HOM considerations for Energy Recovery Linacs and other high-current, CW SRF accelerators

Georg Hoffstaetter (Cornell) for the SRF and CBETA team

(1) Cavity design and construction for high BBU current
(2) Beam-pipe HOM absorber design and construction
(3) HOM testing with and without beam
(4) Beam limits from HOM heating
(5) BBU limits for multi-turn ERLs with realistic HOM

High Order Modes in Superconducting Cavities
HOMSC16, 22 – 23 August, 2016

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

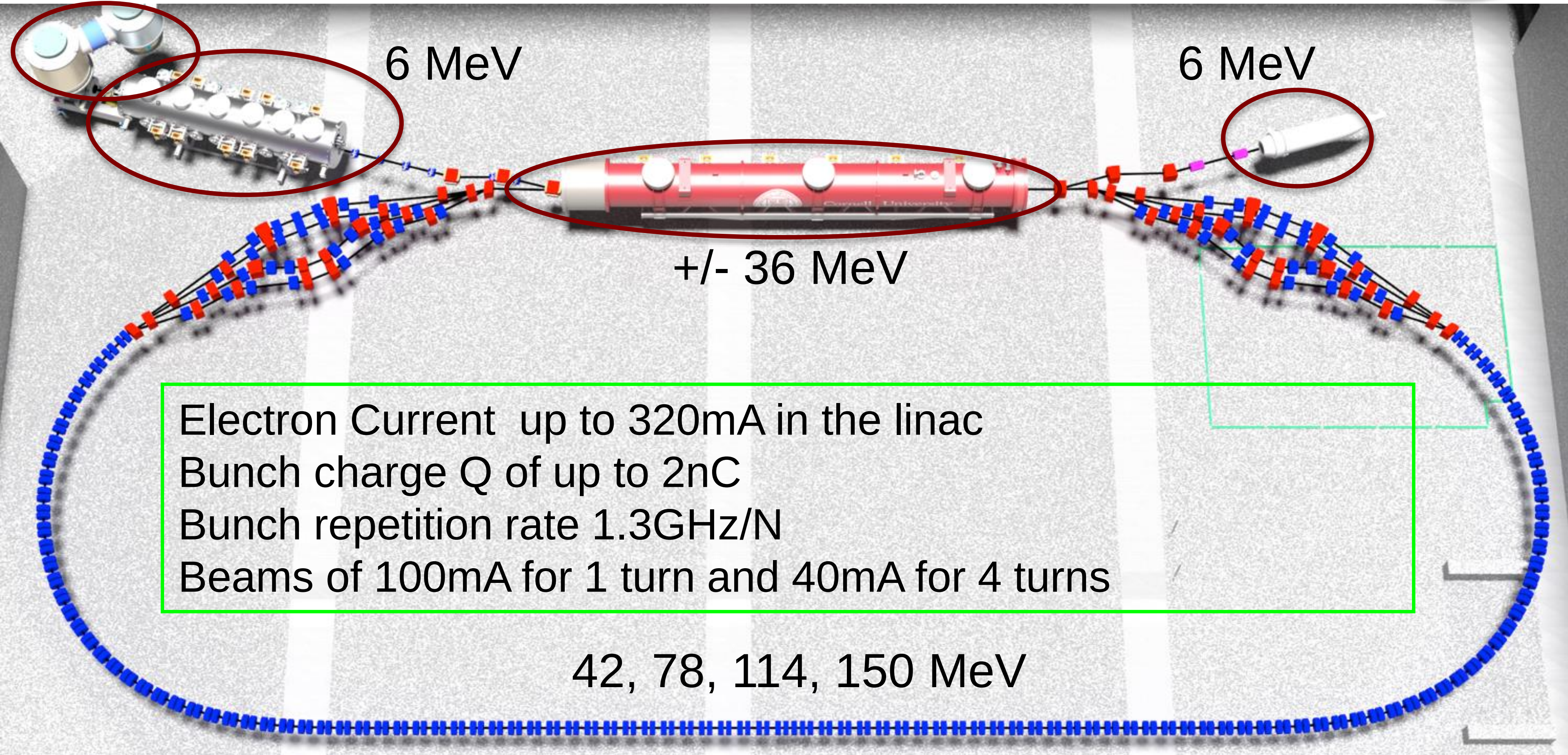
CBETA

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

Cornell's ERL for eRHIC prototyping and beam experiments

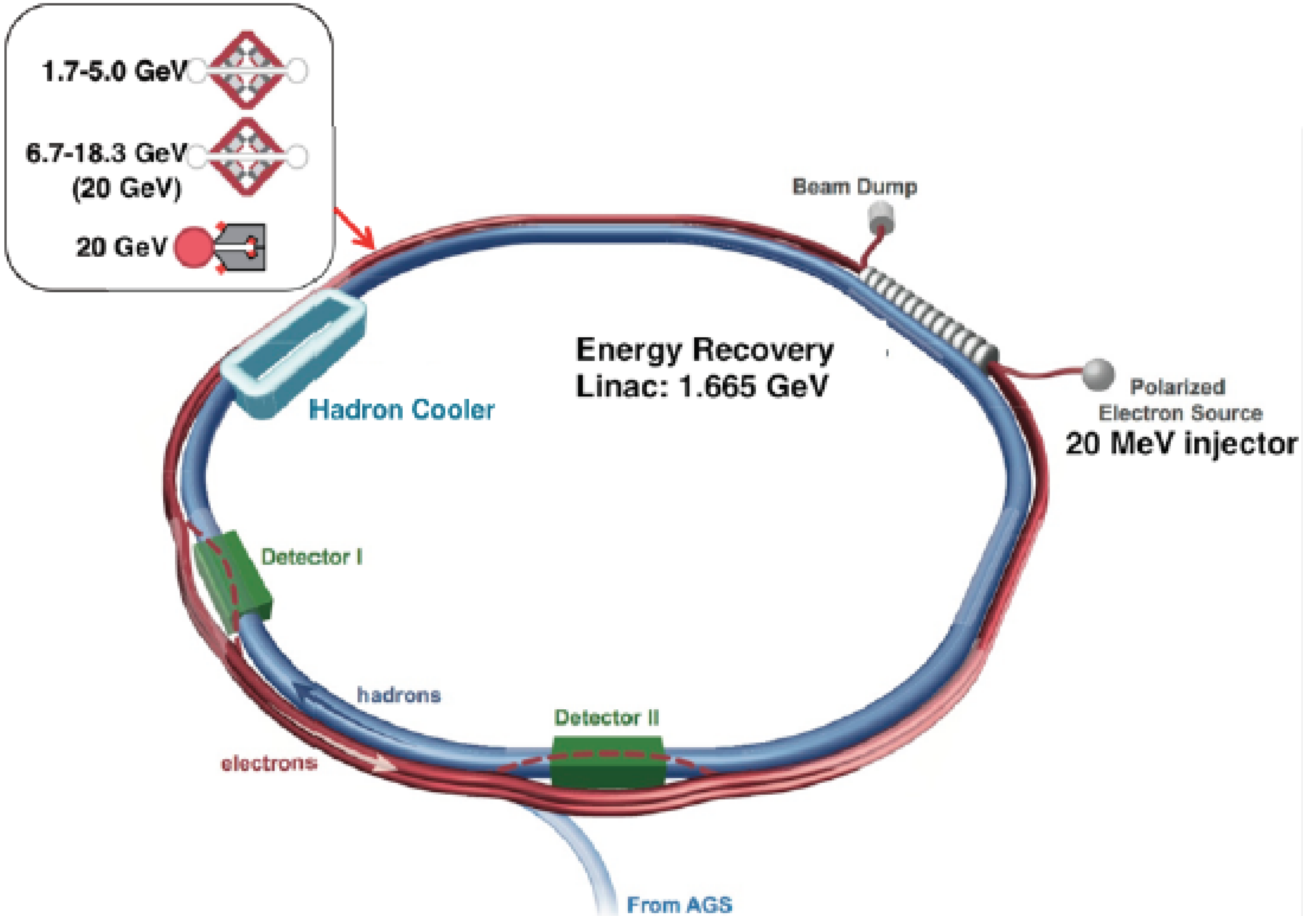
- Cornell DC gun
- 100mA, 6MeV SRF injector (ICM)
- 600kW beam dump
- 100mA, 6-cavity SRF CW Linac (MLC)

Existing components at Cornell

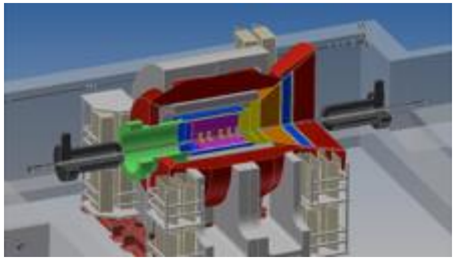


Electron Current up to 320mA in the linac
Bunch charge Q of up to 2nC
Bunch repetition rate 1.3GHz/N
Beams of 100mA for 1 turn and 40mA for 4 turns

