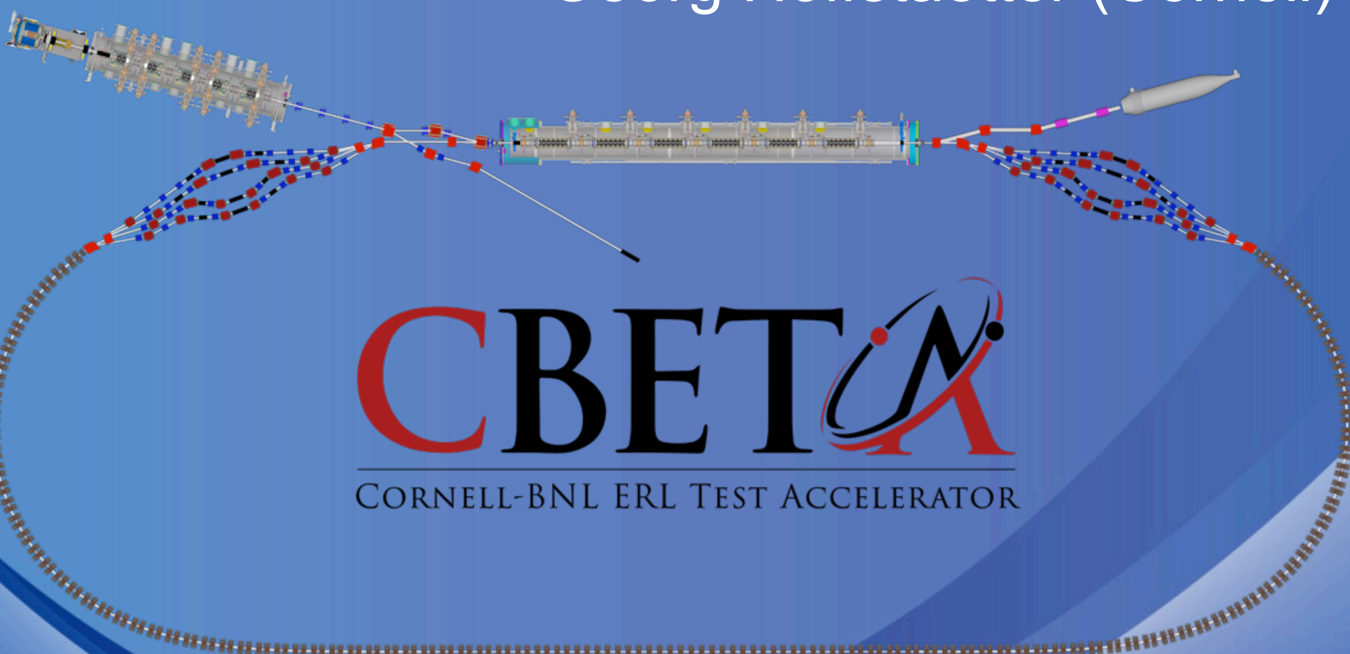
CBETA, an test facility for the EIC

JLAB, 1 November 2018

Georg Hoffstaetter (Cornell)



CBETA

CORNELL-BNL ERL TEST ACCELERATOR

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

Office of Science

U.S. DEPARTMENT OF ENERGY

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

Message

- The accelerator I am presenting has beam parameters of an 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 NS FFA loop with large (x4) momentum aperture
  - has the first long-distance beam through Halbach magnets
  - has the largest electron beam power in an ERL

- It is being constructed in a Cornell/BNL collaboration and its main components have been beam-tested.

- It is commissioned in a world-wide collaboration, incl. JLAB, and an international ERL Technology Collaboration formed that supports such work.

- It has applications beyond EIC research

High Beam Current at Reduced Cost

By **recovering the Energy** of accelerated beams, Energy Recovery Linacs (ERLs) make **large beam powers** possible that would otherwise be prohibitively expensive.

Linacs produce **high beam qualities** for scientific experiments and for industrial applications, but their **beam power is limited** by the available electrical power.

ERLs surpass this power limit: much larger beam currents and beam powers become available because the beam energy is recaptured.

How do ERLs compare to other accelerators?

(a) **high currents**, like storage rings, because the energy is recovered,

(b) **high beam quality** (low emittance, bunch length, and energy spread) like linacs, because each bunch traverses it only once,

(c) **tolerates beam disruption** as each bunch is used only once before it's discarded.

All these strengths of ERLs are beneficial to EIC cooling and for other high beam-intensity applications!

ERLs projects: Electron Ion Colliders

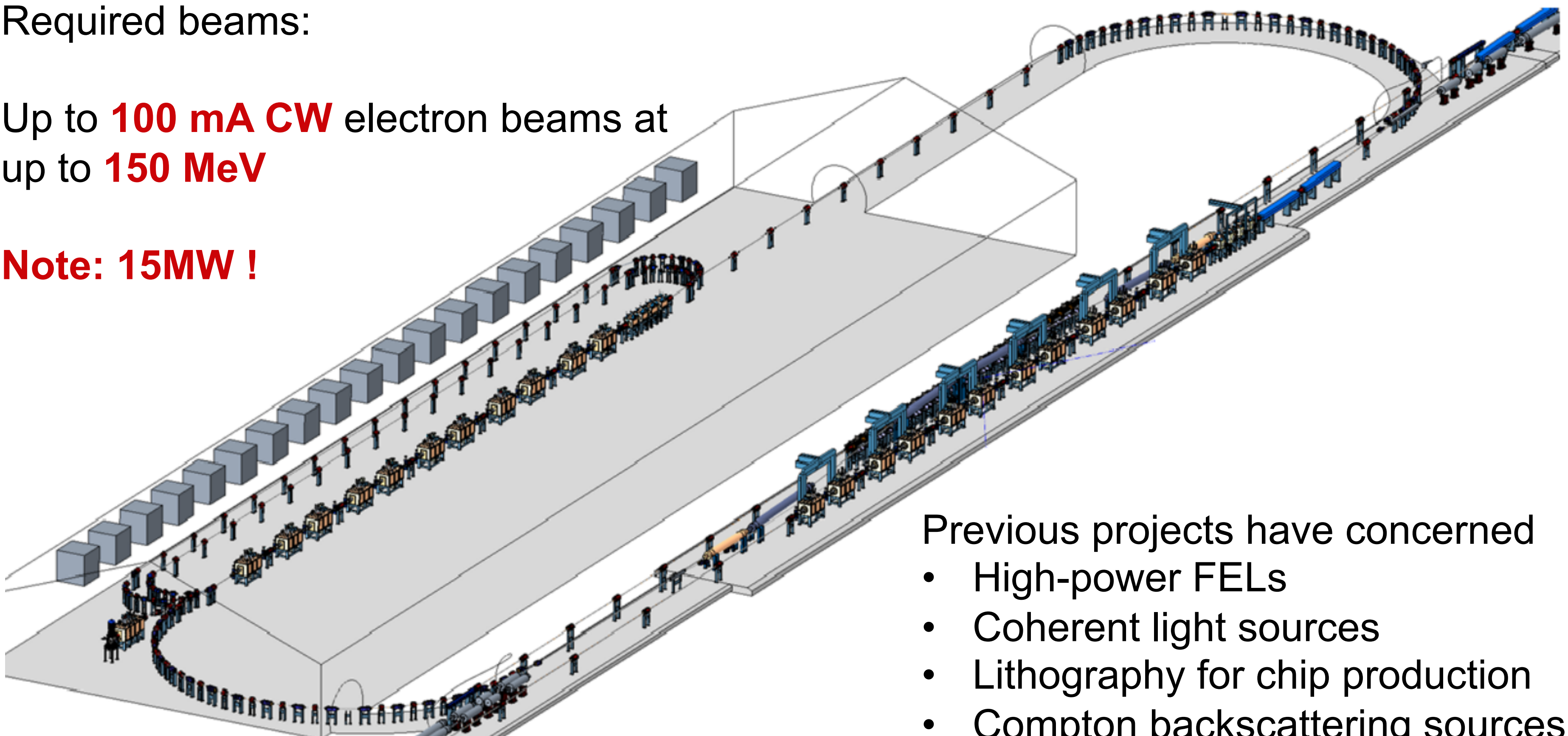
Strong Hadron Cooling for EICs

Both EIC projects, the one at BNL and the one at JLAB, plan to cool the hadron beam with electrons.

Required beams:

Up to **100 mA CW** electron beams at up to **150 MeV**

Note: 15MW !



Previous projects have concerned

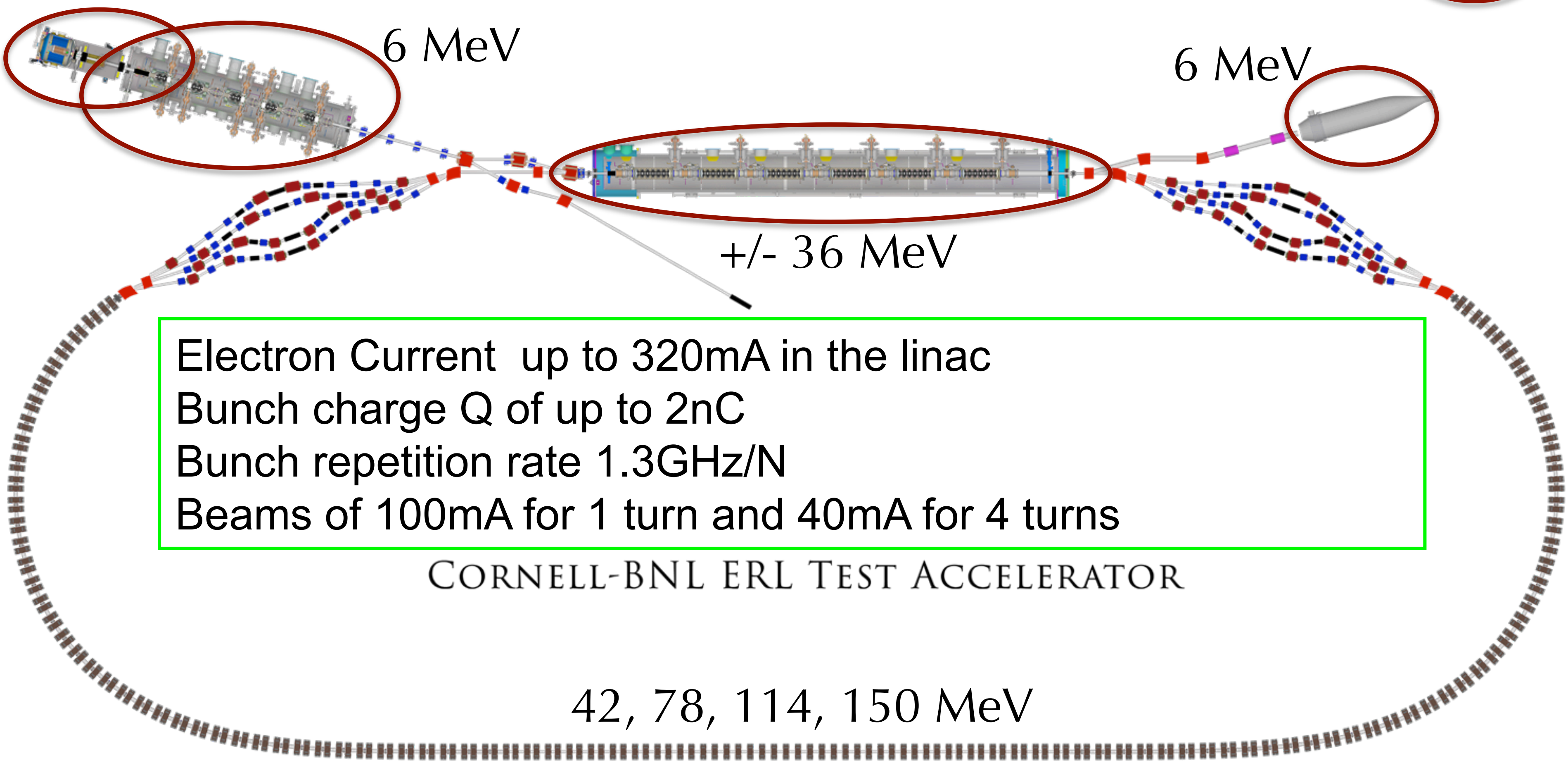
- High-power FELs
- Coherent light sources
- Lithography for chip production
- Compton backscattering sources

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



Previous funding leading to CBETA

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

2012 PD-Design on a hard x-ray 5GeV Cornell ERL, *not built.*

2013 Cornell's ERL injector achieved world record brightness.

2014 White paper for CBETA in Cornell / BNL collaboration.

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!

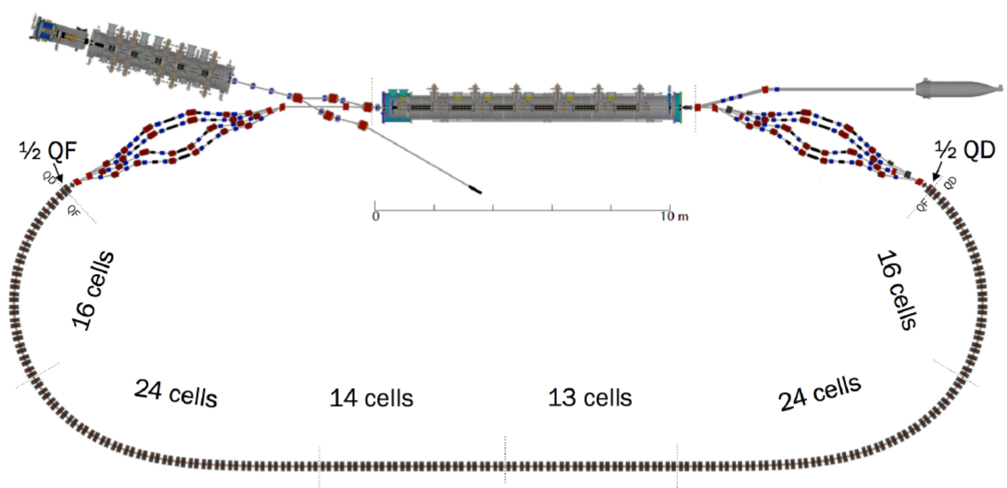
CBETA Design Report

Cornell-BNL ERL Test Accelerator

Principle Investigators: G.H. Hoffstaetter, D. Trbojevic

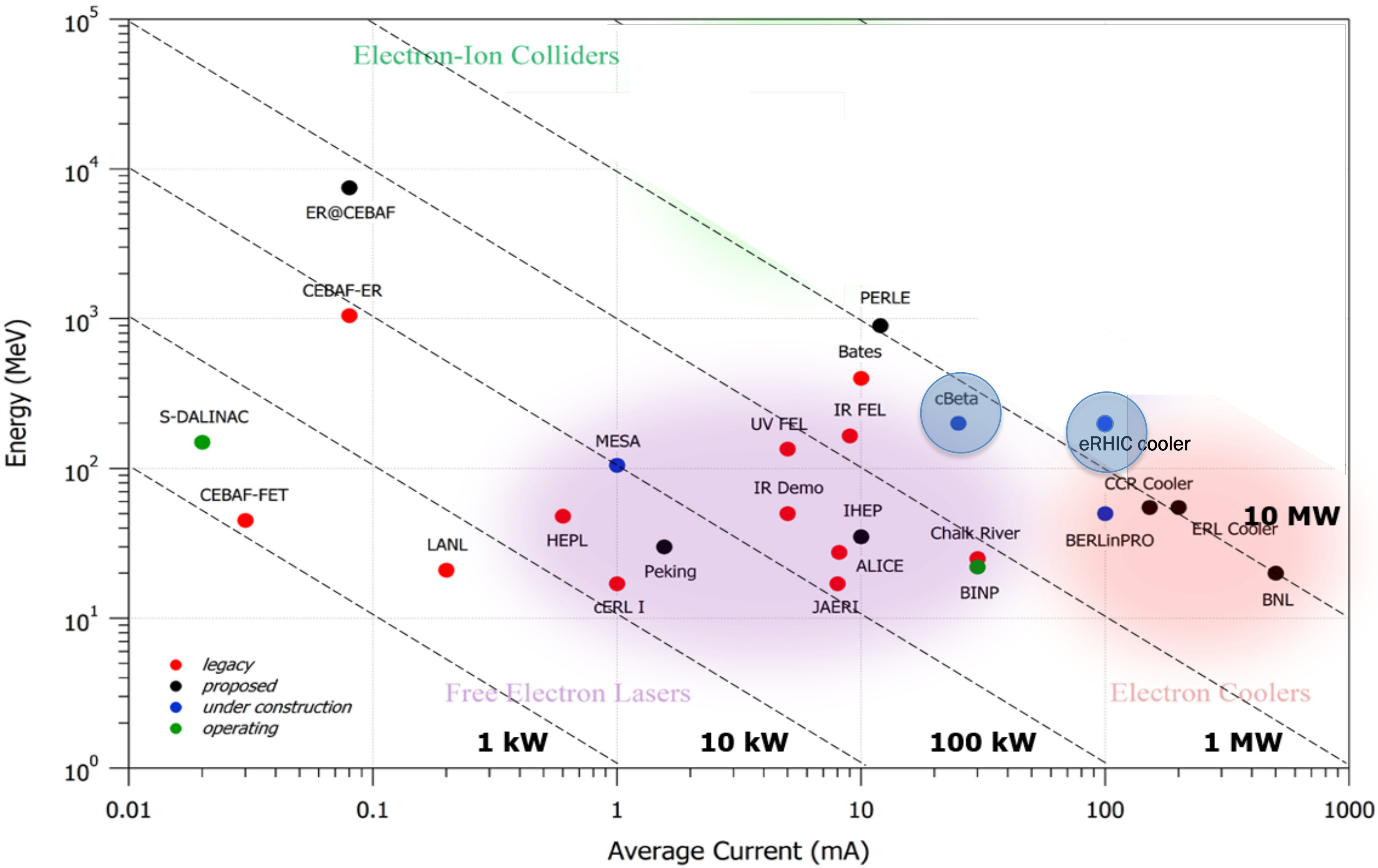
Editor: C. Mayes

Contributors: N. Banerjee, J. Barley, I. Bazarov, A. Bartnik, J. S. Berg, S. Brooks, D. Burke, J. Crittenden, L. Cultrera, J. Dobbins, D. Douglas, B. Dunham, R. Eichhorn, S. Full, F. Furuta, C. Franck, R. Gallagher, M. Ge, C. Gulliford, B. Heltsley, D. Jusic, R. Kaplan, V. Kostroun, Y. Li, M. Liepe, C. Liu, W. Lou, G. Mahler, F. Méot, R. Michnoff, M. Minty, R. Patterson, S. Peggs, V. Ptitsyn, P. Quigley, T. Roser, D. Sabol, D. Sagan, J. Sears, C. Shore, E. Smith, K. Smolenski, P. Thieberger, S. Trabocchi, J. Tuozzolo, N. Tsoupas, V. Veshcherevich, D. Widger, G. Wang, F. Willeke, W. Xu



