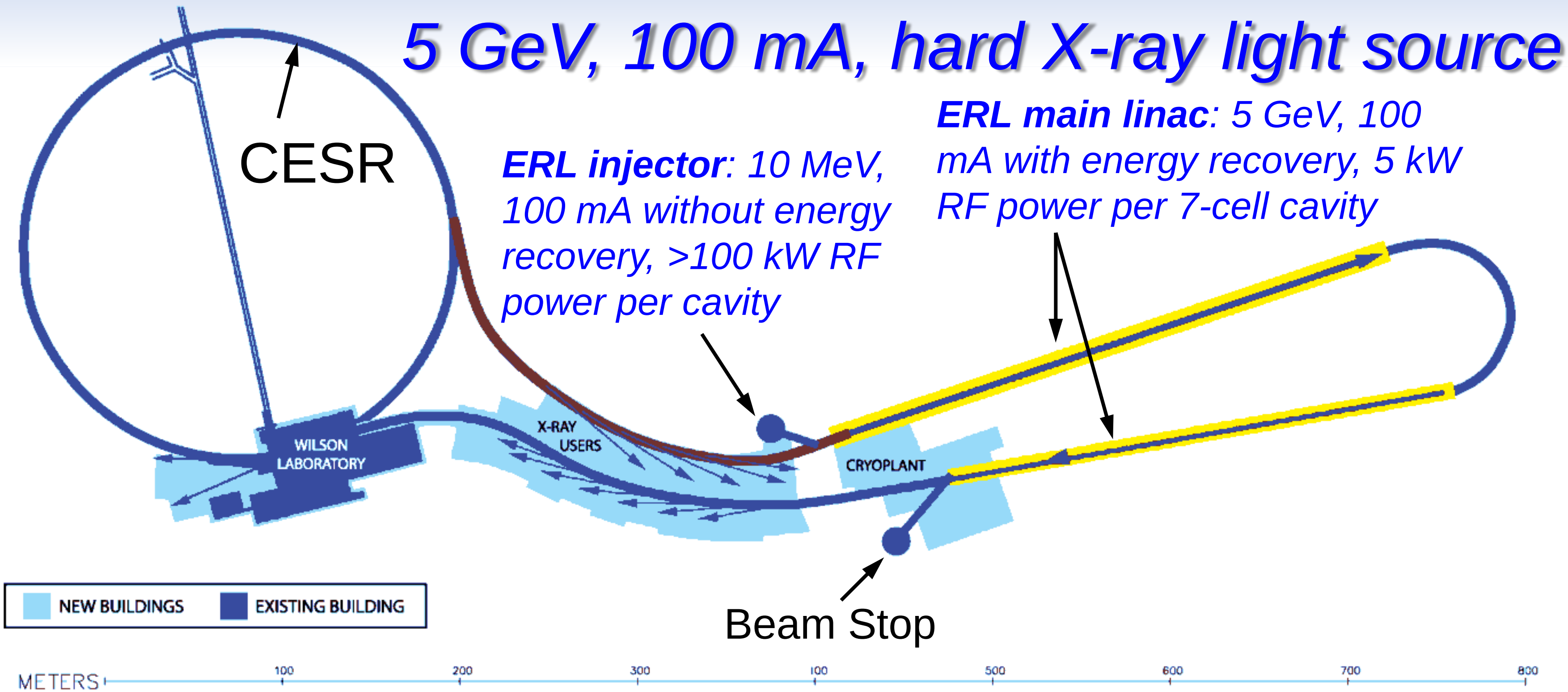
Experience with the Cornell ERL Injector SRF Cryomodule during High Beam Current Operation

Matthias Liepe

Assistant Professor of Physics

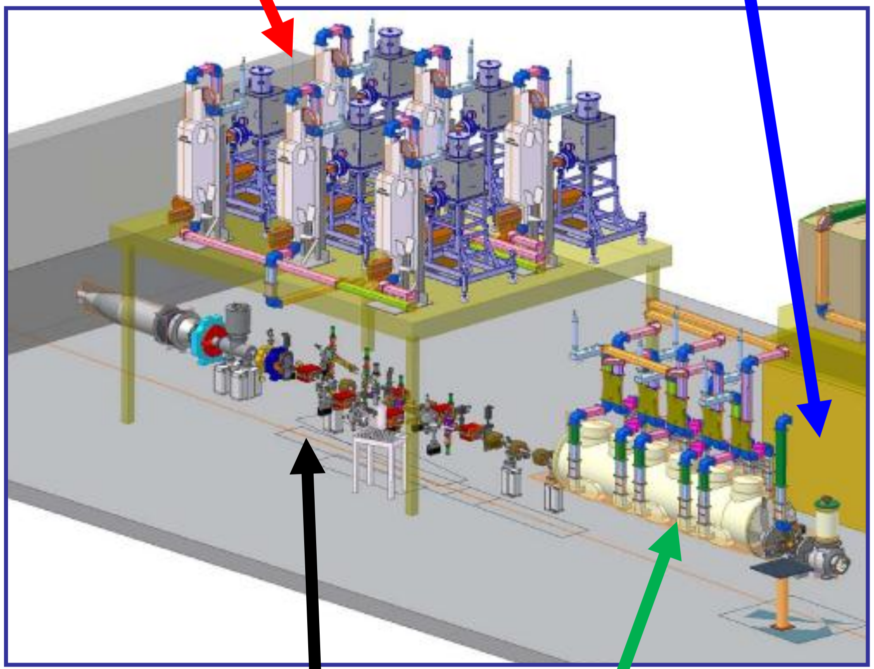
Cornell University

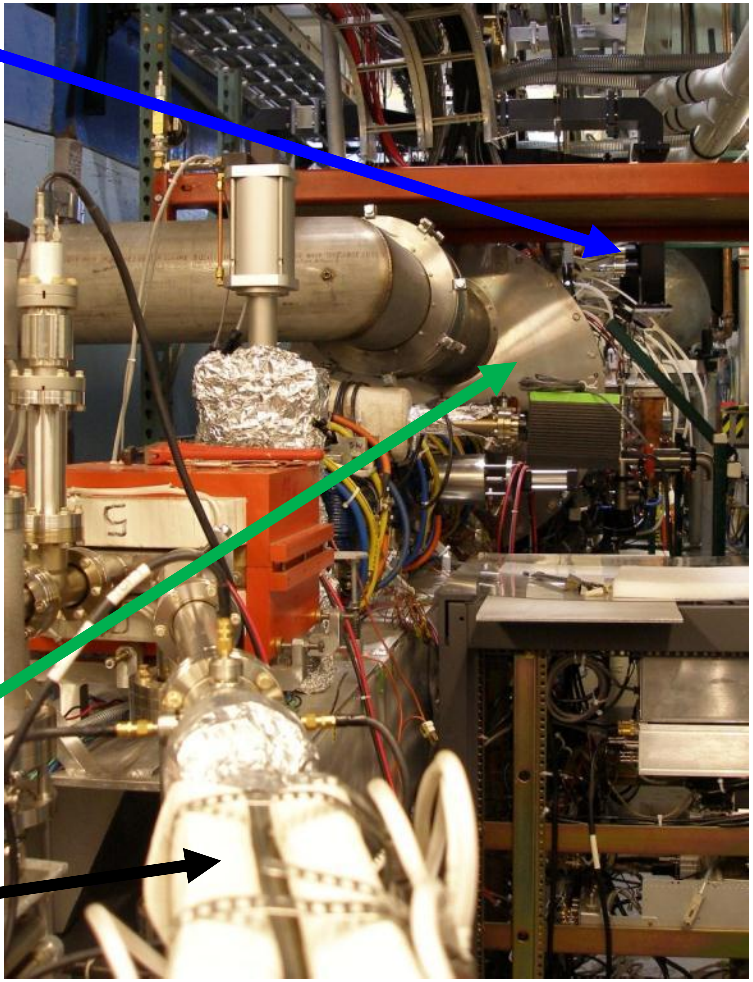
The Cornell Energy Recovery Linac



- Cornell is developing the technology for an Energy Recover Linac (ERL) based x-ray light source.
- An ERL injector prototype has been developed, fabricated, and is currently under commissioning.
- Design work on the main linac cryomodule has started.

High Current SRF Injector Prototype





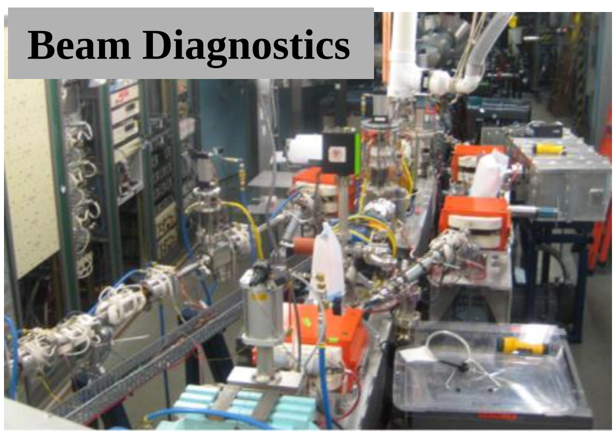
The Cornell ERL Injector

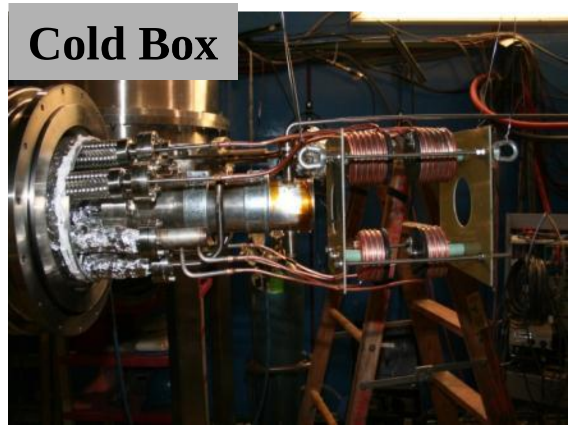
ERL Injector: Technical Components

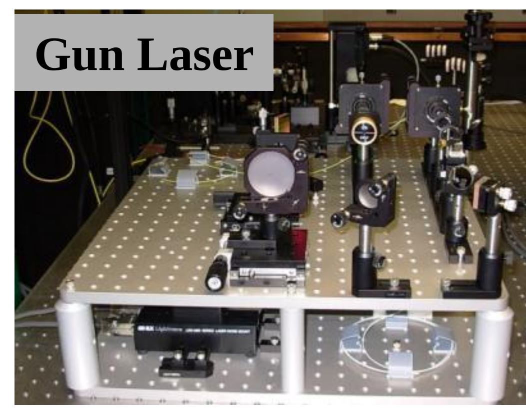

SRF Injector Cryomodule


135 kW cw
Klystrons (e2v)

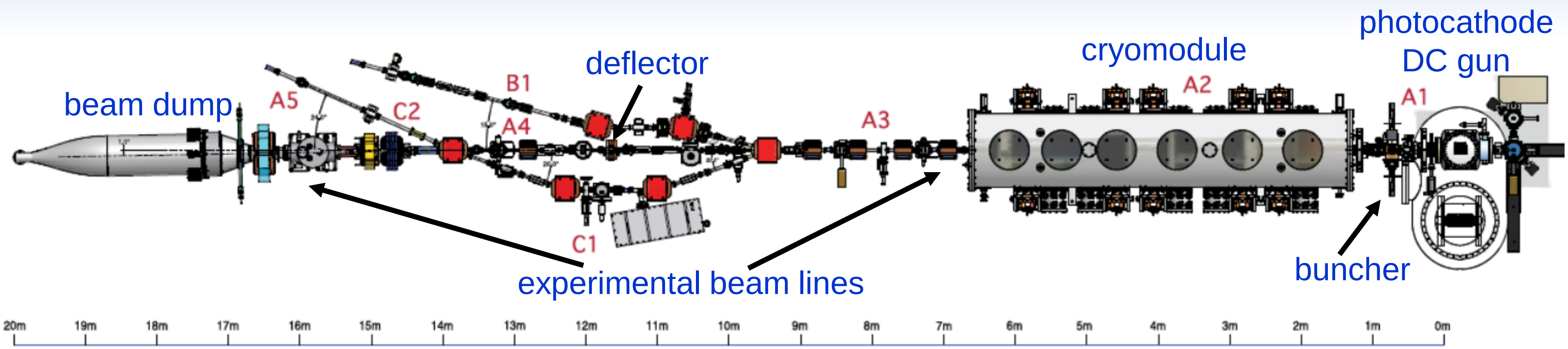

DC Gun


Beam Diagnostics


Cold Box


Gun Laser

The High Current Cornell ERL Injector



	design parameters	Achieved so far
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	125 kW
Nominal gun voltage	500 kV	425 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	25 mA
Bunch length	0.6 mm (rms)	
Transverse emittance	< 1 mm-mrad	

World record for CW injector!

