The Cornell BNL ERL Test Accelerator (CBETA)

PERLE Collaboration Meeting
4 June 2020

Georg Hoffstaetter

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

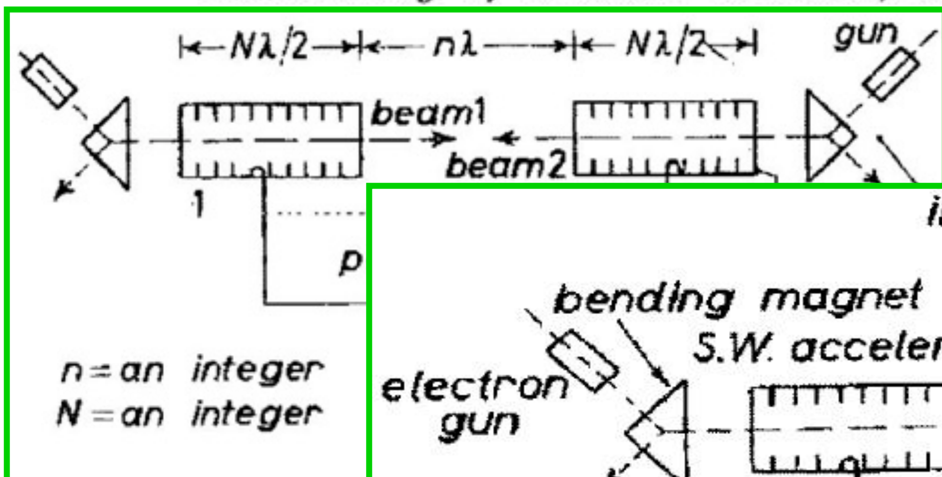
BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

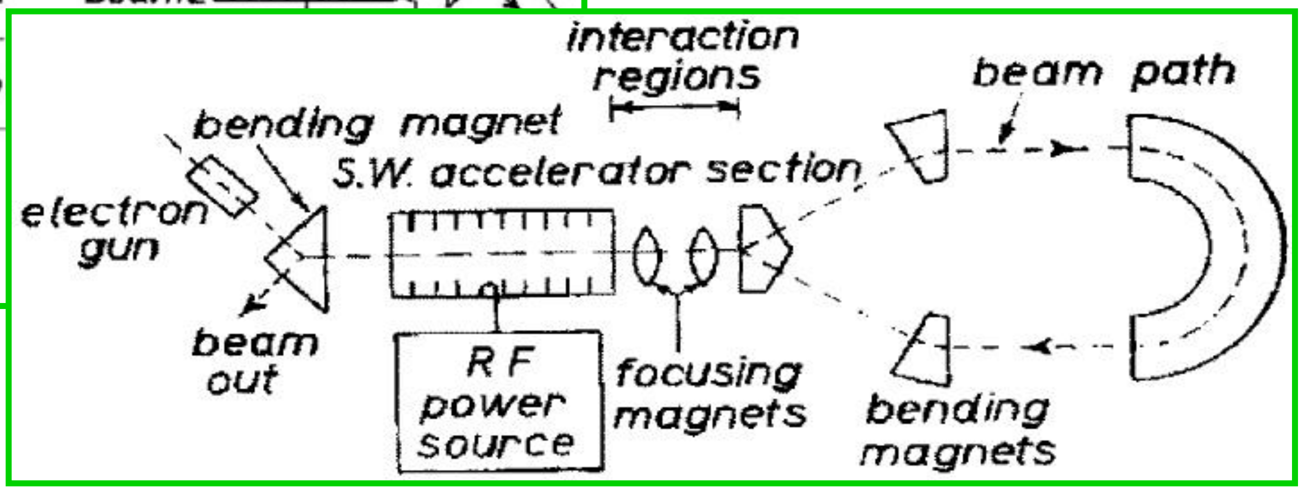
A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. Tigner

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



...Febbraio 1965)



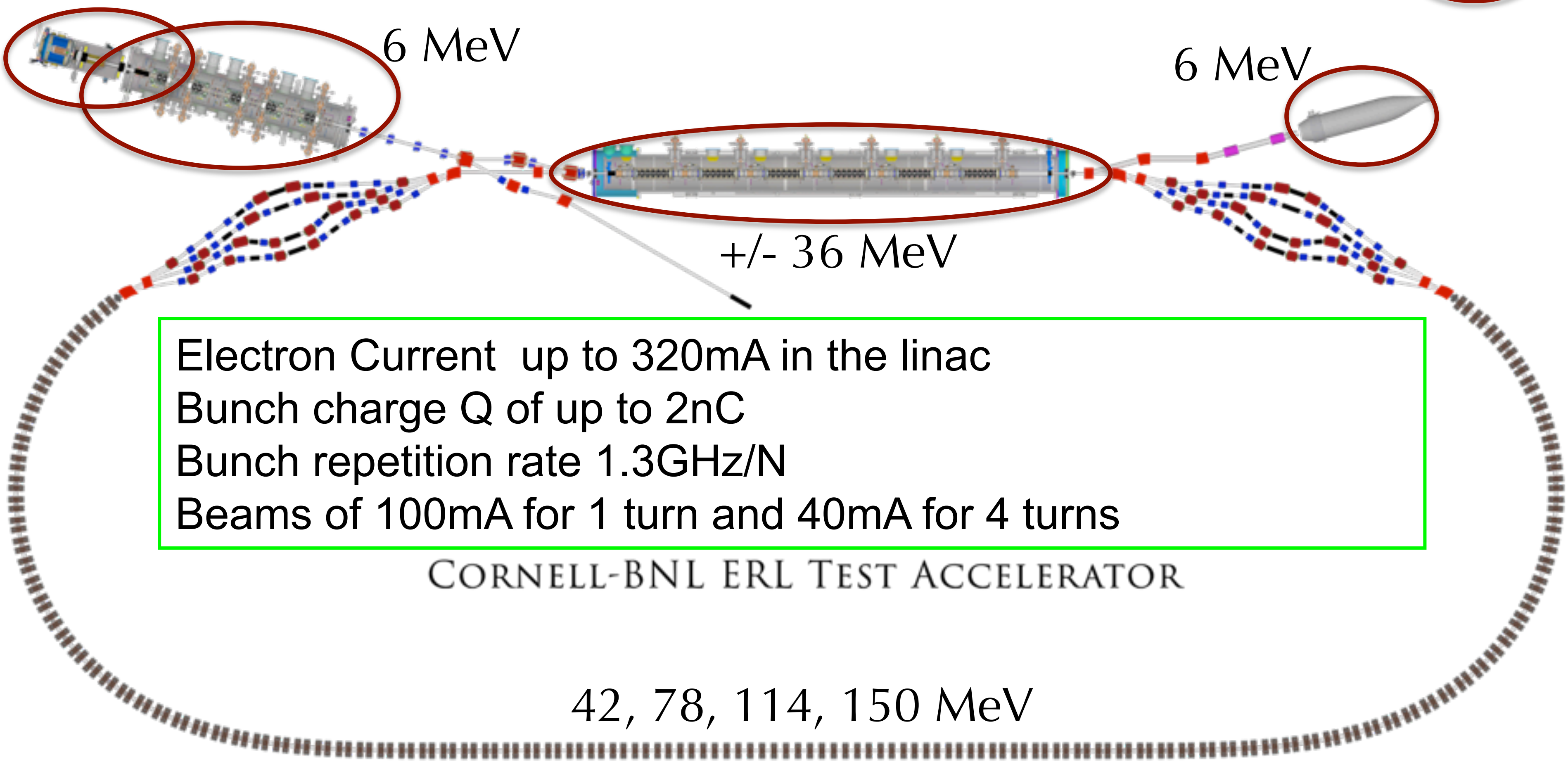
Energy recovery needs continuously fields in the RF structure

- Normal conducting high field cavities can get too hot.
- Superconducting cavities used to have too low fields.

The test ERL in Cornell's hall LOE CBETA

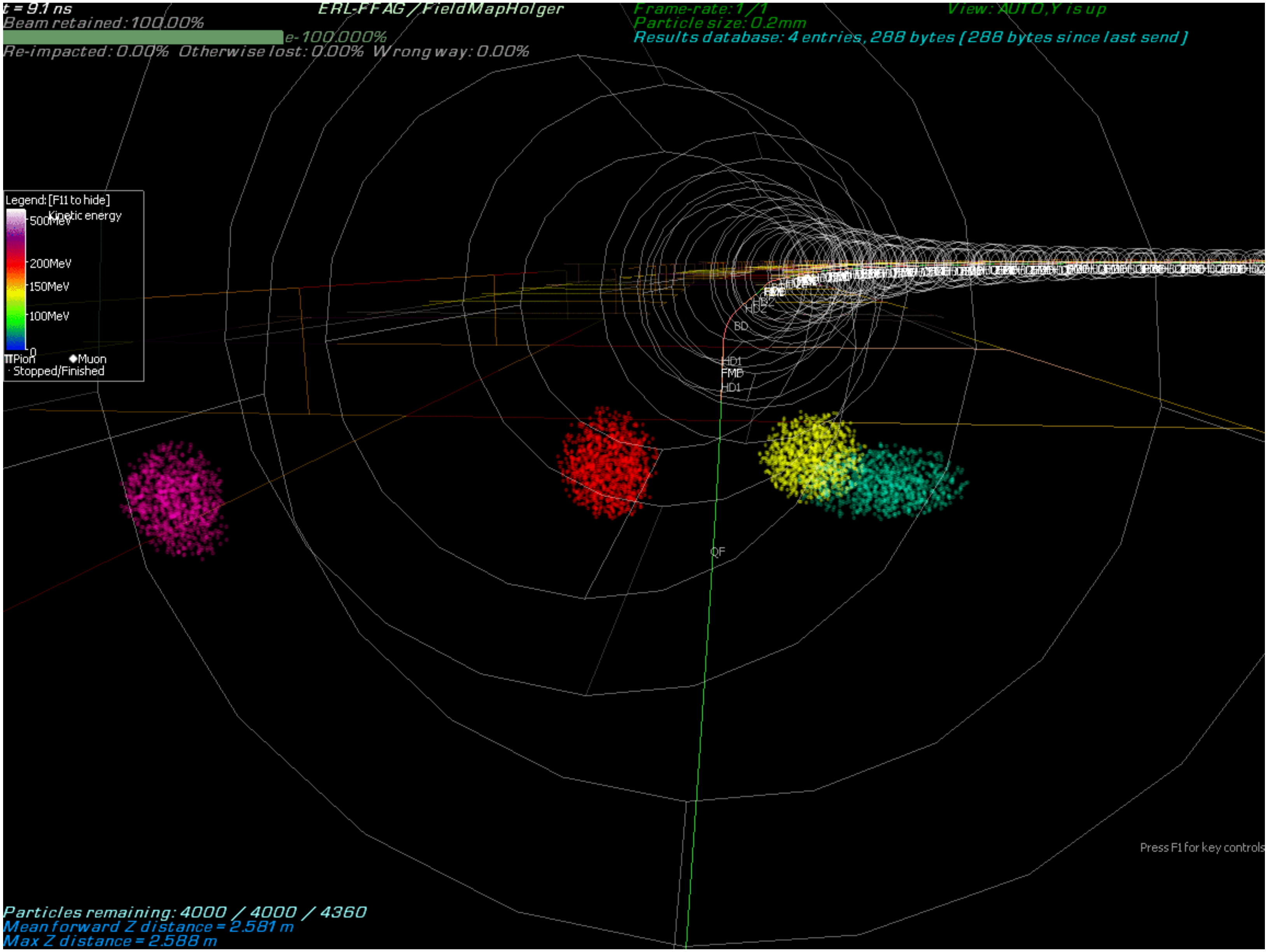
- Cornell DC gun
- 100mA, 6MeV SRF injector (ICM)
- 600kW beam dump
- 100mA, 6-cavity SRF CW Linac (MLC)

Existing components at Cornell



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

Bunche dynamics in 3D field maps



Development of CBETA collaboration

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.