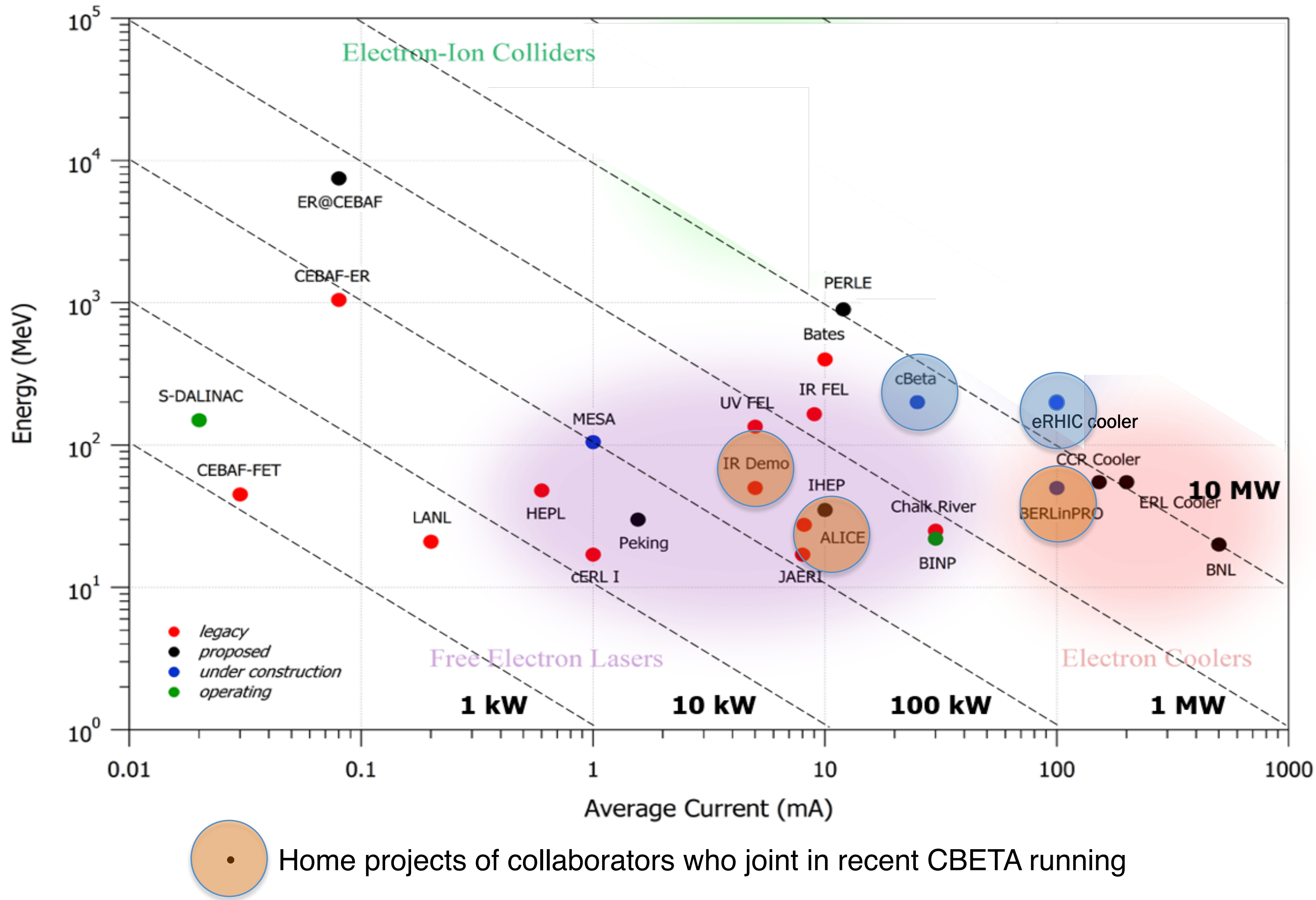
June 8, 2017

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

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

Hall L0E before CBETA

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

L0E cleaned with CBETA

Installation milestones

International Journal of High-Energy Physics

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Feb 16, 2018

Small accelerator promises big returns

Under construction in the US, the CBETA multi-turn energy-recovery linac will pave the way for accelerators that combine the best of linear and circular machines.

The main linac cryomodule

DIGITAL EDITION

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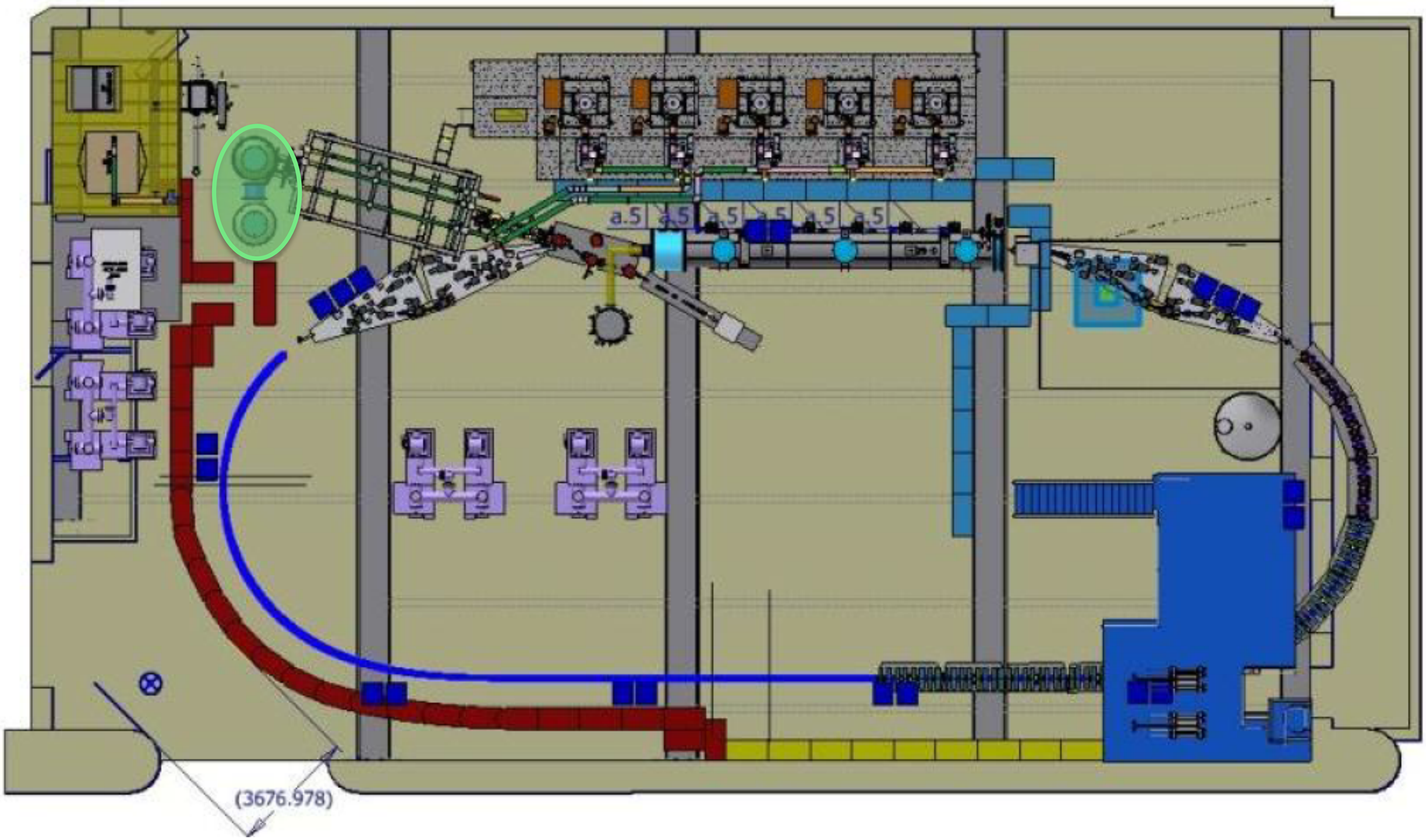
KEY SUPPLIERS

