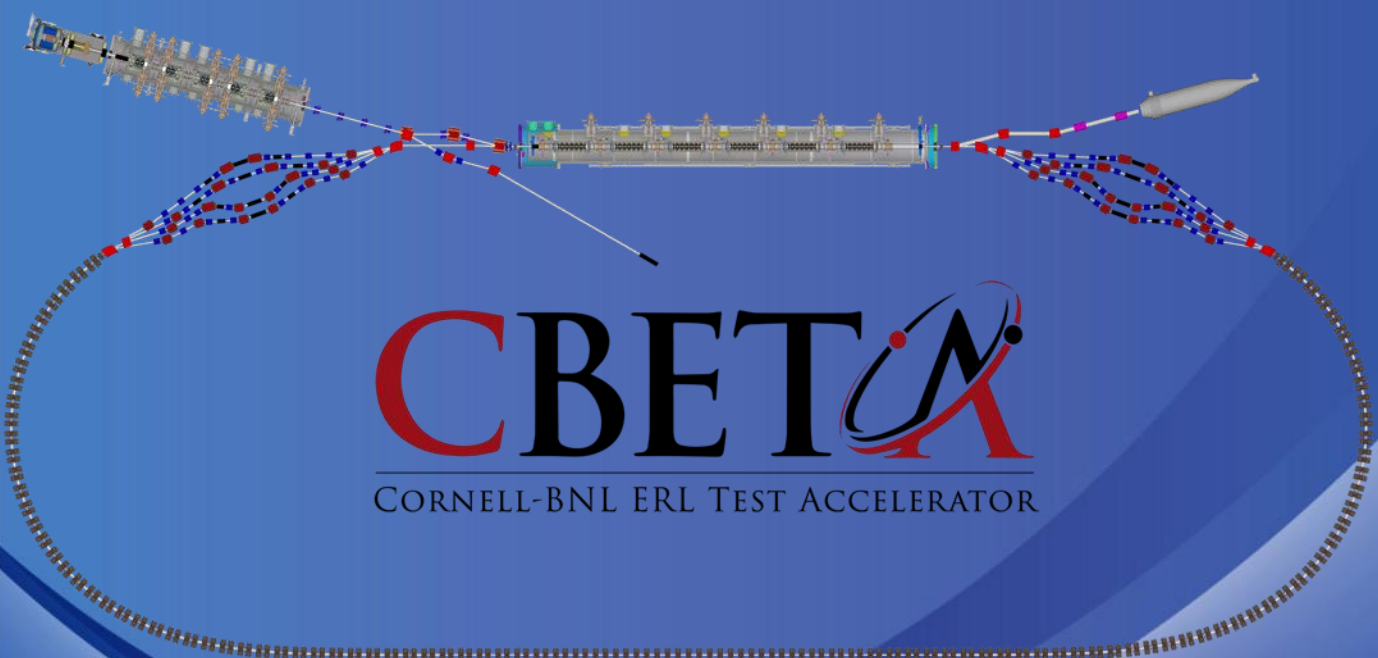
CBETA, a 4-turn ERL with FFA arc

Georg Hoffstaetter (Cornell)



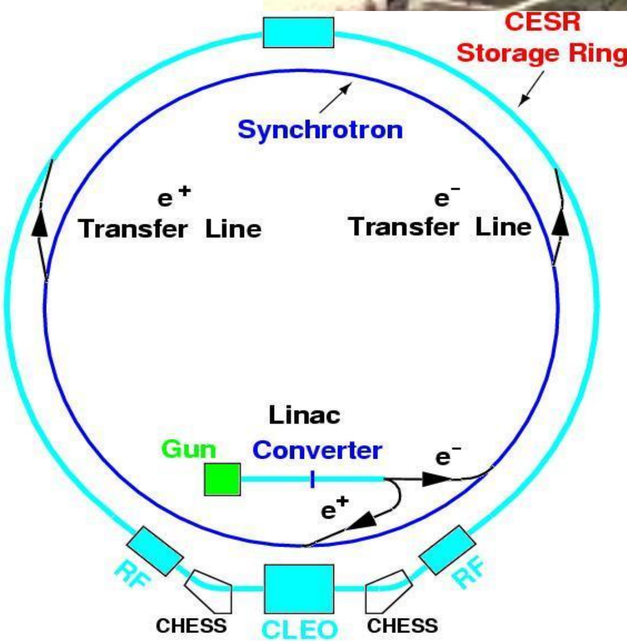
CBETA
CORNELL-BNL ERL TEST ACCELERATOR

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

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Cornell's synchroton and storage ring

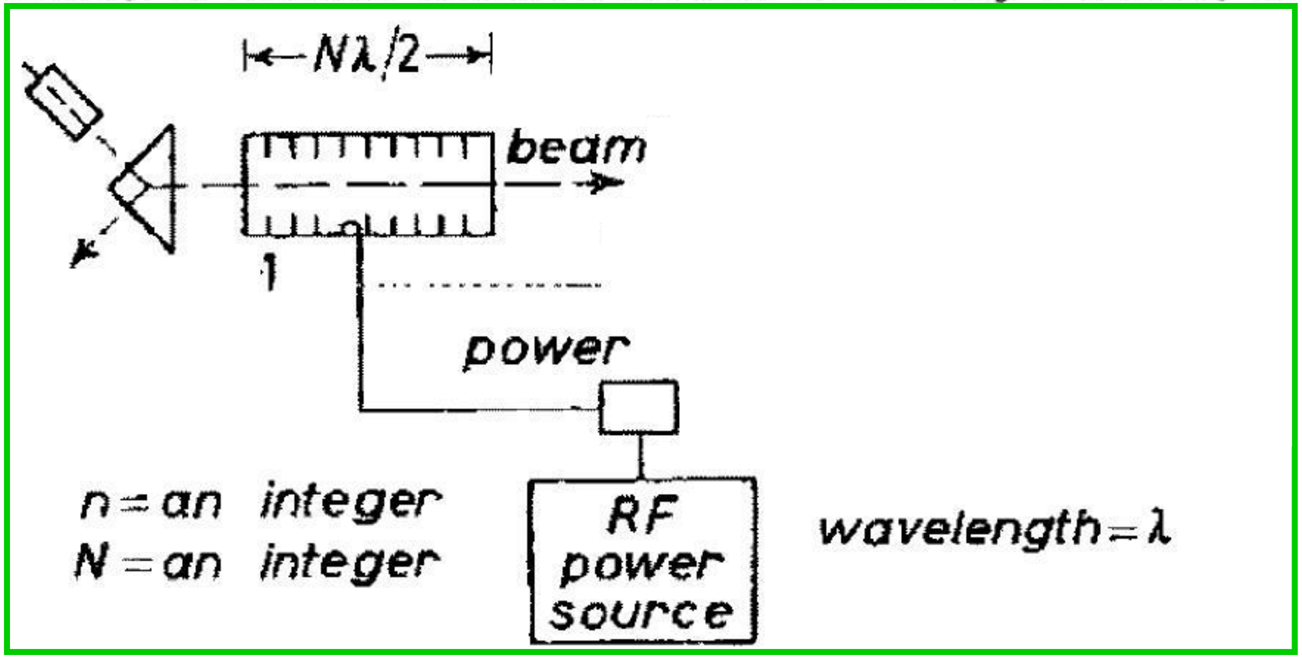


Energy Recovery, a Cornell Invention

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. Tigner

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.



- Linacs produce very high bunch quality (narrow, short, low energy spread)

- Remaining beam energy is discarded (wasted energy).

Energy Recovery, a Cornell Invention

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. TIGNER

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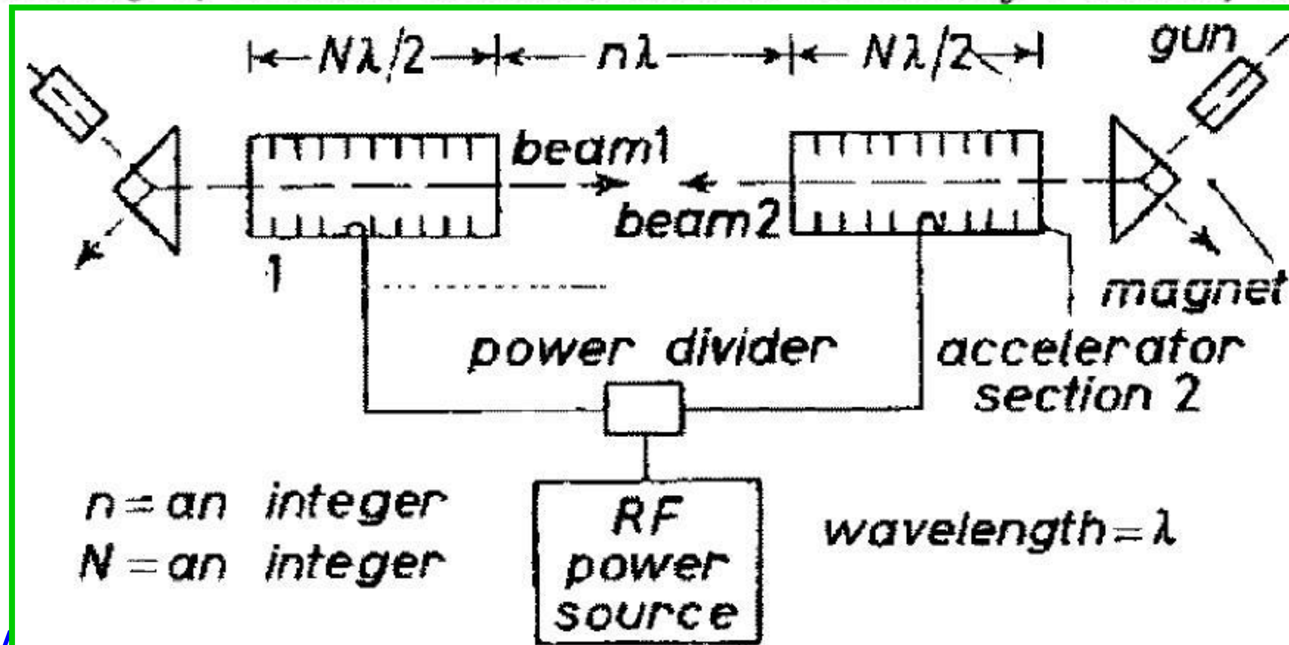

- Energy Recovery Linacs recapture the beam power in Super-Conducting (SRF) Accelerating structures to accelerate more beam.

- This energy saving allows for unprecedented beam powers from Linacs.

Energy Recovery, a Cornell Invention

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

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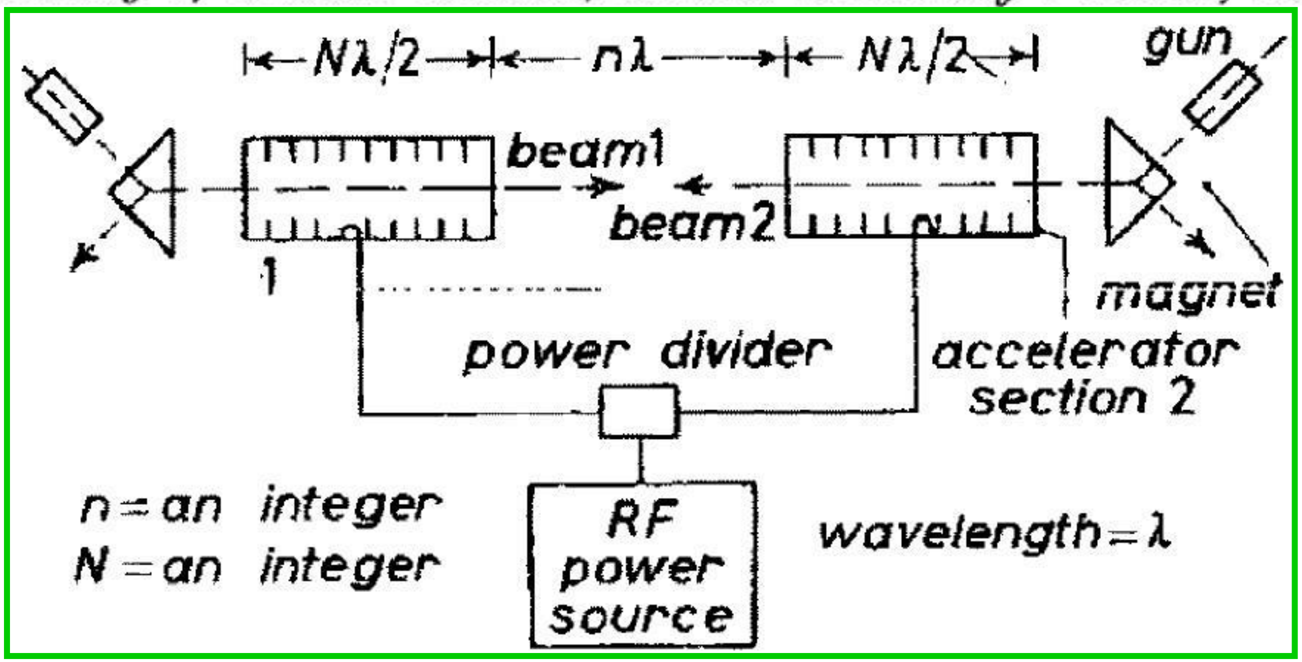

Energy recovery needs continuous beams in SRF structures

- With focus on beam dynamic and SRF, Cornell has been an excellent place for ERL research.

Energy Recovery, a Cornell Invention

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

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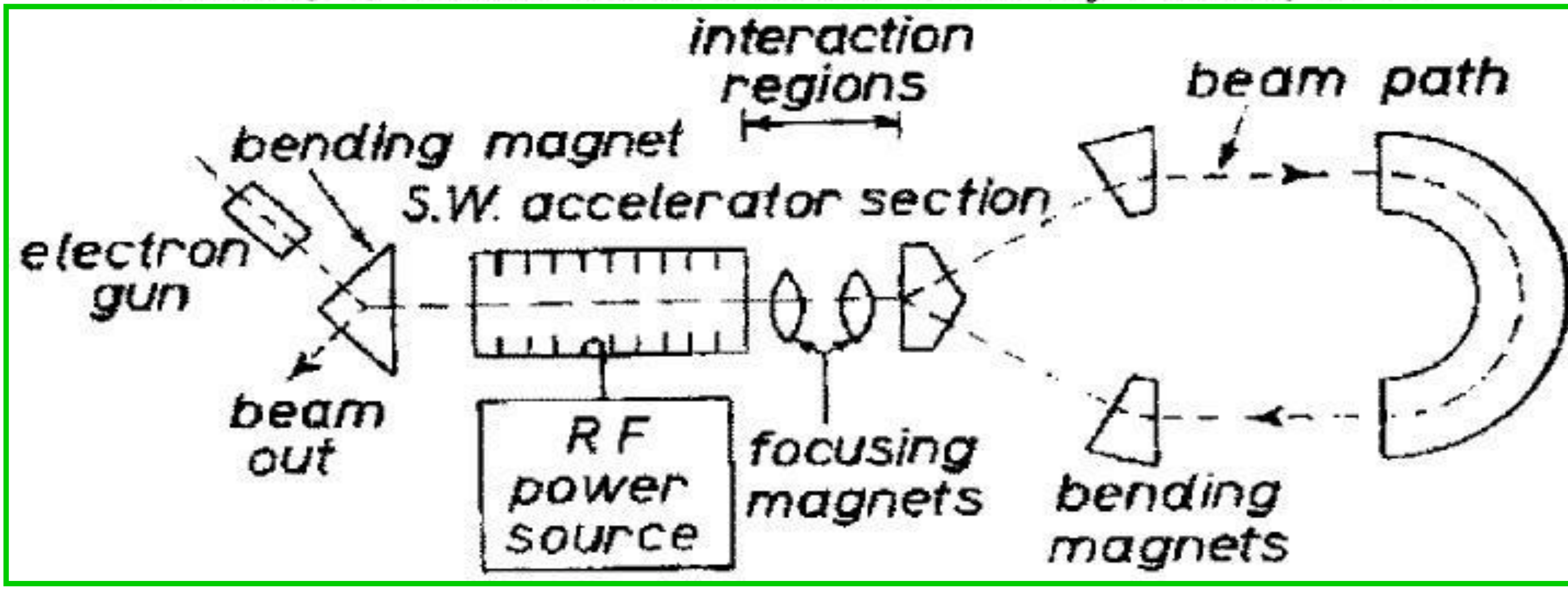


Energy recovery needs continuous beams in SRF structures

- With focus on beam dynamic and SRF, Cornell has been an excellent place for ERL 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?

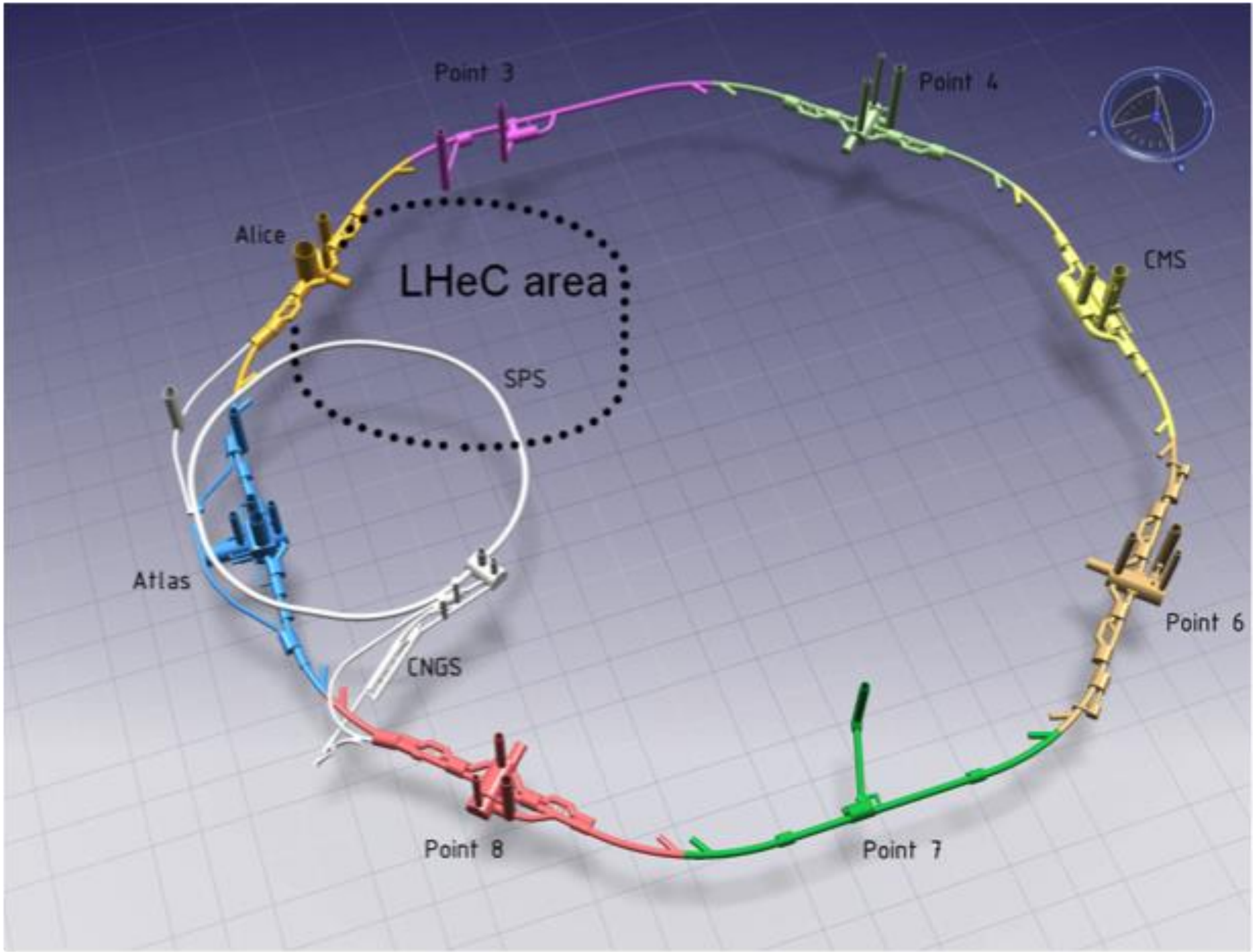
(a) high currents, like storage rings, because the energy is recovered,

(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.

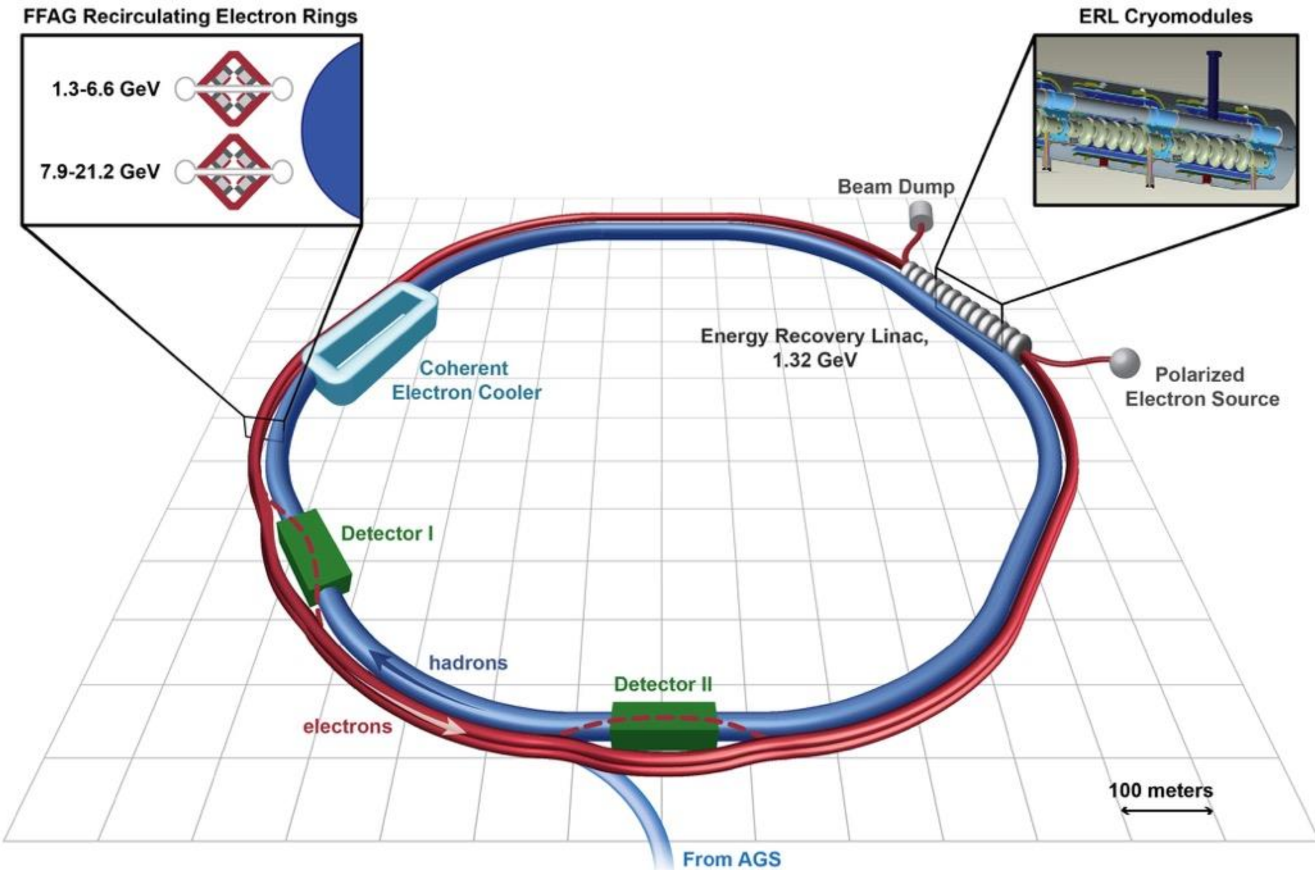
All these strengths of ERLs are beneficial to EIC cooling!