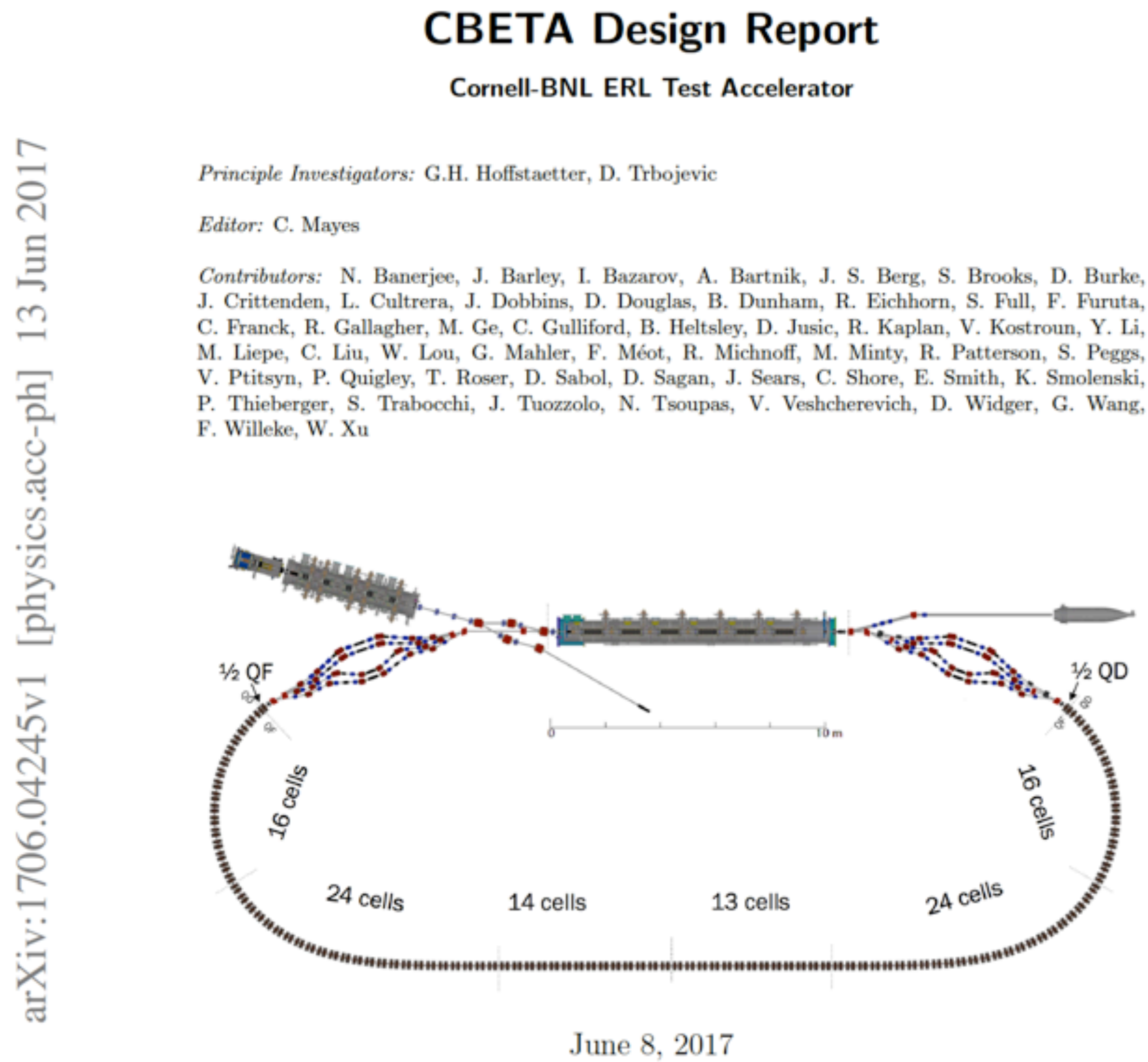
2016 Construction funding by NYS

2017 CBETA Design Report

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

2019 ER with 1 turn & 1st ERL with 4-turns.

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



CBETA Design Report

Cornell-BNL ERL Test Accelerator

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June 8, 2017

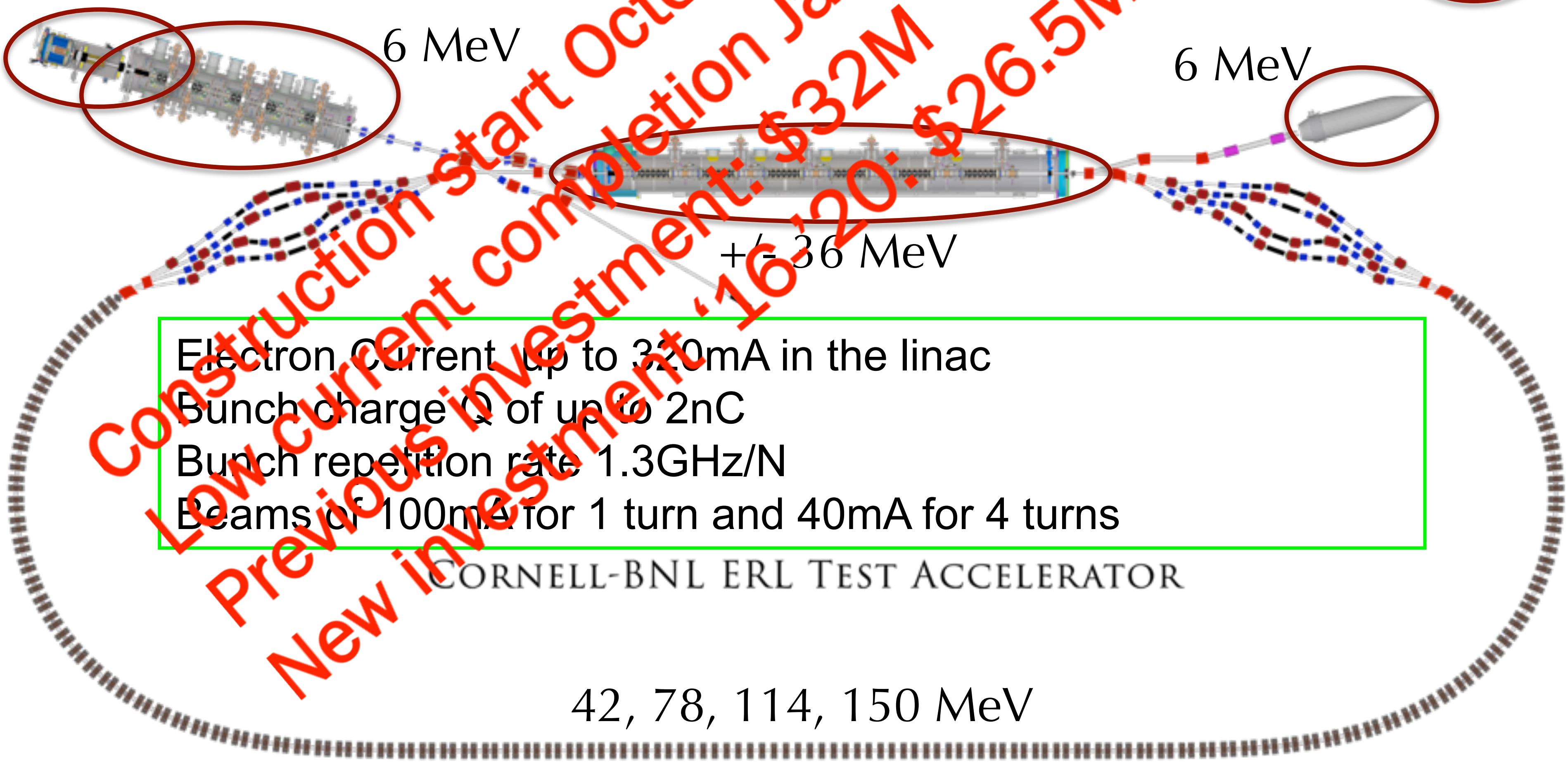
The test ERL in Cornell's hall LOE

CBETA

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

Existing components at Cornell

Construction start October 2016
Low current completion January 2020
Previous investment: $32M
New investment '16-'20: $26.5M



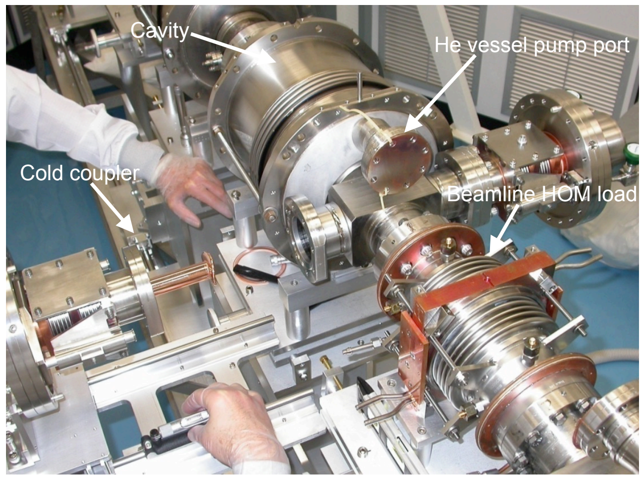
Electron Current up to 320mA in the linac
Bunch charge Q of up to 2nC
Bunch repetition rate 1.3GHz/N
Beams of 100mA for 1 turn and 40mA for 4 turns

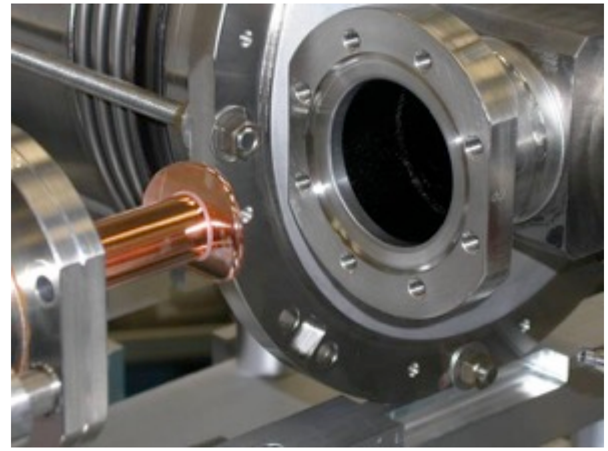
The beam power frontier

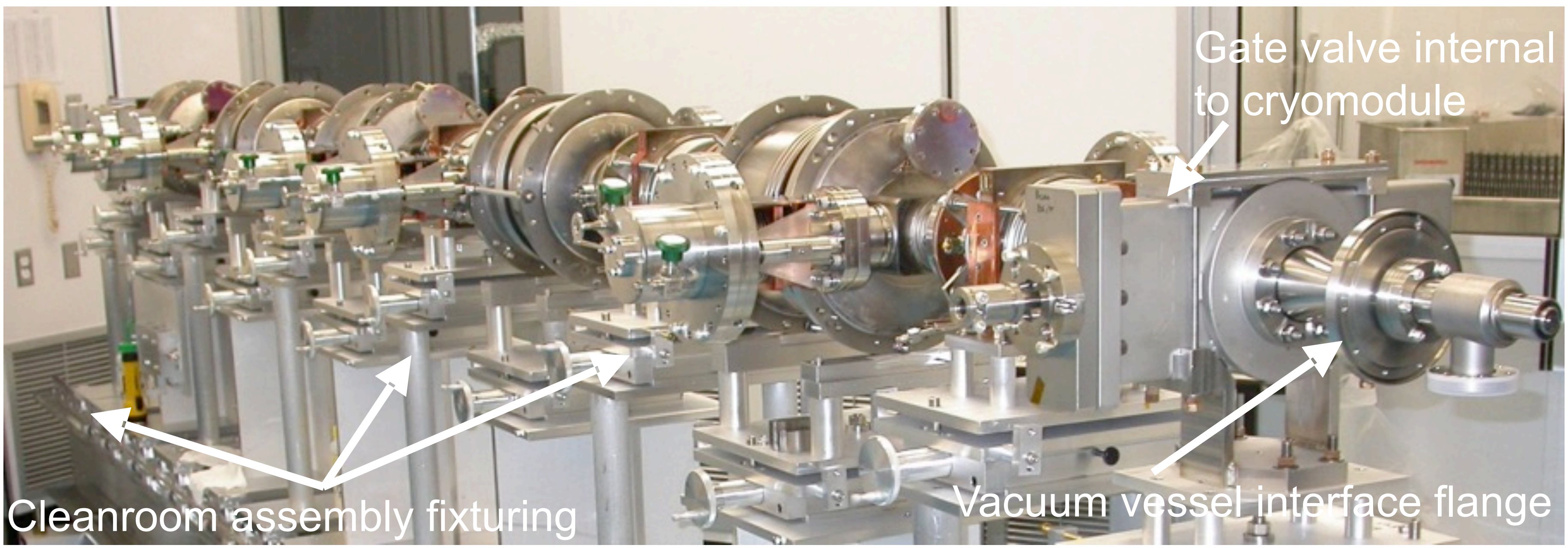
- CBETA has 150MeV / 40mA or 60MeV/100mA: 6MW beam power
- eRHIC cooler ERL has 150MeV and up to 100mA: up to 15mW

Cornell EIC opportunity:
Cavity and Cryomodule components

Attach cold couplers to beamline string







Cornell EIC opportunity: Cryomodule design and construction

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

Hall L0E before CBETA

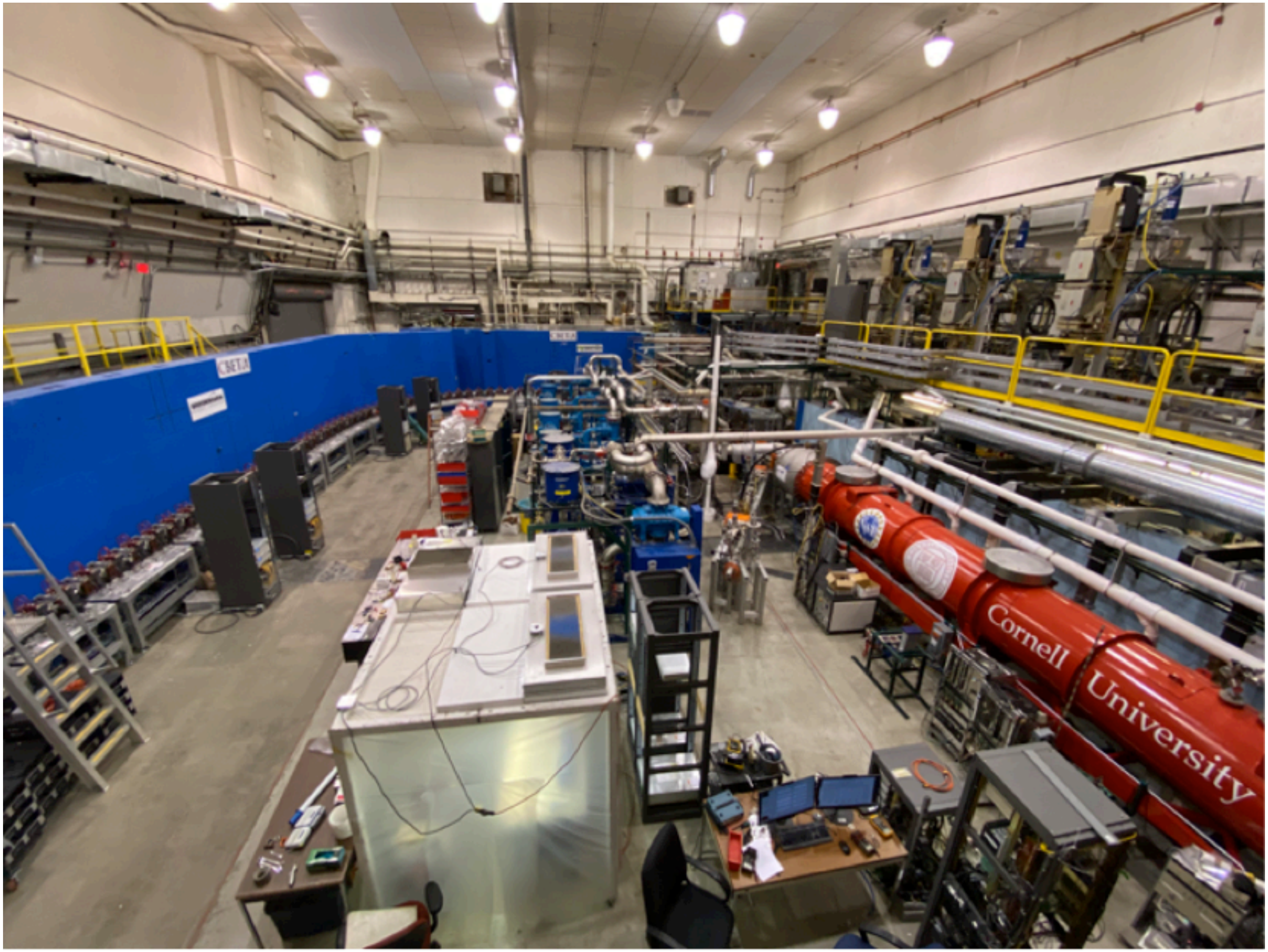
L0E contained approximately 7,000 square feet of Lab and Shop space

