SRF Experience with the Cornell High-Current ERL Injector Prototype

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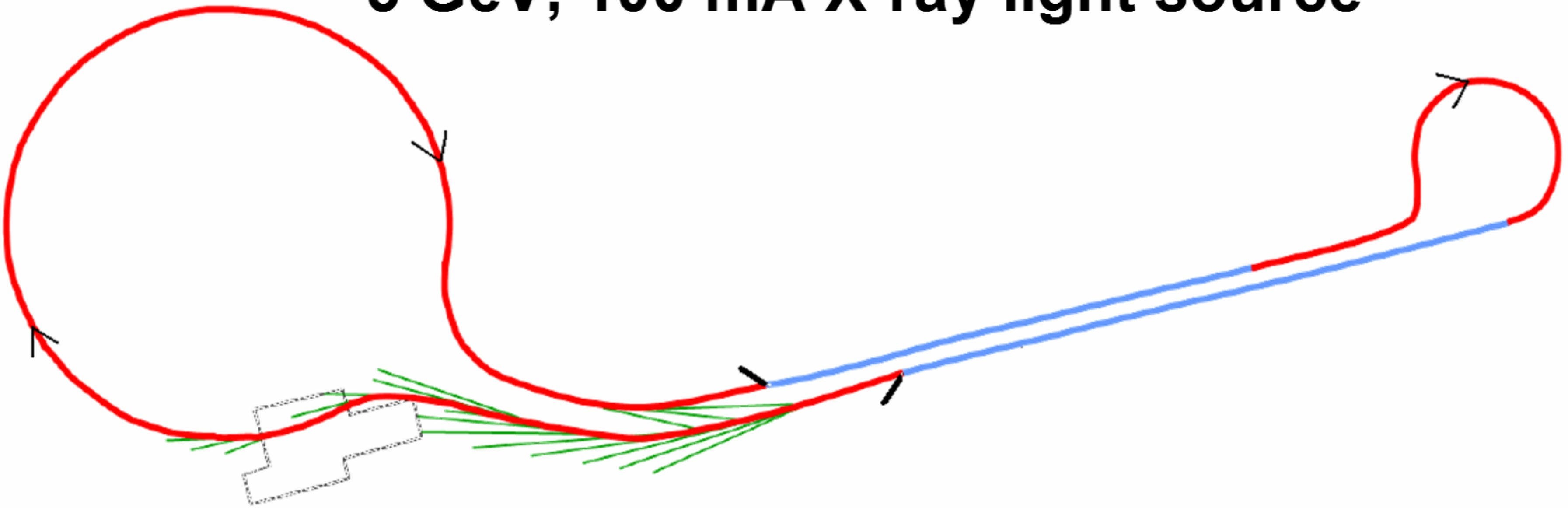
Cornell ERL:
5 GeV, 100 mA X-ray light source



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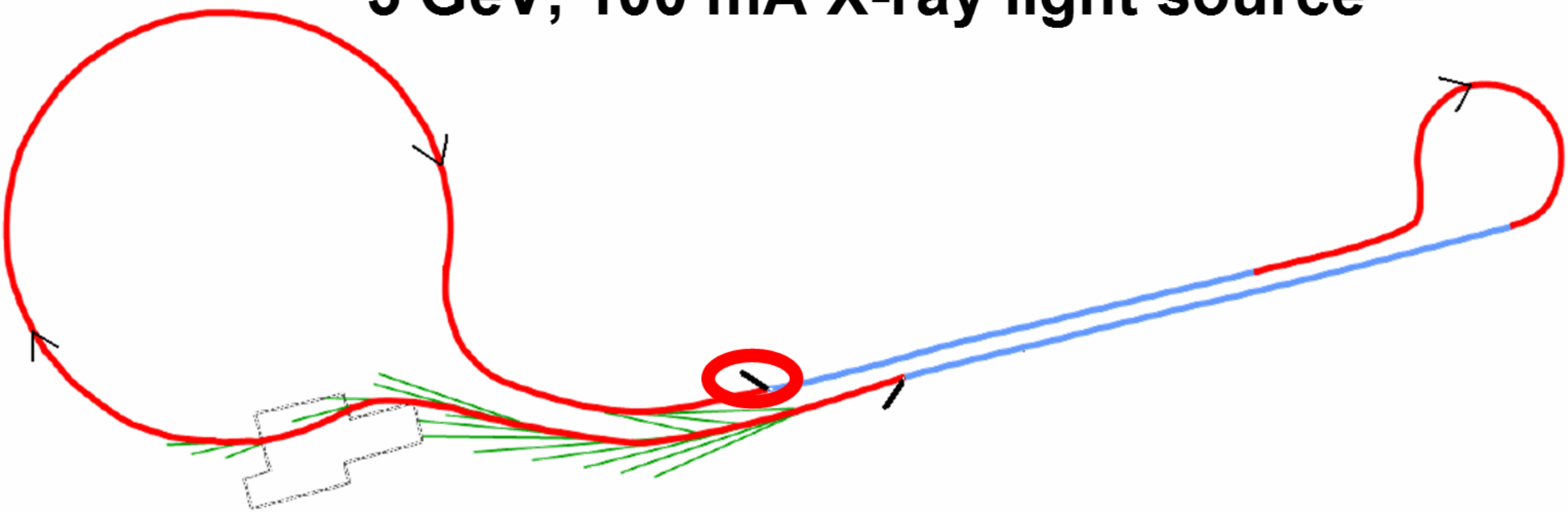
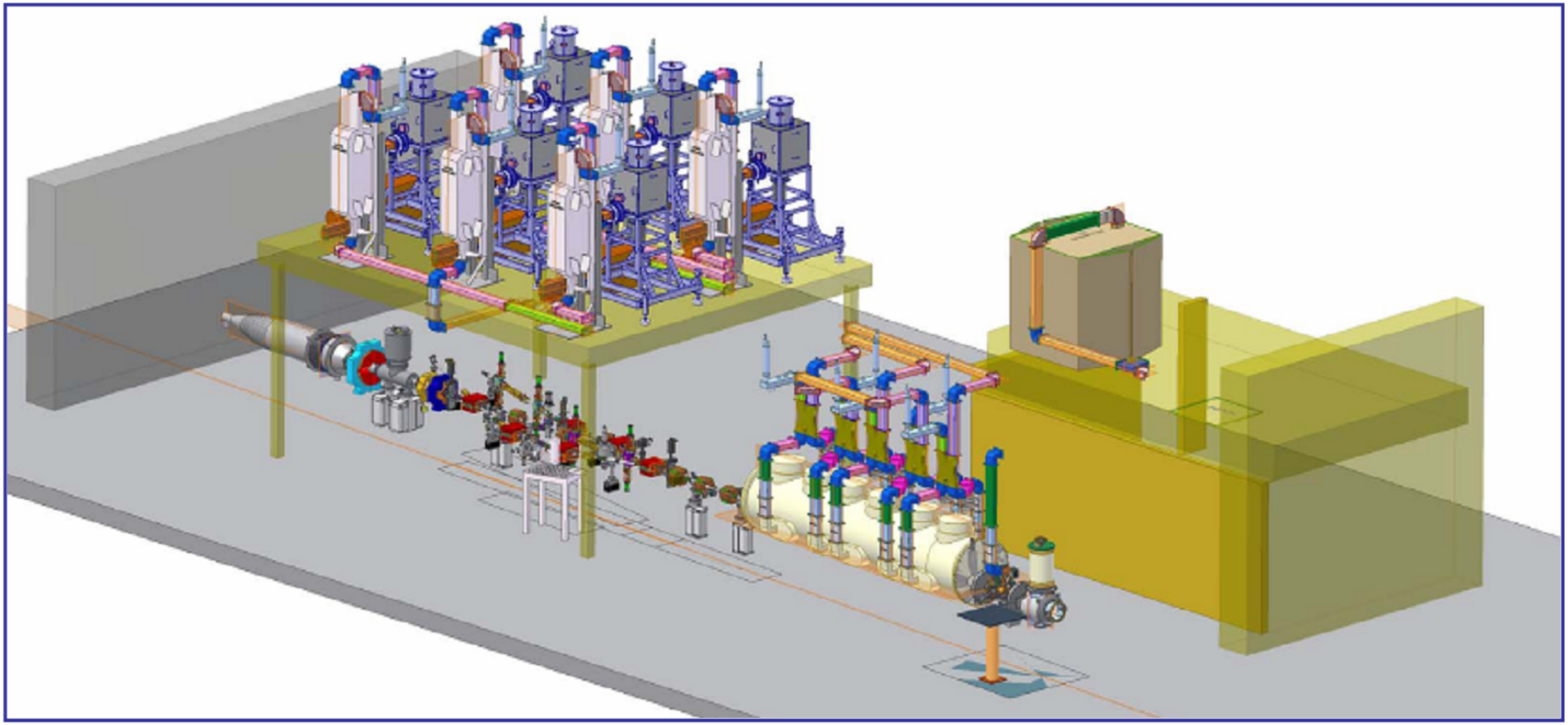


A 100 mA SRF Injector Cryomodule for the Cornell ERL X-ray Light Source



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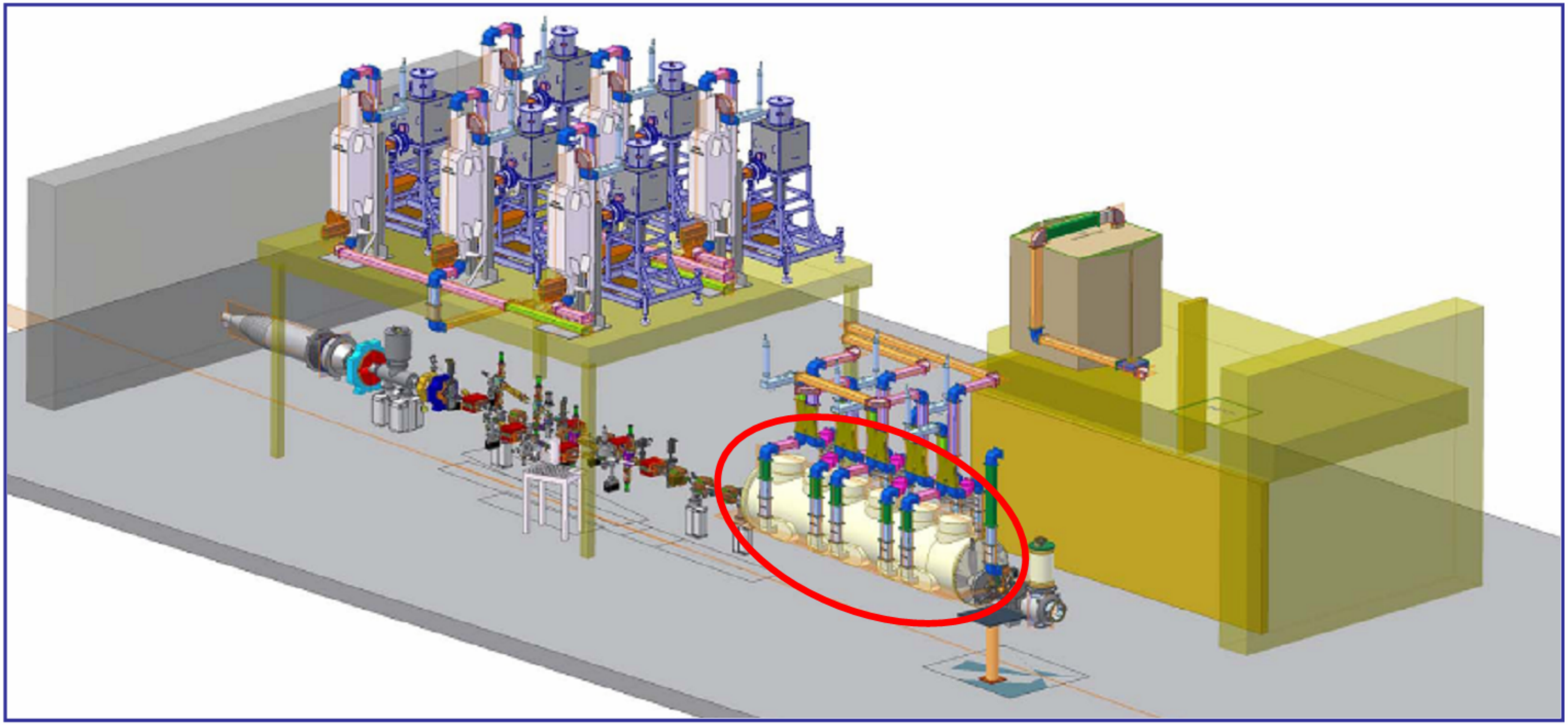

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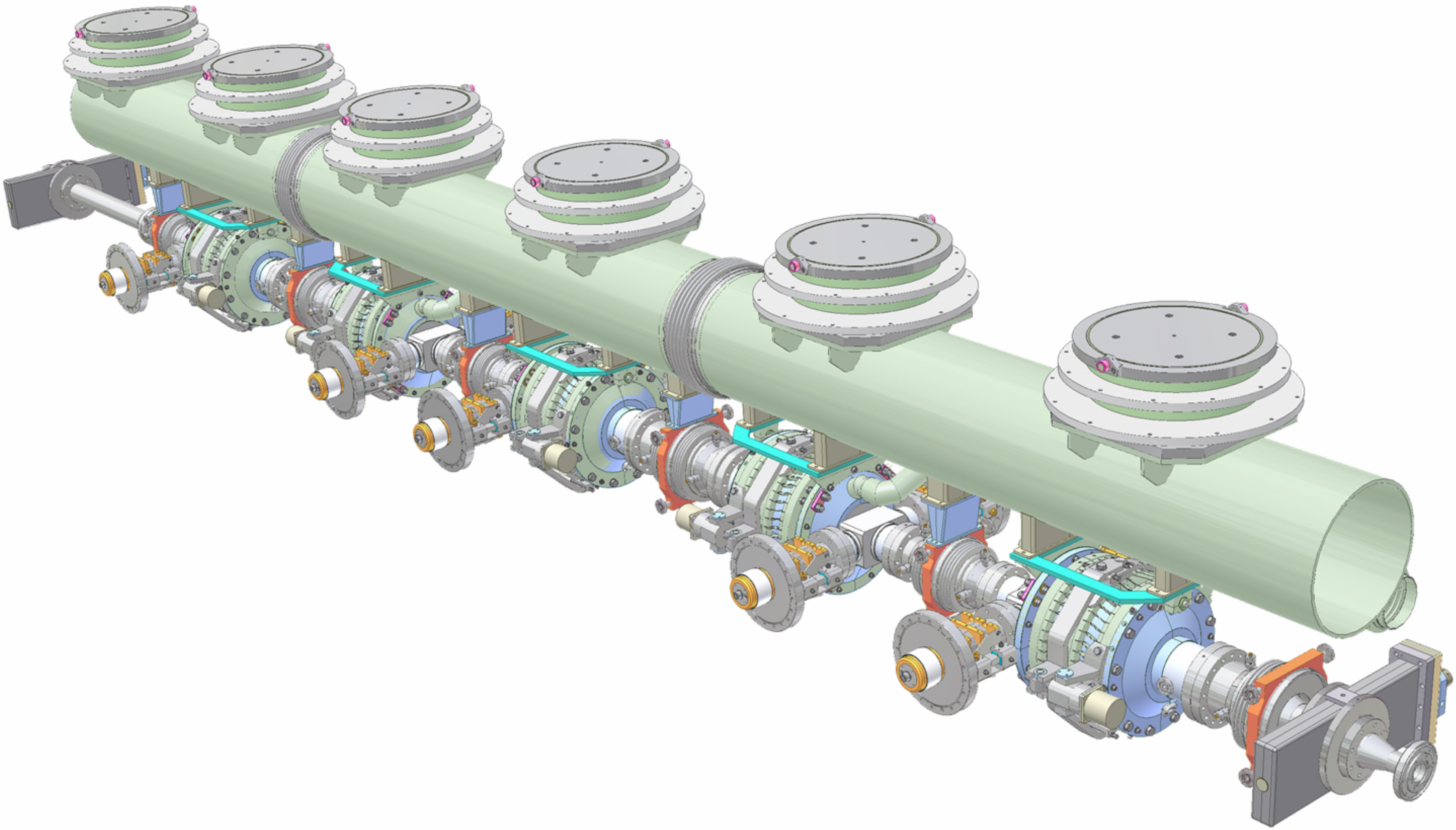


Outline

- Introduction
- Injector Module Design and Innovations
- Beamline Components and Module Assembly
- Cool down, Alignment, Static Loads
- RF System Commissioning
- Initial SRF Performance
- LLRF Field Control
- Cavity Microphonics and Frequency Control
- ERL Injector Cryomodule and Beam Studies
- Outlook

Introduction

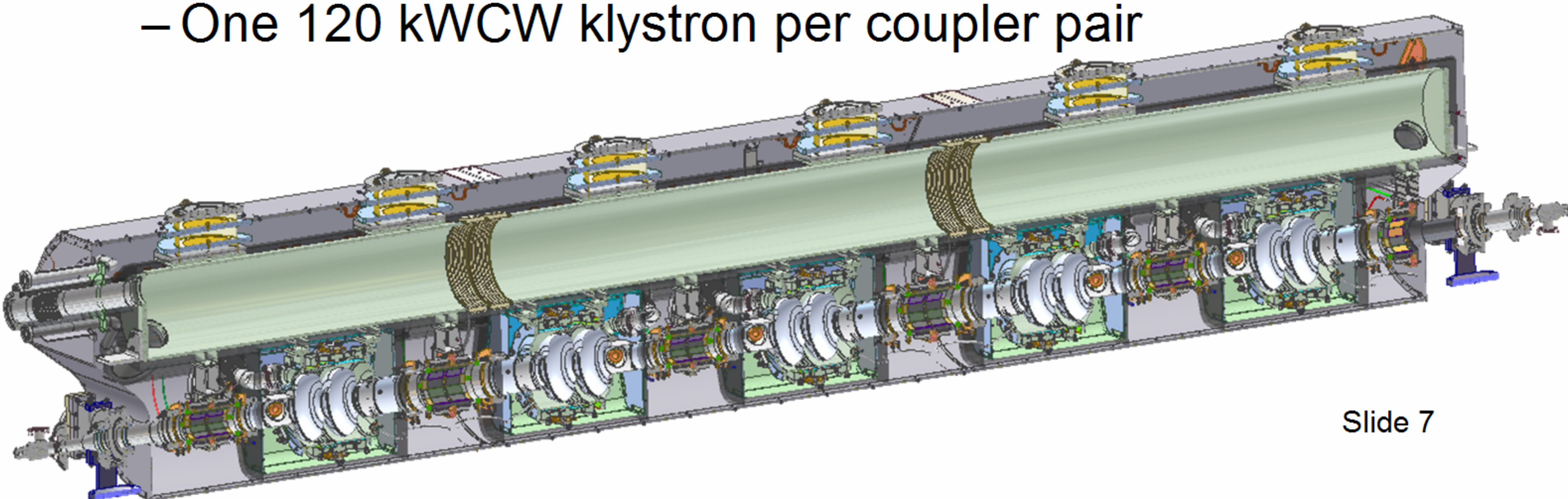
ERL Injector Beam Requirements

- Energy gain: 5 to 15 MeV
- High cw current:
  - 100 mA (77 pC/bunch) @ 5MV, 0.5 MW
  - 33 mA (26 pC/bunch) @ 15MV, 0.5 MW
- High beam power ≤ 0.5 MW
- Short bunch length: 0.6 mm (2 ps)
- Very low emittance ε_n = 0.1-2 mm-mrad

⇒ Well beyond present state-of-the-art!

