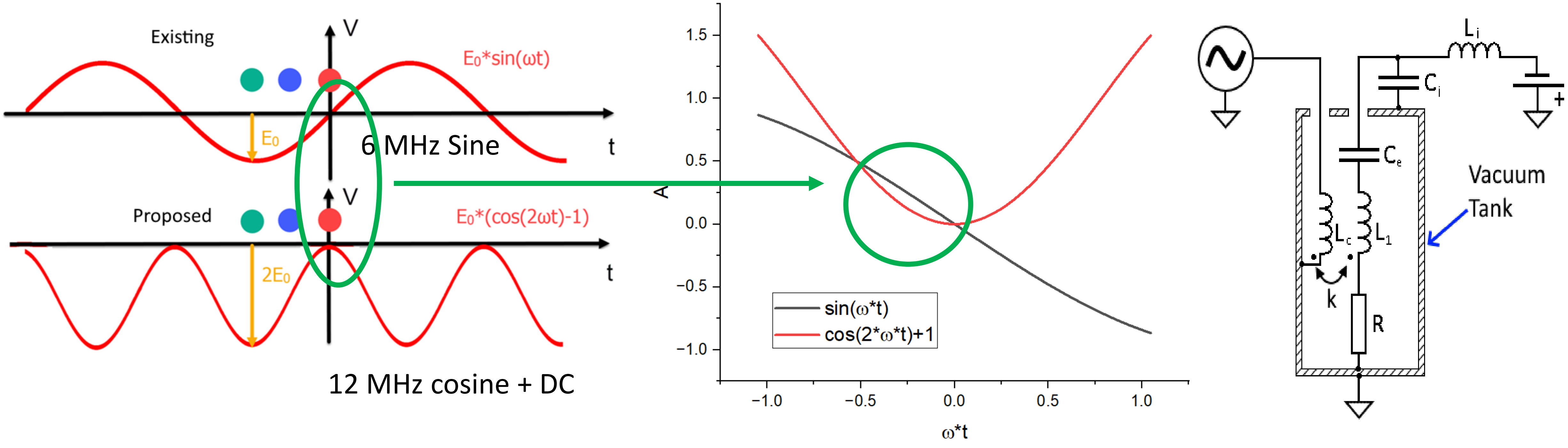


RIB Beam	Energy, MeV	Required voltage, kV
^{6}He	80	59
^{11}C	105	21
^{15}C	200	399
^{15}C	65	61
^{17}F	90	28
^{25}Al	180	30
^{37}K	275	98

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

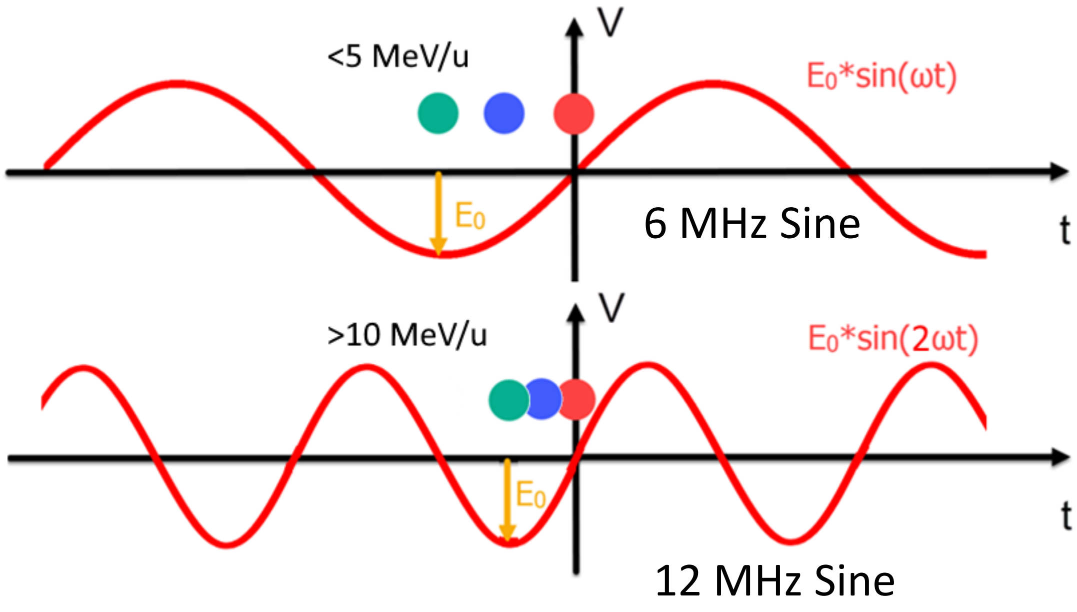
- We proposed to increase the frequency by factor of 2 and overlap RF deflection with DC bias to achieve the same deflection as pure 150 kV RF kick at 6 MHz
  - Cosine instead of sine
- Unfortunately, since the cosine wave deflector's zero point is at the crest, it is very much non-linear around it and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



Phase II sweeper design

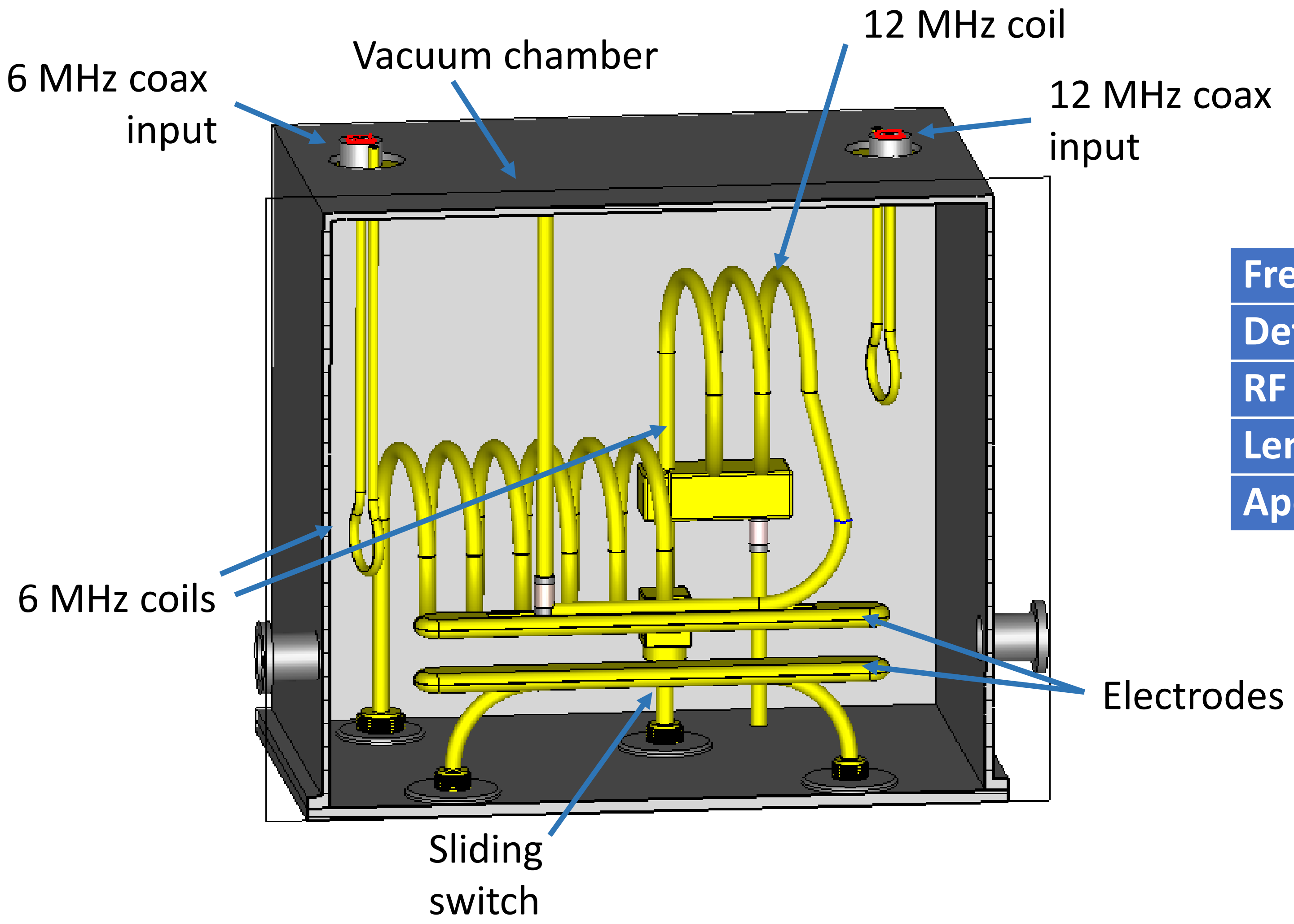
- We had to redesign the sweeper to provide purel RF kick (with no bias) of 150 kV that can also operate at 2 frequencies: 6 MHz and 12 MHz for different ion species.
- The frequency should be manually switched between the experiments in ~hours timeframe.