FEATURED COMPANIES

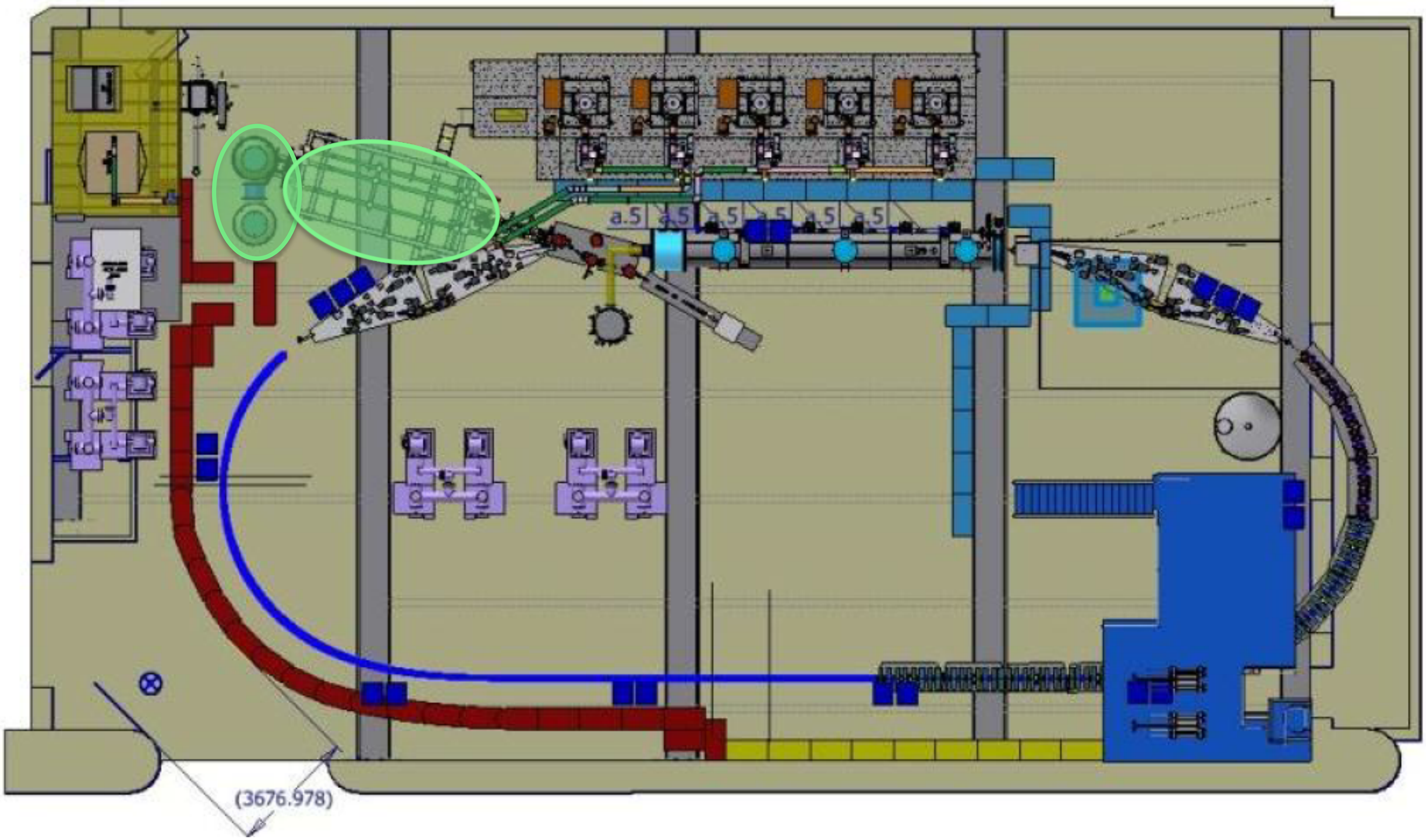
CBETA in its Hall L0E

Installed: DC gun



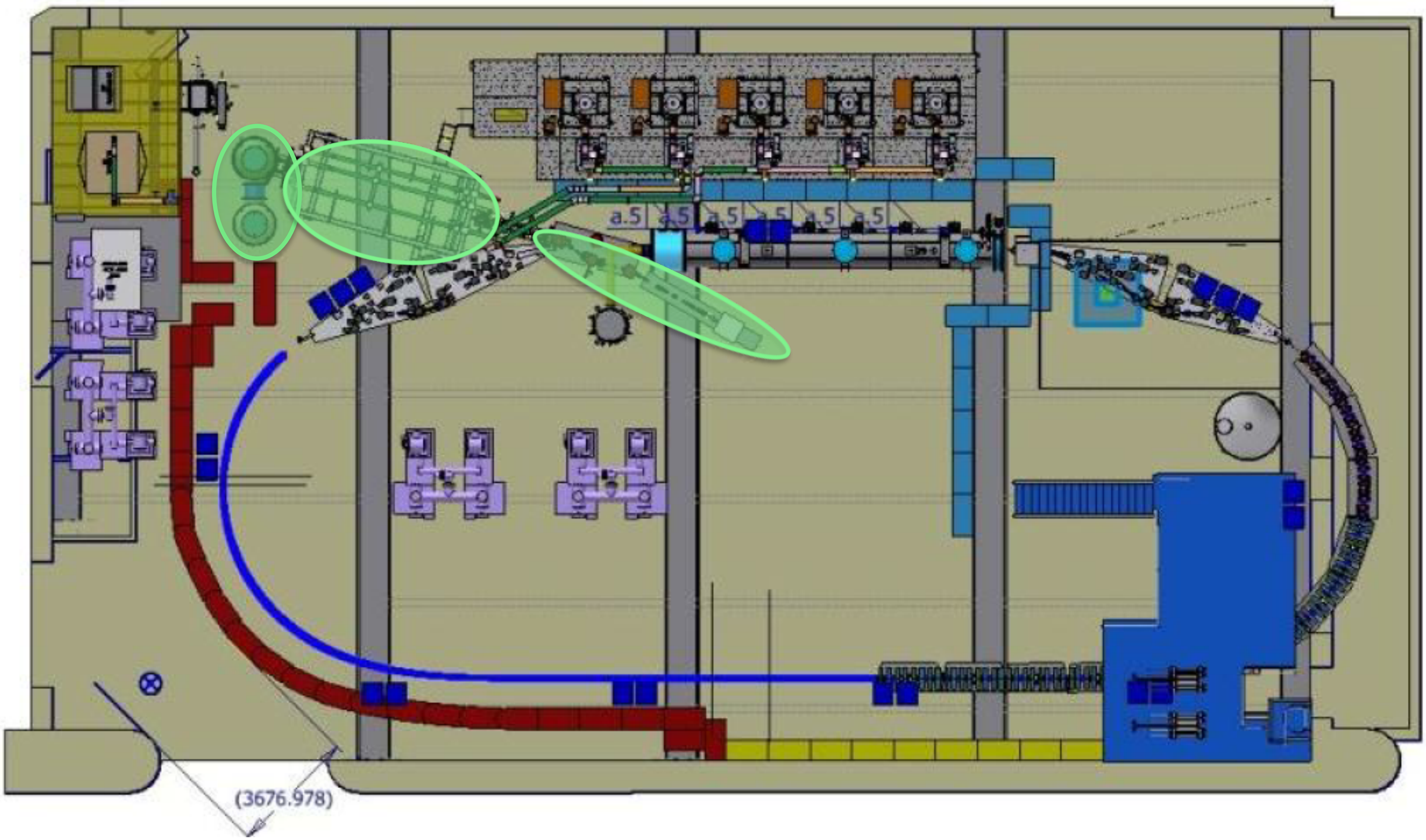
CBETA in its Hall L0E

Installed: DC gun, SRF injector



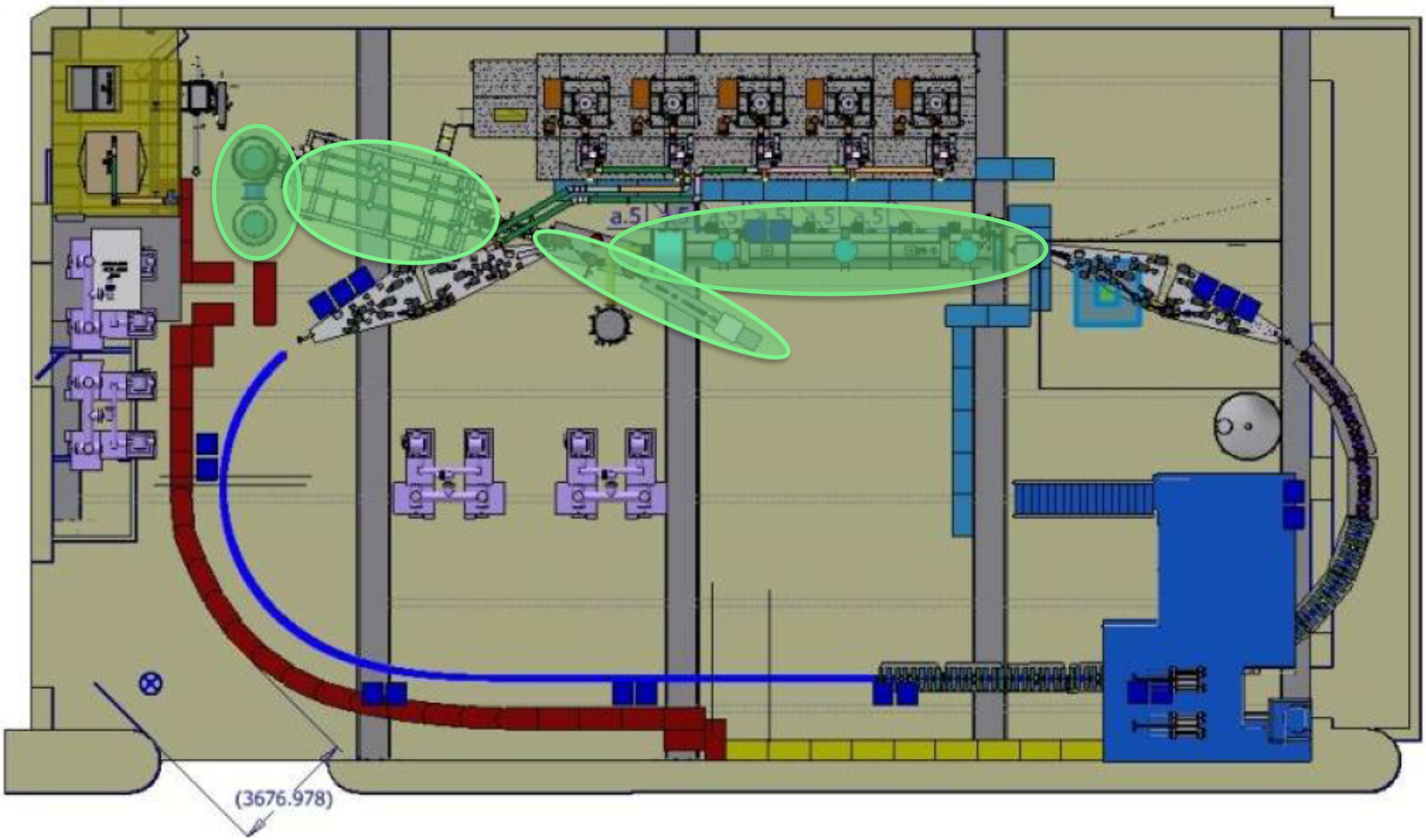
CBETA in its Hall L0E

Installed: DC gun, SRF injector, mirror diagnostics line



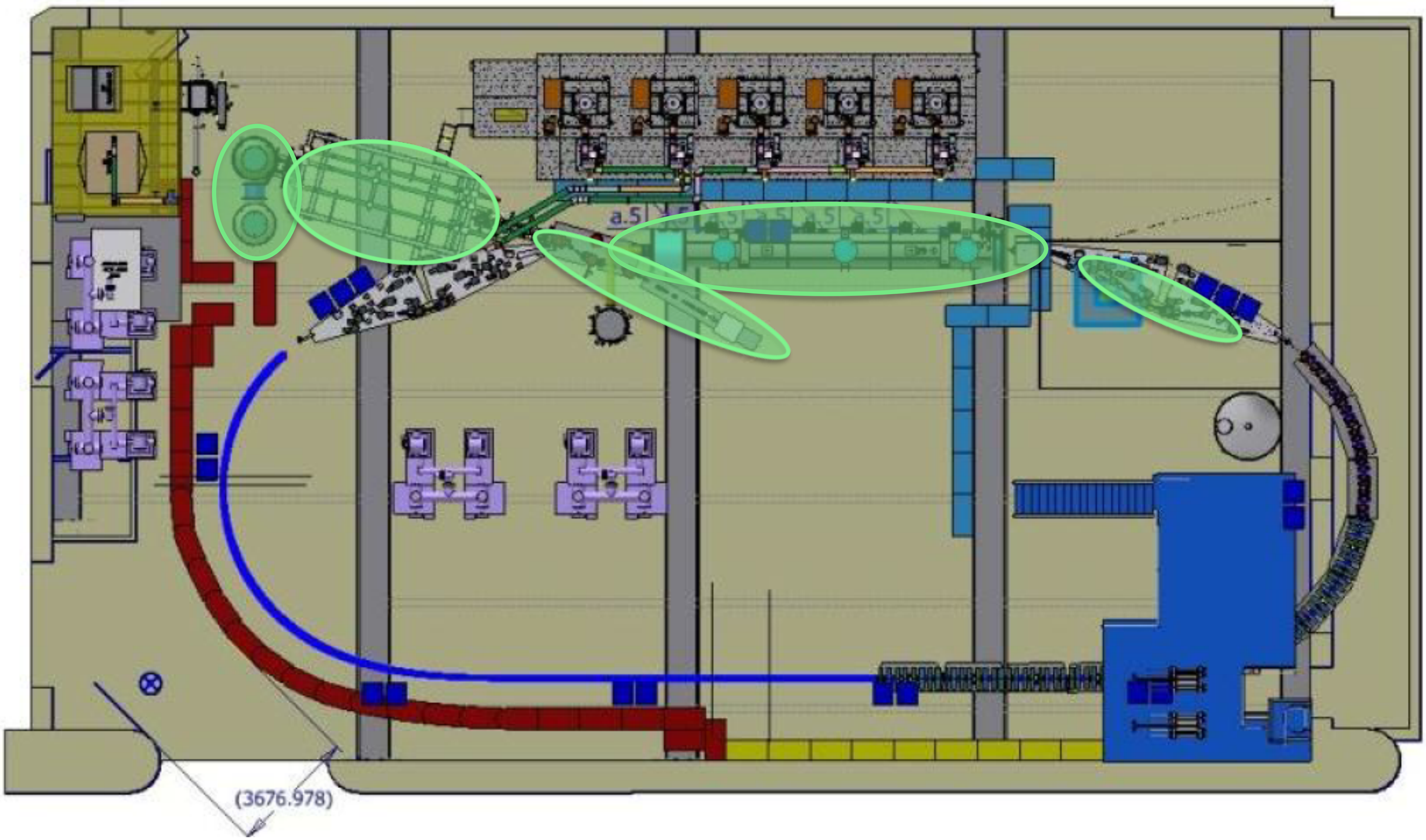
CBETA in its Hall L0E

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



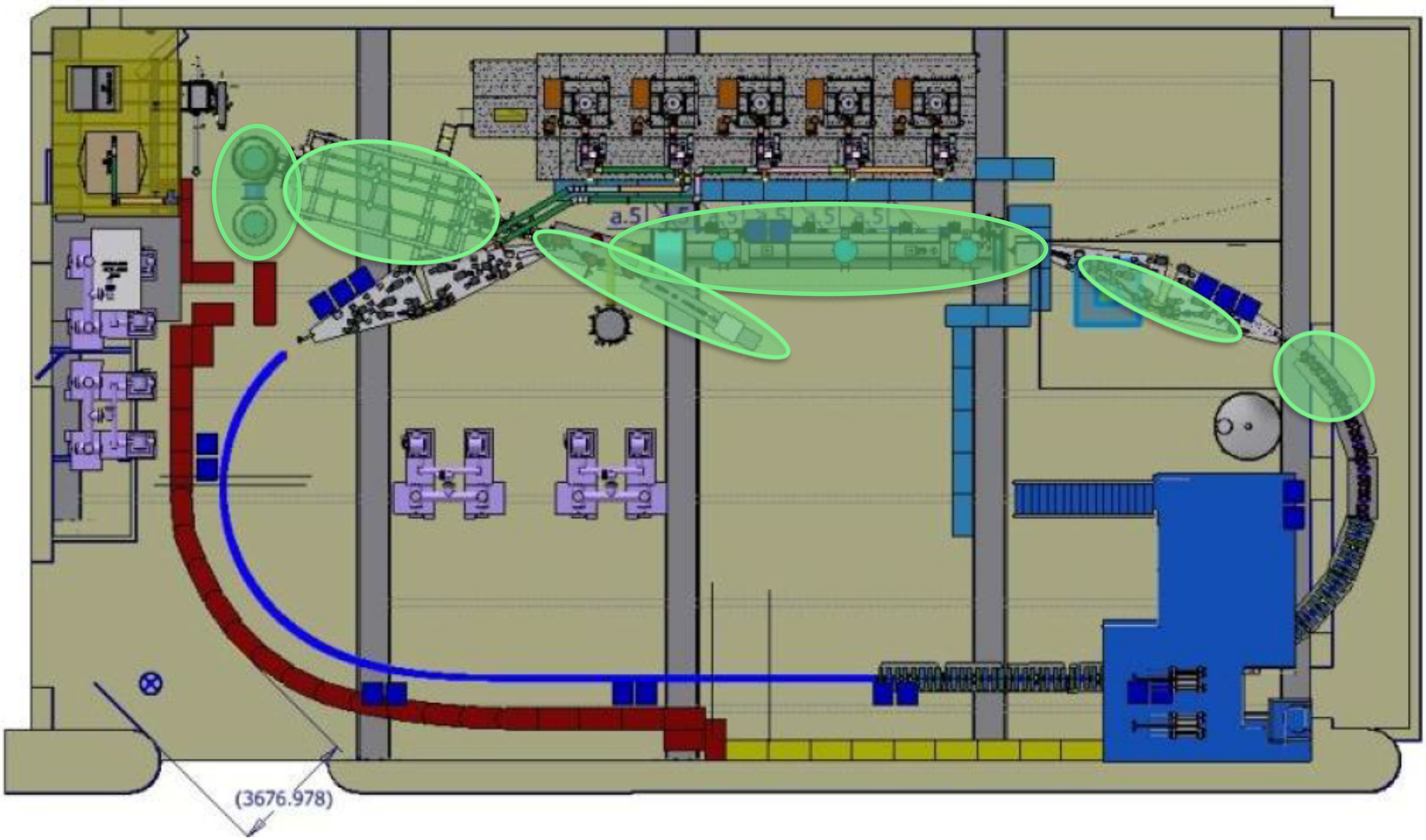
CBETA in its Hall L0E

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



CBETA in its Hall L0E

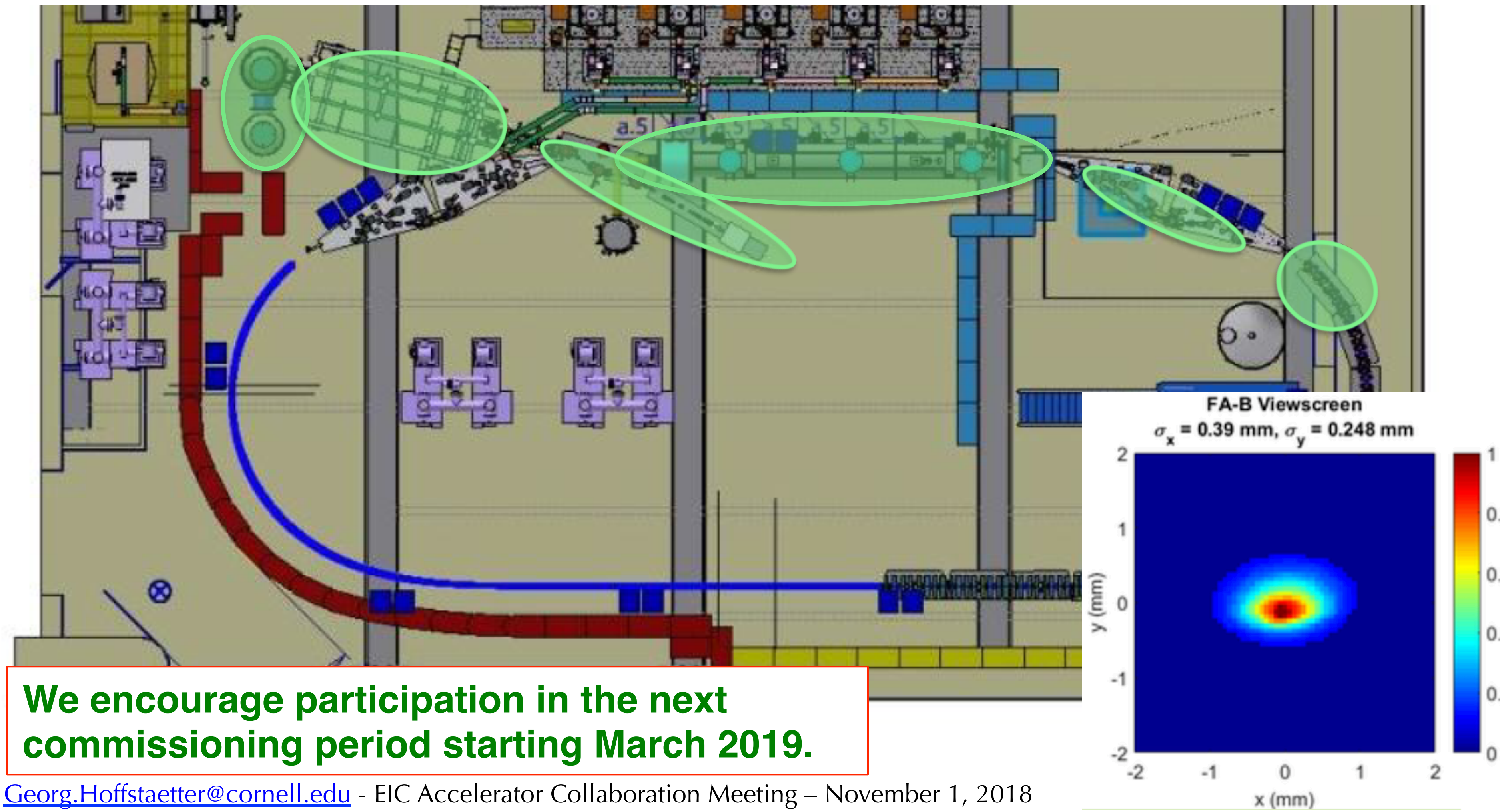
Installed: DC gun, SRF injector, mirror diagnostics line, ERL cryomodule
1st splitter of 8, 1st Fixed Field Alternating-gradient (FFA) girder of 25.



CBETA in its Hall L0E

The ERL Technology Collaboration (ERL-TC) is forming, modeled on the TTC, to support collaborative ERL research.

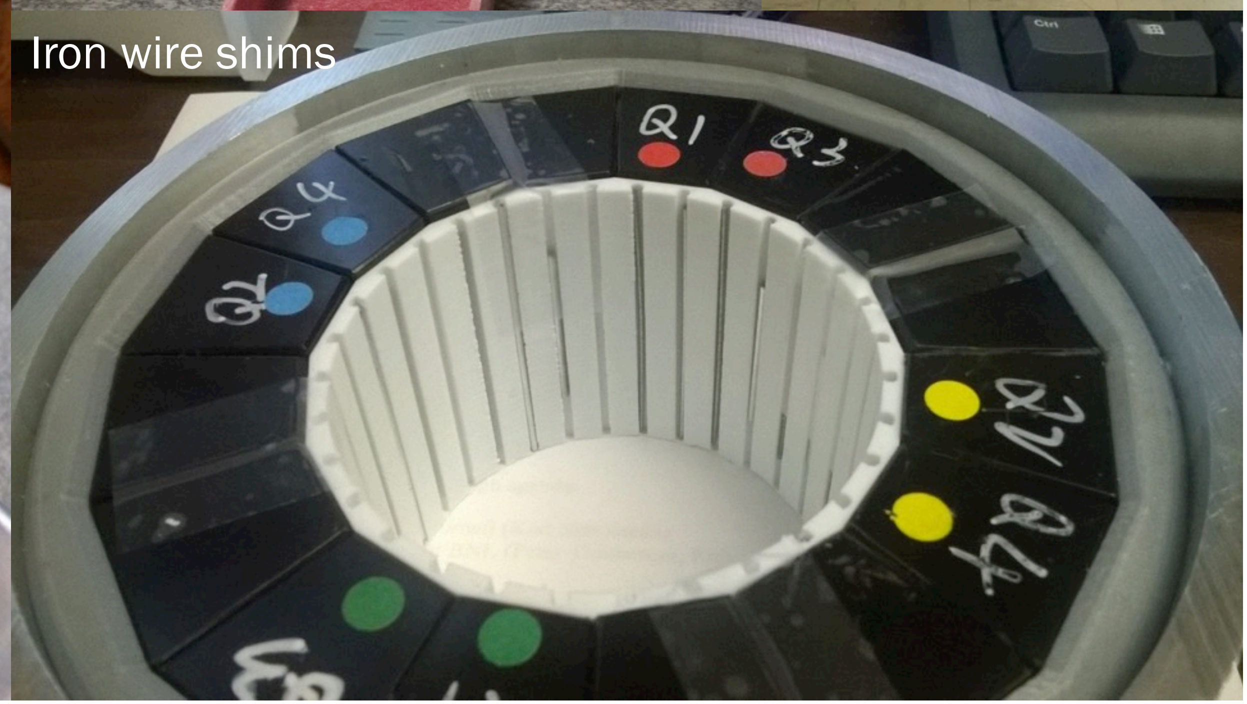
As a first step, visitors from 4 labs are participating in the current commissioning run: 3 from HZB/Germany, 2 from Darebury/UK, 3 from JLAB, 5 from BNL.



We encourage participation in the next commissioning period starting March 2019.