AnERL for LHeC (e-hadron collisions)

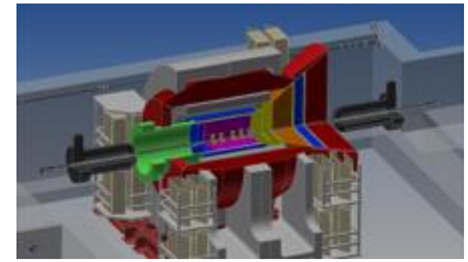


courtesy Oliver Bruening

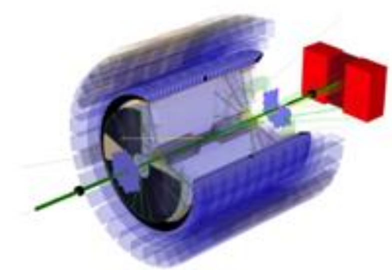
ERL for eRHIC (e-p and e-ions)



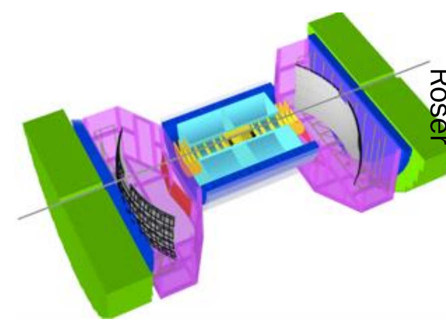
ePHENIX



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)

ERLs for Electron Ion Colliders (EICs)

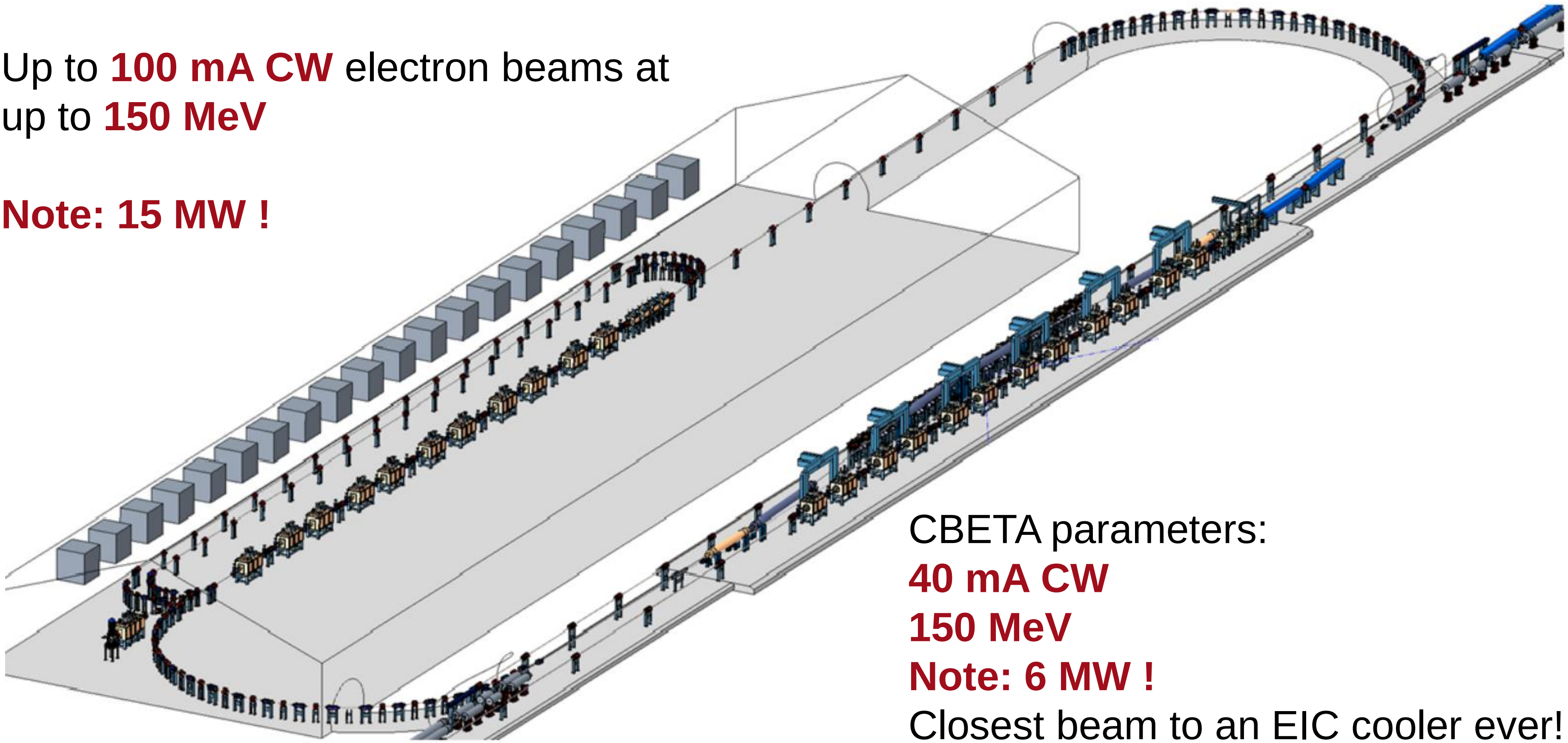
Strong Hadron Cooling for EICs – Boosting the luminosity of JLEIC and eRHIC by **at least a factor of 2**; and the integrated luminosity even more!

Both **JLEIC** and **eRHIC** plan to cool the hadron beam with electrons.

Required beams, e.g. eRHIC pCDR:

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

Note: 15 MW !



CBETA parameters:
40 mA CW
150 MeV
Note: 6 MW !
Closest beam to an EIC cooler ever!

EIC cooling topics

1) ERL operation for high-power beams
- Current limits (instabilities and component heating)
- Startup scenarios
- Simultaneous beam measurements

2) High-power beam propagation
- 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
- Dark currents

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

Other ERL applications will benefit too
- High-power FELs
- Coherent light sources
- Lithography for chip production
- Compton backscattering sources
- High energy colliders, e.g. LHeC

ERL research at Cornell: R&D

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 Construction funding by NYS begins.

2017 CBETA Design Report

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

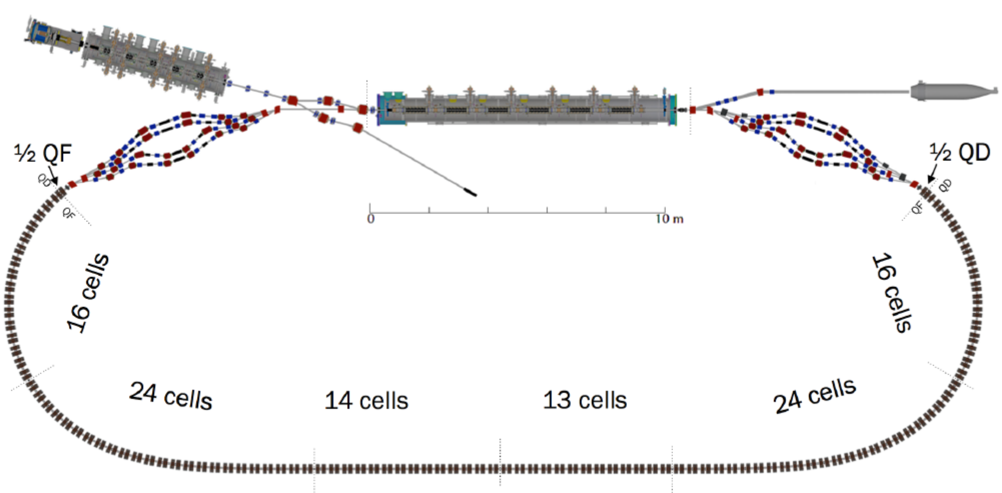
CBETA Design Report

Cornell-BNL ERL Test Accelerator

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

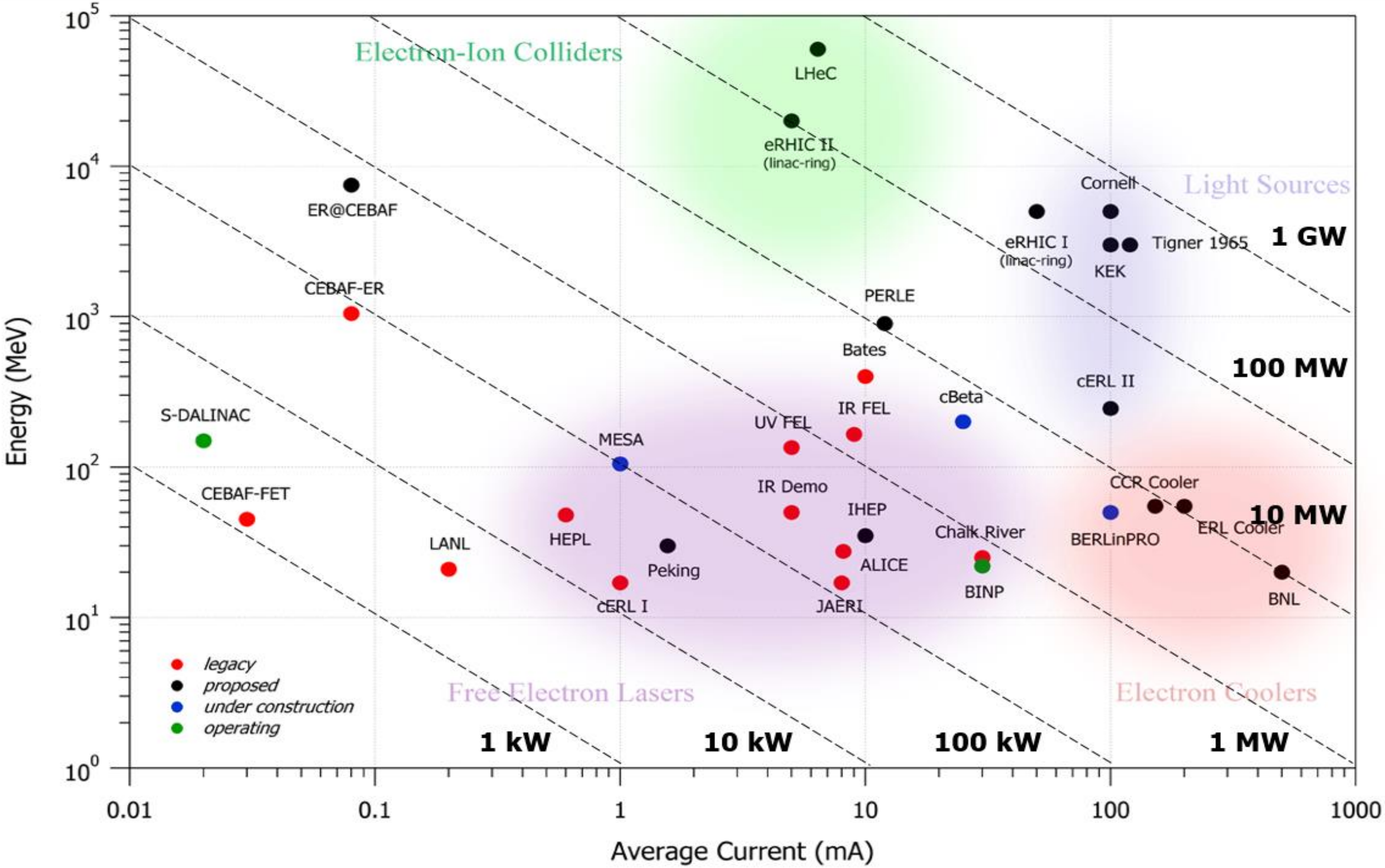
Editor: C. Mayes

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



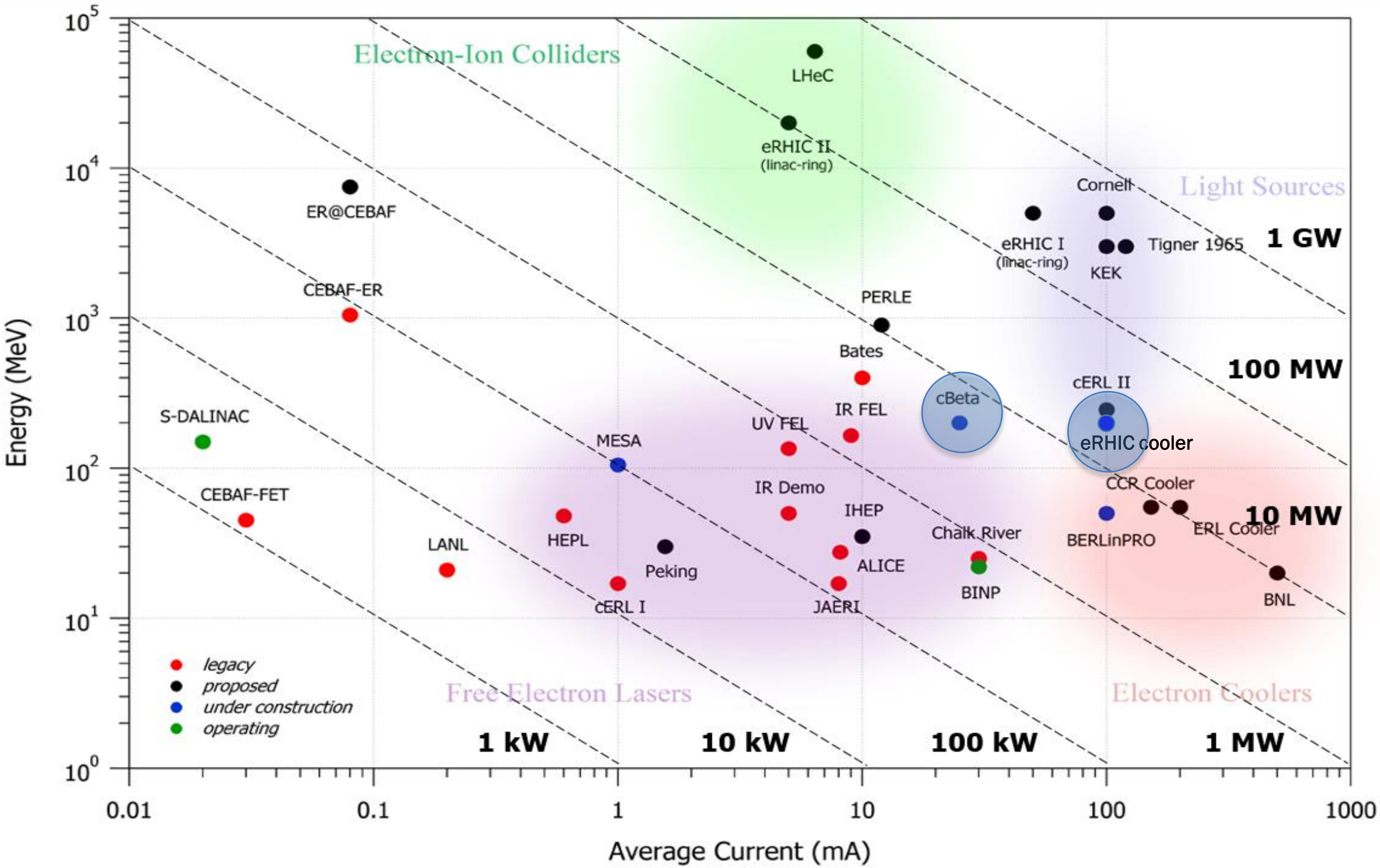
June 8, 2017

The beam power fronteer



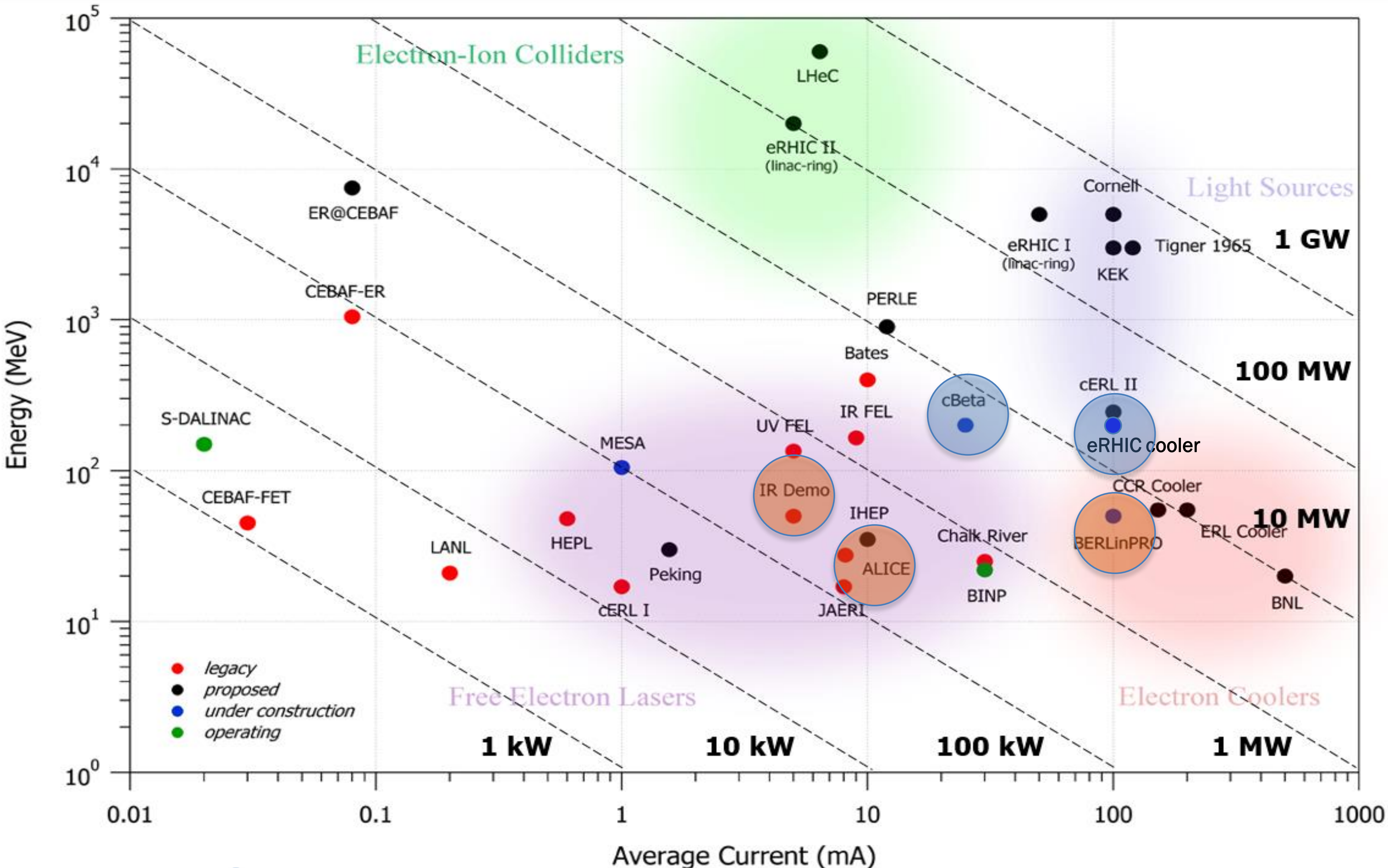
- CBETA has 150MeV and up to 40mA: 6MW beampower

The beam power frontier



- CBETA has 150MeV and up to 40mA: 6MW beampower
- 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

2015 NSAC Long Rang Plan

RECOMMENDATION III

We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new Quantum Chromodynamics (QCD) frontier of ultra-dense gluon fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei. This science will be made possible by the EIC's unique capabilities for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.

