ANL CW RFQ – Design, Construction and Operation in the past 7 Years

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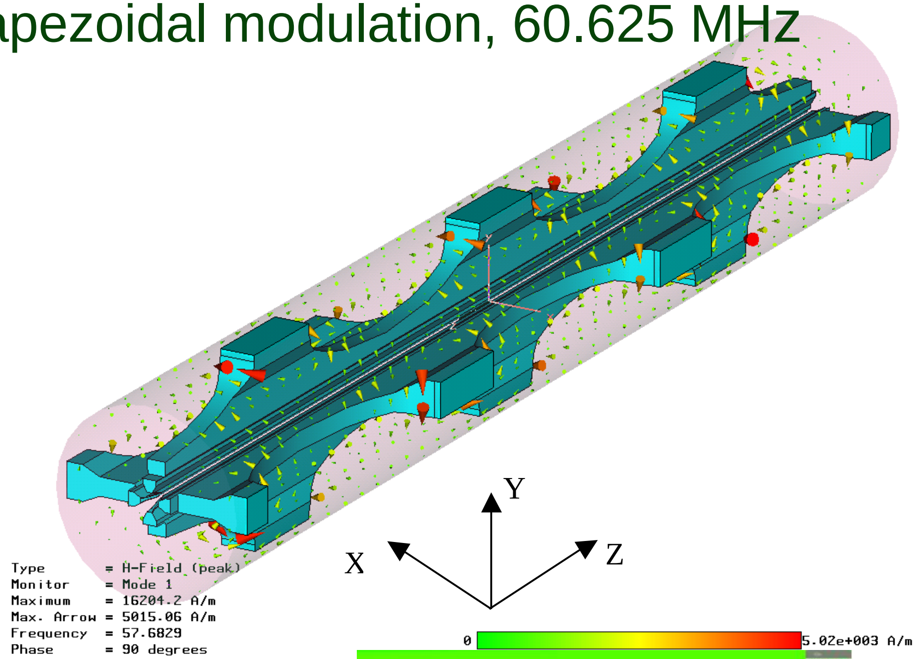
Outline

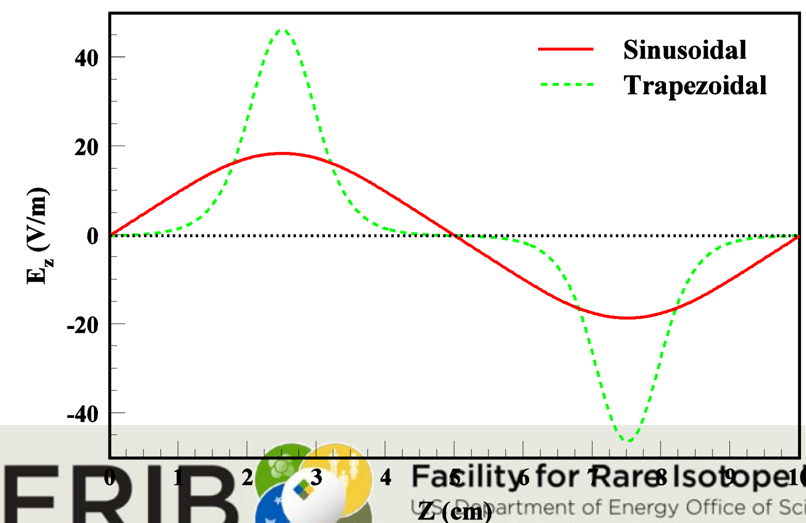
- Design
  - Multi-cell split coaxial structure, 60.625 MHz
    - » Reduced transvers dimensions, ~25” flanges
  - Trapezoidal modulation in the acceleration section
- Construction
  - High temperature brazing
- Testing and commissioning was completed in July 2012
- In routine operation since January 2013
  - The first CW RFQ in routine operation in the USA

Main Parameters

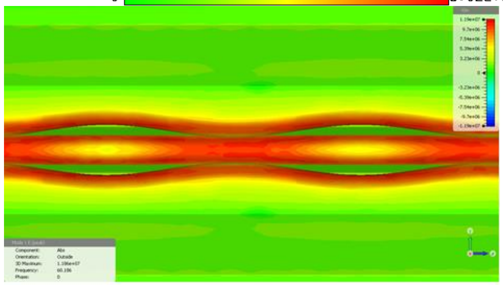
- Multi-cell split-coaxial structure with trapezoidal modulation, 60.625 MHz

	Parameter	Value
1	Duty cycle	100%
2	q/A	1/7 to 1
3	Input Energy	30 keV/u
4	Output Energy	295 keV/u
5	Average radius	7.2 mm
6	Vane Length	3.81 m
7	Inter-Vane Voltage	70 kV
8	RF power consumption	60 kW