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



Sweeper RF design

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



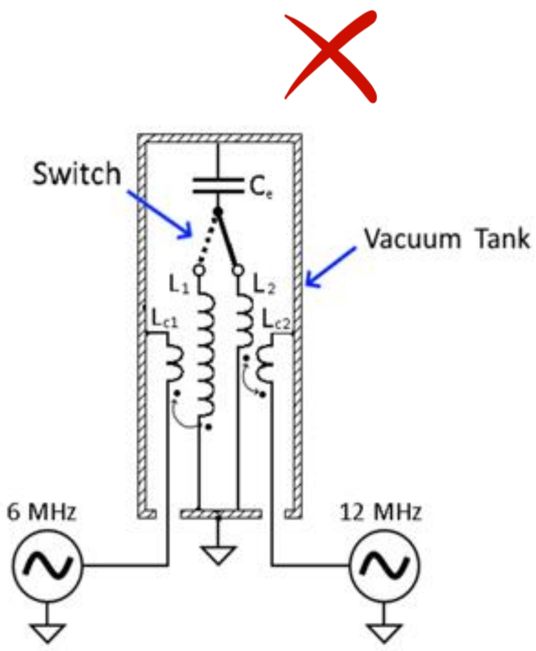
Frequencies	6 + 12 MHz
Deflecting voltage	150 kV
RF power	~11.5 kW
Length	1 m
Aperture (gap)	7.5 cm

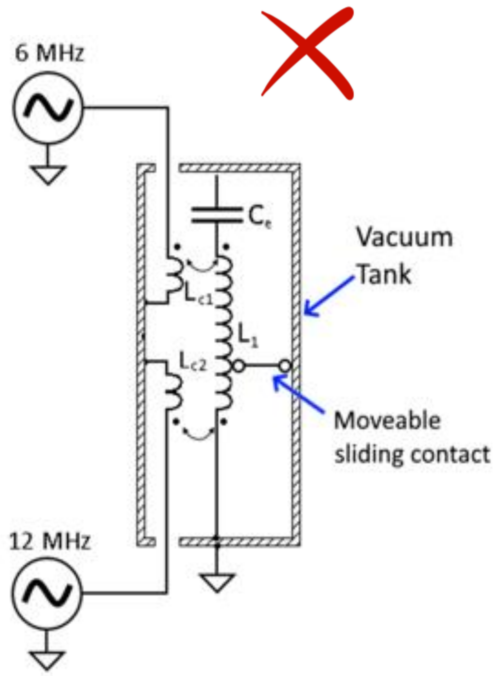
Design challenges

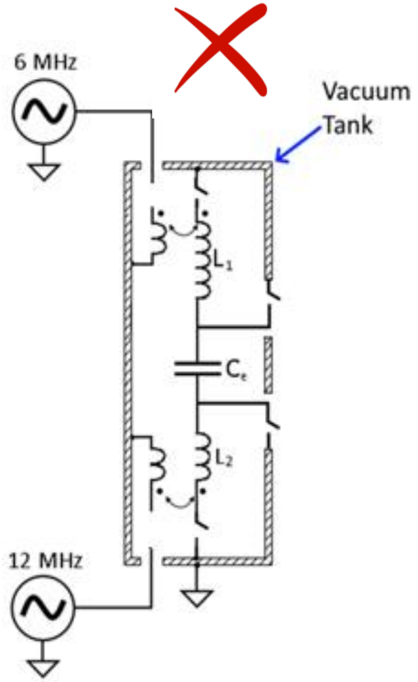
RadiaBeam

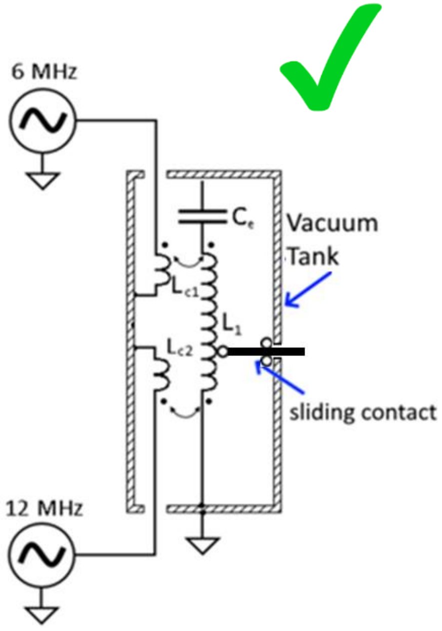
- 1. High peak electric fields
  - Must be kept around 1 Kp at 3x voltage kick
- 2. High RF power losses / heating
  - Scales as ~Voltage^2 (i.e. factor of 10!)
  - Significant enhancement of cooling system
- 3. Two frequencies
  - Two coils
  - Switching mechanism
- 4. Limited footprint
  - Must be 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
- 5. No RF power source available at ANL
  - To be developed and provided by RadiaBeam