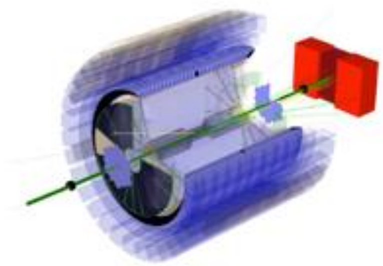
eRHIC Design – need for an ERL



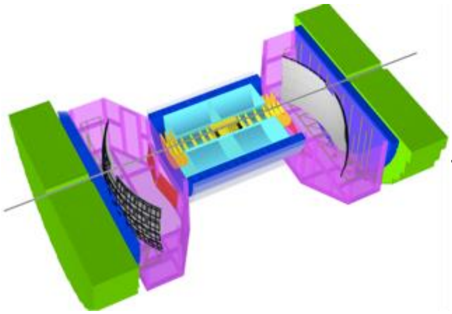
ePHENIX



eSTAR



BeAST

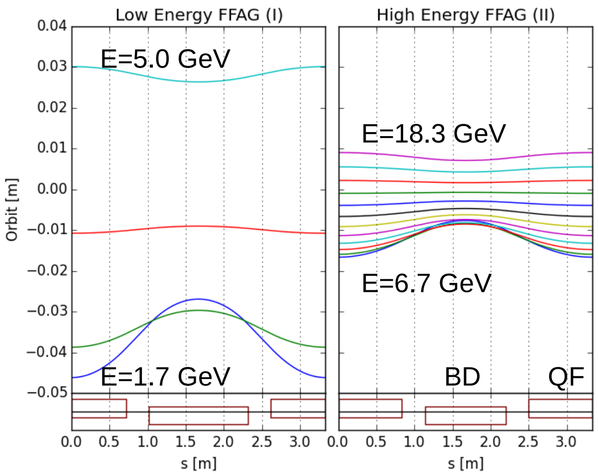


courtesy Thomas Roser

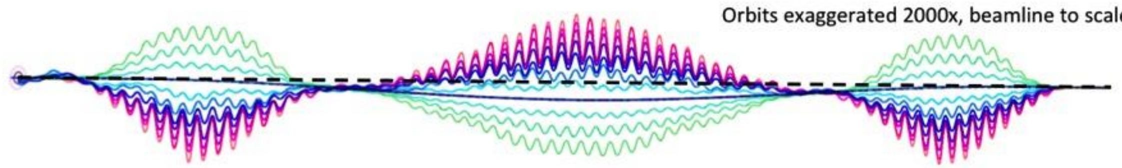
- 1.7 × 10^{33} cm^{-2} s^{-1} for $\sqrt{s}$ = 127 GeV (15.9 GeV e↑on 255 GeV p↑)
- × 10 luminosity with modest improvements (coating of RHIC vacuum chamber)
- × 100 luminosity with shorter bunch spacing (ultimate capability)

eRHIC ERL – 12 turns in only 2 NS-FFAG arcs

- eRHIC uses two FFAG beamlines to do multiple recirculations. (FFAG-I: 1.7-5.0 GeV, FFAG-II: 6.7-18.3 GeV, 20 GeV)
- All sections of a FFAG beamline is formed using a same FODO cell. Required bending in different sections is arranged by proper selection of the offsets between cell magnets (or, alternatively, with dipole field correctors).
- Permanent magnets can be used for the FFAG beamline magnets (no need for power supplies/cables and cooling).



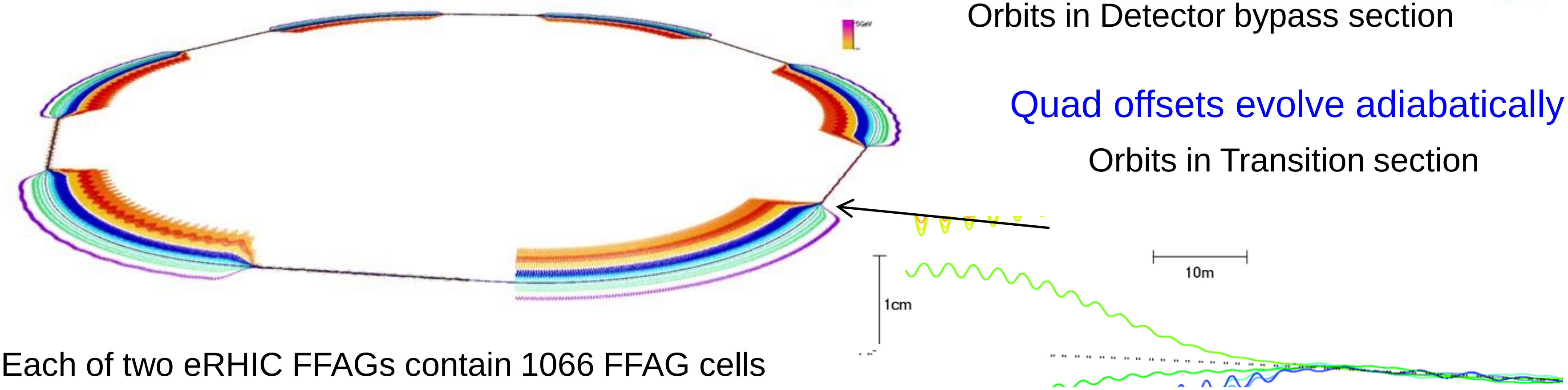
@S.Brooks, D.Trbojevic



Orbits in Detector bypass section

Quad offsets evolve adiabatically

Orbits in Transition section



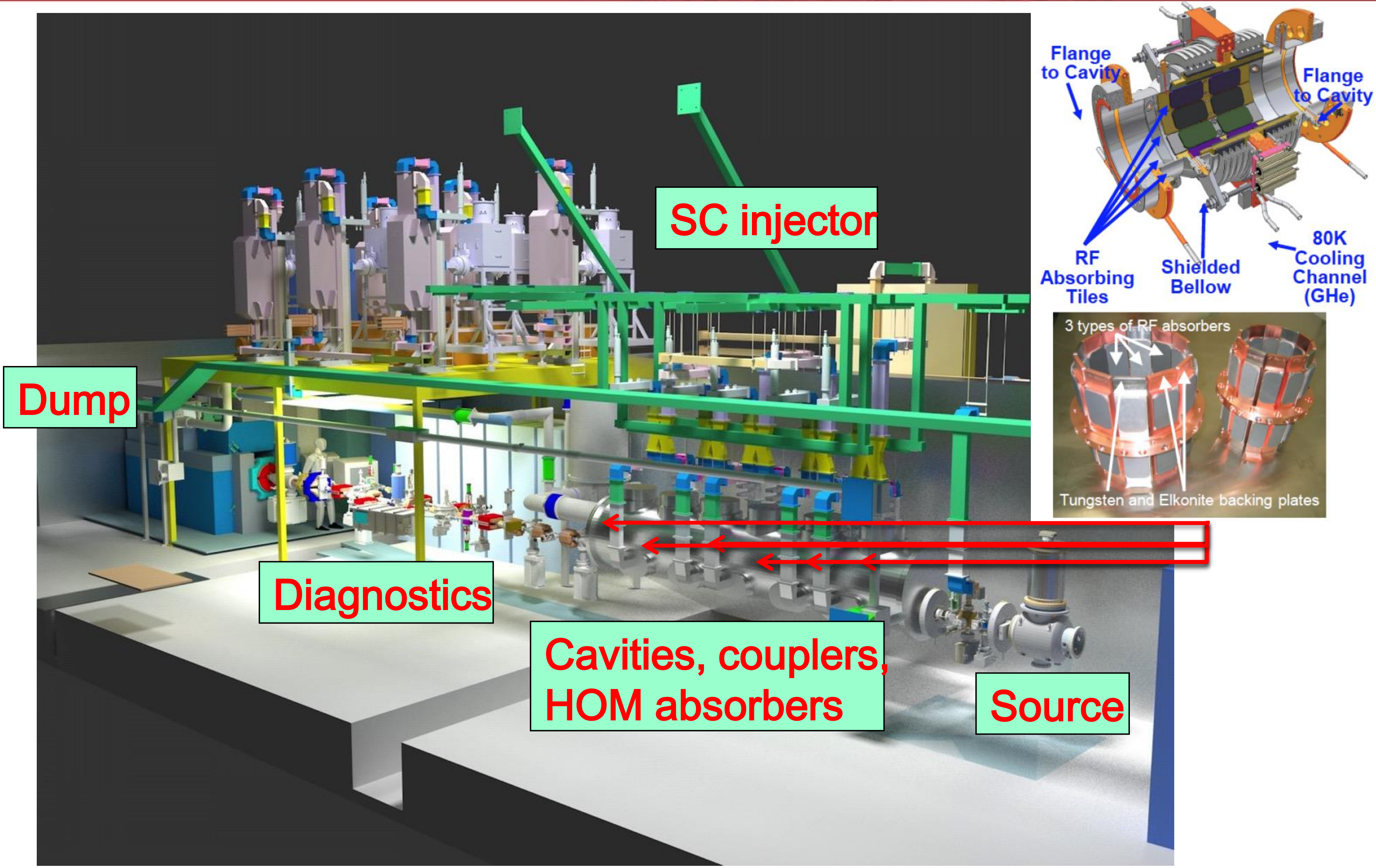
Each of two eRHIC FFAGs contain 1066 FFAG cells

Some of the most important risk items for eRHIC:

1) FFAG loops with a factor of 4 in momentum aperture.
   a) Precision, reproducibility, alignment during magnet and girder production.
   b) Stability of magnetic fields in a radiation environment.
   c) Matching and correction of multiple simultaneous orbits.
   d) Matching and correction of multiple simultaneous optics.
   e) Path length control for all orbits.

2) Multi-turn ERL operation with a large number of turns.
   a) HOM damping.
   b) BBU limits.
   c) LLRF control and microphonics.
   d) ERL startup from low-power beam.

ERL injector at Cornell



The CBETA CDR

Background for CDR

Wrote PDDR for hard X-ray ERL at Cornell in 2012.

Start of CBETA July 2014 White paper December 2014

CDR scheduled for magnet prototypes.

Planed for completion of optics and layout for CDR.

Scheduled this Review to include advise on CDR.

Plan to include committee advise by the end of July.

