56 MHz SRF cavity

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Acknowledgement

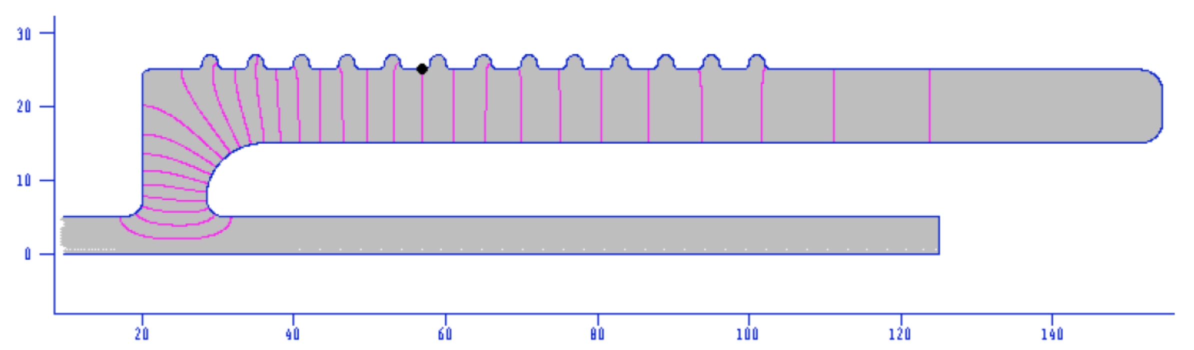
In this talk I present work of a large number of people from different groups across the department.

Just listing everybody involved would take several slides.

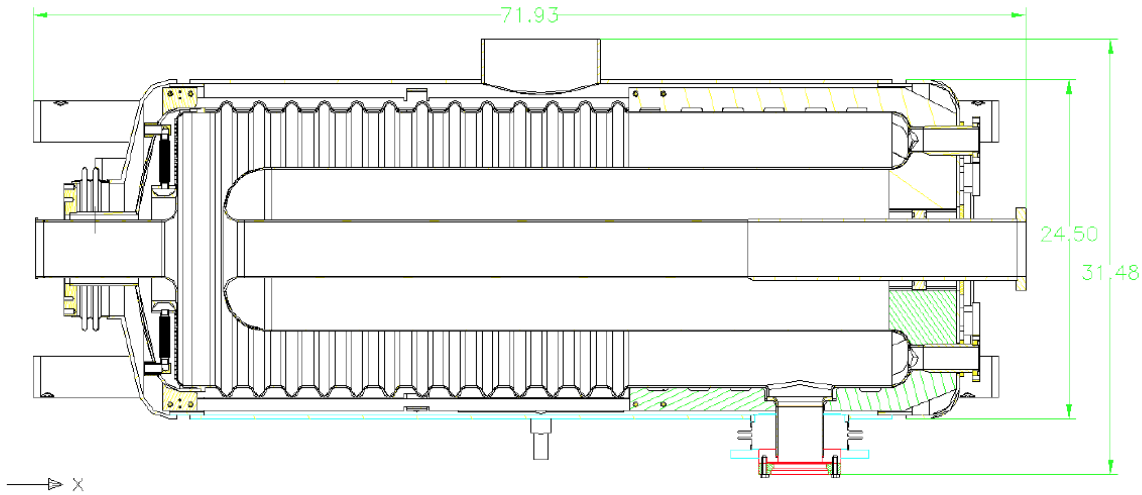
So this slide is an acknowledgement of everybody's contributions and efforts to make this complex and sophisticated project successful.

Outline

- 56 MHz design
  - Cavity & cryomodule
  - HOM couplers
  - Fundamental mode damper
  - Quench detection with IR sensors
  - Frequency tuner
  - Cavity fabrication, processing & testing
- Installation in RHIC tunnel
  - Milestones
  - Cryogenics
  - RF system
  - MPS
- Summary



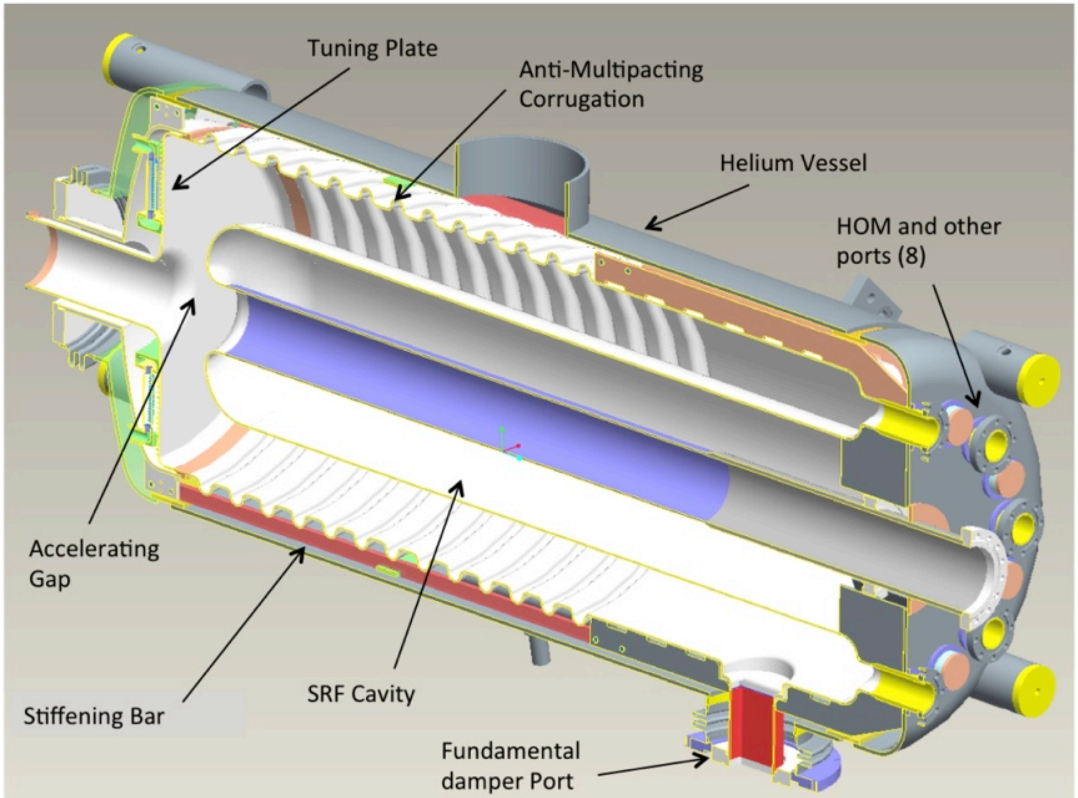
56 MHz cavity

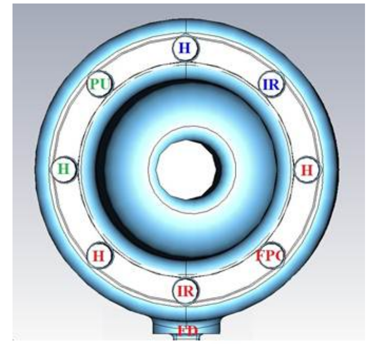


- The purpose of this Quarter Wave Resonator (QWR) is to provide a larger RF bucket (5 times larger than that of 197 MHz cavities) for ions, which should result in higher luminosity of RHIC by: direct adiabatic capture from 28 MHz system, better preservation of longitudinal emittance, elimination beam spillage in satellite buckets, improving luminosity by allowing shorter beta function at the IP.
- This is a "storage" cavity, that is it does not have large tuning range to follow the large frequency change during acceleration from injection energy to energy of experiment and is turned on only after that for re-bucketing.
- One 56 MHz cavity will serve both RHIC rings. It will be the first superconducting RF system in RHIC.

V_{acc}	2.0 MV
Stored energy	140 J
R/Q	80.5 Ohm
Geometry factor	33.5 Ohm
Operating temperature	4.4 K
Q_0 at low fields (assuming R_{res} = 10 nOhm)	3.0×10^9
Q_0 at 2 MV	2.4×10^9
P_{cav} at 2 MV	20.7 W
Q_L	4×10^7
Available RF power	1 kW
Coarse tuning range	25.5 kHz
Coarse tuning speed	3.7 kHz/s
Tuning sensitivity (stepper motor)	17 kHz/mm
Fine tuning range	60 Hz
Tuning sensitivity (piezo)	0.06 Hz/V
LF detuning at 2 MV	-132 Hz
Frequency sensitivity to He bath pressure	0.282 Hz/mbar
Peak detuning due to microphonic noise	1 Hz

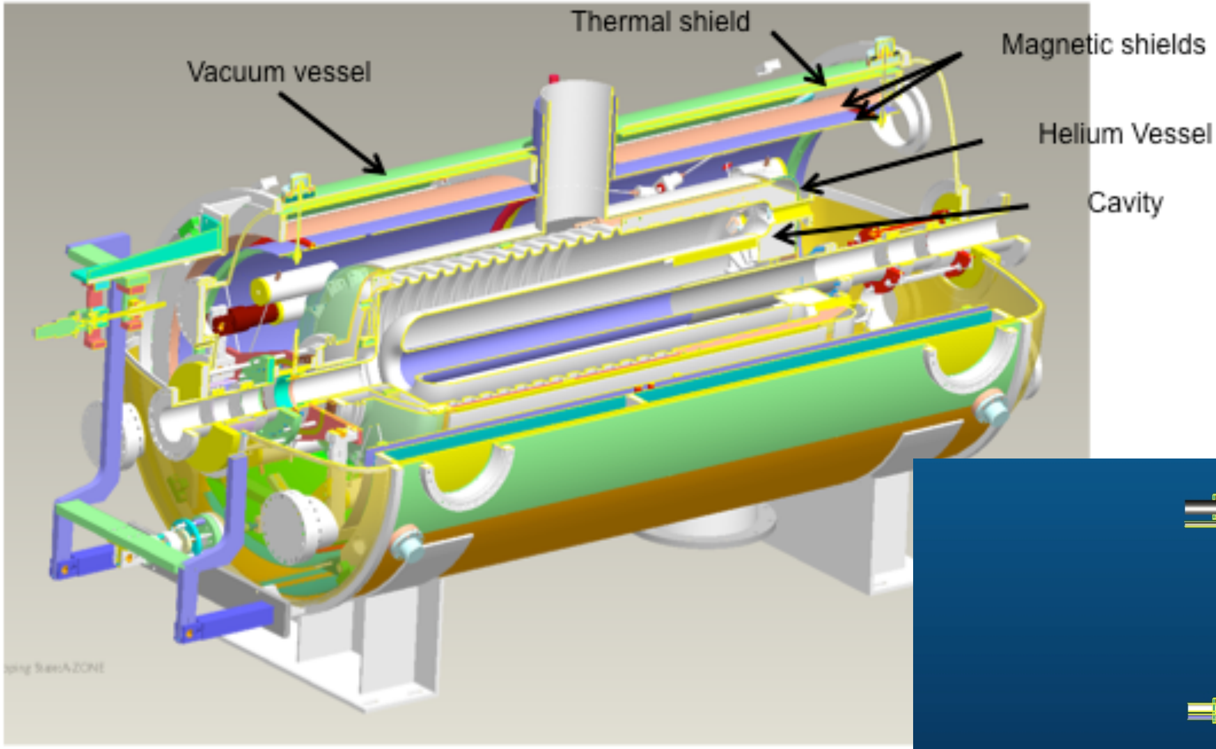
Cavity design

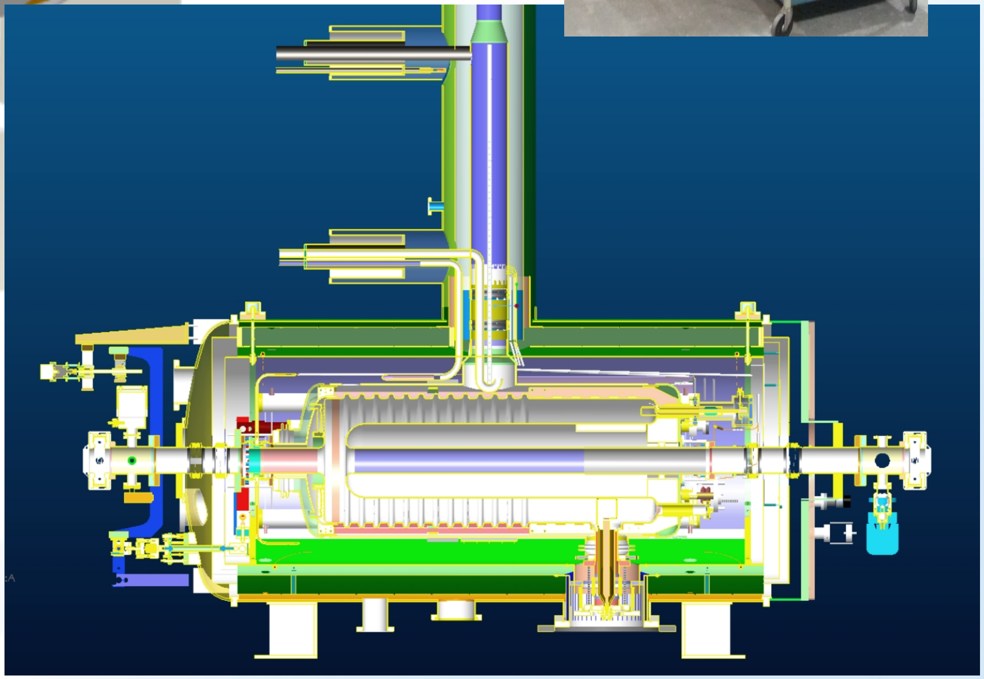


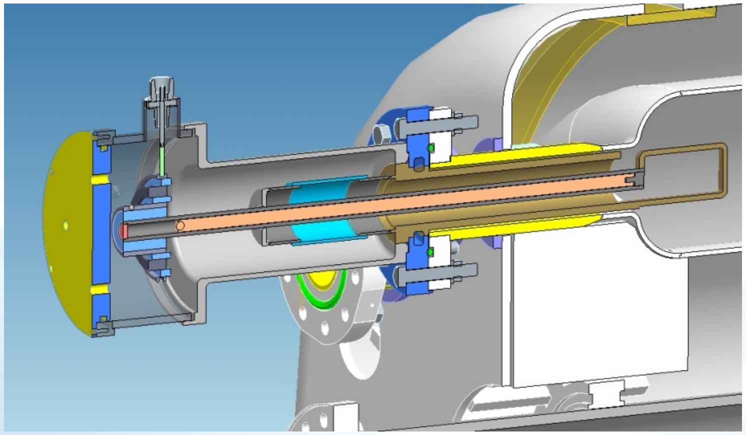


- The cavity is mechanically rigid: its first mechanical mode frequency is 98.5 Hz.
- The cavity is designed to be multipacting-free.
- High degree of higher order mode (HOM) damping is provided by four dampers asymmetrically placed at the "short" end of the cavity.
- Fundamental mode Damper (FD) reduces the cavity fundamental mode *Q* to ~300 during beam injection and acceleration.
- The cavity shape was optimized so that at 2.0 MV we get E_{pk} = 35.3 MV/m, B_{pk} = 83.9 mT, power dissipation ~20 W.
- These numbers are below what was already achieved at other labs in cavities with similar geometries.
- The cavity is tuned to 720th harmonic of the RHIC revolution frequency.
- It is a beam driven cavity. However, there will be a 1 kW RF amplifier. The amplifier will serve to: achieve required amplitude and phase stability and provide conditioning capability.
- At the energy of experiment, first the fundamental damper will be withdrawn and then the cavity frequency will be tuned (approaching from below the beam harmonic) to achieve the operating voltage of 2.0 MV.
- A piezo tuner will be employed to compensate any fast frequency changes.