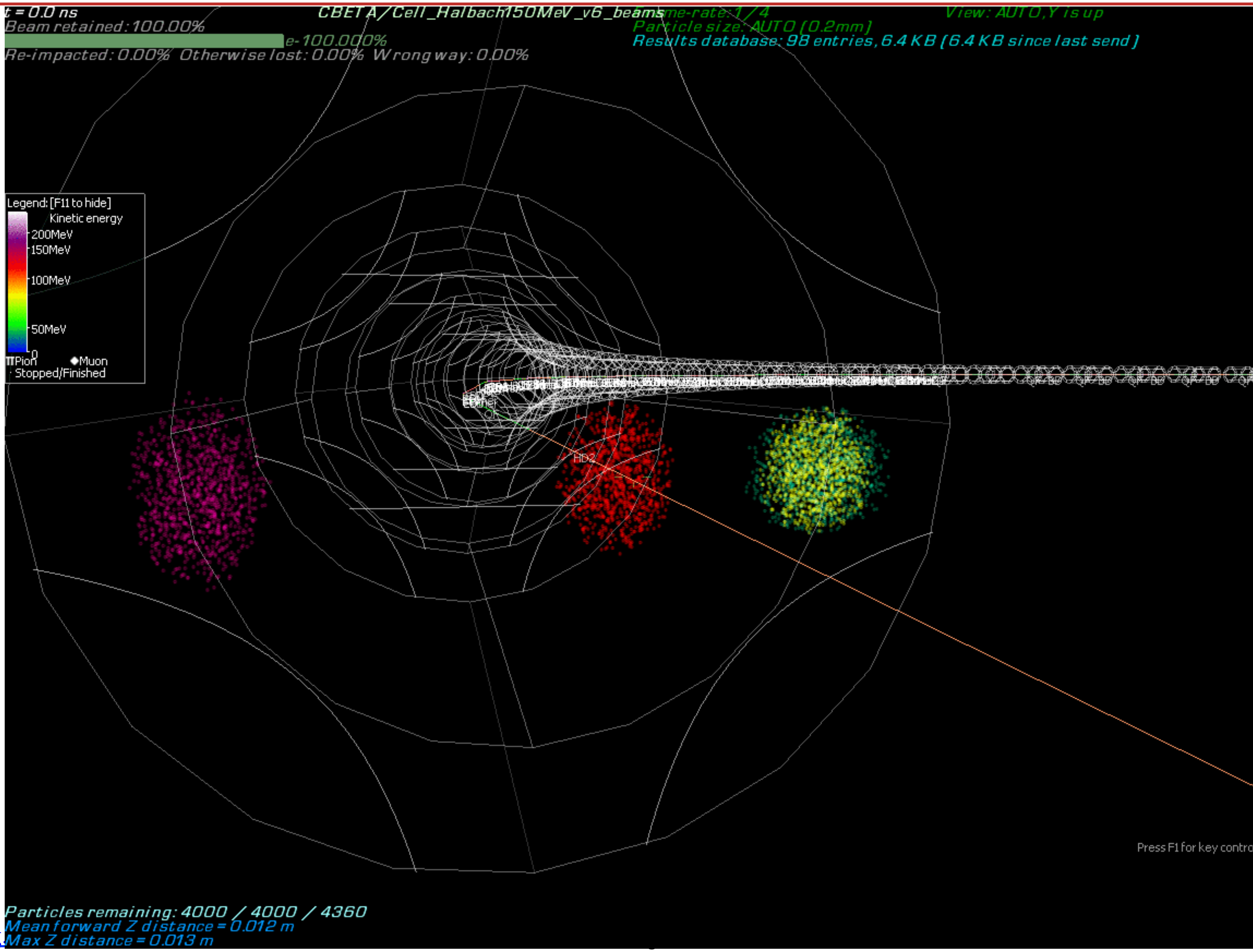
Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

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.



First Girder Construction

Final beam: 7 in one FFA chamber



Commissioning so far

- DC gun currents up to 75mA
- Record injector brightness to the theoretical limits.
- MLC cavities function at high field an Q0 and their microphonics can be regulated.

DC gun, injector, and MLC test

FAT April & May 2018

Main Linac Cryomodule (MLC)

- Calibration
- Maximum energy gain
- Stability

Splitter / Permanent Magnet Arc (PMA)

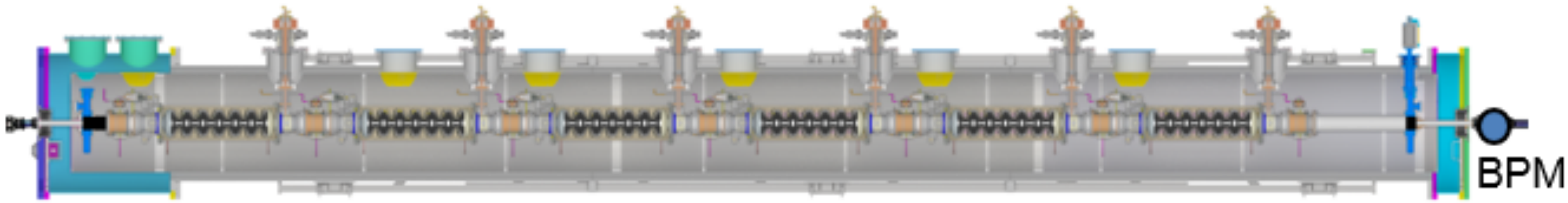
- Linear optics
  - BPM Correction
  - Orbit response
  - Dispersion / R_{56}
  - Tune
- Path length adjustment
- Injection Matching

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

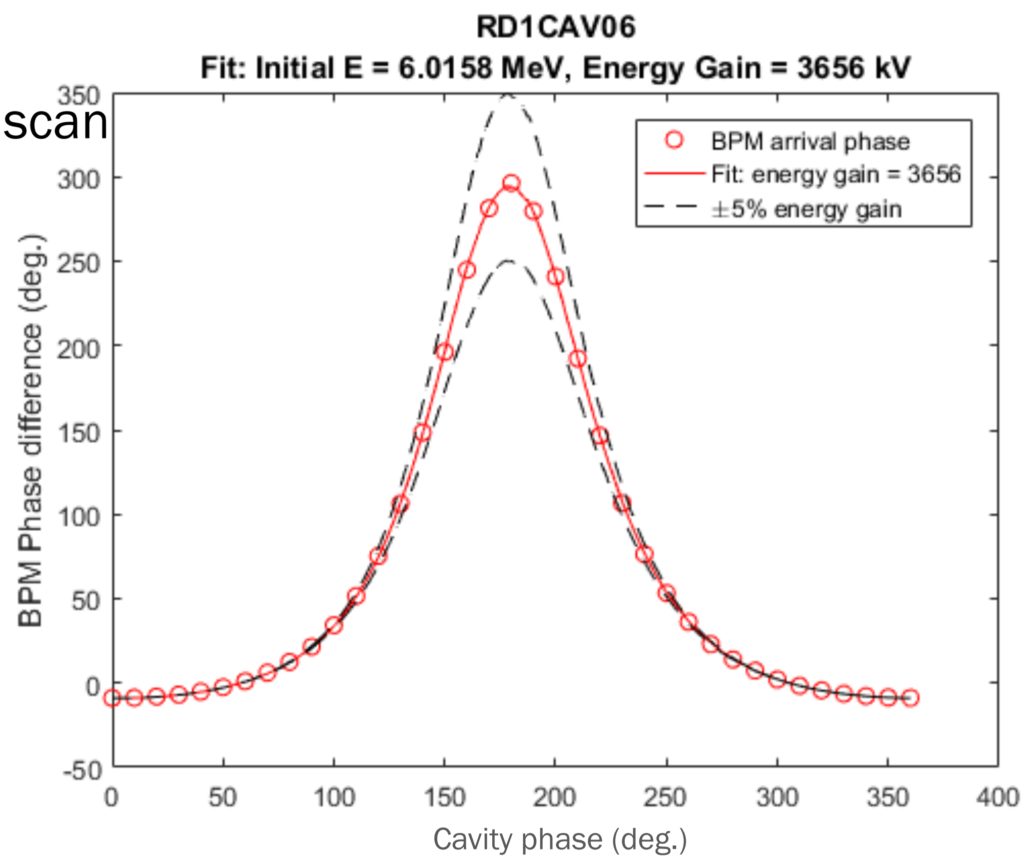


1) Beam enters at 6 MeV

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

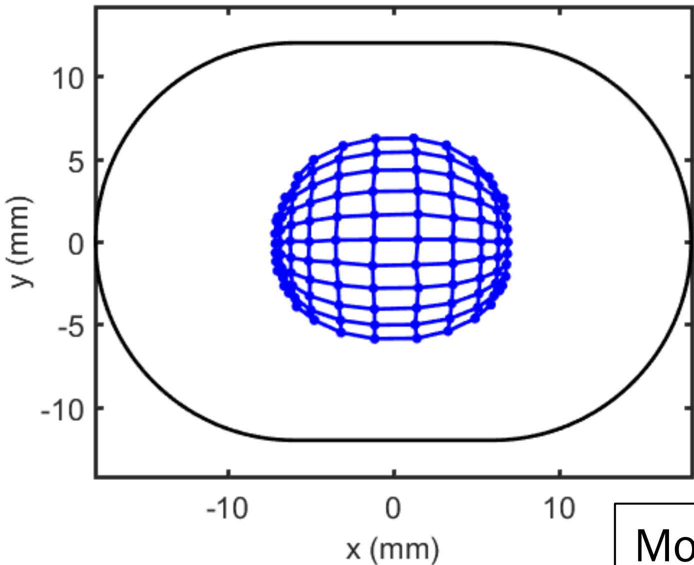
3) Measure arrive time (phase) at downstream BPM

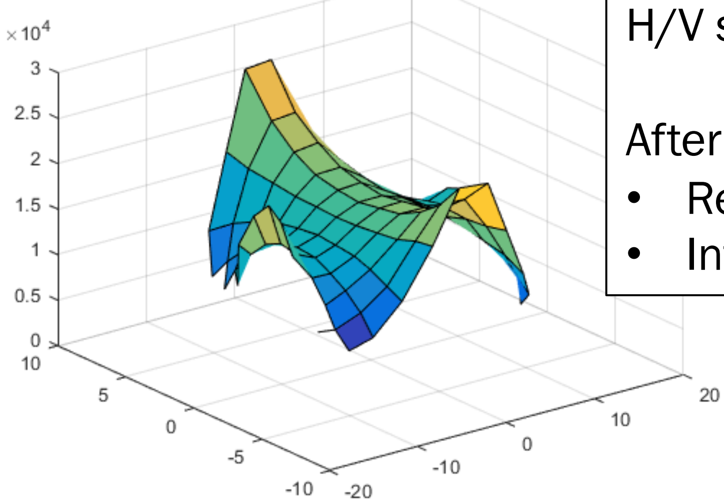
4) Fit to numerical model
   Three fit parameters:
   - Initial energy
   - Cavity energy gain
   - Overall phase



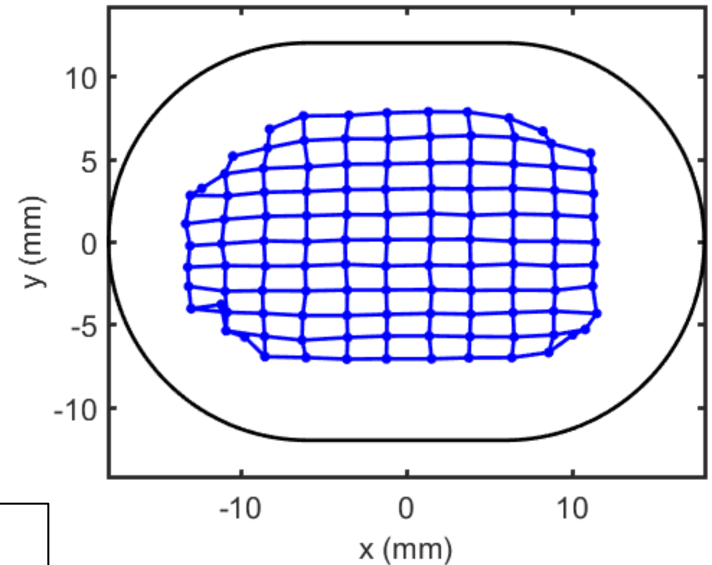
Nonlinear BPM calibration

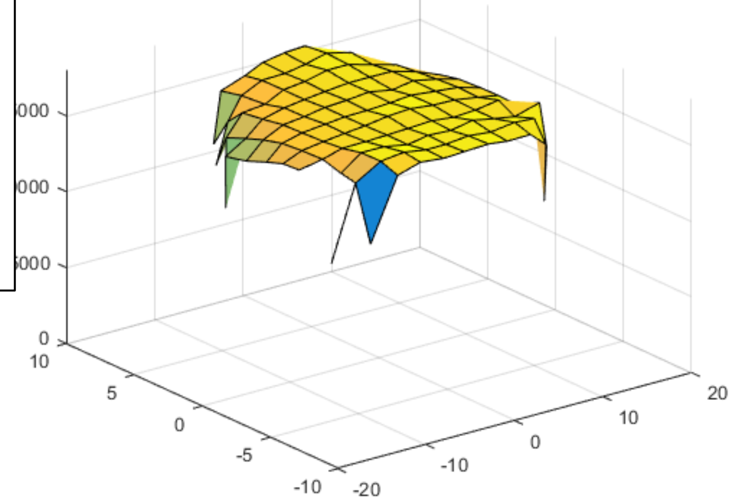
Uncorrected





Corrected





Move beam in equal H/V steps

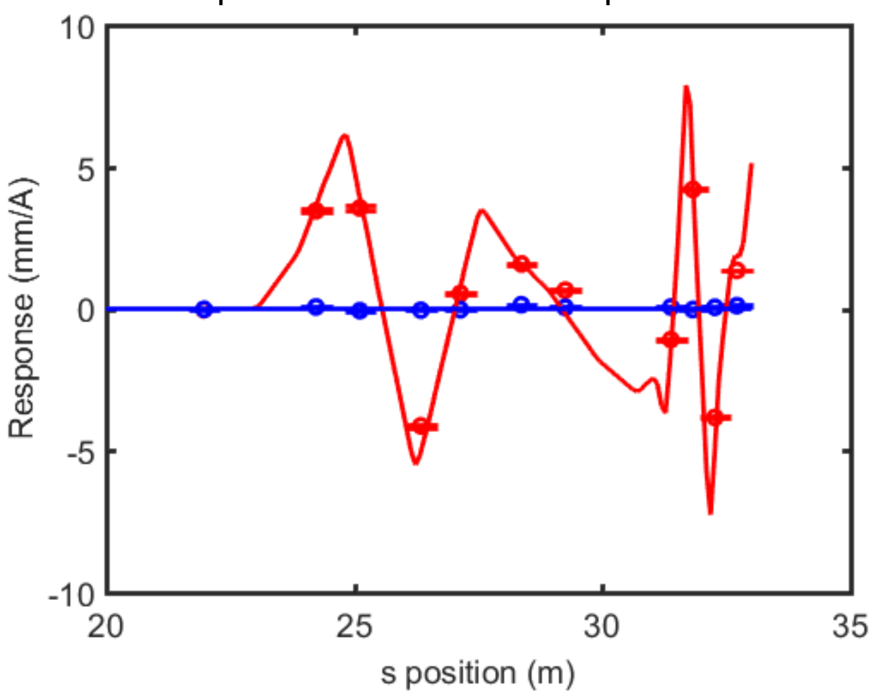
After correction

- Rectangular grid
- Intensity uniform

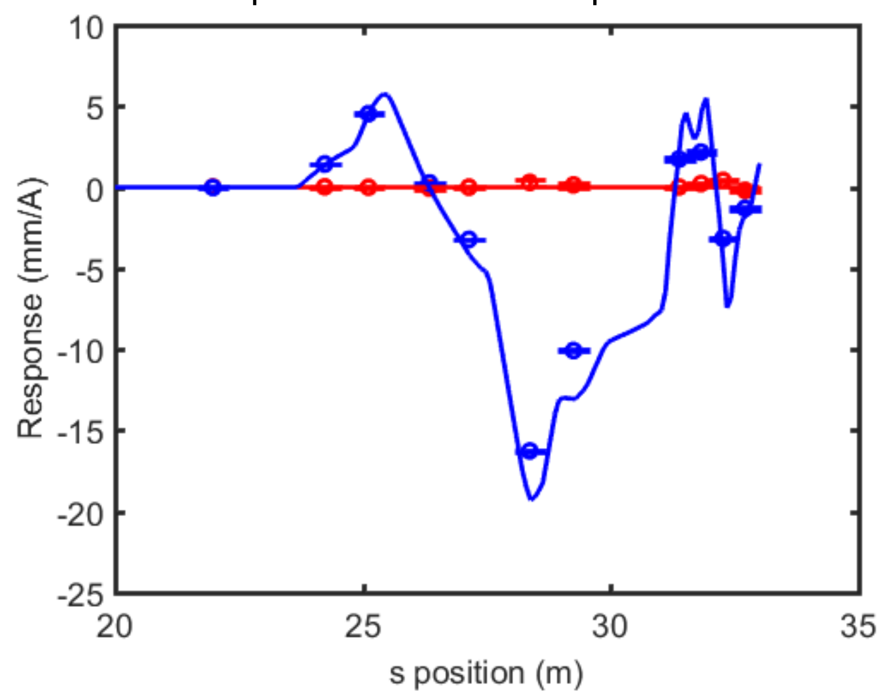
Orbit Response at 42 MeV

- Response data was served live using the on-line model "CBETA-V"
- Detailed measurements were taken to help refine the model off-line