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

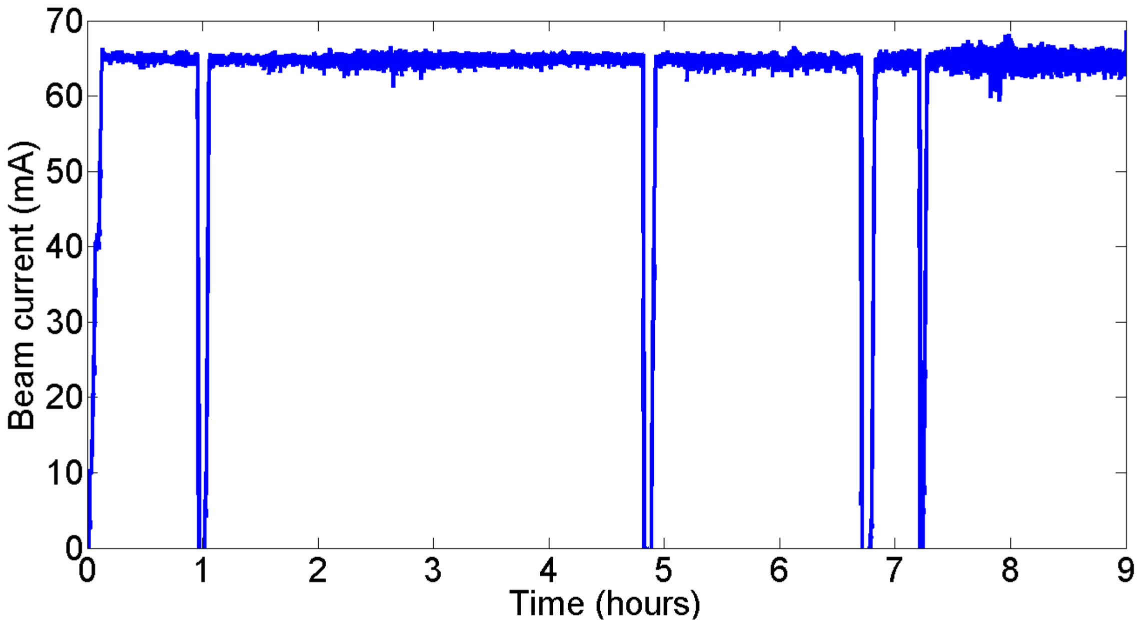
L0E cleaned with CBETA

CBETA installation at Cornell and Magnet work at BNL

CBETA installation at Cornell, 2019



High Current Beams



- Peak current of 75mA (world record)

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

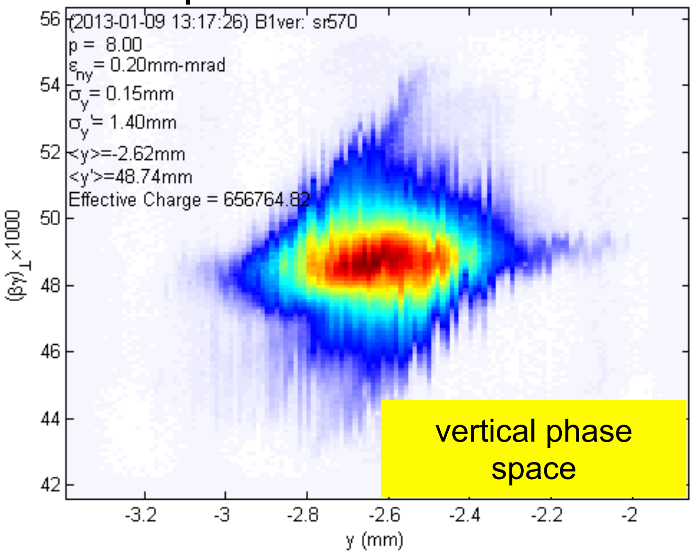
Source achievements:

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

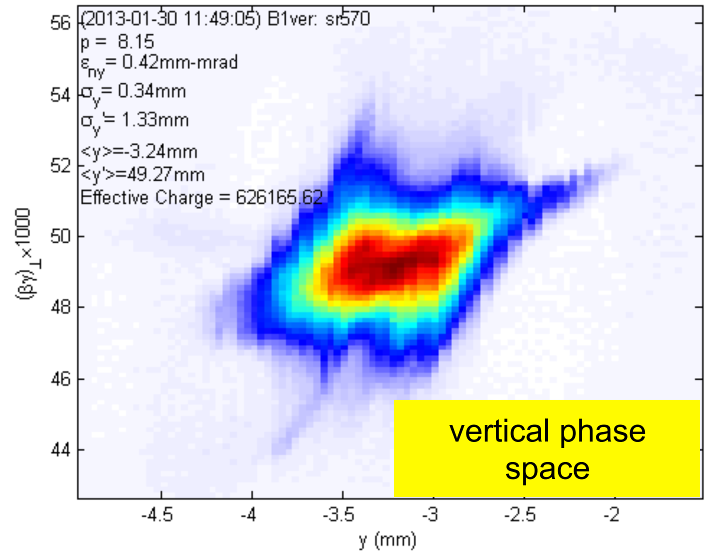
Simulations accurately reproduce photocathode performance with no free parameters, and suggest strategies for further improvement.

✓ Source current can meet CBETA needs

20 pC/bunch



80 pC/bunch



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

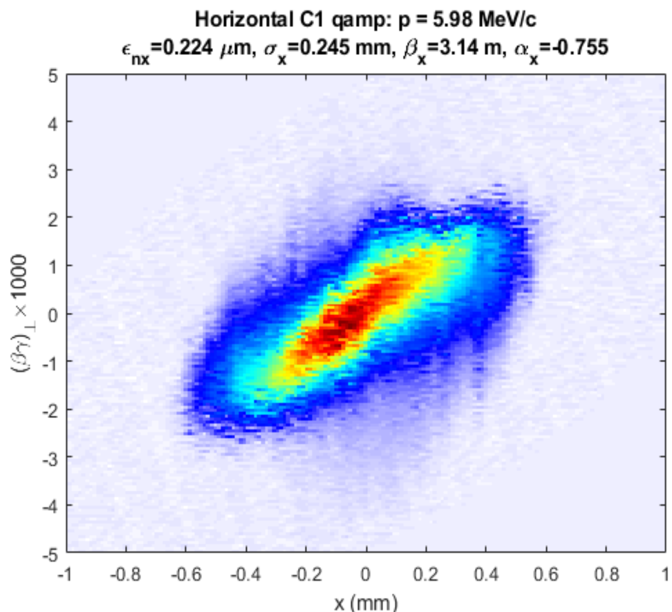
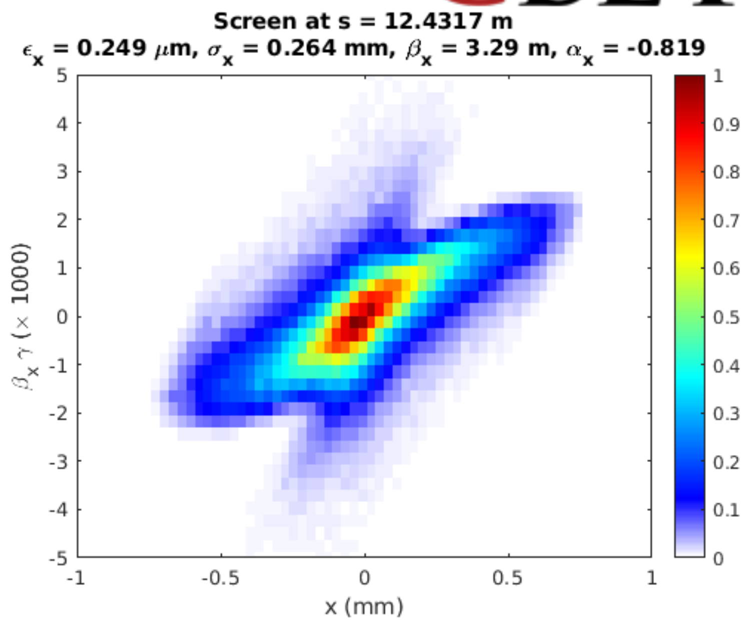
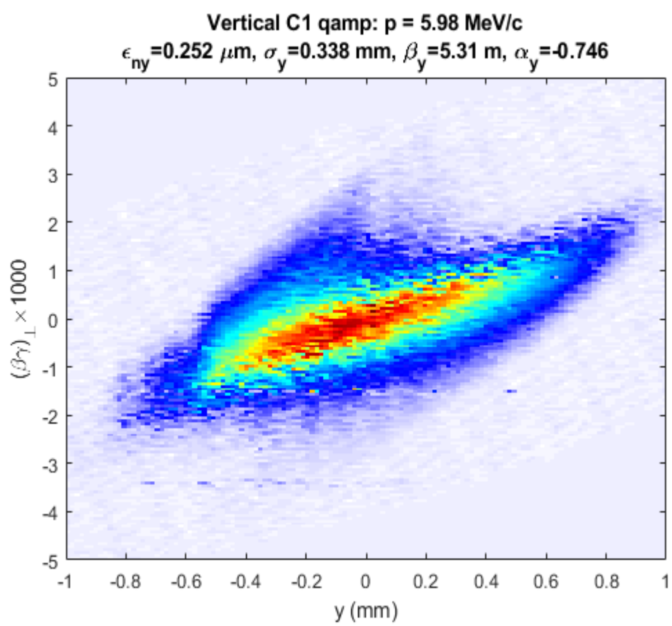
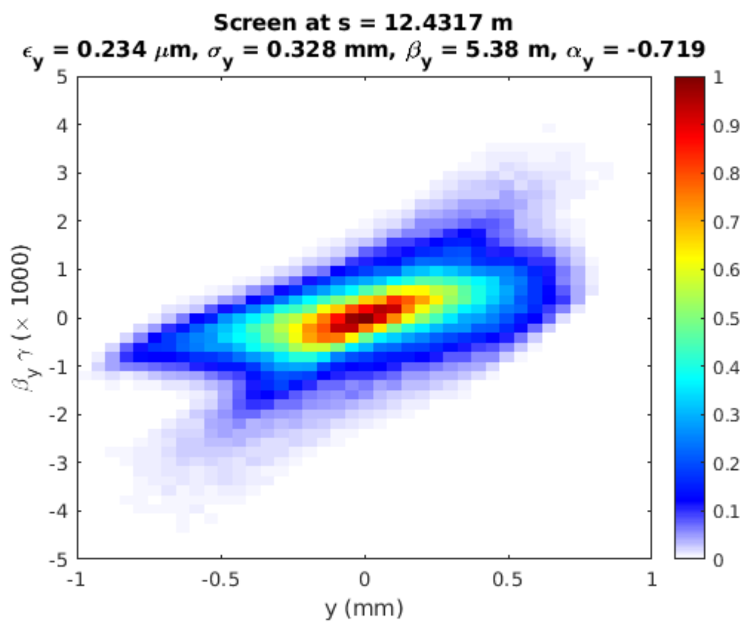
0.23/0.14 mm-mrad | 0.51/0.29 mm-mrad

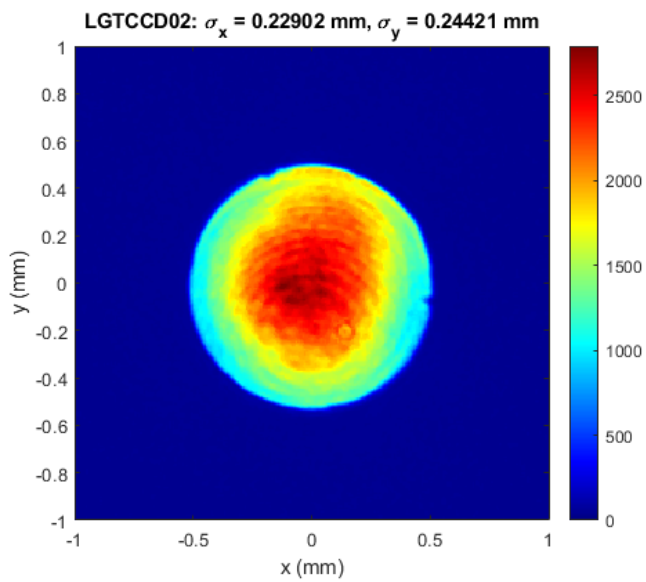
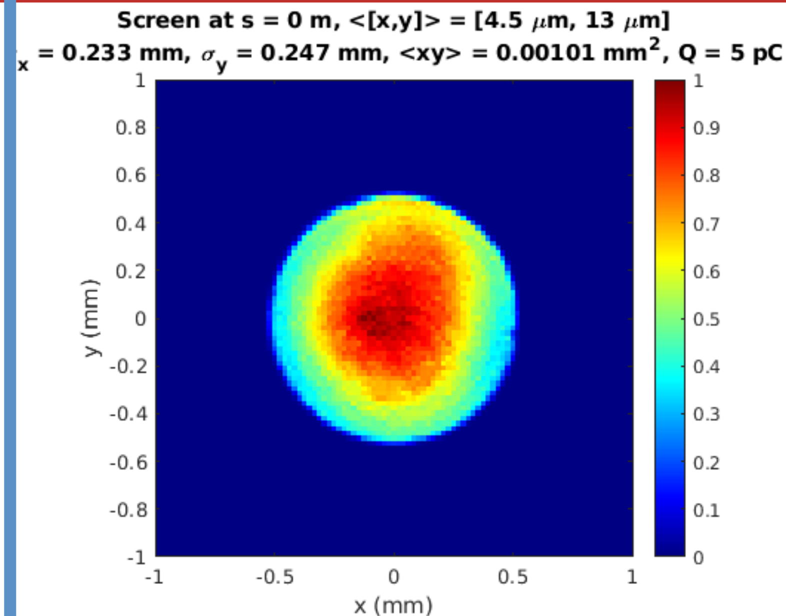
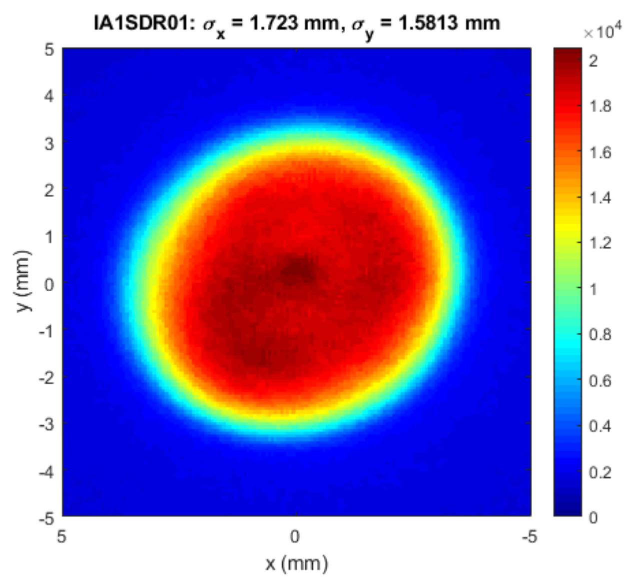
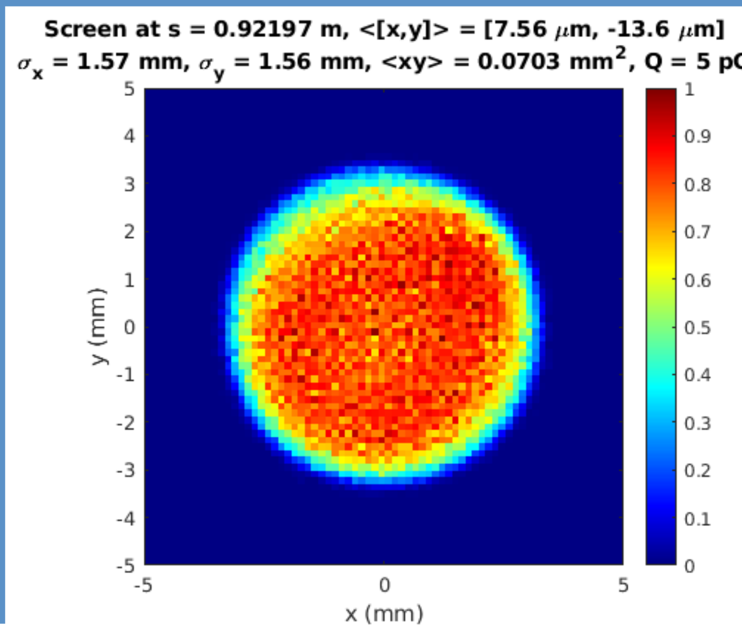
Normalized rms core* emittance (horizontal/vertical) @ core fraction (%)