ERL Injector SRF Answers (I)

- 1.3 GHz SRF 2-cell cavities:
  - 5 cavities
  - 5–15 MV/m to deliver 500 kW power total to the beam
  - Number of cells limited by max. input coupler power
- RF system:
  - 2 coax couplers per cavity for symmetry (twin-coupler)
  - One 120 kWCW klystron per coupler pair



ERL Injector SRF Answers (II)

- Beamline HOM Loads for aggressive damping of HOM's generated by high current and short bunches
- Symmetric beam line for emittance preservation:
  - Twin coax input couplers
  - Round beam line absorbers (no HOM loop couplers)
  - Cold cavity fine-alignment

Numb. of cavities / HOM loads	5 / 6
Accelerating voltage per cavity	1 - 3 MV
Fundamental mode frequency	1.3 GHz
R/Q (circuit definition) per cavity	111 Ohm
Loaded quality factor	4.6×10^4 to 10^6
RF power installed per cavity	120 kW
Required amplit. / phase stab. (rms)	1×10^{-3} / $0.1°$
Maximum beam current (design)	100 mA
Total 2K / 5K / 80K loads	$\approx$ 26 / 60 / 700 W
Overall length	5.0 m

ERL Injector Schedule

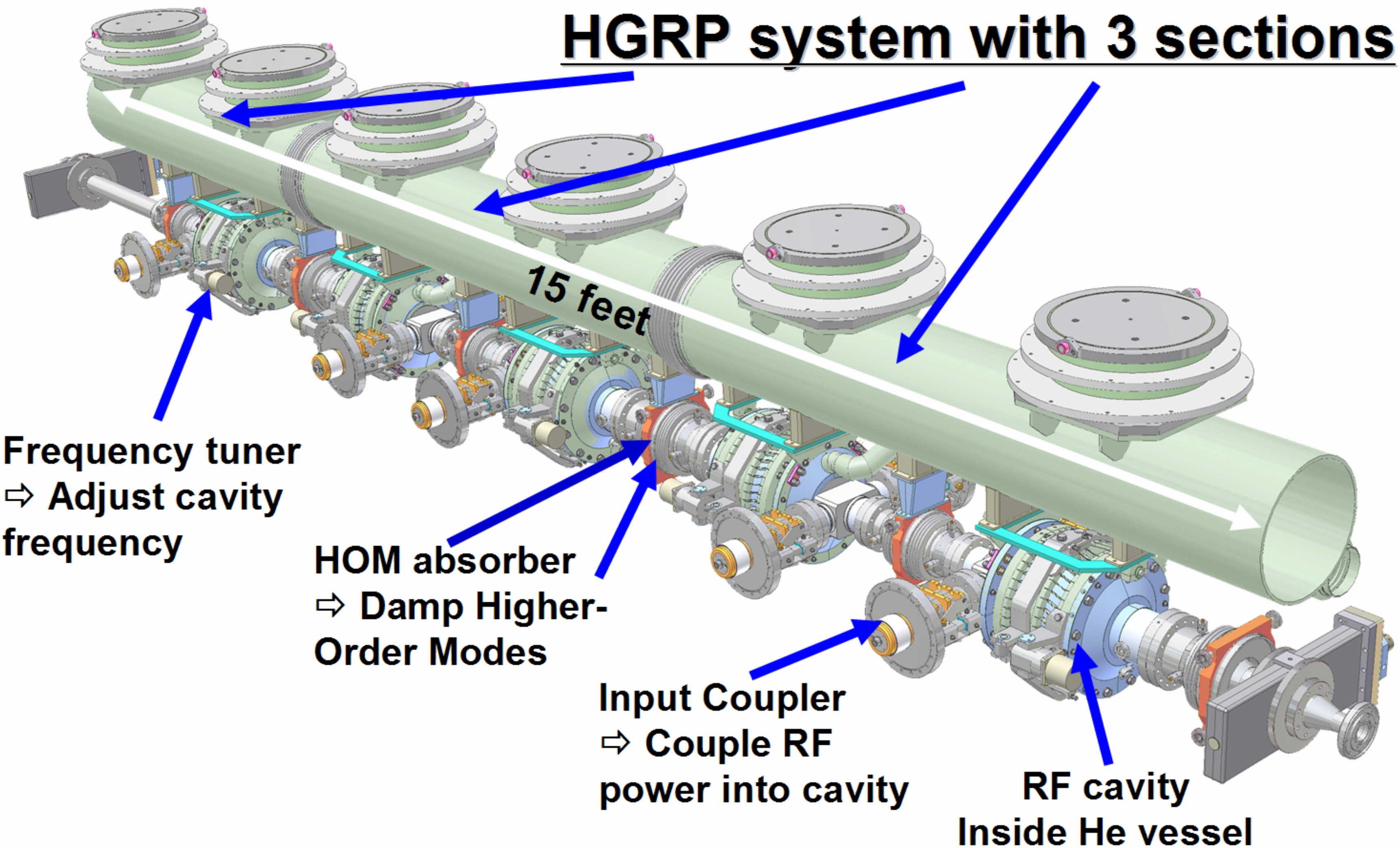
- **August 2007:** Single-cavity horizontal test cryomodule
- **September 2007:** Beam line and cryomodule assembly starts
- **October 2007:** All cavities, tuners, HOM absorbers, and input couplers are fabricated and tested
- **February 2008:** All cryovessel parts fabricated
- **March 2008:** Cryomodule assembly is finished
- **April 2008:** Module installation in ERL injector prototype and cool down
- **June 2008:** First RF
- **July 2008:** First beam

Injector Module Design and Innovations

ERL Injector Cryomodule

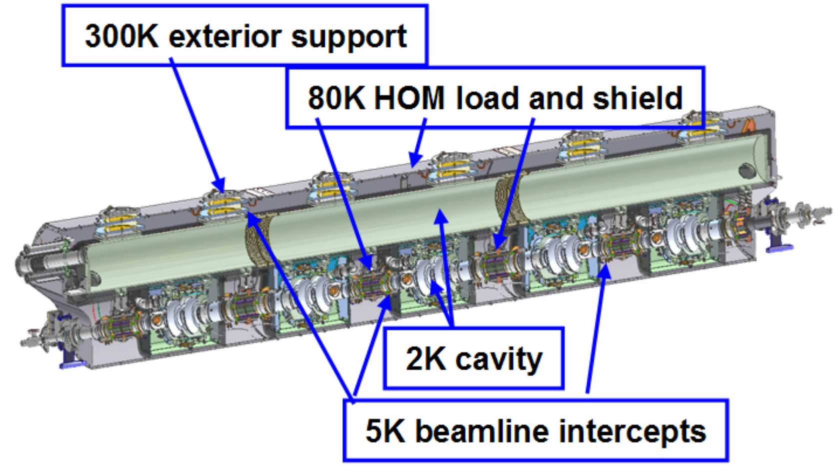
- Use the well-established platform of TTF technology to reduce risk and minimize development time
  - Cavities supported by large diameter Helium-gas return pipe (HGRP)
- Significant modifications for ERL specific needs:
  - Necessary modifications
    - Much higher beam current beam (100 mA, non-pulsed) ⇒ HOMs…
    - Much higher (100 kW per cavity) *average* power transferred to the beam
    - Much higher cryogenic loads
  - Innovations

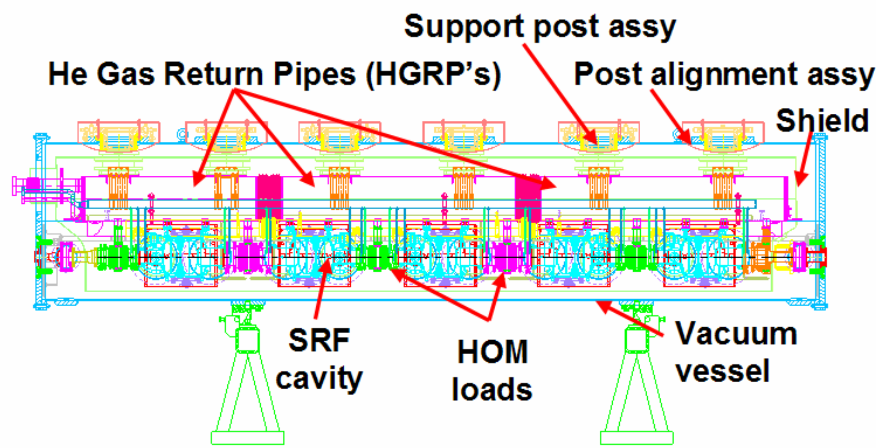
ERL Injector Cryomodule



ERL Injector Cryomodule Design

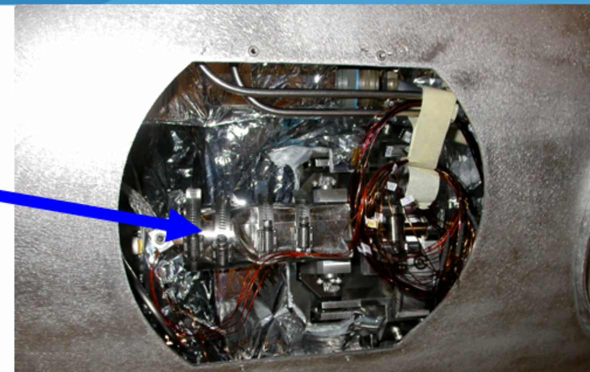
- Necessary changes compared to a TTF cryomodule:
  - Increased diameter of 2K He pipes for high dynamic CW cavity loads
  - Direct gas cooling of chosen 5K and 80K intercept points
  - No 5K shield, only a 5K cooling manifold
  - HOM absorbers between cavities
  - Improved magnetic shielding with 3 shield layers
  - New end-cap and feed-cap concept with reduced length

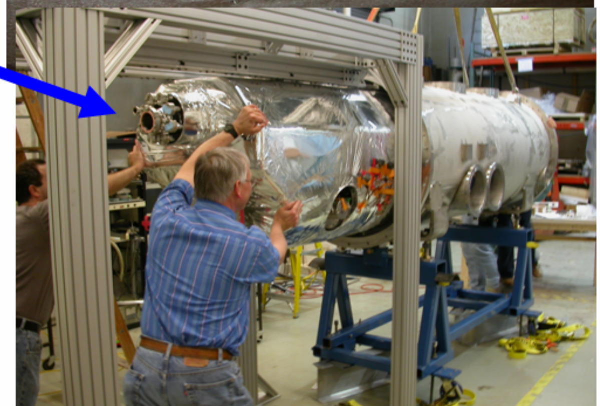


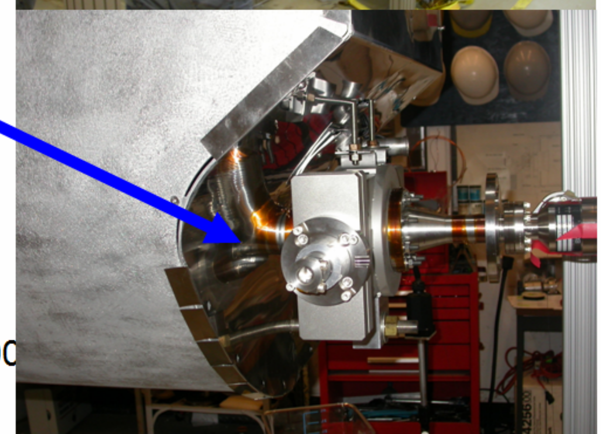


ERL Injector Innovations (I)

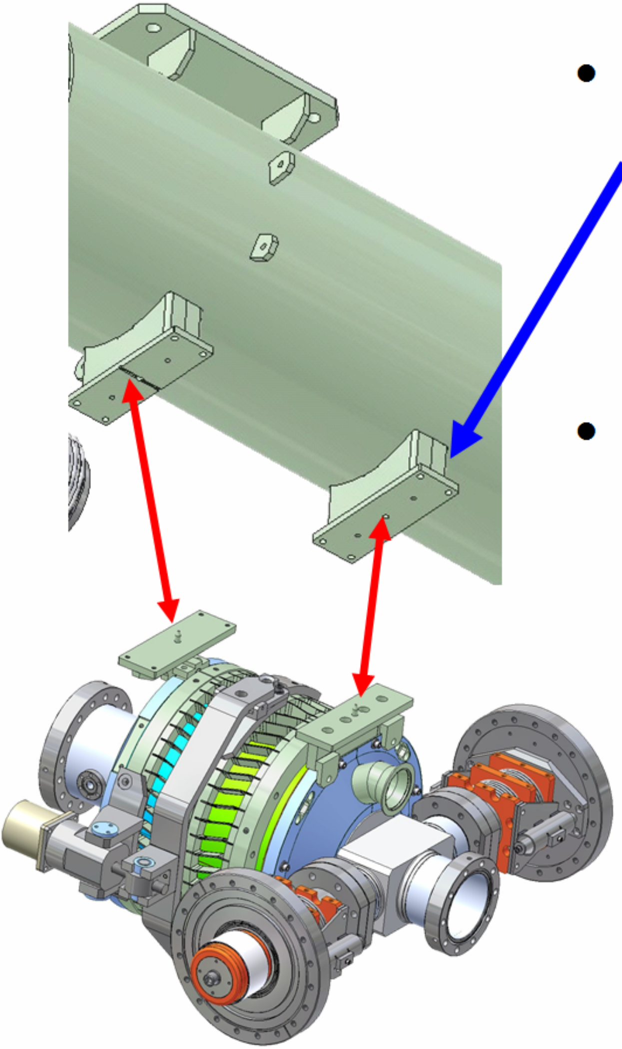
- Tuner stepper replaceable while string is in cryomodule
- Rail system for cold mass insertion into Vacuum Vessel
- In-situ bake of “warm” coupler sections
- Gatevalve inside of module with outside drive



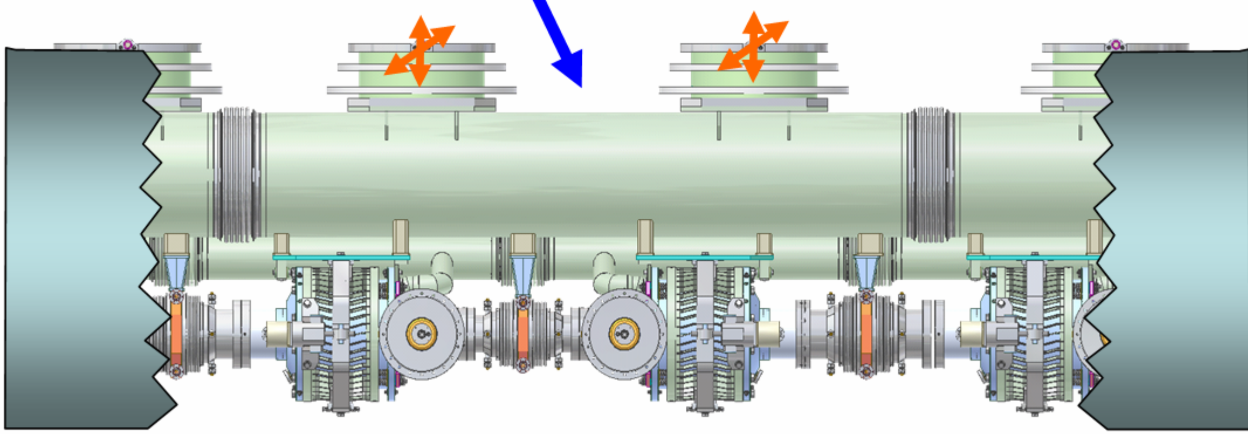




ERL Injector Innovations (II)



- Precision fixed cavity support surfaces between the beamline components and the HGRP
$\Rightarrow$ easy “self” alignment
- Cavity-subunits can be fine-aligned while cavities are at 2K (if required)



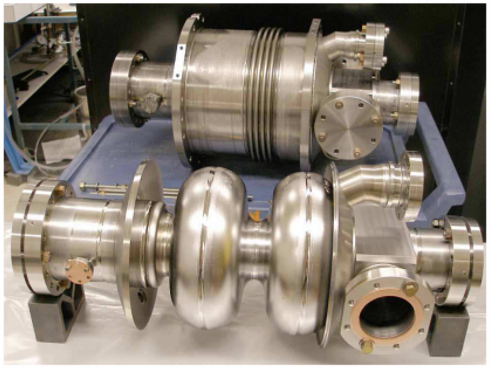
Module Assembly

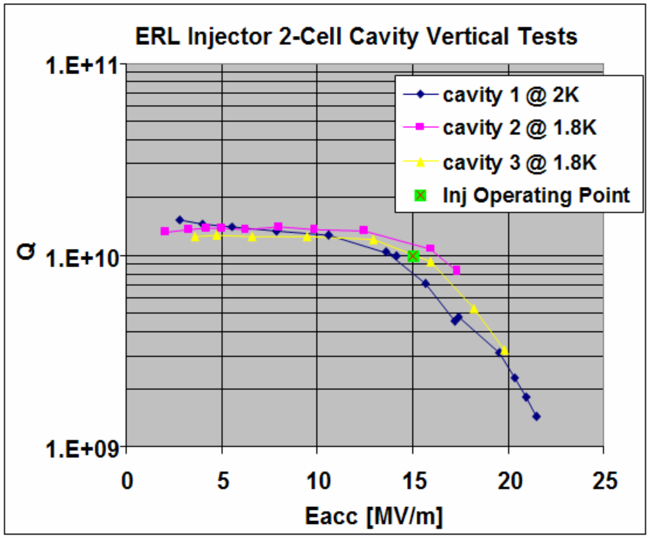
- Beam Line Components
  - String assembly
- Cold mass assembly

Beam Line Components (I)

SRF cavities:

- Designed, fabricated, prepared and tested at Cornell
- Only BCP, no 800C
- All cavities met 15 MV/m spec

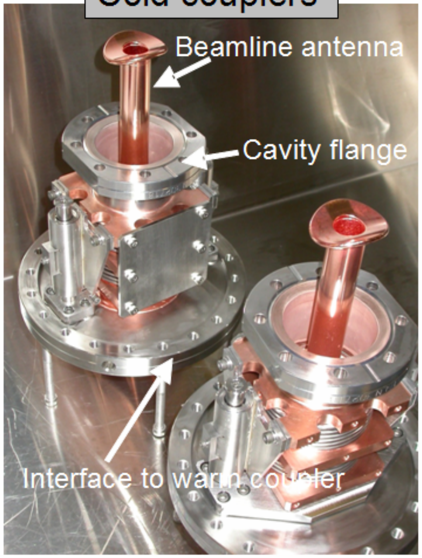




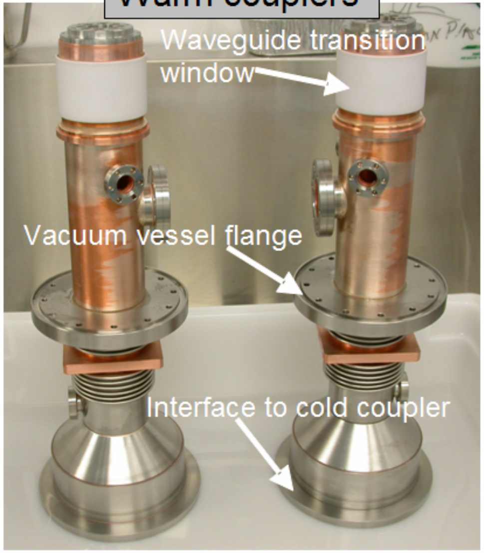
RF input couplers:

- Design by Cornell for high cw power > 50 kW
- 2 prototypes tested up to 60 kW cw, 80 kW pulsed
- 10 production couplers supplied by industry

Cold couplers



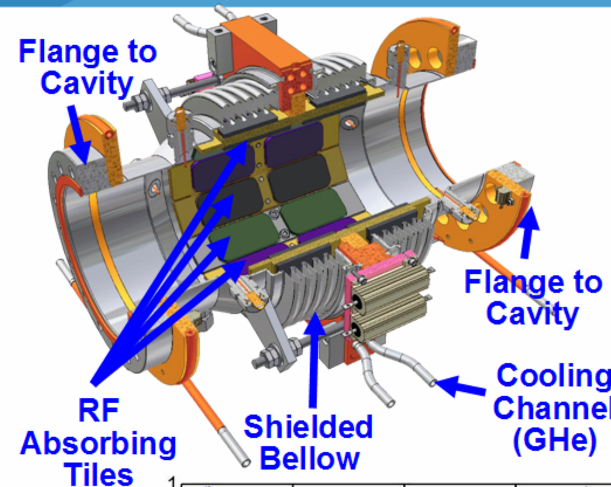
Warm couplers

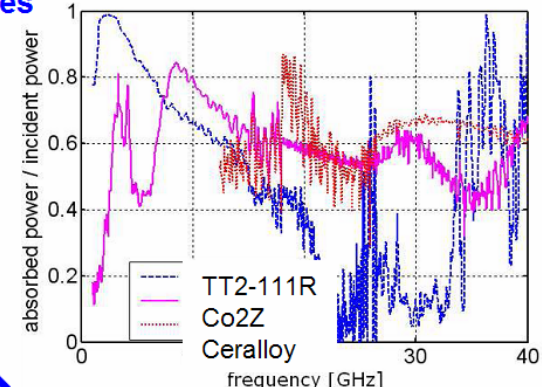


Beam Line Components (II)

