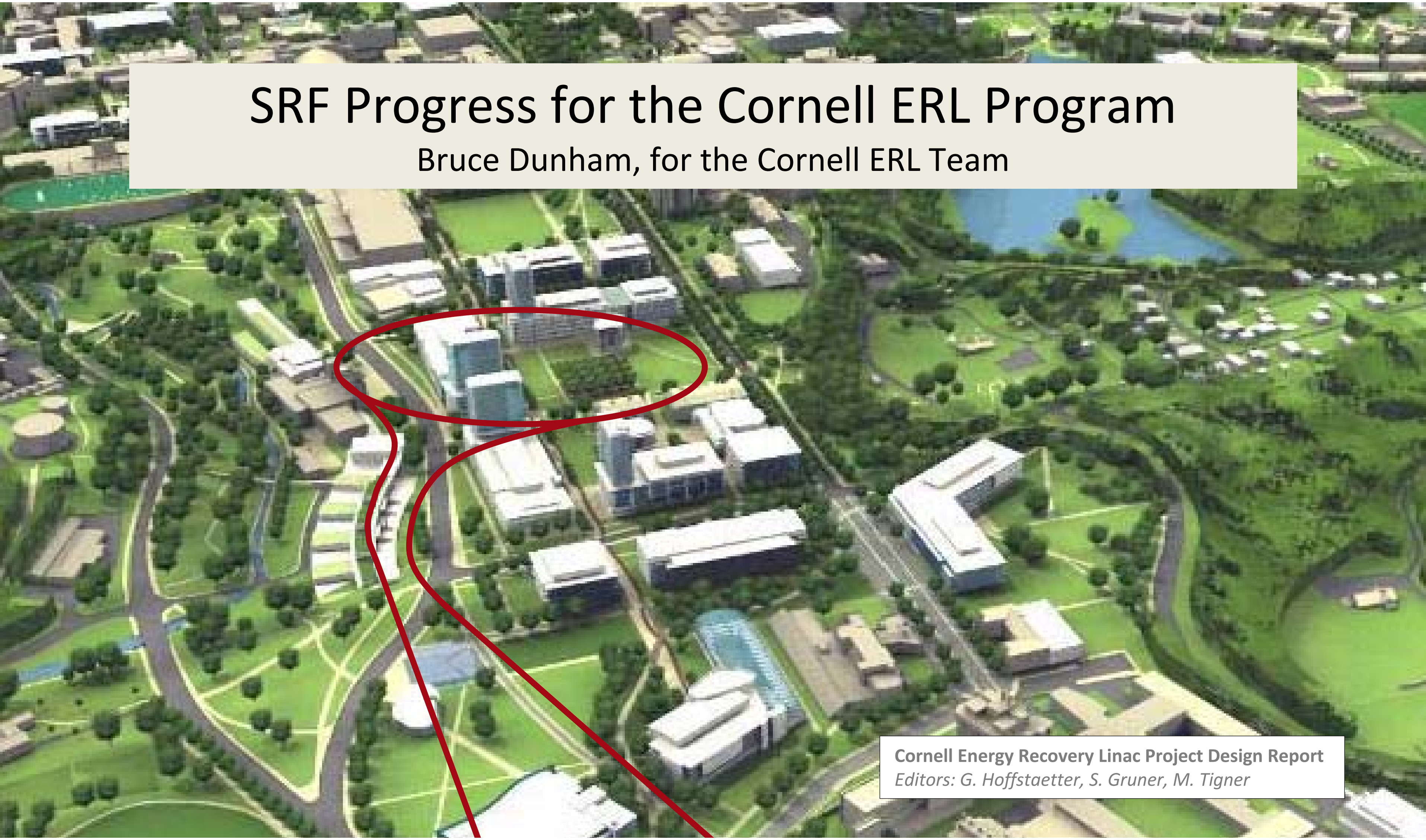
SRF Progress for the Cornell ERL Program

Bruce Dunham, for the Cornell ERL Team



Cornell Energy Recovery Linac Project Design Report
Editors: G. Hoffstaetter, S. Gruner, M. Tigner

Parameters

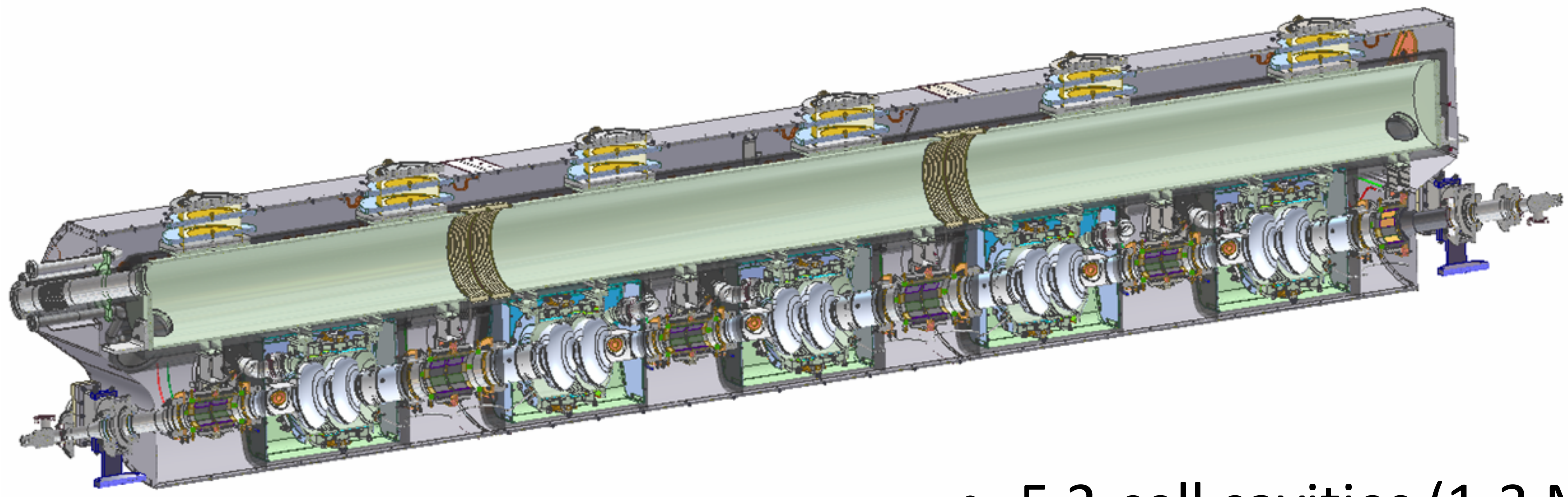
- 5 GeV, 100 mA CW beam
  - 8 pm emittance, 2 ps bunch length
- Stable operation
  - Strong HOMs can cause beam breakup
  - ~200 W HOM power in beamline loads/cavity
- CW operation
  - Q(1.8 K) = 2×10^{10} @ 16.2 MV/m
    - 10 W cryogenic loss from fundamental/cavity
    - ~4 MW wall power

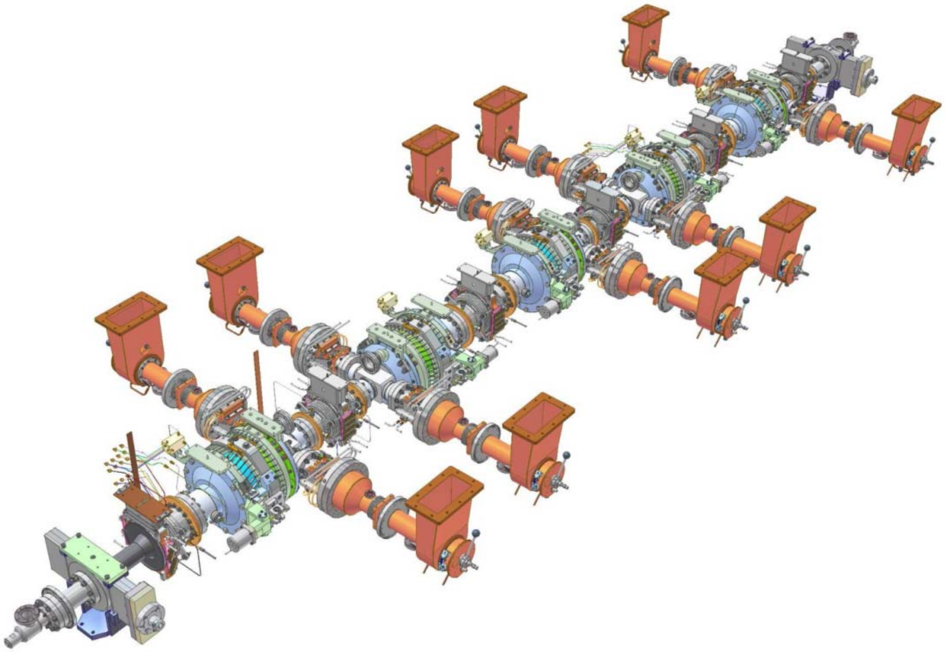
Outline

- Injector Cryomodule
  - overview
  - couplers
  - HOM absorbers
- Main Linac Cavities
  - Horizontal Cavity Tests
  - HOM absorbers
  - Couplers
  - Horizontal Cavity Tests
  - Main Linac Cryomodule
- HTC Beam Tests

Injector Cryomodule

Injector Cryomodule





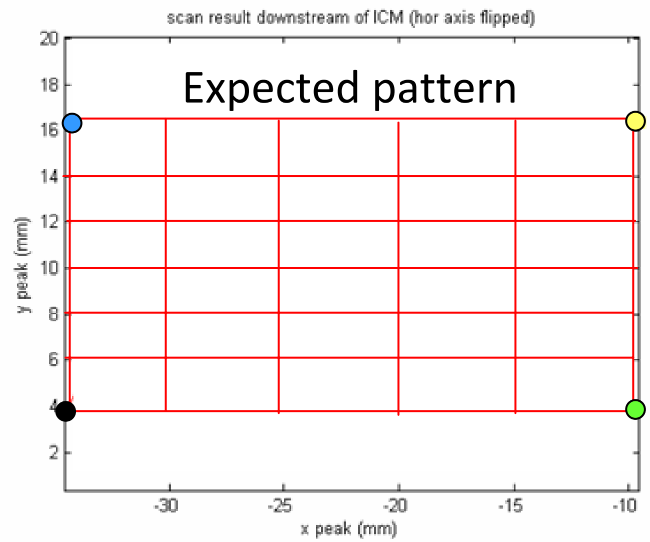
- 5 2-cell cavities (1-3 MV), 1300 MHz
- 2 opposing couplers per cavity (50 kW each)
- HOM loads
- Blade tuners
- Can deliver 500 kW of RF power to the beam

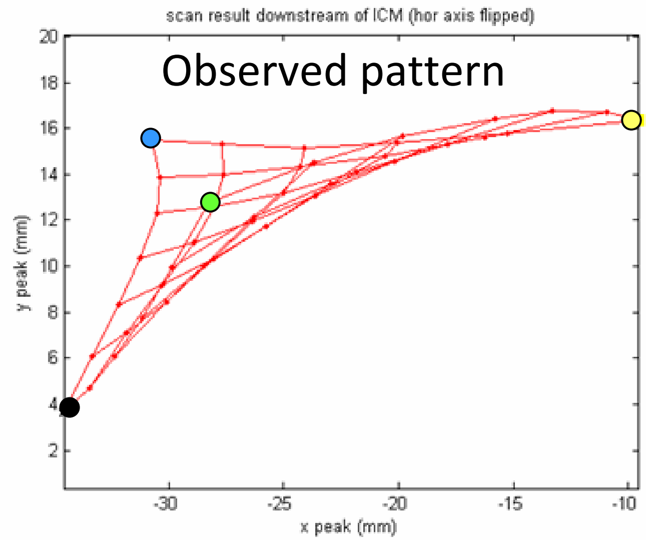
Issues

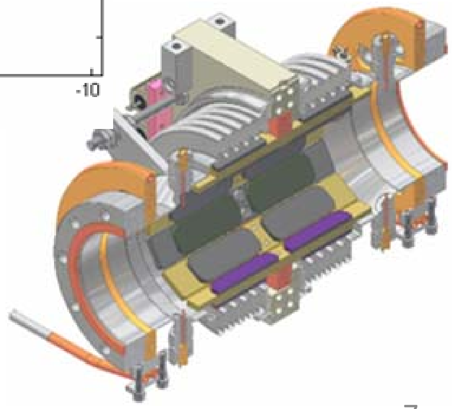
- Coupler conditioning (with beam)
- Coupler quadrupole fields –> beam asymmetry
- HOM RF absorbing tiles
- Coupler cooling
- Cavity alignment critical for low emittance

HOM Charging

Some of the RF absorbing tiles facing the beam became insulating at 80 K. Scattered electrons built up and the resulting electrostatic field distorted the beam. We removed half of the tiles, which still provides adequate HOM damping.

