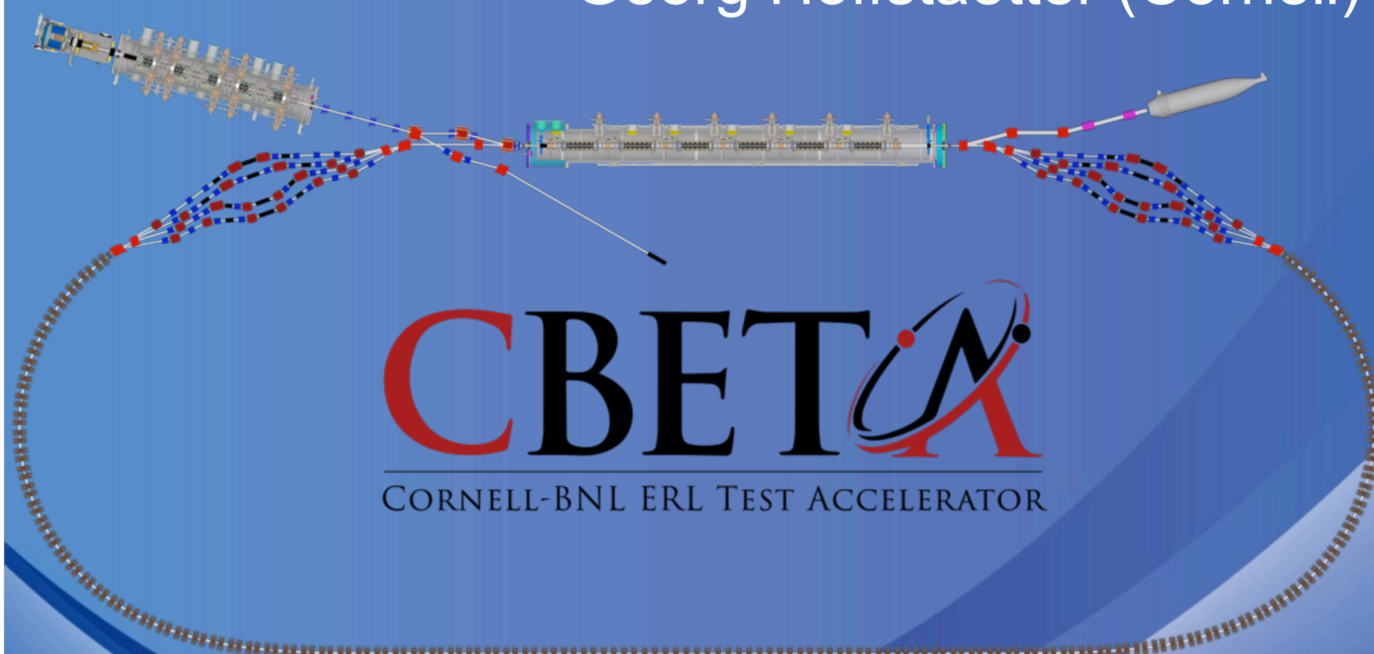
CBETA, the 4-turn ERL with *SRF linacs and permanent magnet beam transport*

LINAC, 27 July 2018

Georg Hoffstaetter (Cornell)



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

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Message

- The accelerator I am presenting has beam parameters of an Electron Ion Collider (EIC) electron cooler and provides a prototype for such an instrument.

- It is unique in that it
  - is the first 4-turn SRF ERL
  - has the first FFA loop with large (x4) momentum aperture
  - Has propagation through permanent Halbach magnets
  - has the largest electron beam power in an ERL

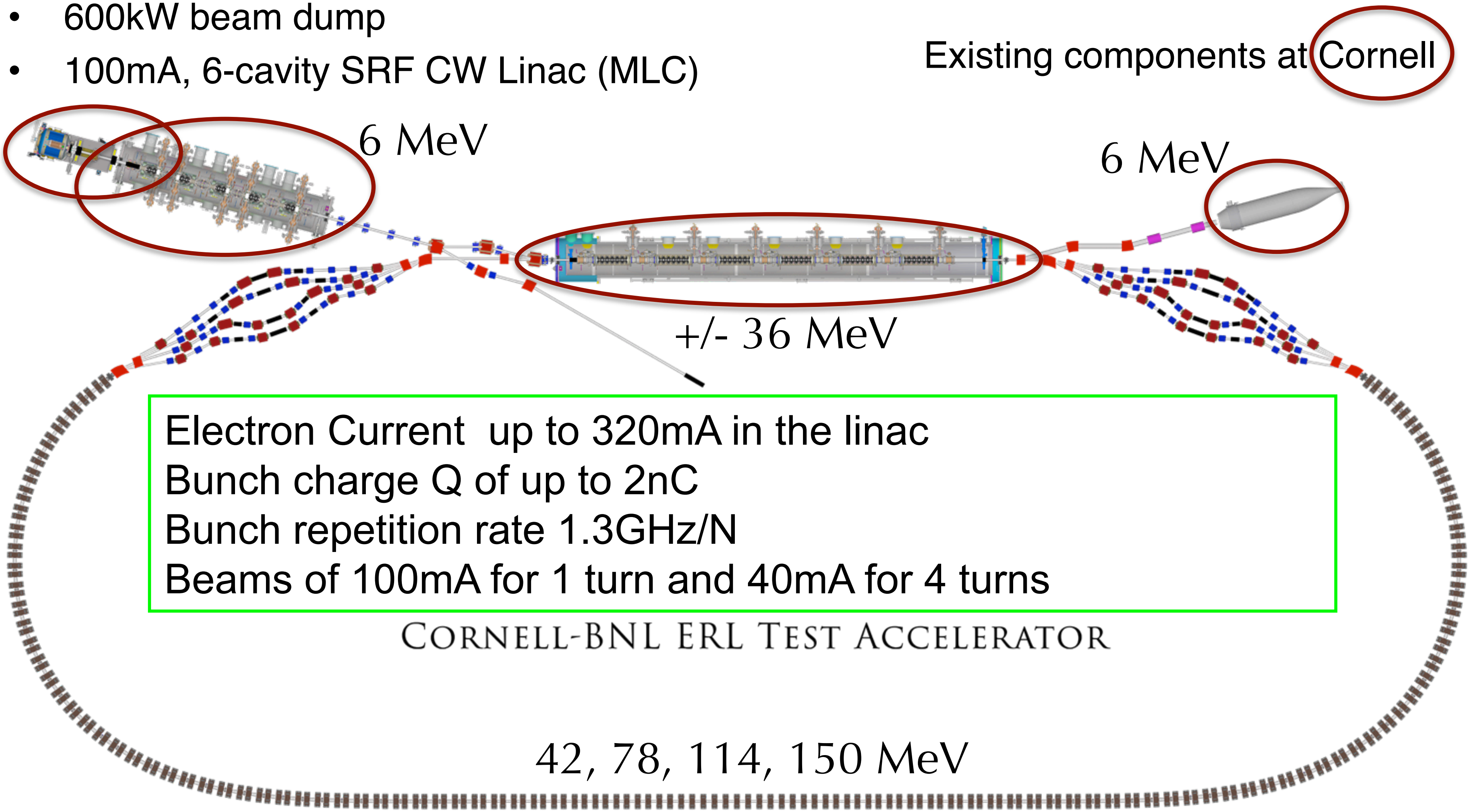
- It is being constructed and its main components have been beam-tested.

- It has applications beyond EIC research

- It is build in a Cornell/BNL collaboration and is commissioned in world-wide collaboration

The test ERL in Cornell's hall LOE

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



Previous funding leading to CBETA

2005 Start of construction of DC photo-emitter gun; to world record current (75mA)

2012 PD-Design Report on a hard x-ray 5GeV ERL; no construction.

2013 Achieved world record brightness

2014 White paper for CBETA with collaborators at BNL.

2016 2nC bunch charge for EIC

2016 Construction funding by NYS begins.

2017 CBETA Design Report

2018 1st beam thorough SRF chain, one separator and one PMA unit.

Staring in 2020, CBETA will be available for R&D on high power beams!

arXiv:1706.04245v1 [physics.acc-ph] 13 Jun 2017

CBETA Design Report

Cornell-BNL ERL Test Accelerator

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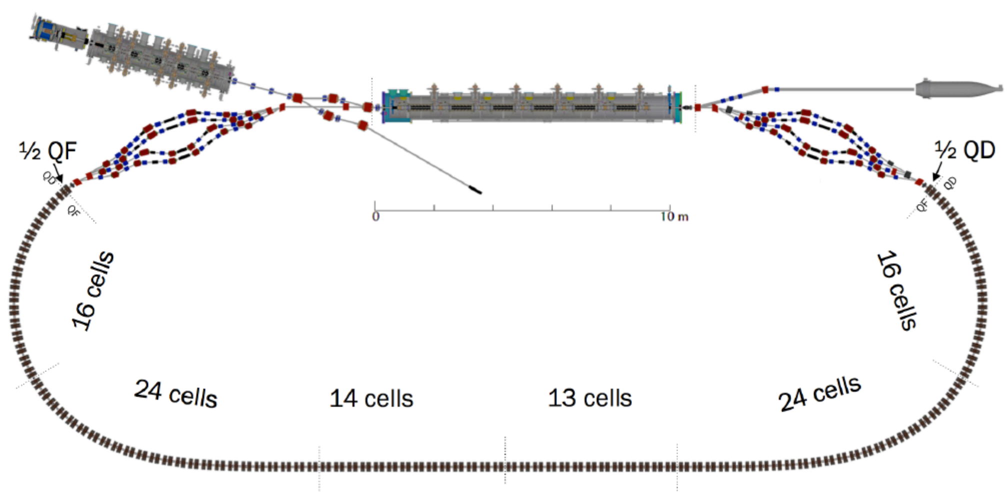
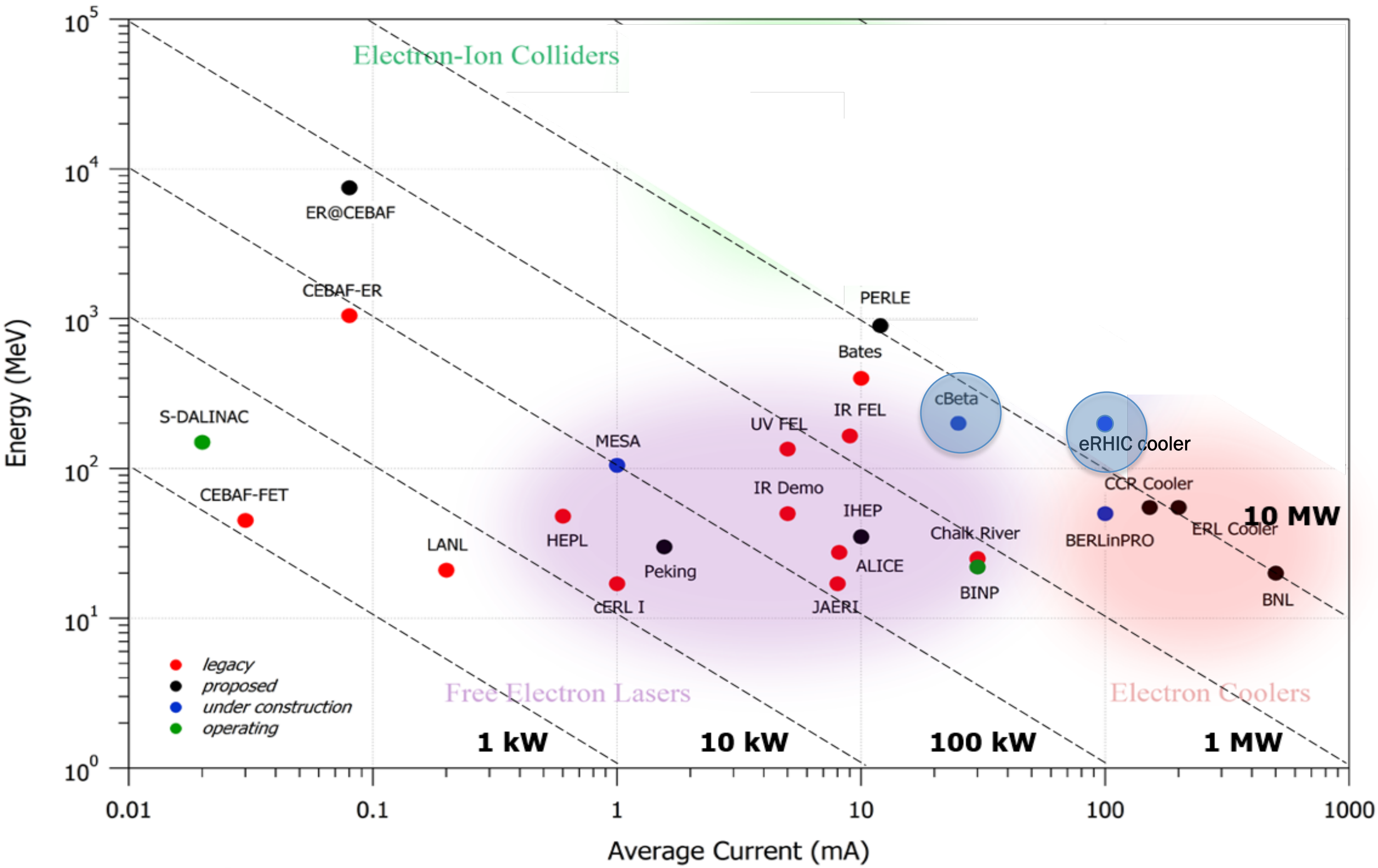