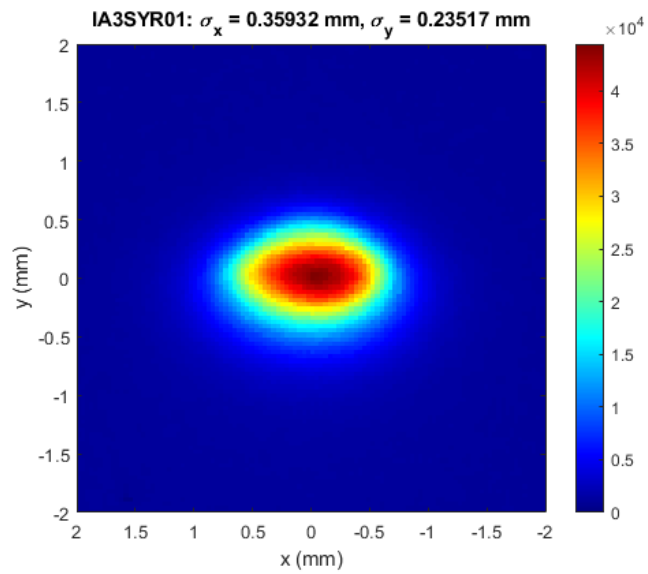
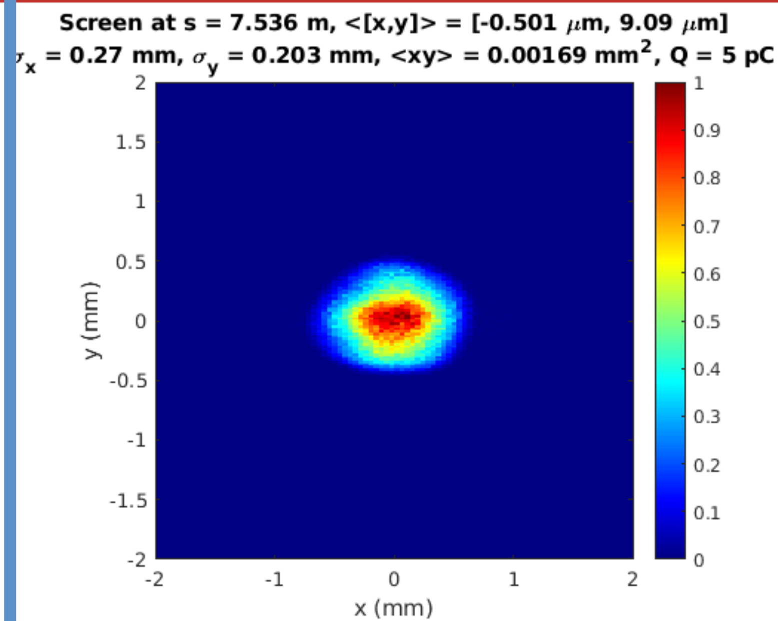
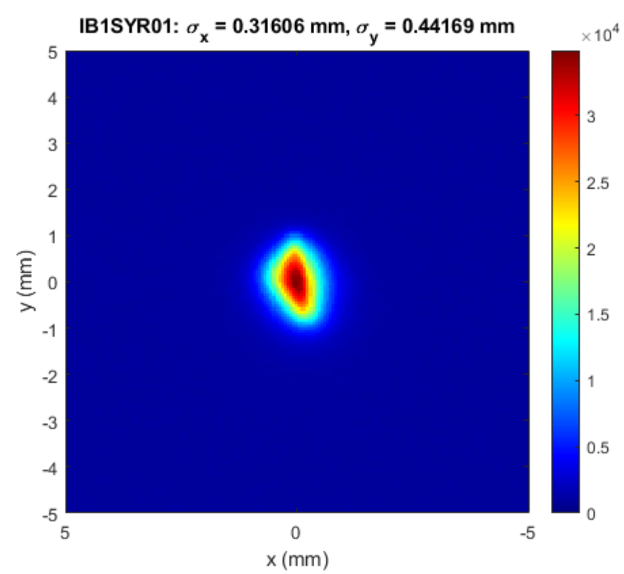
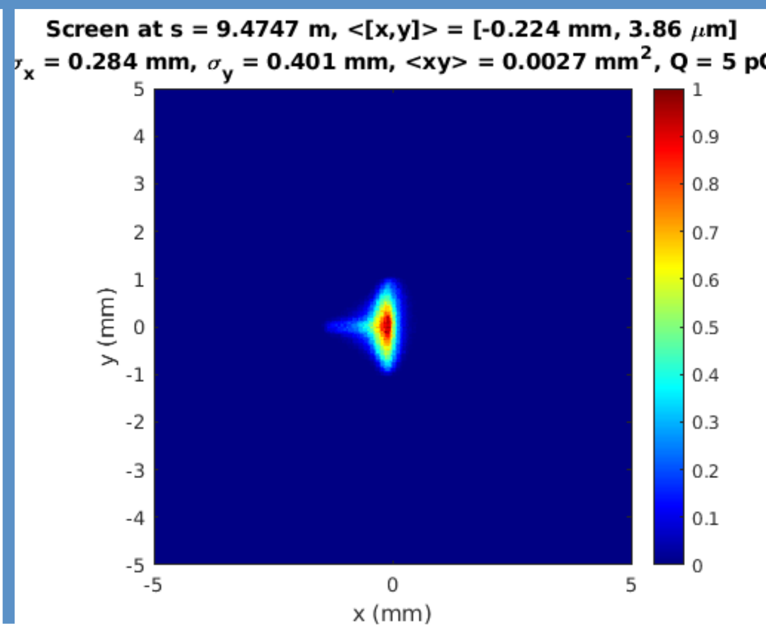
0.14/0.09 mm-mrad @ 68% | 0.24/0.18 mm-mrad @ 61%

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

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

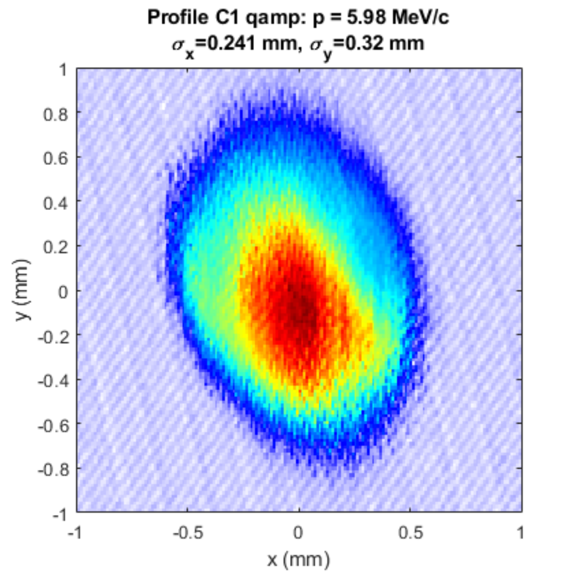
	Measured	Simulation
Horizontal		
Vertical		