CBETA topics to support eRHIC

CBETA study topics important for eRHIC:

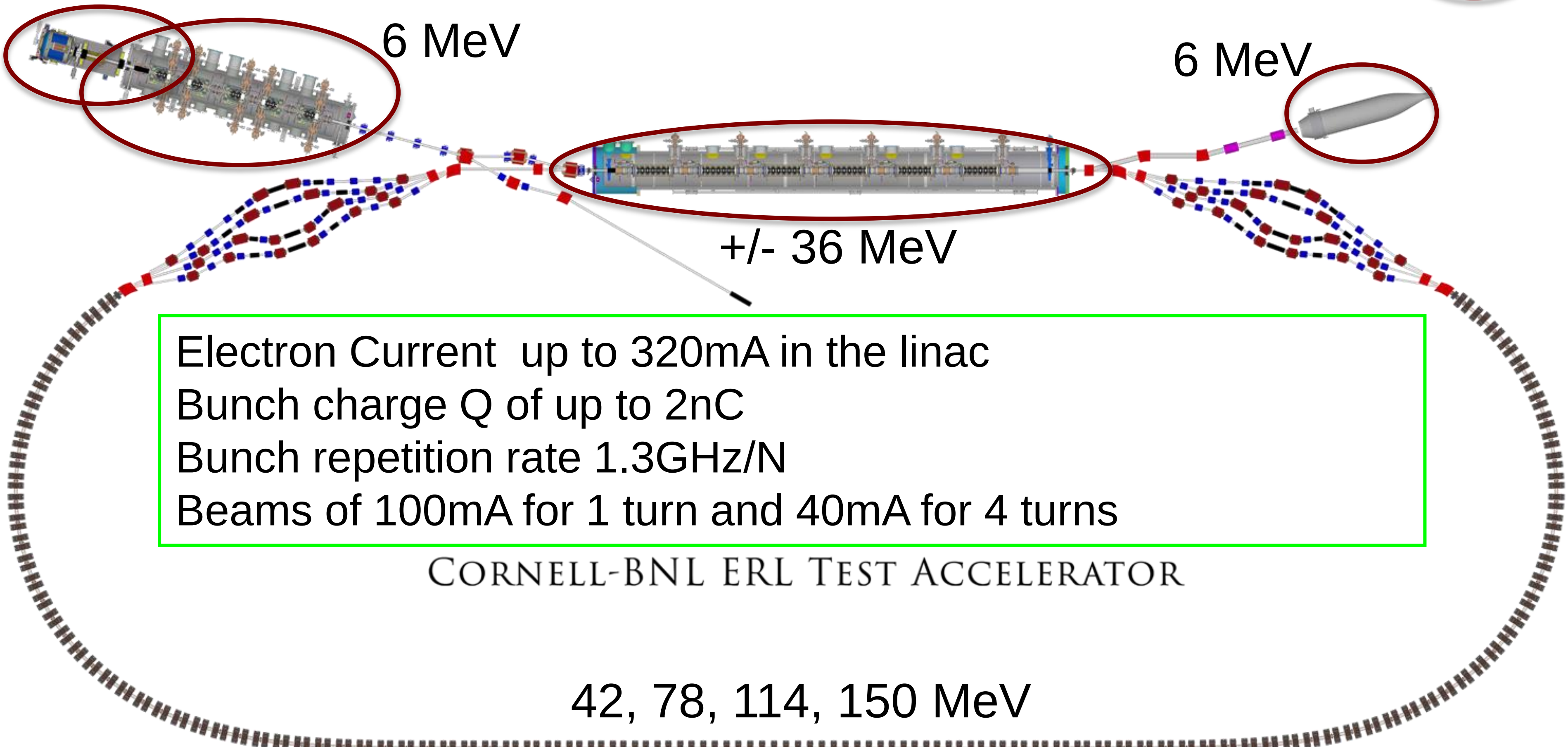
1) **FFAG** loops with a factor of 4 in momentum **aperture**.
   a) Precision, reproducibility, alignment during magnet and girder production.
   b) Stability of magnetic fields in a radiation environment.
   c) **Matching** and correction of multiple simultaneous **orbits**.
   d) **Matching** and 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.**
   e) **Beam parameters of EIC electron coolers**

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)

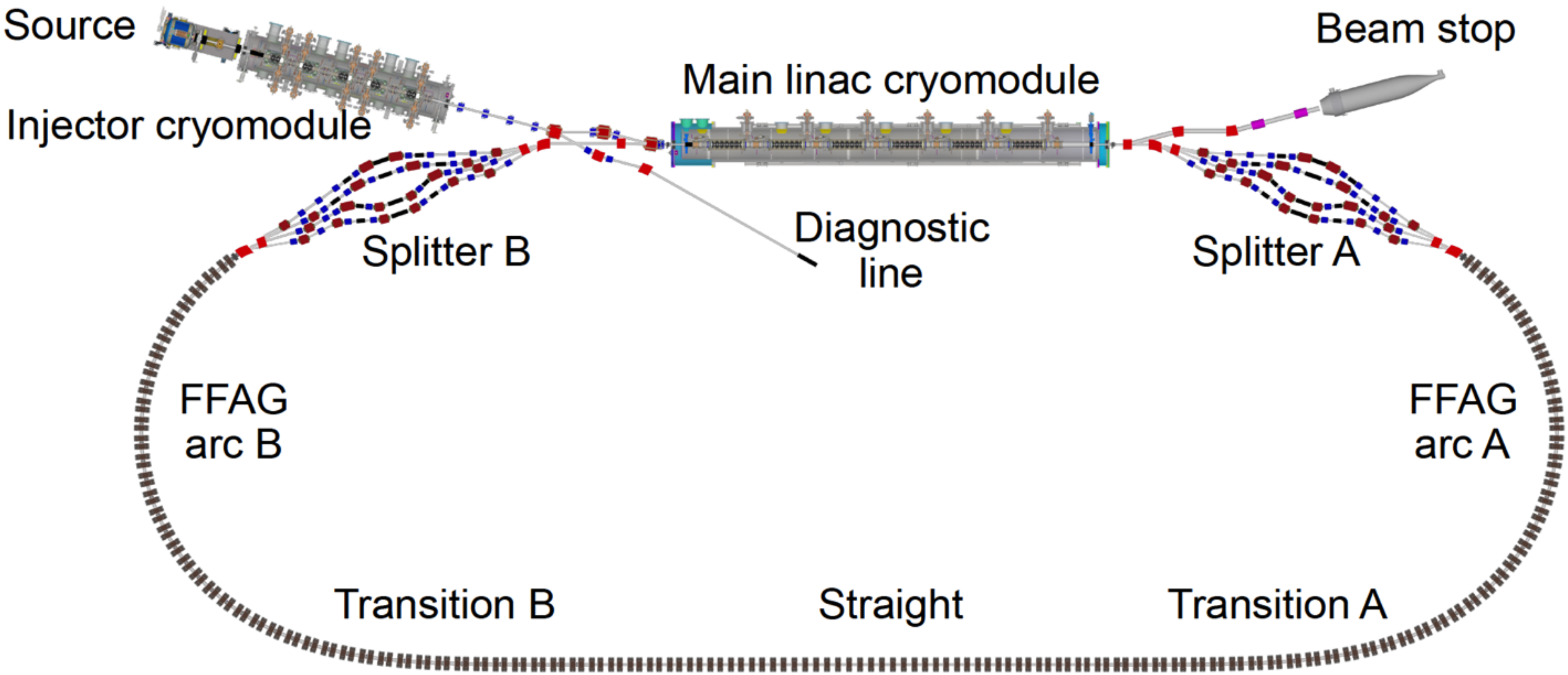
Existing components at Cornell



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

Existing & new equipment

CBETA

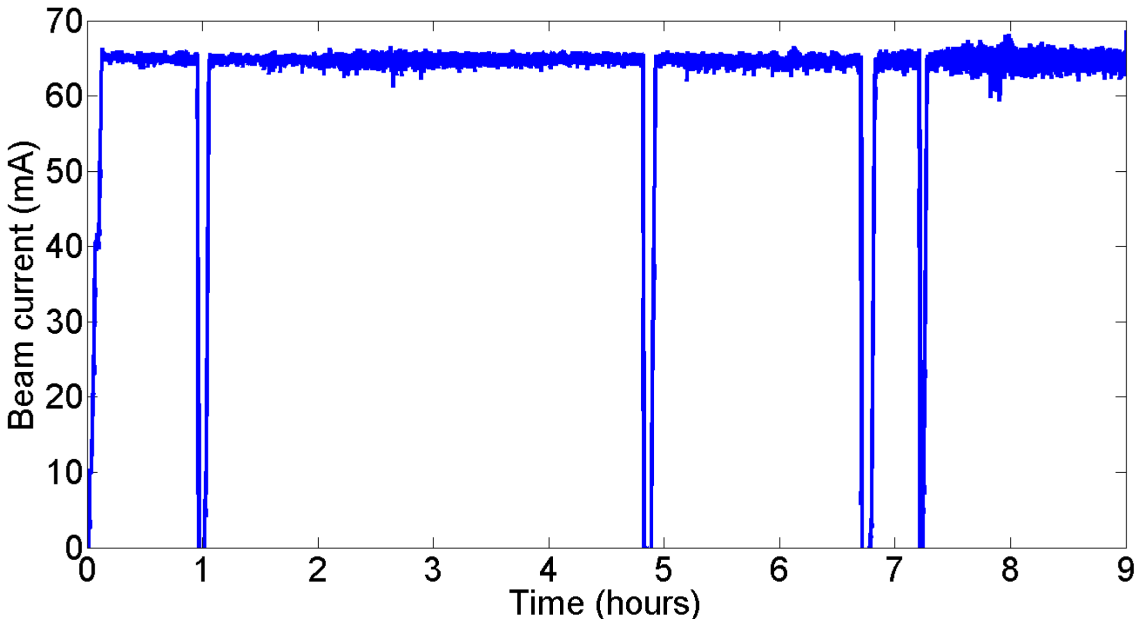


Much equipment & infrastructure exists — 32 M$

Major new equipment: -- 25 M$ new funding

- 2 splitters (electromagnets & tables)
- FFAG arc permanent magnets
- Diagnostics, power supplies etc.

High Current Beams



- Peak current of 75mA (world record)

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

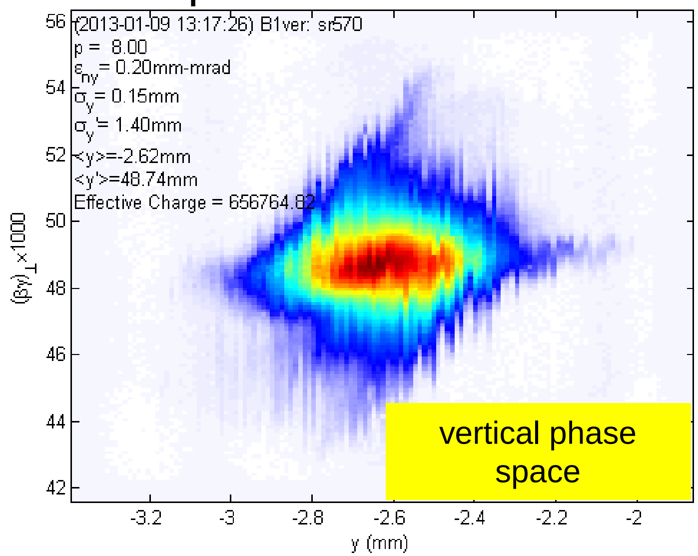
Source achievements:
- 2.6 day 1/e lifetime at 65mA
- 8h at 65mA
- With only 5W laser power (20W are available)
- now pushing to 100mA

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

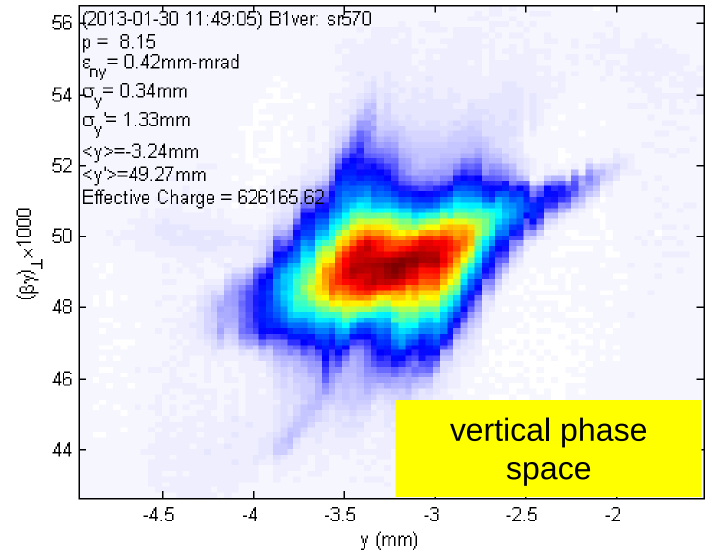
✓ Source current can meet ERL needs

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%

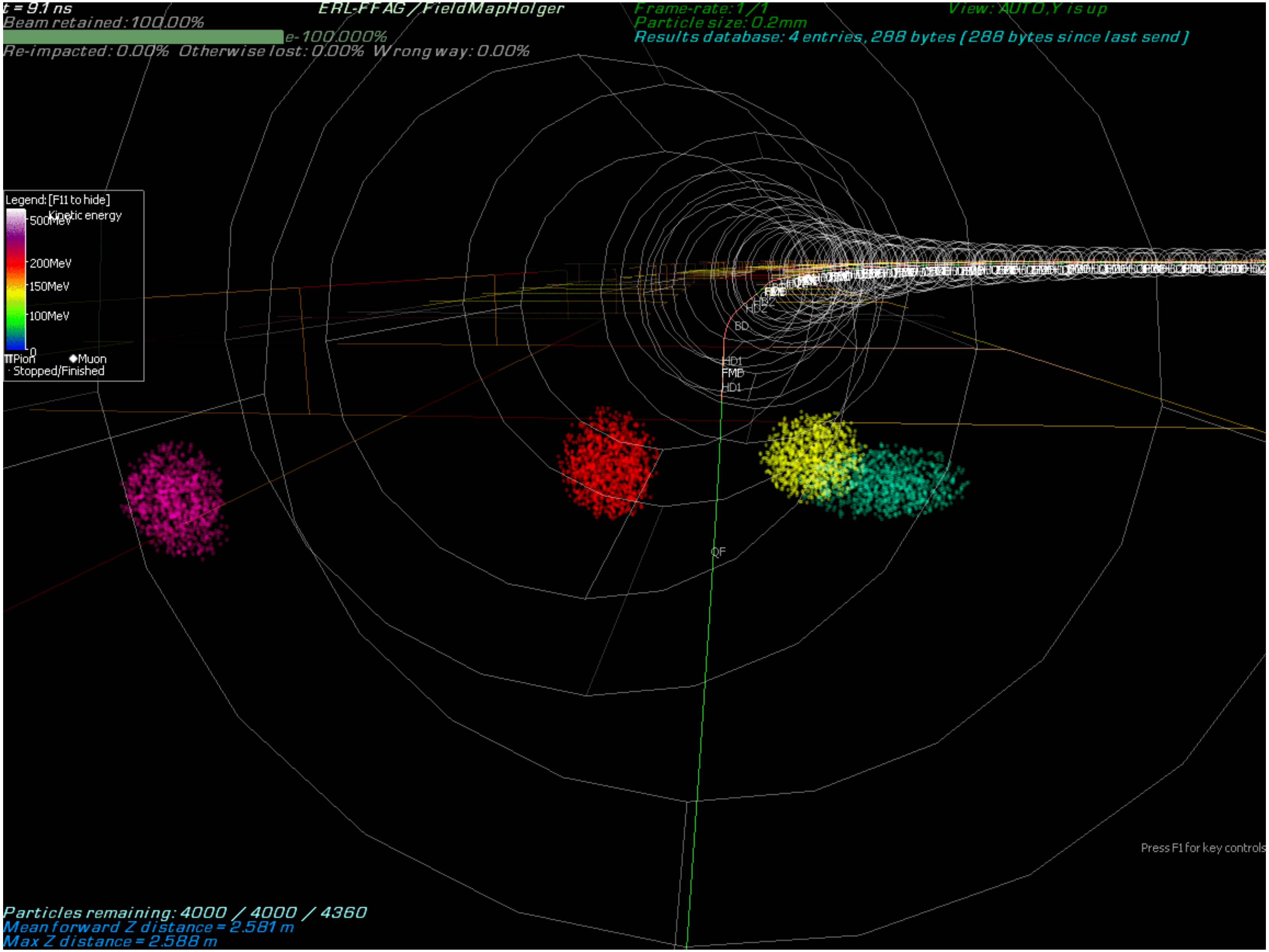
****Phys. Rev. ST-AB 15 (2012) 050703***
ArXiv: 1304.2708

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

Key Performance Parameters and Ultimate Performance Parameters

Parameter	Unit	KPP	UPP (Stretch)
Electron beam energy	MeV		150
Electron bunch charge	pC		123
Gun current	mA	1	40
Bunch repetition rate (gun)	MHz		325
RF frequency	MHz	1300	1300
Injector energy	MeV		6
RF operation mode			CW
Number of ERL turns		1	4
Energy aperture of arc		2	4

