Argonne NATIONAL LABORATORY

Observation of Failure Modes of RF Amplifiers at ATLAS

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U.S. DEPARTMENT OF ENERGY

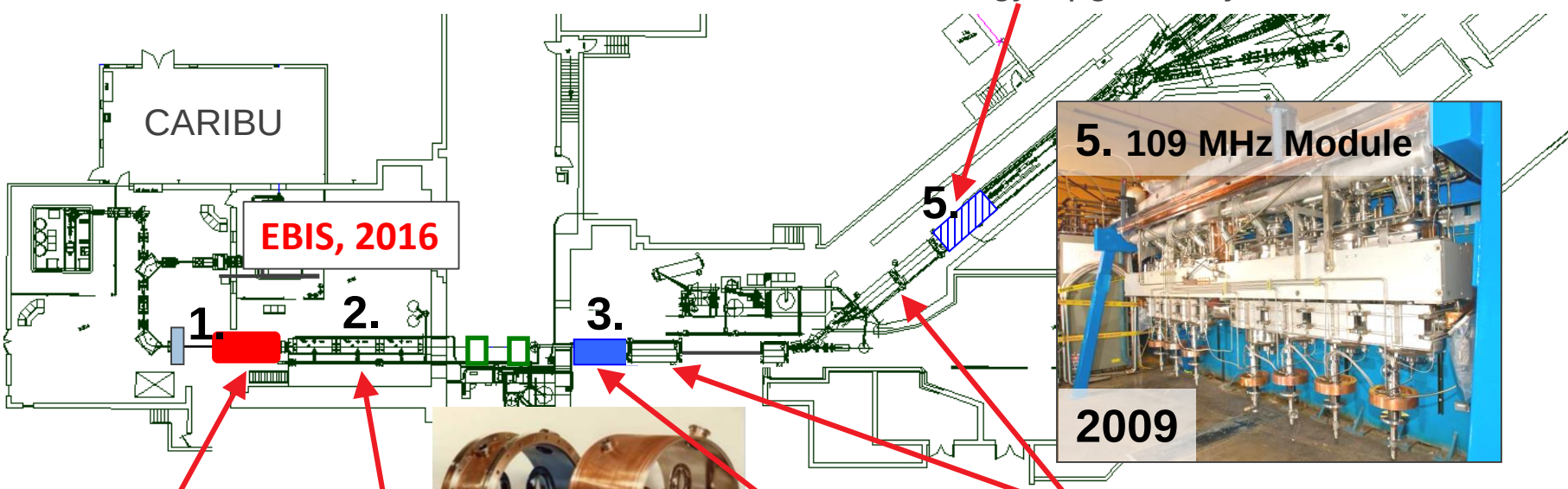
Content

- Introduction to ATLAS
- Recent Efficiency and Intensity Upgrade
- RF System and Failure Modes
- Improvement
- Summary and Future Plan

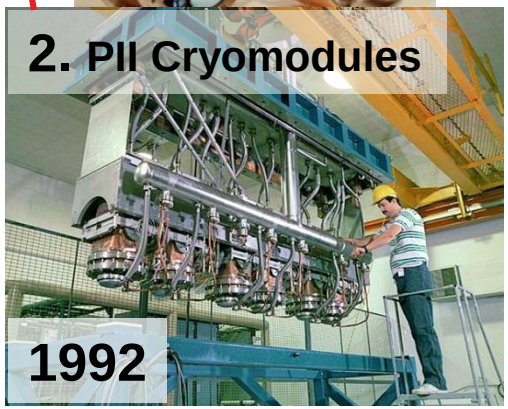
The Present ATLAS Accelerator Cryomodules

8 Cryomodules, 47 SC Accelerating Cavities

109 MHz Energy Upgrade cryomodule



4. Split-ring cryomodules

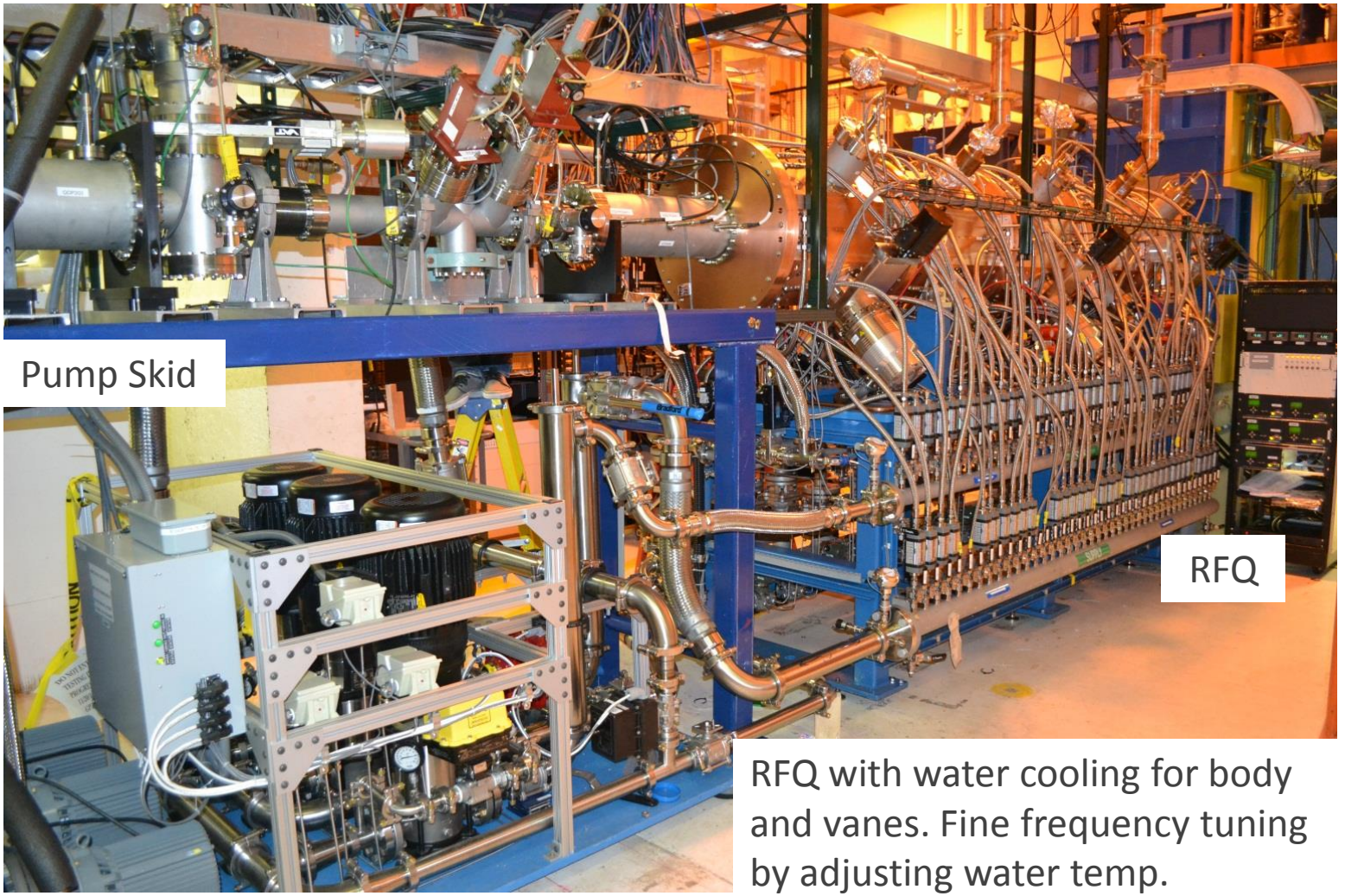


ATLAS Efficiency and Intensity Upgrade

- Increase beam transmission efficiency
  - Radioactive beams from CARIBU (from Proton to Uranium)
- Increase intensity of ion beams
  - Stable ion beams up to 10 pμA, hundreds of electrical microAmps
- This upgrade requires new RF system
  - Two 60 KW amplifiers for 60 MHz RFQ
  - Seven 4 KW solid state amplifiers for New 72 MHz Cryomodule
  - New control system

60.625MHz RFQ and Water Pumps

- Installed in 2012. In operation since January 2013



RFQ with water cooling for body and vanes. Fine frequency tuning by adjusting water temp.

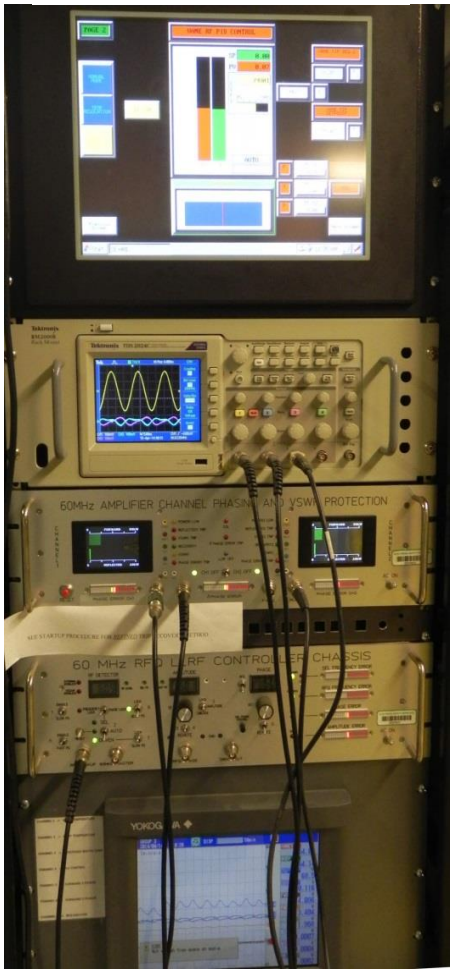
60KW Amplifiers to Provide Power for RFQ

3 1/8” Coax Line.

Two 60KW Amplifiers made by Amplifier Systems. Typically, both are used in operation. But with the adjustment of coupling ports, one amplifier can be used to provide power.