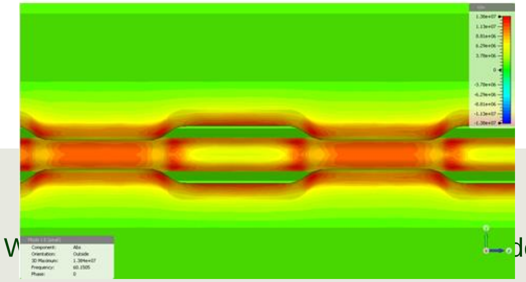




Section with sinusoidal modulation

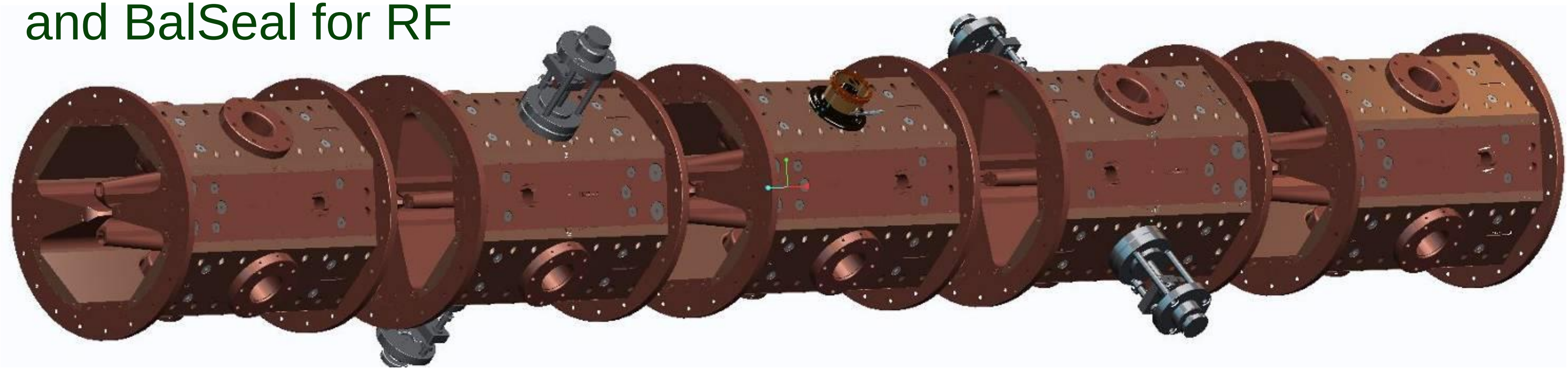


Trapezoidal modulation



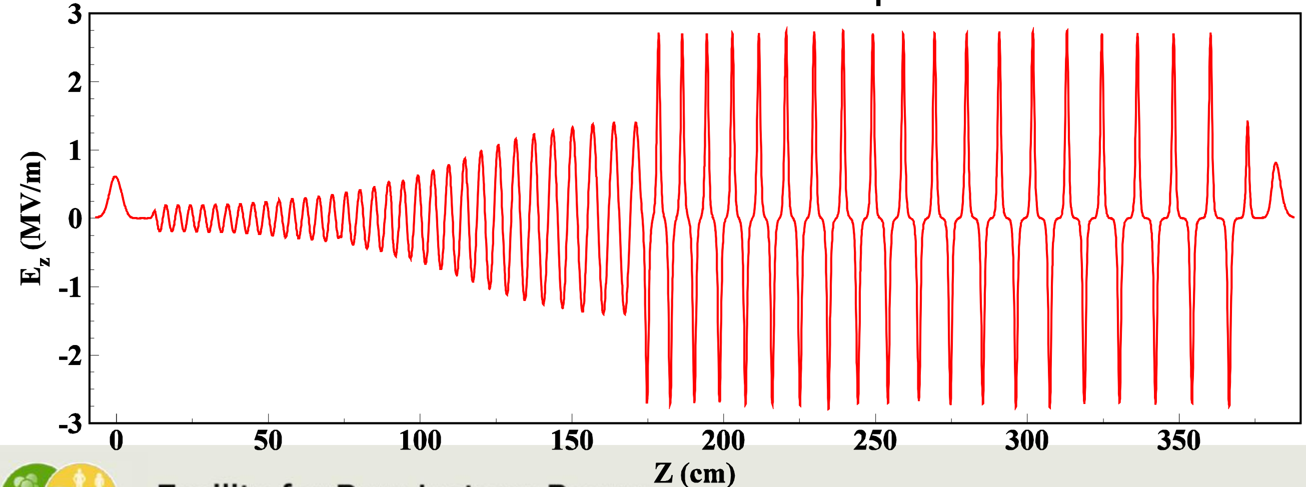
3D Mechanical Model and Accelerating Field Distribution

- 5 brazed copper segments, bolted together via Viton seals for vacuum and BalSeal for RF



