PROGRESS ON SUPERCONDUCTING RF FOR THE CORNELL ENERGY-RECOVERY-LINAC

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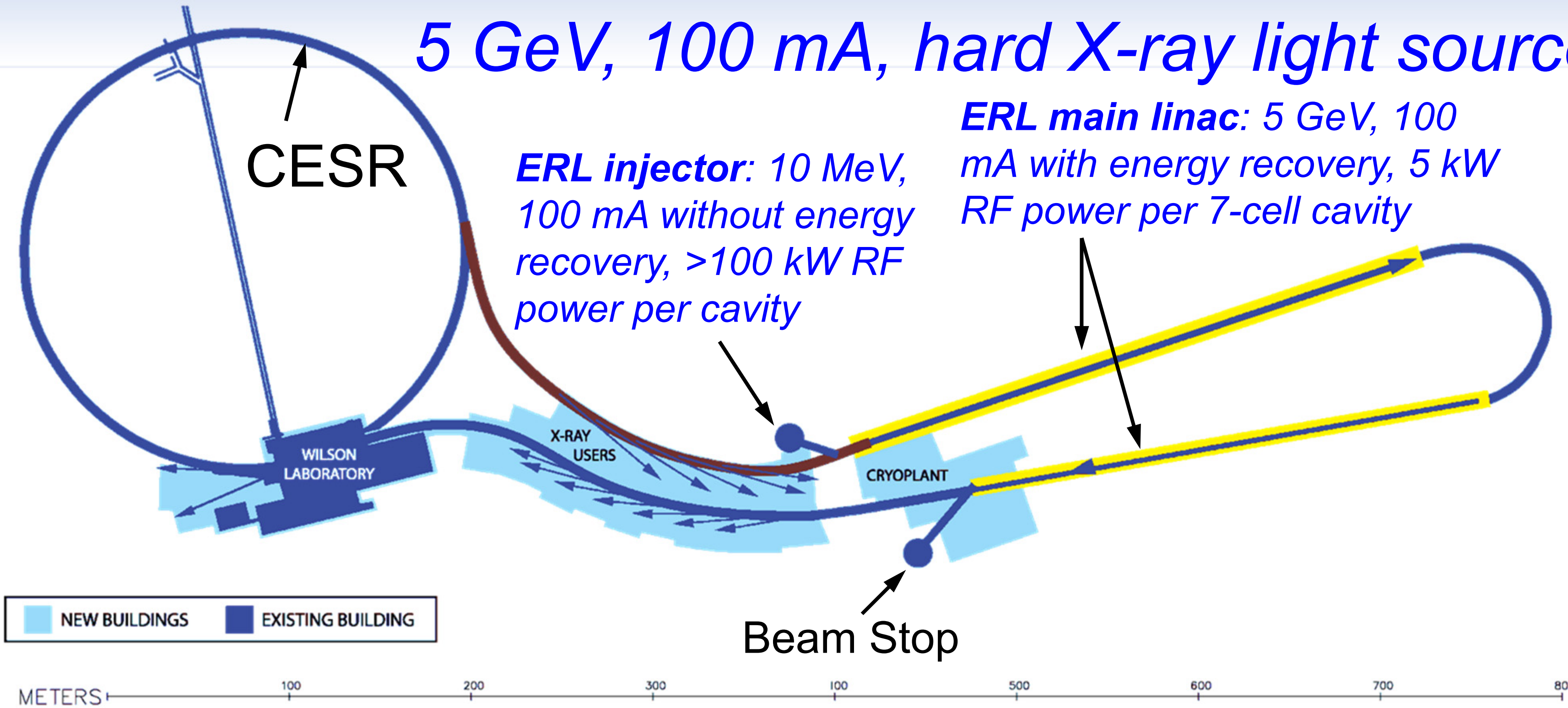
The Cornell Energy Recovery Linac

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



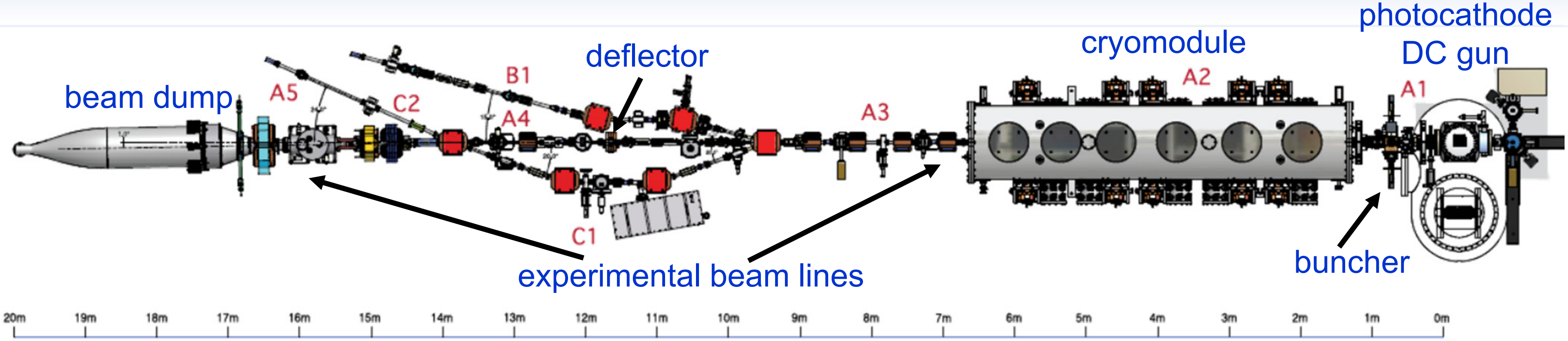
- Cornell is developing the technology for an Energy Recover Linac (ERL) based x-ray light source.
- An ERL injector prototype has been developed, fabricated, and is currently under commissioning.
- Design work on the main linac cryomodule has started.

Outline

- Superconducting RF for the ERL injector
  - Challenges and solutions
- Superconducting RF for the ERL main linac
  - Challenges and solutions
- Summary and outlook

Superconducting RF for the ERL Injector

The High Current Cornell ERL Injector

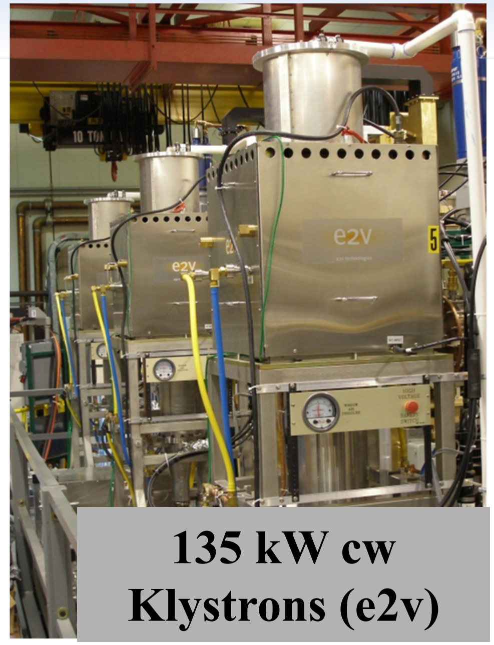


	design parameters	**Achieved so far**
Nominal bunch charge	77 pC	77 pC
Bunch repetition rate	1.3 GHz	50 MHz and 1.3 GHz
Beam power	up to 550 kW	125 kW
Nominal gun voltage	500 kV	350 kV
SC linac beam energy gain	5 to 15 MeV	5 to 15 MeV
Beam current	100 mA at 5 MeV 33 mA at 15 MeV	25 mA
Bunch length	0.6 mm (rms)	
Transverse emittance	< 1 mm-mrad	

World record for CW injector current!

ERL Injector: Technical Components

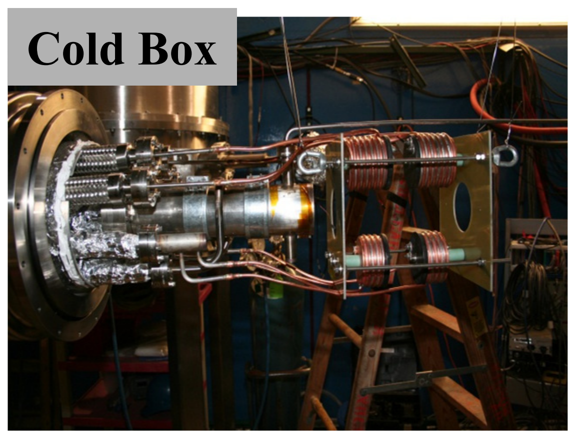

SRF Injector Cryomodule

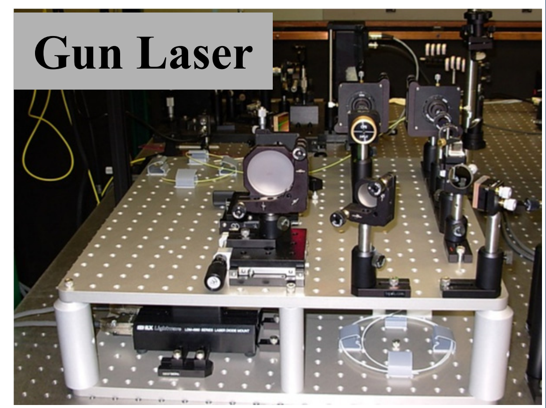


135 kW cw Klystrons (e2v)