The Cornell ERL Injector

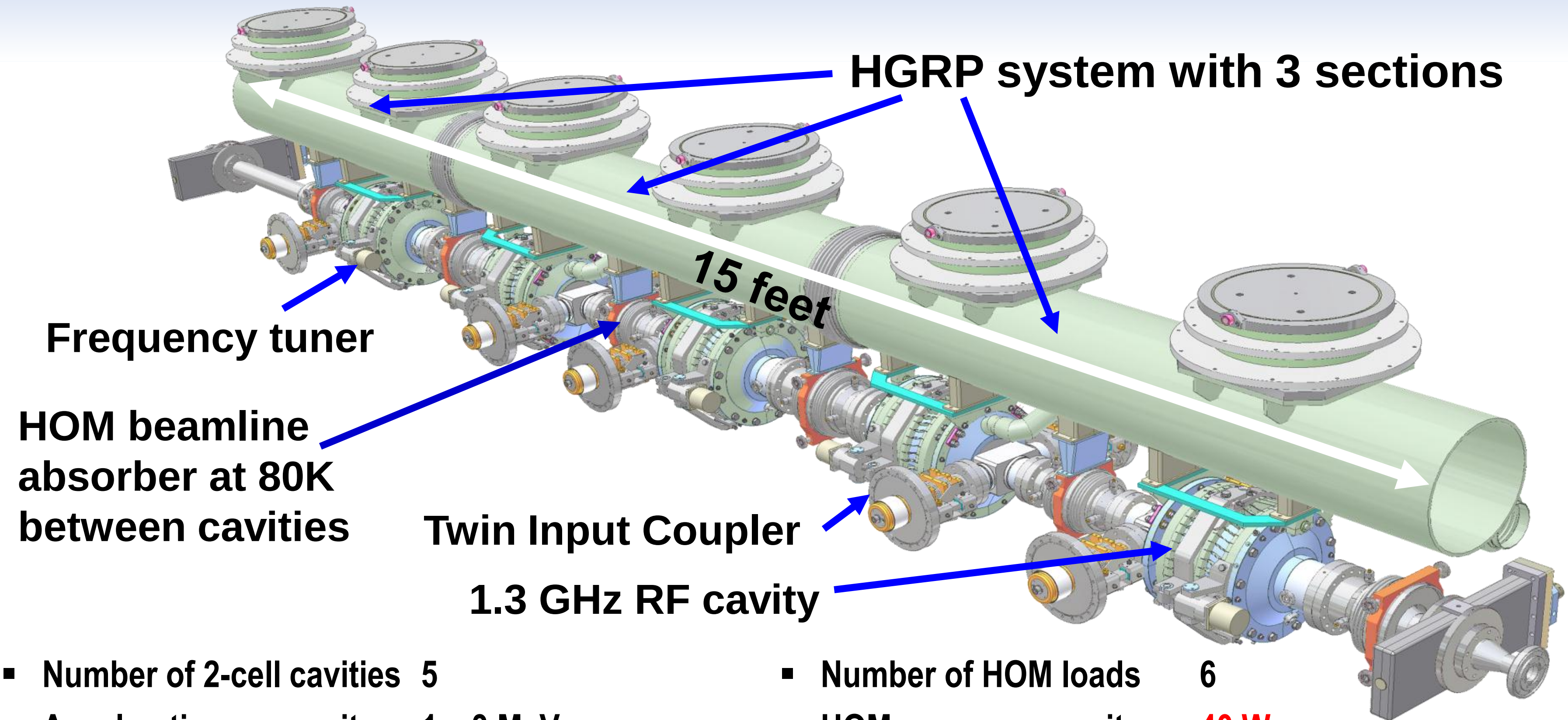
Outline

- SRF Cryomodule for the ERL injector
  - Beamline components, module design and assembly
- Operational Highlights: Pushing the Envelope
  - SRF cavity and coupler performance
  - High current operation
- Summary and outlook

SRF Cryomodule for the ERL injector

Beamline components, module design and assembly

The Cornell ERL 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
- Q_{ext} $4.6\times10^4 - 4.1\times10^5$
- Total 2K / 5K / 80K loads: 30W / 60W / 700W

- Number of HOM loads 6
- HOM power per cavity 40 W
- Couplers per cavity 2
- RF power per cavity 120 kW
- Amplitude/phase stability 10^{-4} / 0.1° (rms)
- ICM length 5 m

ERL Injector SRF: Key Challenges

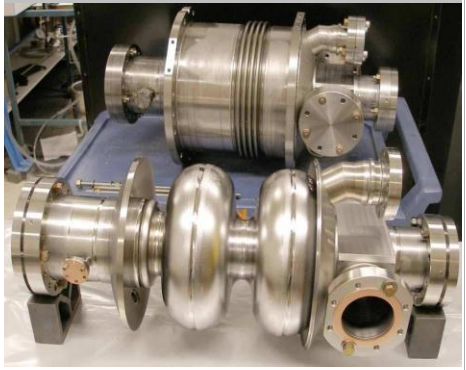
1. Limit emittance growth of the very low emittance beam in the injector module (essential for ERL x-ray performance)
2. Support high beam current operation up to 100 mA with short (2 ps) bunches
3. Transfer up to 100 kW of CW RF power per cavity to the beam
4. Provide excellent RF field / energy stability

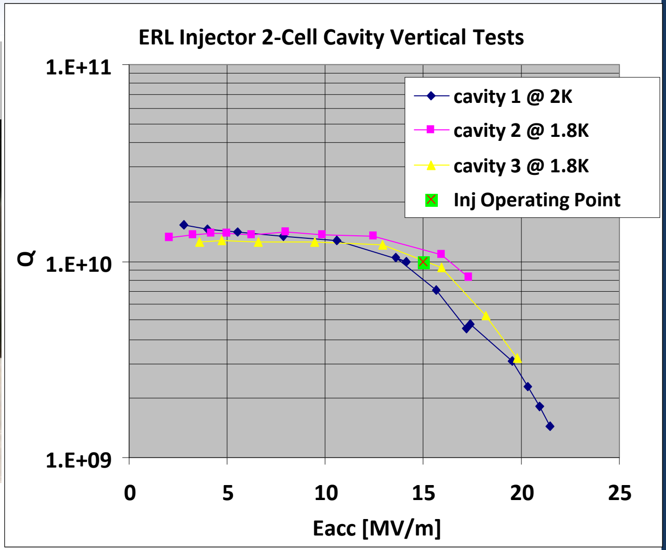
Beam Line Components (I)

SRF cavities:

- Designed, fabricated, and tested at Cornell
- All cavities met 15 MV/m spec in vert. test (BCP only)

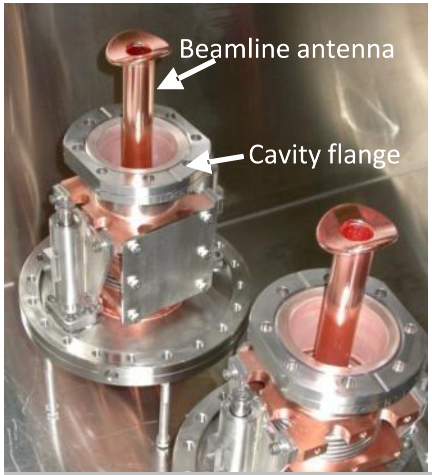
SRF cavities



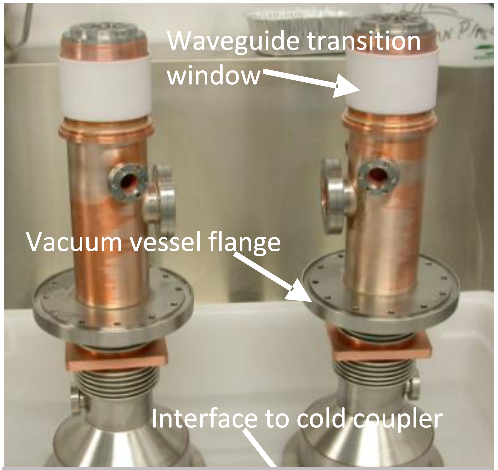


RF input couplers:

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



Cold coupler part

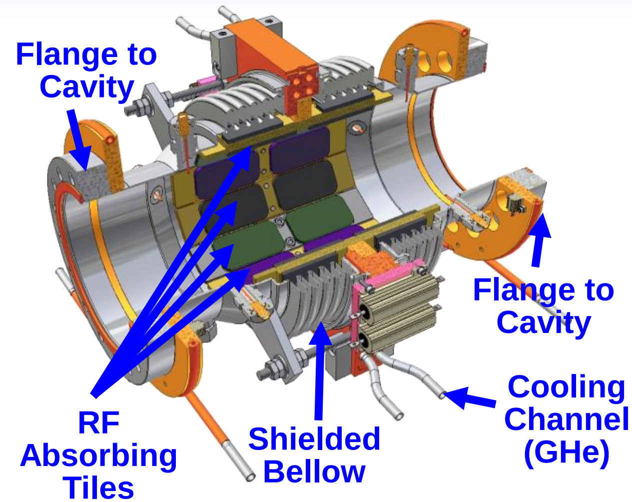


Warm coupler part

Beam Line Components (II)

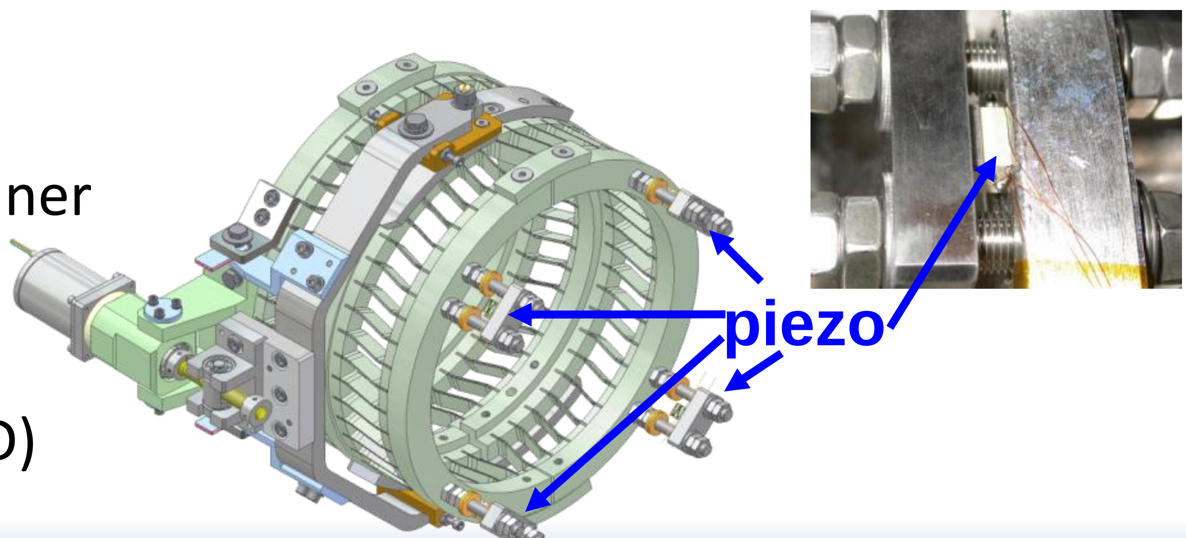
HOM absorbers:

- Design by Cornell for strong, broadband HOM damping (1.5 GHz -> 100 GHz)
- >200 W power handling



Frequency tuners:

- Modification of the DESY/INFN blade tuner
- Added piezos for microphonics compensation (R&D)

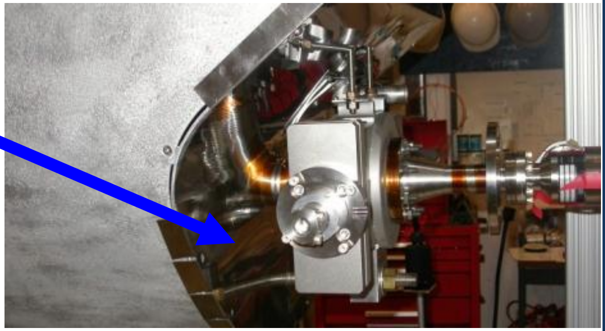


ERL Injector Module Innovations (I)