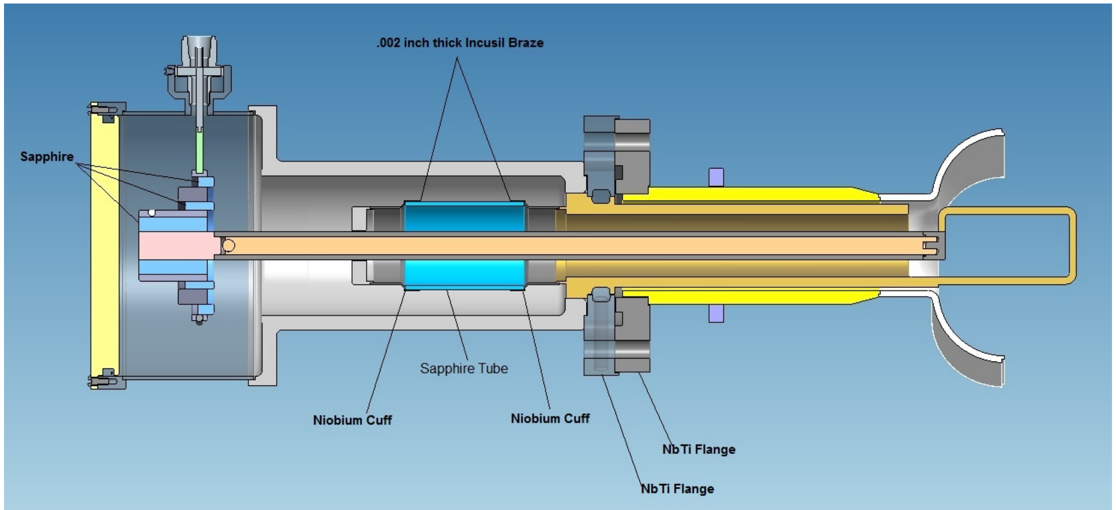
Cryomodule design

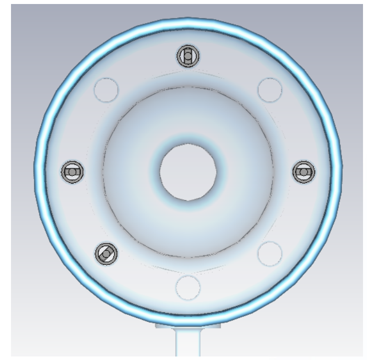




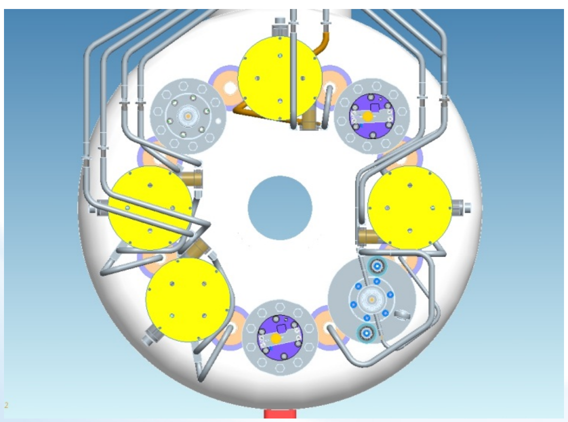


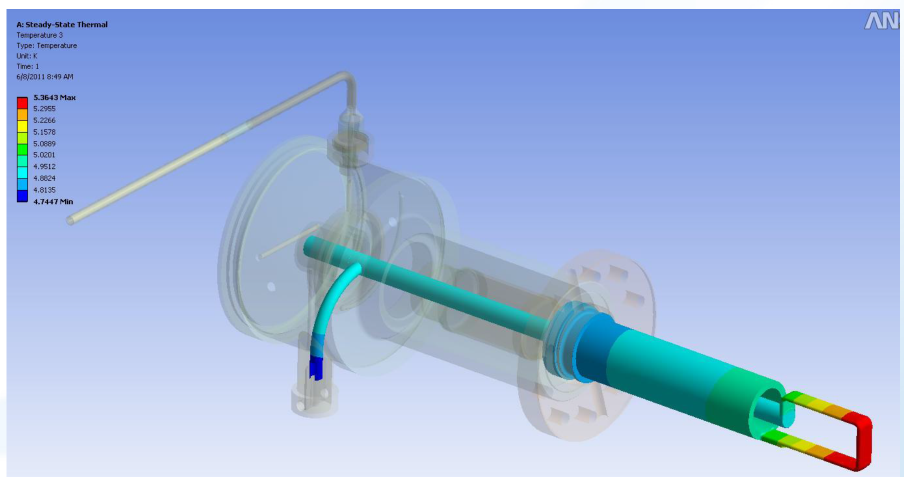
HOM coupler = coupling loop + filter



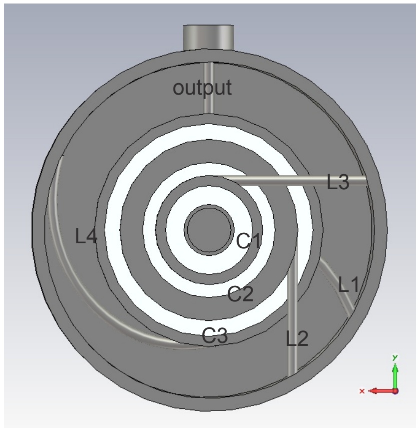


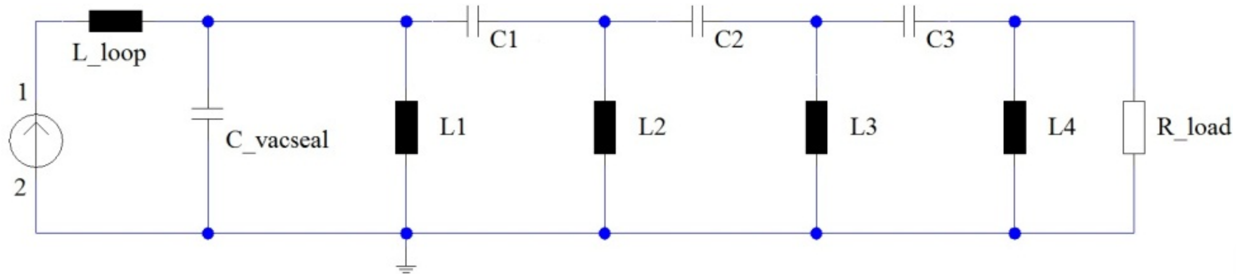
- Optimization of damping for all HOM modes up to 1 GHz, resulted in 4 HOM couplers.
- The couplers are inserted in an asymmetric configuration, which ensures that all modes are damped adequately.
- The NbTi flange will be cooled with helium.
- A high RRR copper rod inside the center conductor improves cooling of the loop. It is LHe-cooled.



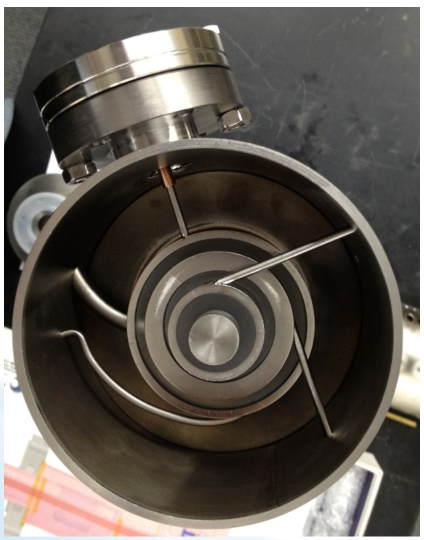


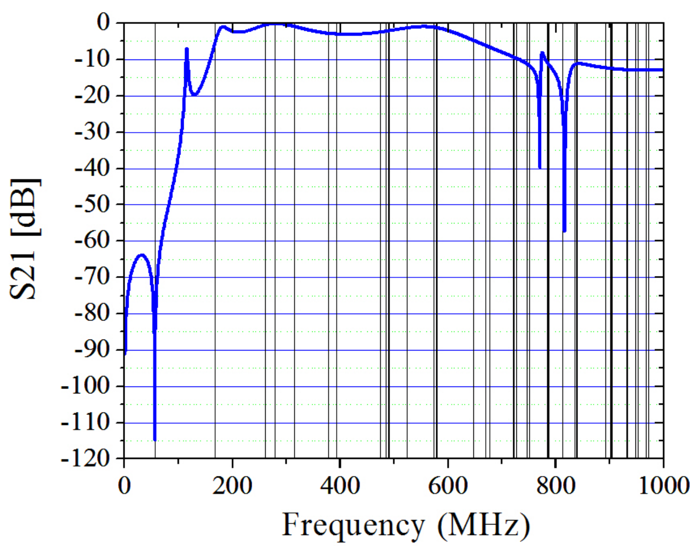
HOM filter

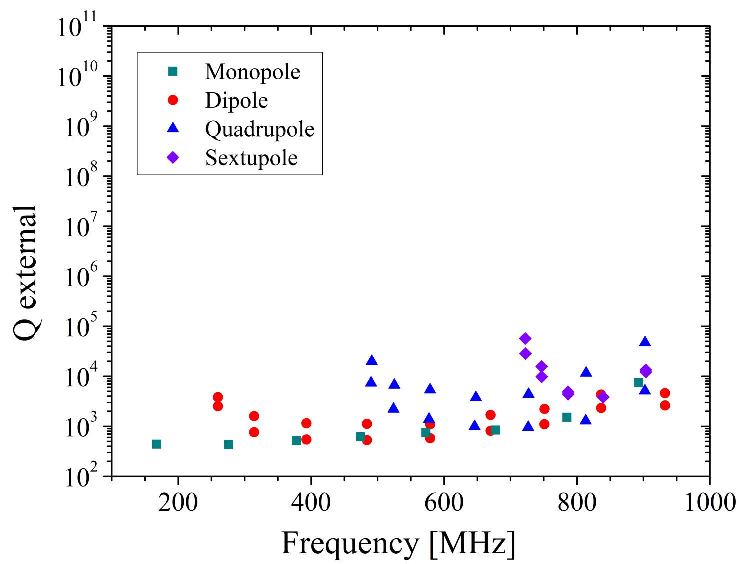




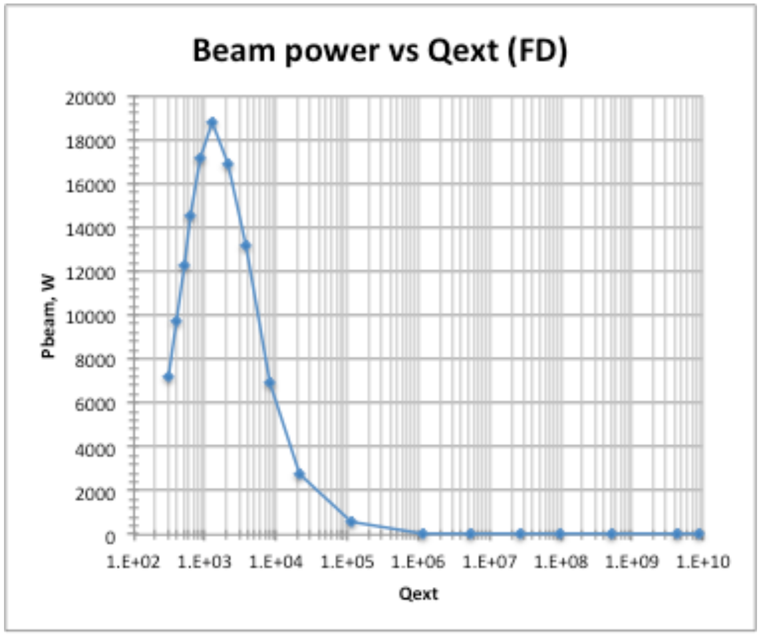
- A Chebyshev-type filter provides -110 dB attenuation at 56.3 MHz, which limits the output power of the fundamental mode to less than 1 mW.
- The total power of the HOM modes excited by the beam in the 56 MHz SRF cavity is ~1.1 W during operation, both rings are included. With the filter installed, the HOM total power output is ~0.33 W/damper.
- Prototype coupler is being fabricated at JLab, production units are on order from Niowave.