Dual-frequency operation







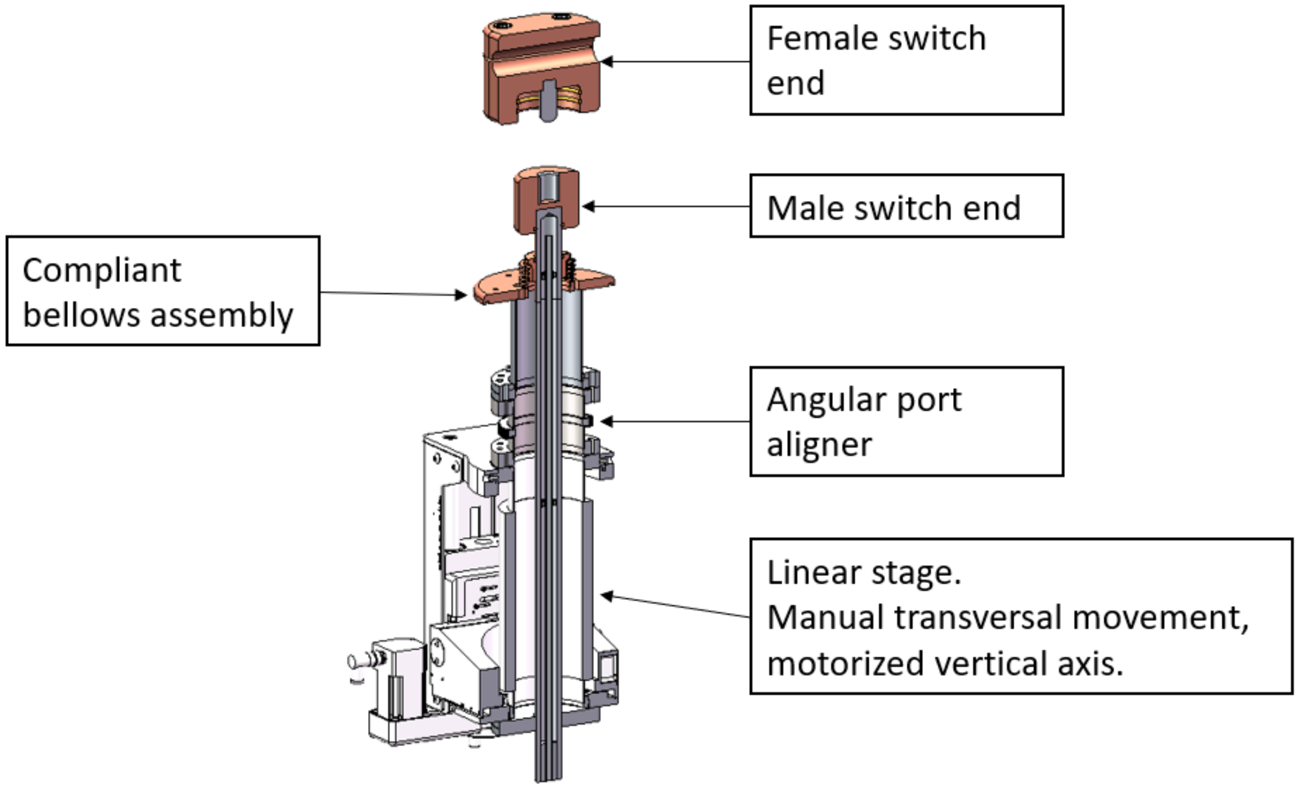


- In-vacuum switch:
  - Problem to connect RF and water inside vacuum volume
- Sliding contact:
  - Problem to connect RF and water inside vacuum volume
  - Very large coil
- Ground switches:
  - Allows water flow thru both electrodes
  - RF leakage
- Sliding GND switch:
  - Two separate coils
  - Vacuum, water, mechanical problems are mild

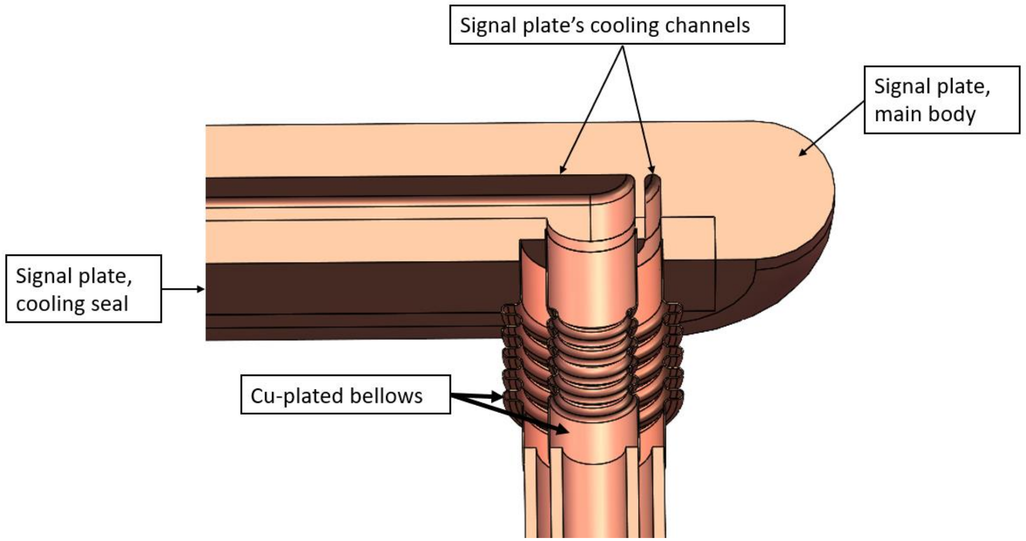
Energy switch design

RadiaBeam

Sliding switch

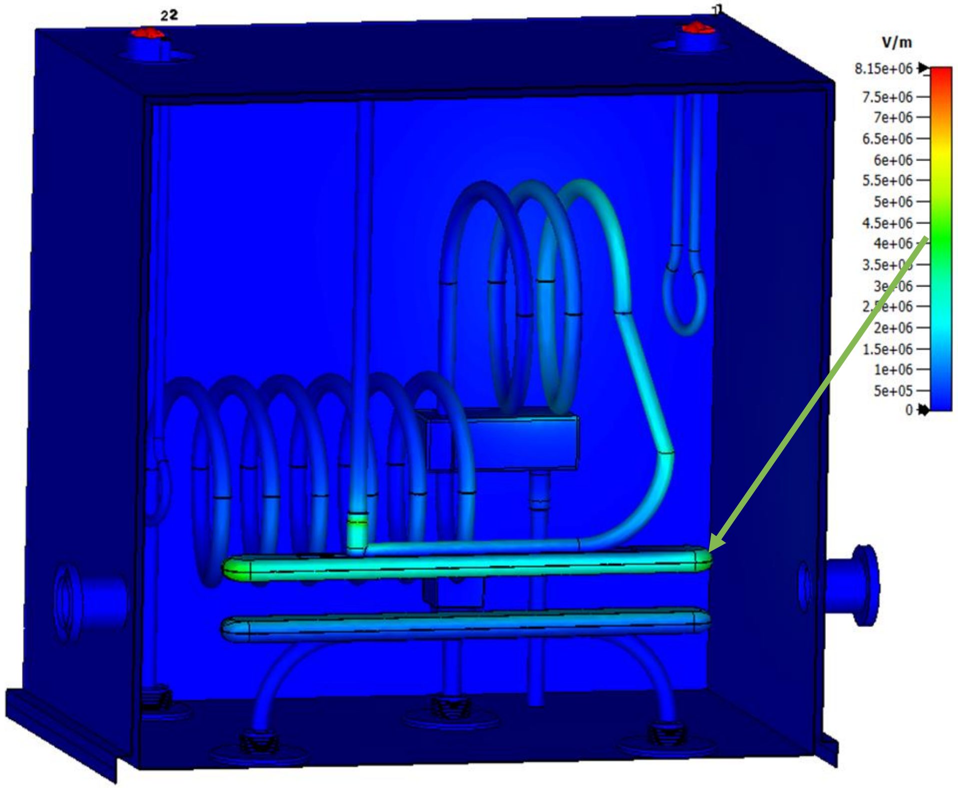


Pipe-in-pipe cooling



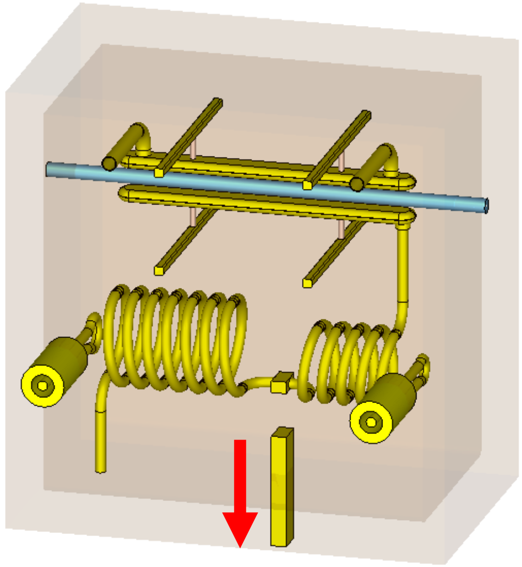
Resonator design considerations

- 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.