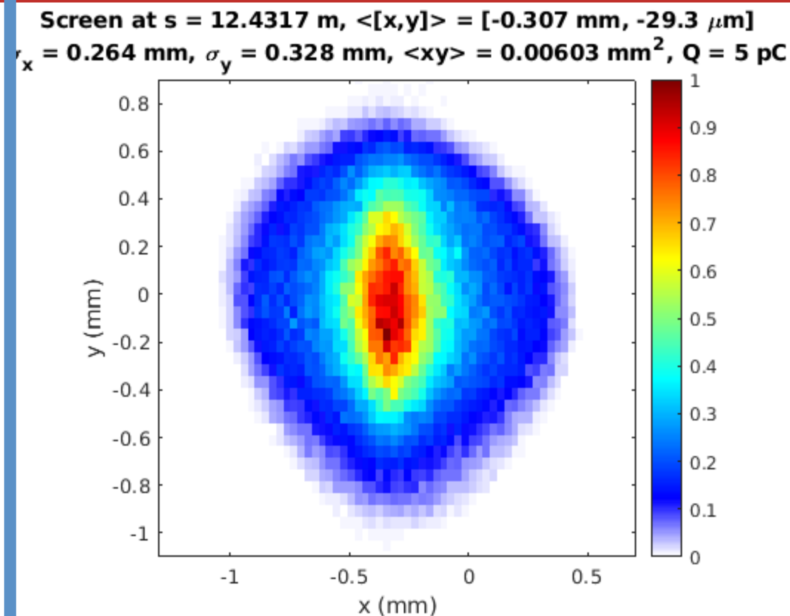
	Measured	Simulation
Laser		
Screen A1		

	Measured	Simulation
Screen A3		
Screen B1		

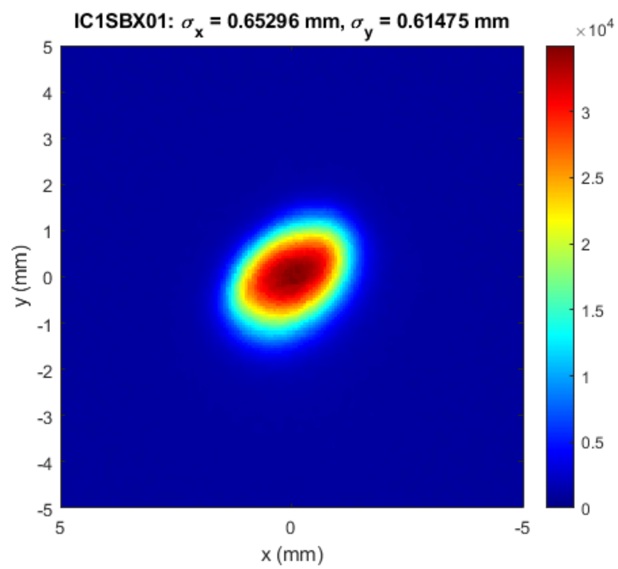
Measured | Simulation

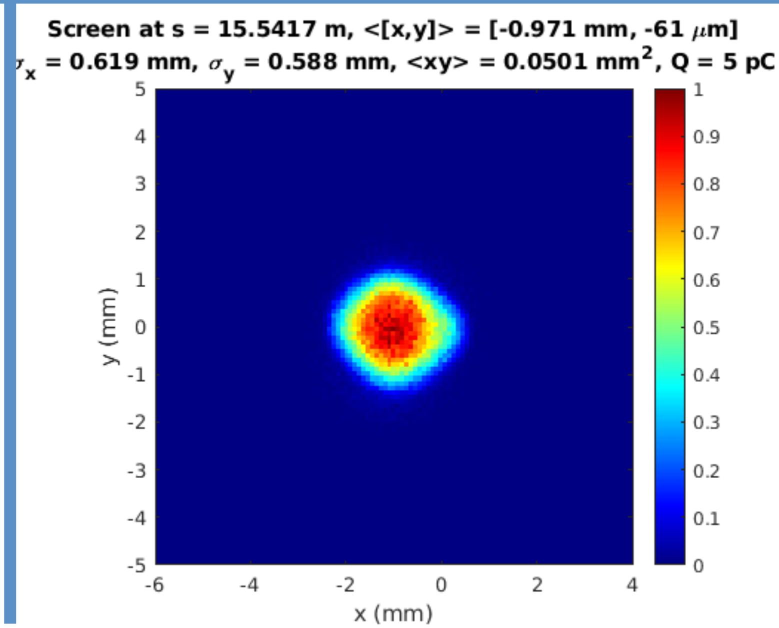
Slits





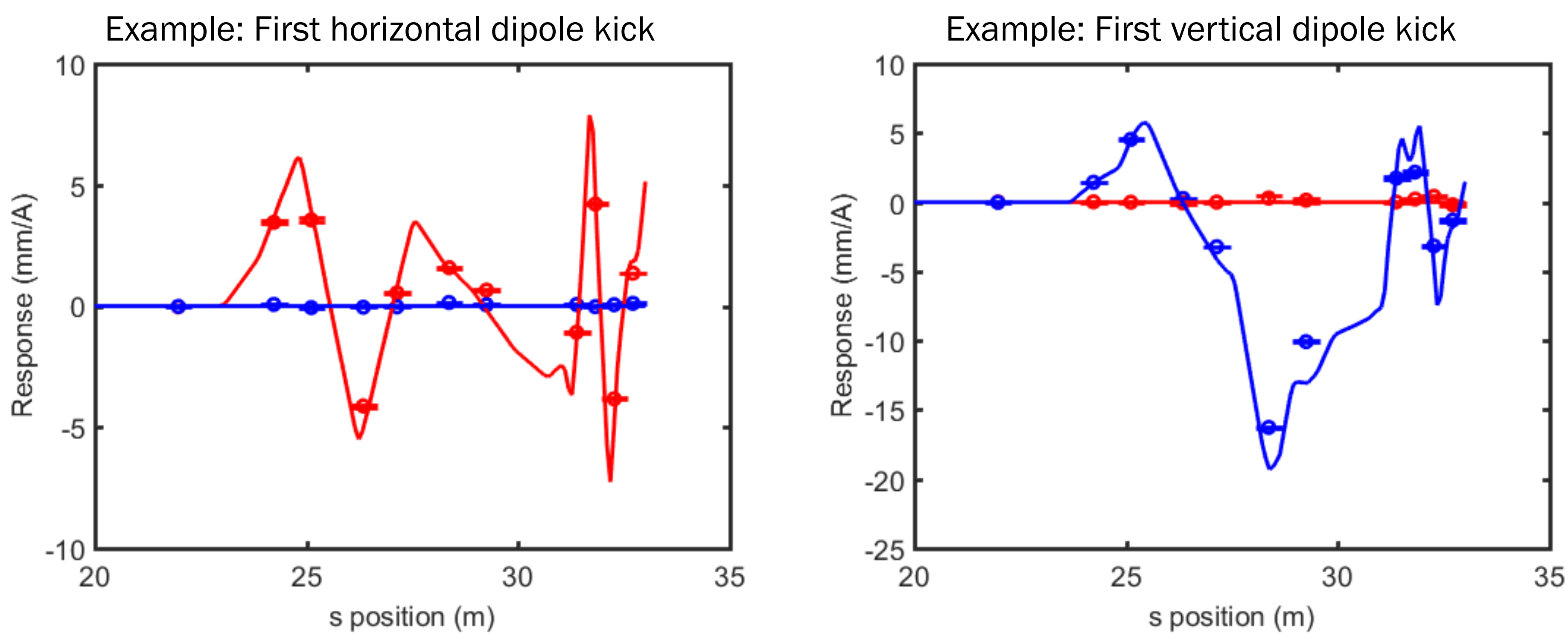
C1





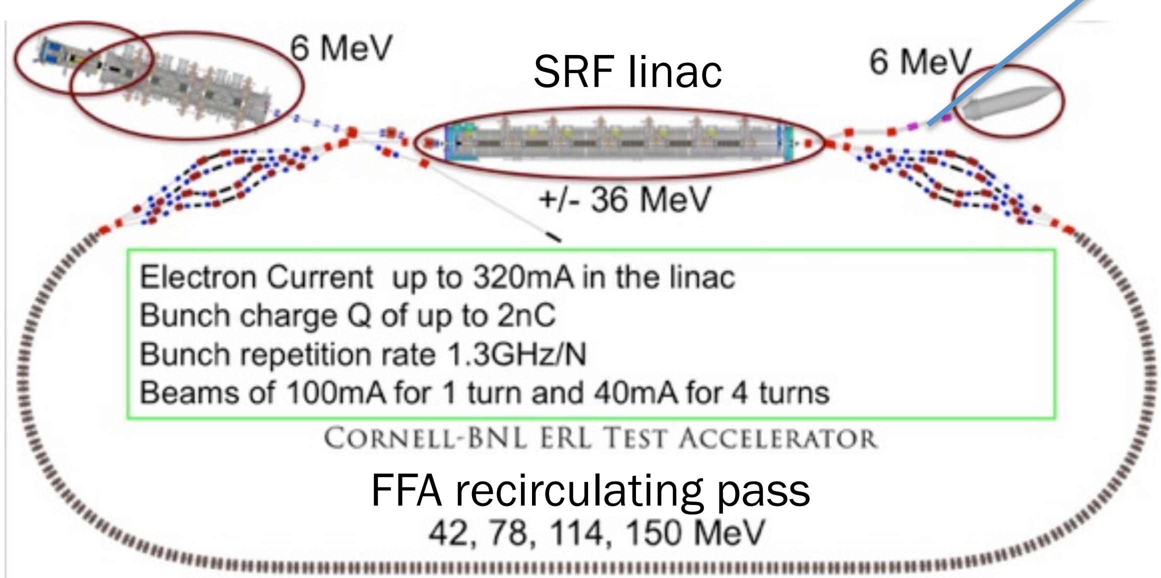
Orbit Response at 42 MeV

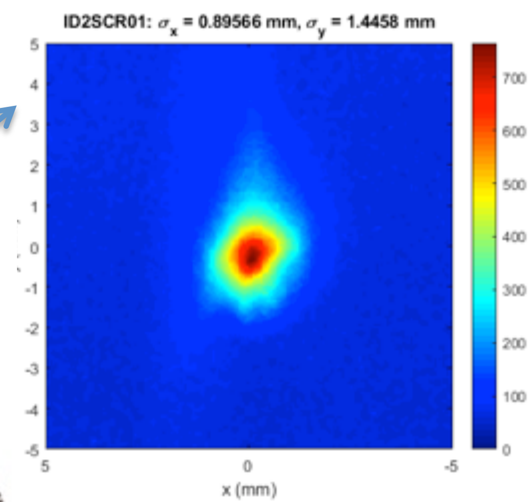
- Response data was served live using the on-line model “CBETA-V”
- Detailed measurements were taken to help refine the model off-line



1st ERL turn in 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 nearly completed – beam about to start.





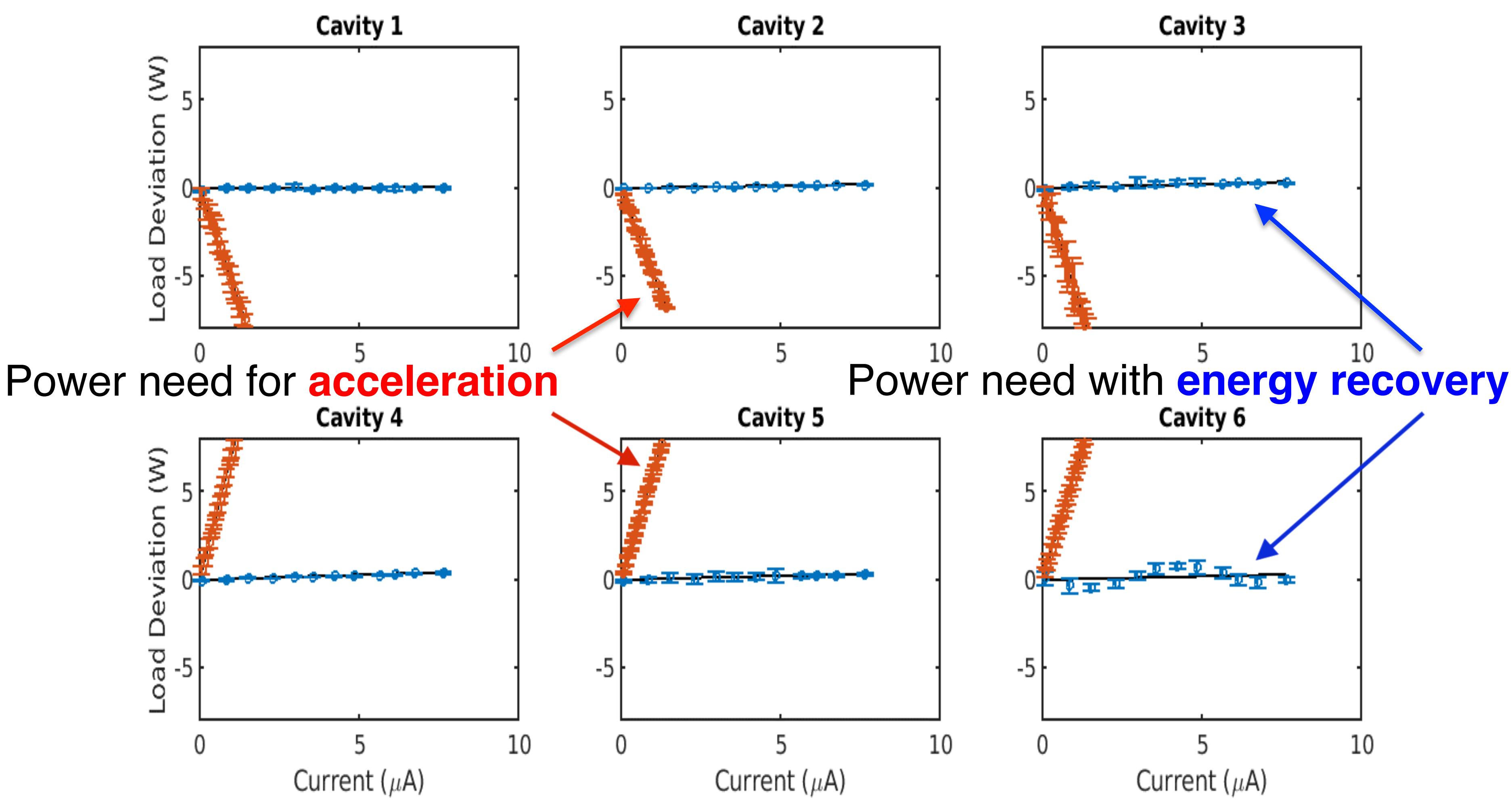
First 1-turn recirculated beam spot @ CBETA (June 10)