Bunche dynamics in 3D field maps



Hall L0E before CBETA

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

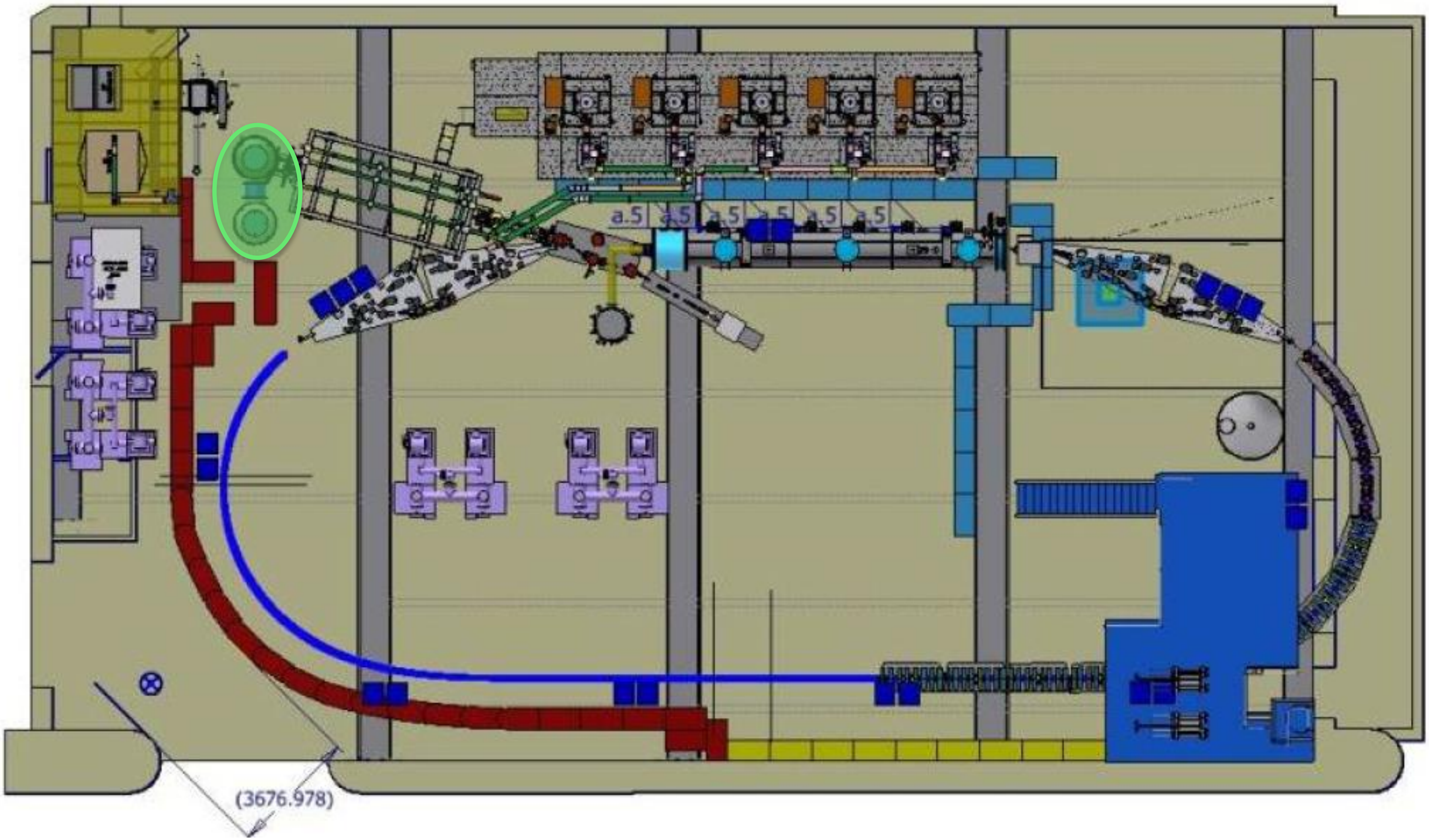
Spring 2015

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

L0E cleaned with CBETA

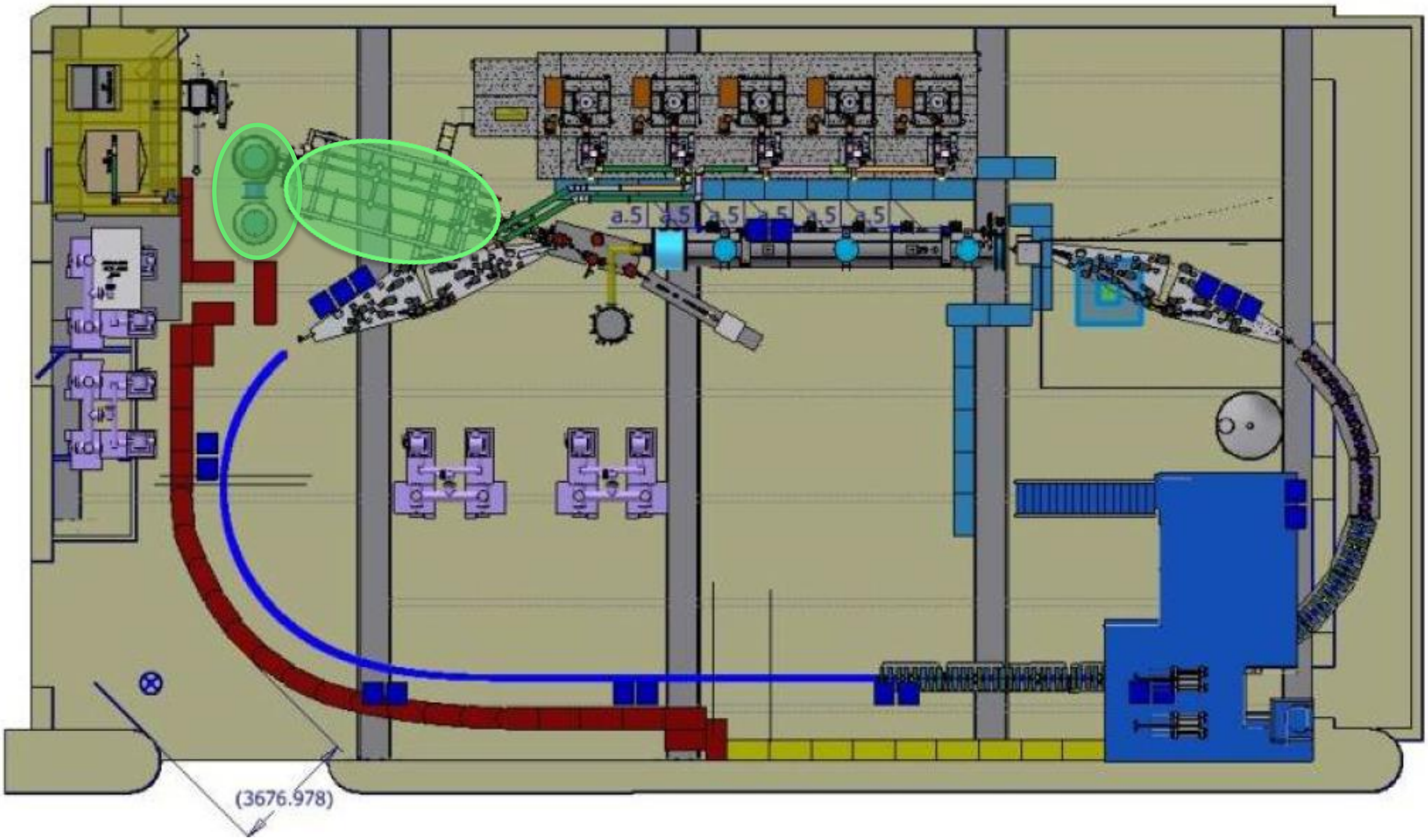
CBETA in its Hall L0E

Installed: DC gun



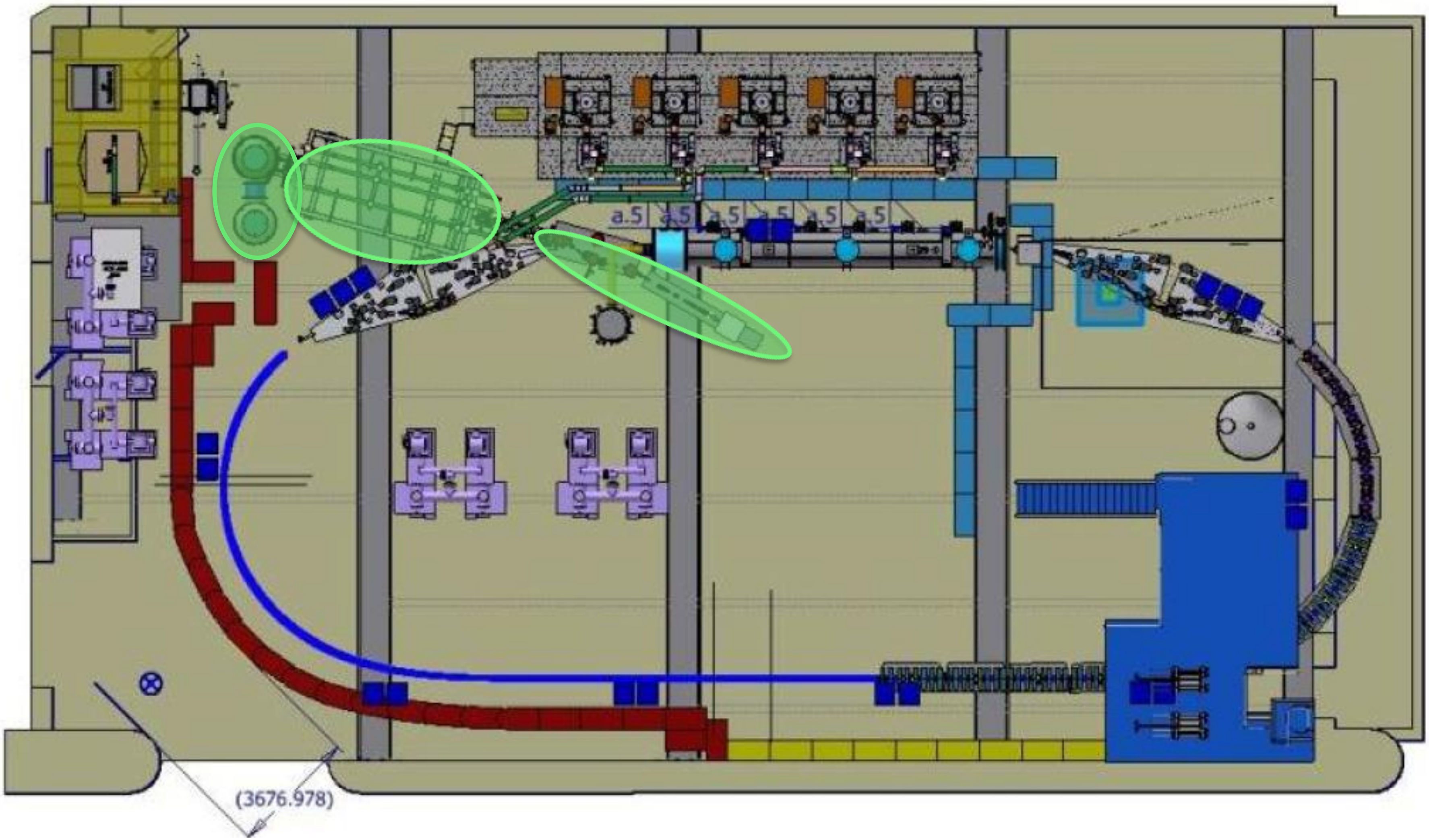
CBETA in its Hall L0E

Installed: DC gun, SRF injector



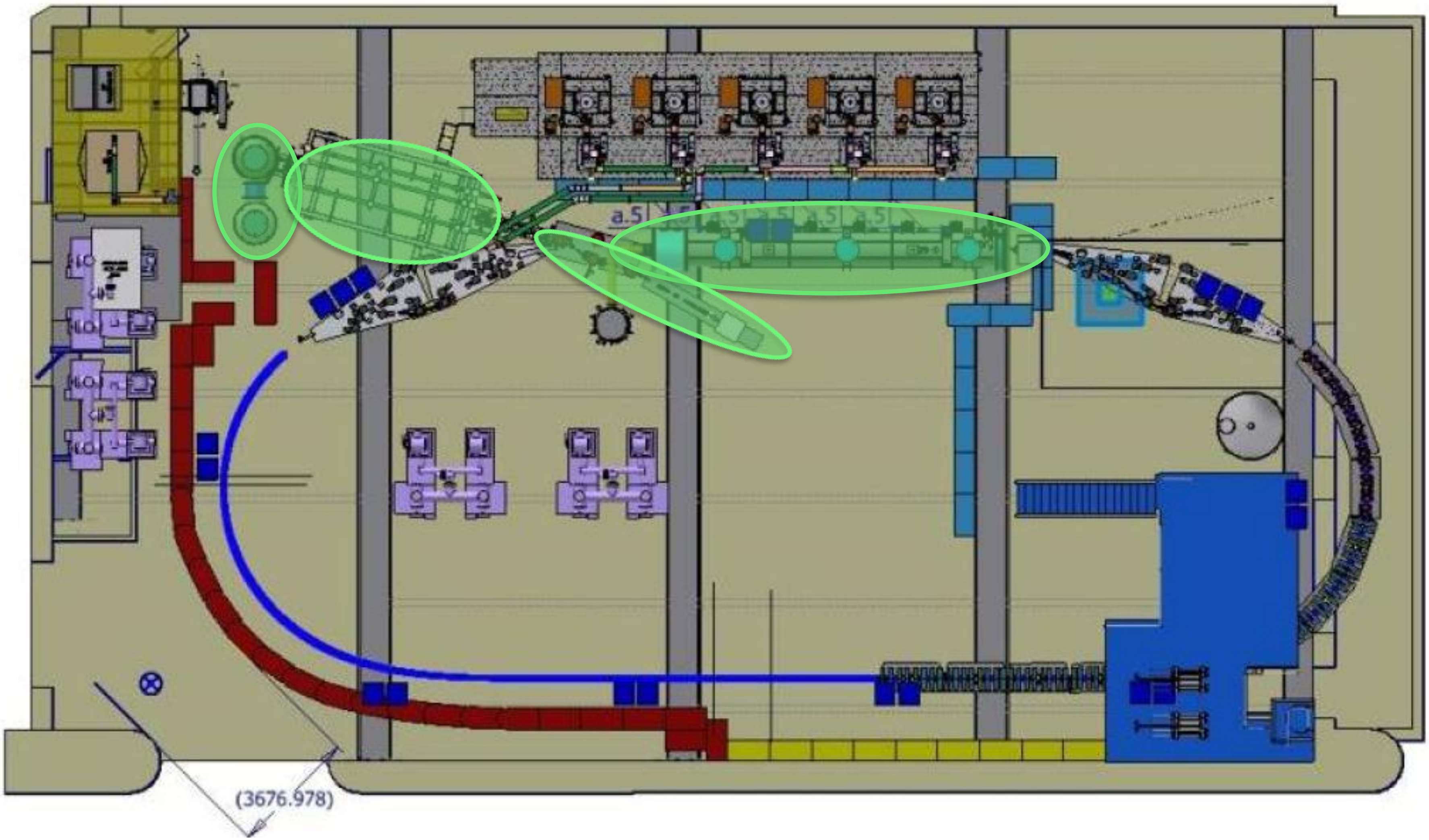
CBETA in its Hall L0E

Installed: DC gun, SRF injector, mirror diagnostics line



CBETA in its Hall L0E

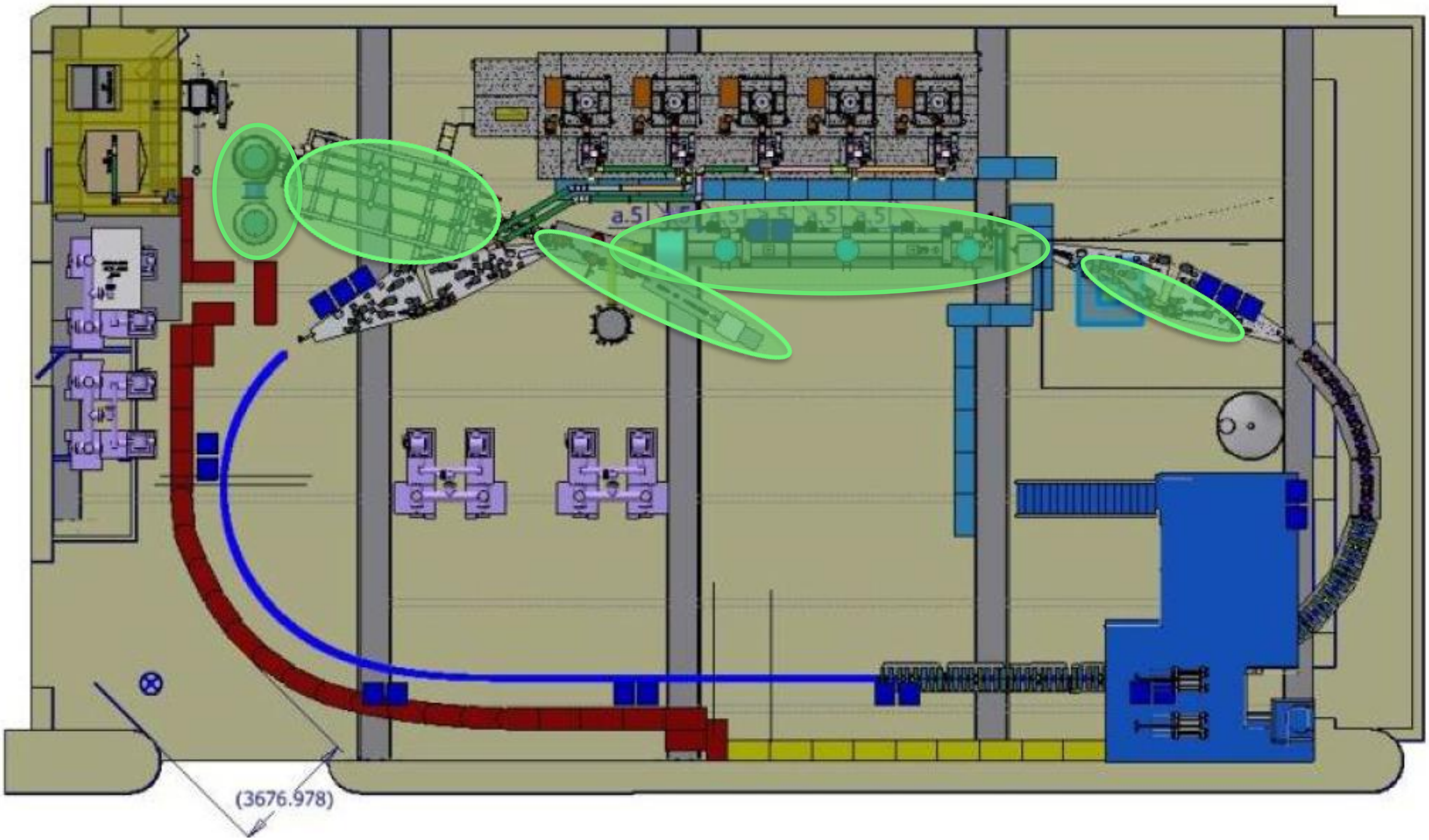
Installed: DC gun, SRF injector, mirror diagnostics line, ERL cryomodule



CBETA in its Hall L0E

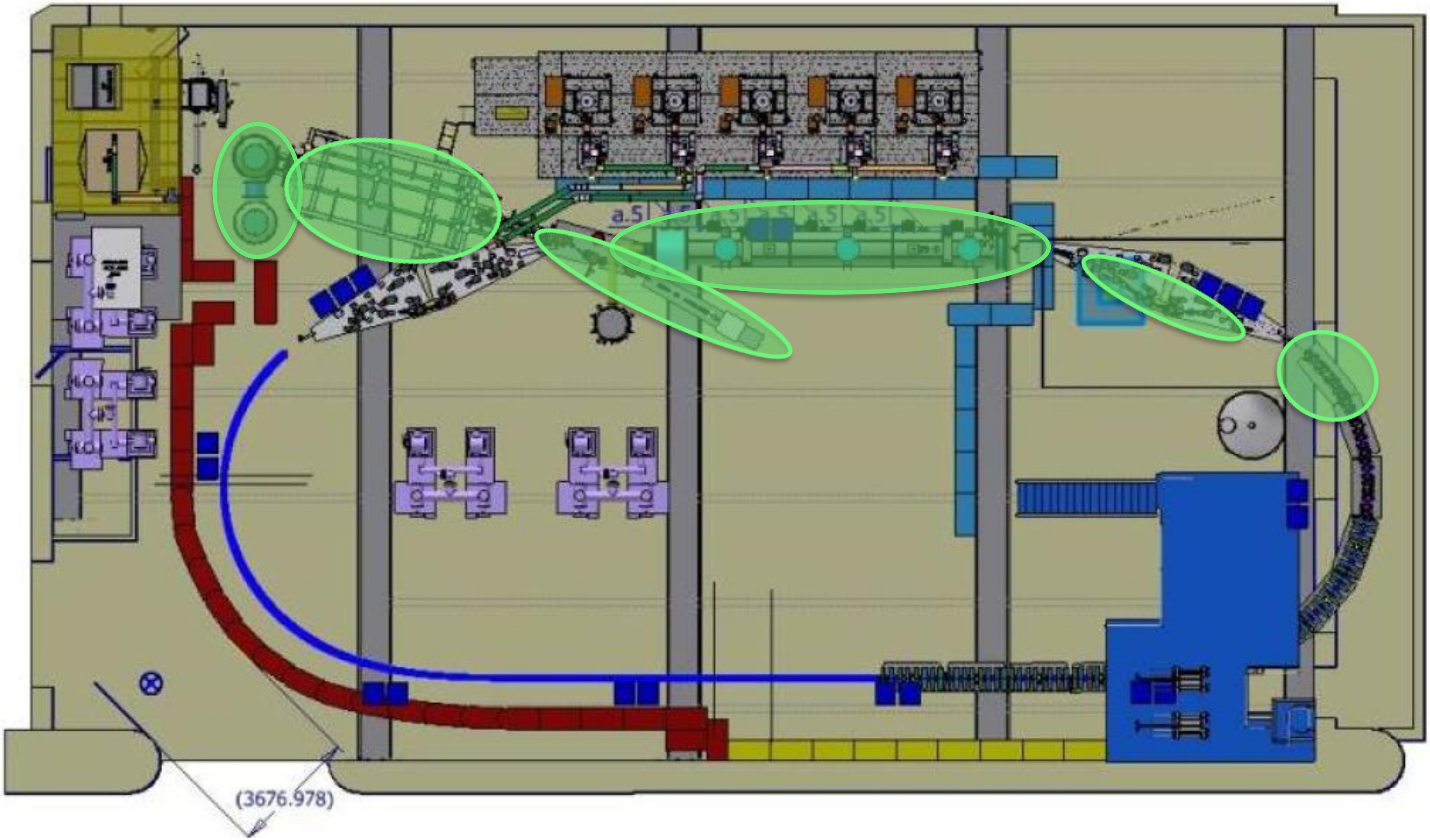
Installed: DC gun, SRF injector, mirror diagnostics line, ERL cryomodule

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.



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

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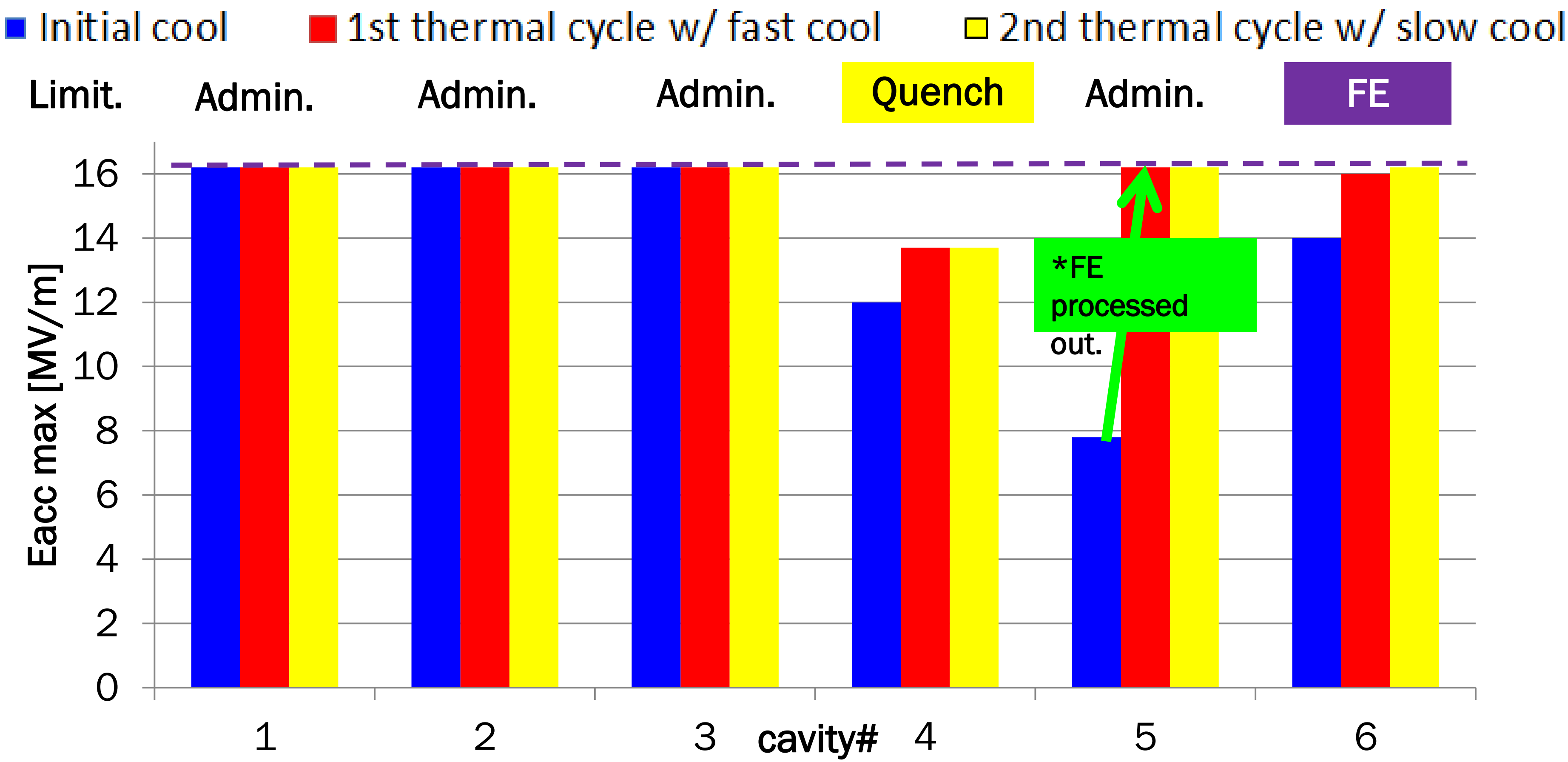
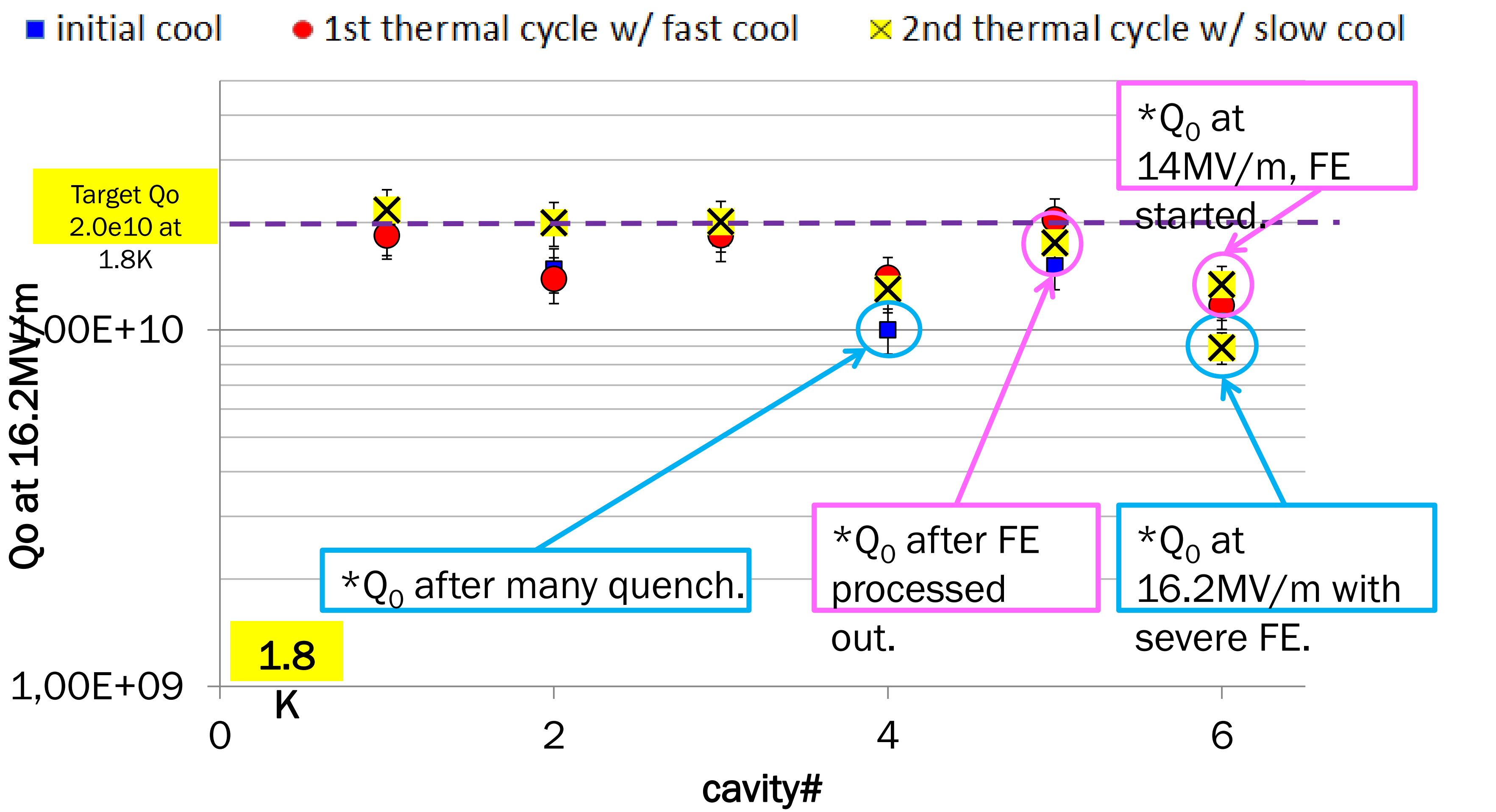
Main linac cryomodule (MLC) achieved accelerating gradients