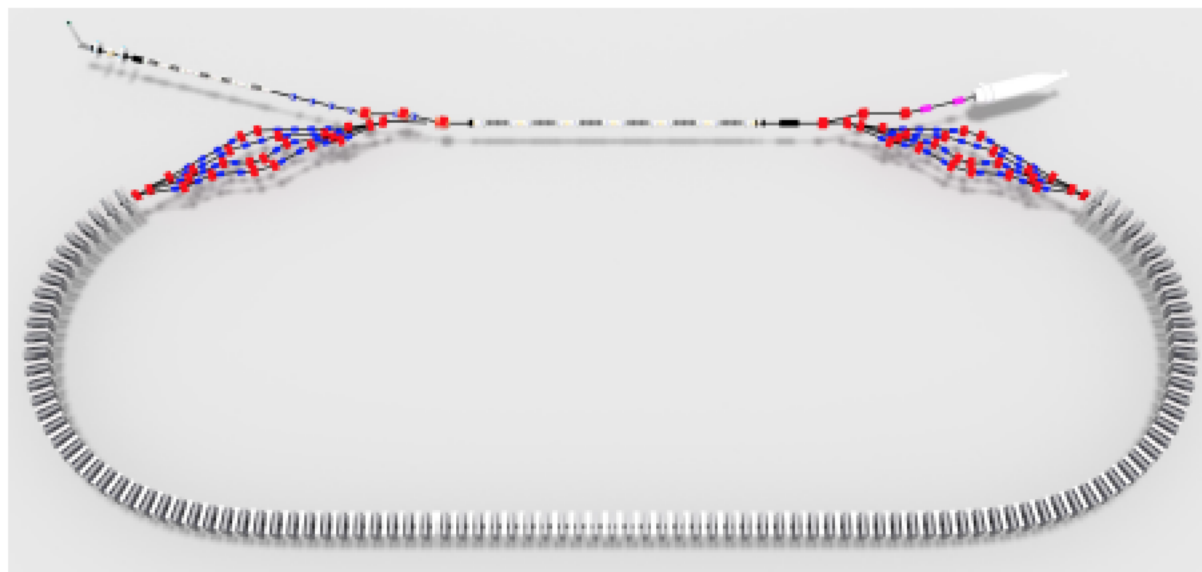
DRAFT

CBETA Conceptual Design Report

Cornell-Brookhaven ERL Test Accelerator

Editors: G. Hoffstaetter and D. Trbojevic

Contributors: J. Barley, I. Bazarov, A. Bartnik, I. Ben-Zvi, J. S. Berg, S. Brooks, D. Douglas, J. Dobbins, B. Dunham, R. Eichhorn, R. Gallagher, C. Gulliford, G. Hoffstaetter, Y. Li, M. Liepe, W. Lou, G. Mahler, C. Mayes, F. Méot, M. Minty, R. Patterson, S. Peggs, V. Ptitsyn, T. Roser, D. Sabol, E. Smith, J. Tuozzolo, D. Trbojevic, N. Tsoupas, H. Witte



June 7, 2016

Why is CBETA at Cornell

Track Record:

a) ERL injector with world-record current (10 times more than the next)

b) ERL injector with world-record emittance (5 times less than the next)

c) SRF cavity shape for high current (30 times more than the next)

d) SRF R&D for ERL Light Sources with world-record low energy loss

e) High Brightness Beam Physics (first full hard x-ray ERL design)

Facilities and Capabilities:

- About 120 accelerator-related employees with decades of experience in accelerator building and operation at the worlds forefront.
- Facilities and experience for building full SRF accelerators and DC guns.
- Space for a 100mA, > 36MeV per turn ERL.

Hall L0E before CBETA

L0E contained approximately 7,000 square feet of Lab and Shop space

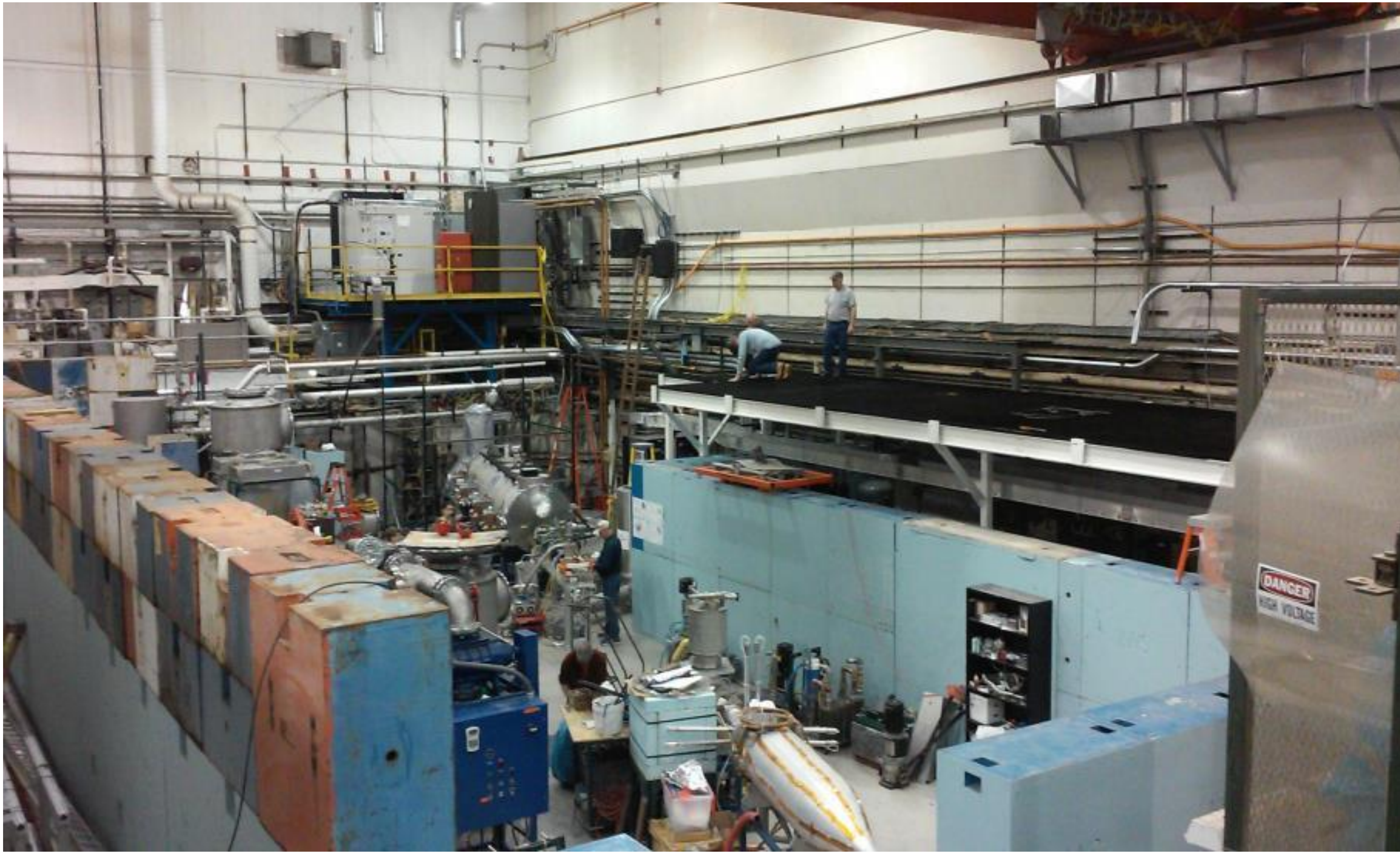
Spring 2015

70% of the existing technical-use space was removed for the initial phase

Fall 2015

The initial installation was completed for the MLC and ERL beamline

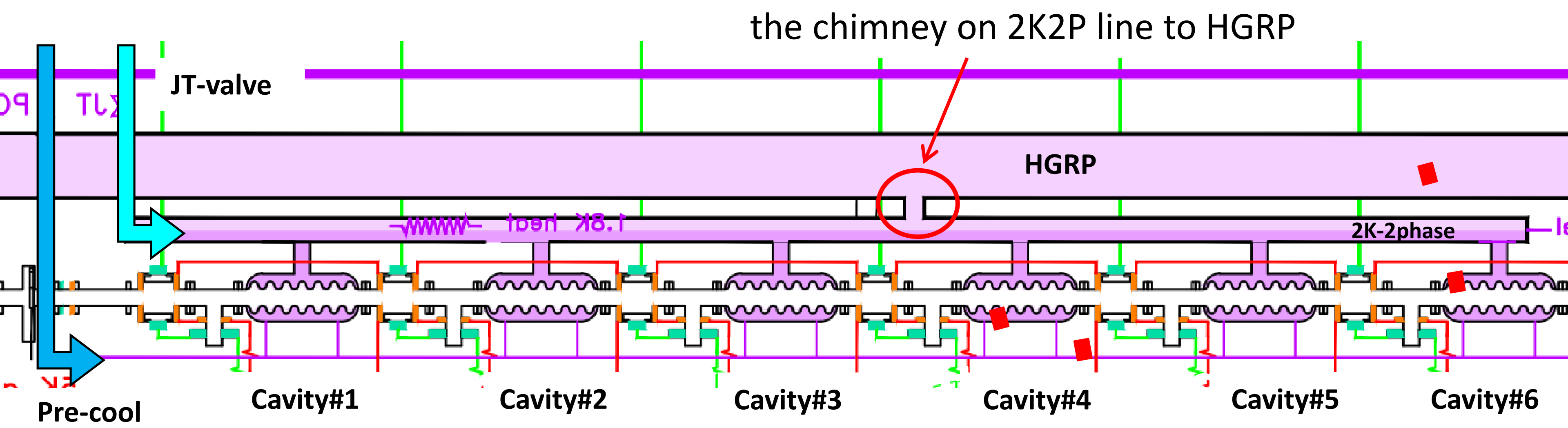
The second phase will accommodate the new loop-layout



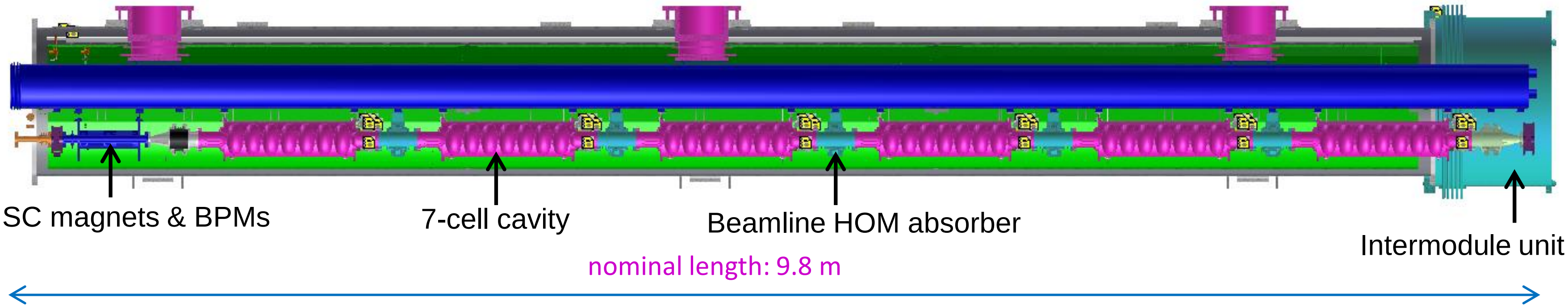
Summer 2016

The second phase is almost complete

Prototype Main Linac Cryomodule MLC



- six packages of 7-cell cavity/Coupler/tuner
- a SC magnets/BPMs package (magnet not installed)
- five regular HOMs/two taper HOMs



