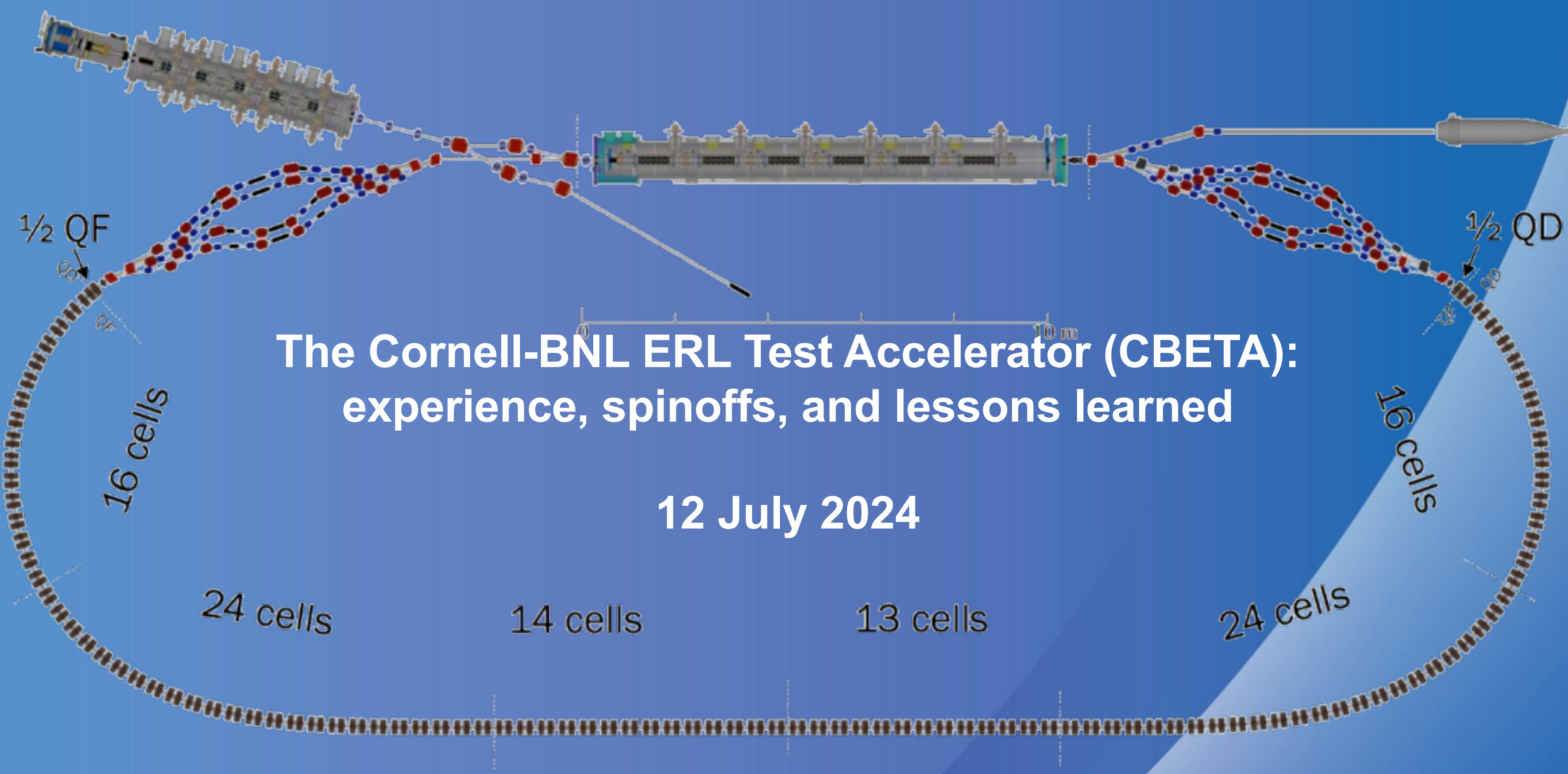


The Cornell-BNL ERL Test Accelerator (CBETA): experience, spinoffs, and lessons learned

12 July 2024

Georg Hoffstaetter de Torquat
for the CBETA collaboration

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

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Abstract

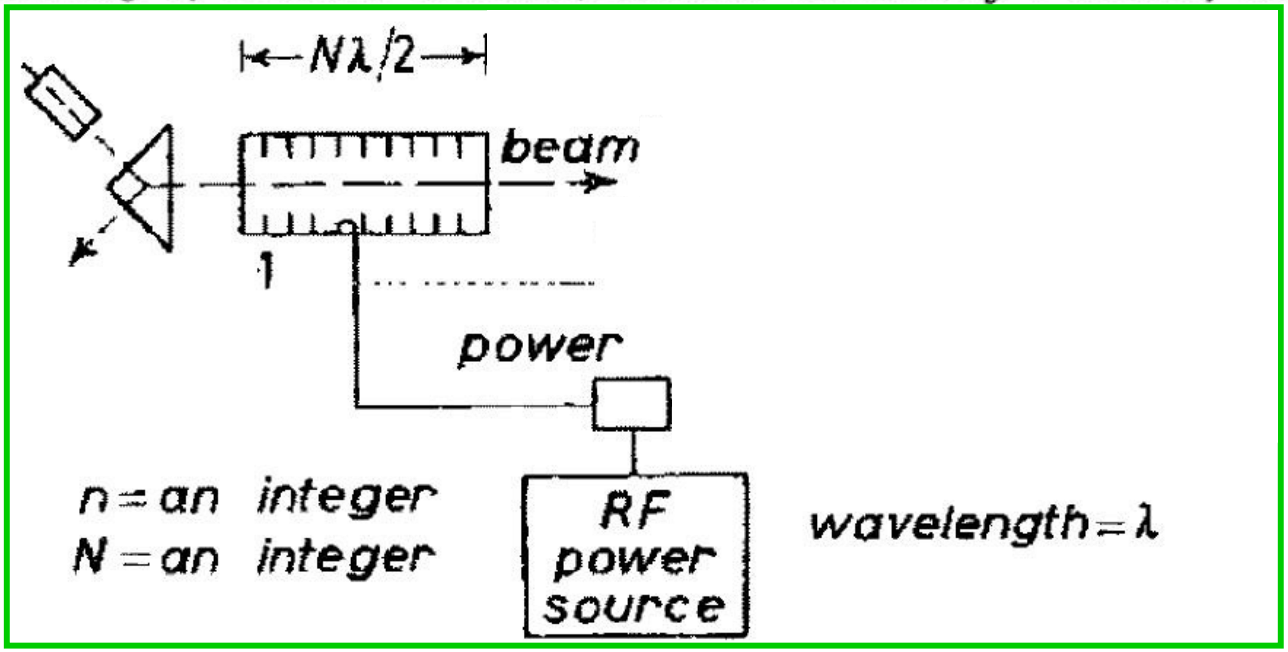
As accelerators become larger and their **beams more power, efficiency becomes an important paradigm**. Energy Recovery Linacs (ERLs), the use of superconducting cavities (**SRF**), and **permanent magnets** address this concern. A collaboration between Cornell University and Brookhaven National Laboratory has designed, constructed, and commissioned CBETA, the Cornell-BNL ERL Test Accelerator at Cornell University, culminating in 4-turn ERL operation at Christmas of 2019. As **first multi-turn ERL that recovers energy into SRF cavities**, CBETA returns the beam 4 times through the same linac to add energy each time; it then returns the beam 4 more times at the decelerating phase of the same linac to recover the beam energy into the E&M field of the SRF cavities. Another first is the **large energy-acceptance return loop** that simultaneously transports 7 beams of different energy through a **Fixed Field Alternating-gradient (FFA) lattice**, which is comprised of permanent magnets. Successfully establishing 4-turn energy recovery at CBETA is especially relevant in the light of the increasing importance that ERLs have obtained: ERLs are **part of the hadron coolers for the EIC**, they are **part of the LHeC plans**, they are an integral component of **ee Higgs Factory design options**, they can be **drivers for low energy nuclear physics experiments**, they have been investigated as **drivers for compact Compton-x-ray sources**, and they have become strong contenders as new **EUV sources for microchip lithography**. The permanent-magnet FFA technology pioneered at CBETA has another promising spin off: it is the basis of an **energy-doubling upgrade option for CEBAF**.

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).

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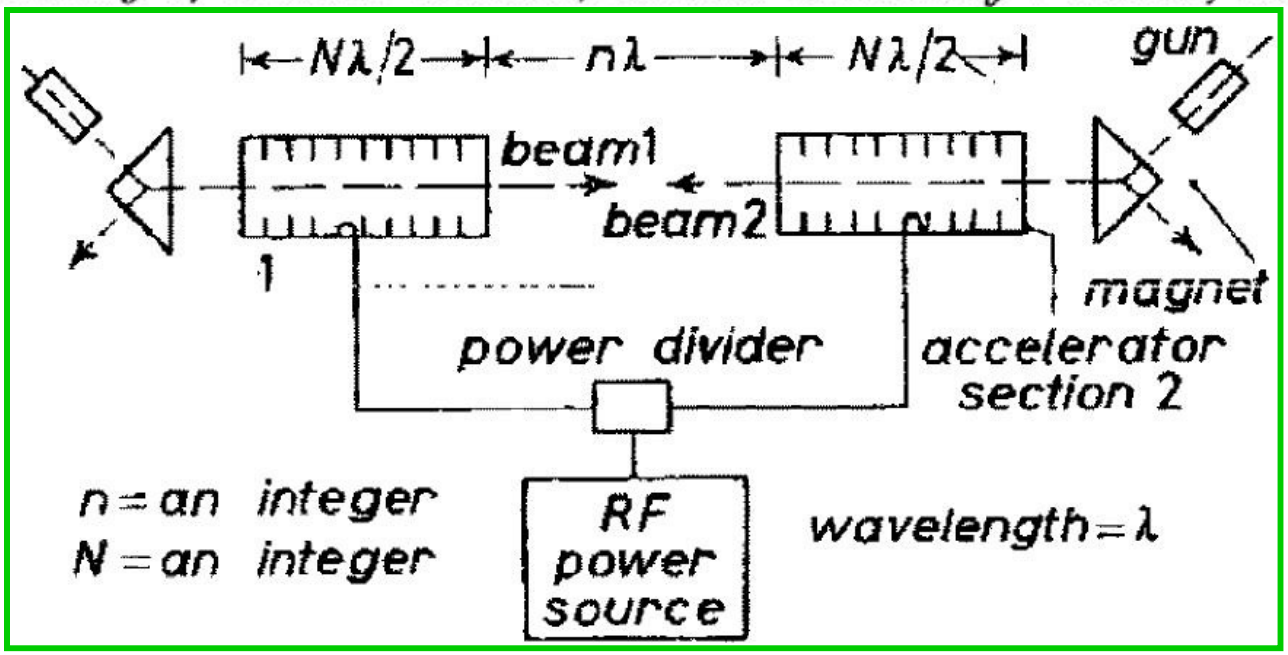

- Energy Recovery Linacs recapture the beam power in Super-Conducting (SRF) Accelerating structures to accelerate more beam.
- This energy saving allows for unprecedented beam powers from Linacs.

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

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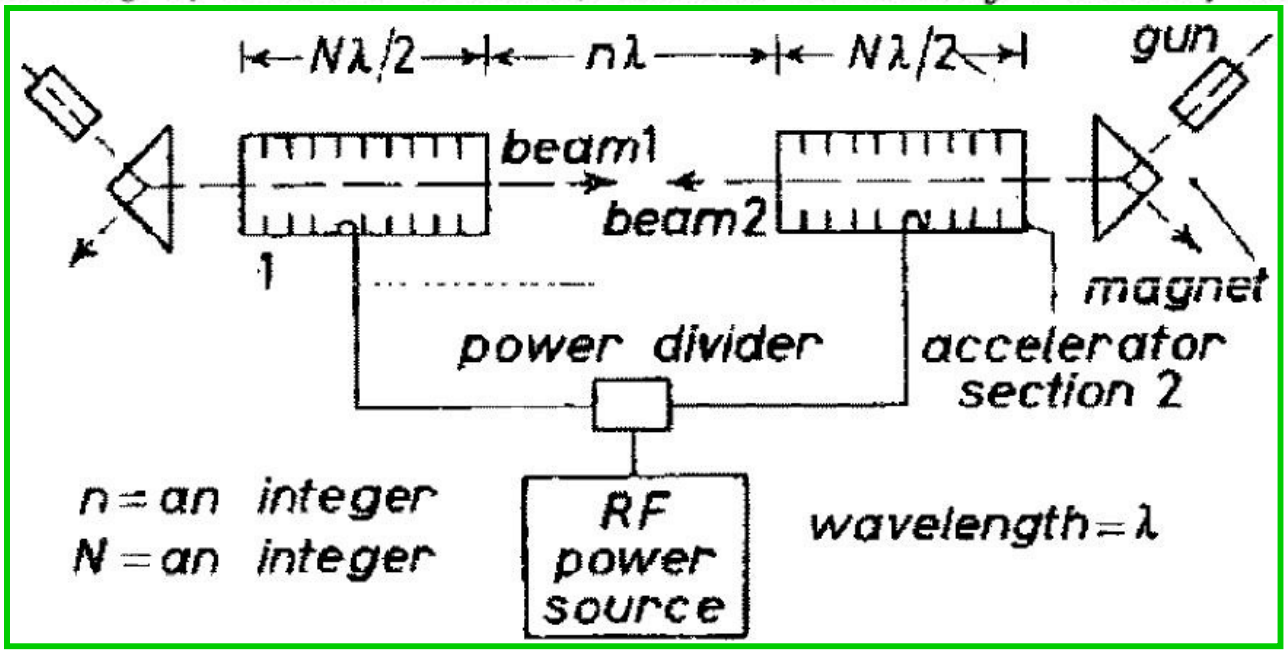

Energy recovery needs continuous beams in SRF structures

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

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

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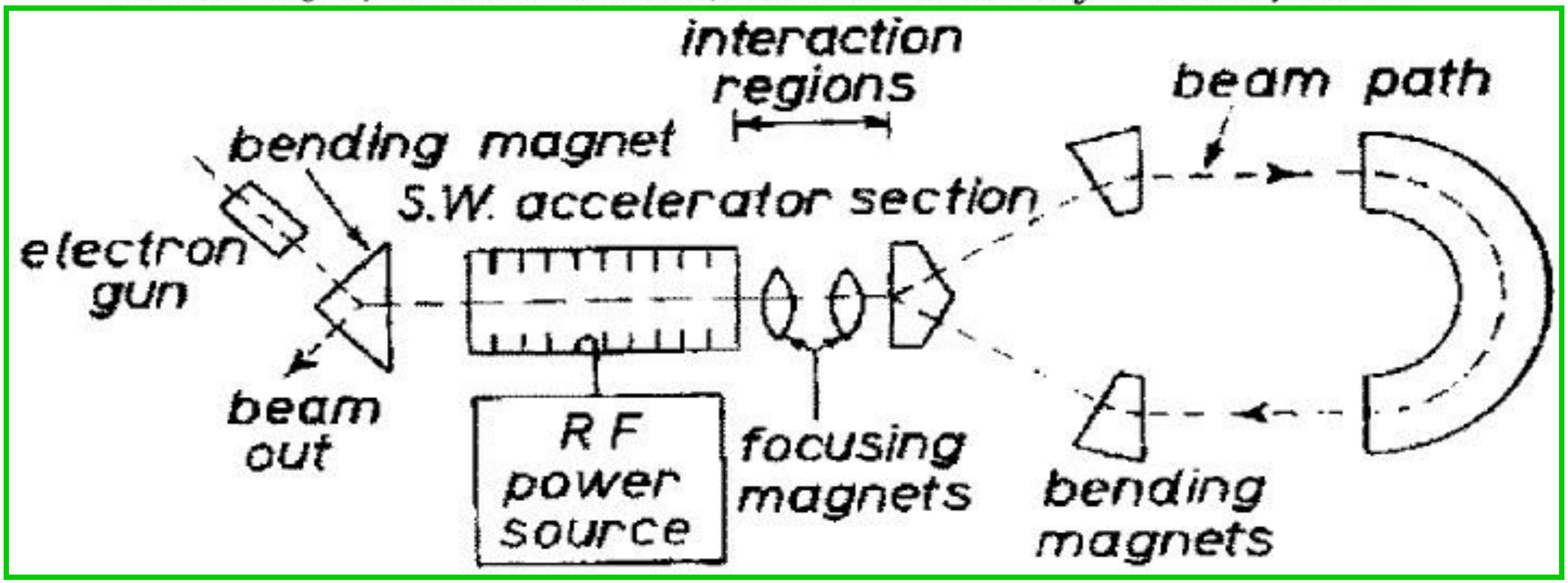


Energy recovery needs continuous beams in SRF structures

- 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!

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.

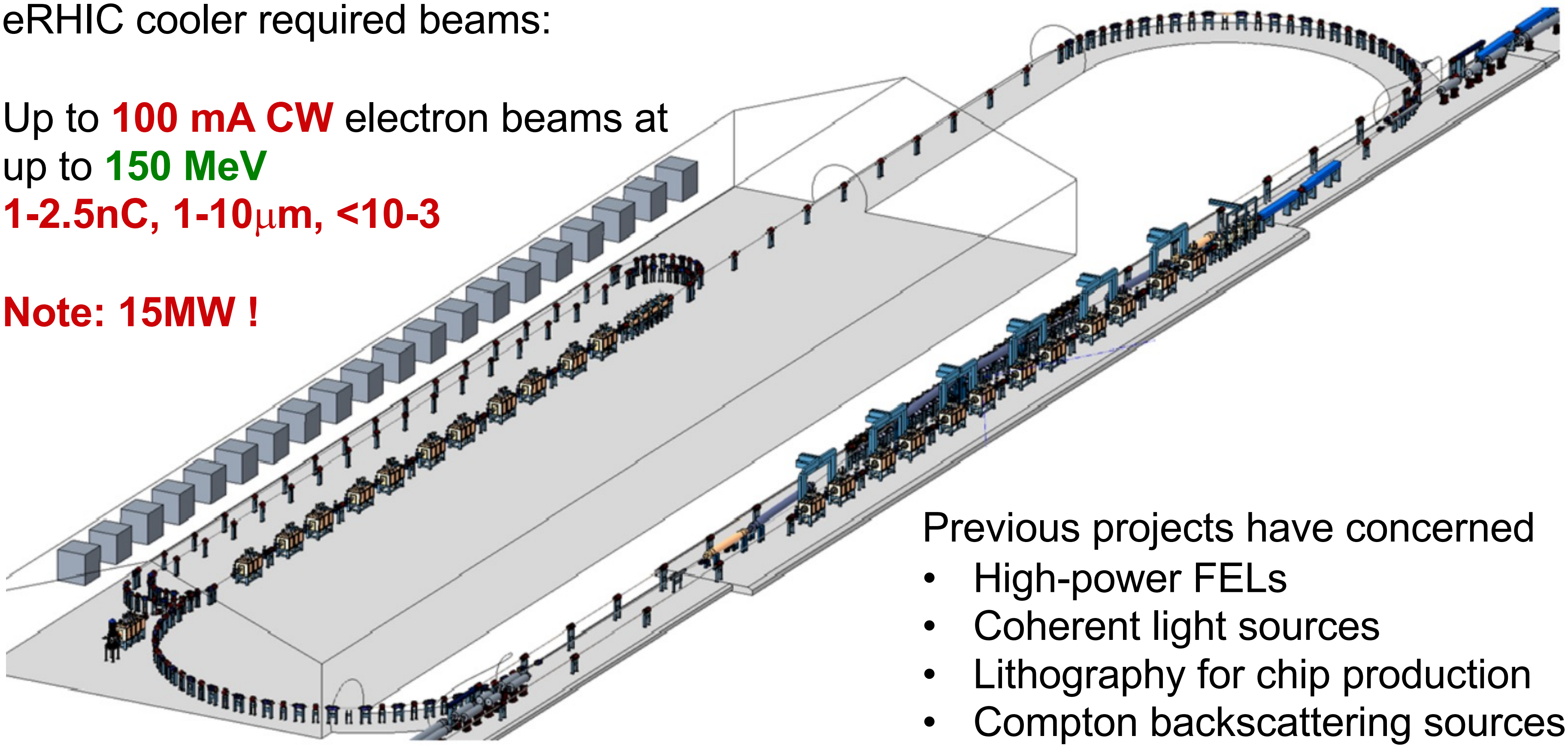
eRHIC cooler required beams:

Up to **100 mA CW** electron beams at up to **150 MeV**
1-2.5nC, 1-10μm, <10-3

Note: 15MW !

JLEIC cooler: magnetized beam

- **3nC, 100mA, 100MeV, 10MW**
- Preserve low energy spread



Previous projects have concerned

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

The NAS study 2018 on an EIC

The importance of **beam cooling for the luminosity of the EIC** has been stressed in **National Academies of Sciences**, Engineering, and Medicine. 2018. "An Assessment of U.S.-Based Electron-Ion Collider Science". Washington, DC: The National Academies Press. https://doi.org/10.17226/25171:

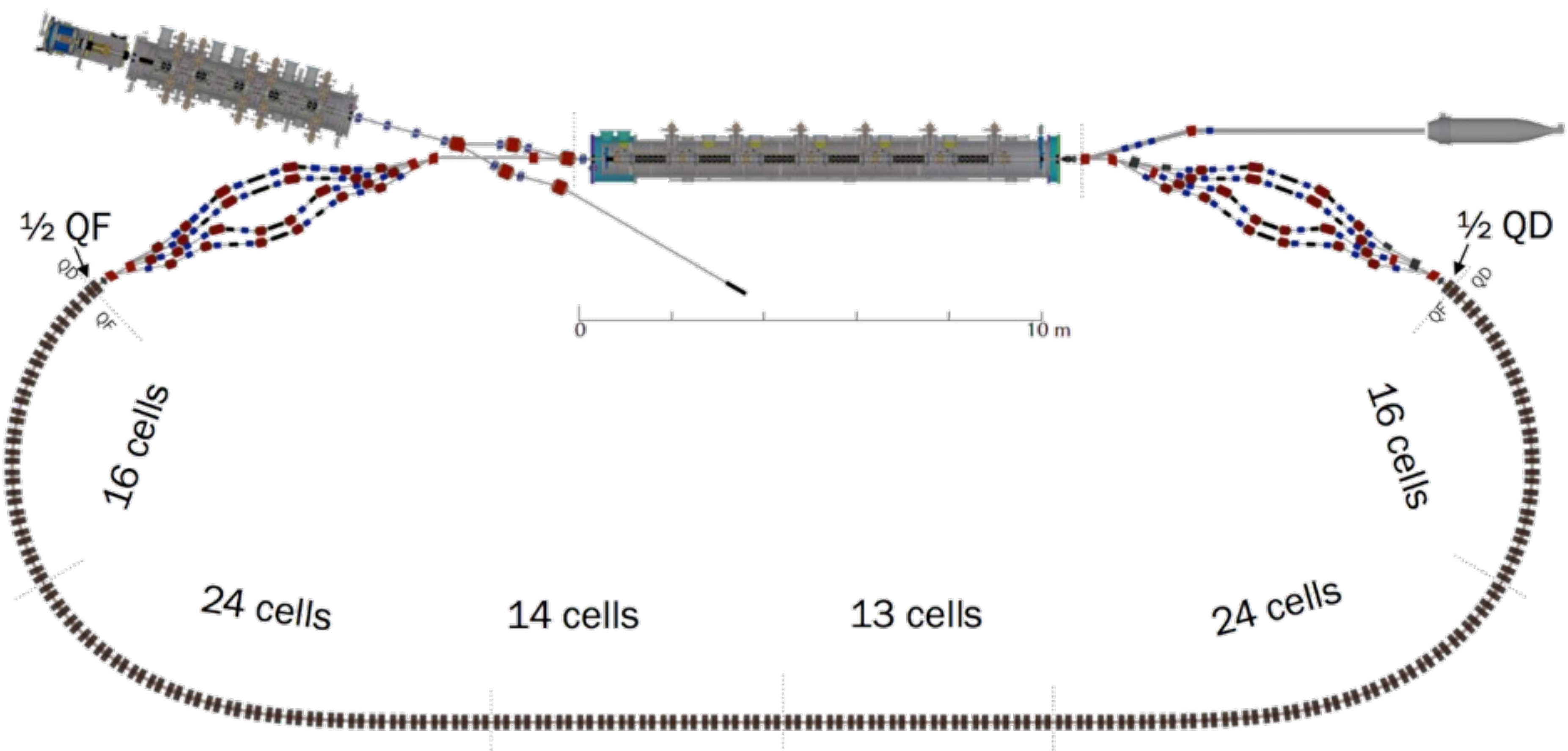
"*To attain the highest luminosities demanded by the science,* ***cooling*** *of the hadron beam is* ***essential****;*" and "*the full luminosity goals of eRHIC require the implementation of a radically new hadron cooling technology.*"