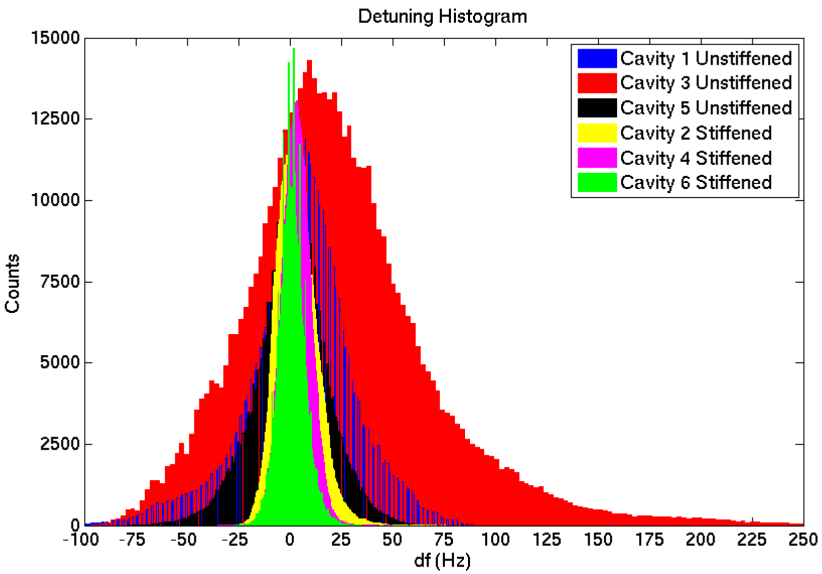
- 5 of 6 cavities had achieved design gradient of 16.2MV/m at 1.8K in MLC.
- Cavity#4 is limited by quench so far, no detectable radiation during test.
- **Enough Voltage for 76MeV per ERL turn (where 36MeV are needed)**

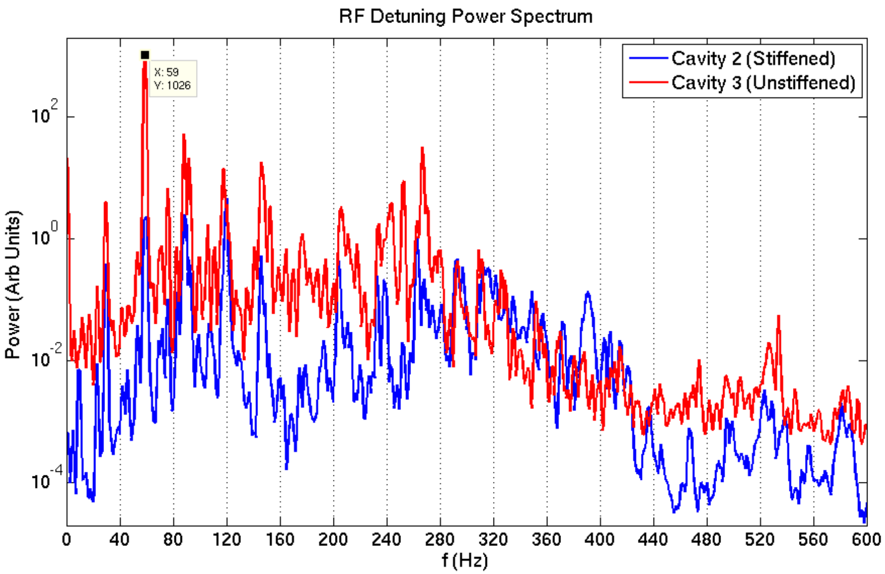
Main linac cryomodule (MLC) achieved surface losses (Q0)



- 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



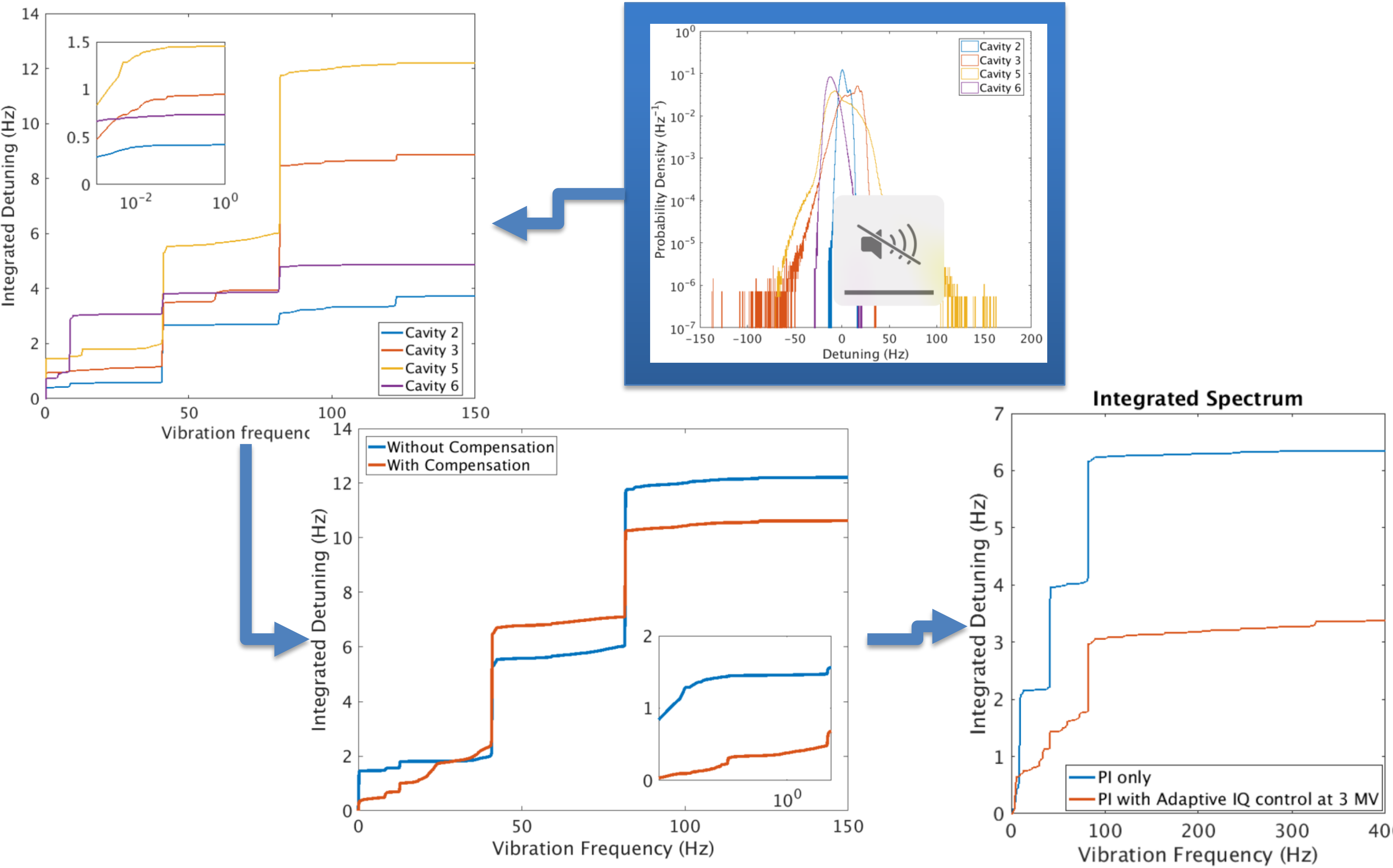


Preliminary results:

- 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.

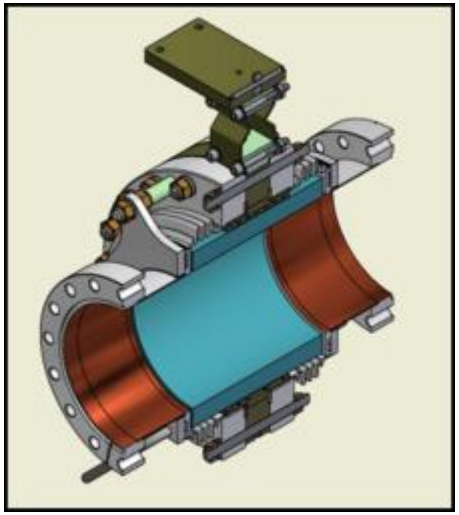
- **Enough Voltage for about 50MeV per ERL turn, if microphonics is not reduced (where 36MeV are needed)**

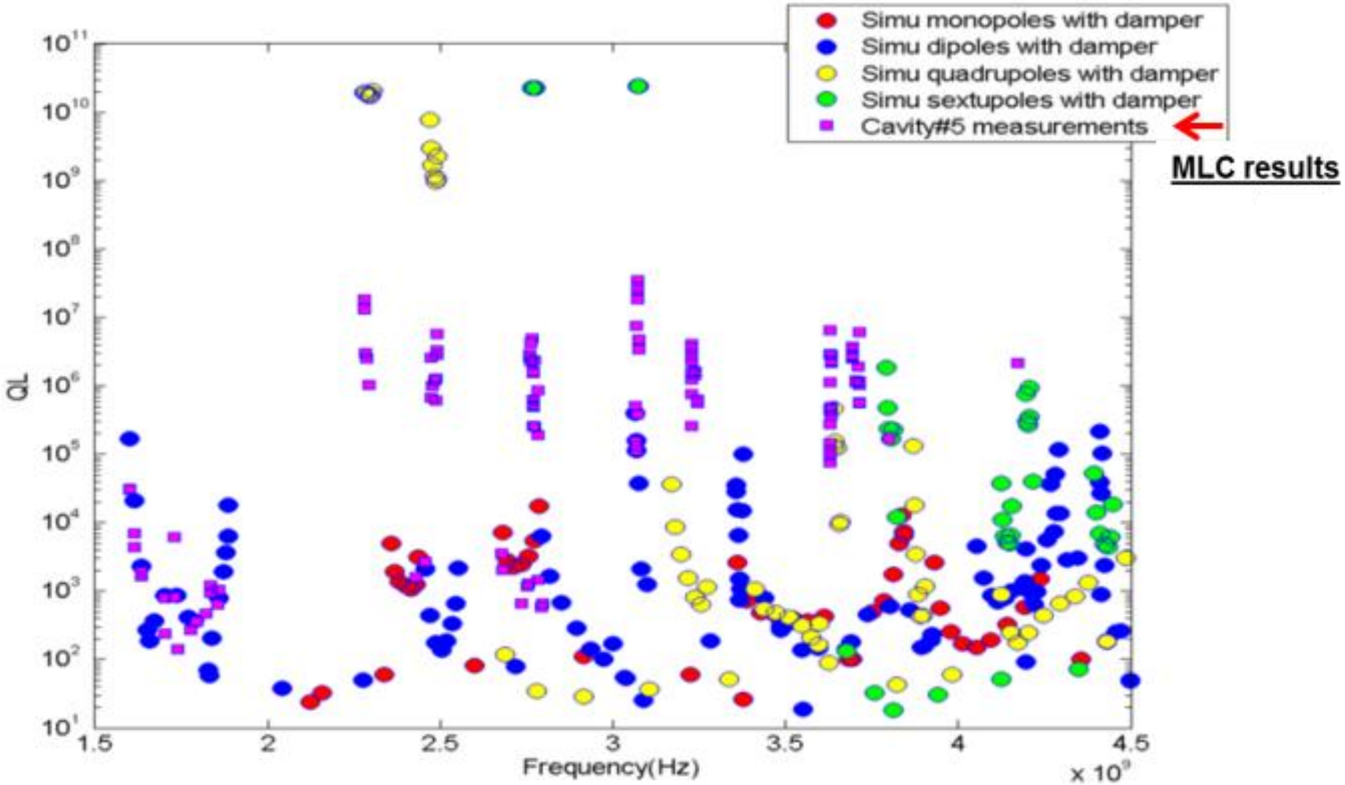
Current limits from HOMs



Algorithm is stable! Reduced peak detuning from 30.2Hz to 15.5Hz.

Current limits from HOMs



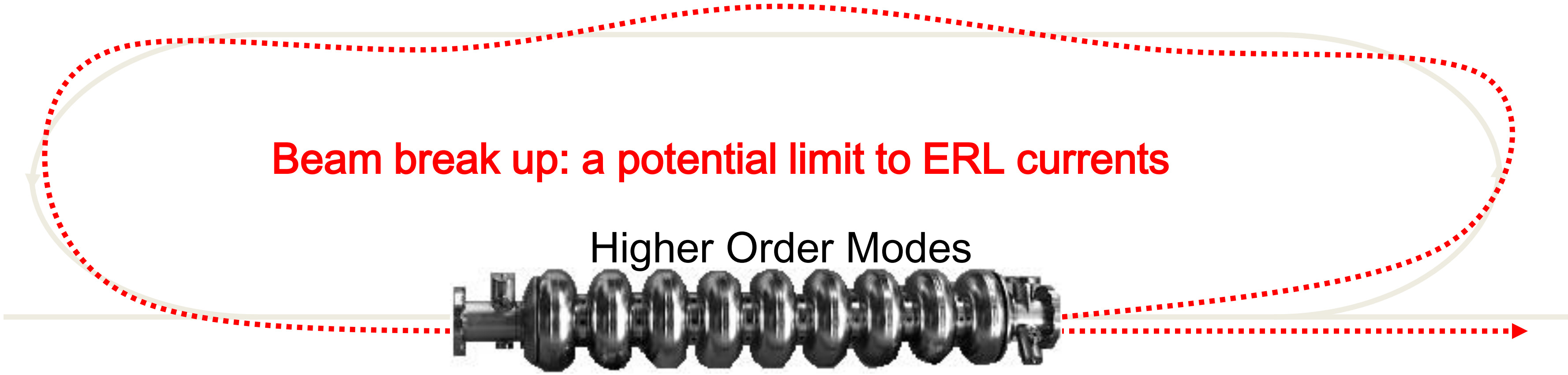


Dipole HOMs on MLC were strongly damped below $Q \sim 10^4$.
Consistent with HTC and simulation results.

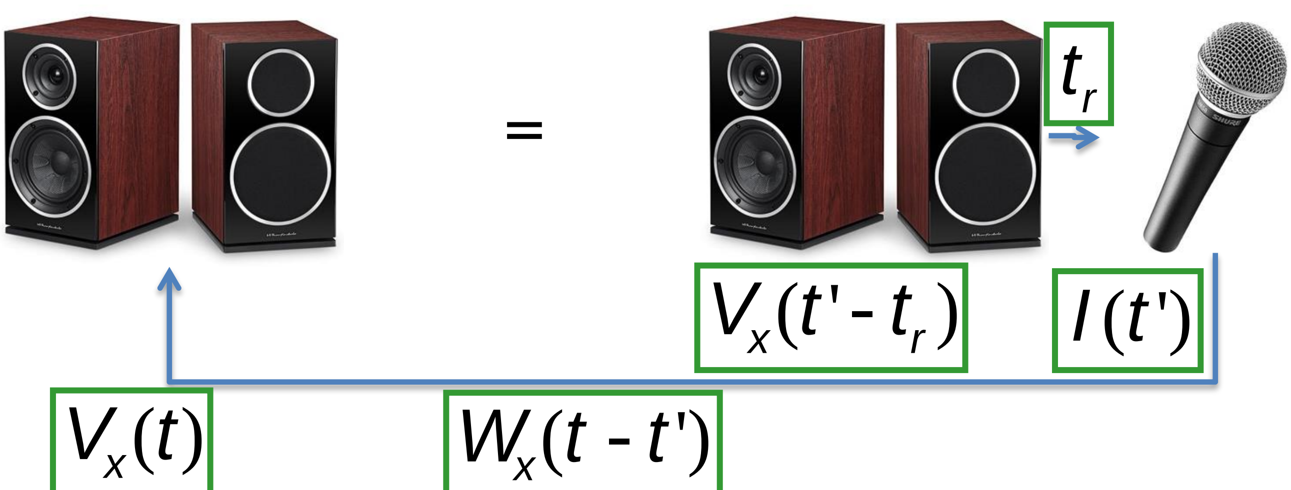
HTC results were:

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

New current limit



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



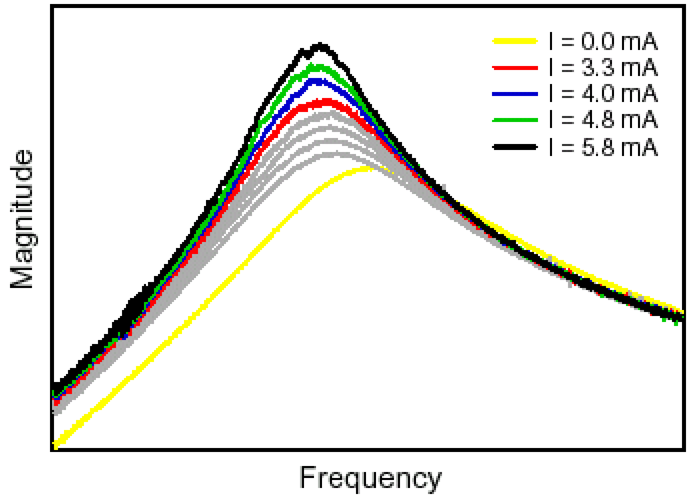
BBU measurements

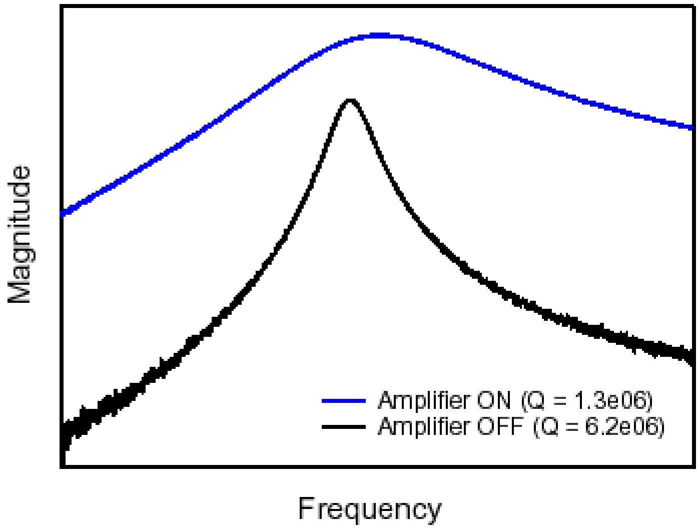
Recall… $I_{threshold} \propto \frac{1}{Q_{HOM}}$

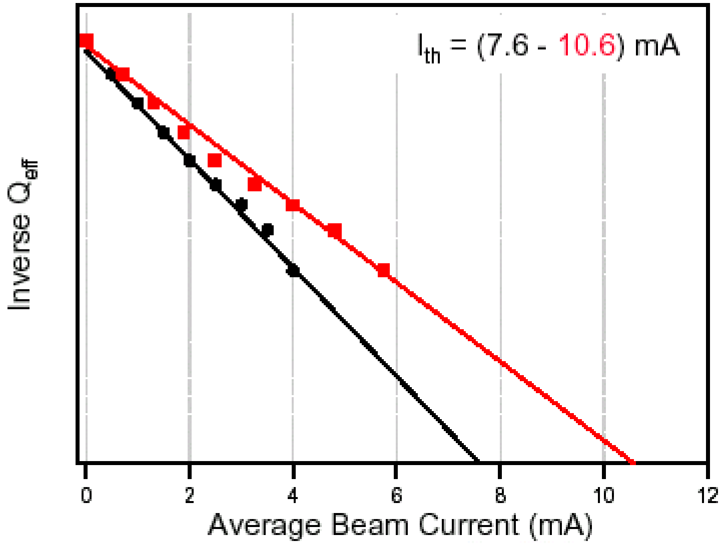
- Damping circuit easily reduced the *Q* of the 2106 MHz mode by a factor of 5

  (Above a factor of about 10, the system becomes sensitive to external disturbances)

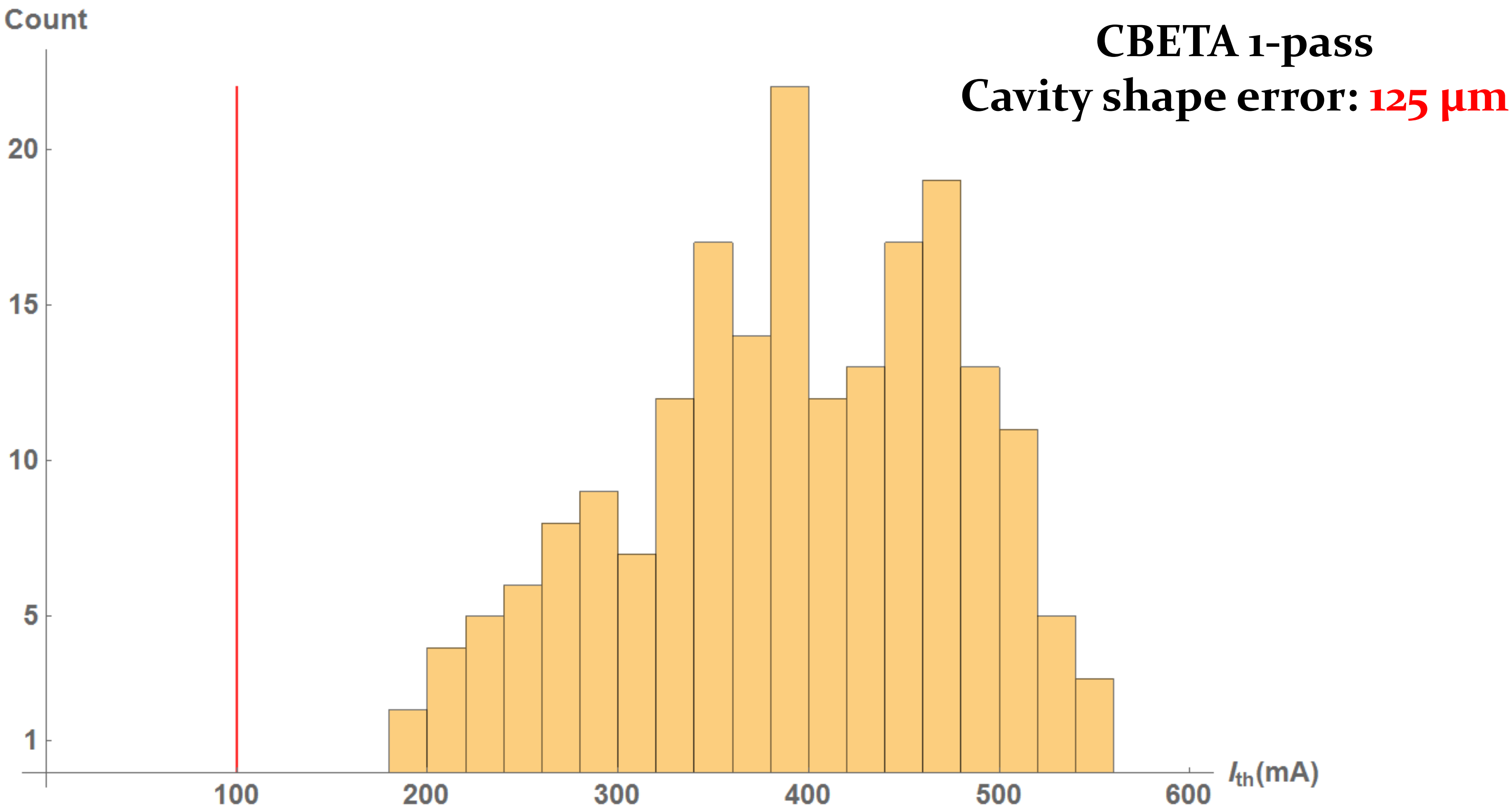
- The threshold is increased accordingly: from 2 mA to ~10 mA