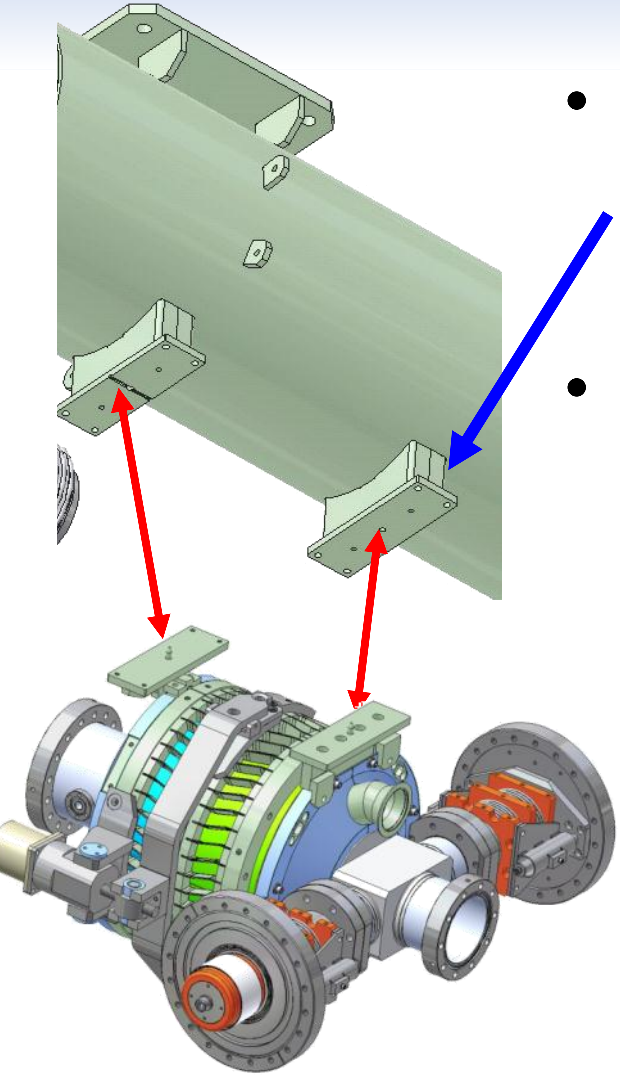
- Tuner stepper replaceable while string is in cryomodule

- Rail system for cold mass insertion into Vacuum Vessel

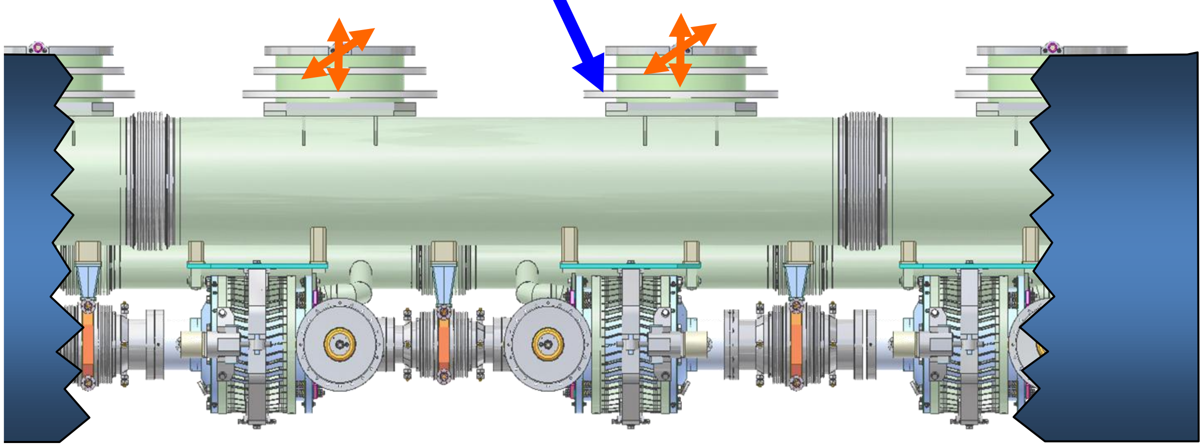
- Gatevalve inside of module with outside drive



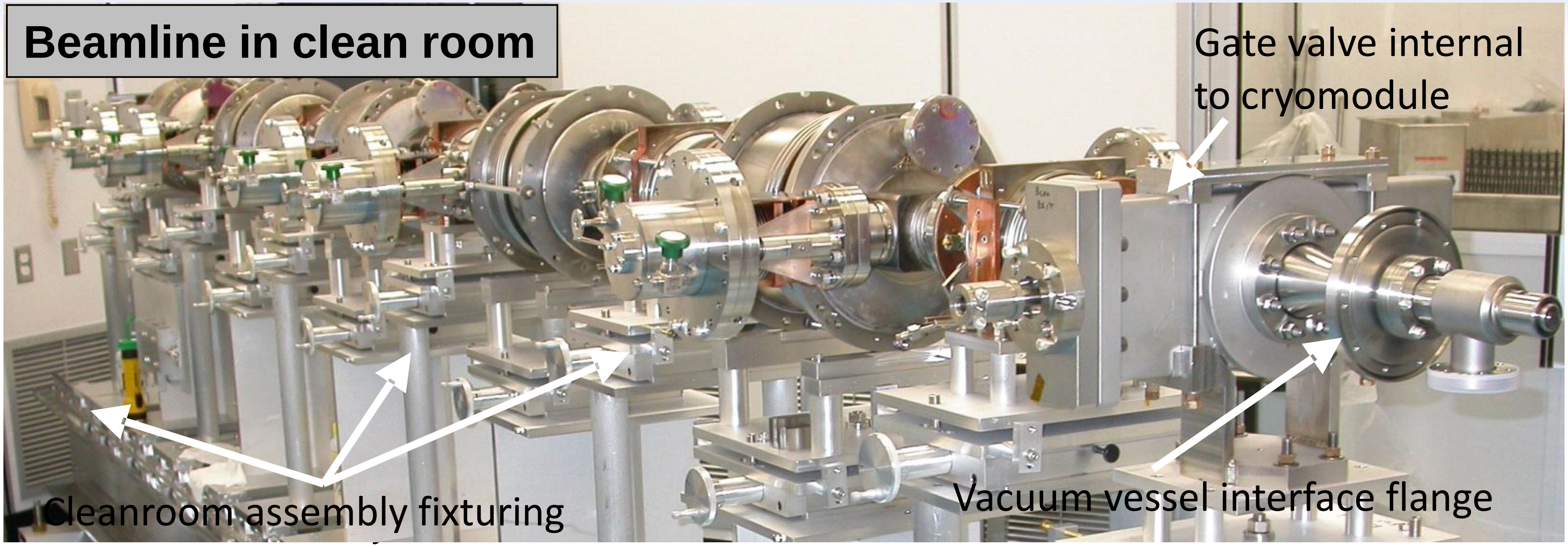
ERL Injector Module Innovations (II)

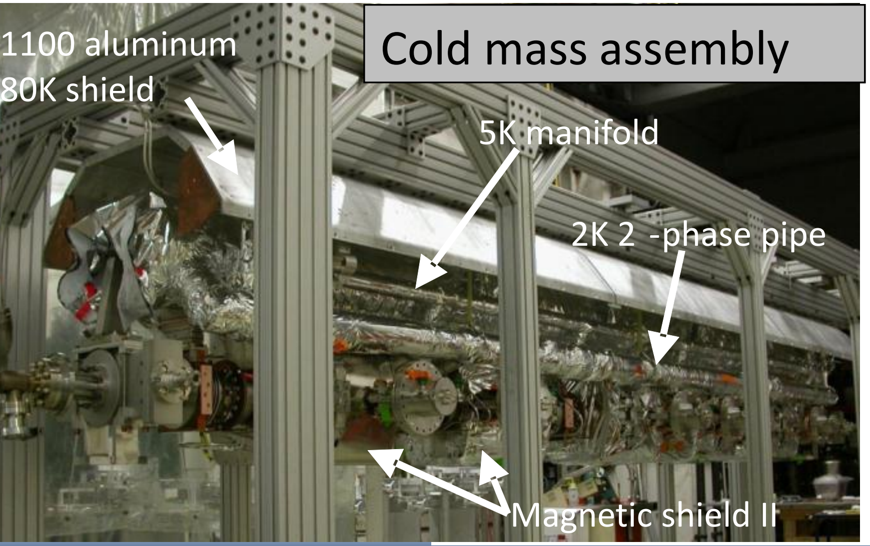


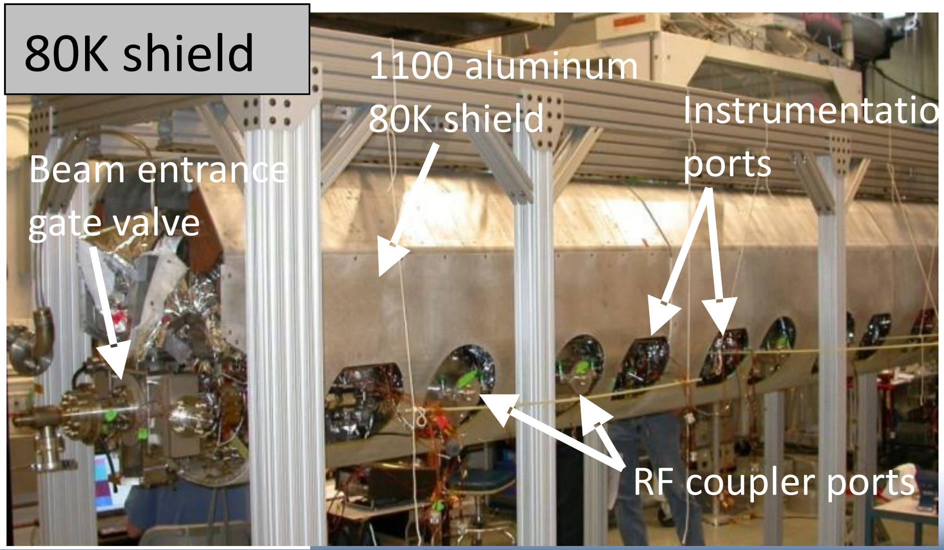
- Precision fixed cavity support surfaces between the beamline components and the HGRP $\Rightarrow$ easy "self" alignment
- Cavity-subunits can be fine-aligned while cavities are at 2K (if required)