Example: First horizontal dipole kick

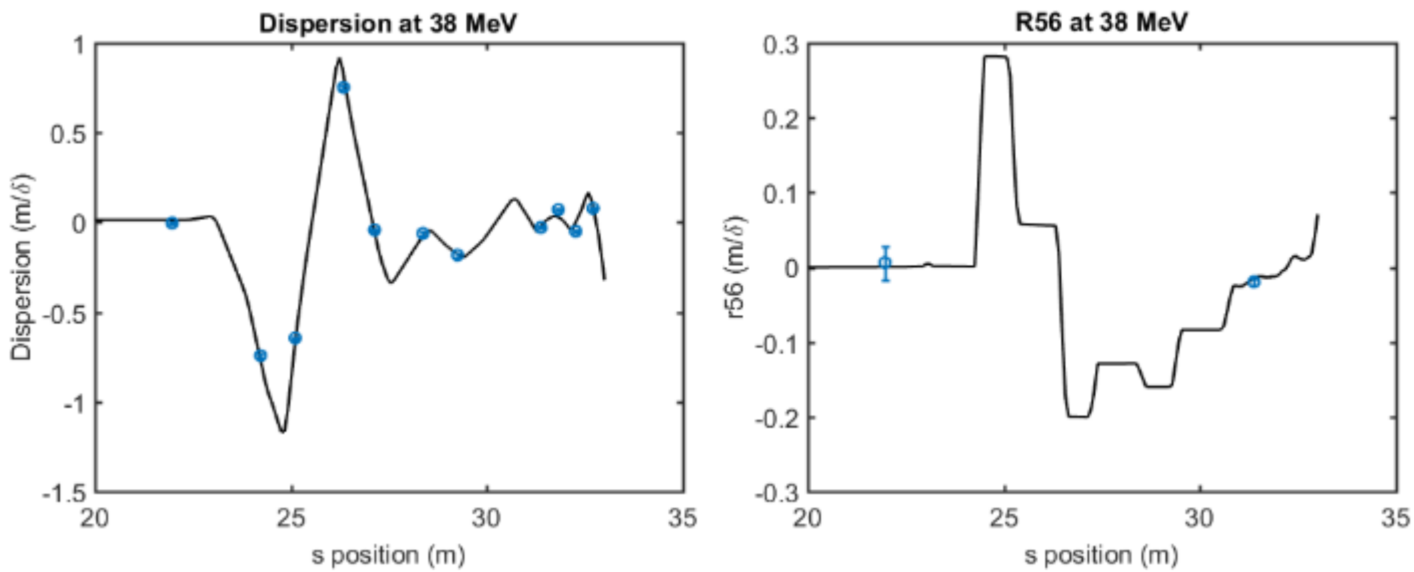


Example: First vertical dipole kick

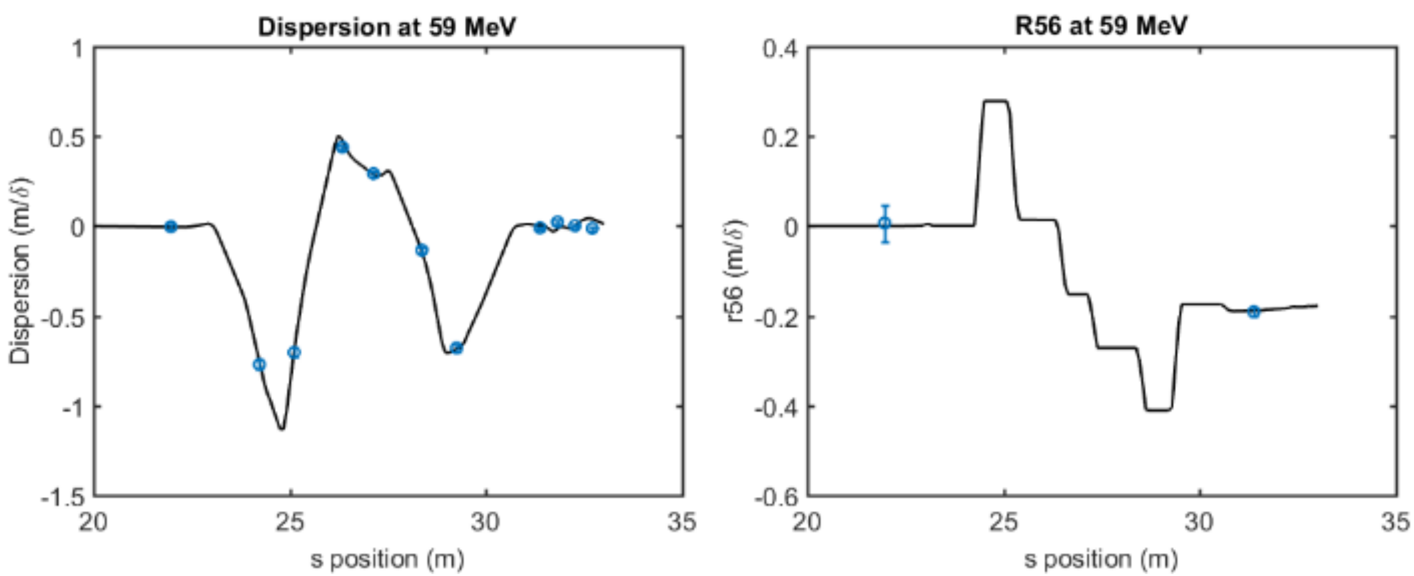


Dispersion and R56 vs. Energy

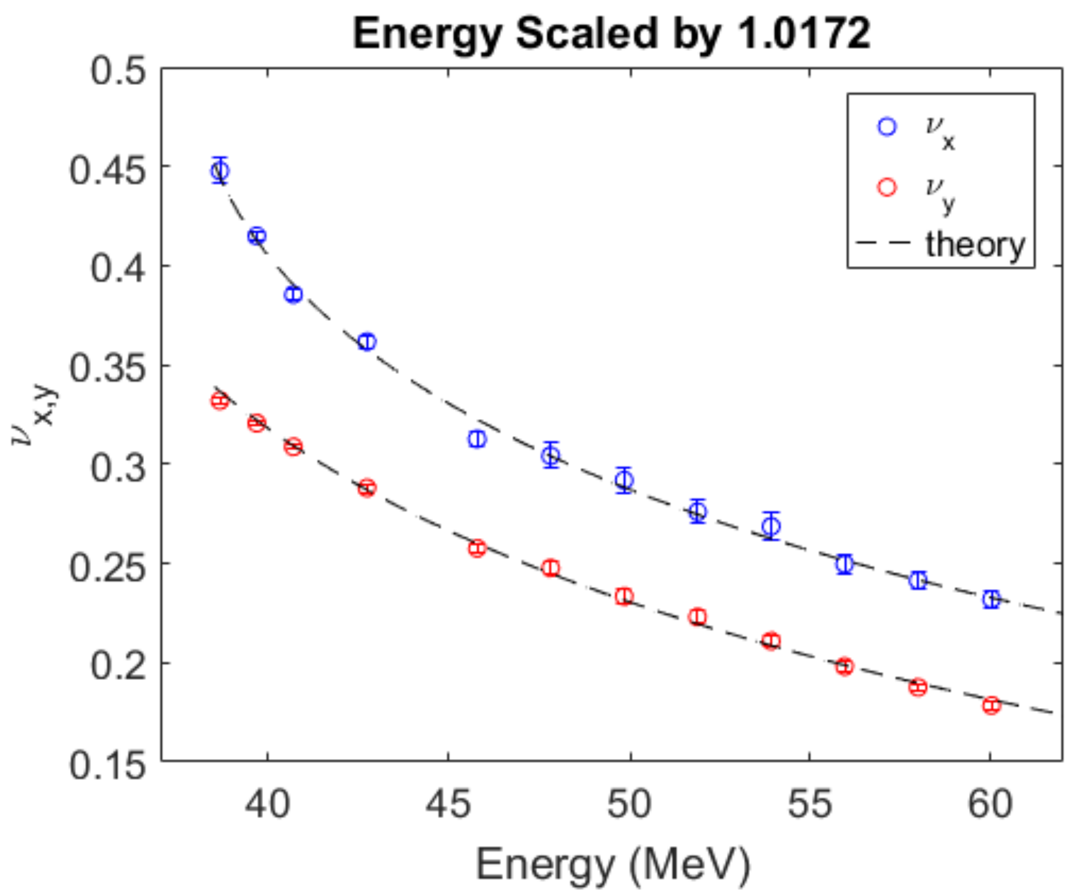
38 MeV

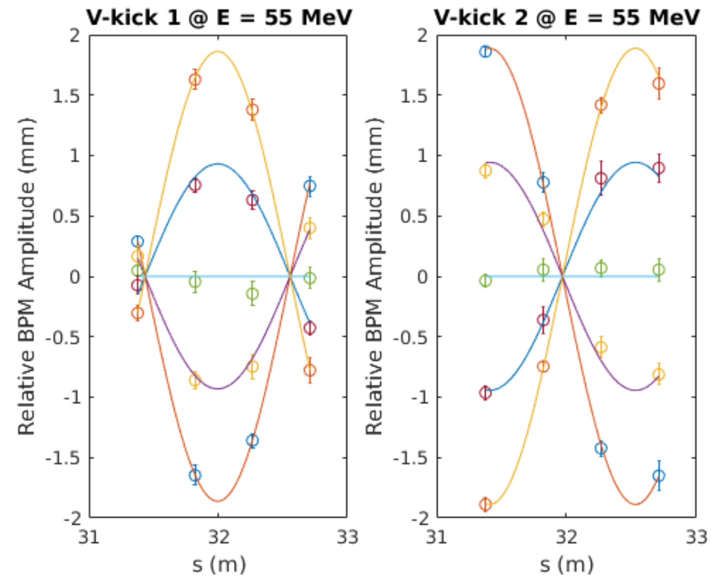


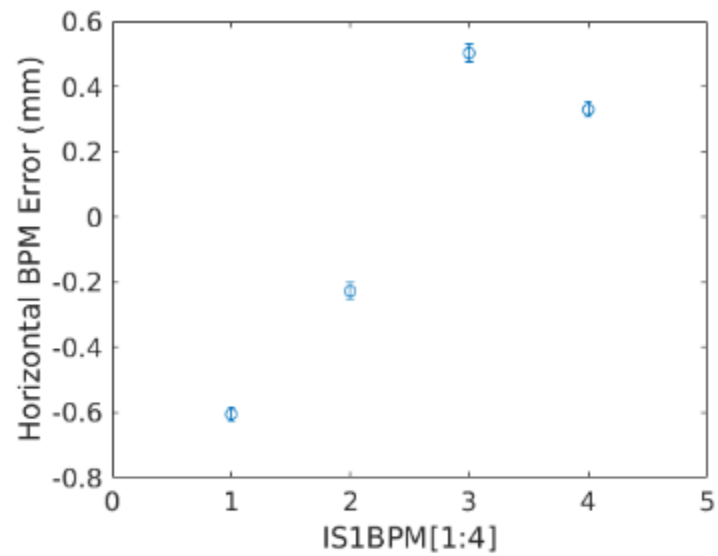
59 MeV



Tune Measurements vs. Energy







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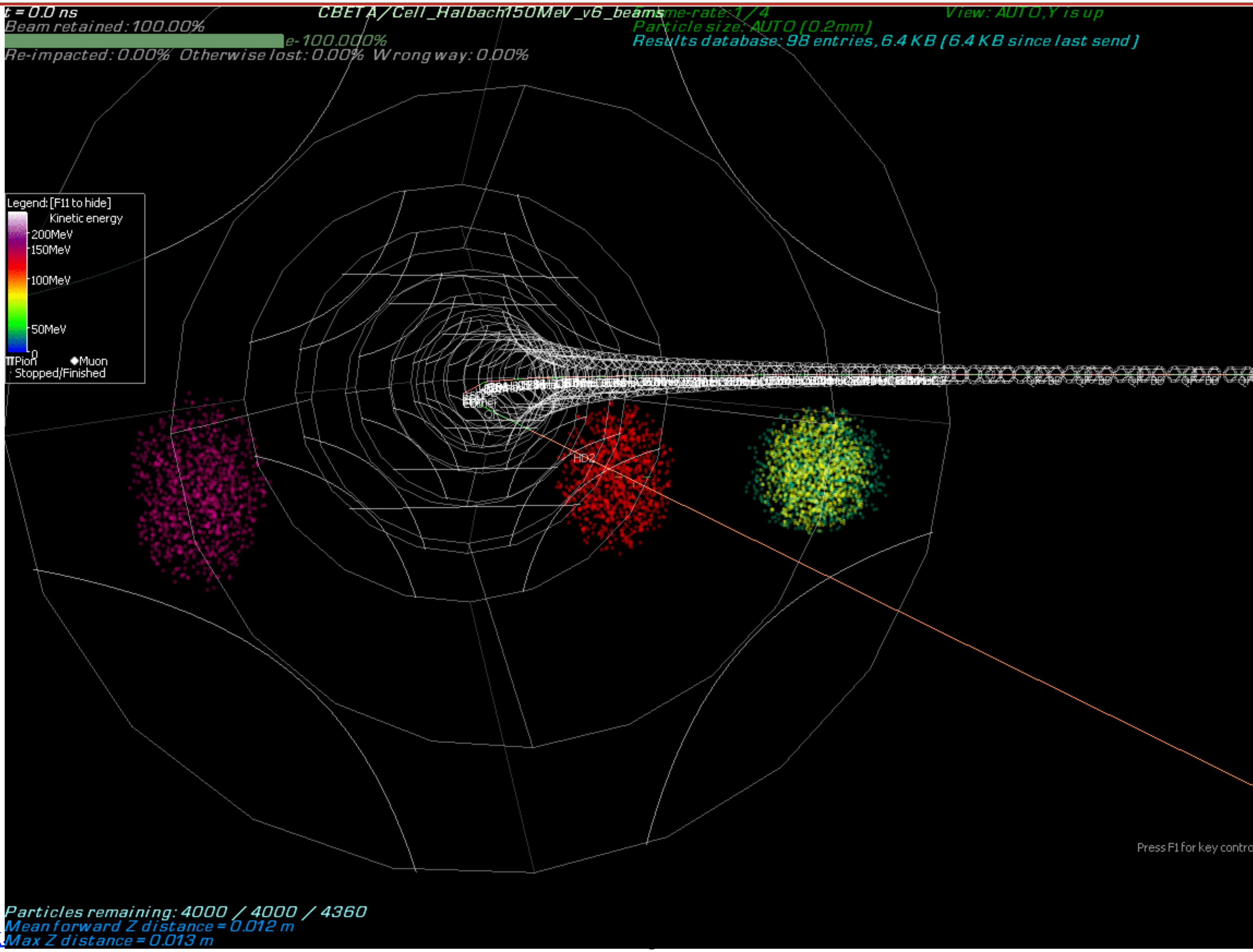
Final beam: 7 in one FFA chamber



CBETA in its Hall L0E

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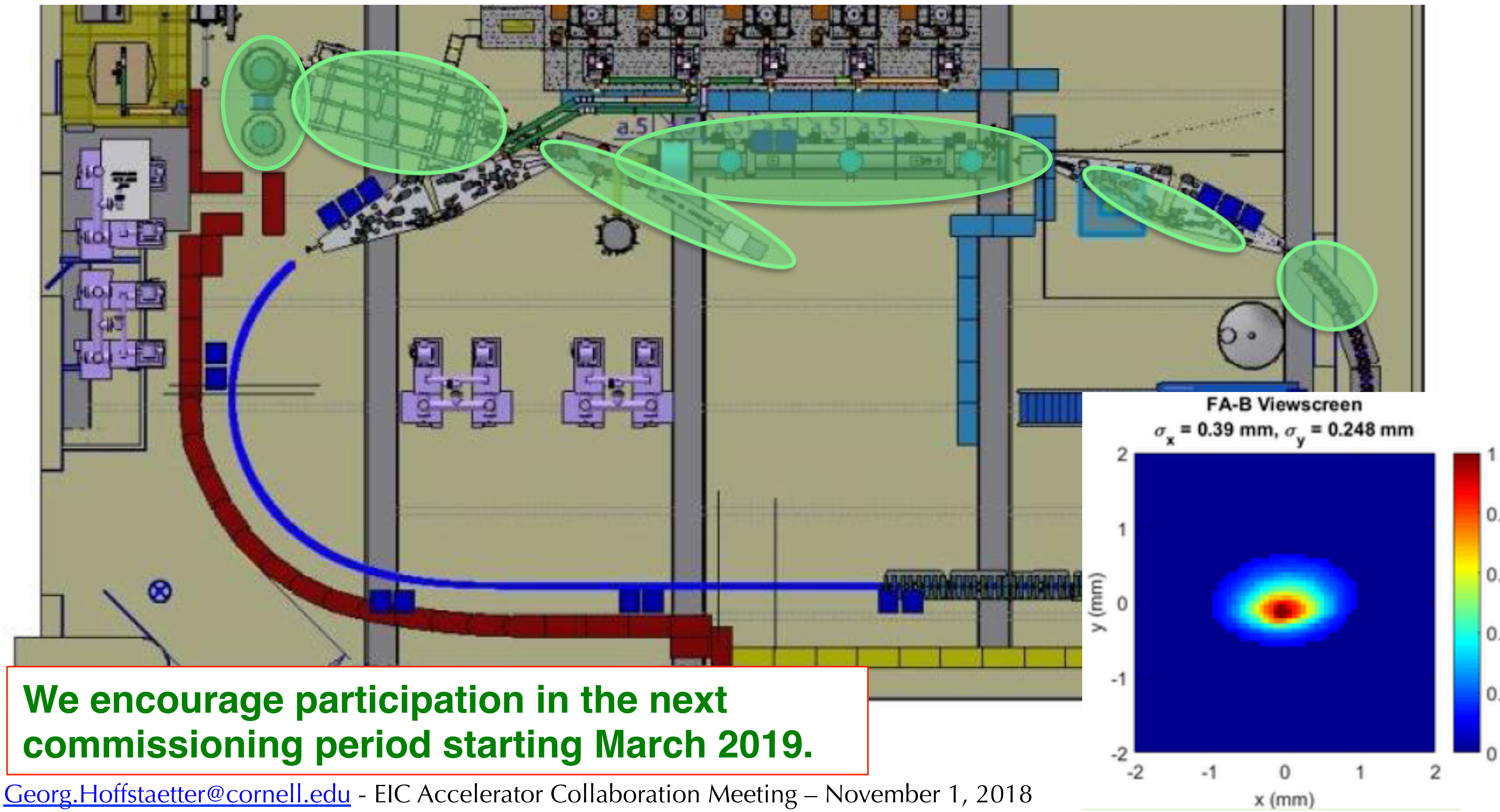

We encourage participation in the next commissioning period starting March 2019.