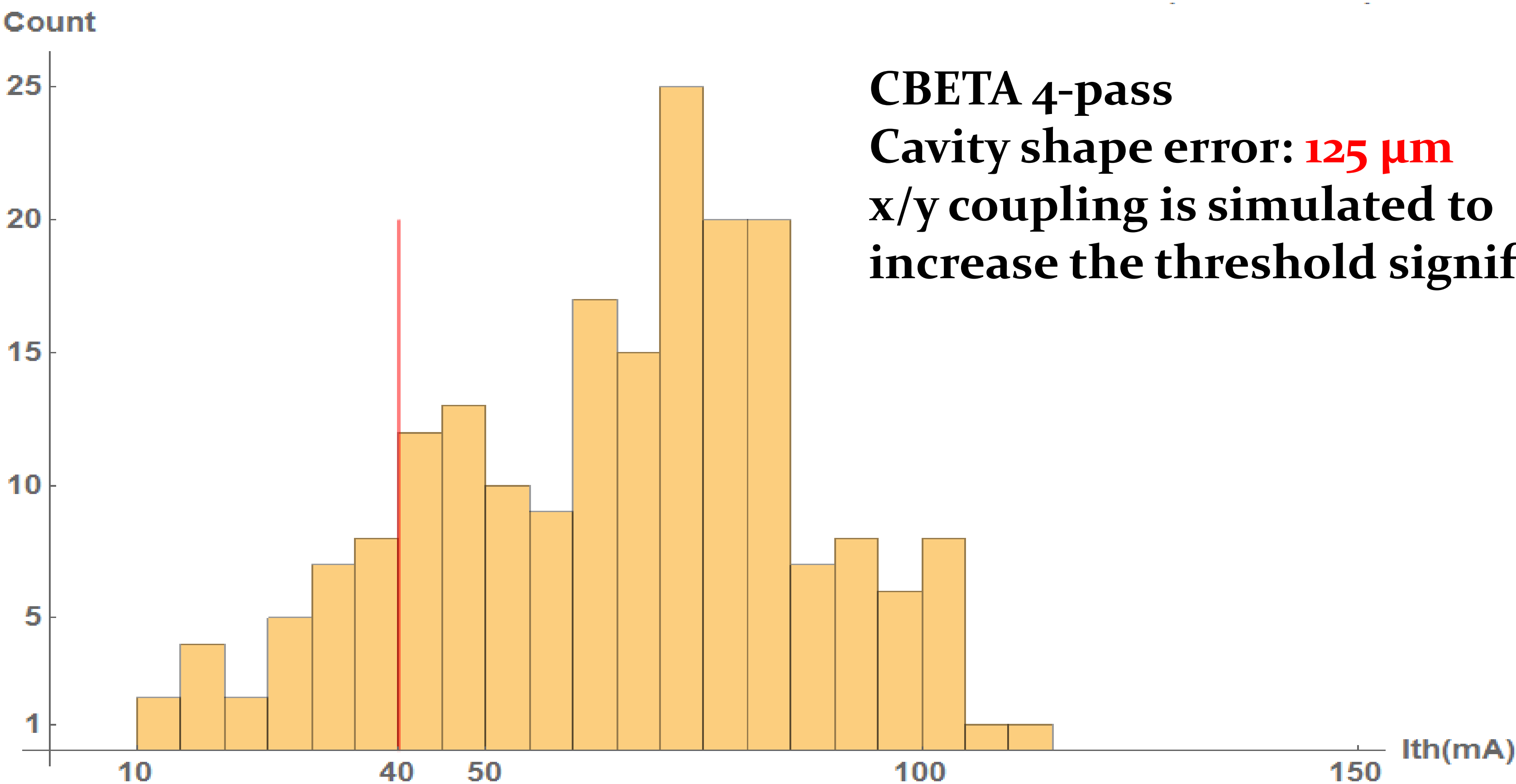


BBU for 1 pass in CBETA



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

BBU for 4 passes in CBETA



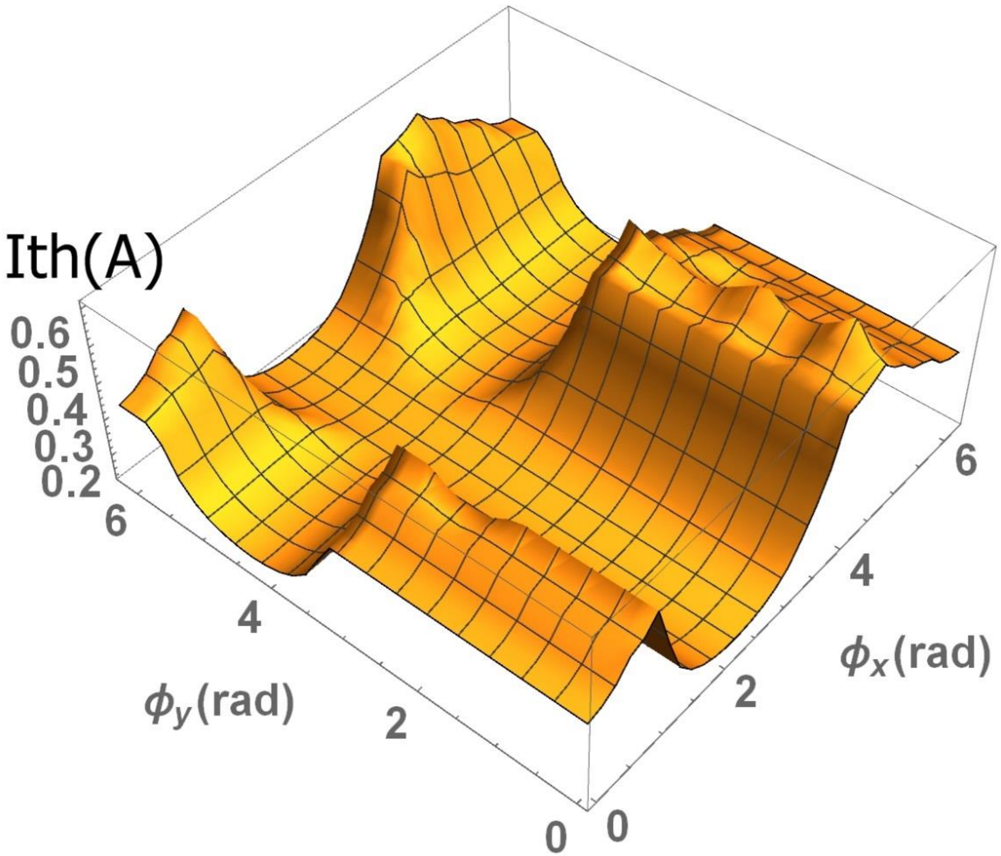
CBETA 4-pass
Cavity shape error: 125 µm
x/y coupling is simulated to increase the threshold significantly

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

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

1-pass ERL with variable phases

I_{th}

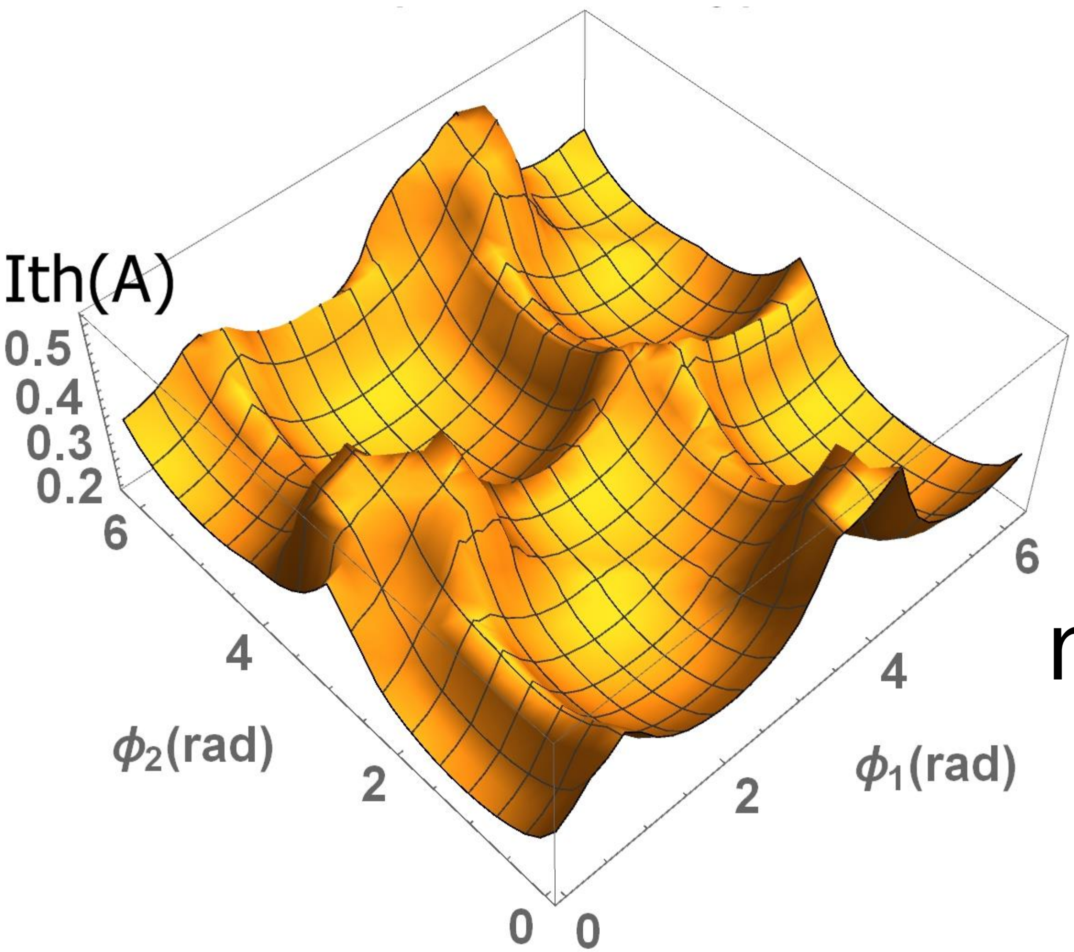


Min = 140 mA
Max = 611 mA
nominal = 342 mA

I_{th} results can improve significantly

1-pass ERL with x/y coupling

I_{th}

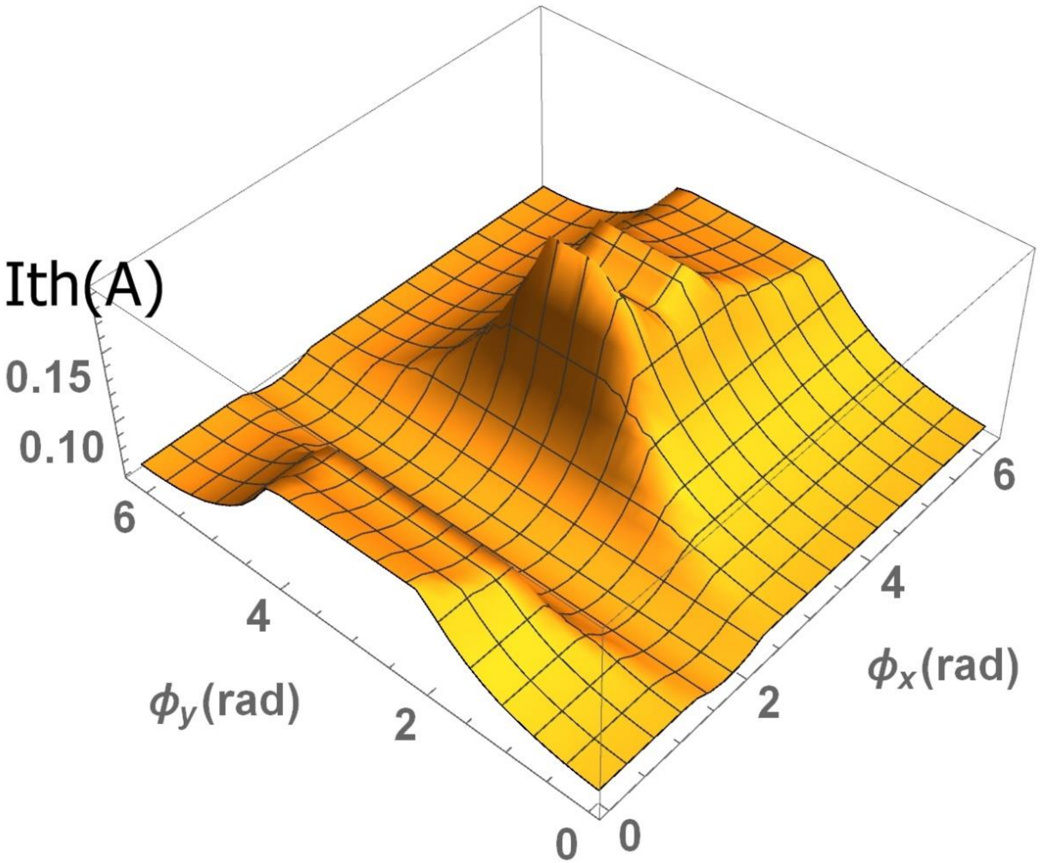


Min = 140 mA
Max = 520 mA
nominal = 342 mA

I_{th} results can improve significantly

4-path ERL with variable phases

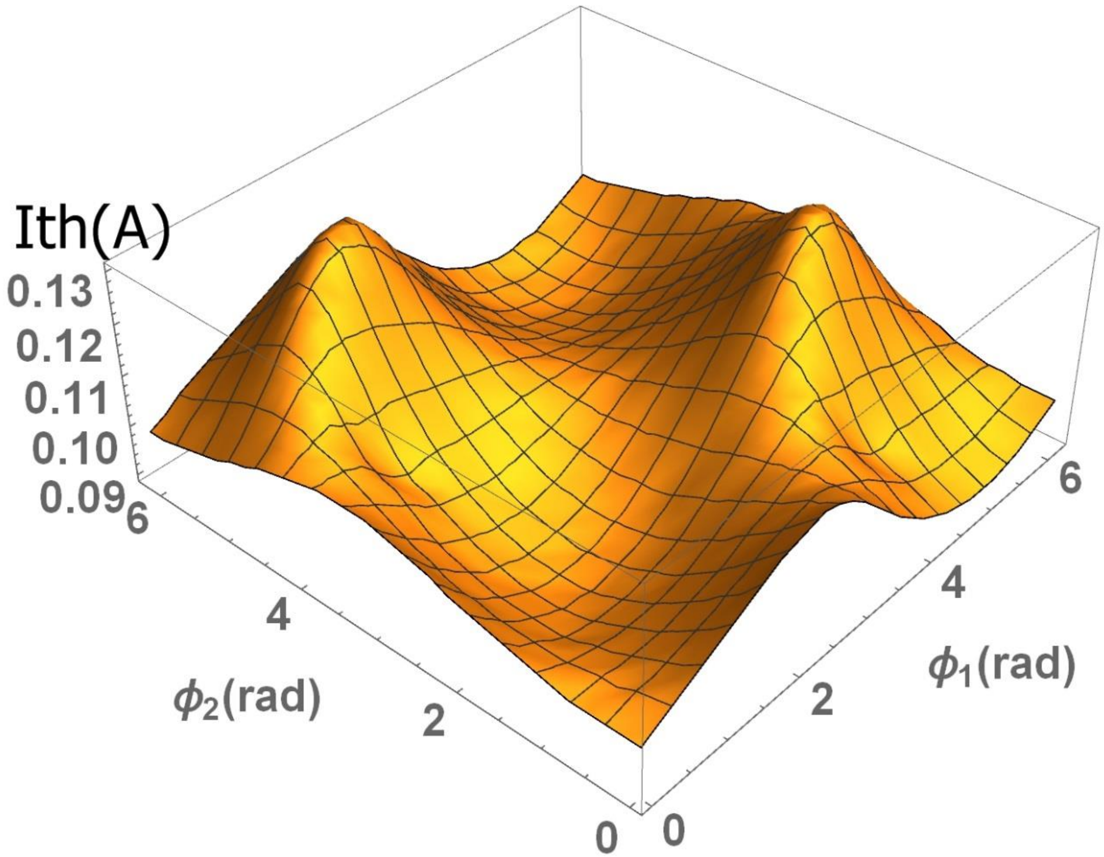
I_{th}



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

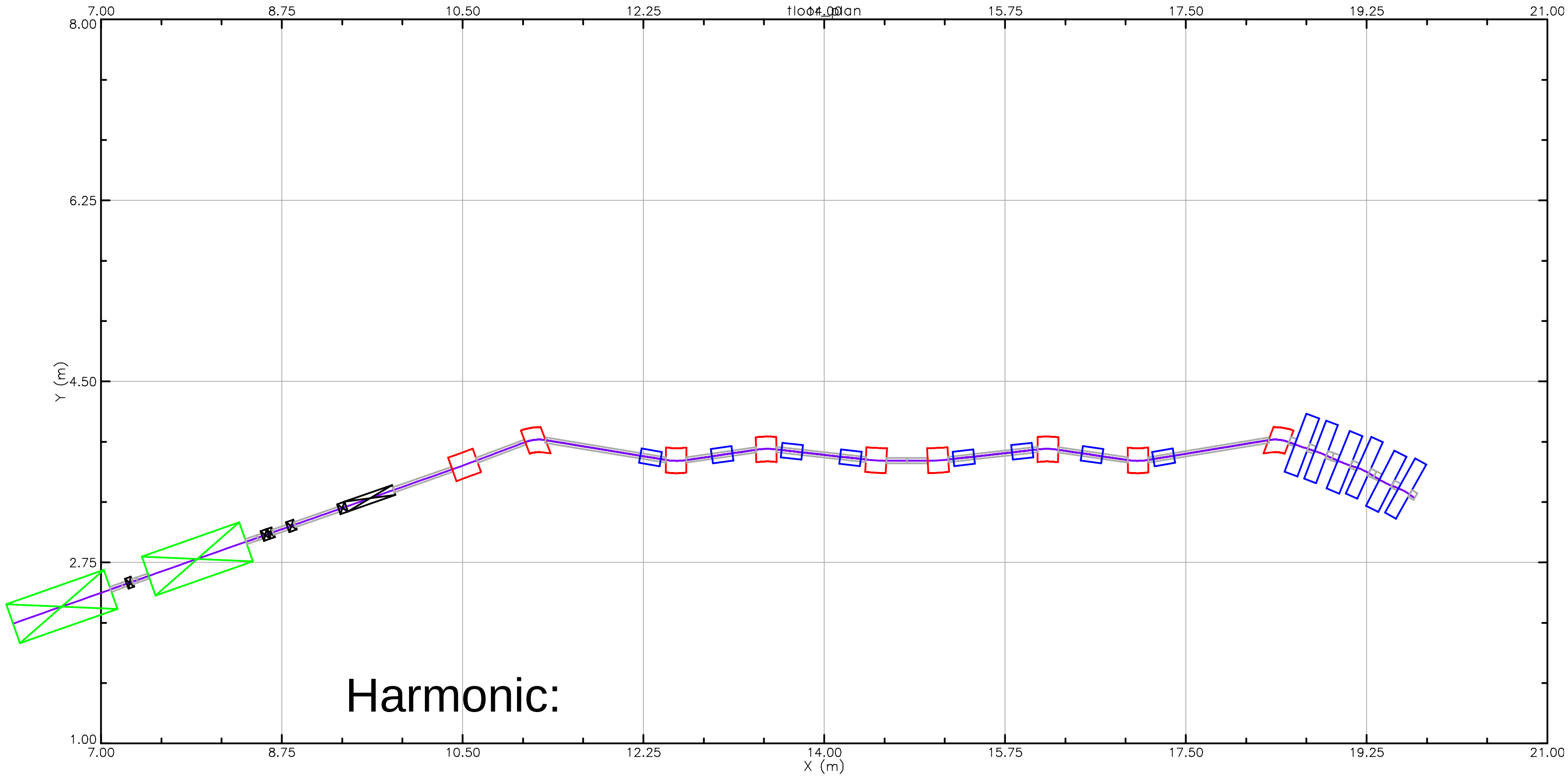
- Is important because the frequencies of the lowest order Quadrupole modes are below the first higher order dipole modes. Their Q can therefore be extremely large.

(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.