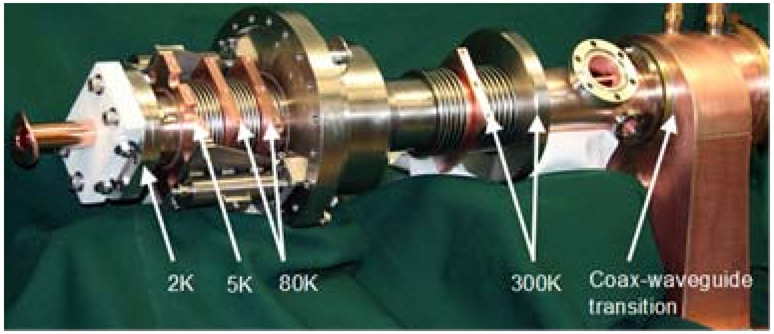


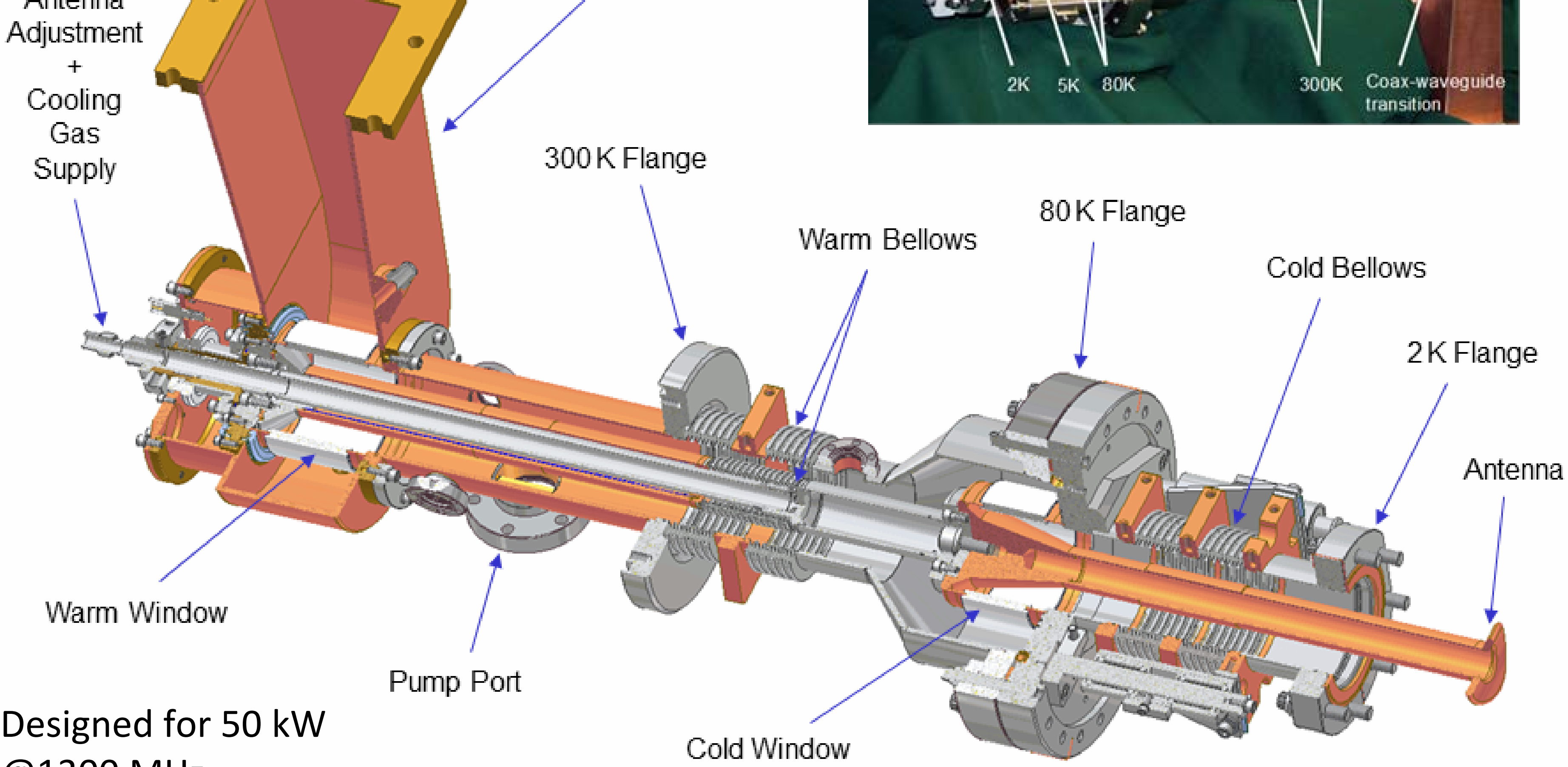




Rastering the beam in a square pattern in front of the cryomodule produce a distorted pattern after the cryomodule

Injector Coupler

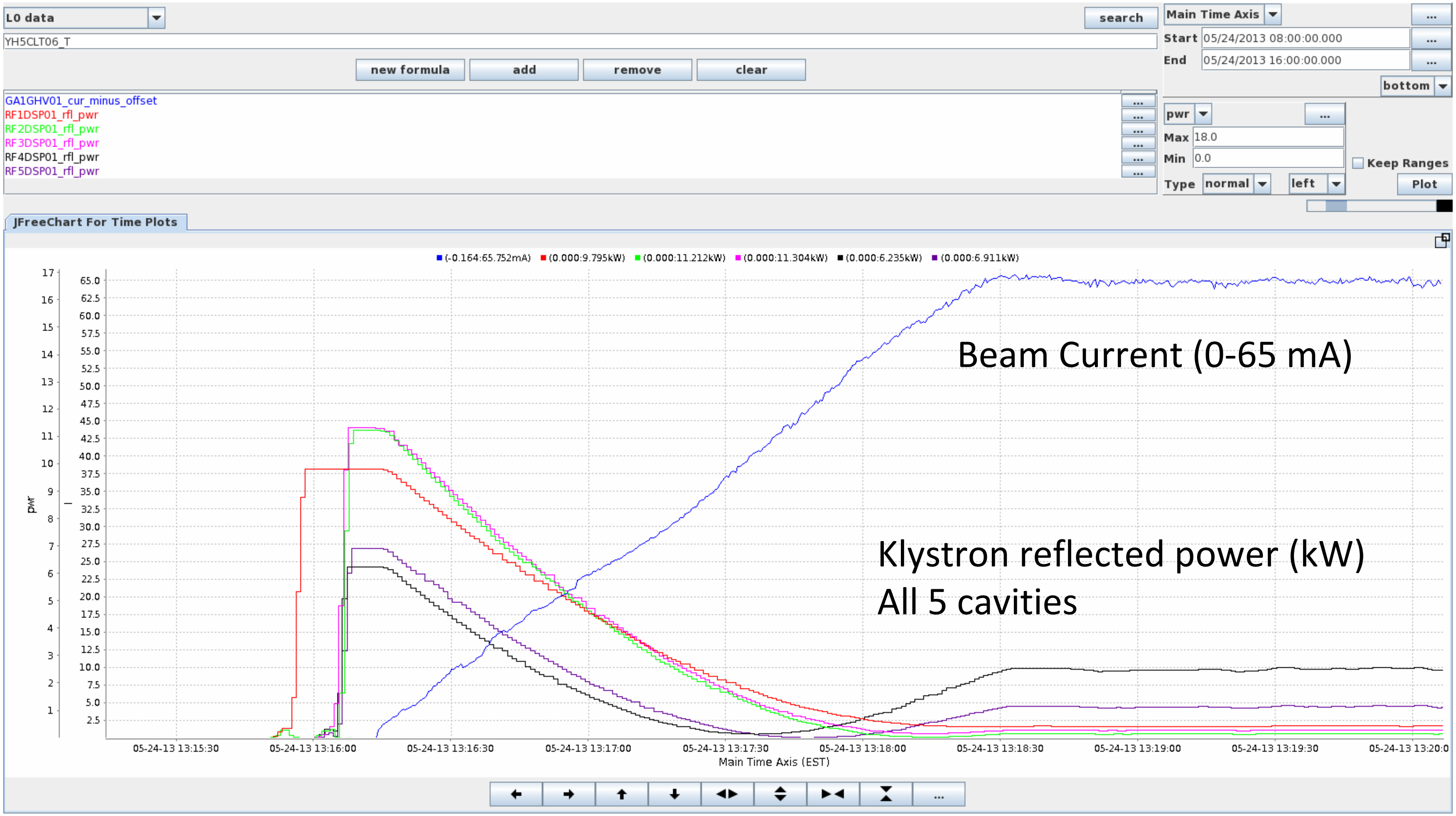




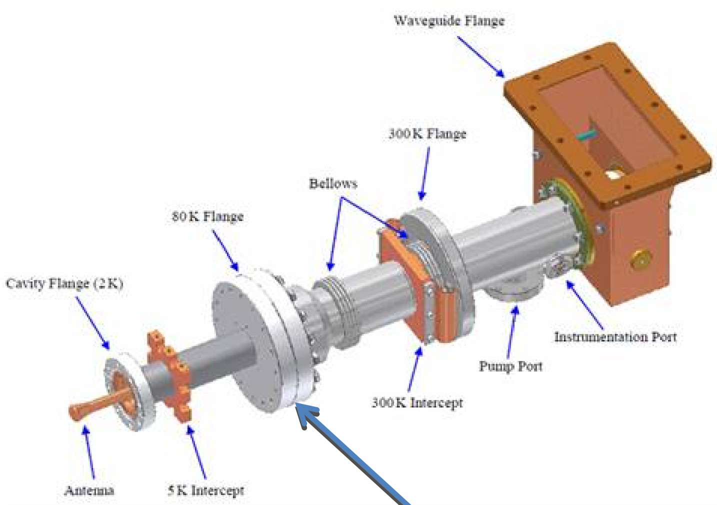
Designed for 50 kW @1300 MHz

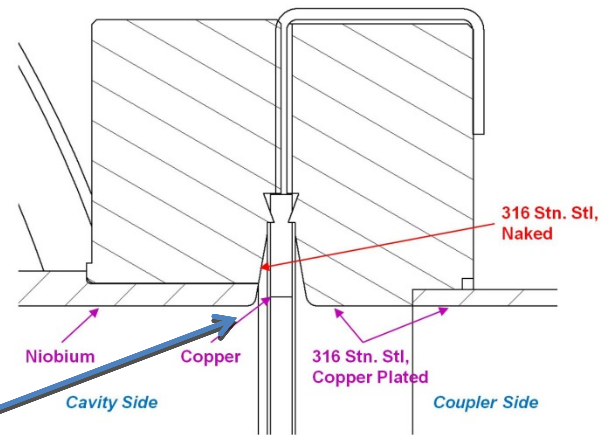
Adjustable coupling

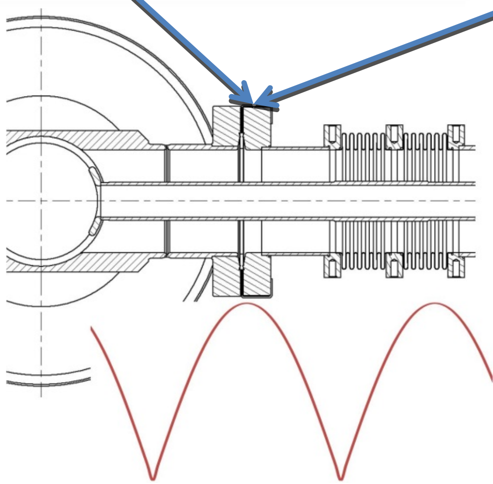
Couplers are adjusted to provide ~0 reflection at the desired current.



RF Coupler Heating Problems







Standing wave max at the flange joint causes excessive heating. A new joint was designed for future couplers.

Anomalous RF coupler heating has caused numerous problems with Q_0 measurements, coupler cooling (He flow), and extended running at higher RF powers. Increasing He flow and changing the antenna position (for high current) gives us enough margin.

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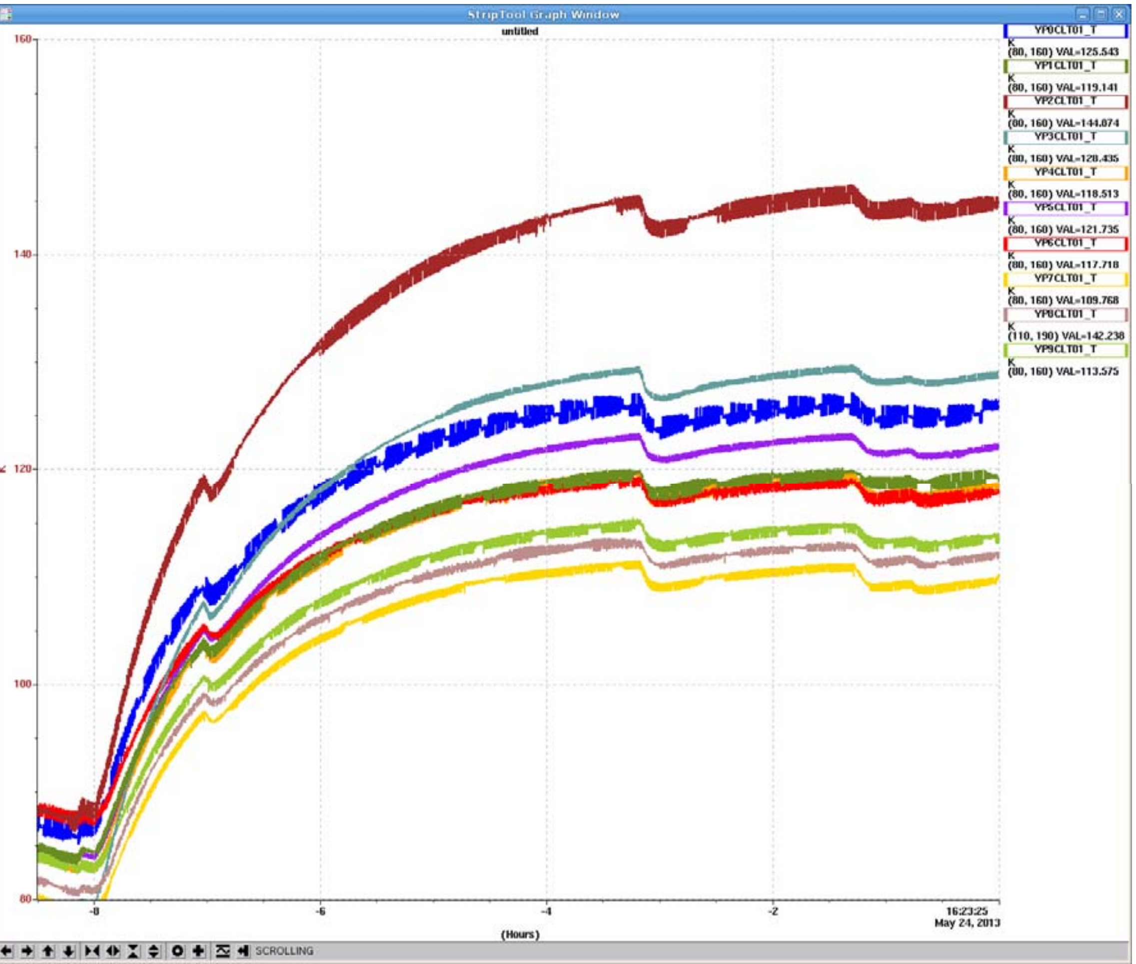
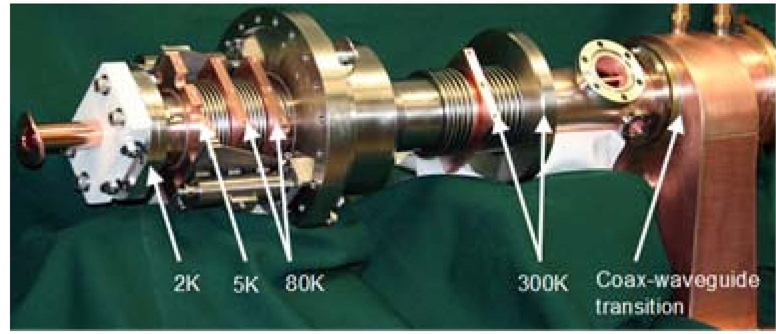
Coupler Heating