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Ge

The path is free for CBETA

#	**Milestone** (at the end of months)	**Baseline**	**Actual**
	Funding start date		Oct-16
1	Engineering design documentation complete	Jan-17	
2	Prototype girder assembled	Apr-17	
3	Magnet production approved	Jun-17	
4	**Beam through Main Linac Cryomodule**	**Aug-17**	
5	First production hybrid magnet tested	Dec-17	
6	**Fractional Arc Test: beam through MLC & girder**	**Apr-18**	
7	Girder production run complete	Nov-18	
8	Final assembly & pre-beam commissioning complete	Feb-19	
9	**Single pass beam with factor of 2 energy scan**	Jun-19	
10	**Single pass beam with energy recovery**	Oct-19	
11	**Four pass beam with energy recovery (low current)**	Dec-19	
12	Project complete	Apr-20	

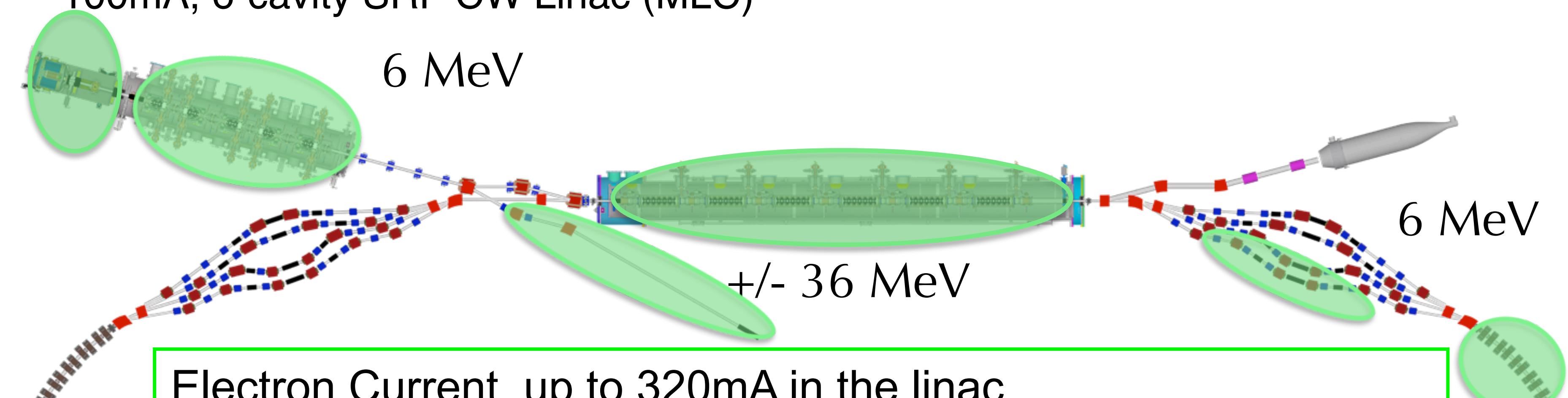
Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

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)

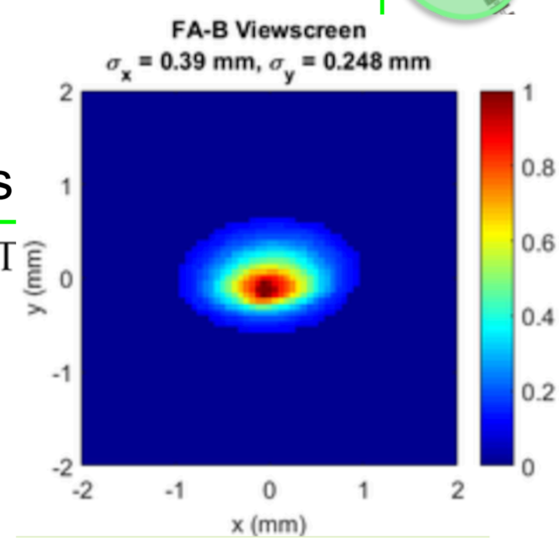
After commissioning to the current NYS funding goals in April 2020

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

1st beam though all essential components:



CBETA is then ready for EIC R&D

Prototyping EIC cooling (unprecedented beam powers of 6MW)

1) ERL operation for high-power beams (note SNS @ 1.4MW, PIP-II@1-2MW)
- Current limits (BBU instabilities and component heating, micro-bunching)
- Startup scenarios
- Simultaneous beam measurements

2) High-power beam propagation
- Beam micro structure that can prevent cooling (pointed out by CeC)
- Loss monitoring, component protection, and shielding
- Intra-beam and rest-gas scattering
- Beam halo dynamics and halo detection

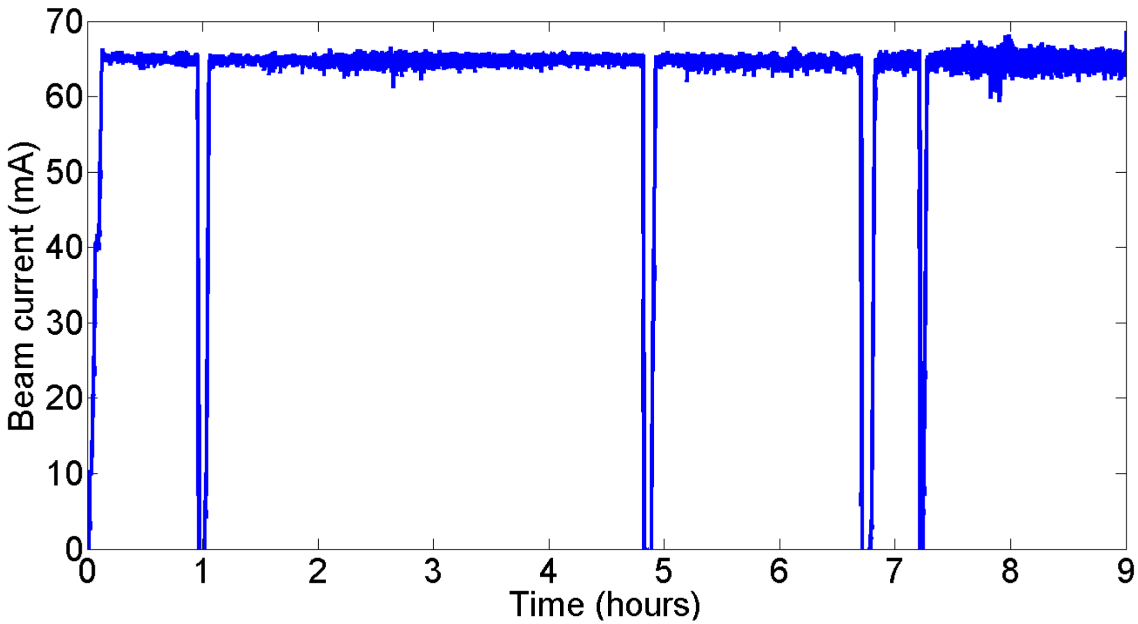
3) High-brightness beam production
- CW electron sources and space-charge dynamics, including dark currents
- High-current polarized beams (see presentation by Luca Cultrera)

4) Low-emittance-growth beam propagation
- High precision magnets
- High precision beam dynamics control

Other EIC topics, e.g. for a linac-ring collider.

Questions?

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, at only 5W laser.

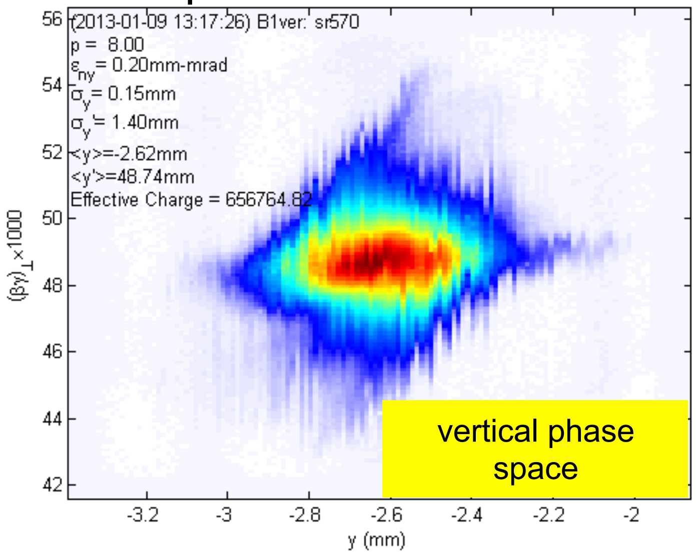
- The gun group is now working on polarized guns of high current (See today at 11:30, High-Current Polarized e-Sources by Luca Cultrera)

- This gun was copied at Cornell and commissioned at BNL for the RHIC Low Energy Run (another successful BNL / Cornell collaboration) as seen on Tuesday at 11:00, Status and Commissioning Results of LEReC by Alexei Fedotov)

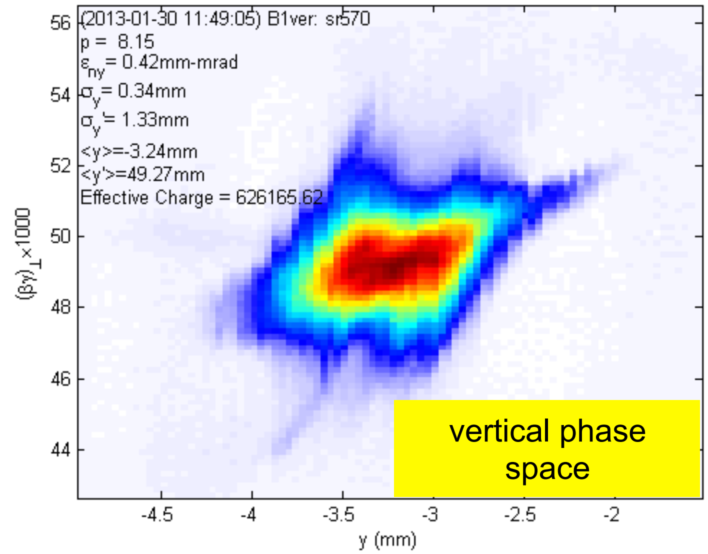
- DC-gun + SRF injector are now prototyped for industrial Mo99 production.

Beam Brightness

20 pC/bunch



80 pC/bunch



Normalized rms emittance (horizontal/vertical) 90% beam, E ~ 8 MeV, 2-3 ps

0.23/0.14 mm-mrad   0.51/0.29 mm-mrad

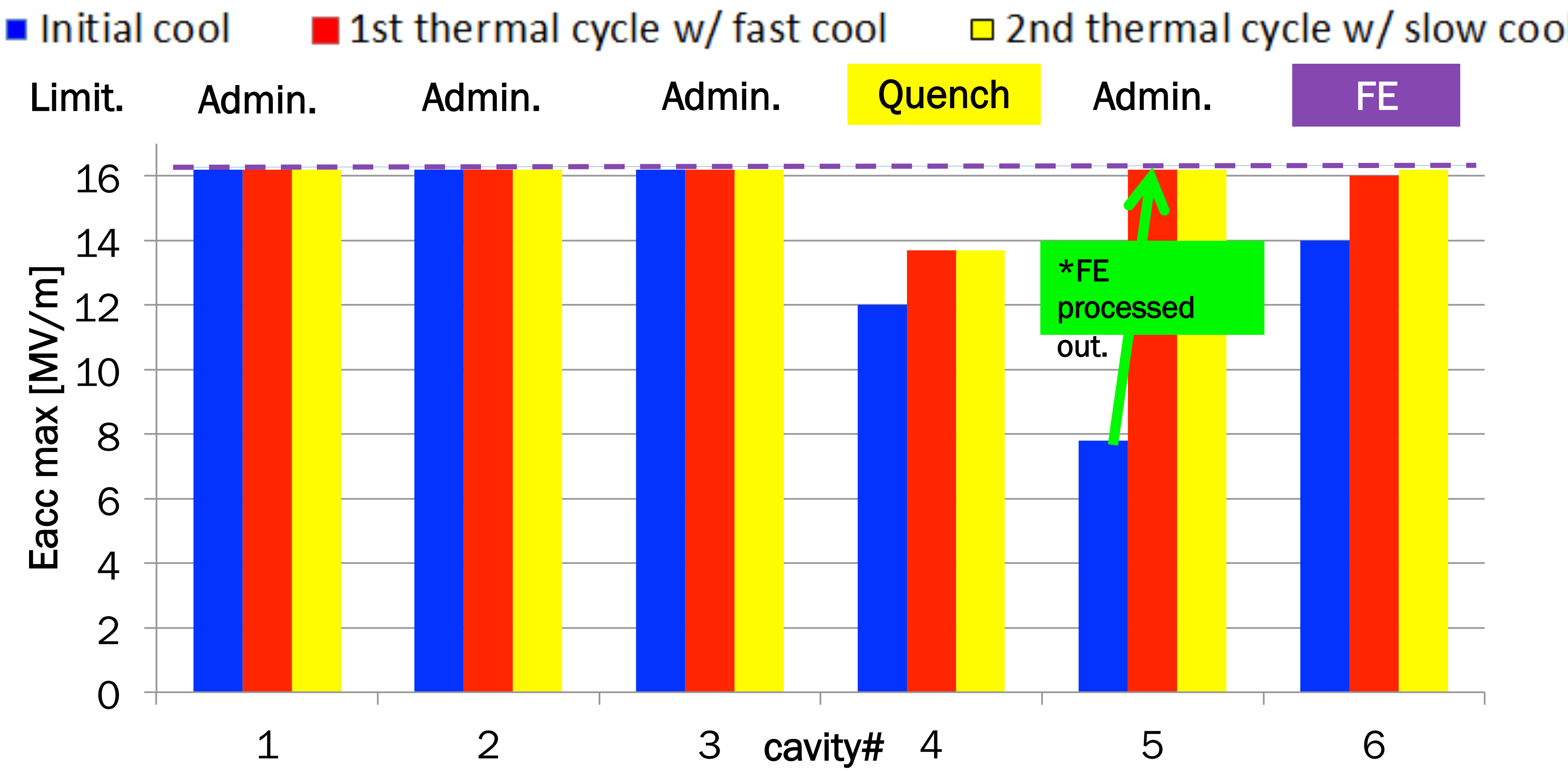
Normalized rms core* emittance (horizontal/vertical) @ core fraction (%)

0.14/0.09 mm-mrad @ 68%   0.24/0.18 mm-mrad @ 61%

Phys. Rev. ST-AB 15 (2012) 050703
ArXiv: 1304.2708

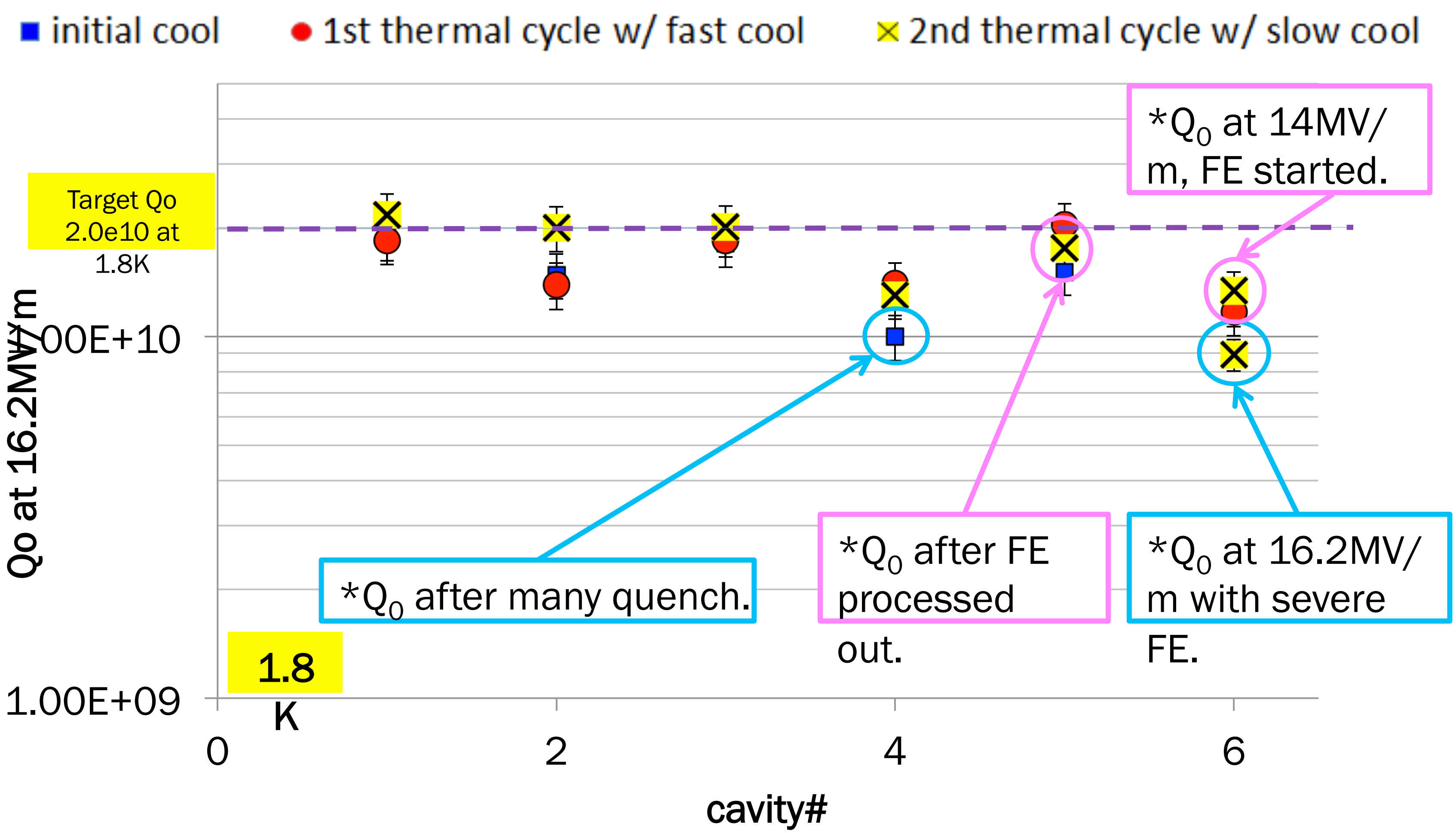
✓ At 5 GeV this gives 20x the world's highest brightness (Petra-III)

Main linac cryomodule (MLC) achieved accelerating gradients



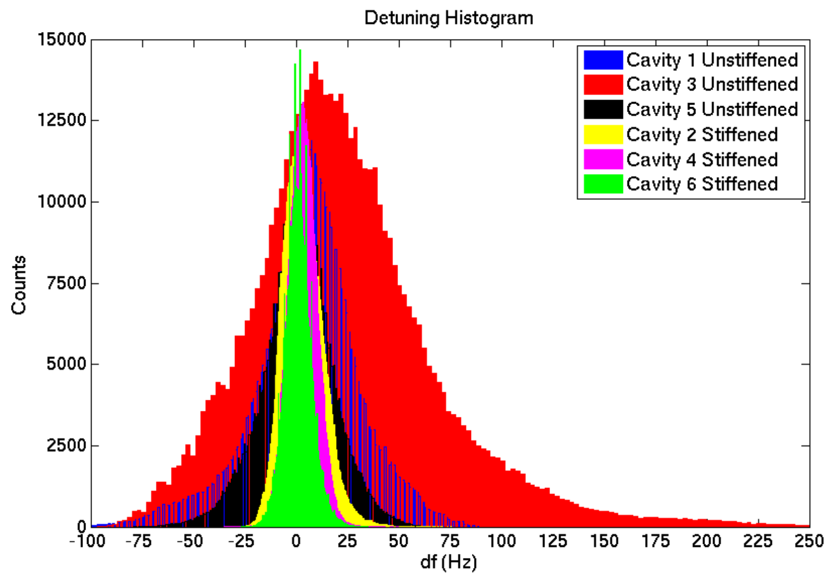
- 5 of 6 cavities had achieved design gradient of 16.2MV/m at 1.8K in MLC.
- Cavity#4 is limited by quench so far, no detectable radiation during test.
- Enough Voltage for 76MeV per ERL turn (where 36MeV are needed)

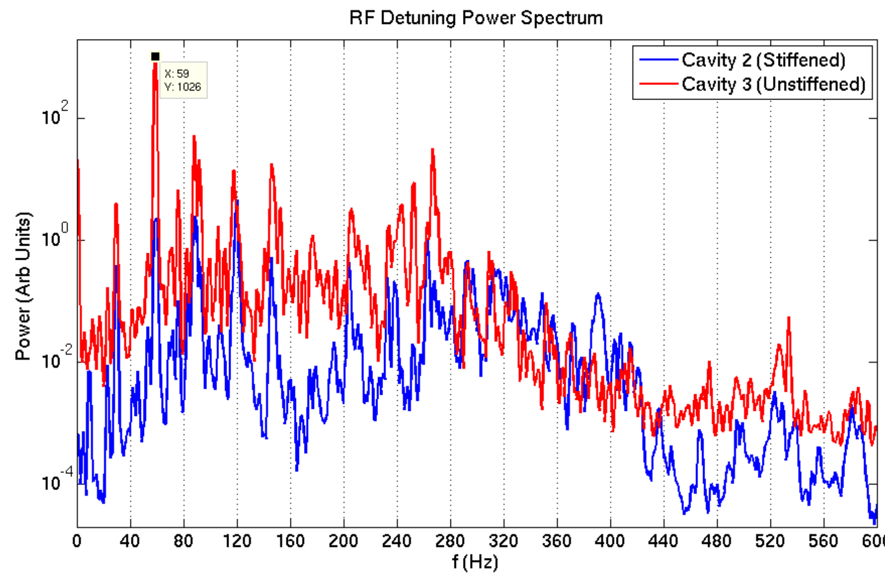
Main linac cryomodule (MLC) achieved surface losses (Q0)



- 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.