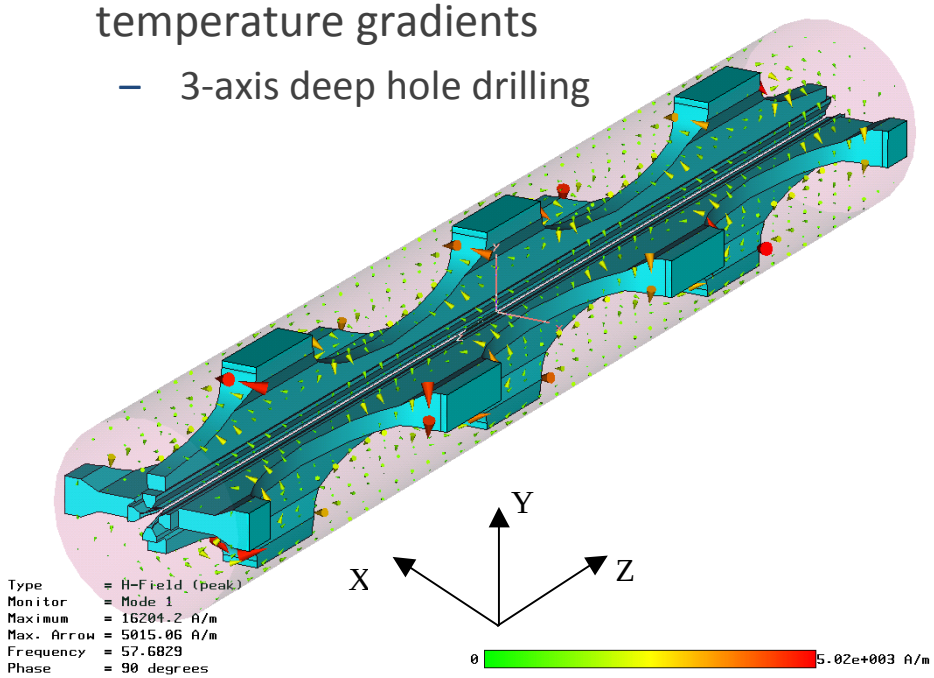
LLRF Contrl Units.

PLC Water CTRL GUI

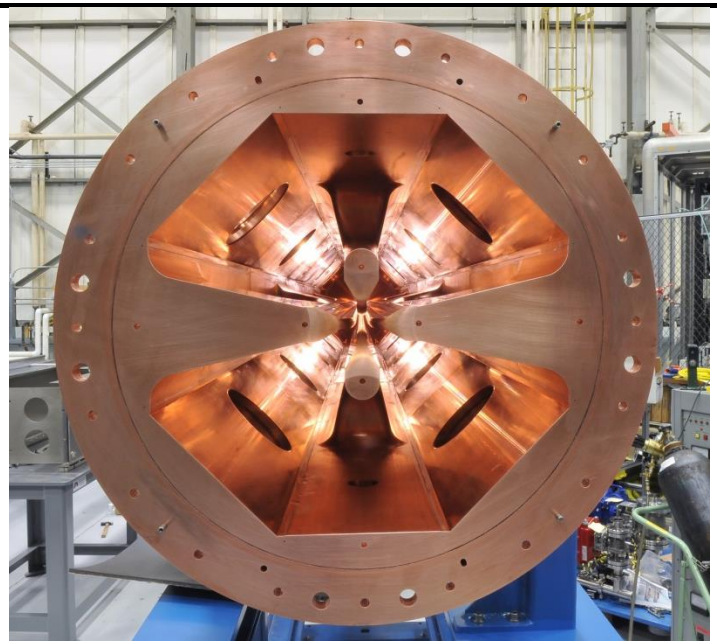


ATLAS CW RFQ

- Total voltage is 2.1 MV
- Novel multi-segment split-coax structure
  - Internal size is 19” only for 60 MHz
  - Strongly coupled segments
  - Reduced number of tuners
  - Bead pull measurements are not required
- Cooling system is optimized to reduce temperature gradients
  - 3-axis deep hole drilling

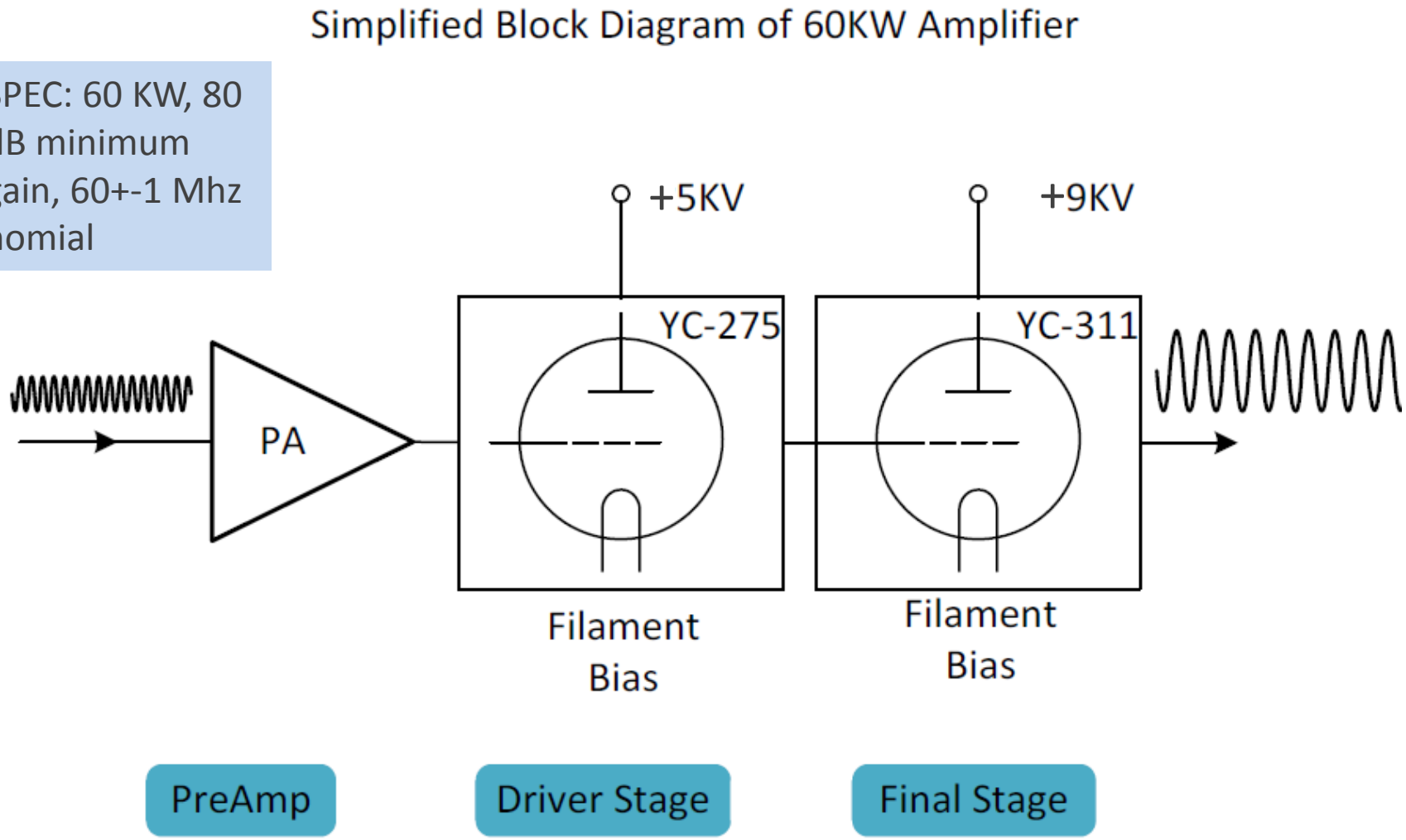


	Parameter	Value
1	Duty cycle	100%
2	q/A	1/7 to 1
3	Input Energy	30 keV/u
4	Output Energy	295 keV/u
5	Average radius	7.2 mm
6	Vane Length	3.81 m
7	Inter-Vane Voltage	70 kV
8	RF power consumption	60 kW