Temperatures reach equilibrium in 4 hours



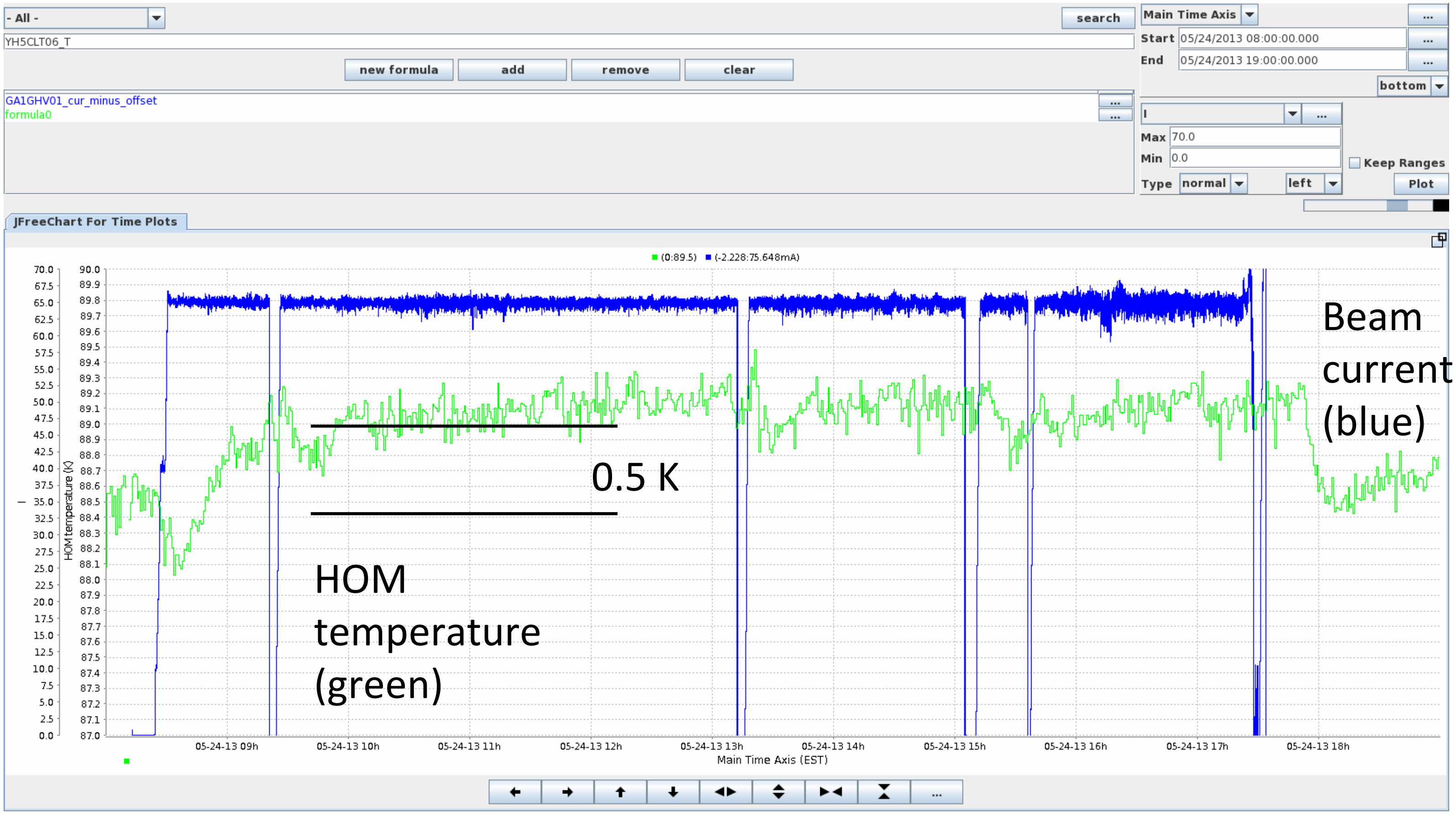
We found that the couplers get quite warm during high power operations.

The flow to the HOM's and couplers are in parallel, but we discovered the coupler tubing is too small. So the HOM's get more flow, and the couplers less than designed for.

Coupler Summary

- No dipole kick as we desire, but a 'quadrupole' focusing exists, distorts beam at low energies.
- First pair of couplers must be ***after*** the first cavity in the injector
- flange problem, fixed with new seal in next design iteration
- inadequate cooling – tubing diameter mismatch
- Need to use the beam for conditioning at high average powers

Do HOM loads heat up?



At most 0.5K temperature rise (65 mA, 4 MeV, 2-3 ps rms bunch length), corresponds to about 4 Watts per coupler

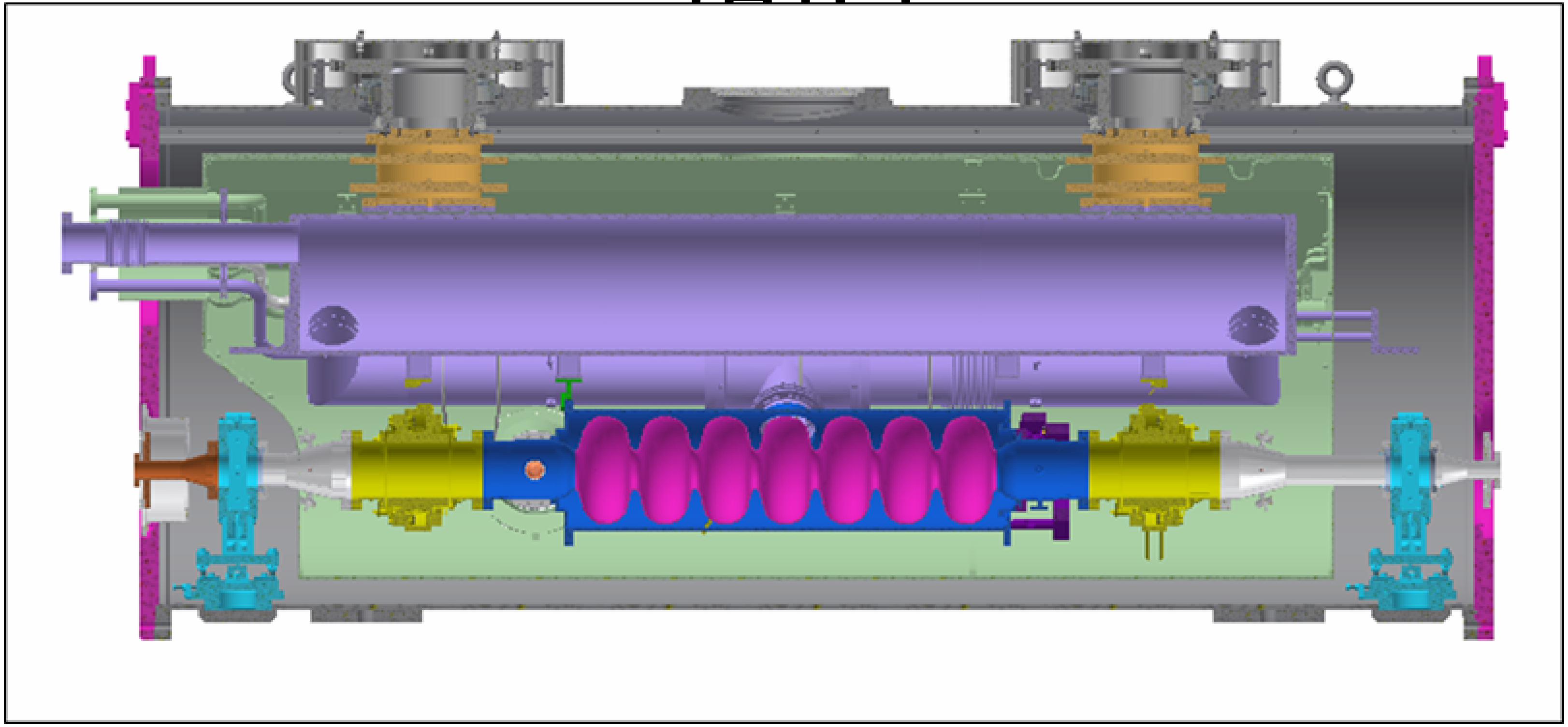
List of Issues/Improvements

Injector Cryomodule

- Centering the beam on the first two cavities is critical for emittance. Need 10 um alignment of beam to cavity centers (using two pairs of correctors before and a bpm after the ICM)
- really need bpm’s inside the cryomodule, plus another corrector
- HOM power ~4 Watts at 65 mA, 4 MeV (HOM’s overdesigned? Cavities designed well?)
- HOM loads and couplers are expensive and difficult to manufacture
- Need to improve coupler cooling
- Beam conditioning of couplers to reach high currents is necessary

ERL Main Linac: Cavities and Cryomodule

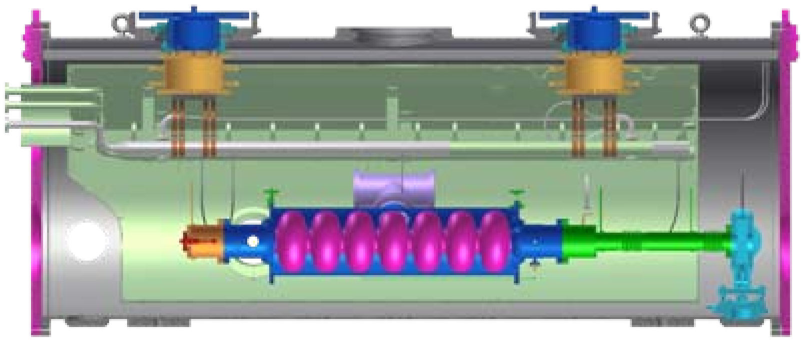
Horizontal Test Cavity (HTC)

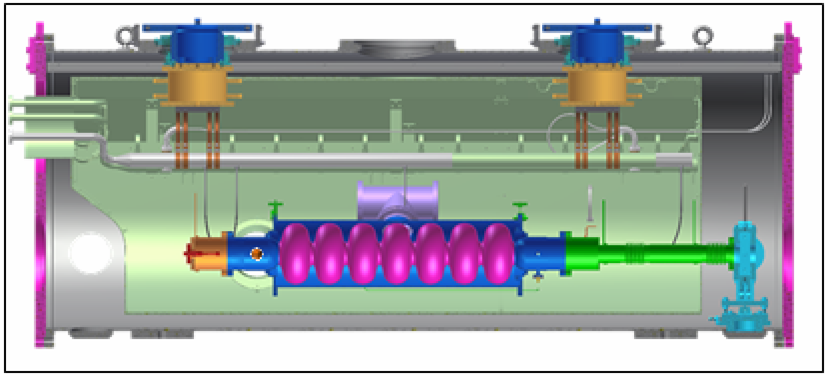


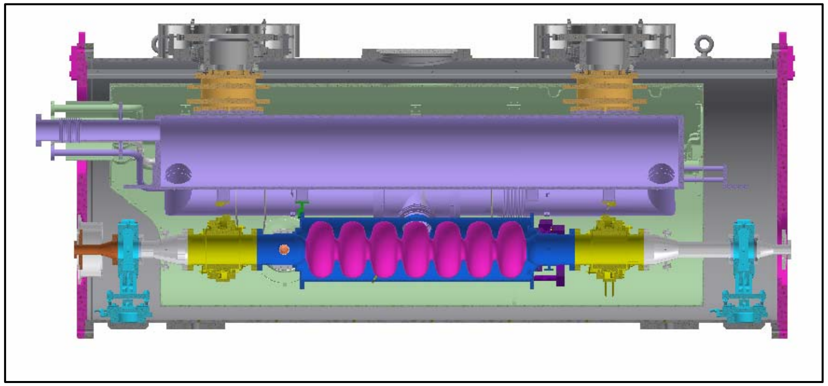
Tests to answer the question: *can cavity performance in a horizontal cryostat be as good as vertical tests?*

HTC Tests

- HTC-1: Follow vertical assembly procedure as closely as possible
- HTC-2: Include side mounted, **high power RF input coupler**
- HTC-3: Full cryomodule assembly-high power RF input coupler and **beam line HOM loads**