ERL Injector Module Assembly at Cornell



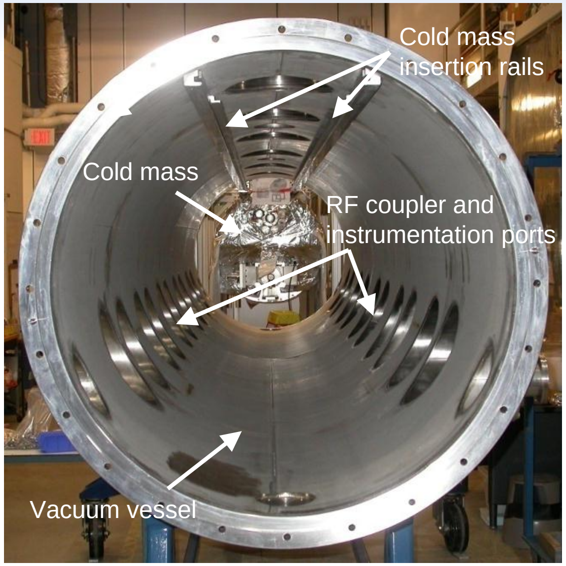


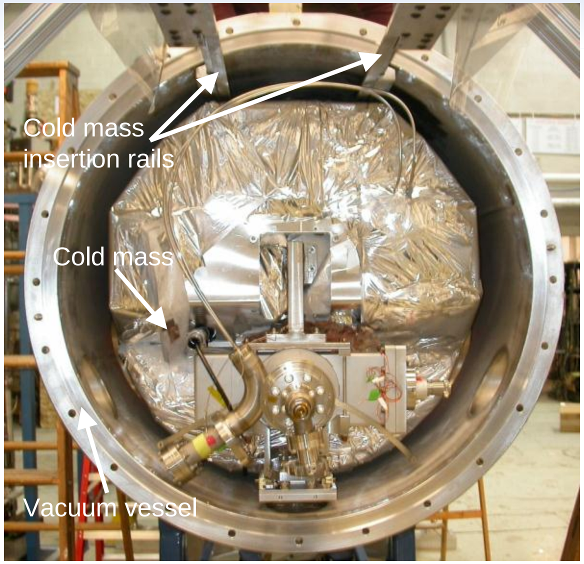


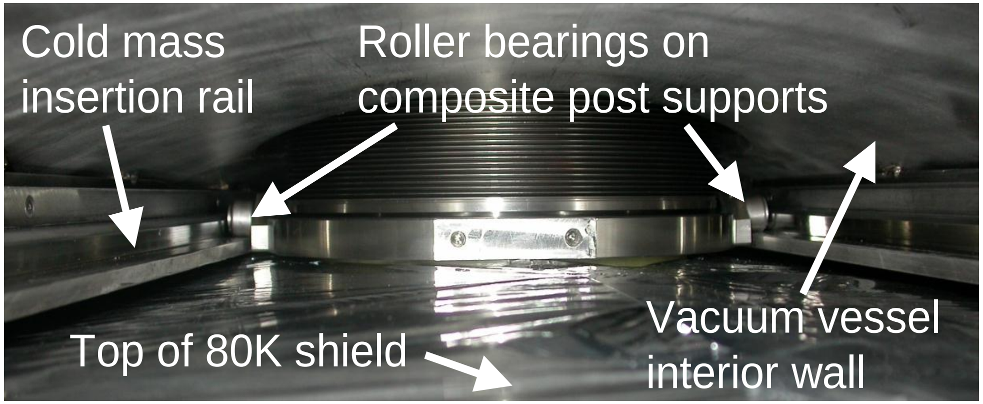
SRF Cryomodule for the ERL injector

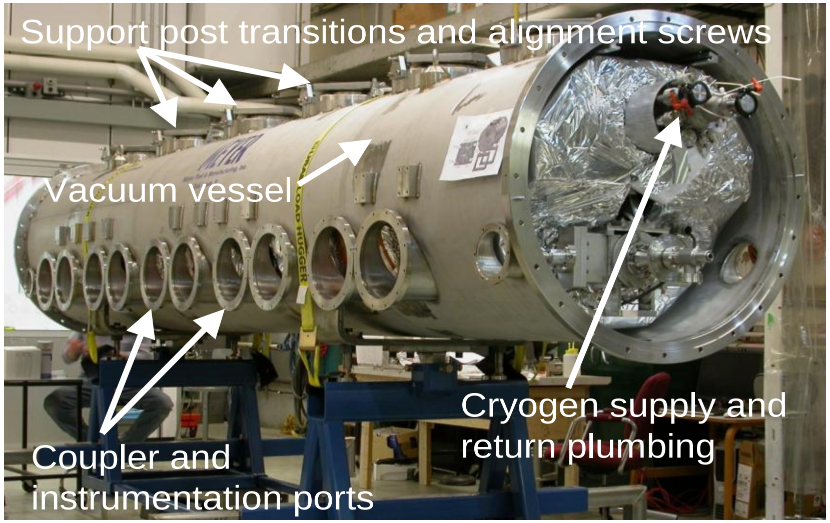
ERL Injector Module Assembly at Cornell

Cold mass rolled into vacuum vessel







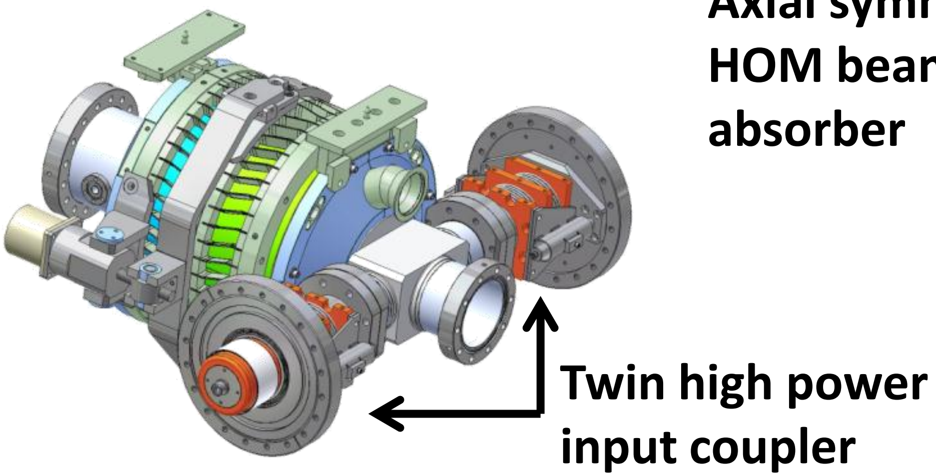


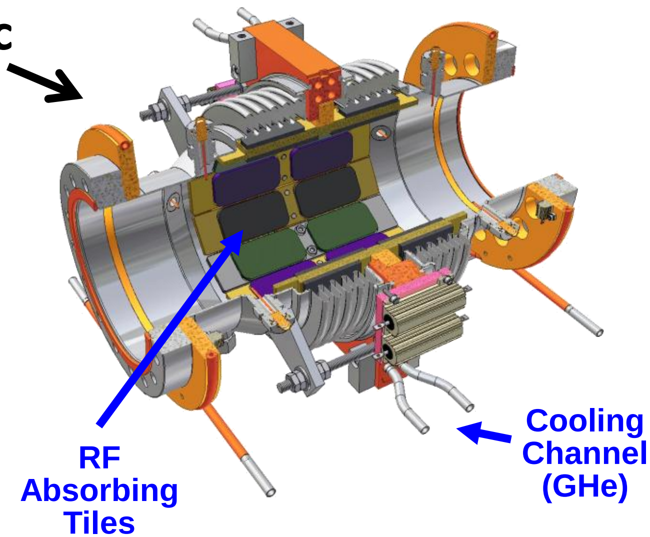
Operational Highlights: Pushing the Envelope

SRF cavity and coupler performance
High current operation

Emittance Preservation and Cavity Alignment

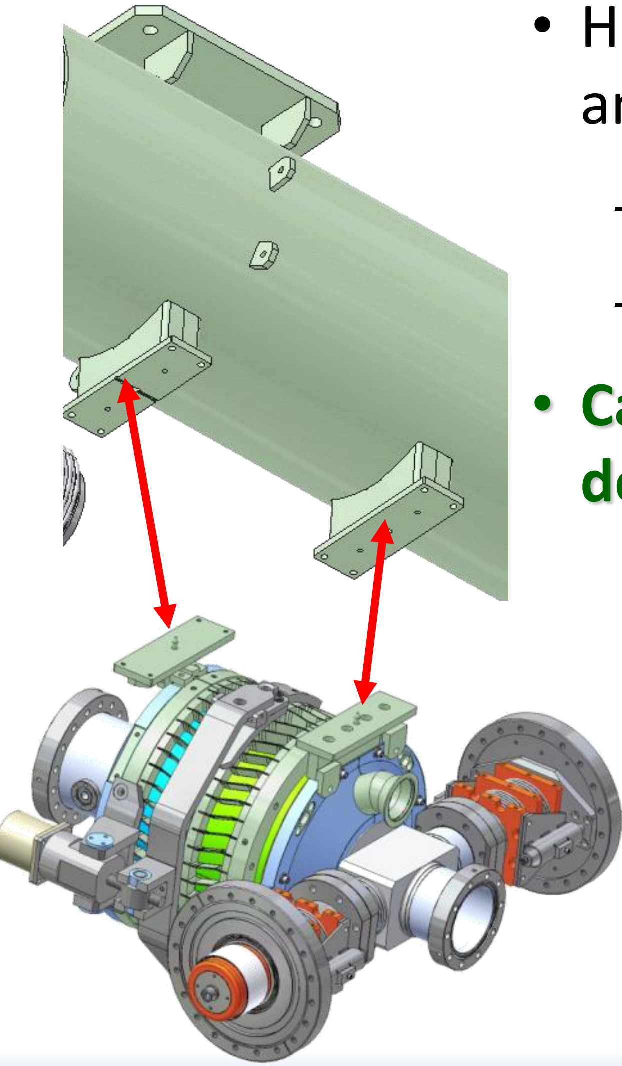
- Avoid transverse kick fields:
  - Symmetrized beam line in injector module



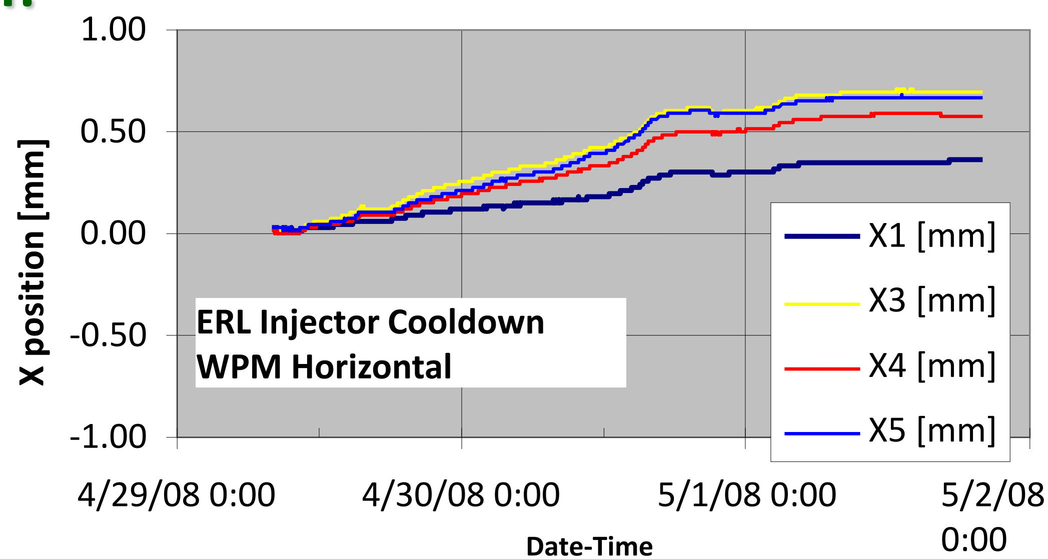


  - Excellent cavity alignment ($\pm$0.5mm required, **$\pm$0.2mm achieved**)

Fixed High Precision Cavity Support and Alignment



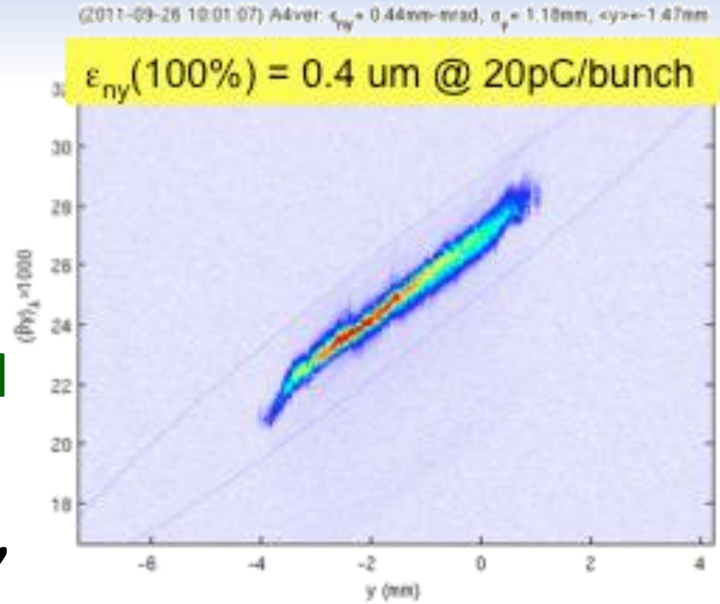
- High precision supports on cavities, HOM loads, and HGRP for “self” alignment of beam line
  - Rigid, stable support
  - Shift of beamline during cool-down as predicted
- **Cavity string is aligned to ±0.2 mm after cool-down!**

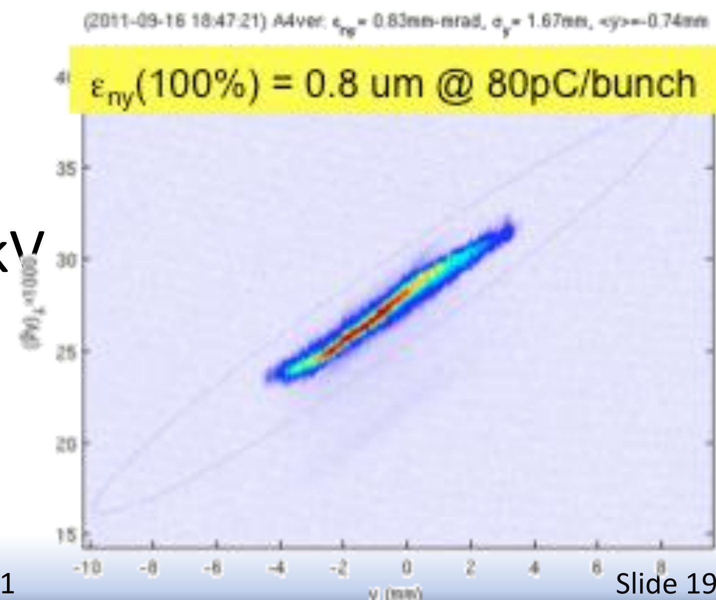


Beam Emittance

- At low bunch charge (at 5 MeV):
  - Normalized **emittance** is close to thermal limit at cathode for given laser size: ε_N = **0.2 to 0.4 mm mrad**