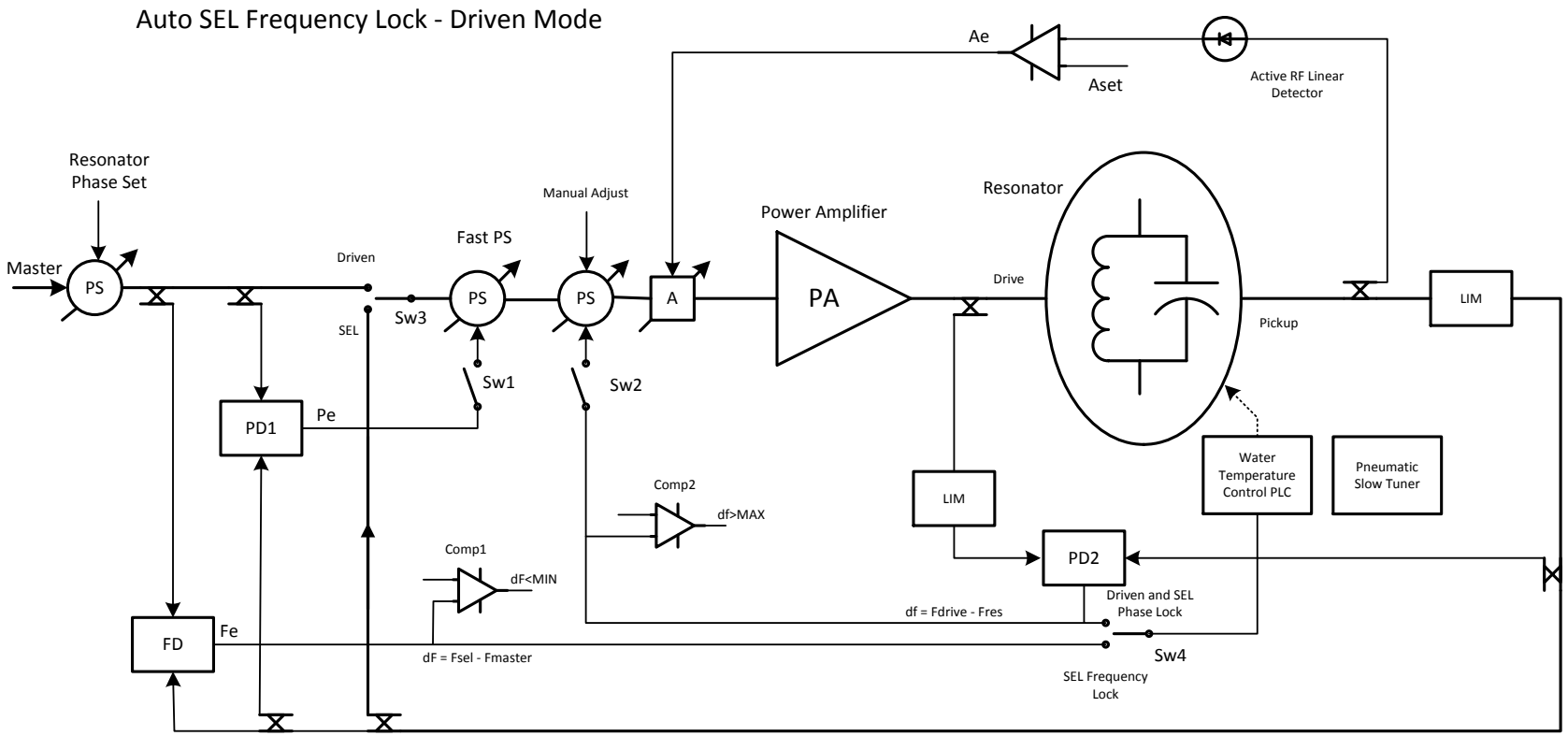


Simplified Block Diagram of 60KW Amplifier

SPEC: 60 KW, 80 dB minimum gain, 60+-1 Mhz nomial

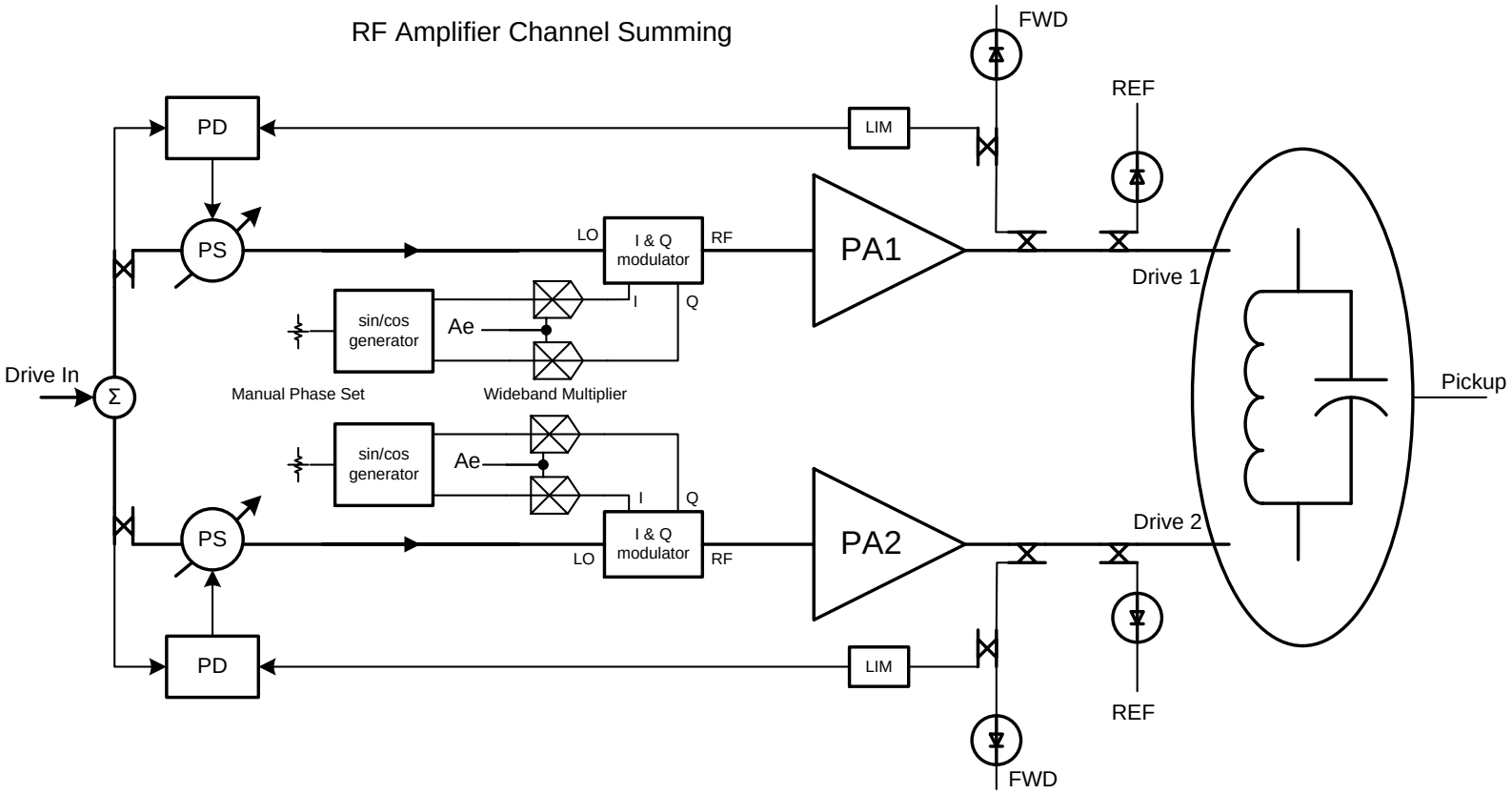


SEL - Driven Mode System



-allows for driven mode, SEL frequency and phase lock mode and Auto
-SEL frequency lock mode for RF power fill-in, driven for acceleration in Auto

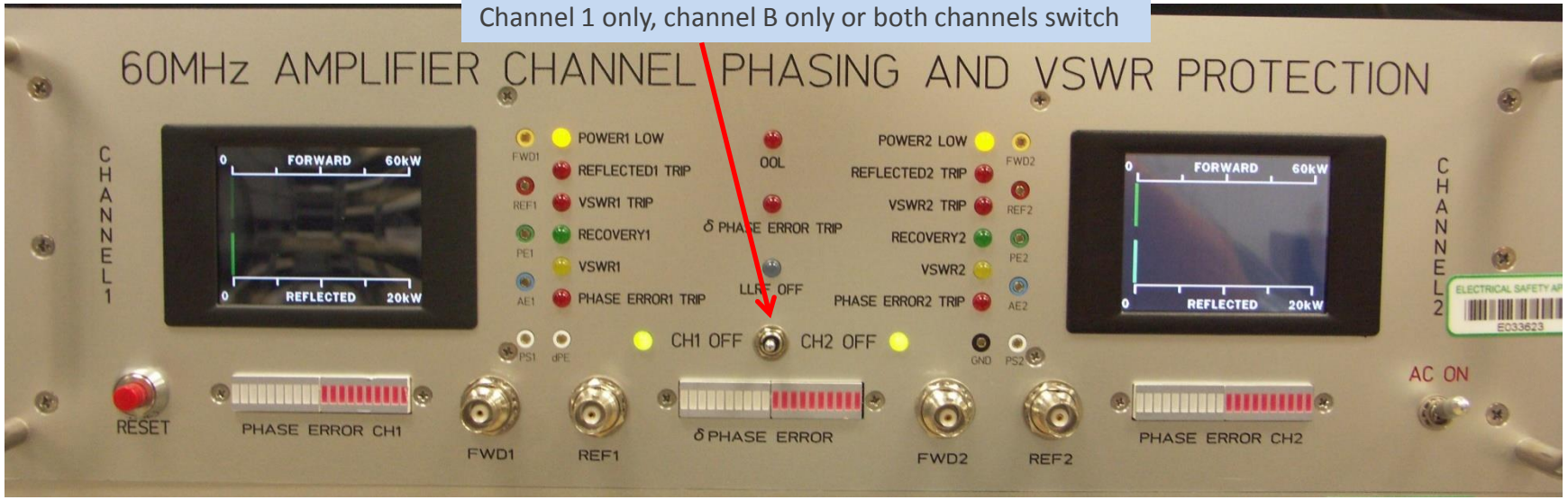
Summing Two RF Amplifiers for ATLAS RFQ



-two individual phase stabilization loops
-I&Q modulator used as 360 degrees phase shifter and fast amplitude regulator

LLRF Control for ATLAS RFQ

Channel 1 only, channel B only or both channels switch



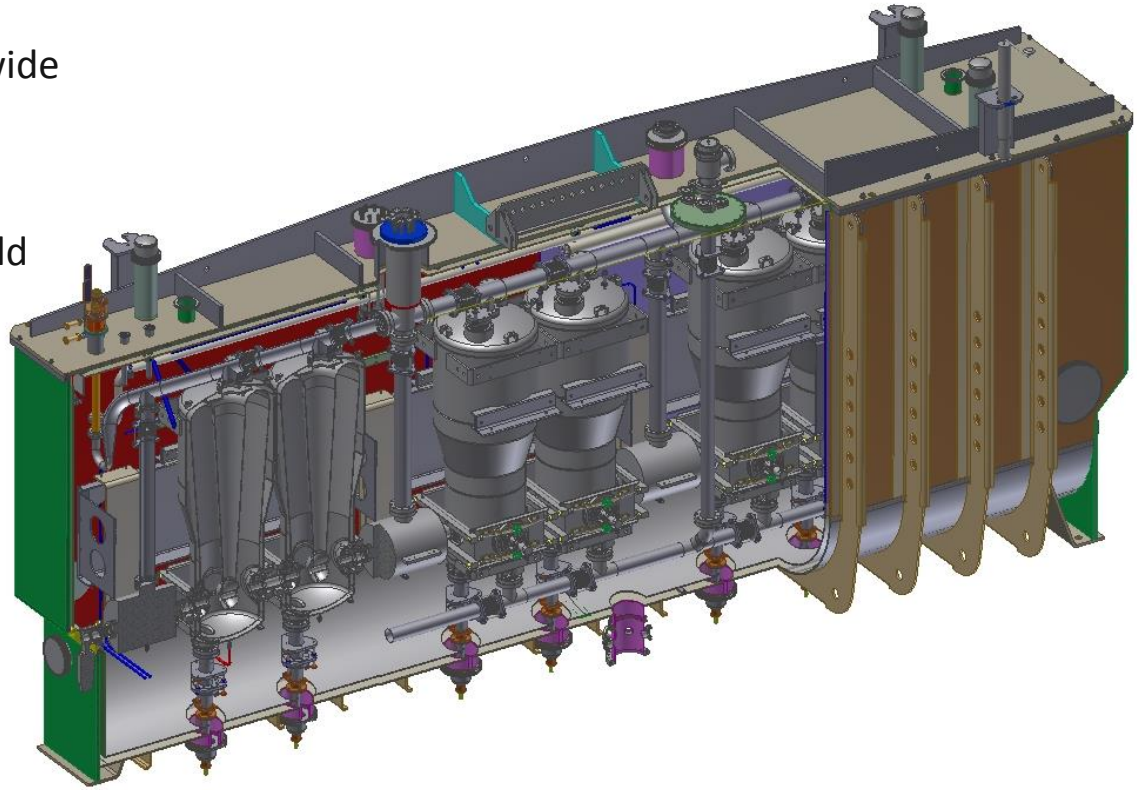
Cryomodule of 7 QWRs and 4 SC Solenoids

- Seven β = 0.077, 72.75 MHz quarter-wave cavities
- Four 9-Tesla superconducting solenoids
- Replaces 3 old cryomodules with split-ring cavities
- Total design voltage is 17.5 MV, 4.5K cryogenic load is 70 W
- Will be operated to provide ~20 MV, 4.5K cryogenic load is 85 W