"*Energy recovery linacs (****ERLs****), a special type of recirculating linac, presently offer the* ***only credible concept for electron cooling*** *of high-energy, colliding beams,*"

"*Several of these [required accelerator] advances are common to all EIC designs and include …* ***high-current (multiturn) ERL technology****.*"

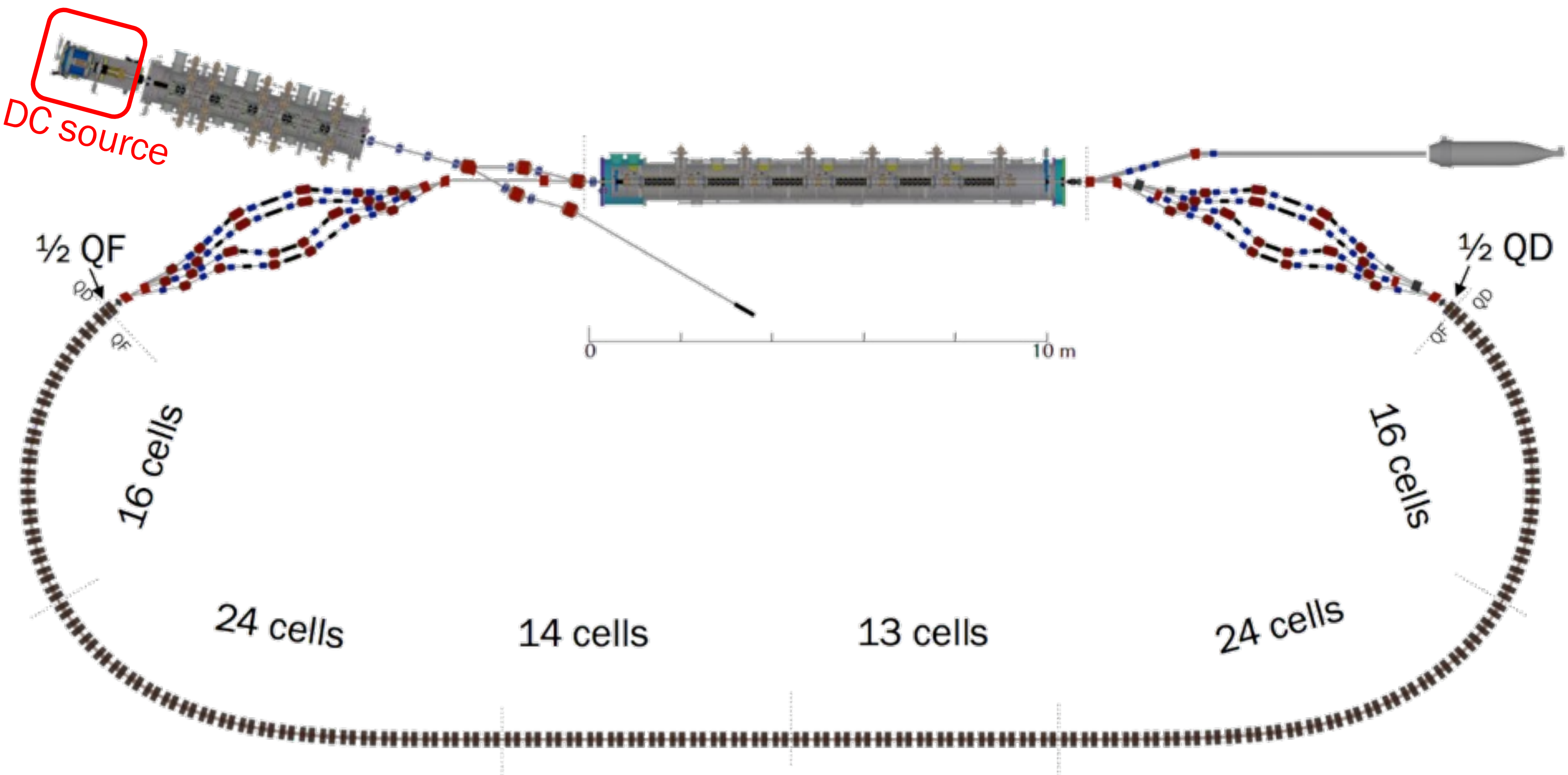
"The CBETA project will serve as prototype."

The test ERL at Cornell



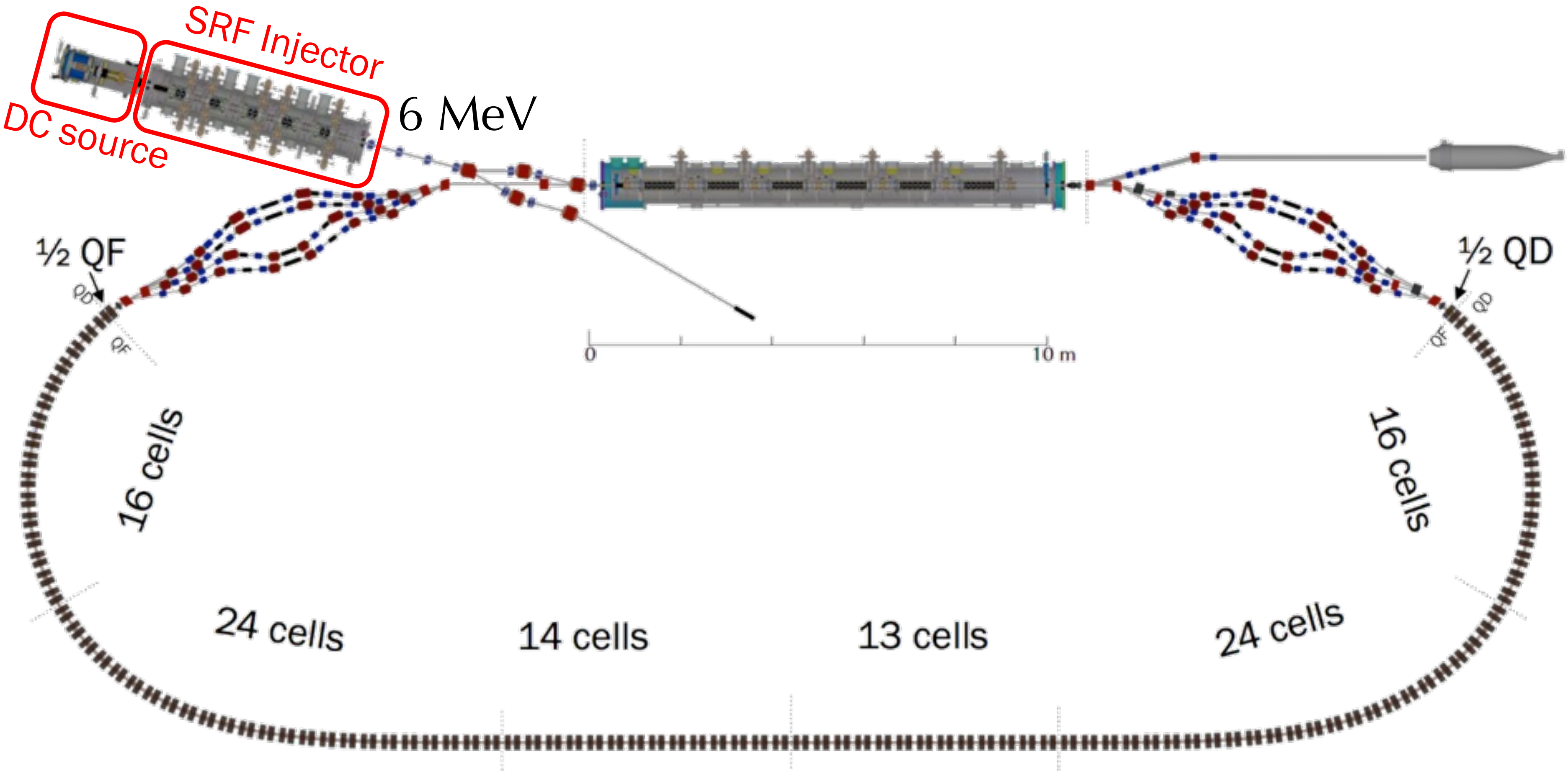
The test ERL at Cornell

- Cornell DC gun, 2nC peak



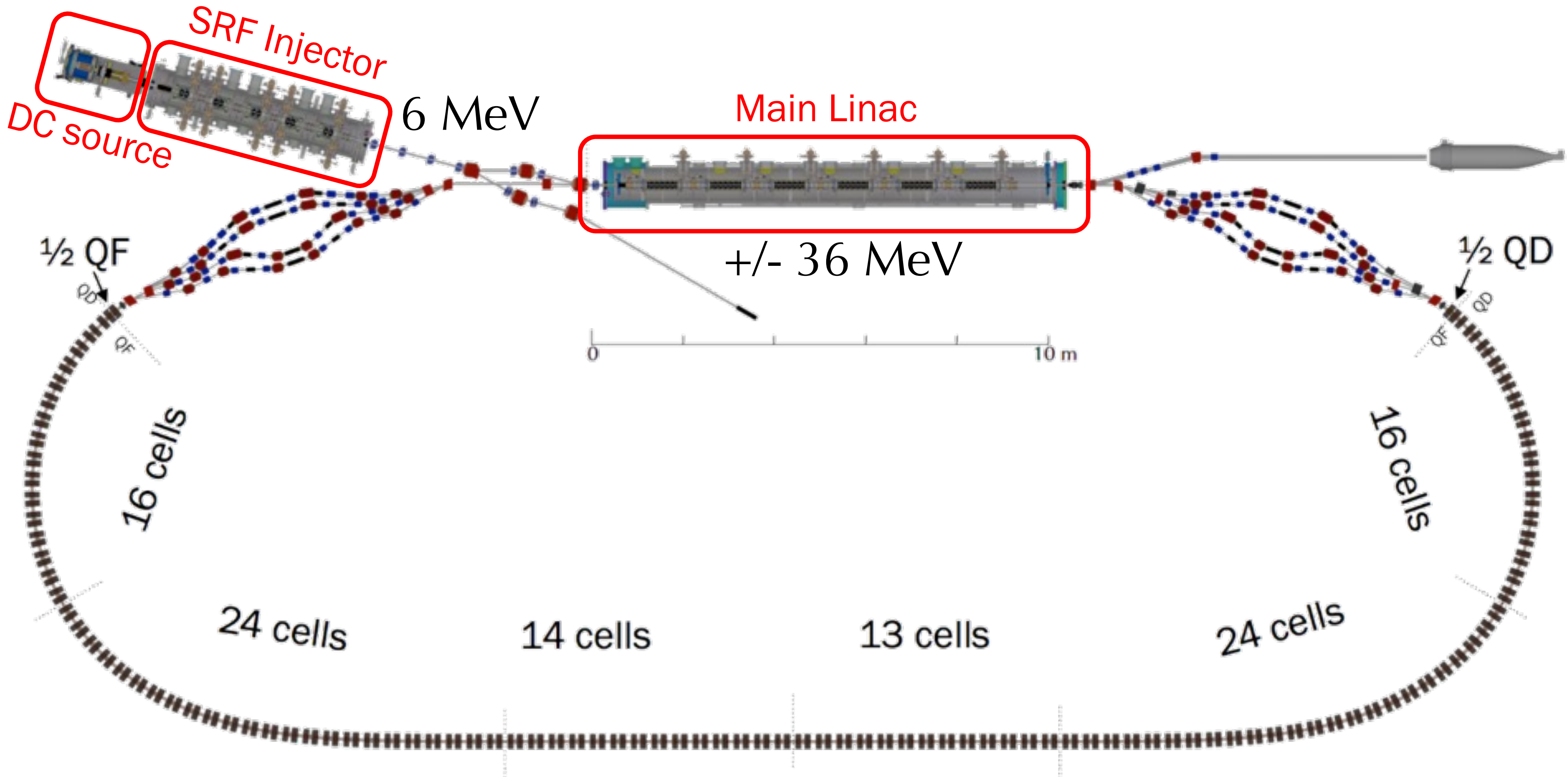
The test ERL at Cornell

- Cornell DC gun, 2nC peak
- 100mA, 6MeV SRF injector (ICM), 1.3GHz



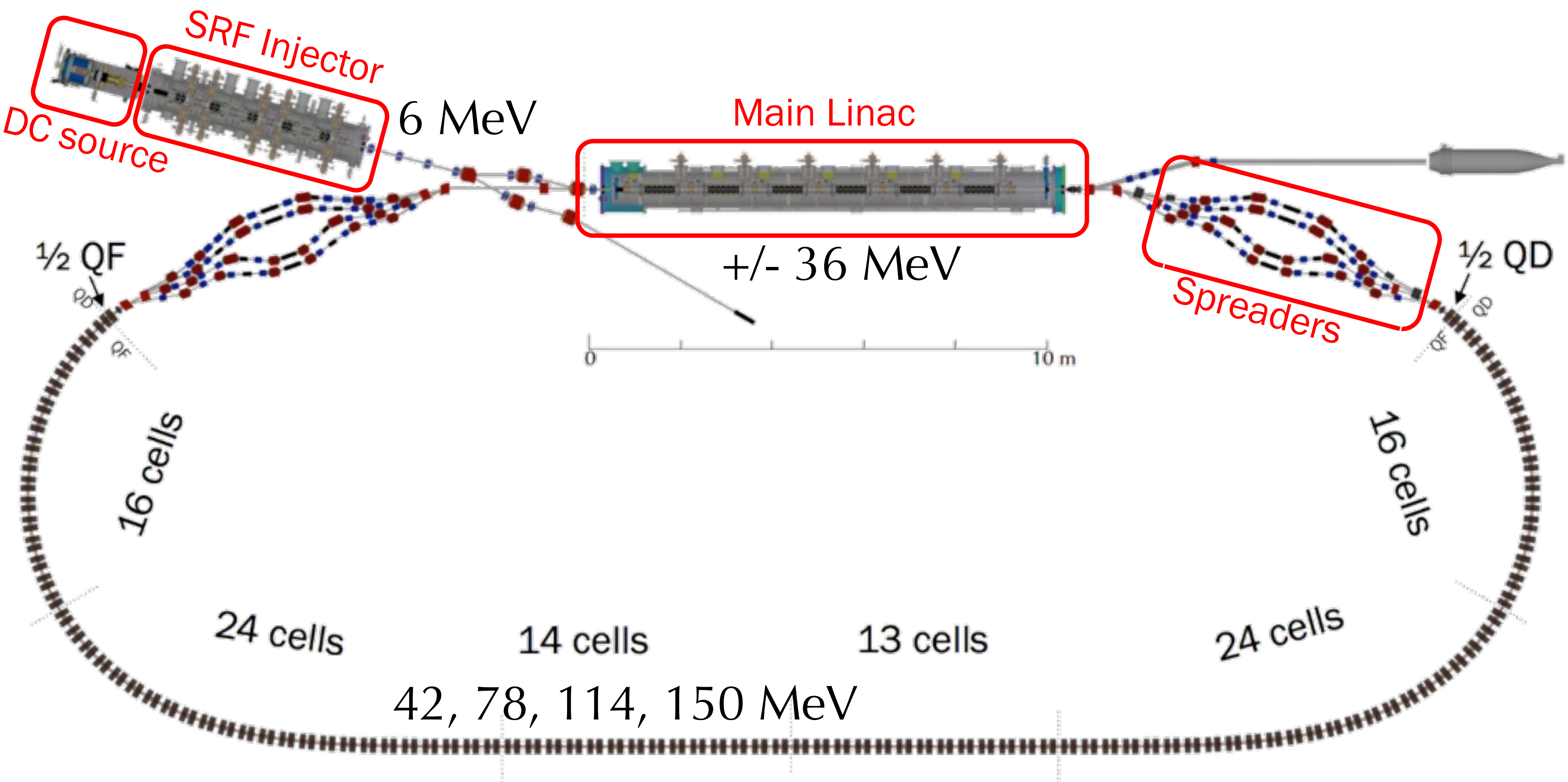
The test ERL at Cornell

- Cornell DC gun, 2nC peak
- 100mA, 6MeV SRF injector (ICM), 1.3GHz
- 320mA, 6-cavity SRF CW Linac (MLC), 1.3GHz



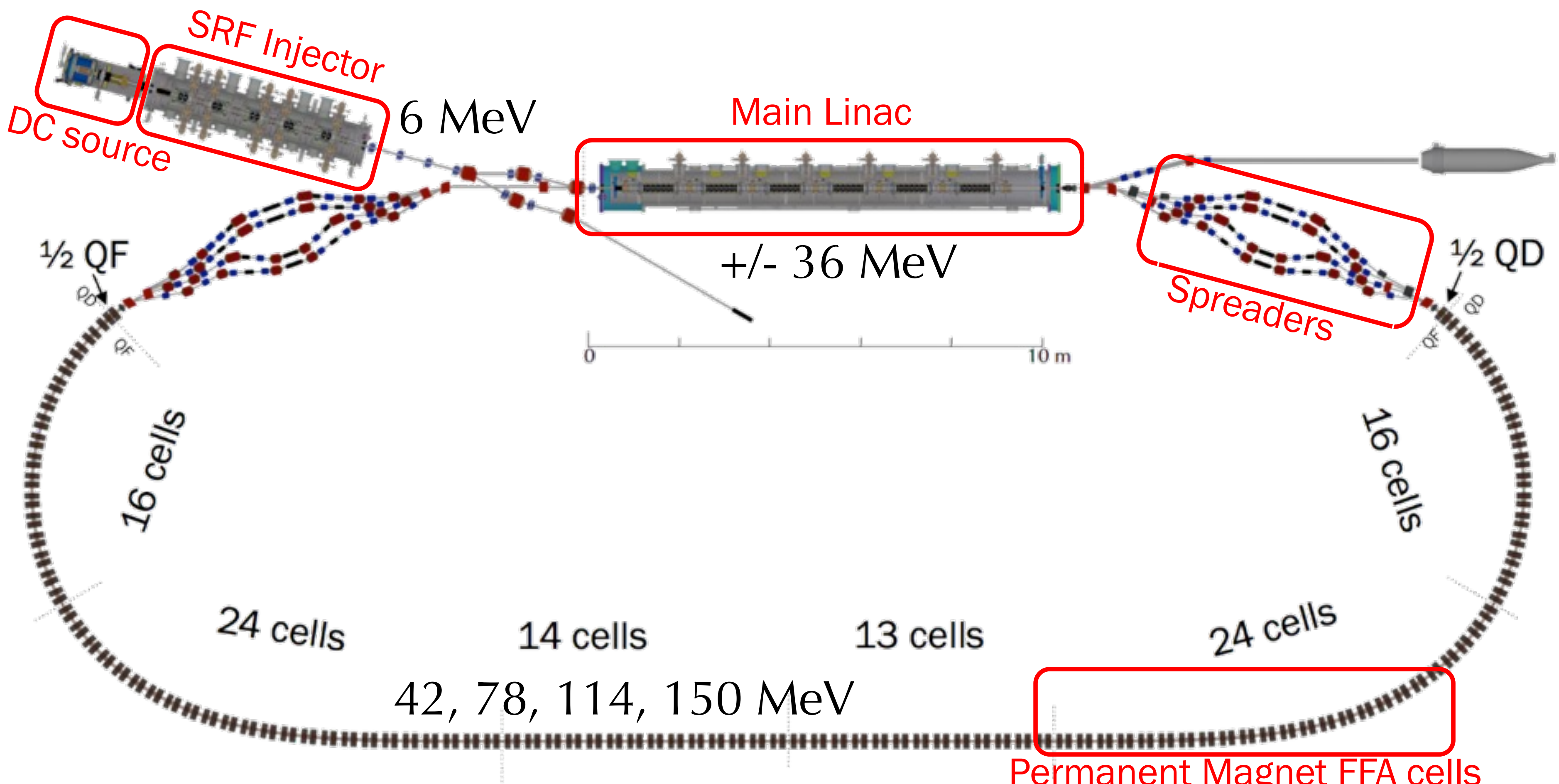
The test ERL at Cornell

- Cornell DC gun, 2nC peak
- 100mA, 6MeV SRF injector (ICM), 1.3GHz
- 320mA, 6-cavity SRF CW Linac (MLC), 1.3GHz
- 4 Spreaders / Combiners with electro magnets



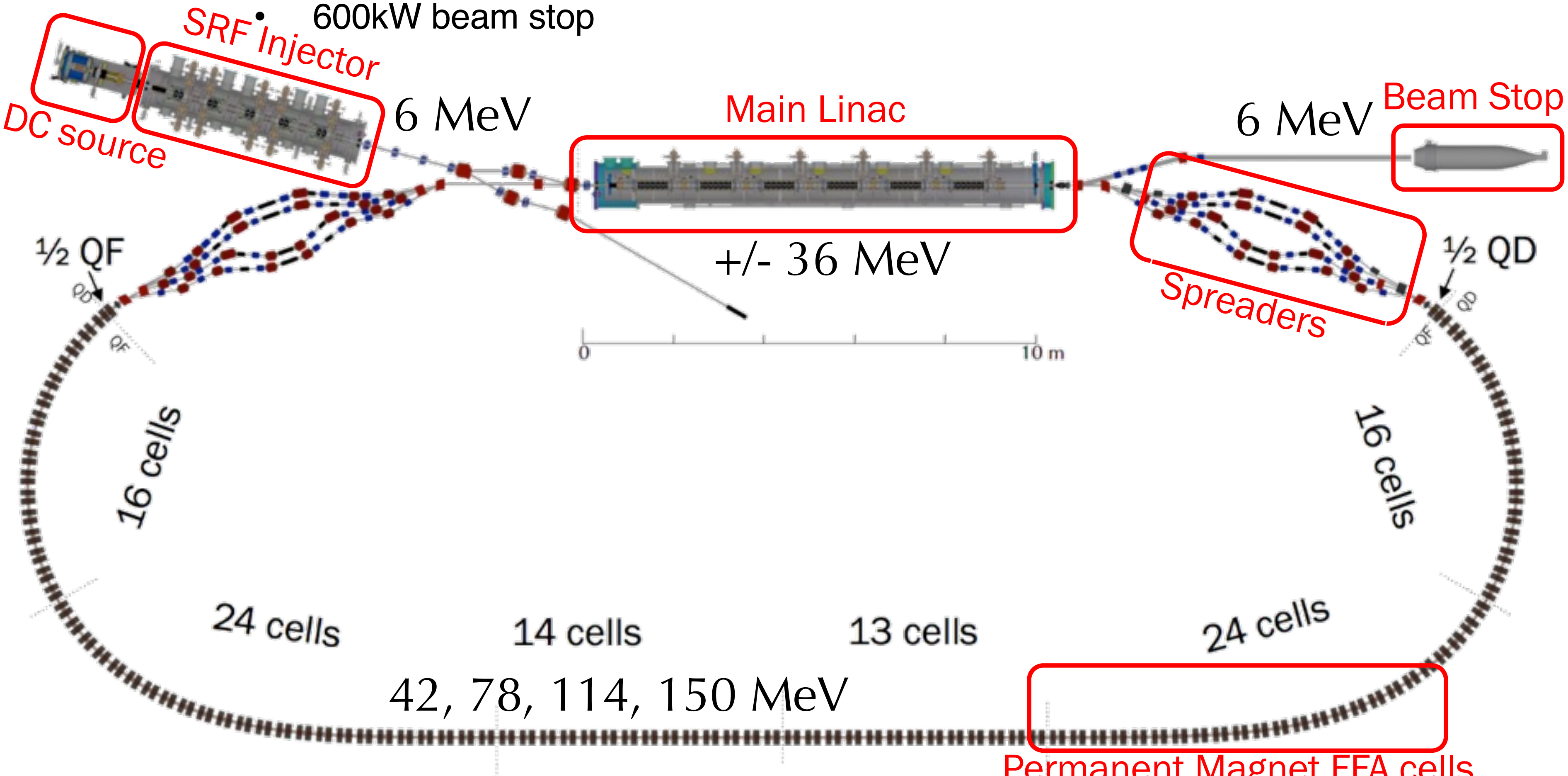
The test ERL at Cornell

- Cornell DC gun, 2nC peak
- 100mA, 6MeV SRF injector (ICM), 1.3GHz
- 320mA, 6-cavity SRF CW Linac (MLC), 1.3GHz
- 4 Spreaders / Combiners with electro magnets
- FFA cells with permanent magnets, 3.8 energy aperture, 7 beams.

