Status of the Cornell ERL Injector Cryomodule

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This work is supported by NSF-0131508 and DMR-0937466

XXV LINEAR ACCELERATOR CONFERENCE
LINAC10
TSUKUBA, JAPAN
SEPTEMBER 12 - 17, 2010

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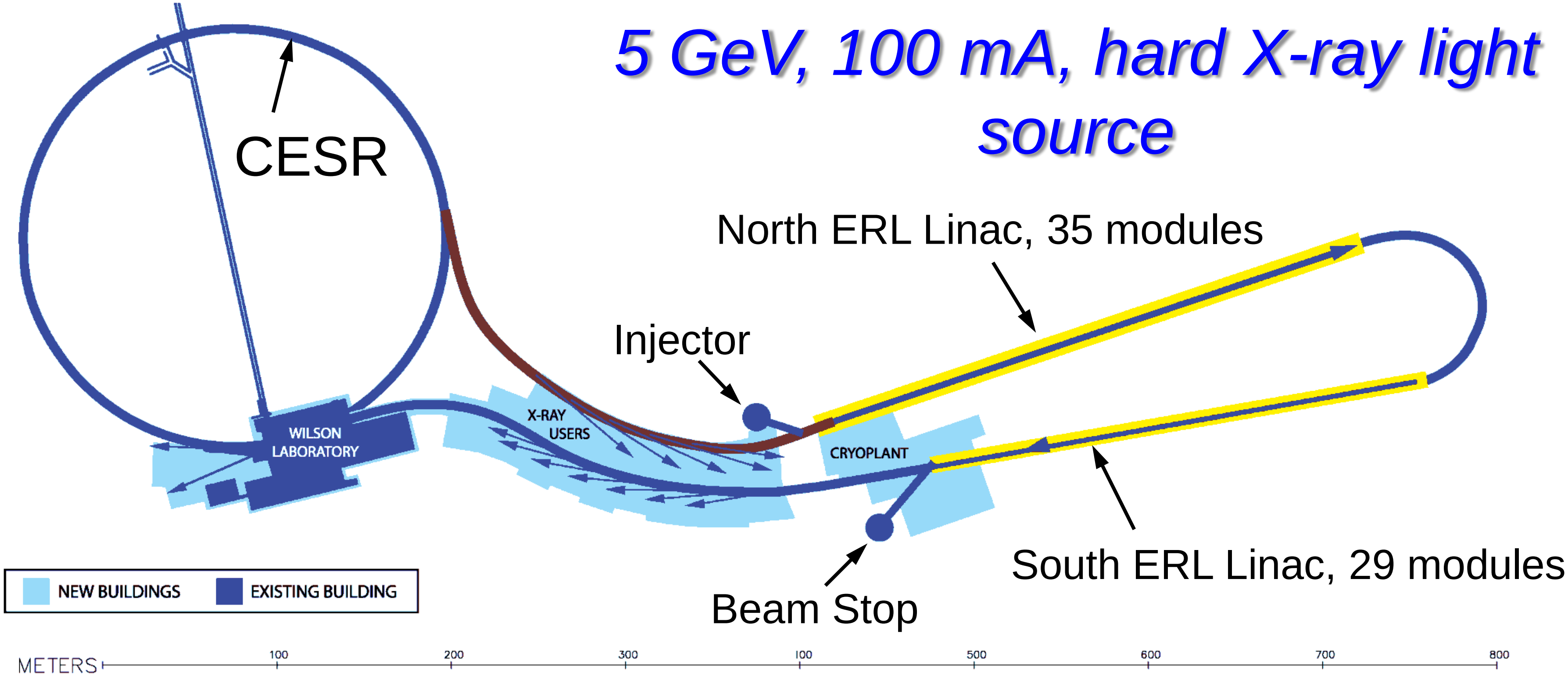
The Cornell Energy Recovery Linac Project

5 GeV, 100 mA, hard X-ray light source



- Cornell is designed are pursuing funding for a Energy Recover Linac (ERL) based x-ray light source.
- A project design and description report is near completion.
- An ERL injector prototype has been developed, fabricated, and is currently under commissioning.

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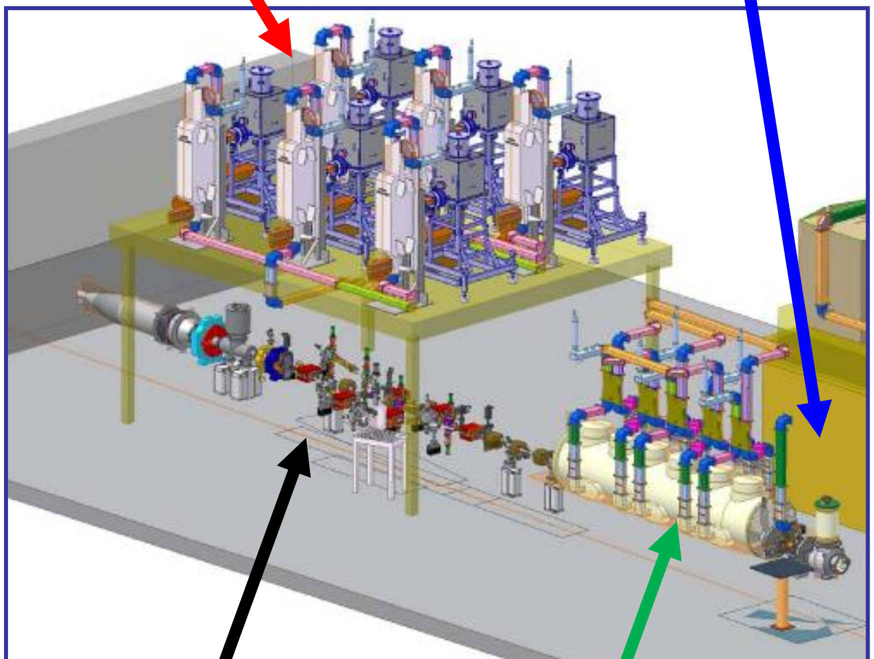
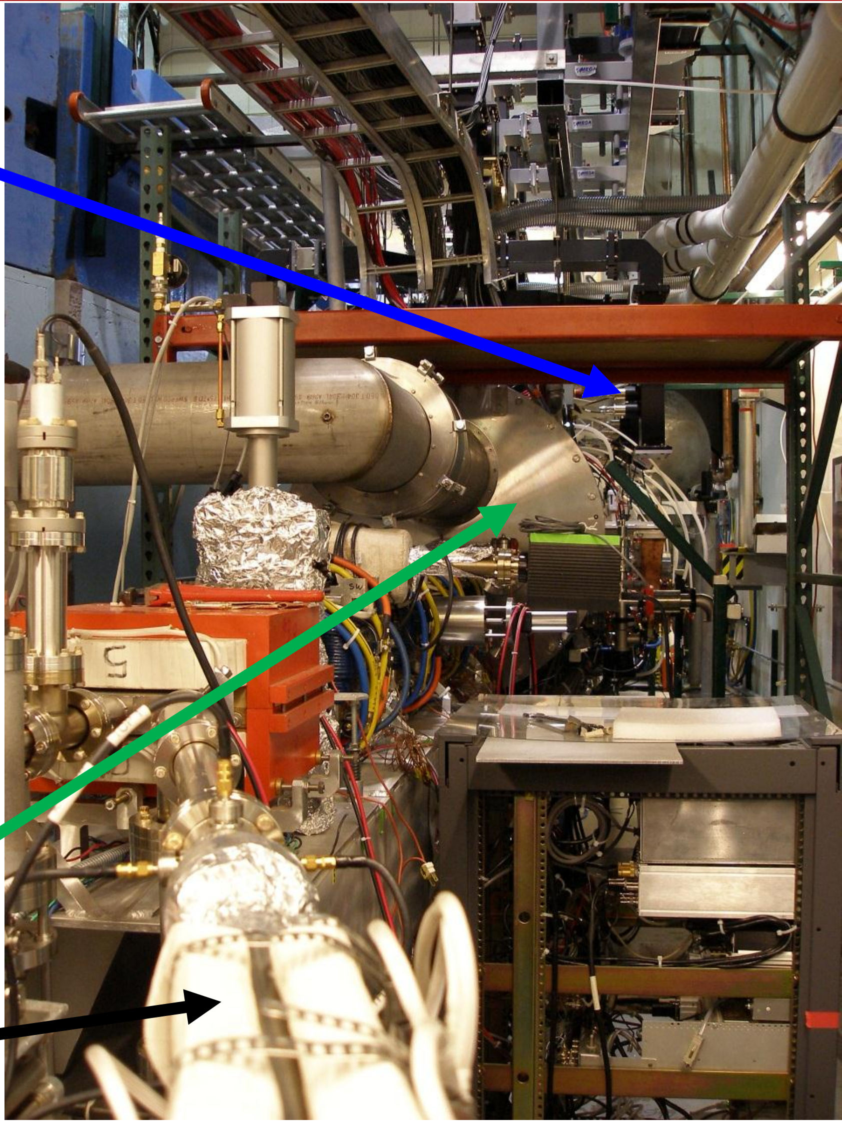
A 100 mA SRF Injector for the Cornell ERL X-ray Light Source



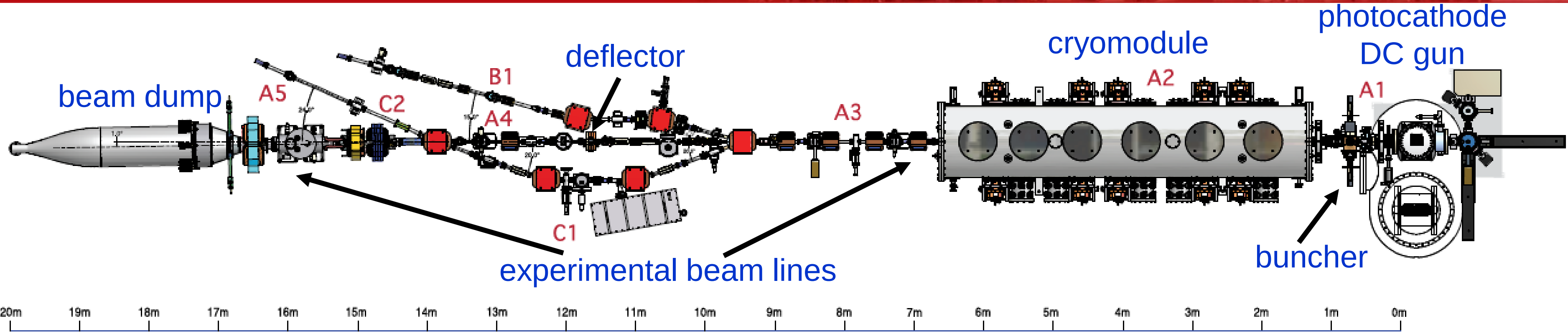


Outline

- Introduction
  - The ERL Injector Prototype at Cornell
  - The ERL Injector SRF Cryomodule
- Initial Challenges and Solutions
  - HV power supply, gun, laser, and cryomodule rework
- Highlights: Pushing the envolope
  - Beam results
  - Cryomodule performance
- Outlook

Introduction:
The ERL Injector Prototype at Cornell
The ERL Injector SRF Cryomodule

Cornell 100 mA ERL Injector

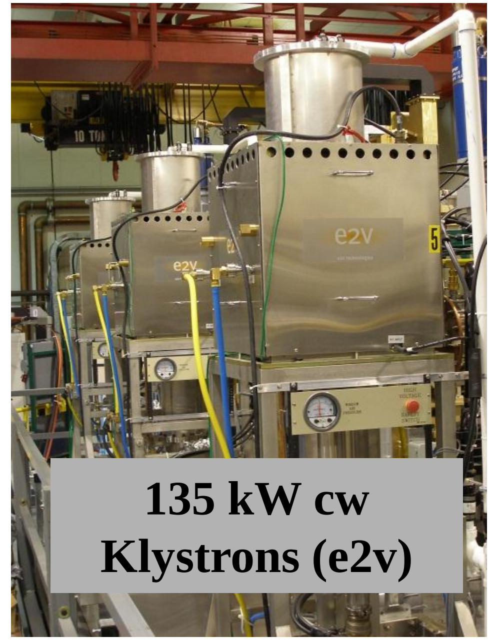


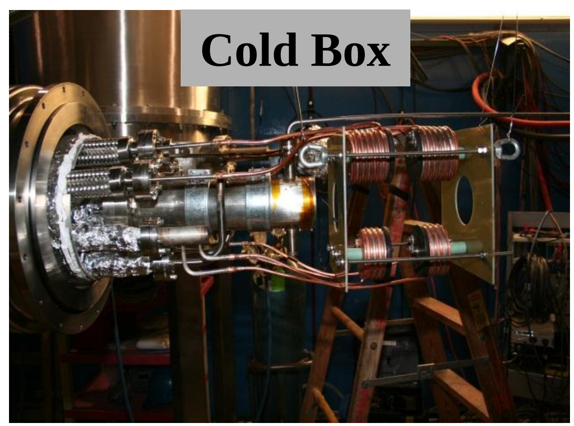
	design parameters
Nominal bunch charge	77 pC
Bunch repetition rate	1.3 GHz
Beam power	up to 550 kW
Nominal gun voltage	500 kV
SC linac beam energy gain	5 to 15 MeV
Beam current	100 mA at 5 MeV
	33 mA at 15 MeV
Bunch length	0.6 mm (rms)
Transverse emittance	< 1 mm-mrad

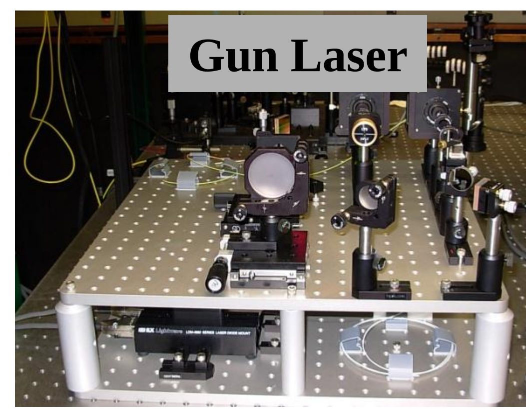
ERL Injector Schedule

2001:	ERL prototype proposal submitted
2005:	NSF funds the injector part of the proposal
Sept. 2006:	1st beam from the DC gun
Sept. 2007:	Beam line and cryomodule fabrication and assembly starts
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 test period starts
August 2009:	End of first test period; rework of DC gun and SRF cryomodule starts
April 2010:	First beam after cryomodule rework

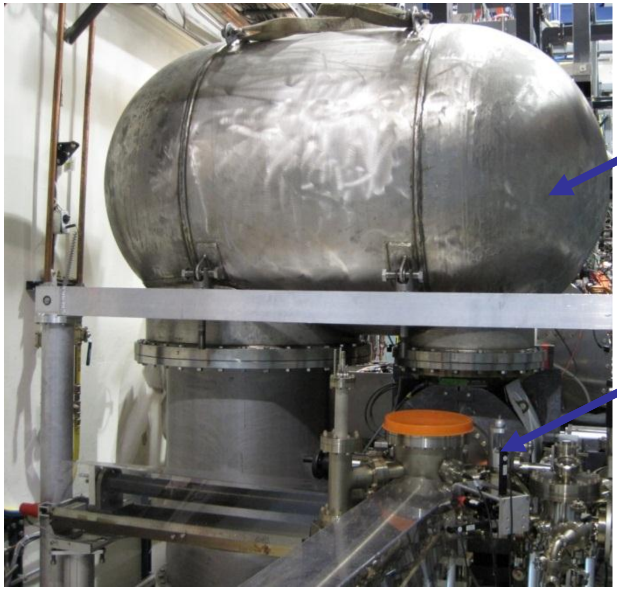
100 mA ERL Injector: Technical Components