HOM absorbers:

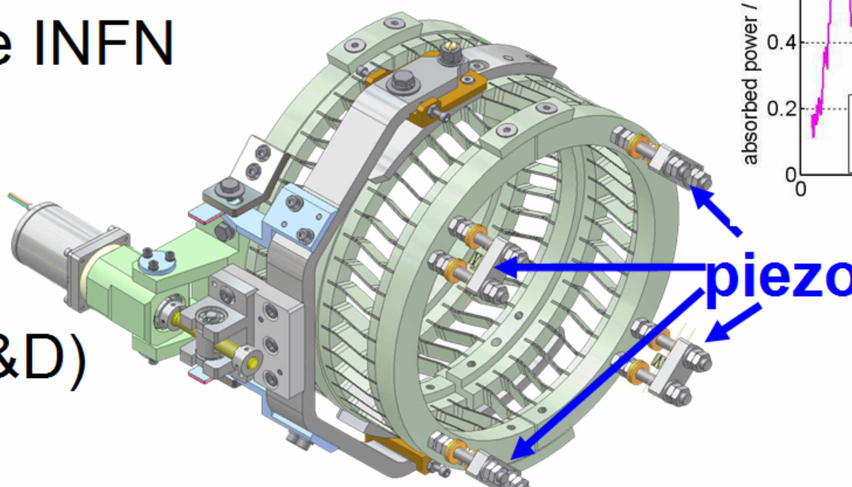
- Design by Cornell for strong, broadband HOM damping
- 6 production loads fab'ed by industry

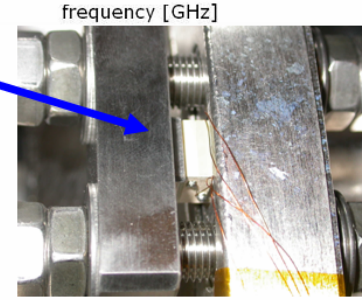




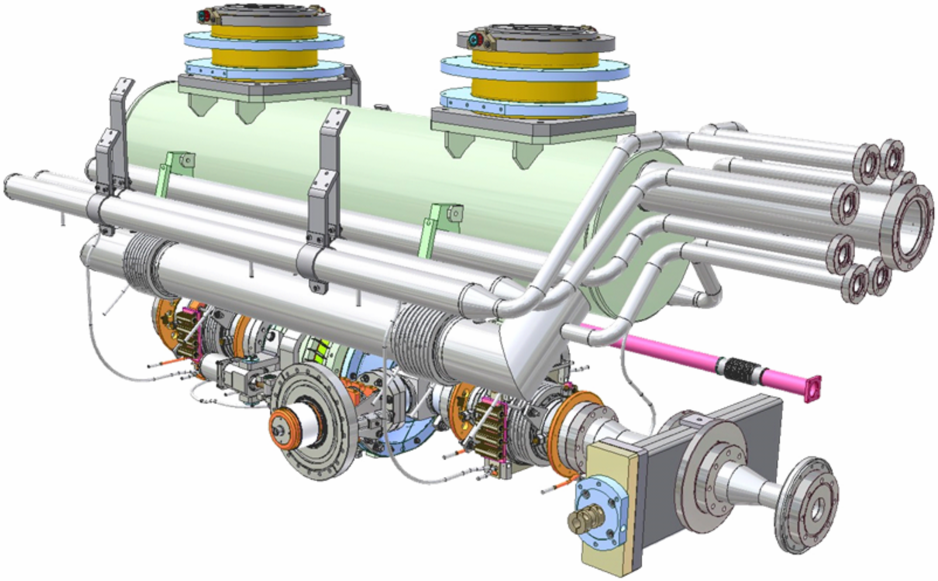
Frequency tuners:

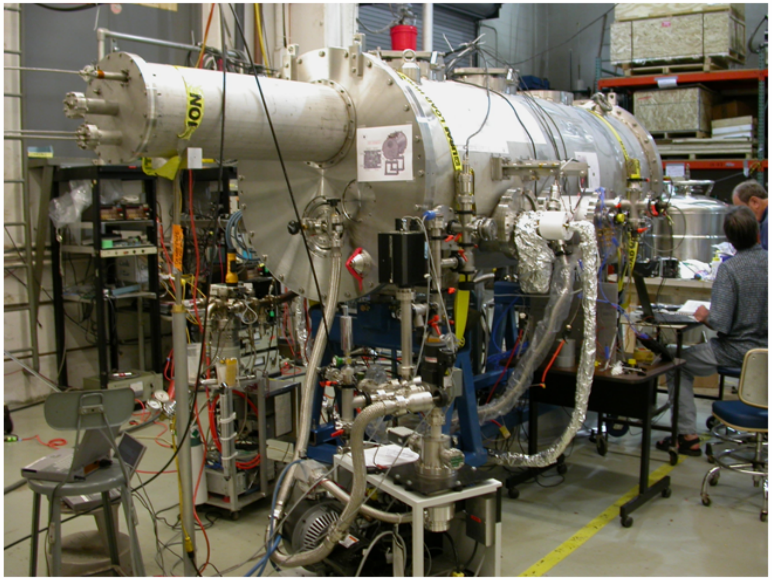
- Modification of the INFN blade tuner
- Added piezos for microphonics compensation (R&D)
- 6 units fabricated by industry





Along the Way: The Test Cryomodule

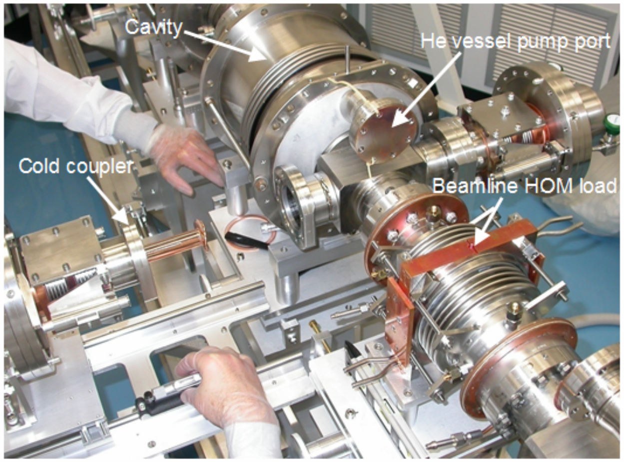


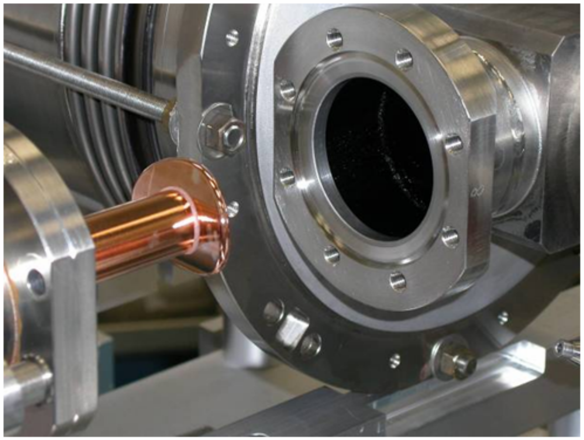


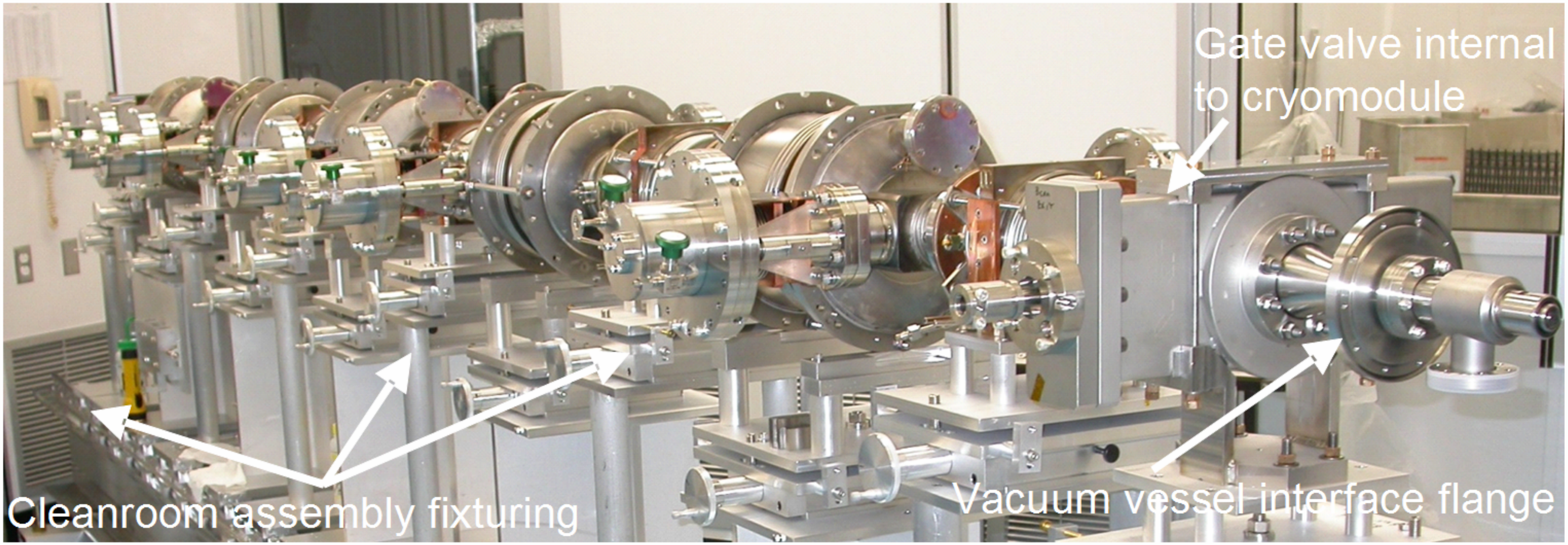
- *Single* cavity test version of full injector module
  - Same concept,…
  - … just shorter
  - spare 2-cell cavity
  - spare tuner
  - prototype HOM loads
  - prototype couplers
- Tested successfully in 2007

Beamline String Assembly

Attach cold couplers to beamline string



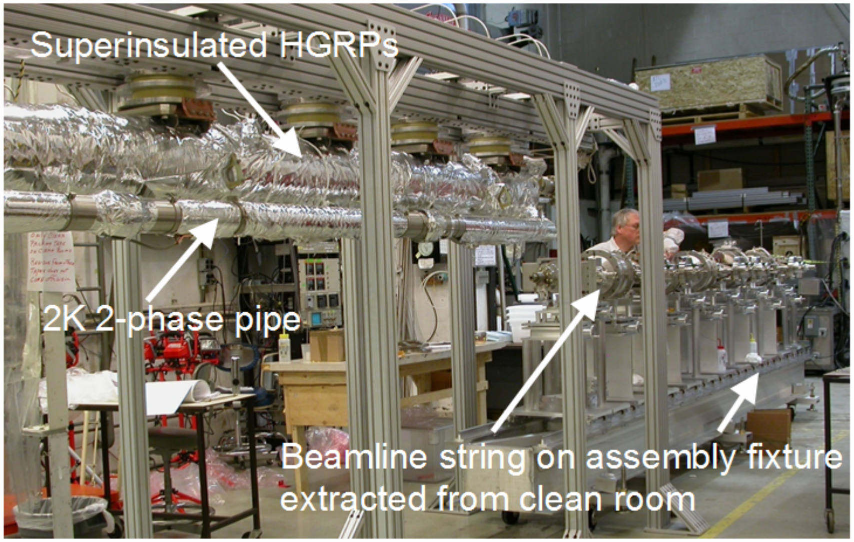




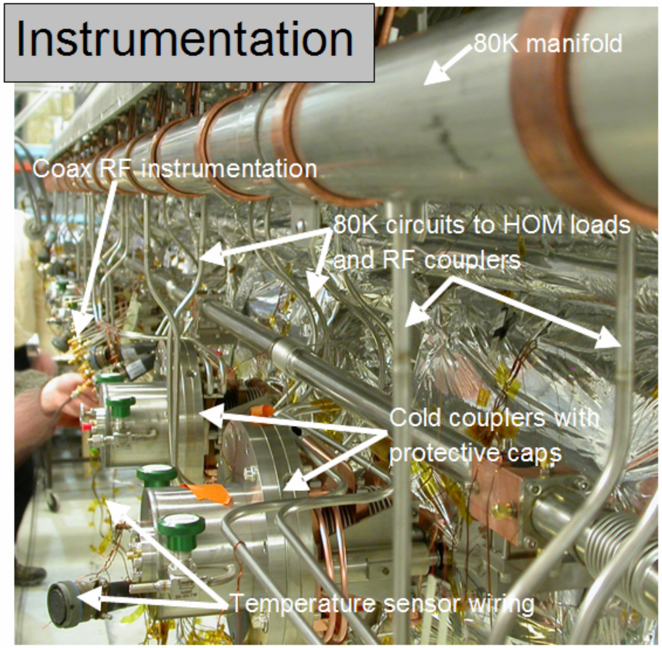
Cornell Laboratory for
Accelerator-based Sciences and Education (CLASSE)

Cold Mass Assembly at Cornell University (I)

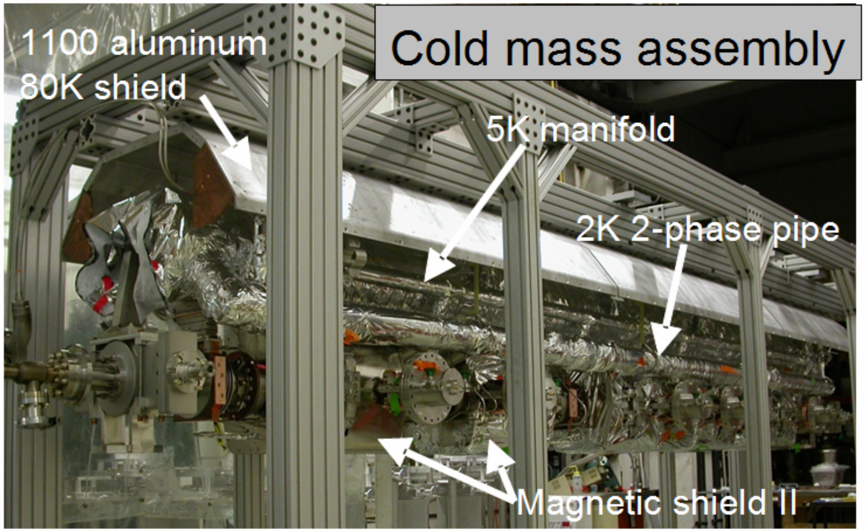
Beamline string rolling under HGRPs



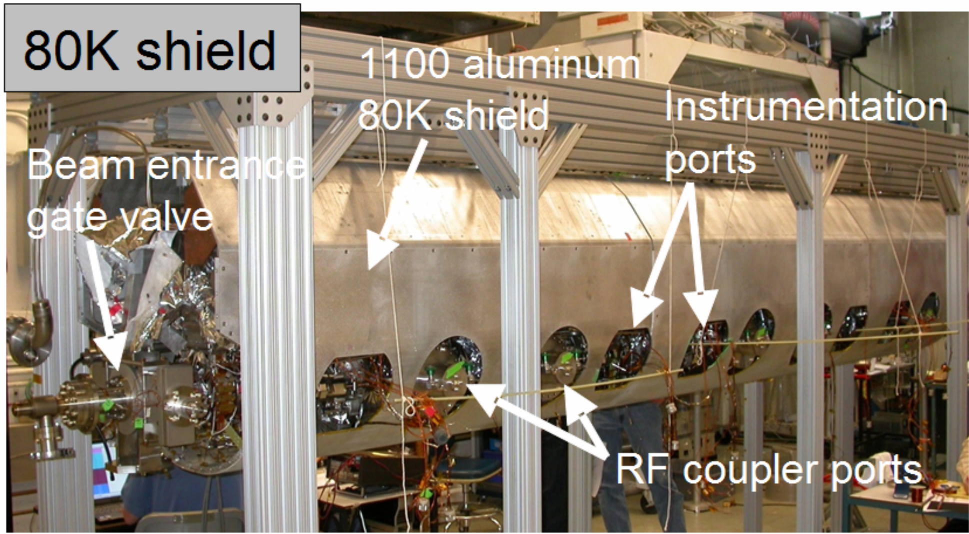
Instrumentation



Cold mass assembly

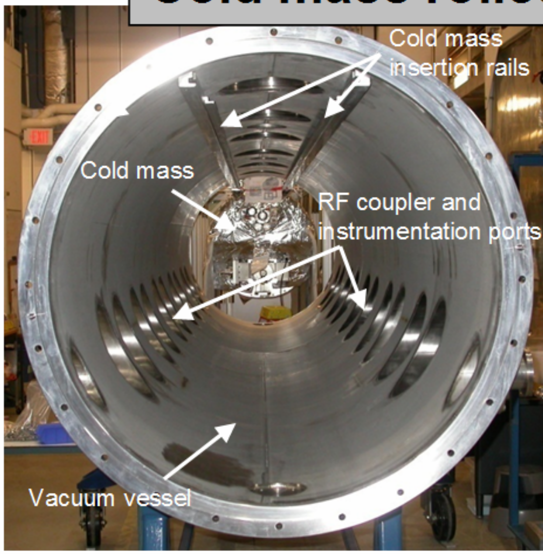


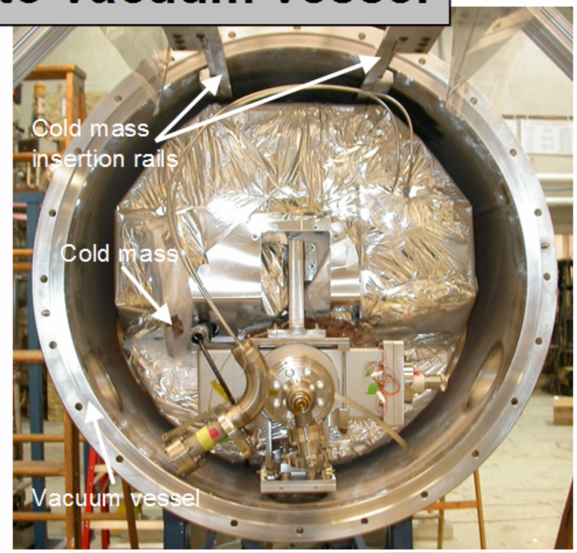
80K shield

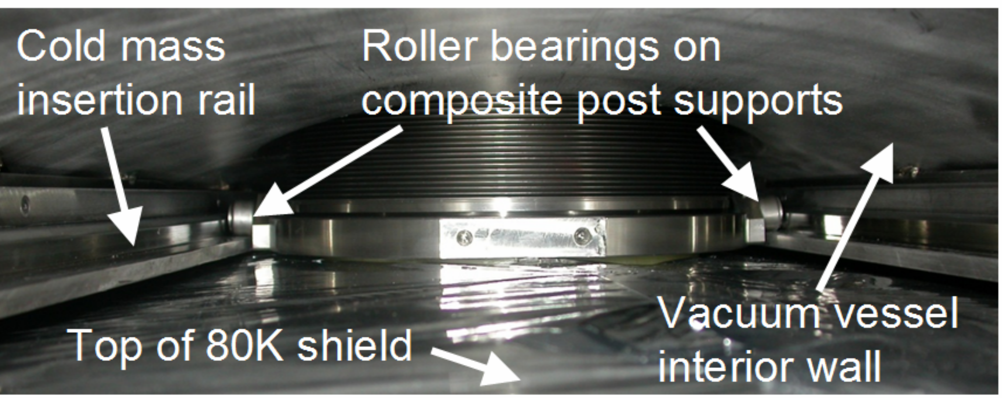


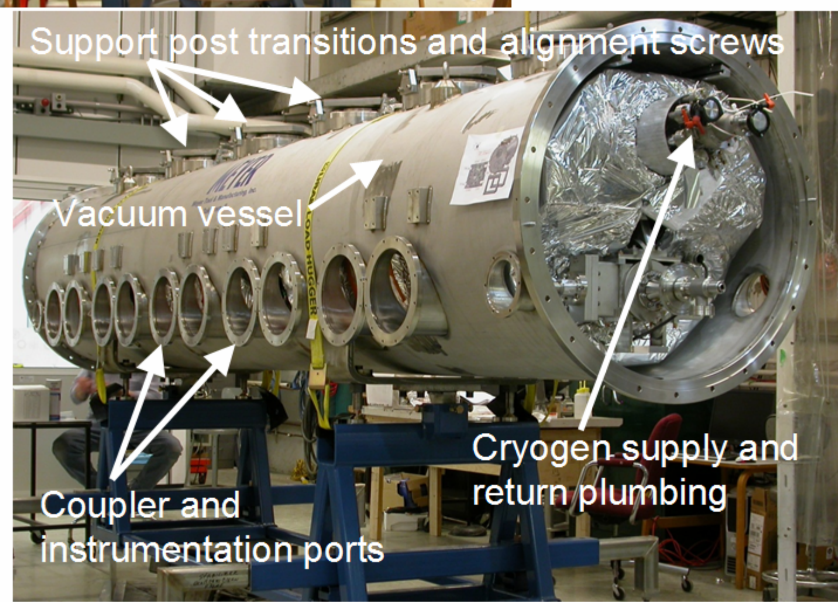
Cold Mass Assembly at Cornell University (II)