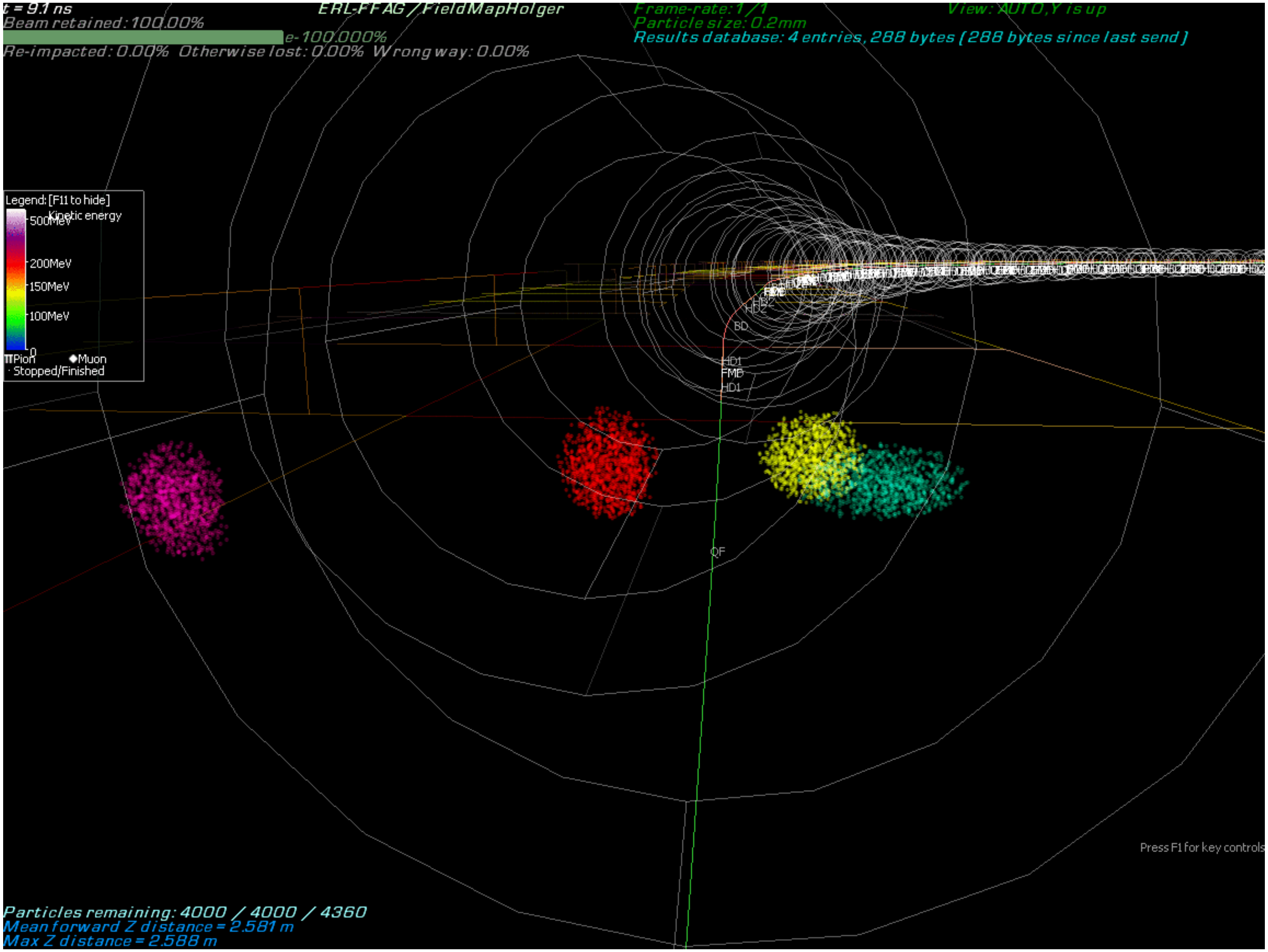


The test ERL at Cornell

- Cornell DC gun, 2nC peak
- 100mA, 6MeV SRF injector (ICM), 1.3GHz
- 320mA, 6-cavity SRF CW Linac (MLC), 1.3GHz
- 4 Spreaders / Combiners with electro magnets
- FFA cells with permanent magnets, 3.8 energy aperture, 7 beams.
- 600kW beam stop



Bunche dynamics in 3D field maps



Development of the CBETA collaboration

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 Construction funding by NYS

2017 CBETA Design Report

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

2019 ER with 1 turn, high efficiency

2019/20 1st multi-turn SRF ERL

CBETA is now available for R&D on high power beams!

CBETA Design Report

Cornell-BNL ERL Test Accelerator

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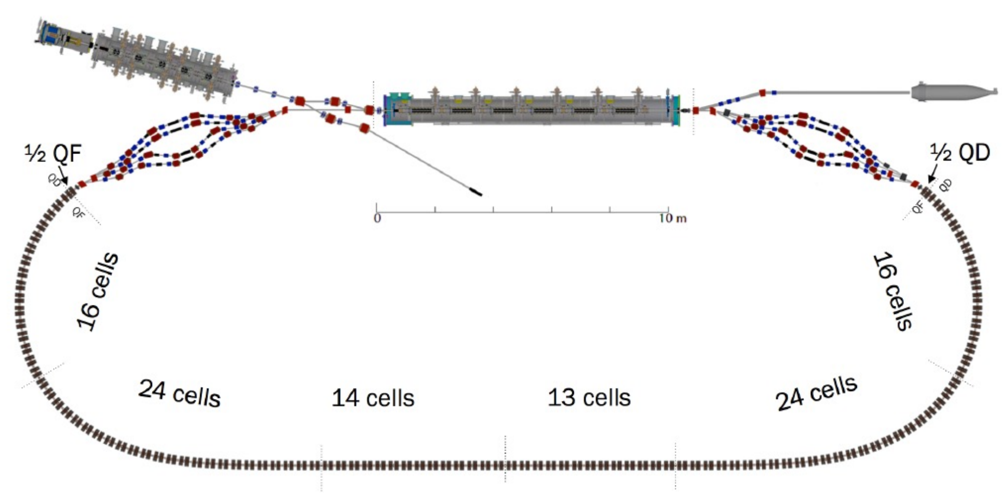
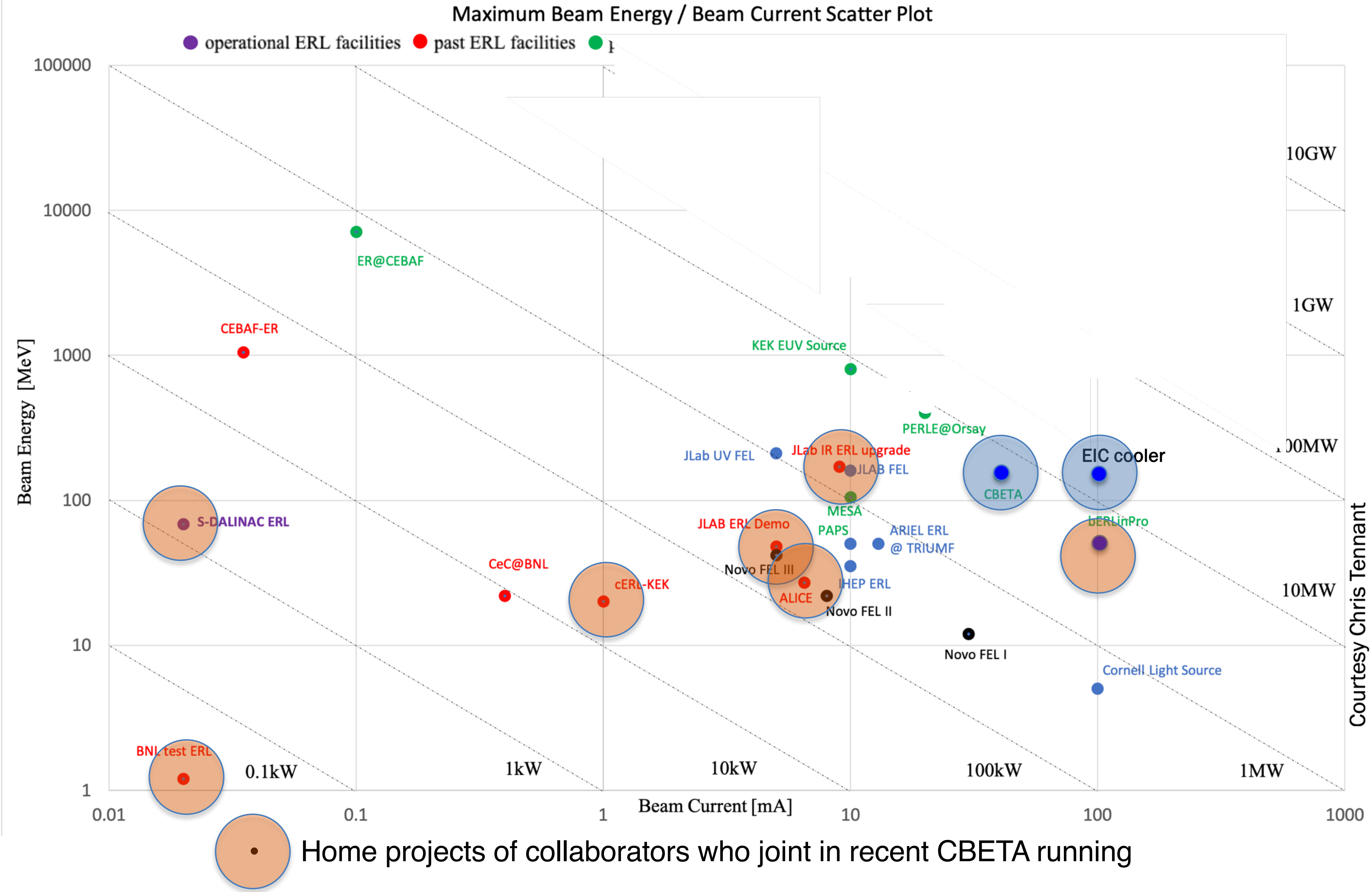


June 8, 2017

The beam power frontier

- CBETA has 150MeV / 40mA or 60MeV/100mA: 6MW beam power
- EIC cooler ERL has 150MeV and up to 100mA: up to 15MW

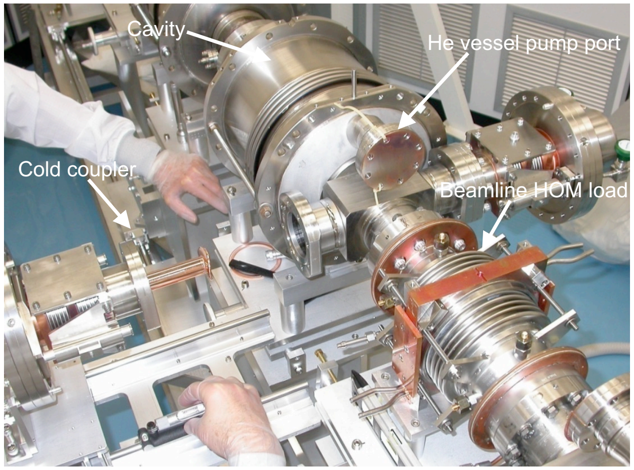
Collaborators at the beam power frontier

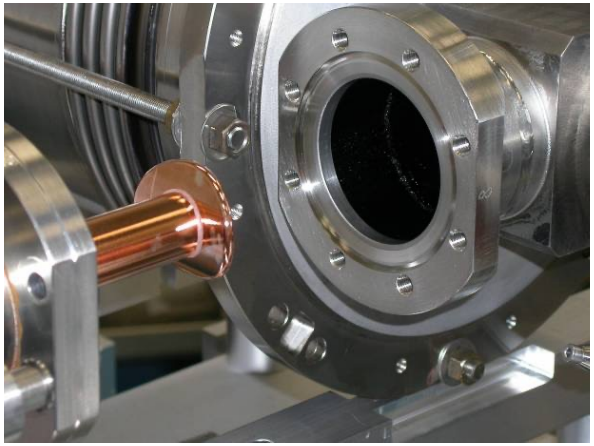


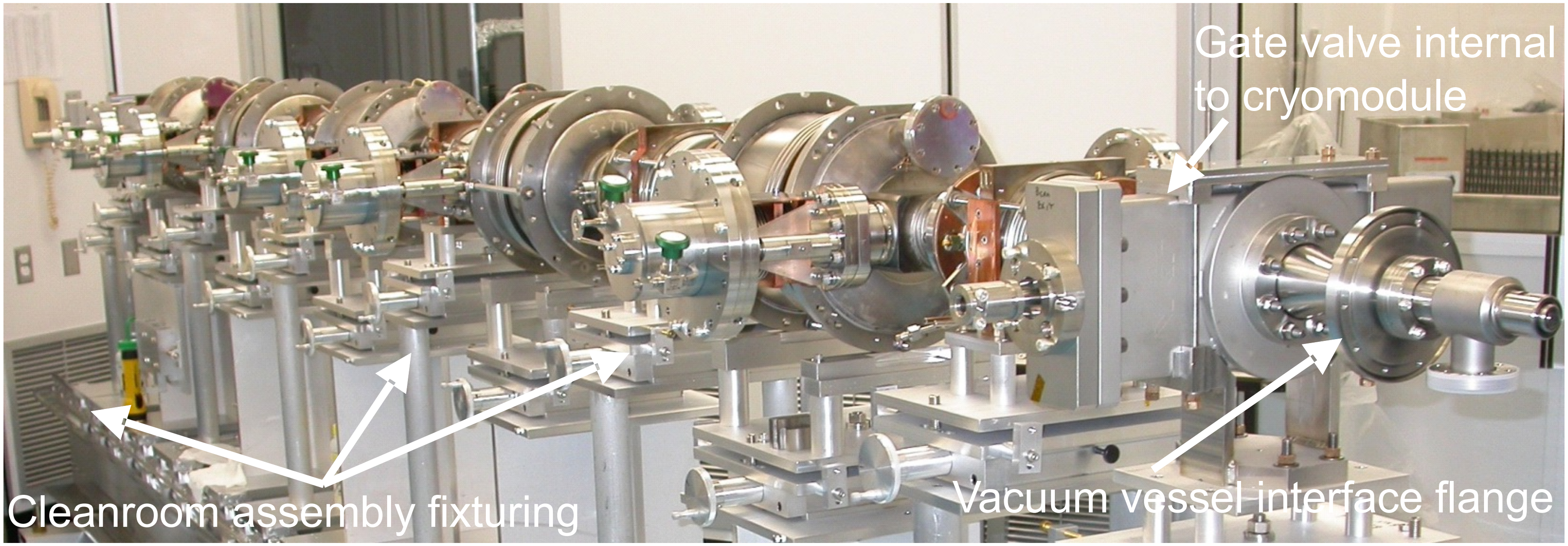
Home projects of collaborators who joint in recent CBETA running

In-house production from DC-source to SRF linac, from cathodes to the full accelerator

Attach cold couplers to beamline string







In-house production from DC-source to SRF linac, from cathodes to the full accelerator