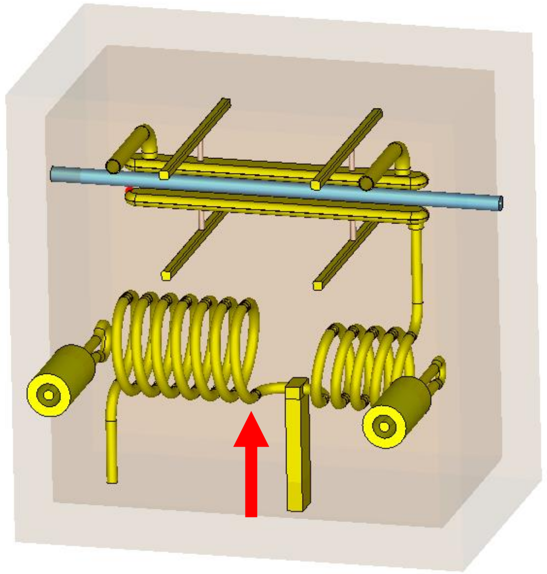


Resonator RF design

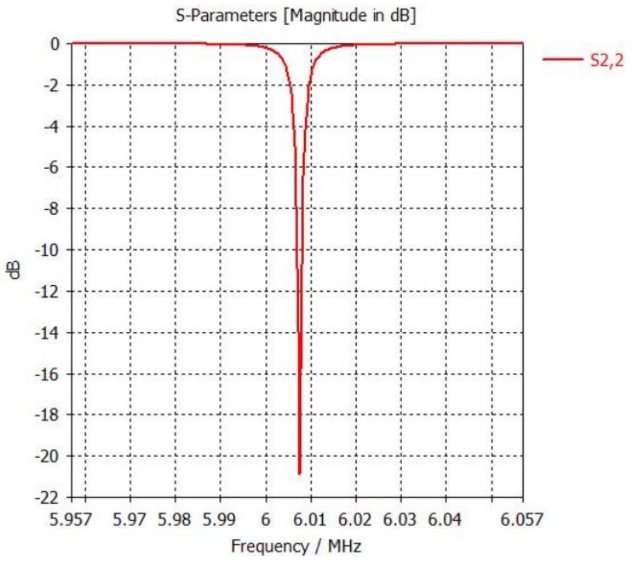
6 MHz mode

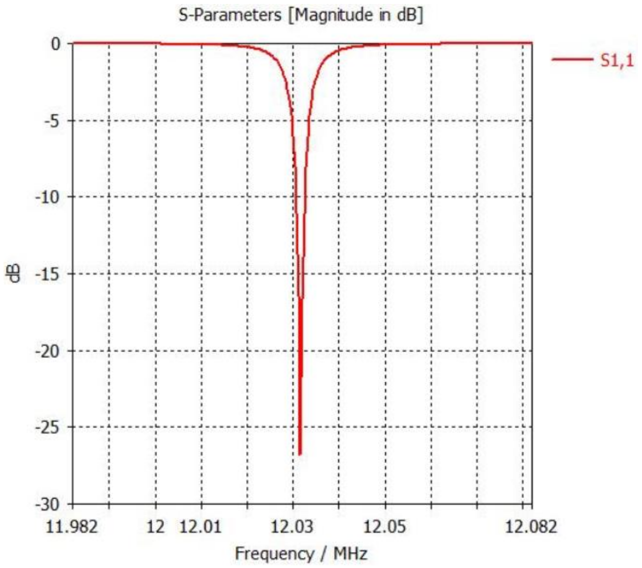


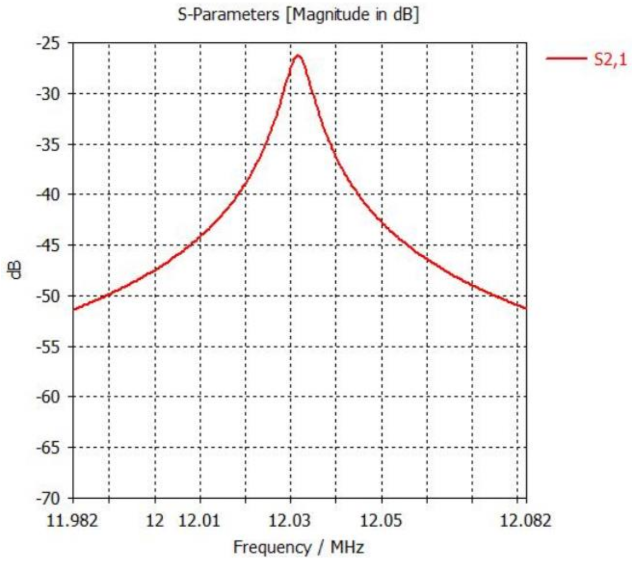
12 MHz mode



Parameter	6 MHz	12 MHz
RF power for 150 kV	9500 W	10.8 kW
Coil dimensions	Coil 1: 7 periods, D=290 mm, H=455 mm, Coil 2: 4.5 periods, D=232 mm, H= 292.5 mm	Coil 2: 4.5 periods, D=232 mm, H= 292.5 mm
Coil pipe ID/OD	29 mm/35 mm	
Vacuum tank	L×W×H 1280 mm × 750 mm× 1000 mm	
Ground legs pipe ID/OD	44 mm/50 mm	
Kp	4.7 MV/m	5.7 MV/m
Peak E (150kV)	5.37 MV/m	5.43 MV/m
Peak E (150kV)/Kp	1.14	0.95