Cold mass rolled into vacuum vessel

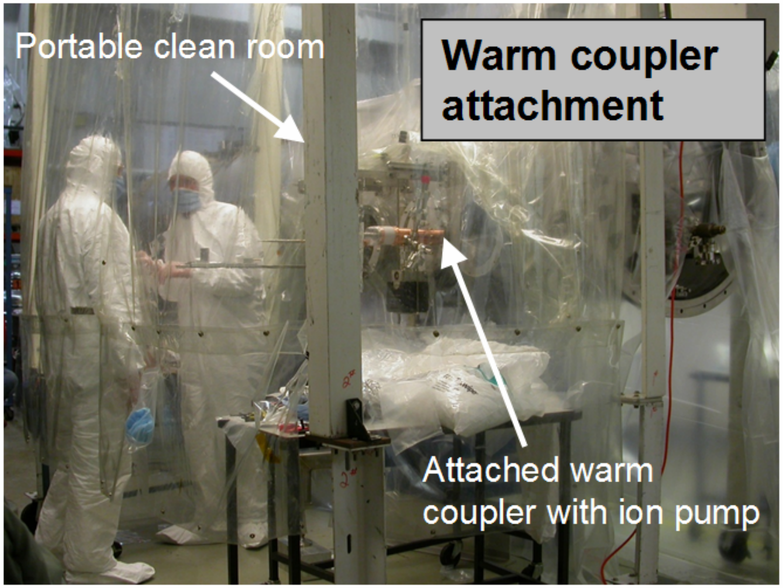




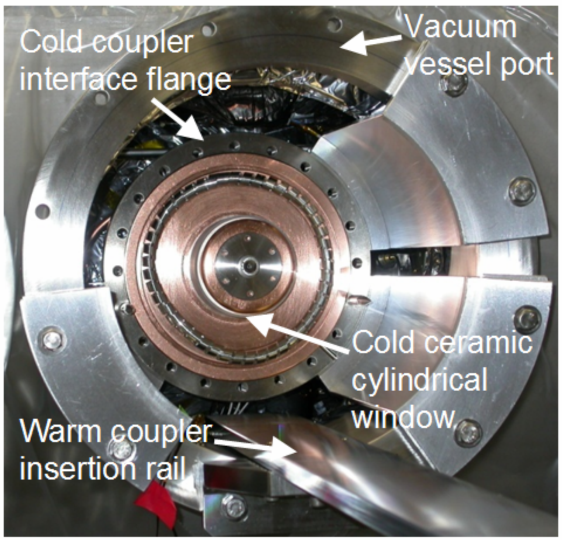




Cold Mass Assembly at Cornell University (III)



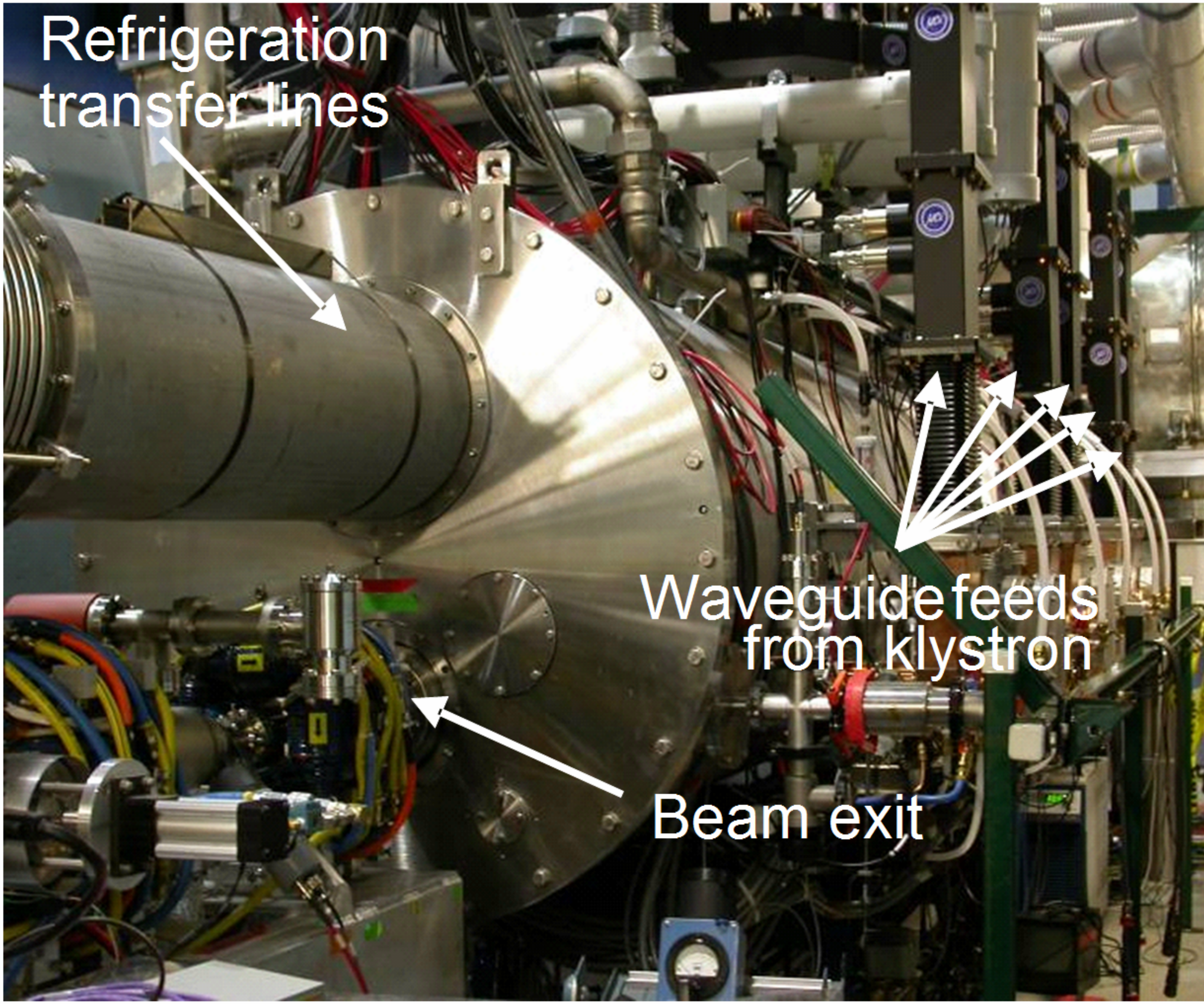
Transport from Newman Lab to Wilson Lab



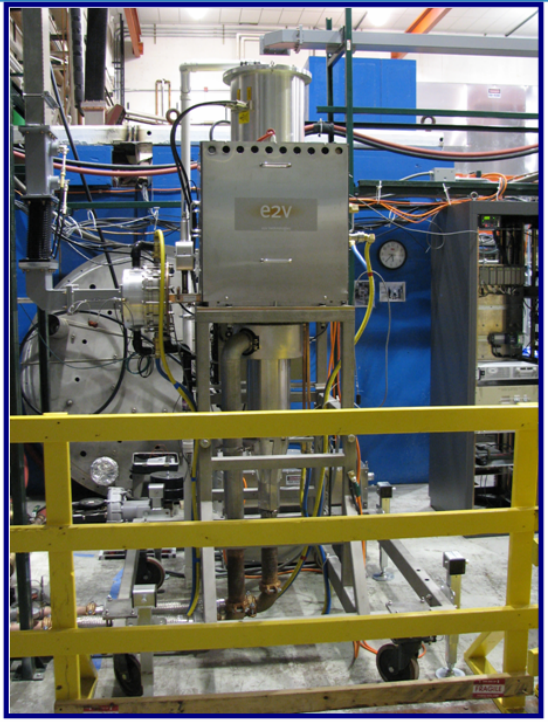
Insight from the Assembly:

- First assembly revealed no significant design problems
- Fast, easy assembly (once we had all parts)
- Fixed cavity alignment concept works well
- Full 3D modeling (including assembly drawings) extremely helpful

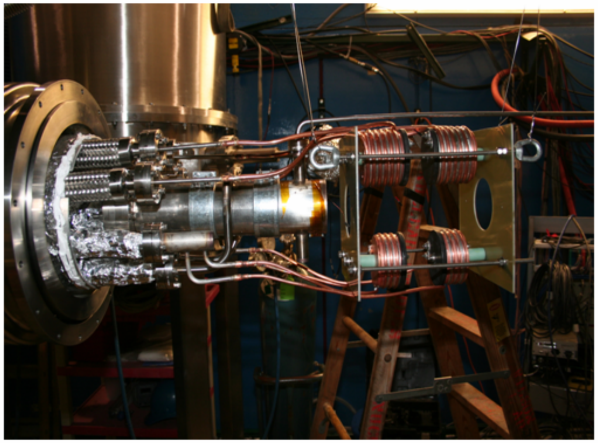
Injector Module installed in the ERL Prototype



Test Infrastructure



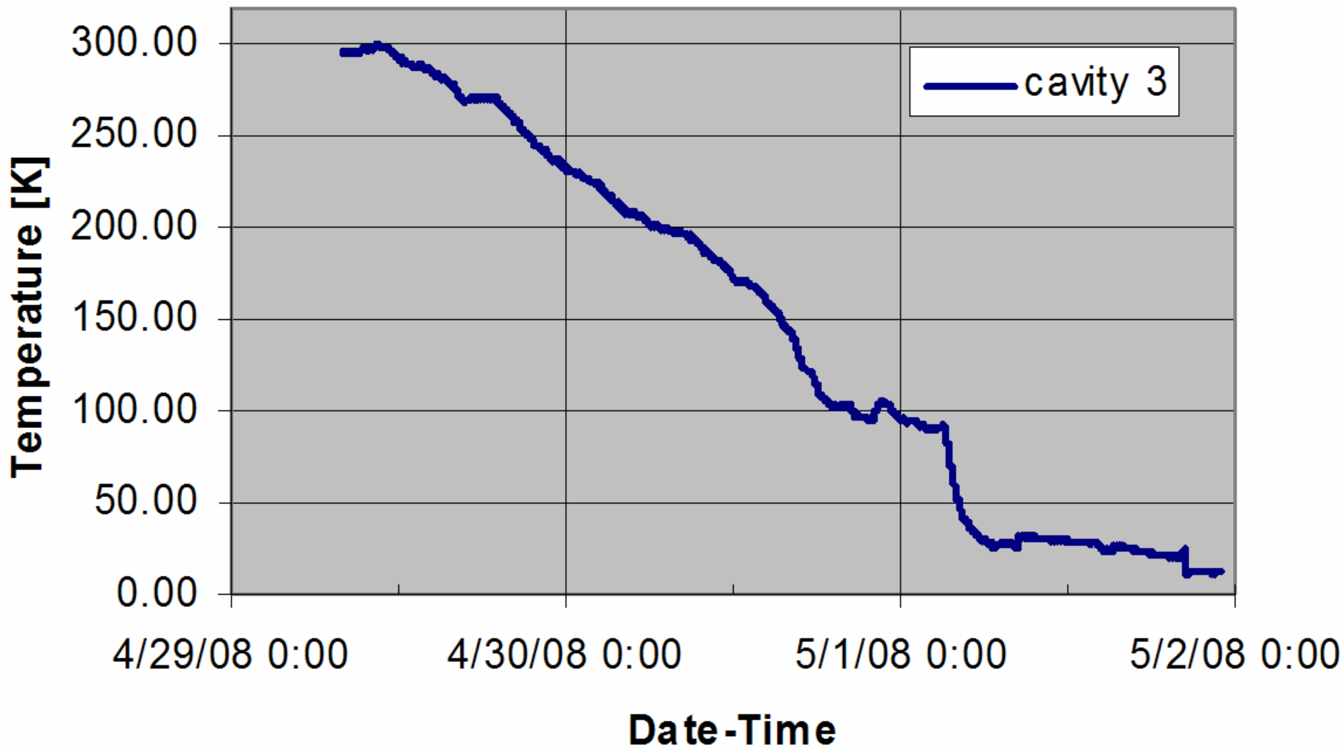
- 135 kW cw power klystron (e2v)
- Cold-box with 2K, 5K, 80K heat exchanger
- 120 W @ 2K pumping skid/ refrigerator



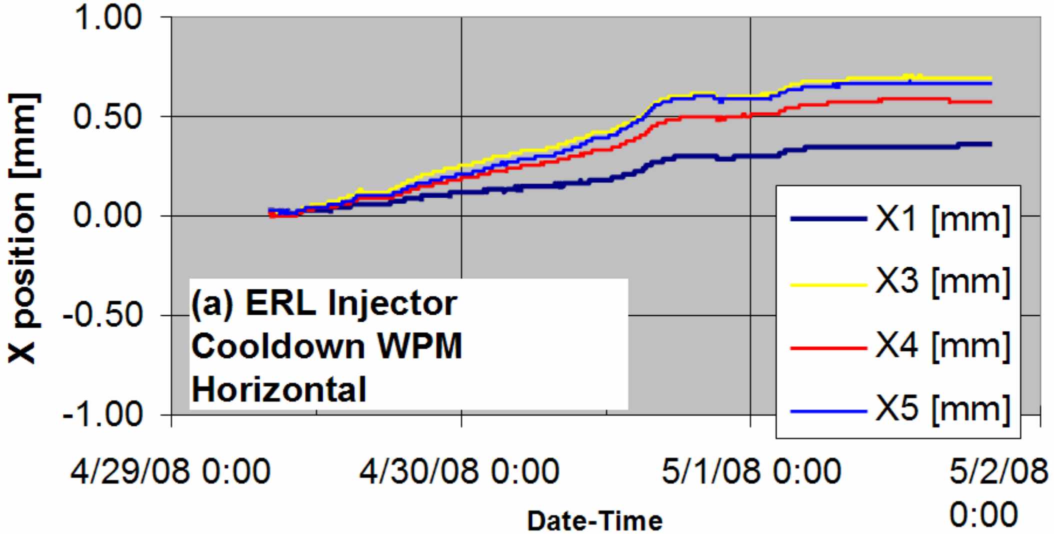
Cool-down and Cavity Alignment and Static Heat Loads

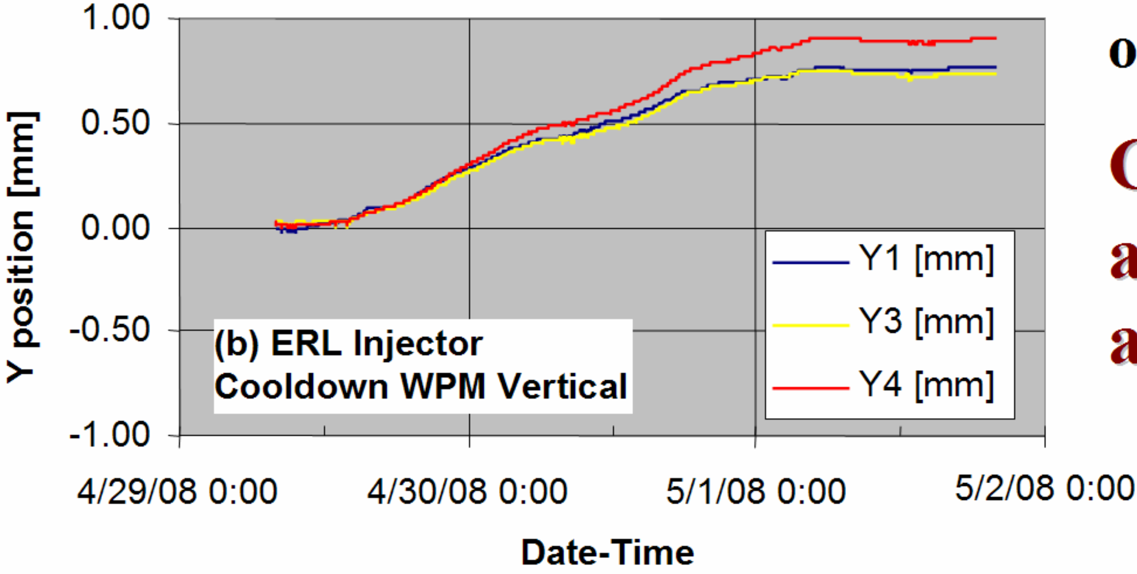
ERL Injector Cooldown

- Injector cryomodule cool-down to 4.2K in 2.5 days to minimize thermal stresses (<10 K/hour)
- No vacuum or cryogen leaks



Cavity Position Shift During Cool-Down





Wire Position Monitor (WPM) Datalog

Expected δx= 0.38 mm, observed δx = 0.58 mm

Expected δy= 0.94 mm, observed δy = 0.81 mm

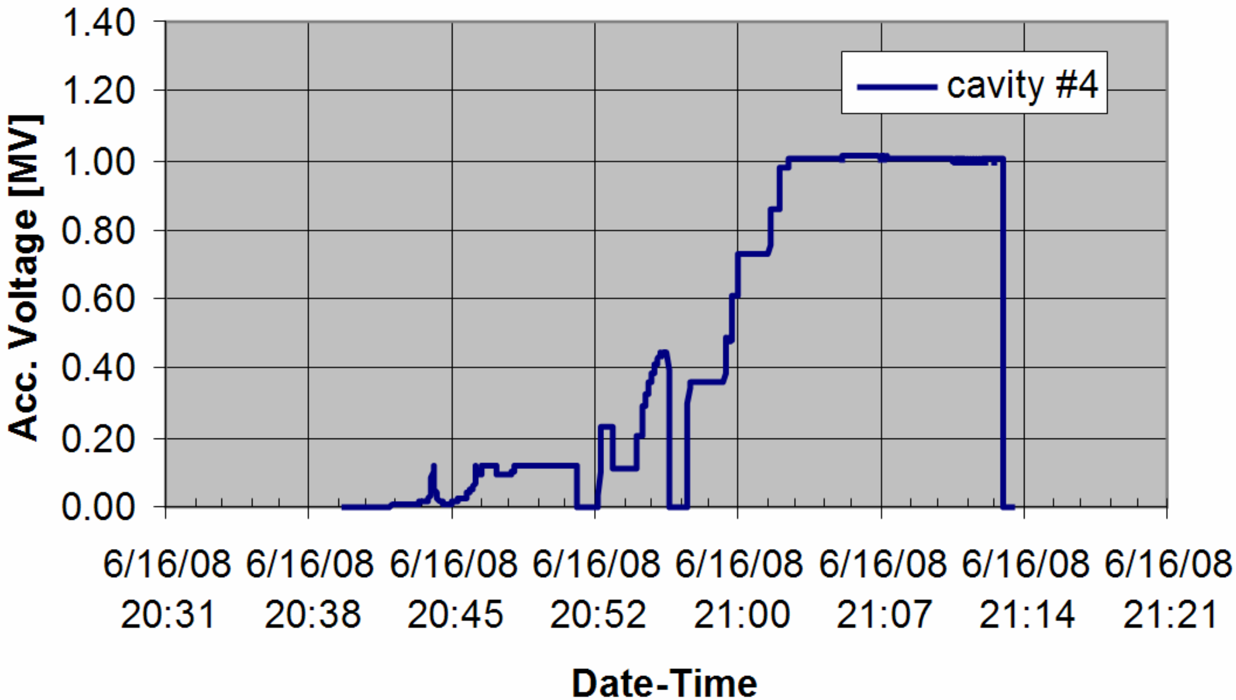
Cavity string is aligned to ±0.2 mm after cool-down!