Peak electric fields from EM-Studio

1.31 Kilpatrick Sinusoidal | 1.61 Kilpatrick Trapezoidal



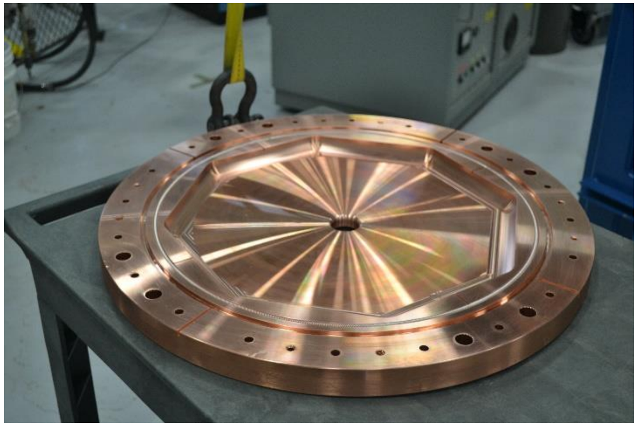
High Temperature Furnace Brazing

Segment prepared for the brazing

Segment 1 after the brazing with CuSil alloy

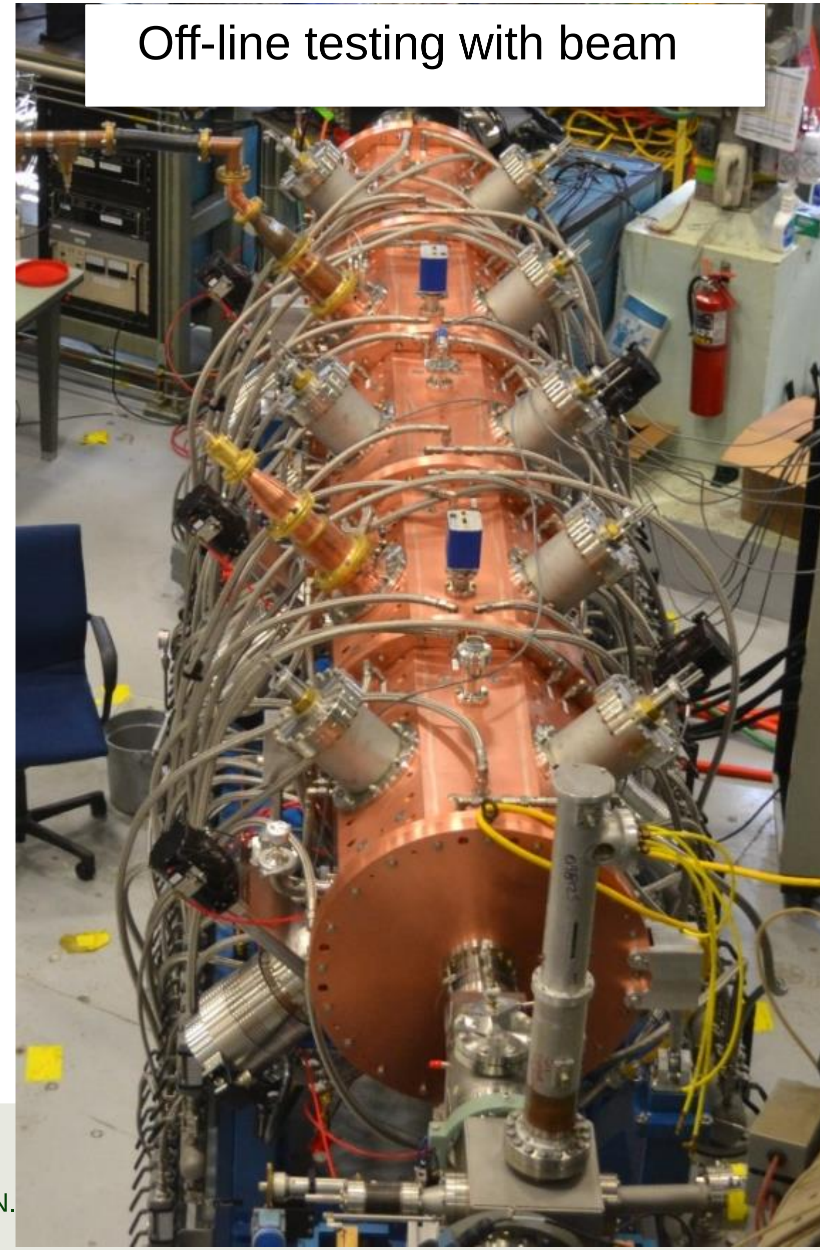
Assembly of Brazed Segments

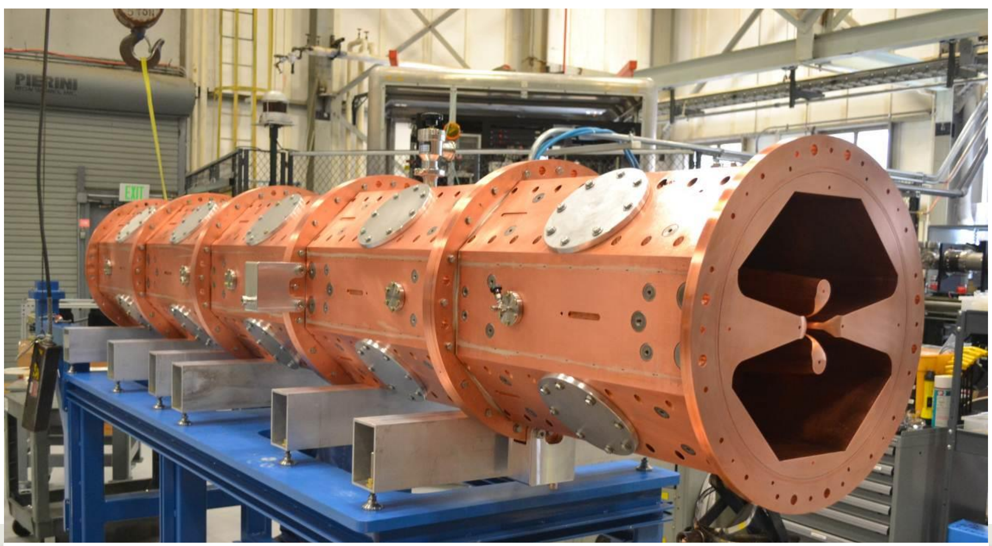
End plate with BalSeal



BalSeal for tuners and couplers

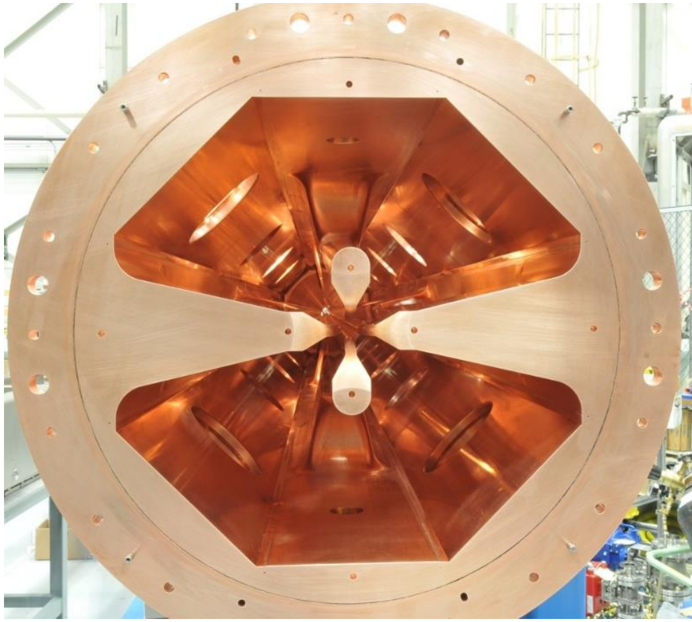
Off-line testing with beam