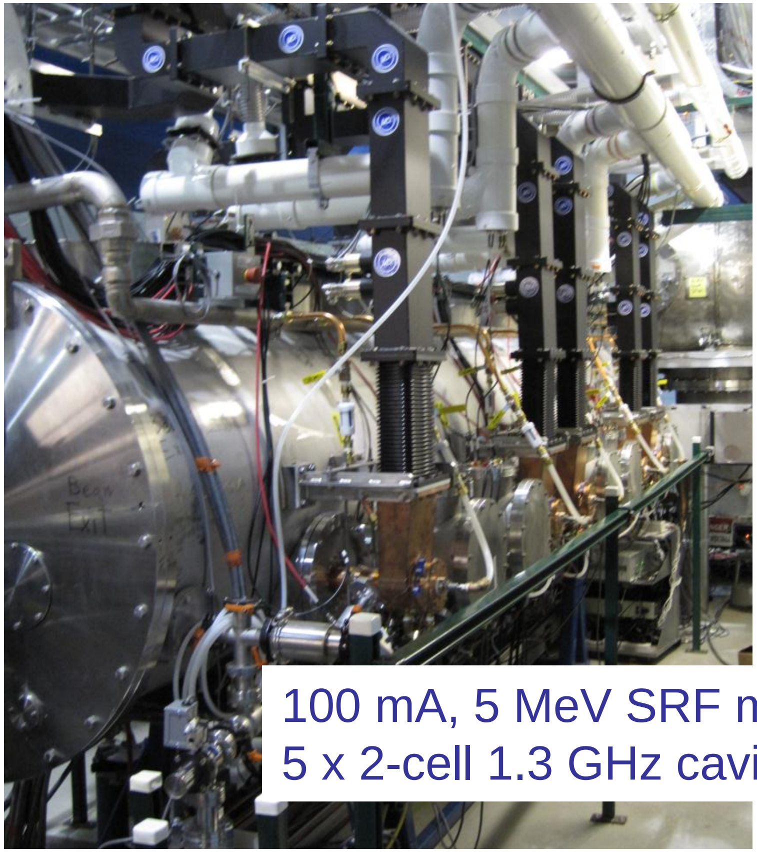


Cornell 100 mA ERL Injector

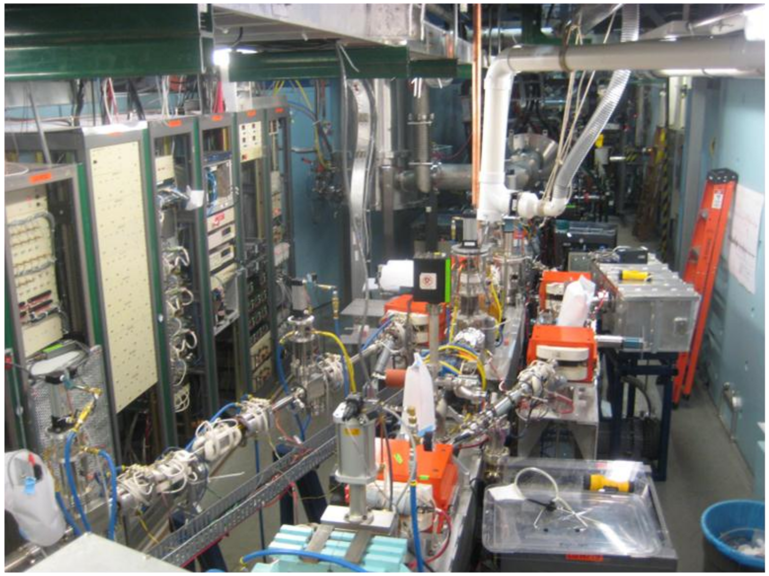


SF6 tank

DC gun

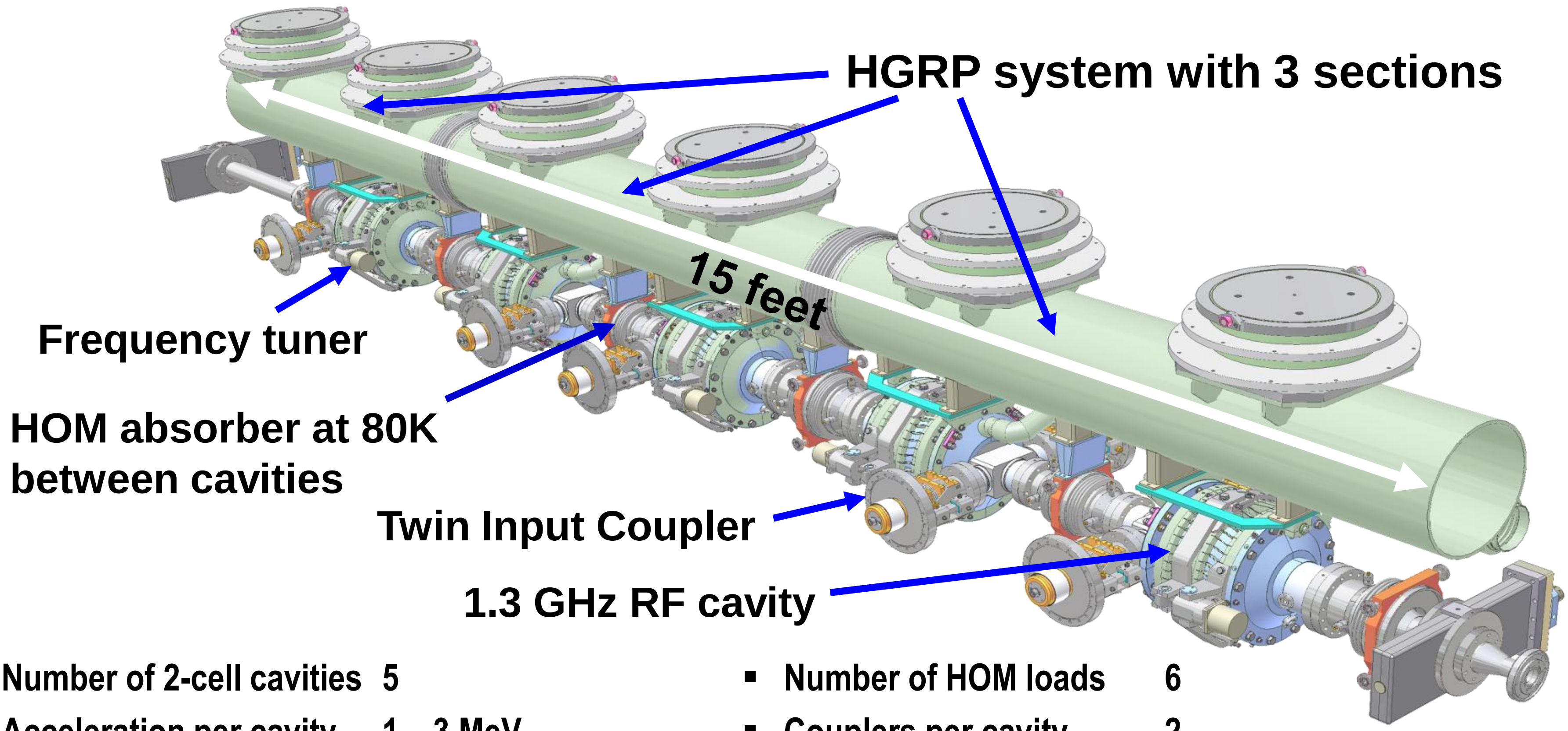


100 mA, 5 MeV SRF module
5 x 2-cell 1.3 GHz cavities



Diagnostics section
- emittance measurement systems
- deflecting cavity
- view-screens
- BPMs, BLMs, Faraday-cups, …

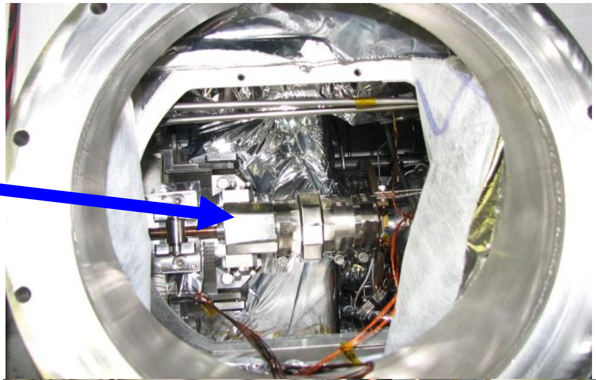
ERL Injector Cryomodule



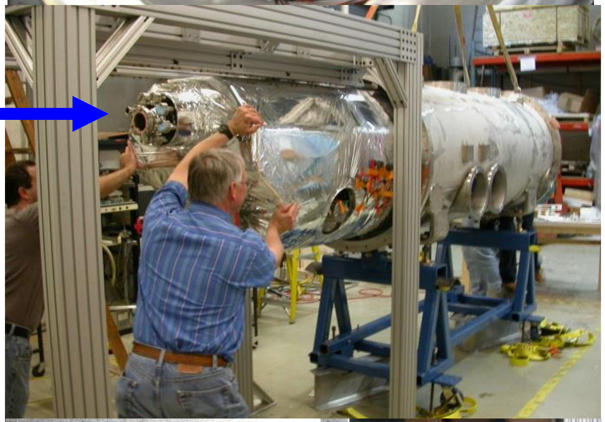
- Number of 2-cell cavities 5
- Acceleration per cavity 1 – 3 MeV
- Accelerating gradient 4.3 – 13.0 MV/m
- R/Q (linac definition) 222 Ohm
- Qext $4.6\times10^4 - 4.1\times10^5$
- Total 2K / 5K / 80K loads: 30W / 60W / 700W
- Number of HOM loads 6
- Couplers per cavity 2
- RF power per cavity 120 kW
- Amplitude/phase stability 10^{-3} / 0.1° (rms)
- ICM length 5 m

ERL Injector Module Innovations (I)

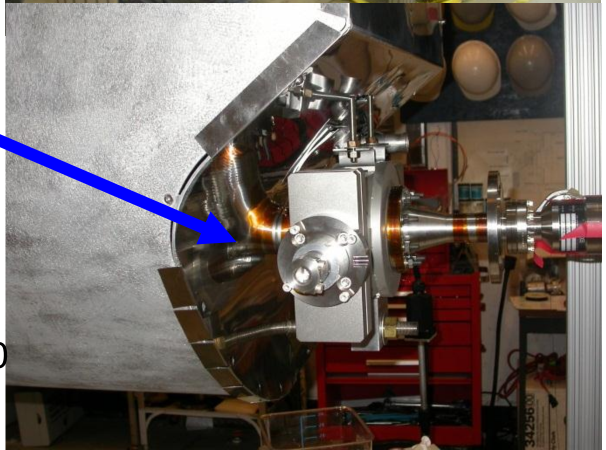
- Tuner stepper replaceable while string is in cryomodule



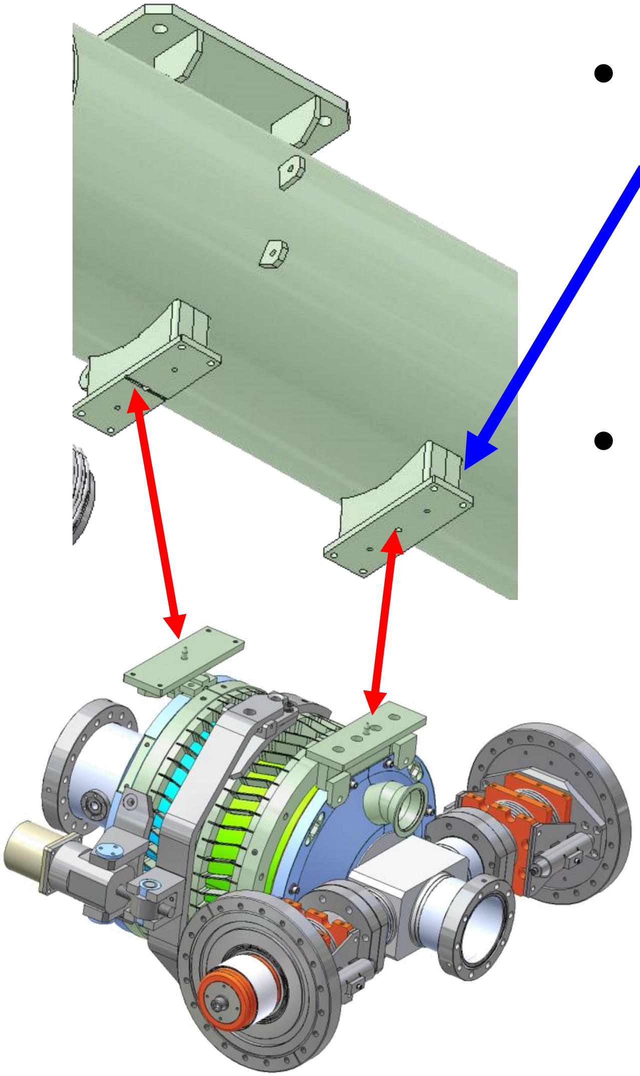
- Rail system for cold mass insertion into Vacuum Vessel



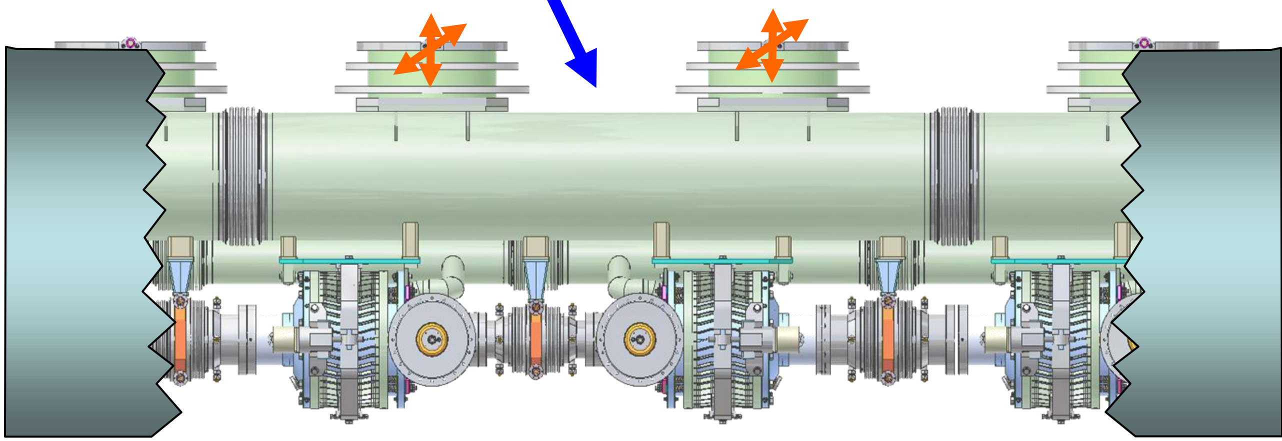
- Gatevalve inside of module with outside drive



ERL Injector Module Innovations (II)



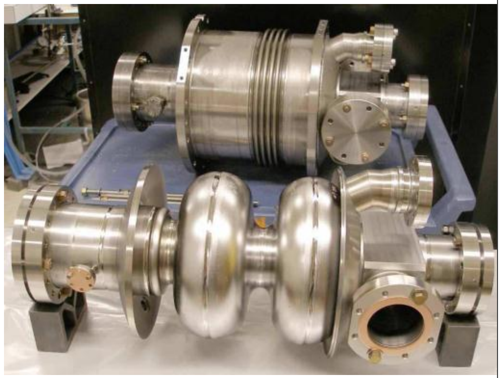
- Precision fixed cavity support surfaces between the beamline components and the HGRP
  $\Rightarrow$ easy “self” alignment
- Cavity-subunits can be fine-aligned while cavities are at 2K (if required)

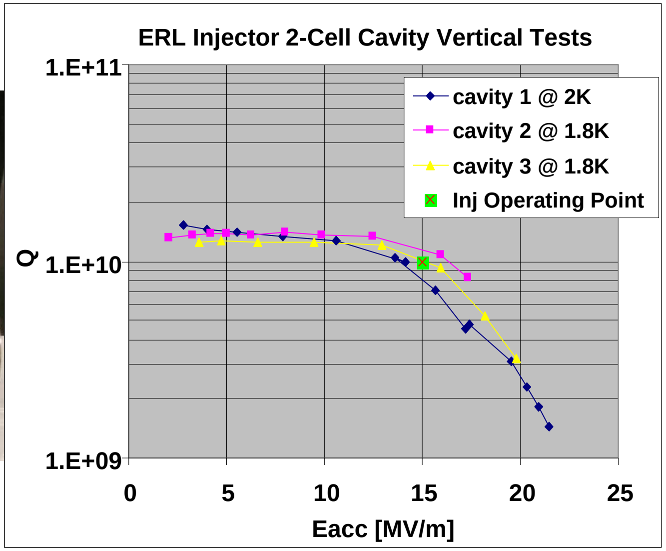


Beam Line Components (I)

SRF cavities:

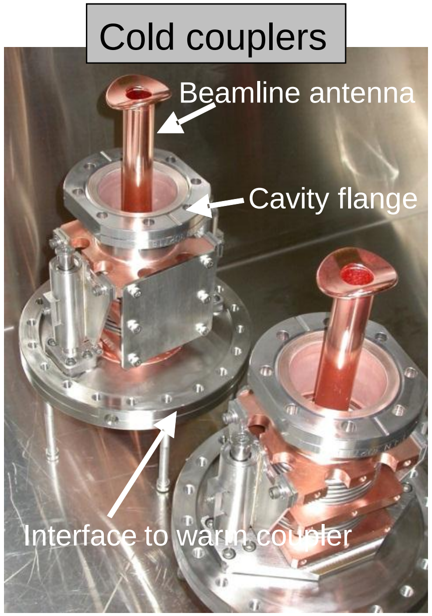
- Designed, fabricated, prepared and tested at Cornell
- Only BCP, no 800C
- All cavities met 15 MV/m spec in vert. test

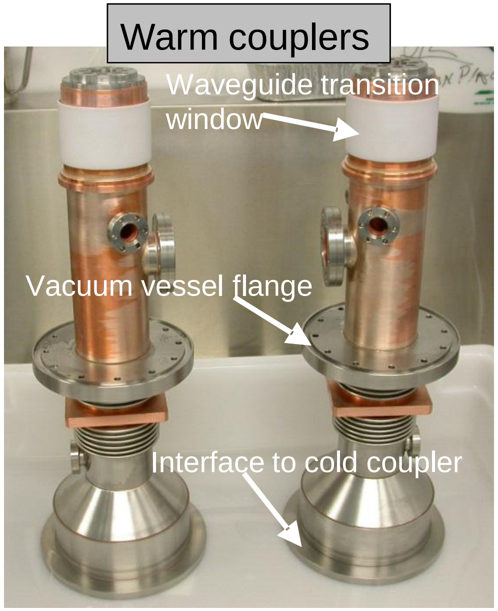




RF input couplers:

- 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

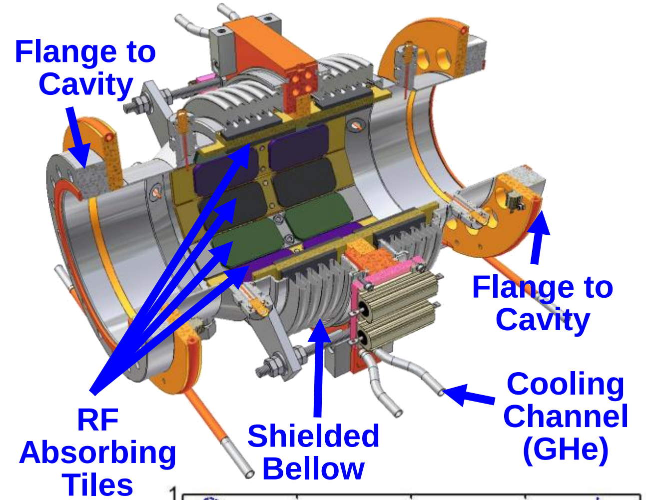


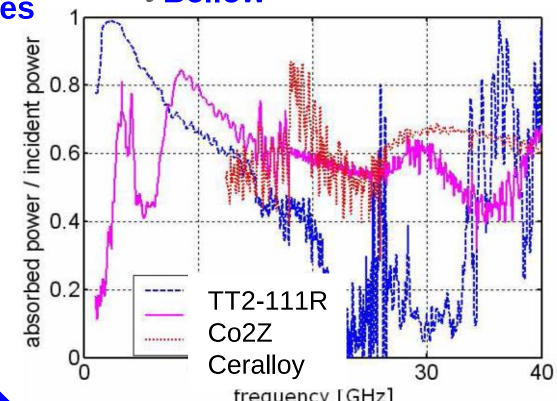


Beam Line Components (II)

HOM absorbers:

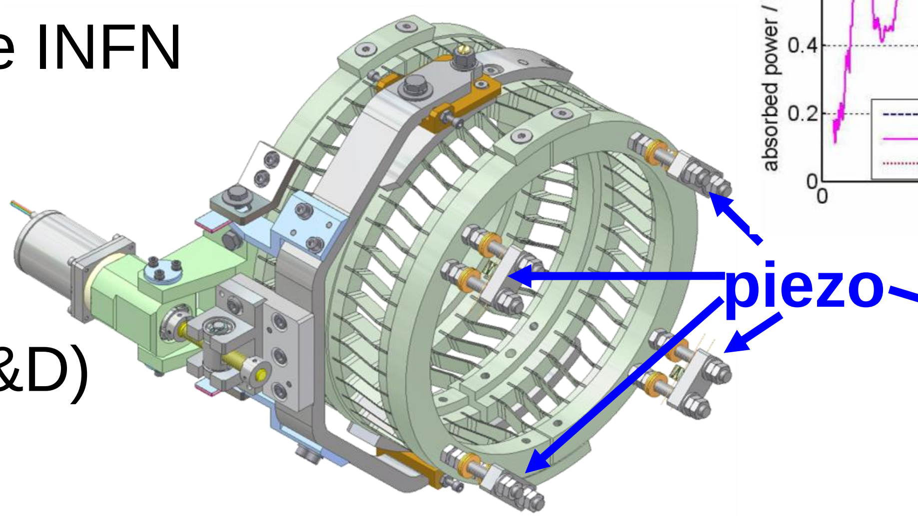
- Design by Cornell for strong, broadband HOM damping
- 6 production loads fab'ed by industry

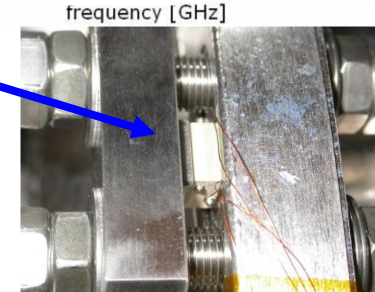




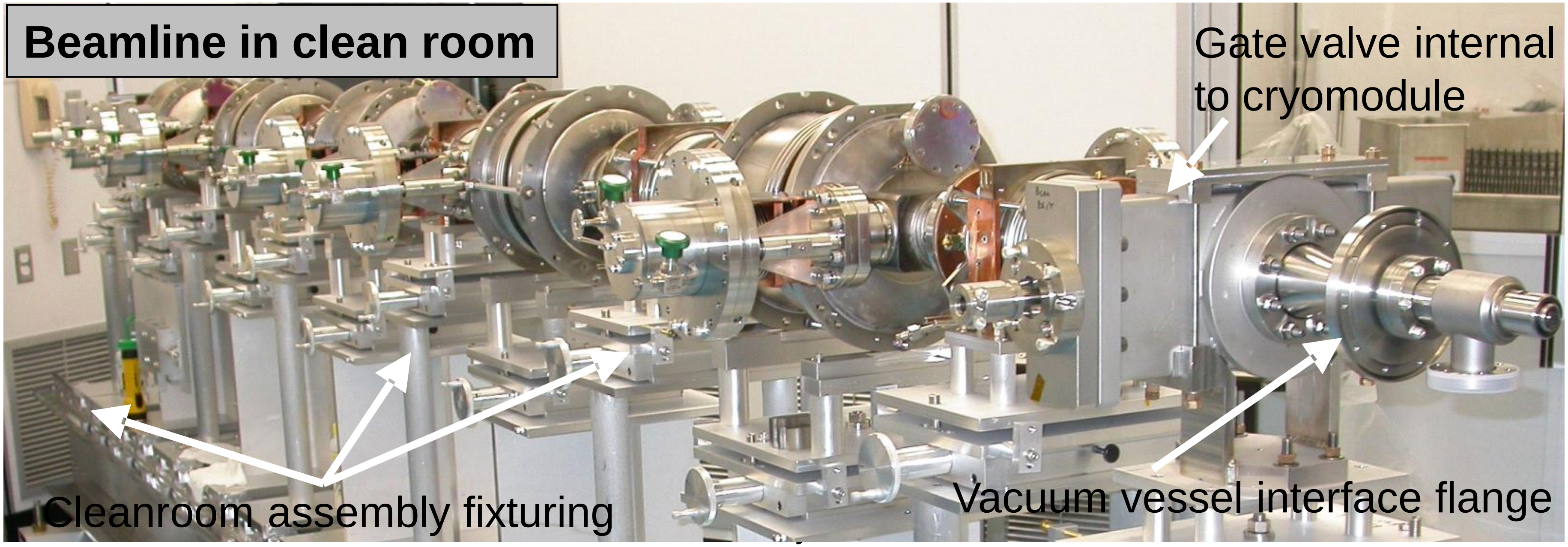
Frequency tuners:

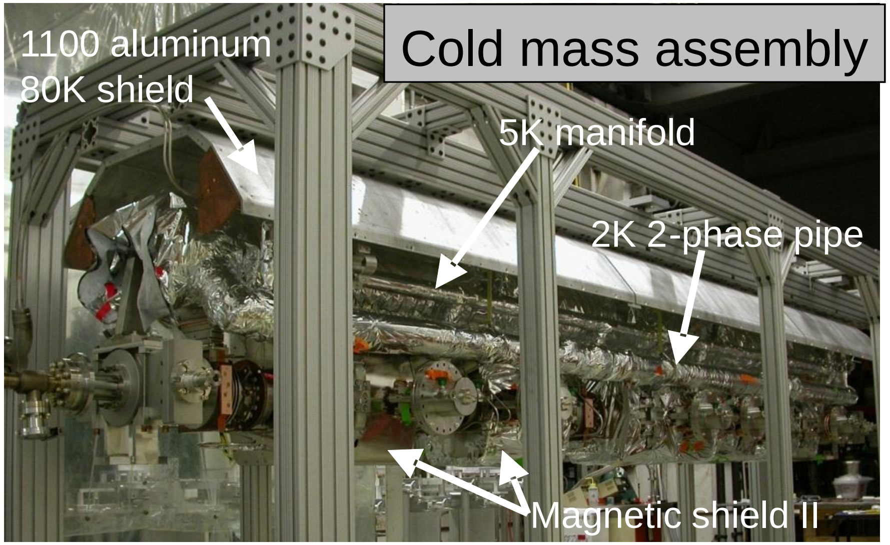
- Modification of the INFN blade tuner
- Added piezos for microphonics compensation (R&D)
- 6 units fabricated by industry

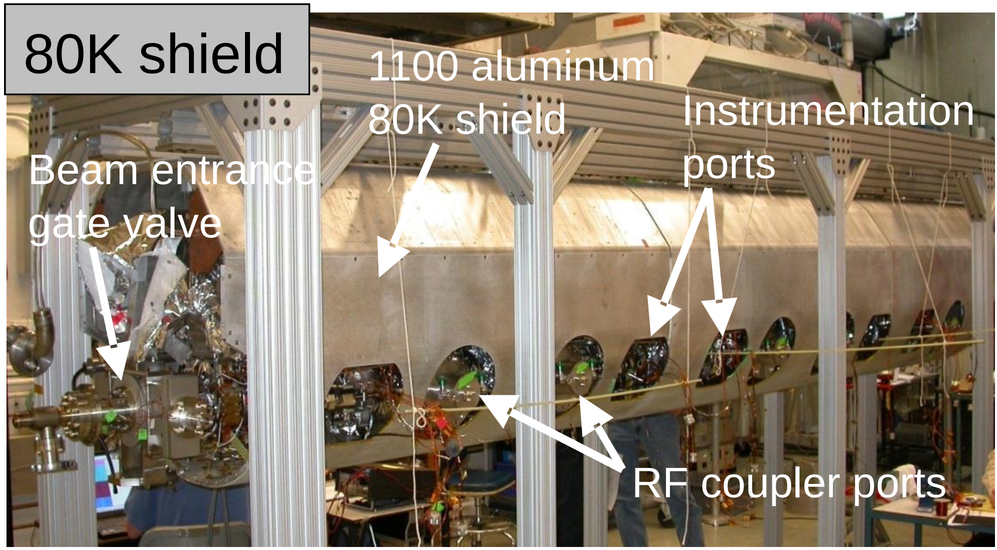




ERL Injector Module Assembly at Cornell

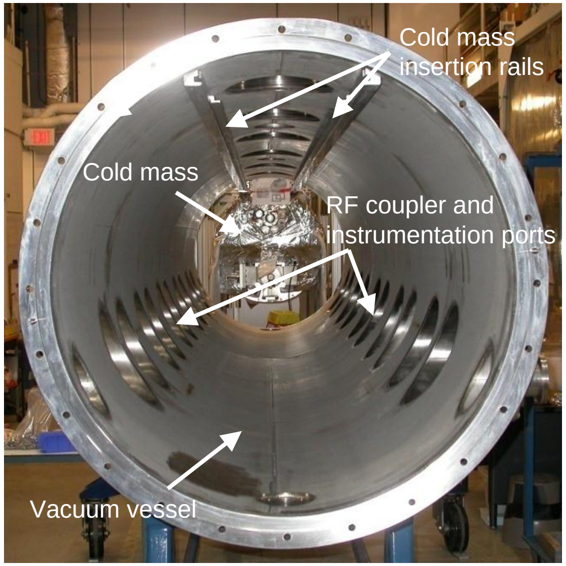


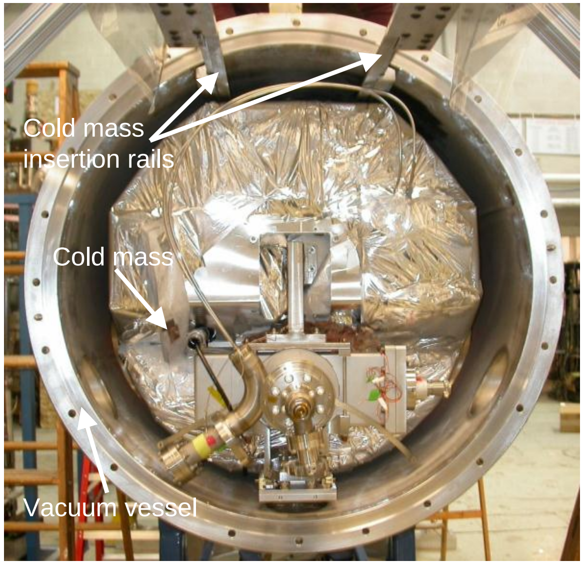


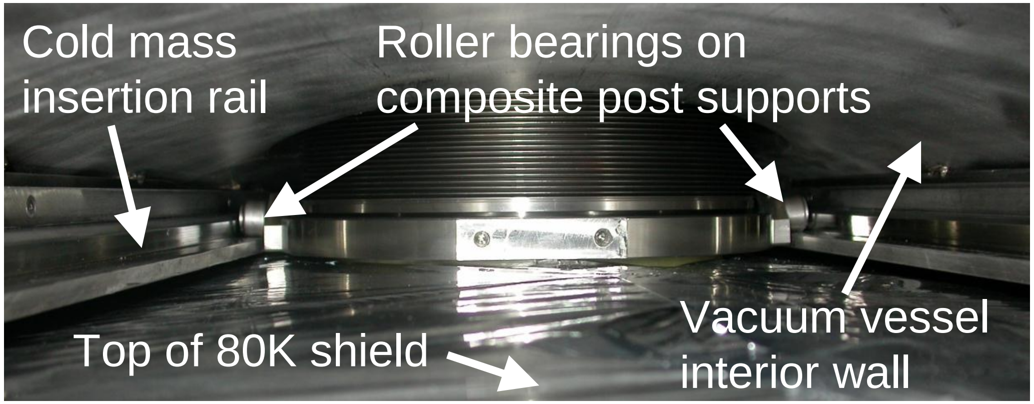


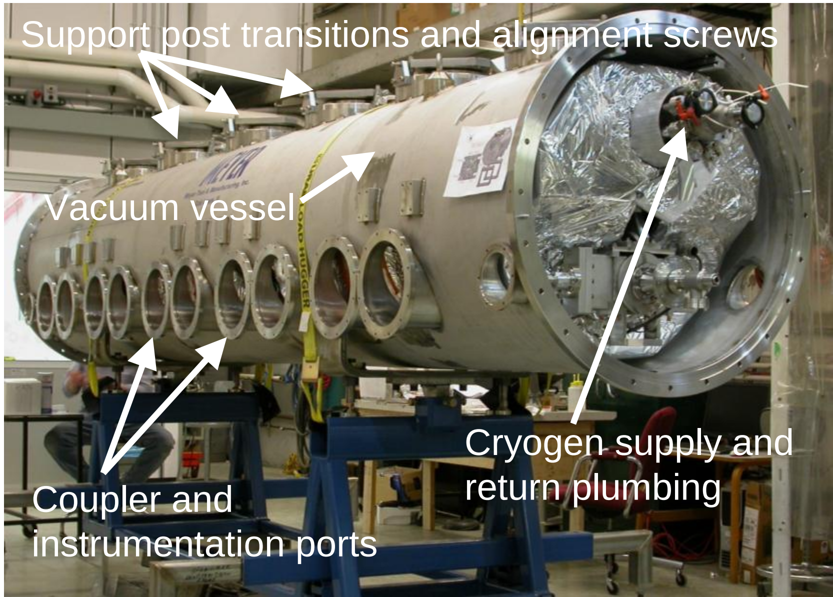
ERL Injector Module Assembly at Cornell

Cold mass rolled into vacuum vessel









Initial Challenges and Solutions: HV power supply, gun, laser, and cryomodule rework

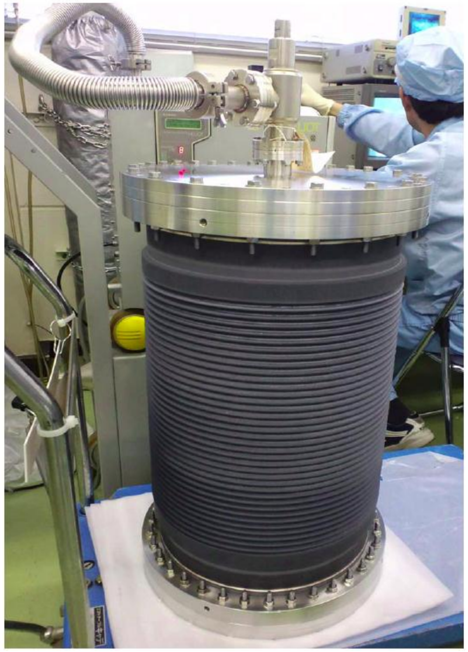
Initial Challenges

- The first run period (July 2008 – August 2009) revealed a few issues, that needed to be addressed:
  - Gun ceramics: punch-through events
  - Laser: stability and power handling issues
  - Gun HV: poor stability (control loop got unstable above a few mA of current)
  - Injector cryomodule: lower than expected cavity Q_0, HOM load absorber tiles charging
- **Solutions where implemented during a recent shut-down. Commissioning and beam studies have re-started now.**

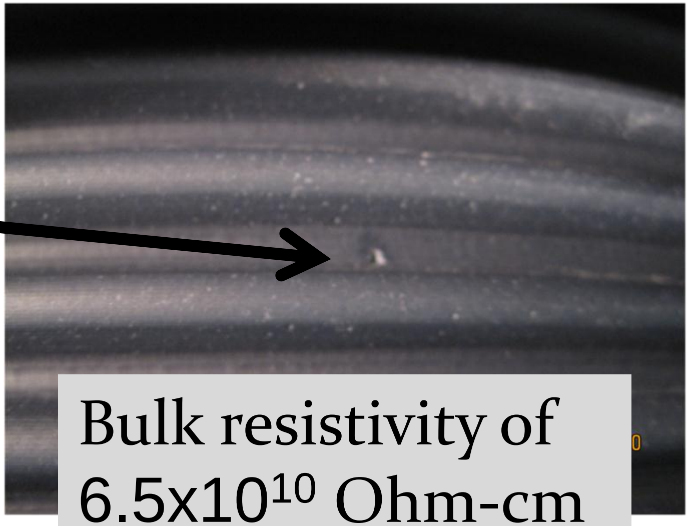
Gun Ceramic: Issue

DC photogun operational for over 3 years

- Strong points: quick photocathode removal & activation, excellent vacuum (good lifetime)
- Issues:
  - *Field emission & ceramic puncture* (425→250 kV)

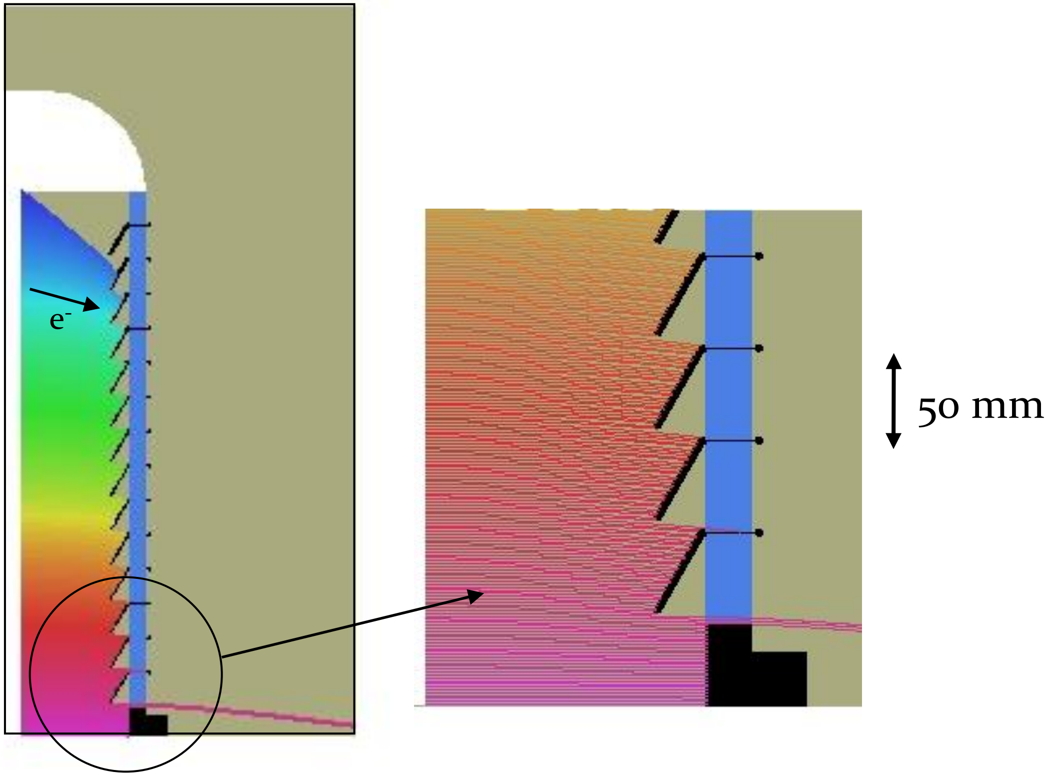


Field emitted electrons can build up on the insulator and punch through (had event at 450 kV)



Bulk resistivity of 6.5×10^{10} Ohm-cm

Gun Ceramic: Solution



- Designed a segmented insulator with intermediate guard rings to catch any field emitted electrons before they reach the insulator material.
- **Will be installed in the fall ⇒ >500 keV**

Gun HV Power Supply

- 750 kV, 100 mA power supply
- Built by vendor (Kaiser Systems)
- Nice and small, but:
  - Need to run current over wide dynamic range – pA to 100 mA.
  - When running at a few mA current, the HV stability was not very good.