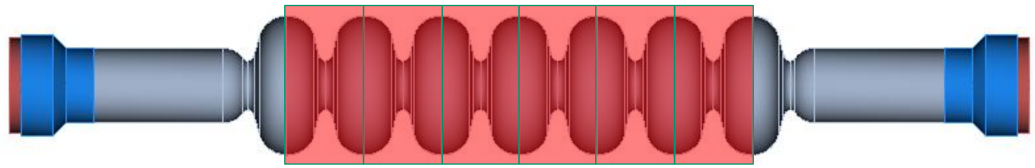
Main linac cryomodule assembly for CW beams

- MLC assembly was completed
- Cooled down fall 2015, field, Q, and microphonics tested.
- Further cold studies will start August 2016

High Current Cavity Design Strategy

- Central focus: Maximize threshold current through ERL
- Optimization over ~100 degrees of freedom
  - Center cell geometry
  - End cell geometry
  - Beam line HOM absorbers
- Simulate ERL performance with realistically shaped cavities

Accelerating Structure Overview

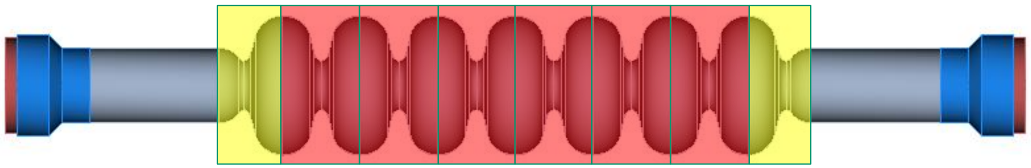


Goal: Maximize I_{th} > 100 mA (under constraints)

Center cells

- Geometries are (nominally) identical
- Responsible for general properties of HOM spectrum
    - Controls frequencies of HOM passbands and dispersion relations
    - Determines cell-to-cell coupling and how sensitive HOM spectrum is to variation in cell shape

Accelerating Structure Overview



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End cells

- Asymmetric design helps prevent trapped modes
- Responsible for coupling HOMs to HOM absorber
  - Directly controls quality factors of HOMs

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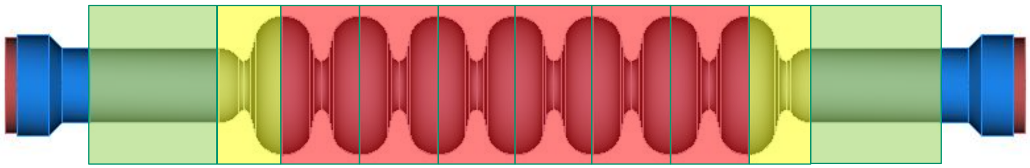

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Beam Pipe

- Should be short to improve linac fill factor but long enough to avoid dissipating too much power from the fundamental mode

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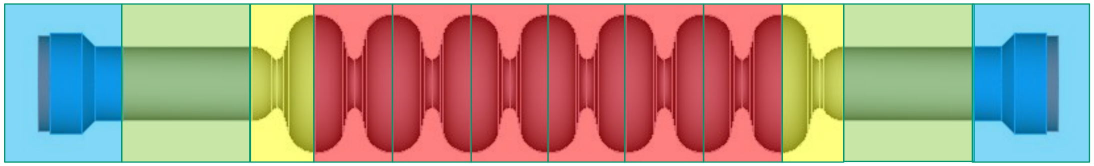

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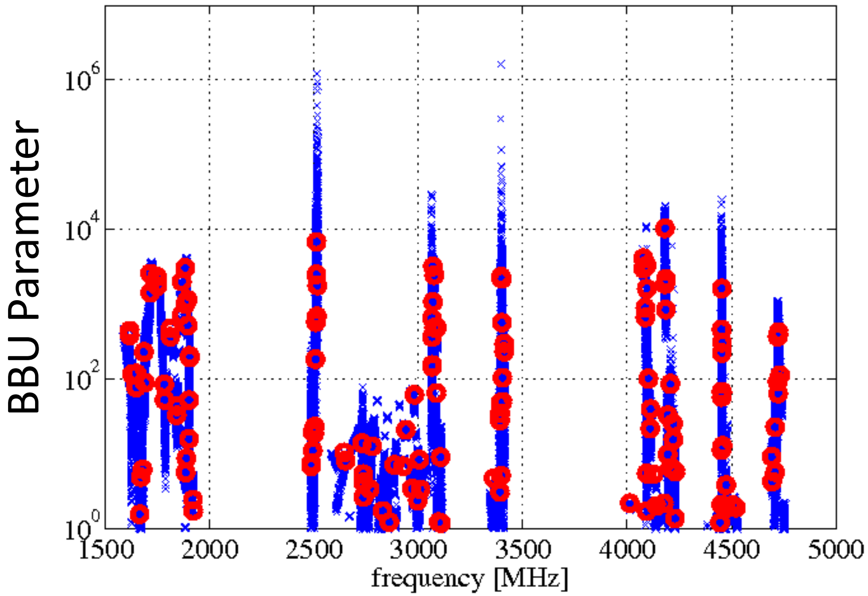
HOM load

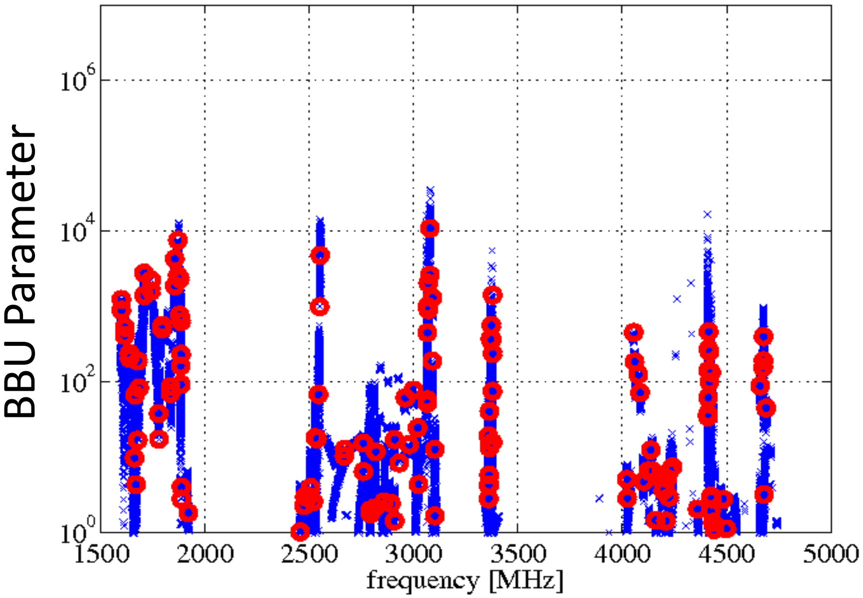
- Absorber material properties determine specific mode losses.

Center Cell Optimization

Baseline Center Cells



Enhanced cell-to-cell coupling

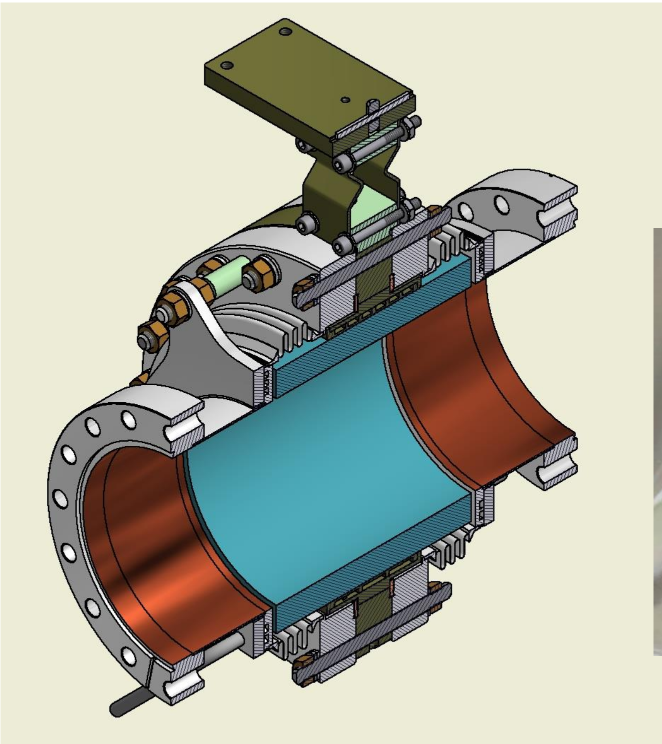


o HOM properties with no fabrication variation

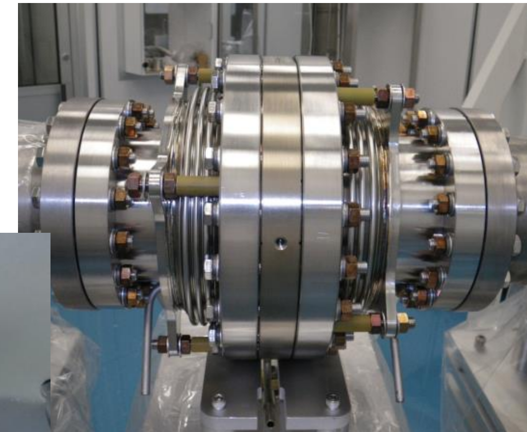
x HOM properties with 1/16 mm variation

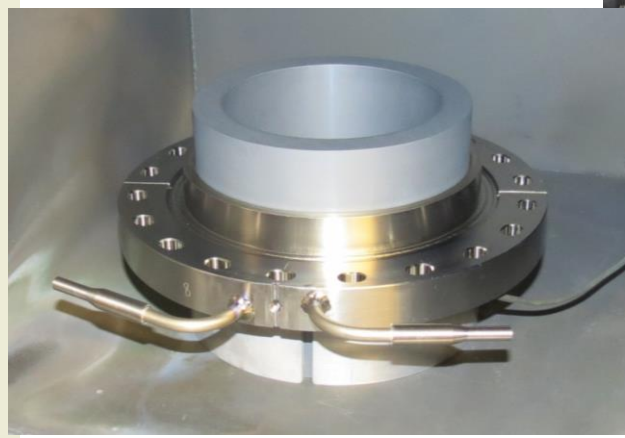
Band	1.8 GHz	1.9 GHz	2.5 GHz	2.7 GHz	3.1 GHz	3.4 GHz
Baseline Design	192	95	31	277	55	10
New Design	188	73	107	227	47	20