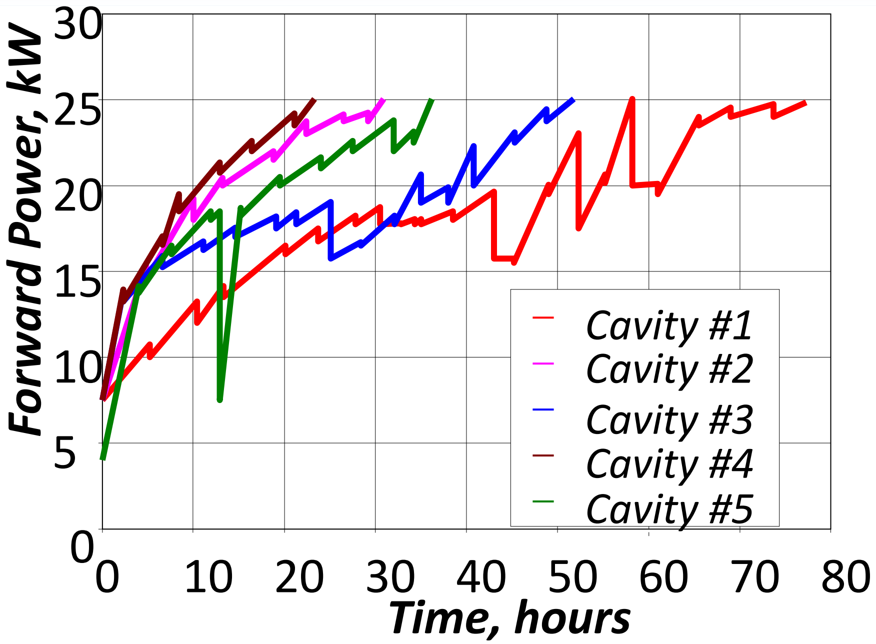
- At higher bunch charge (10 MeV, 77 pC):
  - ε_N = **0.8 mm-mrad** for 100% beam (core emittance = 0.3 mm-mrad)
  - Increasing the gun voltage to 500 kV is expected to reduce this number further

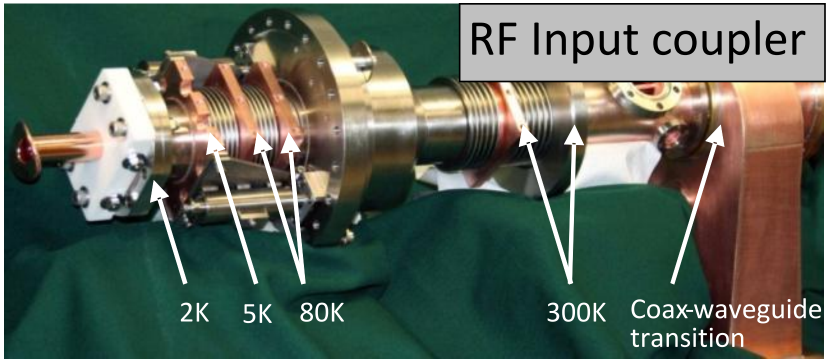




SRF Cavities and High RF Input Power

- SRF cavities meet gradient spec and have transferred >25 kW cw each to the beam
- Individual input couplers processed up to 25 kW cw
- Prototypes tested **up to 60 kW cw**, 80 kW pulsed

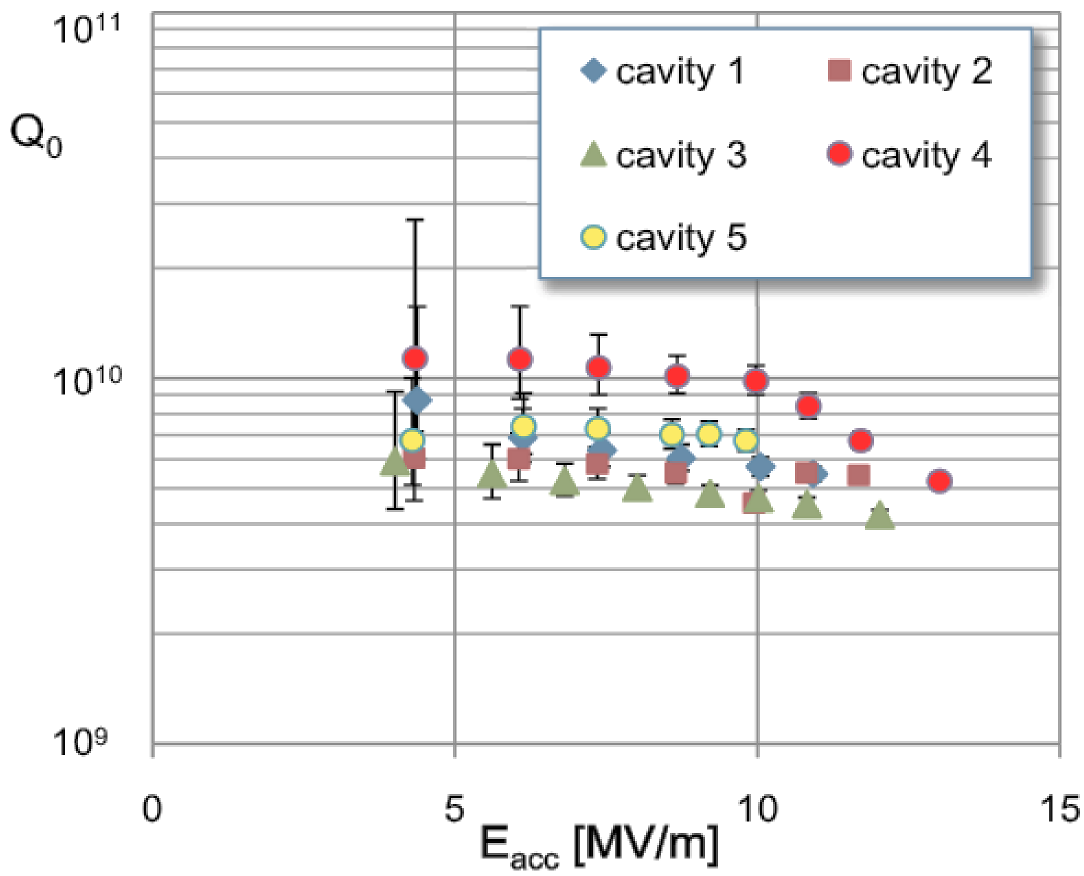




Operational Highlights

SRF Cavity Intrinsic Quality Factor

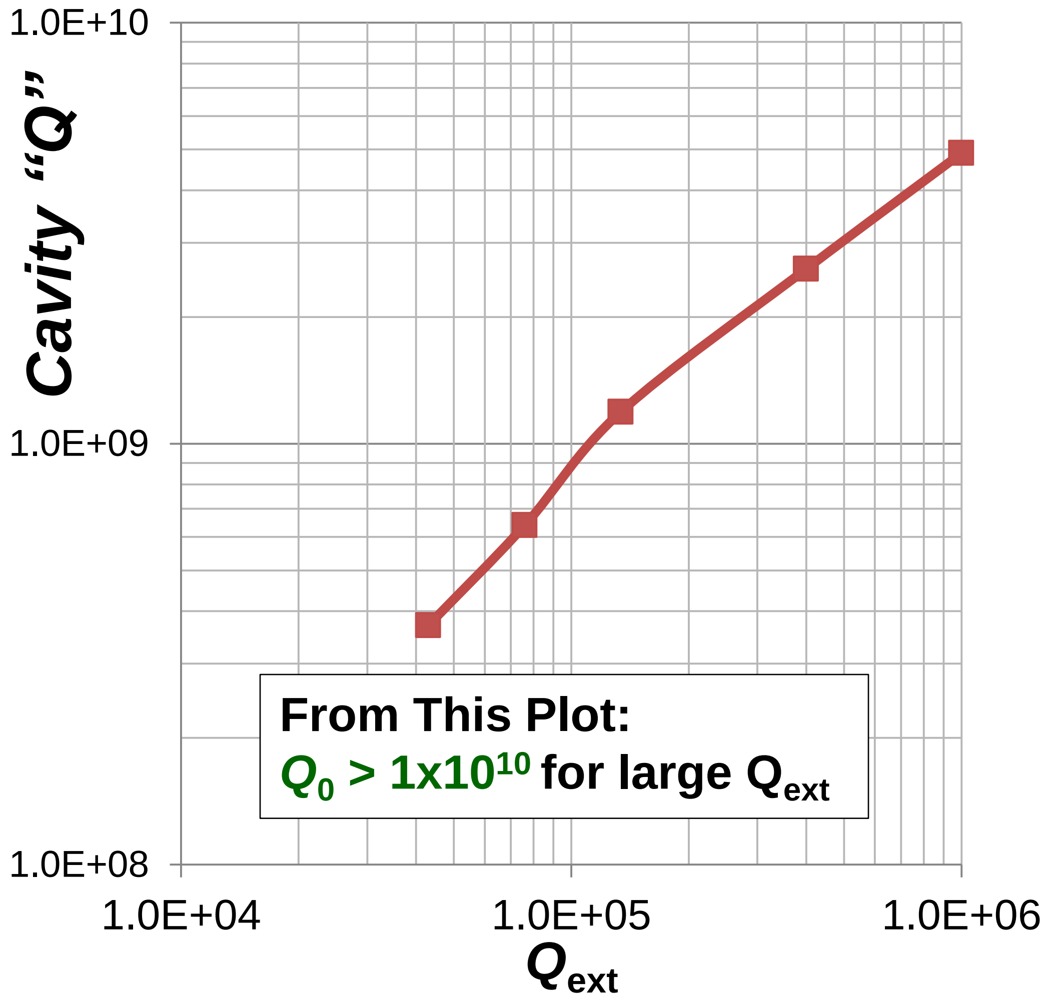
- Measurements of cavity dynamic 1.8K head loads shows intrinsic Q's of $5 \cdot 10^9$ to $1 \cdot 10^{10}$
- Expected: $Q \sim 1.5 \cdot 10^{10}$
- Source of increased RF losses?



Operational Highlights

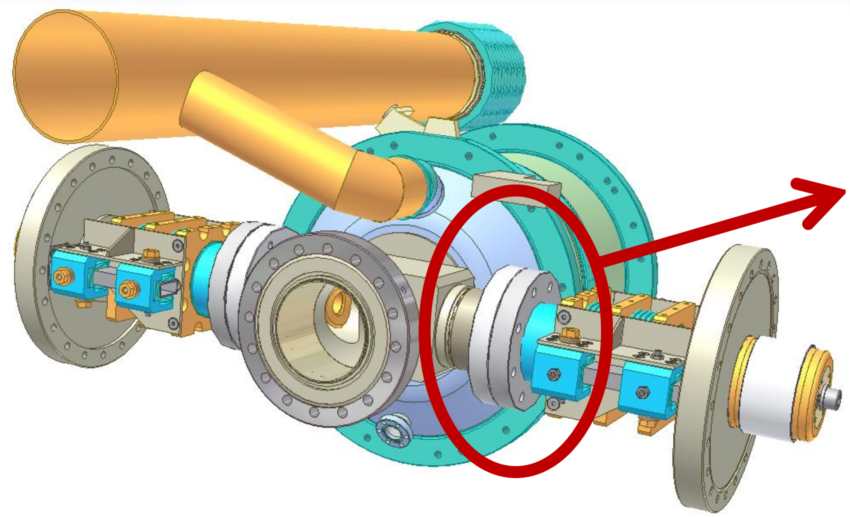
Cavity "Q_0" vs. External Q_{ext}

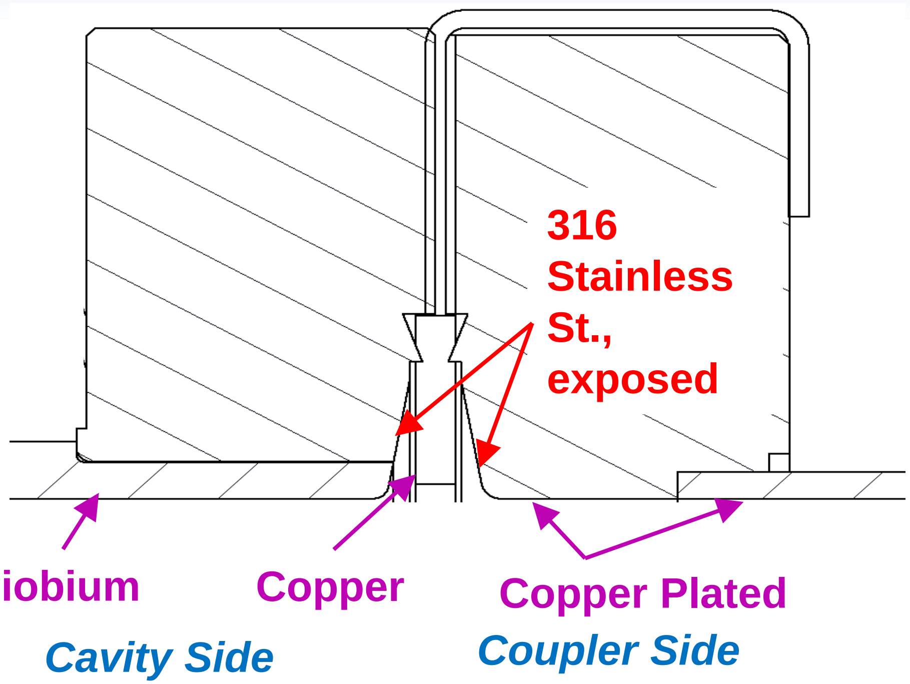
- Measured impact of input coupler coupling on Q_0
  -> found losses increase with coupling
- Note: Operate at very low Q_{ext} (high beam current)
  -> large RF power/field in input coupler