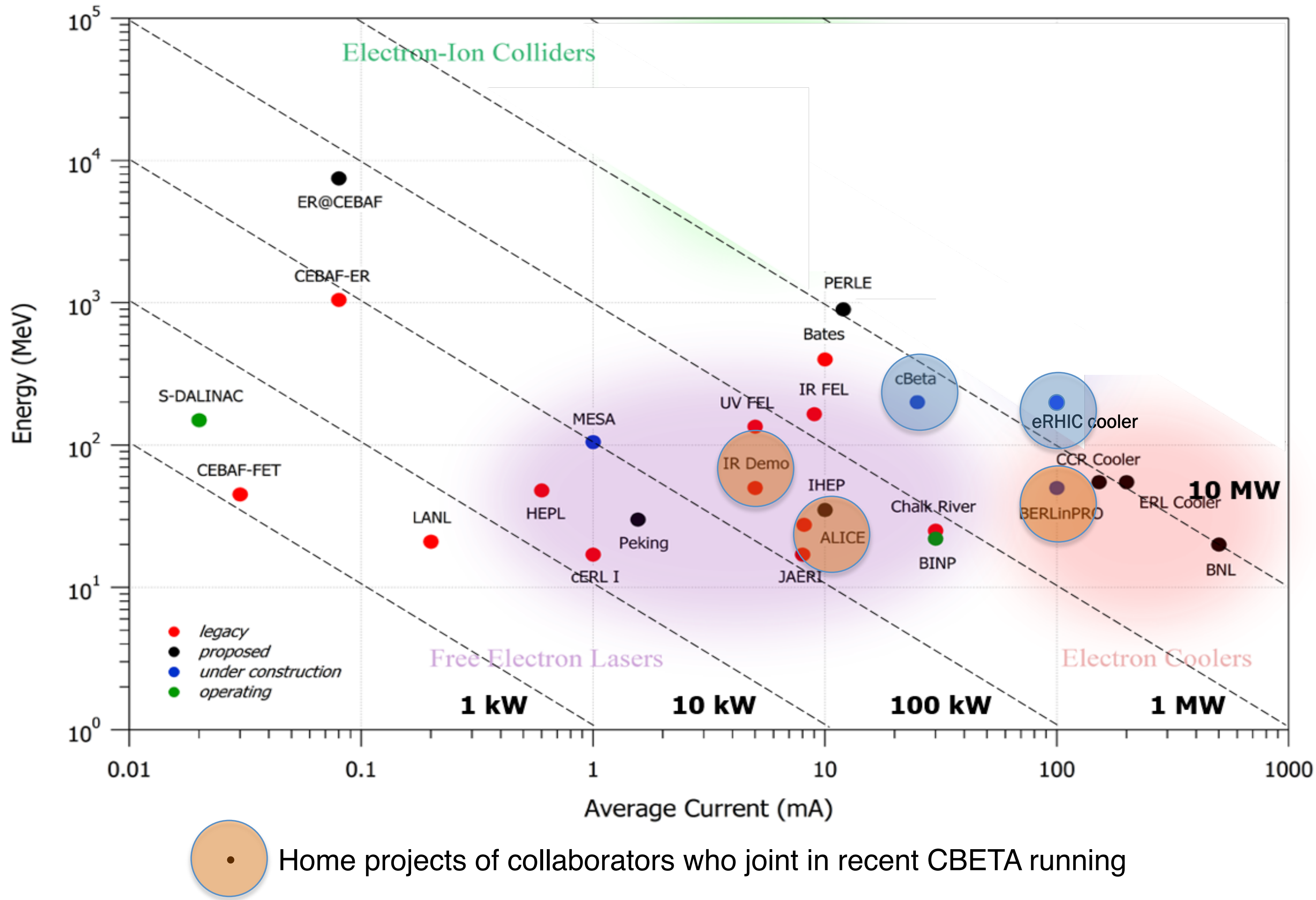
June 8, 2017

The beam power frontier



- CBETA has 150MeV and up to 40mA: 6MW beampower => Delete black
- eRHIC cooler ERL has 150MeV and up to 100mA: up to 15mW

The beam power frontier



Home projects of collaborators who joint in recent CBETA running

Hall L0E before CBETA

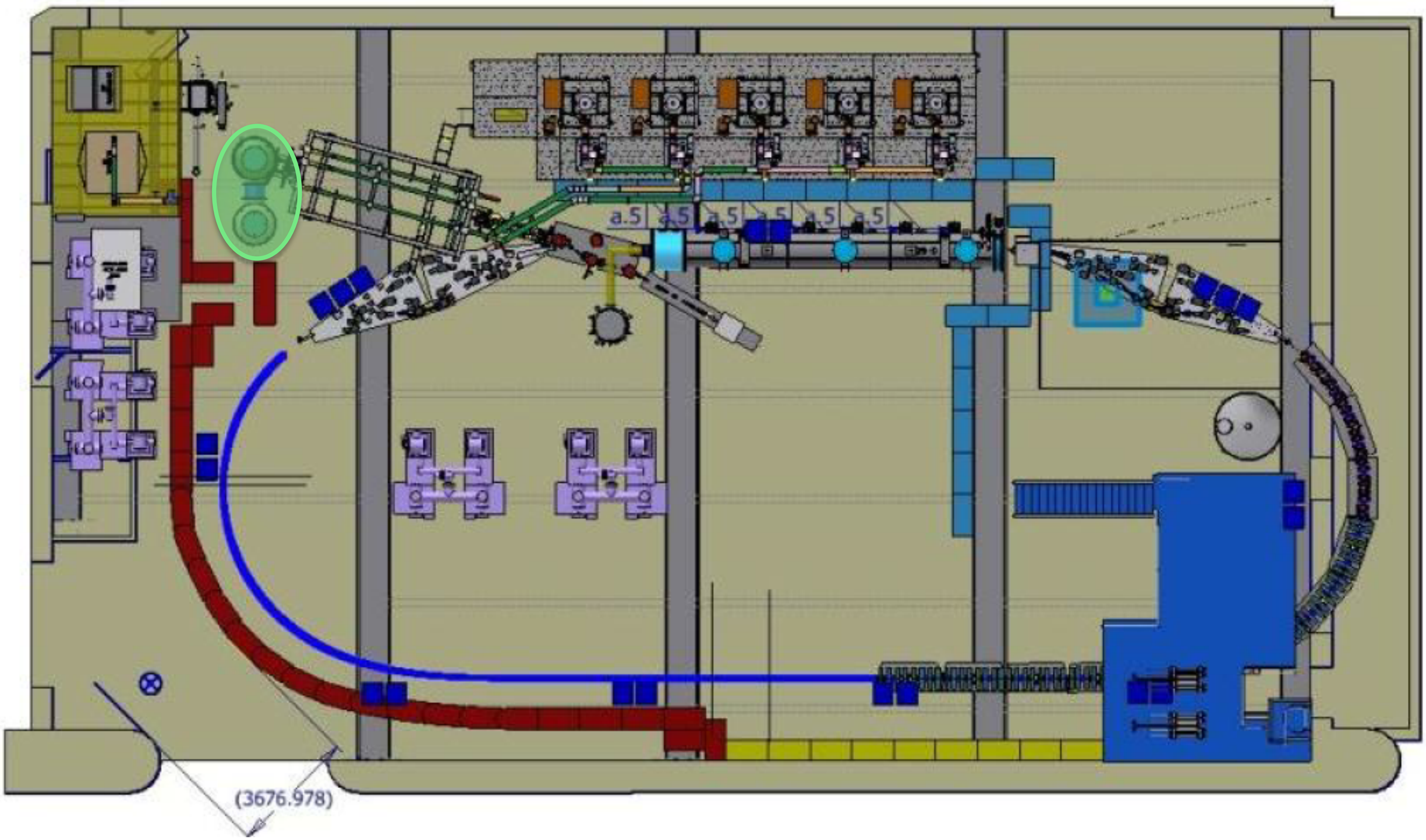
L0E contained approximately 7,000 square feet of Lab and Shop space