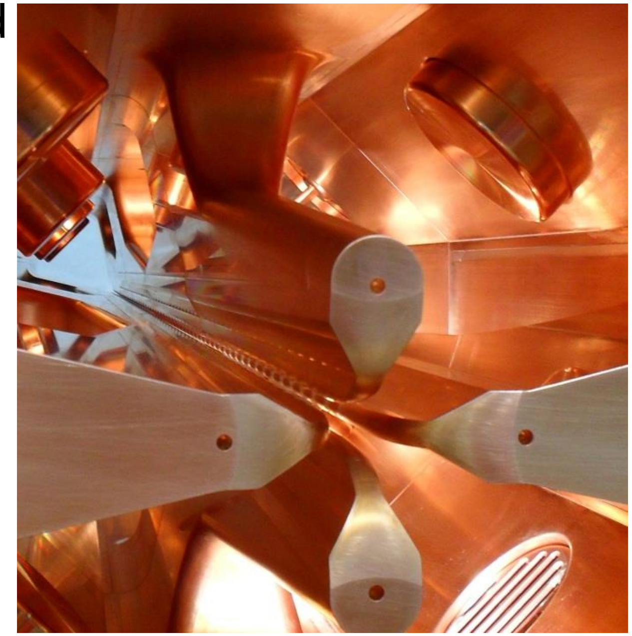


Strongly coupled structure, no bead pull measurements are required

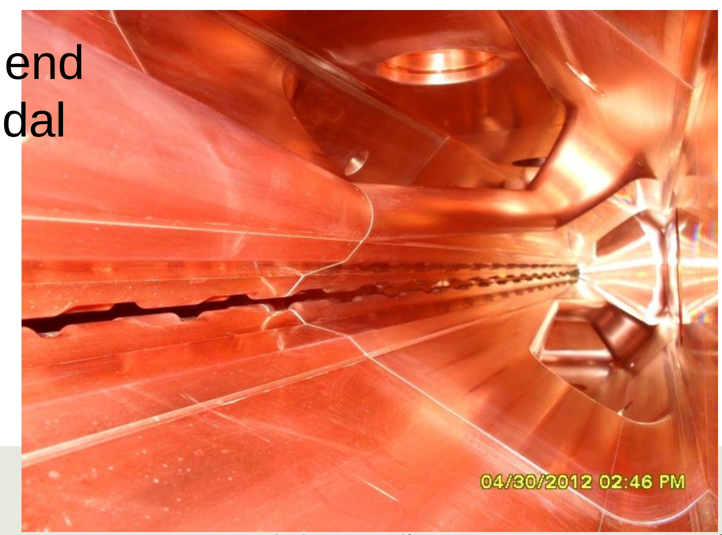
Internal Views



Low energy end

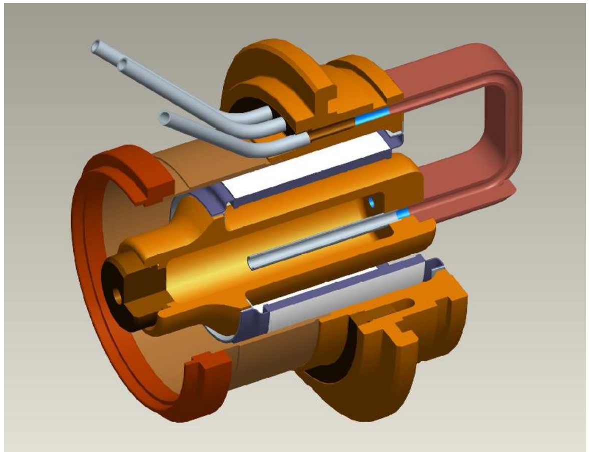


High energy end with trapezoidal modulation



RF Coupler

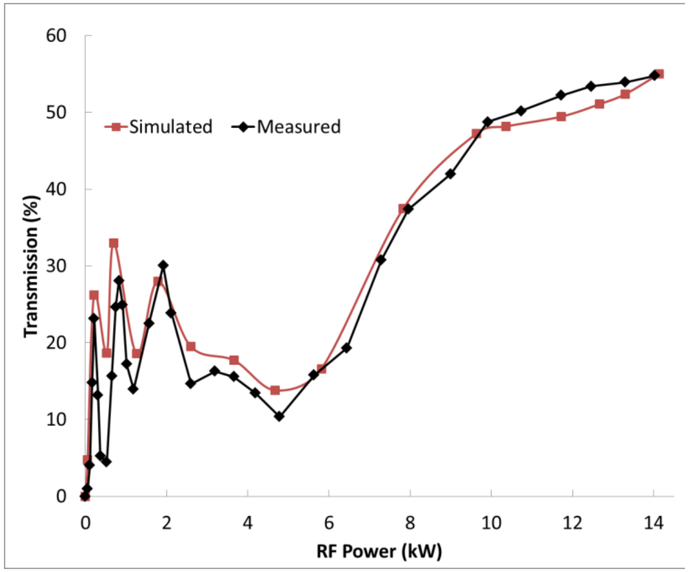
- Coupler model

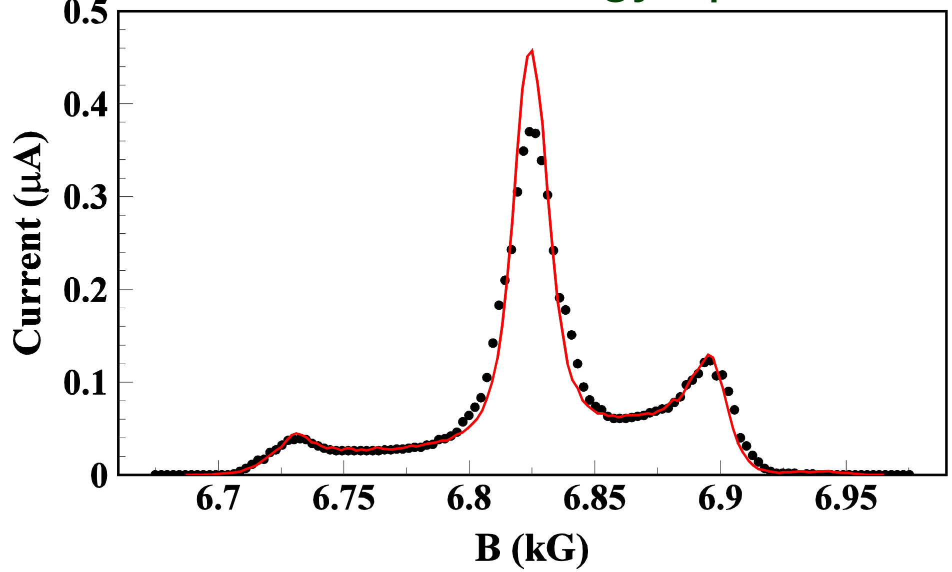


Coupler components

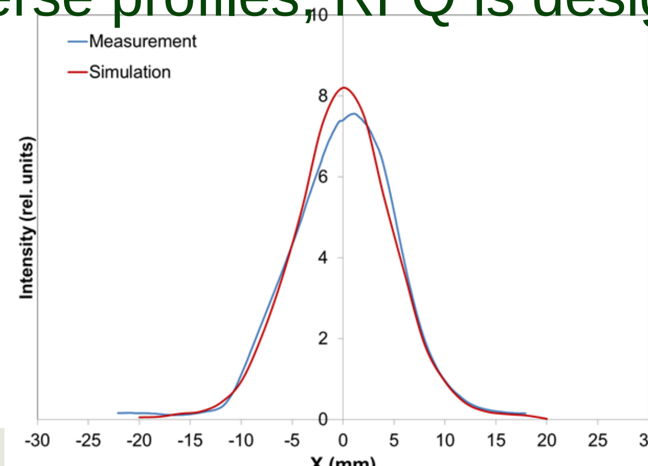
Off-Line Testing Was Done on July 2012 with Oxygen Beam