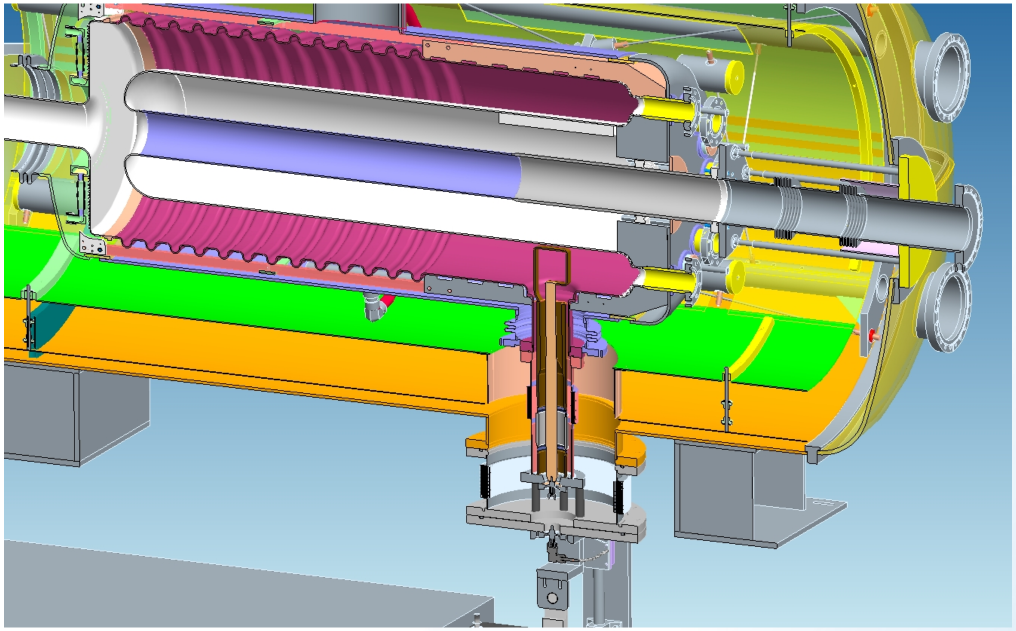






Fundamental mode Damper

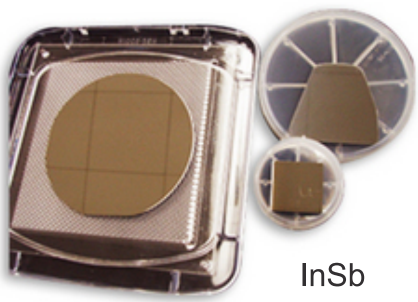




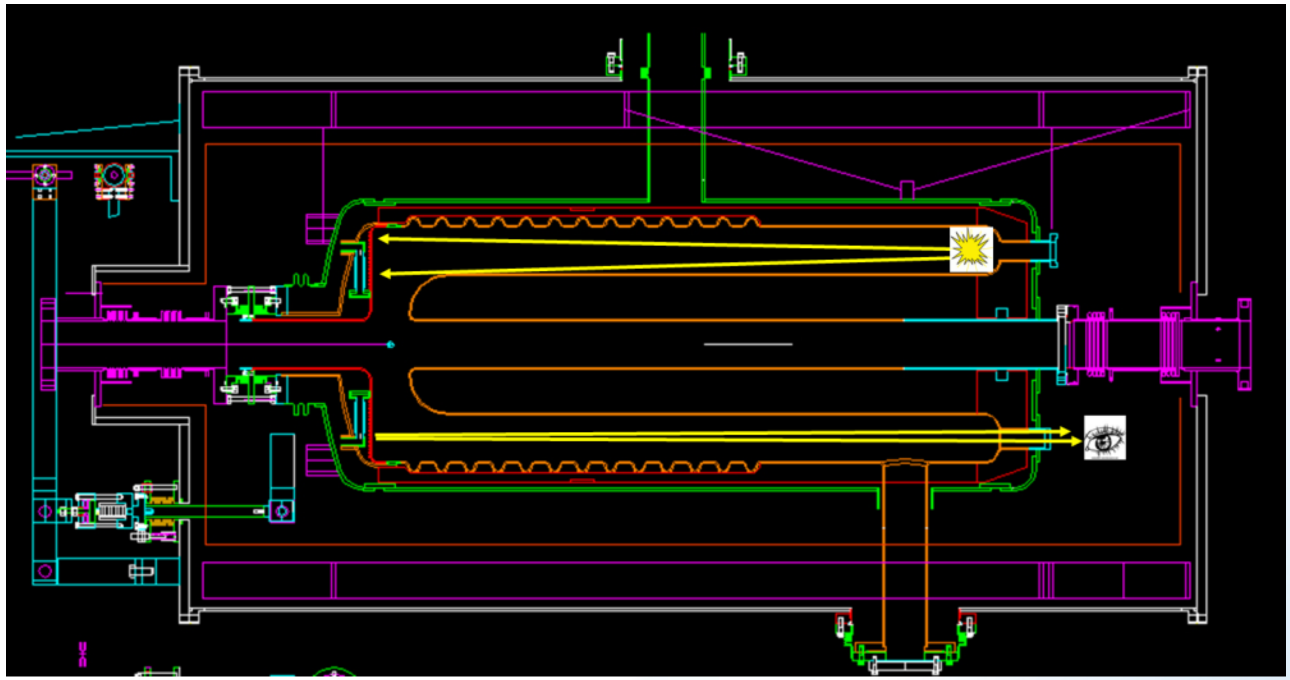
- FD is a unique component of the 56 MHz cavity. It will be inserted during the acceleration and retracted at store.
- Heavy damping (Q_{load} = 300) makes the cavity "invisible" (= low impedance) to the beam during acceleration, therefore no large frequency tuning range is needed. It is moved between two positions by a stepper motors outside of the cryostat.
- At a total beam current of 0.6 A, RF power extracted via FD is ~7 kW in fully inserted position. During motion the power will peak at about 19 kW and then quickly decrease to a very low value.
- FD, fundamental power coupler and RF pick-up probe are fabricated by MPF.

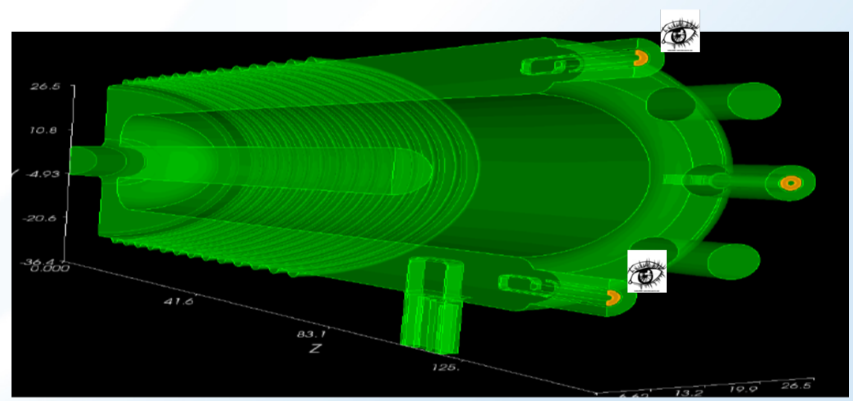
IR sensors for quench detection

MCT
(HgCdTe)



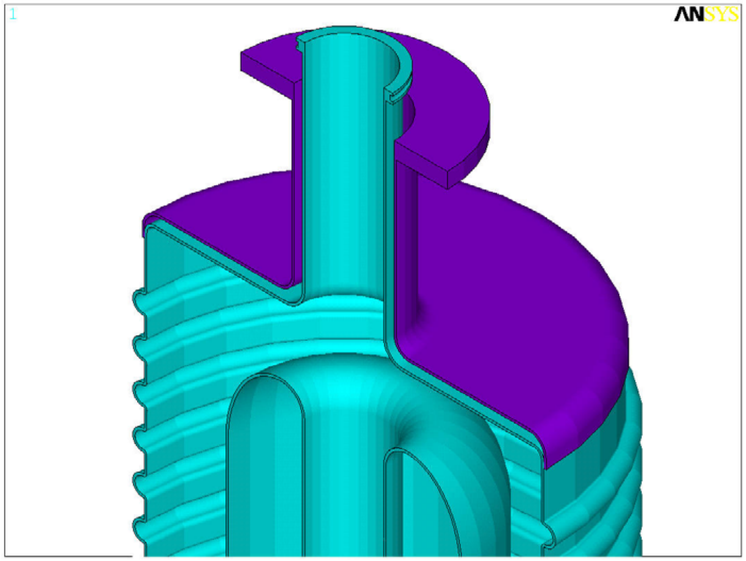
InSb

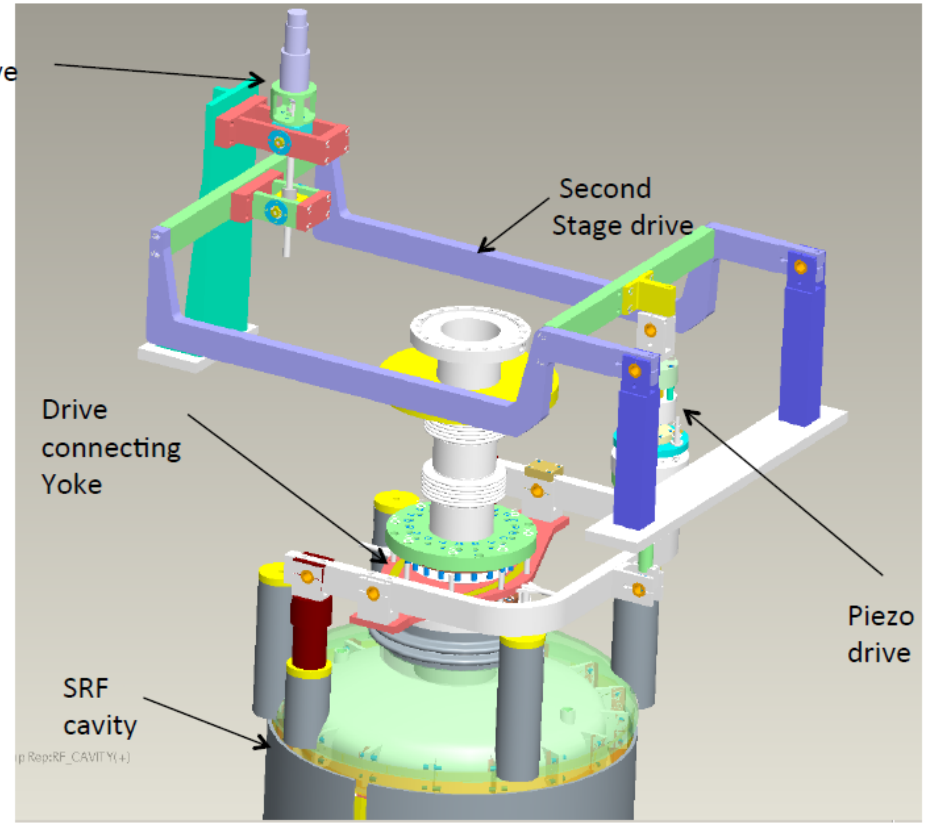




- Purpose: detect thermal radiation from a quench event on the HOM dampers.
- Sensors look into the cavity from end ports and detect IR radiation reflected from the hotspot
  - Nb highly reflective at IR wavelengths
- Two units on 2 end ports. Each unit includes, mounted on a ZnSe window:
  - a detector, HgCdTe or InSb
  - a pulsable thermal source for testing: test one by flashing the source on the other

Frequency tuner



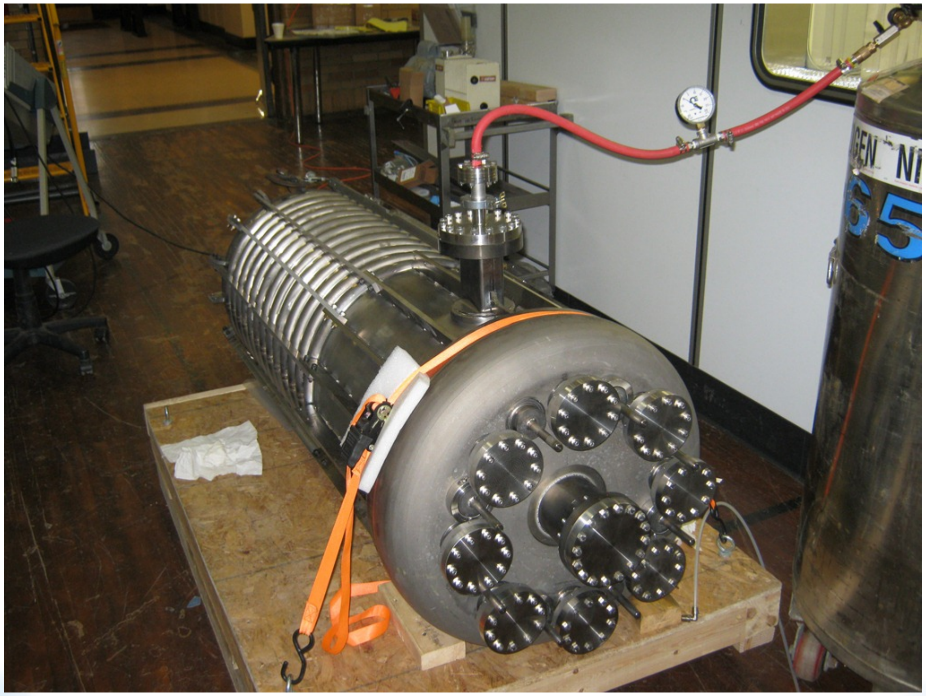


- Mechanical tuning of the RF cavity resonance frequency will be achieved by physically pushing or pulling the upper part of the SRF cavity (tuning plate) to change the gap.
- A tuning mechanism mounted on the helium vessel will provide both fast and slow tuning for the SRF cavity to change its fundamental resonance frequency.
- The tuner plate is an internal structure of the RF cavity vessel. A crown head is welded over the tuner plate to take helium pressure. The tuner plate is free from helium and vacuum pressure.
- Total leverage ratio is 24.88.

Cavity fabrication

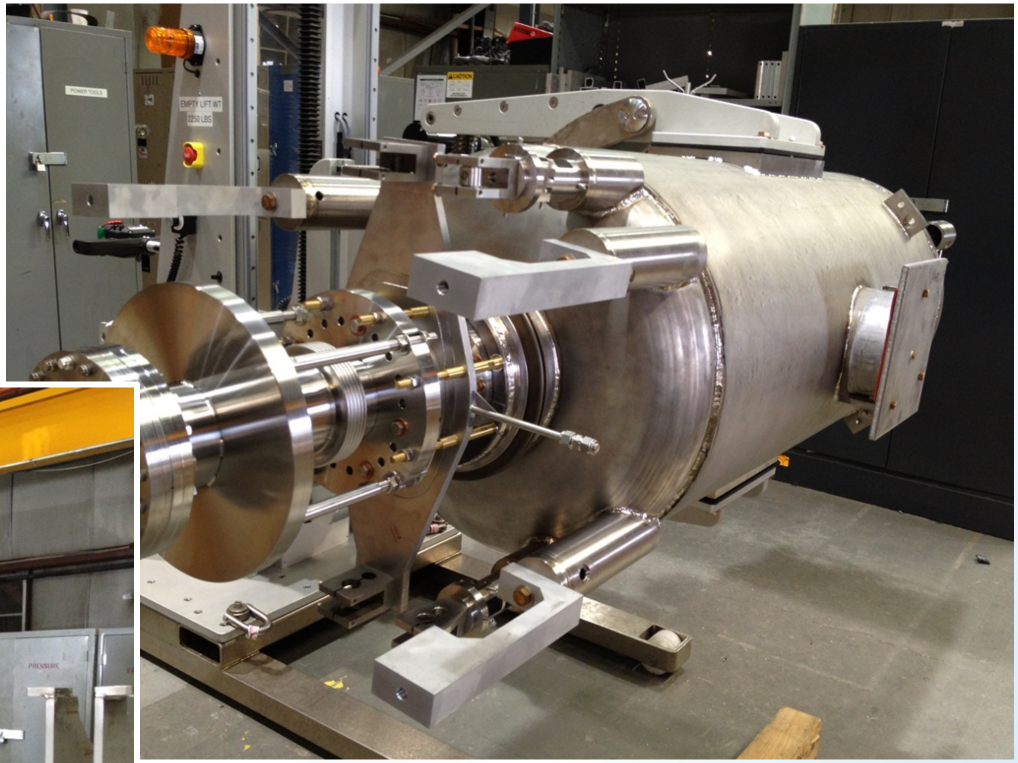
Cavity and helium vessel were fabricated at Niowave.