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

L0E cleaned with CBETA

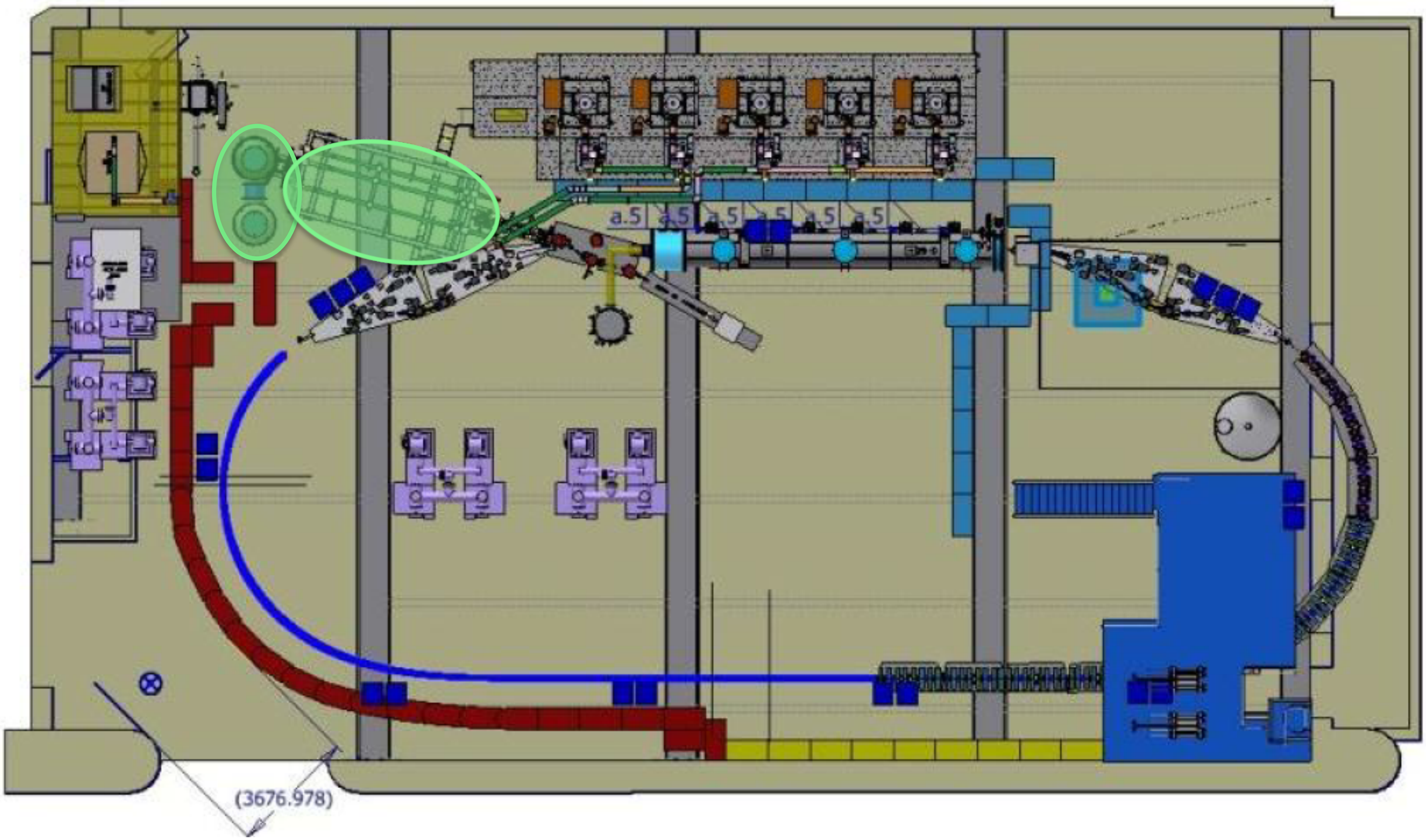
CBETA in its Hall L0E

Installed: DC gun



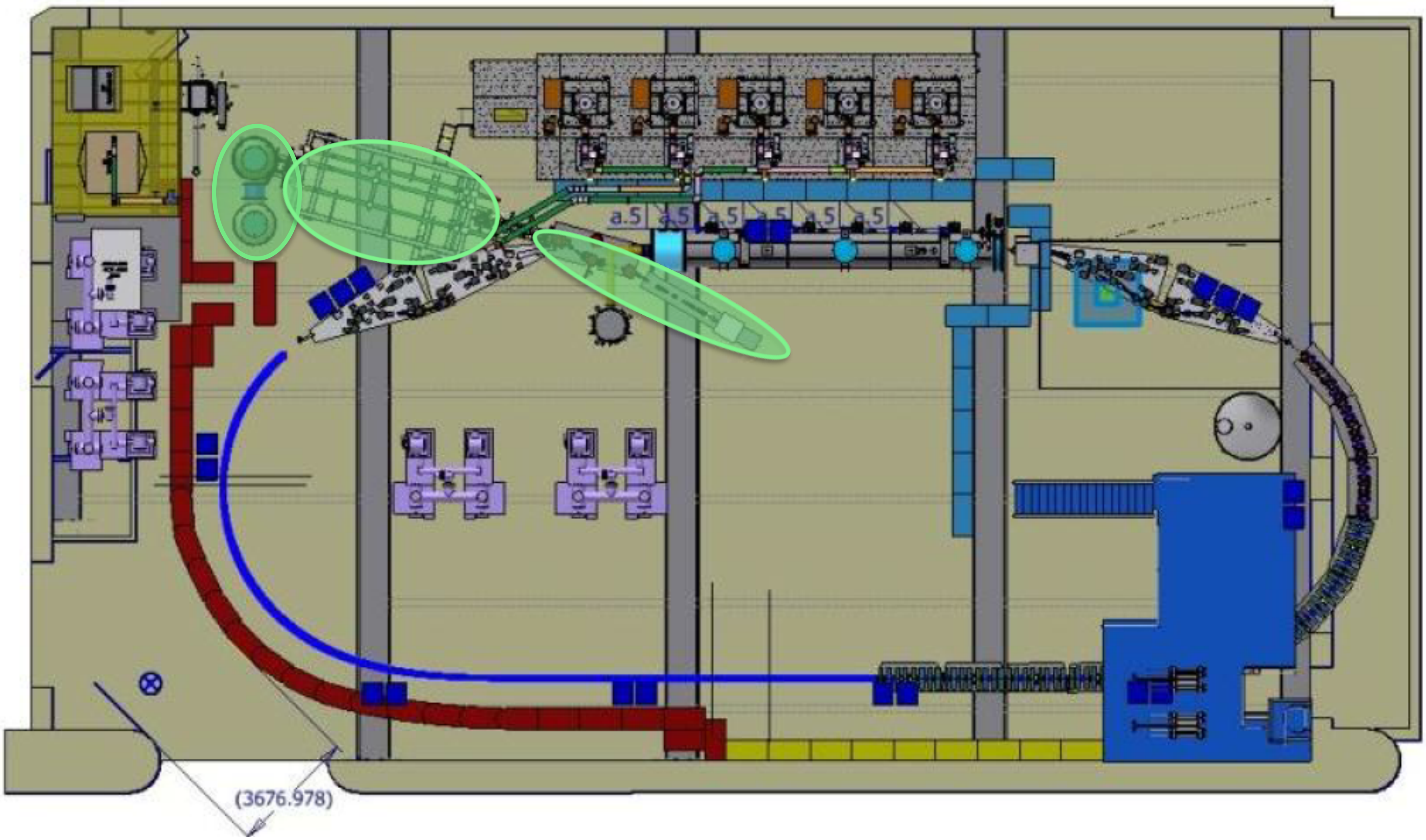
CBETA in its Hall L0E

Installed: DC gun, SRF injector



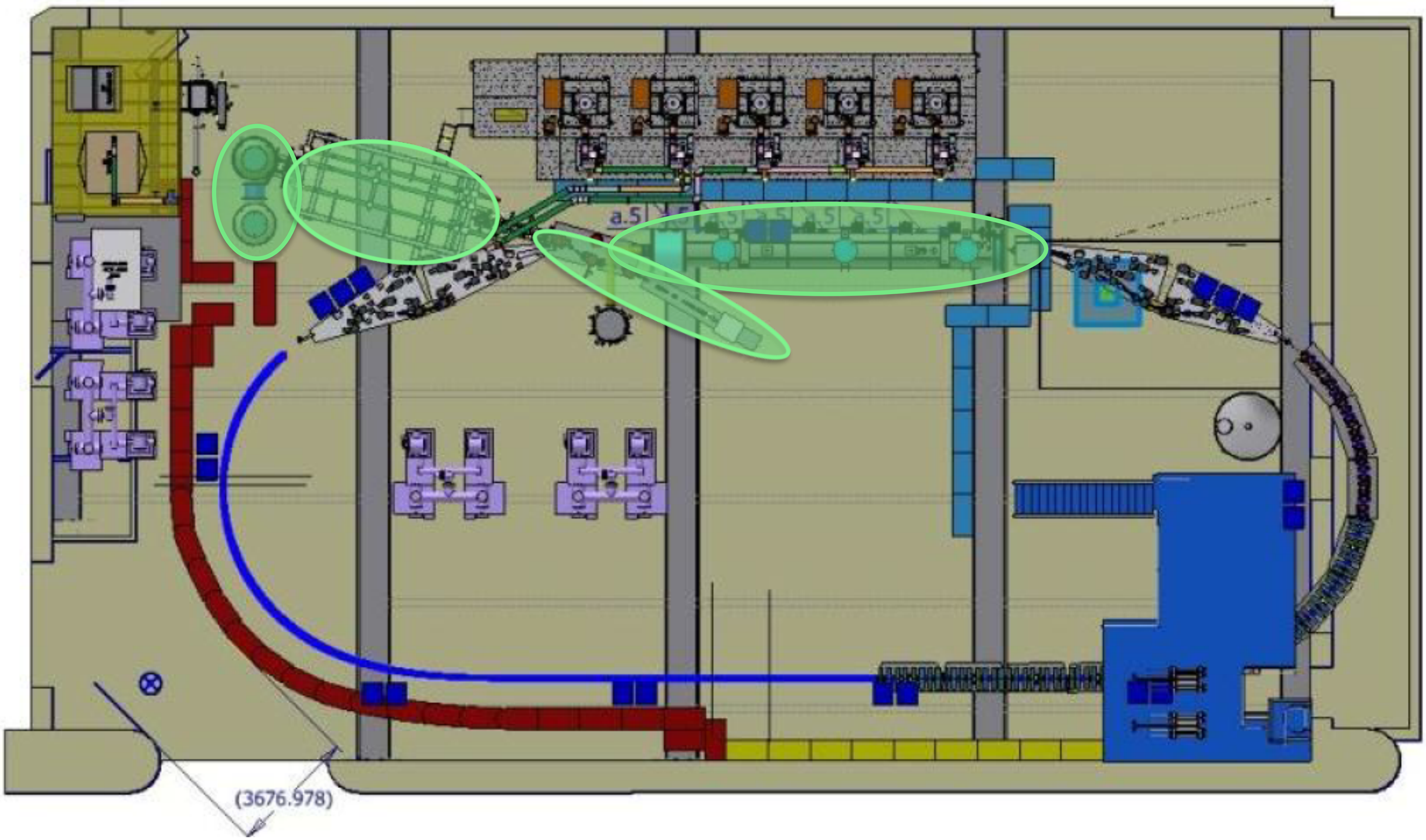
CBETA in its Hall L0E

Installed: DC gun, SRF injector, mirror diagnostics line



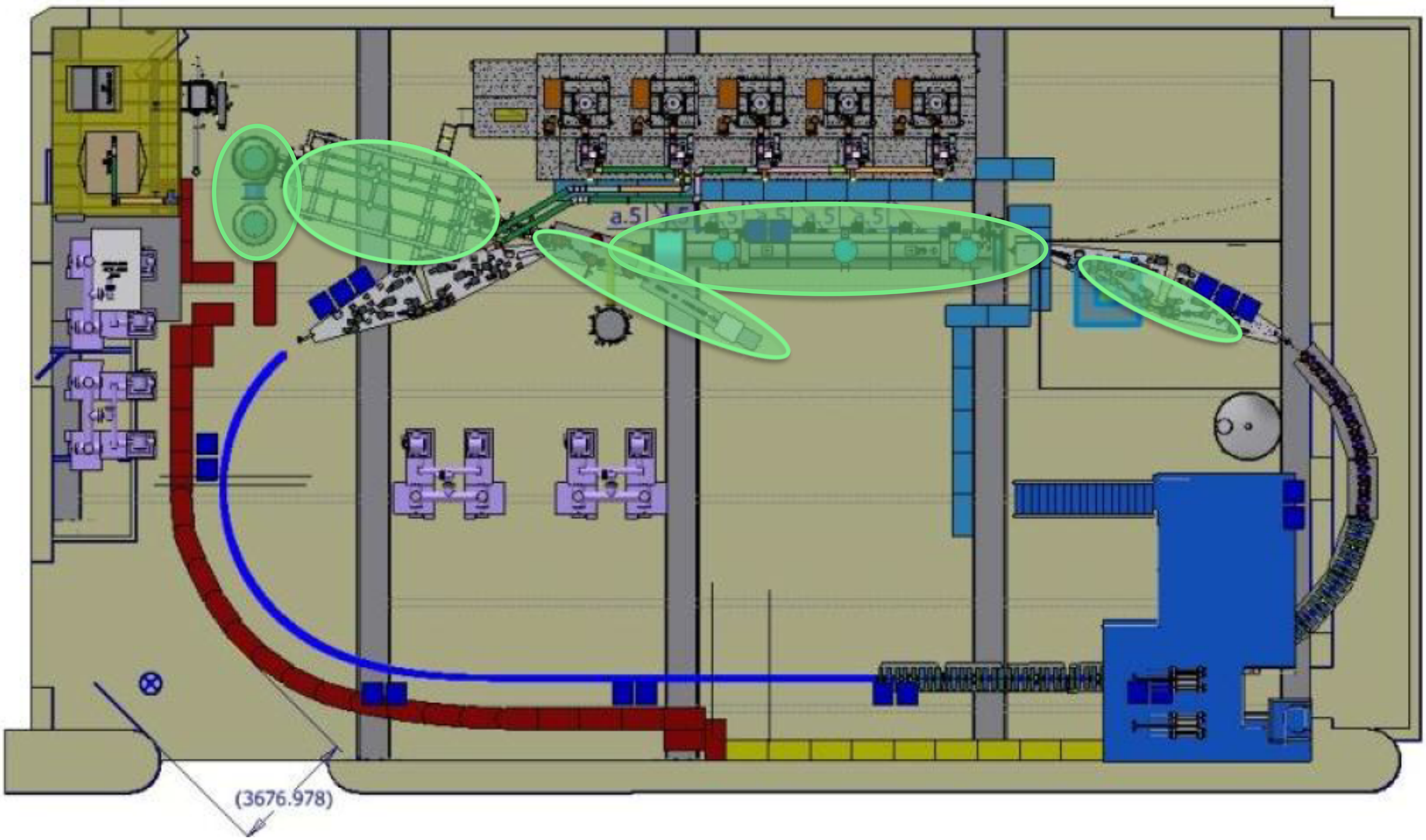
CBETA in its Hall L0E