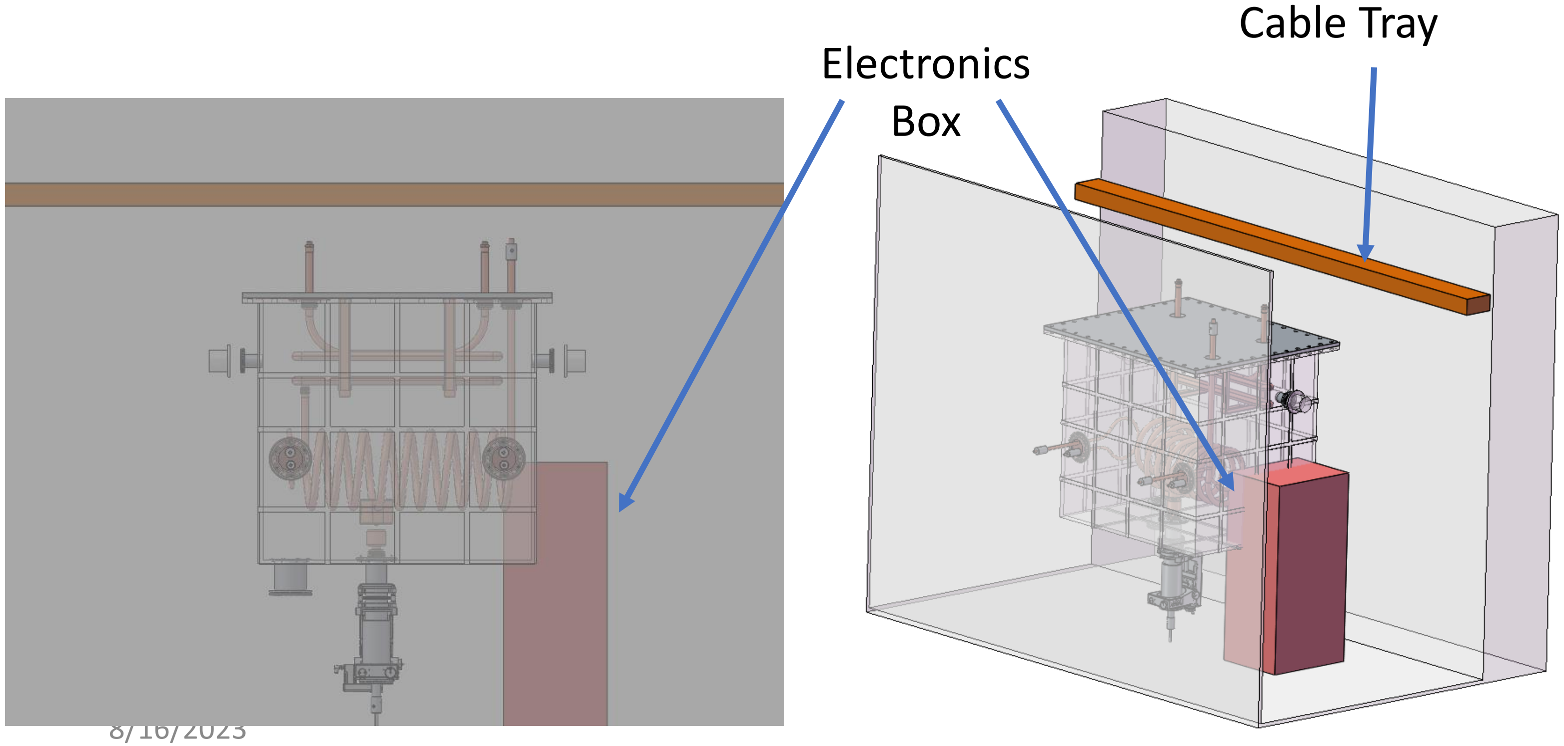


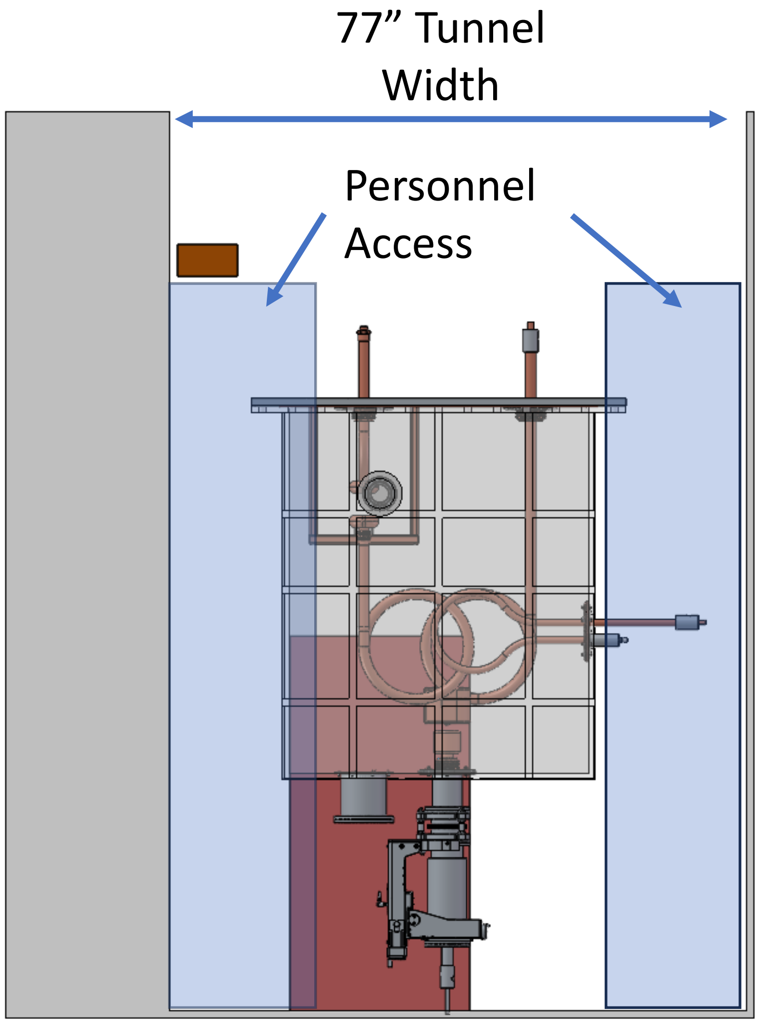




Engineering design

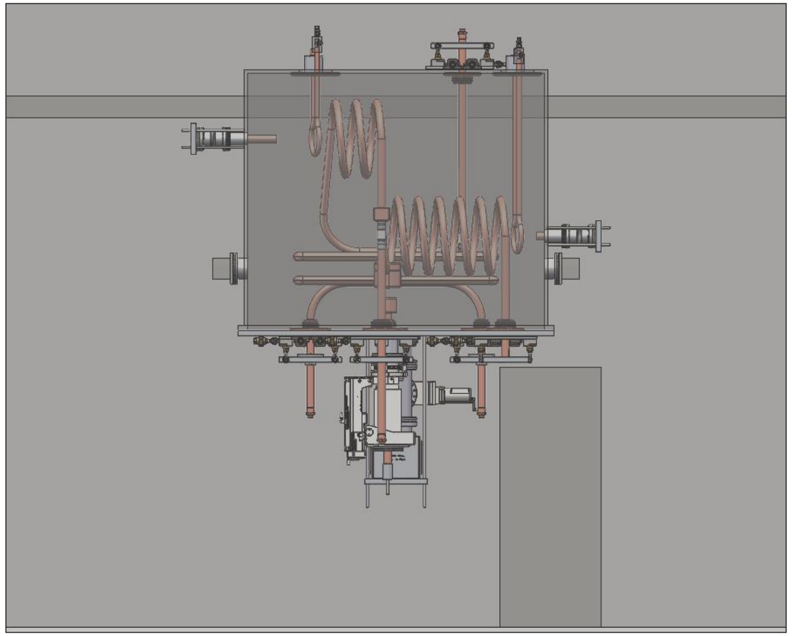
- Engineering design was ready in 2022, demonstrated good performance, but didn’t fit ATLAS tunnel
  - Significant redesign required due to previously unknown / unspecified ANL restrictions
- Interferences
  - Electronics box
  - Cable tray
- Beamline tunnel size
  - Personnel access
  - Ceiling limited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