    ⇒ Limited high current operation to a few mA so far.
- Solution: Vendor improved control loop stability to reduce HV ripple

  ⇒ **High current operation restarts this week.**

Module Re-work to address low Q_0 and Absorber Charging

3 weeks later

"module in boxes"

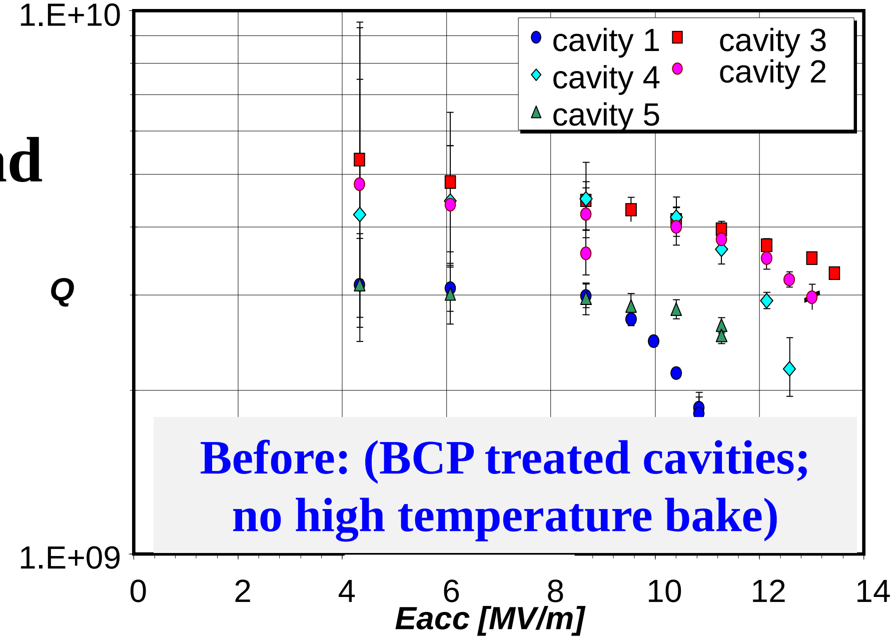
~3 months later

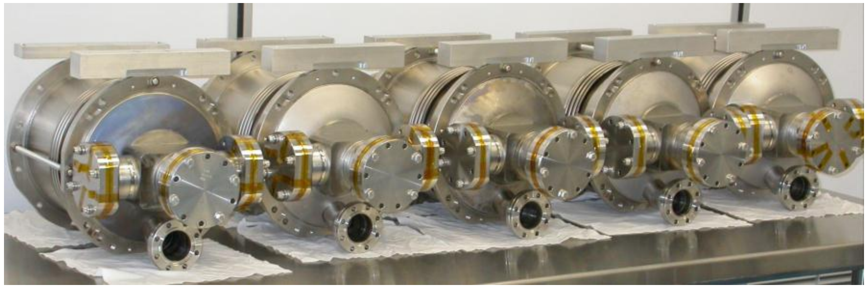
– Re-processed SRF cavities
– Fixed absorber charging problem

Cavity Re-Processing

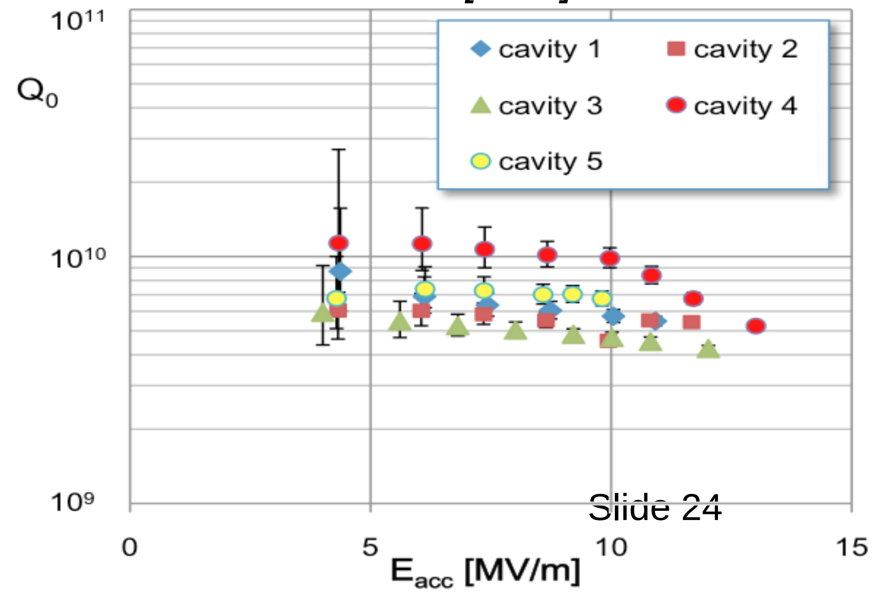
Before:

- Cavities met gradient specs, but had low intrinsic quality factors Q_0 ($Q \approx 3$ to $5 \cdot 10^9$ at 2K). Q_0 degradation over time?





After module re-work:



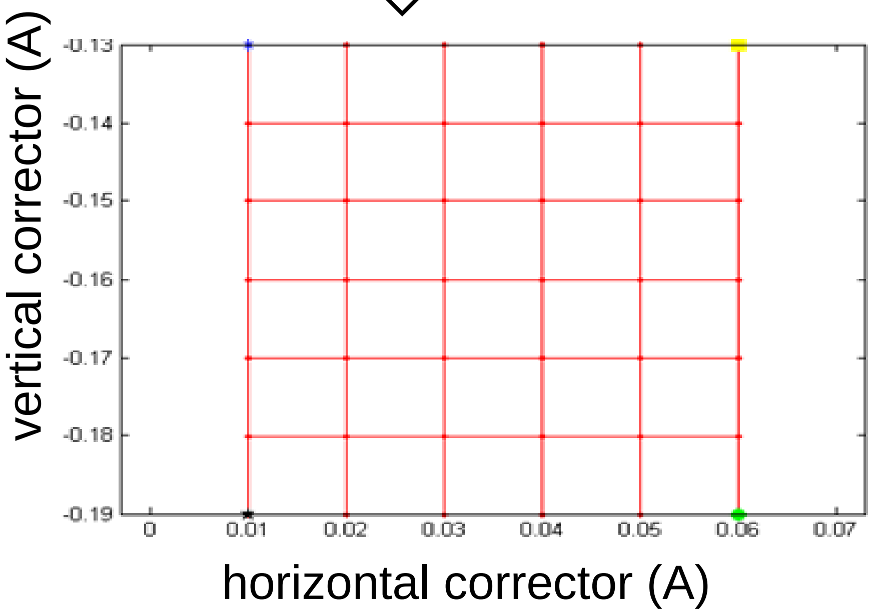
- Intrinsic quality factors improved ($Q \approx 6 \cdot 10^9$ to $1 \cdot 10^{10}$ at 2K)
- No indication of Q-degradation

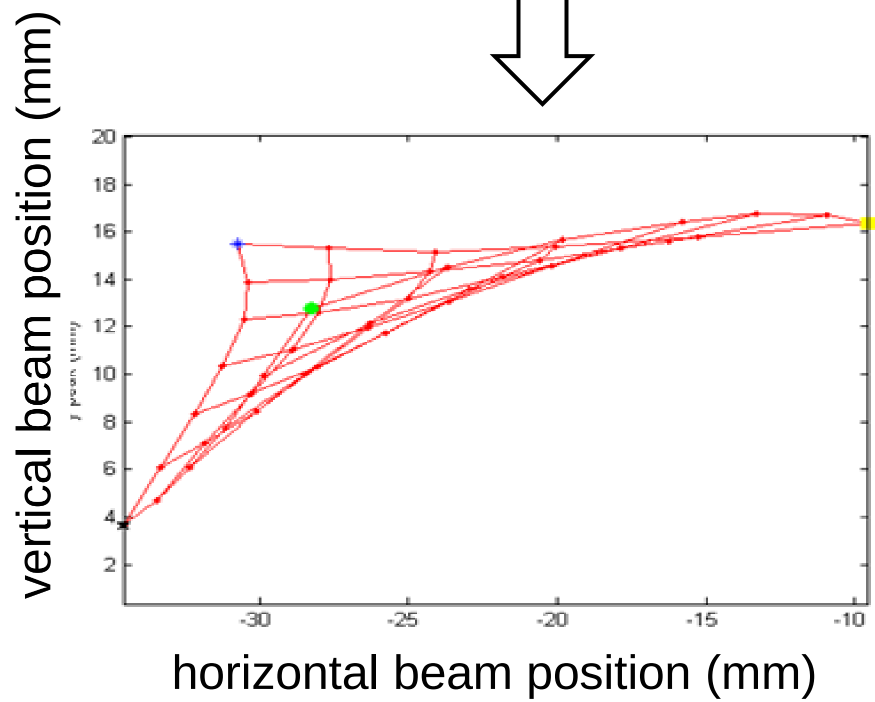
Charging of HOM Absorber Tiles

Before rework of cryomodule (measured with 250 keV beam!):

corrector pair → cryomodule → beam position measurement

all cavities switched off





⇒ Transverse kick fields in the injector cryomodule!

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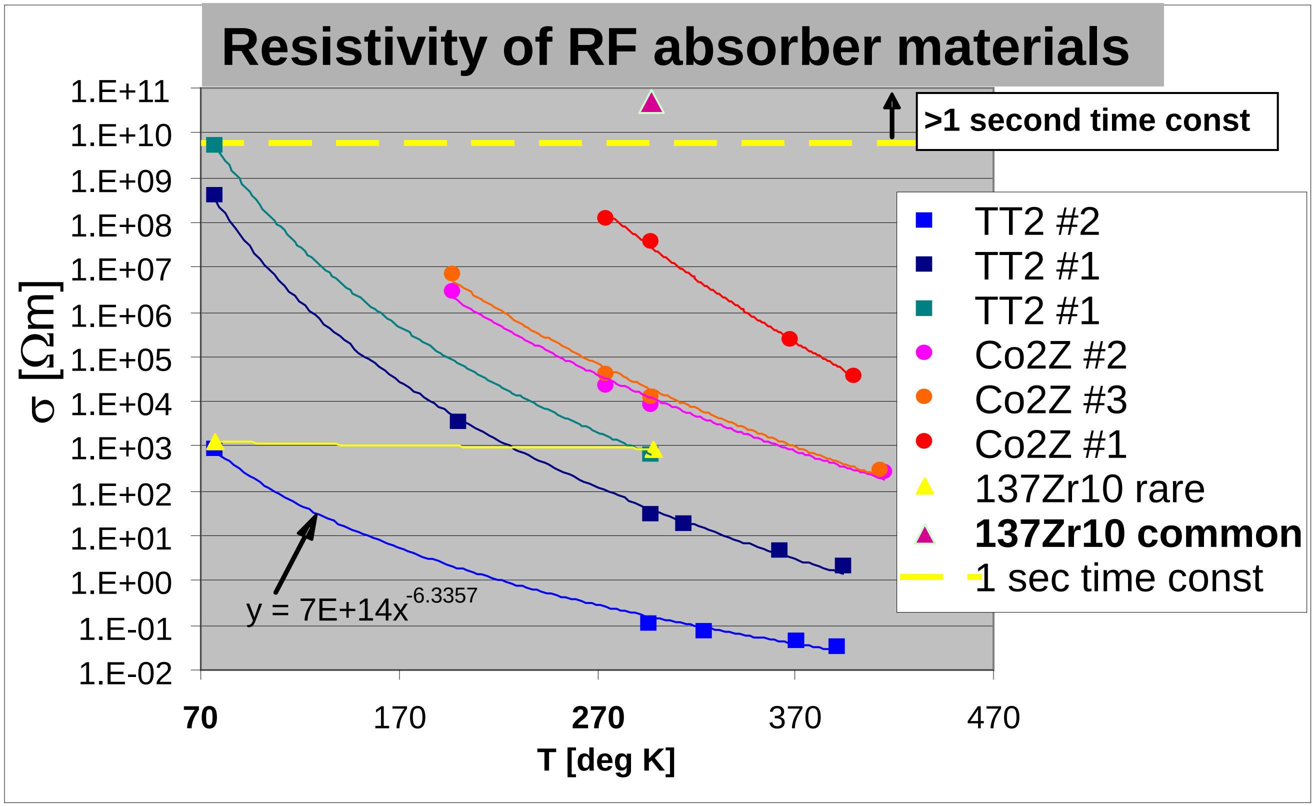
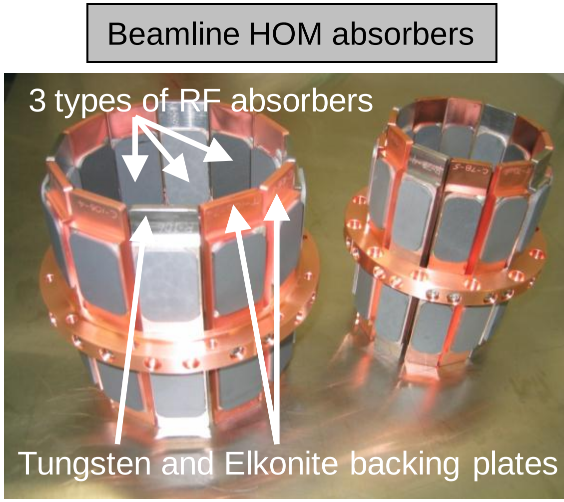
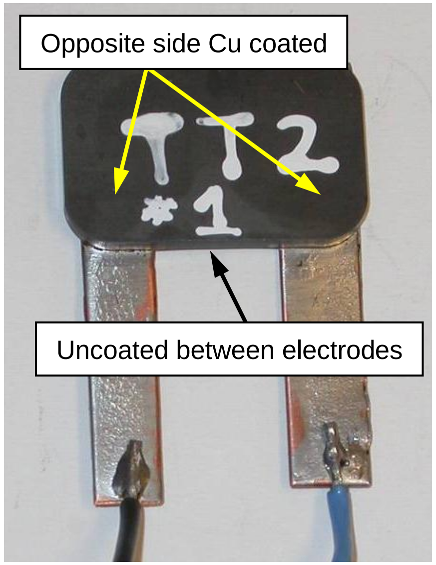
Charging of HOM Absorber Tiles







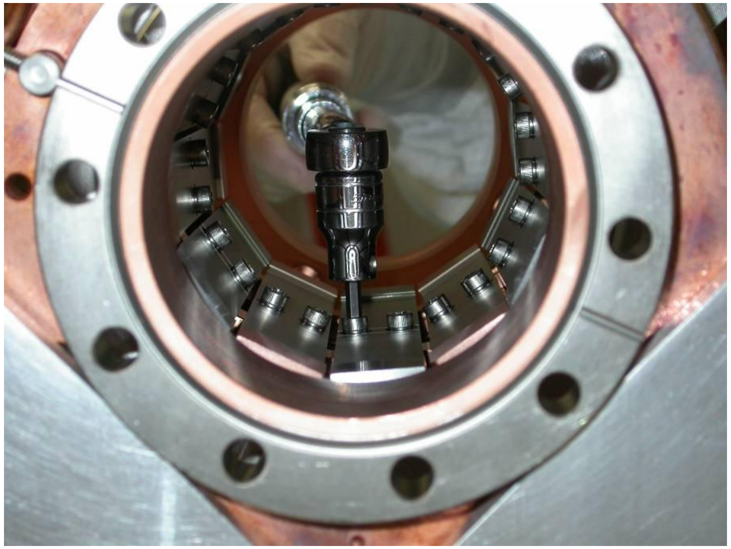
- **Low resistivity of HOM absorber tiles**: will hold charge for seconds to days!
  - Worst offender: **Ceramic 137Zr10**, followed by ferrite Co2Z and TT2
- Small beam loss charged up absorber tiles -> kV **electric** fields at beam position!