5.2 m long x 2.9 m high x 1.1 m wide

Vacuum Vessel
Room Temperature Magnetic Shield
Aluminum Heat Shield
(MLI not shown)

Compact design, focusing period
Includes 2 cavities and 1 solenoid



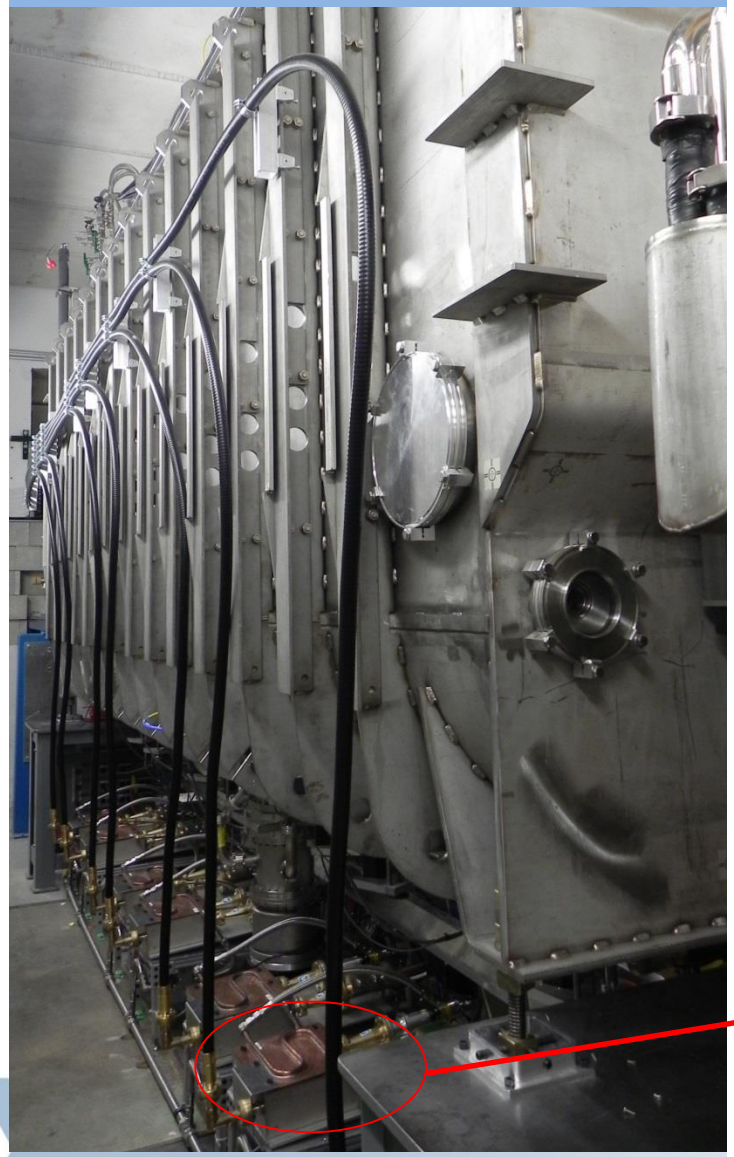
Summary of Performance for New Cryomodules

	New	G-Tank	
	Beta=0.077	**Beta=0.15**	**Comment**
Number of Cavities	7	7	
Number of Solenoids	4	1	
Operating Temperature	4.5 K	4.5 K	
Voltage per Cavity in Cryomodule	>2.5 (4.1) MV	>2.0 (3.0) MV	Cavity limit in parentheses
Performance Limiting System	?	VCX fast tuner	
E_{PEAK} in Cryomodule	40 (70) MV/m	26 (39) MV/m	Cavity limit in parentheses
B_{PEAK} in Cryomodule	57 (100) mT	47 (69) mT	Cavity limit in parentheses
Power to Helium/Cavity	5 W @2.5 MV	8 W @ 2 MV	

Stored Energy @1MV/m of the new Cryomodule: 0.15 J

New 72.75 MHz Booster A SC Cryomodule

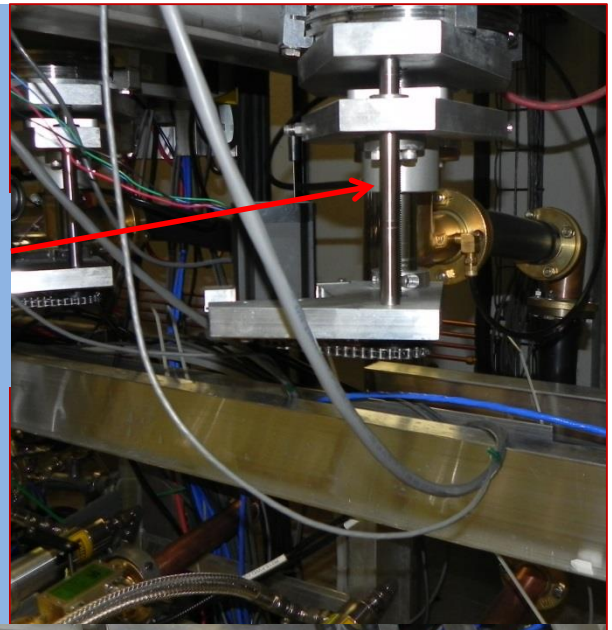
5.2 m long x 2.9 m high x 1.1 m wide

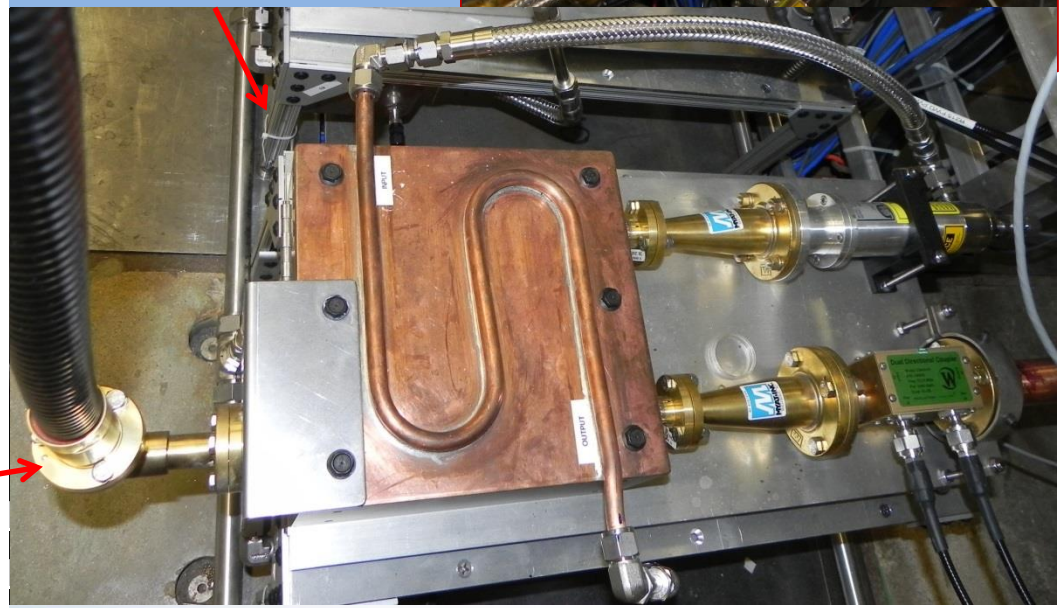


Left:
Cryomodule A

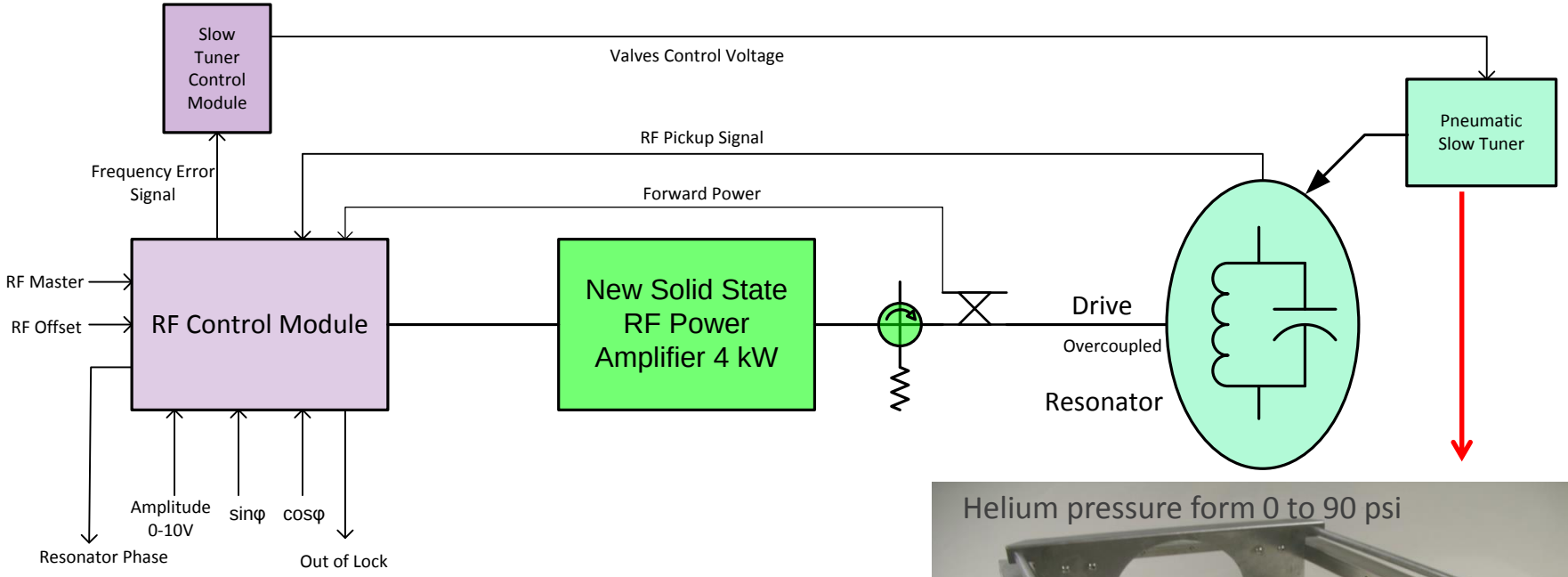
Right Upper: RF Coupling Port

Right Bottom: 5 kW Circulator and Dummy Load with Water Cooling.