Cornell HOM Beamline Absorbers



Absorbing Material:
Doped SiC (SC-35
from Coorstek

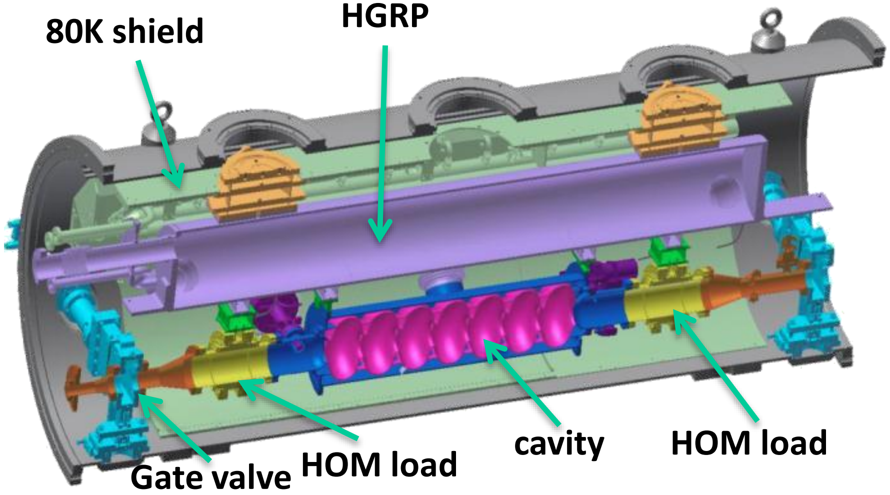




Cooling Passage
Configuration of 80K
Cooling Jacket

The HOMSC workshop series started in 2010 with a call to discuss development of this HOM absorber.

Horizontal Test Cryostat (HTC) with 1st ERL cavity



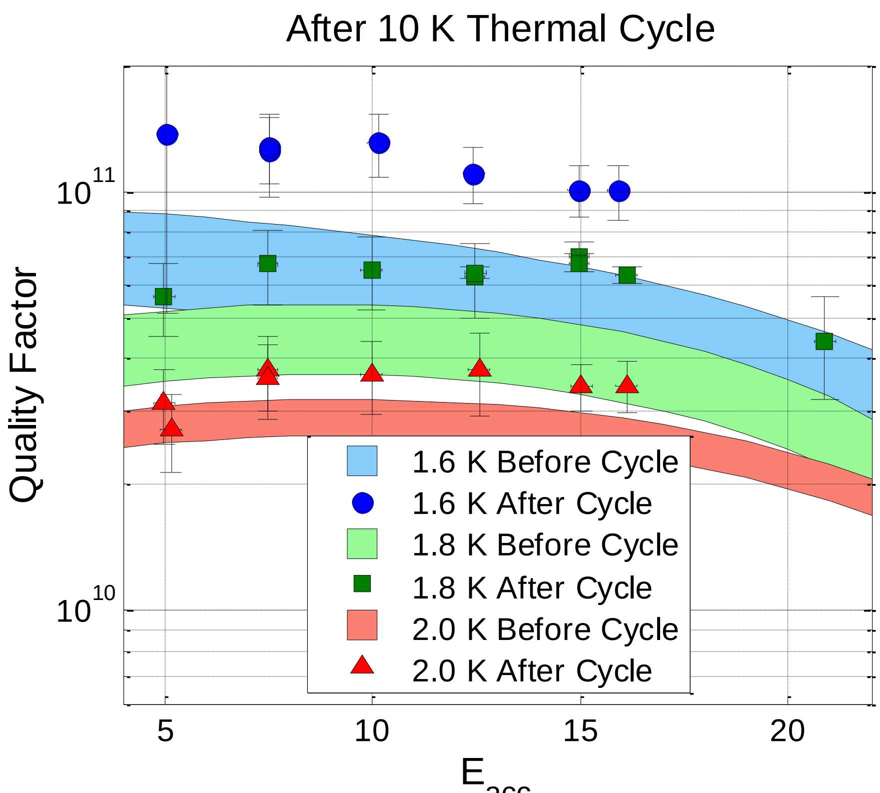
- Much better Q0 than the ERL spec.
- Increased state of the art expectations for other projects, e.g. LCLS-II.
- Became essential for high-Q cavity research, incl. for N-doped cavities.

Horizontal Test Cryostat:

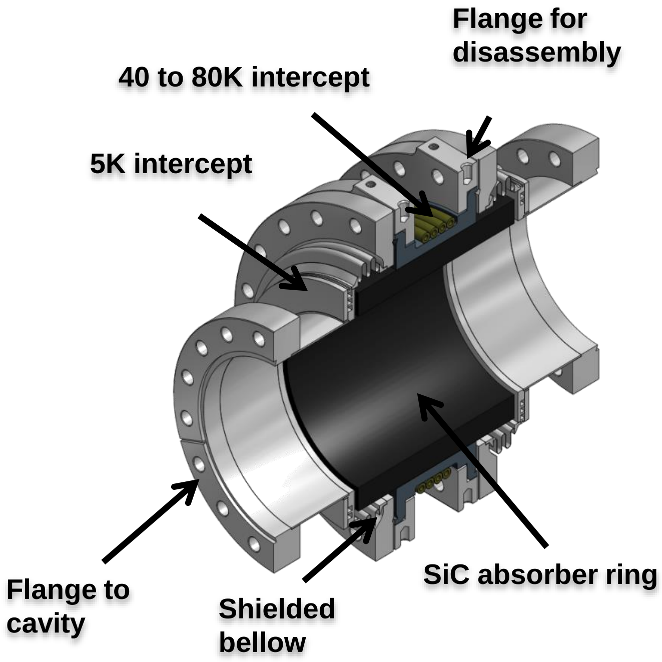
16MV/m, 1.8K: Q_0 = 2.E10 (reached with coupler)

Q_0 = 3.5E10 without coupler

Q_0 = 6E10 with coupler and HOM absorbers (held the world record)