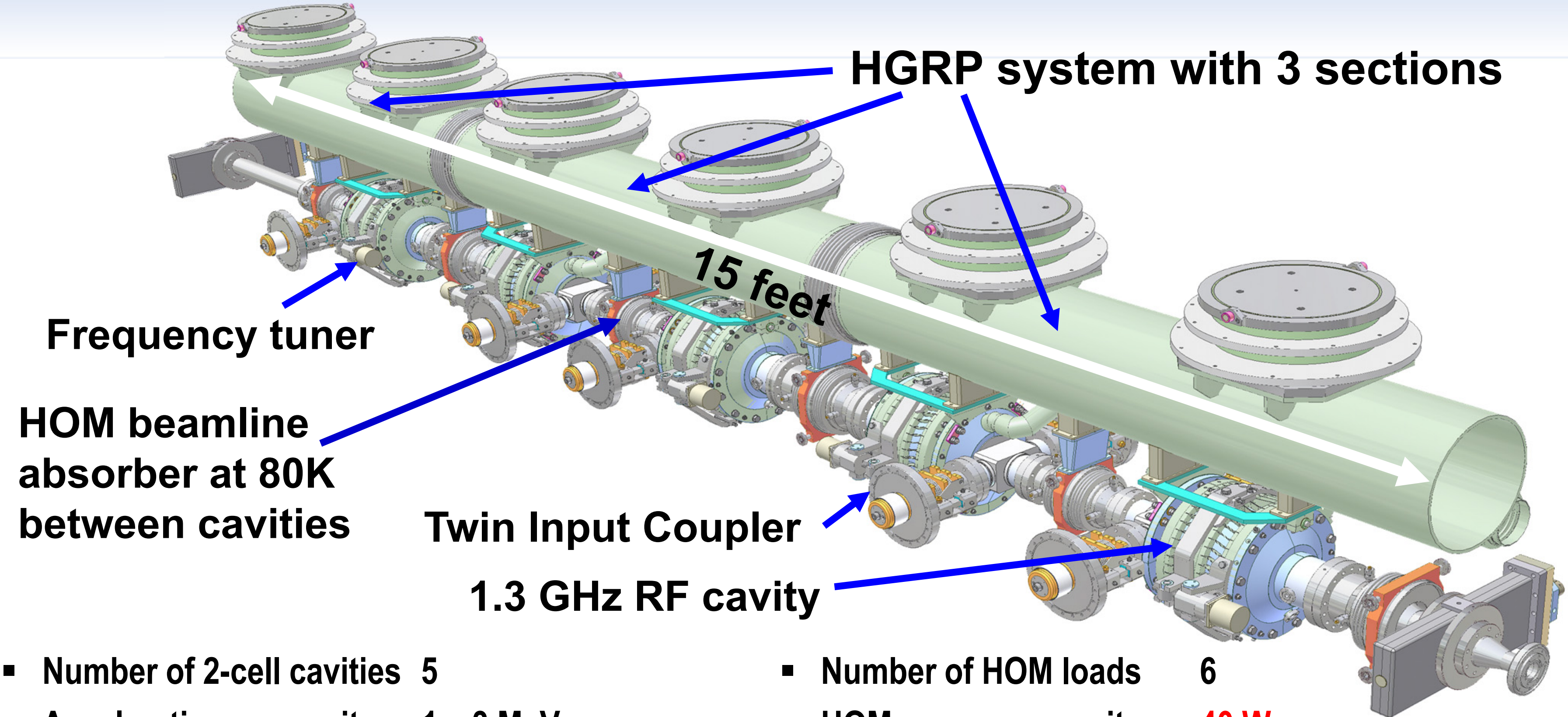

DC Gun


Beam Diagnostics


Cold Box


Gun Laser

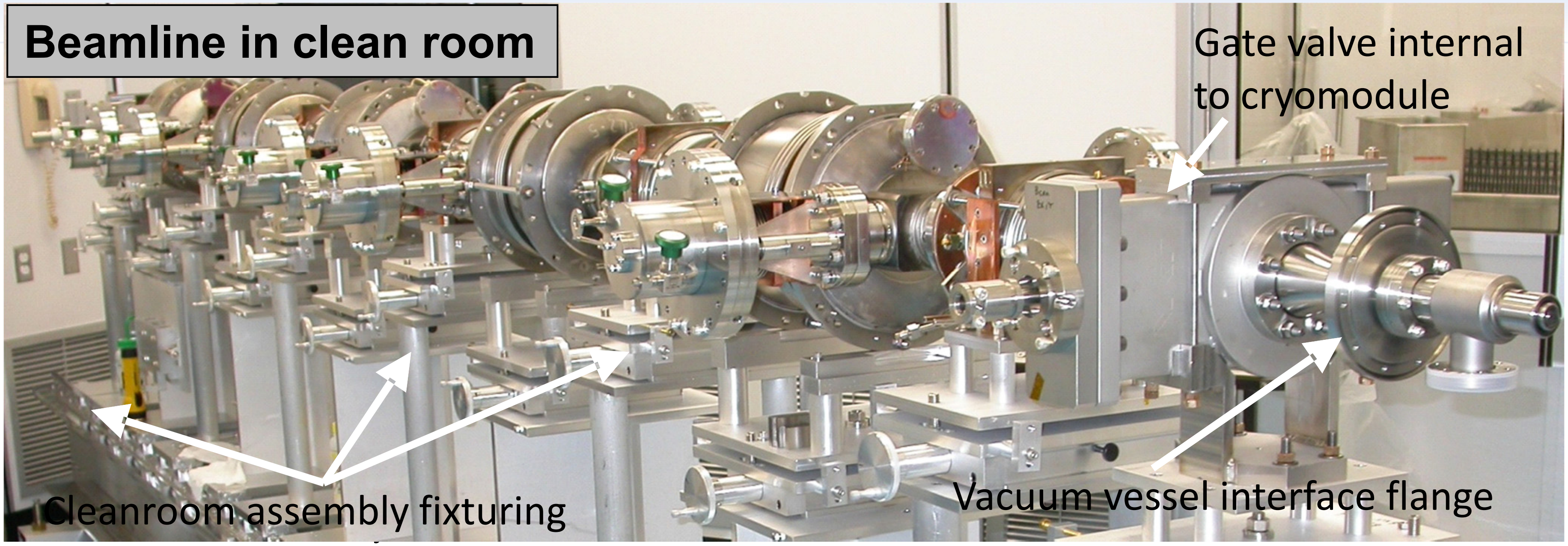
The Cornell ERL Cryomodule

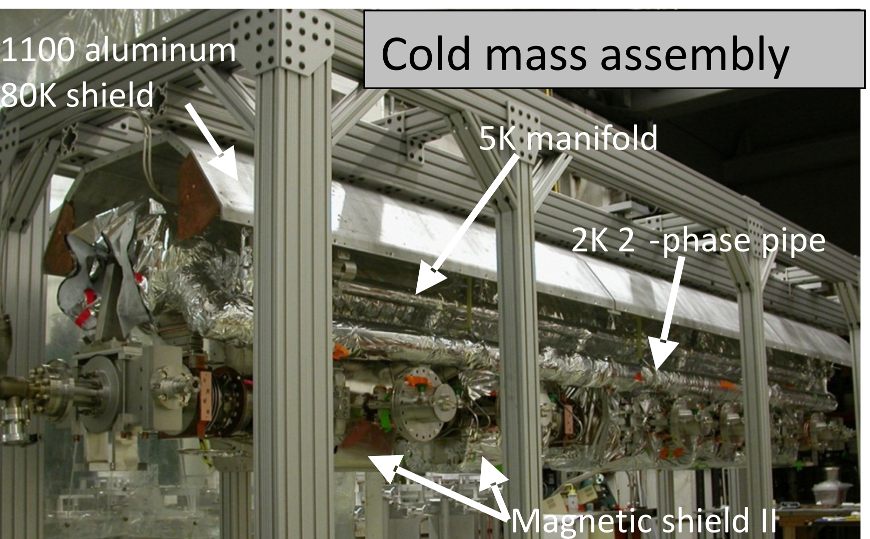


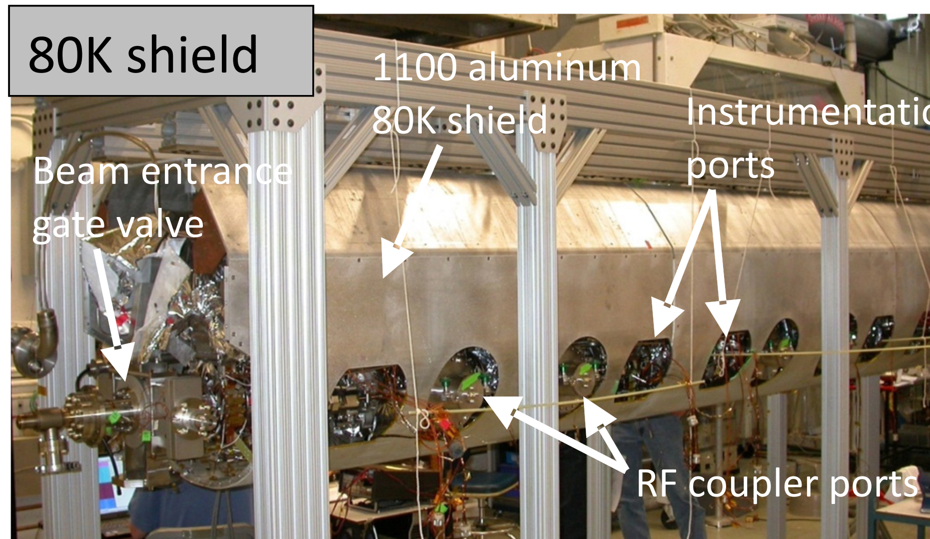
- Number of 2-cell cavities 5
- Acceleration per cavity 1 – 3 MeV
- Accelerating gradient 4.3 – 13.0 MV/m
- R/Q (linac definition) 222 Ohm
- Q_{ext} $4.6\times10^{4} – 4.1\times10^{5}$
- Total 2K / 5K / 80K loads: 30W / 60W / 700W

- 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 Module Assembly at Cornell