Static Heat Leak to 1.8 K

- Measured by closing the JT valve in the LHe feed and measuring the LHe boil-off rate.
- Heaters on the 1.8K system were used for calibration.
- Measured: 10.3 ± 2 W
- Expected: 9 W
- Dominating part of this static heat load comes from thermal conduction from "4.5K intercepts" in the input couplers, support posts and HOM loads to the 1.8 K system.
- "4.5K system" of the cryomodule is currently at an elevated temperature of about 6K (non-ideal heat exchange in the refrigerator system)

  ⇒ increases total 1.8K static load from 5 W to 9 W.

First Field Ramp-Up



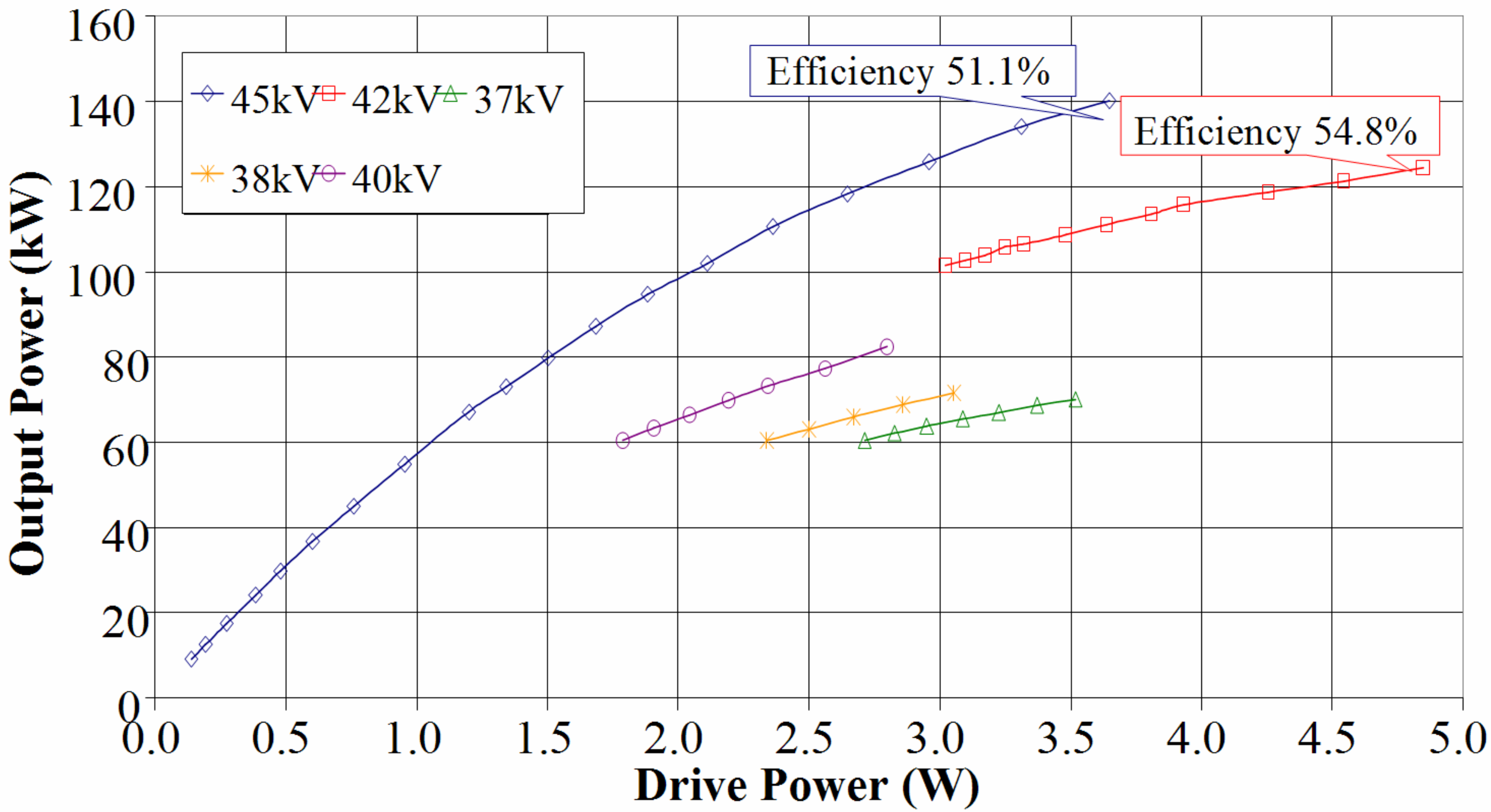
- **After cool-down, frequency spread between cavities was only 17 kHz!**
- **All 5 cavities easily powered to minimum gradient of 5MV/m within minutes**
- **All 5 cavities showed Q ≈ $1 \cdot 10^{10}$ at 1.8K shortly after cool-down**

RF System Conditioning

120 kWCW RF Klystrons

- 7-cavity K3415LS tube manufactured by e2v
- 5 klystrons, each delivering up to 120 kW of CW RF power to individual cavities via twin input couplers
- Saturated output power of about 160 kWCW
- To provide stable regulation of the cavity field, the klystron must have a non-zero gain and therefore cannot operate in saturation.
- The klystrons passed the factory acceptance test meeting specifications at 135 kW before shipping
- The tubes were installed, tested again at Cornell, and are performing well

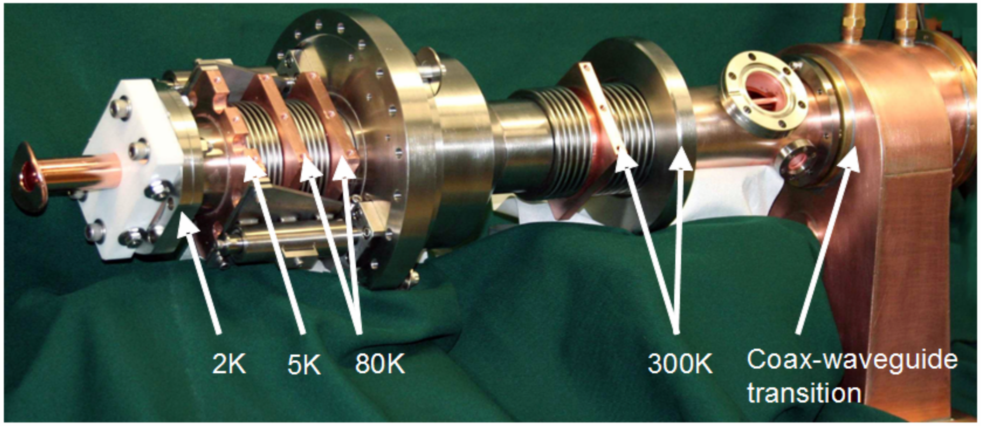
Transfer Curves of the K3415LS Klystrons



- Efficiencies exceeding 50% at 120 kW output power

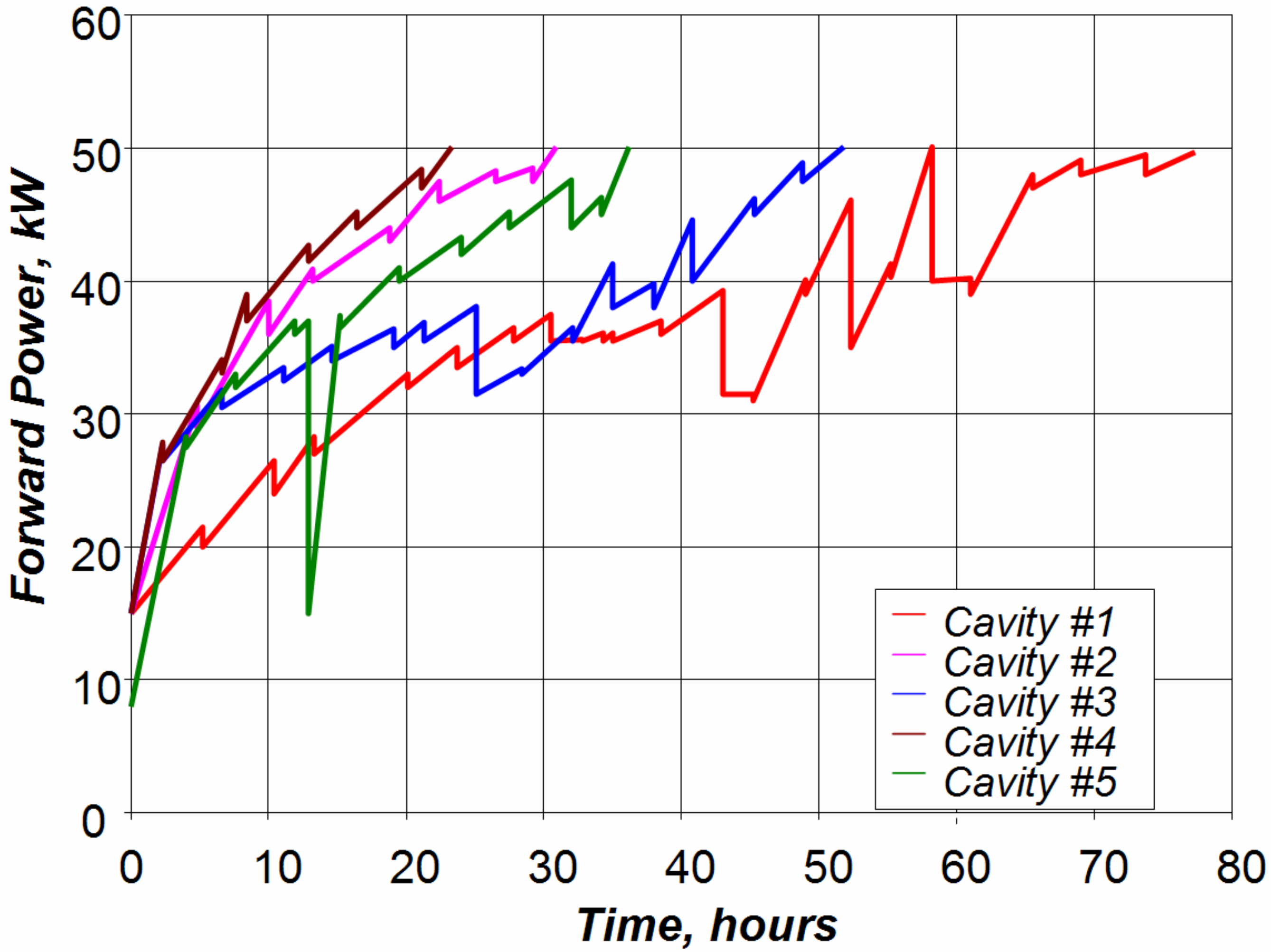
RF Input Couplers (I)

- All twin input couplers have so far been processed in pulsed mode up to 50 kW under full reflection
- None of the input coupler parts were baked after final assembly to the beam line.
- The "warm" part of the couplers can be baked in situ via heating elements installed on the couplers in the module, if it should be required to reach power levels above 50 kW.



RF Input Couplers (II)

- **All couplers conditioned well, reaching 50 kW in pulsed operation under full reflection within 25 to 75 hours of processing (RF on time).**

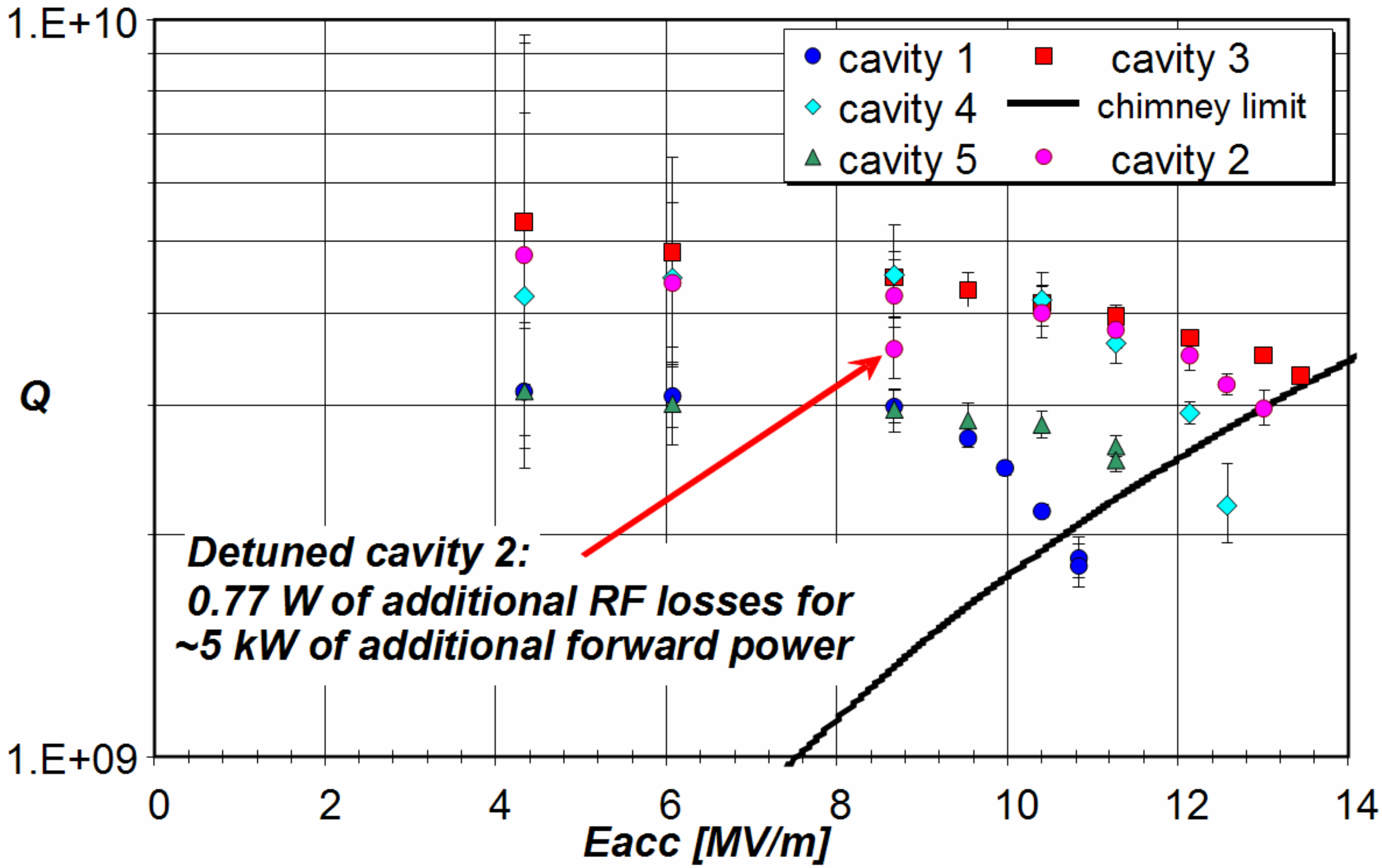


SRF Cavity Performance in the ERL Injector Cryomodule

SRF Cavity Performance

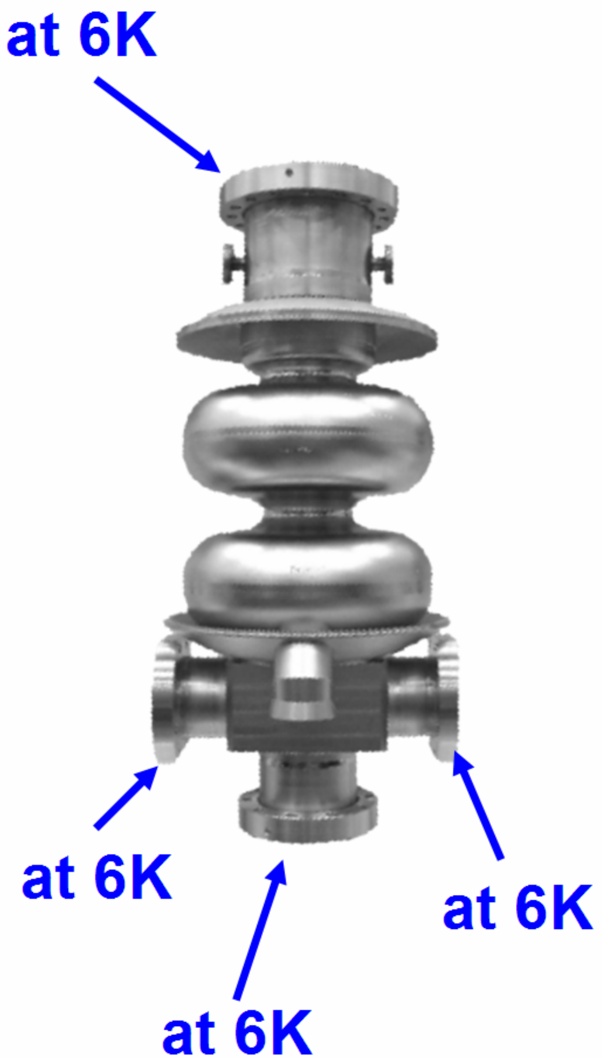
- Initial cavity performance looked good ($Q \approx 1{\cdot}10^{10}$ at 1.8K)
- But: more detailed measurements later showed low intrinsic quality factors Q_0 for all 5 cavities
- Q degradation over time?
- Currently, the total voltage of the module is limited to 14 MV by cryogenics (~12 MV/m), close to maximum specification of 15 MV.
- Cavity processing is ongoing to further increase maximum field gradients
- Pulsed gradients: 16 to 24 MV/m (BCP treated cavities)

Intrinsic Q vs. E_{acc} at 2K



- Field emission at higher Eacc
- Voltage limit due to the chimney heat flux transfer, not quench
- Cavities on either end of the module show lowest Q