Installed: DC gun, SRF injector, mirror diagnostics line, ERL cryomodule



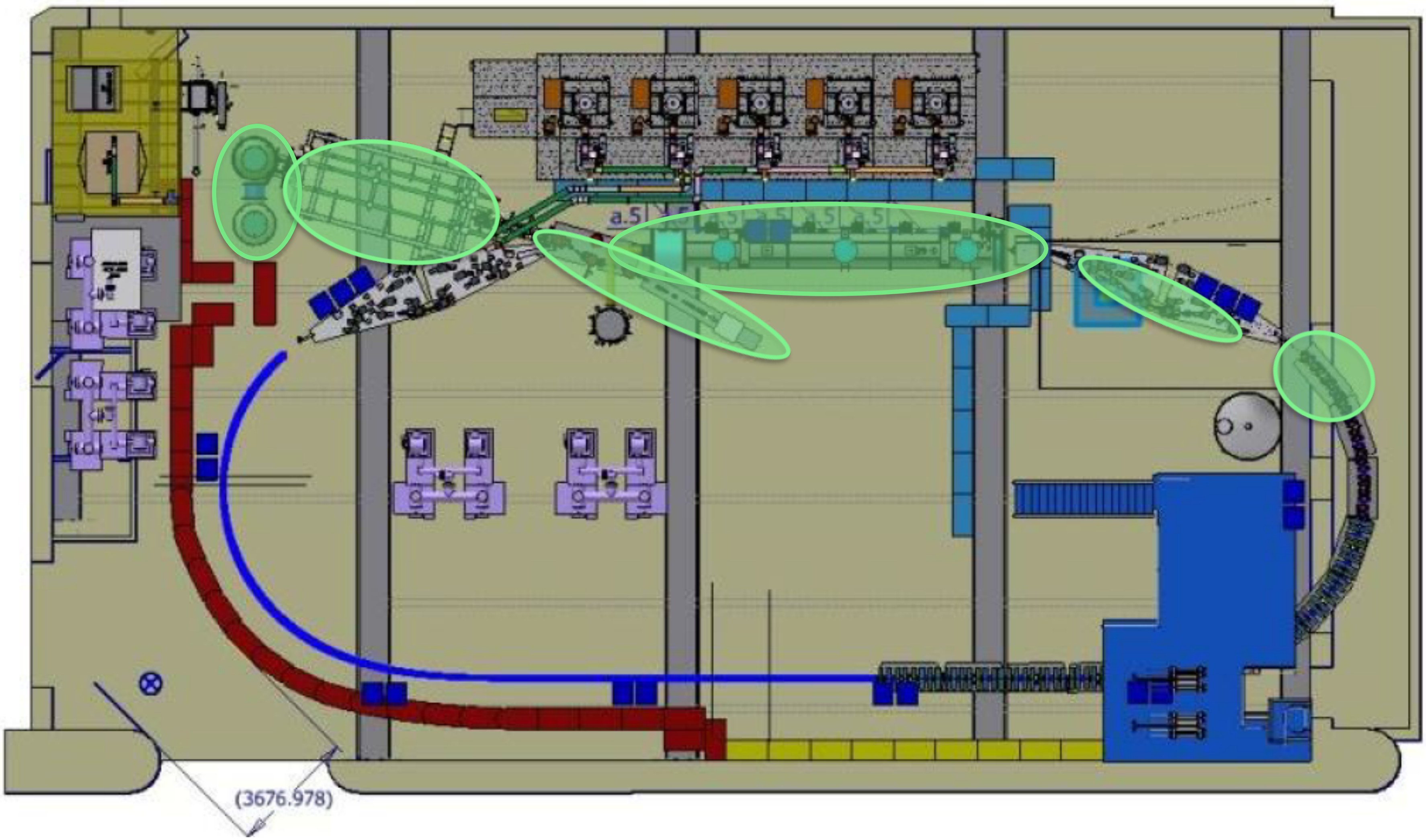
CBETA in its Hall L0E

Installed: DC gun, SRF injector, mirror diagnostics line, ERL cryomodule
1st splitter of 8

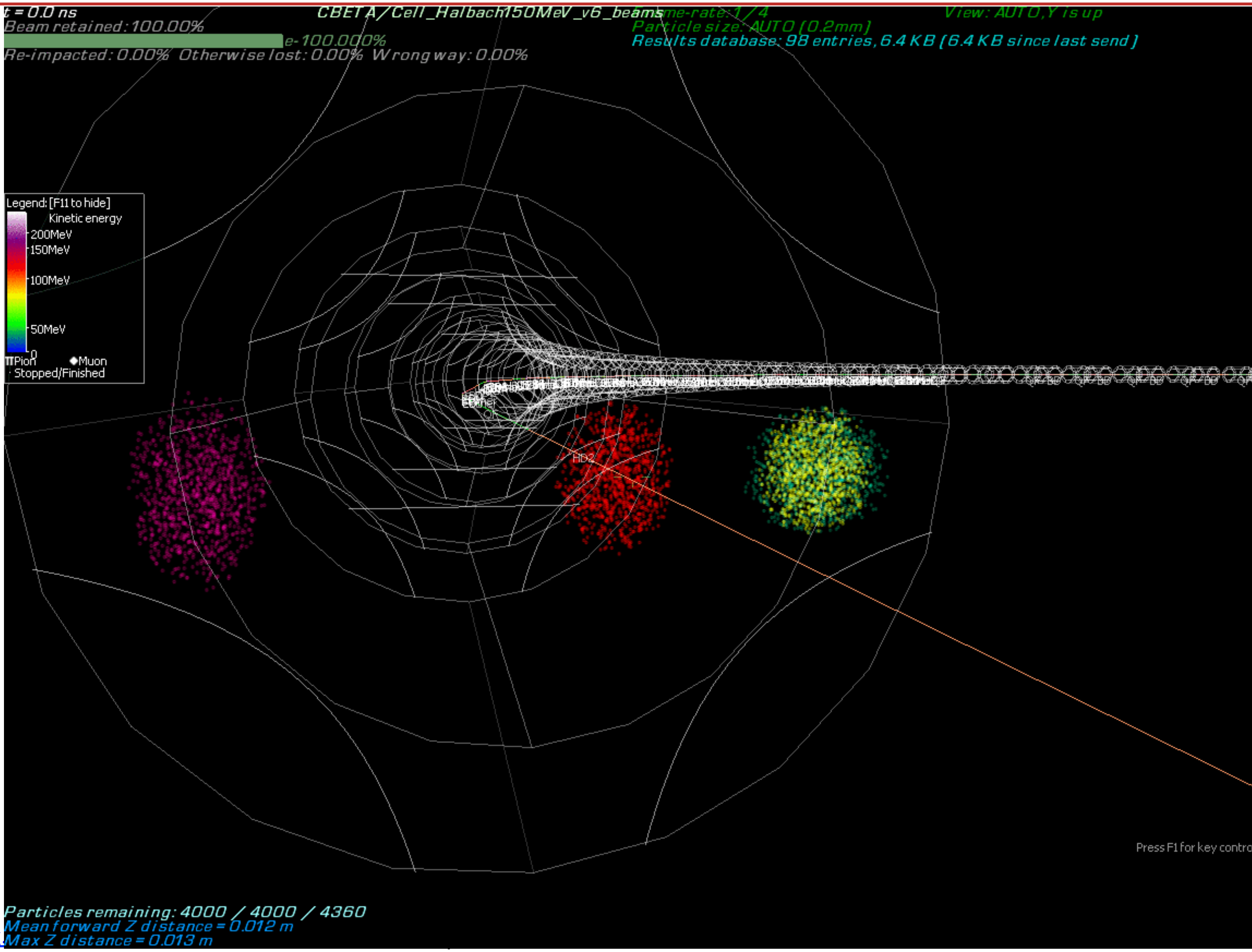


CBETA in its Hall L0E

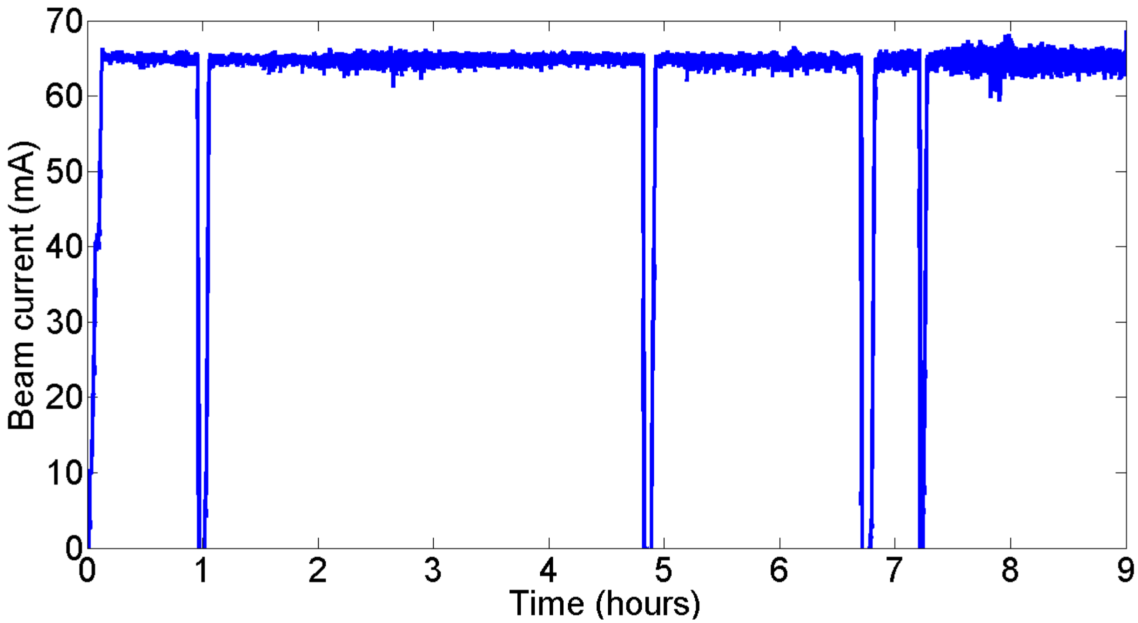
Installed: DC gun, SRF injector, mirror diagnostics line, ERL cryomodule
1st splitter of 8, 1st Fixed Field Alternating-gradient (FFA) girder of 25.