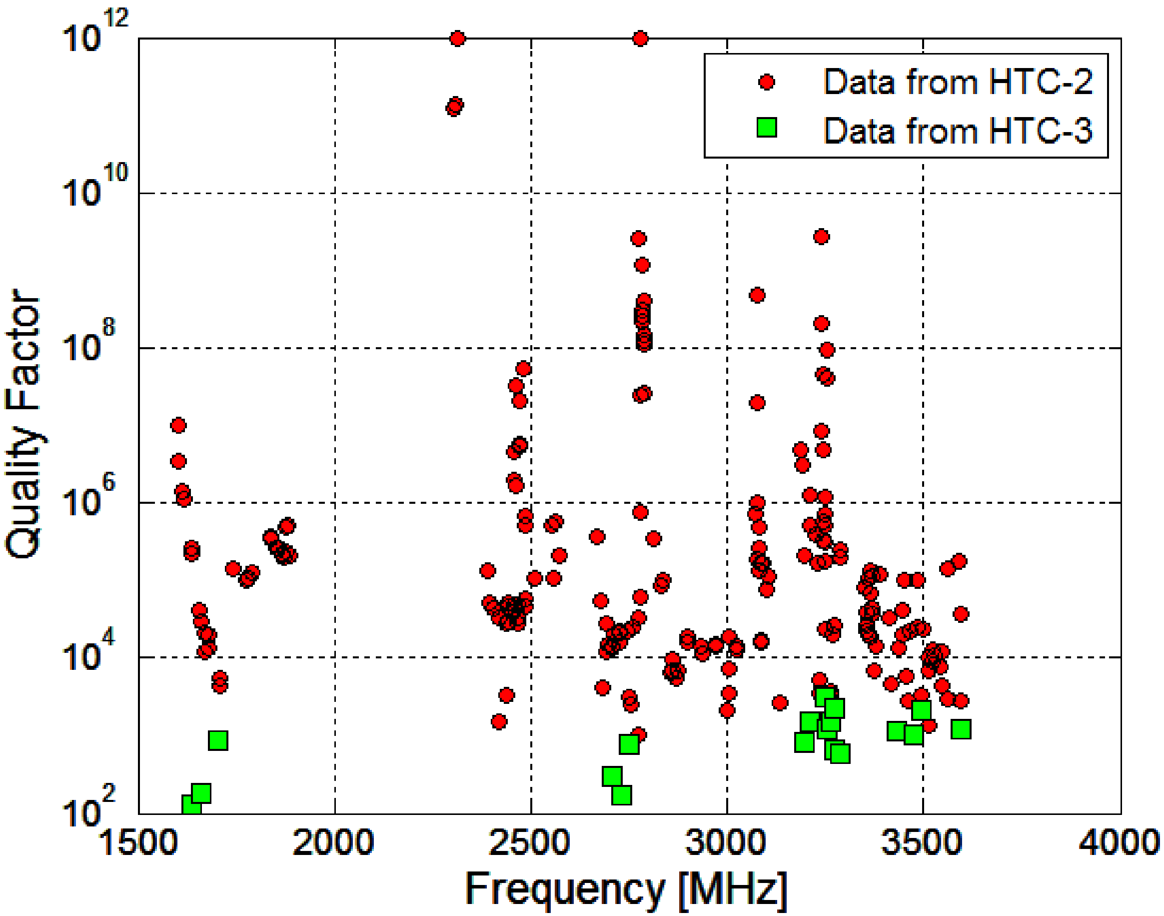


HTC HOM damping



HTC-2: No HOM Absorbers

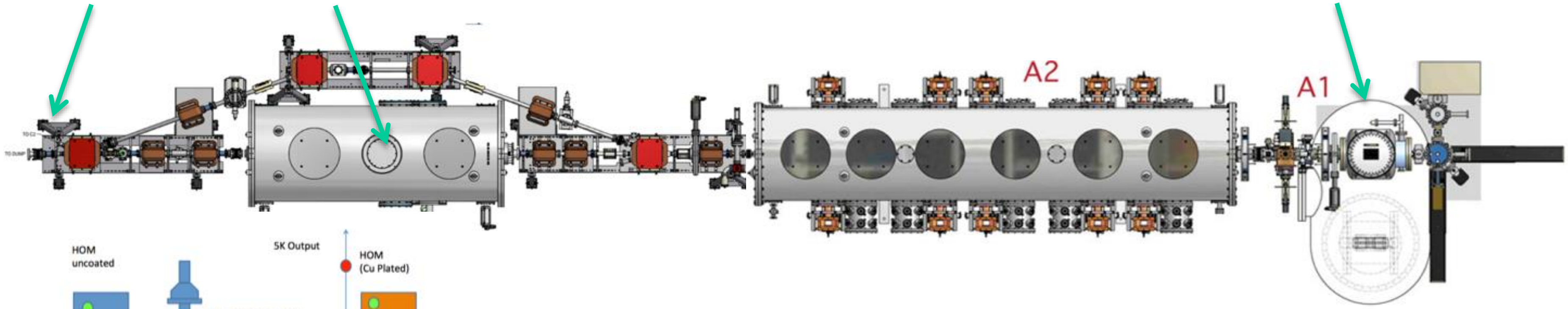
HTC-3: With HOM Absorbers

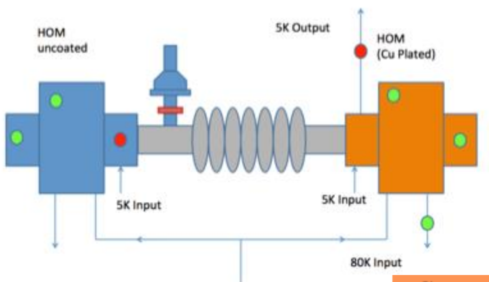


Beamline HOM absorbers strongly damp dipole HOMs to under Q ~ 10^4

HOM measurements with beam

BPM **7-cell cavity in cryostat** **gun**

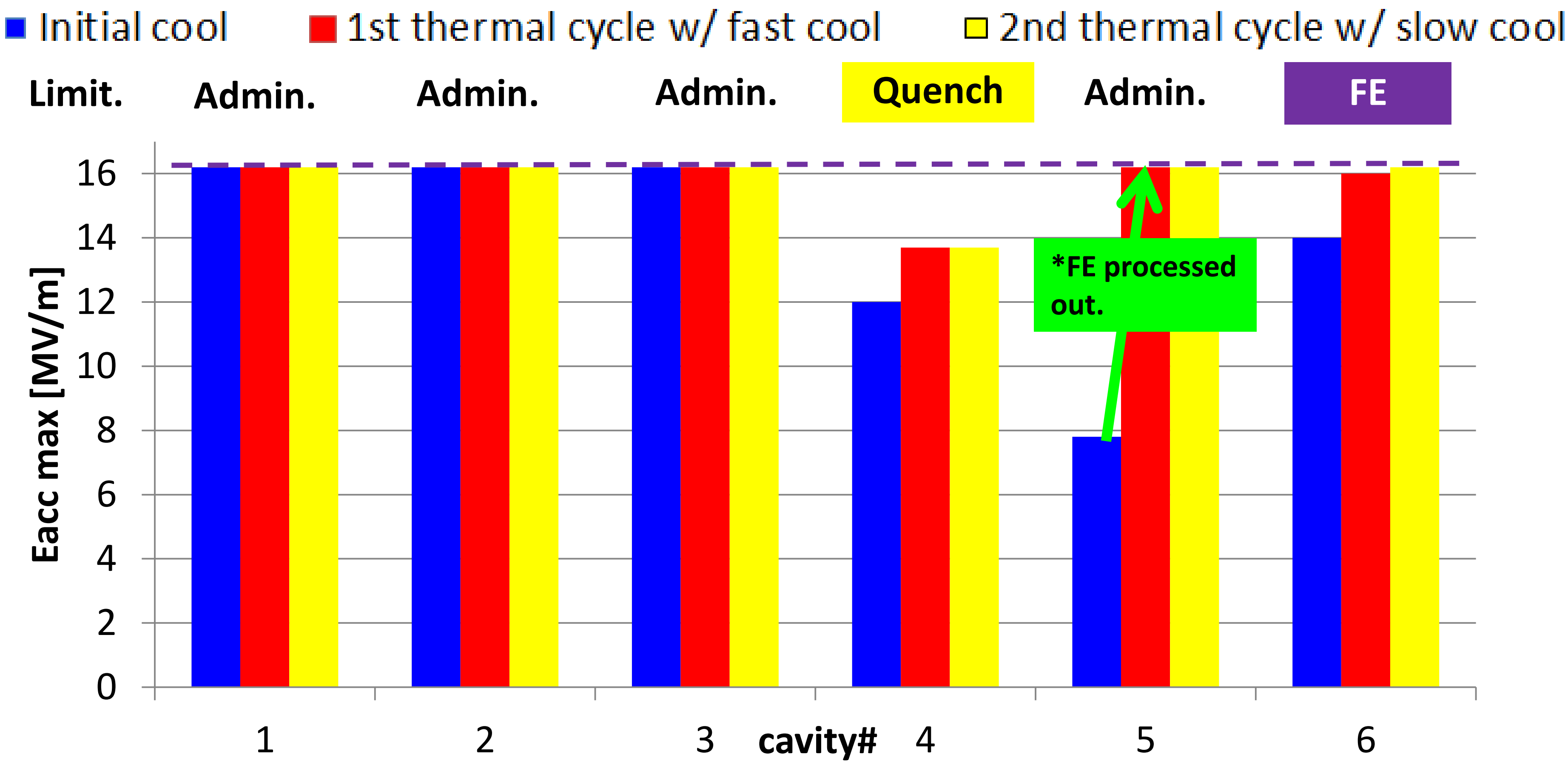




Current, bunch length	ΔT (beam pipe behind Abs.) coated/uncoated	ΔT (80K gas temp) coated/uncoated	ΔT (80K absorber temp) coated/uncoated	ΔT (5K flange next to cavity) coated	ΔT, beam pipe to cavity coated/uncoated
25 mA, 3.0 ps	0.075/0.075	1.14/0.82	1.02/0.975	0.007	0.076/-.005
40 mA, 3.4 ps	0.2475/0.335	2.95/2.16	2.72/2.53	0.021	0.179/0.009
40 mA, 2.7 ps	0.2975/0.425	3.00/2.22	2.772/2.63	0.027	0.203/0.014

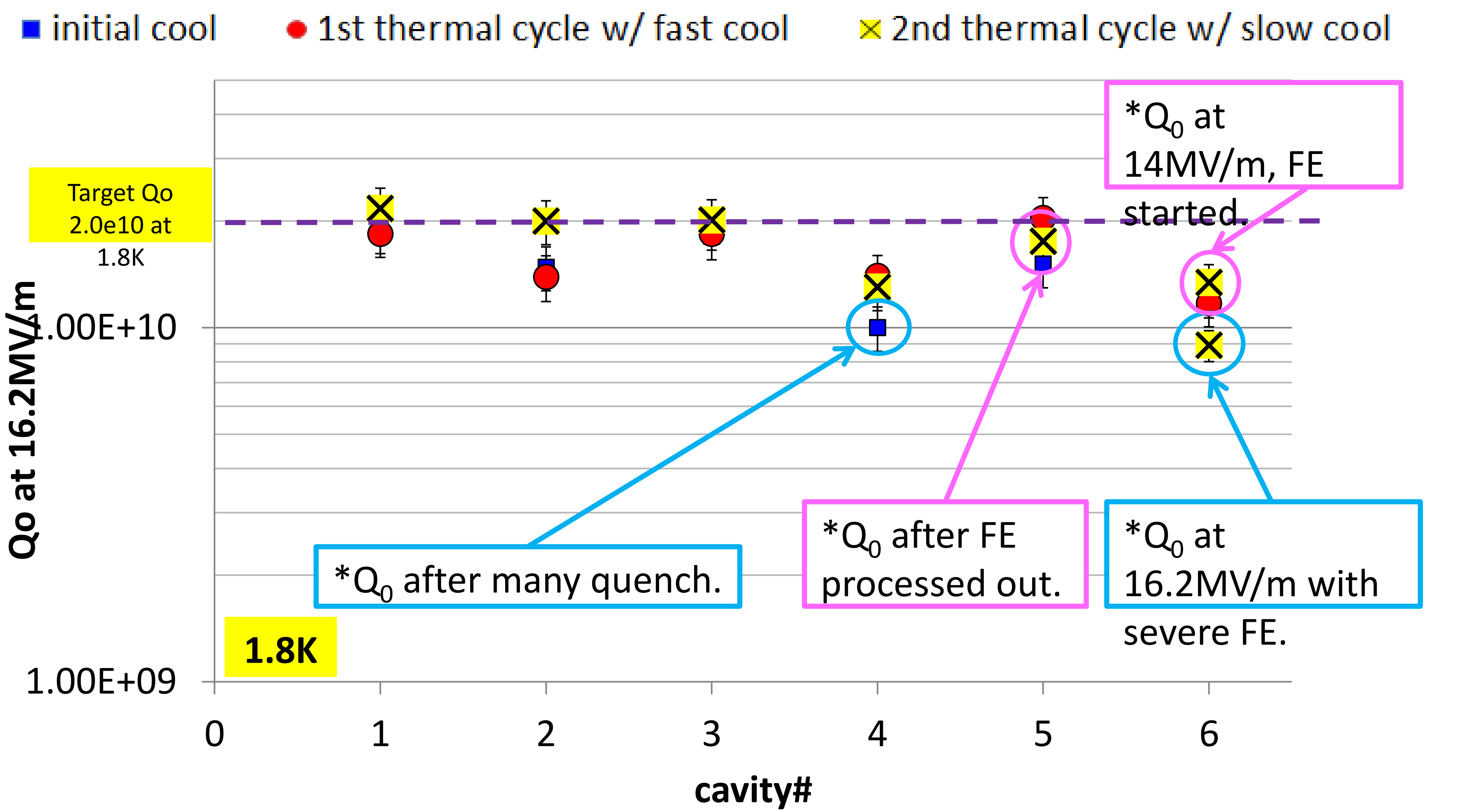
- No charge-up of the HOM absorber observed.
- HOM heating was less than expected, limits to 400mA total ERL current.
- **This establishes the current limit of 40mA for the 4-turn CBETA ERL**