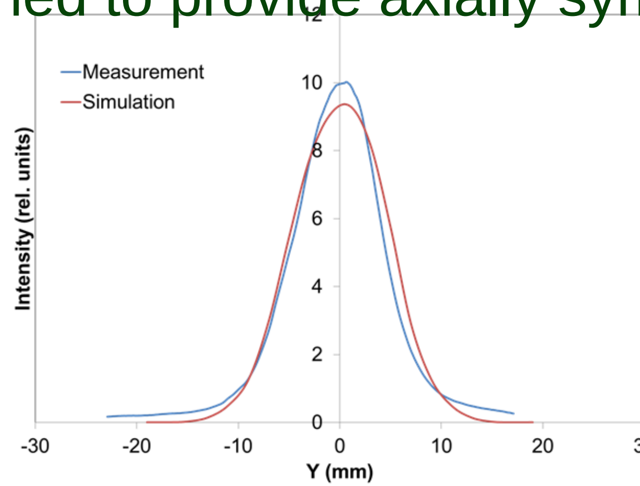
- Transmission — Energy spread



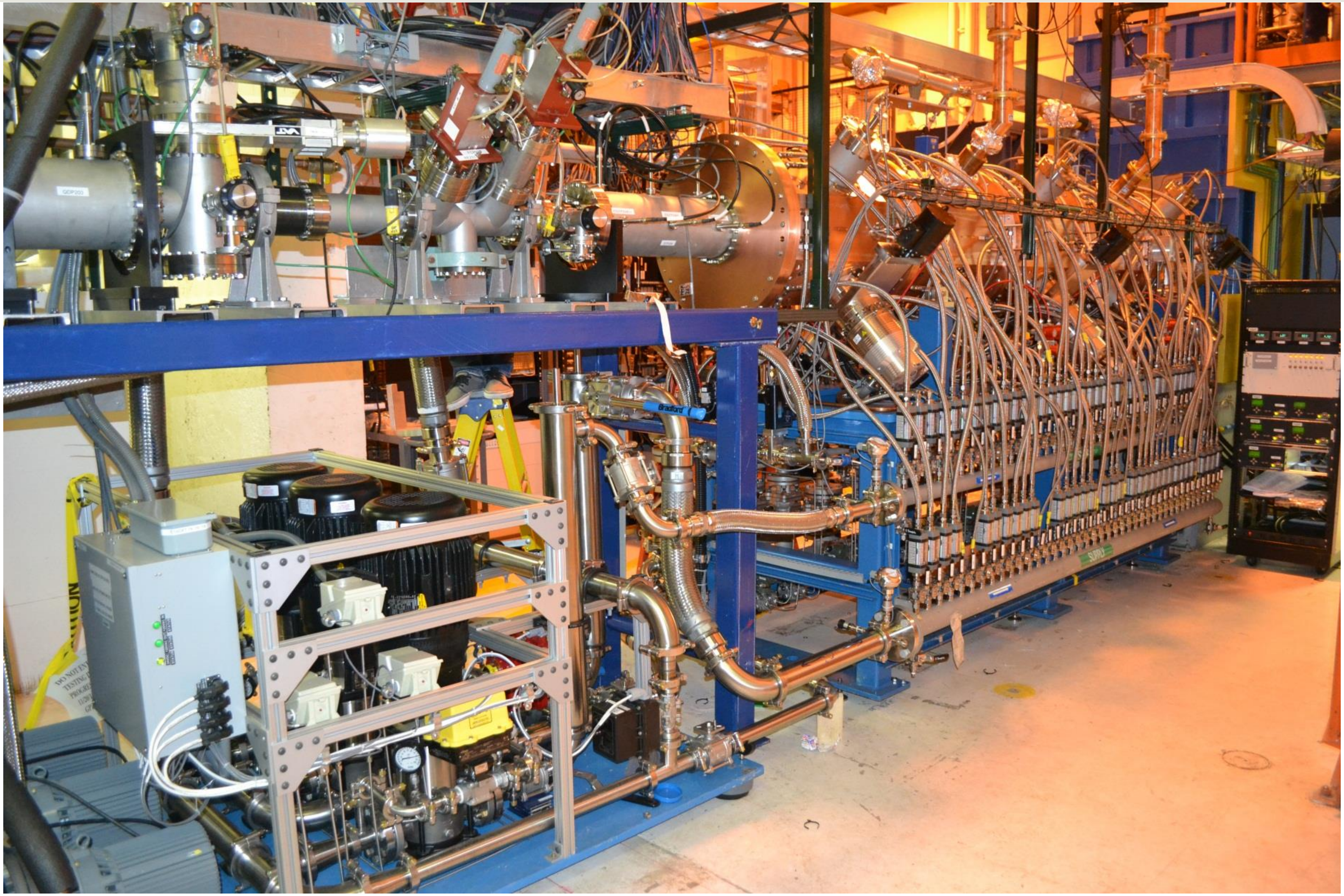


- Transverse profiles, RFQ is designed to provide axially symmetric beam





In Operation Since January 2013

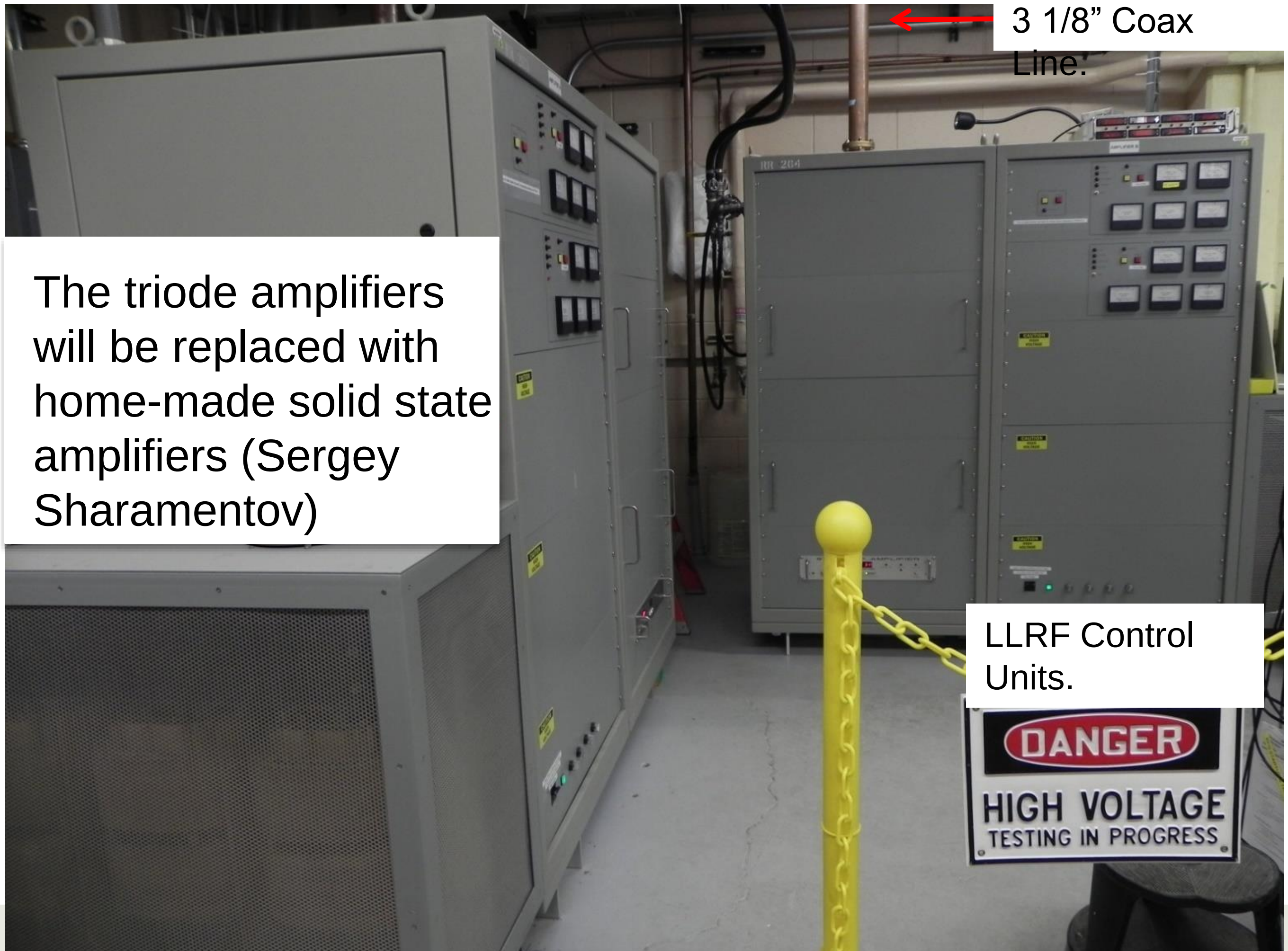


Two 60 kW Amplifiers Provide Power for RFQ

- Was bought with very low budget, main contributor to downtime of the RFQ system