Cavity pressure test at Niowave



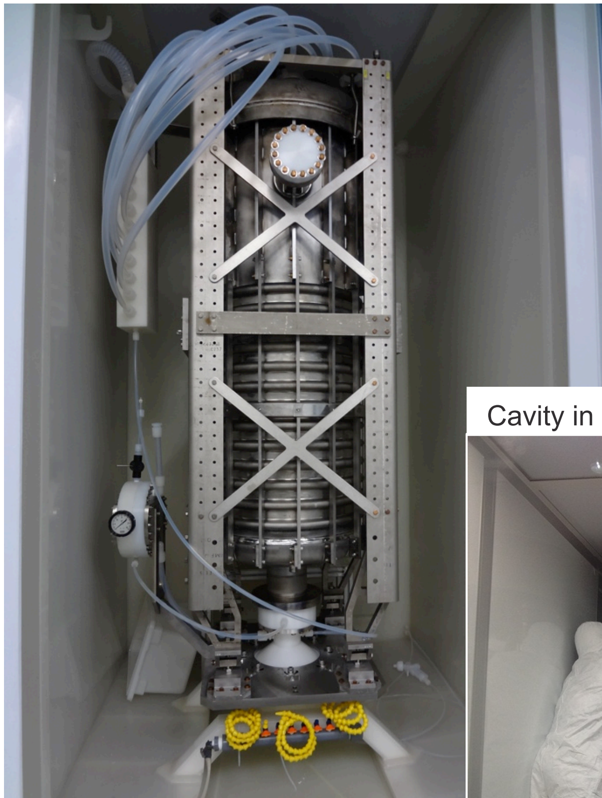
Cavity arrived at BNL (no helium vessel yet)

Mock-up assemblies in 905



Cavity processing

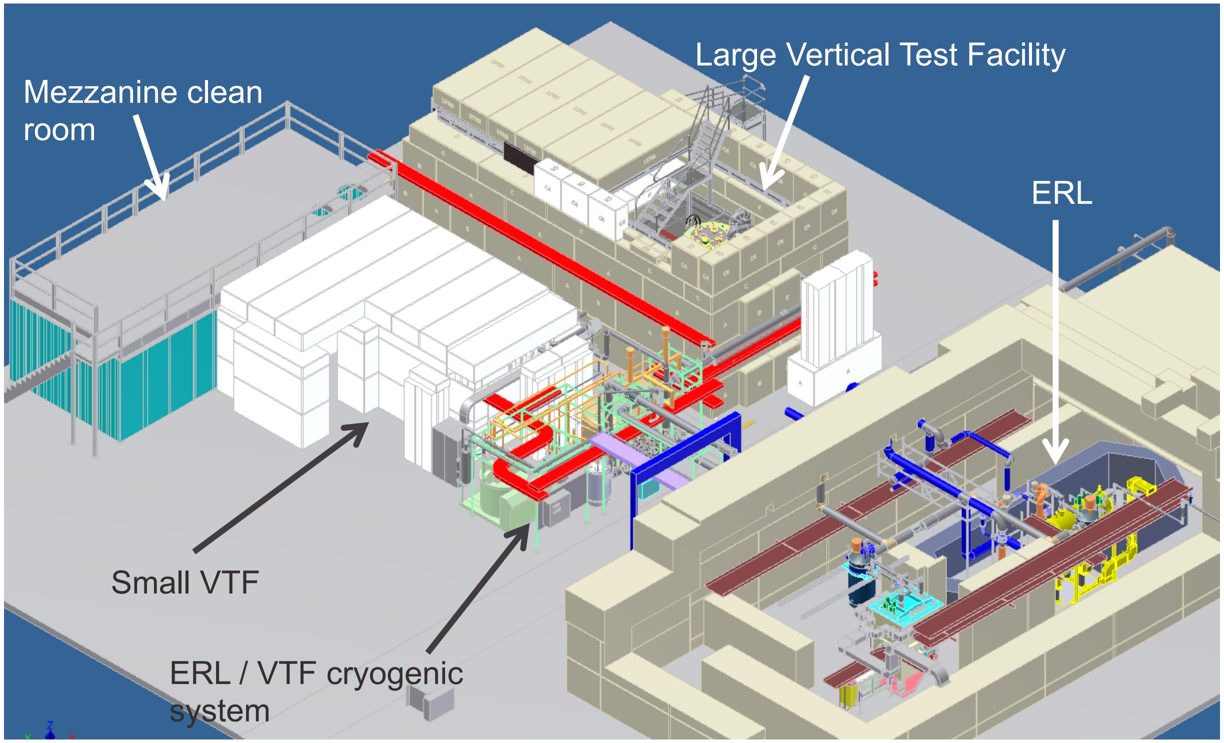
Cavity in BCP cabinet at AES



Cavity in Class 100 cleanroom at BNL

- To achieve good performance, preparation of the SRF cavities involves several important steps:
  - The cavity surface must be free of manufacturing defects. About 150 μm of material is etched out by Buffered Chemical Polishing (BCP) process to remove the damaged layer.
  - Vacuum baking at 600°C for 10 hours is performed for hydrogen removal.
  - Light BCP (~20 μm) to prepare fresh cavity surface.
  - Any residual particulate contamination is removed by High Pressure water Rinsing (HPR).
  - All subsequent cavity preparations are done in Class 100 or better clean room environment to facilitate particulate-free assembly until the cavity vacuum volume is closed up.
- After the cavity is processed, its performance is tested in a vertical cryostat.
- For BCP and HPR, we have a joint BNL/AES facility at AES.
- At C-AD, we have SRF VTF facility in building 912, which includes a 800°C vacuum oven, Mezzanine clean room (Class 100 and Class 10,000 areas), and large and small Vertical Test Facilities (LVTF and SVTF) coupled to a dedicated ERL/VTF refrigeration system.

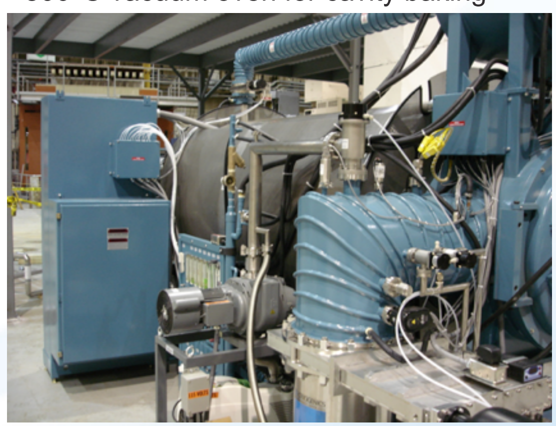
SRF facilities in building 912



Mezzanine clean room

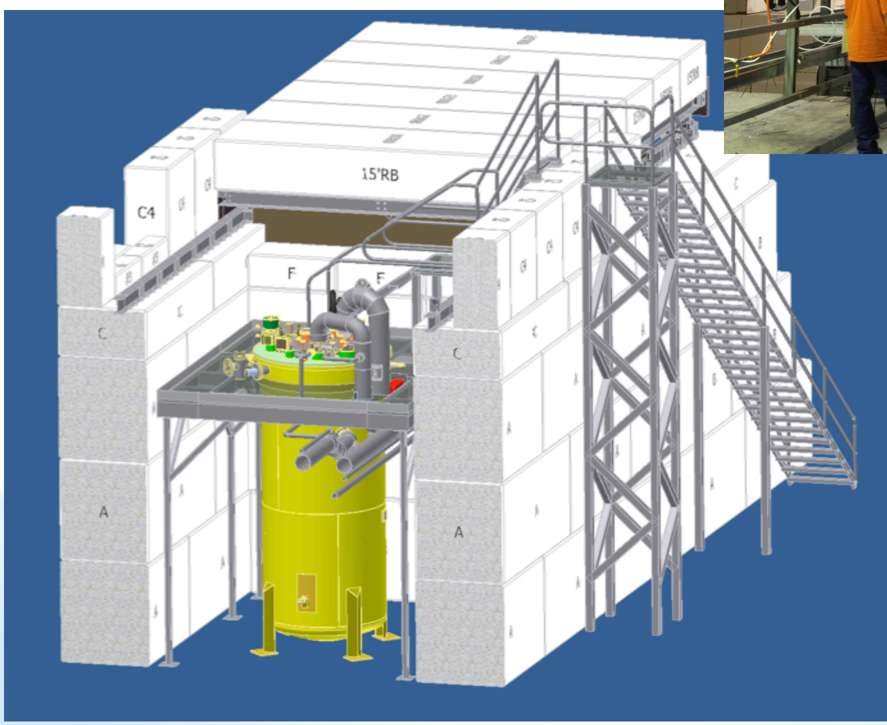
ERL/VTF cryogenics

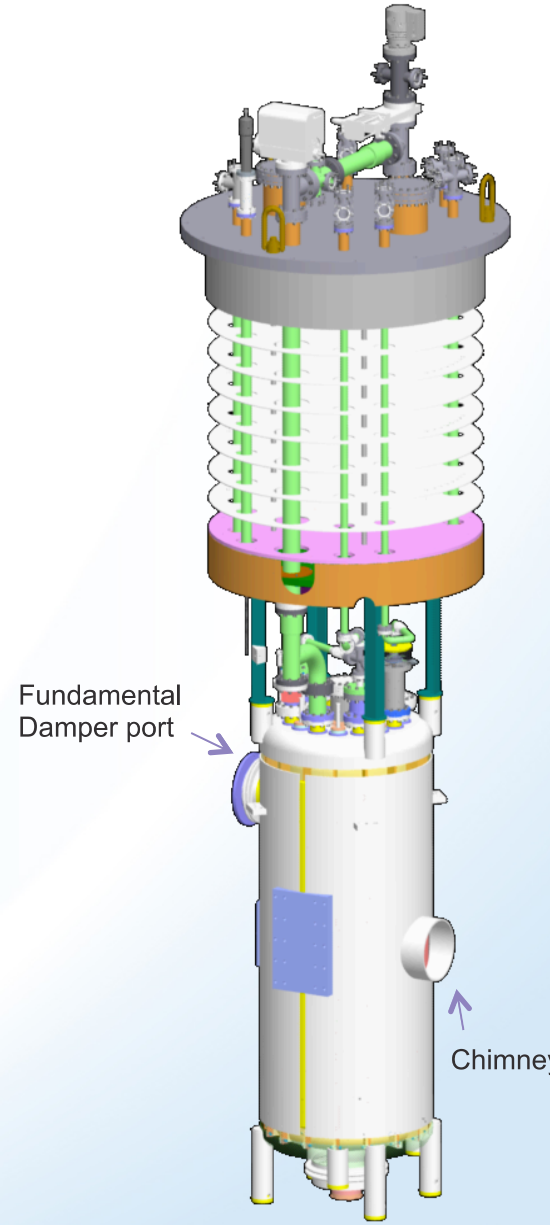
800°C vacuum oven for cavity baking



LVTF setup

VTF dewar top plate



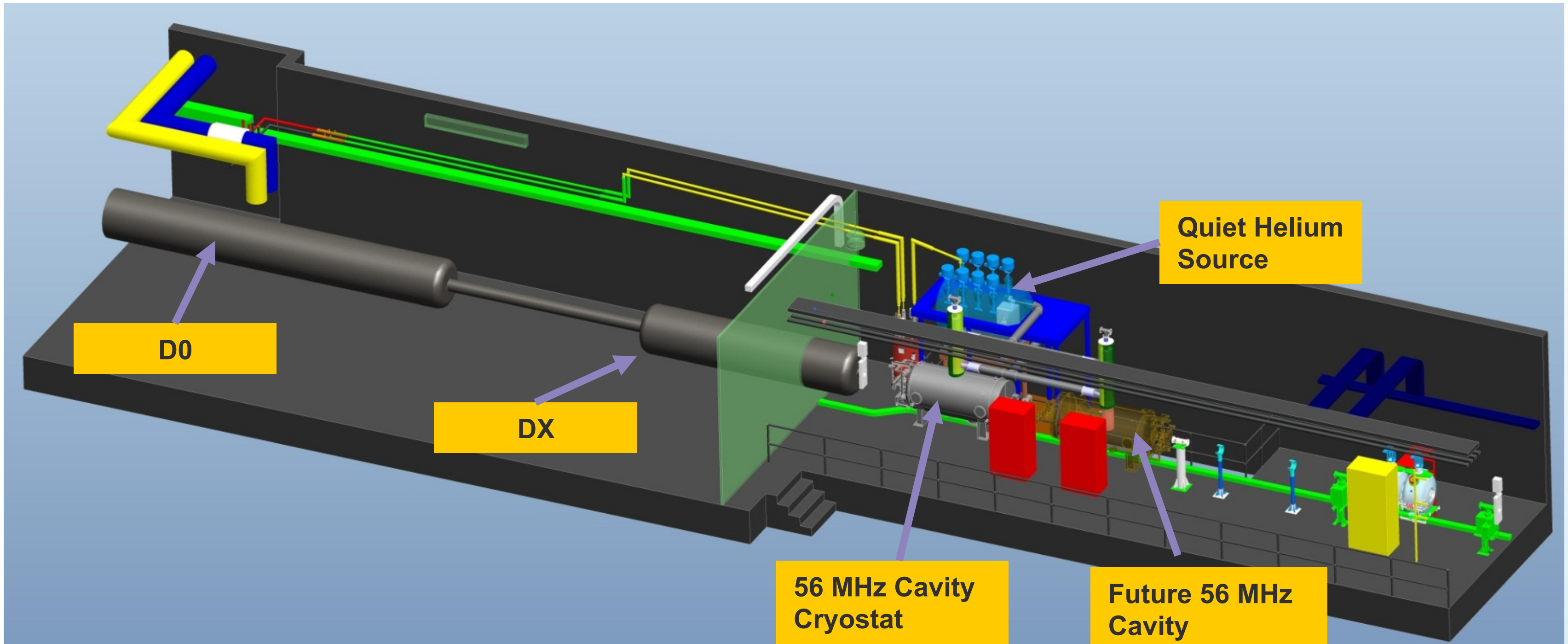


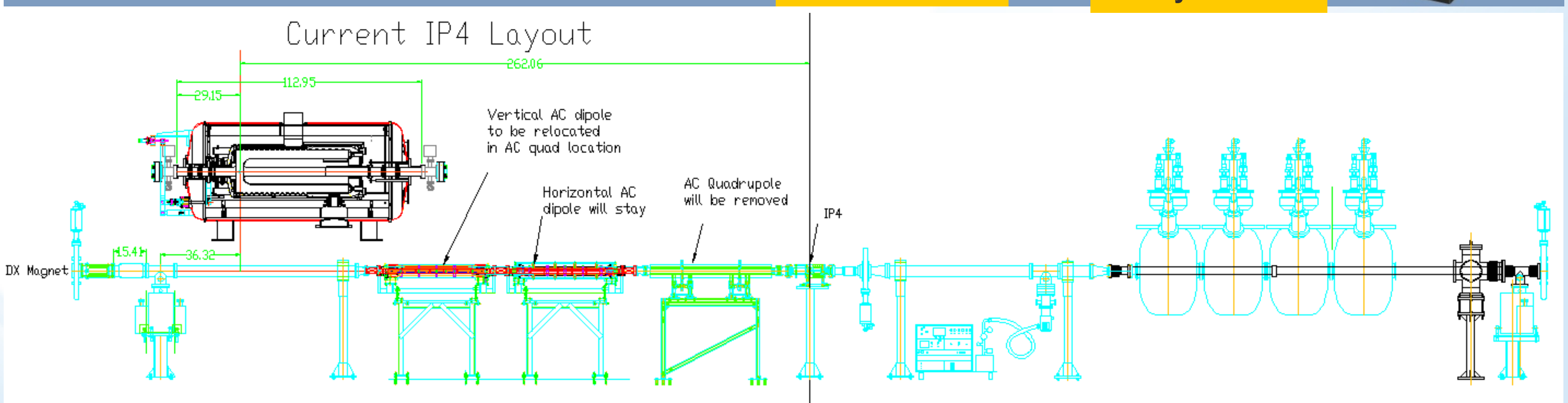
56 MHz project milestones (accomplished)