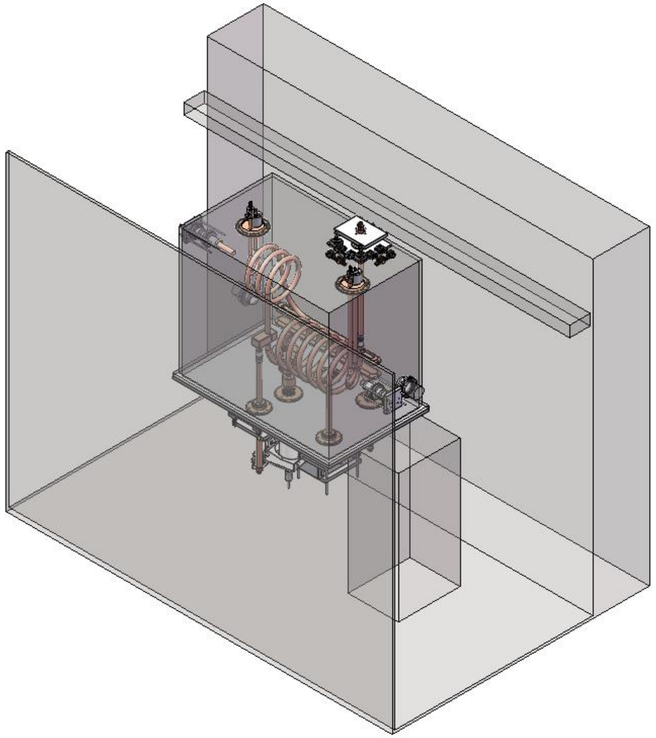


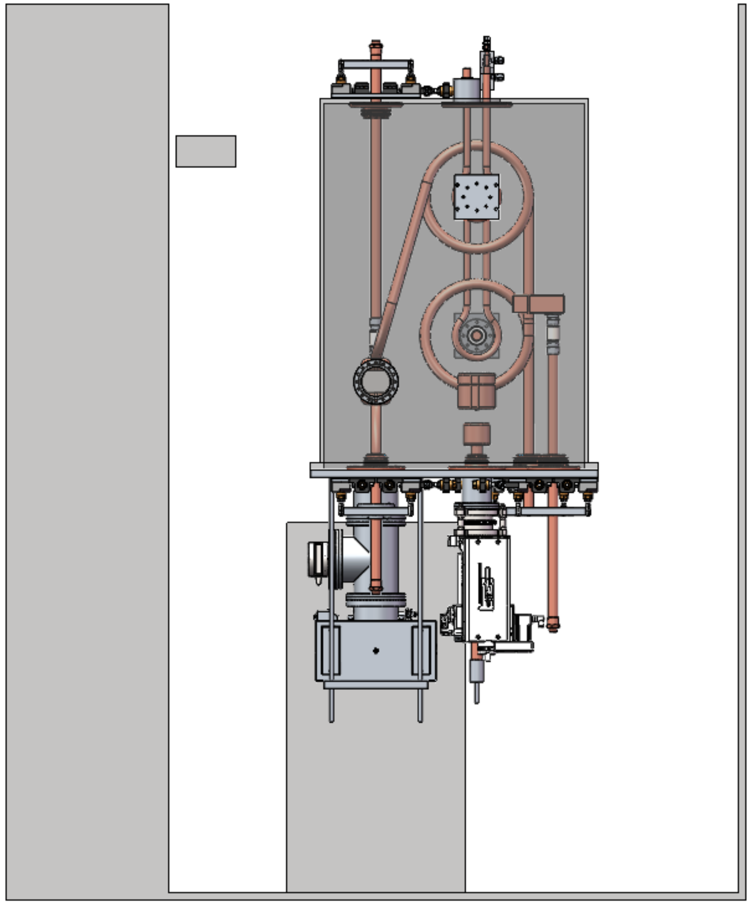


Redesigned model

- Significantly more compact
  - Higher power density…
- Reviewed by ANL and sufficient personnel access reserved
- All interferences resolved
- Conceptual installation plan reviewed

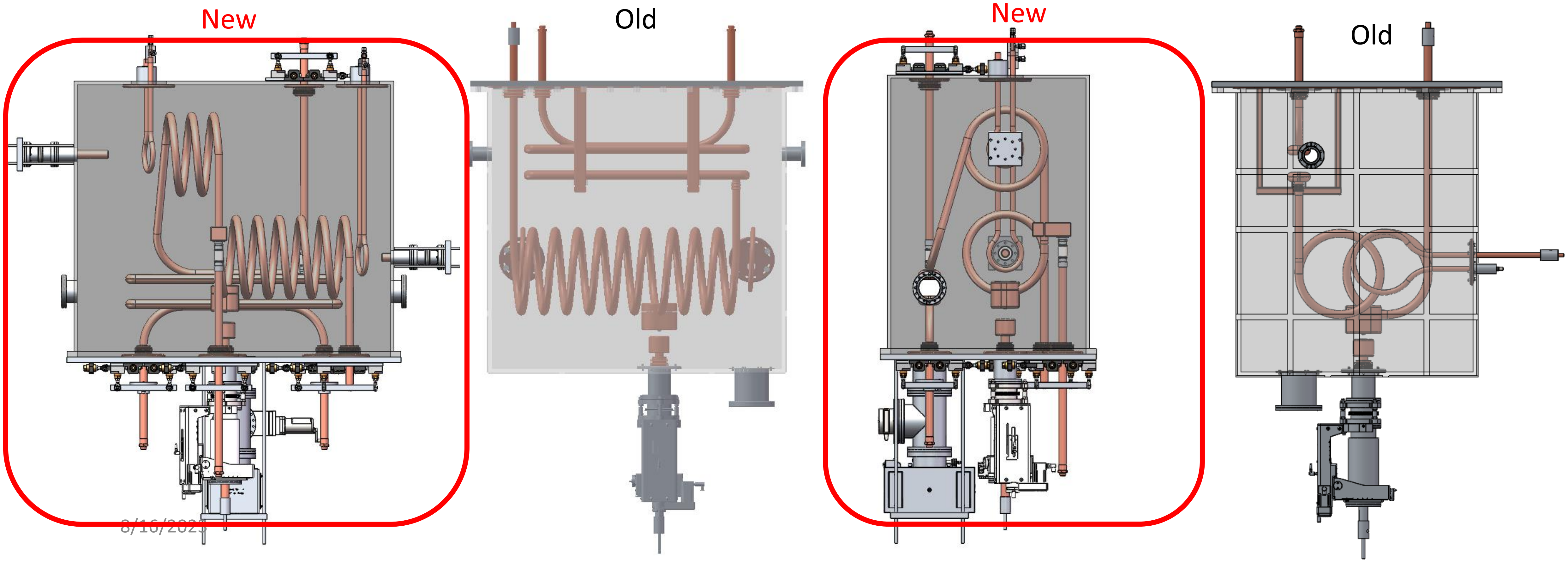






Latest design summary

- Main build plate placed on bottom
- Coupling loops placed vertically
- Coils modified and permitted to use water to vacuum braze joints
- Electrode and coil mounts redesigned for alumina vs macor
- Note locations of beampipes