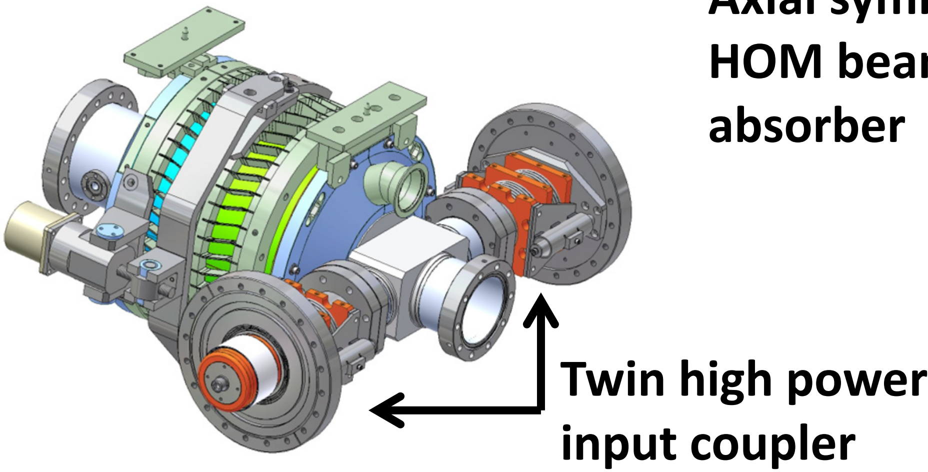


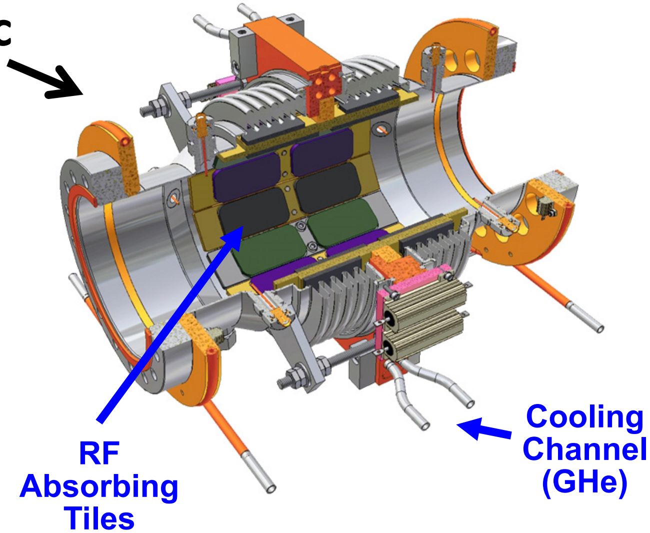
ERL Injector SRF: Key Challenges

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

Emittance Preservation and Cavity Alignment

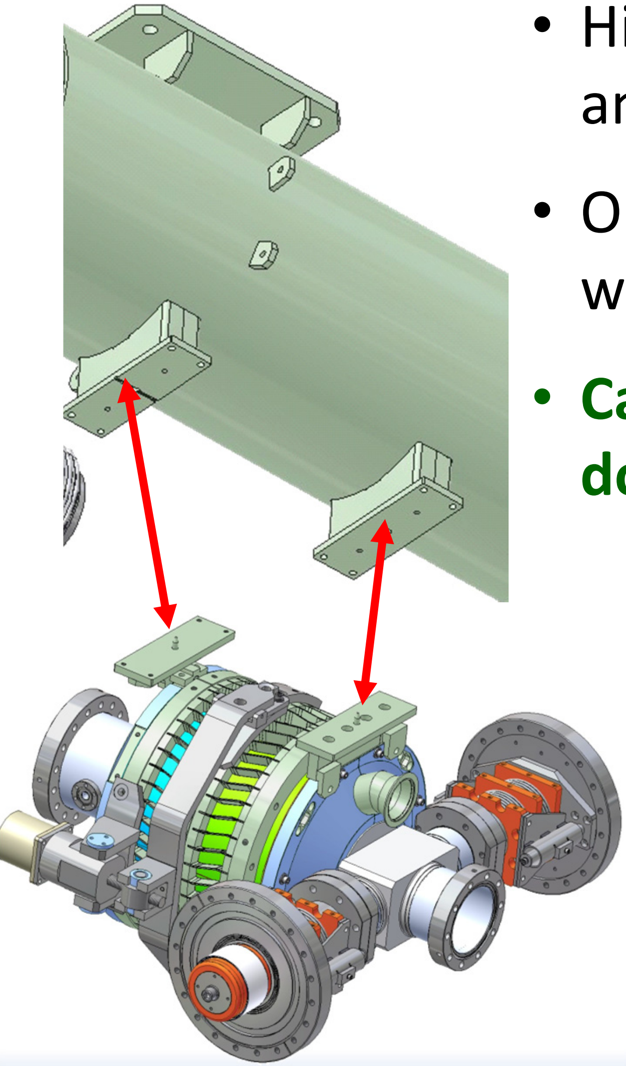
- Avoid transverse kick fields:
  - Symmetrized beam line in injector module



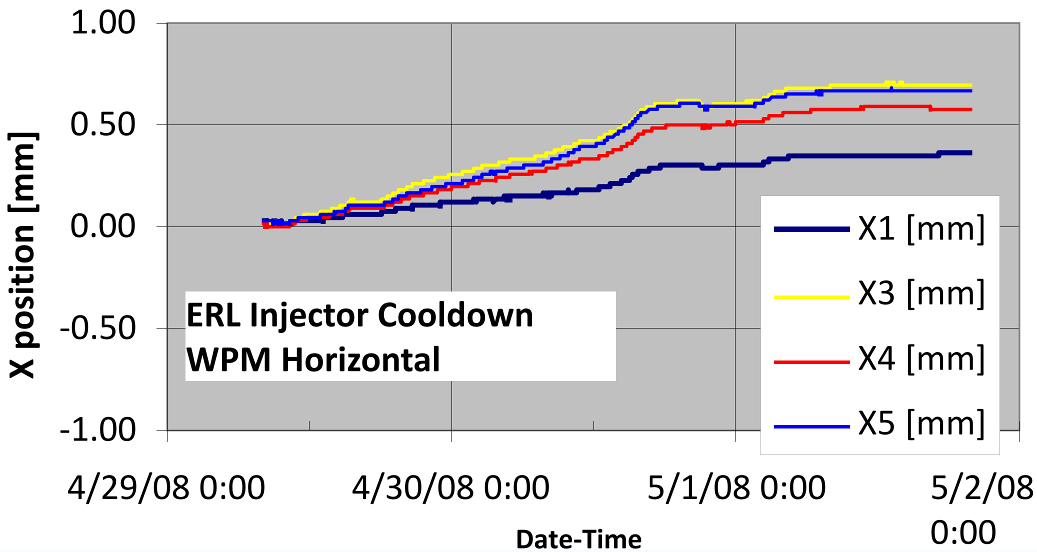


  - Excellent cavity alignment (±0.5mm required, **±0.2mm achieved**)

Fixed High Precision Cavity Support and Alignment

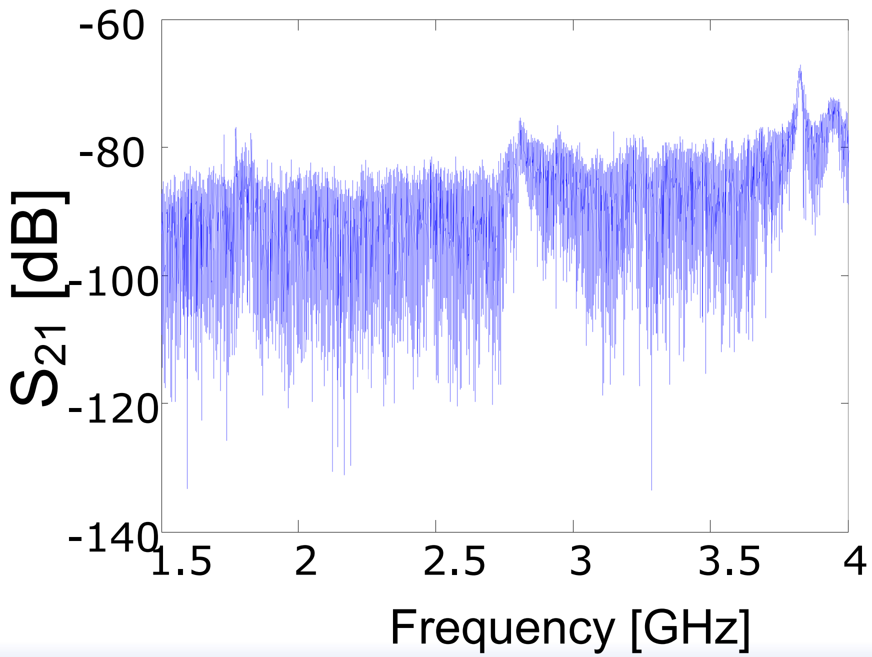


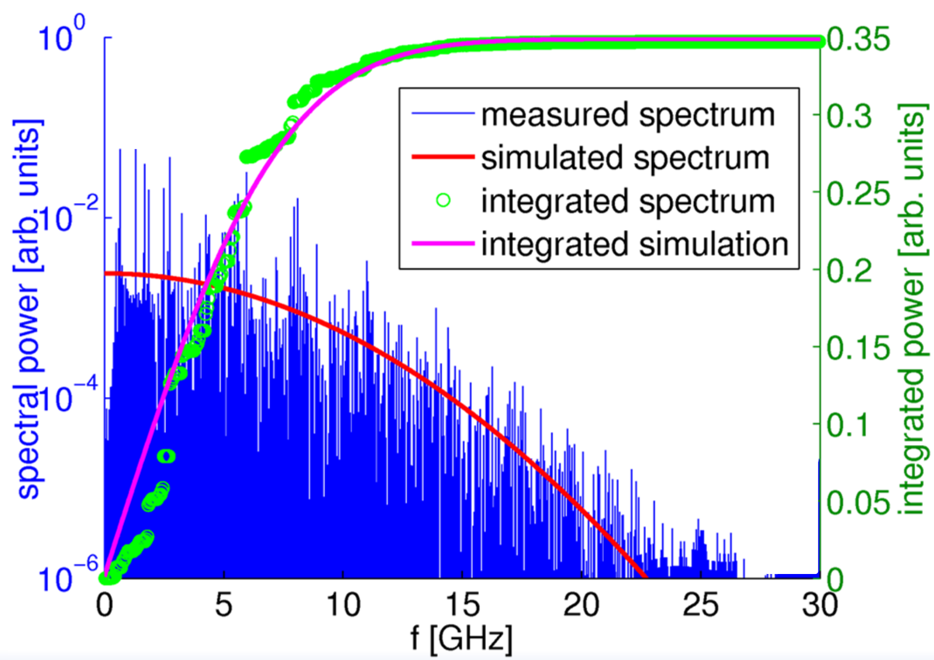
- High precision supports on cavities, HOM loads, and HGRP for “self” alignment of beam line
- Only very rough initial alignment is needed when beamline is assembled in clean room
- **Cavity string is aligned to ±0.2 mm after cool-down!**



High Current Operation and HOMs

- HOM damping and HOM spectra measurements confirm excellent damping with **typical Qs of a few 1000**
- Total HOM power measurement gives longitudinal loss factor in good agreement with ABCI simulations
- Successfully operated injector SRF module with **beam currents of 25 mA**
  - ΔT of HOM absorbers small (<0.5K). **Module should easily handle operation at >100 mA.**