- ✓ Feb 2012 — Cavity received from manufacturer (Niowave)
- ✓ Mar-May 2012 — Heavy BCP etching removing 150 µm (BNL/AES)
- ✓ Jun 2012 — High temp bake @ 600°C (BNL)
- ✓ Jul-Sep 2012 — Helium vessel welding (Niowave)
- ✓ Dec 2012 — Light BCP etching removing 20 µm (BNL/AES)
- ✓ Dec 2012 — High power water rinse (BNL/AES)
- ✓ Jan 2013 — Sealed in clean room under vacuum, ready to assemble for testing (AES)
- ✓ Jul 2013 — Cavity assembly to the LVTF top plate in the Mezzanine cleanroom is complete, the insert is in LVTF for testing
- o Jul 2013 — Vertical testing is in progress

Installation in RHIC

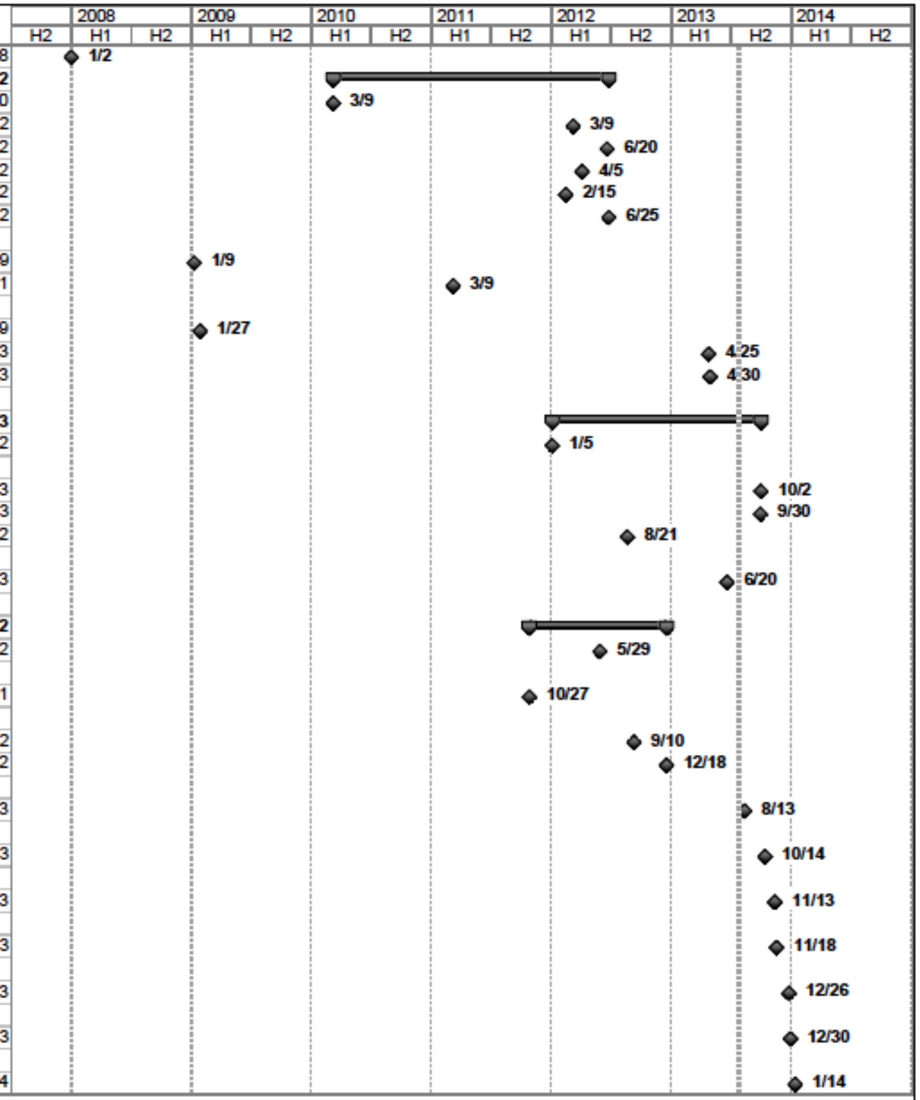
56 MHz cavity will be installed in the IP4 area





56 MHz project schedule

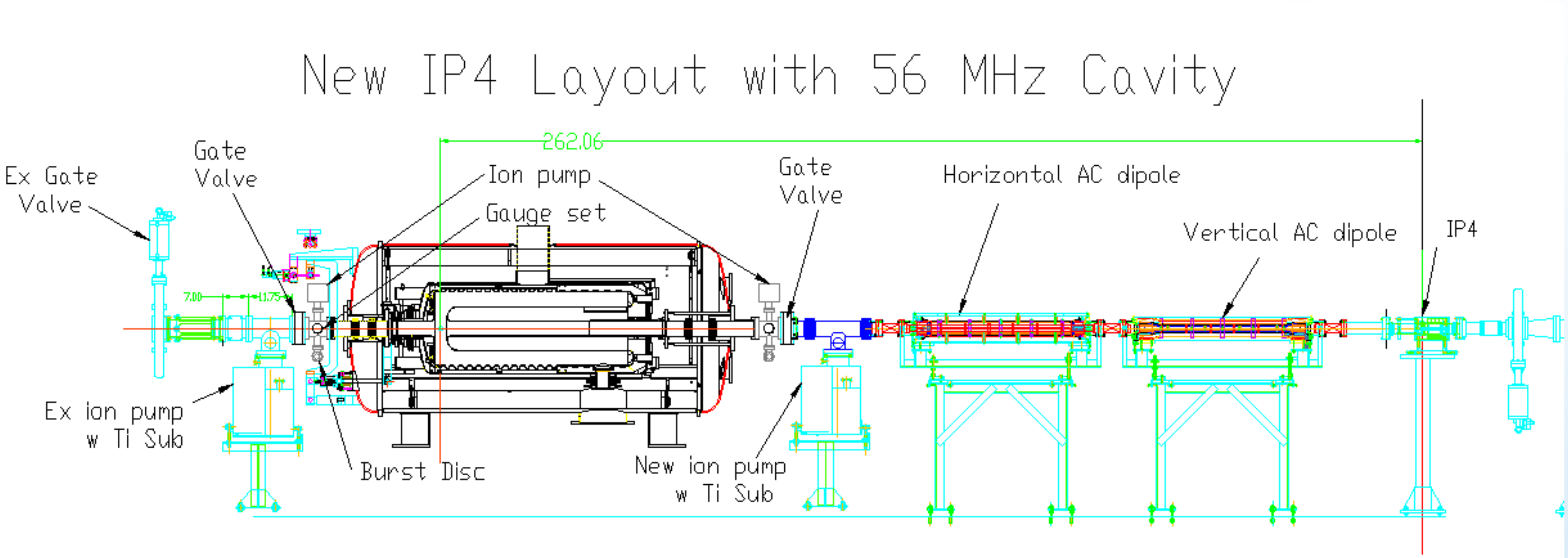
ID	Task Name	Duration	Finish
1	56 Mhz SRF Cavity Program Start, Blue Ring AIP Funding Released	0 days	Wed 1/2/08
2	**Design Development**	**599 days**	**Mon 6/25/12**
3	56 MHz SRF Cavity with Helium Vessel Design Complete	0 days	Tue 3/9/10
4	HOM Dampers Design Complete	0 days	Fri 3/9/12
5	Fundamental Damper Design Complete	0 days	Wed 6/20/12
6	Fundamental Power Coupler Design Complete	0 days	Thu 4/5/12
7	Cavity Tuner Design Complete	0 days	Wed 2/15/12
8	Cryomodule Component Design Complete	0 days	Mon 6/25/12
9			
10	External Design Review Complete	0 days	Fri 1/9/09
11	Second External Design Review Complete	0 days	Wed 3/9/11
12			
13	LESHC & ASSRC Reviews (Initial)	0 days	Tue 1/27/09
14	LESHC Action Items Closed	0 days	Thu 4/25/13
15	ASSRC Review (Finall)	0 days	Tue 4/30/13
16			
17	**Component Procurement**	**454 days**	**Wed 10/2/13**
18	Cavity Fabrication Complete	0 days	Thu 1/5/12
19			
20	HOM Dampers Procurement Complete	0 days	Wed 10/2/13
21	Fundamental Damper Procurement Complete	0 days	Mon 9/30/13
22	Fundamental Power Coupler Procurement Complete	0 days	Tue 8/21/12
23			
24	Cryomodule Component Procurement Complete	0 days	Thu 6/20/13
25			
26	**Testing and Processing Equipment**	**298 days**	**Tue 12/18/12**
27	Vertical Test Facility Complete	0 days	Tue 5/29/12
28			
29	Cavity Process Tooling Complete	0 days	Thu 10/27/11
30			
31	Cavity String & Transport Tooling Complete	0 days	Mon 9/10/12
32	Cryomodule Assembly Tooling Complete	0 days	Tue 12/18/12
33			
34	Cavity Processing Complete, including Vertical Testing	0 days	Tue 8/13/13
35			
36	Cavity String Assembly Complete	0 days	Mon 10/14/13
37			
38	Cavity Cryomodule Assembly Complete	0 days	Wed 11/13/13
39			
40	Cryomodule moved to RHIC Tunnel	0 days	Mon 11/18/13
41			
42	ASSRC Walkthough Checklist Complete	0 days	Thu 12/26/13
43			
44	In-Tunnel Installation Complete	0 days	Mon 12/30/13
45			
46	All Cavity Sysyem Complete / Run Approval Received	0 days	Tue 1/14/14



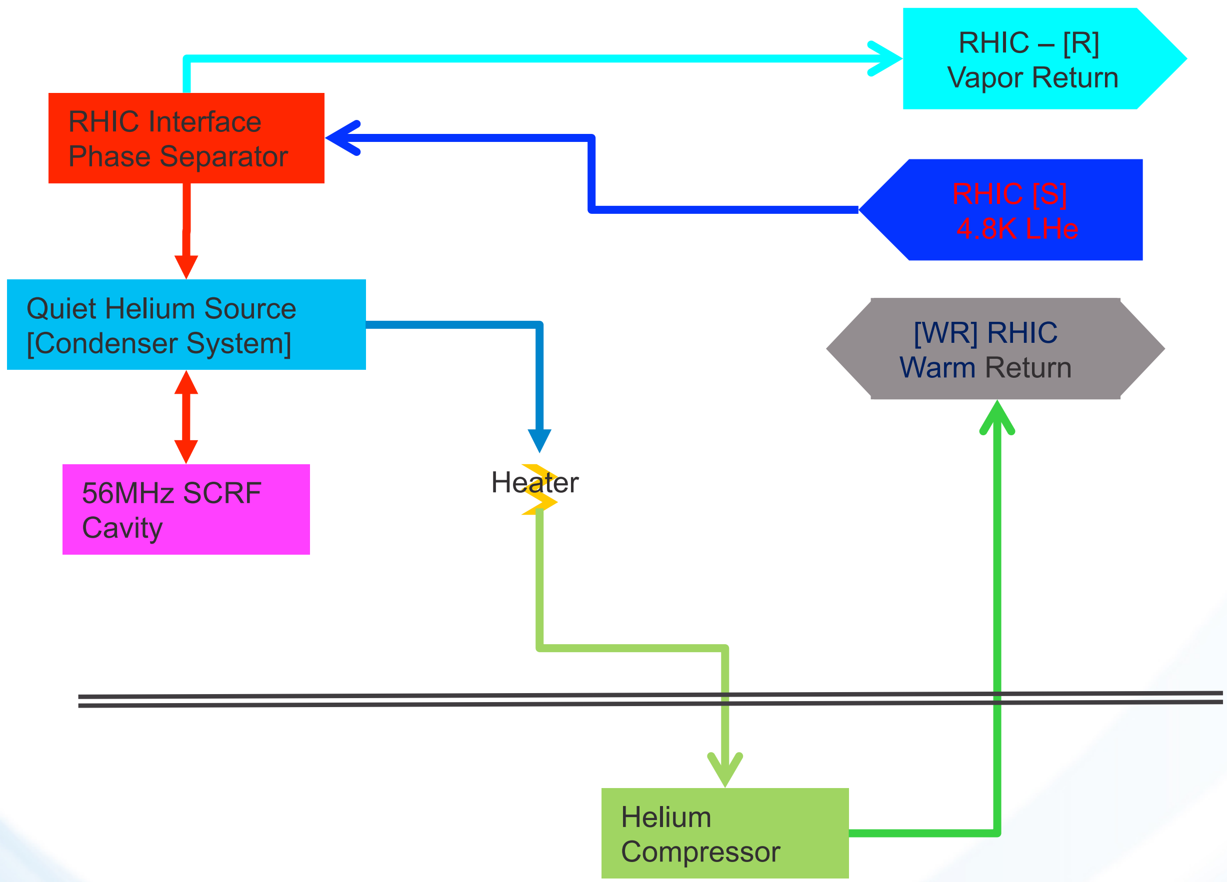
56 MHz project milestones

❑ Aug 8, 2013	Cavity processing, including VTF testing, is complete
❑ Sep 30, 2013	FD procurement is complete
❑ Oct 2, 2013	HOM coupler procurement is complete
❑ Oct 14, 2013	Cavity string assembly is compete
❑ Nov 13, 2013	Cryomodule assembly is complete
❑ Nov 18, 2013	Cryomodule moved to RHIC tunnel
❑ Dec 26, 2013	ASSRC walkthrough checklist is complete
❑ Jan 14, 2014	All systems are complete / Run approval is received

IP4 Layout (vacuum system components)