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

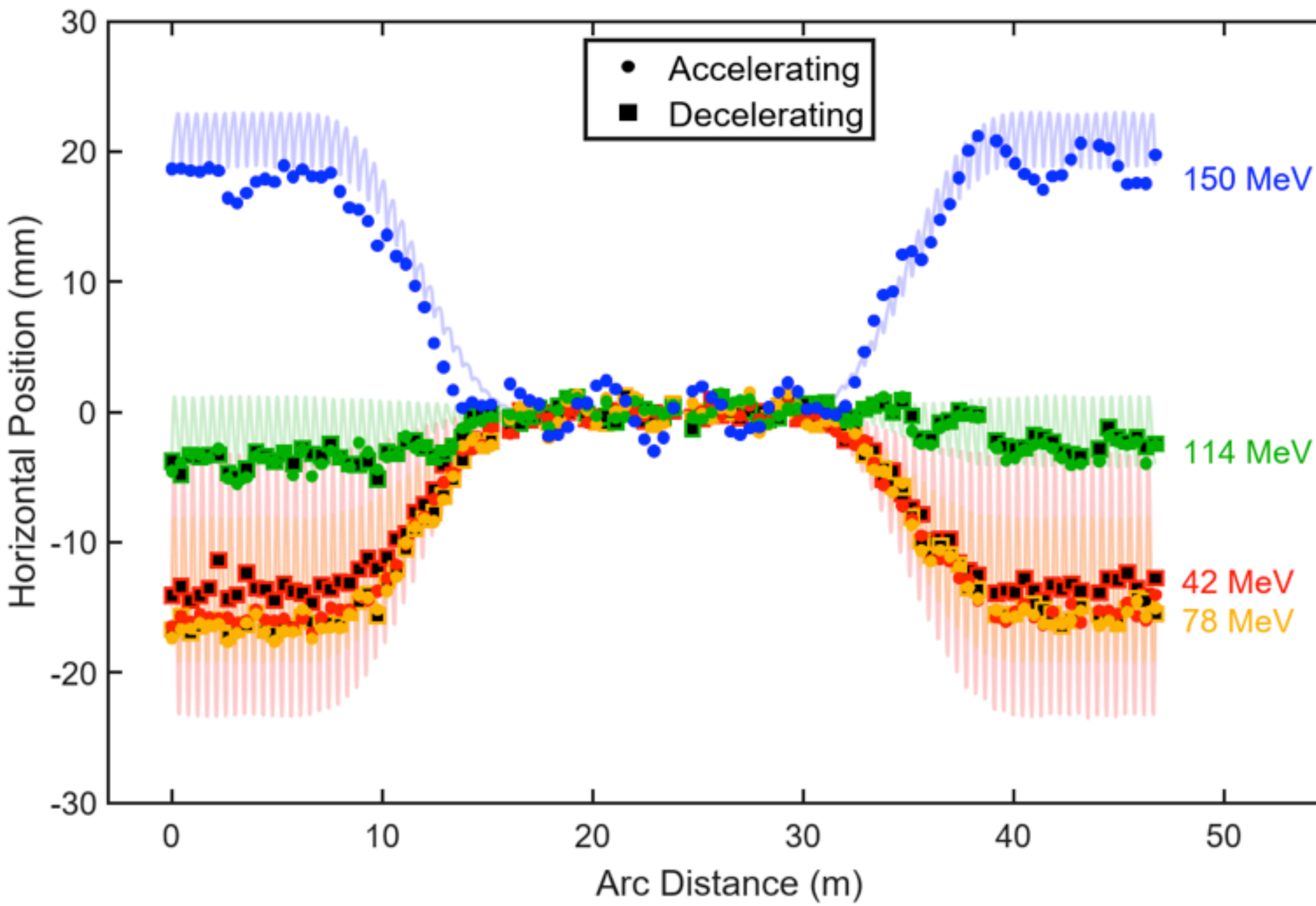
Energy Recovery in every cavity

CBETA

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



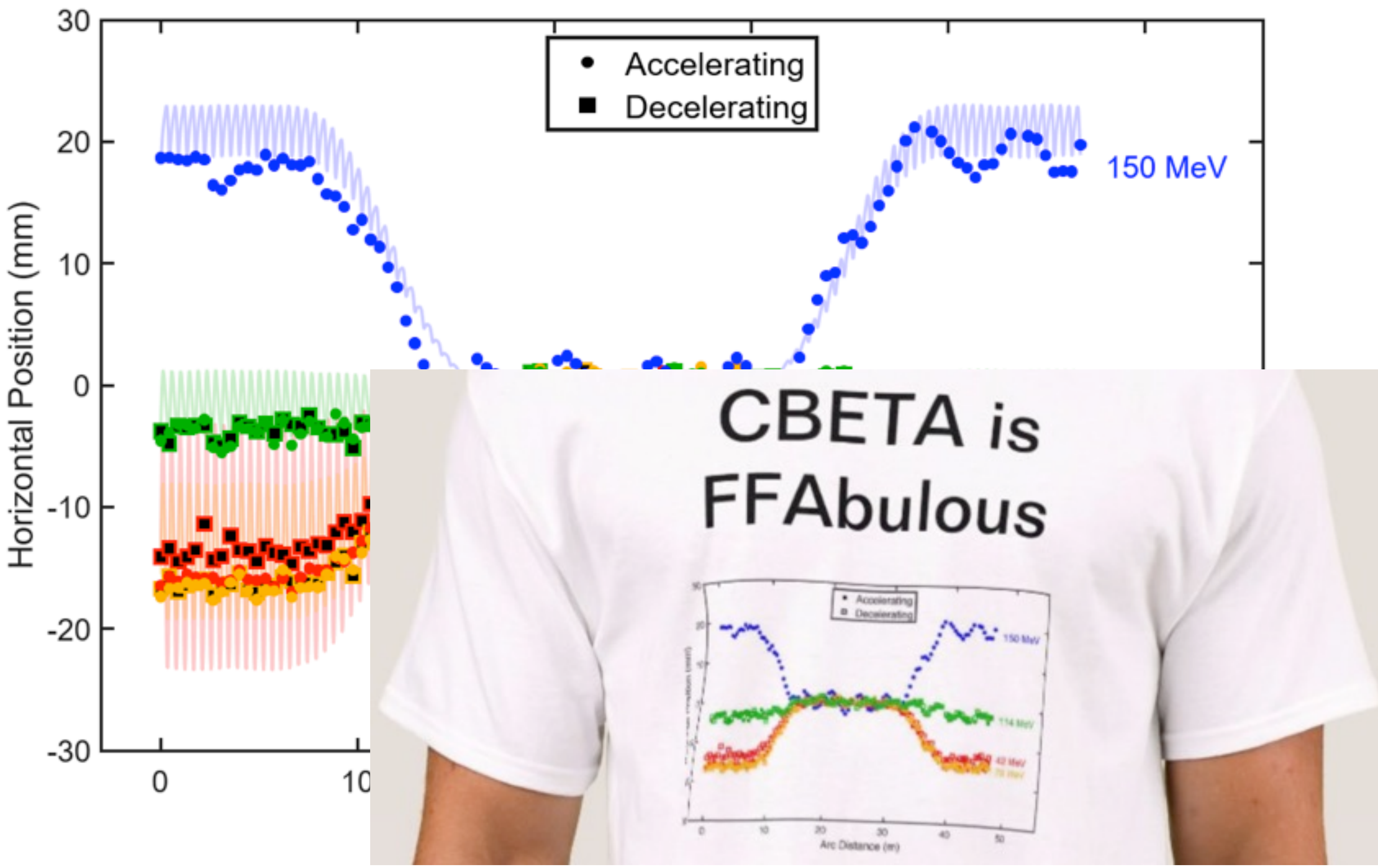
Horizontal Orbits



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

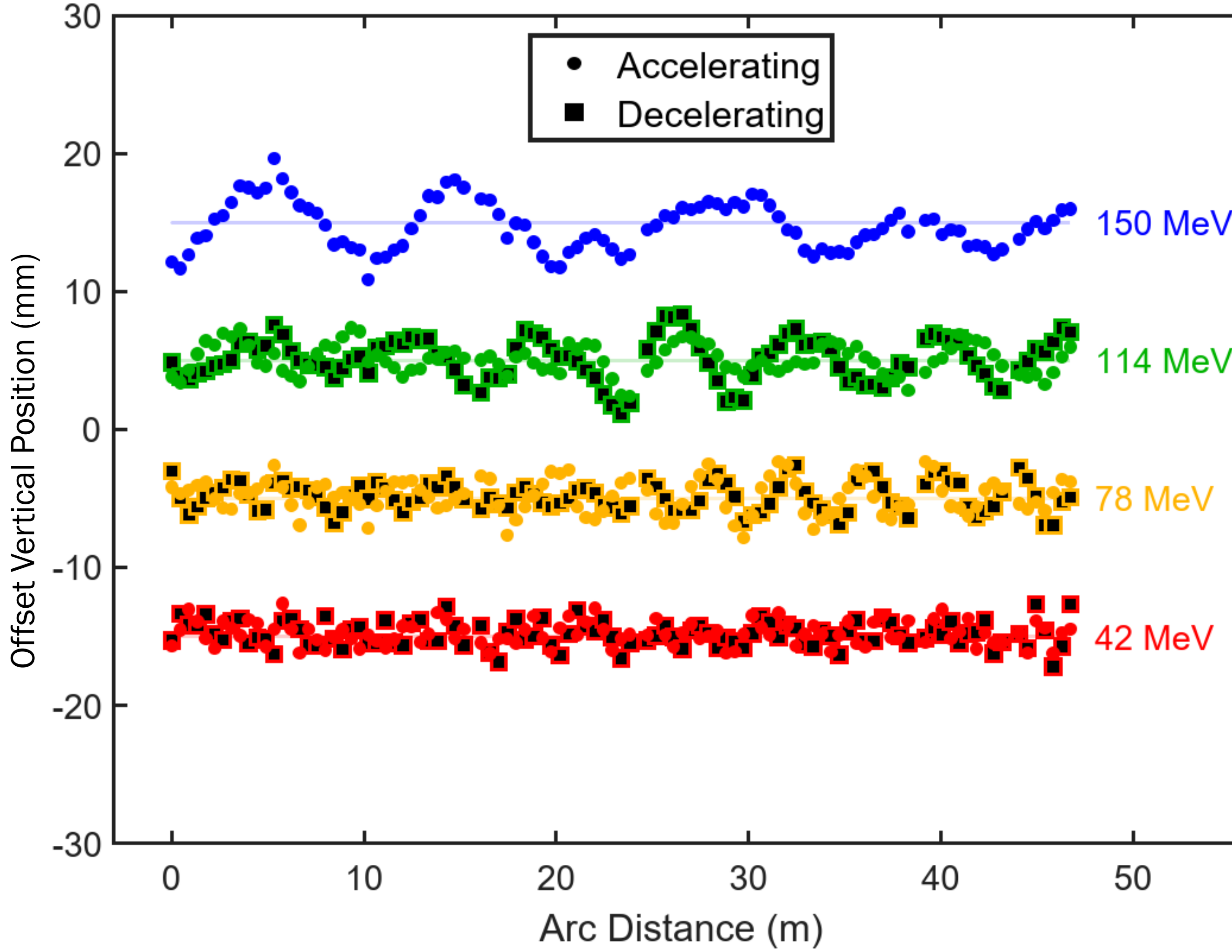
Horizontal Orbits

CBETA



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

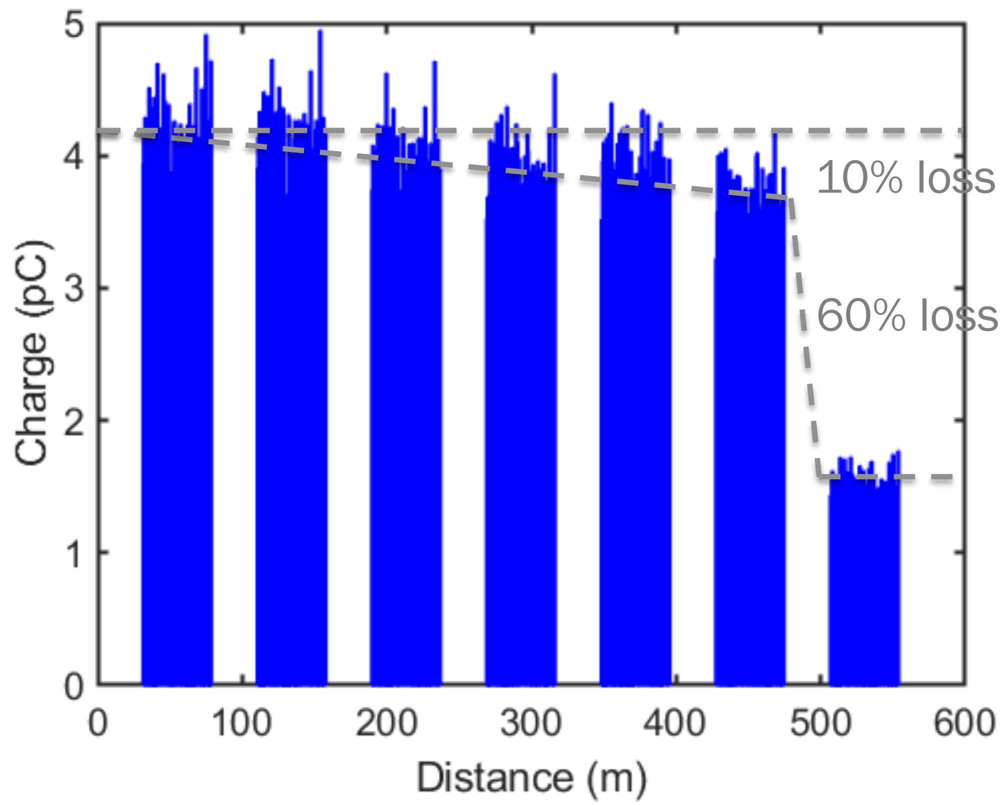
Vertical orbits



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	

Transmission

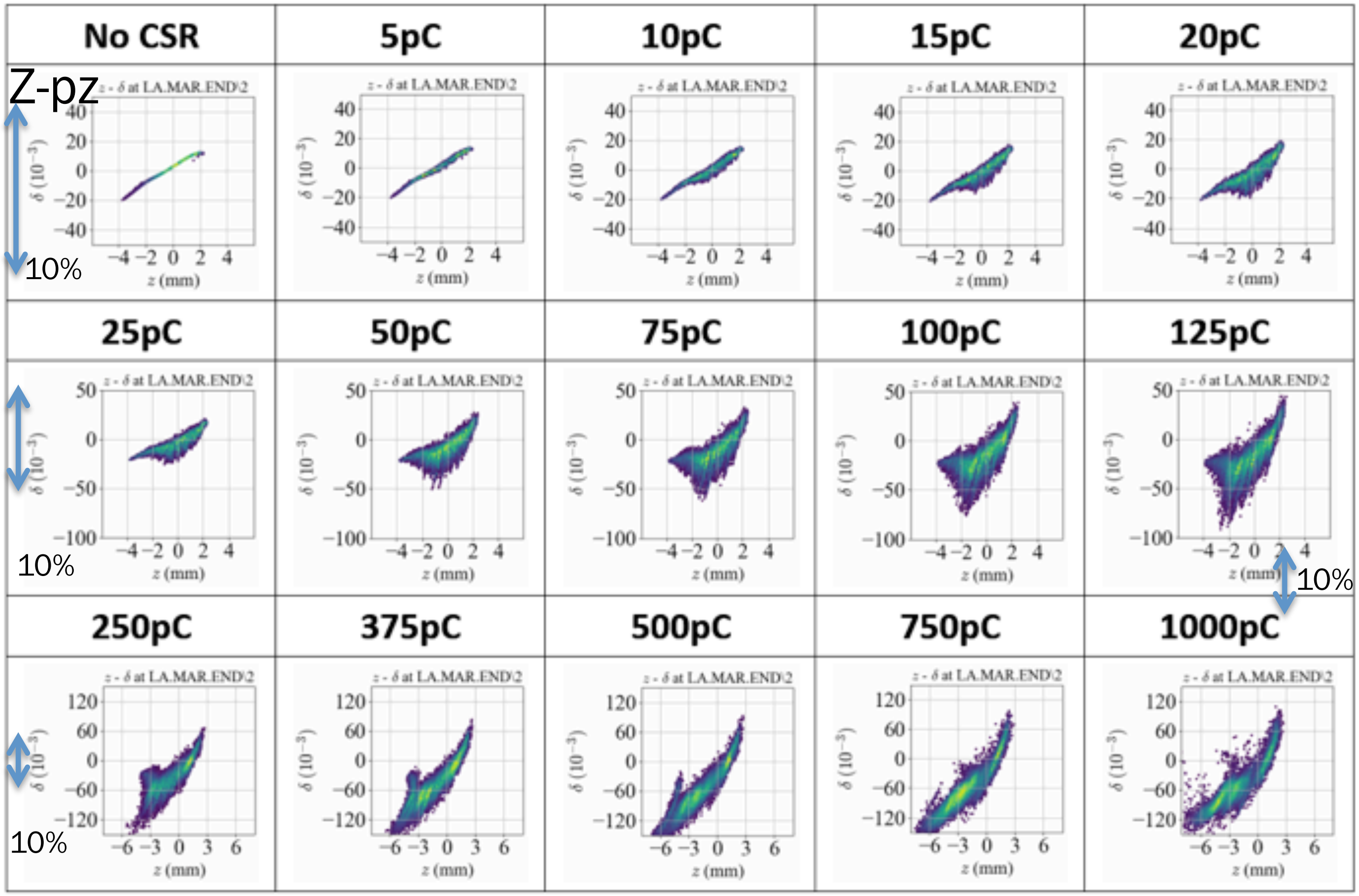


- Gradual 10% loss
- Additional 60% loss after 2nd pass through R2
- Percentages improve with lower initial charge (not shown)

CSR dynamics: energy spread

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.



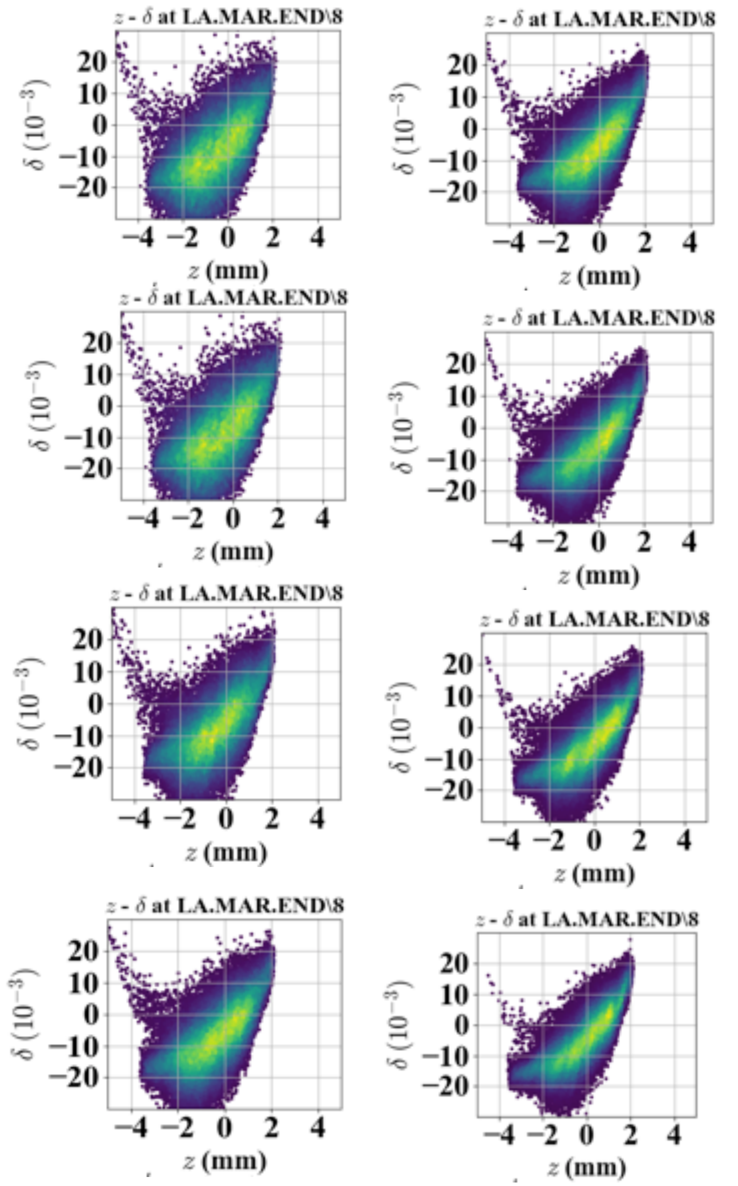
Final energy aperture ~ 5%

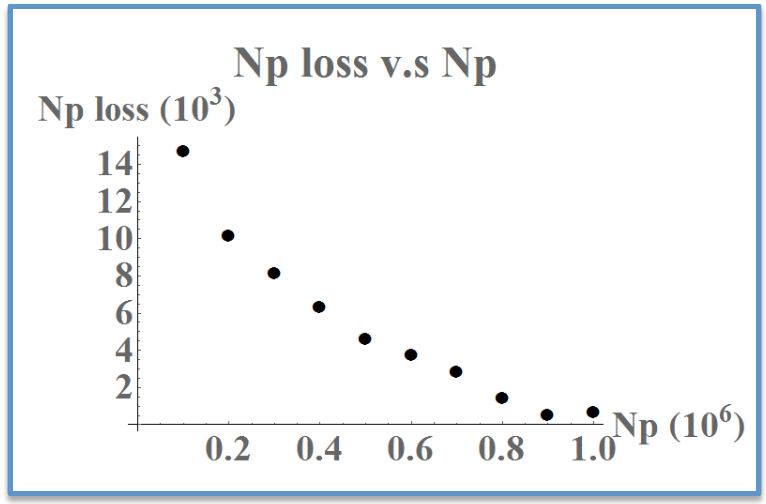
Important contributions of CBETA:

- 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.