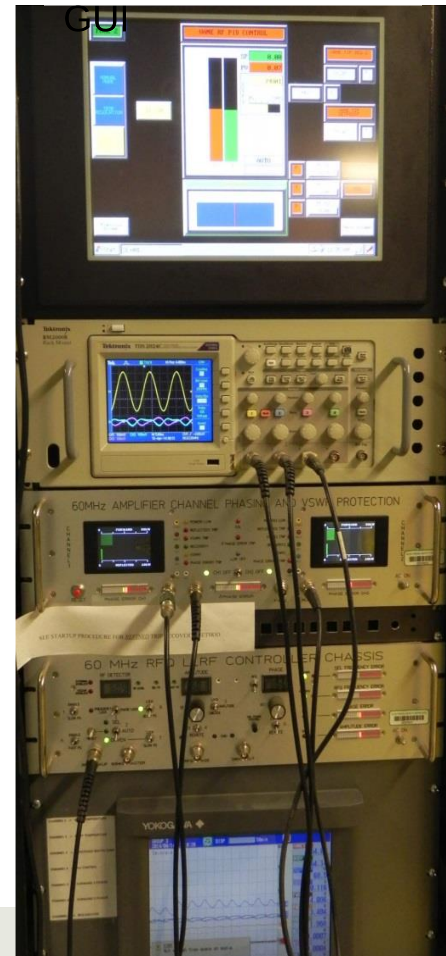
3 1/8” Coax Line:

PLC Water CTRL GUI



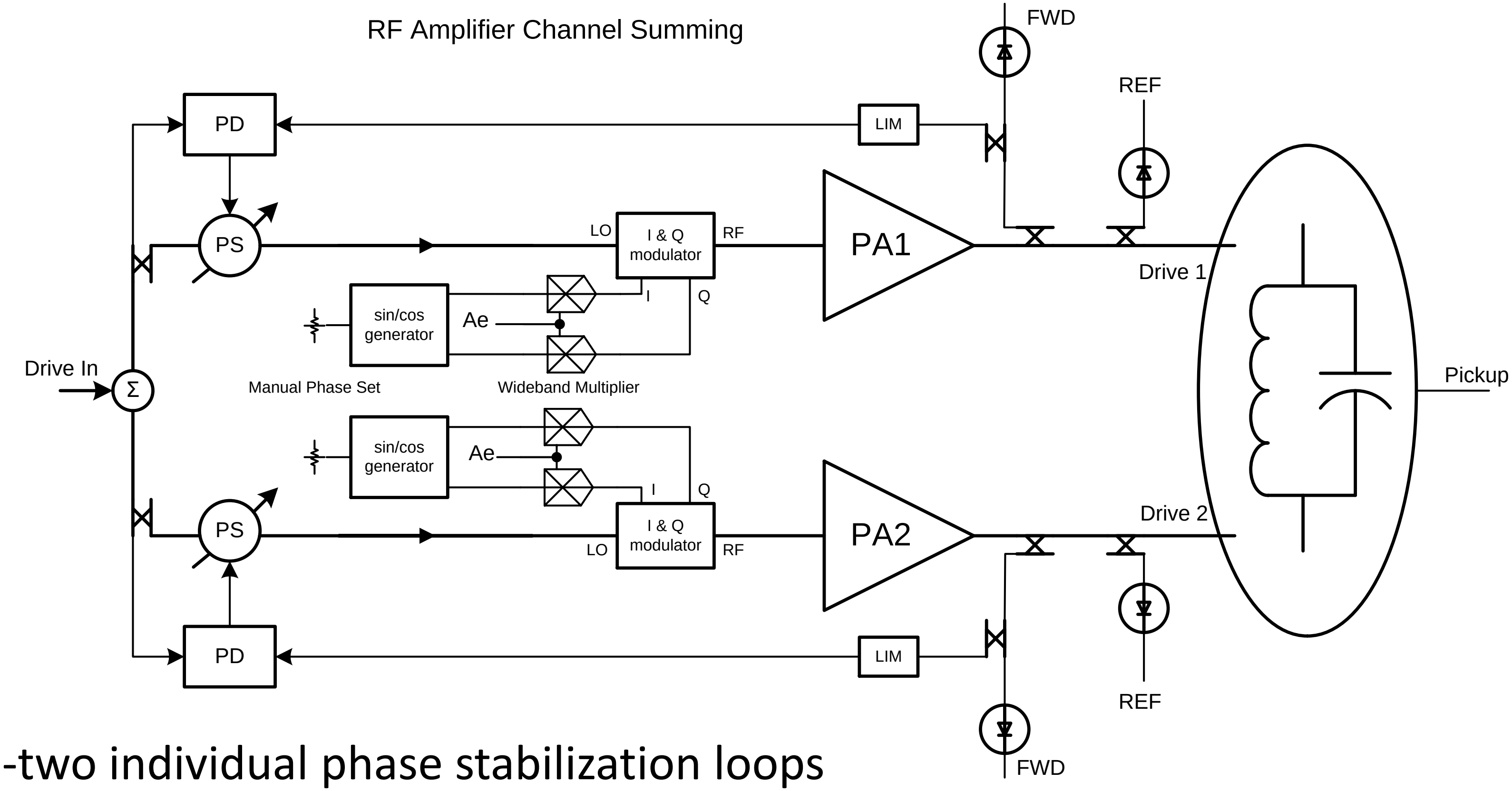
The triode amplifiers will be replaced with home-made solid state amplifiers (Sergey Sharamentov)

LLRF Control Units.