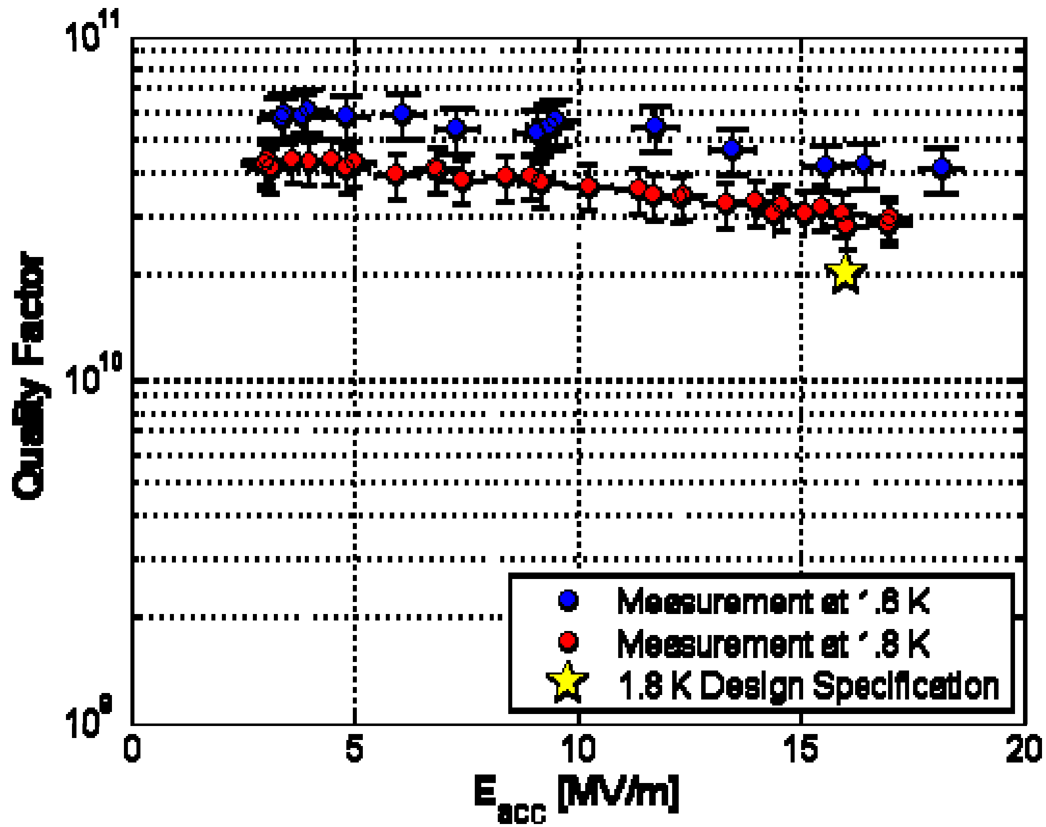




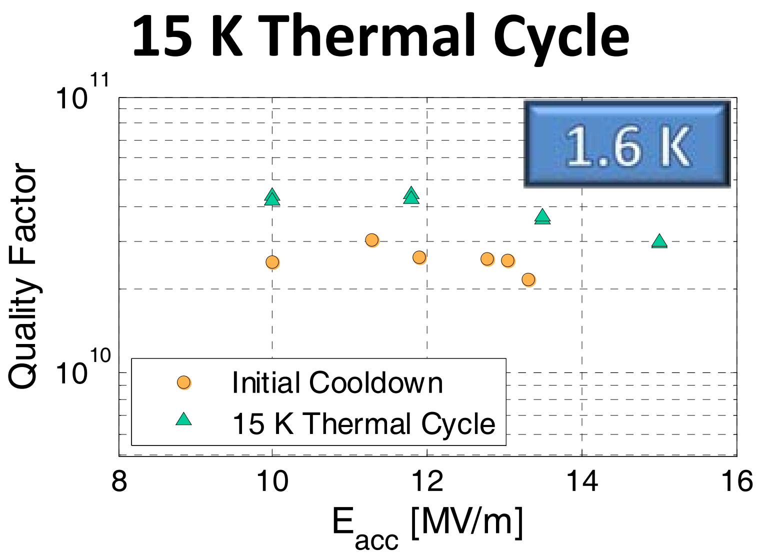


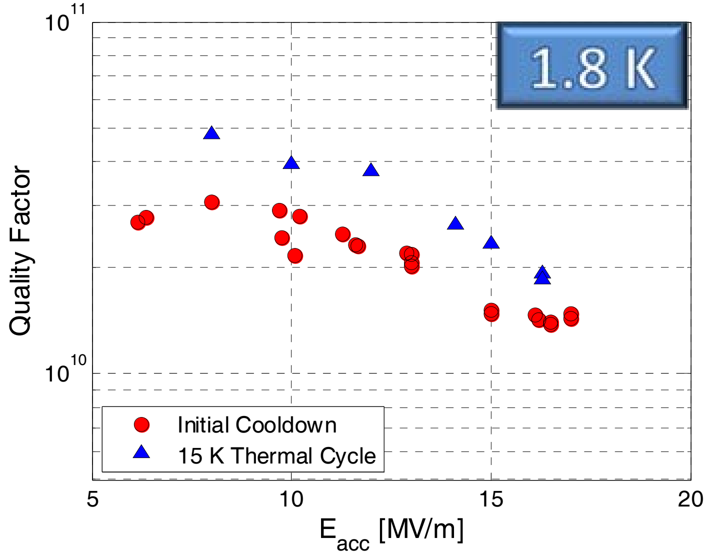
HTC-1: Results

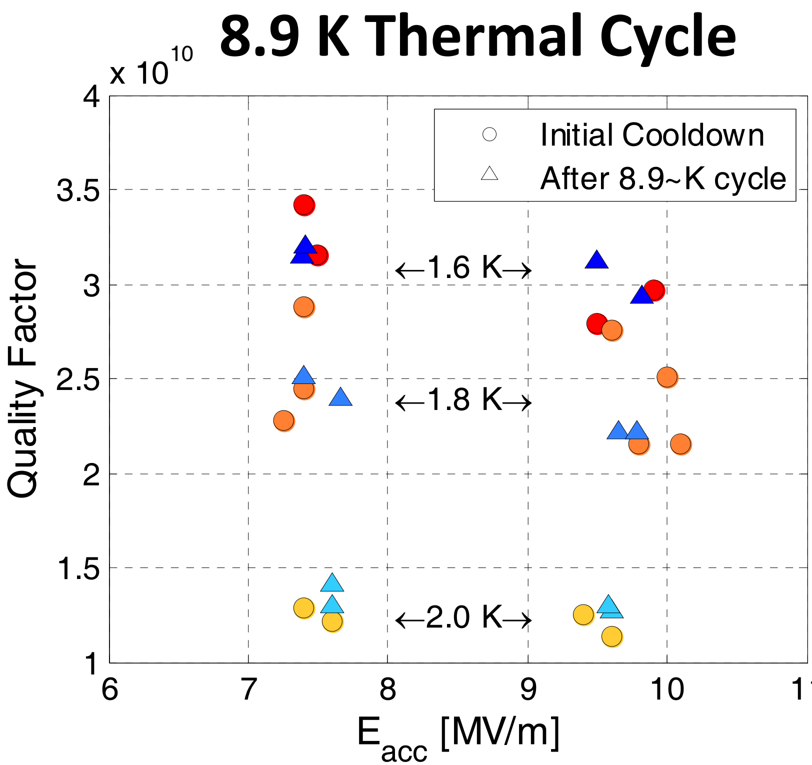
- Cavity exceeded Q specification at 1.8 K by 50%, reaching 3×10^{10}
- Q(1.6 K, 5 MV/m) = 6×10^{10}
- Exceeded gradient specifications
- RF-based and calorimetric-based Q measurements yielded consistent values



HTC-2 (cavity + coupler)





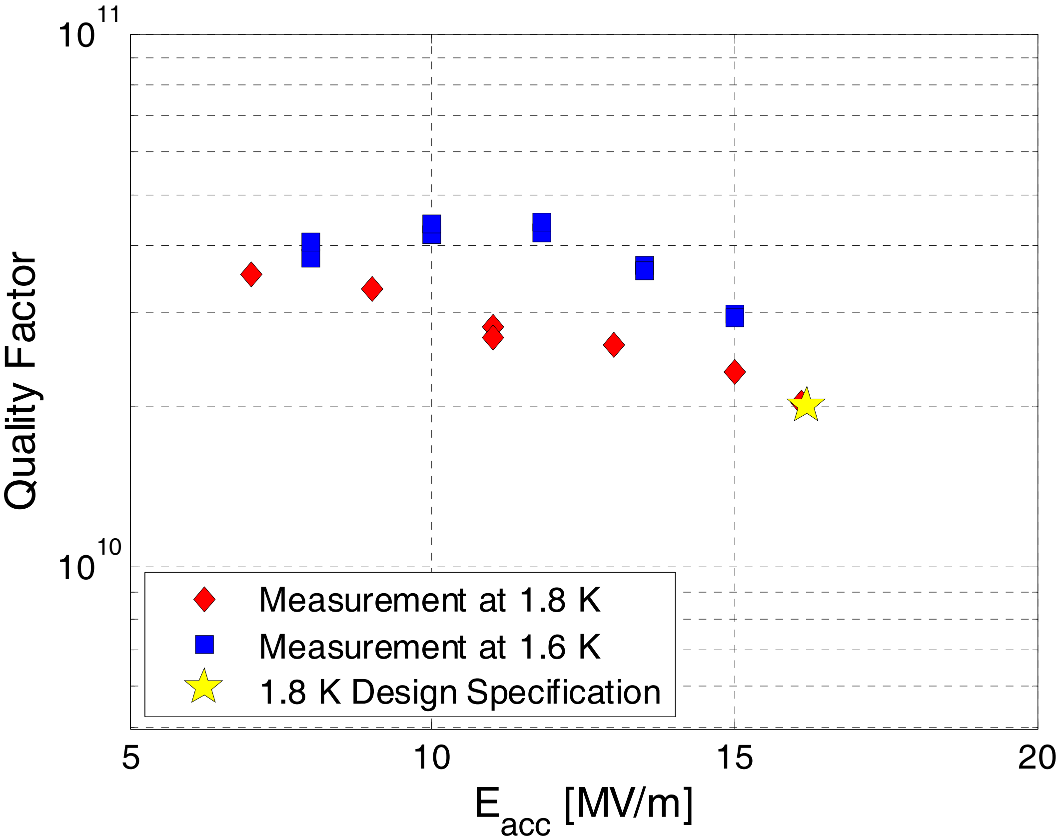


HTC-2 measurements did not find a statistically significant increase in Q for 8.9 K thermal cycle.

Benefit occurs for 8.9 K < T < 15 K

HTC-2: Results

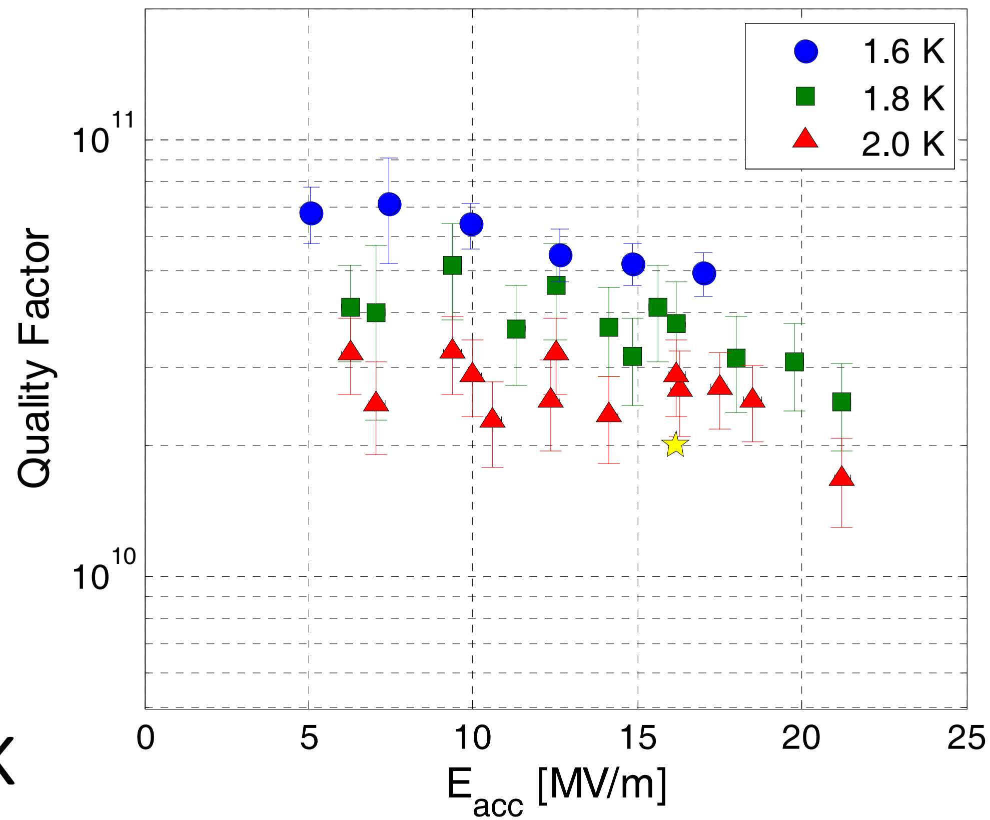
- Quality factor, gradient specifications achieved
- Administrative limits prevented higher field measurements (not limited by quench)
- Lower Q (than HTC-1) due to high radiation levels