Main linac cryomodule (MLC) achieved accelerating gradients



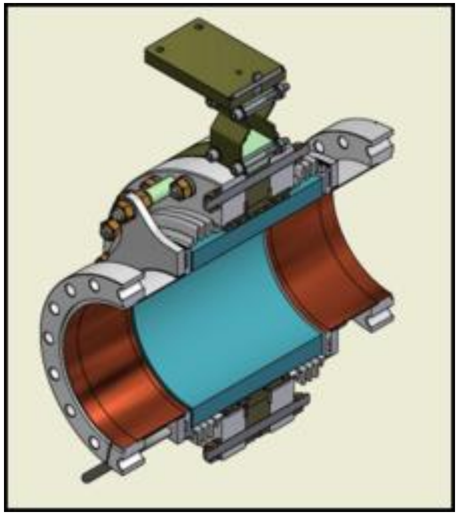
- 5 of 6 cavities had achieved design gradient of 16.2MV/m at 1.8K in MLC.
- Cavity#4 is limited by quench so far, no detectable radiation during test.
- **Enough Voltage for 76MeV per ERL turn (where 36MeV are needed)**

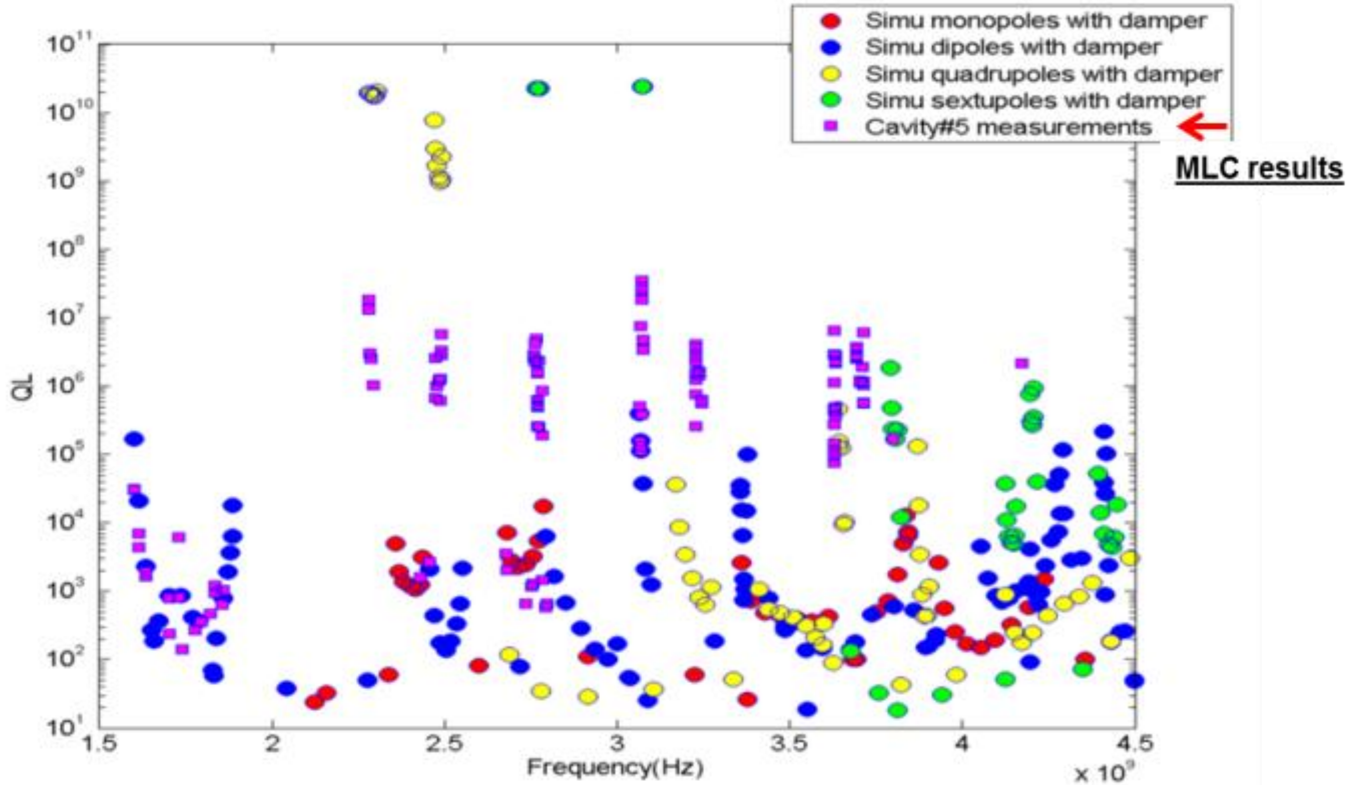
Main linac cryomodule (MLC) achieved surface losses (Q0)



- 4 of 6 cavities had achieved design Q_0 of 2.0E+10 at 1.8K.
- Q_0 of Cavity#6 had severe FE at 16MV/m.
- **Enough cooling for 73MV per ERL turn (where 36MeV are needed)**

Current limits from HOMs



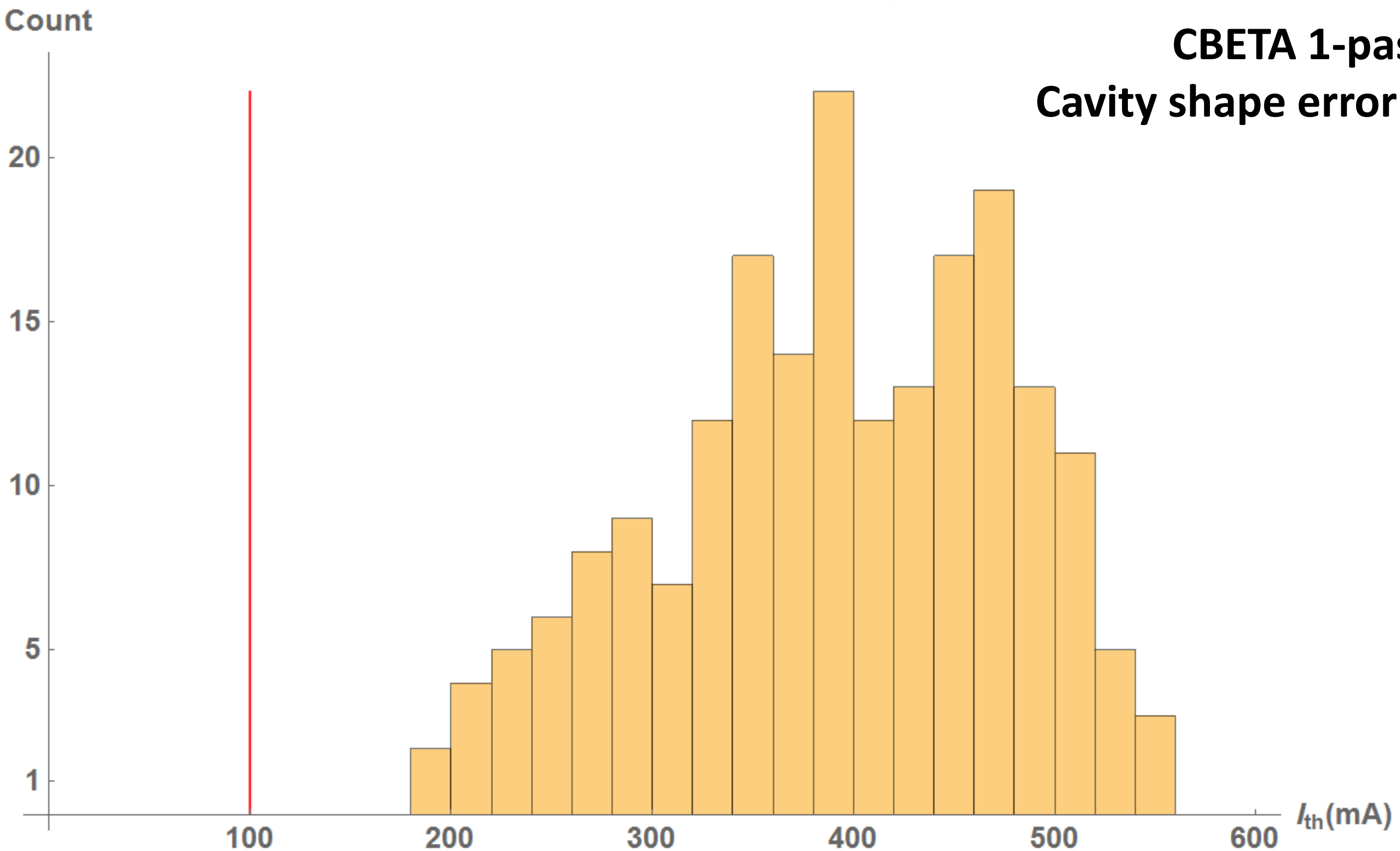


Dipole HOMs on MLC were strongly damped below $Q\sim10^4$.
Consistent with HTC and simulation results.