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

Hall L0E before CBETA

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

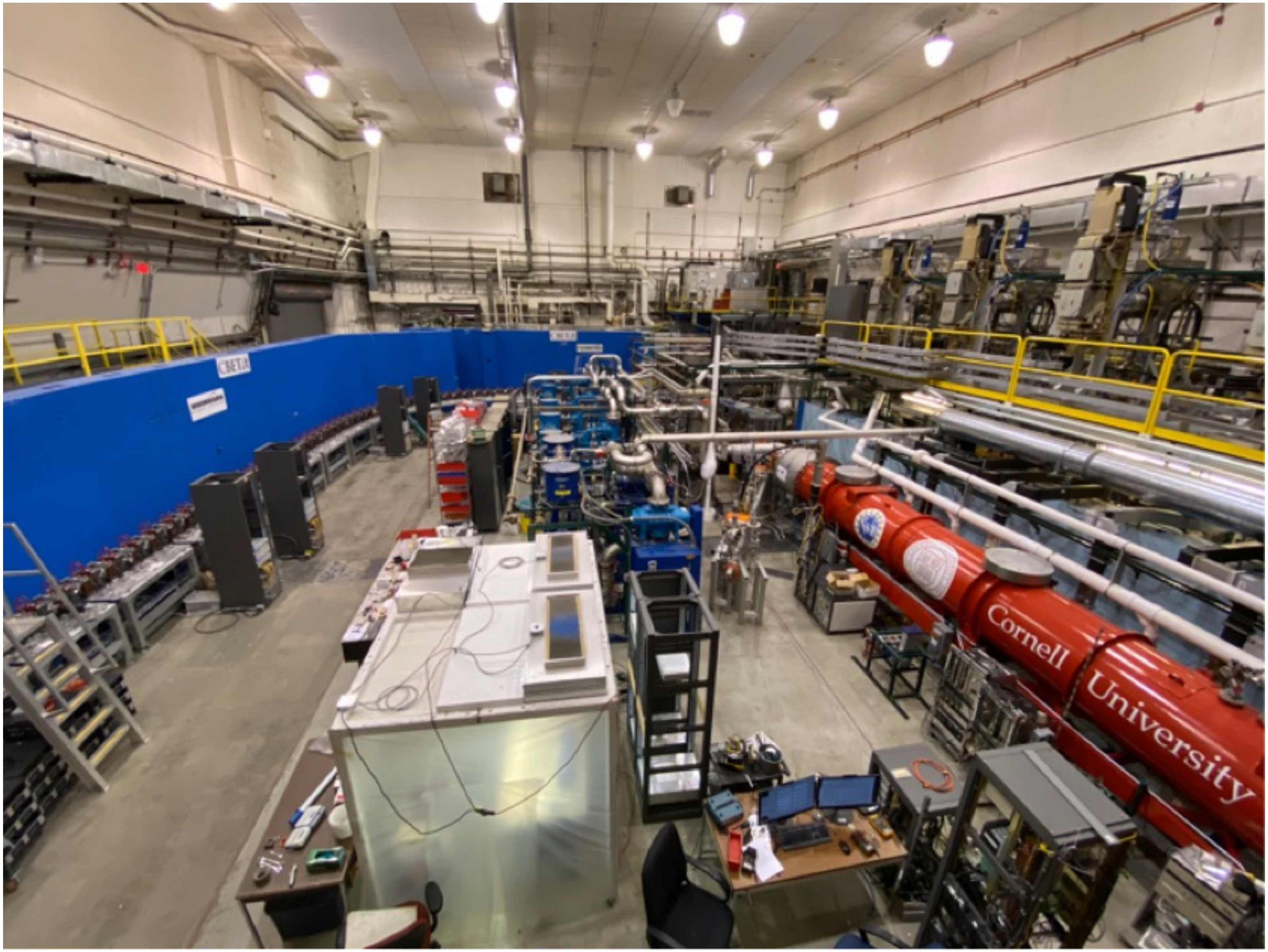
Spring 2015

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

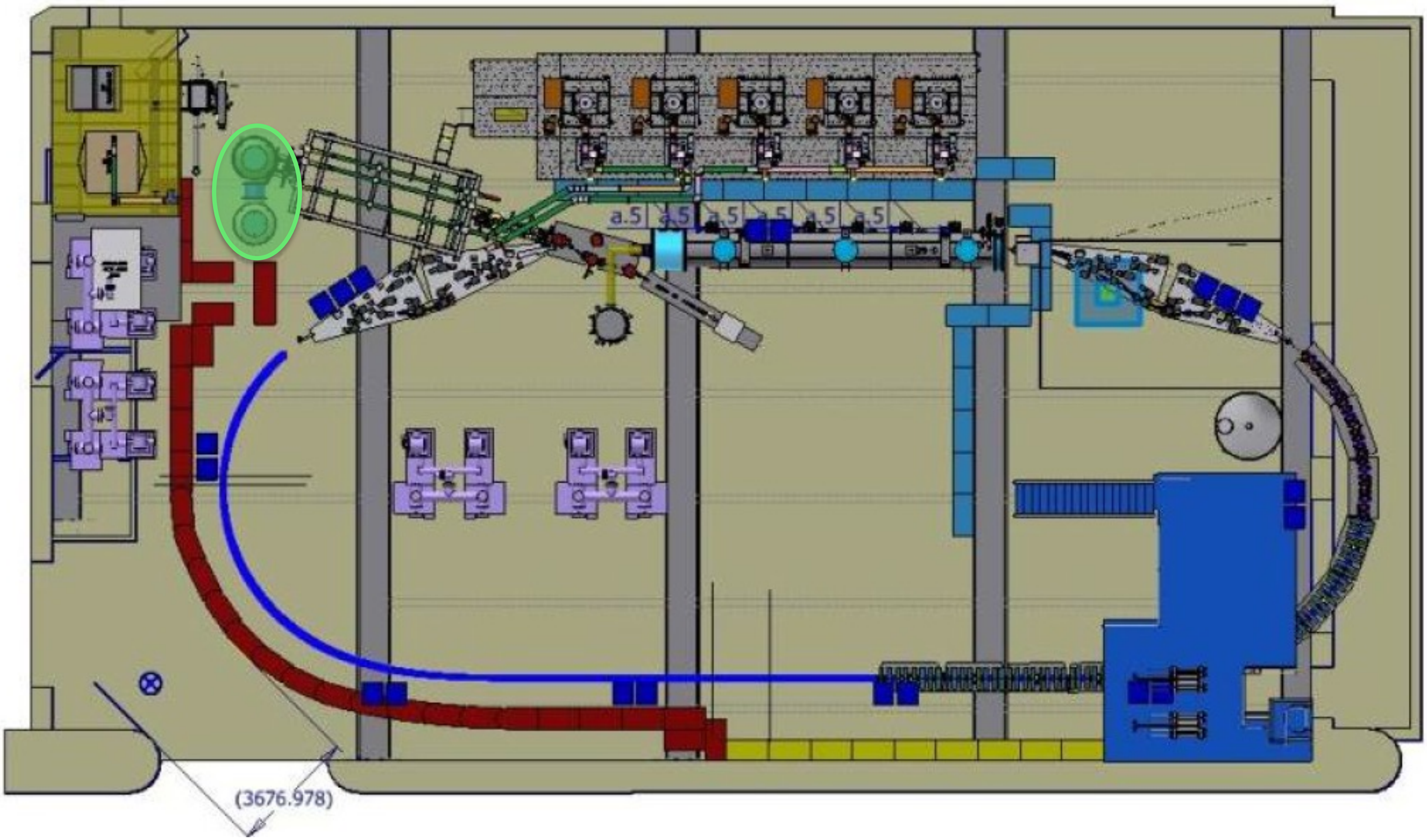
L0E cleaned with CBETA

FFA permanent magnet work from BNL

CBETA installation at Cornell, 2019

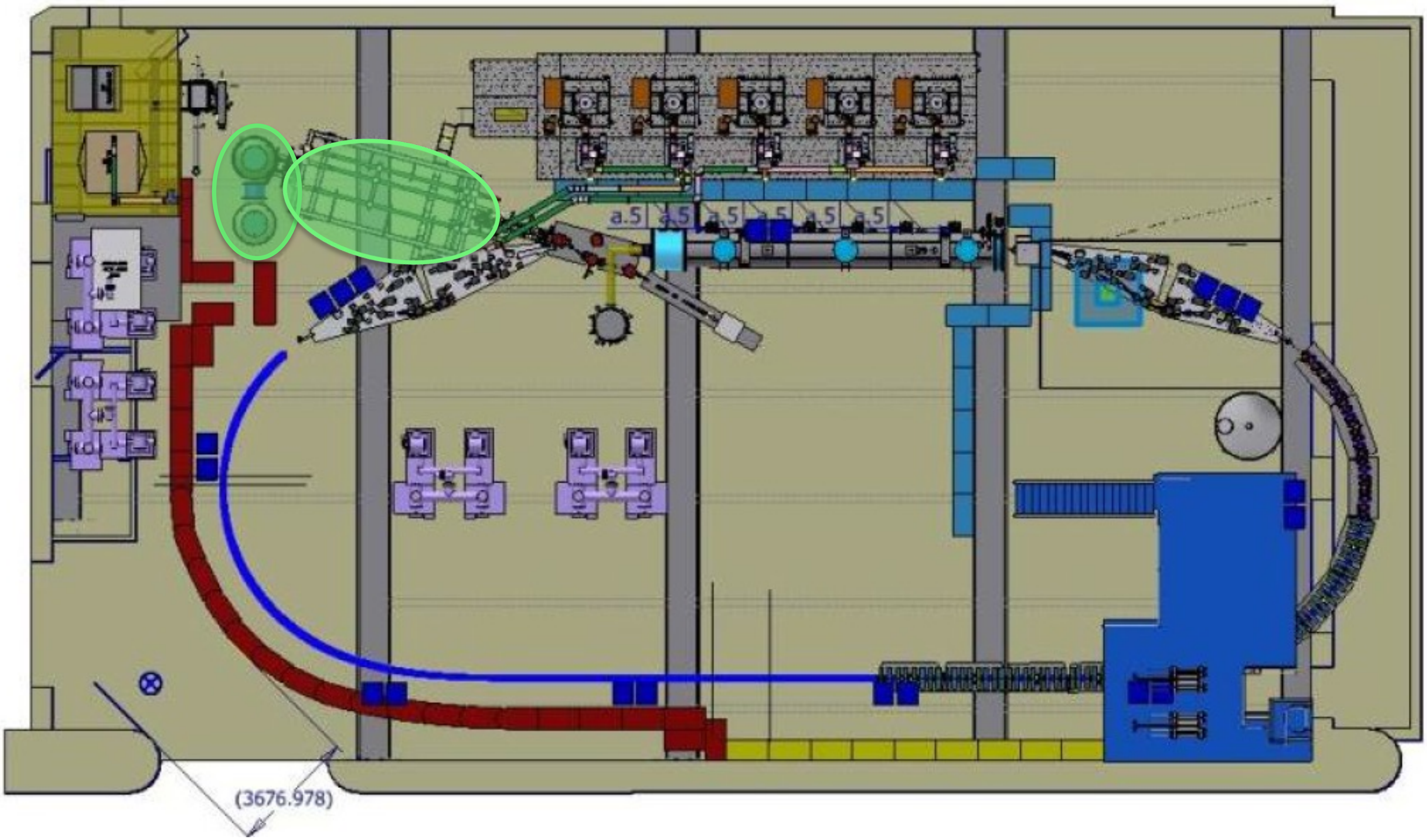


Installed: DC gun

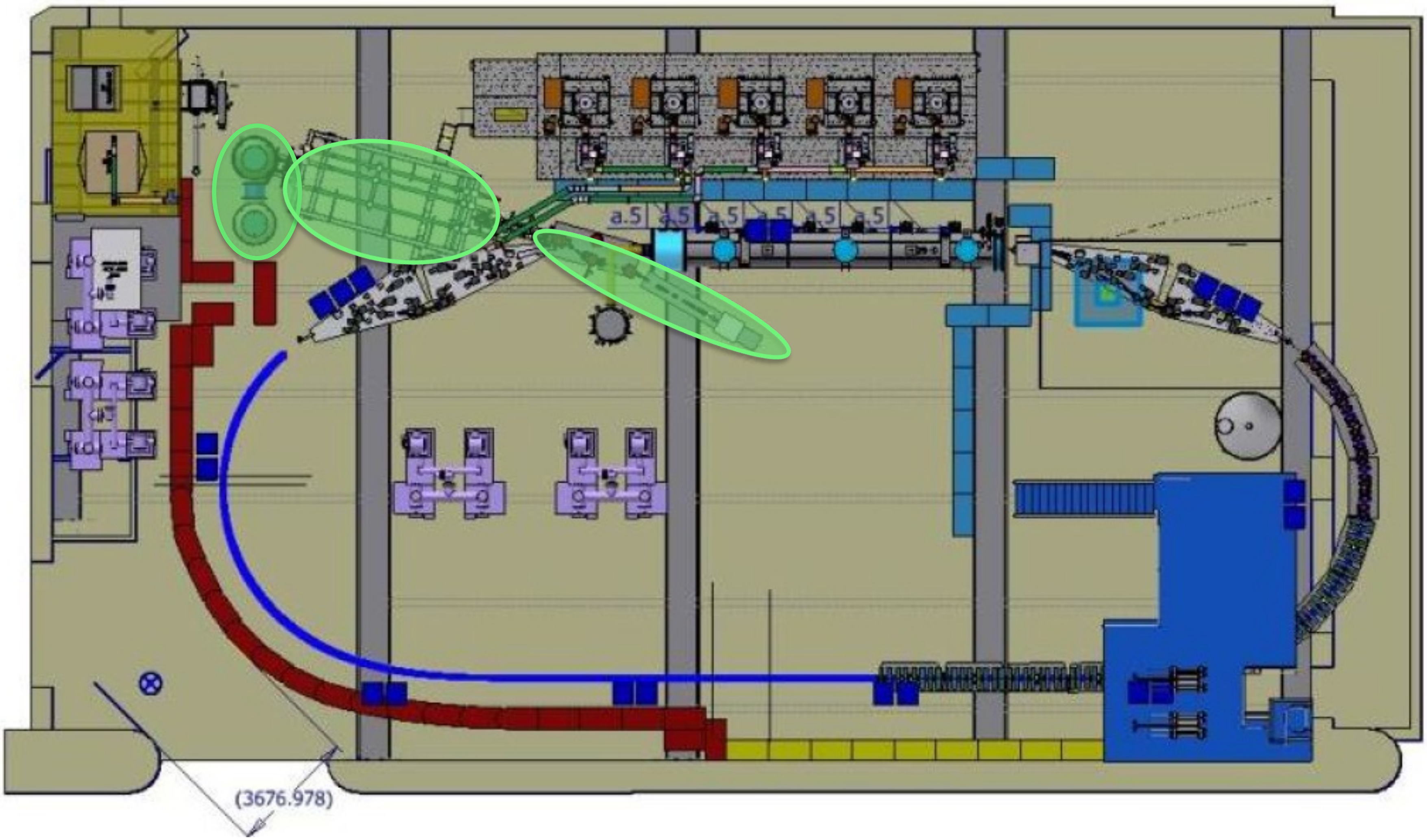


CBETA in its Hall L0E

Installed: DC gun, SRF injector

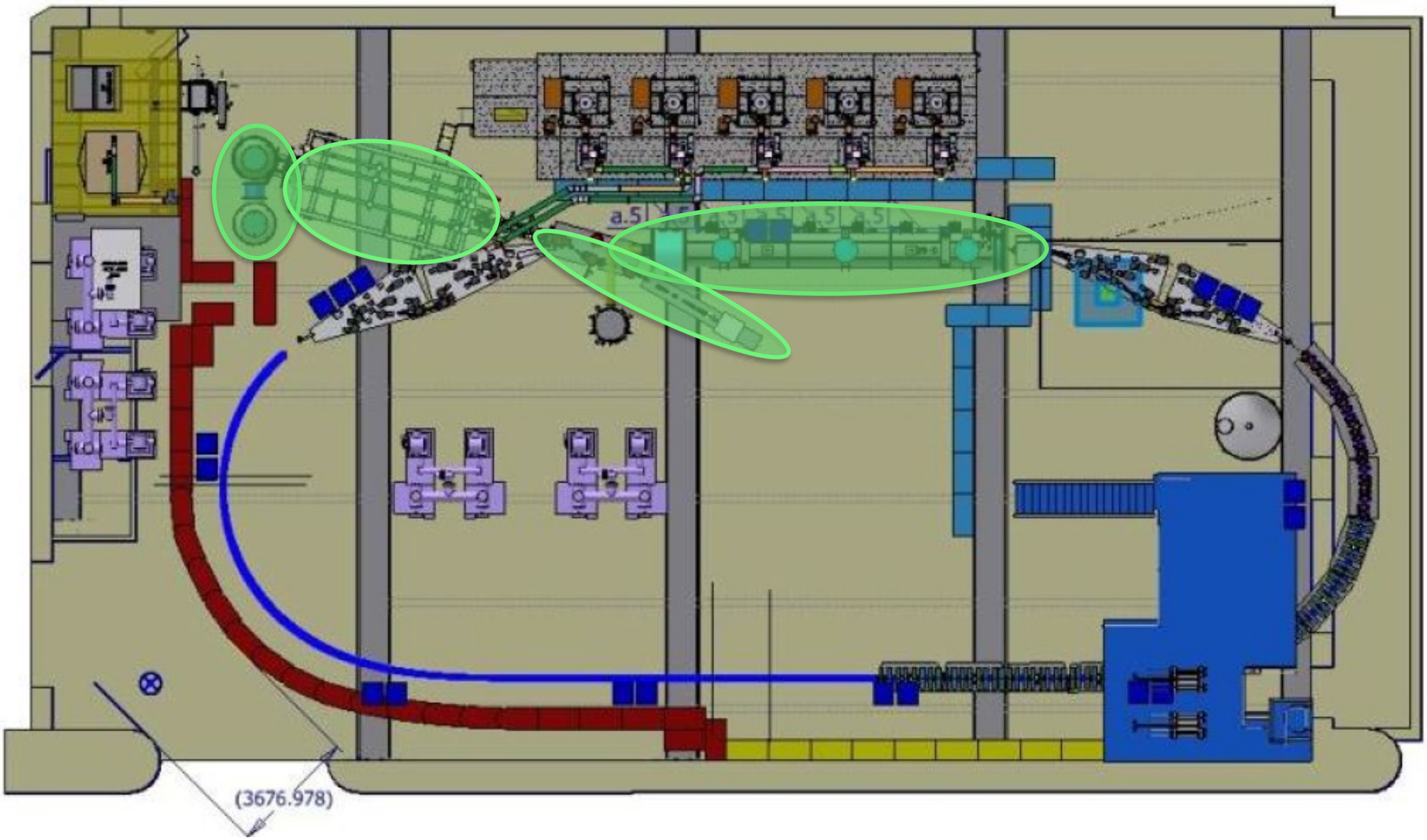


Installed: DC gun, SRF injector, mirror diagnostics line



CBETA in its Hall L0E

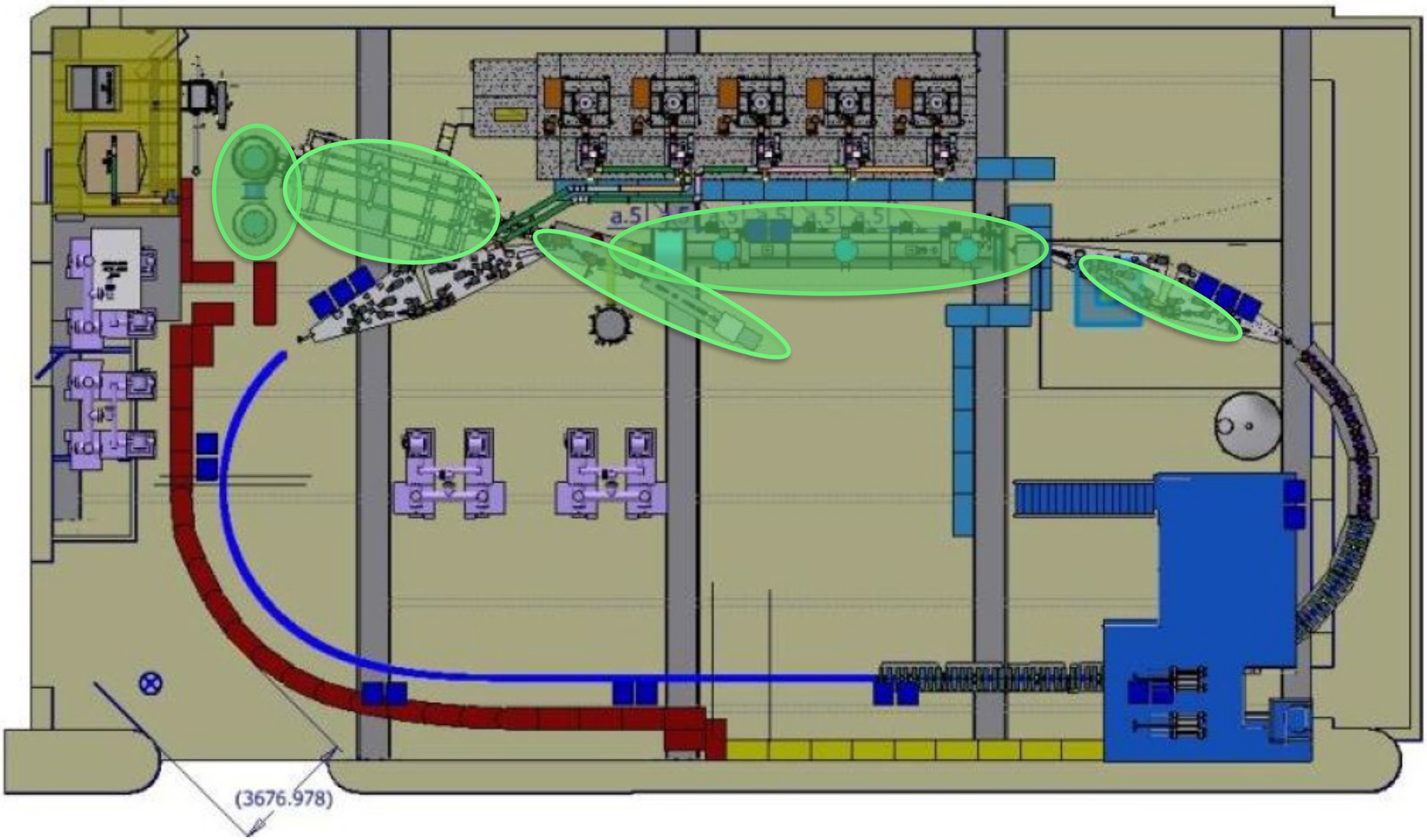
Installed: DC gun, SRF injector, mirror diagnostics line, ERL cryomodule



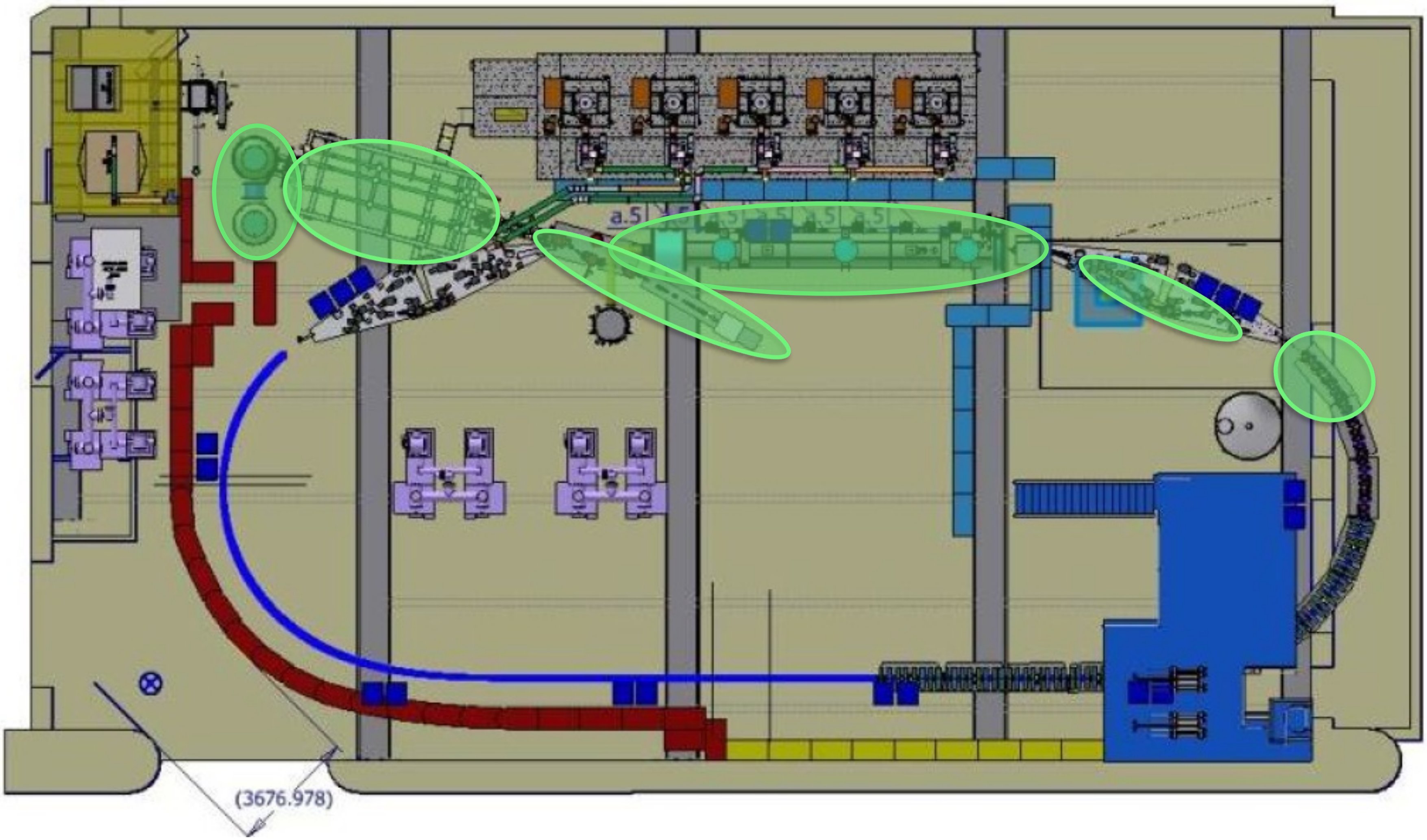
CBETA in its Hall L0E

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

1st splitter of 8



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



Achieved parameters

CBETA

Cornell **DC gun**

- 75mA short term, 65mA for hours
- Detailed **phase space diagnostics** for space charge dominated beams.
- Study of 2nC bunch charges

High power **SRF injector linac**

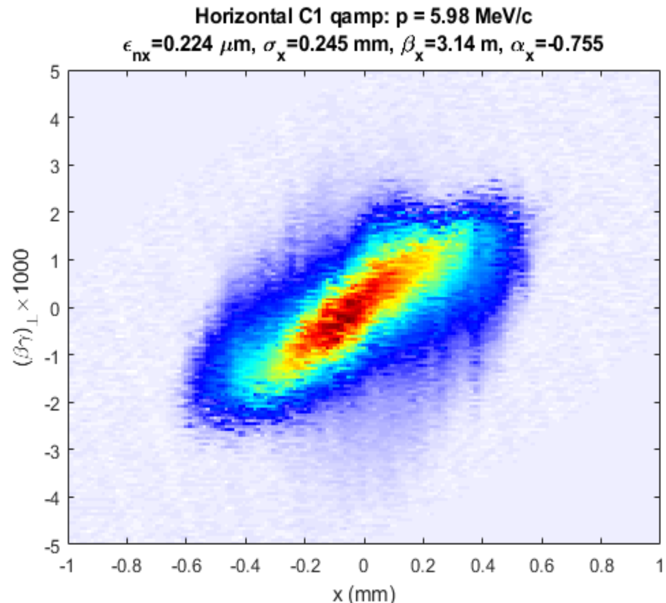
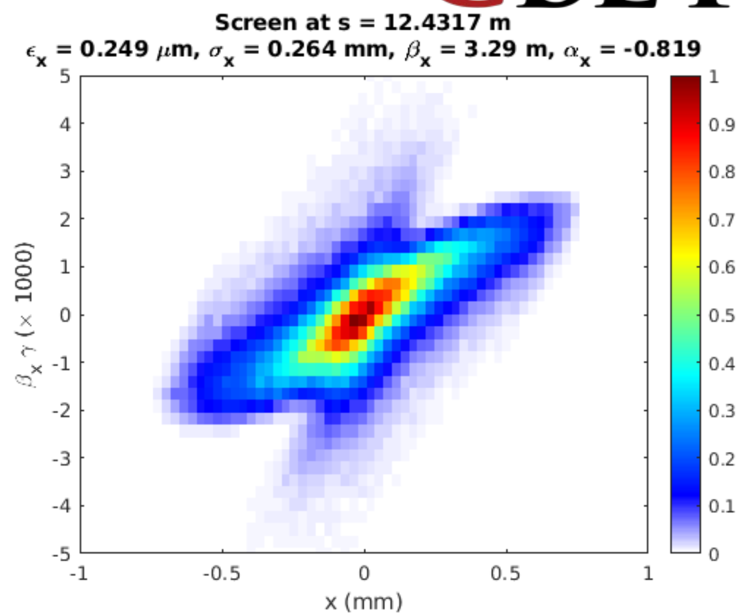
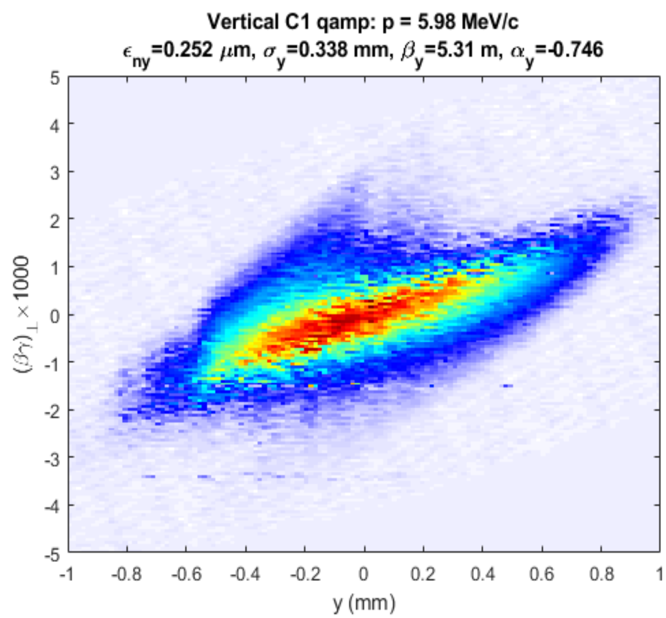
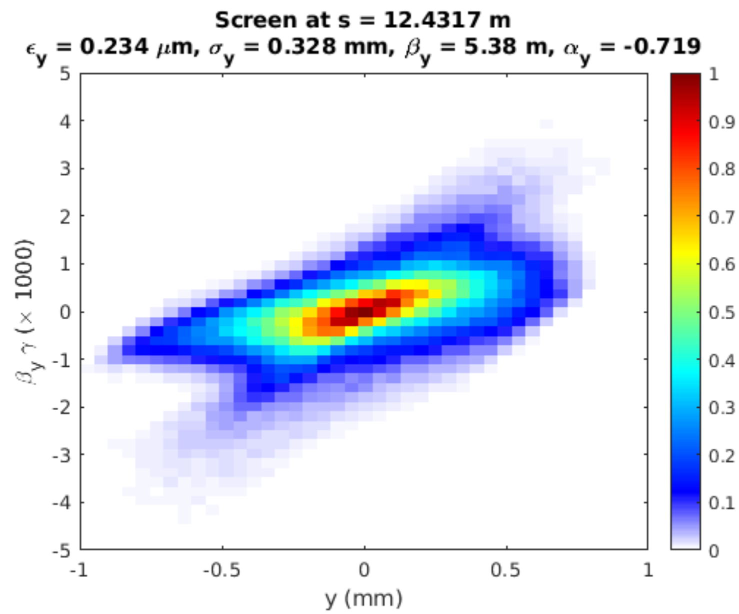
- Tested up to 13.5MeV
- Tested up to 75mA
- Investigation of ion / beam interactions

ERL main SRF linac

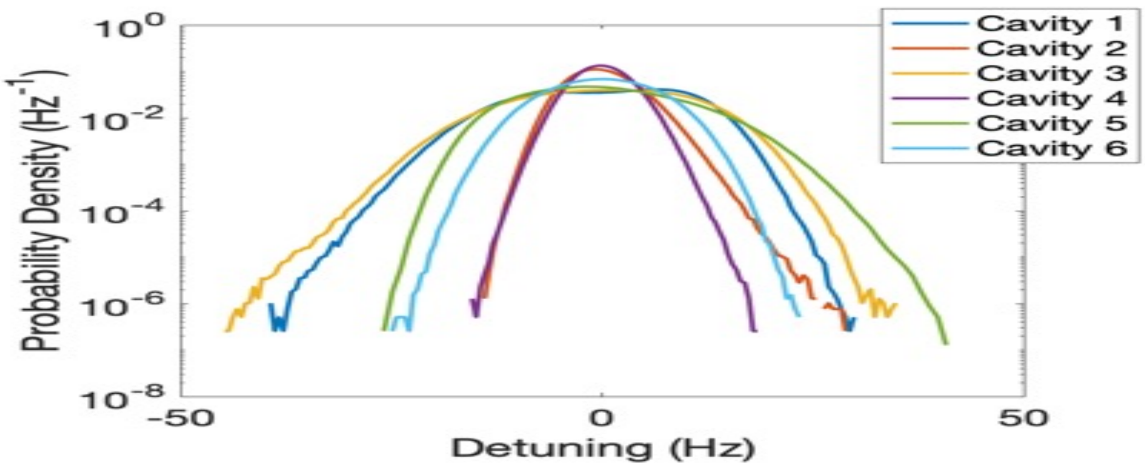
- Operated with **1-turn ERL and 99.4% ERL efficiency**
- Operated with **4-turn ERL**
- Detection of **micro bunching**
- 1-turn current limited to 70mu for radiation protection.
- 4-turn current limited to 1nA because of 50% beam loss in the last recovery loop.