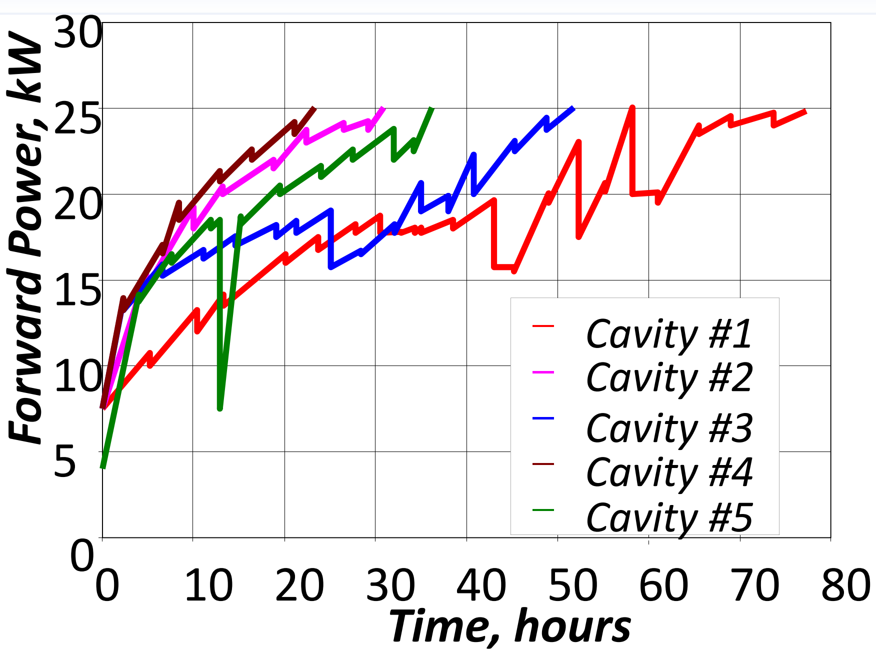


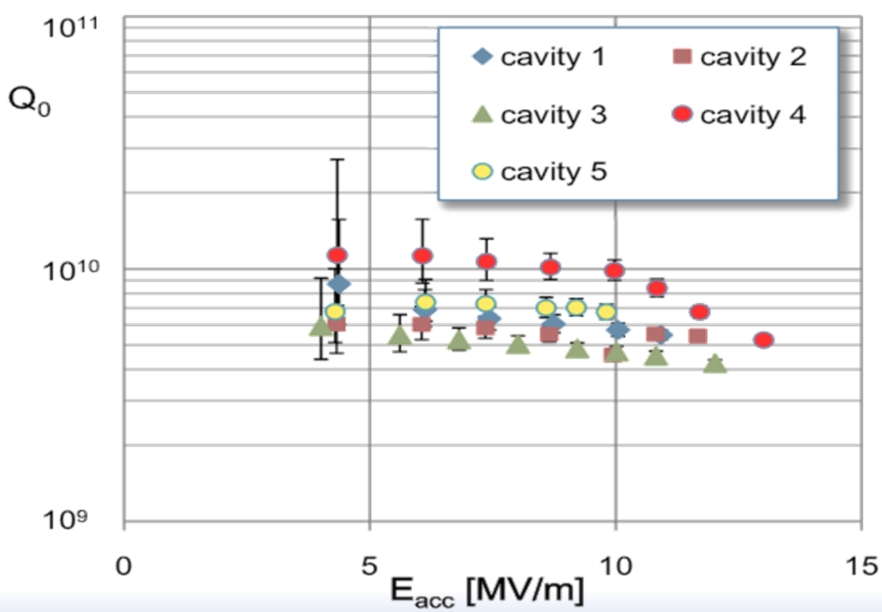


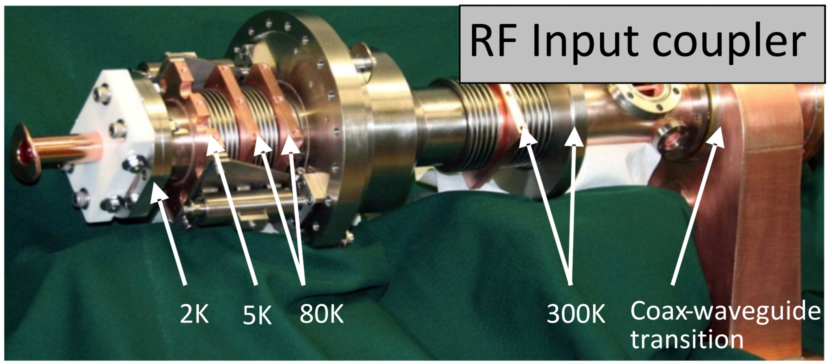
See paper TUP063

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

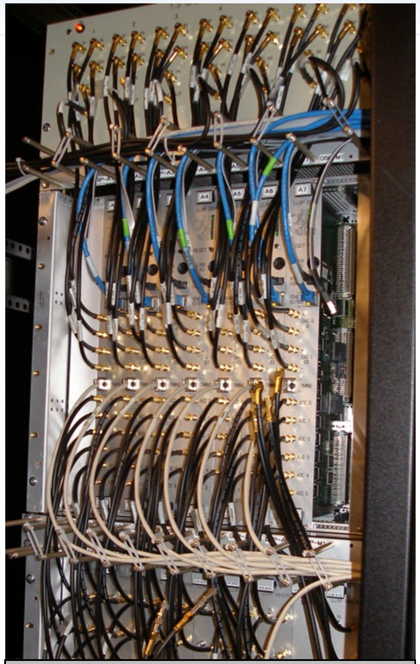




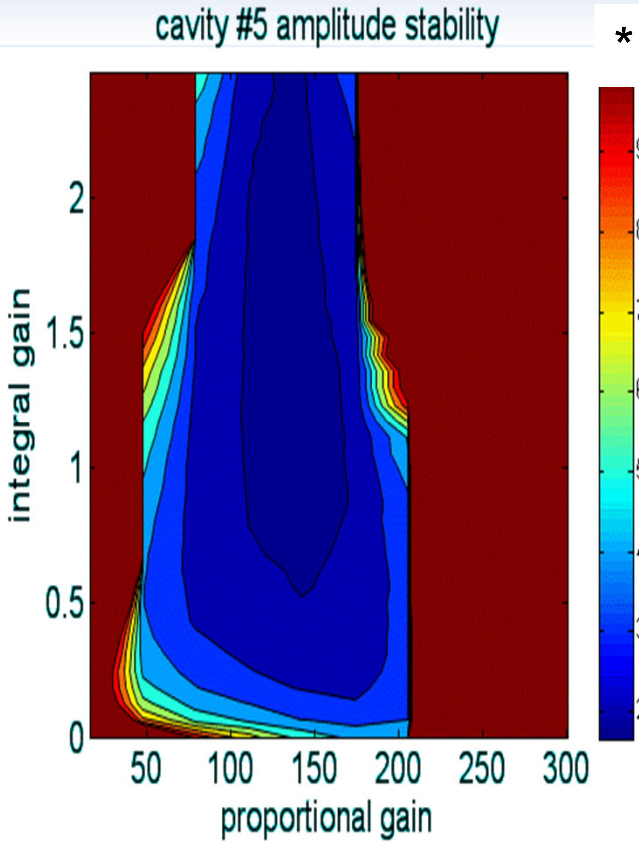


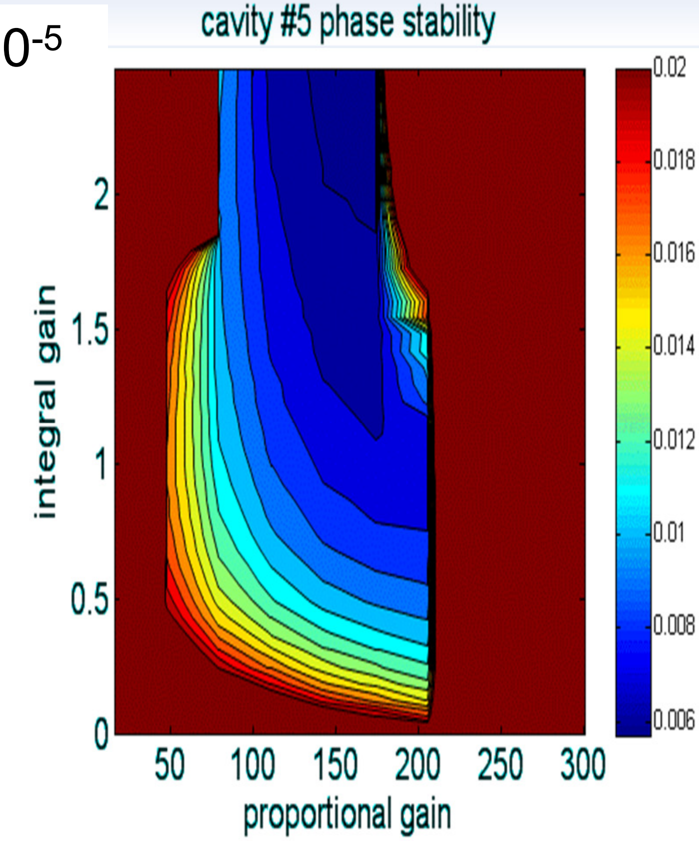
Superconducting RF for the ERL Injector

LLRF Field Control and Field Stability



Cornell digital LLRF control system





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

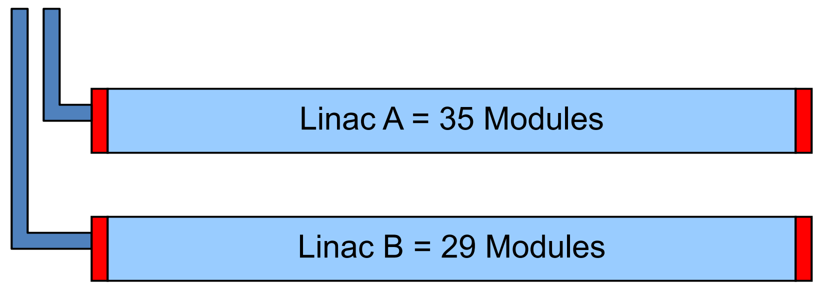
(in loop measurements) **phase: $\sigma_P < 0.01$ deg**

Superconducting RF for the ERL Main Linac

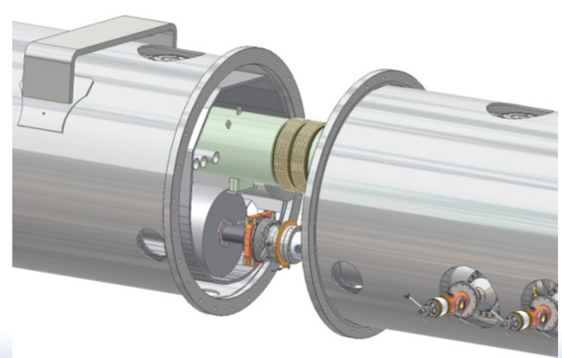
Cornell ERL Main Linac

Cavities per cryomodule	6
Cryomodules per linac	35 / 29
# linacs	2
# cavities	384
# cryomodules	64
Cryomodule length [m]	9.82
Linac length [m]	344 / 285
Total active length [m]	~310
Module Filling factor	0.49
Final energy [GeV]	5.0
Gradient [MV/m]	16

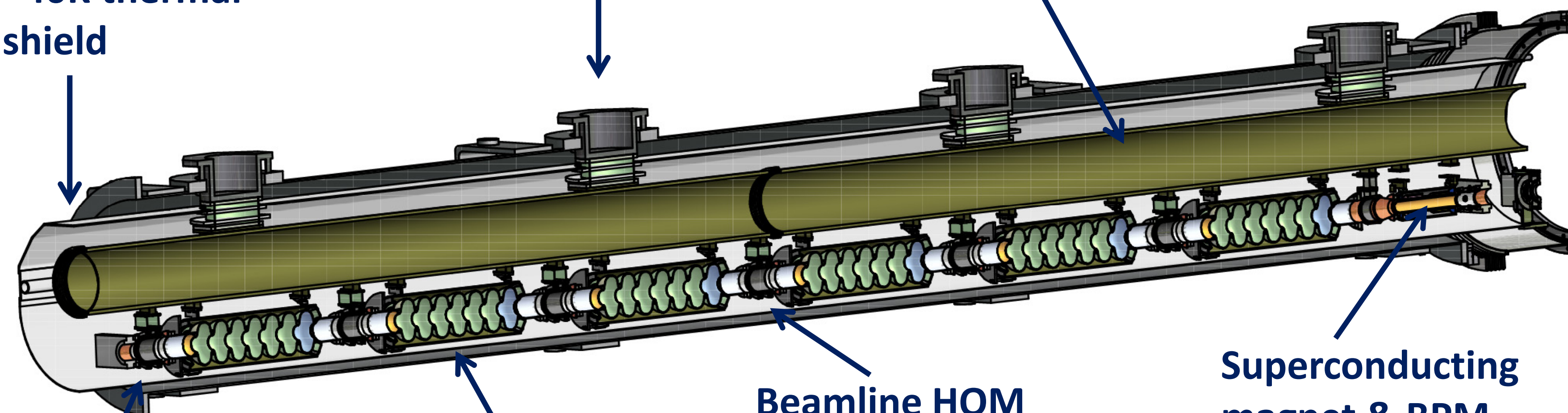
- 5 GeV total, 384 cavities
  - 13 MV per cavity (~16 MV/m)
  - 64 identical cryomodules, each with 6 cavities and a single quadrupole magnet
- Two continuous linac sections:



= 0.25m Cold-warm transition



Cornell ERL Main Linac Cryomodule



- Number of 7-cell cavities 6
- Acceleration gradient **16.2 MV/m**
- R/Q (linac definition) 774 Ohm
- Qext **6.5×10^{7}**
- Total 2K / 5K / 80K loads: **76W / 70W / 1500W**

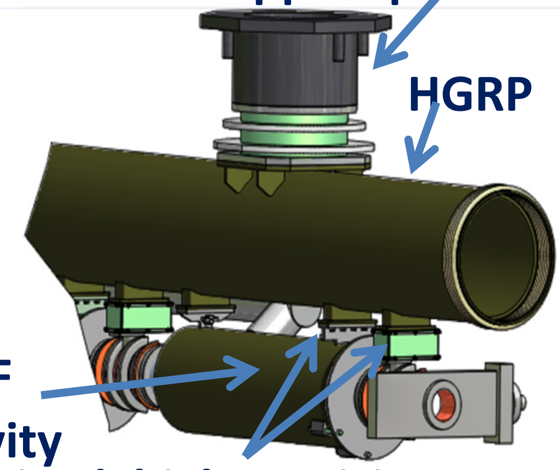
- Number of HOM loads 7
- HOM power per cavity 200 W
- Couplers per cavity 1
- RF power per cavity **5 kW**
- Amplitude/phase stability 10^{-4} / 0.05° (rms)
- Module length 9.8 m

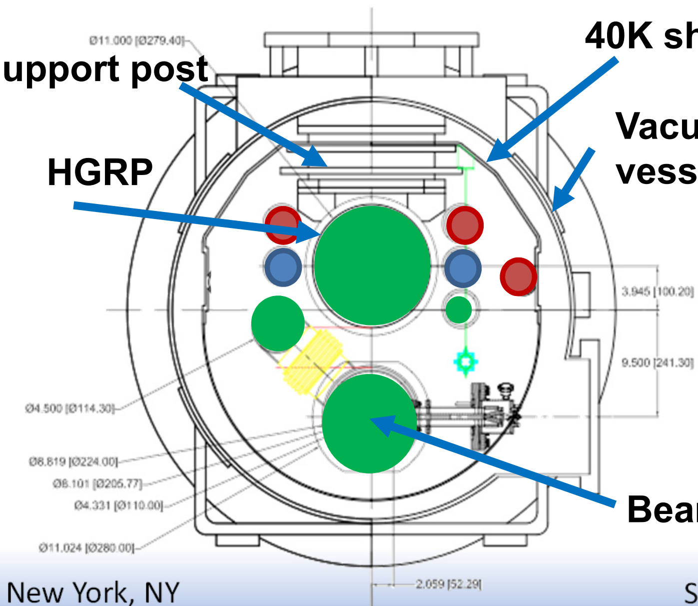
Main Linac SRF: Key Challenges

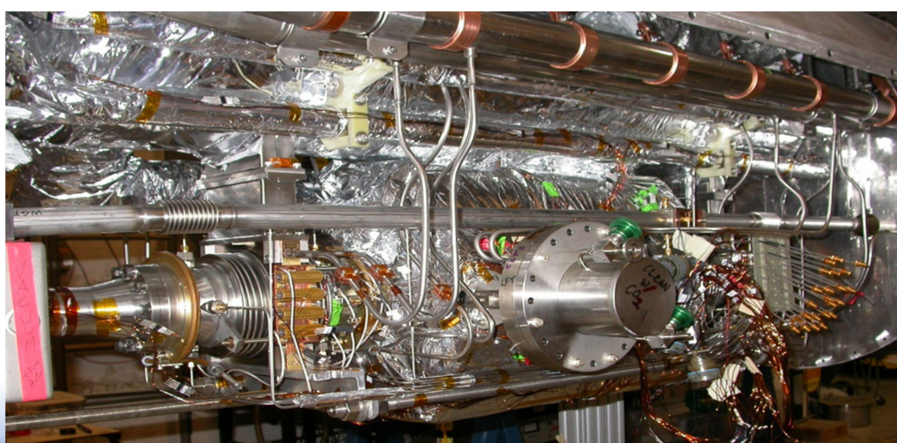
1. Support efficient CW cavity operation with high dynamic cryogenic loads
2. Support high beam current ERL operation up to 2x100 mA with short (2 ps) bunches
3. Efficiently operate the SRF cavities at a high loaded quality factor $Q_L \geq 6.5 \times 10^7$ while still achieving excellent RF field stability.

Main Linac Cryomodule Design

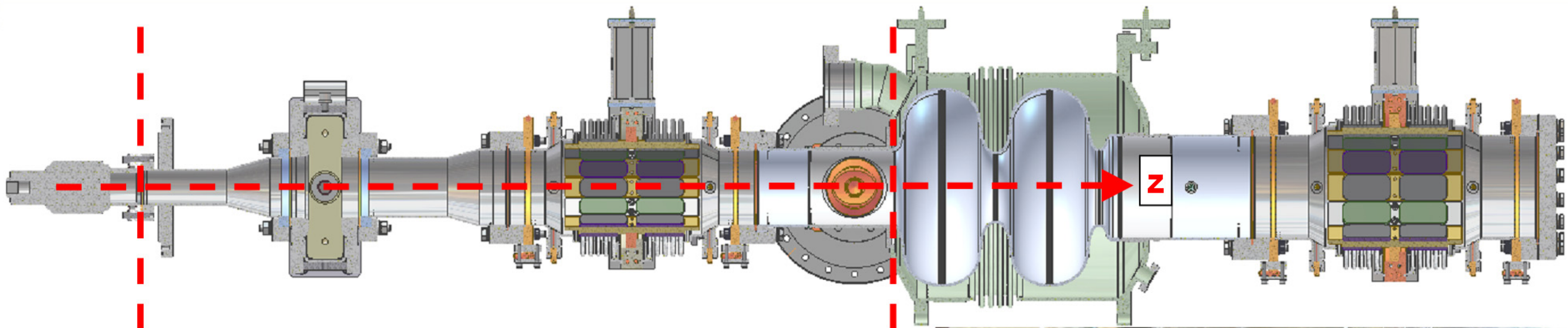
- **Fixed, high precision supports for the cavities and the HOM loads**
- **One thermal shield at ~40K**
- **Cryogenic manifolds sized for high dynamic heat loads**
- **Three layers of magnetic shielding**