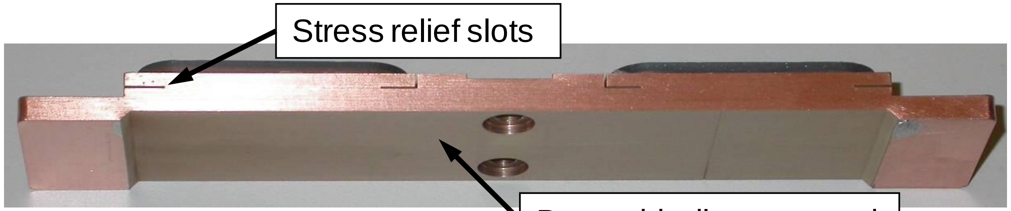
Solution: HOM Absorber Re-Work

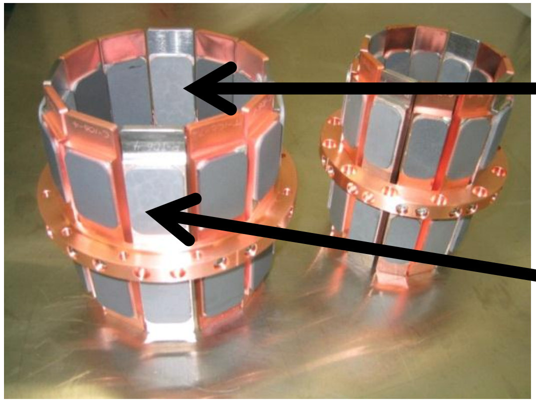
→ Removed all tiles from the inside of the HOM absorber (facing the beam; outside tiles are shielded from the beam by metal plates)

→ HOM damping still sufficient for 100 mA ERL injector

→ Cut stress relief slots in the tiles to reduce stresses during cool down further

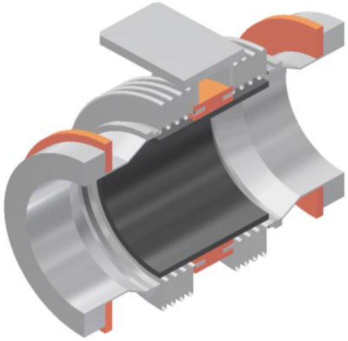






Future HOM loads: New RF absorber materials identified:

- graphite or CNT loading of ceramic
- prototype next- generation load this year



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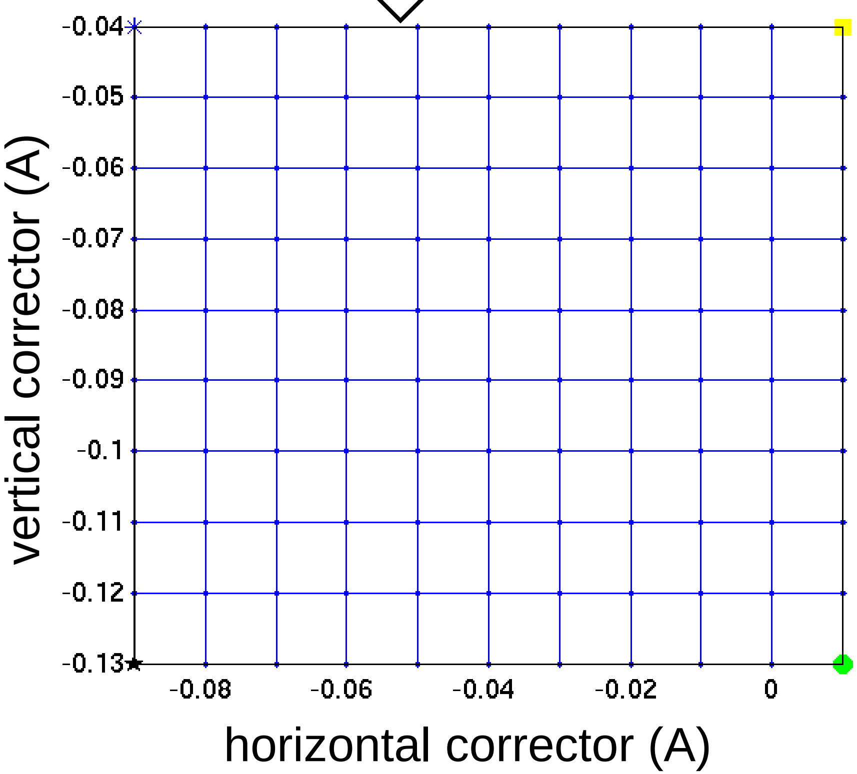
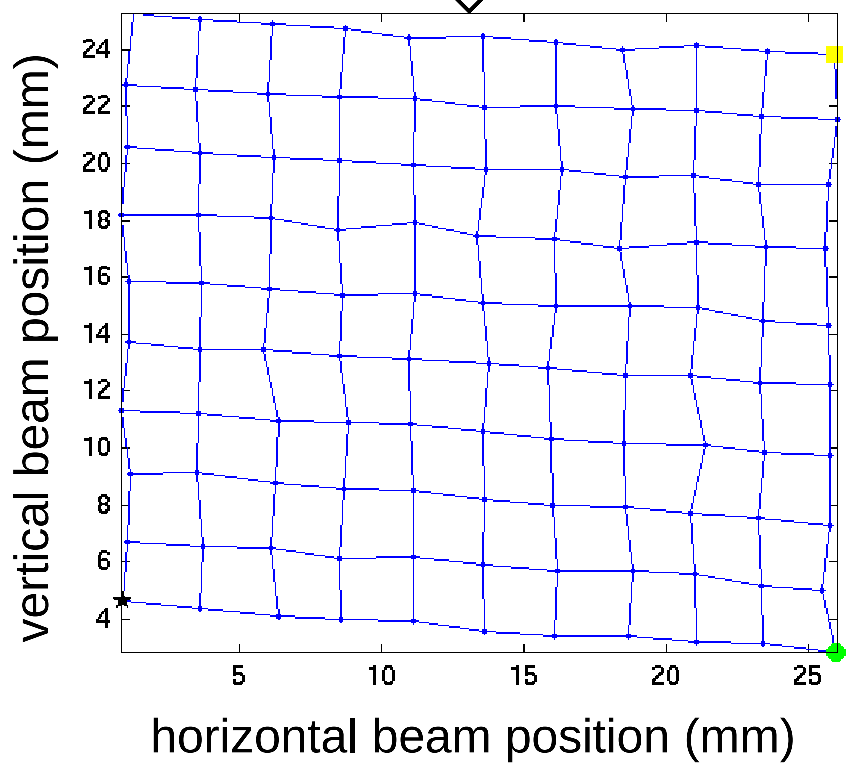
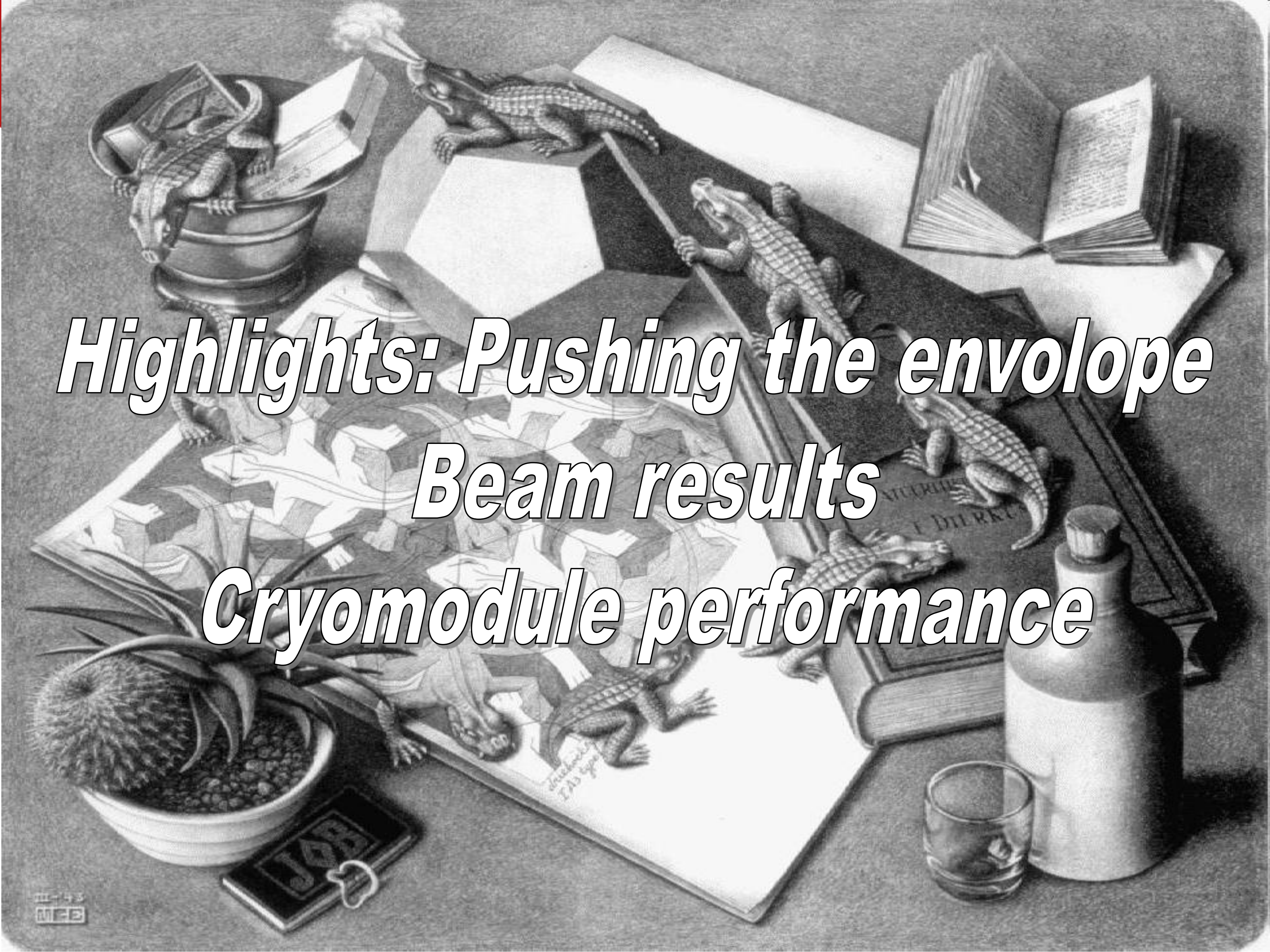




Highlights: Pushing the envolope

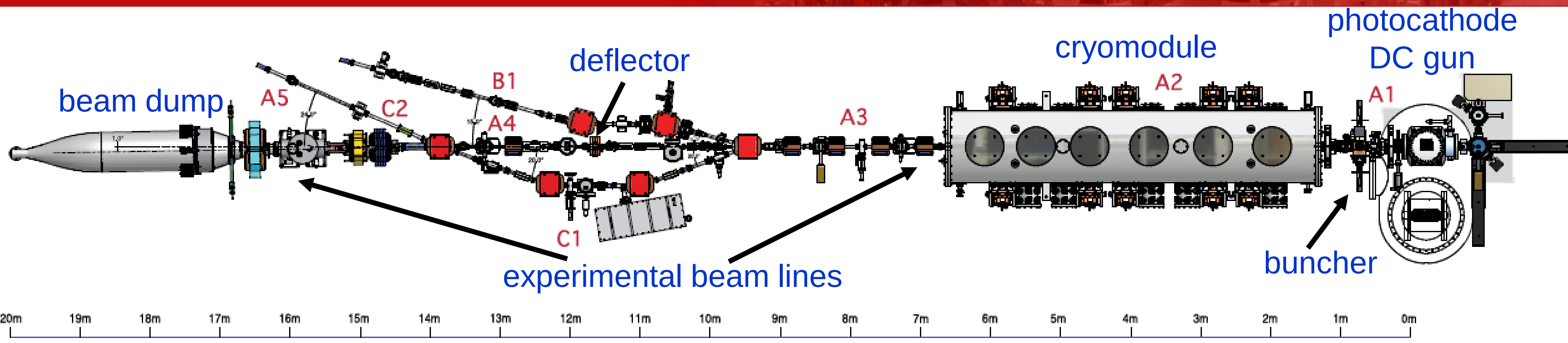
Beam results

Cryomodule performance



Beam Results

Beam: Current Status

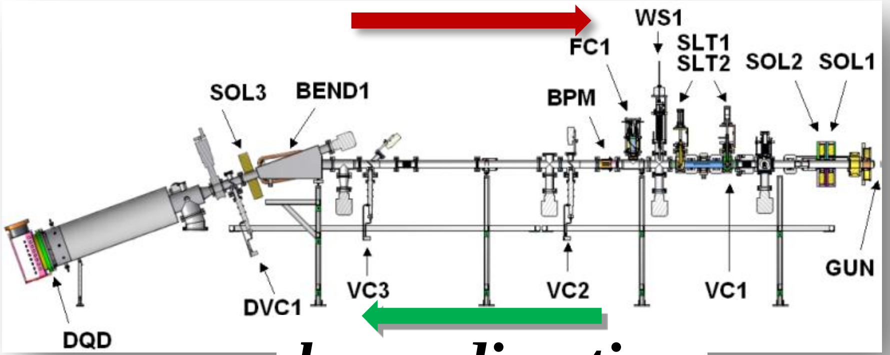


	design parameters	**achieved**
Nominal bunch charge	77 pC	77 pC
Bunch repetition rate	1.3 GHz	50 MHz and 1.3 GHz
Beam power	up to 550 kW	45 kW
Nominal gun voltage	500 kV	350 kV
SC linac beam energy gain	5 to 15 MeV	5 to 15 MeV
Beam current	100 mA at 5 MeV 33 mA at 15 MeV	9 mA Improved HV power supplies is installed now, and high current studies.
Bunch length	0.6 mm (rms)	
Transverse emittance	< 1 mm-mrad	

Highlight: High current status

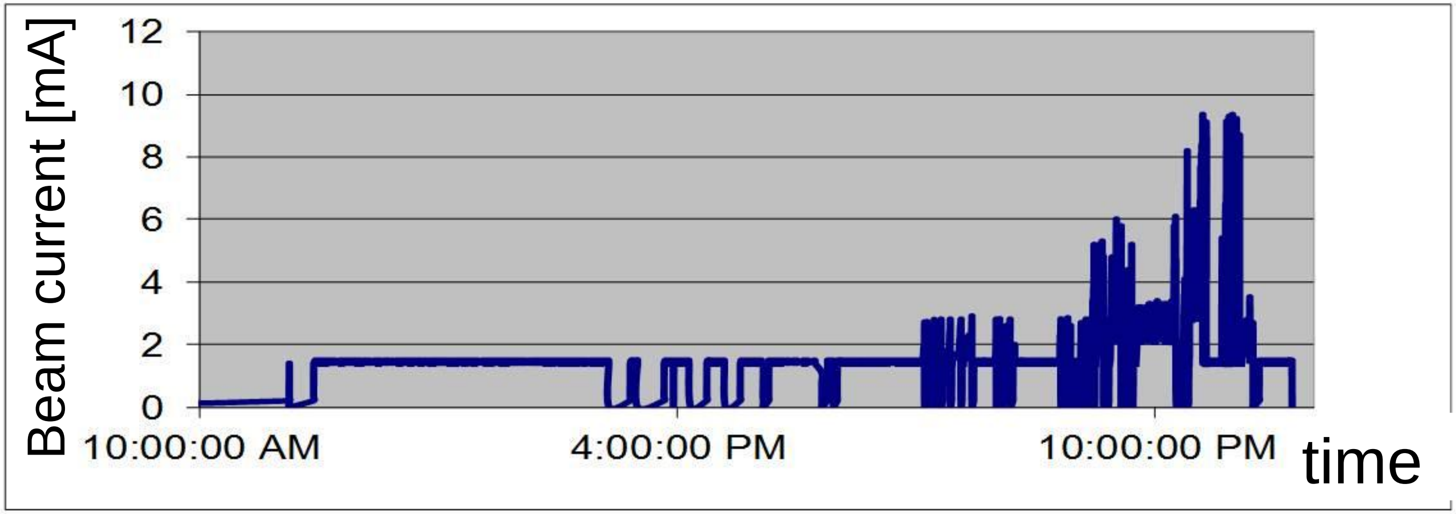
- **20 mA** DC current demonstrated from the gun (limited by gas back-stream from the dump)

gas backstream from the dump



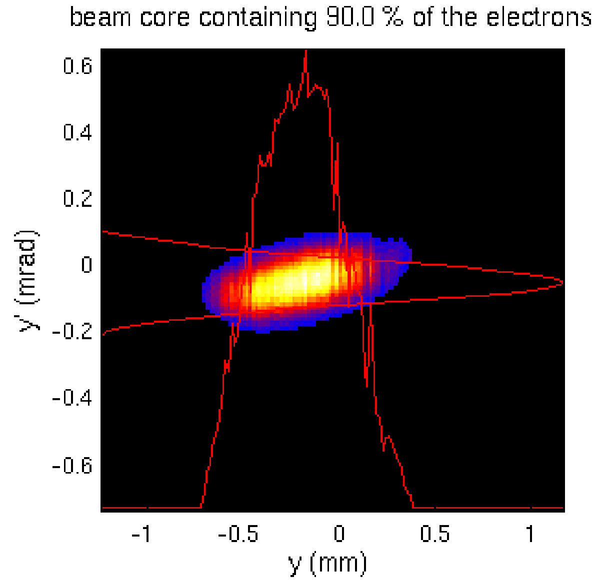
beam direction

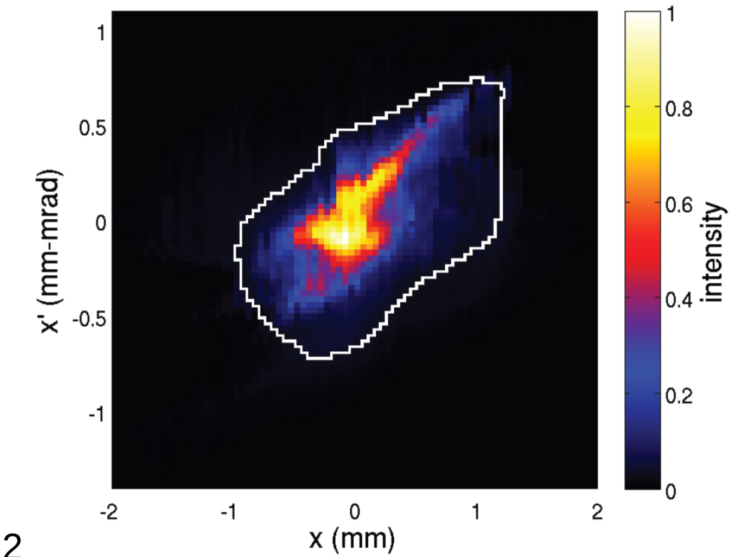
- 5 MeV beam running so far reached ~**9mA**
  (currents will be ramped up further starting this week with improved HV power supply in place now…)



Highlight: Beam Emittance

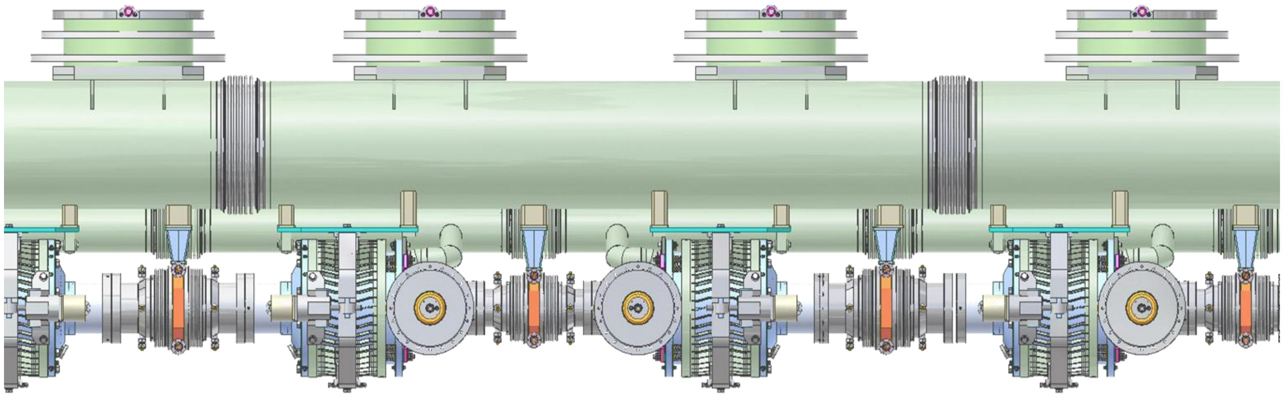
- At low bunch charge (at 5 MeV):
  - Normalized **emittance** in both planes is close to thermal limit at cathode for given laser size: 0.2 to 0.4 mm mrad
- At higher bunch charge (10 MeV, 77 pC):
  - $\varepsilon_{N,90}$ = 1.6 mm-mrad for 90% beam core
  - Increasing the gun voltage to 500 kV is expected to reduce this number further