HTC results were:

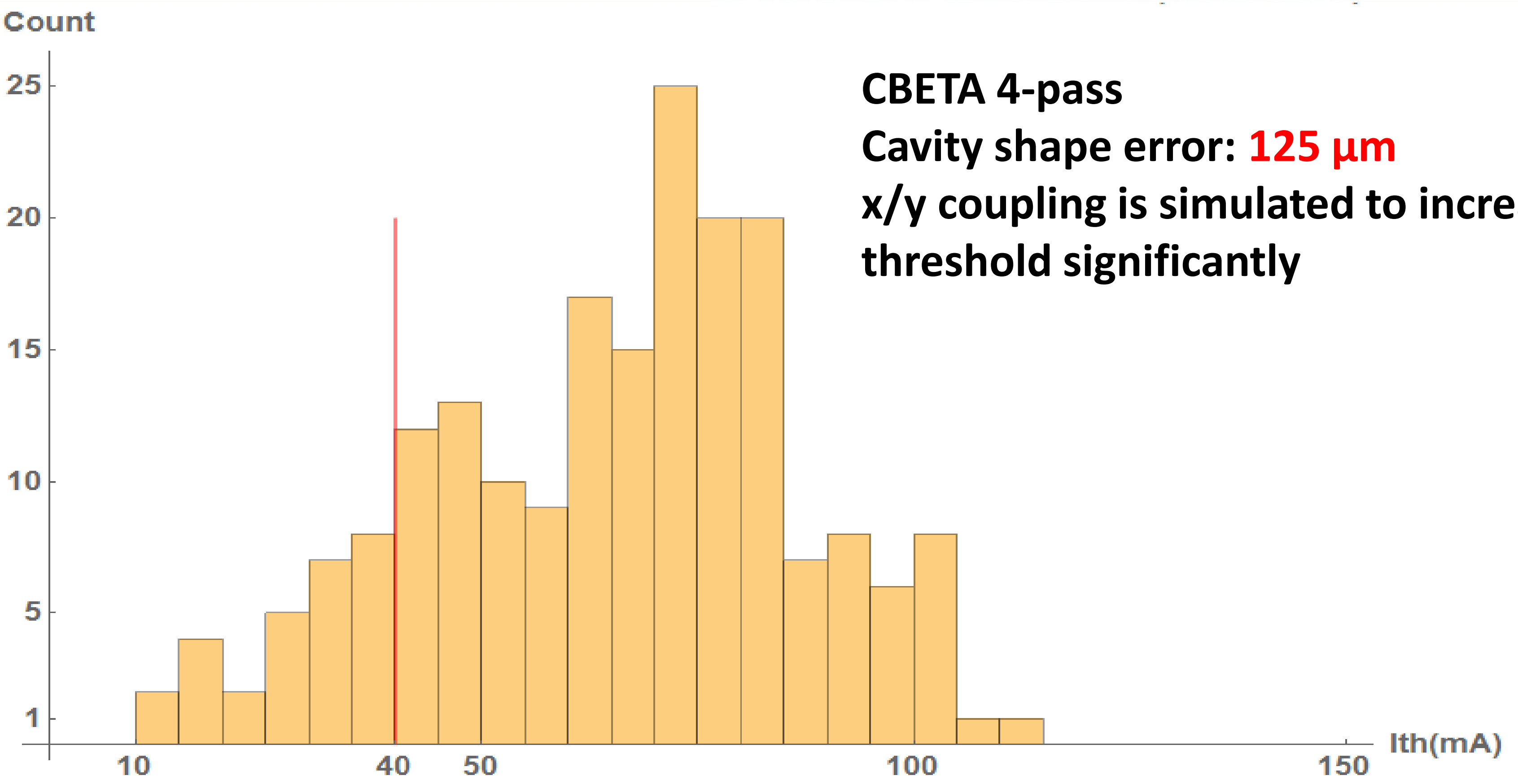
- **HOM heating: currents are limited to < 40mA in CBETA**
- **BBU no HOM limits BBU to below 100mA in one turn**

BBU for 1 pass in CBETA



100% of simulations have $I_{\mathrm{th}}>$ 100mA

BBU for 4 passes in CBETA



CBETA 4-pass

Cavity shape error: 125 µm

x/y coupling is simulated to increase the threshold significantly

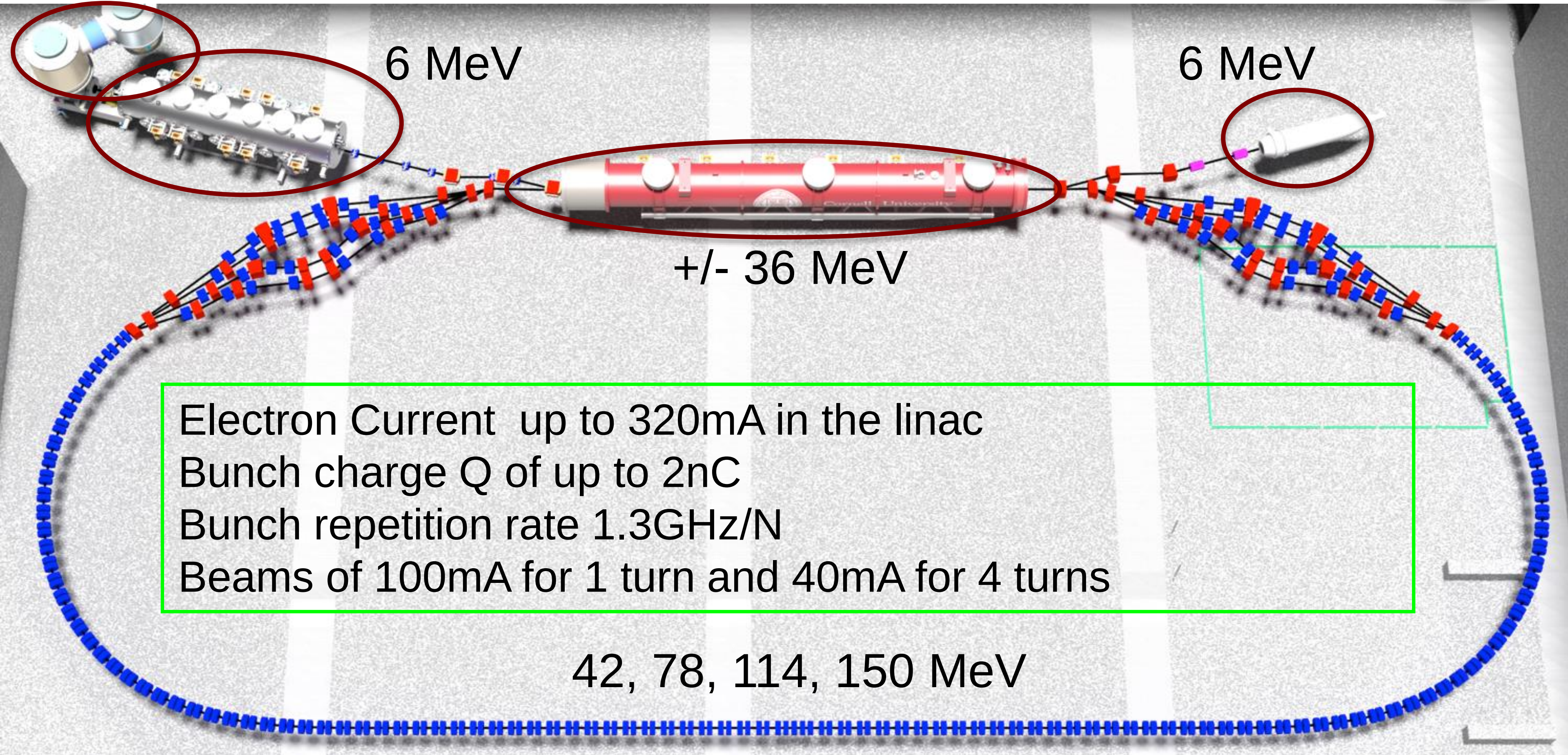
100% of simulations have I_{th} > 100mA

86% of simulations have I_{th} > 40mA

CBETA: FFAG-ERL

- Cornell DC gun
- 100mA, 6MeV SRF injector (ICM)
- 600kW beam dump
- 100mA, 6-cavity SRF CW Linac (MLC)

Existing components at Cornell



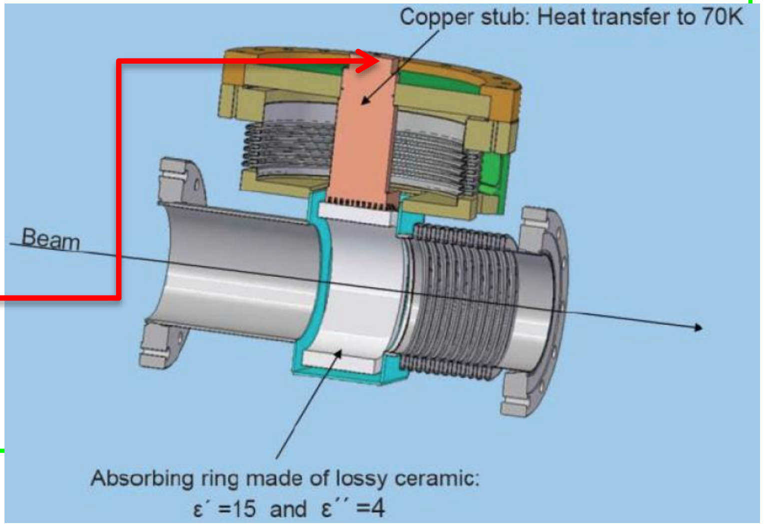
Summary

Cornell is building a 4-turn Energy Recovery Linac (ERL) with a beam current limited by HOMs through
(a) HOM heating
(b) The Beam-Breakup (BBU) instability

Cornell has already built the Injector Cryomodule (ICM) and the Main Linac Cryomodule (MLC) with beam-pipe HOM absorbers.

- The ICM has accelerated 75mA CW without HOM-heating problems.
- The cavity arrangement of the MLC with HOM absorbers has been tested with beam.
- HOM-absorber heating limits to 320mA in the MLC, or 40mA for a 4-turn ERL beam.
- HOM measurements with and without beam indicate the a 1-turn ERL with 100mA should be possible.
- BBU calculations: 100mA one-turn ERL is possible, 4-turn ERL may be possible

To operate accelerators CW linacs with larger currents, HOM absorption at room temperature become advisable. Designs for this should be developed.



Questions

Discussion

?