Cause of low Q_0

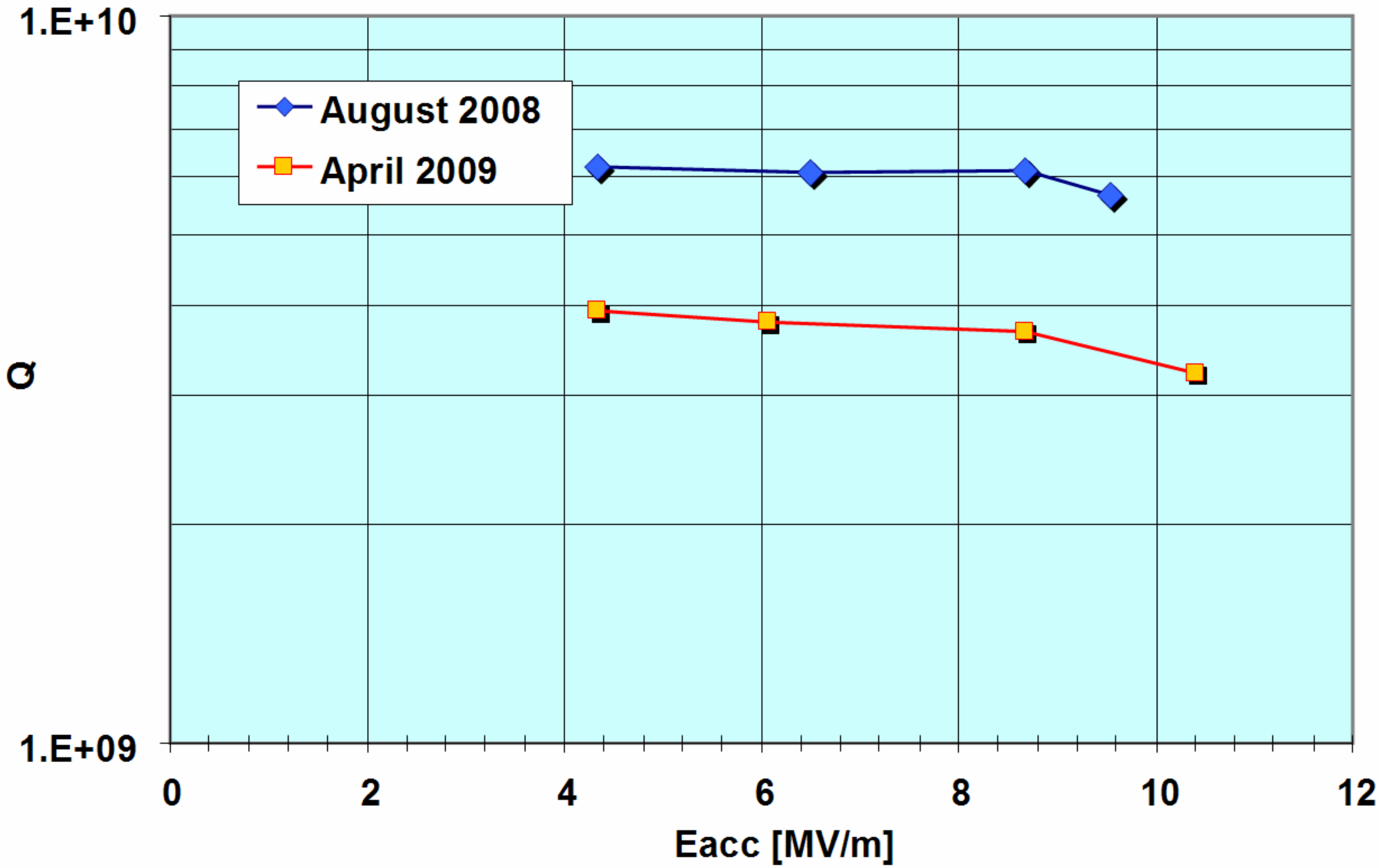


- Likely several contributors
- First simulations and measurements indicate that losses in the beam tube and coupler regions contribute significantly to the overall dynamic cavity losses
- Cavity flanges are thermally anchored to a "4.5K" cooling circuit
- But: "4.5K" system is currently at 6K (inefficient heat exchanger in cold box)

$\Rightarrow$ increased BSC resistance in beam tube sections ($R_{BCS} \propto \exp(T)$)

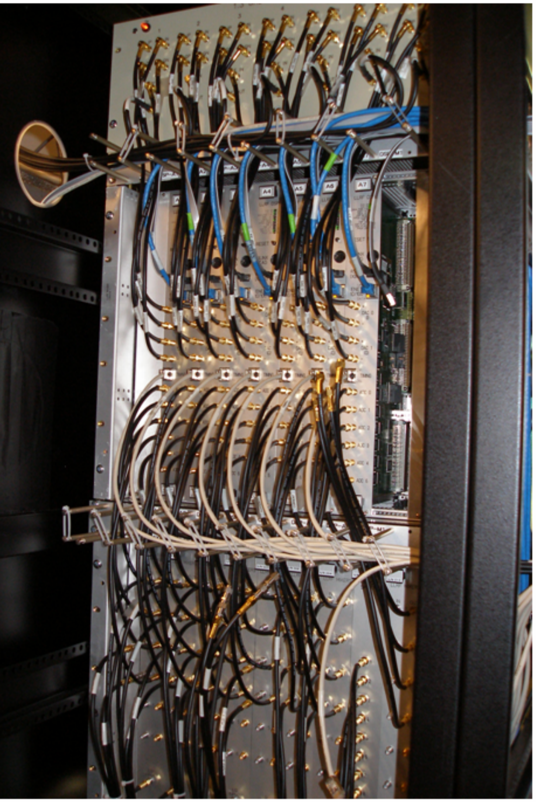
Q Degradation ?

Intrinsic quality factor Q vs. E_{acc} for all cavities together



LLRF Field Control

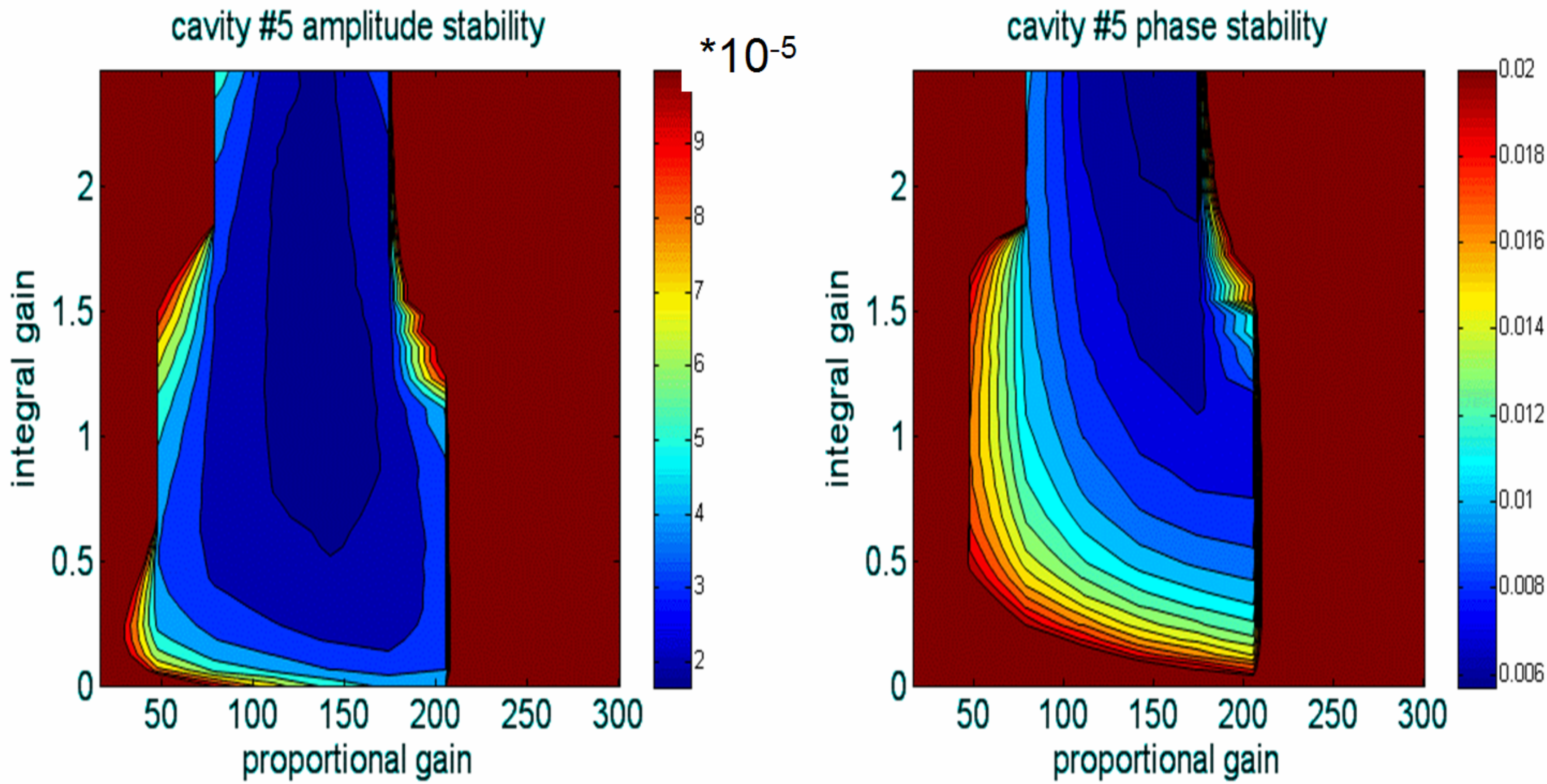
LLRF Field Control



- LLRF electronics for the ERL injector is a new, improved generation of LLRF system previously developed for CESR
  - Faster hardware for lower loop latency (<1μs)
  - Increased ADC resolution (16 bits)
- Performs well with excellent field stability
- LLRF electronics also used to measure
  - Beam current amplitude and phase noise (using BPM signals)
  - Soon: beam position in module via HOM probe signals on the HOM loads between cavities
- Detailed studies of LLRF gain/stability and microphonic noise are under way

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

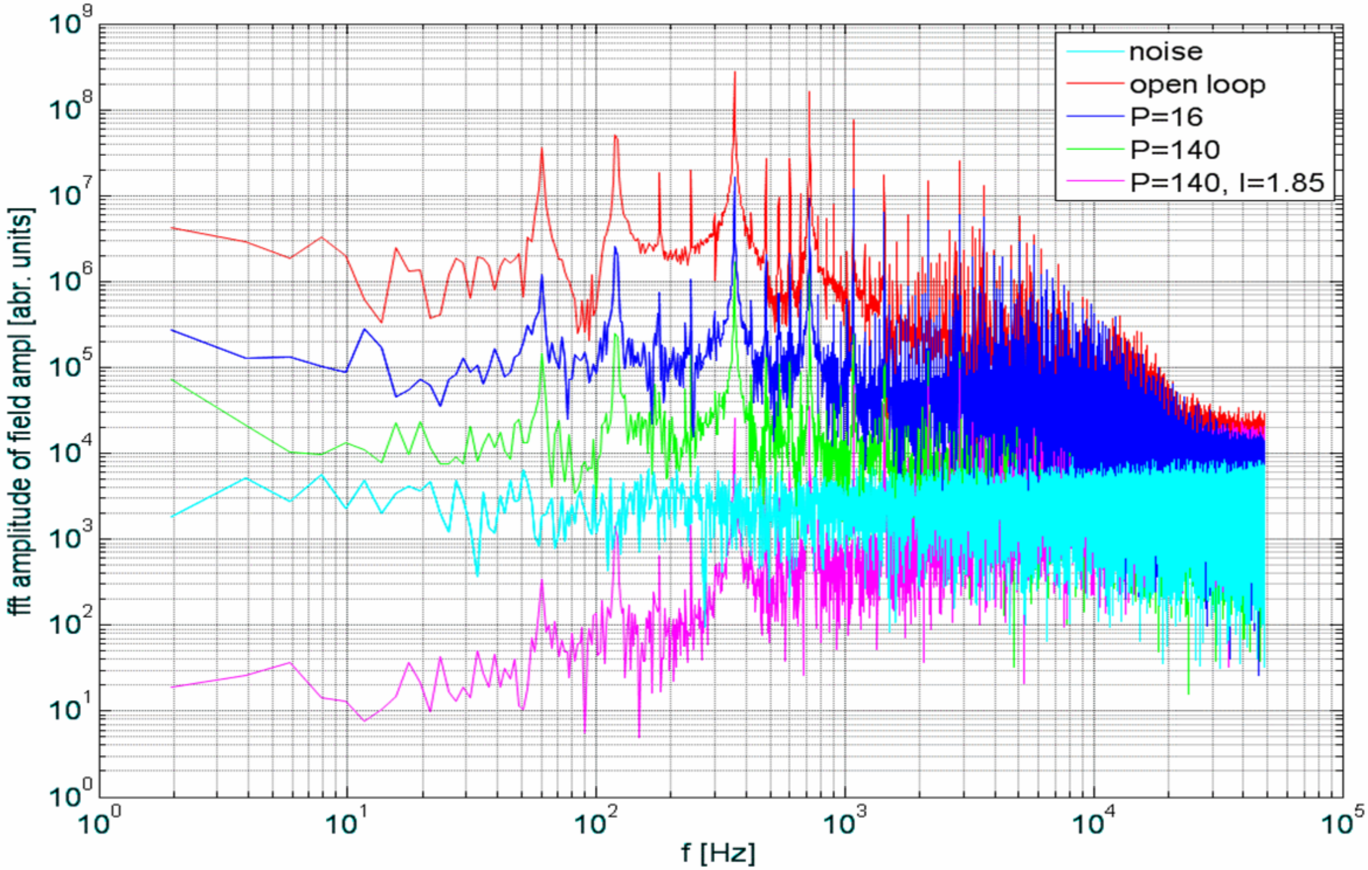
Gain Optimization for PI Field Control Loop



Excellent field stability achieved: amplitude: $\sigma_A/A < 2\cdot10^{-5}$

phase: $\sigma_P < 0.01$ deg

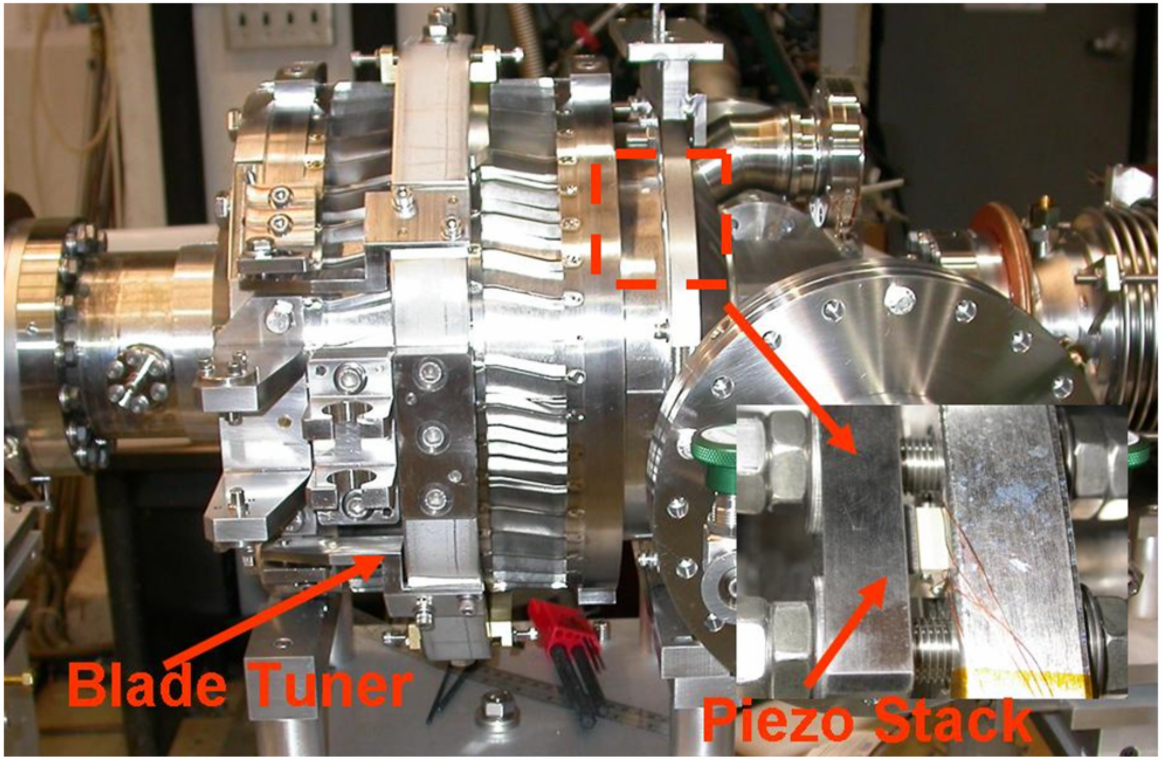
Gain Optimization for PI Field Control Loop



- Main source of field perturbation is a strong ripple on the klystron HV
- Ripple has relative amplitudes of several percent and frequencies ranging from 360 Hz to may kHz.

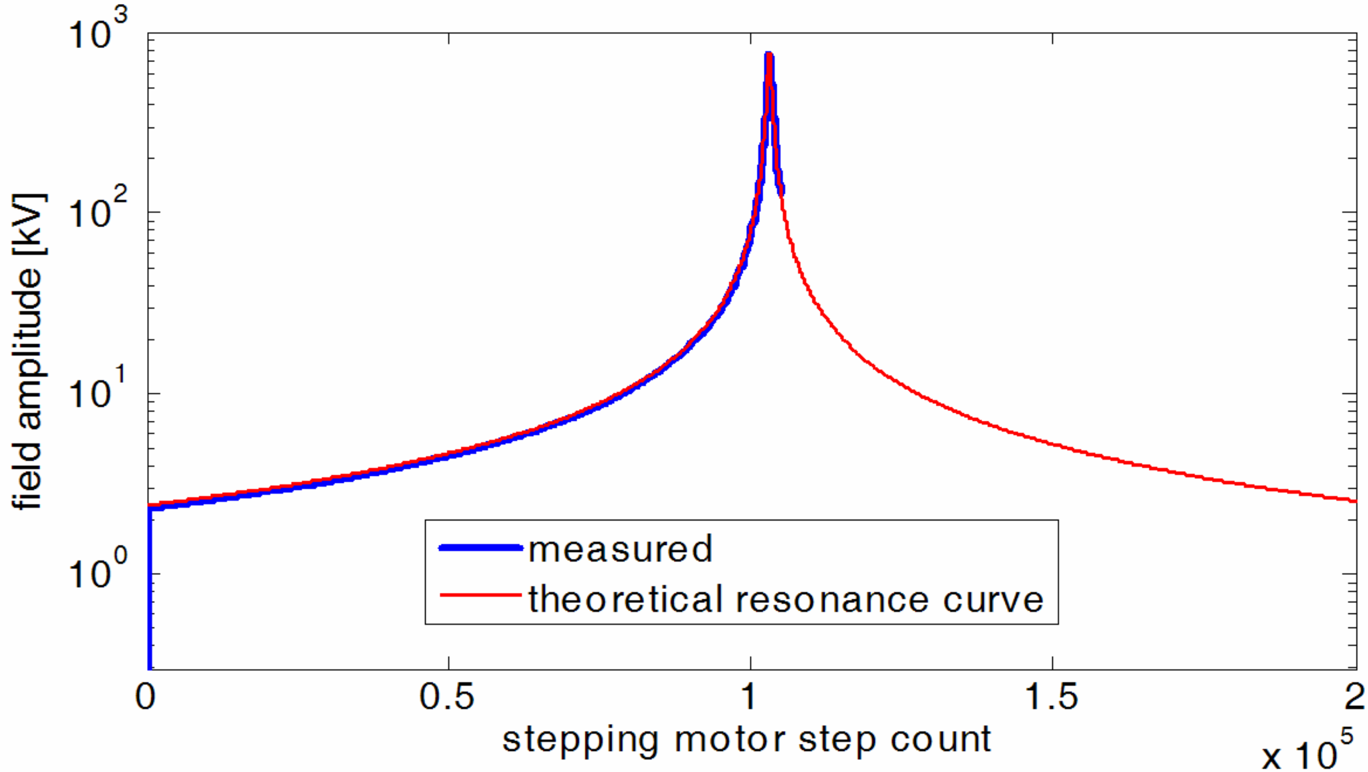
Cavity (De)tuning

SRF Cavity Frequency Tuner



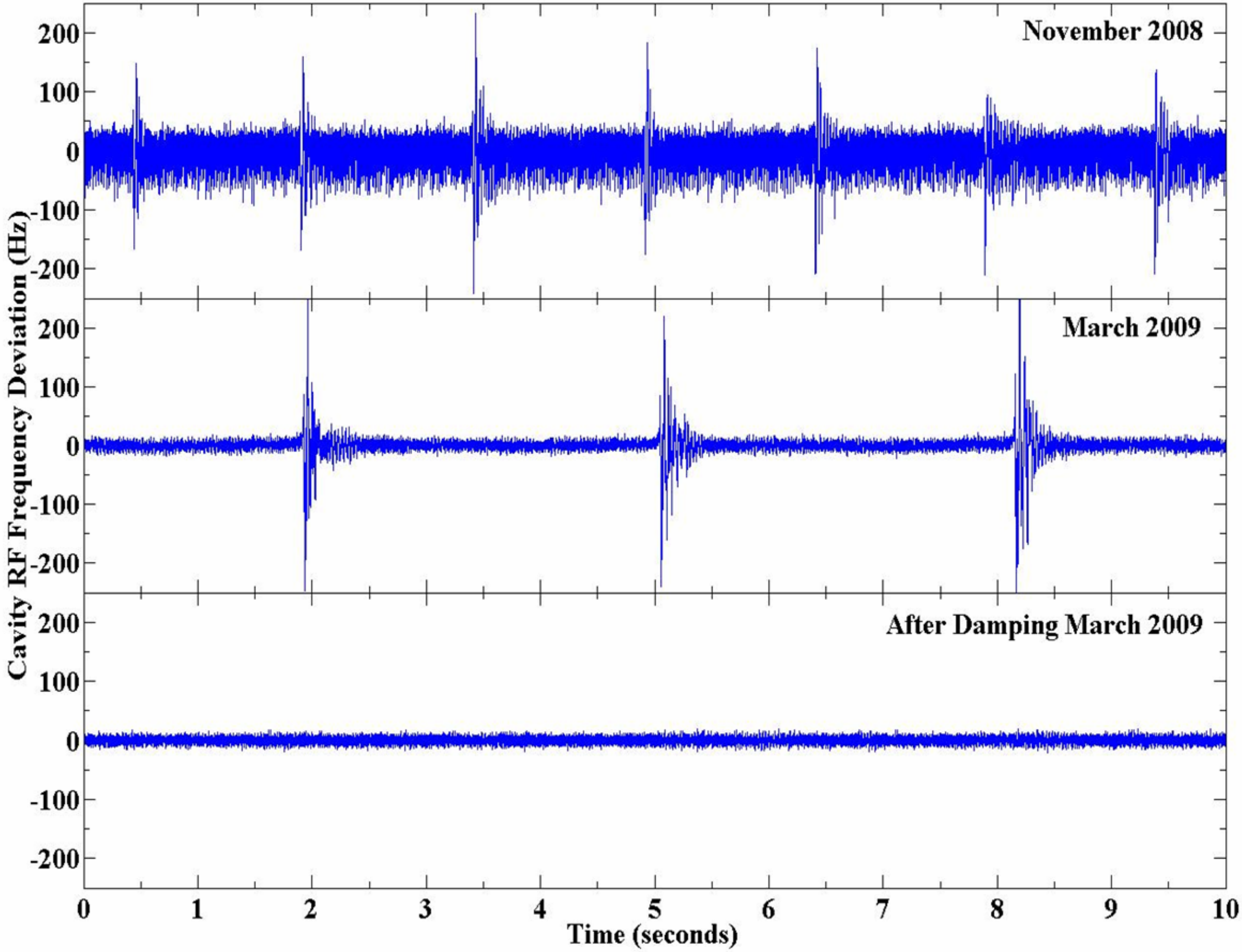
- Modification of the INFN blade tuner
- Tuning range:
  - 500 kHz stepper
  - 500 Hz piezo
- Added piezos for microphonics compensation (R&D for ERL main linac)