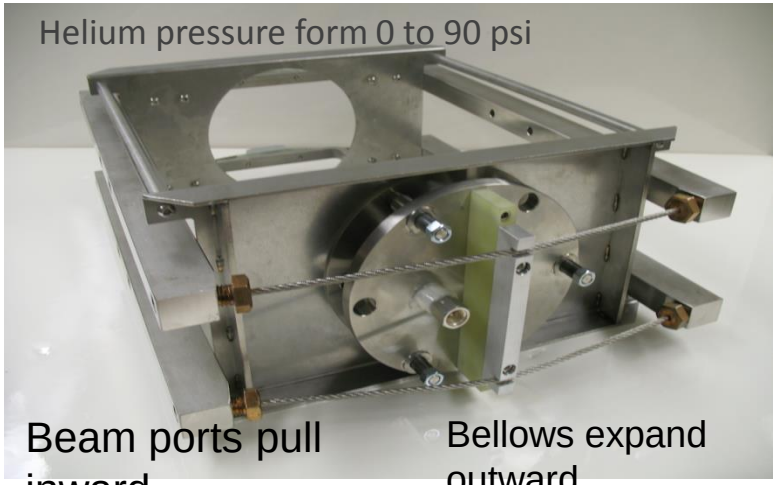




New 72.75 MHz Resonator RF System



Control System

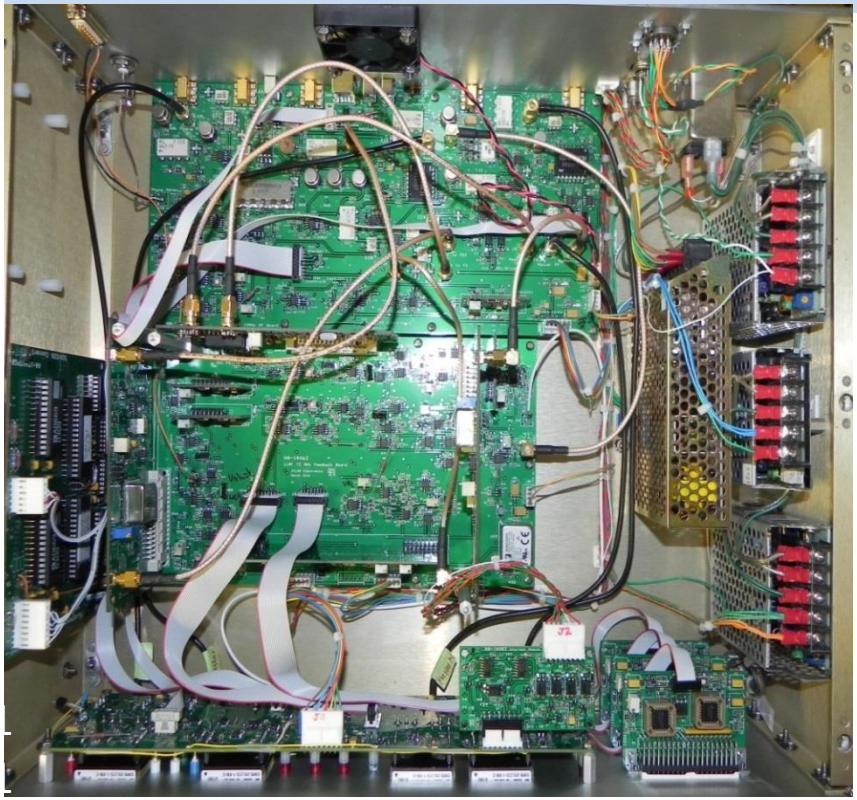


- Over-coupling is a main feature for phase lock
- Transmission through the Cryomodule is almost 100%

Power Supply, Amplifier and LLRF Control Unit

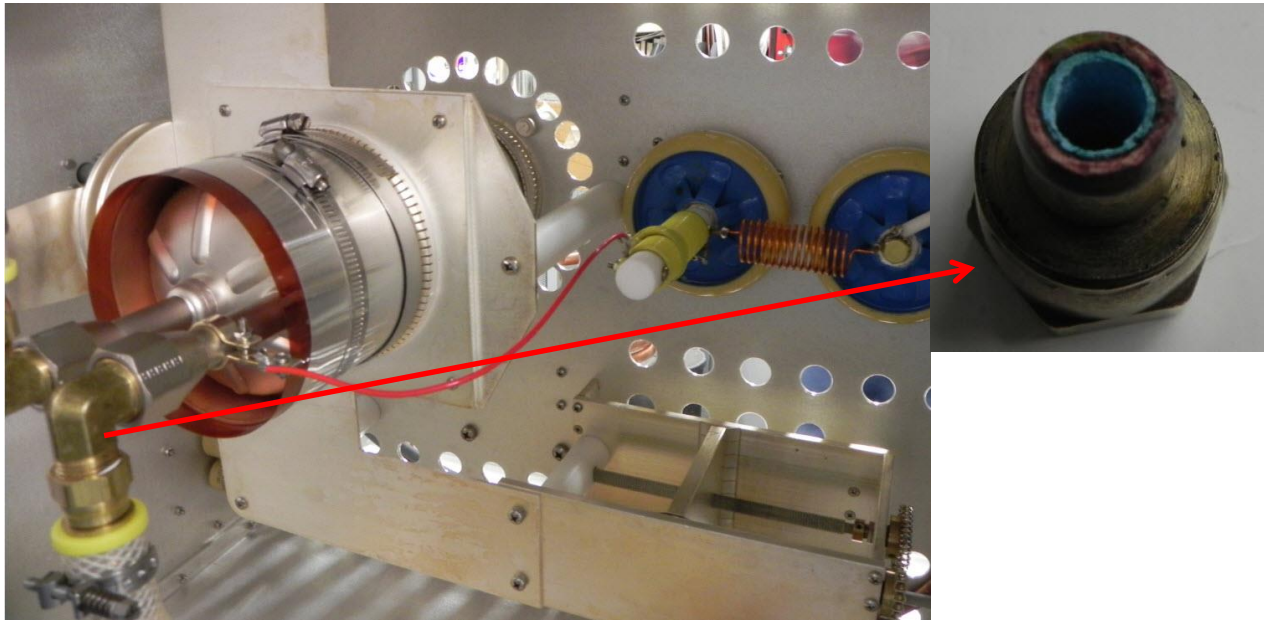
Model: TOMCO BT4K-Alpha
SPEC: 4 KW, 3 Phase AC 208V, 72.75+-1 Mhz nomial. Use LDMOS

- Slow Tuner control is integrated into LLRF controller
- Contains two phase detectors, frequency detector, three phase shifters and two RF limiters
- Provides regulation of resonator phase and amplitude
- **Provides RF power interlock resonator temperature and circulator cooling water for ARIS**



Corrosion of Brass Fittings

Original fittings inside the amplifier were brass fittings. They are vulnerable to DI cooling water and corrosion happened.



* Deionized (DI) Water causes corrosion of Brass fittings

Most likely net chemical reactions:

$Cu + H_2O \rightarrow CuO + 2\ H_{ads}$ (or $Cu_2O + 2\ H_{ads}$)