Bunche dynamics in 3D field maps



High Current Beams



- Peak current of 75mA (world record)

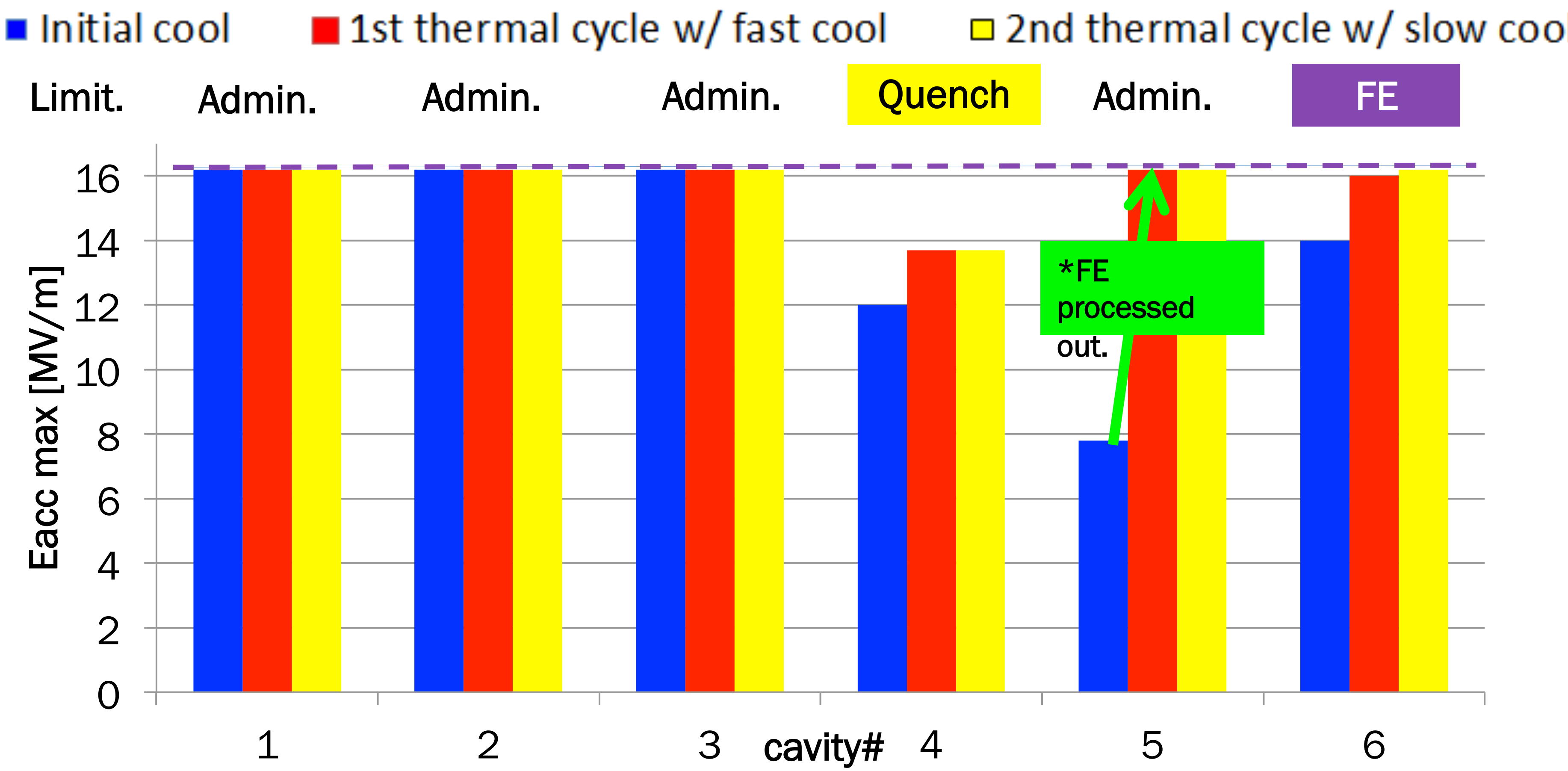
- NaKSb photocathode
- High rep-rate laser
- DC-Voltage source

Source achievements:
- 2.6 day 1/e lifetime at 65mA
- 8h at 65mA
- With only 5W laser power (20W are available)
- now pushing to 100mA

Simulations accurately reproduce photocathode performance with no free parameters, and suggest strategies for further improvement.

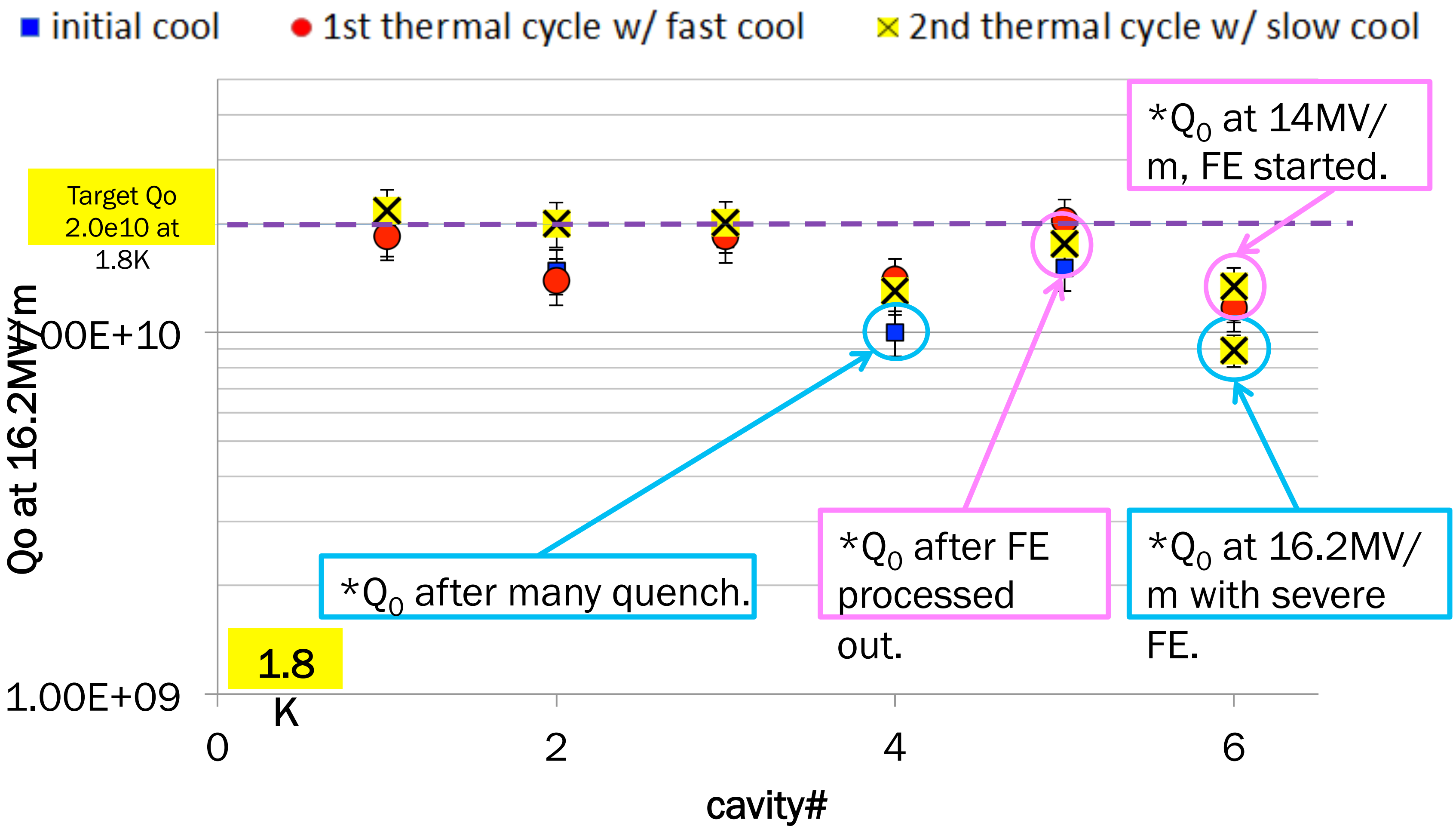
✓ Source current can meet ERL needs

Main linac cryomodule (MLC) achieved accelerating gradients



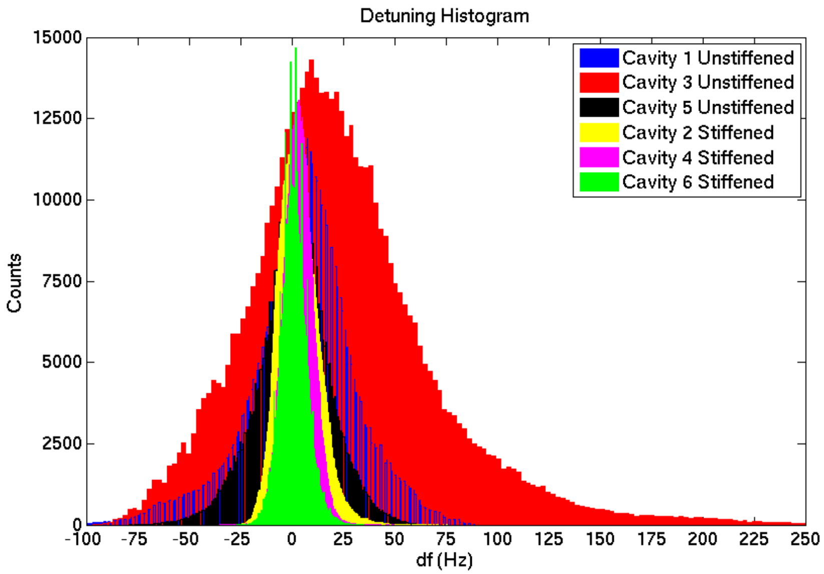
- 5 of 6 cavities had achieved design gradient of 16.2MV/m at 1.8K in MLC.
- Cavity#4 is limited by quench so far, no detectable radiation during test.
- Enough Voltage for 76MeV per ERL turn (where 36MeV are needed)

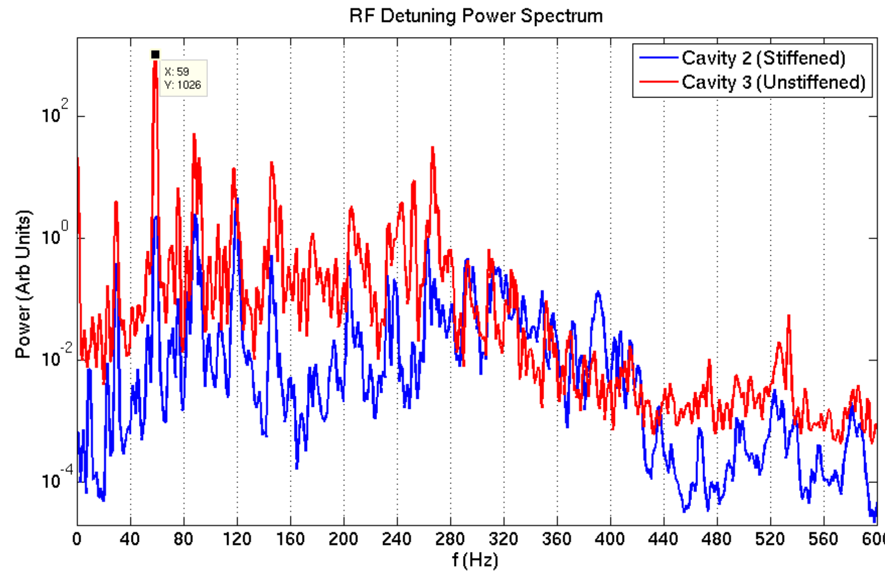
Main linac cryomodule (MLC) achieved surface losses (Q0)



- 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)**

RF Detuning Measurements





Preliminary results:

- Stiffened cavities have ~30Hz detuning, Un-stiffened cavities have ~150Hz detuning.
- Design specs are ~20Hz.
- Detuning spectrum showed large peaks at 60 Hz, 120 Hz.