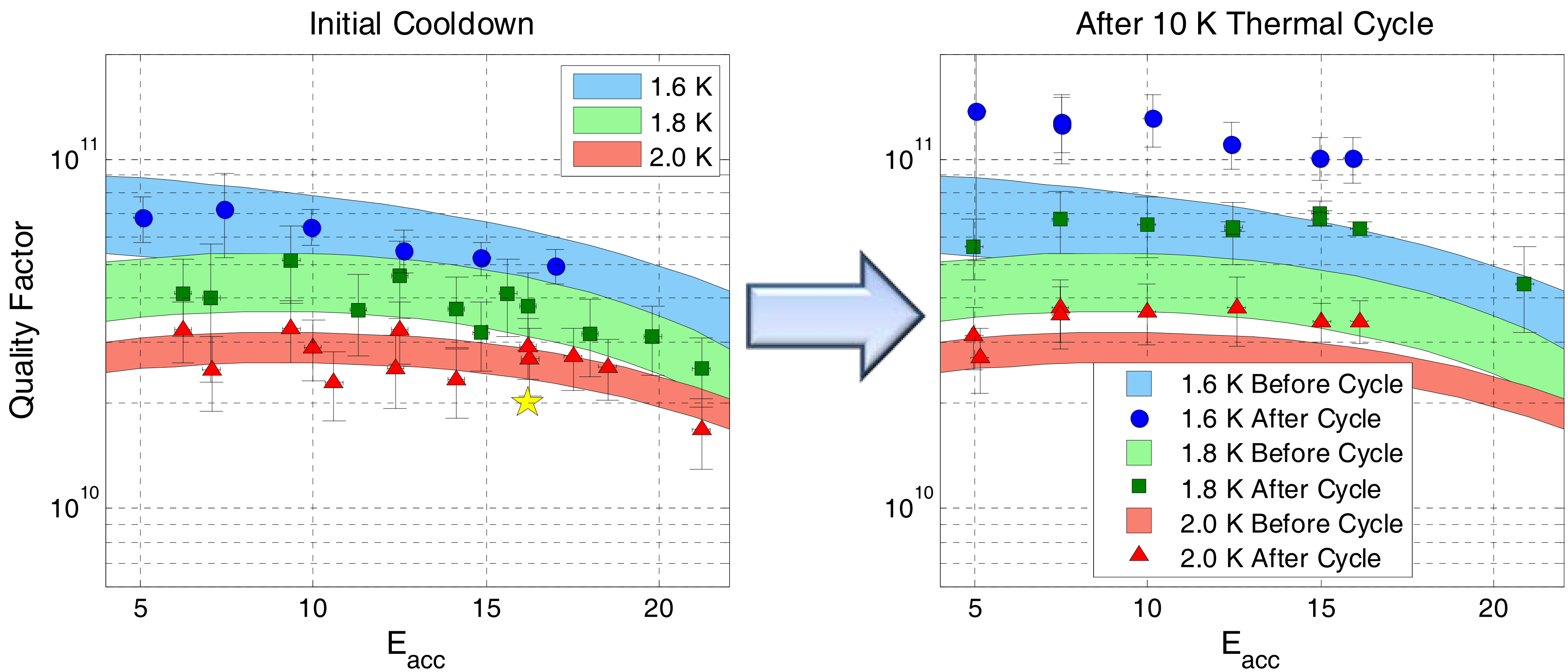
HTC-3 (cav+coupler+HOM)

- Initial Q vs E measurements performed using both digital LLRF system and phase lock loop system to cross check results

- Exceed Q, gradient, specifications on initial cooldown, even at 2.0 K



HTC-3: Results



Initial Cooldown at 16.2 MV/m

Q(2.0 K) = 2.5 x 10^{10}

Q(1.8 K) = 3.5 x 10^{10}

Q(1.6 K) = 5.0 x 10^{10}

10 K thermal cycle at 16.2 MV/m

Q(2.0 K) = 3.5 x 10^{10}

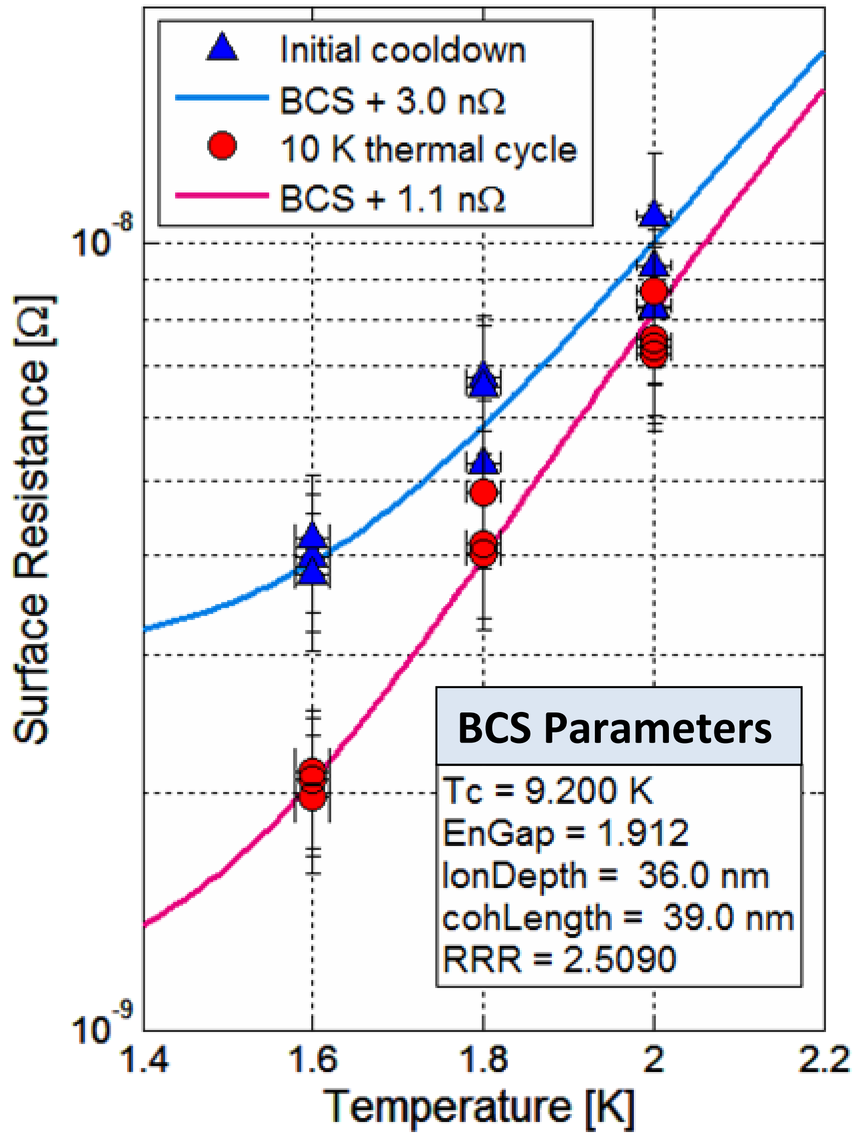
Q(1.8 K) = 6.0 x 10^{10}

Q(1.6 K) = 10.0 x 10^{10}

HTC-3: Nb properties

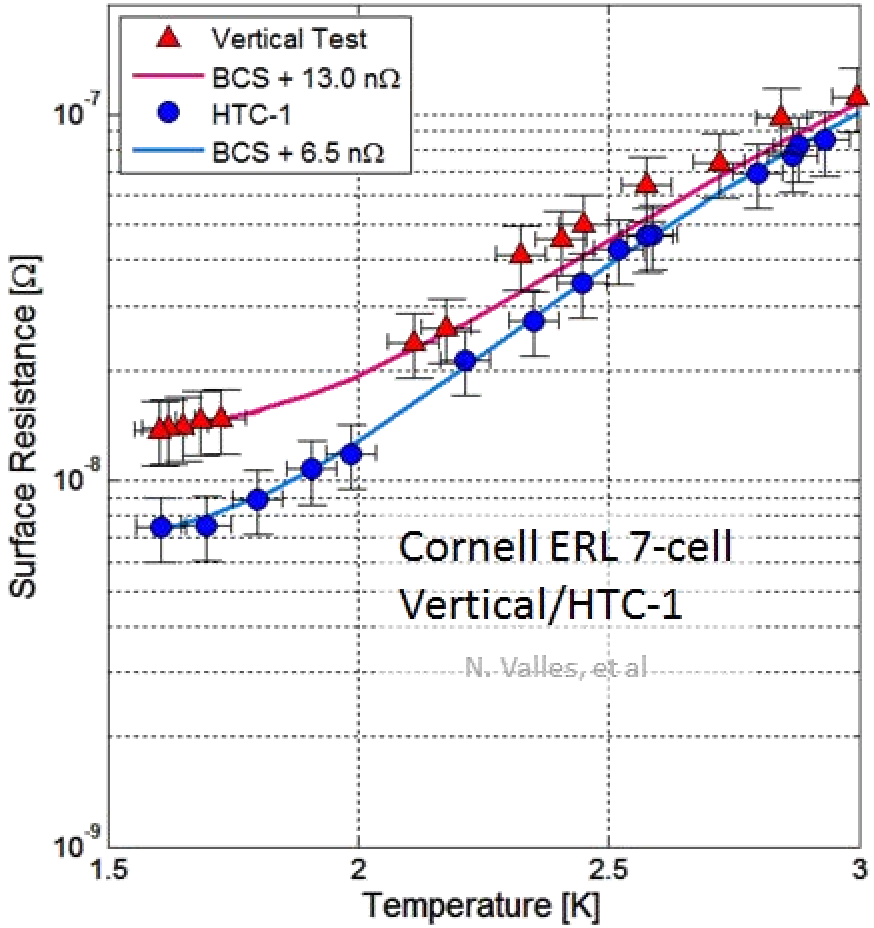
- SRIMP used to fit SRF properties of cavity before and after thermal cycle

- Assumption: Material properties remain constant during cycle. Only residual resistance changes.

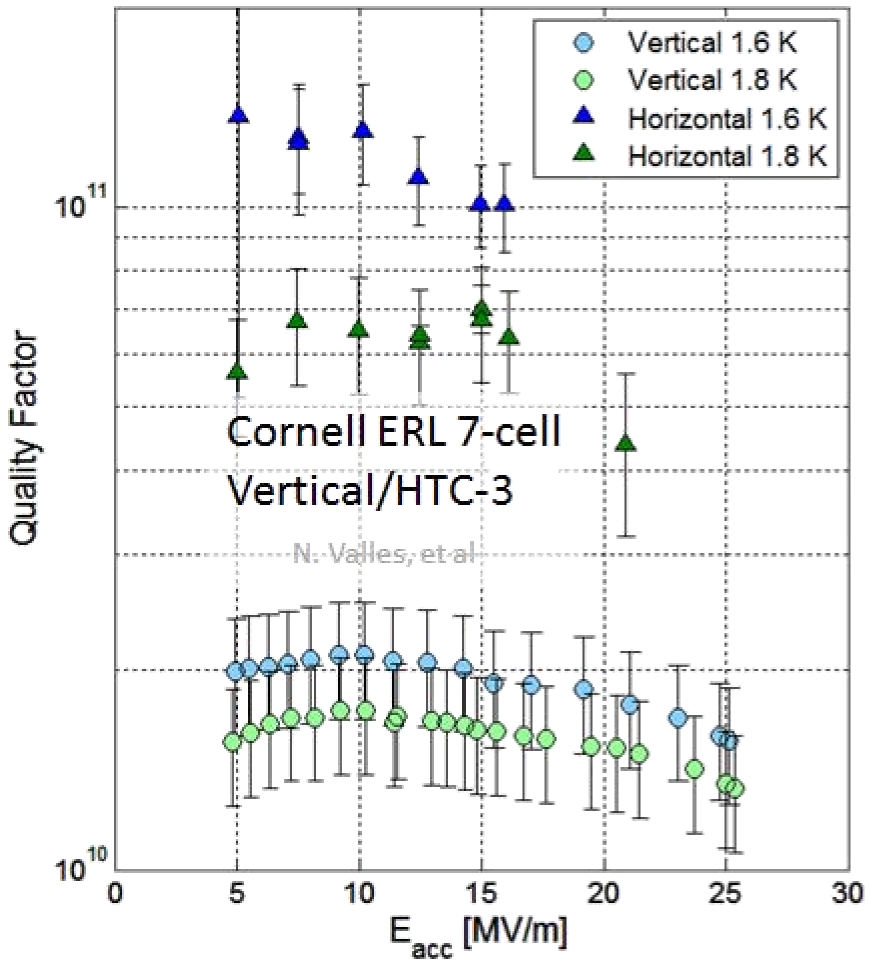


Vertical Test/Horizontal Test

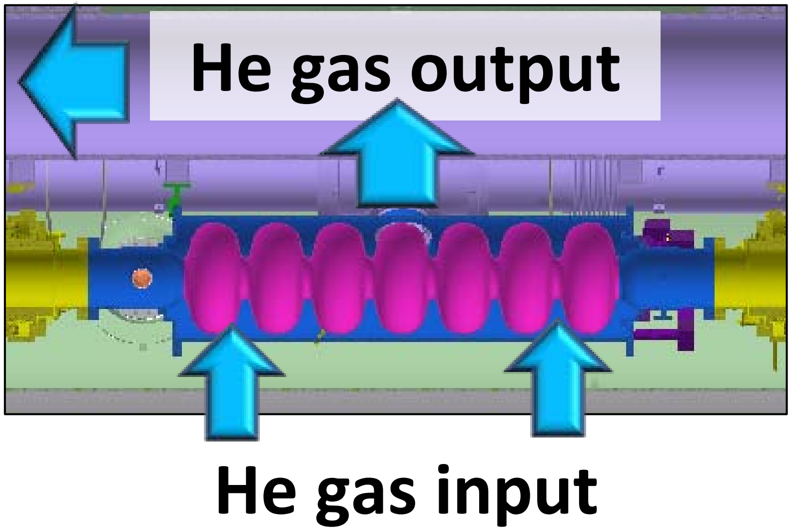
Surface Resistance Comparison
Vertical/HTC-1 Test