$2\ H_{ads} \rightarrow H_2$

$H_2 + ½\ O_2 \rightarrow H_2O$

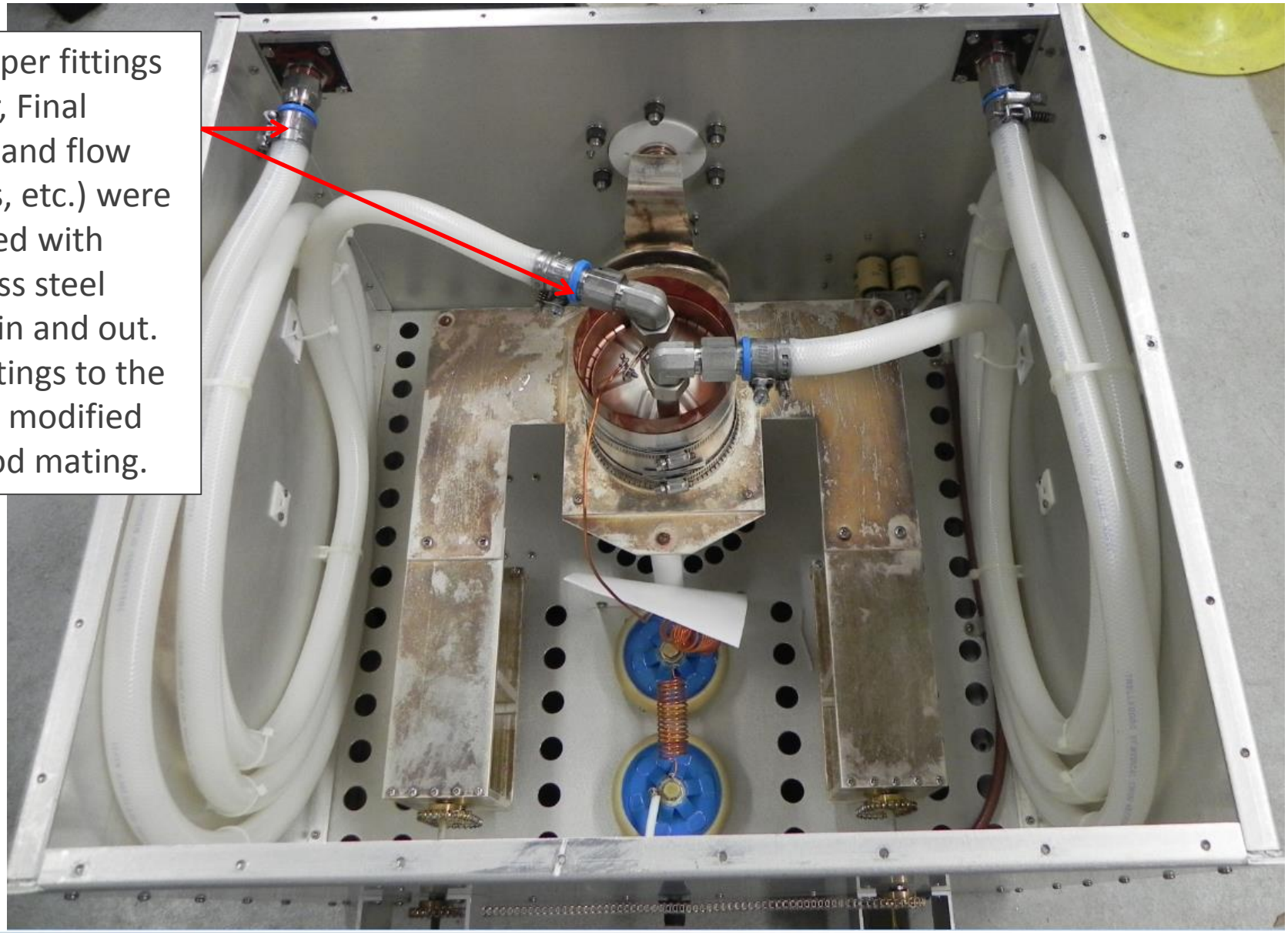
Fix: 1. Replaced all brass fittings with stainless steel fittings

2. Separate the cooling water for RFQ (normal water)and the Amplifier System

Lesson: Use stainless steel fittings at Design stage if using DI water!

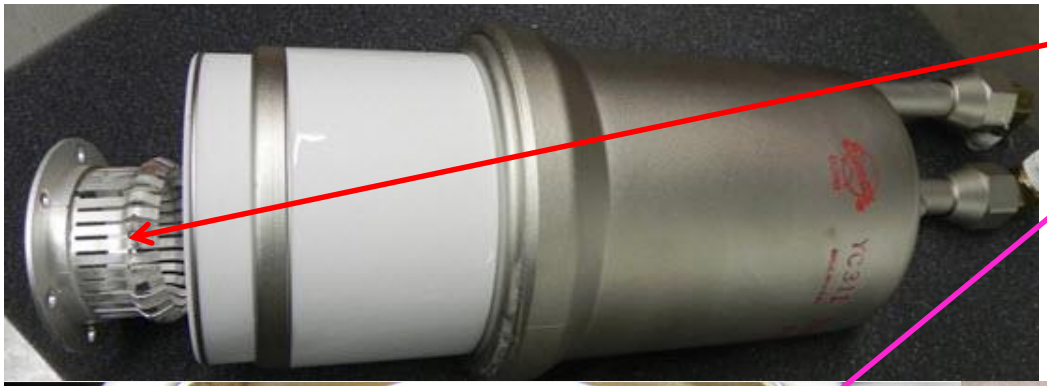
Replacement of Brass Fittings

All copper fittings (Driver, Final stages and flow meters, etc.) were replaced with stainless steel fitting in and out. The fittings to the tube is modified for good mating.