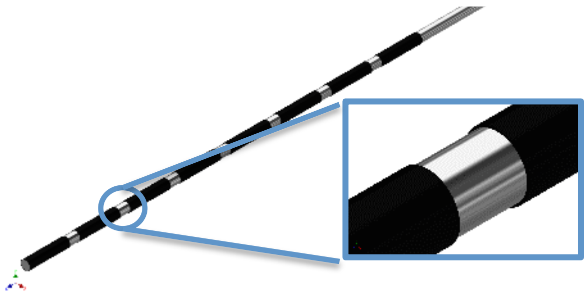
- **Enough Voltage for about 50MeV per ERL turn, if microphonics is not reduced (where 36MeV are needed)**

SRF microphonics stabilization

PhD work (Nilanjan Banerjee)
became essential for CBETA operation

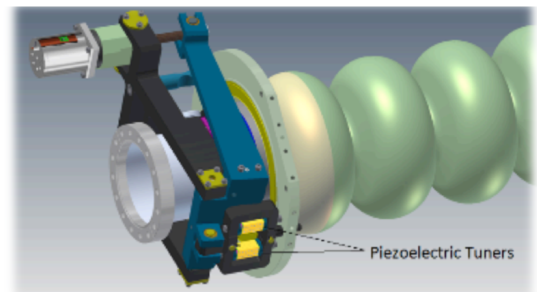
1) Specified 70 potential microphonic sources

2) Identified thermo-achoustic sources

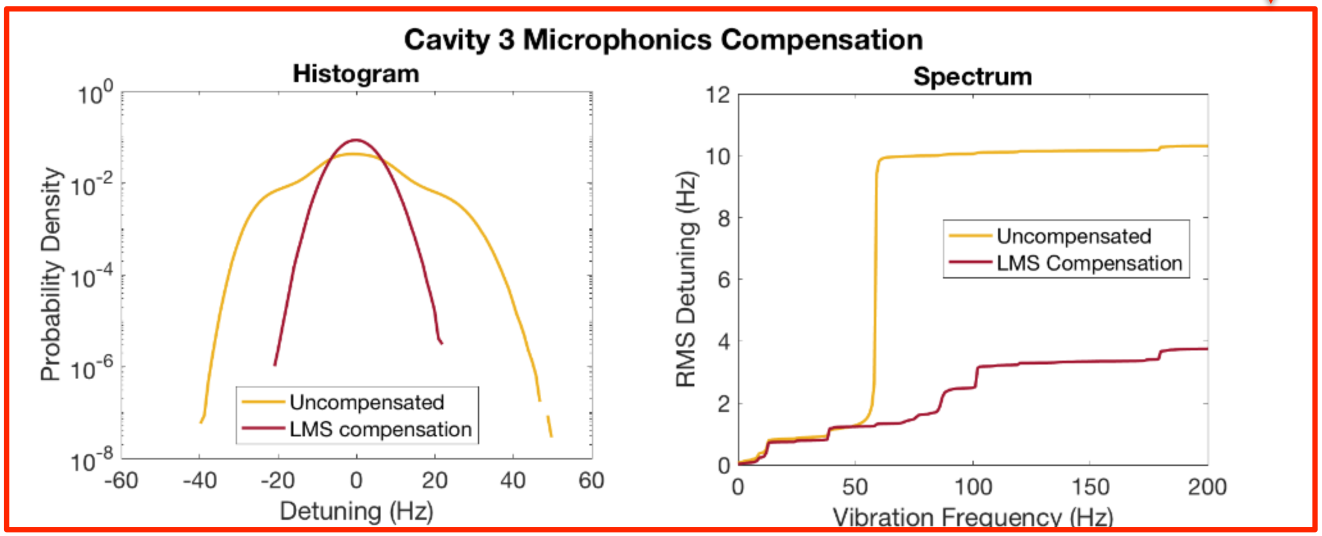


Valve Modification

2) Deigned piezo control software



Active Compensation

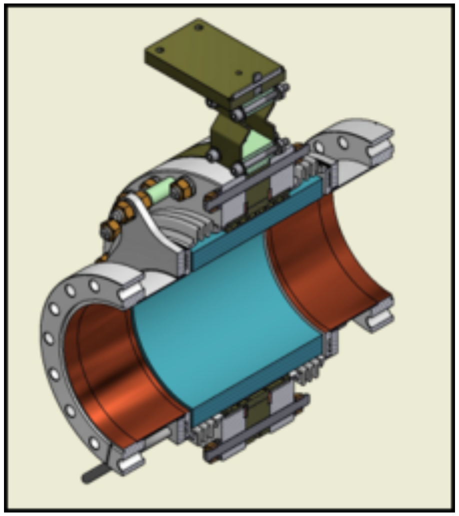


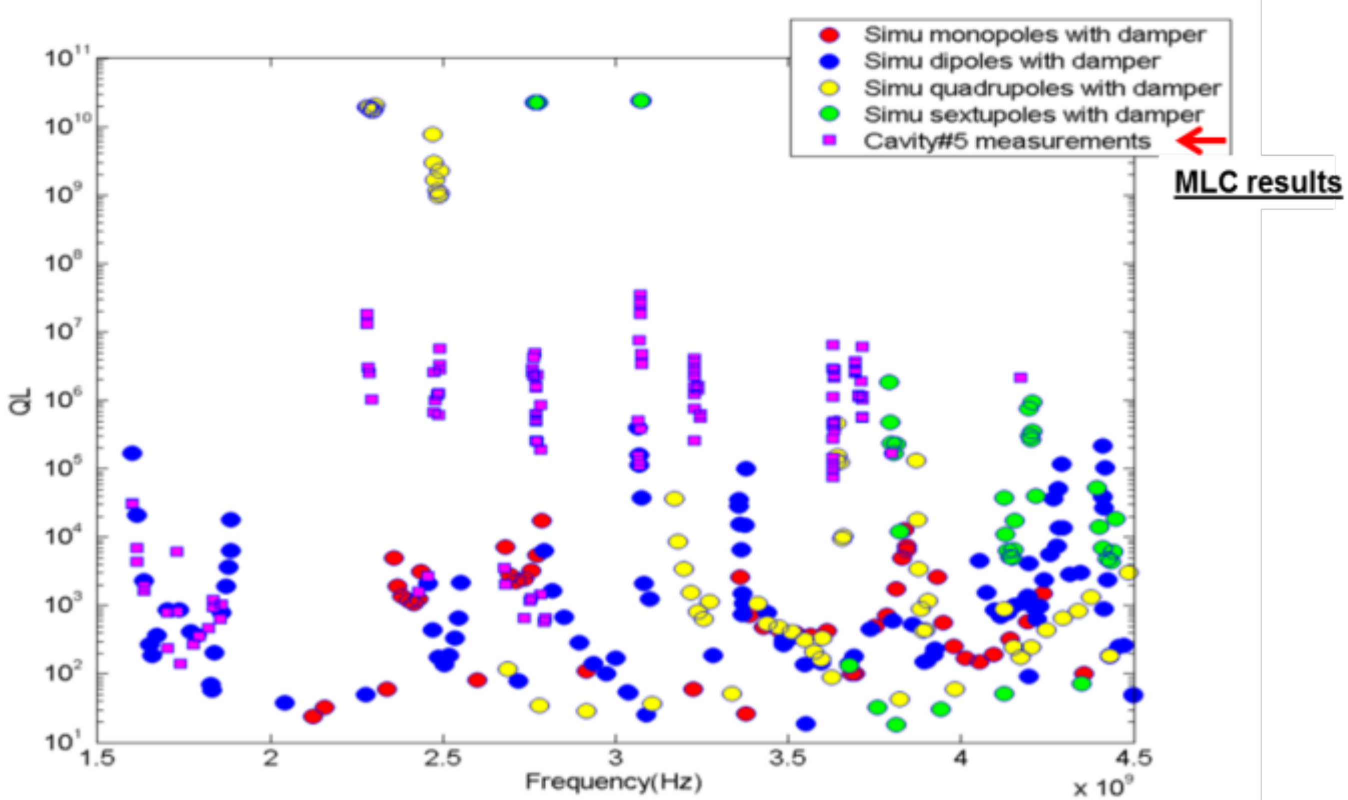
LCLS-II needs similar controls!

and we are in touch with LCLS-II teams at FNAL and JLAB.

Novel microphonics compensation reduces peak detuning by a factor of 2!

Current limits from HOMs



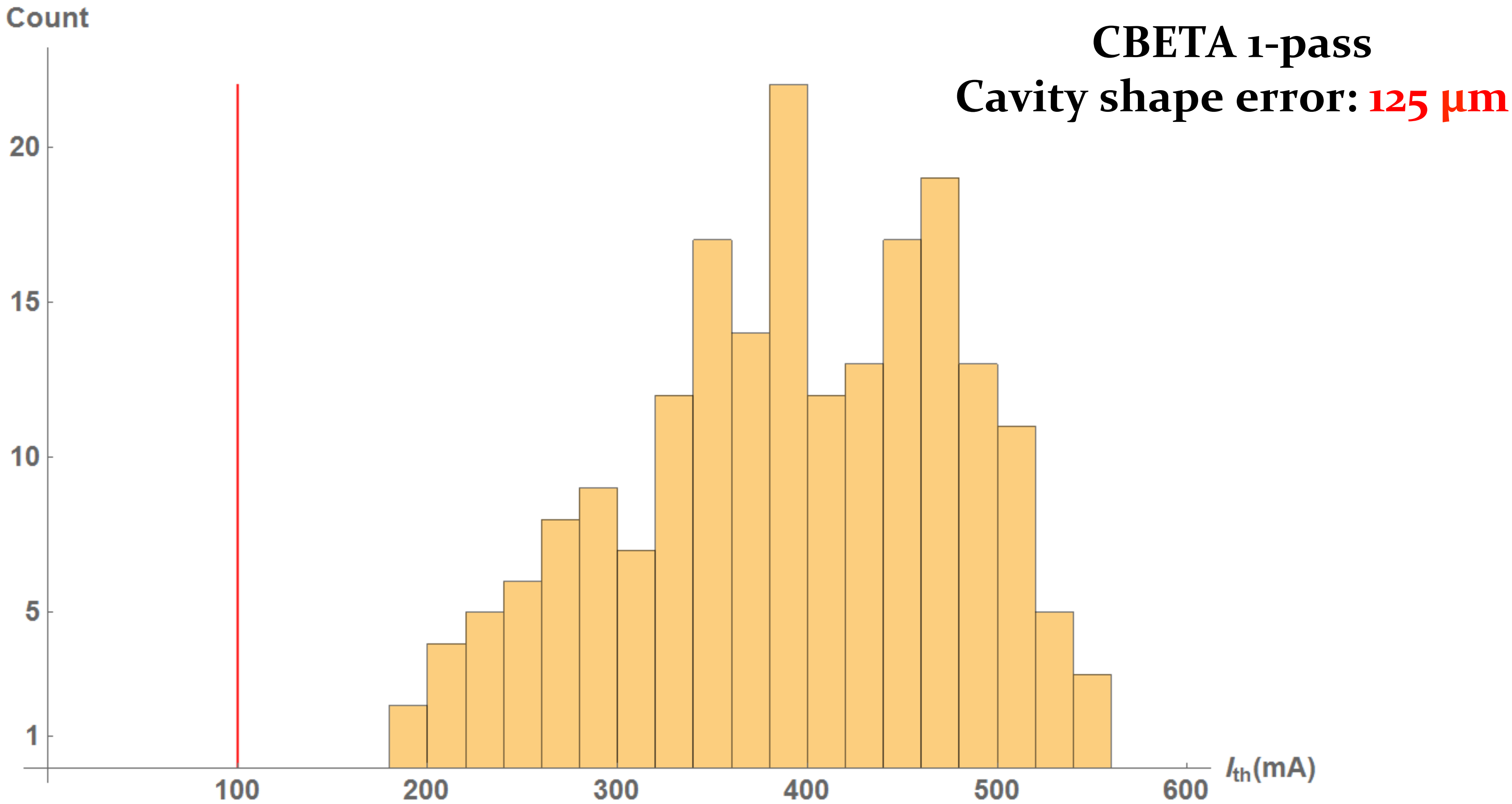


Dipole HOMs on MLC were strongly damped below Q~10⁴.
Consistent with HTC and simulation results.