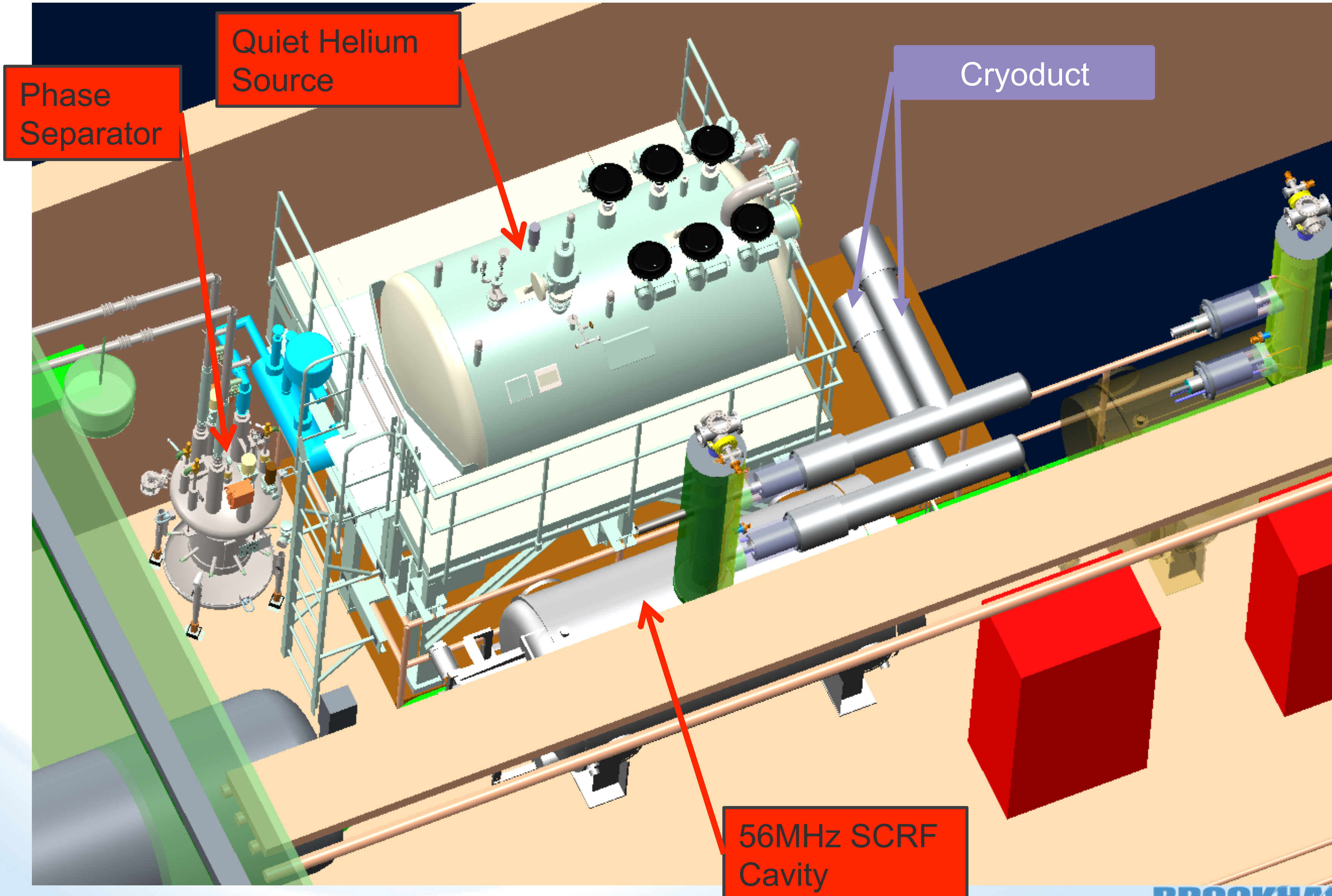


Cryogenic system at IP4



- **Condenser/Boiler**
  - ✓ Condenses the boil-off vapor
  - ✓ Condenser/Boiler design heat load is 200 W
  - ✓ Heat transfer surface area 39.5 m^2 (condenser) & 33 m^2 (boiler)
  - ✓ Condenser side is operated at 4.4 K and 1.2 bar
  - ✓ Boiler side is operated at 4.3 K and 1.09 bar
- **Condenser Load Heater**
  - ✓ A 50 W load heater is mounted in the helium bath to balance the effect of dynamic heat load to maintain a constant heat load on condenser side, and therefore a constant pressure.
- **HOM Cooling Loop**
  - ✓ Each HOM is cooled by a helium siphon loop – liquid helium enters HOM and outgoing tube is heated to induce helium flow and remove the heat generated within the HOM.

Cryogenic system layout



Cryogenic system schedule

Item	Status
Helium Compressor	In house
QHS (Condenser Cryostat) and piping	To be delivered before Oct 2013
Warm Piping	In progress – to be complete before Dec 2013
Final cavity connections and final I/O check out	Before Start of RHIC Run – Jan 2014

RF system

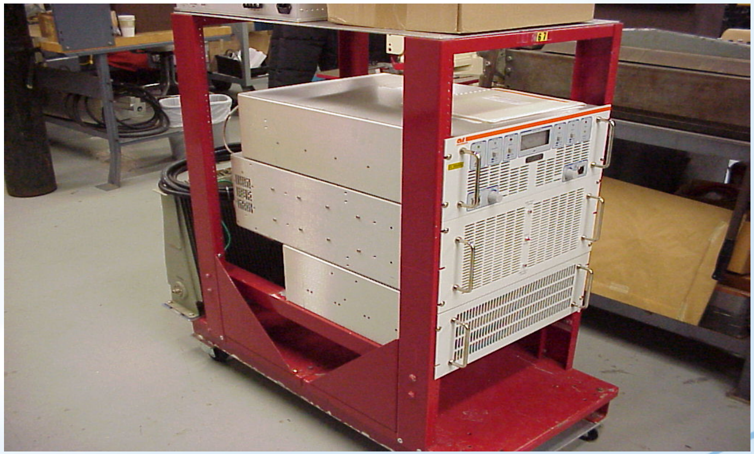
- The 56 MHz SRF cavity is a beam driven cavity. RF system needs power only to fight microphonics detuning (1 Hz peak):

$$P_{forw}^{pk} = \frac{V_c^2}{R/Q} \cdot Q_{ext} \cdot \left(\frac{\delta\omega_m}{\omega} \right)^2 = 0.63 \text{ kW}$$

- However, the power coming back from the cavity to RF amplifier is

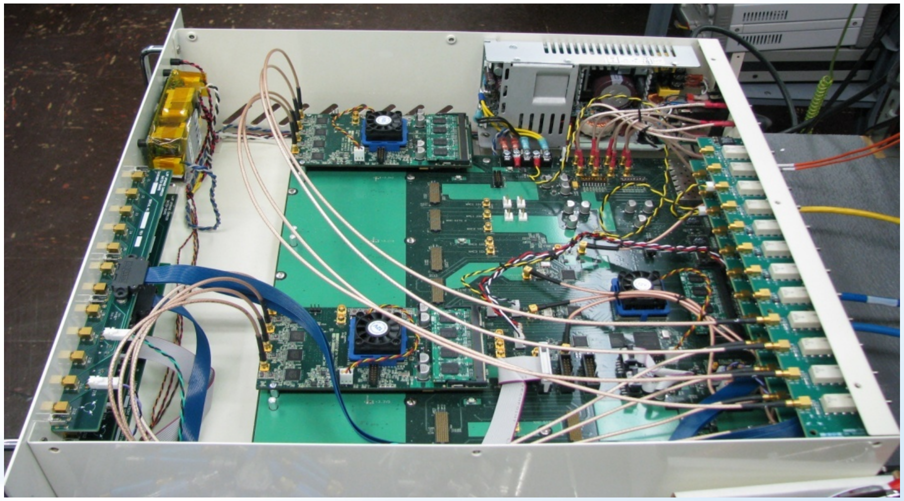
$$P_{refl}^{pk} = \frac{V_c^2}{R/Q \cdot Q_{ext}} \left[1 + \left(Q_{ext} \cdot \frac{\delta\omega_m}{\omega} \right)^2 \right] = 1.88 \text{ kW}$$

- 1 kW RF power amplifier was purchased from AR. Its initial testing was OK, but it failed recently during re-testing and is back at the vendor for repairs.
- A spare amplifier is on order from TOMCO

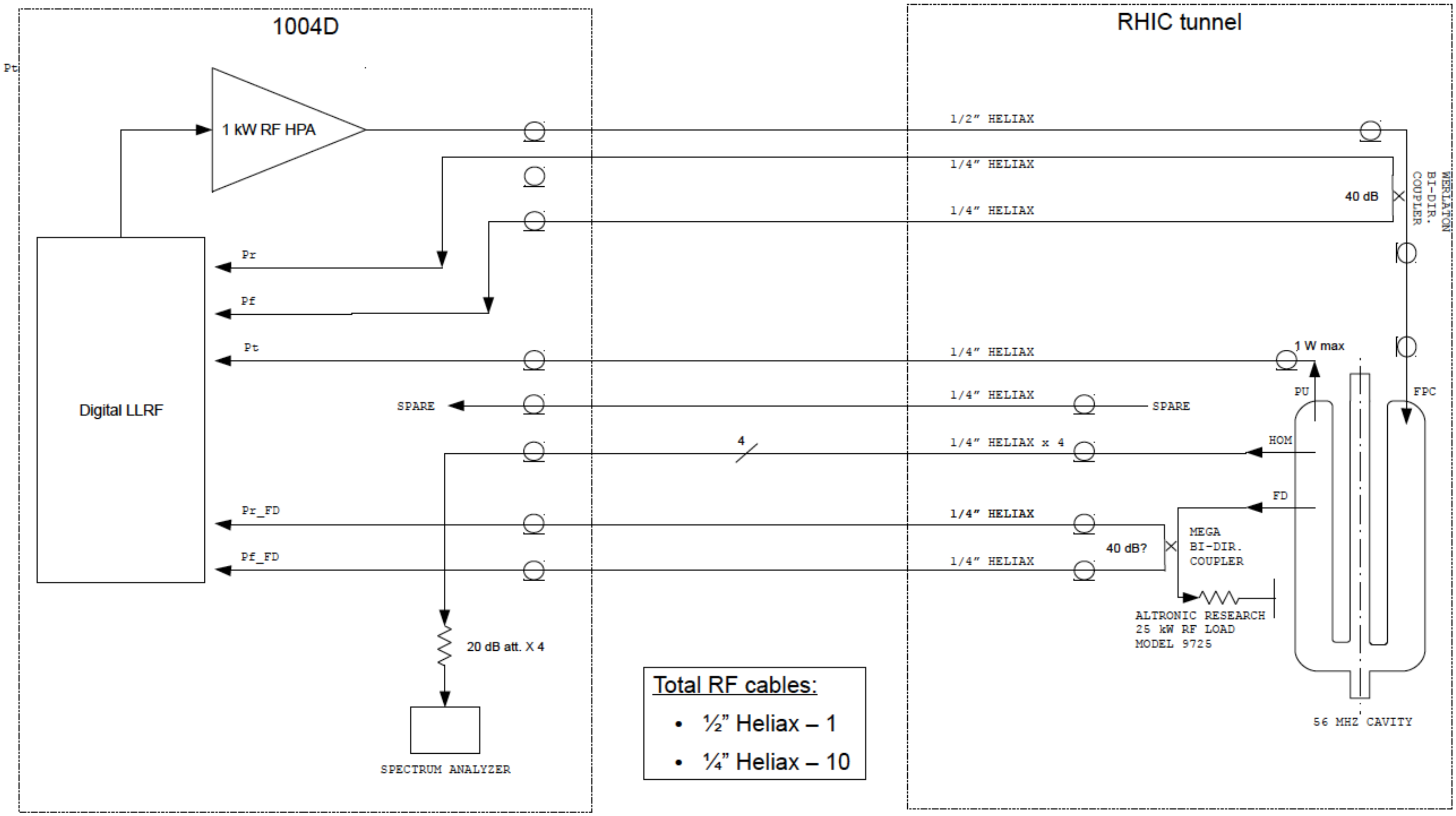


LLRF control requirements

- Cavity field control objectives
  - Amplitude and phase: 1E-4 rms ("AC" variation only, absolute "DC" voltage and phase determined by beam and cavity detuning).
- Adiabatic turn on under control of state machine slowly pushing cavity frequency toward beam frequency, via stepper tuner.
- "Slow" feedback via piezo tuner for control of cavity impedance to maintain nominal 2.0 MV on the gap.
- "Fast" feedback via LLRF drive and 1kW PA to compensate microphonic detuning, i.e. "AC" variations about the nominal 2.0 MV setpoint within a few hundred Hz modulation bandwidth.
- Cavity and machine protection.
- 56 MHz system is a variant of the recently developed generic LLRF Controller, currently being used at EBIS, AGS, RHIC and ERL.



RF connections



Total RF cables:

- ½" Heliax – 1
- ¼" Heliax – 10

Off-normal events, consequences and actions

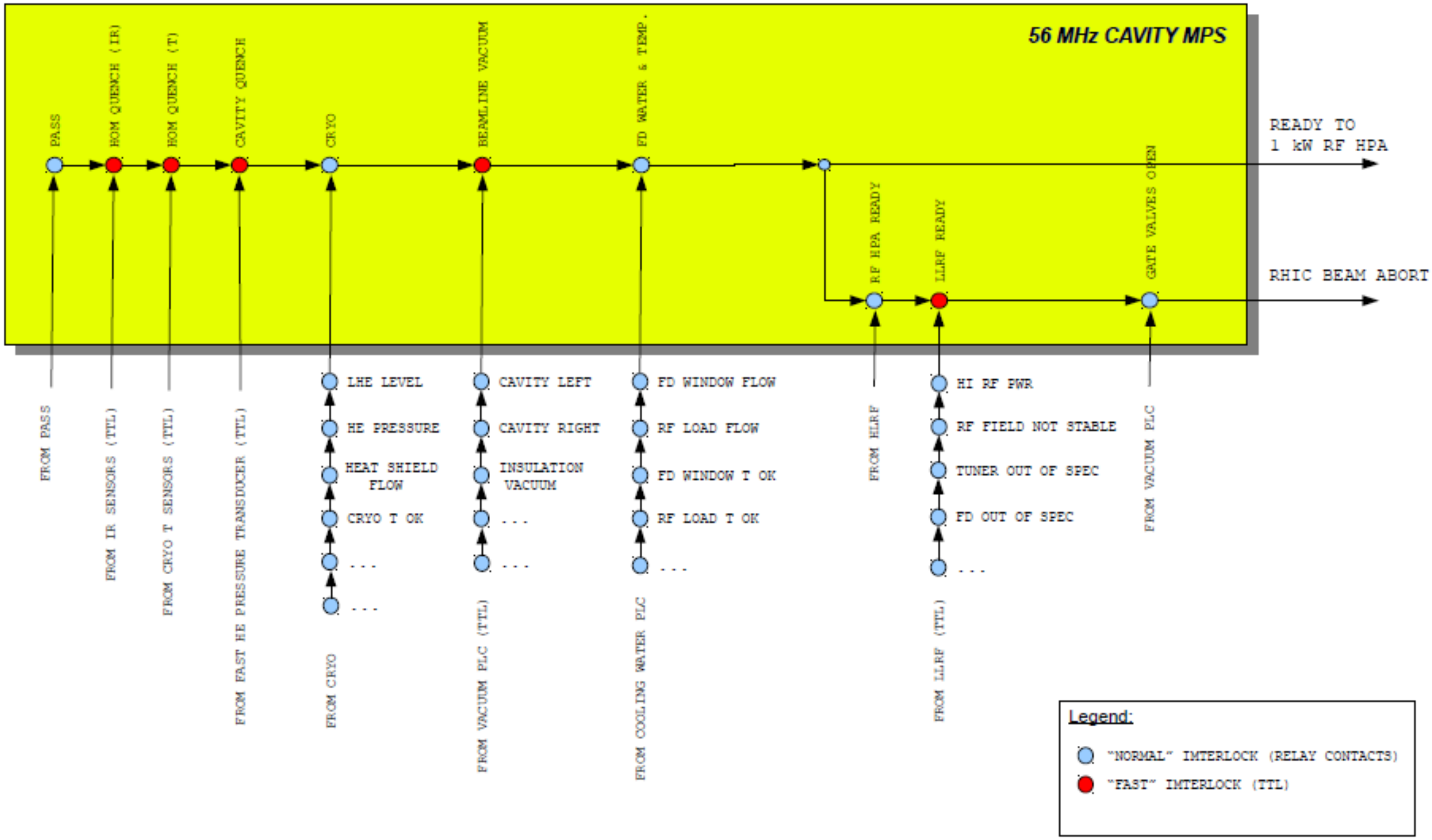
Event	Impact on cavity	Consequences	Sensors & signals
Cavity quench	Excessive heat dissipation	Helium bath pressure burst	Fast rise of the He bath pressure; Excessive 28 MHz RF power demand
HOM damper quench	Excessive heat dissipation	Elevated HOM damper temperature	IR & Temperature sensors
RF system trip	No RF power for field regulation	High amplitude/phase noise	LLRF or High power RF is not ready
Tuner malfunctioning	Cavity voltage out of spec	Cavity quench	"Tuner is out of spec" from LLRF
Cryogenic problem	Loss of He pressure/level control	High He pressure / low liquid He level	He pressure or LHe level are out of spec
Cavity/beam pipe vacuum leak	Poor vacuum	Numerous, depending on scenario	Signals from vacuum gauge and pump controllers
Insulation vacuum leak	High heat leak to LHe	High He pressure/low liquid level	He pressure or LHe level are out of spec
Multipacting	Excessive local heating	Vacuum spike, cavity quench, elevated temperature	Signals from vacuum gauge and pump controllers
FD malfunctioning	Excessive RF power	FD overheating	FD temperature sensors; High RF load power from LLRF
Beam dump	-	No beam induced voltage	"Beam dump" from RHIC Control System
Beam current too low	-	Not possible to maintain voltage	"Low beam current" from either RHIC Control System or LLRF