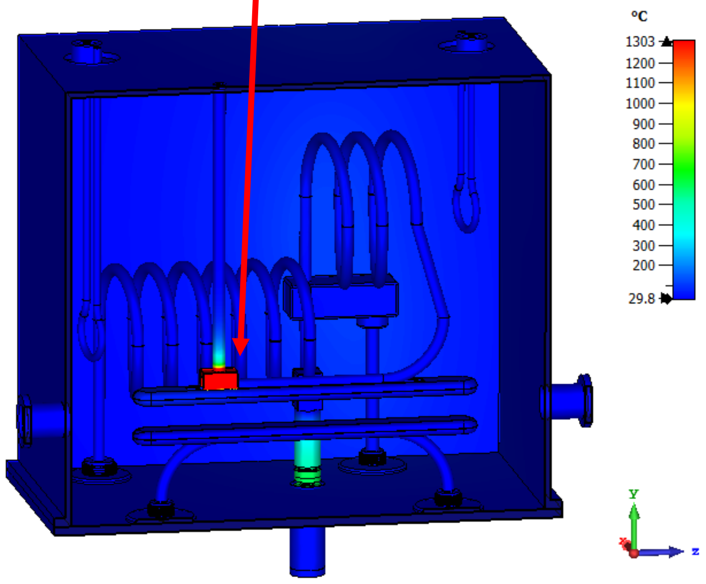


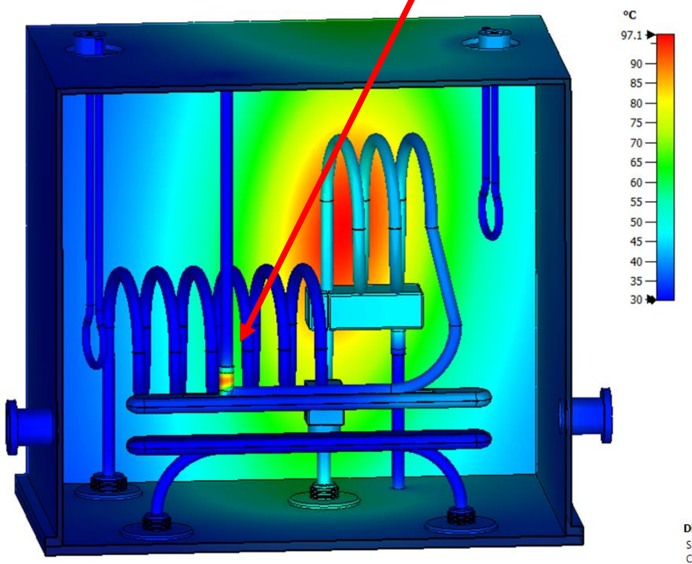
Last major challenge: electrode support

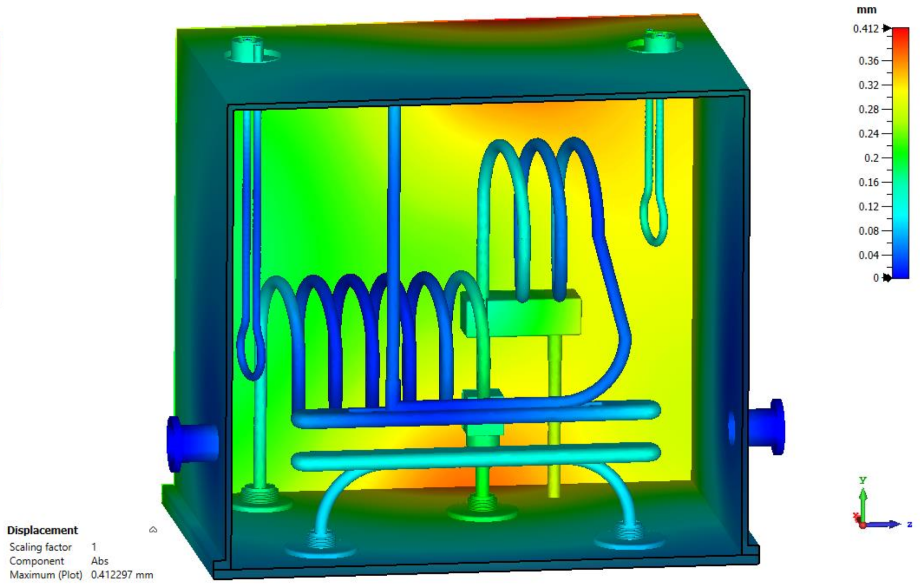
PEEK support
1300 C

Alumina support
<100 C

~150 microns
deformation





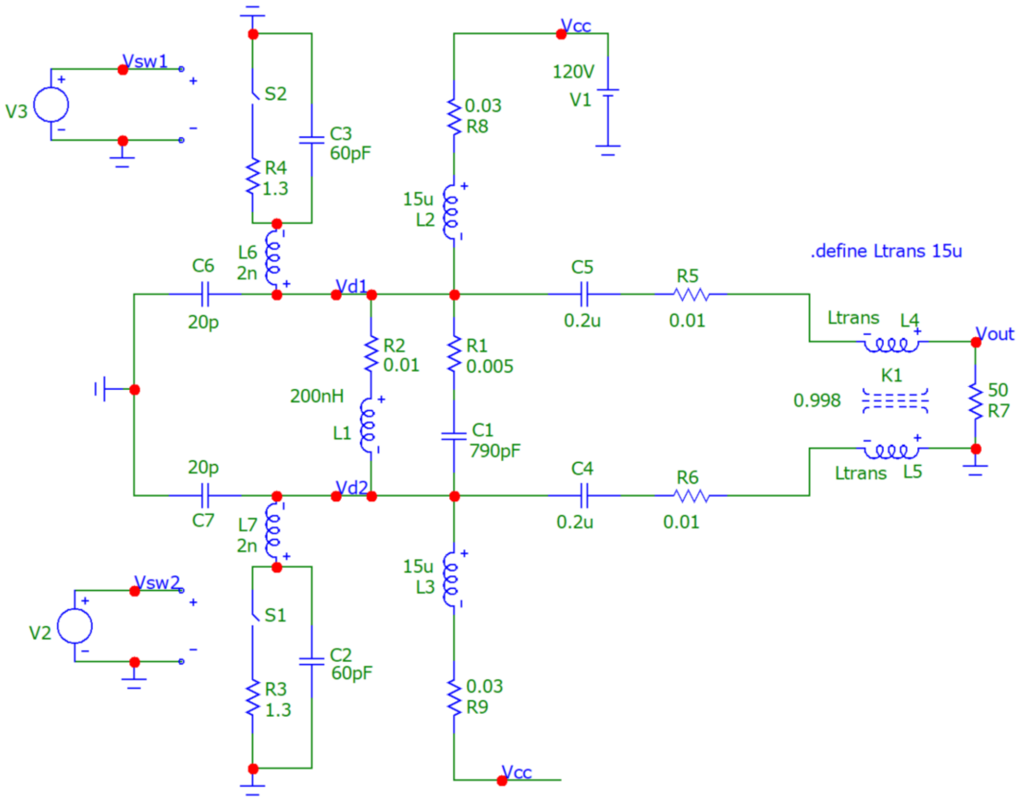


Remaining engineering activities

- Detail alumina supports and build testing prototypes
- Incorporate EIA connector detail for power couplers
- Coils (primary and couplers)
  - Add fine features for MFG
    - Forming
    - brazing
  - order material
  - design winding tooling
- Frequency switch
  - Detailed engineering
  - Mechanical test stand development
- Detailed engineering of electrodes to minimize form variance
- Chamber
  - Finalize geometry
  - Perform initial mechanical analysis
  - Generate quoting drawings
  - Begin discussions with vendor and place order
- Design system support stand
- Consider transportation and assembly nuances during all of the above

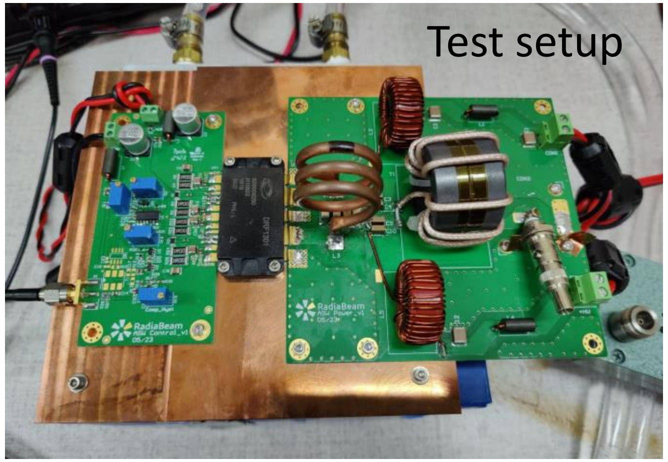
RF source design

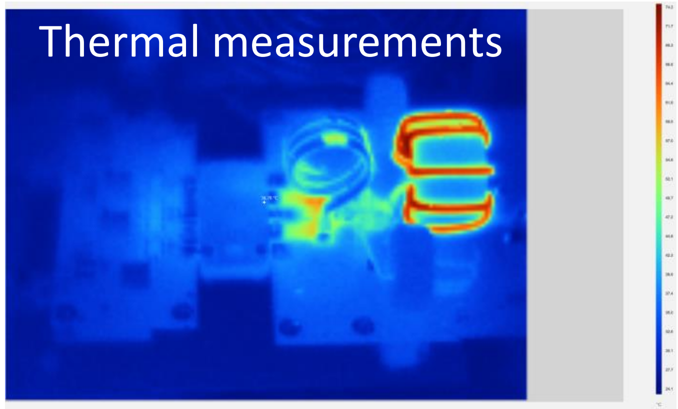
- Push-pull current mode class-D power amplifier
  - Doesn't need an RF transformer, which resulted in a high amplitude of voltage oscillations at the transistors and matching elements.
- 1 kW module is optimal:
  - A further increase in power leads to a drop in efficiency and increases the requirements for the power supply and cooling system
  - We attempted to replace transistors with others with a lower channel resistance (DRF1311) did not lead to improvements. The manufacturer of these transistors made a mistake in the documentation and channel resistance was the same