Operational Highlights

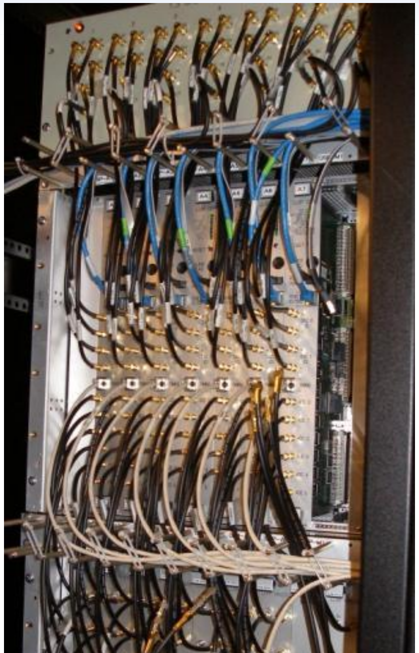
RF Losses at Input Coupler Flange



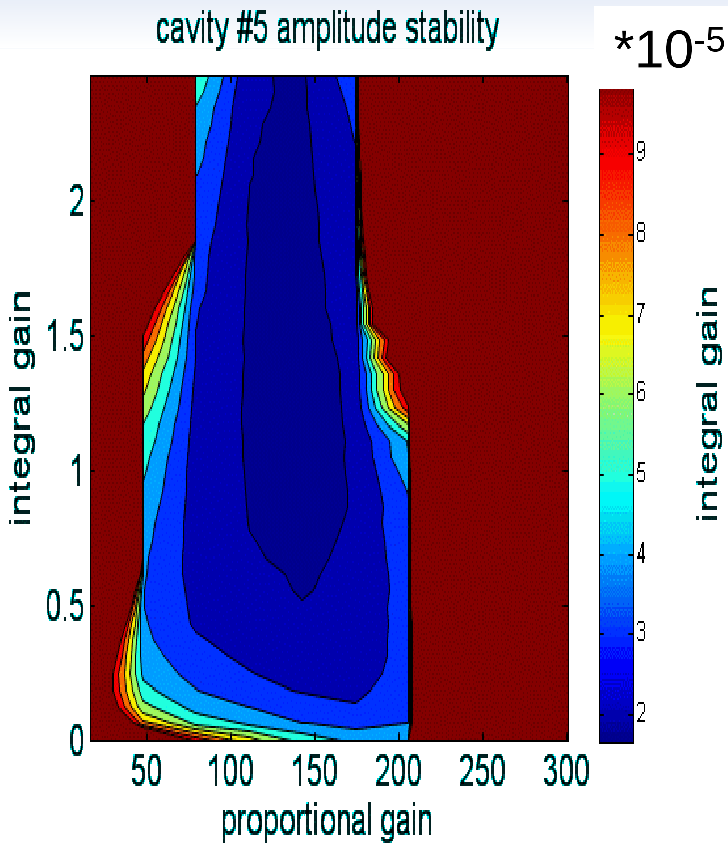


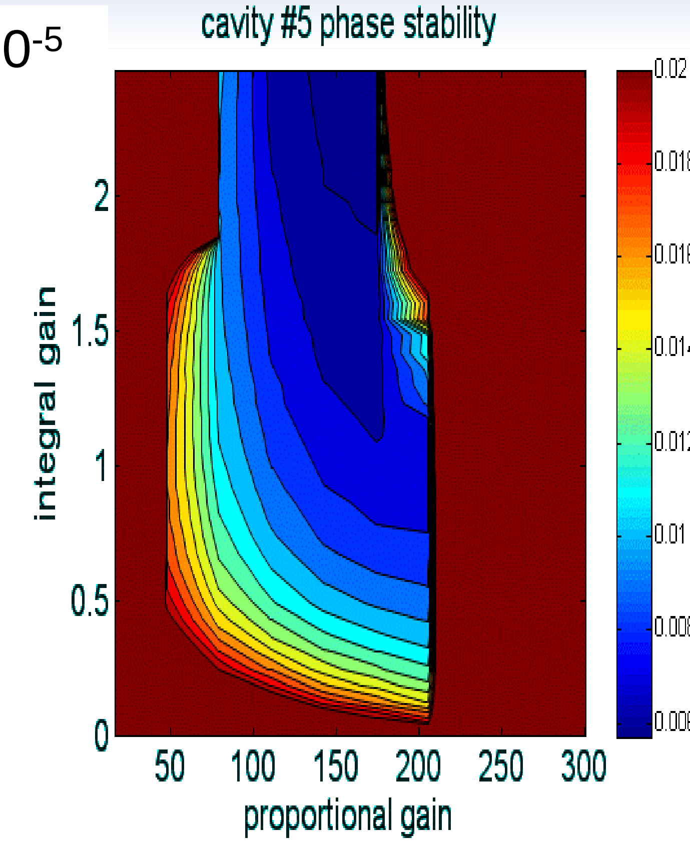
- Exposed stainless steel near knife edge of input coupler Conflat flanges responsible for increased RF losses at strong couplings (confirmed by simulations)
- New **zero gap/impedance flange design** developed for ERL main linac cavity can be used to eliminate this extra loss

LLRF Field Control and Field Stability



Cornell digital LLRF control system





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

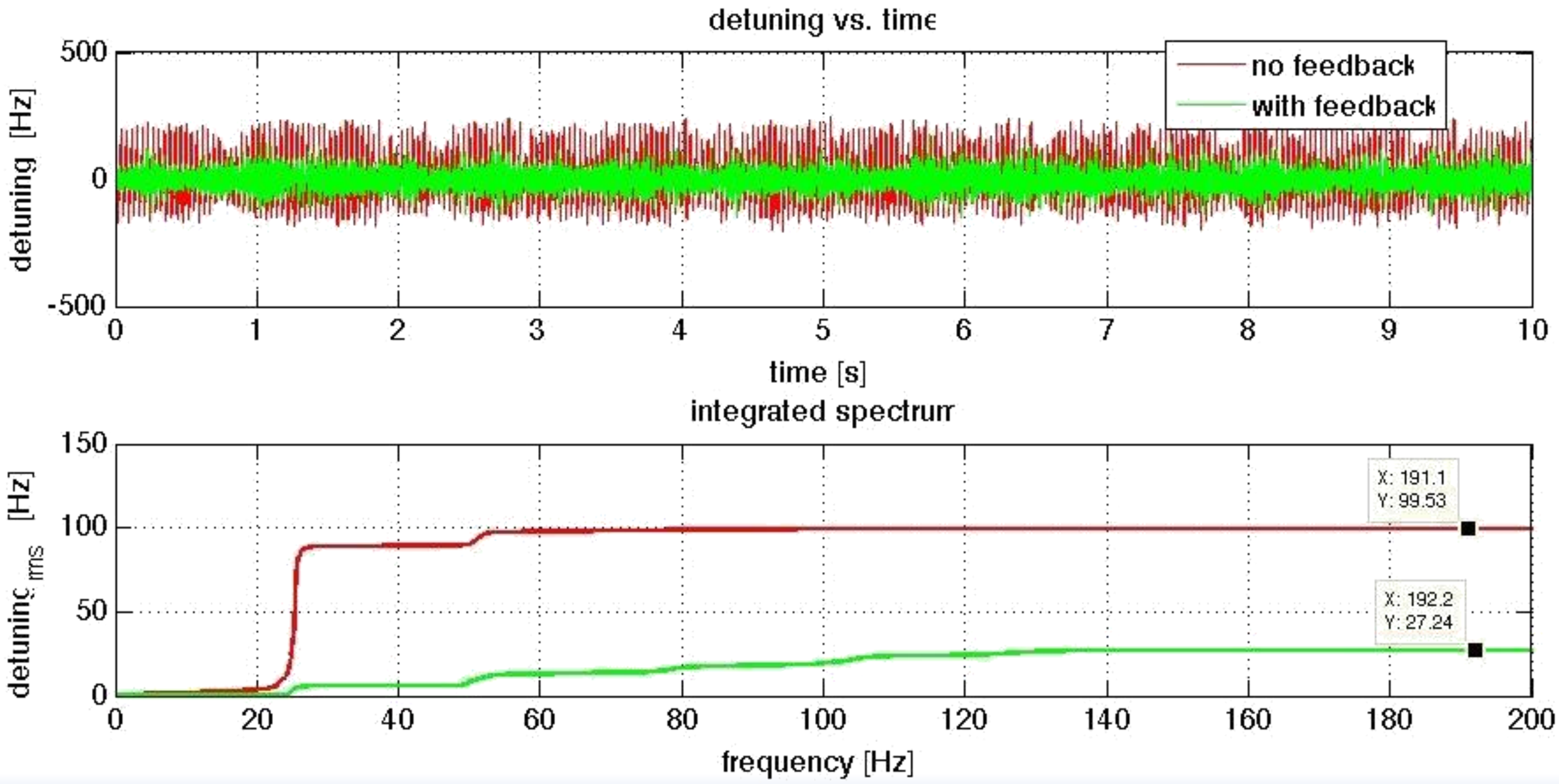
(in loop measurements) **phase: $\sigma_P < 0.01$ deg**

Highlight: Active Microphonics Control

Piezo Feedback on Tuning Angle/Cavity Frequency:

$\Rightarrow$ Reduces rms microphonics by up to 70%!

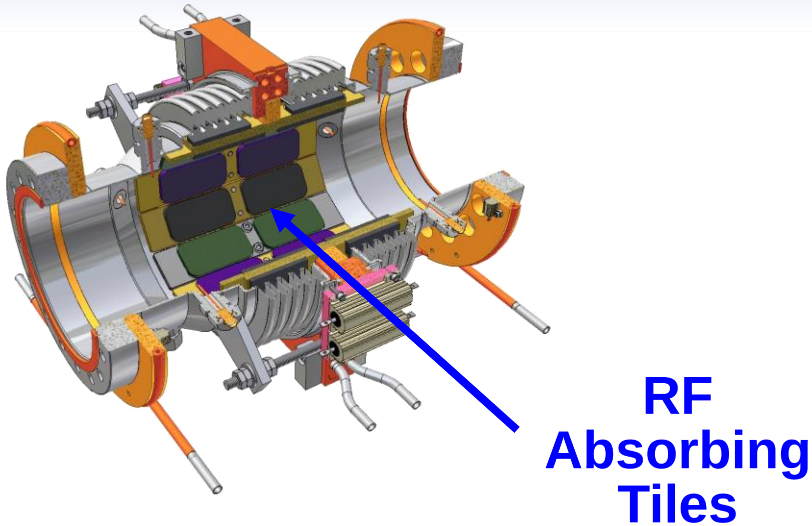
$\Rightarrow$ Important for ERL main linac, where $Q_L > 5 \cdot 10^7$ and $P_{RF} \propto \Delta f$!