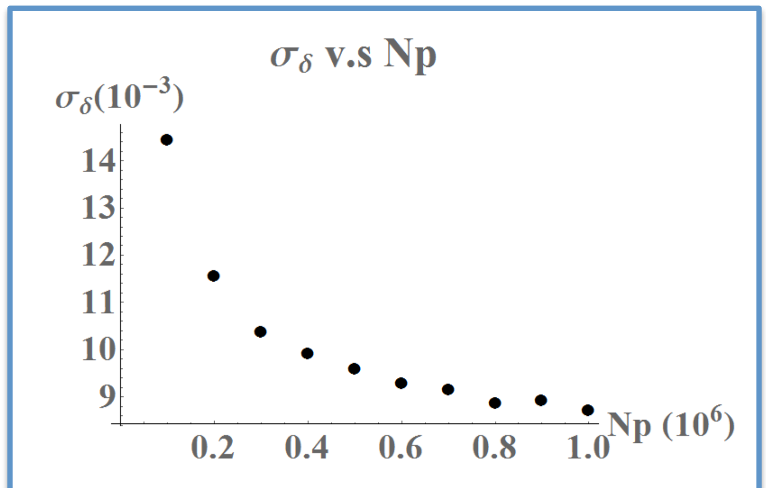
CSR dynamics: micro-bunching

CBETA





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

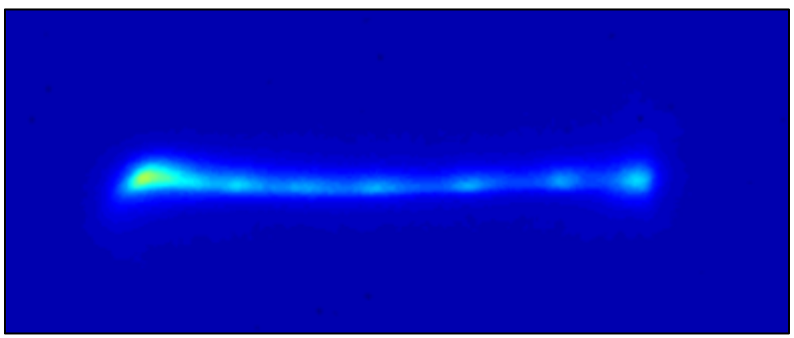


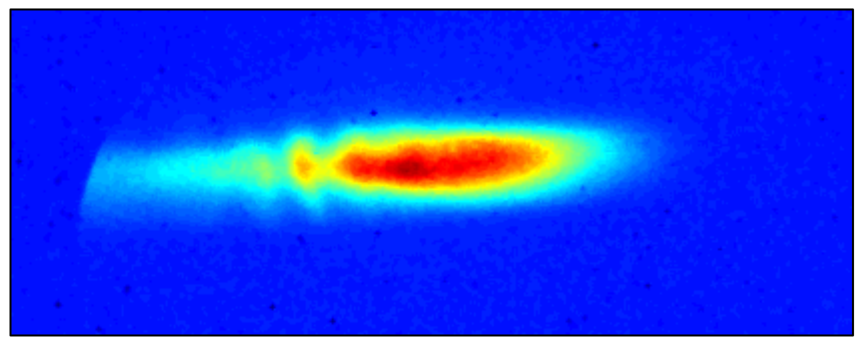
Opportunity: use CBETA for detailed phase space analysis of initial beam to check they don't have micro-bunches and can be used for cooling.

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?





Indications of micro-bunching

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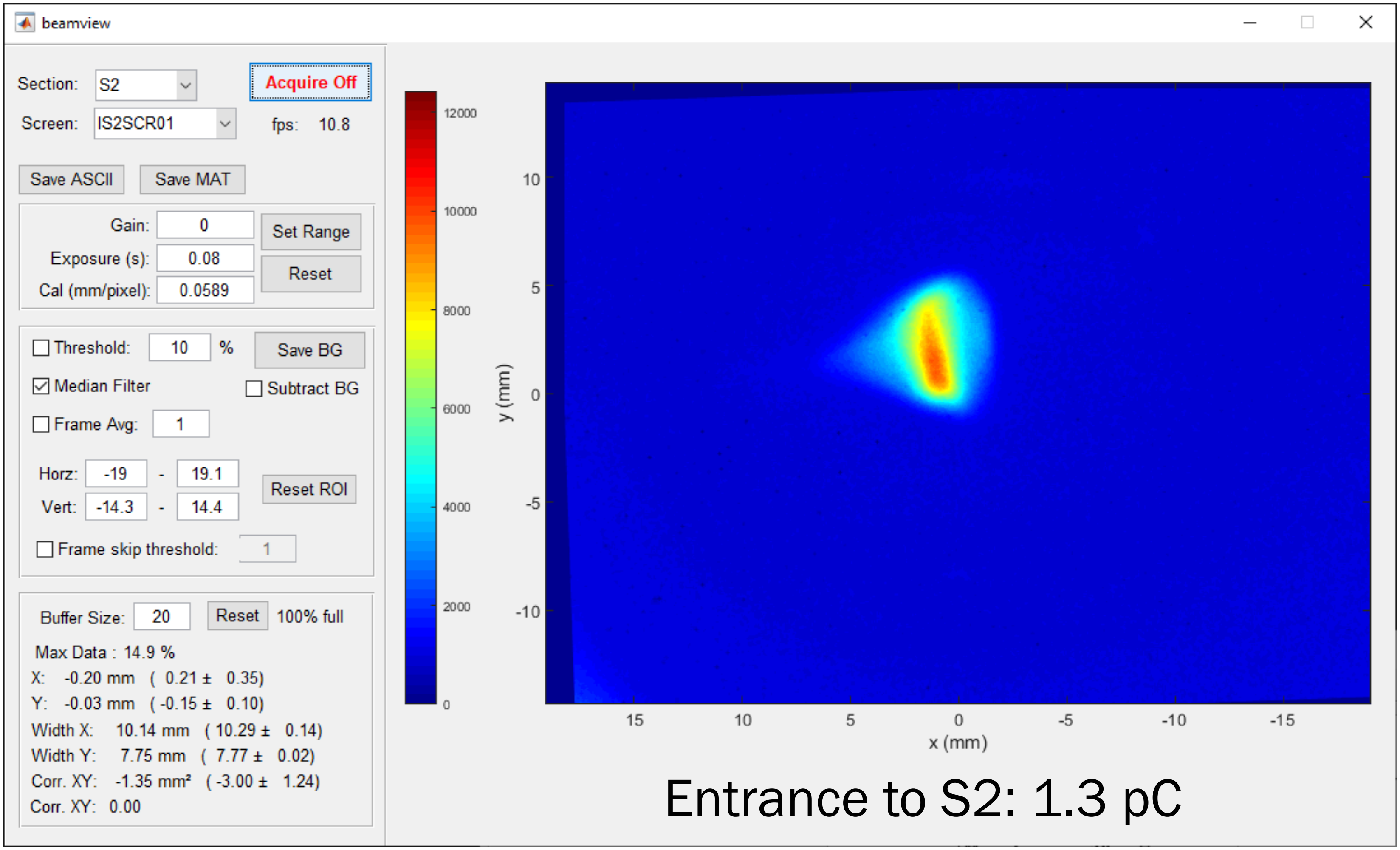
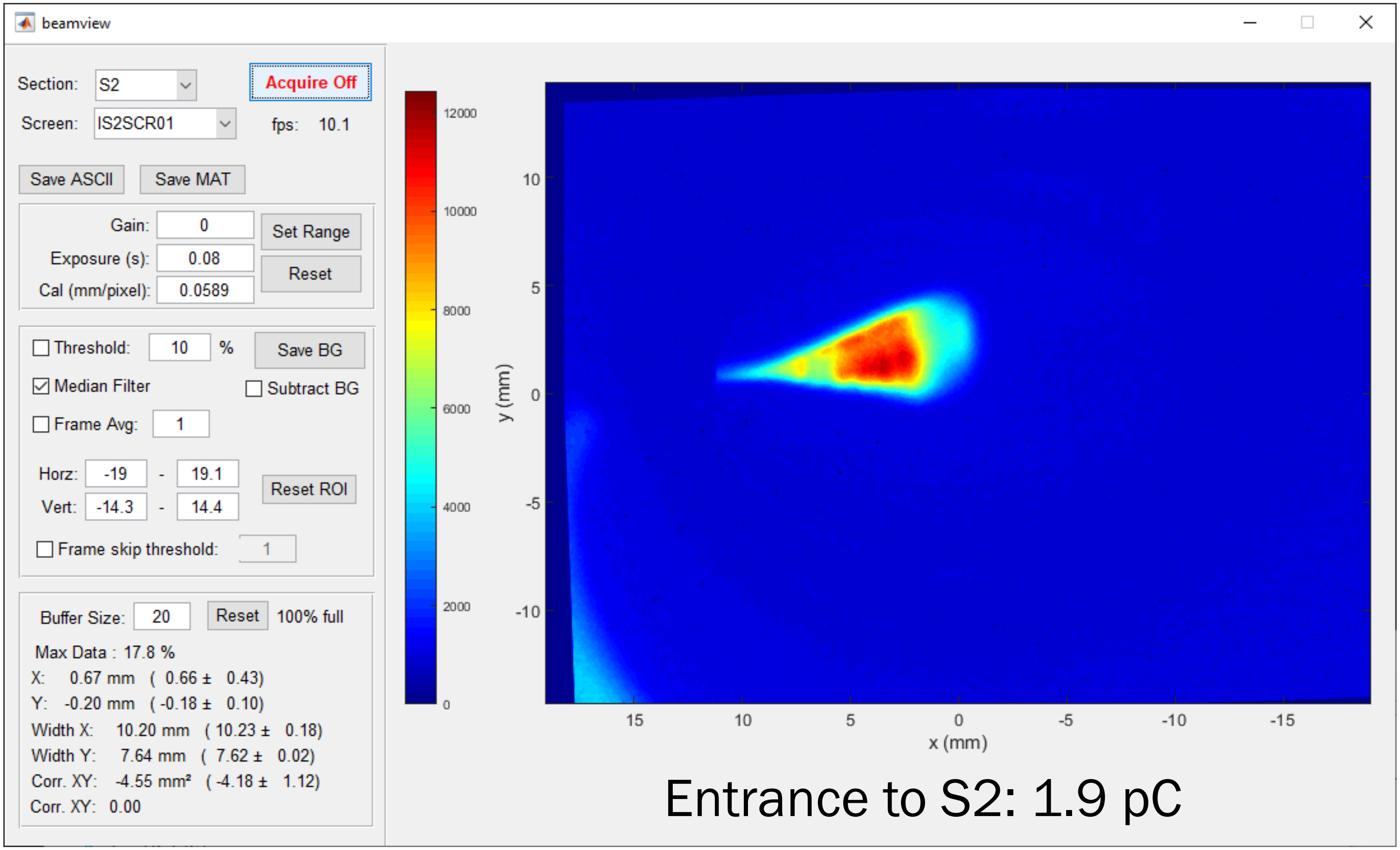