Initial Cavity Tuning to Resonance after Cool-Down



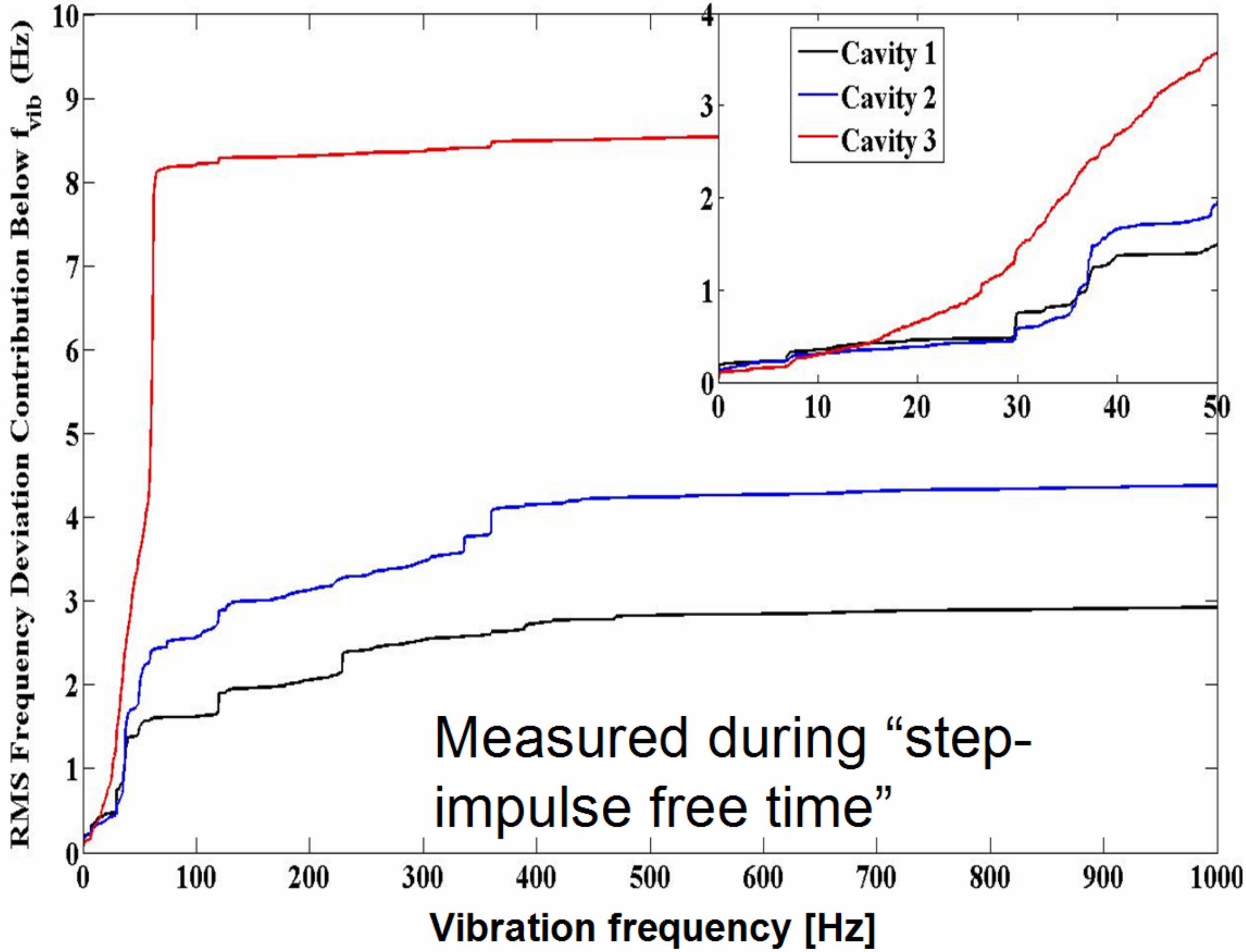
- **Tuned 100,000 steps (300 KHz)**
- **LLRF system can easily detect fields with cavity detuned by several >500 bandwidths!**

Microphonics in the Injector Module



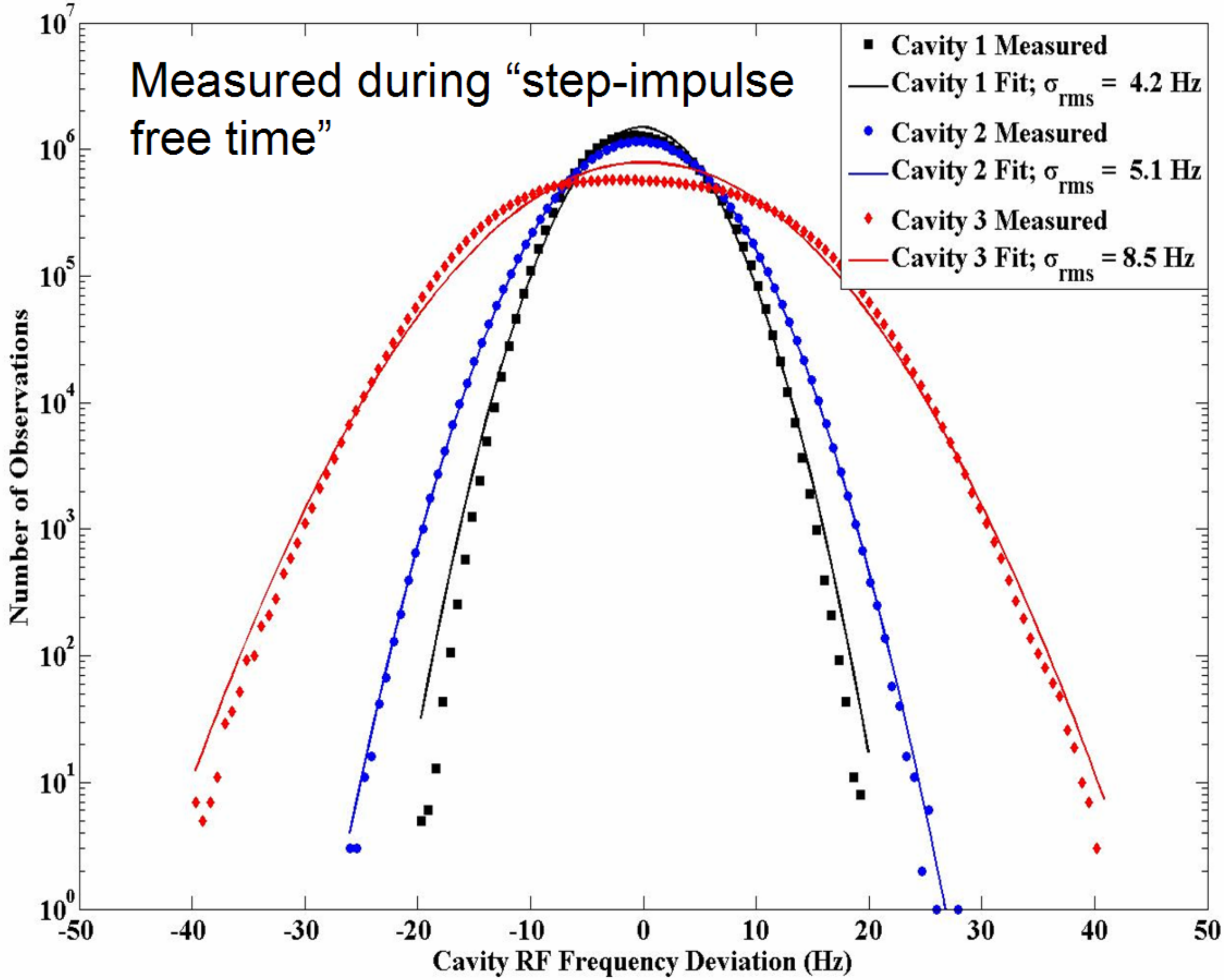
- Significant changes over time
- Step impulses related to cryo-system?

Integrated Microphonics Spectrum



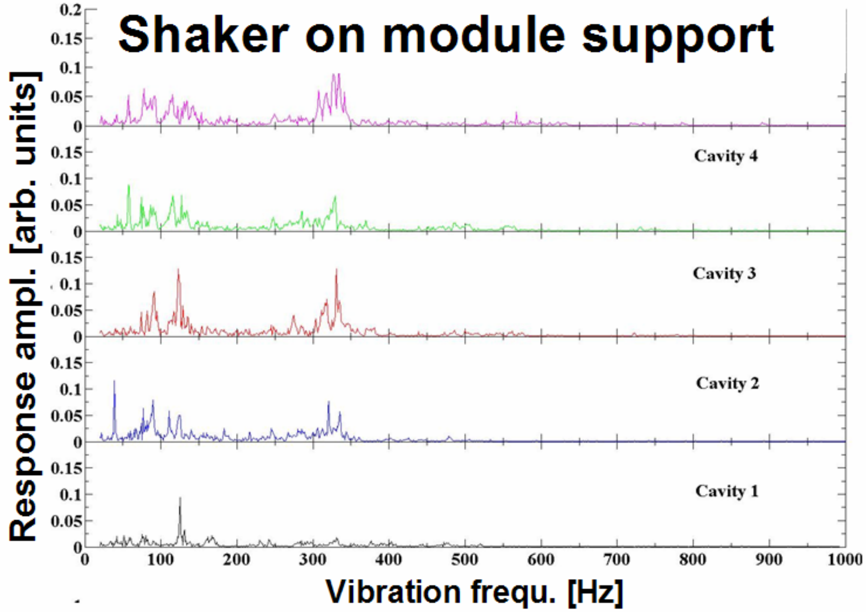
- Significant differences between cavities
- σ_f = 3 to 8 Hz

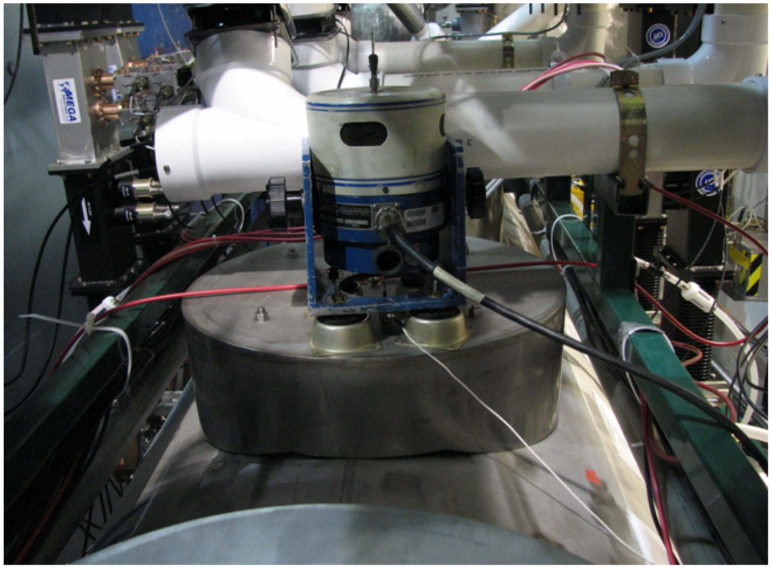
Microphonics Histogram



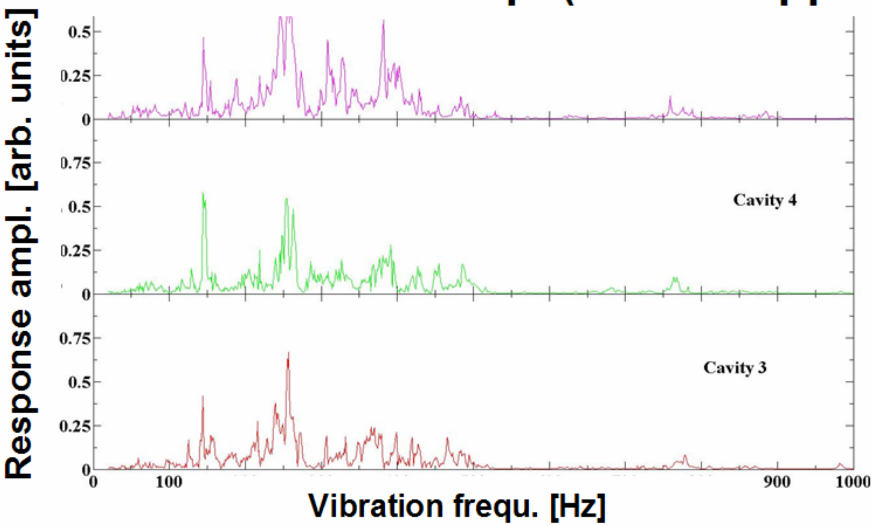
- Graph shows histogram of 30 Million samples over a period of 1 hour
- $\Delta f_{max} < 5^*\sigma_f$
- No extreme outliers

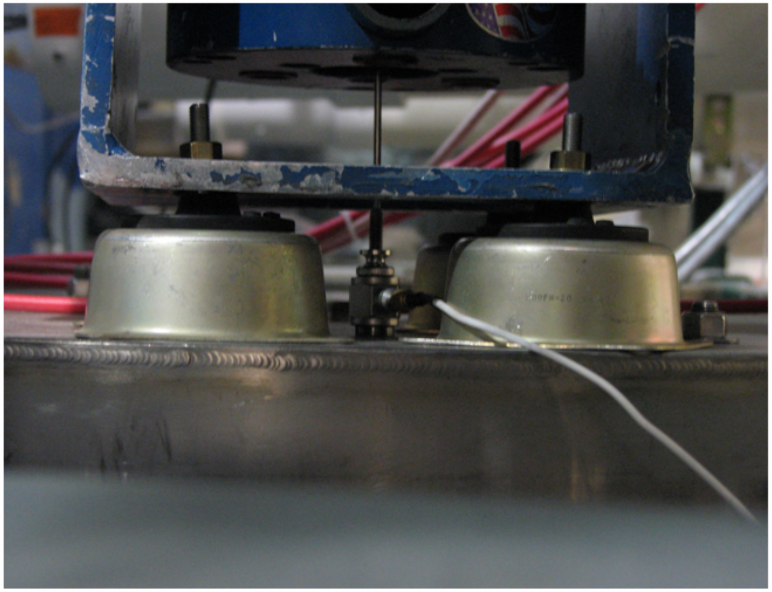
Mechanical Coupling Characterization Measurements with a Modal Shaker





Shaker on module top (HGRP support)



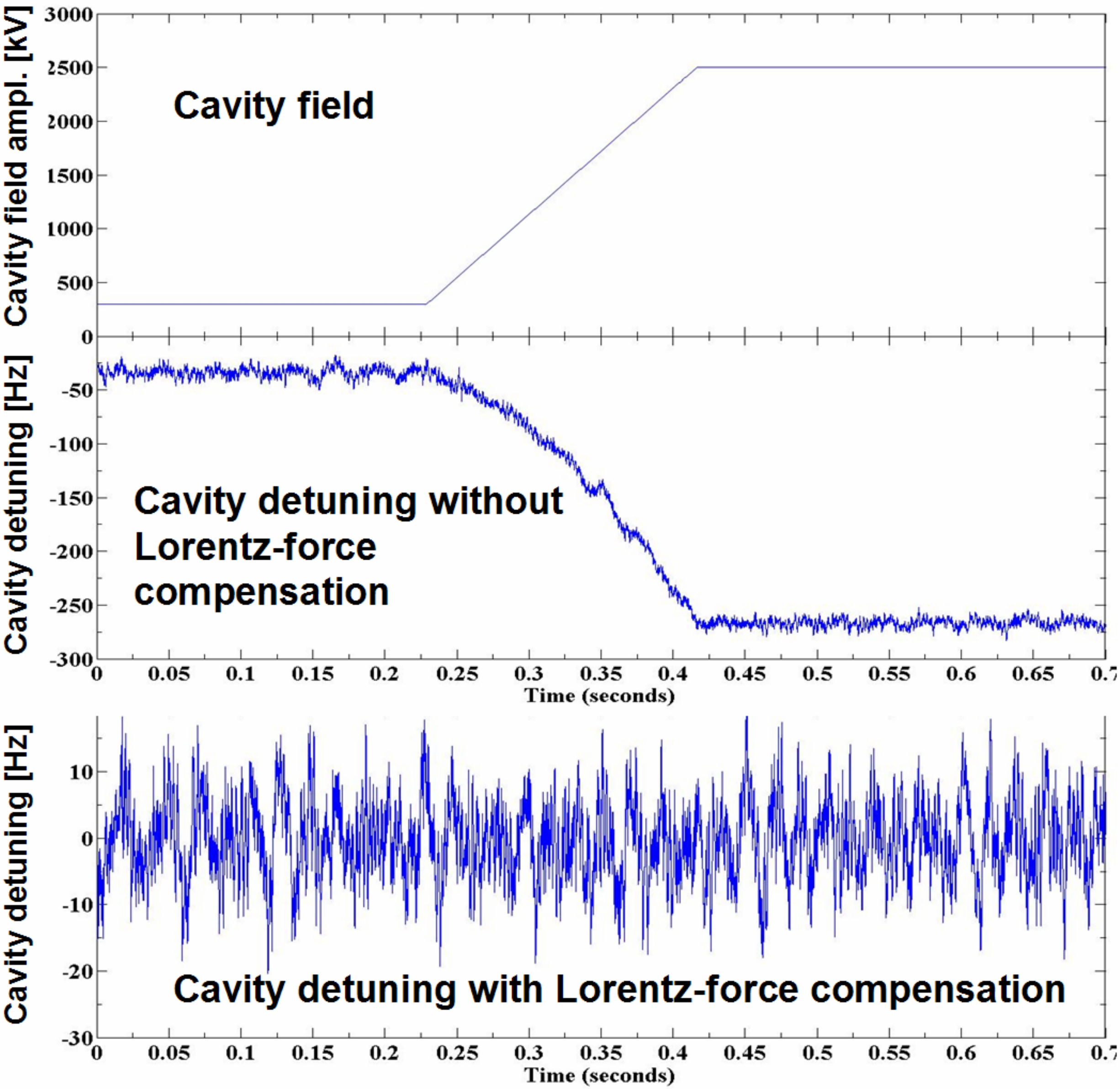


Mechanical Coupling Characterization Measurements with a Modal Shaker

Excitation Point	Excitation Force	Detectable With Cavity Accelerometer	Detectable On Cavity RF Frequency (>0.1Hz modul.)
Coupler Waveguide	110 N (25 lbs)	No	No
Coupler	110 N (25 lbs)	No	No
Cryomodule Saw-Horse Support	110 N (25 lbs)	Yes	No
Helium Gas Return Pipe Support	110 N (25 lbs)	Yes	Yes
Beam Line	10 N (2 lbs)	No	No
Helium Supply/Return	110 N (25 lbs)	No	No