Reaction to all off-normal events should be:
- dump the beams in RHIC
- turn RF OFF
- detune the cavity to "home" position
- fully insert FD

Machine protection system

Flow chart for the 56 MHz SRF cavity MPS

S. Belomestnykh
March 29, 2013

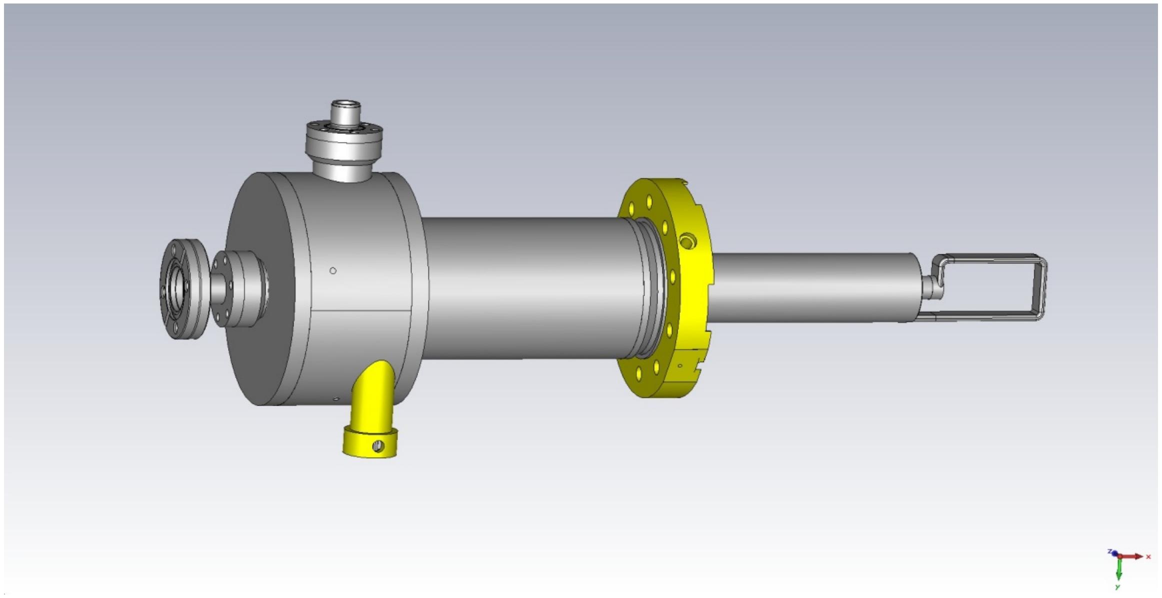


Summary

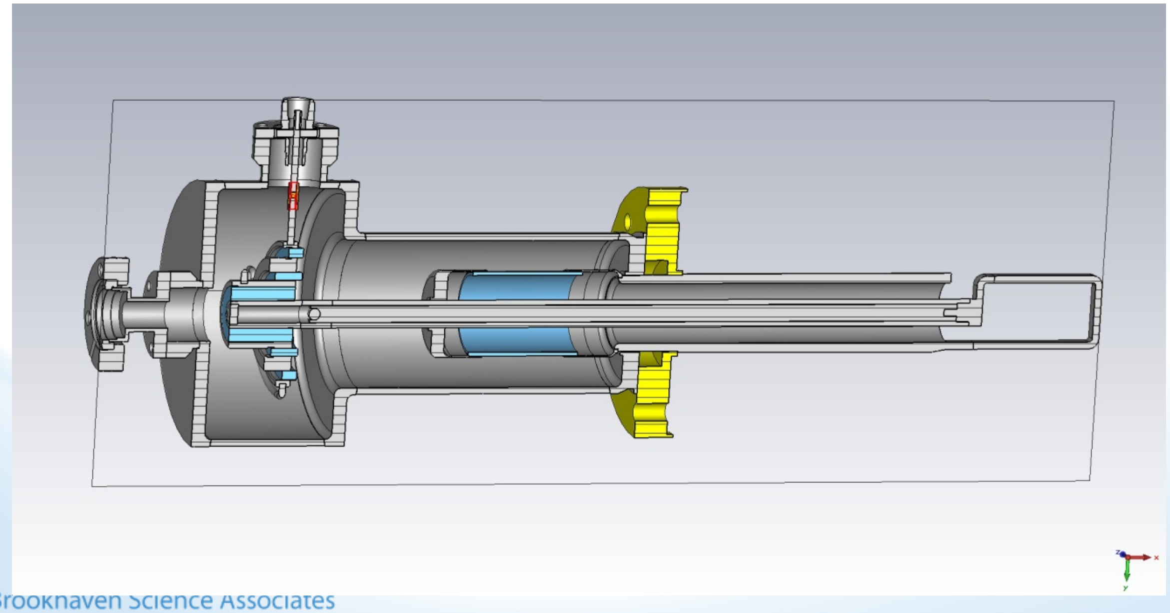
- 56 MHz cavity fabrication and processing is complete
- Vertical test of the cavity is in progress
- Cryostat fabrication is progressing well, many components are fabricated and dry-fitted
- The most critical components for the project at the moment are HOM couplers and FD
- Current schedule allows installation for Run-14 and everybody is working hard to make this happen
- Summary

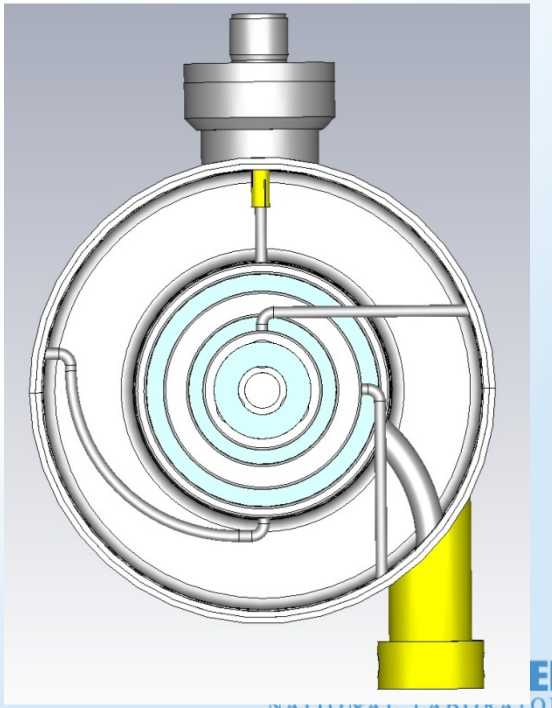
Backup slides

HOM couplers



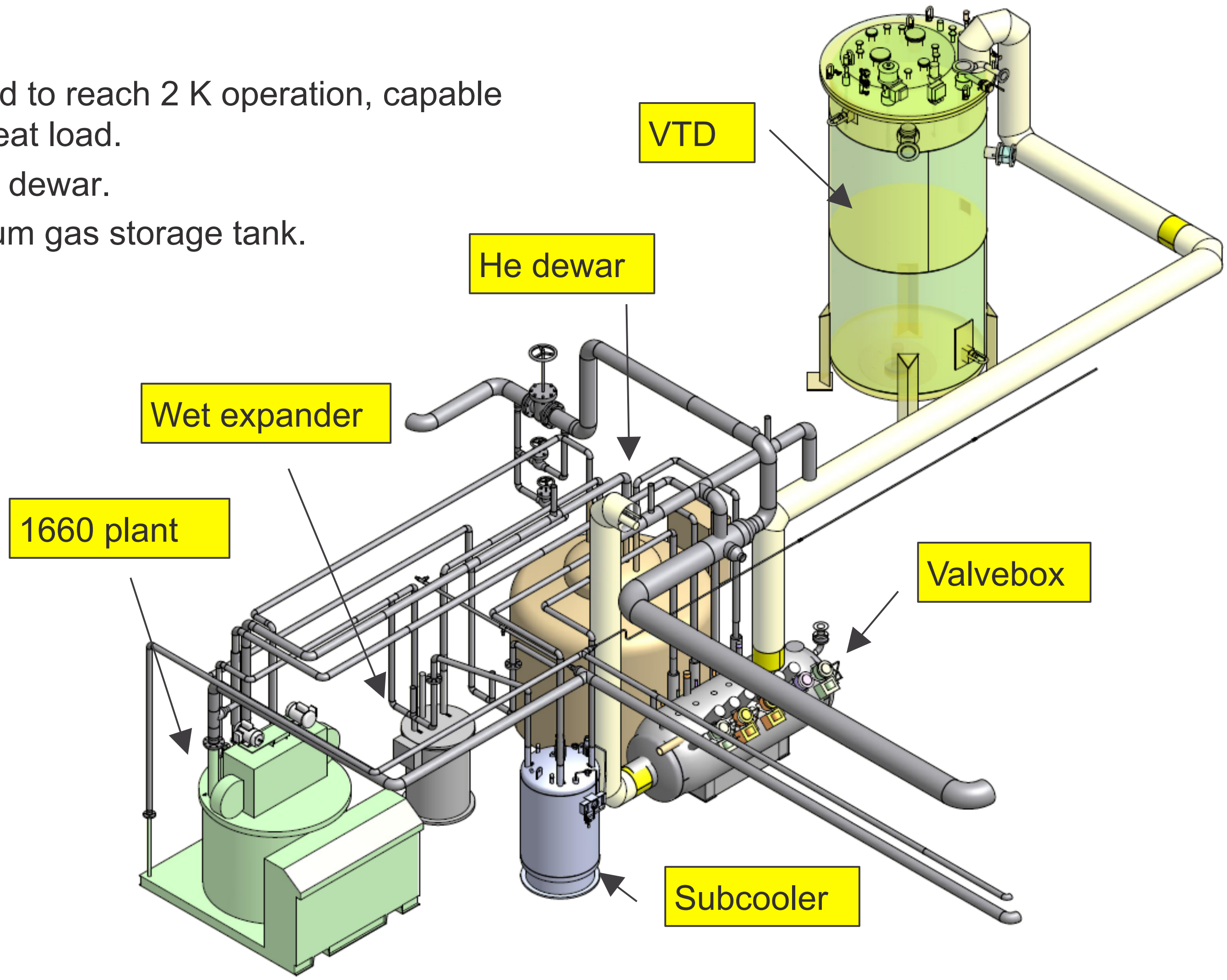
- The final version is remodeled from the Niowave wave version. Dimensions changed in some components, but maintained same high performance.
- Prototype will be fabricated in Jlab.
- Reuse some of the components from Niowave.