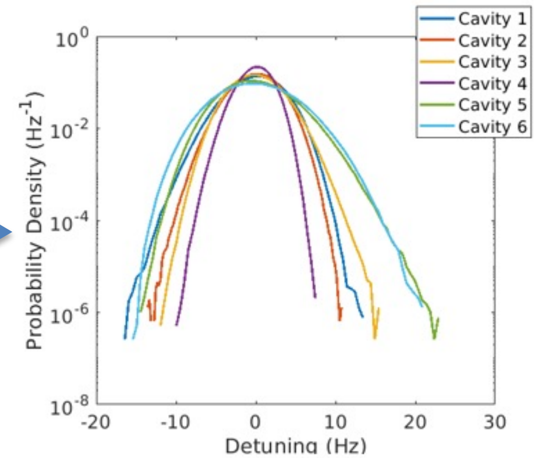
FFA return loop

- 7 simultaneous beams (at 42, 78, 114, 150MeV)
- Hardly measurable beam losses in the FFA region

	Measured	Simulation
Horizontal		
Vertical		

Microphonics stabilization of SRF





Cavity	Stiffened	Old Peak Detuning (Hz)	New Peak Detuning (Hz)	Field (MV)
1	No	78	17	6 (8.5)
2	Yes	18	15	6 (8.5)
3	No	280	16	6 (9.5)
4	Yes	18	11	6 (10)
5	No	163	23	6 (10)
6	Yes	33	22	6 (10)

After mitigating several vibration sources, the peak detuning was 23 Hz among all cavities.

54Hz detuning can be tolerated with 5kW RF sources.

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.

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:

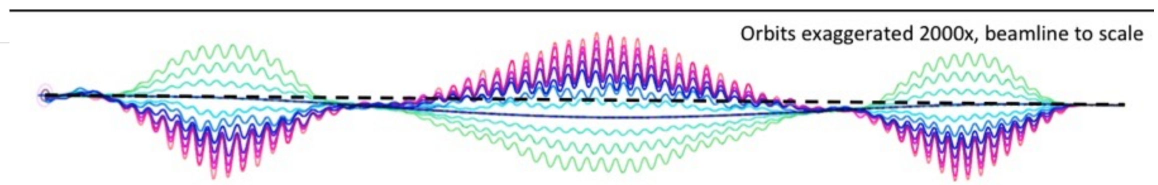
For < 10% emittance and beam-size growth

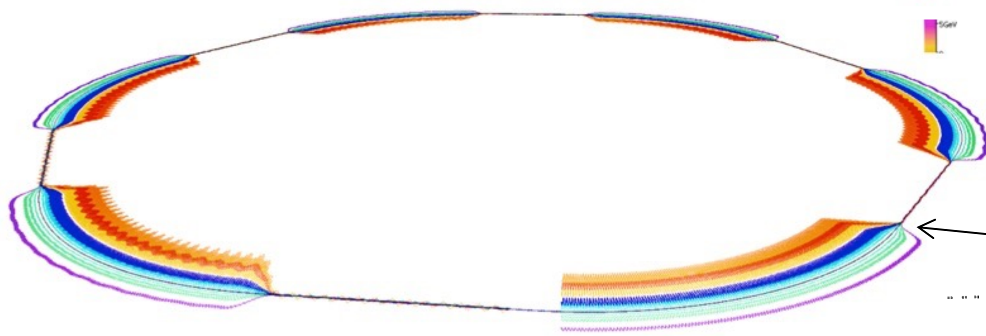
$$\sqrt{\Sigma_n(\frac{b_n}{lim\_b_n})^2 + (\frac{a_n}{lim\_a_n})^2} < 0.75$$

First Girder Construction

Adiabatic optics, orbit, and dispersion changes.

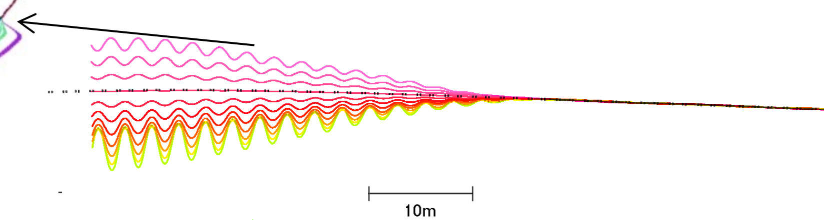
@S.Brooks, D.Trbojevic



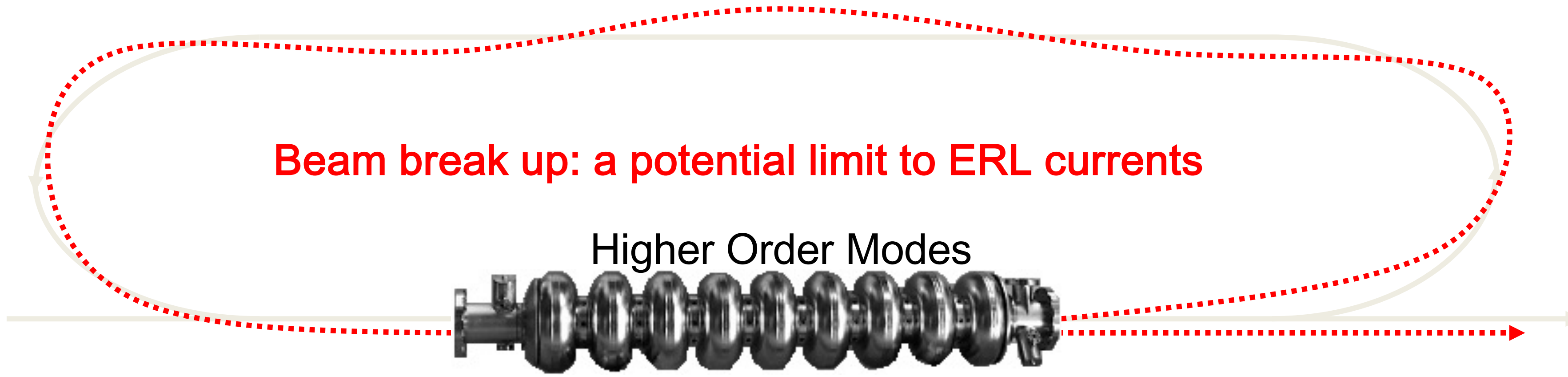


Quad offsets evolve adiabatically

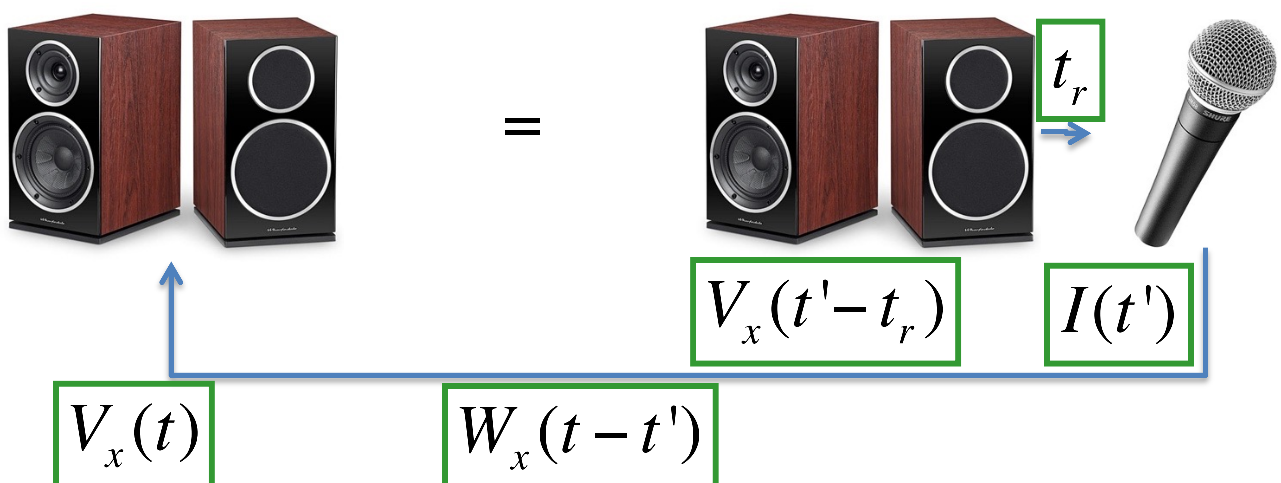
Orbits in Transition section



New current limit



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

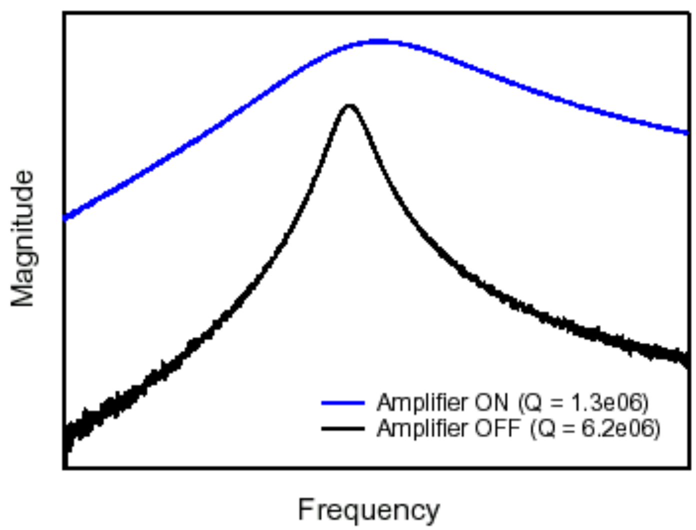


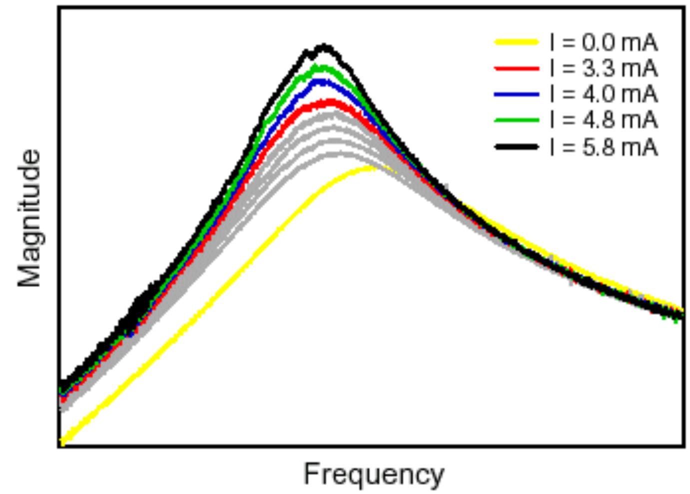
Recall… $I_{threshold} \propto \frac{1}{Q_{HOM}}$

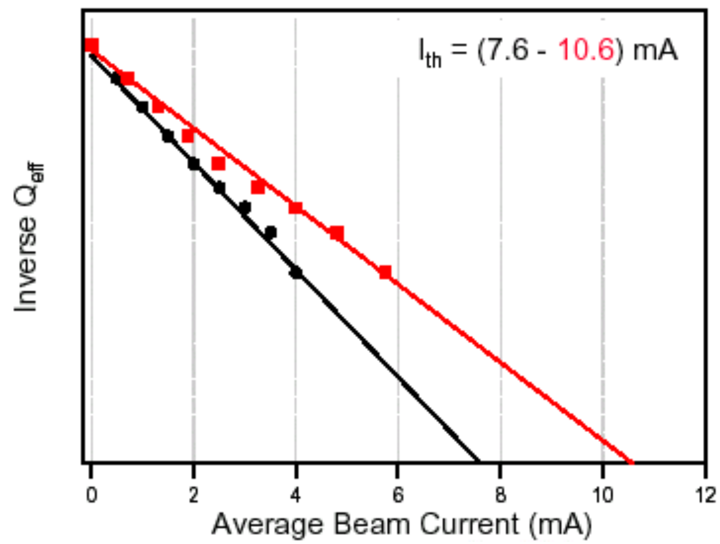
- Damping circuit easily reduced the *Q* of the 2106 MHz mode by a factor of 5

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

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

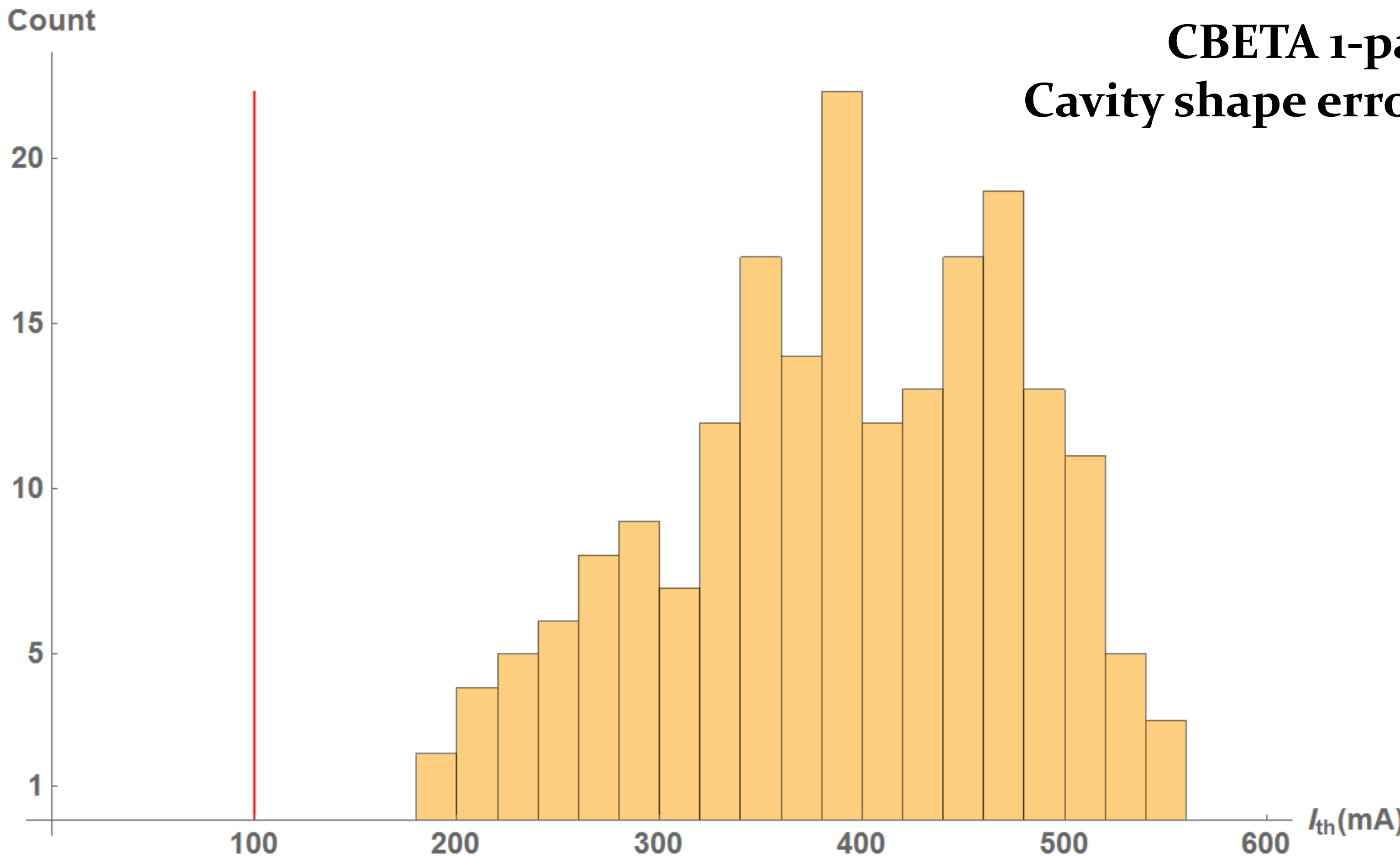




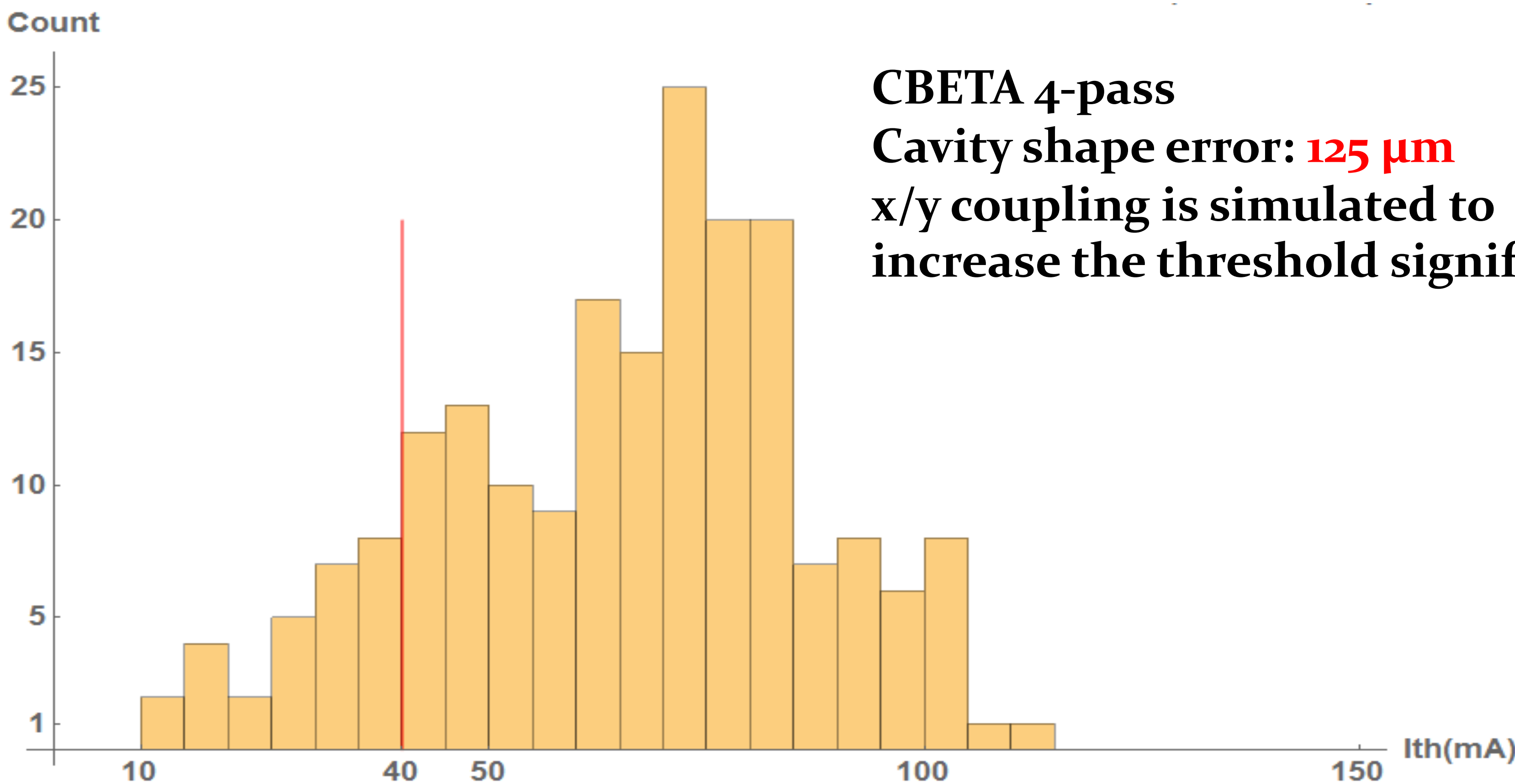


BBU for 1 pass in CBETA

CBETA 1-pass
Cavity shape error: 125 μm



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



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

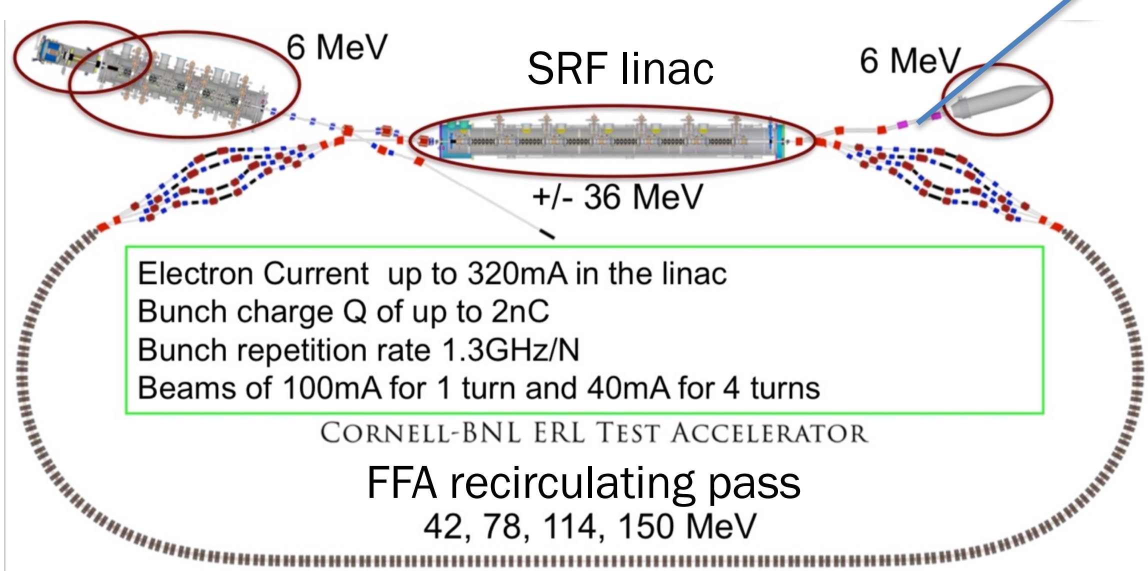
100% of simulations hav I_{th} > 100mA

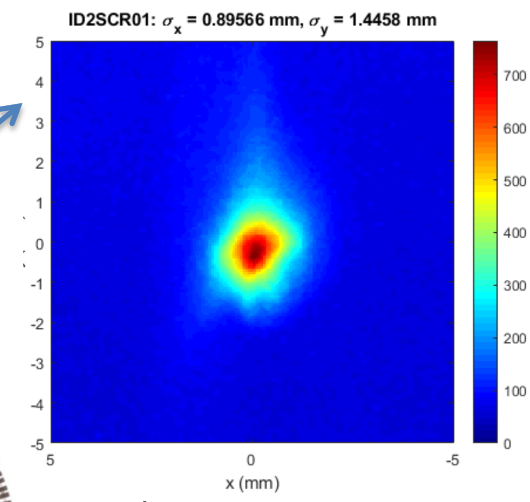
86% of simulations hav I_{th} > 40mA

1st ERL turn in CBETA

CBETA

- At least 100 mA current will be needed for eRHIC hadron cooler (design limit for 1-turn CBETA)
- BNL and collaborators gained and demonstrated expertise in high-power ERLs
- Successful operation, including energy recovery in each cavity (June 24th, 2019).
- Full 4-turn construction was completed immediately after this achievement.