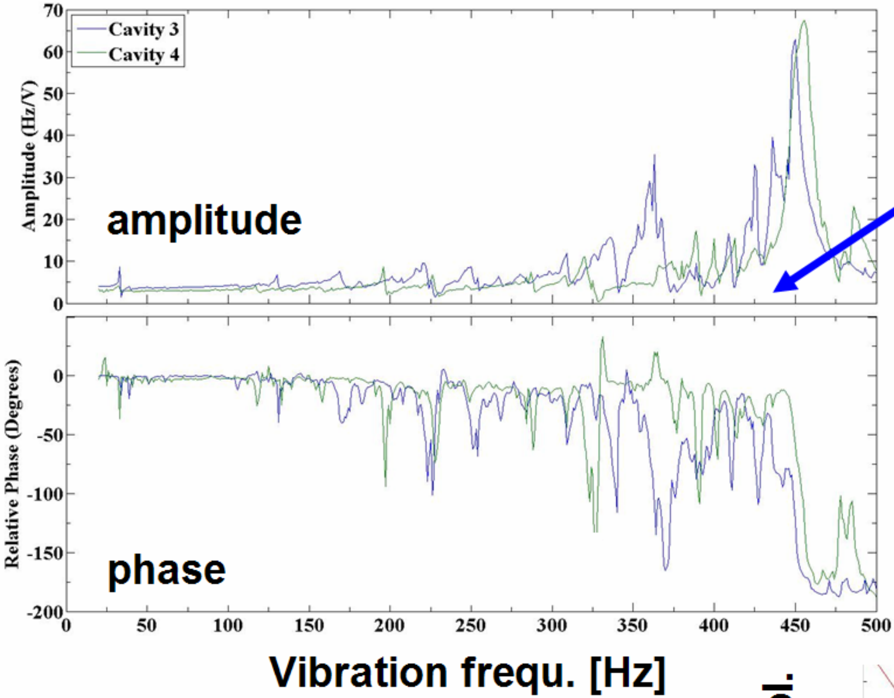
- Ground vibrations and other mechanical vibrations do **not** strongly couple to the SRF cavities
- Main contribution to cavity microphonics comes from fast fluctuations in the He-pressure and the cryogenic system

Active Compensation of Lorentz-Force Detuning



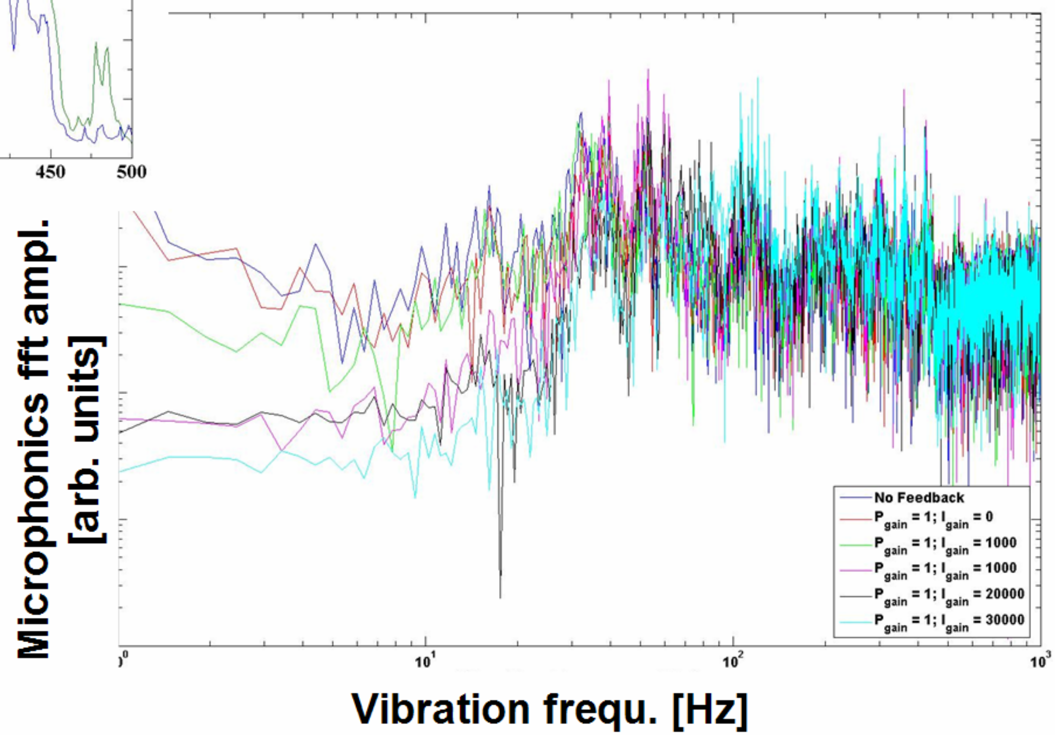
- Piezo-electric actuators implemented in the cavity frequency tuners
- Used feedback loop for active compensation
- Works very reliably

Active Compensation of Microphonics?



- Microphonics feedback challenging because of complex transfer function piezo → Δf with mechanical resonances

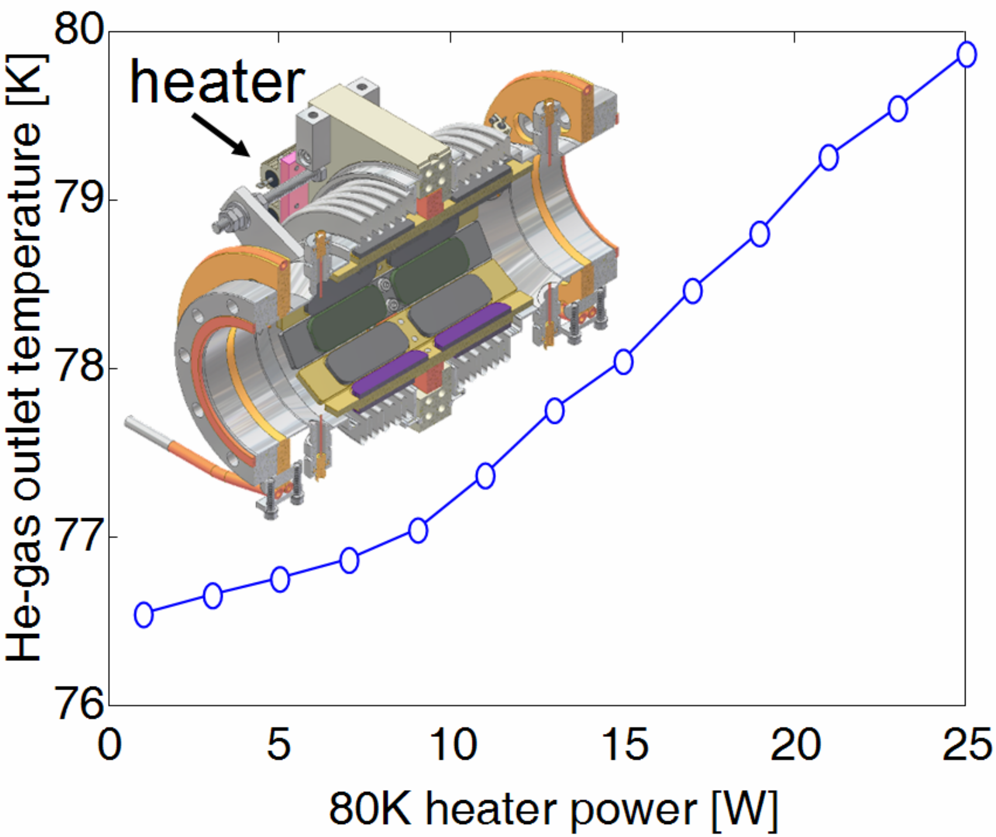
- This work has just started…
- So far: reached stable control with 20 Hz bandwidth



Beam Measurements

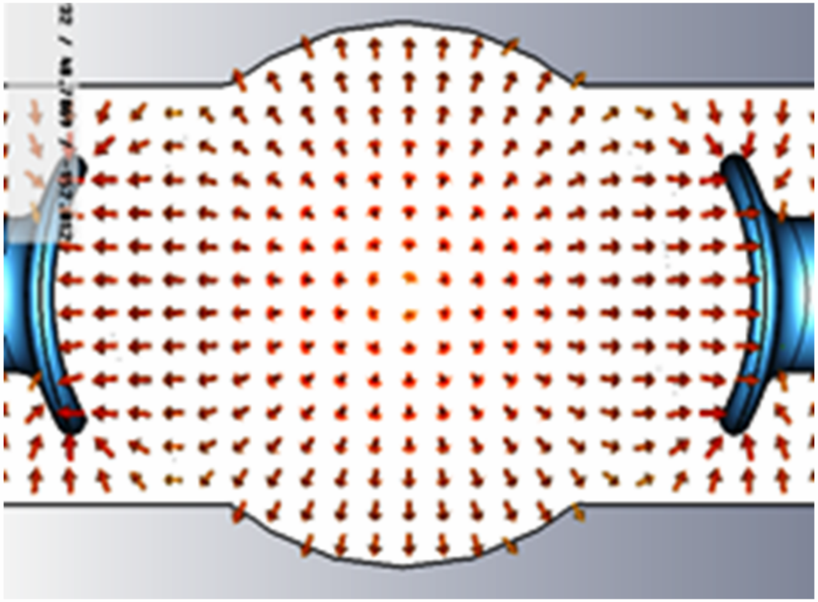
See TU2GRI01

HOM Power



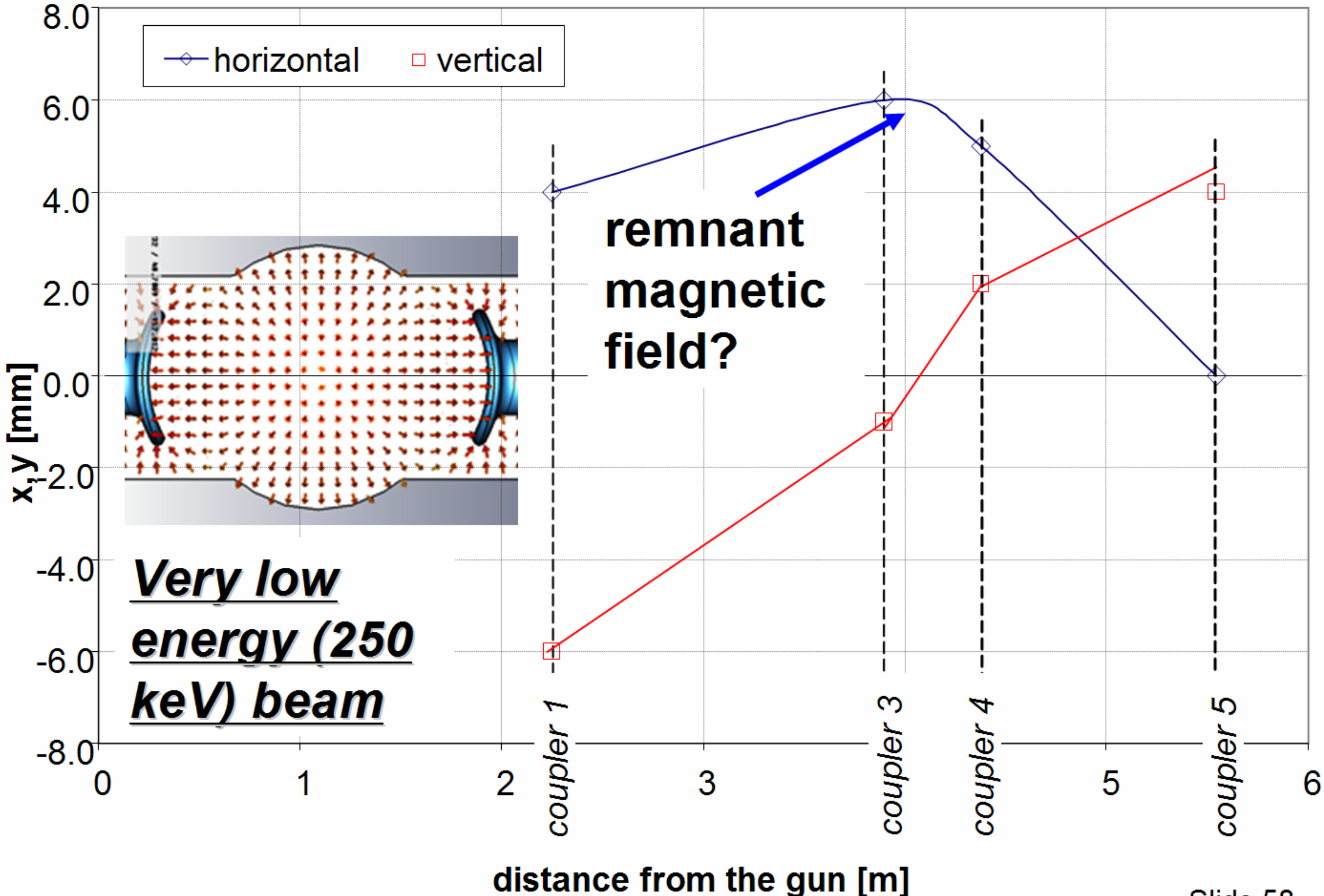
- HOM absorbers allow for measuring the total HOM power excited by the beam
- Heaters on the HOM loads for calibration
- Maximum beam current so far 4 mA -> only a few mW of HOM power/ cavity
- At higher bunch charges and currents, several W of HOM power per load!

RF Coupler Kick as a BPM



- Orbit can be estimated by measuring transverse *kicks by the RF fields in the input coupler regions*.
- The RF field is exited by a forward power of up to 1 kW *with strongly detuned cavities*.
- By measuring magnitude and direction of the kick to the beam, the beam position in the coupler region can be determined.

250 keV Beam Trajectory determined by RF Coupler Kicks

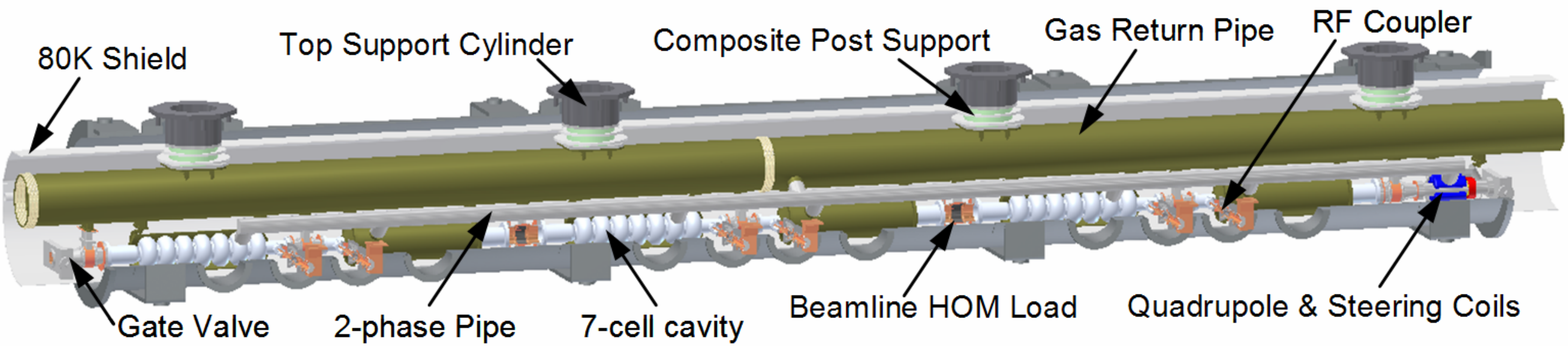


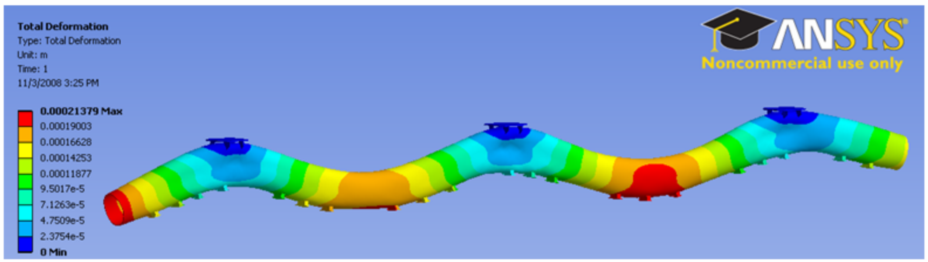
Summary and Outlook

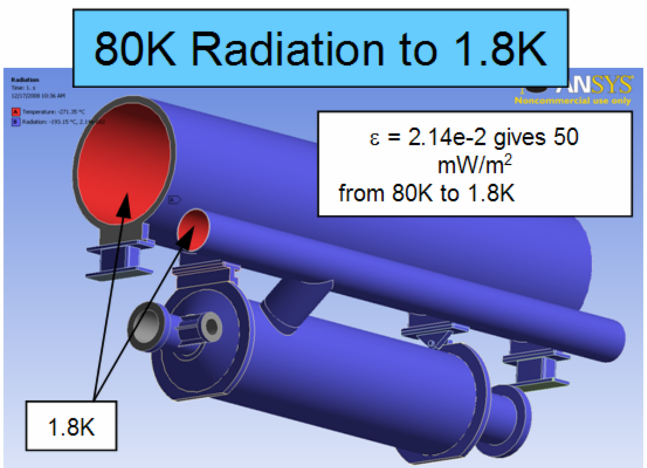
Summary and Outlook

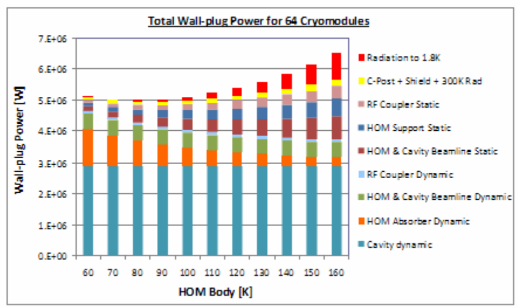
- Extensive commissioning and testing of the Cornell SRF ERL injector prototype cryomodule has started
- Progresses well
- Future work will focus on cavity conditioning, microphonics compensation, and high beam current effects.

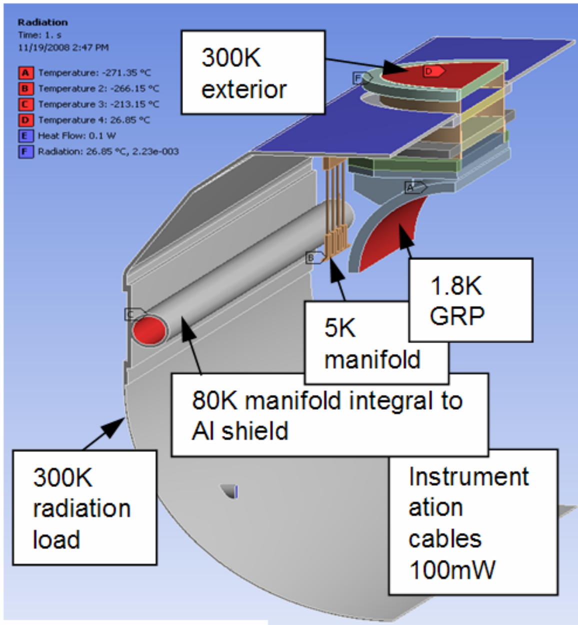
To come:
The ERL Main Linac Cryomodule











See papers WE6RFP002, TU5PFP051, TU5PF058