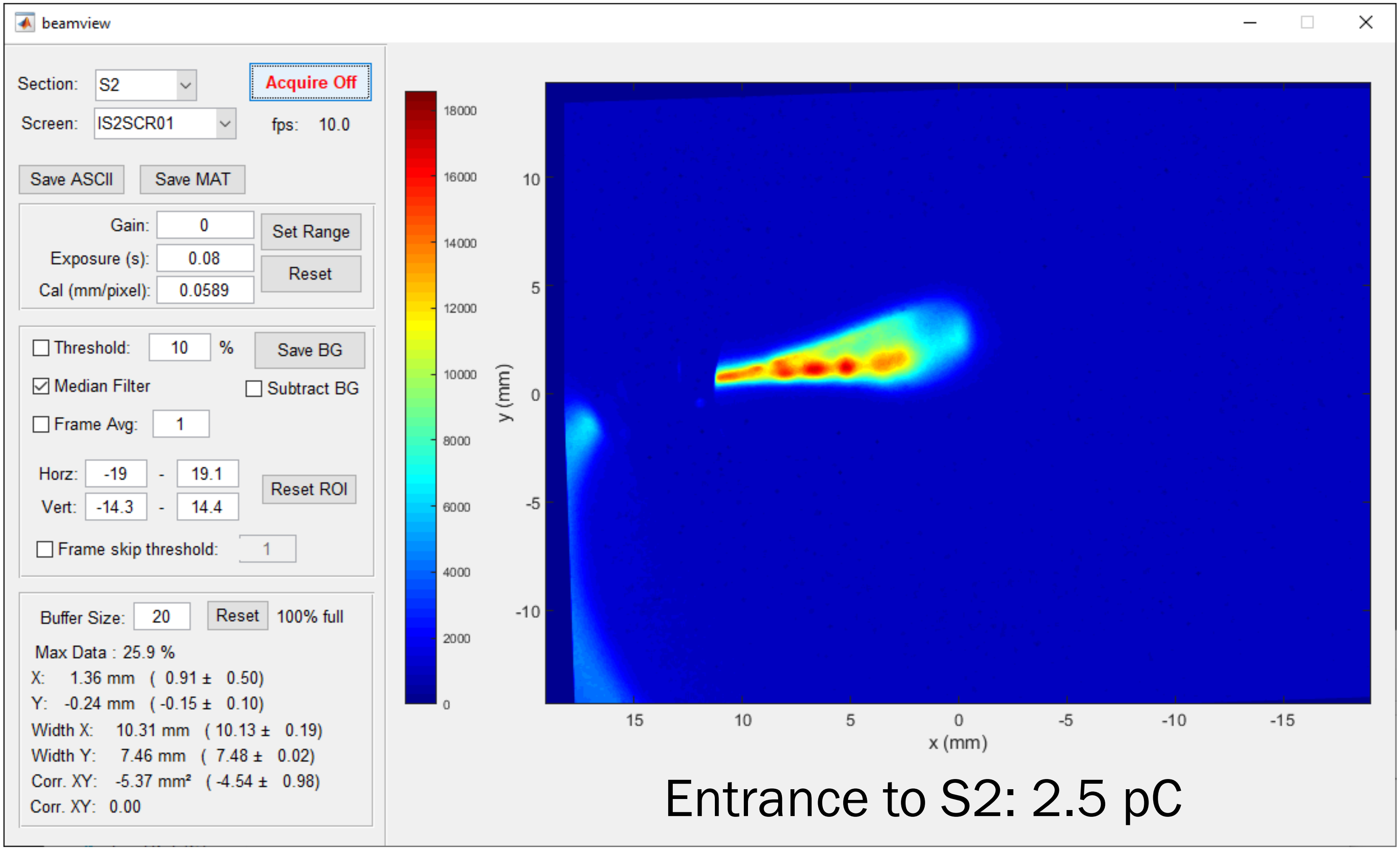
Entrance to S2: 1.3 pC

Indications of micro-bunching



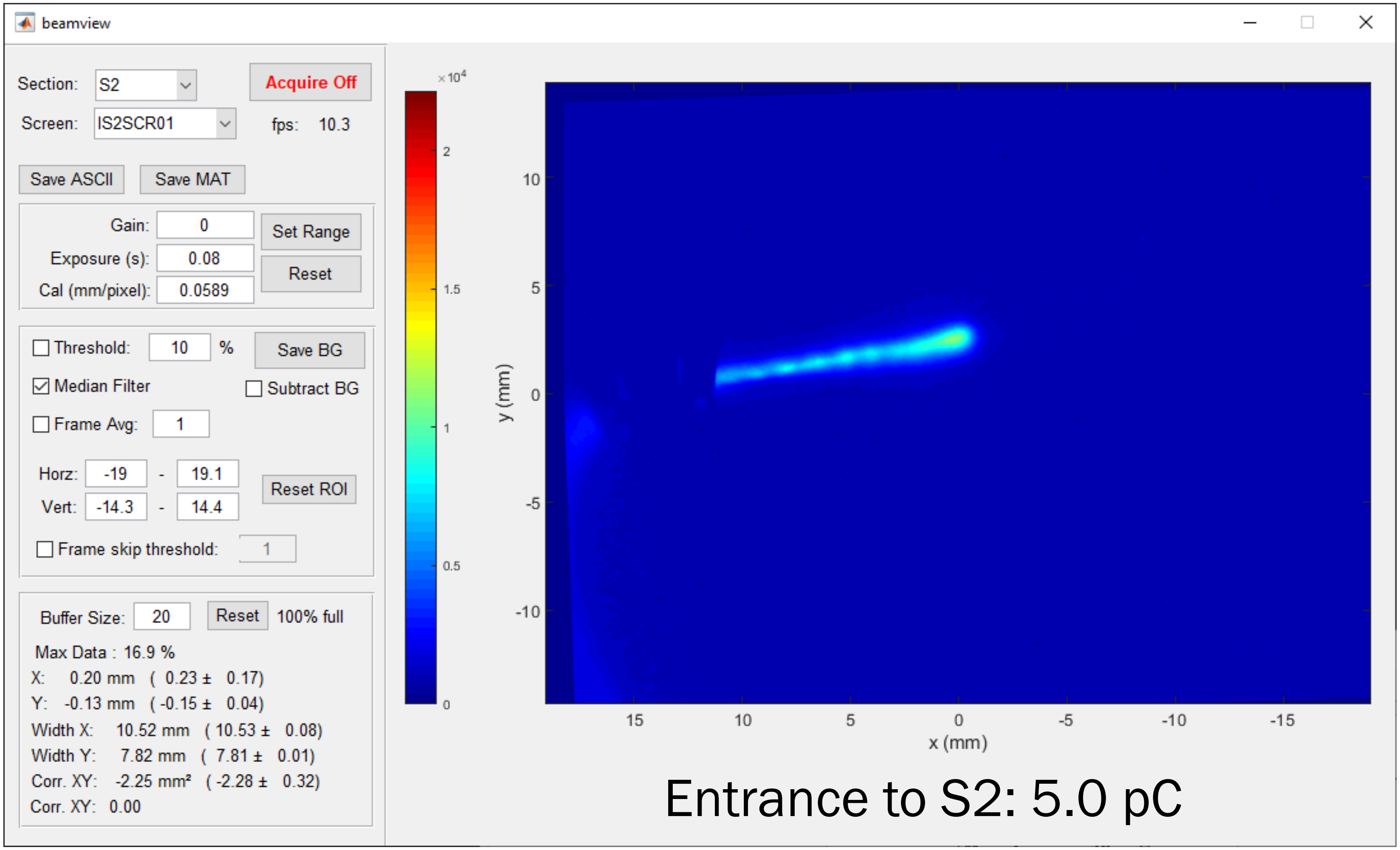
Entrance to S2: 1.9 pC

Indications of micro-bunching



Entrance to S2: 2.5 pC

Indications of micro-bunching



Entrance to S2: 5.0 pC

Achievements

- **CBETA has fulfilled all milestones on time (as of contract with NYSERDA)**. It is quite remarkable that the milestones set 3.5 years ahead of time were all met in time.

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- **CBETA found many important operational topics important for ERL, e.g. for hadron coolers**, e.g. for sensitivity to magnet errors in a compact accelerator, for crosstalk between adjacent beam lines, time of flight dependence on orbit distortions, methods for energy measurements with time of flight and optics, multi-beam orbit measurement and correction.

- **The EIC needs hadron cooling to stably achieve its highest luminosities.** The EIC cooling community determined that the ERLs needed for EIC hadron cooling require R&D that can all be addressed with CBETA.

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- **CBETA is an accelerator physics treasure trove**; it is able to investigate not only important topics for EIC hadron cooling, but it addresses topics important for many other potential new accelerator applications, e.g. medical isotope production, computer chip lithography, and future highest-energy electron/positron collider.

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- **The EIC needs hadron cooling to stably achieve its highest luminosities.** The EIC cooling community determined that the ERLs needed for EIC hadron cooling require R&D that can all be addressed with CBETA.

- **CBETA is an accelerator physics treasure trove**; it is able to investigate not only important topics for EIC hadron cooling, but it addresses topics important for many other potential new accelerator applications, e.g. medical isotope production, computer chip lithography, and future highest-energy electron/positron collider.

- **CBETA has included the international communit**y, leading to an ERL-Technology collaboration where 8 labs from three continents help commission CBETA. This collaboration is worth continuing to CBETA and other ERL projects.

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

International ERL collaboration

Questions ?

CBETA benefits (1): Hadron cooling for the EIC

Some challenges for Hadron cooling for the EIC (boosting luminosity by at least 3)

- The needed beam parameters have not been demonstrated yet: **150MeV**, **1nC**, up to **100mA**, with sufficient **smooth distribution** to imprint proton information and with **sufficiently small emittances**.

CBETA can address all these issues

- CBETA energy: **150MeV**, injector achieved **> 1nC**, **separately 75mA**, record **small emittances** at 80pC.
- Are DC sources and SRF linacs good for **1nC with 100mA**?
- Can the **microstructure** be **sufficiently small** after a merger, i.e. in the cooling section?
- Can an **ERL loop** (at 42MeV**) transport 1nC**, incl. CSR and micro bunching.
- Does **CSR scale with energy** as expected to 150MeV?
- Can CSR be effectively **shielded** by a vacuum chamber?
- Accumulation of **ions** in high-current DC electron beam.

EIC cooling workshop

This workshop was organized by Fermilab and U-Chicago
Y.K.Kim and S.Nagaitsev – workshop chairs
Also, sponsored by Cornell's CBB (supporting grad. students)

EIC cooling final ERL recommendations

“Research Needs for ERLs for EICs

What research do we still have to do?

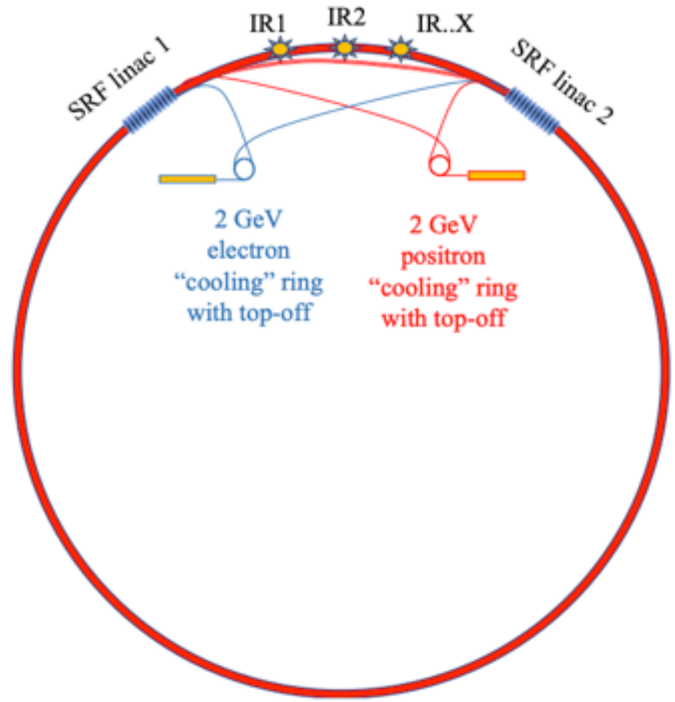
- Need high current tests of injectors
- Still much design work to do (CSR arcs e.g.)
- Prototyping is ongoing.
- Definitely need ERL testbed facility for high current beams to test:
    - Halo
    - Beam loading
    - BBU
    - Transients
- Full scale tests are expensive”

Summary presentation of the ERI Cooling Workshop (S.Nagaitsev)

CBETA already provides a full scale test, able to study all these topics.

Spinoff of EIC work: ERL & FFA for the FCC-ee

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



Future High Energy Circular e^+e^- Collider using Energy-Recovery Linacs

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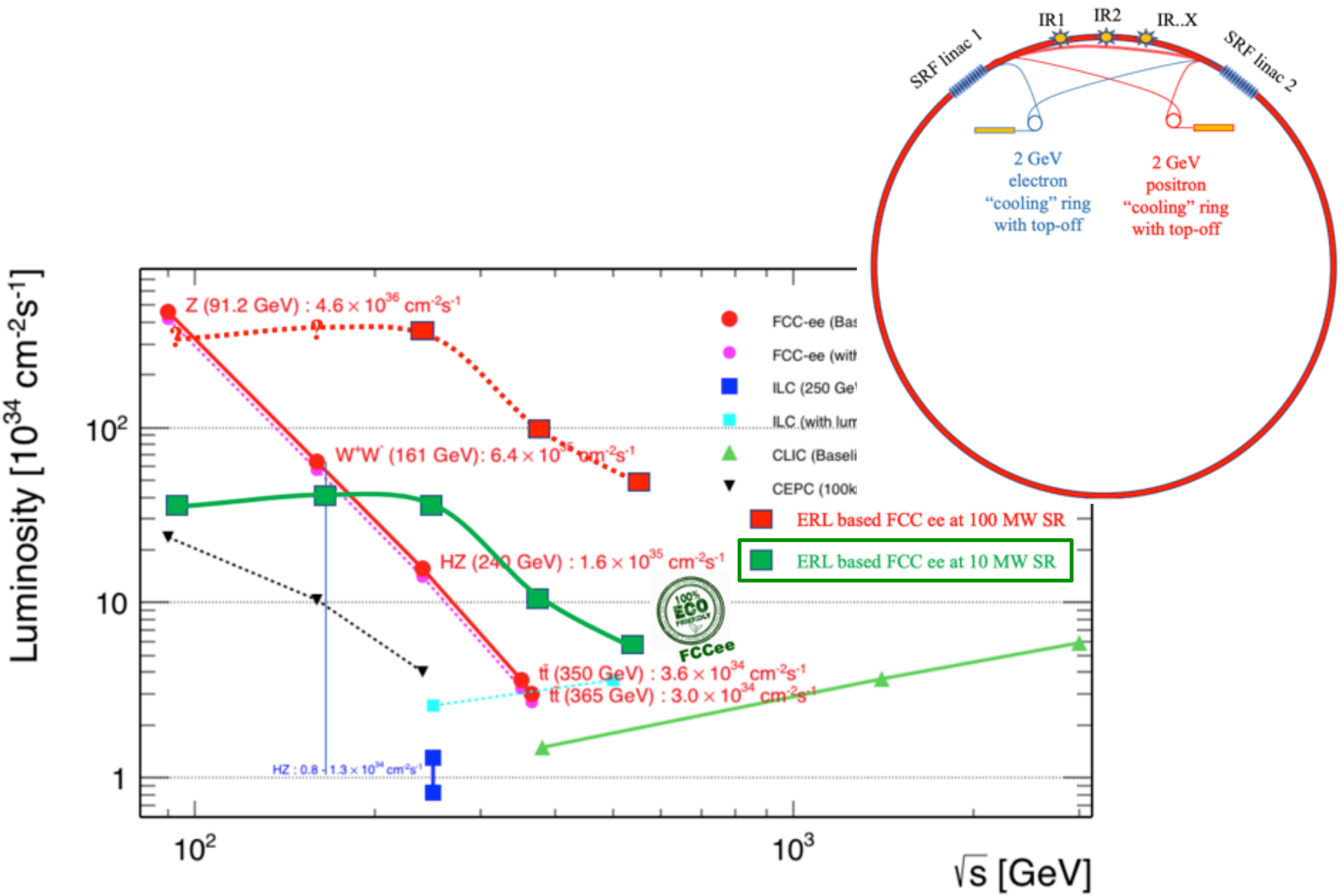
In this paper we present alternative approach for Future Circular electron-positron Collider. Current 100 km circumference design with the top CM energy of 365 GeV (182.5 GeV beam energy) is based on two storage rings to circulate colliding beams [1-2]. One of the ring-ring design shortcomings is enormous power consumption needed to compensate for 100 MW of the beam energy losses for synchrotron radiation. We propose to use energy recovery linac located in the same tunnel to mitigate this drawback. We show in this paper that our approach would allow a significant – up to an order of magnitude – reduction of the beam energy losses while maintaining high luminosity in this collider at high energies. Furthermore, our approach would allow to extend CM energy to 500 GeV (or above), which is sufficient for double-Higgs production.

CBETA benefits (2): ERL & FFA for the FCC-ee



CBETA benefits (3): Applicability of injector region

The CBETA front end (DC-source and Injector linac) is ready for various applications:

- **Ultrafast Electron Diffraction (UED)** is an active field with much experimental interest. We are ready to test the **applicability of the DC source and the ICM**. (High current and high voltage)

- **Medical isotope production** through the gamma-n reaction can use high-current, several 10MeV beams from the **DCS and several ICMs**. We are ready to test the applicability and reliability of this concept. (A company is already testing the principle and plans to license components from Cornell.)

- Cancer therapy through a high power SRF linac for electron, proton, or ions benefits from **applicability tests of the ICM**.

CBETA benefits (4): Applicability of multi-turn ERLs

While the following applications are not or may not be reasonable for a user facility in L0E, we are ready to investigate the applicability of CBETA technology for:

- **Medical Isotope production** machines using ERLs, where lost electron energy through isotope production targets can be accepted with the FFA beam line within $dp/p < \pm 60\%$ (patent in preparation by outside group).
- **Micro-chip production:** a EUV FEL can be driven by a multi-turn ERL to provide photons for computer chip lithography (main research at the KEK cERL).
- **Compact Hard X-ray sources**: Multi-turn ERL can produce hard x-ray beams from Compton scattering (similar to the ASU project).
- **Compact gamma-ray sources**: Multi-turn ERL can produce gamma ray beams for nuclear physics (as envisioned for PERLE at LAL).
- **Gas-jet collider** experiments where CBETA's electrons make nuclear physics interactions with target atoms from the jet (as proposed with Richard Milner).

CBETA benefits (5): Applicability of PMs and FFAs

- **Proton cancer therapy gantries**. This would dramatically reduce the patient delivery system cost, which is the major obstacle in instituting widespread use of this new radiation method for cancer therapy. Proton cancer therapy provides what could be significant improvements over the more common X-ray radiation systems, because the X-rays propagate through the patient body while protons or heavier carbon particles deposit almost all of the energy into the tumor. (Test applicability in the FFA section)

- **Radiation damage** studies

- **Small synchrotrons using permanent magnets** for proton cancer therapy applications. Using permanent magnets prevents the need for including many costly, power hungry electro-magnet power supplies.