RF source test results

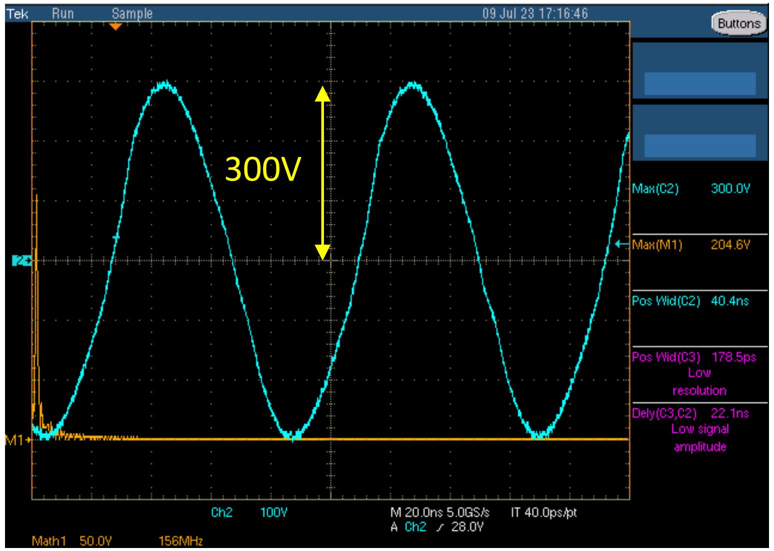
- We are building 16 kW CW Class-E solid-state amplifiers for 6 and 12 MHz
- 1 kW pallets built and tested at RadiaBeam – 87% efficiency achieved;
- Need x16 of both types and 16-to-1 power combiners





166 ^oF

Output voltage on 50 Ω load



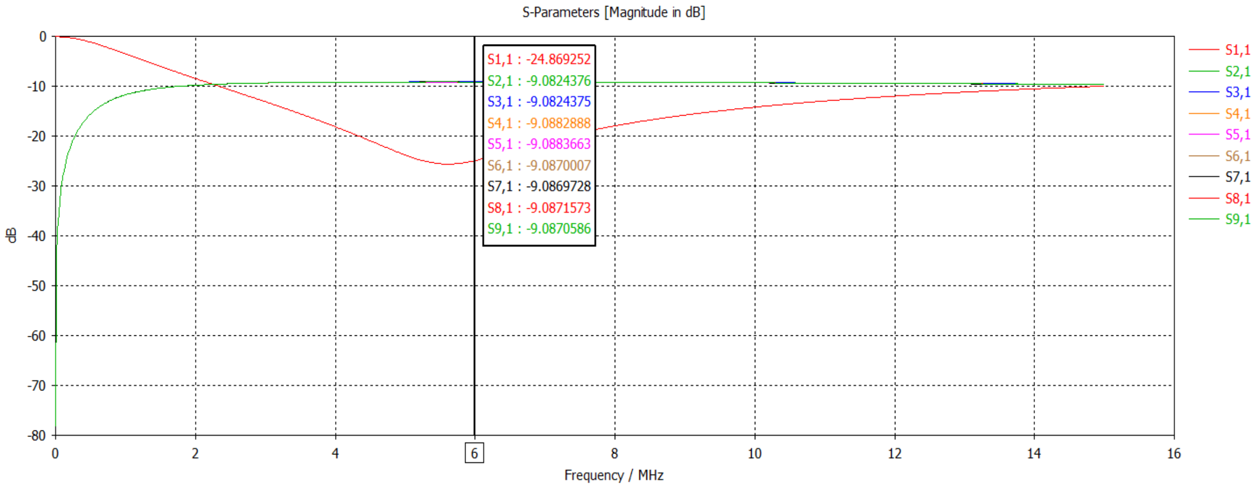
Measured parameters:

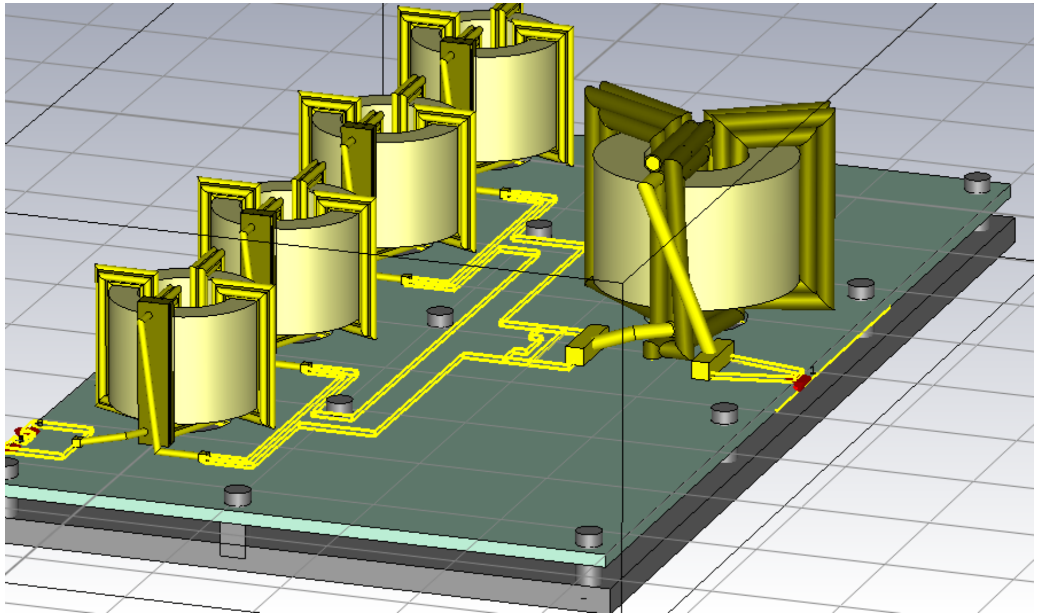
- Frequency: 12.125 MHz
- Input voltage: 130 VDC
- Input current: 8.4 A
- Resonator tank: 250 nH || 600 pF
- Output power: 900 W
- Efficiency: 82.4 %

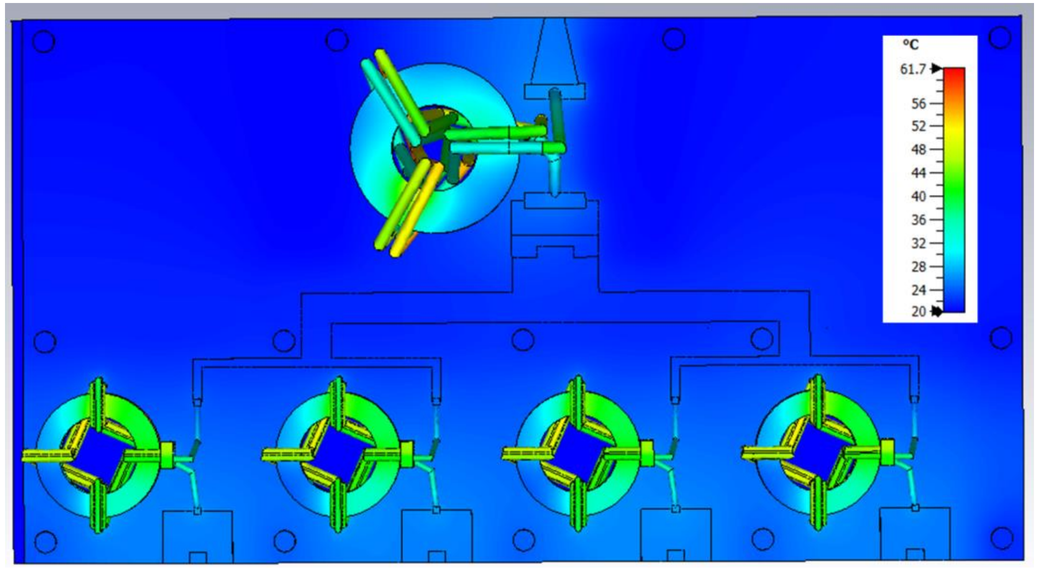
Power combiner

RadiaBeam

- 16 1-kW modules will be combined into a single 16 kW module
  - 3-stage binary
  - Transformer-based (RF ferrite)







Scalable design: we can add modules in the future

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
- Currently, finalizing the engineering features (stand, tuners, fiducials etc.)
- Plan to start fabrication and procurement by Oct. 1
- RF power system is demonstrated and modules are being produced
- NCE will probably be needed, but the success chances are high

- Project Team:
  - Alexander Smirnov, Ronald Agustsson, Aurora Araujo, Evgeny Ivanov and Sergey Kutsaev

- Special acknowledgements:
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