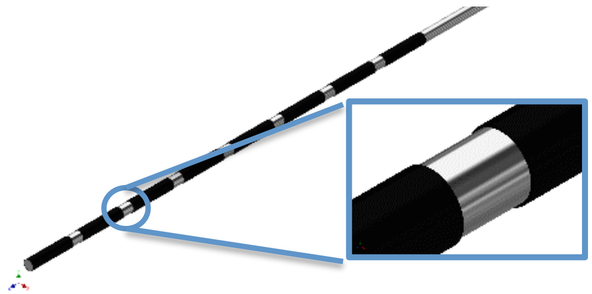
- **Enough Voltage for about 50MeV per ERL turn, if microphonics is not reduced (where 36MeV are needed)**

SRF microphonics stabilization

PhD work (Nilanjan Banerjee)
became essential for CBETA operation

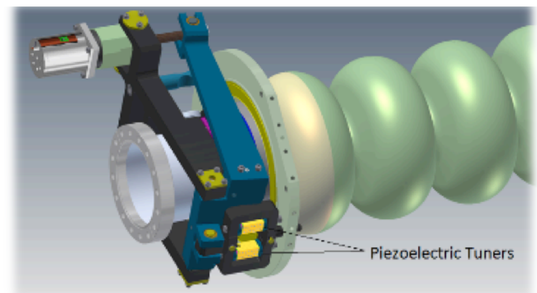
1) Specified 70 potential microphonic sources

2) Identified thermo-achoustic sources



Valve Modification

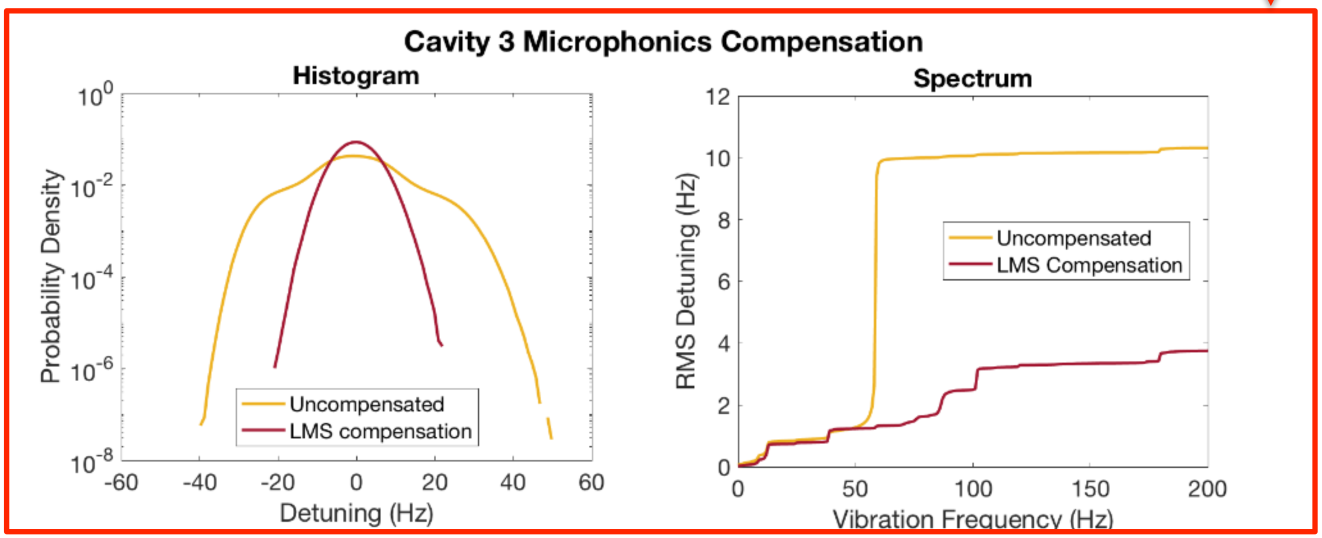
2) Deigned piezo control software



Active Compensation

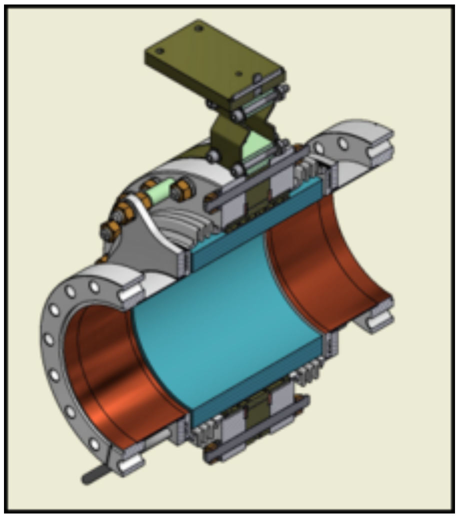
LCLS-II needs similar controls!

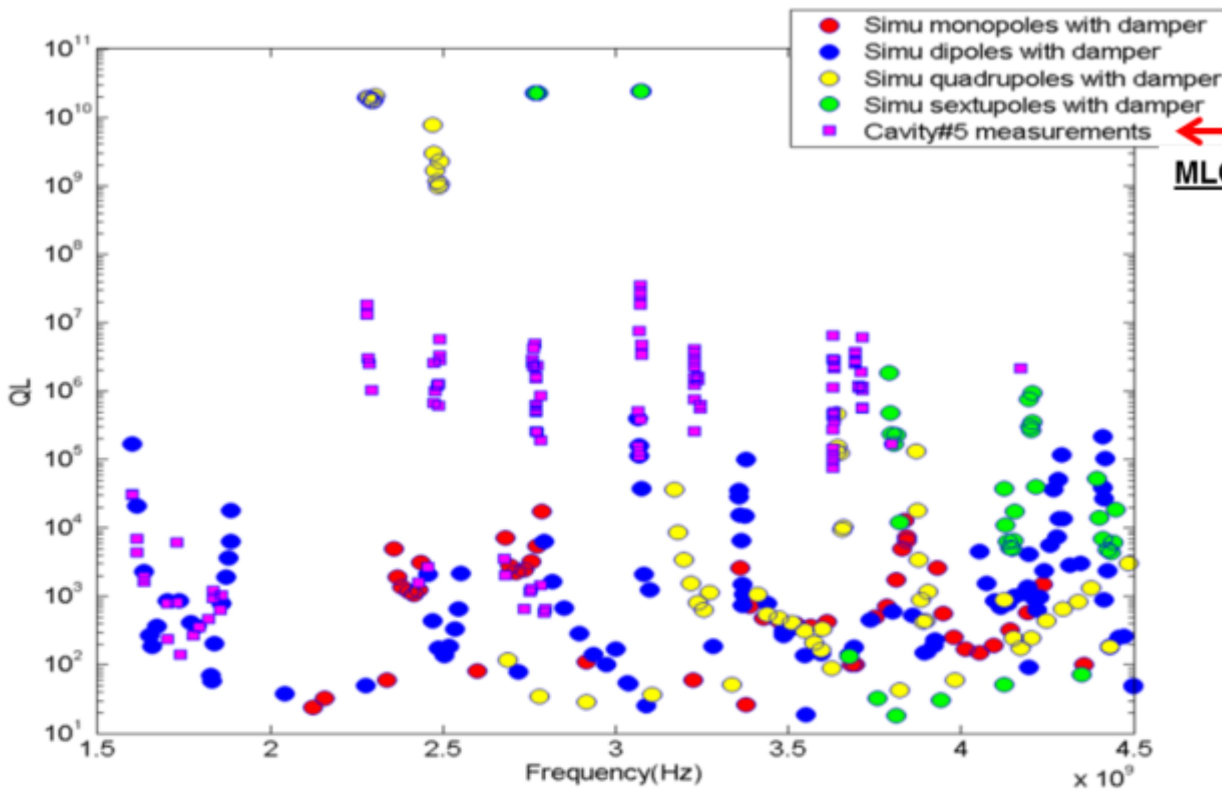
and we are in touch with LCLS-II teams at FNAL and JLAB.



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

Current limits from HOMs



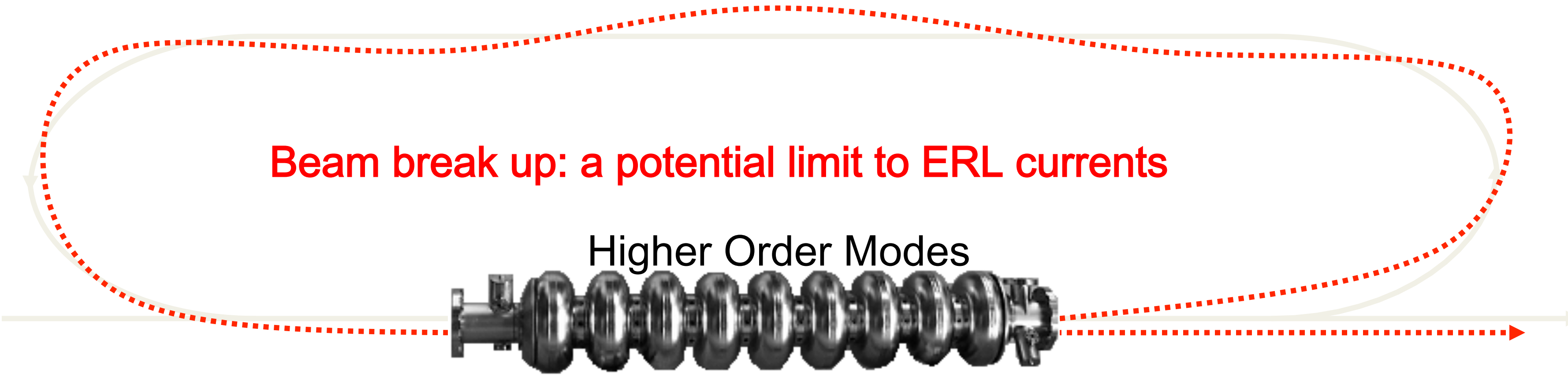


Dipole HOMs on MLC were strongly damped below $Q \sim 10^4$.
Consistent with HTC and simulation results.

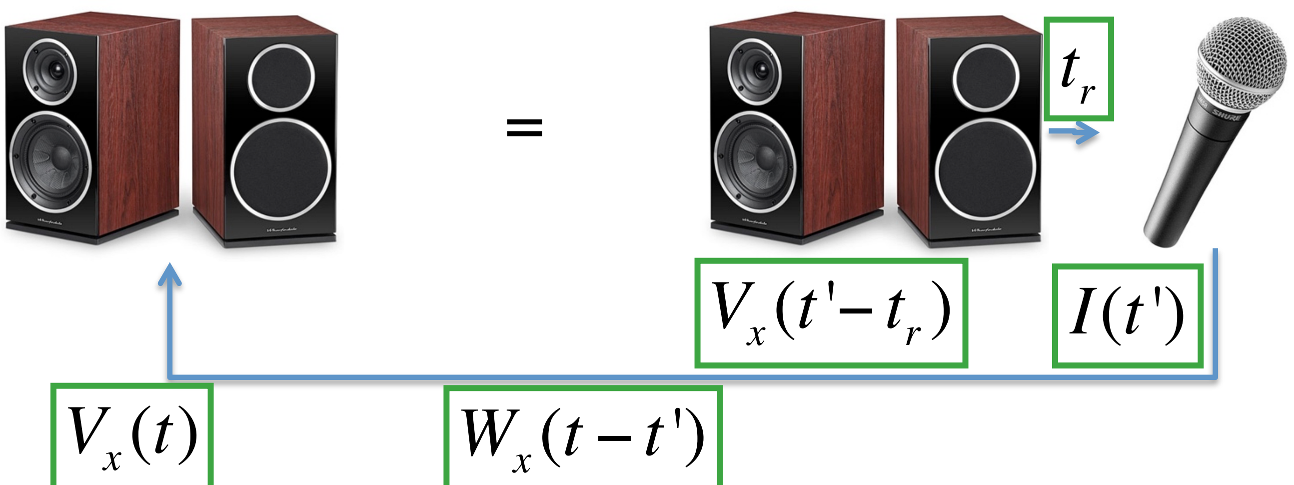
HTC results were:

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

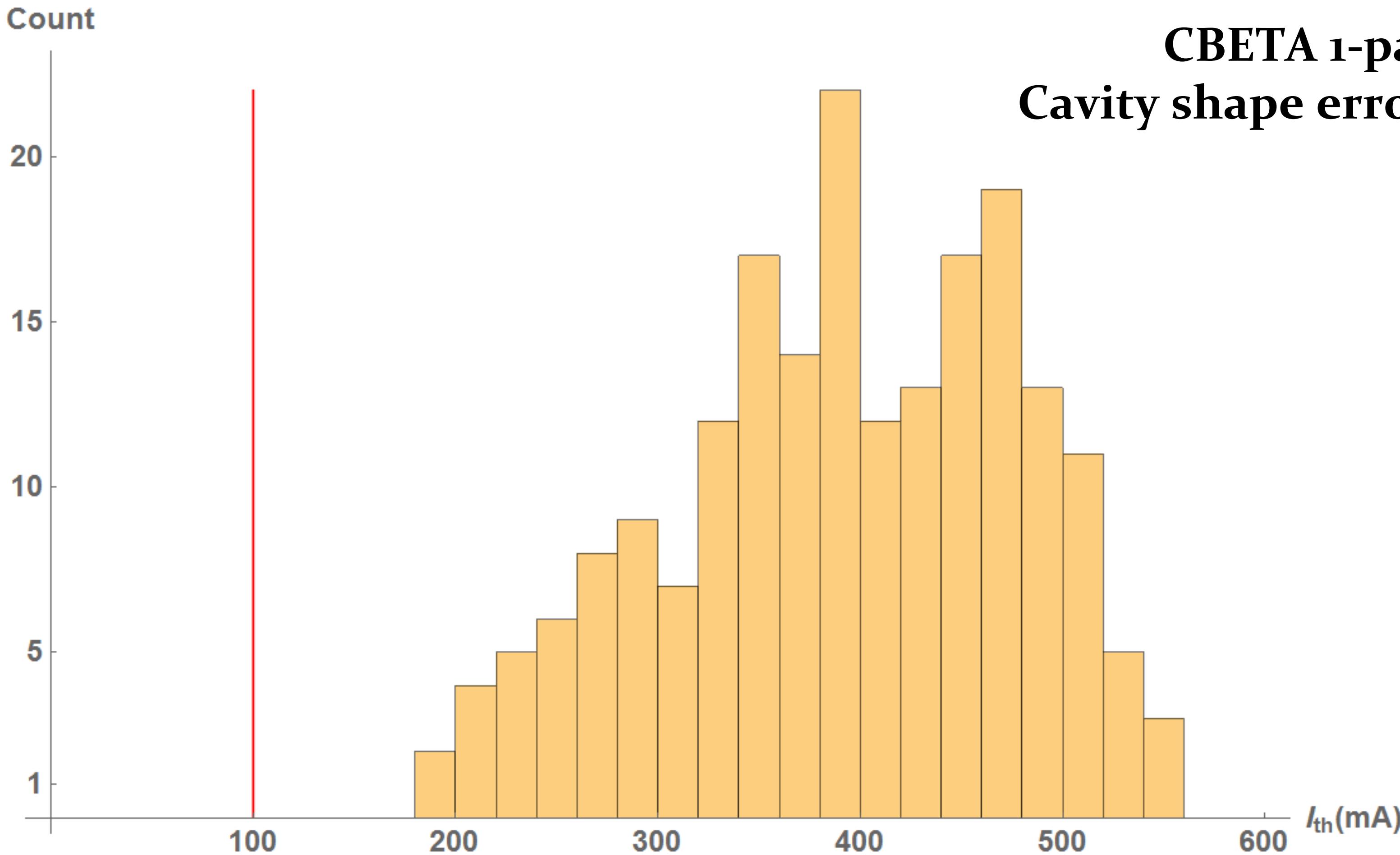
New current limit



$$V_x(t) = T_{12}\,\tfrac{e}{c}\int_{-\infty}^{t} W_x(t-t')V_x(t'-t_r)I(t')dt'$$



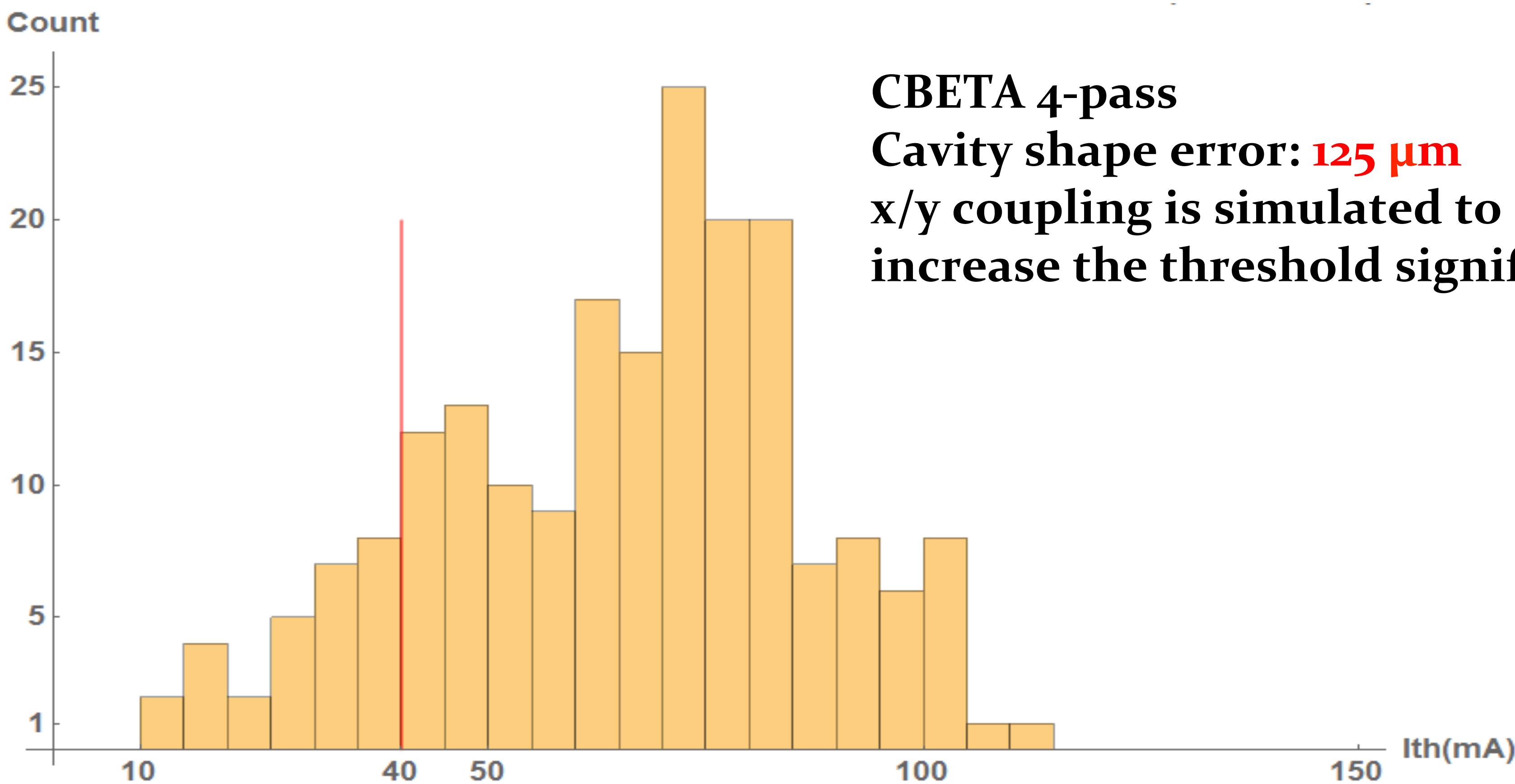
BBU for 1 pass in CBETA



CBETA 1-pass
Cavity shape error: 125 µm

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

BBU for 4 passes in CBETA



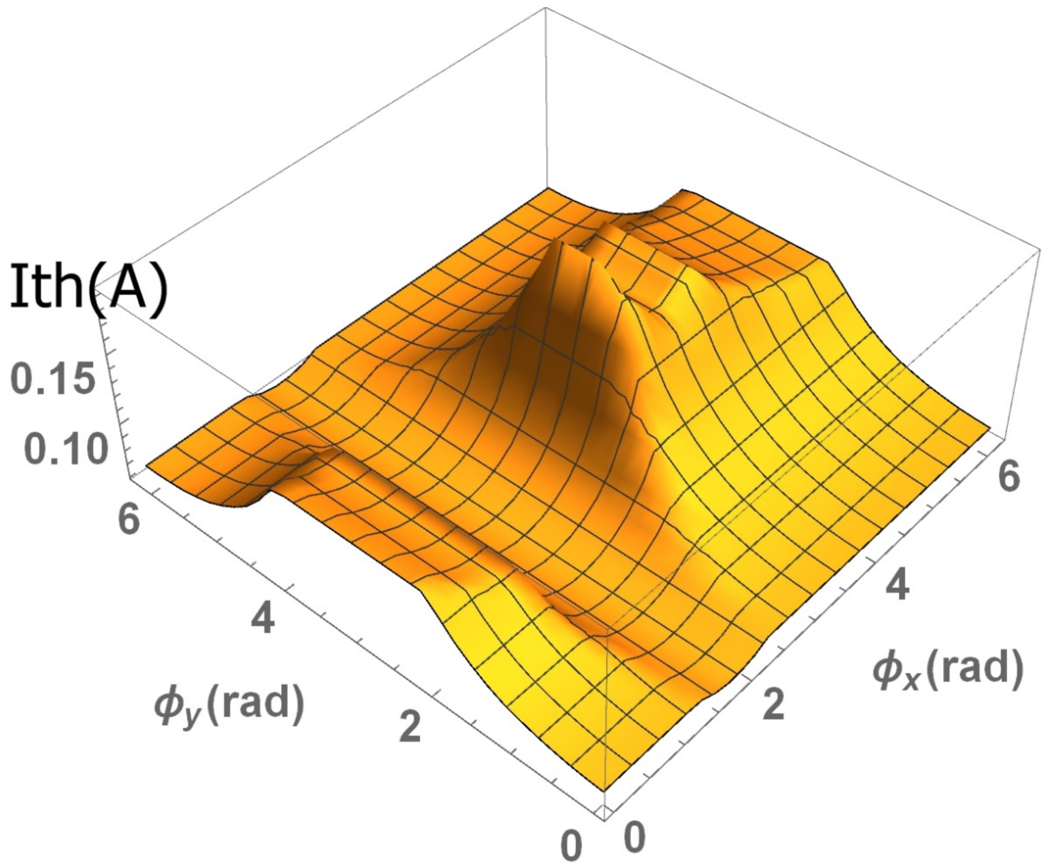
CBETA 4-pass
Cavity shape error: 125 μm
x/y coupling is simulated to increase the threshold significantly

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

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

4-path ERL with variable phases

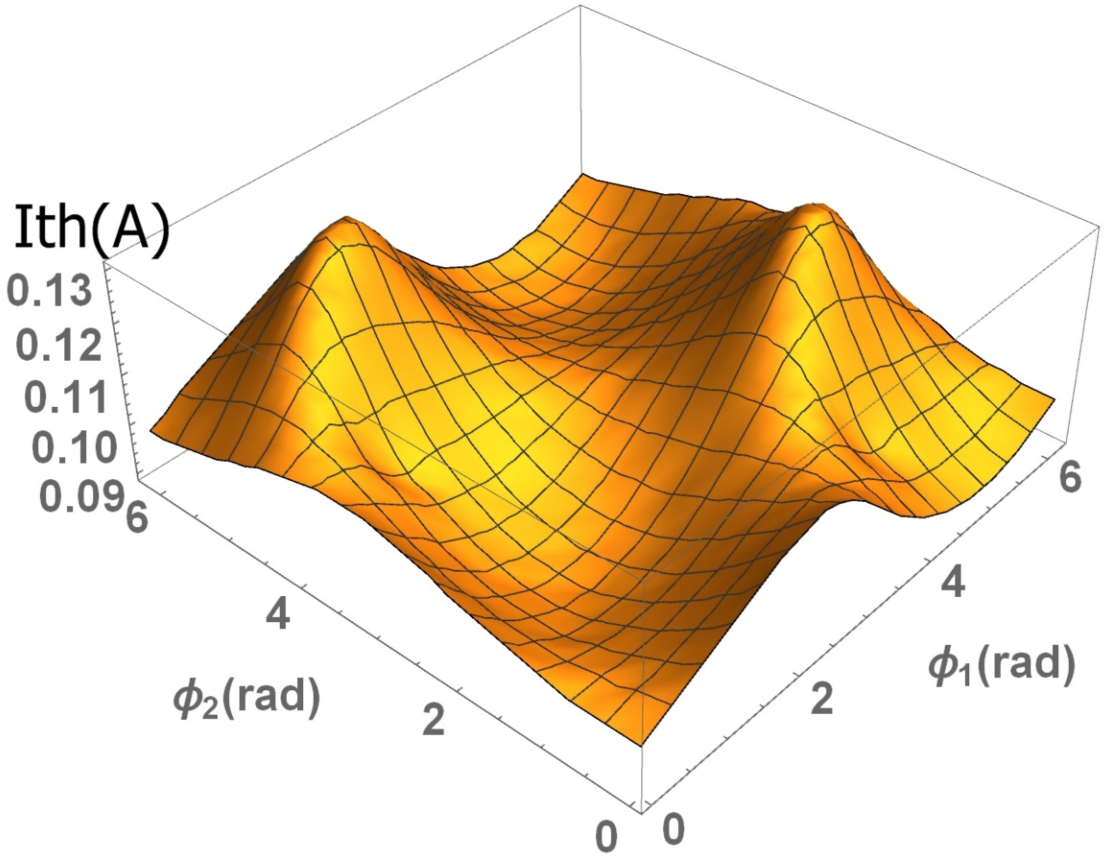
I_{th}



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

I_{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.

Next-order BBU

Don't forget that there is

(A) Transverse Dipole BBU that is often considered and there are good codes

(B) Longitudinal BBU

- contained in the BMAD simulation code
- It is important because they excite monopole (accelerating) modes with very large Q
- Is minimized by T56=0 for all cavity couplings
- Phase and time-of-flight tricks need to be checked against this instability.

(C) Quadrupole BBU

- Is important because the frequencies of the lowest order Quadrupole modes are below the first higher order dipole modes. Their Q can therefore be extremely large.

(D) Higher-order multipole BBU: Check out the simple scaling formulas in [1]

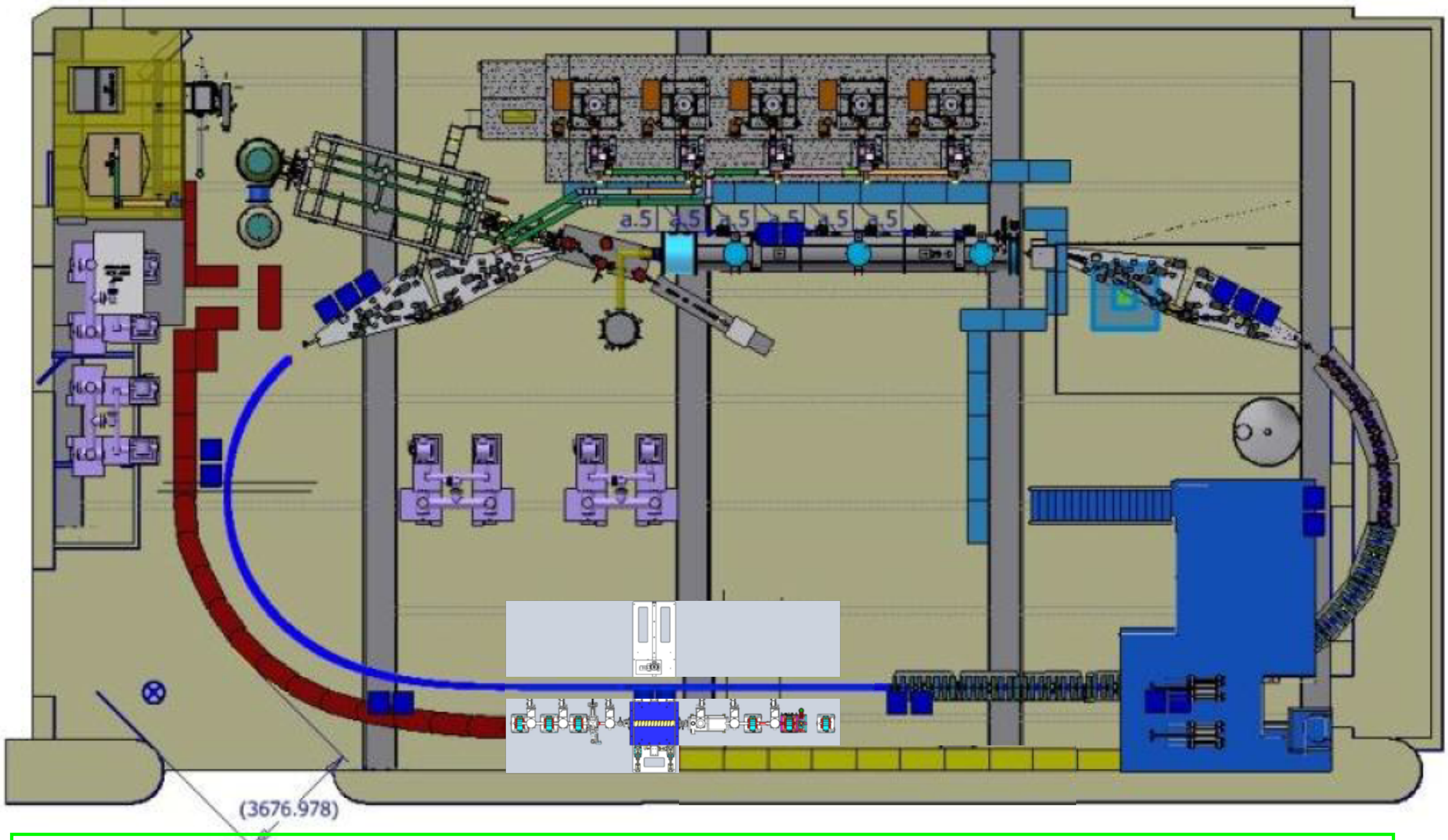
- Is usually benign if (C) is ok. But it can be important for similar reasons at (C).

[1] Recirculative BBU, G.H. Hoffstaetter in A. Chao, M. Tigner, Accelerator Handbook.

If EIC R&D would not come …

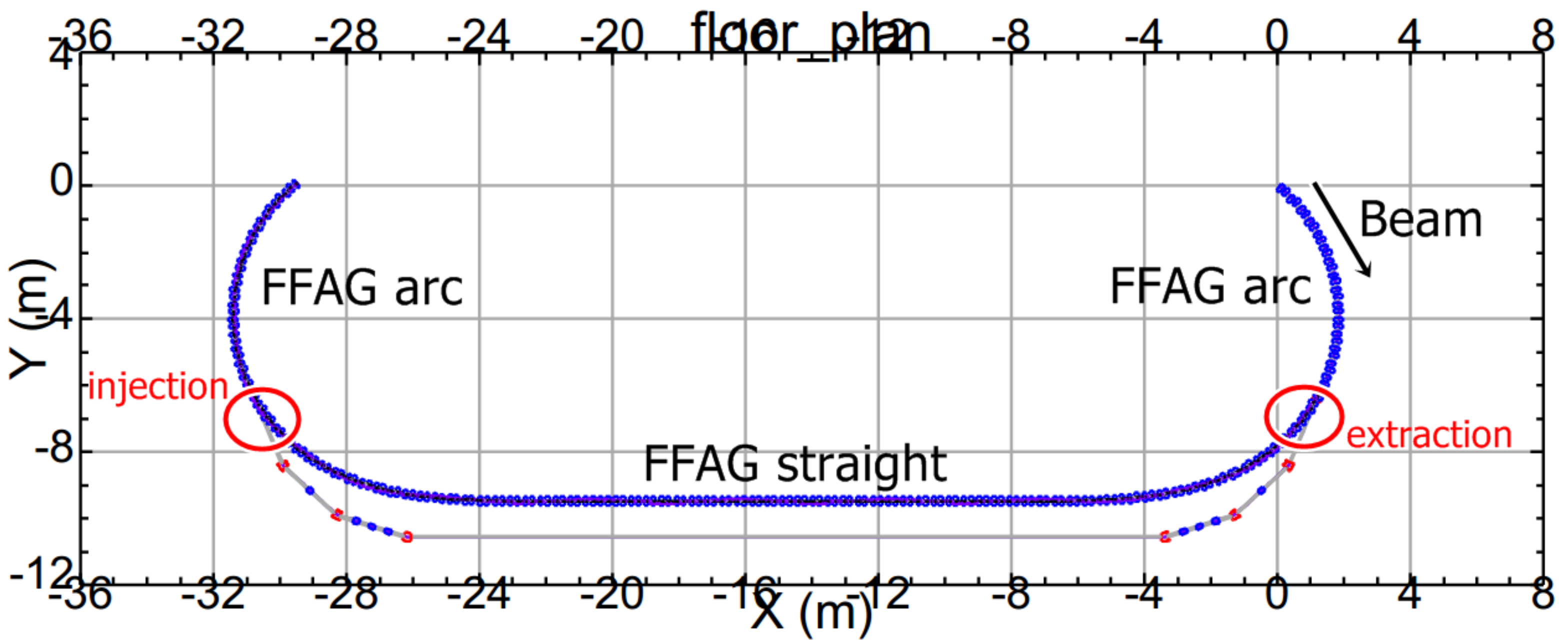
- **Continued commissioning for EIC studies (including electron cooling)**
- **DarkLight – an experiment to find dark matter particles**
- Compact Compton source for hard x-rays – complementing CHESS' range
- THz laser – complementing CHESS' range
- Beam for time-resolved electron diffraction from 1-6MeV
- Beam for **Plasma Wakefield Acceleration with High Transformer Ratio**
- ASML medical isotope cavity testing with beam
- Generic ERL accelerator physics
- Preparations for Perle
- Preparations for LHeC
- High-Power beam dynamics testing
- Permanent magnet and Fixed-Field Alternating-Gradient test bed for future accelerators

(A) DarkLight



The Darklight detector will fit around the resonantly extracted CBETA beam, if the movable support is redesigned.
Cornell is in contact with the DarkLight collaboration to submit a joint proposal.

Layout of extraction beam line



Extraction line contains:

Extra dipoles to guide the beam

Extra quadrupoles to maintain beam optics

Questions?