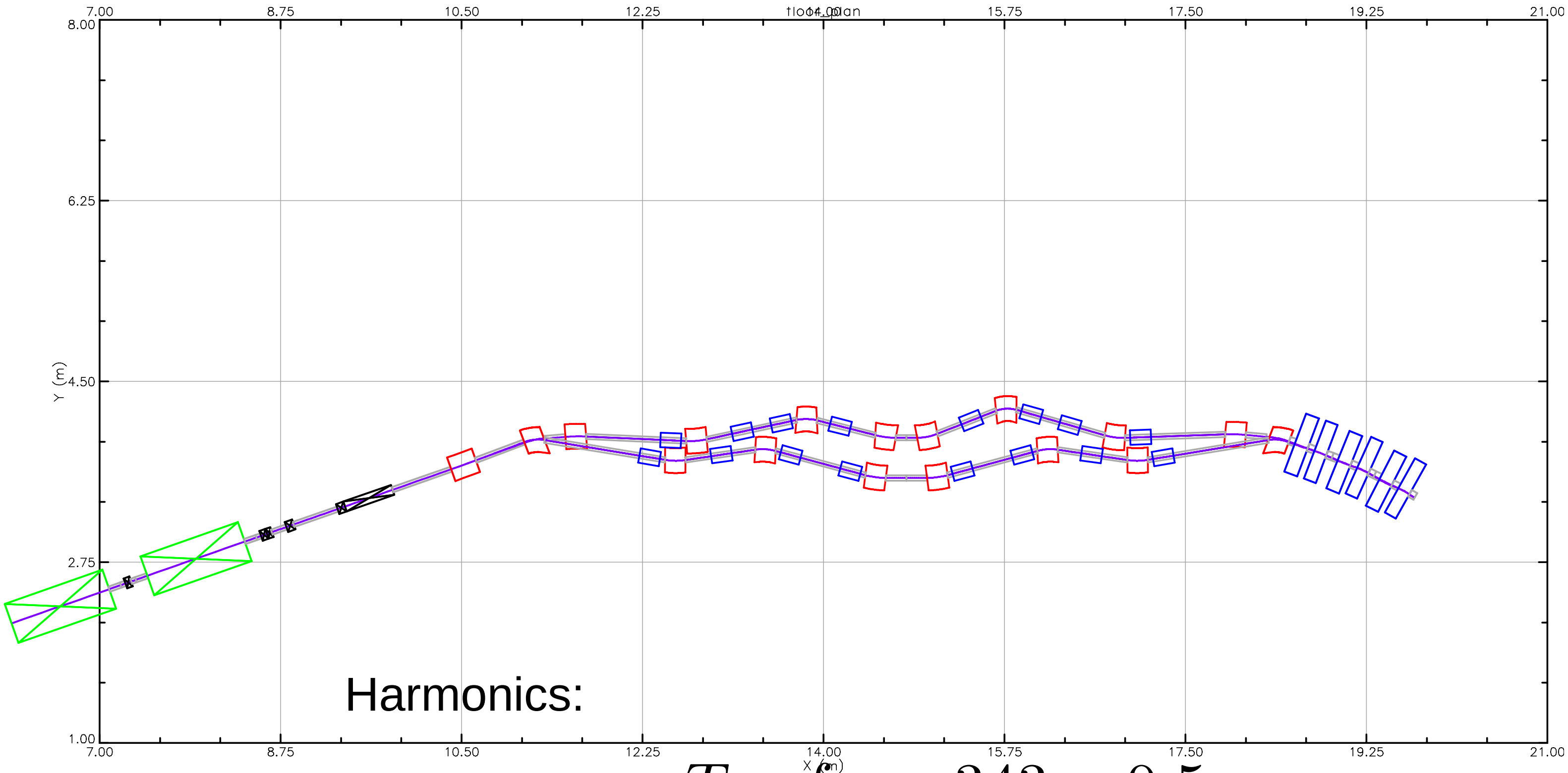
Path length: 1-pass ERL



Harmonic:

$$T_1 \cdot f_{\mathrm{rf}} = 343 - 0.5$$

Path length: 2-pass ERL

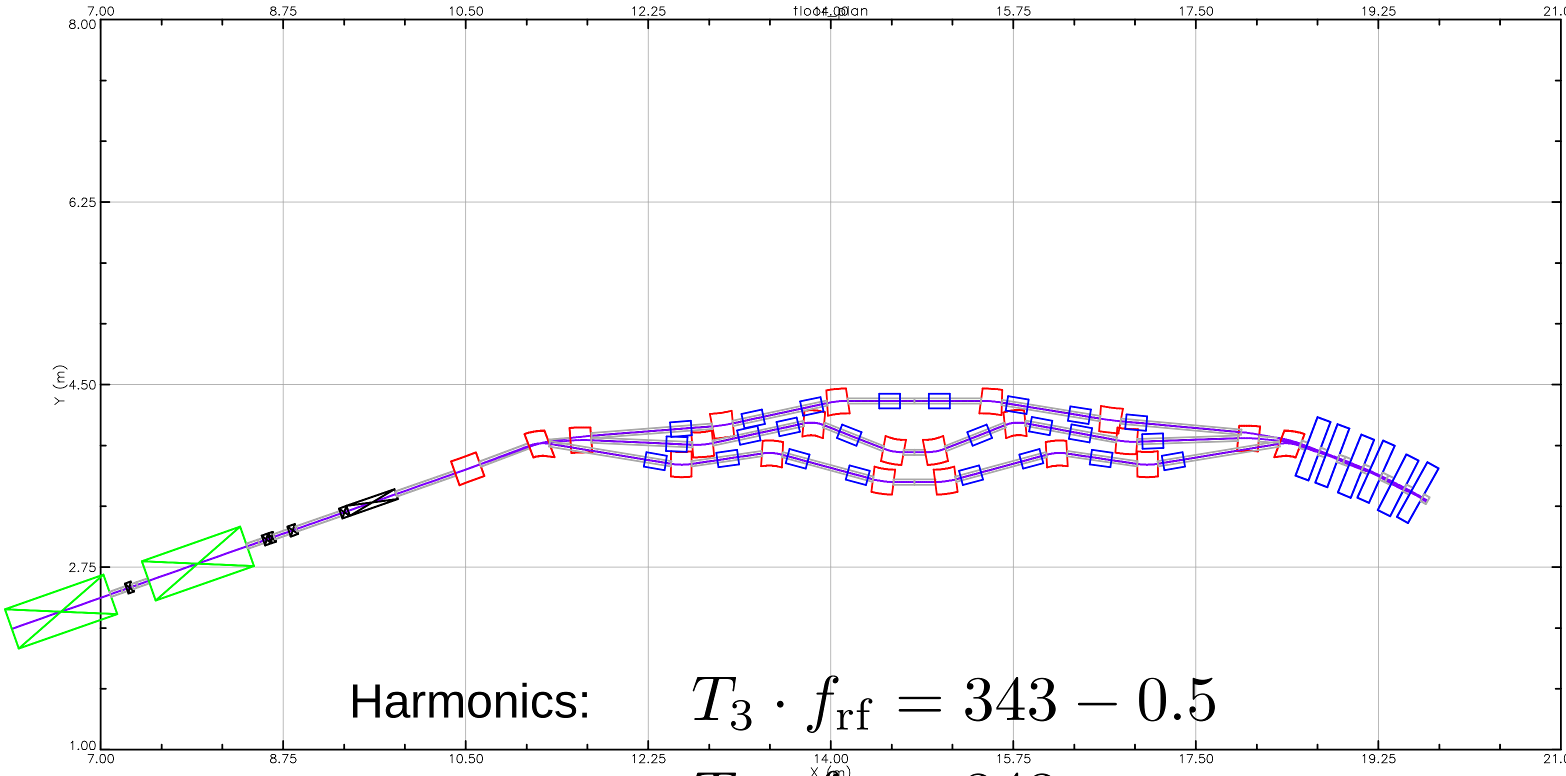


Harmonics:

$$T_2 \cdot f_{\mathrm{rf}} = 343 - 0.5$$

$$T_1 \cdot f_{\mathrm{rf}} = 343$$

Path length: 3-pass ERL



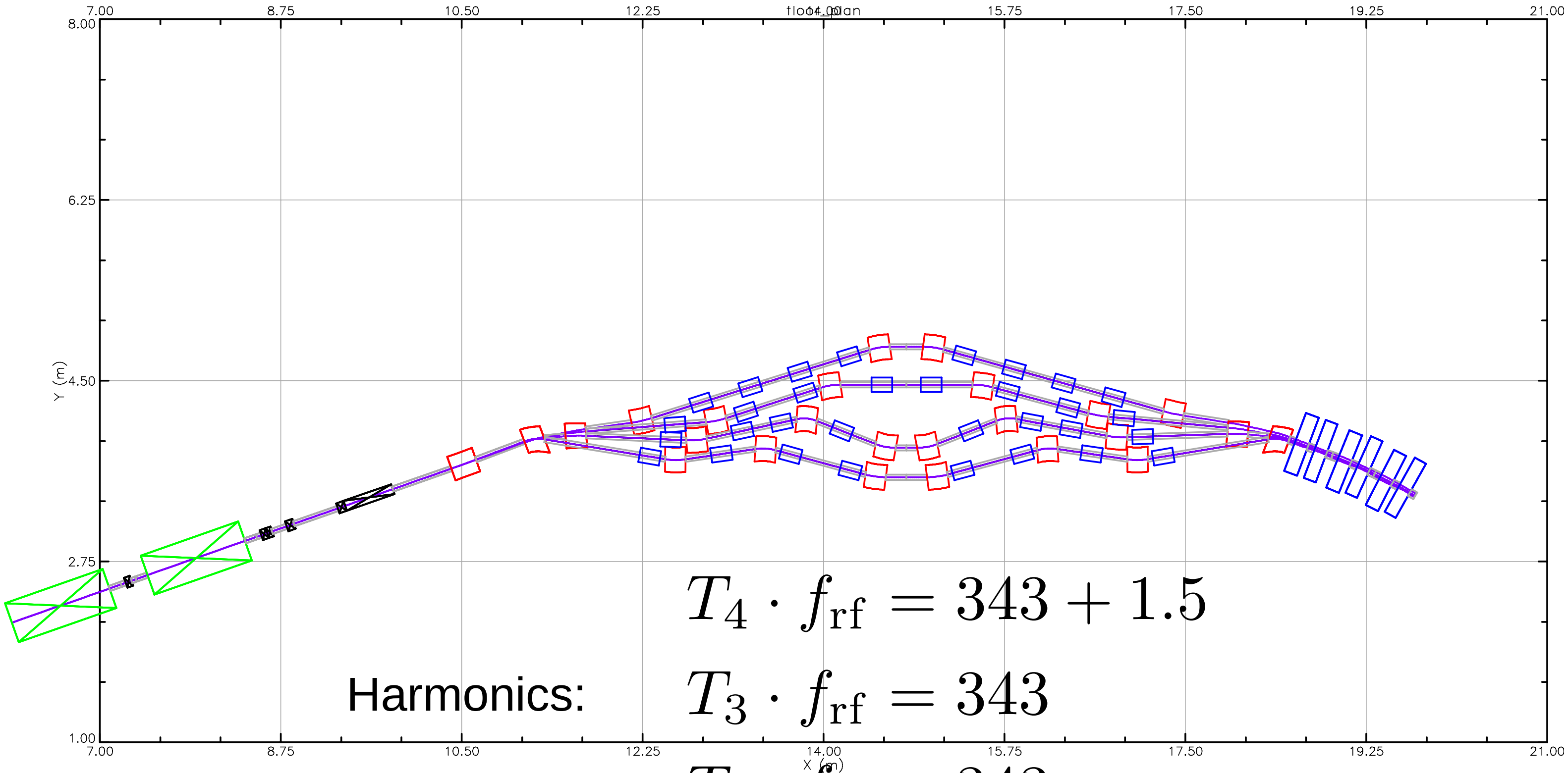
Harmonics:

$$T_3 \cdot f_{\mathrm{rf}} = 343 - 0.5$$

$$T_2 \cdot f_{\mathrm{rf}} = 343$$

$$T_1 \cdot f_{\mathrm{rf}} = 343$$

Path length: 4-pass ERL



Harmonics:

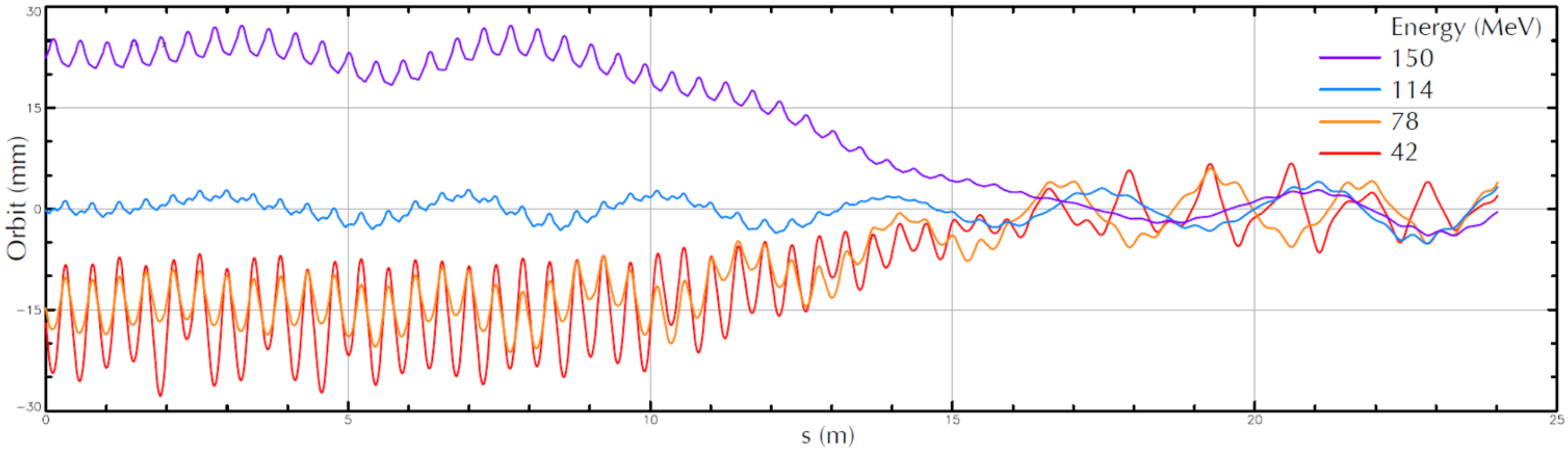
$$T_4 \cdot f_{\mathrm{rf}} = 343 + 1.5$$

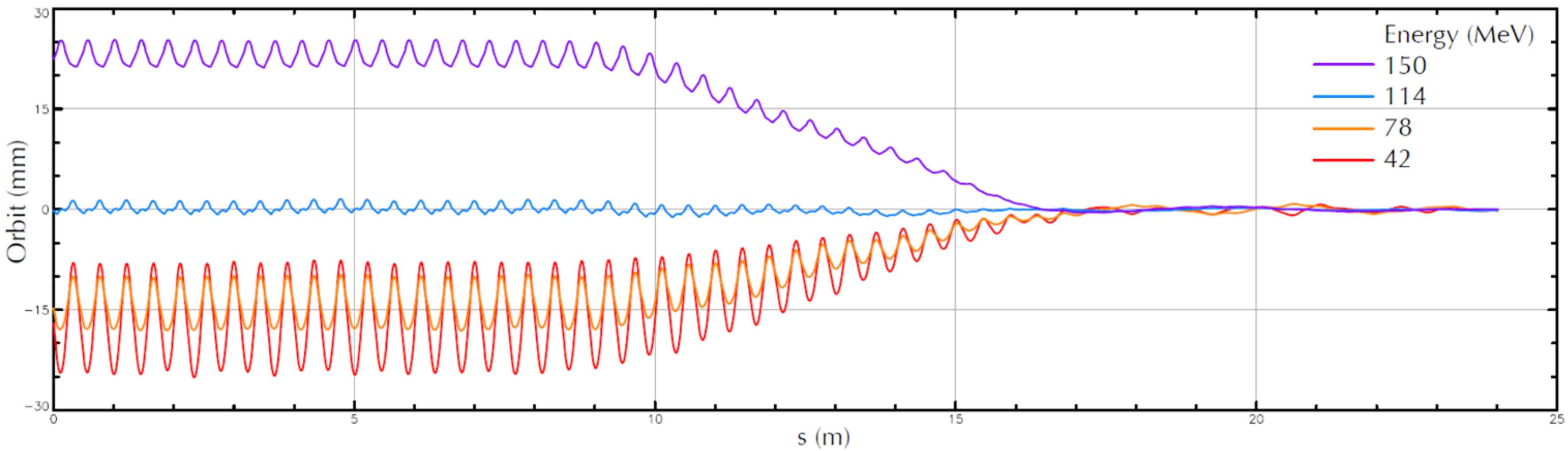
$$T_3 \cdot f_{\mathrm{rf}} = 343$$

$$T_2 \cdot f_{\mathrm{rf}} = 343$$

$$T_1 \cdot f_{\mathrm{rf}} = 343$$

Orbit Correction of 4 Beams





Courtesy C. Mayes

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 QF


PoP magnet series


PoP BD


Iron wire shims

Multipole tolerances in the FFAG

Individual Multipole limits (for < 10% emittance and beam-size growth)

b2	37	a2	140
b3	30	a3	90
b4	26	a4	80
b5	21	a5	65
b6	21	a6	63
b7	19	a7	58
b8	21	a8	56
b9	18	a9	53

$$B_x + iB_y = \frac{b_n + ia_n}{L}(x+iy)^n$$

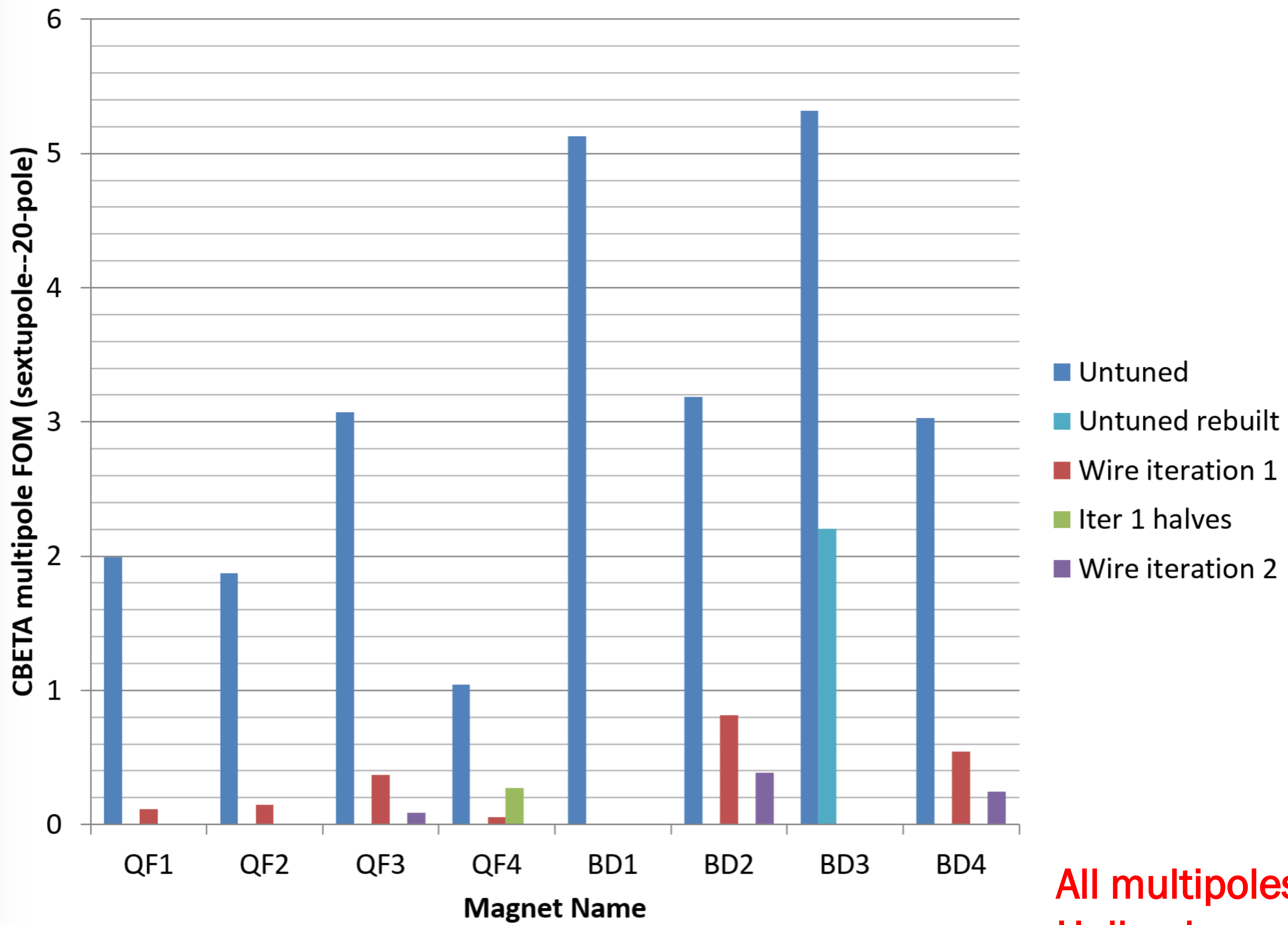
$$b_n = \left[10^{-4}\frac{GL}{r_0^{n-1}}\right]u_0$$

Multipole limits:

For < 10% emittance and beam-size growth

$$\sqrt{\Sigma_n(\frac{b_n}{lim\_b_n})^2 + (\frac{a_n}{lim\_a_n})^2} < 0.75$$

Iron Wire Shimming Improvement



All multipoles of the Halbach magnets can be corrected as required.

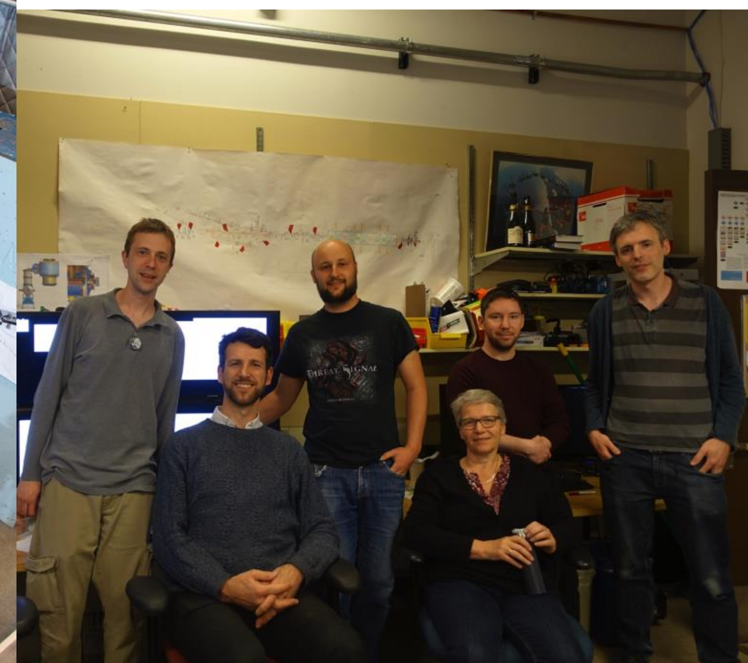
First Girder Construction

International interest in CBETA

We are forming a **collaboration interested in ERLs for EICs, e.g. coolers**.

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

Cornell's CBETA team with collaborators from BNL in the back: S. Peggs & S. Berg.