Quality factor vs Gradient
Vertical Test → HTC-3



High Q Cryomodules



- Magnetic shielding is essential
- Thermal gradients across cavity should be minimized to get high Qs
- Cavity temperature gradient ~0.2 K
- Cool down rate through T_c: ~ 0.4 K/hr

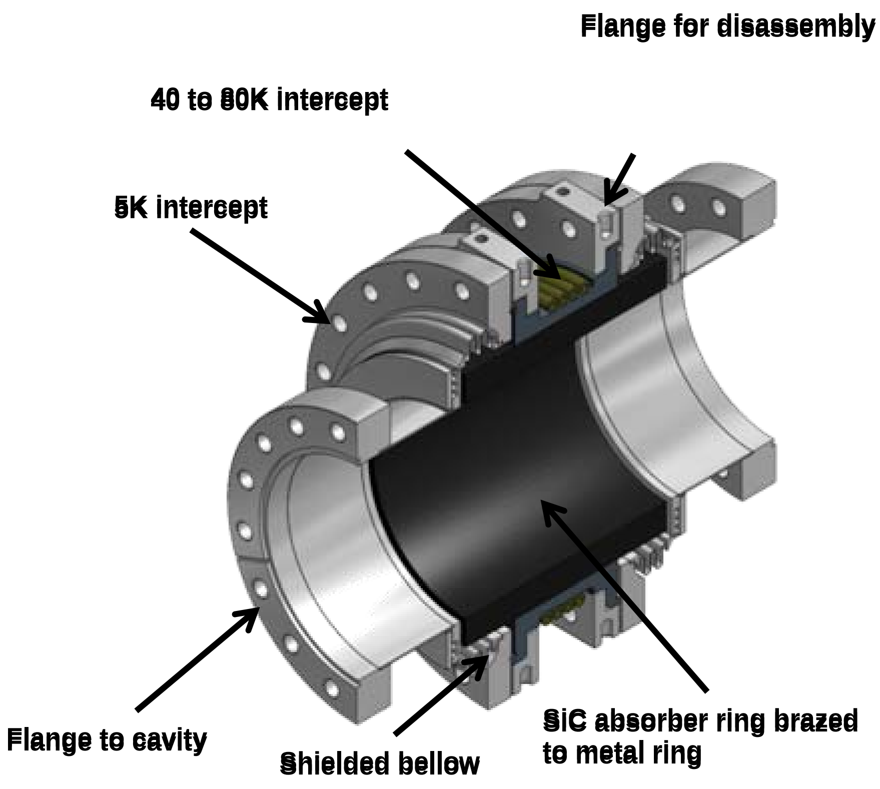
6 Cernox temperature sensors mounted on top and bottom of end cells and center cell

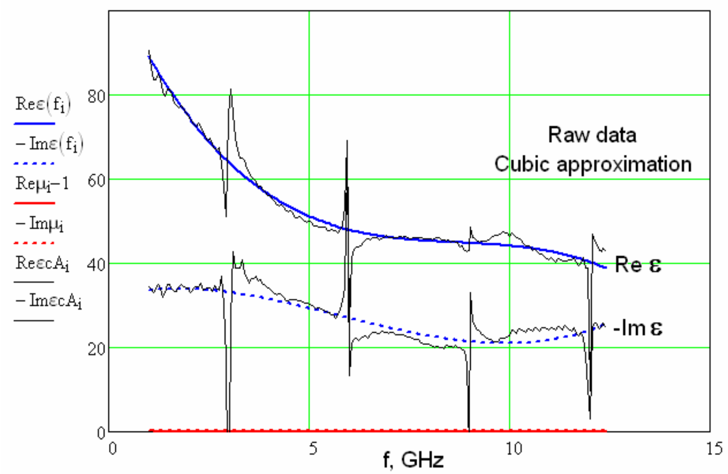
HTC Summary

- Prototype main linac cavity far exceeded Q, E specifications in horizontal test cryomodule
  - Gradient exceeds 20 MV/m without quench
- HTC-1: World record Q for multicell cavity in horizontal cryomodule Q(5 MV/m, 1.6 K) ~ 6×10^{10}
- HTC-3: Exceeded our own record, achieving Q(E ≤ 16.2 MV/m, 1.6 K) ≥ 10^{11}
  - Obtained 1.1 nOhm residual resistance
- Future: HTC being installed in ERL Injector for beam testing

HOM Absorbers for the Main Linac Cryomodule

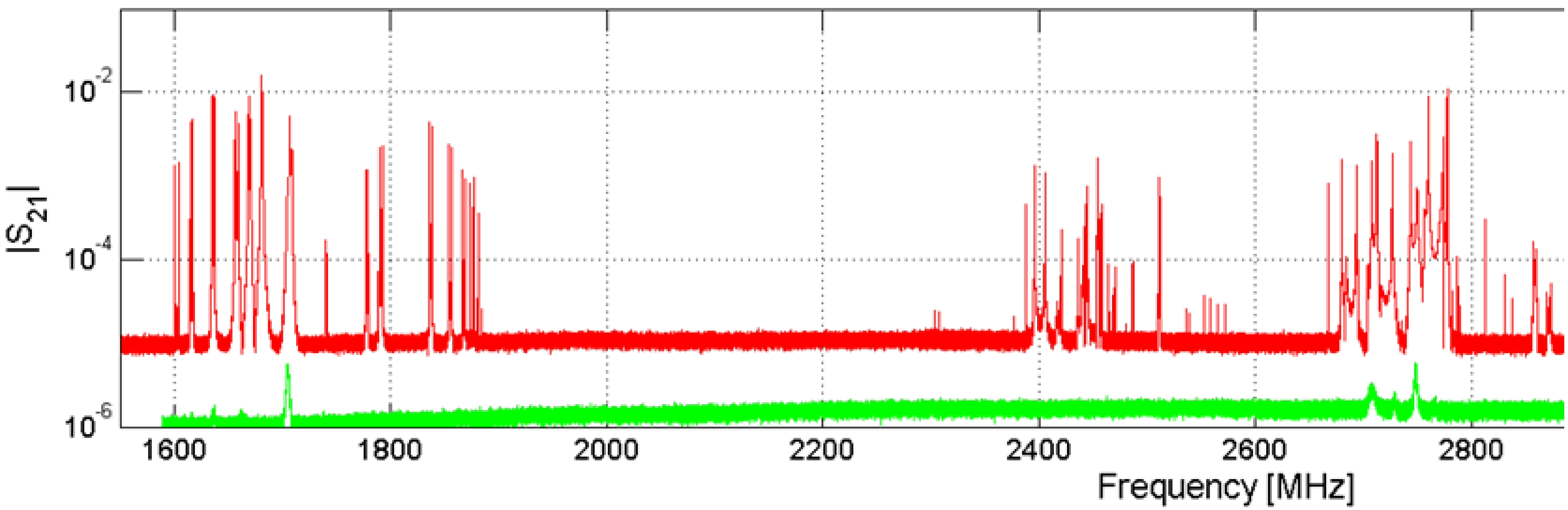
HOM absorbers



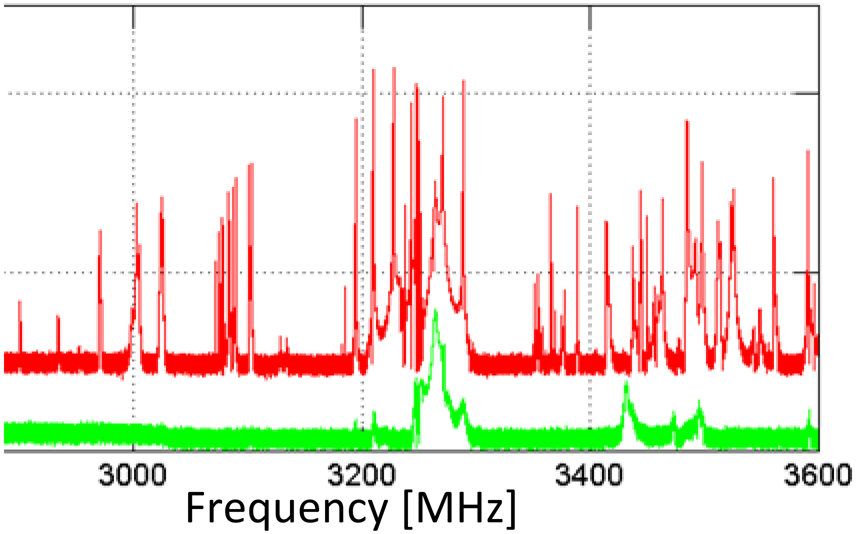


RF properties at 77K, scaled to ε_0

HOM Spectrum

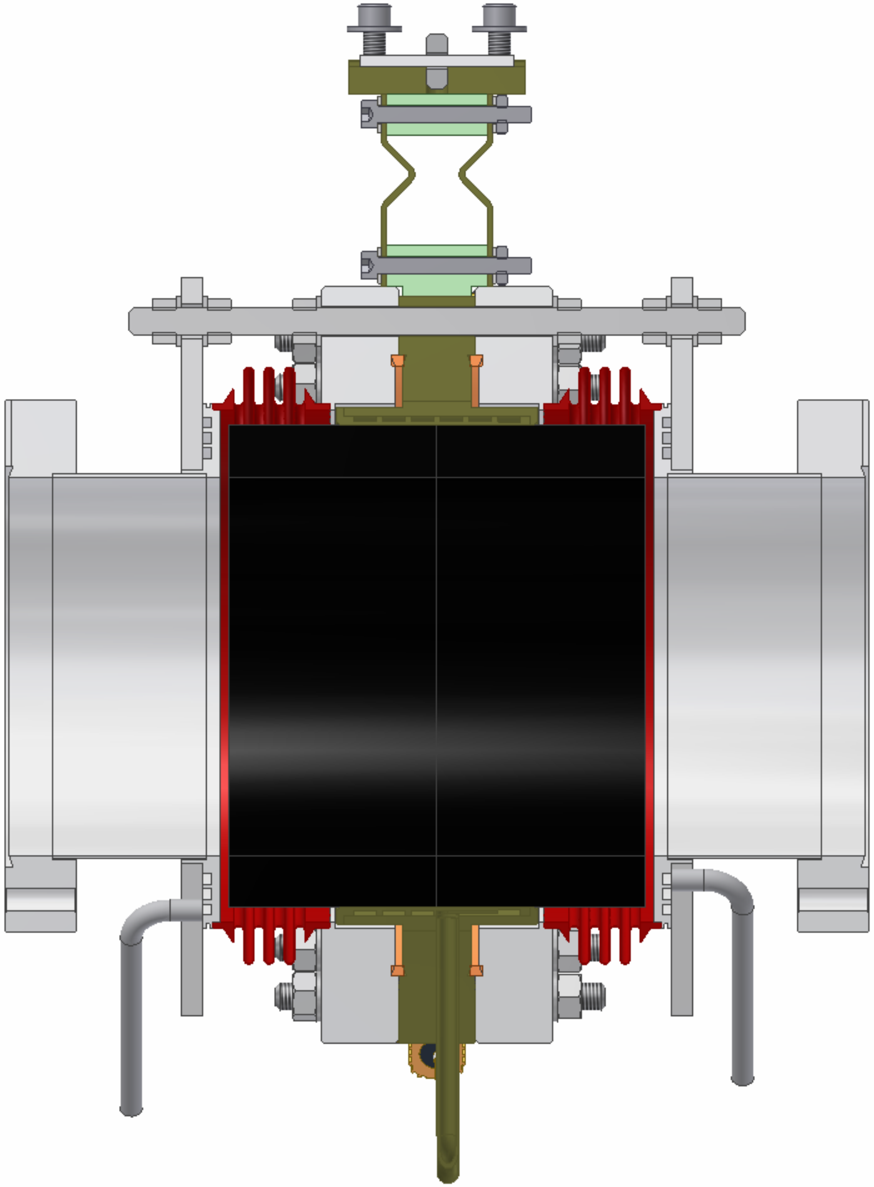


No HOM Loads
With HOM Loads



$Q_0 > 2*10^{10}$ for the fundamental mode

HOM – Next Steps



- SiC is not a nice material
- Strong outgasing
- High particle contamination
- Tends to chip

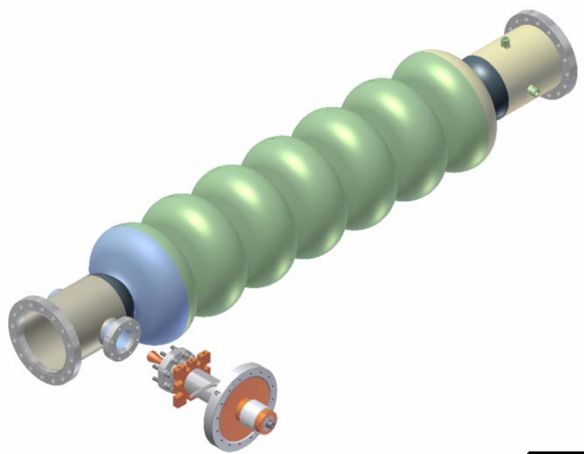
- Ceradyne Ceralloy® 1370CS AlN Absorber
- 250mm nominal length ±6mm
- Welded Titanium Cooling Sleeve shrink fitted to AlN cylinders provides 80K cooling
- Welded SS grooved plate provides 5K thermal anchor
- 8 – 50W heaters mounted to outside to provide up to 400W auxillary heating