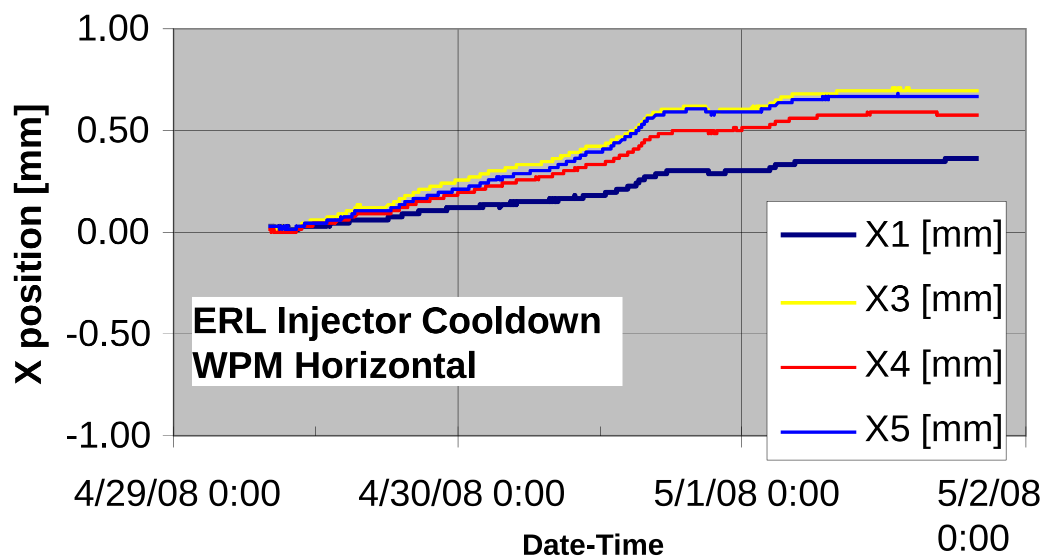
SRF Injector Cryomodule Highlights

Highlight: Cavity Alignment



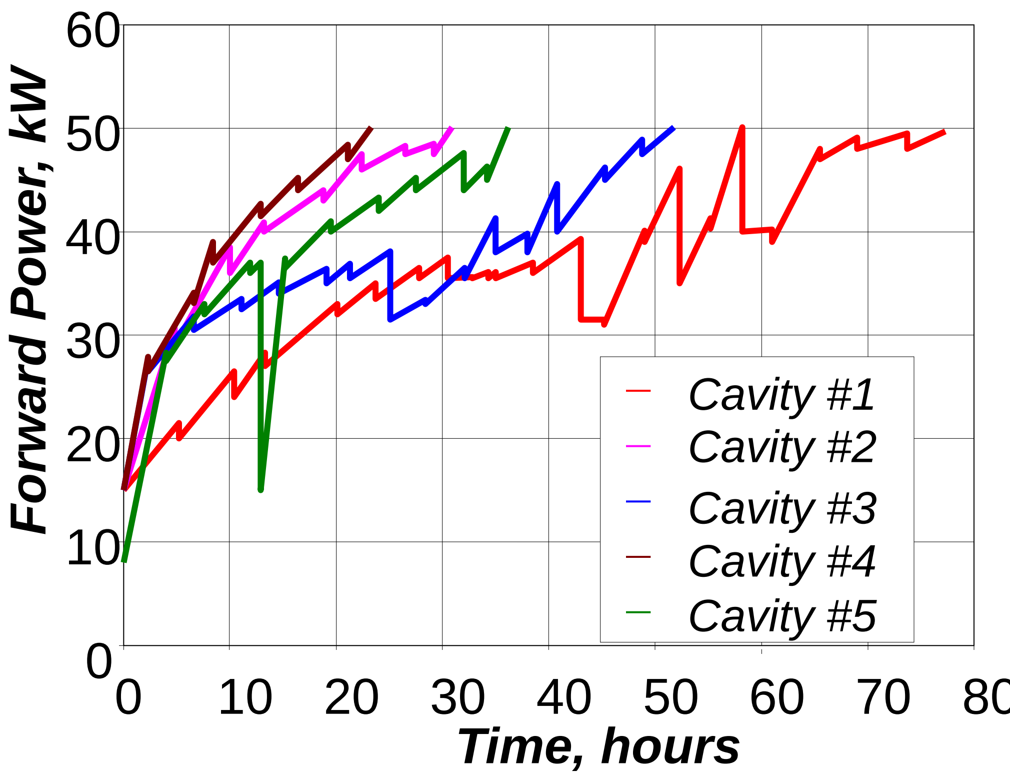
- Shift of cold mass during module cool down (from Wire Position Monitor)
  - **Expected: dx= 0.38 mm**
    dy= 0.94 mm
  - **Observed: dx = 0.58 mm**
    dy = 0.81 mm

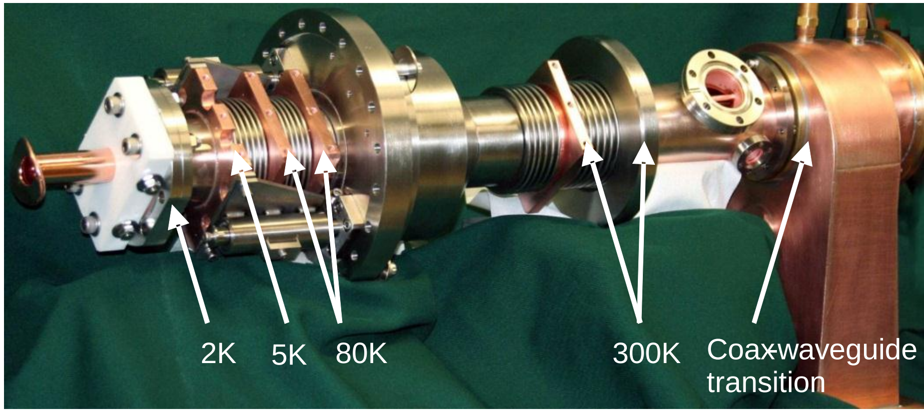
Cavity string is aligned to ±0.2 mm after cool-down!



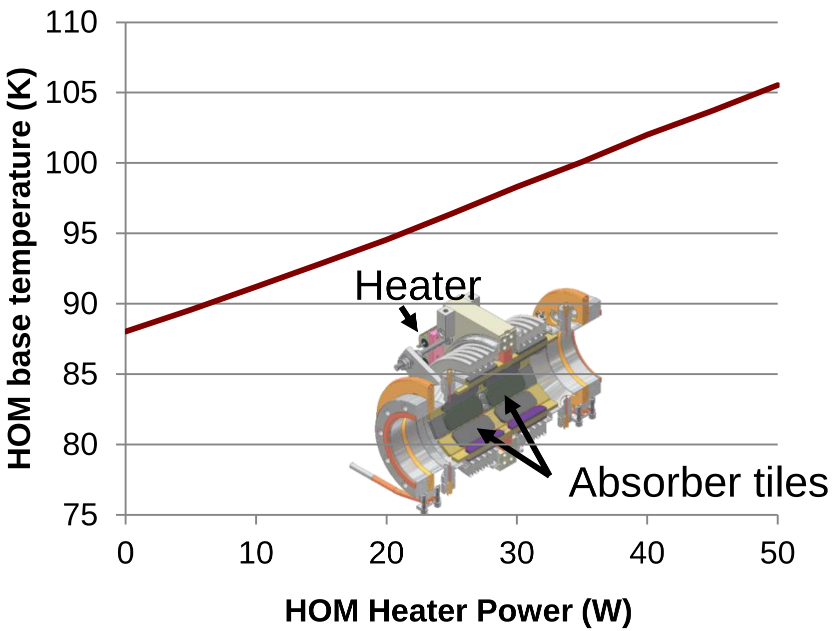
Highight: RF Input Couplers

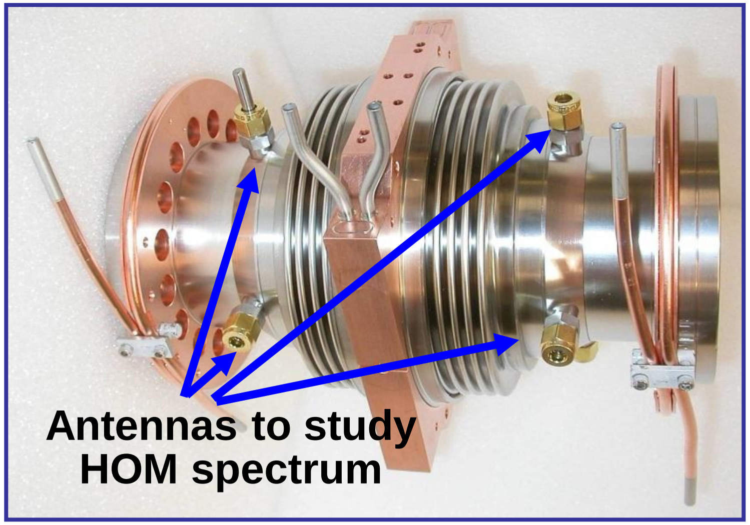
- All twin input couplers have been processed in pulsed mode up to **50 kW** under full reflection
  - **25 to 75 hours** of processing (RF on time).
- DC voltage can be applied to center conductors (the original intent was to provide bias voltage for suppressing multipacting).
- This proved to be very useful tool for beam diagnostics.





Highlight: HOM Studies

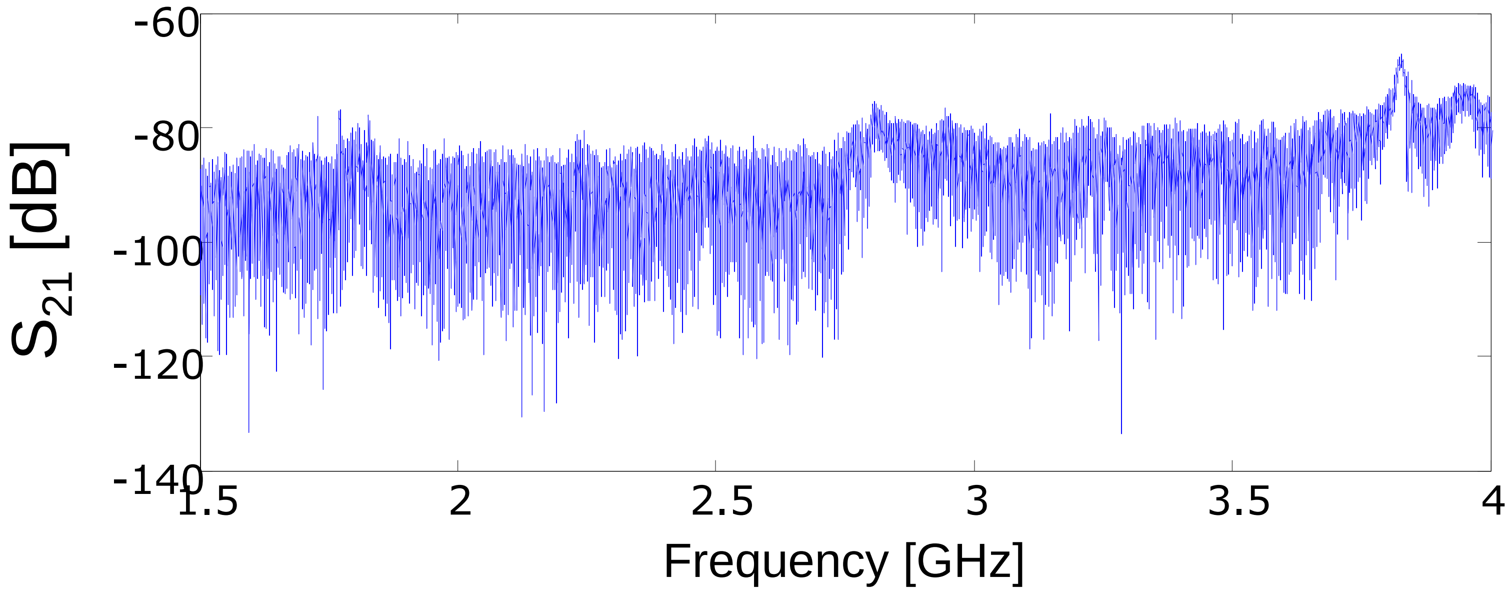




- HOM absorbers allow for calorimetric measurement of the total HOM power excited by the beam.
- Heaters on the HOM loads used for calibration
- Maximum beam current so far 9 mA → only a few 100 mW of HOM power per cavity → undetectable
- At higher bunch charges and currents, we expect several 10W of HOM power per load!
- 8 HOM antennas per load:
  - Working on prototype electronics to use HOM load antennas as BPMs (will use beam induced signal at 2.6 GHz)
  - Study HOM spectrum.

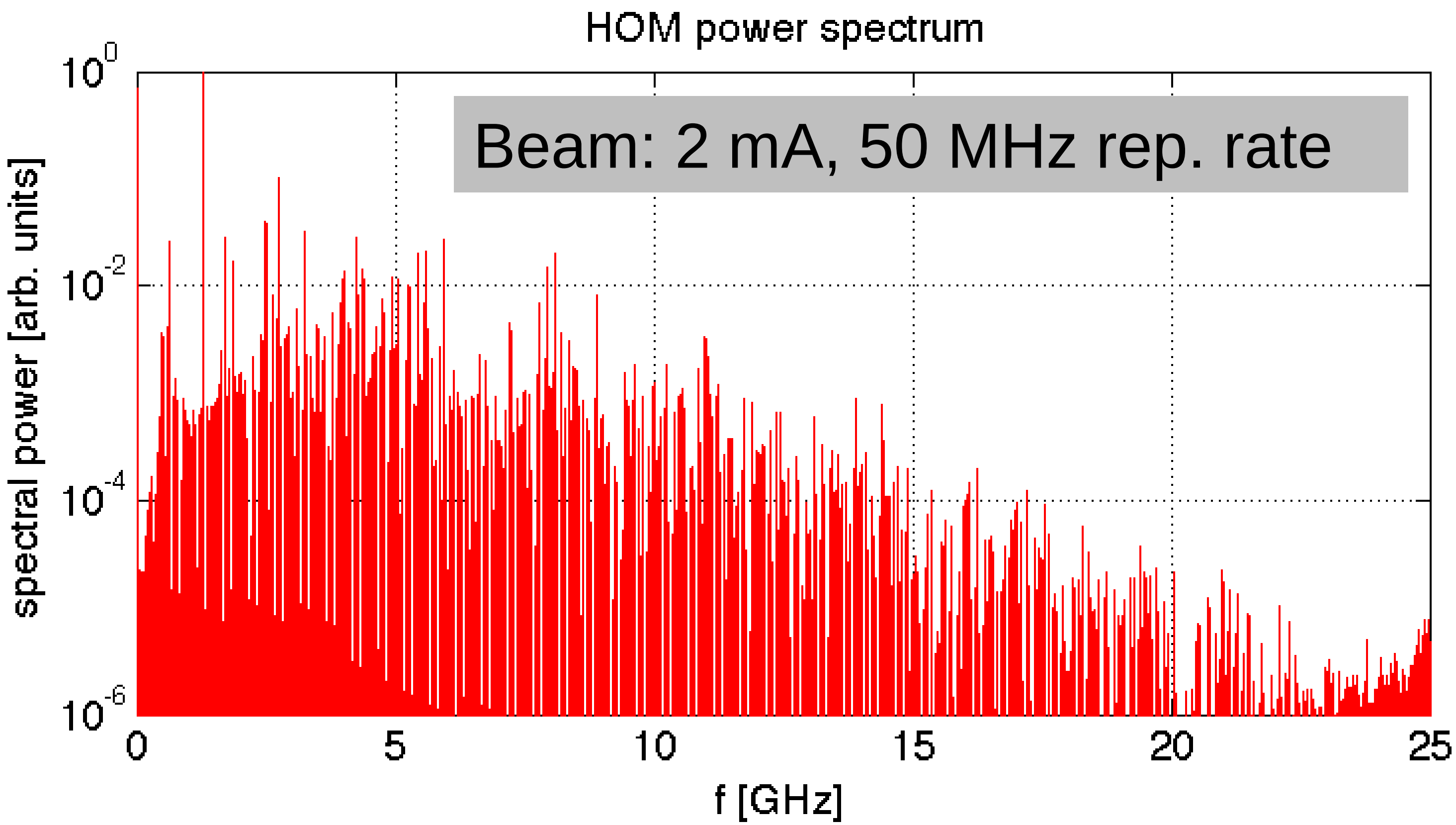
Highlight: HOM Damping

- Preliminary network analyzer measurements of HOM damping in the ERL injector module confirm strong suppression of monopole and dipole HOMs (typical Q's of a few 1000)