Power Summing in Resonator

- The first 2 years the RFQ was operated without RF circulators
  - Resulted in frequent trips of the amplifier due to reflected power



-two individual phase stabilization loops

-I&Q modulator used as 360 degrees phase shifter and fast amplitude regulator

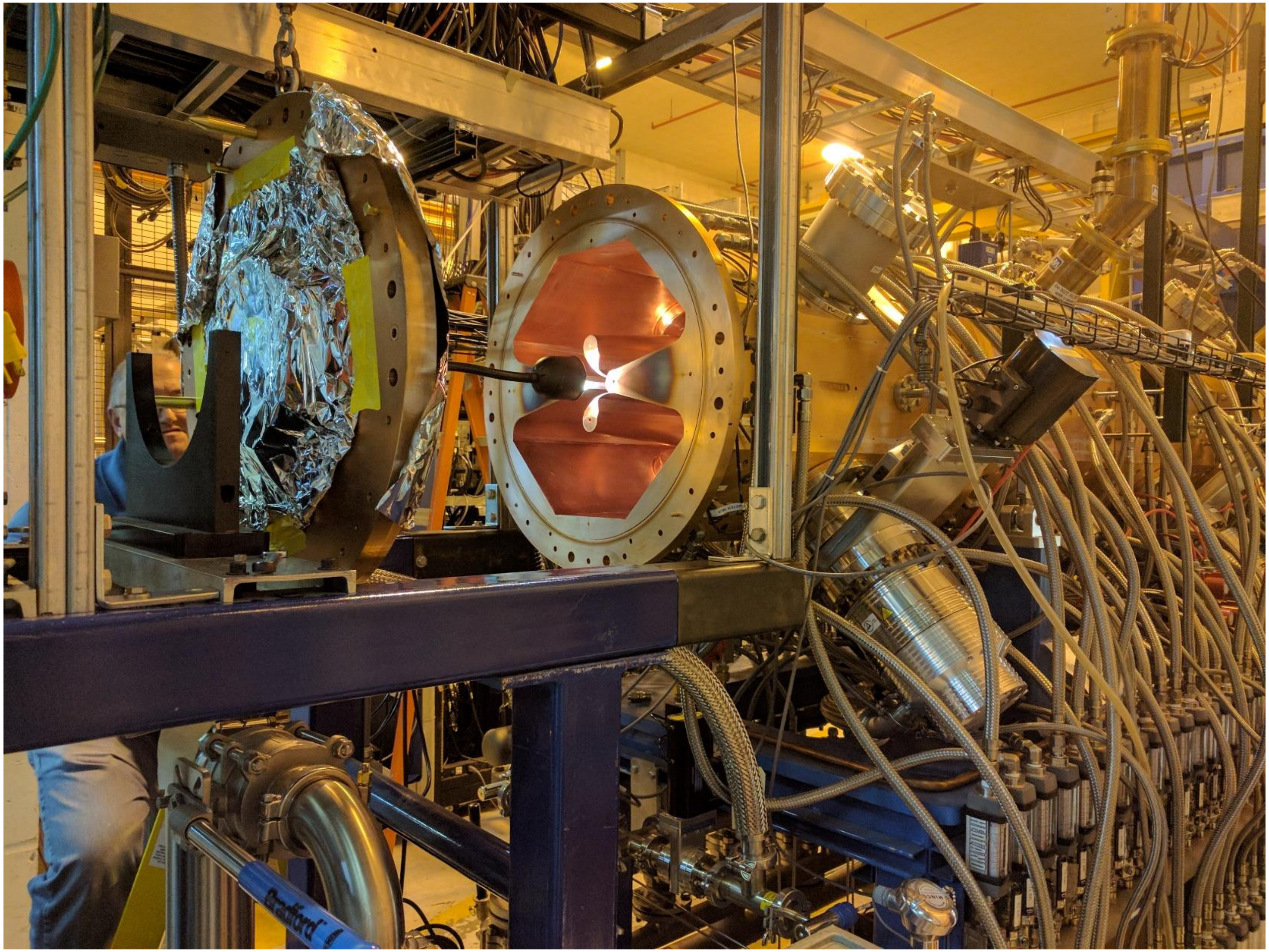
Operational Experience

- CW operation all the time
- On service ~4500 hours per year, accumulated about 28000 hours
- Initially was conditioned up to 74 kV without a single sparking
  - Conditioning took 4 hours, just to keep vacuum below $5 \cdot 10^{-7}$ Torr
- Observed multipacting at power level <1 kW
  - Quickly conditioned
- Operated over last >6 years for all ion species with $M/q \leq 6.7$
- Vacuum during the operation at the highest power is $2 \cdot 10^{-7}$ Torr
- Reliability is >92%
  - Amplifier trips are main contribution
  - A new solid state amplifier is being developed to replace the vacuum tube amplifier

Features of CW Operation

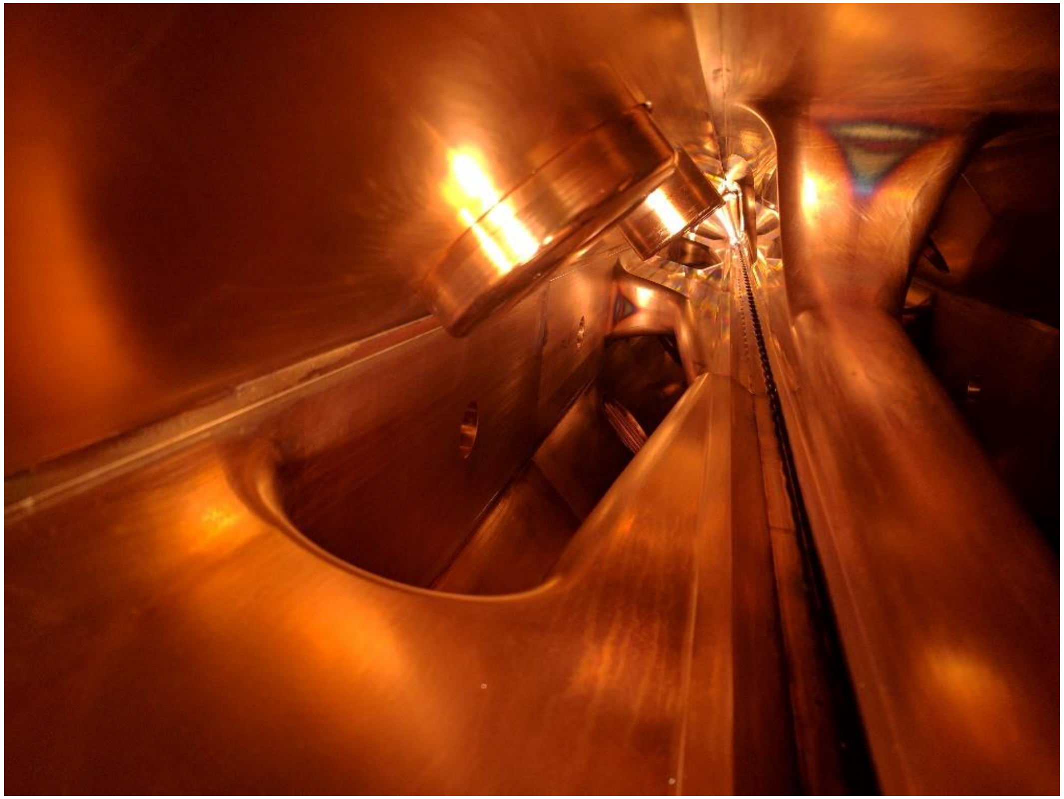
- ATLAS RFQ experiences sparking vary rarely
  - May happen during the turning on
- If sparking happens there is no system to restore resonator operation quickly, within milliseconds
  - Sparking can trip RF and resonator cools down very quickly
- The frequency is tuned with the water temperature which is achieved by mixing warm and cold water flows
- Once resonator becomes cold, the recovery time takes ~15 min for experienced operators, takes longer for unexperienced operators
- LLRF was not designed to operate in pulsed mode originally
  - The pulsed conditioning was introduced in 2017 to condition the resonator in pulsed mode prior the highest power operation
- Although it is not an issue for the ATLAS RFQ but for high power CW RFQs it is desirable to have LLRF capable to operate in pulsed mode and provide automatic recovery from the sparking writhing in time scale < 1 sec before the resonator cools down