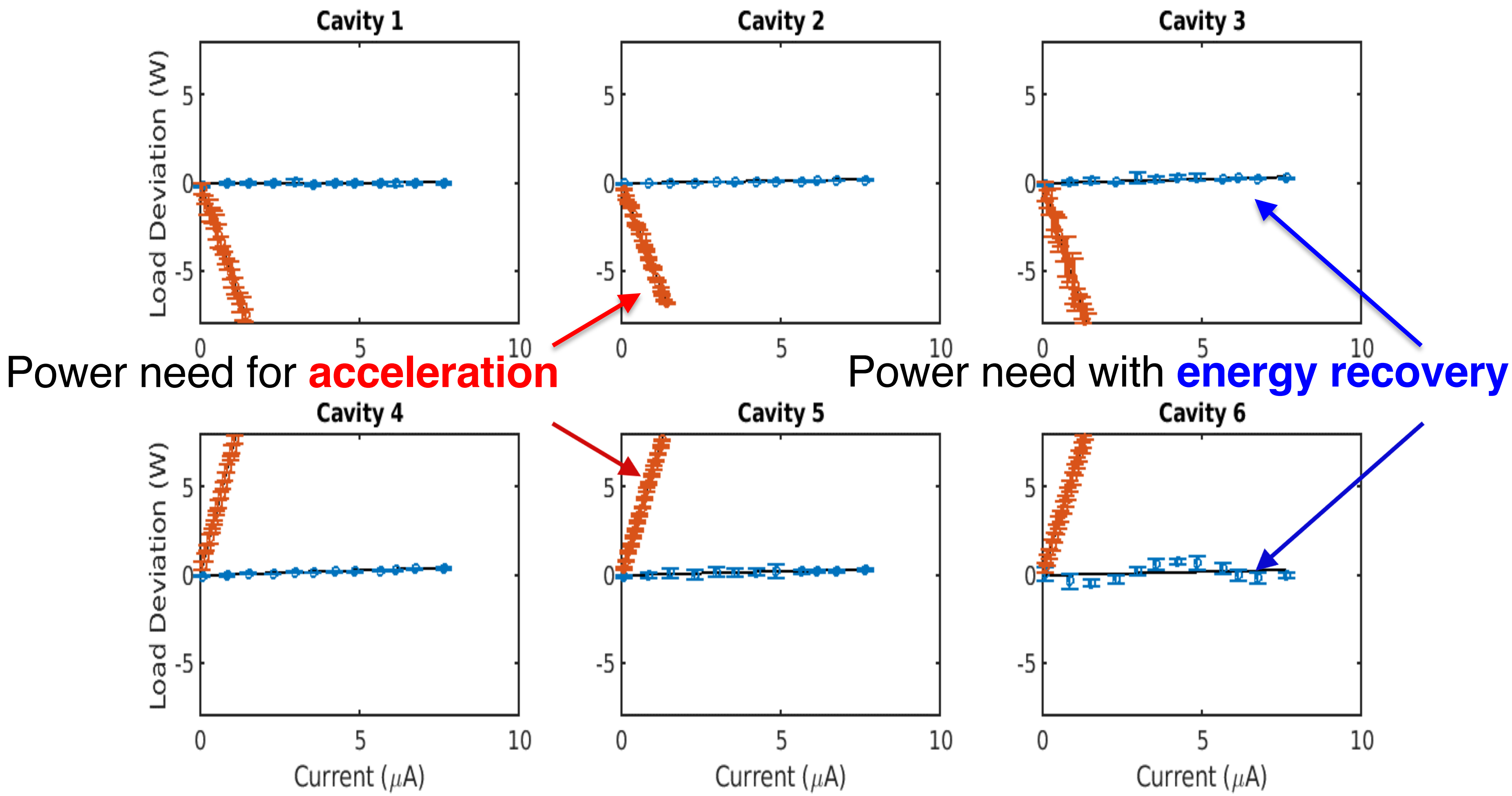




First 1-turn recirculated beam spot @ CBETA (June 10)

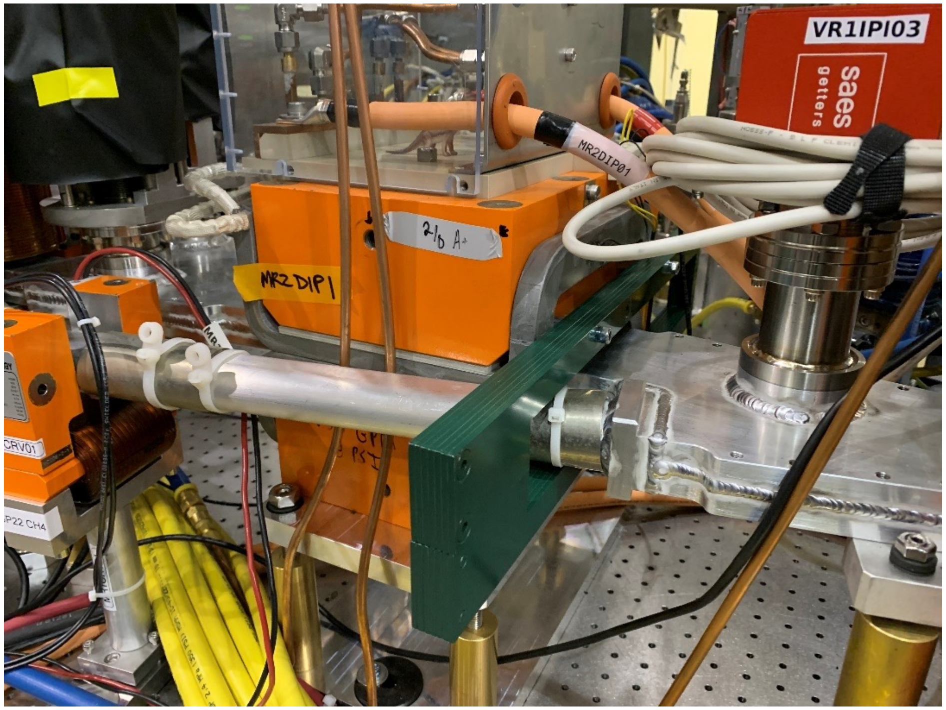
Energy Recovery in every cavity

- Transmission 99.6 ± 0.1% ; energy recovery > 99.8%
- Measured up to 8 μA
- Each cavity accelerates beam **without** receiving **external power** for it.



Spreader / Combiner Stray Fields

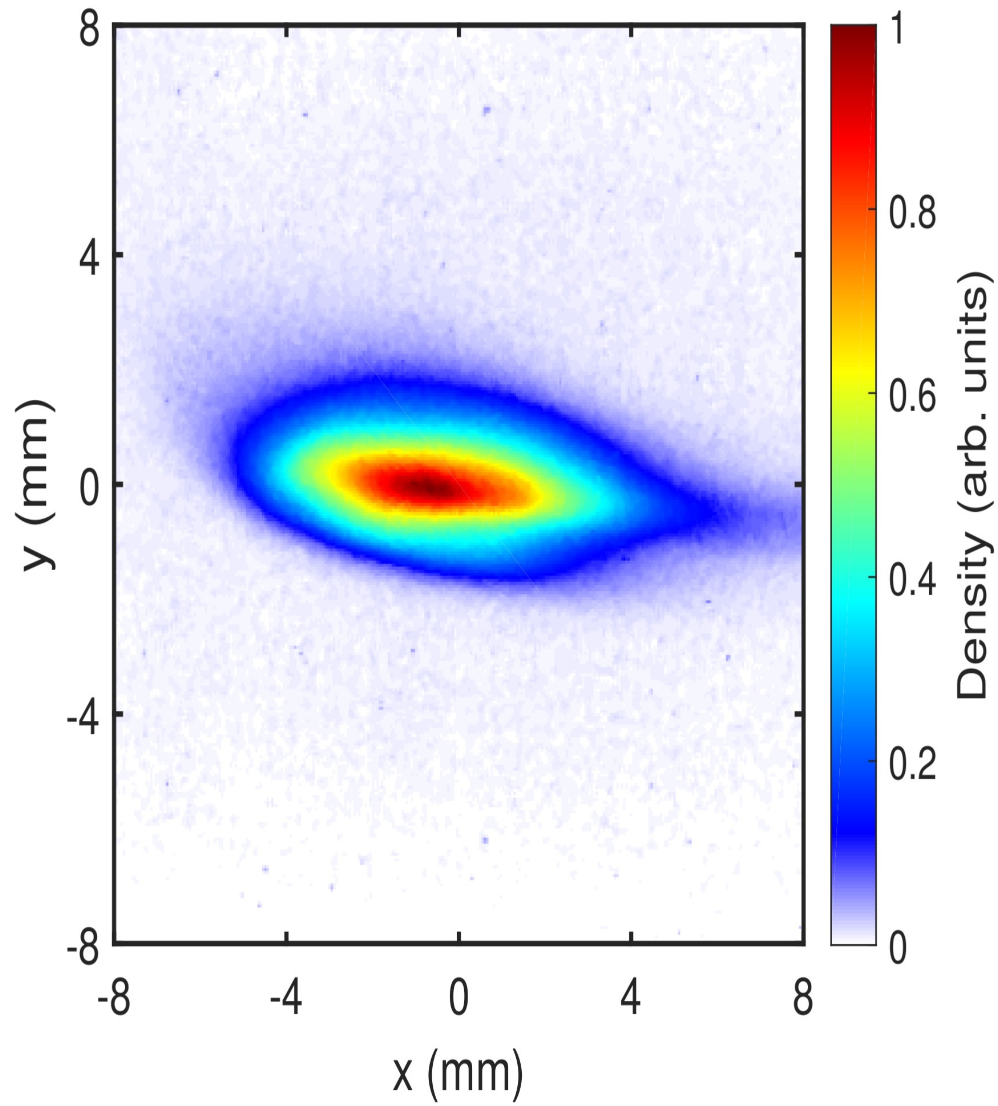
- Splitter magnet density was expected to be a significant problem
- Largest expected problems: septa 1 magnets
  - Field clamps from detailed modeling, engineering
  - Reduced stray field effect by factor of 40



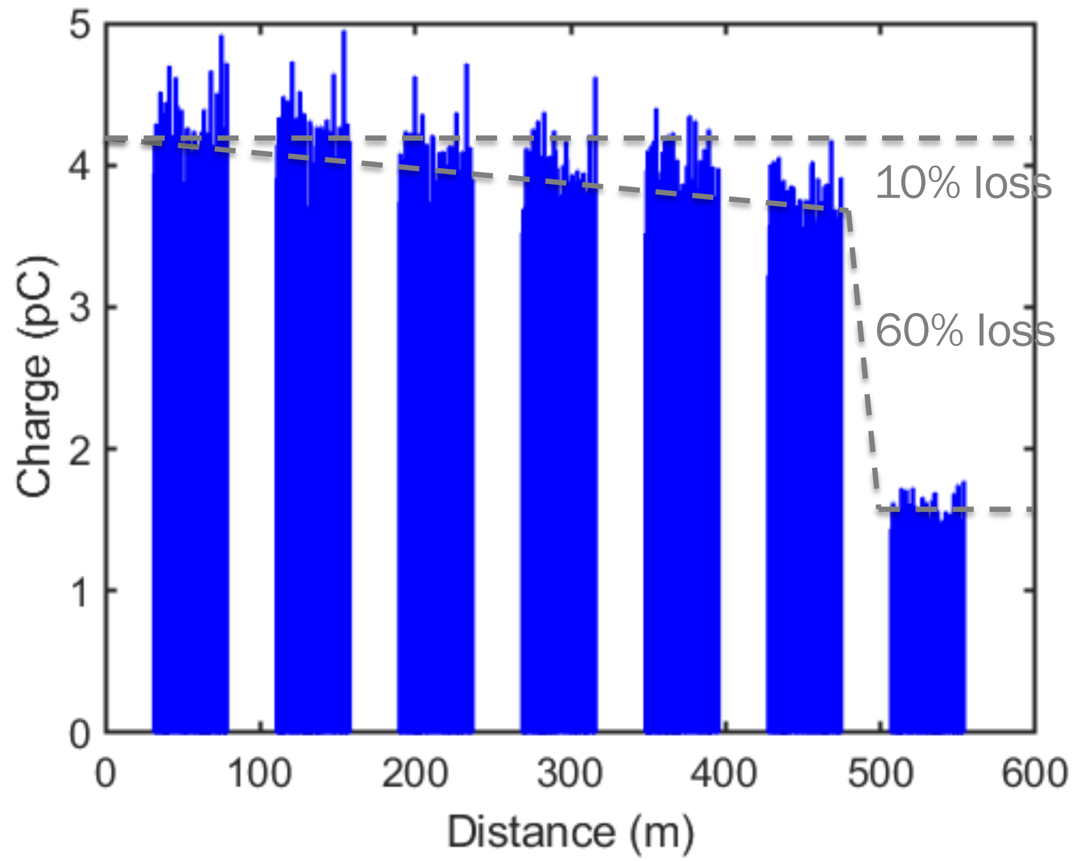
- No time for engineering, nor often space for other magnets…

Multi-turn energy recovery achieved on December 24, 2019!

Beam on the first viewscreen in the beam stop line



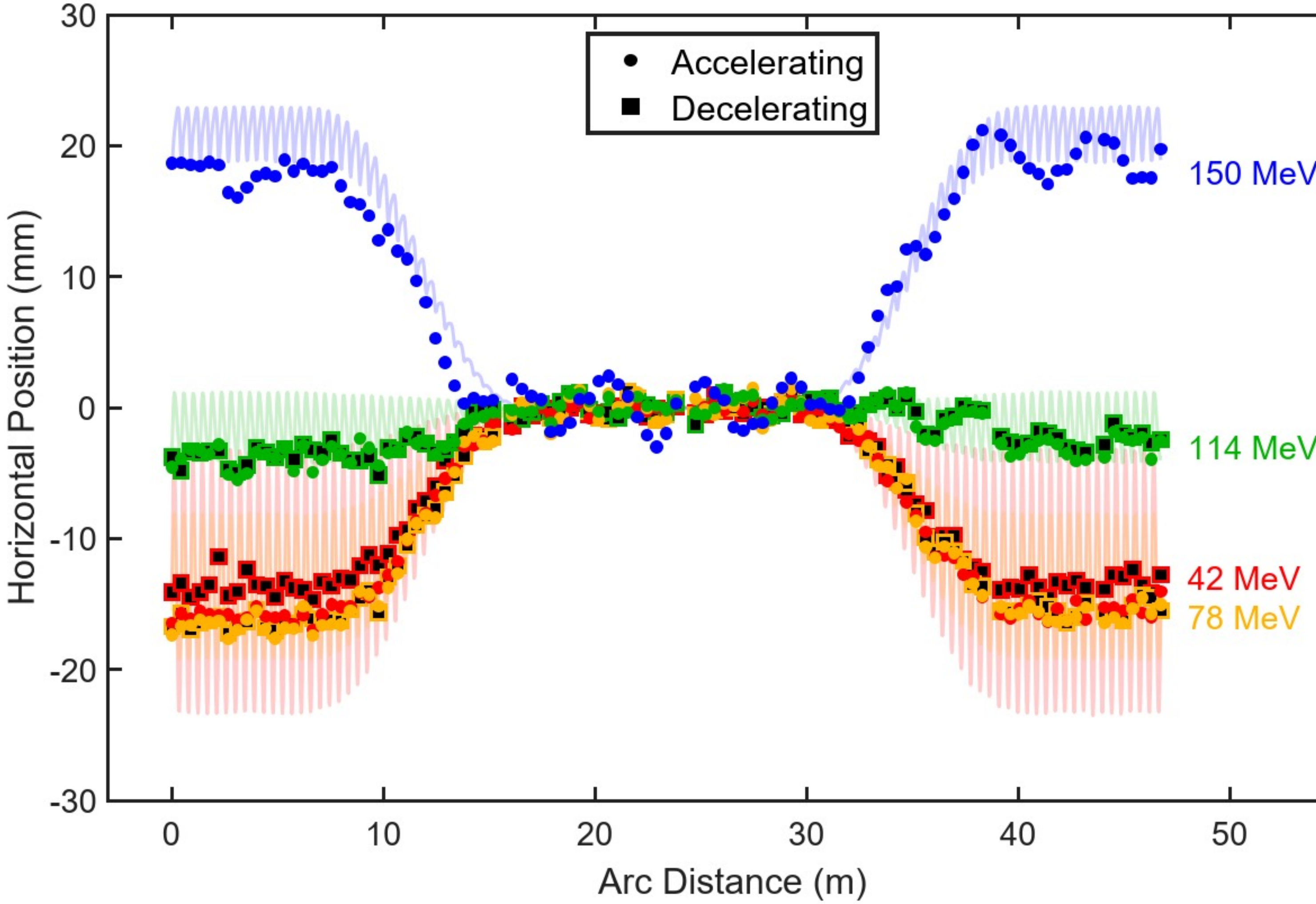
Beam loss through 7 return loops



- Beam losses in all 7 passes through the FFA are low.
- Between the FFAs there are 6 passes with gradual 10% losses
- Before the 7th FFA pass there is a 60% loss (in Recombiner-2)

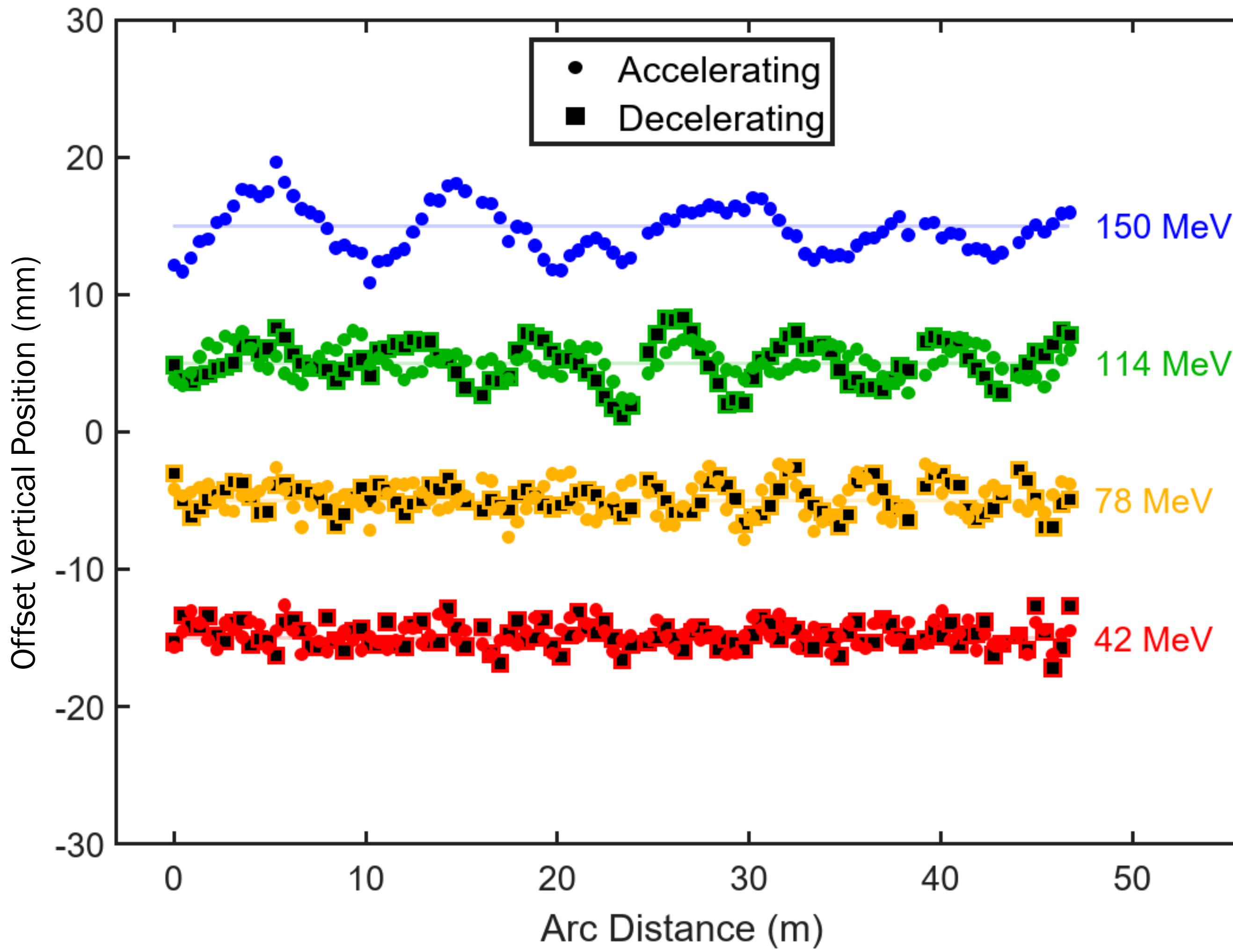
- Percentages improve with lower initial charge (not shown)

7 horizontal orbits in the FFA

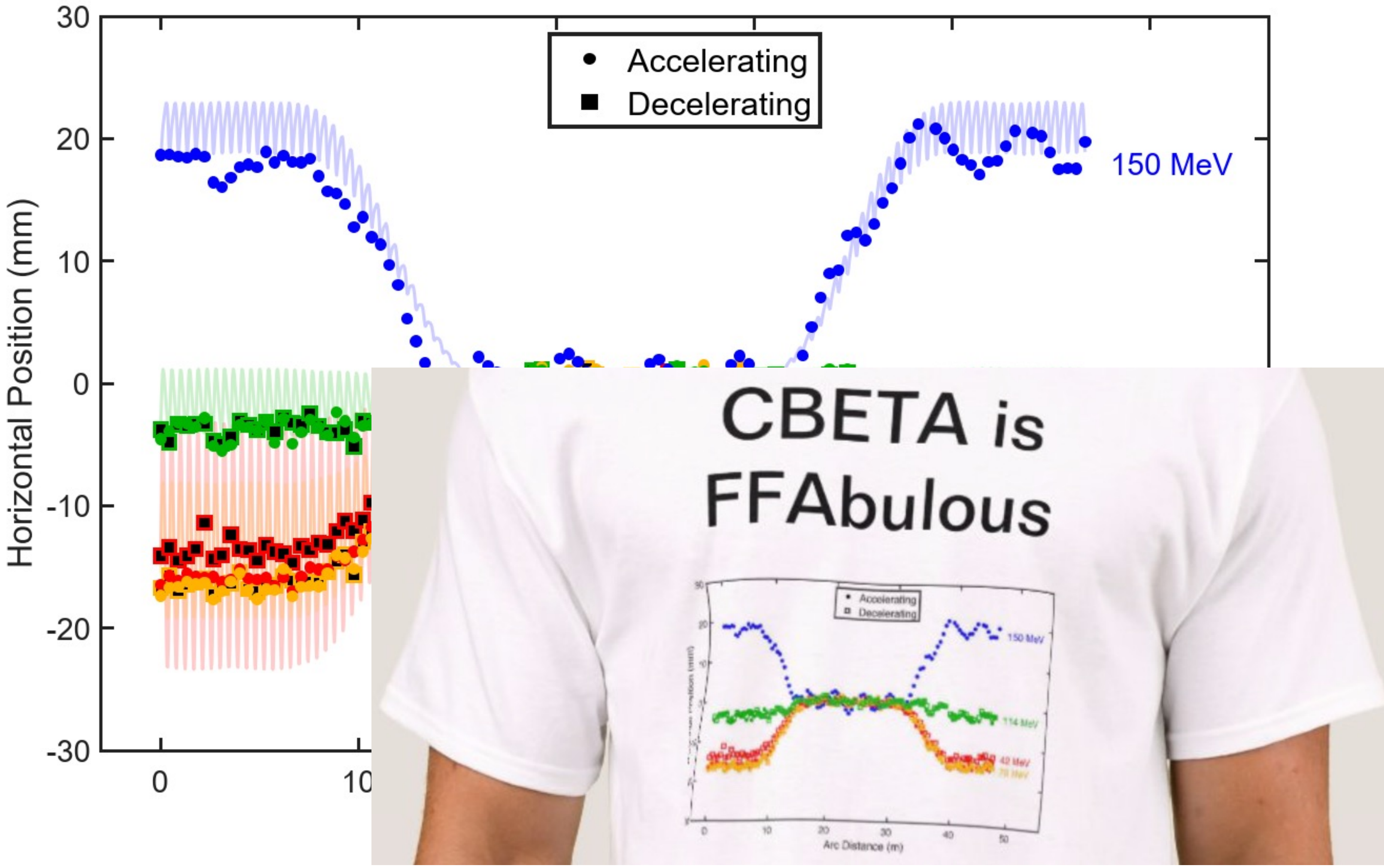


Note: Final 42 MeV orbit (red) has systematic error due to poor transmission

Simultaneous orbit correction

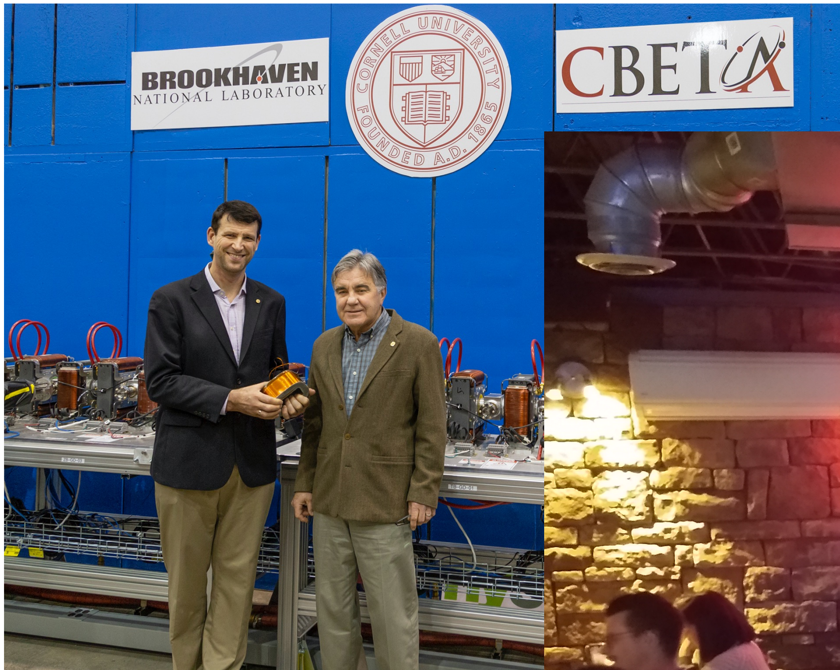


7 horizontal orbits in the FFA



Reports appeared in Nature, Forbes Magazine, IEEE Spectrum, reddid.com, and others.