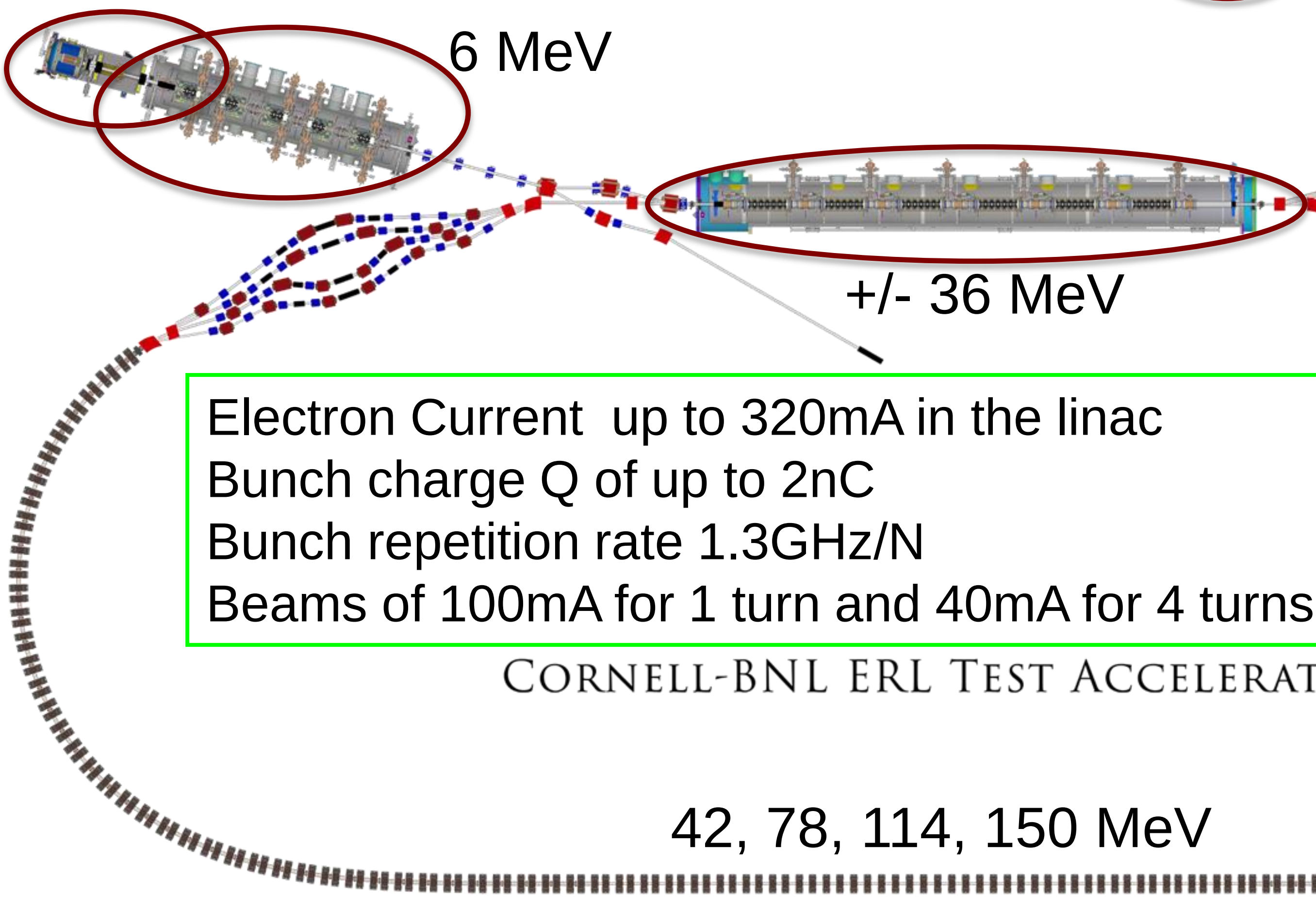


1st set of international visitors for Commissioning (r to l): D. Kelliher & J. Jones (Daresbury), B. Kuske & J. Völker (HZB).

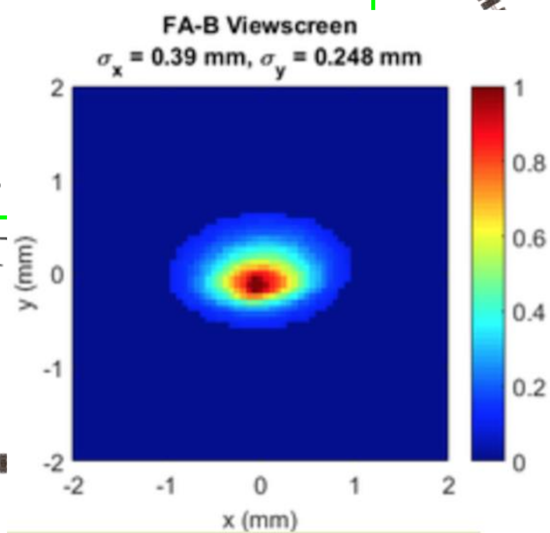
April 18: Beam through the fractional arc!

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

Tested



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

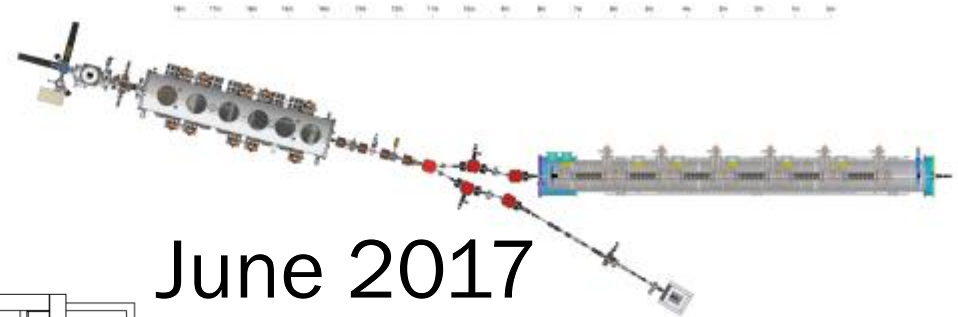


The path is free for CBETA

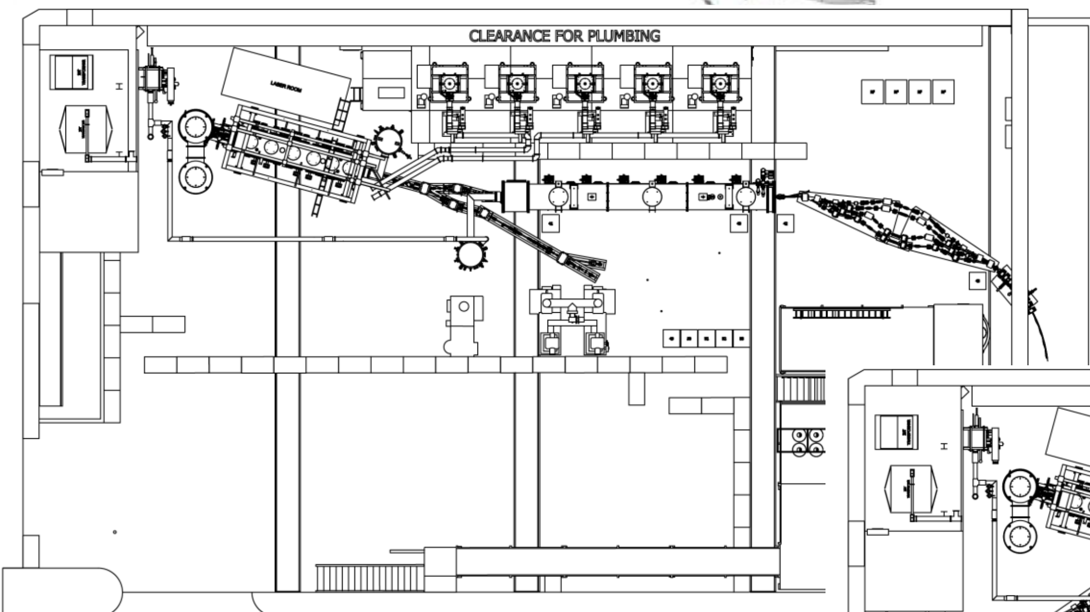
#	**Milestone** (at the end of months)	**Baseline**	**Actual**
	Funding start date		Oct-16
1	Engineering design documentation complete	Jan-17	
2	Prototype girder assembled	Apr-17	
3	Magnet production approved	Jun-17	
4	**Beam through Main Linac Cryomodule**	**Aug-17**	
5	First production hybrid magnet 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	

Beam Commissioning

2016

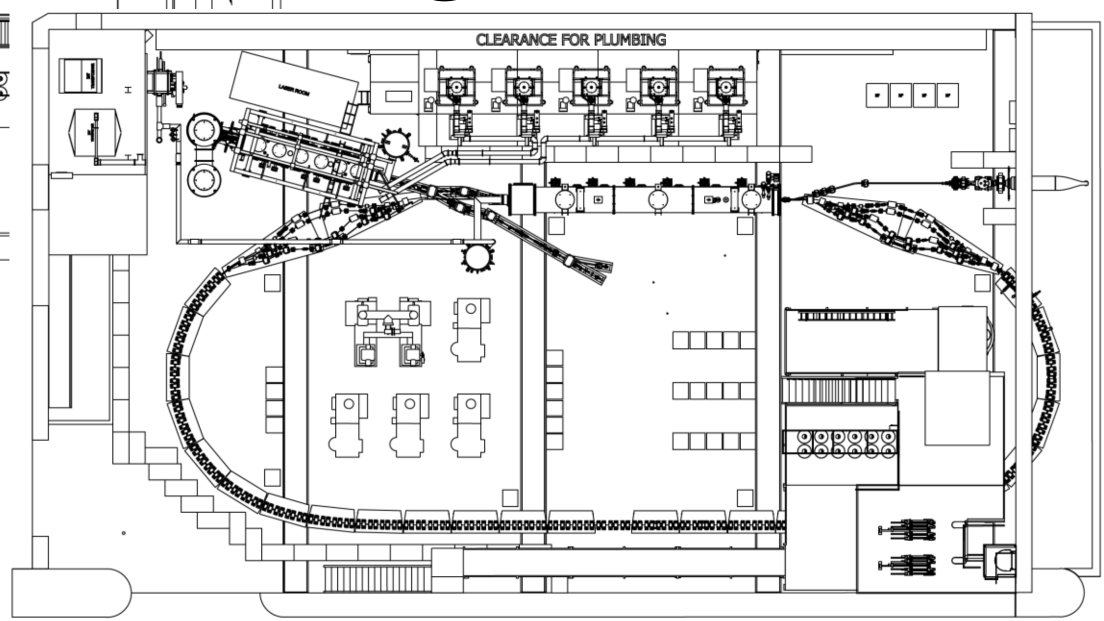


June 2017



April 2018: FAT

August 2019: 1-turn



Push toward 4-tunr ERL until April 2020

A collaborative proposal between BNL, Cornell, and JLAB to DOE-NP is being submitted for EIC e-cooling studies with CBETA

Simulations
  Halo, bunch-charge limitations, microbunching, magnetized gun.
Diagnostic development
  halo diagnostics, CSR and microbunching diagnostics.
  time-resolved post-mortem analysis of beam loss.
Low Level RF
  RF control system on the MLC using pulsed and CW beams to benchmark the simulations.
Commissioning to high-intensity
  Push to the highest possible current
  single bunch chargetoward 1 nC.
Extraction design
  150 MeV beam-extraction lines. Demonstrate 110 MeV operation in 3-pass ER mode, largest possible values (50 mA?) in 3-pass ER mode.

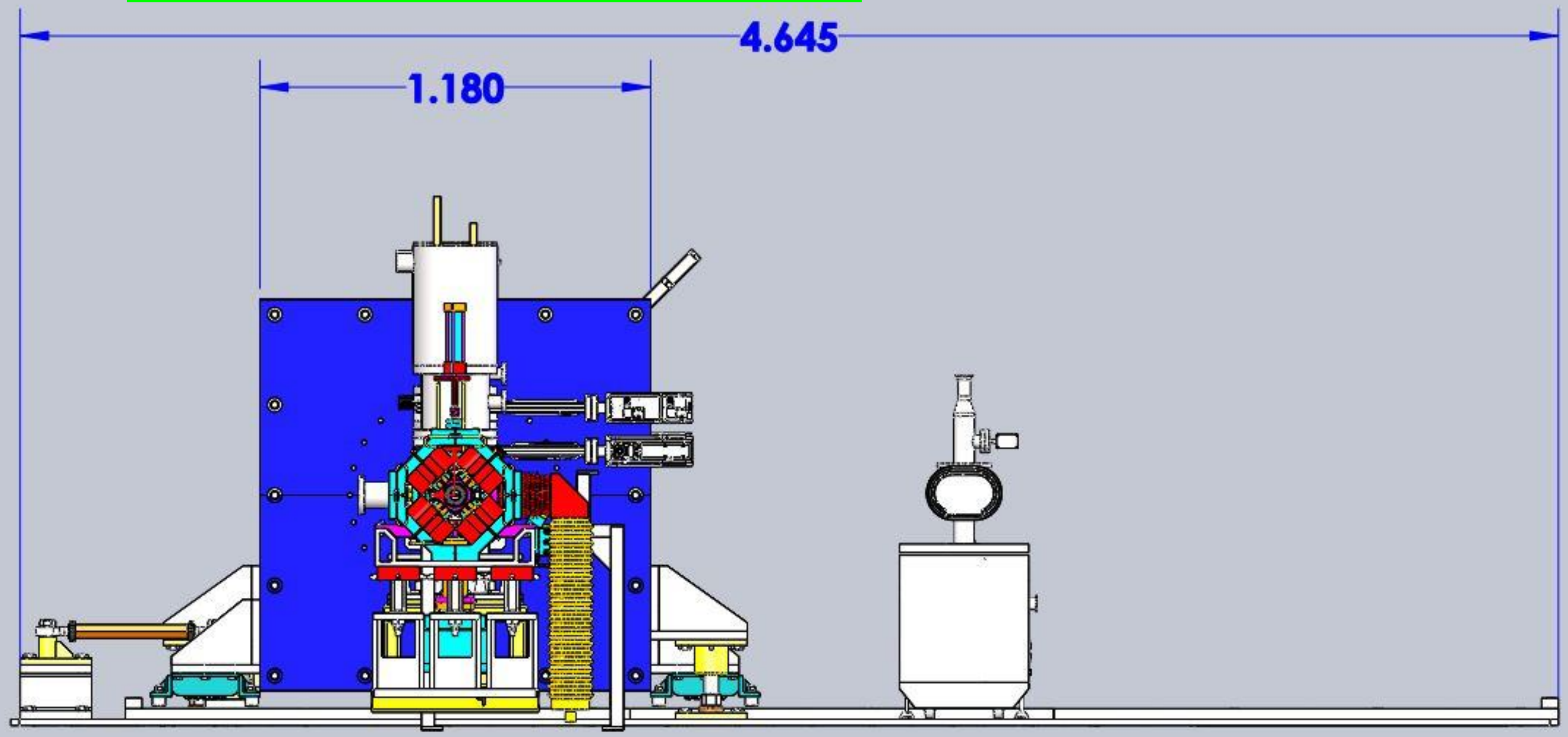
If EIC R&D would not come …

- **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

If EIC R&D would not come …

- DarkLight – an experiment to find dark matter particles

The Darklight detector at JLAB

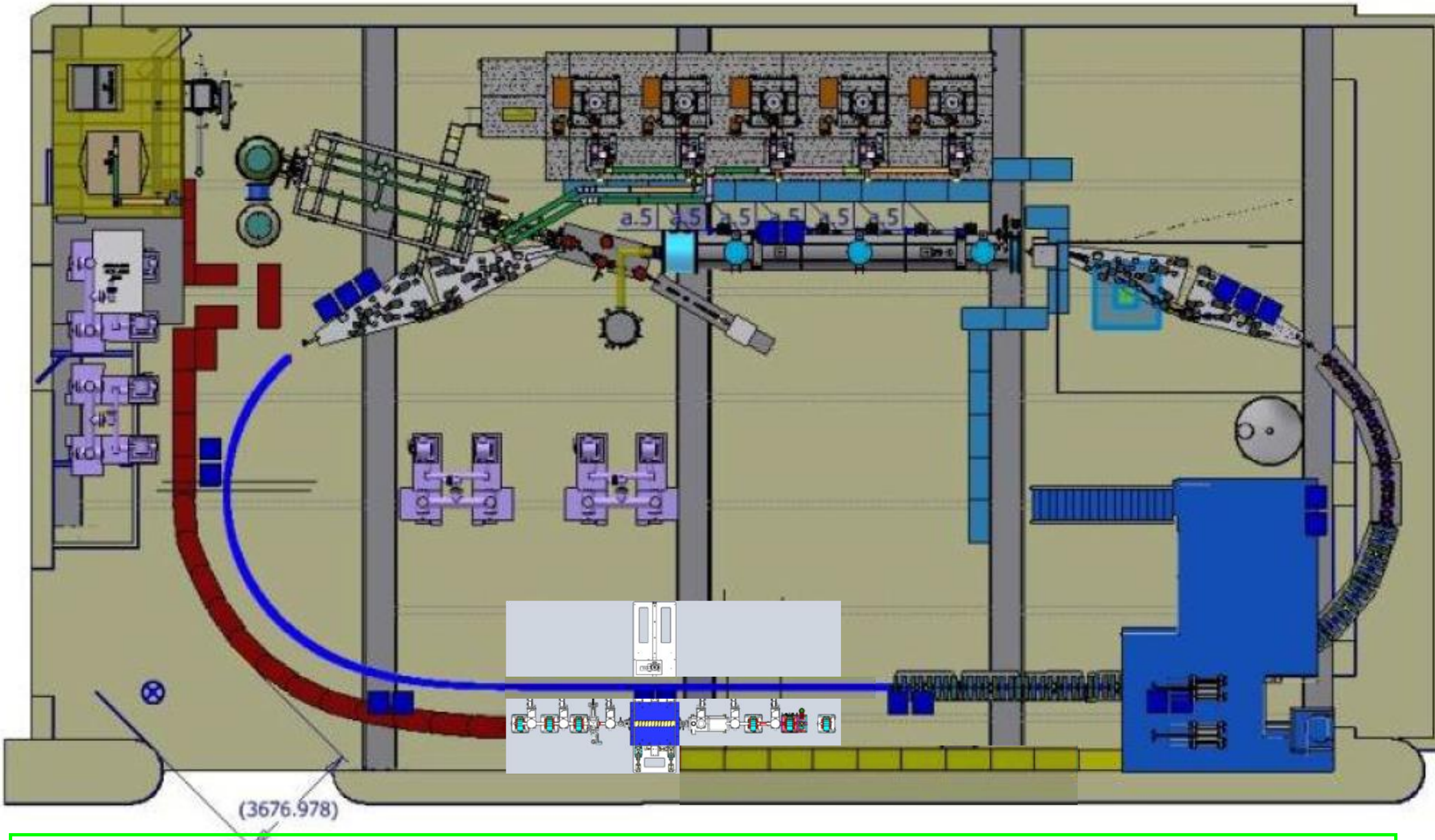


Movable support

Movable support

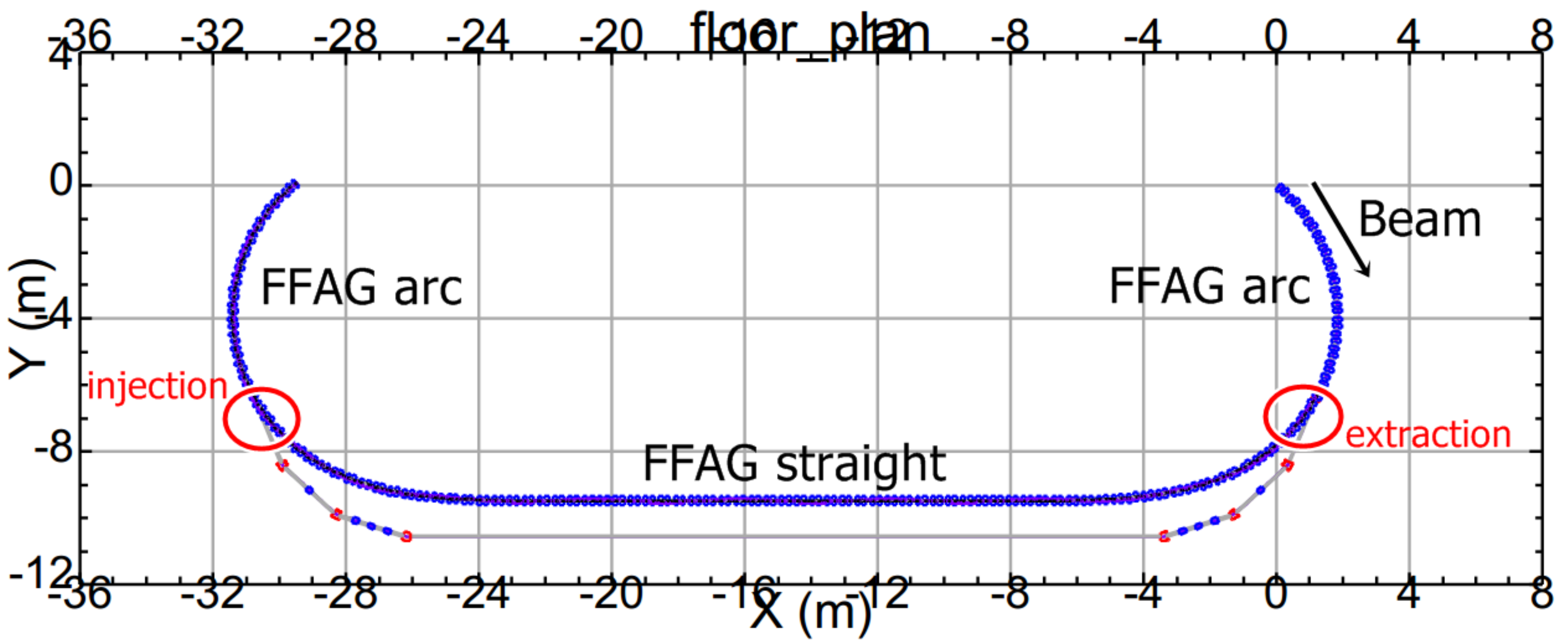
Pump station for the gas jet.

(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.

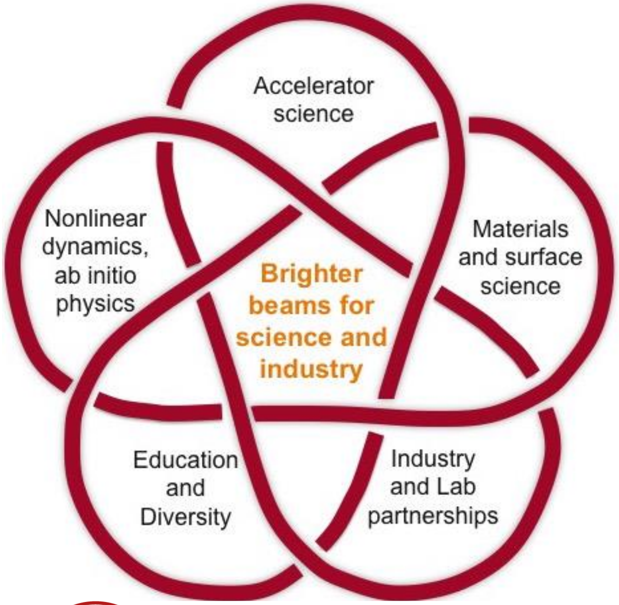
Layout of extraction beam line



Extraction line contains:

- Extra dipoles to guide the beam
- Extra quadrupoles to maintain beam optics

Also: Center of Bright Beams (CBB)



CBB is an NSF funded Science and Technology Center (for 5 years, extendable to 10 years)

CBB Vision:

Better particle beams for applications ranging from giant colliders to table top electron microscopes enabling new opportunities for science and industry.

CBB Mission:

Transform the reach of electron beams by increasing their brightness x100 and reducing the cost and size of key enabling technologies.

Transfer the best of these technologies to national labs and industry.

Cornell University
University of Florida
The University of Chicago
UCLA
University of Toronto
BYU
University of Maryland
Chicago State University
Morehouse College
Clark Atlanta University
Berkeley Lab
Fermilab
TRIUMF

Questions?