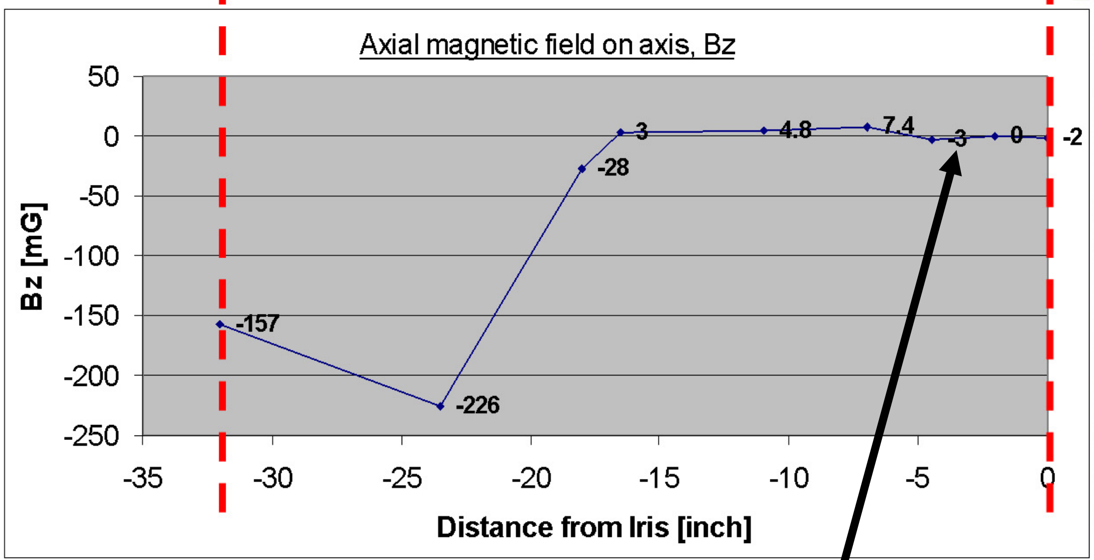


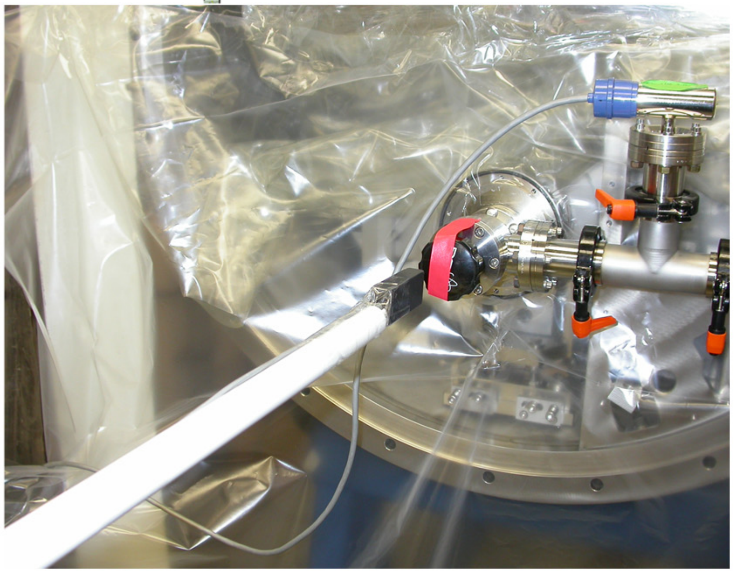




Magnetic Shielding at Residual Resistance

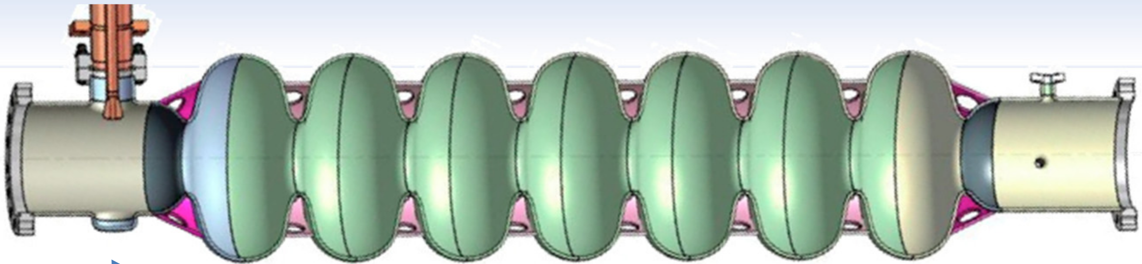






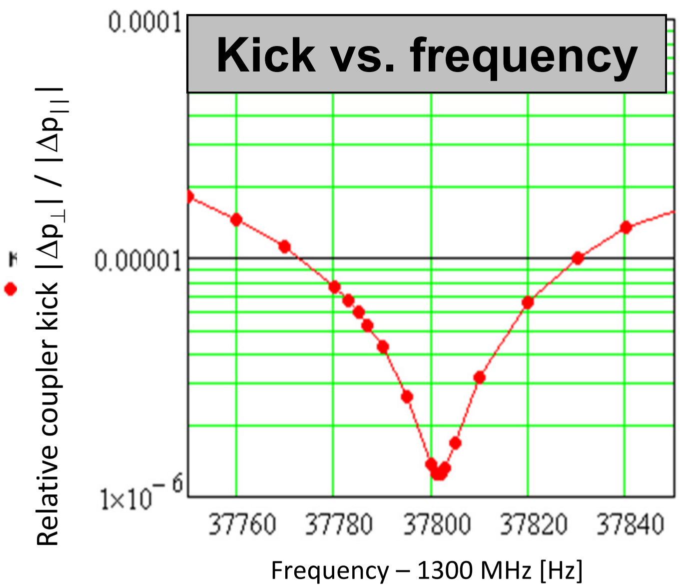
B < 3 mG -> contribution to R_{res} < 1 nΩ

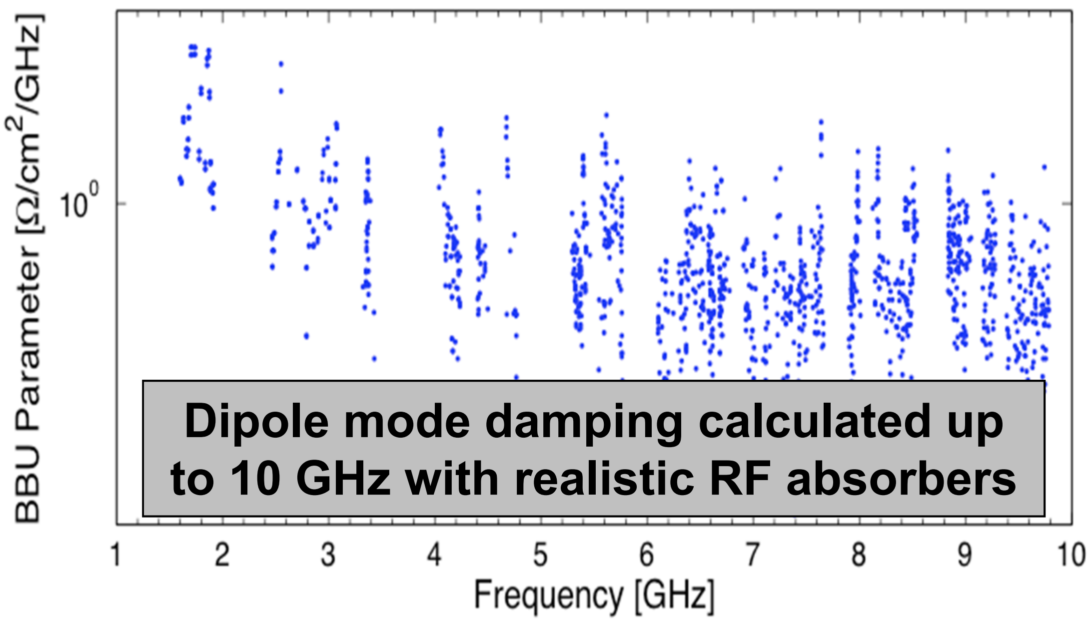
ERL Main Linac Cavity: RF Design (I)



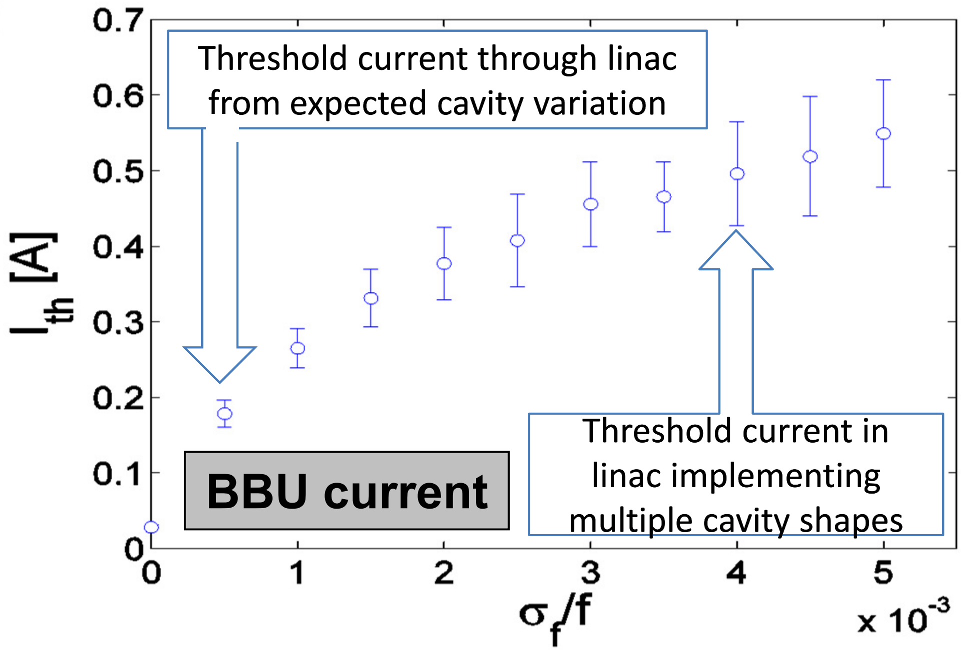
Coupler kick compensation

Cell shape optimization for high R/Q of fundamental mode and strong HOM damping

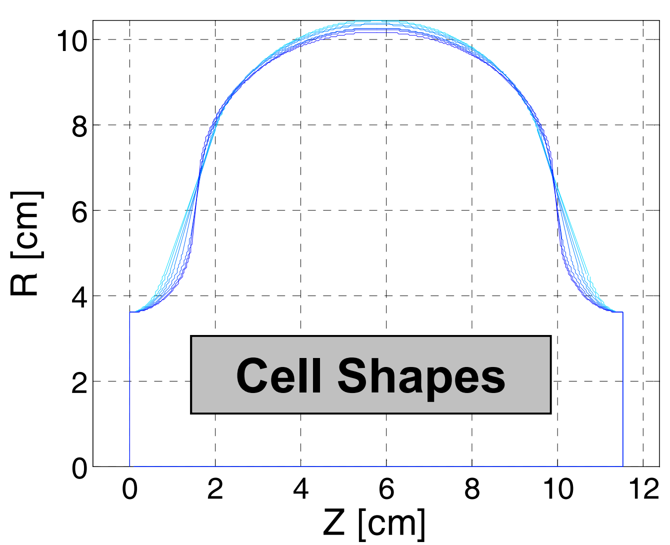


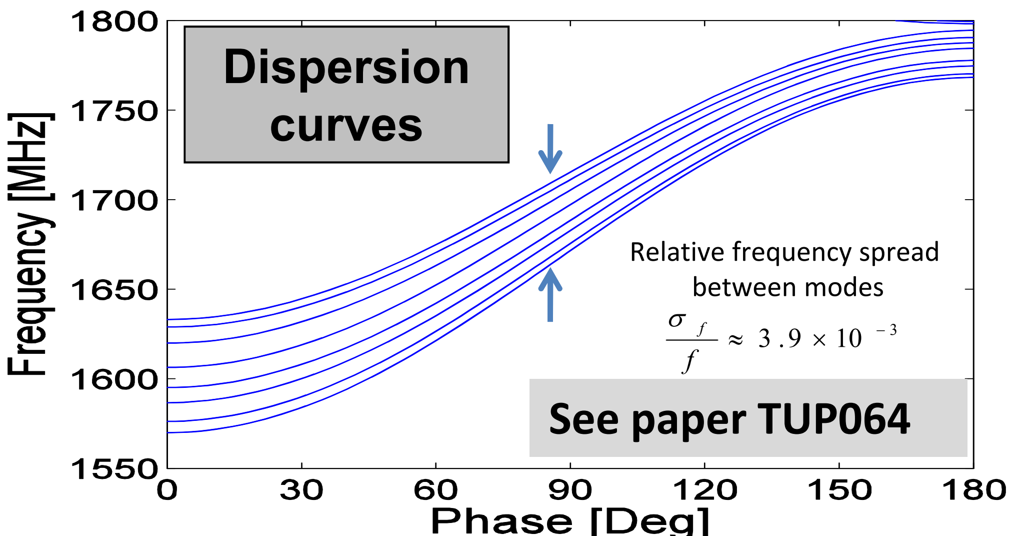


ERL Main Linac Cavity: RF Design (II)