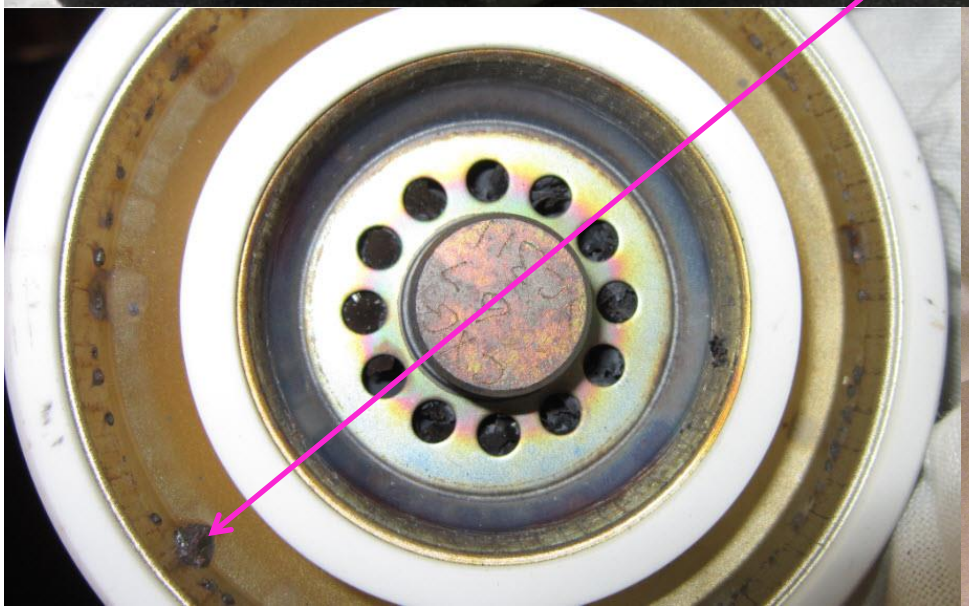


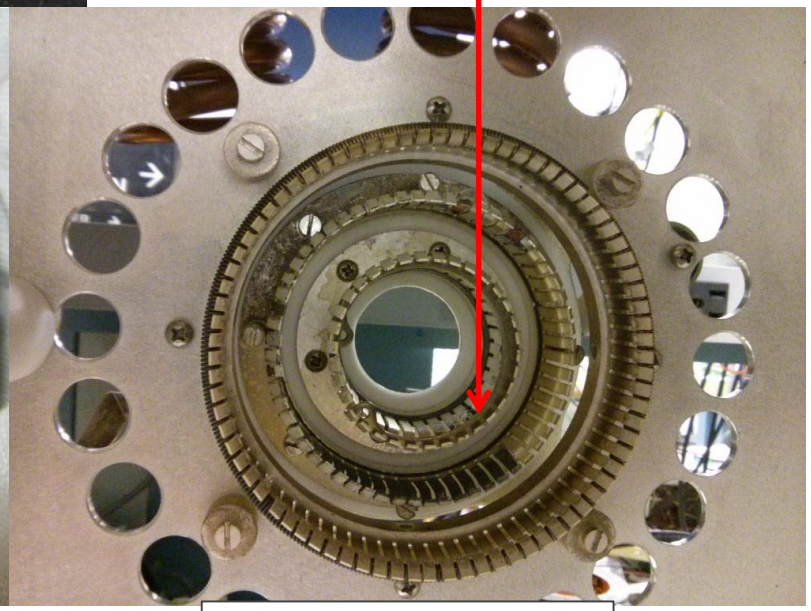
Final Stage Vacuum Tubes Failure

- The big vacuum tube YC-311 failure



- Socket failure
- Tube failure
- Sometimes both

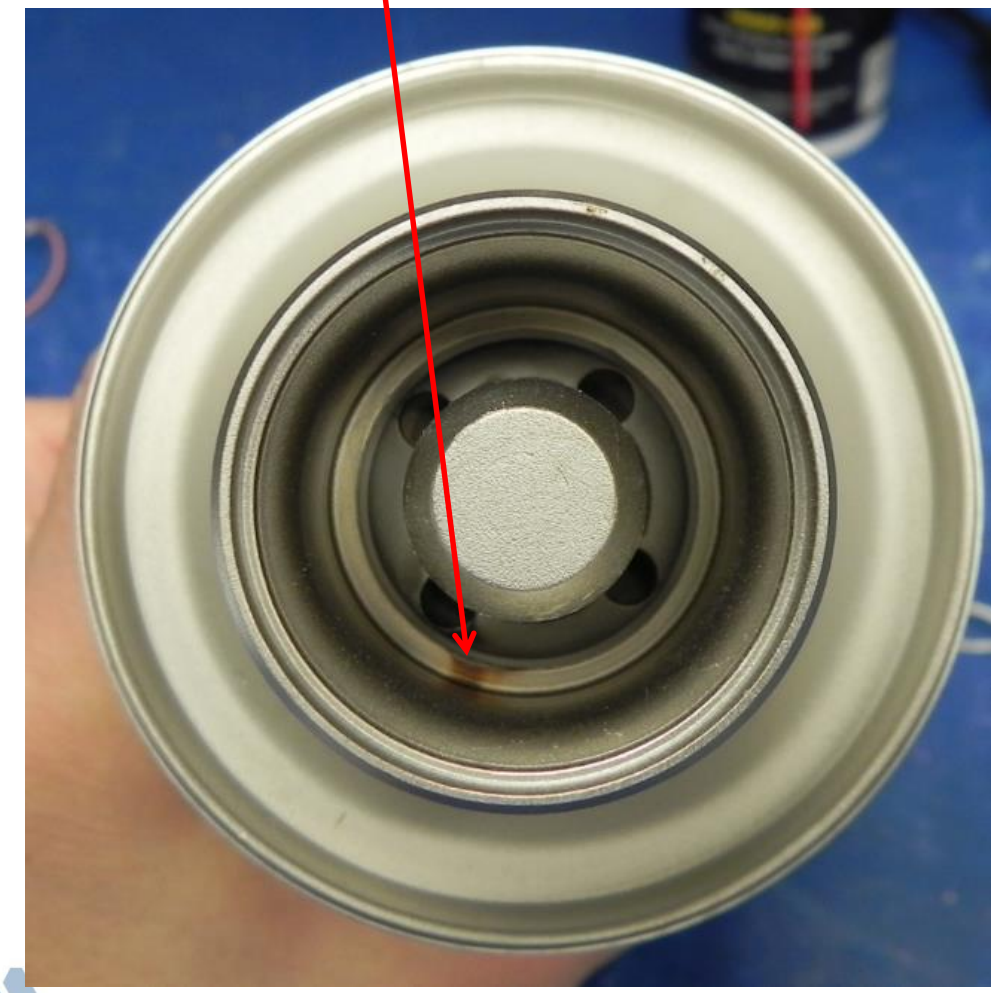




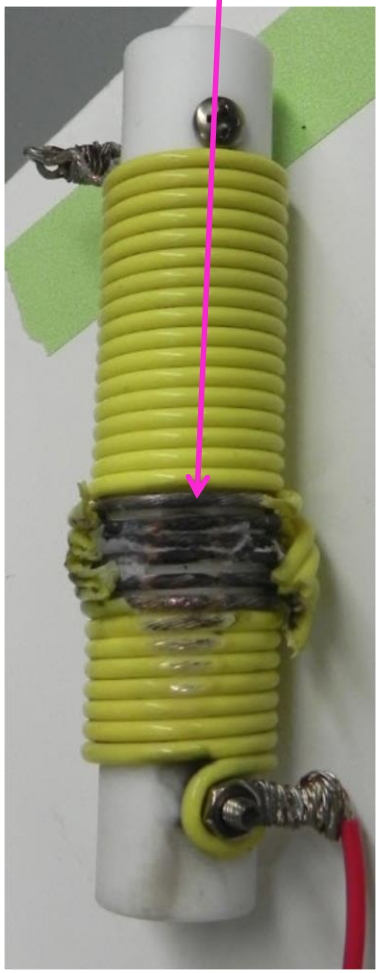
Non-uniform burning marks.

Other Failures (Less Frequently)

- The driver stage vacuum tube YC-275 failure

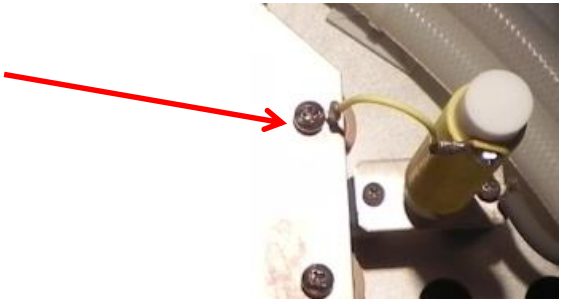


- Broken Inductor due to resonance



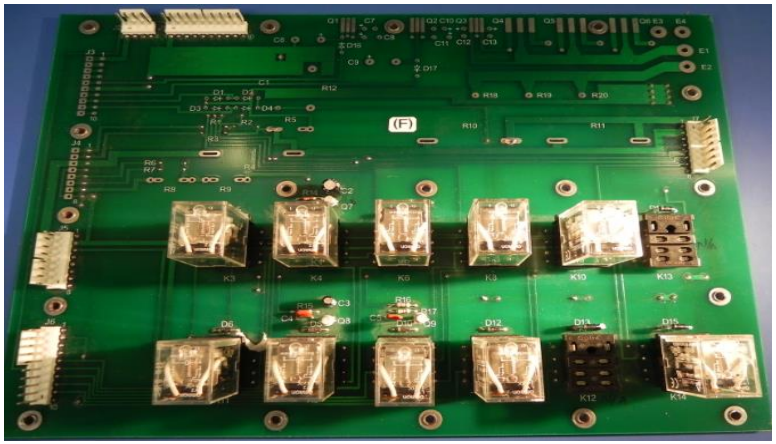
Tube Failure Reduction

- Retaining ring for filament socket
- Replace damaged sockets with new sockets
- **One trick**: You may noticed that the non-uniform discoloration on the sockets. So check the tube position after putting the whole assembly into position. This way to avoid the position shift of the tube. If position is not up right, the contact between the tube and the socket may not be **Good**! Somewhere may conduct higher current than other area.
- Added 50KW **circulator** and interlock circuitry to protect the system and reduce the reflected power to the amplifier. The majority damage of the final stage tube is due to the high reflected power when without circulator presented. Of cause, when using the copper fittings, the corrosion inside the tube degraded the performance of the tube and cooling effects of the water. It make the contribution to the tube failure.
- New inductor with modified value to avoid resonance.
- Better insulator for output capacitors: better isolation
- PID loop parameters optimization
- New powerful fans inside the amplifier for better cooling



Other Improvement 1

- Fuse change and addition (fast blow, lower cost)
- Board via modification (for High I)



- HV rectifier wiring was replaced with HV wires
- Driver tube filament transformer AC connector replacement

50KW Circulator

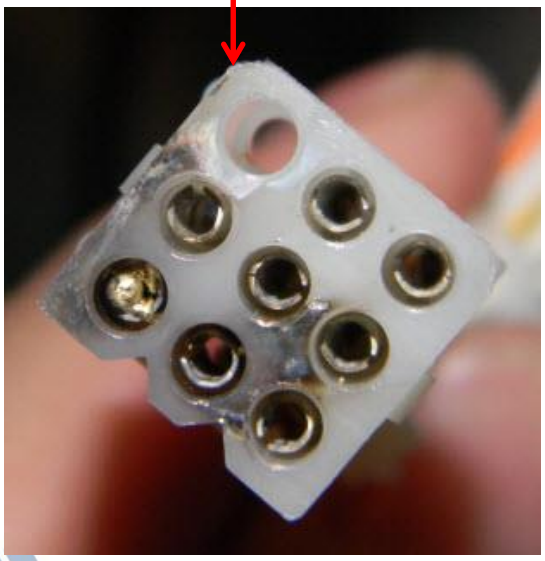
- Circulator
- Dummy load
- Directional coupler
- Flow meter with interlock

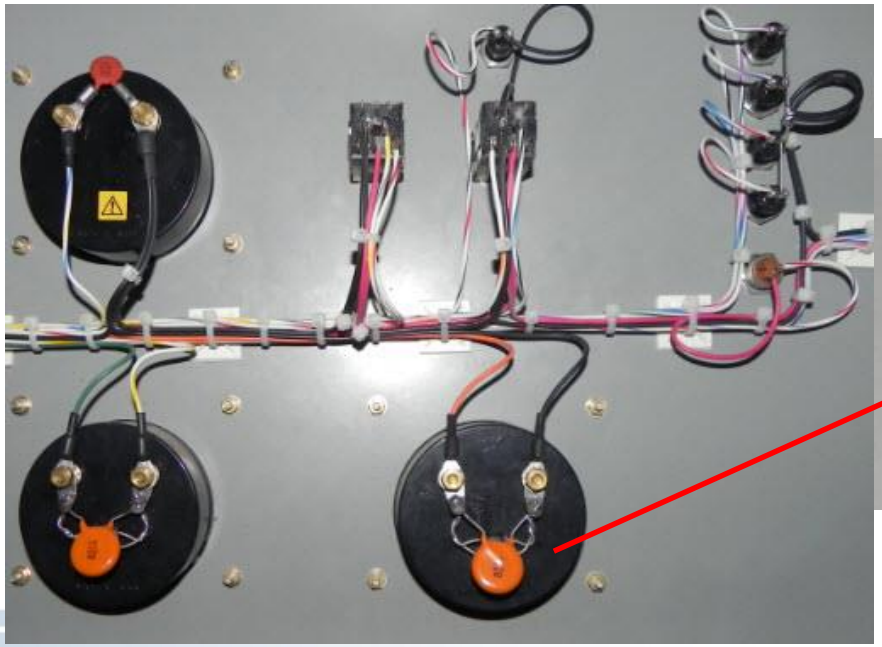
Interlock with reflected power long pulse protection.

Other Improvement 2

- Built amplifier system room to alleviate the effects of environment (moisture, dusk, temperature, etc.)
- Protection for front panel meters: TVS instead of regular diodes
- Inside connectors (ongoing)