Main Linac Couplers

ERL Main Linac Coupler

Each 7-cell cavity of the Cornell ERL Main Linac has one coupler

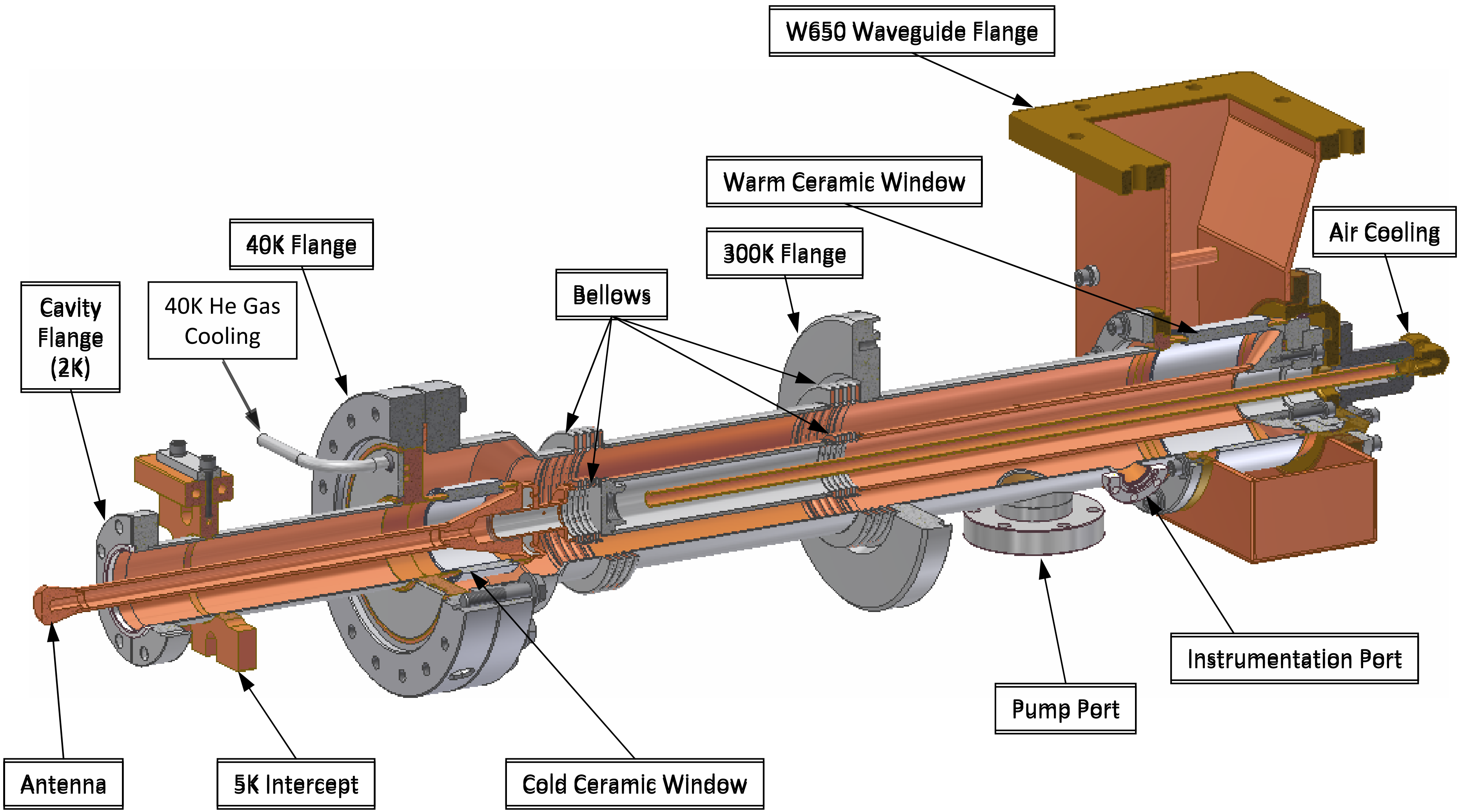
Operating frequency	1.3 GHz
Maximum power (CW)	5 kW
Q_{ext} (fixed)	6.5×10^{7}



Heat Load for 5 kW of RF power

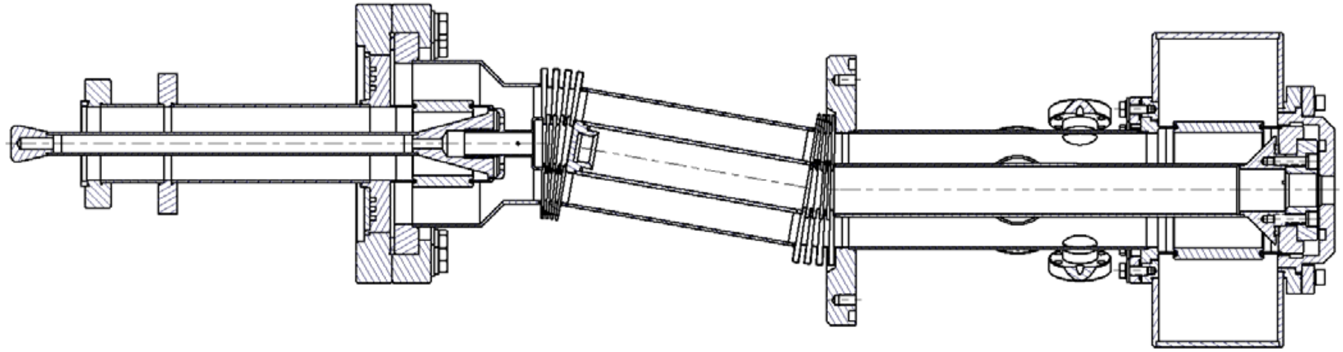
	Static Heat Load	*Dynamic Heat Load*	*Full Heat Load*
To 2 K	*0.05 W*	*0.06 W*	*0.11 W*
To 5 K	*0.64 W*	*0.32 W*	*0.96 W*
To 40 K	*3.78 W*	*5.94 W*	*9.72 W*

ERL Main Linac Coupler



ERL Main Linac Coupler

Coupler has great flexibility for accommodating large movement (> 10 mm) of cold mass inside the cryomodule during the cool down.



Summary of the Main Linac coupler performance:

- Two couplers have been fabricated by CPI, Beverly and tested at Cornell on the test stand up to 5 kW CW. No major issues were noticed during the test.
- One coupler was attached to the prototype linac cavity. The cavity was successfully tested (w/o beam) with great results achieved inside the horizontal test cryomodule (HTC).
- Five more couplers are ordered for the Main Linac Cryomodule (MLC) Prototype.

7-cell Cavities

7-cell cavities

Un-stiffened cavities (#2, #3, #4)

All cavities were designed, built and tested at Cornell

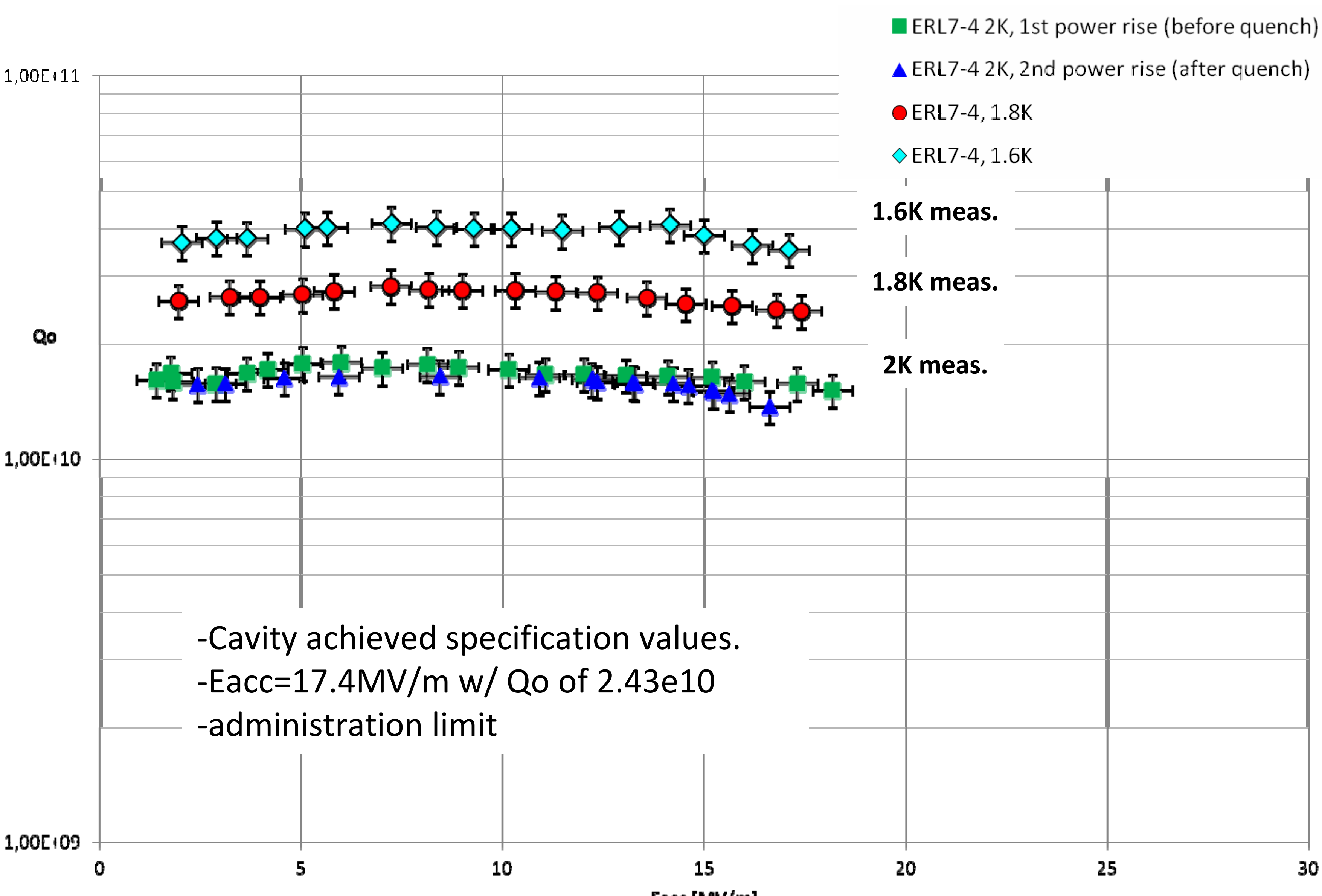
ERL 7-cell surface preparations

1.Bulk BCP	(140um)
2.Degassing in TM furnace	(650C*4days)
3.Freq. and flatness Tuning	
4.Final BCP	(10um)
5.120C bake in TM furnace	(120C*48hrs)
6.HF rinse	
7.VT w/ T-map	

Process summary, un-stiffened ERL 7-cells

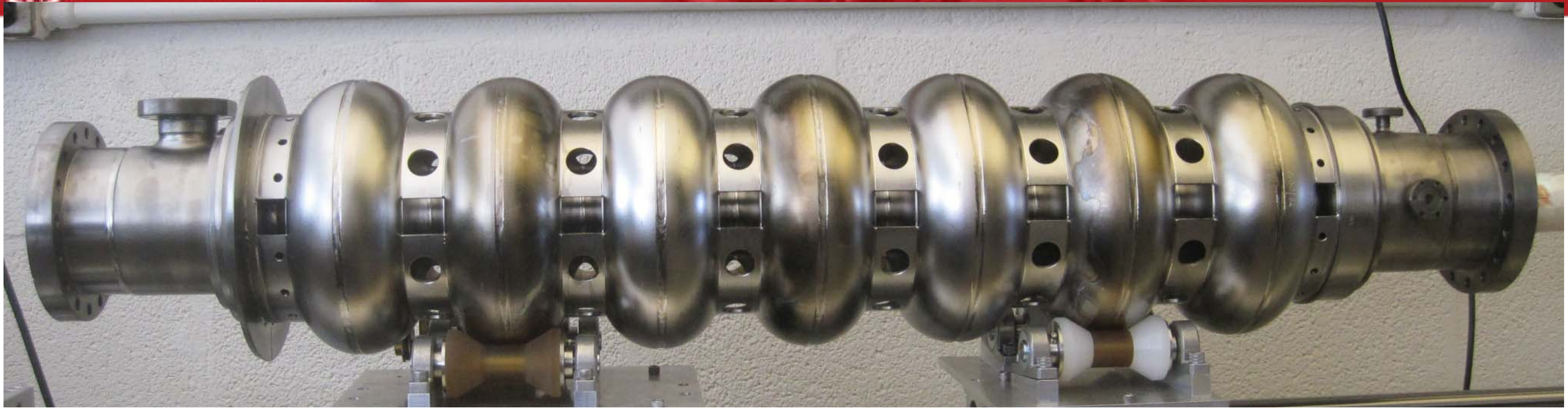
	ERL7-1 (HTC)	ERL7-2	ERL7-3	ERL7-4
Bulk BCP	140um (witness sample)	135±10 um (cavity equator)	138±5 um (cavity equator)	132±7 um (cavity equator)
Degassing	Jlab, 650C*10hrs	TM-furnace 650C*4days	TM-furnace 650C*4days	TM-furnace 650C*4days
tuning	88%	94%	91%	92%
Final BCP	10 um	10 um	10 um	10 um
120C bake	On insert	TM-furnace	On insert	TM-furnace
HF rinse	No	Yes	Yes	Yes
VT 1^{st} (1.8K)	17MV/m, 1.6e10 (No T-map , old insert)	17MV/m, 1.53e10 w/ T-map	Limited by FE w/ T-map	17.4MV/m, 2.4e10 w/ T-map
	HTC1, HTC2 (high rad)			
Re-process	-BCP(10um) -120C bake(in clean room, old set-up) -HF rinse	-Cavity length is too long, re-built & re-test are planed	Re-process to cure FE -BCP(10um) -120C bake(TM-furnace) -HF rinse	
	HTC3, 16.2MV/m, 6.0e10 @1.8K			
VT 2^{nd} (1.8K)			17MV/m, 2.8e10 No T-map (PC down)	
Next		Re-built	He vessel welding	He vessel welding