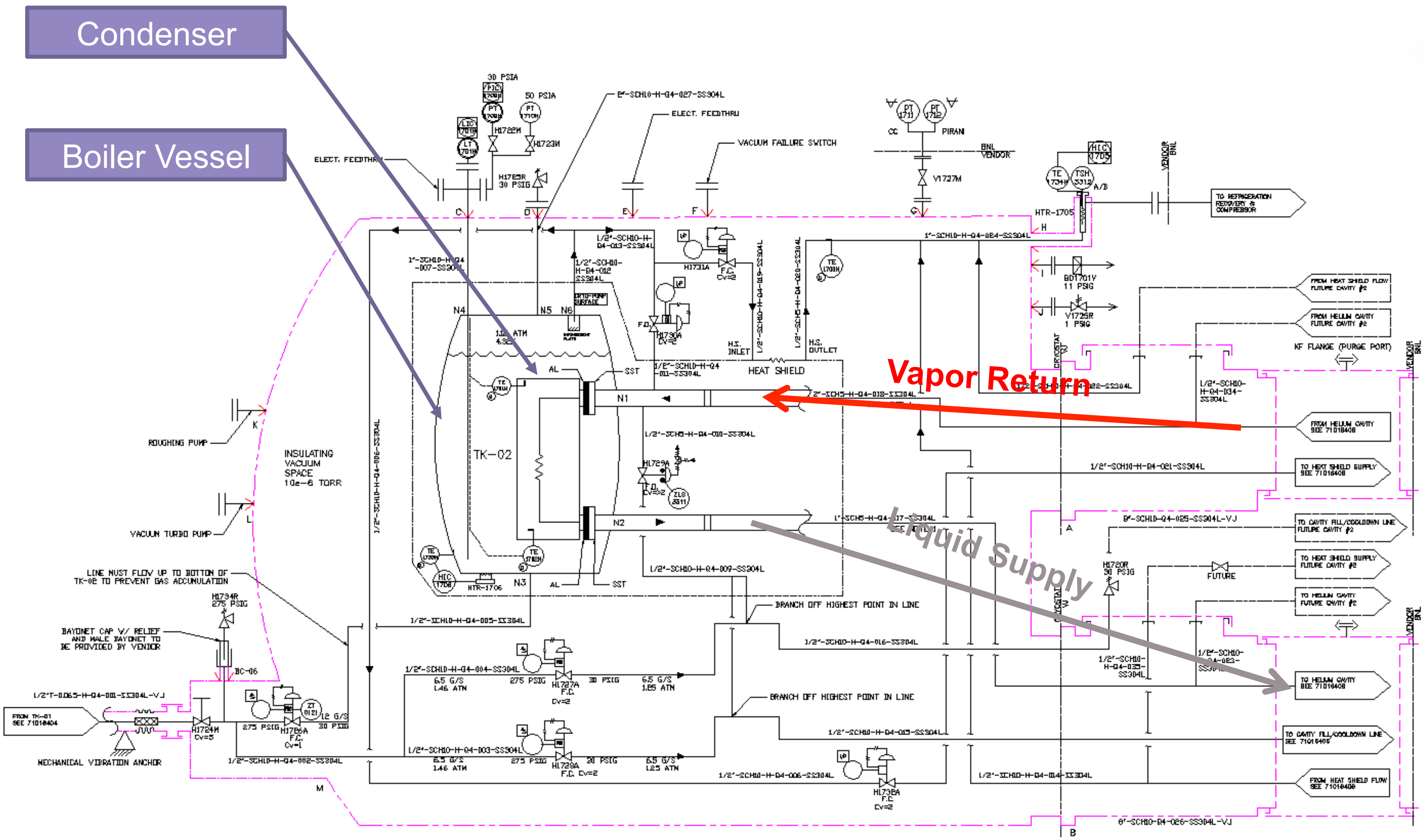


ERL/VTF cryogenic system

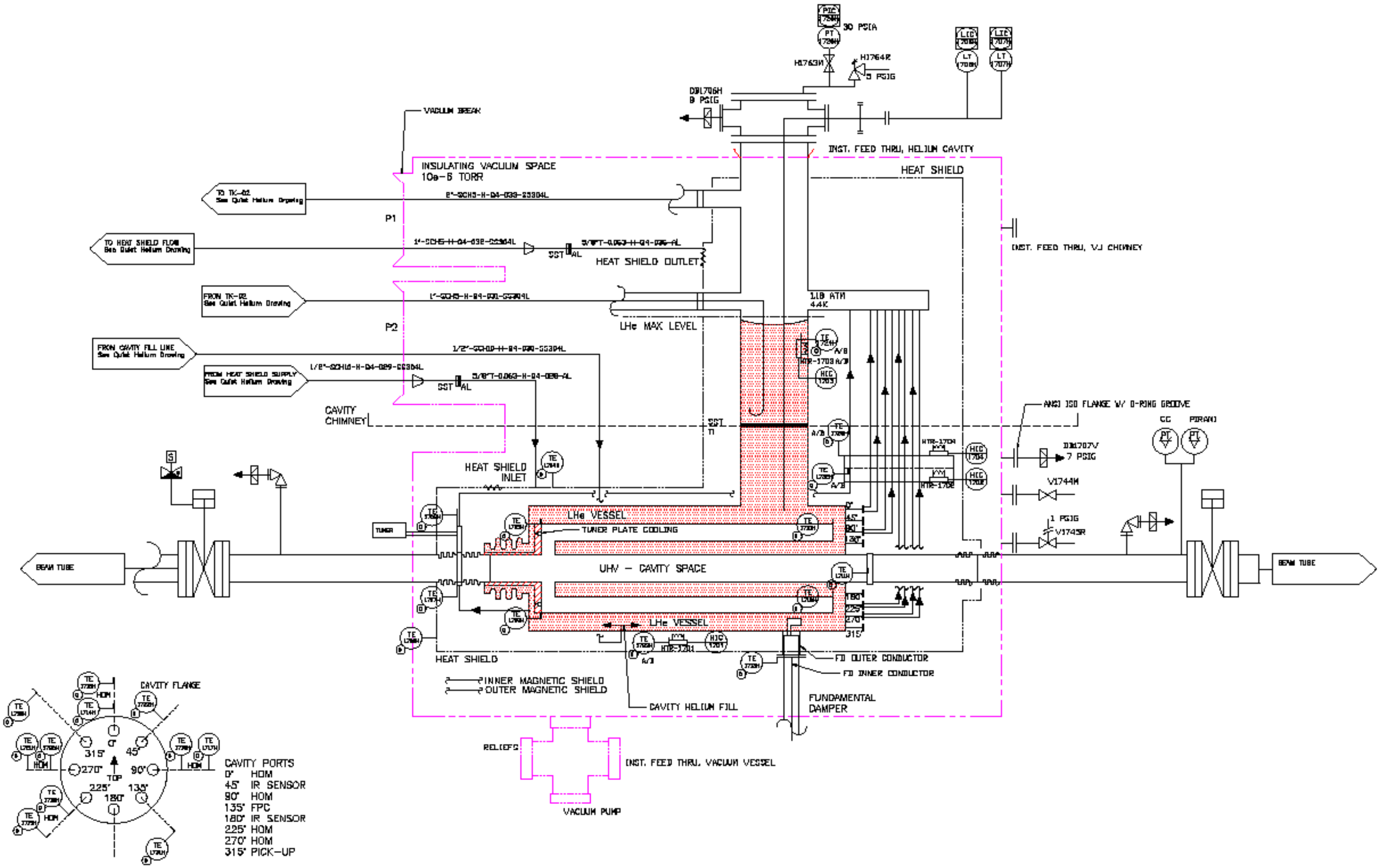
- 360 W 4 K refrigerator.
- A liquid ring pump is used to reach 2 K operation, capable of handling a 100 watt heat load.
- 1000 gallon LHe storage dewar.
- 38,000 gallon warm helium gas storage tank.



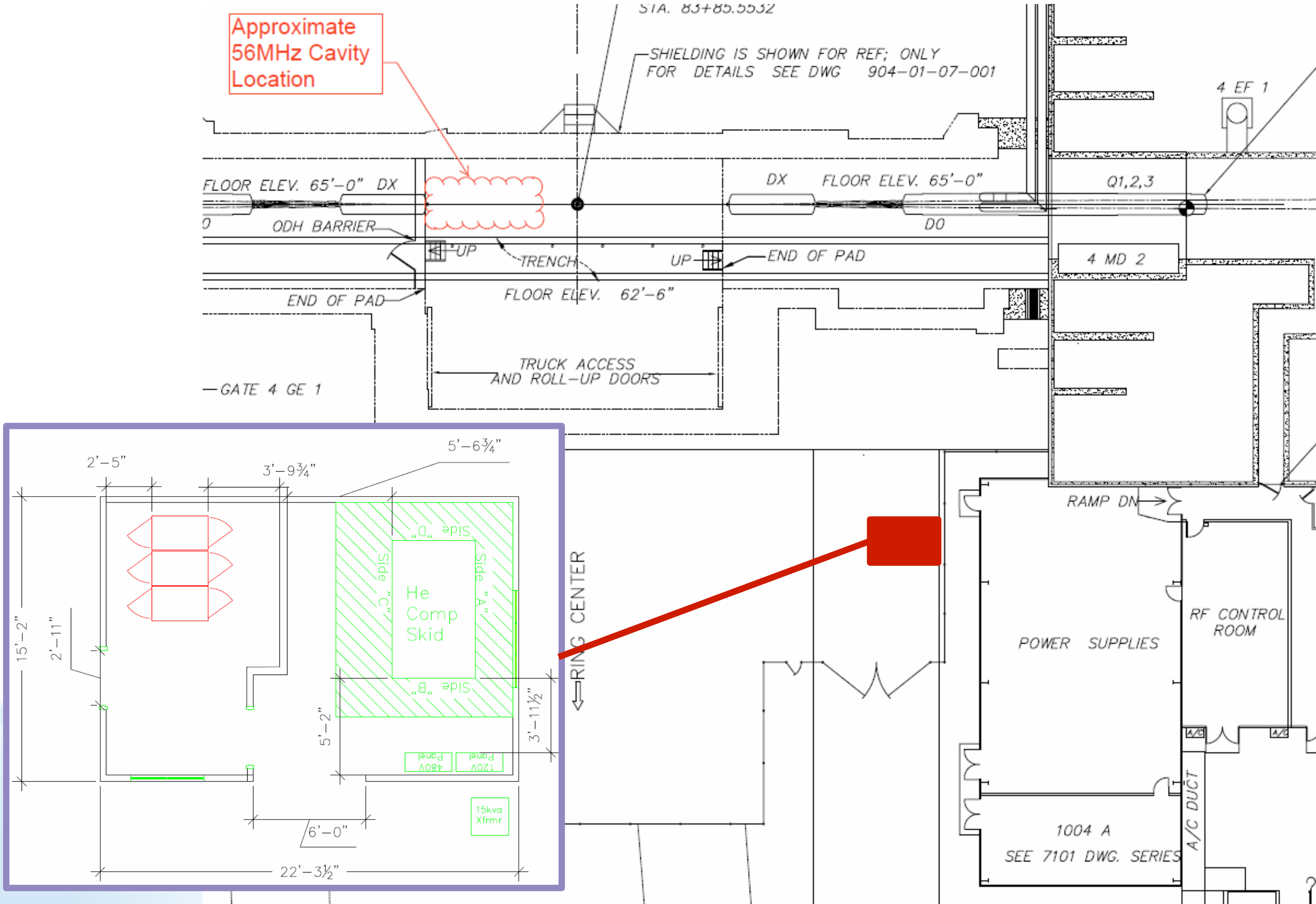
QHS P&ID – Interface review



56 MHz SRF Cavity Cryomodule P&ID

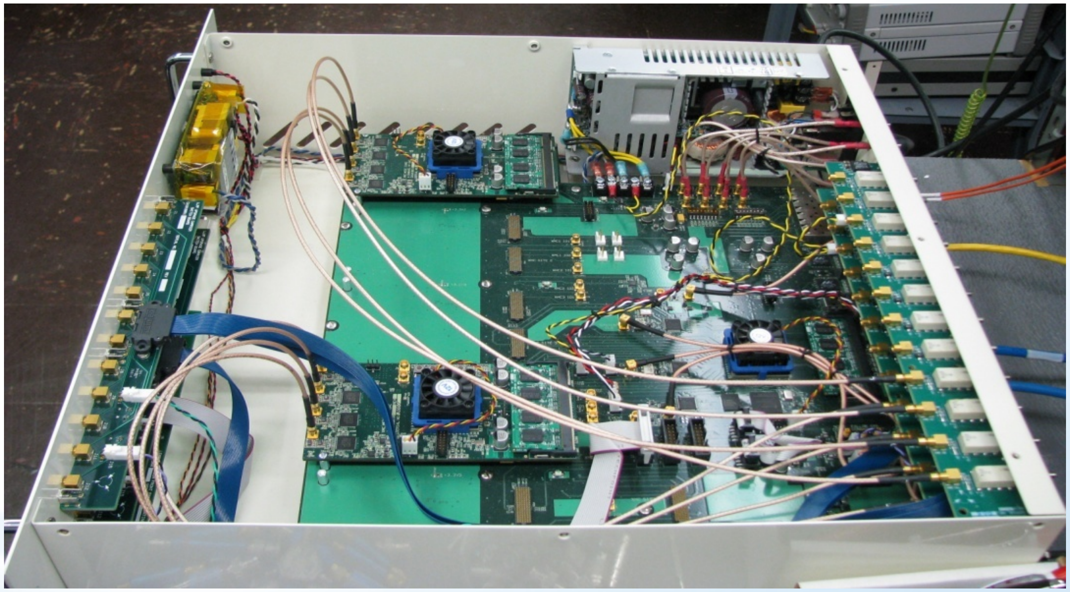


Small helium compressor location

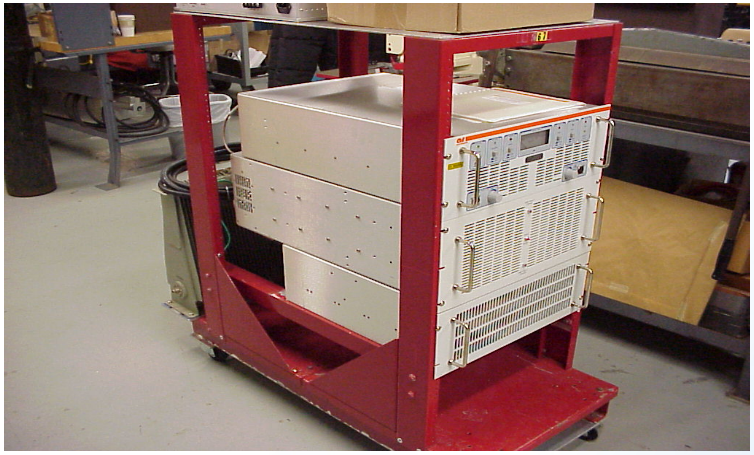


Generic LLRF controller

- 56 MHz system is a variant of the recently developed generic LLRF Controller, currently being commissioned at both RHIC and the EBIS injector for RHIC.
- Two major components from which any Controller is configured:
  - "Controller" = "Carrier Board" + "Daughter Modules"
- A LLRF Controller is a stand-alone configurable, modular, hardware / software platform, the basic building block from which a complete LLRF system is built up.
- Carrier Board
  - Stand alone control system interface, daughter host platform, communication hub, timing, data acquisition management, power …
- Daughter Module
  - Provide system specific functionality (ADCs, DACs, DSP, etc.) and signal processing horsepower.



1 kW RF power amplifier (AR)



- SPECIFICATIONS
- Model KAA5040M16
- RATED POWER OUTPUT..1000 Watts
- INPUT FOR RATED OUTPUT ....1.0 mW maximum
- POWER OUTPUT @ 1dB COMPRESSION...................1000 Watts minimum @ 56 MHz, ± 5 MHz
- FLATNESS...± 2.0 dB maximum unleveled, ± 0.5 dB leveled
- FREQUENCY RESPONSE...56 MHz +/- 5 MHz instantaneously
- GAIN ....60 dB minimum
- GAIN ADJUSTMENT RANGE.......................................30 dB typical
- INPUT IMPEDANCE...50 Ohm nominal
- OUTPUT IMPEDANCE...50 Ohm nominal
- MISMATCH TOLERANCE ....infinite
- PROTECTION..VSWR, over-temperature, overdrive, Integrated 1000W
- circulator
- MODULATION CAPABILITY...Will faithfully reproduce AM, FM, or pulse modulation
- appearing on the input signal
- HARMONIC DISTORTION ....-46 dBc to -10 dBc (-25 dBc min @ 56 MHz, ±5 MHz)
- SPURIOUS OUTPUTS...–70 dBc maximum

1 kW RF power amplifier (TOMCO)

Technical Specifications

Item	Specification	Notes
Model	BT1K-Alpha	All solid-state, 6th generation LDMOS
Operating class	Class A/AB linear	Linear amplifier, faithfully reproduces all forms of modulation The transistors are biased close to class A operation.
Rated power	1kW CW minimum	The amplifier is approximately 1dB into power compression at this power level
Frequency	56MHz	
-1dB bandwidth	At least 4MHz	
Input power for rated output	0dBm max	Gain at 1kW output is 60dB
Efficiency Mains to RF	30% typical	At rated output power, into a 50 ohm load Includes PSU efficiency of ~91%.
Spurious outputs	<-70dBc measured from DC to 2GHz	At rated output power
Harmonics	<-30dBc	At rated output power
Linearity	+/-1dB from -20dB up to full power	
Front panel LED indicators	DC Power, Enable, Selected, Shutdown, Overdrive, Over temp, Fwd Power, Refl Power, PA module status. Digital readouts of forward and reflected power.	
Mains power	The amplifier operates from a single-phase or 2-phase connection rated 100-264V phase-to-neutral (for a single-phase supply) or 100-264V phase-to-phase (for a two-phase supply). The mains supply must include a safety earth.	Total mains power rating 4kVA minimum.
AC power connection	Screw terminals at the rear of the interface unit	
Protection	Overtemp / cooling faults	
	Over-drive	
	Out-of-band inputs	
Maximum load	Operates with up to 100% reflected power	The amplifier is unconditionally stable