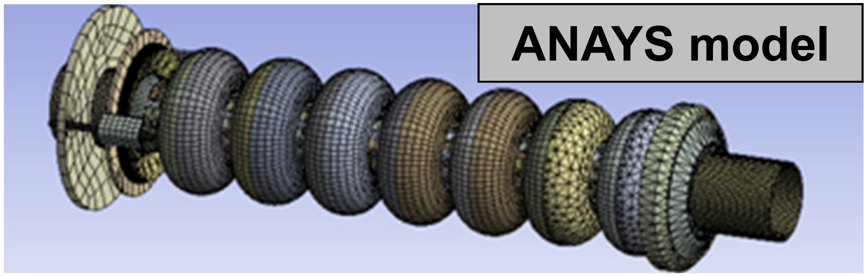


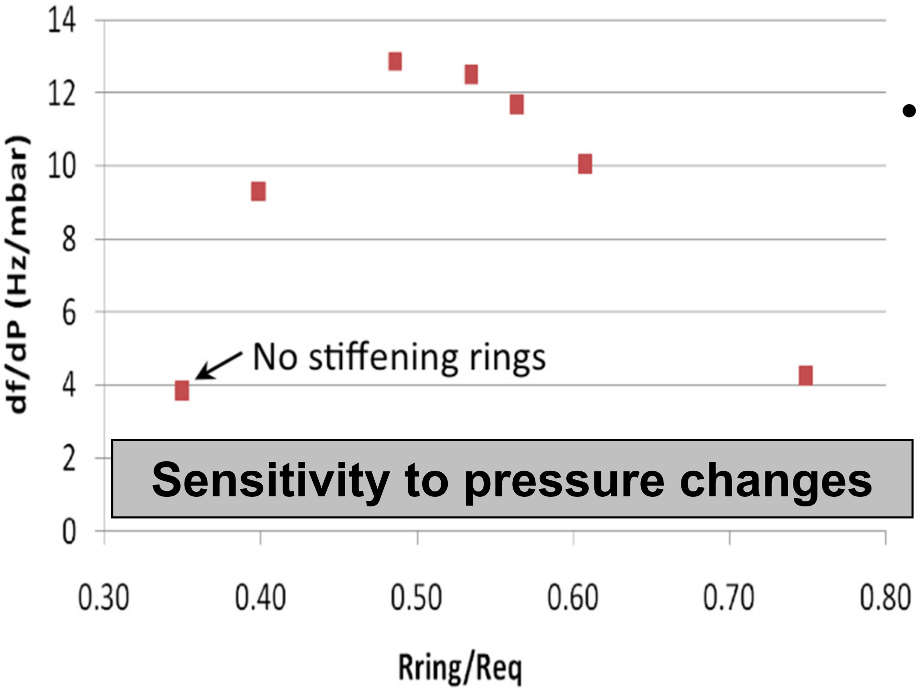
- **Relaxed cavity shape tolerances:**
  - **increase the HOM frequ. spread**
  - **increase the risk of trapped HOMs**
- **Solution:**
  - **use several classes of cavities, which are small, controlled variations of the baseline 7- cell cavity design**
  - **yields threshold current >4 times above design value**





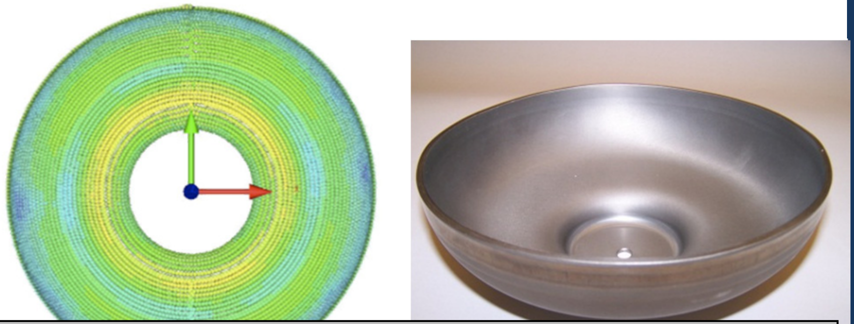
ERL Main Linac Cavity: Mechanical Design and Prototyping





Sensitivity to pressure changes

- **Cavity was optimized for low microphonics**
- **Stiffening rings between the cells**
  - **reduce sensitivity of the fundamental mode frequency to changes in the LHe bath pressure (main source of cavity microphonics)**
- **Prototype cavities under fabrication**
  - **will be tested without and with beam in test/prototype cryomodules.**



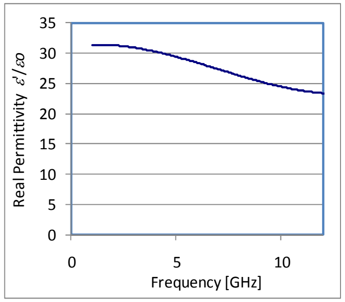
Precision of cell shape (±0.2 mm)

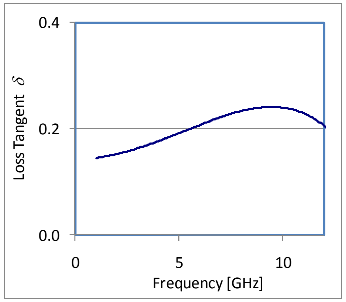
HOM Beamline Loads and RF Absorbing Materials

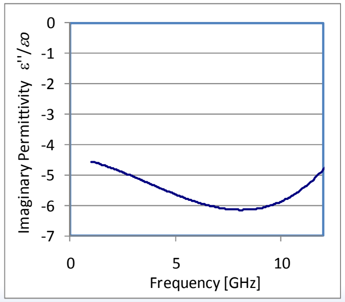
Two reliable RF absorbing materials meeting all specifications have been identified:

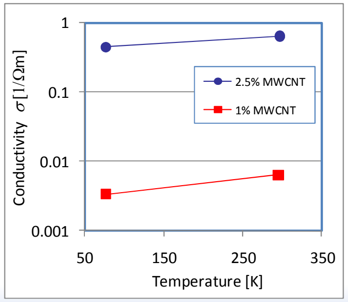
- graphite loaded SiC,
- carbon-nanotube loaded ceramics

Carbon-Nanotube Absorber

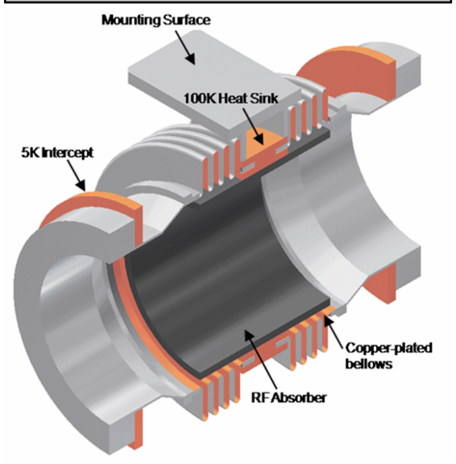




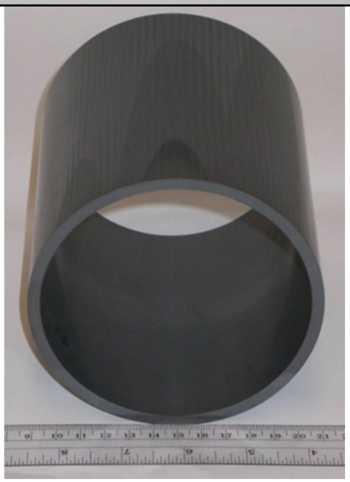




HOM Damper

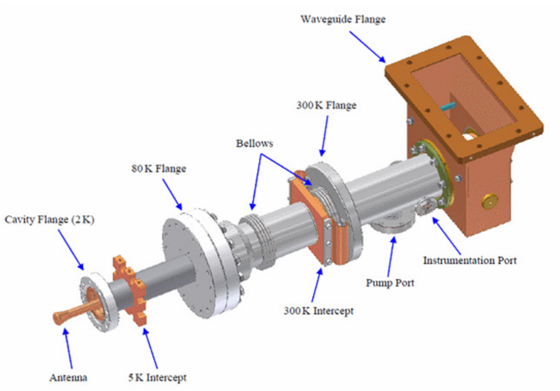


SiC Absorber Ring

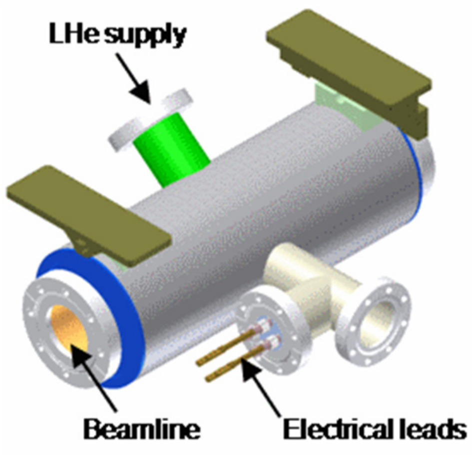


ERL Main Linac: Other Components

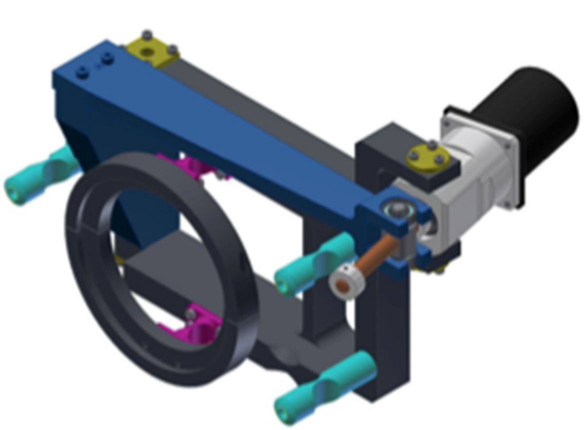
5 kW Input Coupler



Cold Magnet



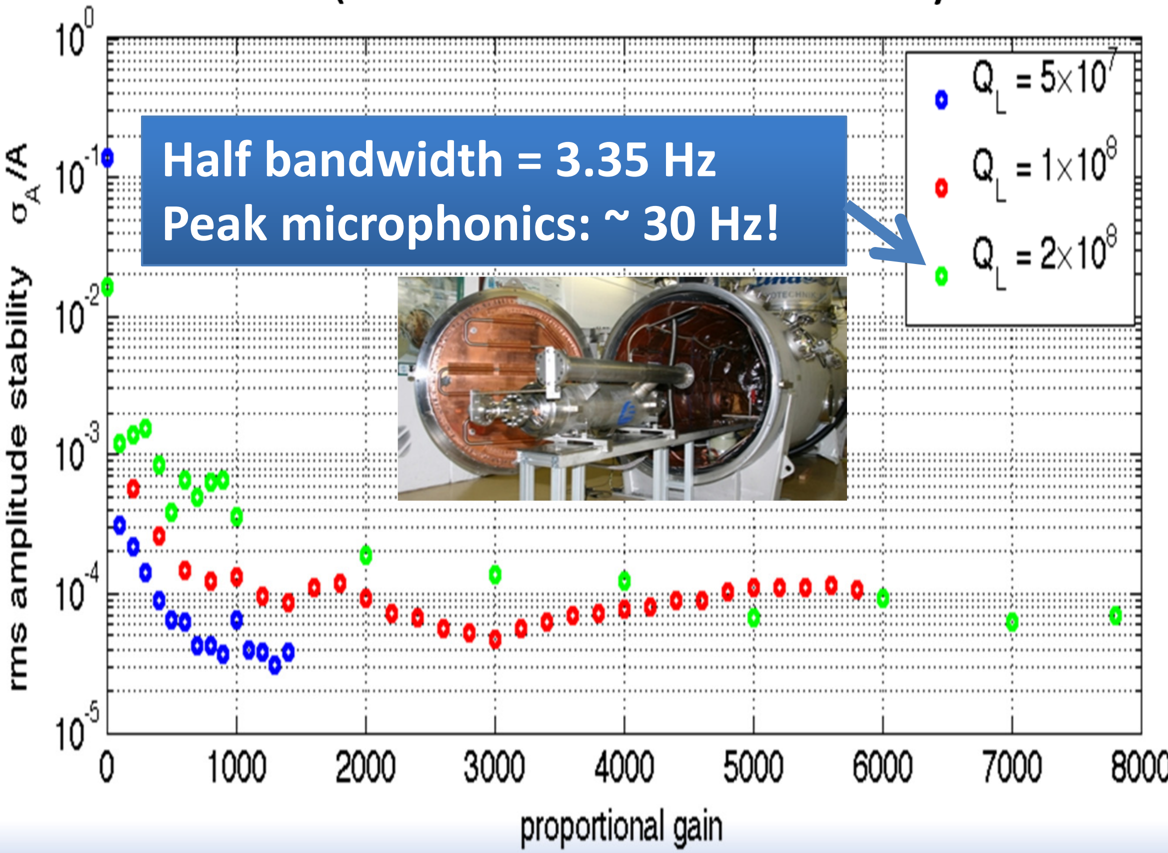
Frequency Tuner



- Simplified 5 kW CW input coupler
- Superconducting magnet package
- Cold tuner (slow and fast piezo driven)