Vertical Test cavity #4



-Cavity achieved specification values.
-Eacc=17.4MV/m w/ Qo of 2.43e10
-administration limit

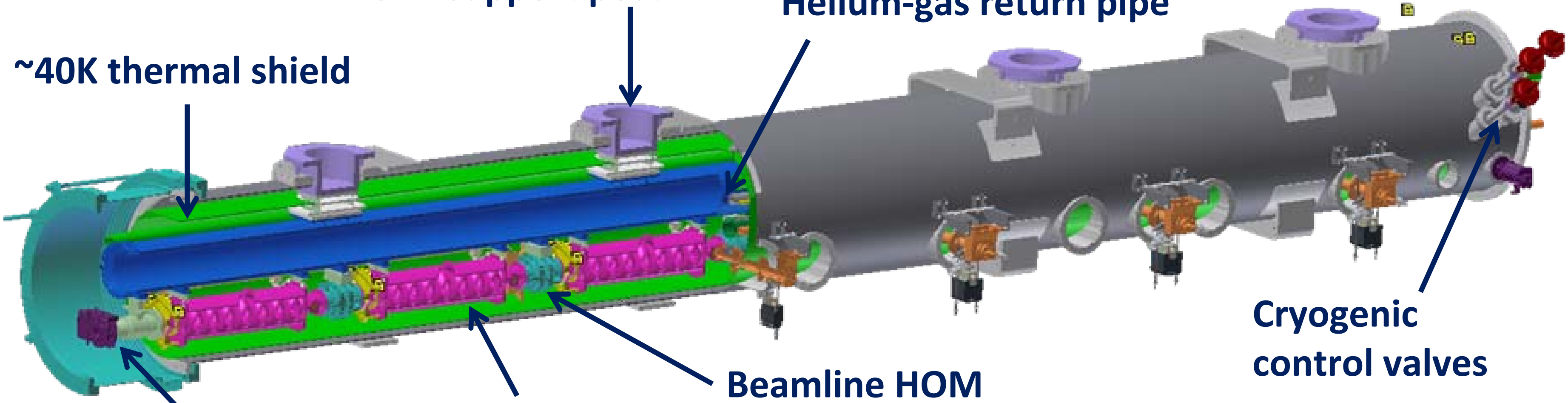
First Stiffened Cavity



Outline

Cryomodule

Cryomodule



- Acceleration gradient — 16.2 MV/m
- Q_{ext} — 6.5×10^{7}
- RF power per cavity — 5 kW
- Amplitude stability — $2\text{x}10^{-4}$ (rms)
- Phase stability — 0.1° (rms)

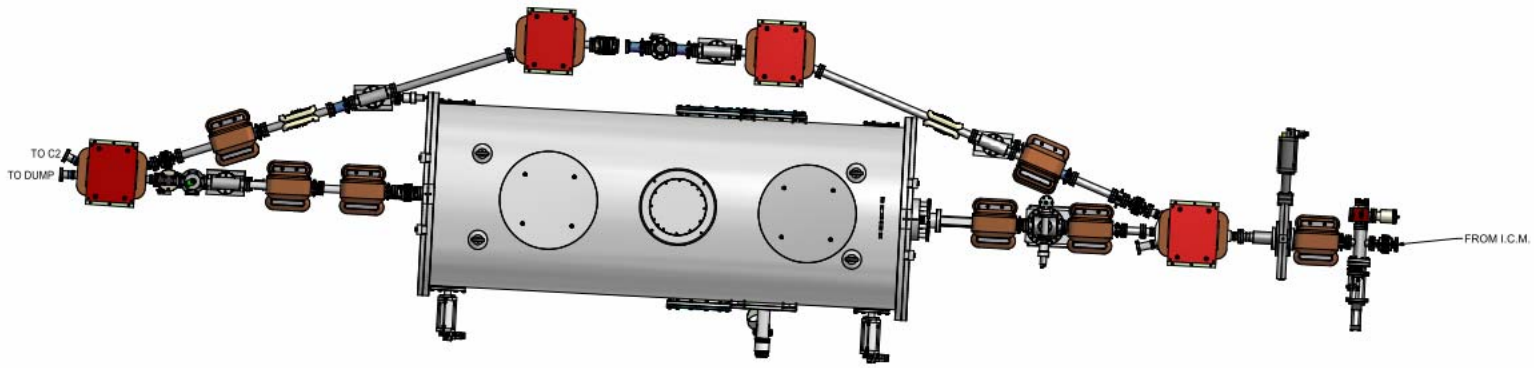
<u>STATUS</u>

Design complete

Procuring parts

Construction starting

What's Next?



Summer:

Install the 7-cell cavity (horizontal test cryostat) in the injector

Fall-Spring:

- Measure higher-order cavity modes using the beam*
- Transport high average current (7-cell cavity off) to test new HOM loads
- Continue to push current up towards 100 mA

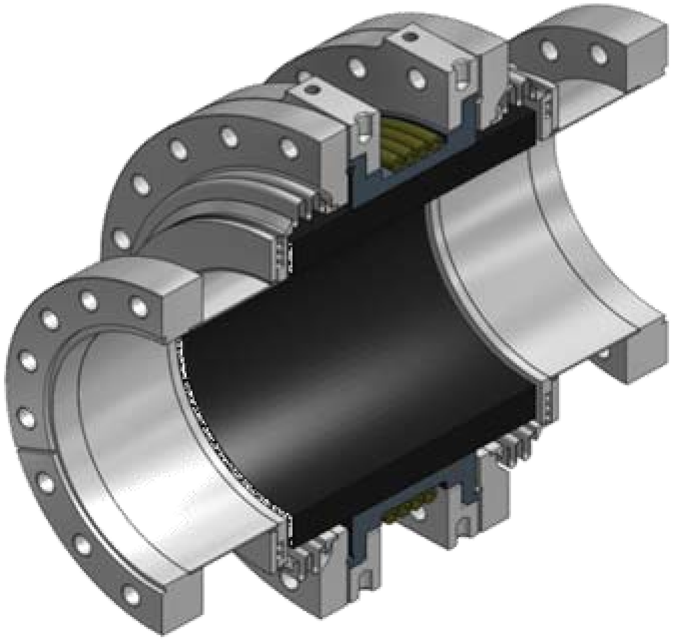
*following N. Baboi, 'Studies on Higher Order Modes in Accelerating Structures for Linear Colliders"

Outline

This work is supported by the National Science Foundation grant

DMR-0807731

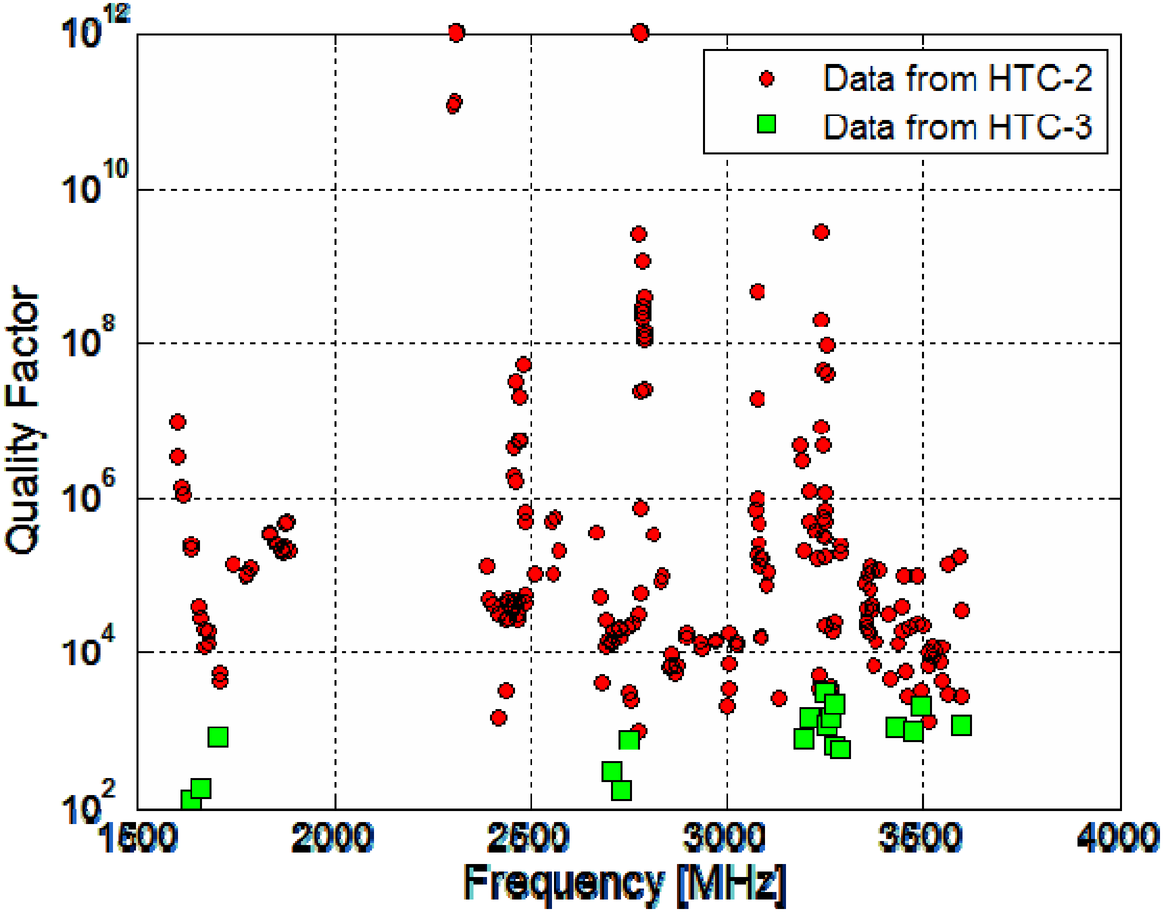
HOM Damping in the HTC



Beamline HOM absorbers strongly damp dipole HOMs to under Q ~ 10^4

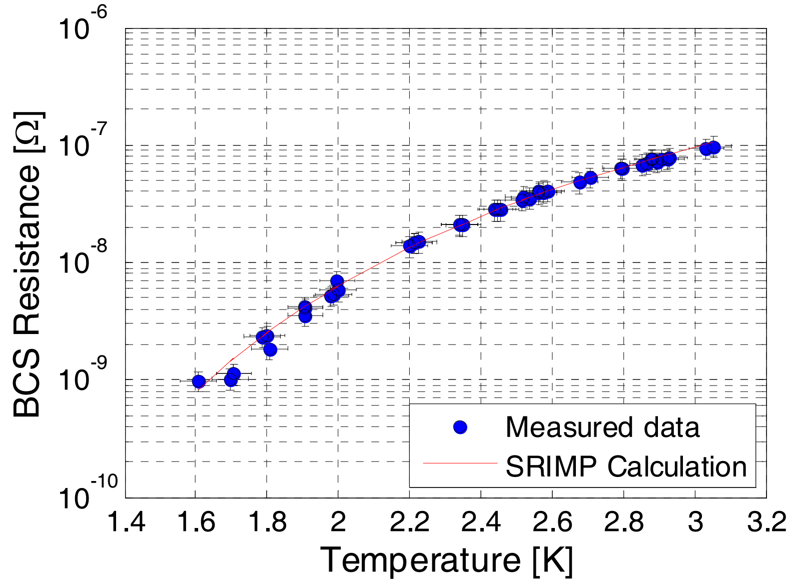
HTC-2: No HOM Absorbers

HTC-3: With HOM Absorbers



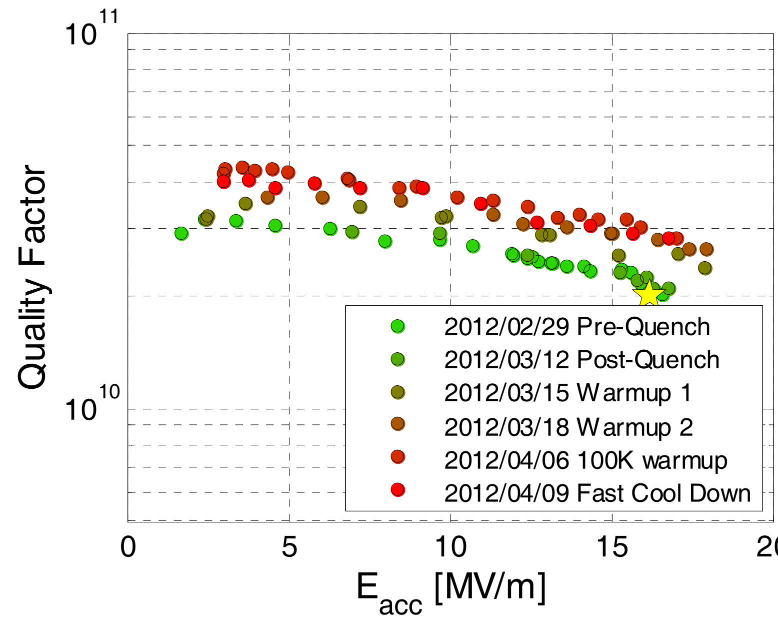
HTC-1 (cavity only)

Superconductor properties



- $T_c = 9.15$ K
- Resid. resistance = 6.5 nΩ
- RRR of RF layer = 11.8

Thermal Cycling Investigation



Temperature Cycling

- First cycle > 10 K
- Second cycle > 15 K
- Final cycle > 100 K