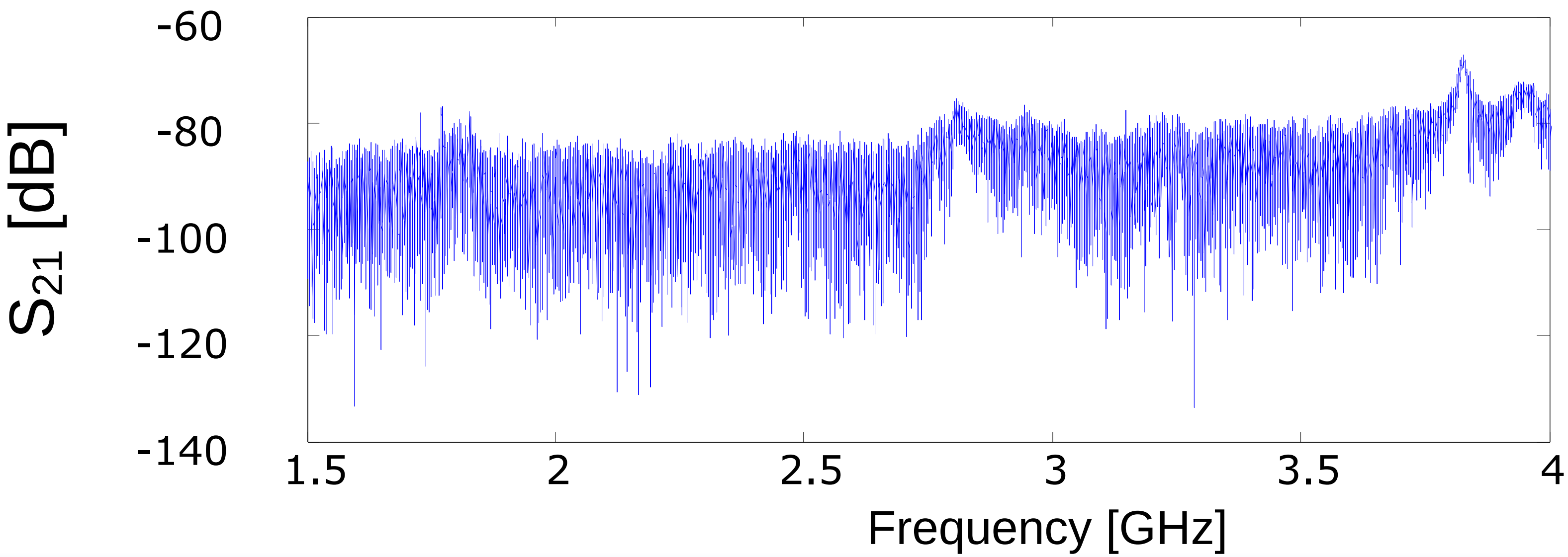


Operational Highlights

HOMs and High Current Operation

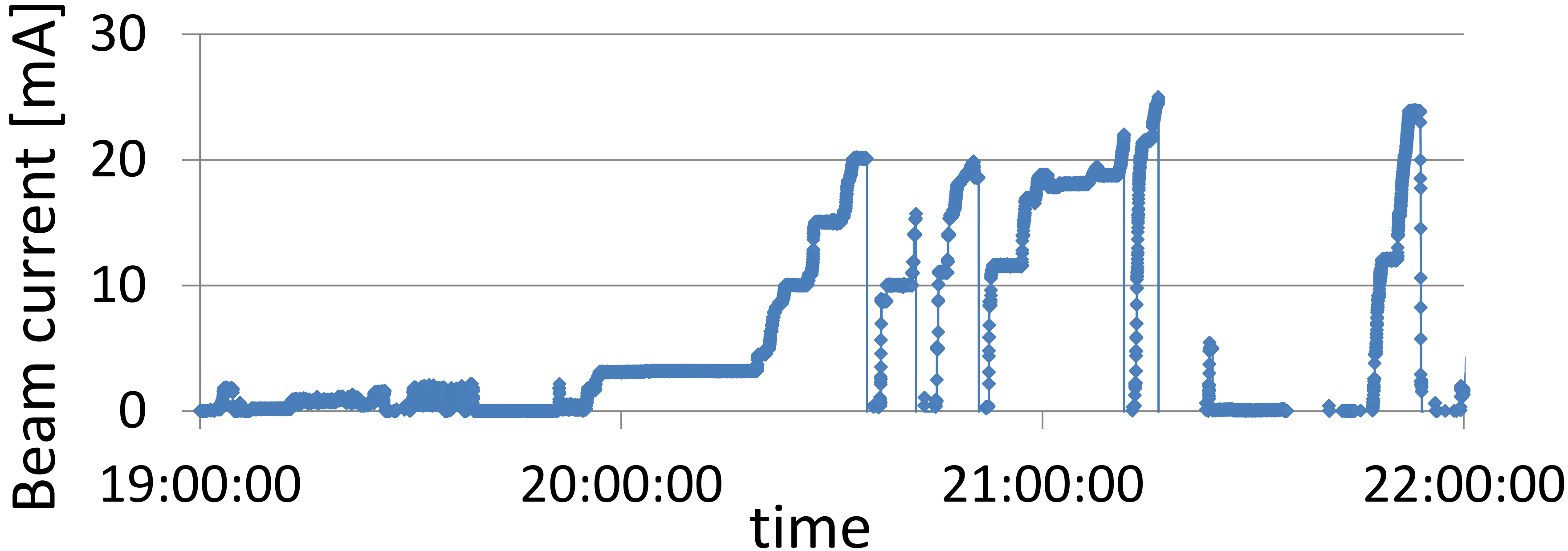
- Beamline HOM absorber between cavities very effective
- HOM damping and HOM spectra measurements confirm excellent damping with **typical Qs of a few 1000**



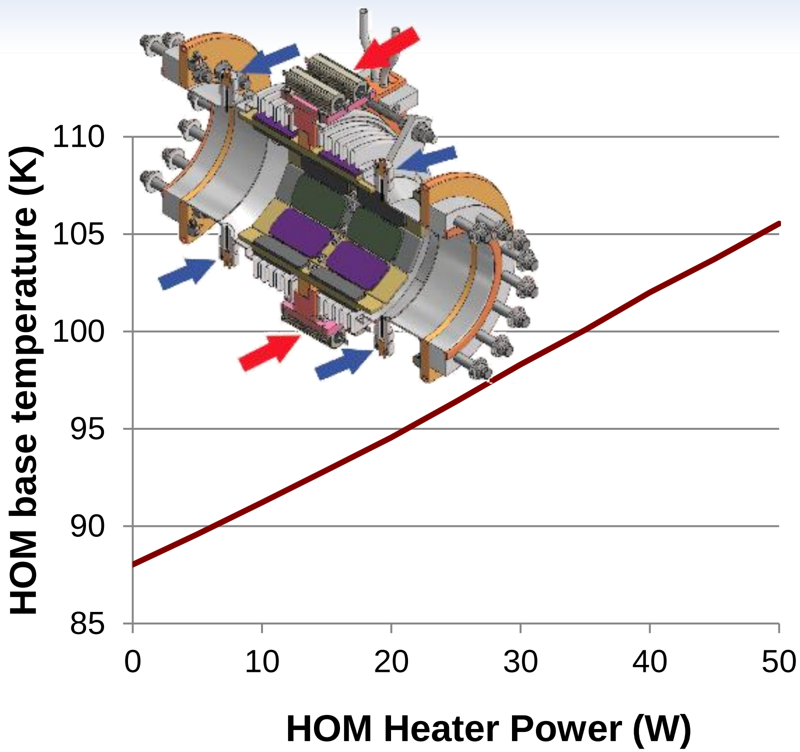


High Current Cryomodule Operation

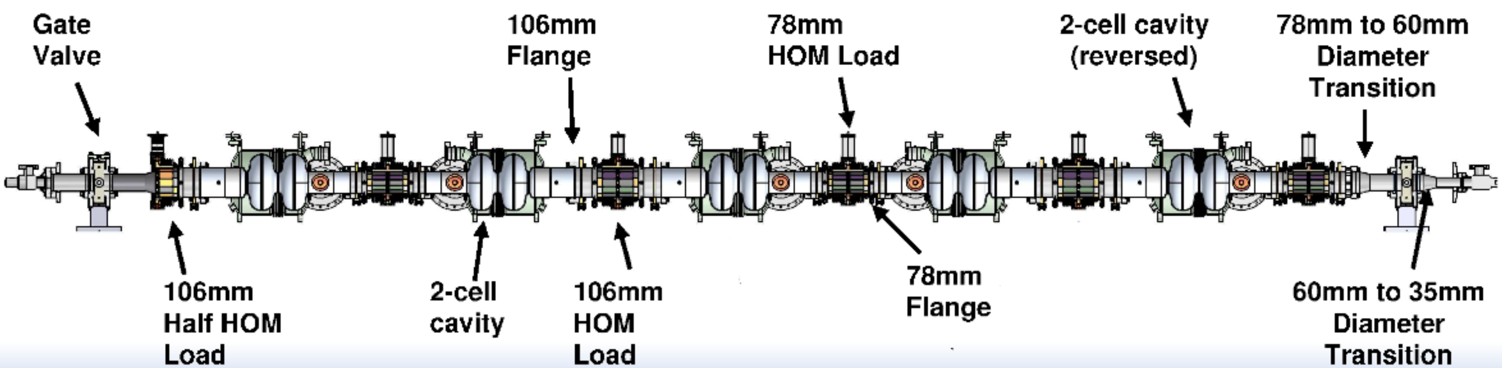
- Successfully operated injector SRF module with **beam currents of 25 mA**
  - No increase in 1.8K dynamic load observed
  - ΔT of HOM absorbers small (<0.5K). **Module should easily handle operation at >100 mA.**



Cryomodule Loss Factor

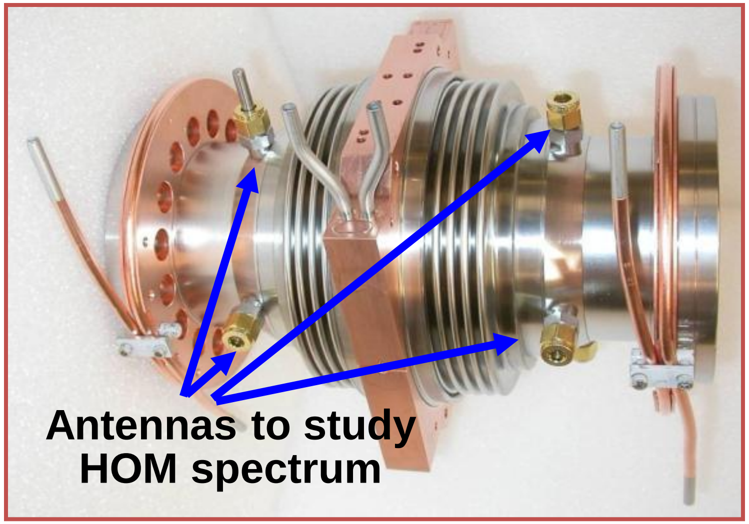


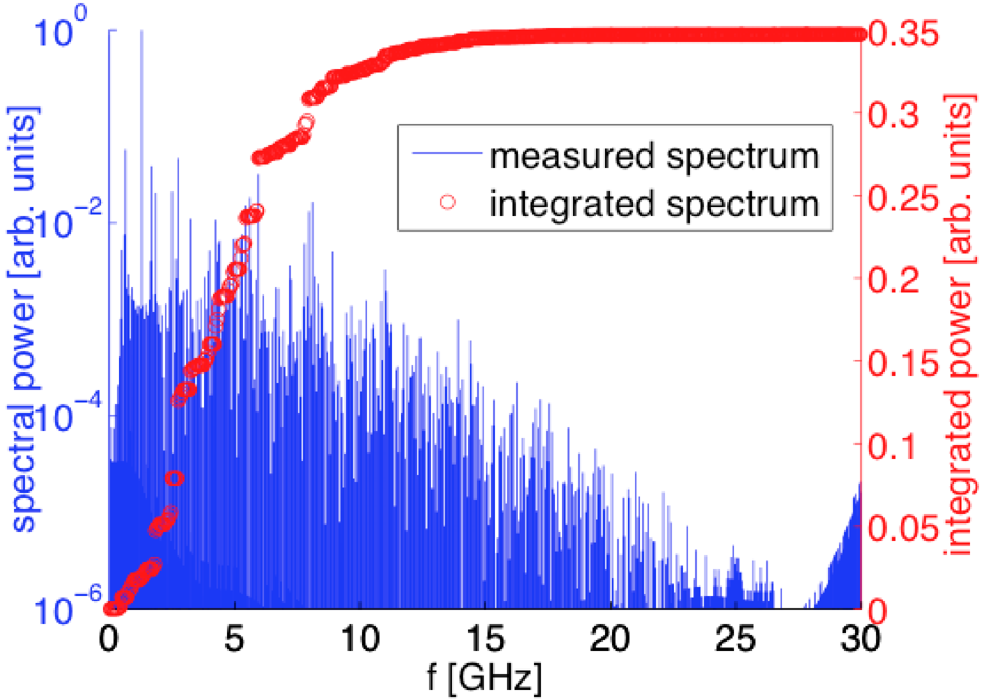
- HOM absorbers allow for calorimetric measurement of the total HOM power excited by the beam
- Heaters on the HOM loads used for calibration
- **Total HOM power measurement at ~20 mA gives longitudinal loss factor in good agreement with ABCI simulations (~20 V/pC at σ_b=1 mm)**