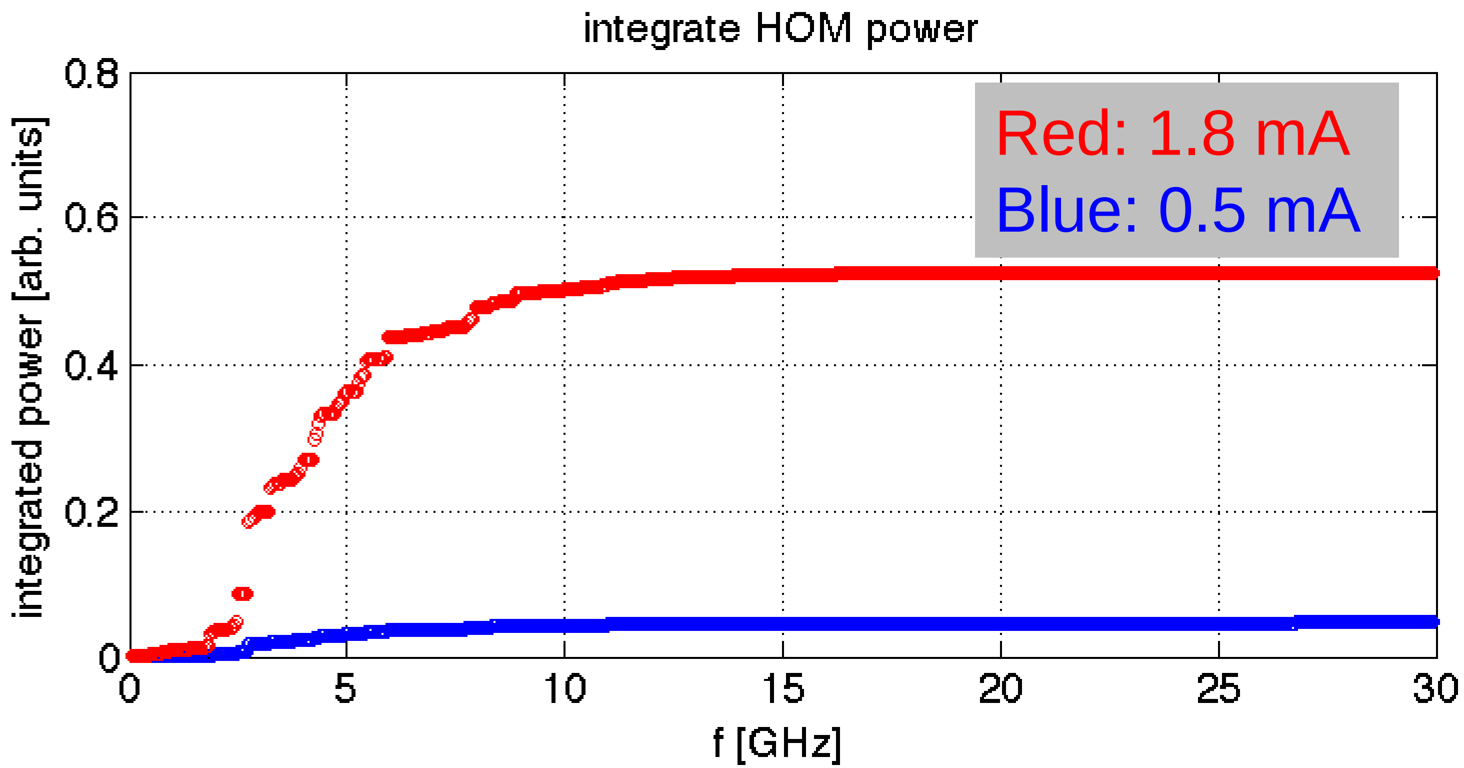
Highligh: Spectrum of HOMs excited by Beam

- Use HOM pickup antennas
- Gives estimate of R/Q*Q of modes excited

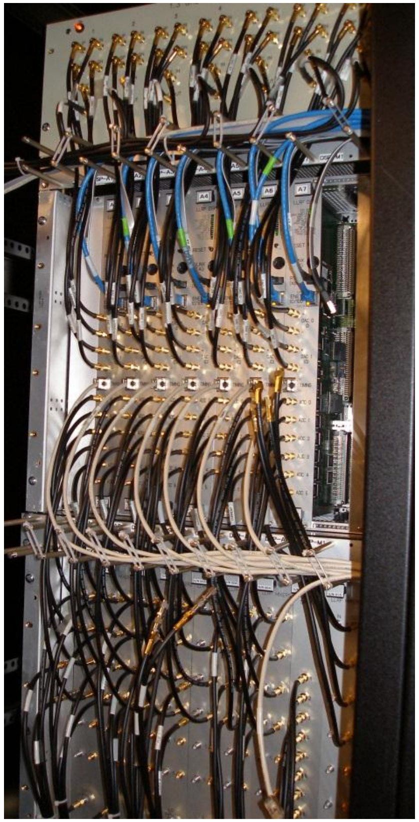


Highlight: Integrated HOM Power Spectrum

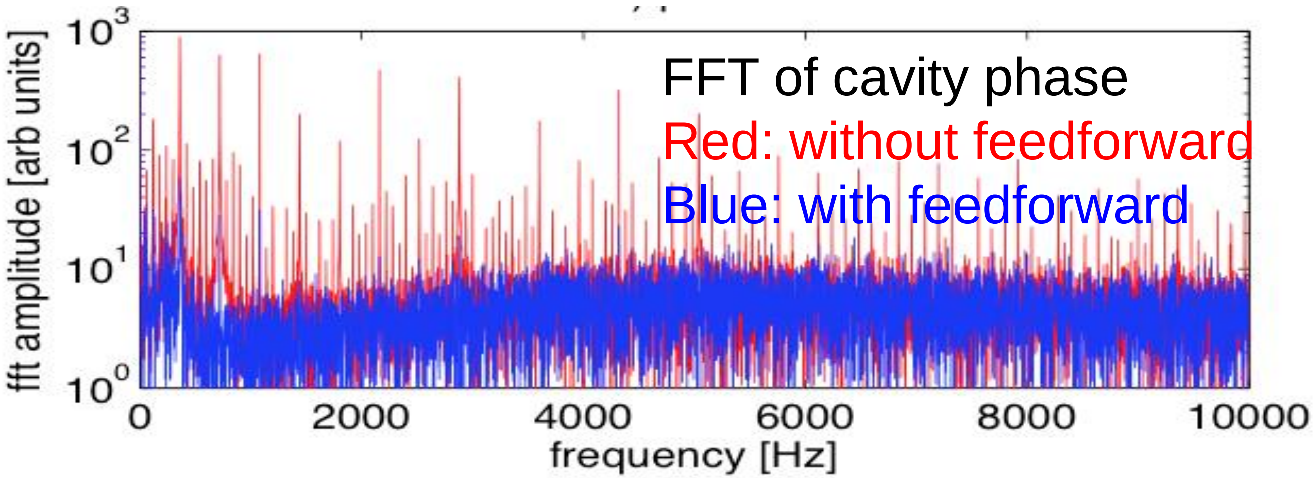
- Allows to study change with bunch charge and bunch length
- Contains information on longitudinal bunch profile and cavity impedance
- Just started…much more to come…



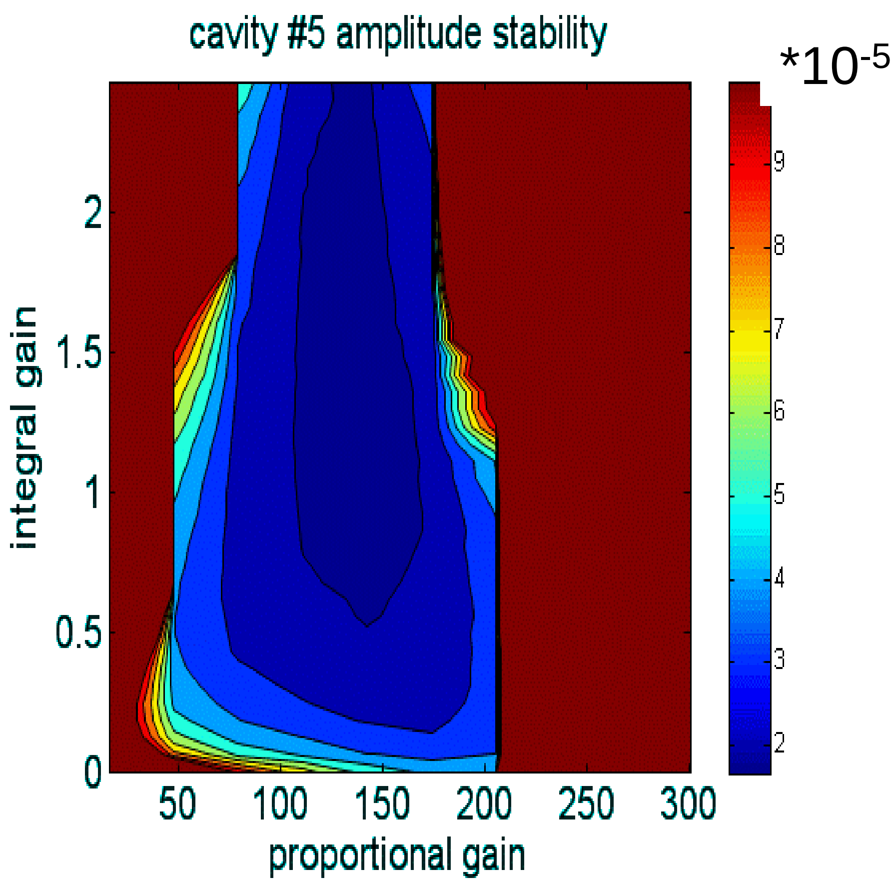
Highlight: LLRF Field Control

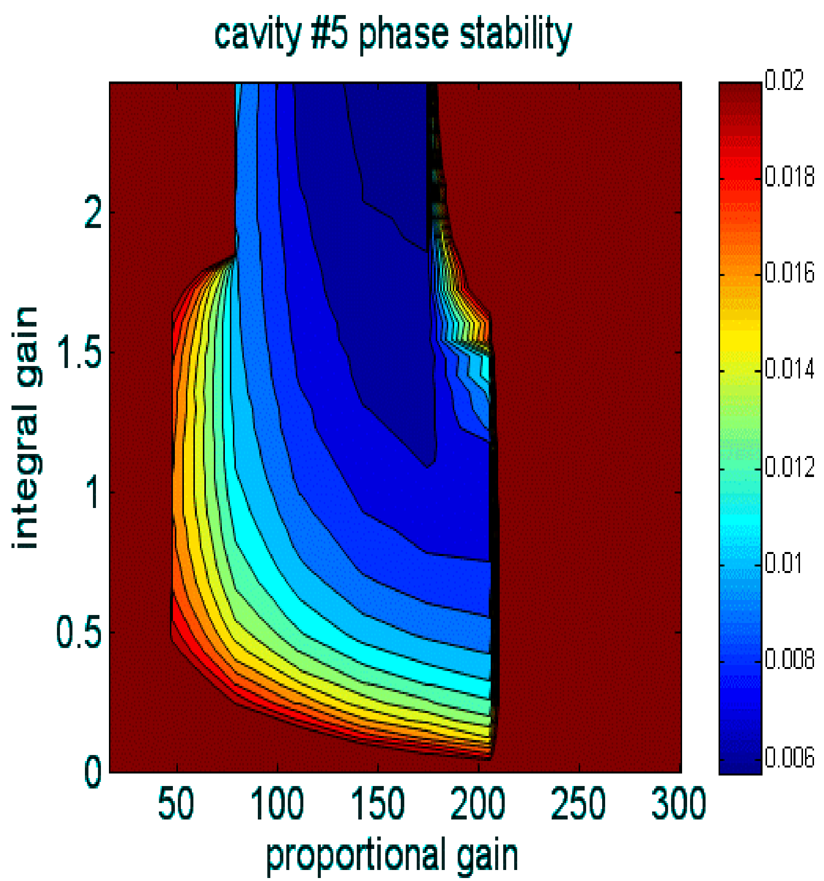


- LLRF electronics for the ERL injector is a new, improved generation of LLRF system previously developed for CESR
  - <1 μs latency feedback loop
  - Beam current feedforward
  - Klystron HV ripple feedforward
  - Fast tuner loops for microphonics compensation
  - Built in state machine
- Performs well with excellent field stability



Highlight: RF field stability



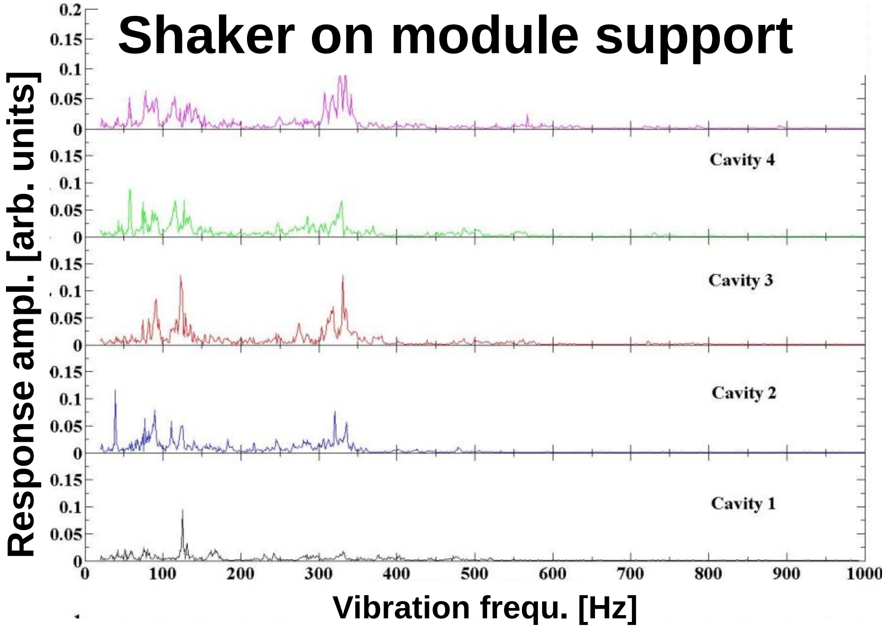


Excellent field stability achieved: amplitude: $\sigma_A/A < 2\cdot10^{-5}$

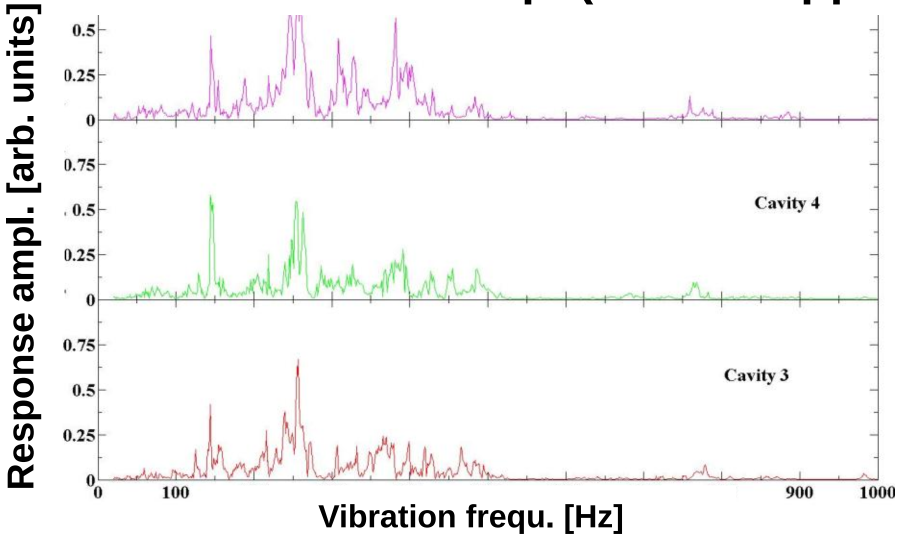
phase: $\sigma_P < 0.01$ deg

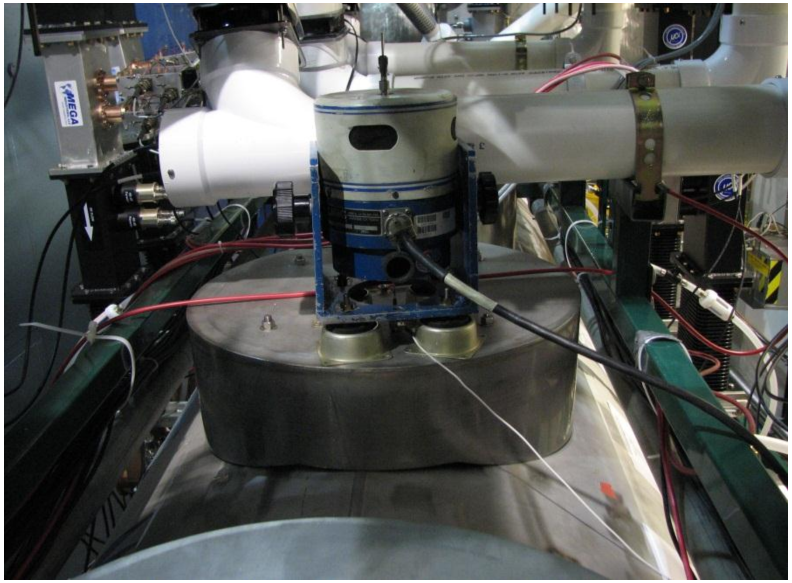
Highlight: Mechanical Coupling Characterization Measurements with a Modal Shaker

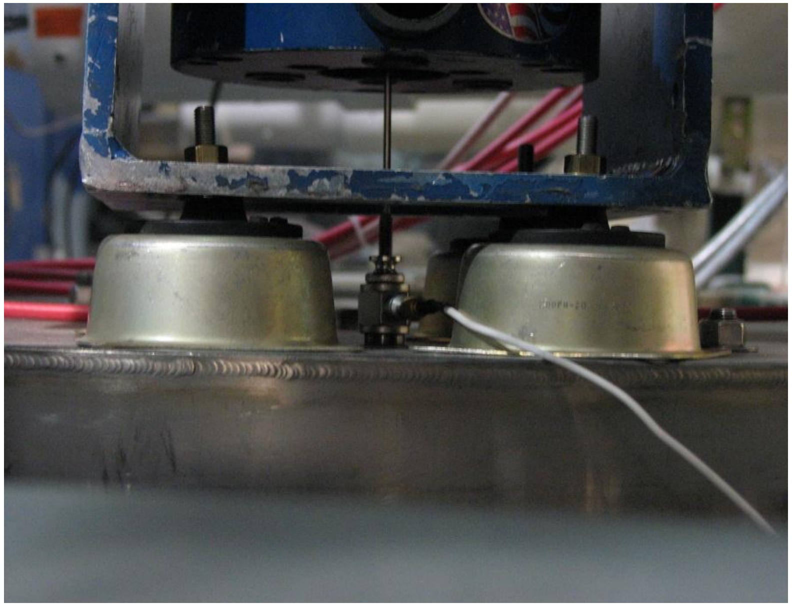
Shaker on module support



Shaker on module top (HGRP support)