LLRF Field Control and Operation at Very High Loaded Q

- **Demonstrated highly efficient operation of a full 9-cell cavity at very high loaded quality factors up to $2 \cdot 10^8$** (Test of Cornell's LLRF system at HoBiCaT at HZB)



– **Exceptional field stability: $\sigma_A/A < 1 \cdot 10^{-4}$, $\sigma_\varphi \sim 0.01°$**

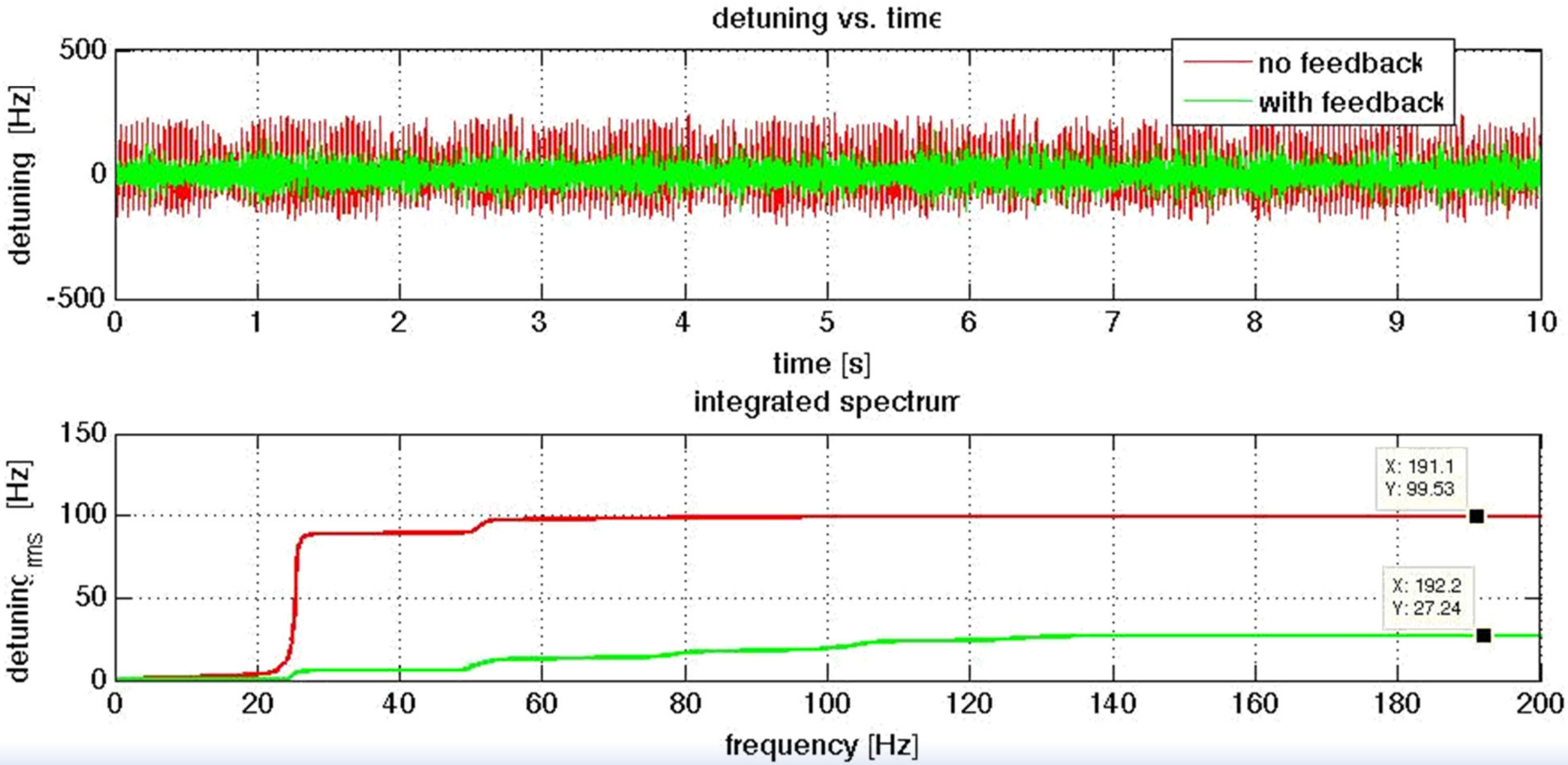
– **Fast RF field ramp up in 0.5 s to high fields with piezo tuner**

Active Microphonics Compensation

Piezo feedback on cavity frequency (ERL injector cavity):

⇒Reduced rms microphonics by up to 70%!

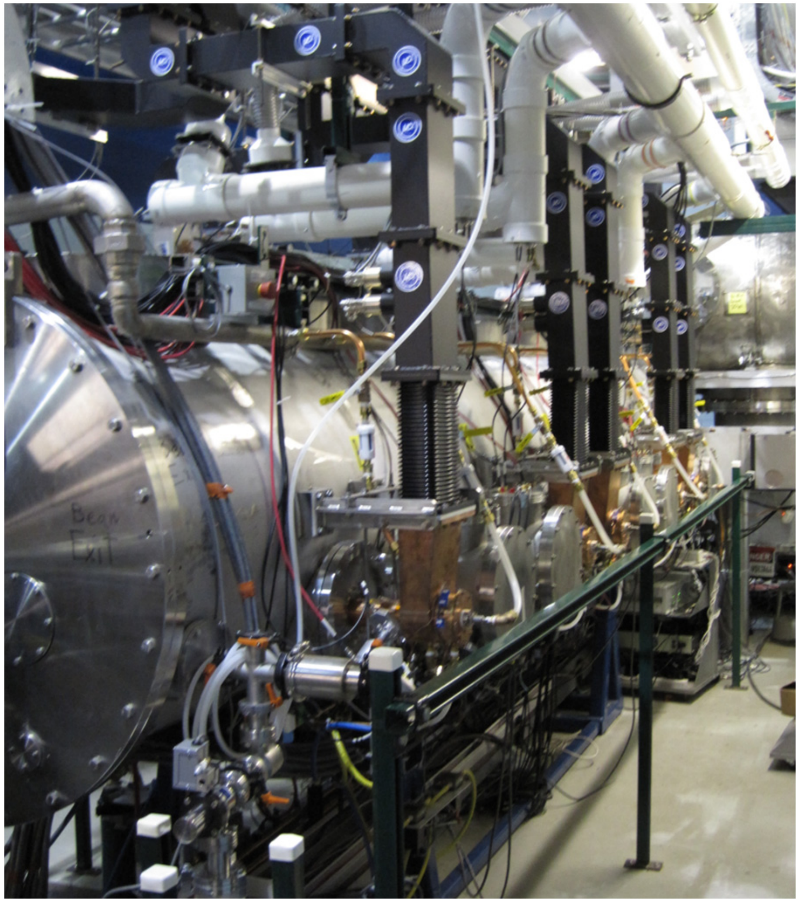
⇒Important for ERL main linac, where $Q_L > 5 \cdot 10^7$ and $P_{RF} \propto \Delta f$!



Summary and outlook

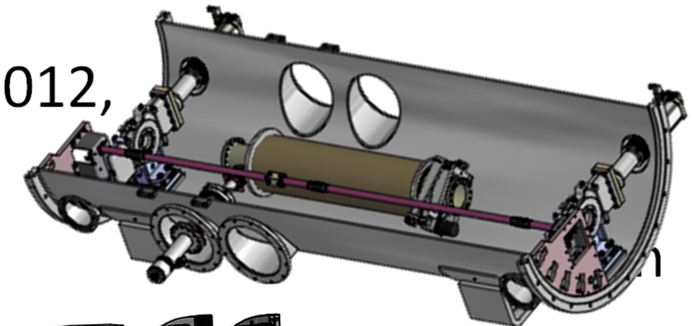
Summary and Outlook

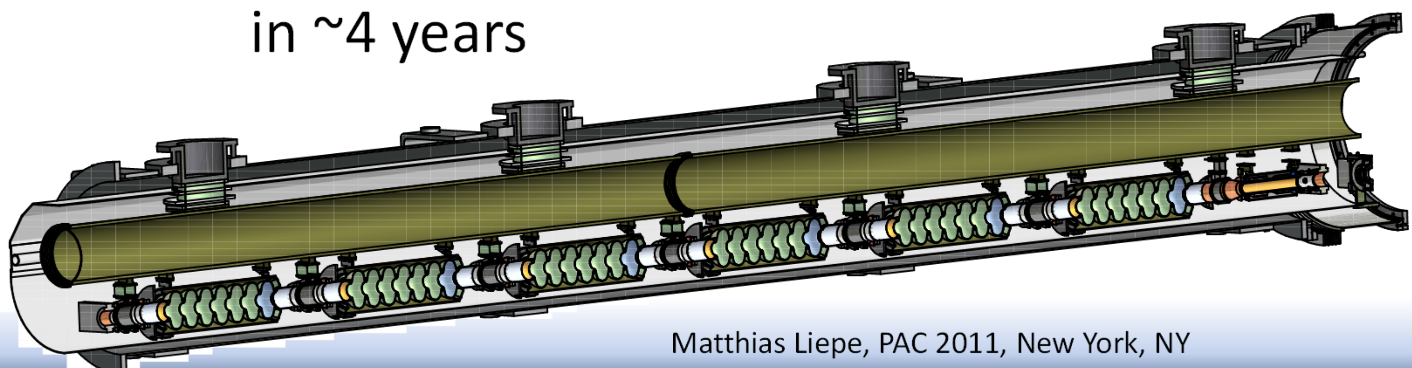
- ERL injector cryomodule:
  - Designed, constructed, and successfully tested
  - **Cryogenics, cavity alignment, cavity voltage, input couplers, LLRF field control, and HOM damping all meet or exceed specs**
  - 25 mA cw beam accelerated to 5 MeV; should easily support 100 mA operation



Summary and Outlook

- ERL main linac cryomodule:
  - Module design well underway
  - Cavity design optimized for high currents and efficient cavity operation; cavity fabrication has started
  - Plan:
    - One cavity test module: starting 2012, including beam test
    - Full prototype main linac module in ~4 years





End

Thanks for you attention!