HTC results were:

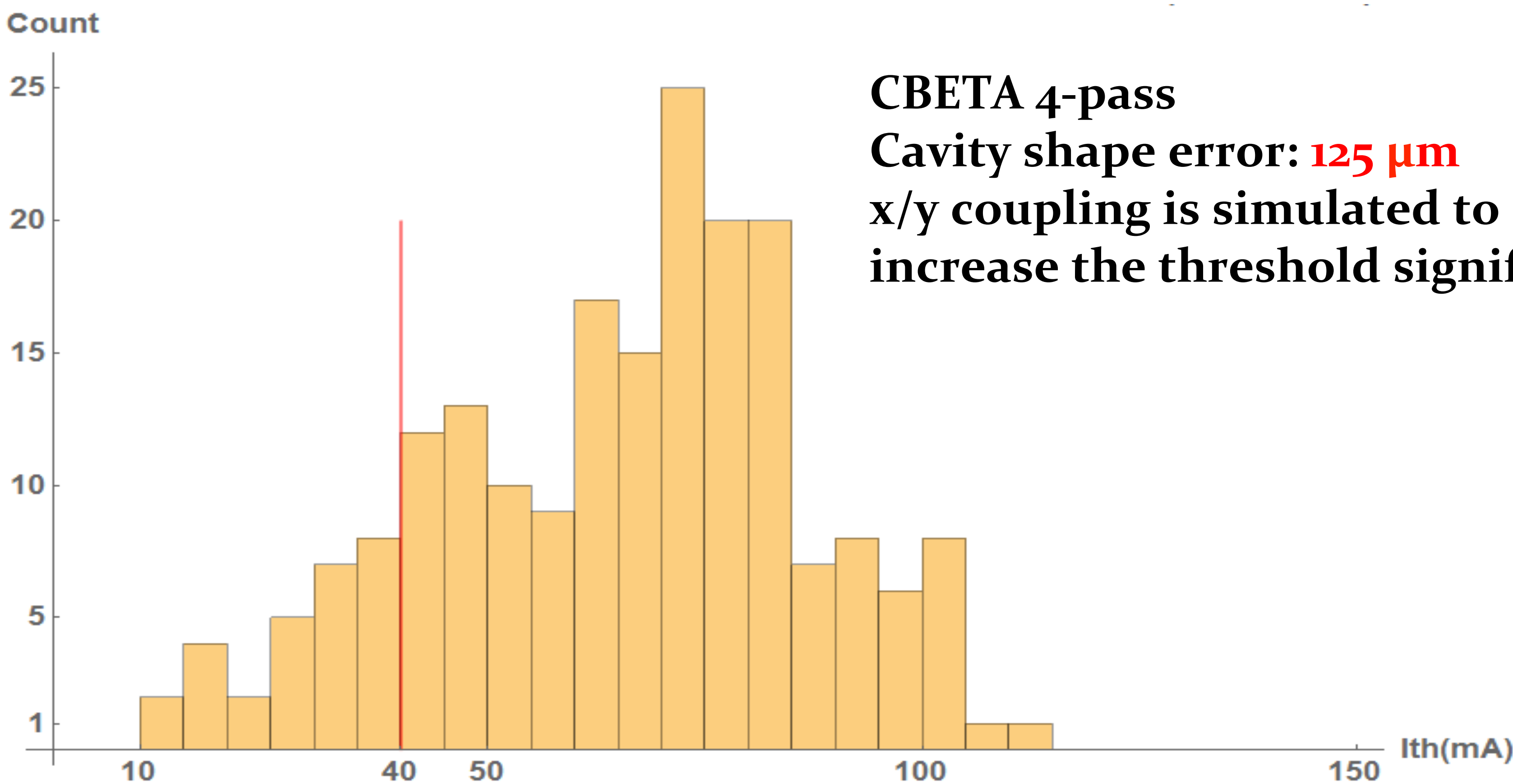
- **HOM heating: currents are limited to < 40mA in CBETA**
- **BBU no HOM limits BBU to below 100mA in one turn**

BBU for 1 pass in CBETA



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

BBU for 4 passes in CBETA



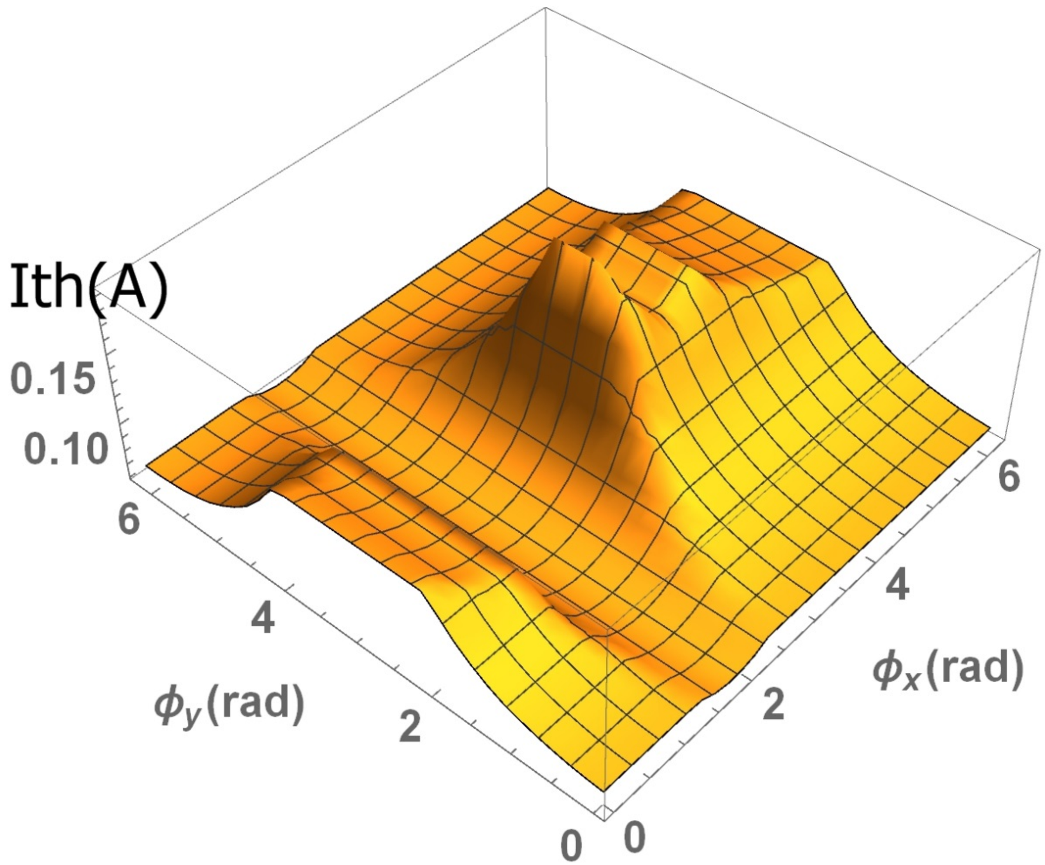
CBETA 4-pass
Cavity shape error: 125 µm
x/y coupling is simulated to increase the threshold significantly