Internal View in 2017

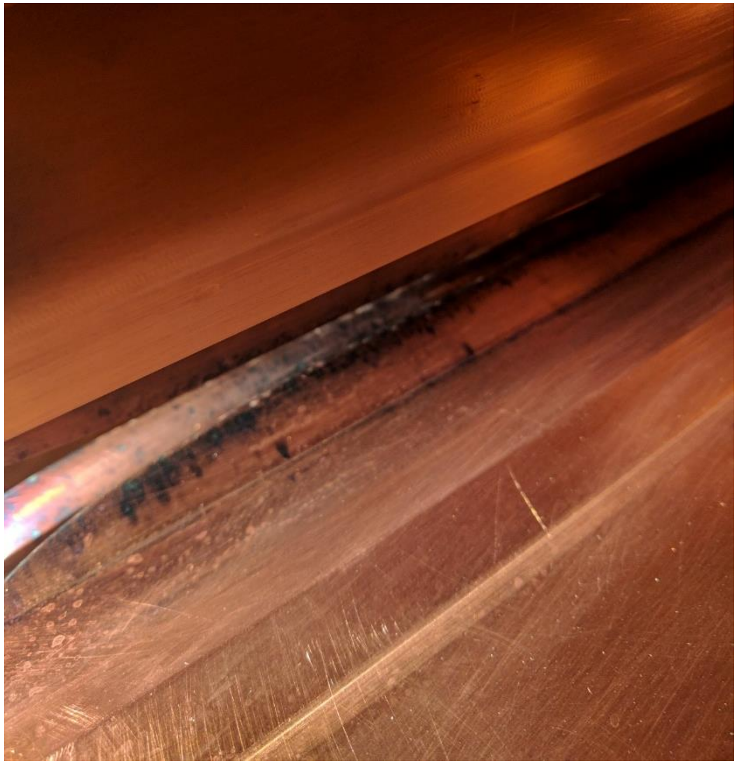


Internal View

Multipacting in high magnetic field area

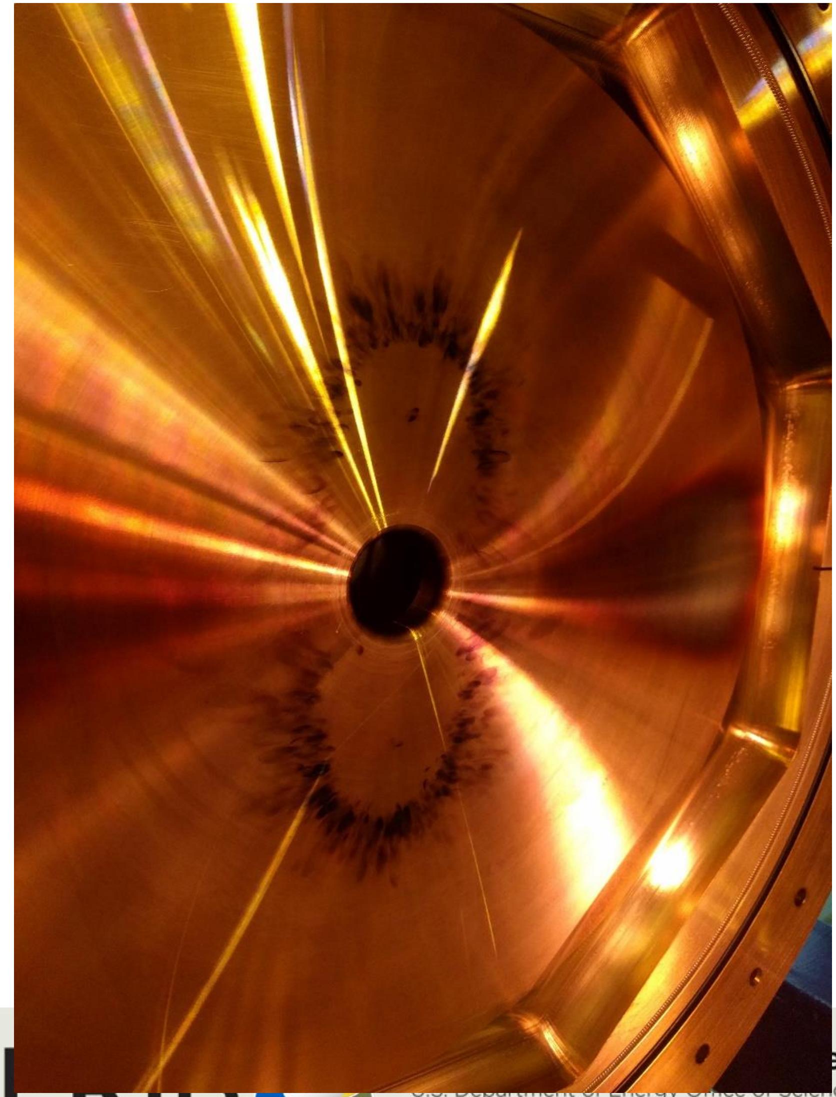


Radial matcher



Internal View

End flange



Low energy end

Path to 100% Reliability of a CW RFQ in Long Term Operation

- Robust RF amplifier, 100% reliability
- RF circulators are must
- To minimize power load into the RF coupler consider summing of RF power in the resonator
- High temperature brazing is the best technology for CW RFQs
  - Provides the same Q_0 as in simulations, minimizes RF losses
  - Mechanical and alignment errors are reduced to 25-50 μm
- RF BalSeal works well
- Design peak fields: Kilpatrick should be as low as possible, <1.6
- Vacuum with full power RF, < upper 10^{-8} Torr
- LLRF:
  - Cold start in Self-excited mode
  - Fast, within milliseconds, recovery from occasional trips
  - Should support pulsed mode for possible RF conditioning if required
- Minimized time for cold start-up of the RFQ, 15 min for ATLAS RFQ

Summary

- The technology and operation for a heavy-ion CW RFQ is well established and proven

Acknowledgments

- Many thanks to Matt Hendricks and Sergey Sharamentov from Argonne National Laboratory for the information about the RFQ operation in the past several years