HOM Spectrum Measurements

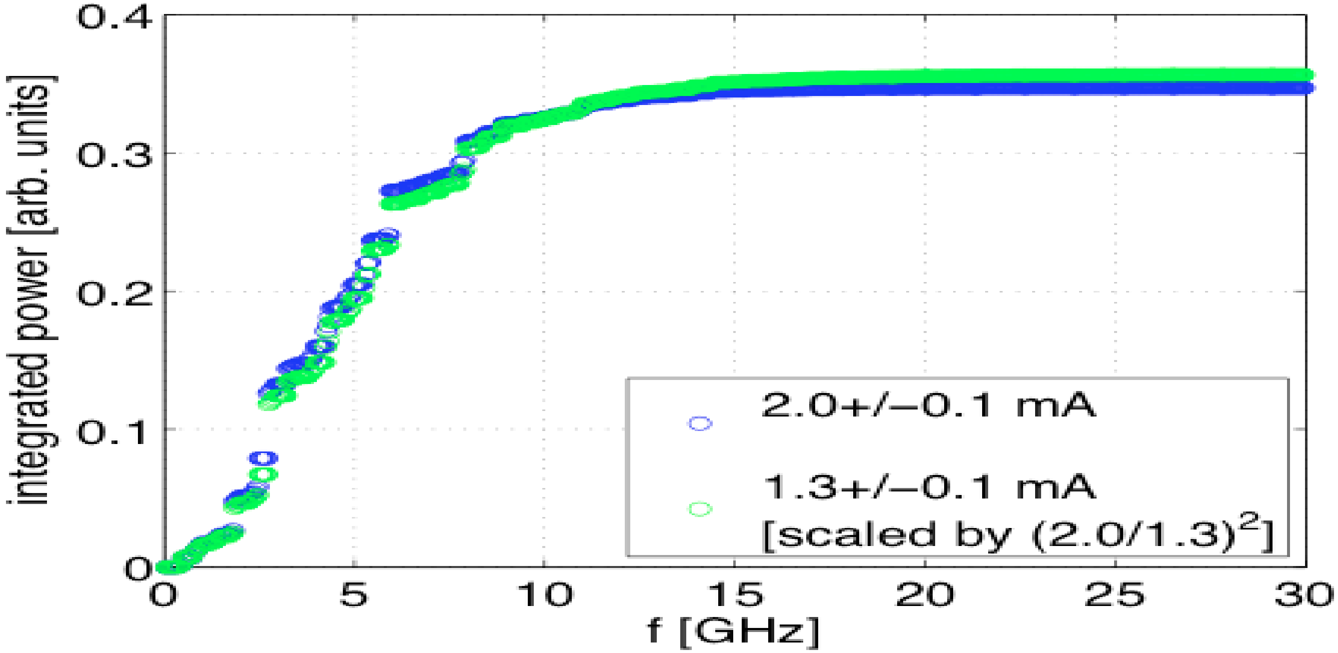
- 8 HOM antennas per load:
  - Used as BPMs
  - Allow studying HOM spectrum





Operational Highlights

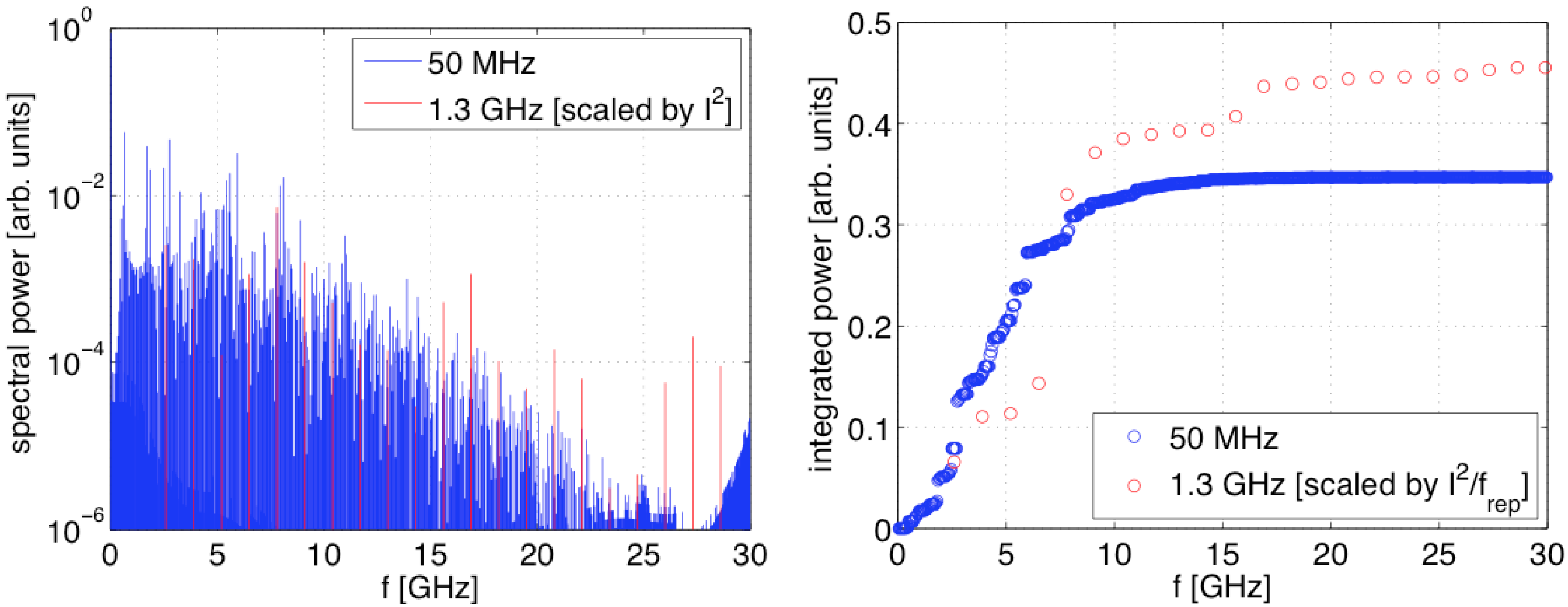
HOM Spectrum: Scaling with Beam Current



- Changed bunch charge (and thus beam current), but kept bunch length and repetition rate constant
- Total HOM power: $P \propto IQ_b$ as expected

Operational Highlights

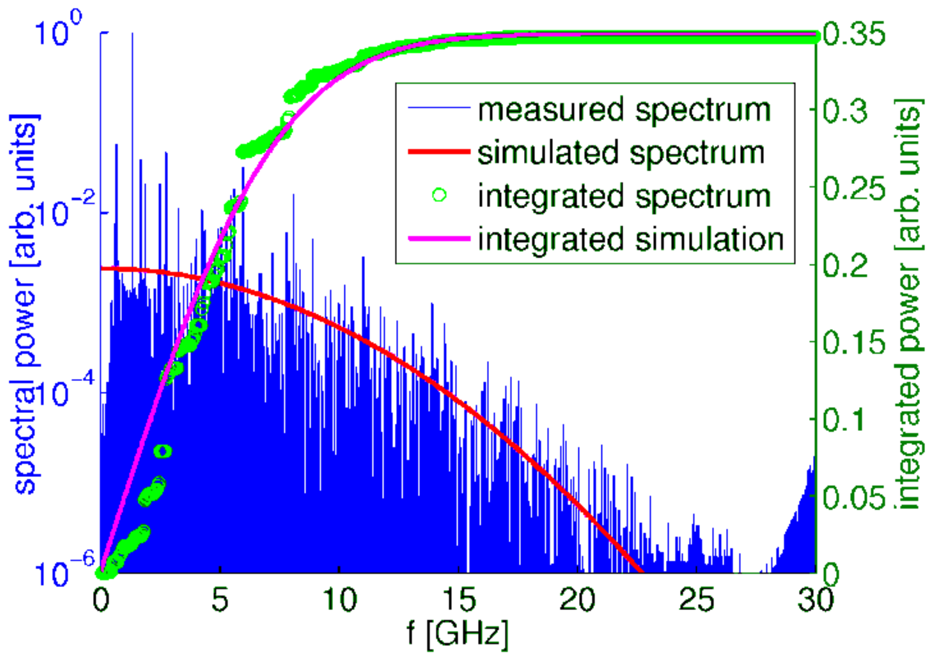
HOM Spectrum: Scaling with Bunch Repetition Rate

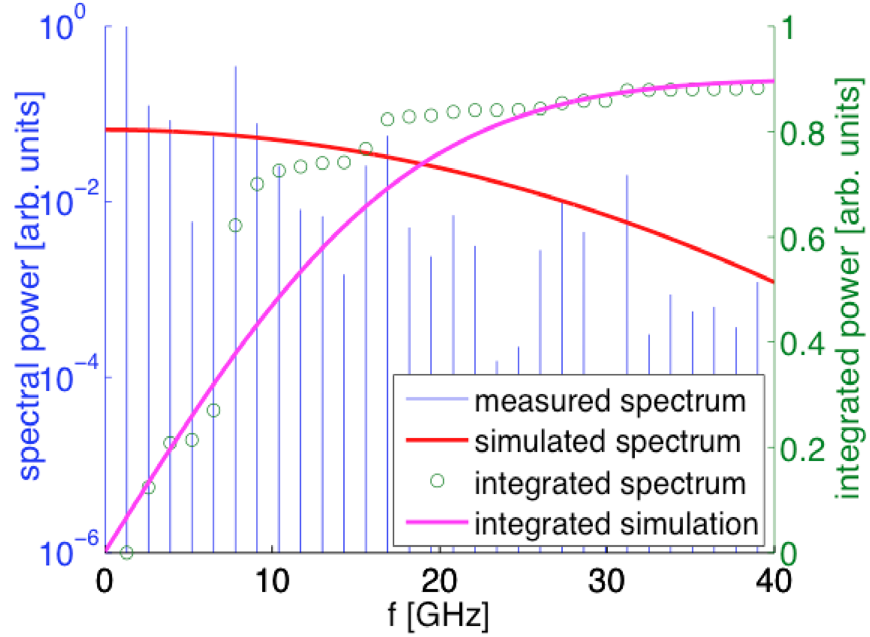


- Changed bunch repetition rate
- Total HOM power: $P \propto IQ_b$ as expected

Operational Highlights

HOM Spectrum: Comparison with ABCI Simulations



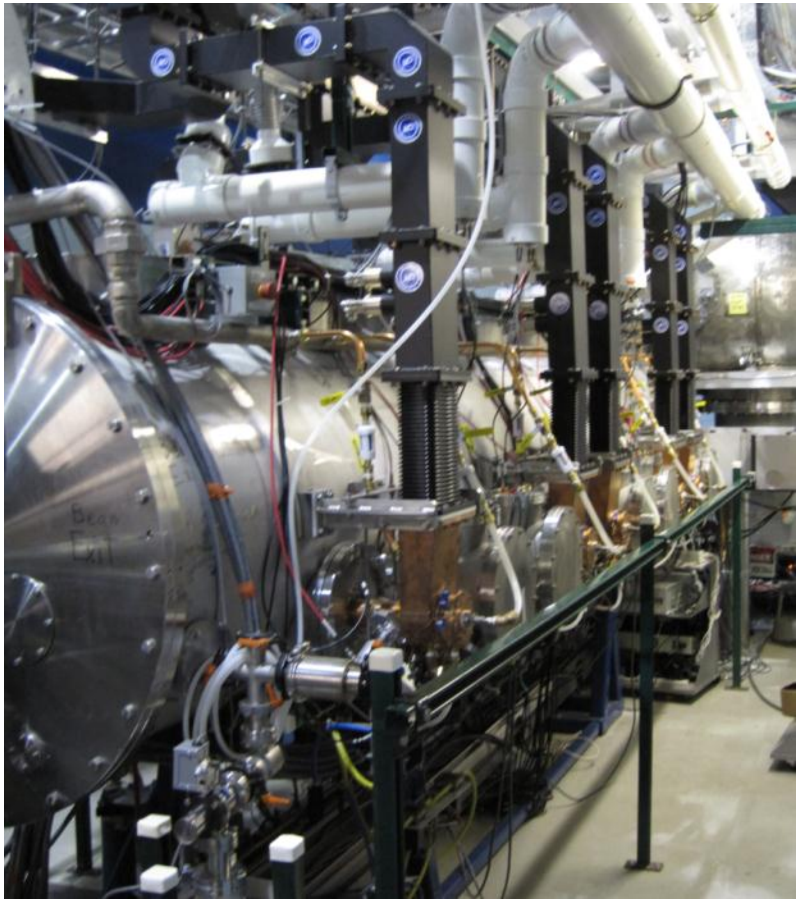


- Spectrum and total loss factor in good agreement with ABCI simulation results for given bunch length

Summary and outlook

Summary

- ERL injector cryomodule:
  – Designed, constructed, and successfully tested
  – **Cryogenics, cavity alignment, cavity voltage, input couplers, LLRF field control, and HOM damping all meet or exceed specs**
  – 25 mA cw beam accelerated to 5 MeV; should easily support 100 mA operation



The End

Thanks for you attention!

ERL-SRF team: D. Hartill, G. Hoffstaetter, M. Liepe, S. Posen,
P. Quigley, V. Shemelin, M. Tigner, N. Valles,
V. Veshcherevich