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

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

4-path ERL with variable phases

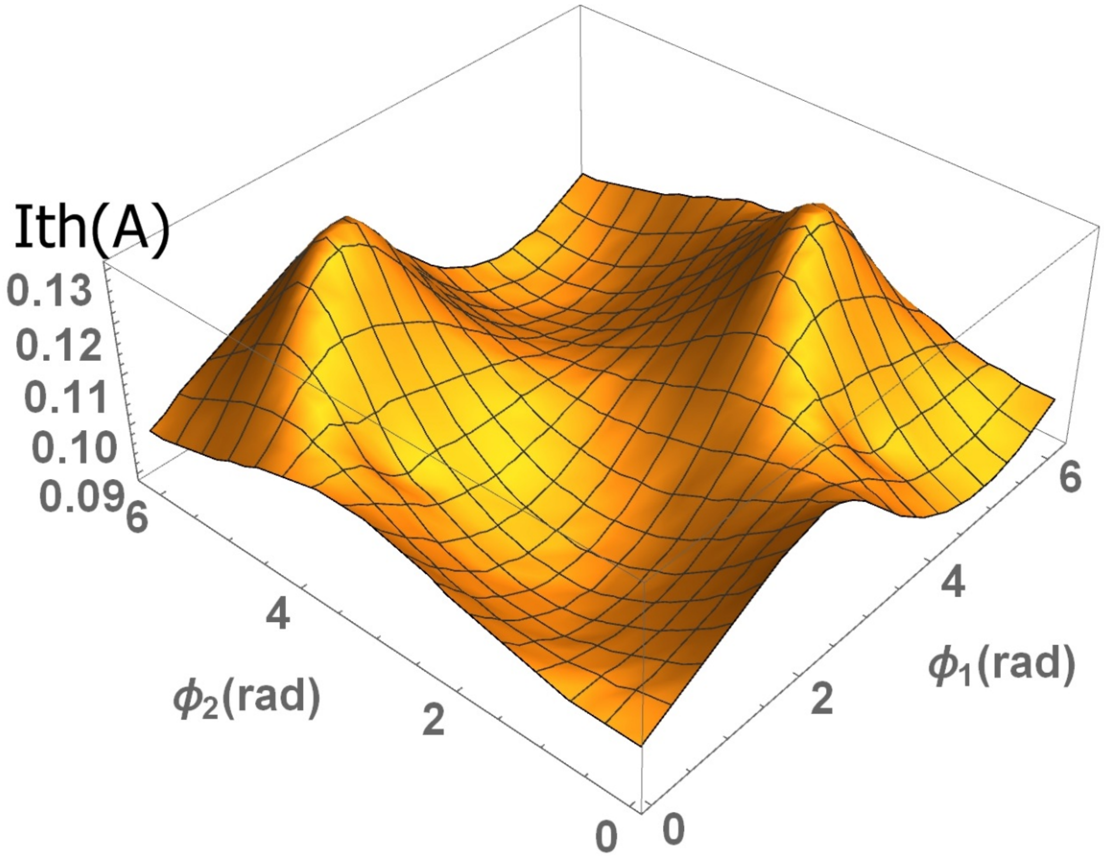
$I_{\rm th}$



Min = 61 mA
Max = 193 mA
Nominal = 69 mA

$I_{\rm th}$ results can improve

4-path ERL with x/y coupling



Min = 89 mA
Max = 131 mA
Nominal = 69 mA

I_{th} results can improve

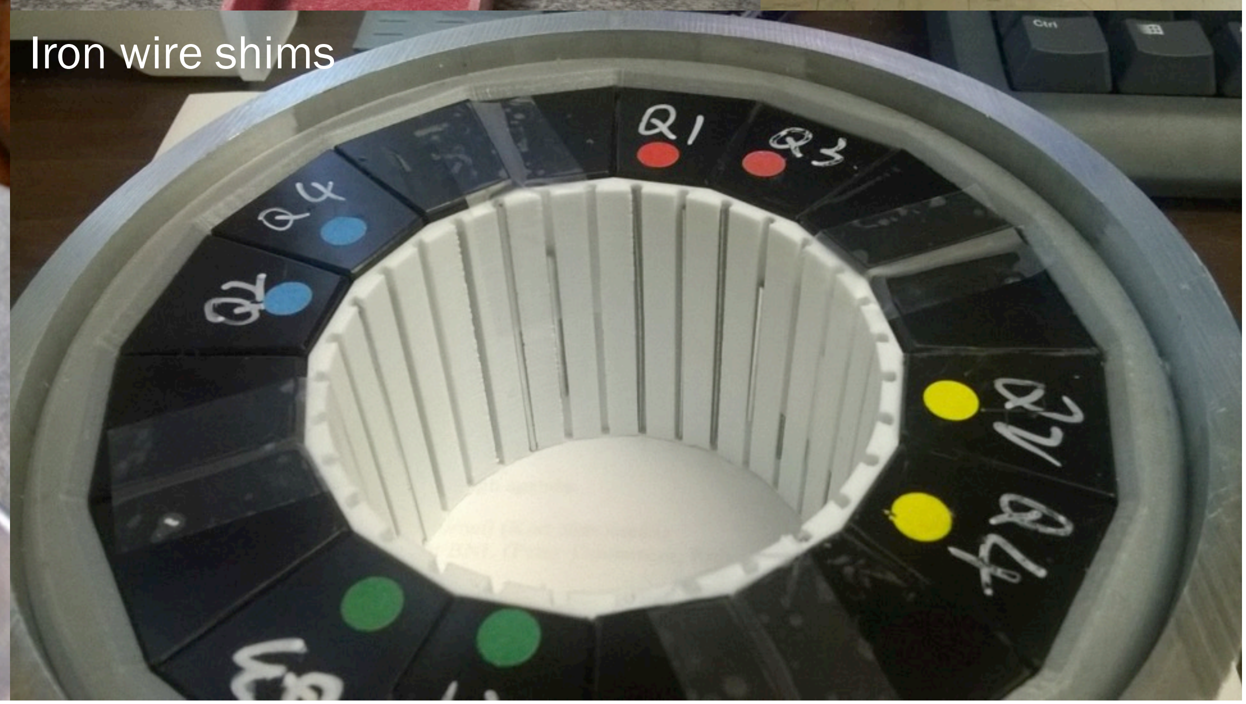
Conclusion: In 1-path ERLs the benefit from coupling and phase optimization can be significant. In multi-turn ERLs this benefit is much diminished.

12 proof-of-principle magnets (6 QF, 6 BD) have been built as part of CBETA R&D.
Iron wire shimming has been done on 3 QFs and 6 BDs with good results.


PoP BD


PoP QF


PoP magnet series

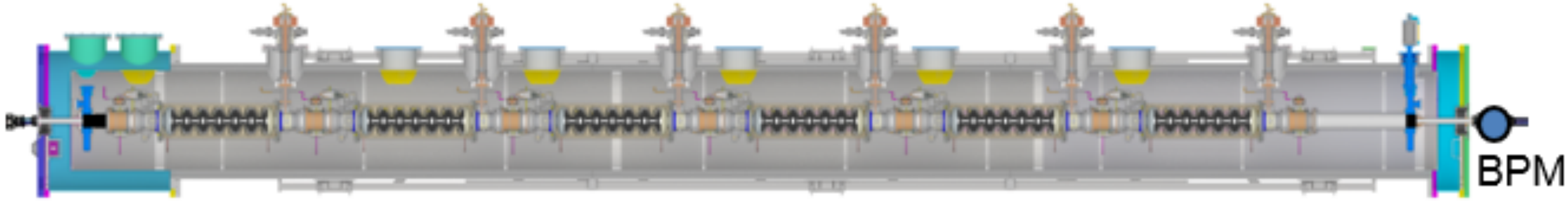

Iron wire shims

Energy gains in cavities

Cavity	Stiffened	Field (MV) Design (Peak)
1	No	6 (9.5)
2	Yes	6 (10)
3	No	6 (7.5)
4	Yes	6 (10)
5	No	6 (8.5)
6	Yes	6 (11.3)

We have reached and exceeded our specifications by ~50 %!

MLC Cavity Calibration



1) Beam enters at 6 MeV

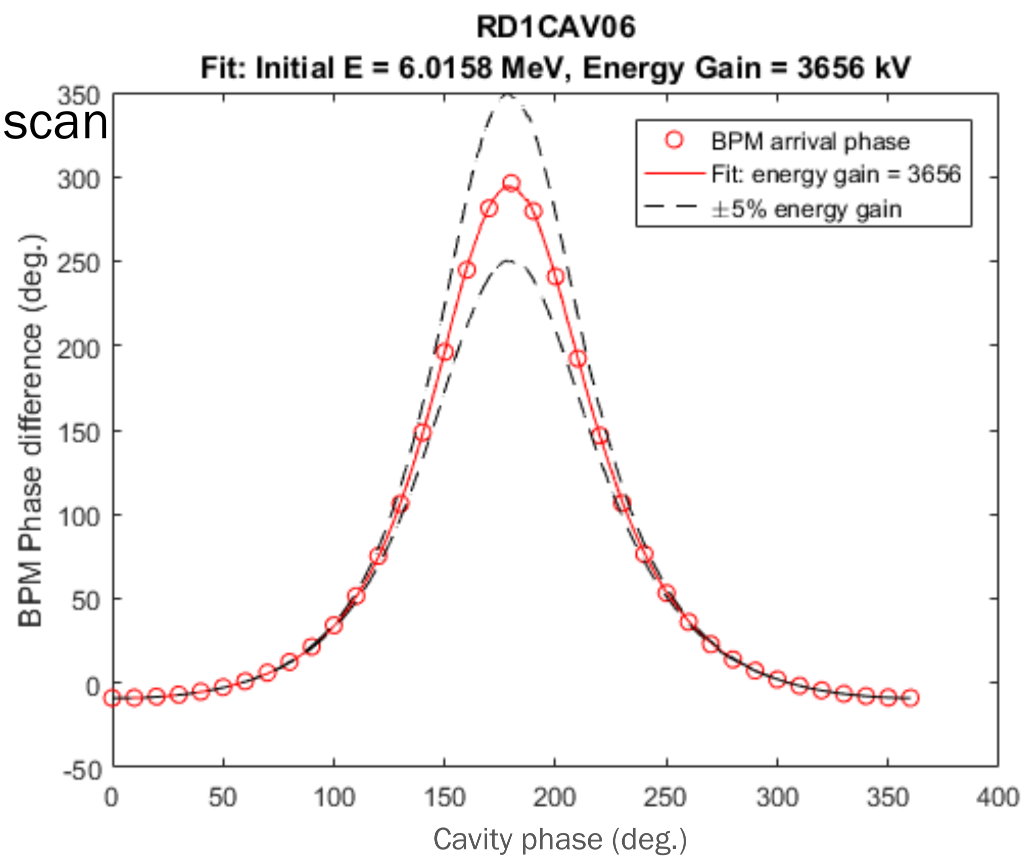
2) Set cavity to ~few MeV energy gain, scan phase 0-360º

3) Measure arrive time (phase) at downstream BPM

4) Fit to numerical model

Three fit parameters:

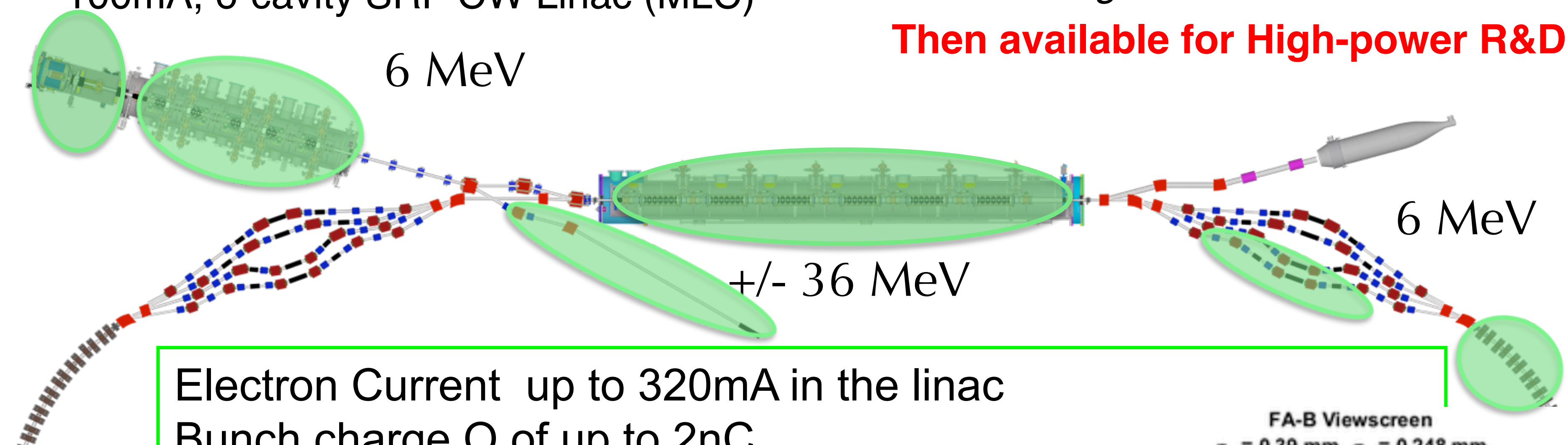
- Initial energy
- Cavity energy gain
- Overall phase



The test ERL in Cornell's hall LOE CBETA

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

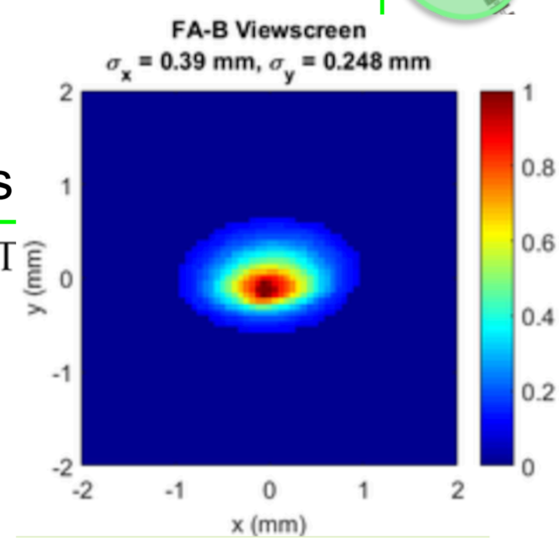
Existing components at Cornell
Investment value: $32M
Return loop closed with
NYS funding: $25
Then available for High-power R&D



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

CORNELL-BNL ERL TEST ACCELERAT

1st beam though all essential components:



Questions?