Celebrating



Milestone: The world's first 4-turn SRF ERL

CBETA

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The CBETA accelerator at Cornell University, New York, is designed to recoup the energy it pours into making high-energy electron beams. Credit: Cornell University

(And many other outlets, including redit.com)

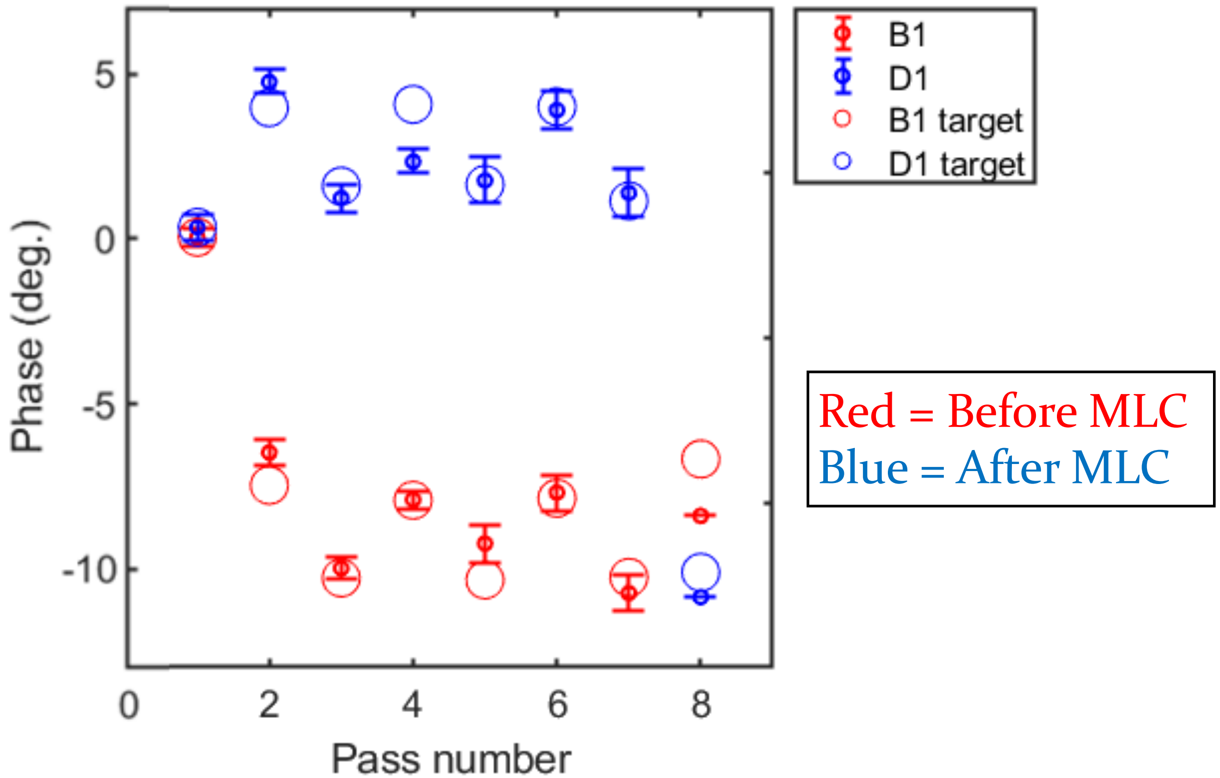
PAR

The particle accelerator that's serious about recycling

Most linear accelerators are energy hogs, but a new model recovers waste energy that can be ploughed back into the system.

Georg.Hoffstaetter@Cornell.edu

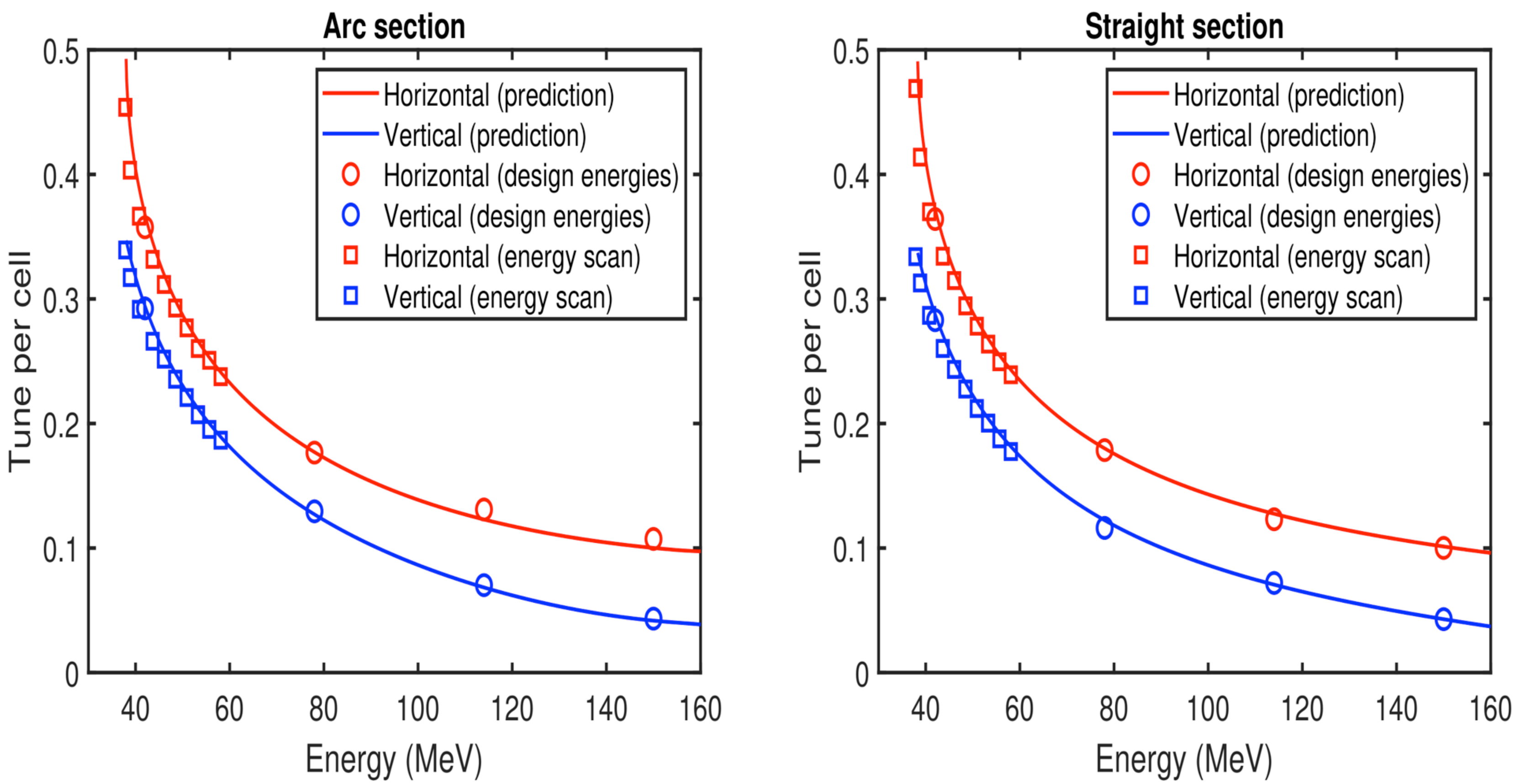
Control of ERL return times inc. FFA transit times



- Phases are shown relative to 1st pass for pass 1-4, and offset by 180° for pass 5-8
- Circles are target values from an optimized ER in each cavity
- Transmission seemed to require accuracy better than 2 degrees

FFA cell phase advance

- Energy scan measured during 1-turn run (39 - 59 MeV)
- Design energies measured during 4-turn run (42, 78, 114, 150 MeV)
- Measurements show a good agreement with the FFA model

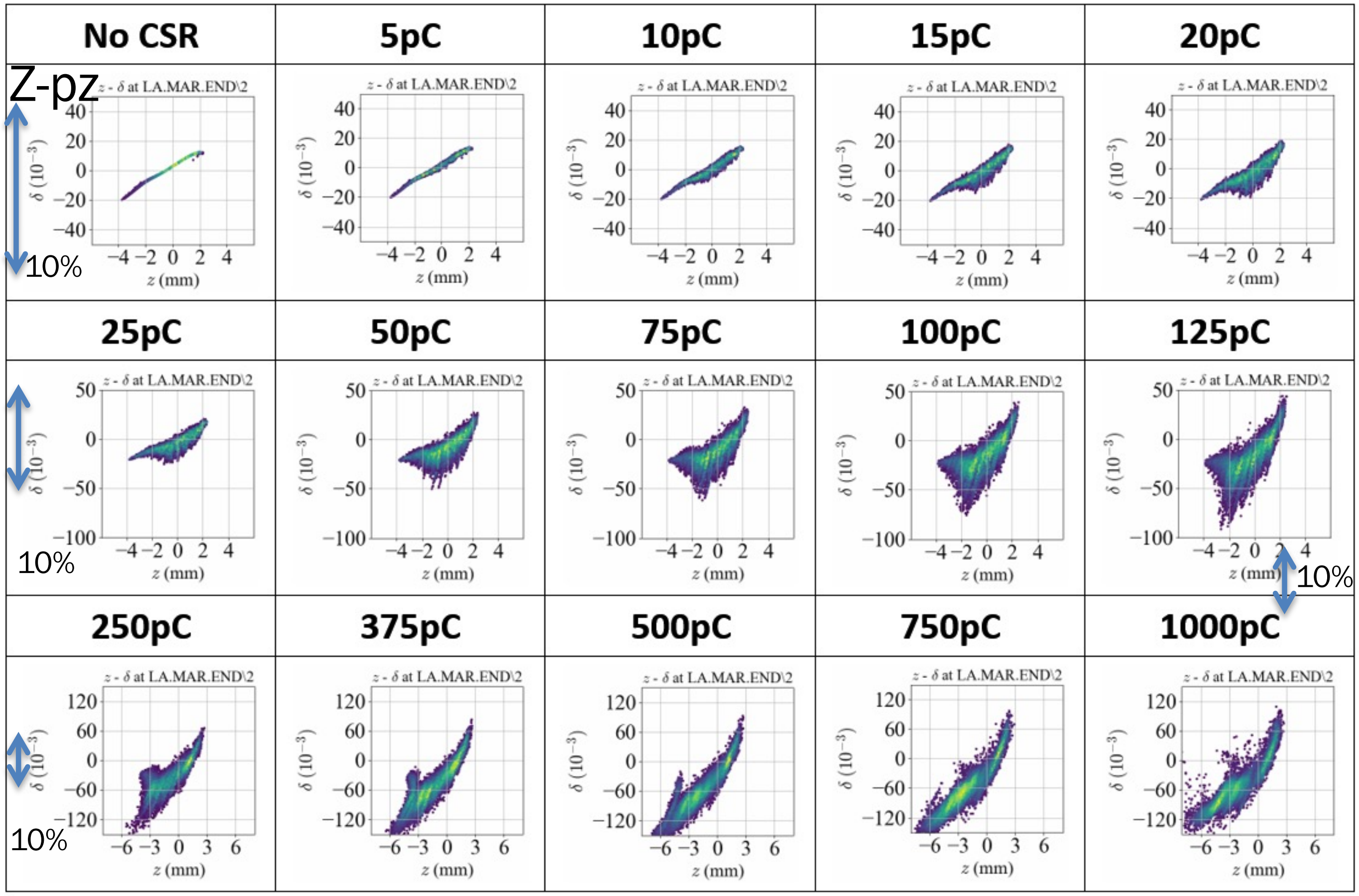


CSR dynamics: energy spread

CBETA

Even for 1 loop,
The energy spread is very significant.

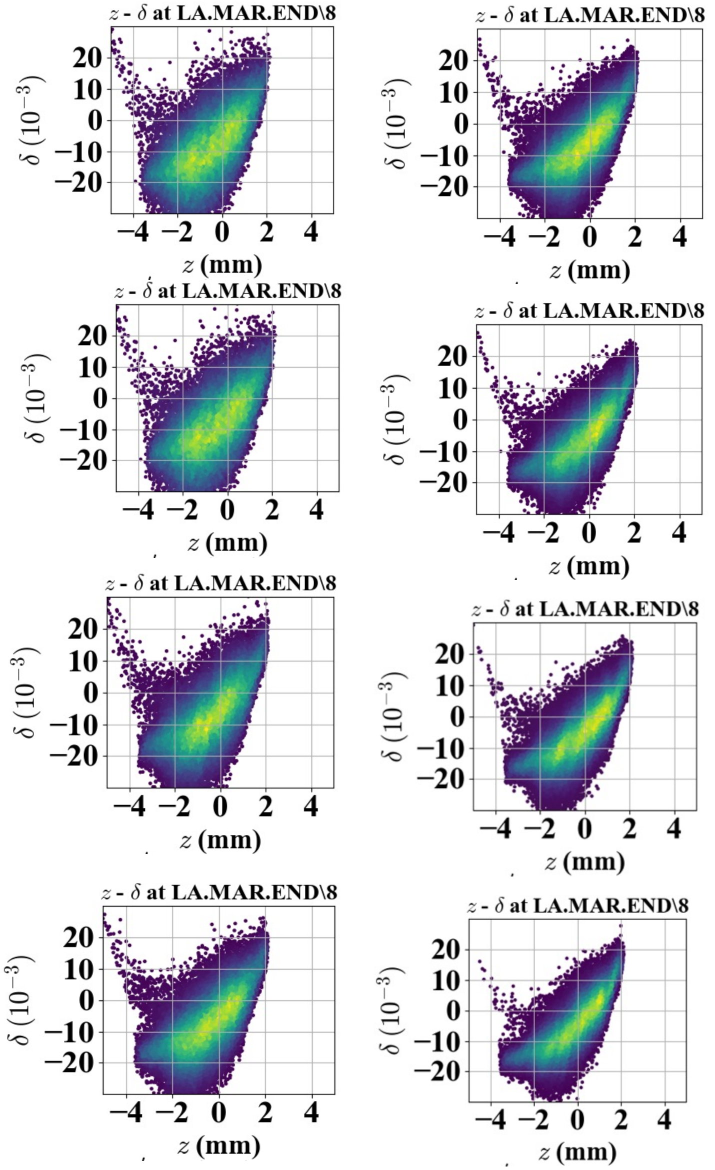
Consequences:
Do not bend 1nC bunches of a cooler around ERL arcs but cool after a full 150MeV SRF linac and then have a 15MW single turn ERL.

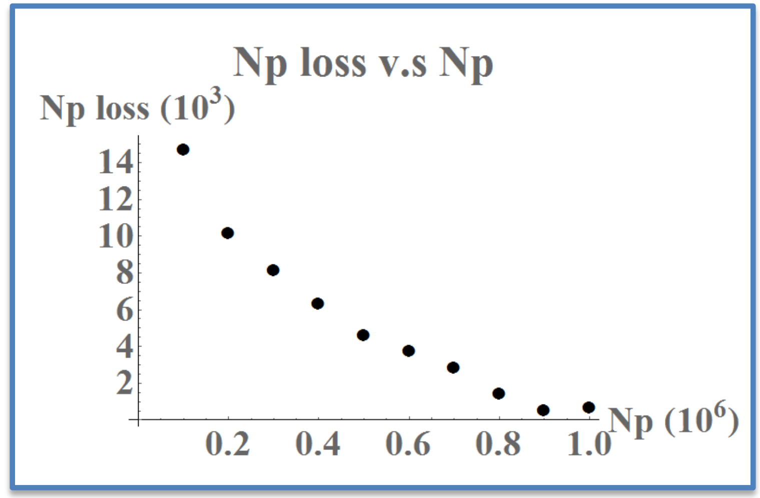


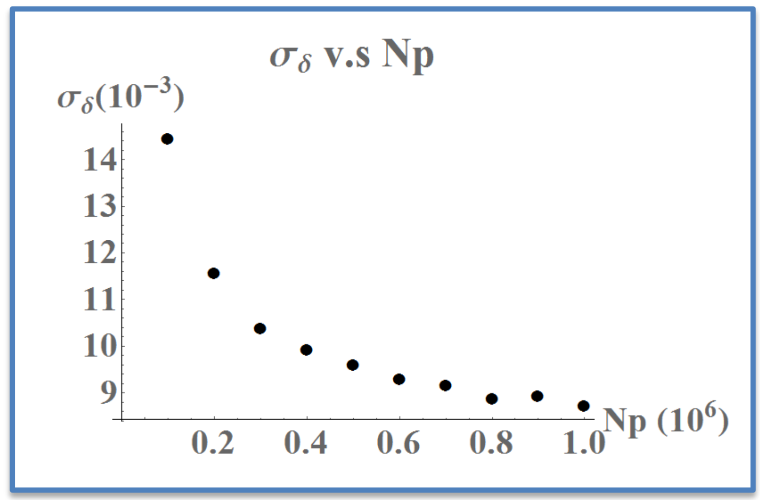
Final energy aperture ~ 5%

Important contributions of CBETA:
- 1 to 4-turn RCL to measure CSR damage.
- 4-turn ERL for increase sensitivity to CSR damage
- 1-turn ERL for high currents
- CSR in CBETA is very well understood, ready to be compared to measurements.

CSR dynamics: micro-bunching







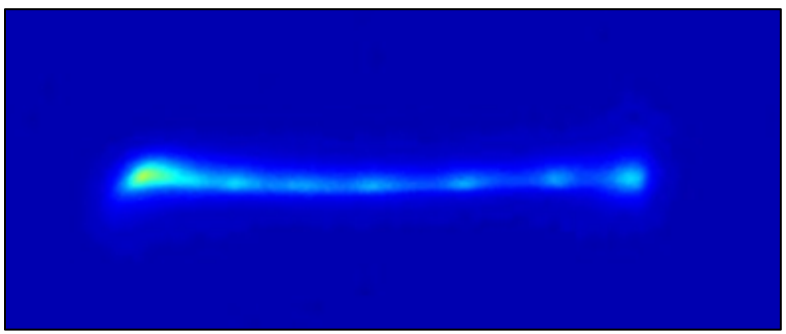
Np chart		
100k	500k	900k
200k	600k	1M
300k	700k	
400k	800k	

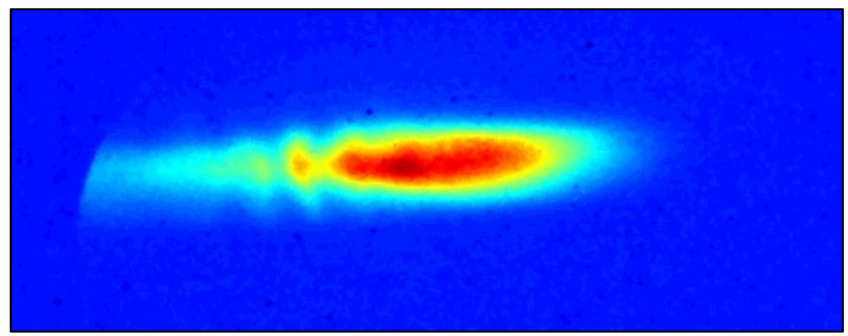
Opportunity: use CBETA for detailed phase space analysis of initial beam to check they don't have micro-bunches and can be used for cooling.

Indications of micro-bunching

Occasionally, we would see a charge-dependent structure on the beam profile

- As early as the beginning of the second pass
- Charge dependent
- Single bunch effect
- Optics dependent
    - causing the instability or just accidentally letting us see it?





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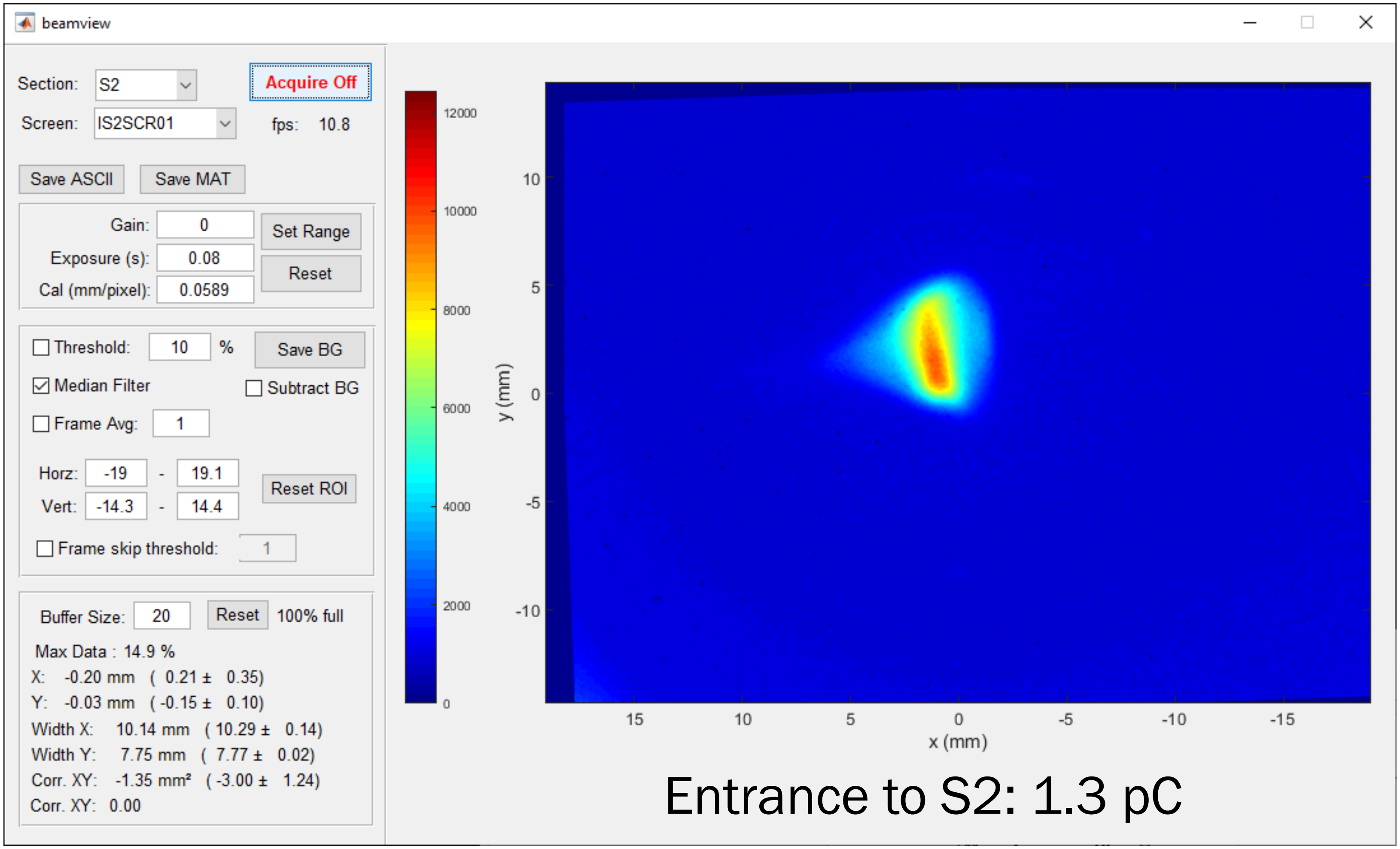