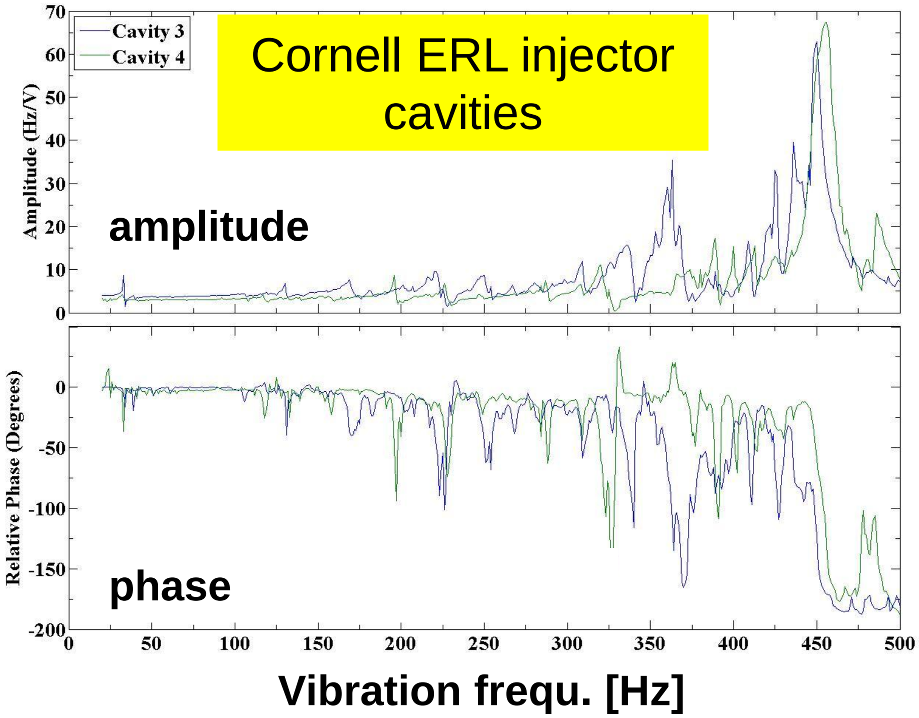
Highlight: Mechanical Coupling Characterization Measurements with a Modal Shaker

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

Highlight: Active Microphonics Control

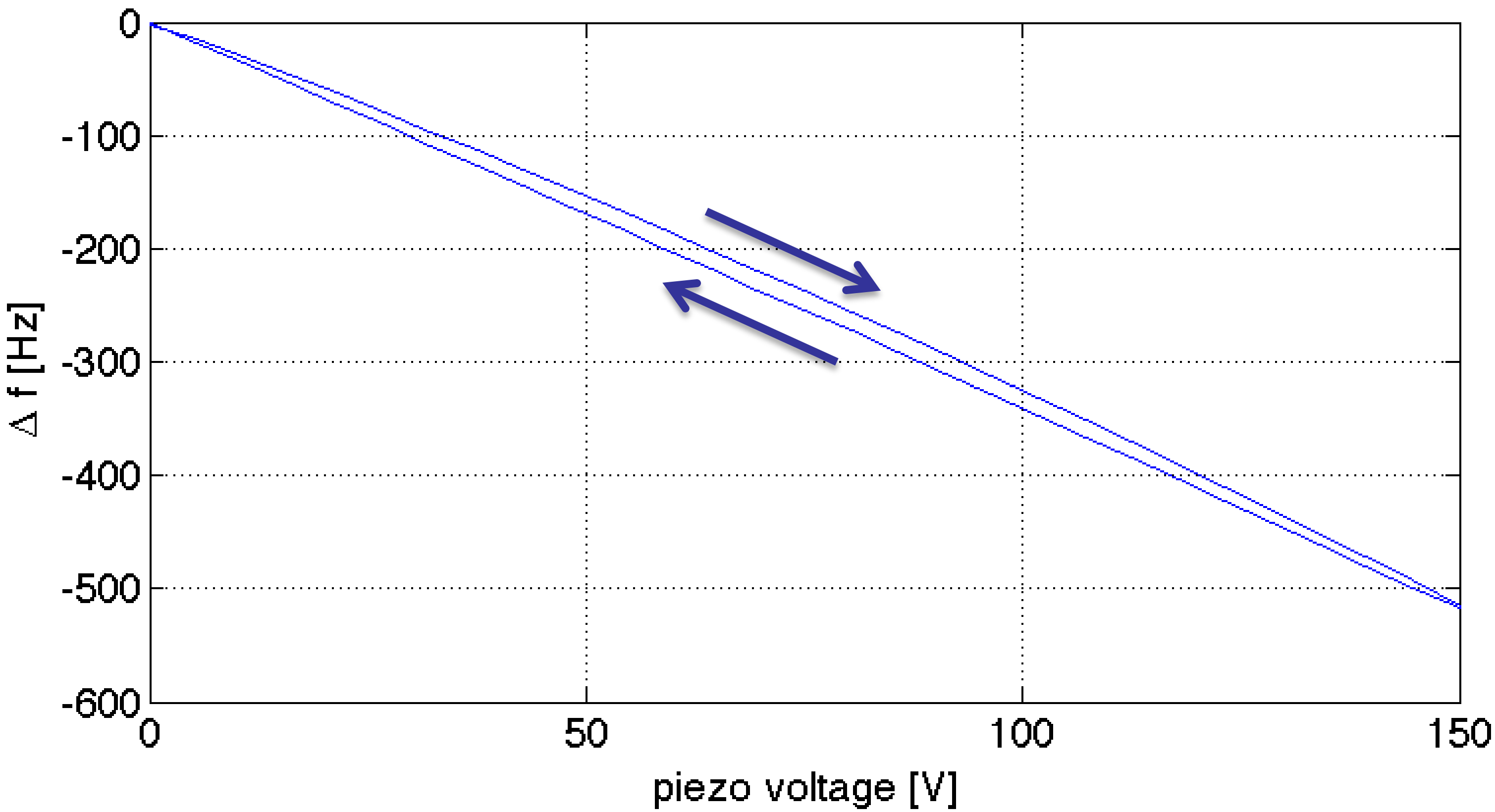
- Use fast frequency tuner (usually piezo-electric driven)



- Microphonics feedback challenging because of complex transfer function piezo → Δf with mechanical resonances
- Linearity and small hysteresis important!

Highlight: Active Microphonics Control

Piezo Hysteresis Curve: DC frequency shift vs. applied voltage to all 4 piezos:



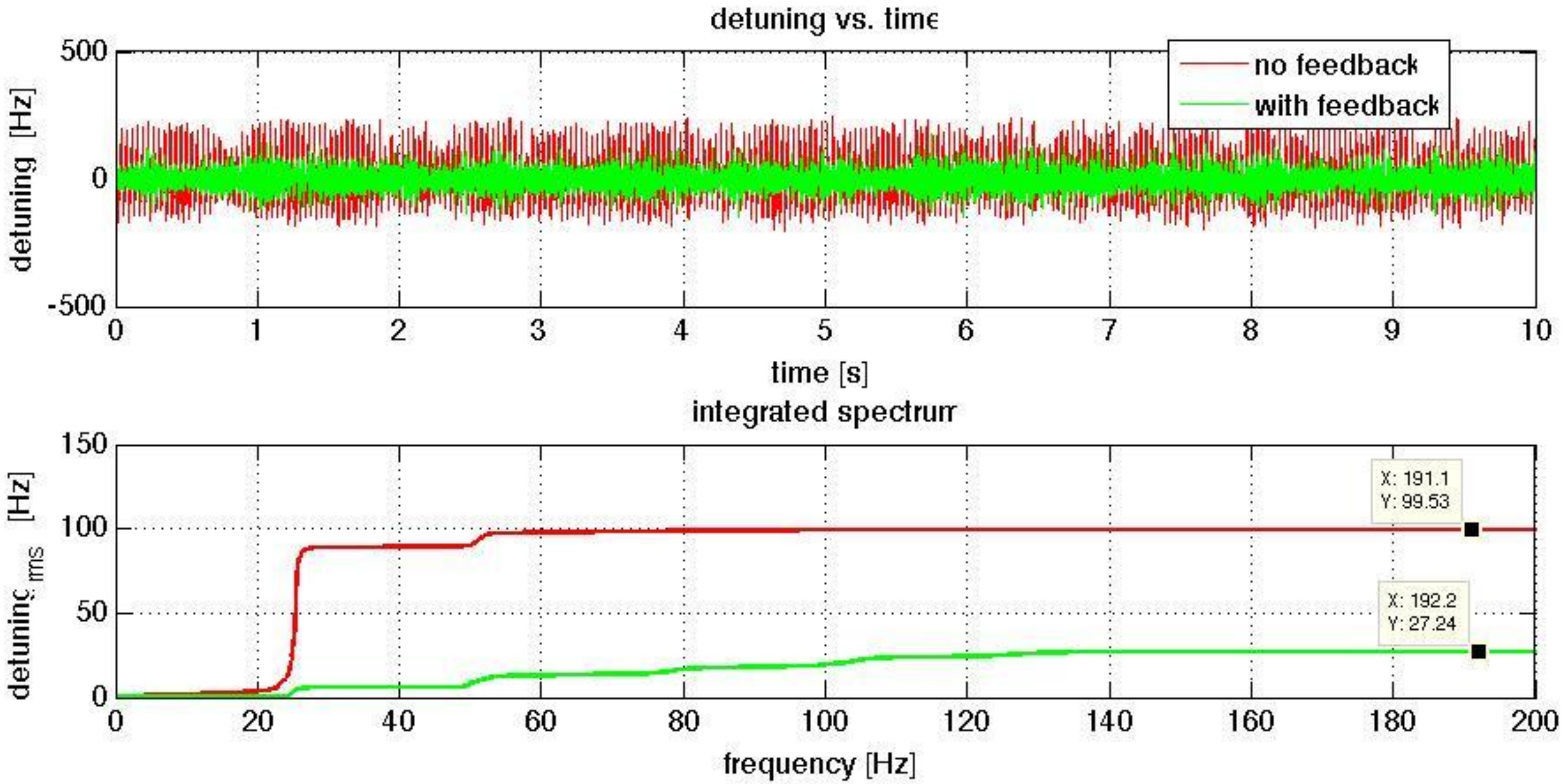
$\Rightarrow$ **Good linearity**
$\Rightarrow$ **Small hysteresis**

Highlight: Active Microphonics Control

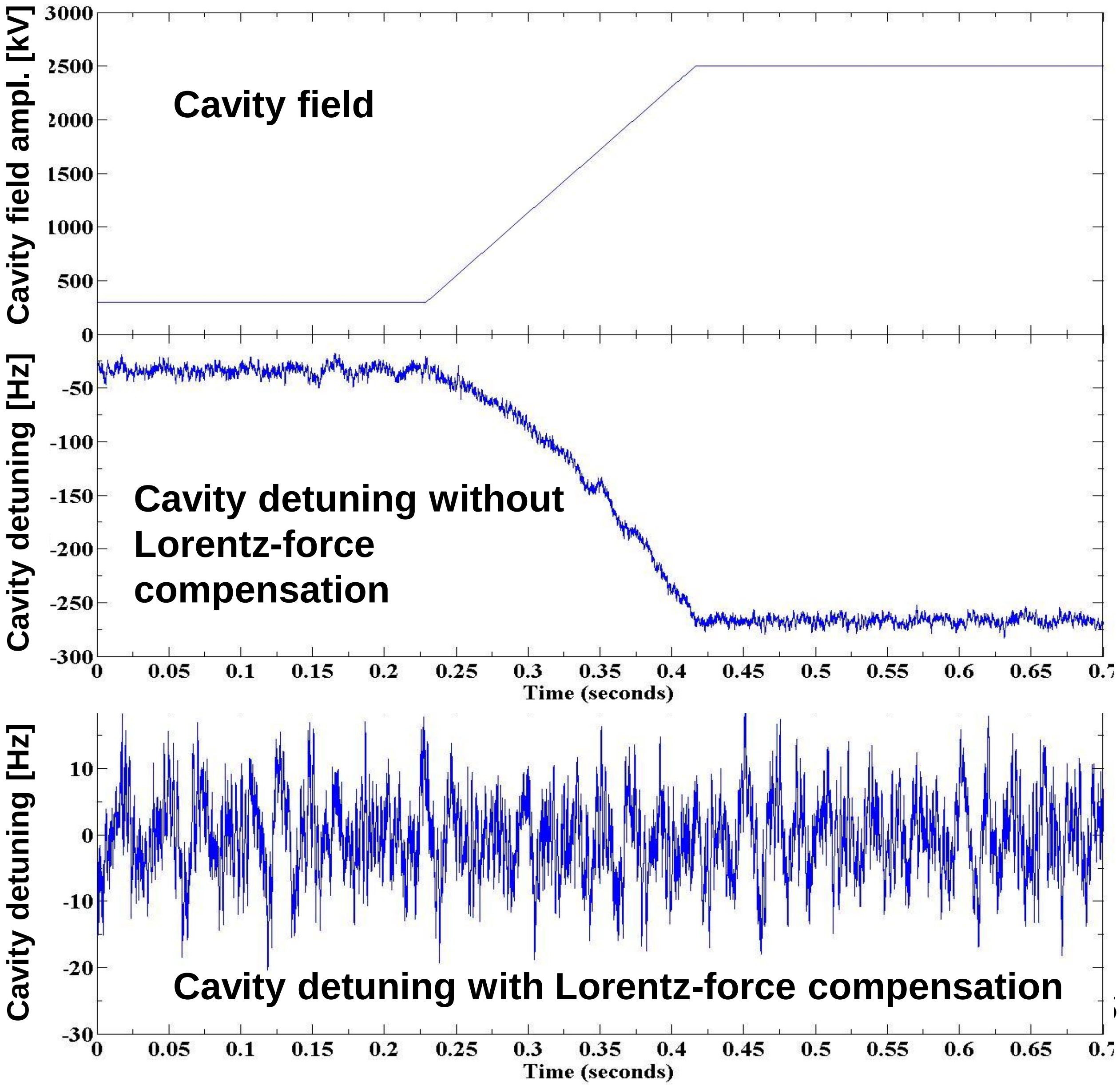
Piezo Feedback on Tuning Angle/Cavity Frequency:

⇒ Reduces rms microphonics by up to 70%!

⇒ Important for ERL main linac, where Q_L>5·10^7 and $P_{RF} \propto \Delta f$!



Highlight: Active Compensation of Lorentz-Force Detuning



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

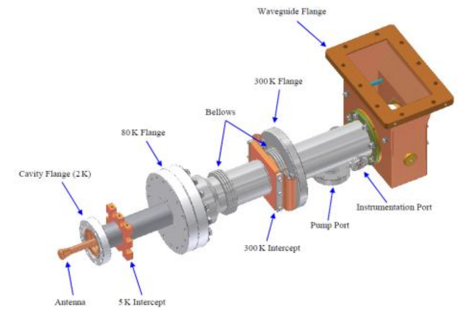
Outlook

Summary and Outlook

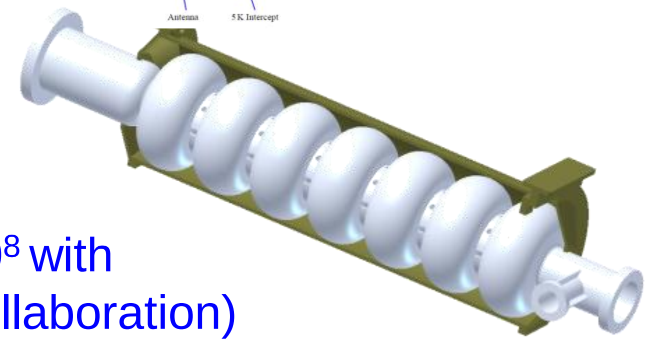
- Initial commissioning of the Cornell ERL injector has revealed a few issues which needed to be addressed
  - Solutions were found and successfully implemented.
- Testing of the Cornell SRF ERL injector prototype cryomodule was very successful:
  - **cryogenics, cavity alignment, cavity voltage, input couplers, LLRF field control, and HOM damping all meet or exceed specs**
- Beam properties near design values have been shown:
  - good emittance which will further decrease with higher gun voltage
  - Beam current is on its way up →100 mA in reach

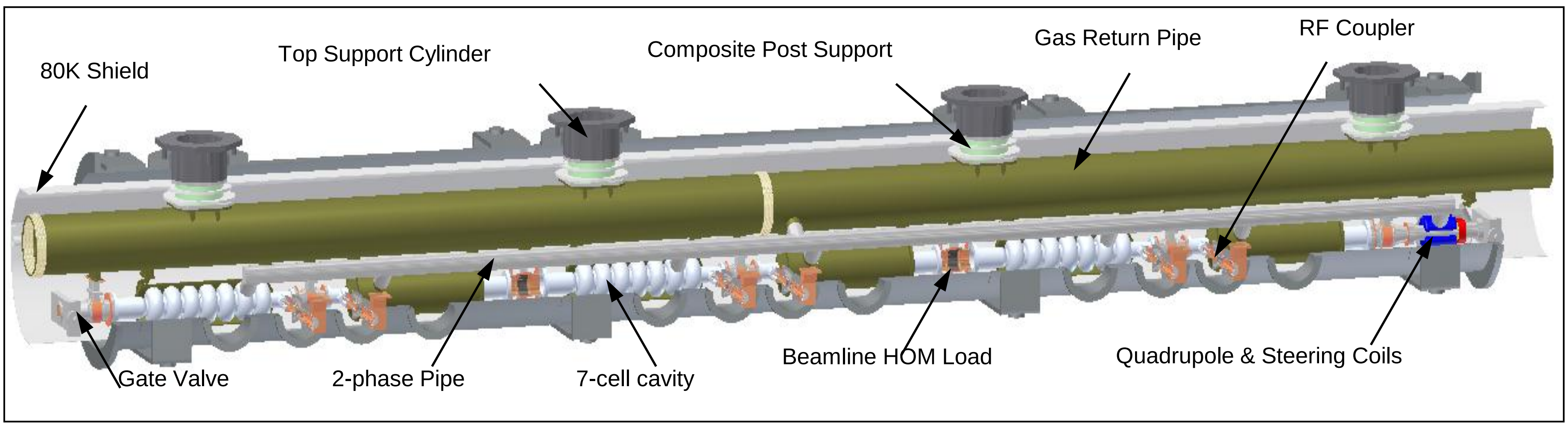
To come: ERL Main Linac

- Main Linac cryomodule 10 m long
  - 6 cavities, 7-cells/cavity, 16.2 MV/m
  - Beamline HOM loads
  - 1 quadrupole, X-Y steering coils



- Development and prototyping has started
  - Main linac cavity design: **see paper THP034 by Nick Valles**
  - Successfully operated a 9-cell cavity at $Q_L=2\cdot10^8$ with exceptionally high field stability (Cornell-HZB collaboration)





The End