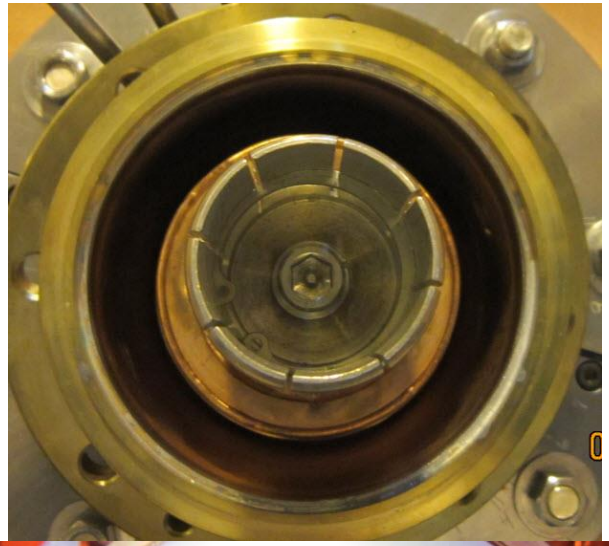
Cooling fan

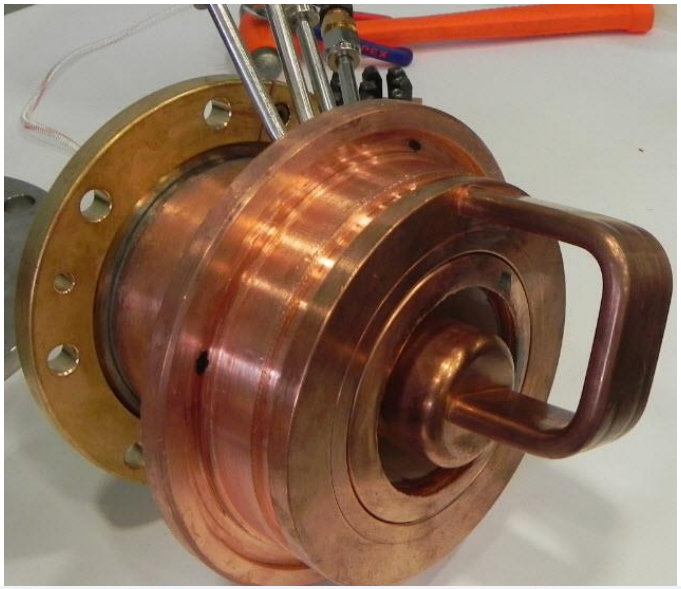


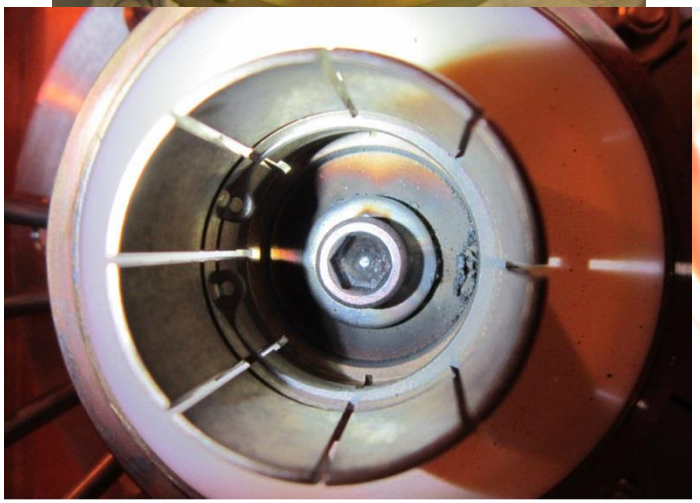


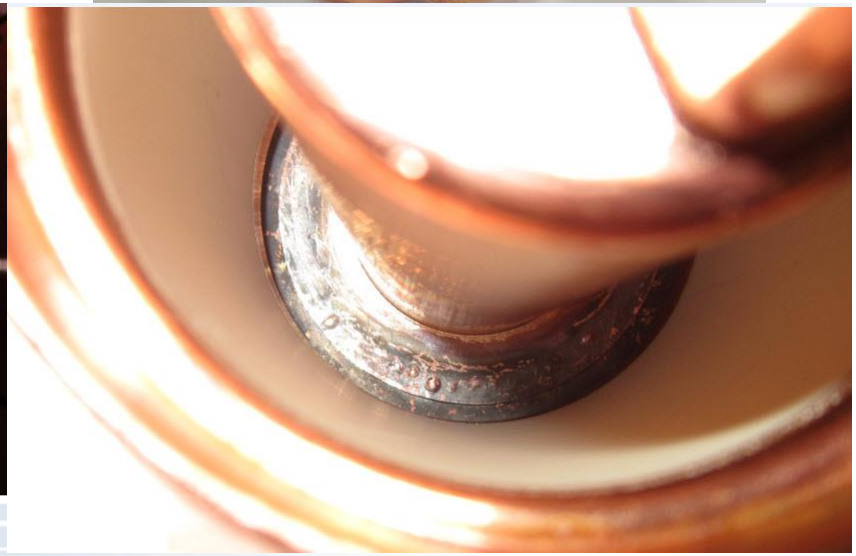
Other Improvement 3

- RF power coupling port should be checked and/or replaced if high reflected power is constantly observed.





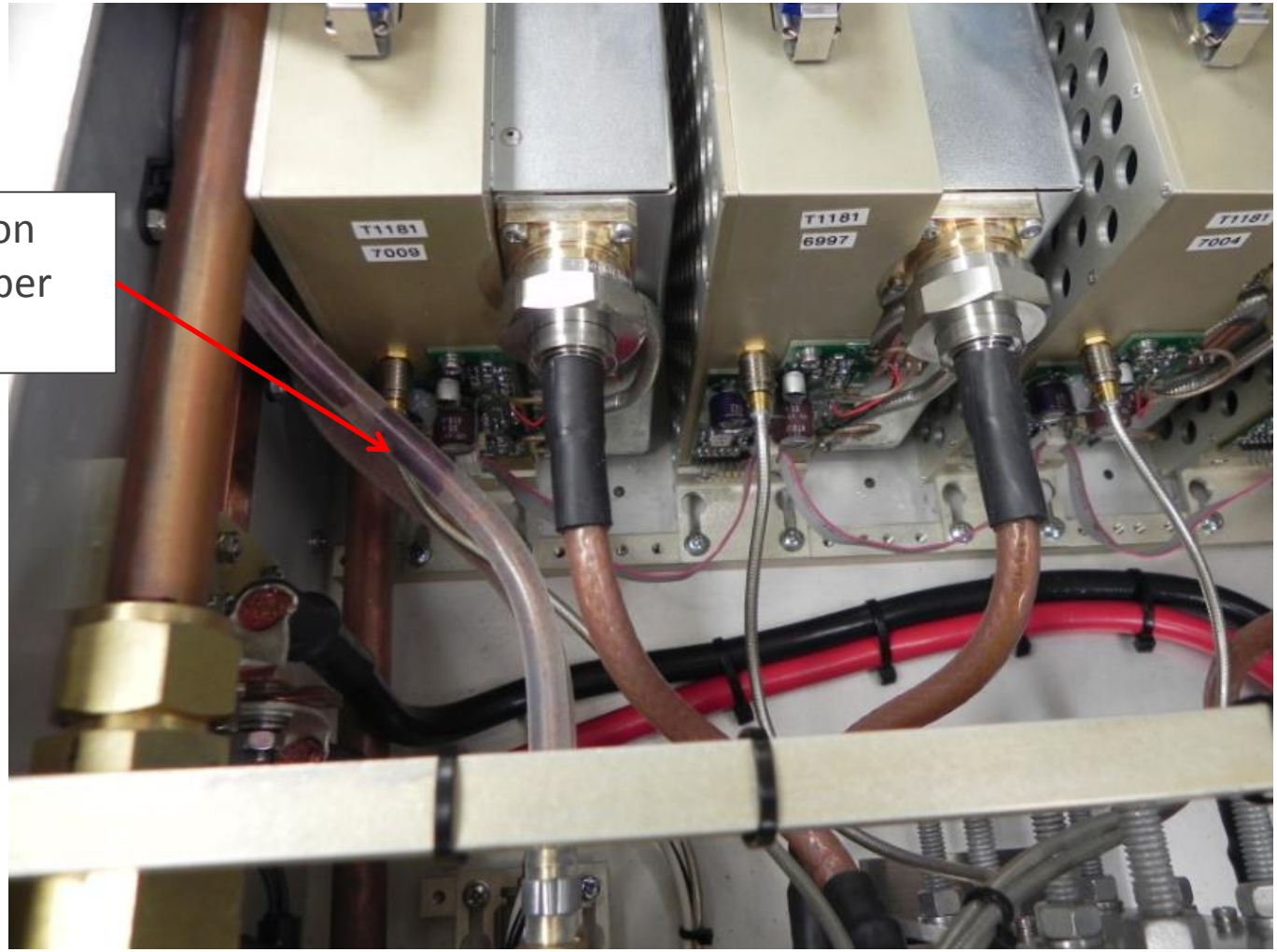




72MHz 4KW Solid State Amplifier

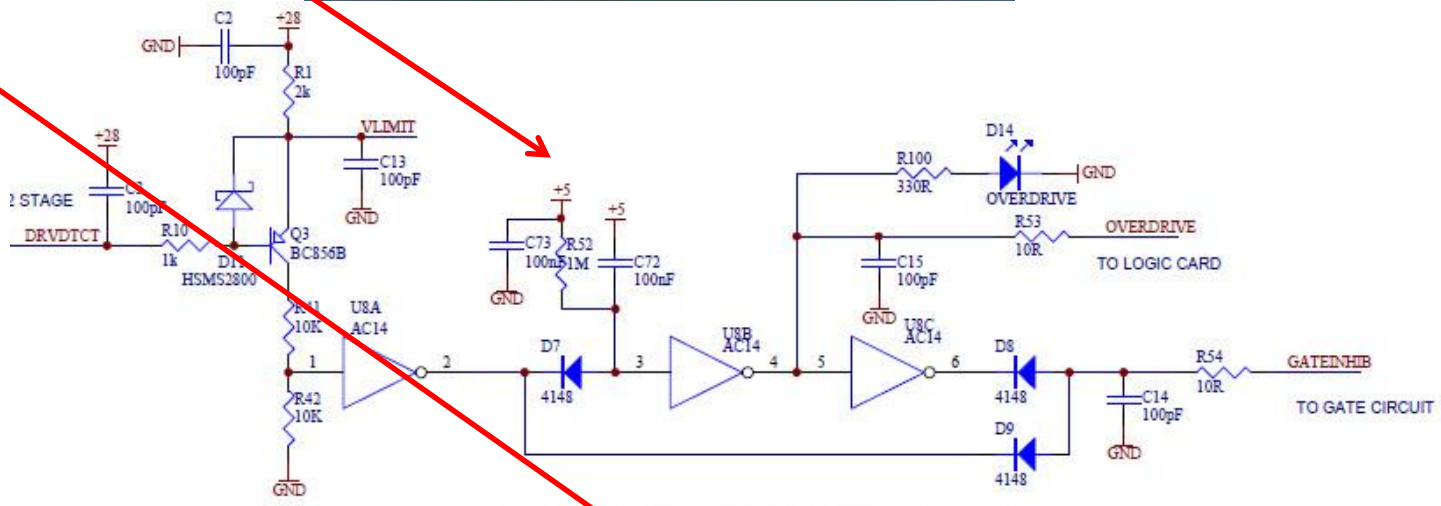
- **Brass Fitting Corrosion** due to DI water. Changed the cooling water to normal water later.

Discoloration due to copper corrosion.



72MHz 4KW Solid State Amplifier

- RF Detector Failure (One Amp.): Used new detector
- (not Failure) Sensitive overdrive protection threshold (One Amp.): Adjusted the threshold
- 5V auxiliary power supply diode failure (one Amp.): Used external power supply
- One Module: LED failure.



Summary

- Numerous Amplifier Failure Modes have been observed and studied
- Solid State Amplifiers show satisfied high reliability
- Improvement has been made over the time and much better reliability has been achieved

Future Plan:

- RFQ Amplifier System: Add Circulator/Dummy load between Driver and Final Stages
- RFQ Amplifier System: Pulse Study and Better Protection
- RFQ Amplifier System: Better interconnect wires and connectors for higher current
- Solid State Amplifier: change the diode in Auxiliary Power Supply Circuitry
- Others

End

Backup Slides

New ATLAS accelerator configuration