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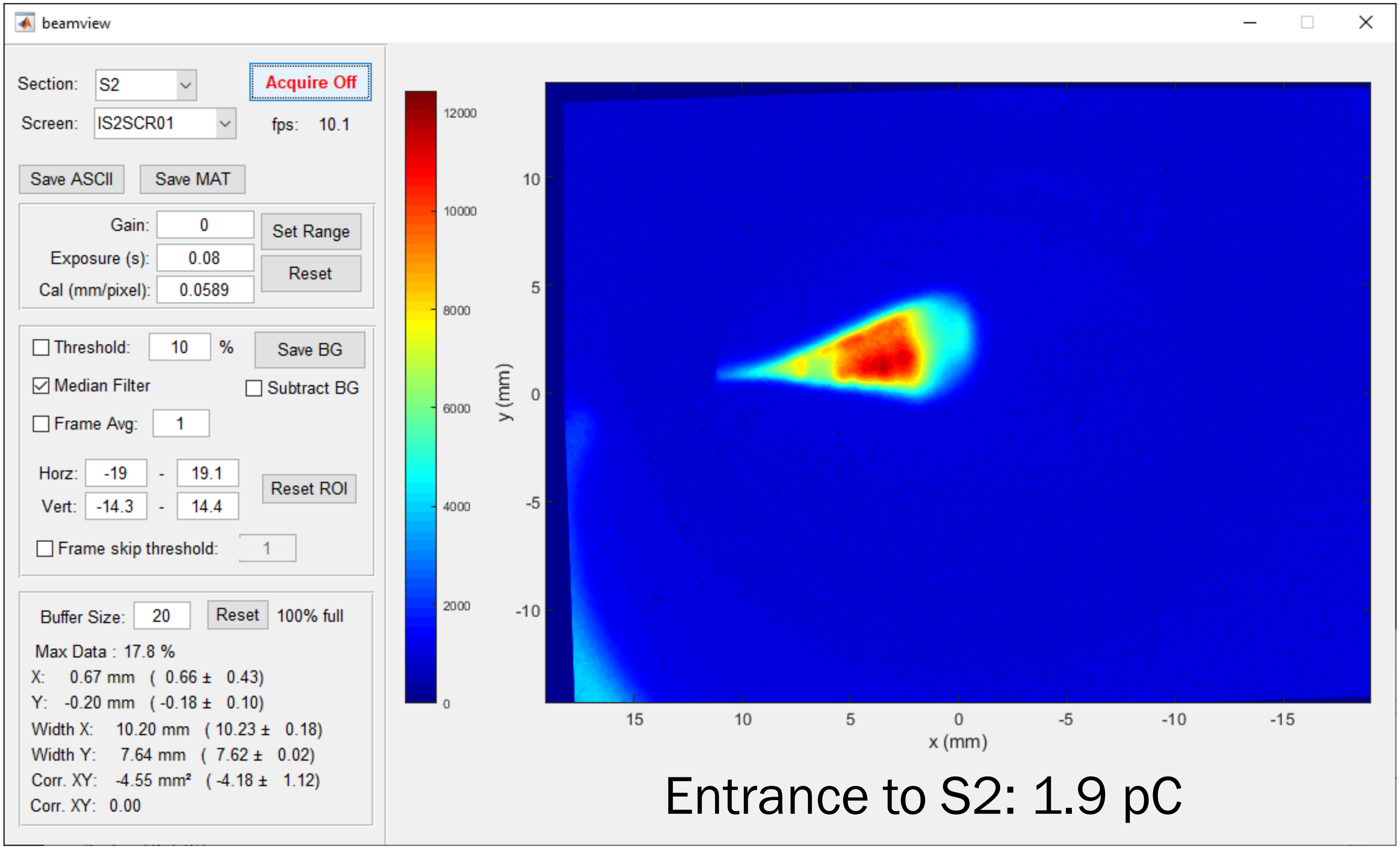

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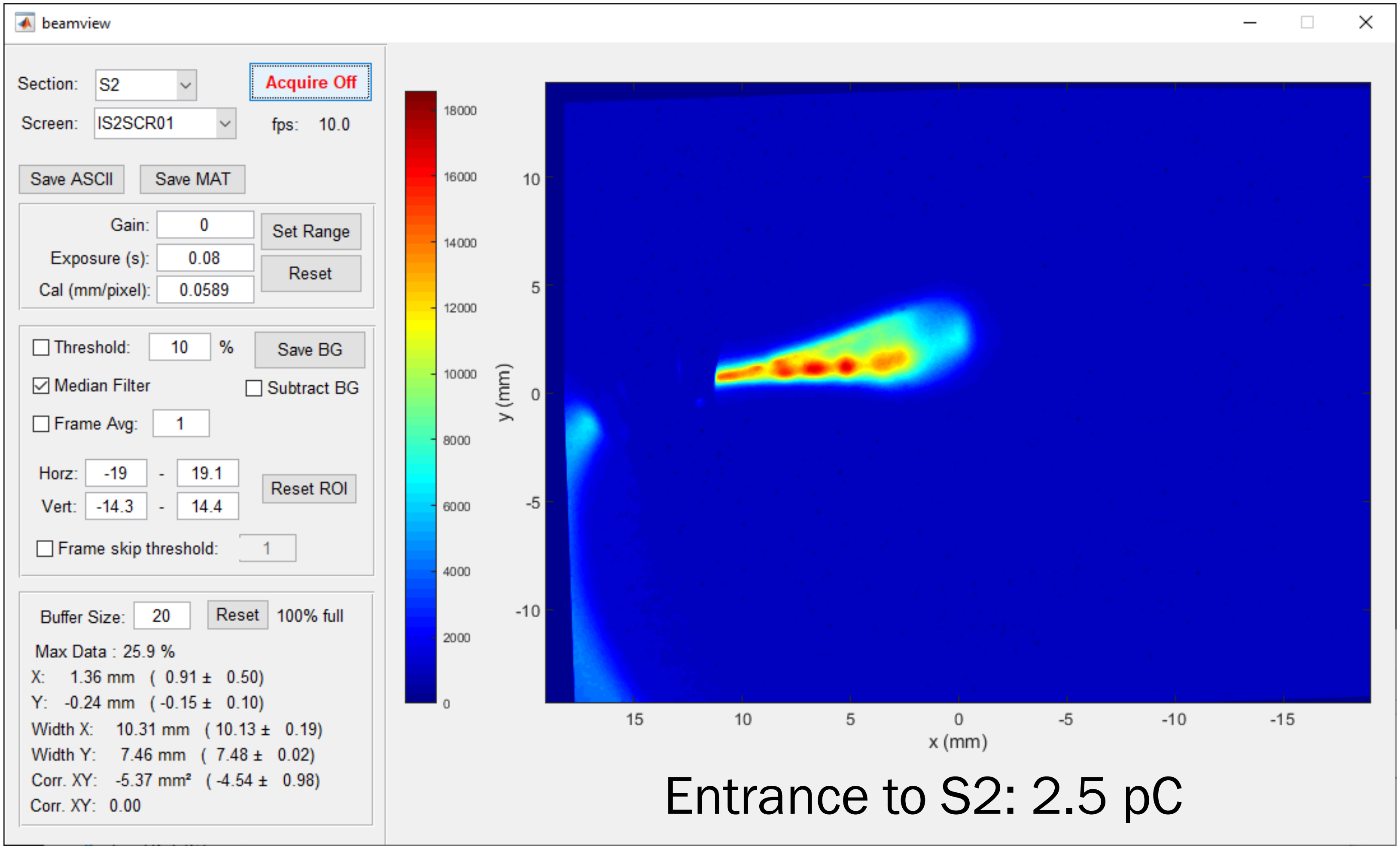
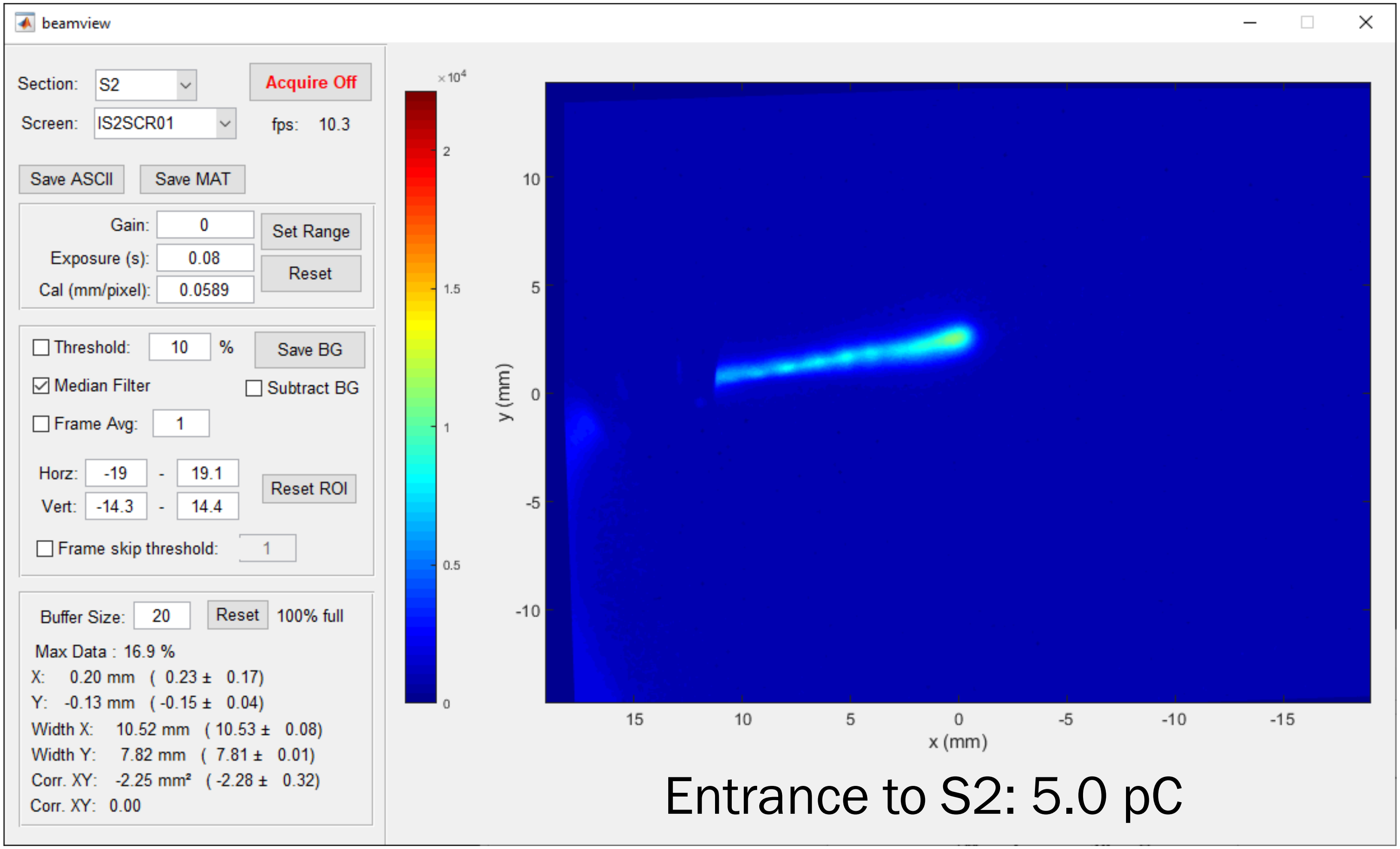


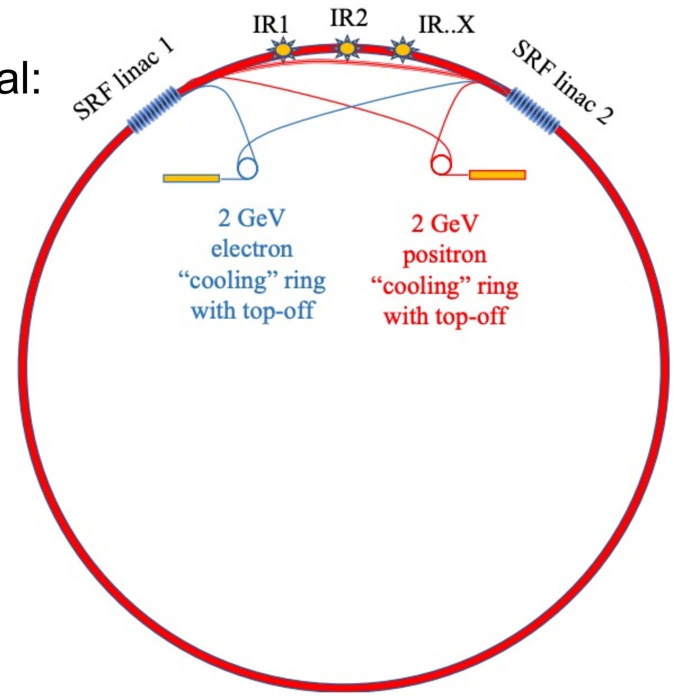
Entrance to S2: 2.5 pC

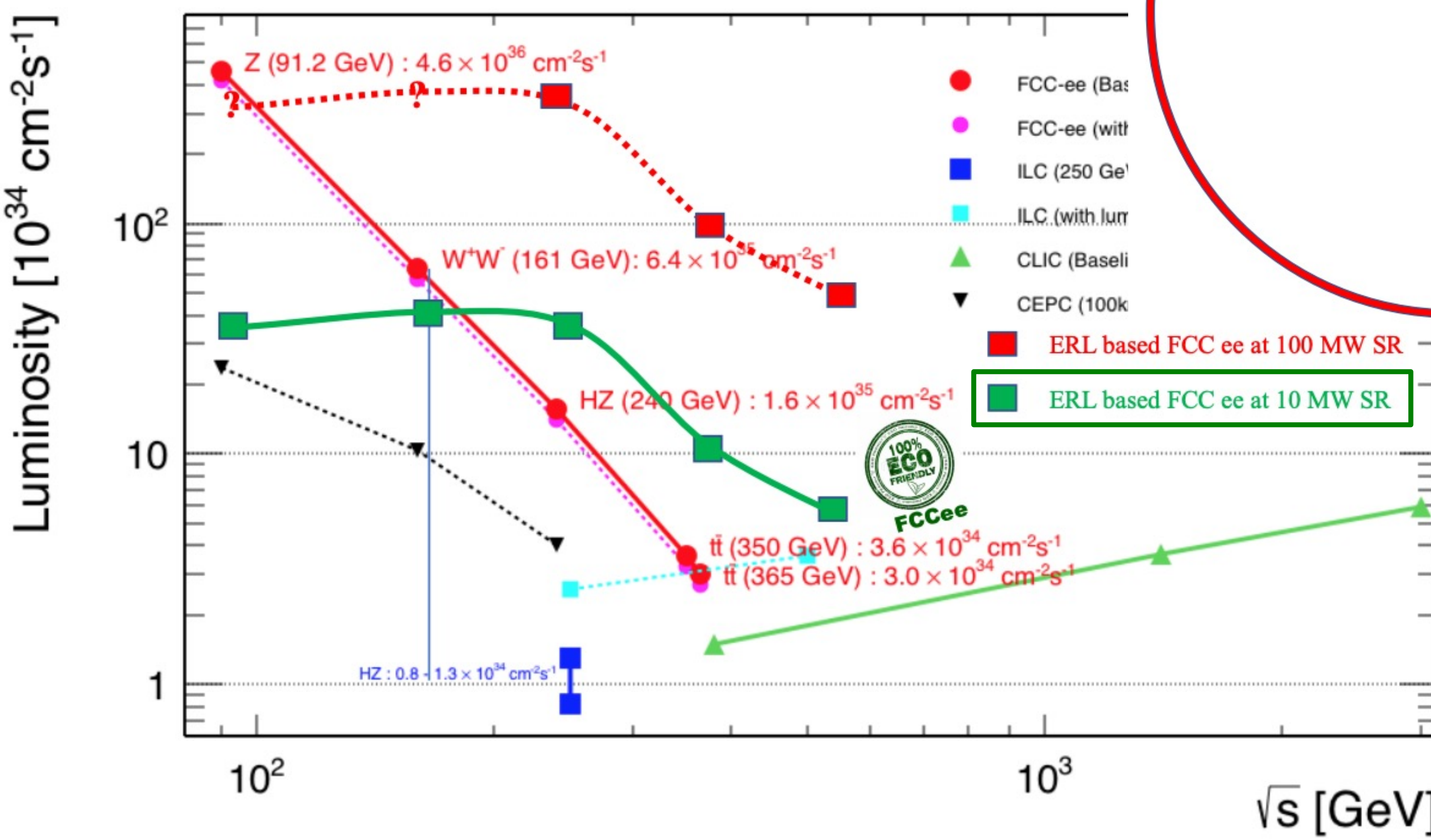
Indications of micro-bunching



Only one more example of CBETA studies amongst several:

Linac ring colliders with ERLs and FFAs are now actively discussed in the FCC-ee community.





International ERL collaboration

Acknowledgements

CBETA

Thank you to everyone on the CBETA team, including:

D. Trbojevic[1], G. Hoffstaetter[2], R. Michnoff[1], N. Banerjee[2], J. Barley[2], A. Bartnik[2], I. Bazarov[2], J.S. Berg[1], L. Borak[1], S. Brooks[1], D. Burke[2], J. Crittenden[2], J. Crone[3], L. Cultrera[2], K. Deitrick[2], J. Dobbins[2], C. Franck[2], R. Gallagher[2], C. Gulliford[2], B. Heltsley[2], R. Hulsart[1], J. Jones[3], D. Jusic[2], R. Kaplan[2], D. J. Kelliher[3], G. Mahler[1], F. Meot[1], V. Kostroun[2], B. Kuske[4], Y. Li[2], M. Liepe[2], W. Lou[2], M. McAteer[4], T. Miyajima[5], K. Ming[5], B. Muratori[3], S. Peggs[1], P. Quigley[2], J. Renta[1], T. Roser[1], D. Sabol[2], D. Sagan[2], J. Sears[2], C. Shore[2], E. Smith[2], K. Smolenski[2], C. Stoll[1], S. Thomas[1], S. Trabocchi[1], N. Tsoupas[1], J. Tuozzollo[1], V. Veshcherevich[2], J. Völker[4], D. Widger[2], H. Witte[1]

(1) BNL (2) Cornell University (3) STFC (4) HZB (5) KEK

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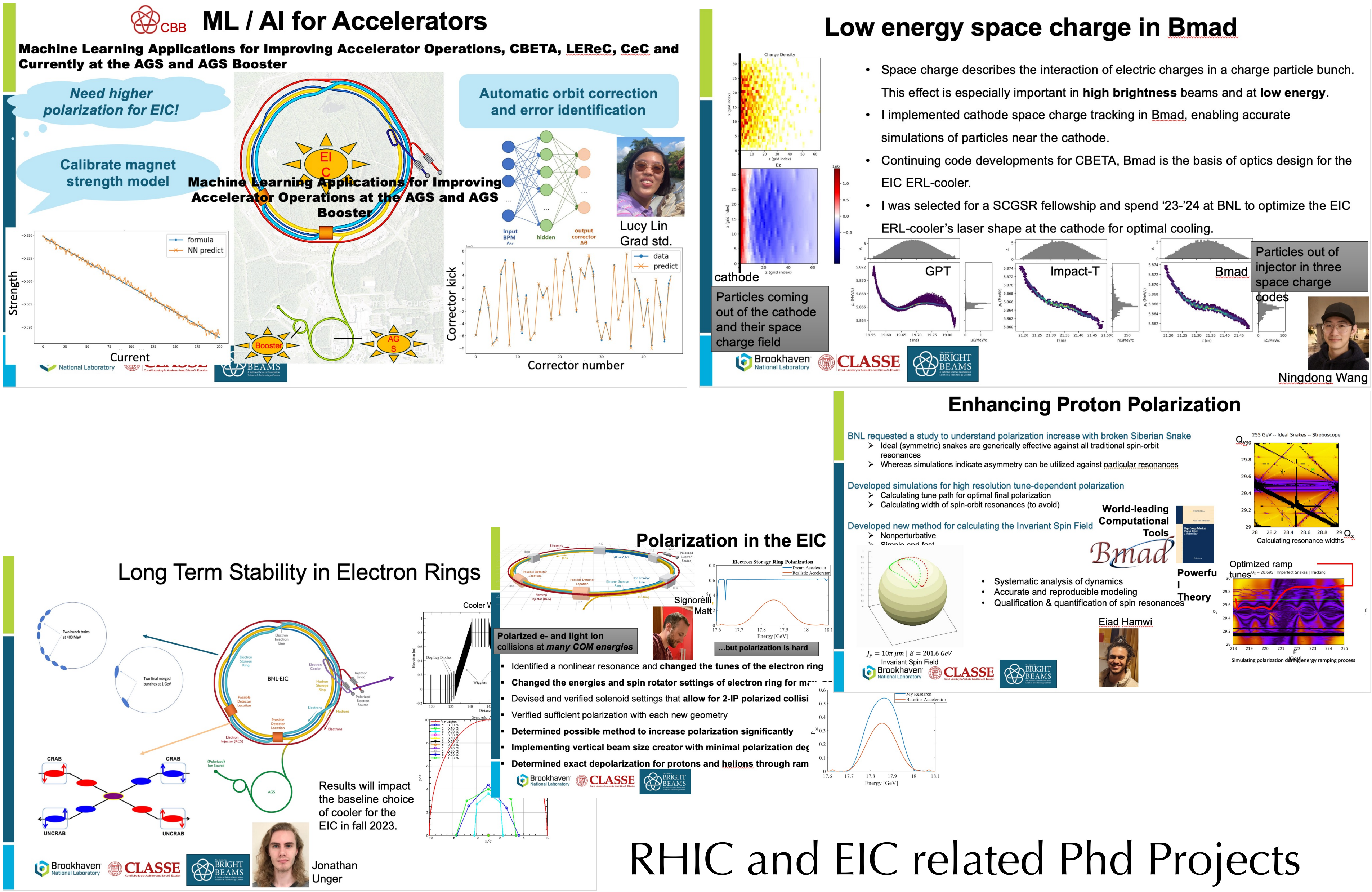
- **Has build a strong team connecting Cornell to BNL, there the EIC is being built.**

Continuing Cornell / BNL collaboration

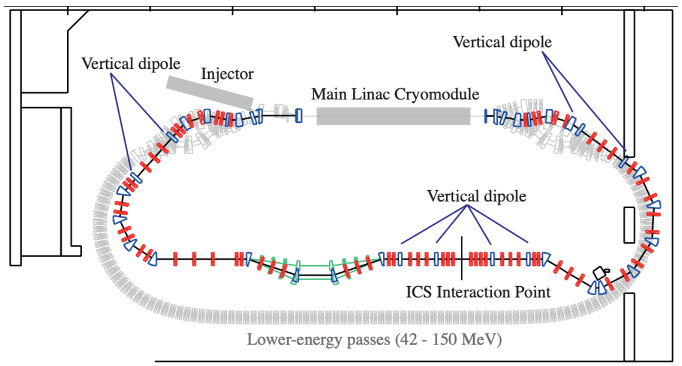


RHIC and EIC related Phd Projects

Spinoffs

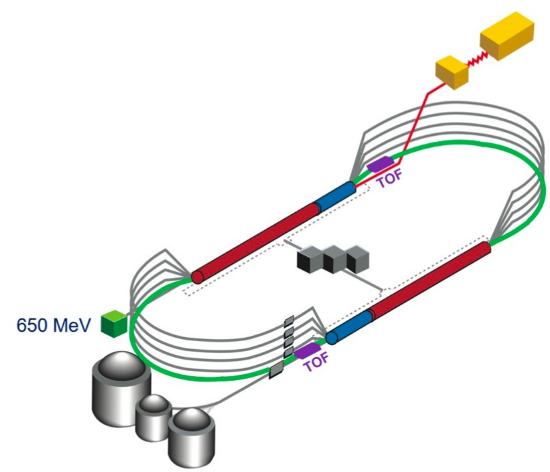
SRF Energy Recovery:

- **Part of the hadron coolers for the EIC**
- **Design of a compact Compton source extension of CBETA (Phys Rev paper)**
- **Part of the LHeC plans**
- **ee Higgs Factory design options**
- **Drivers for low energy nuclear physics experiments**
- **Drivers for compact Compton-x-ray sources**
- **New EUV sources for microchip lithography**



The permanent-magnet FFA technology

- **Energy-doubling upgrade option for CEBAF**
- **Permanent magnet design for the NSLS-II upgrade at BNL**



Questions ?

References

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- G. Hoffstaetter *et al.*, "CBETA Design Report, Cornell-BNL ERL Test Accelerator", https://arxiv.org/abs/1706.04245
- C. Gulliford *et al.*, "Measurement of the per cavity energy recovery efficiency in the single turn Cornell-Brookhaven ERL Test Accelerator configuration" Phys Rev AB (2021)
- K. Deitrick *et al.*, "Intense monochromatic photons above 100keV from an inverse Compton source" Phys Rev AB (2021)