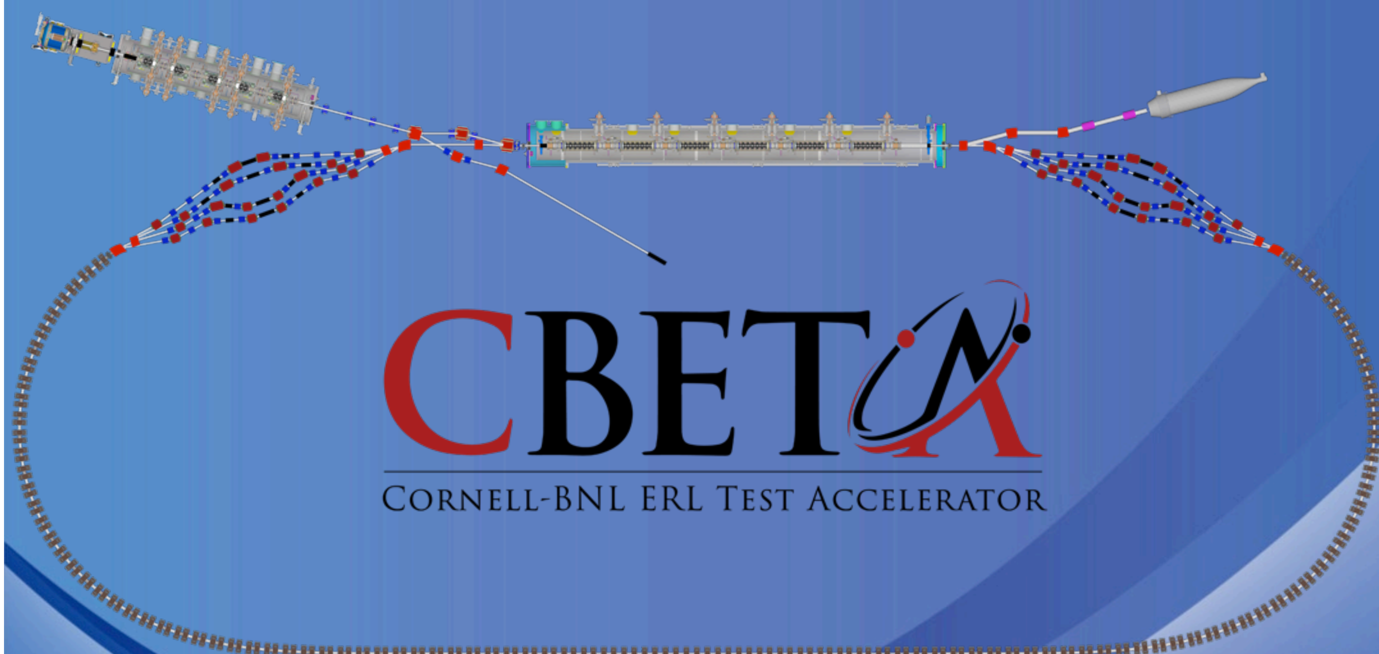
CBETA, a 4-turn ERL Based on SRF Linac: Construction and Commissioning

Georg Hoffstaetter (Cornell)

For the CBETA collaboration team



CBETA

CORNELL-BNL ERL TEST ACCELERATOR

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

Office of Science

U.S. DEPARTMENT OF ENERGY

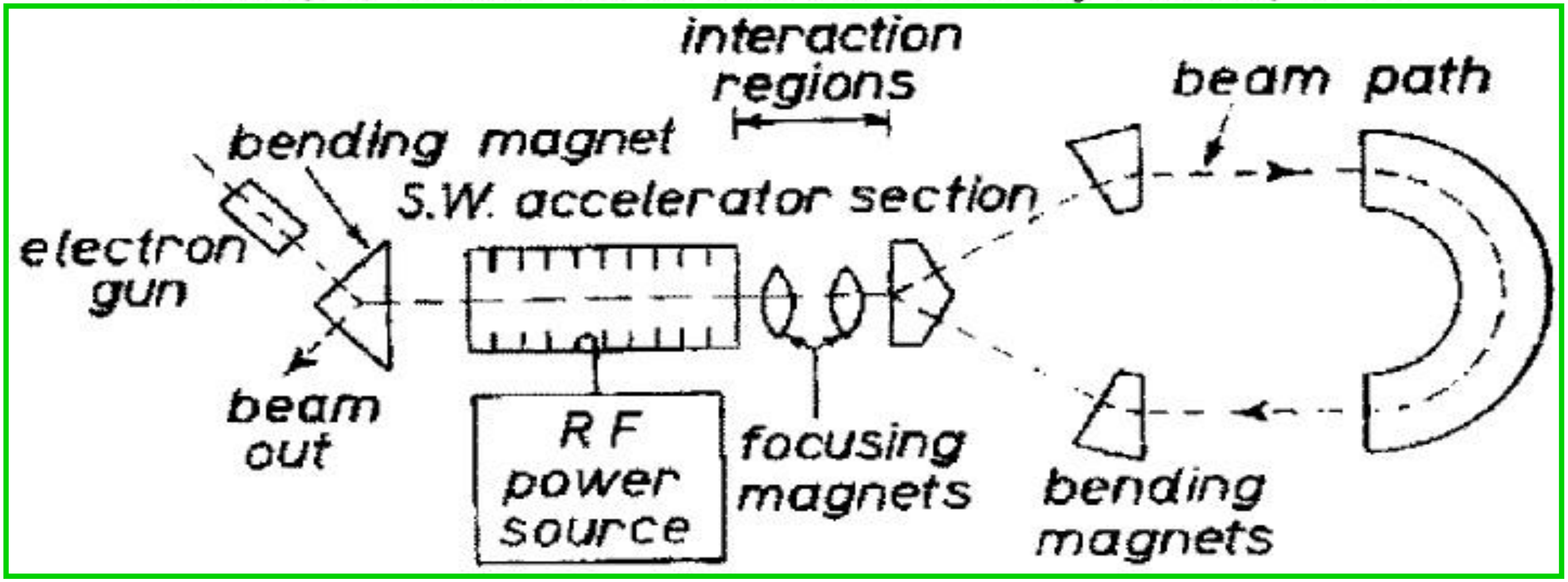
Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

Energy Recovery, published 1965

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

M. TIGNER

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



Energy recovery needs continuous beams in SRF structures

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

ERLs are designed to cause damage

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,

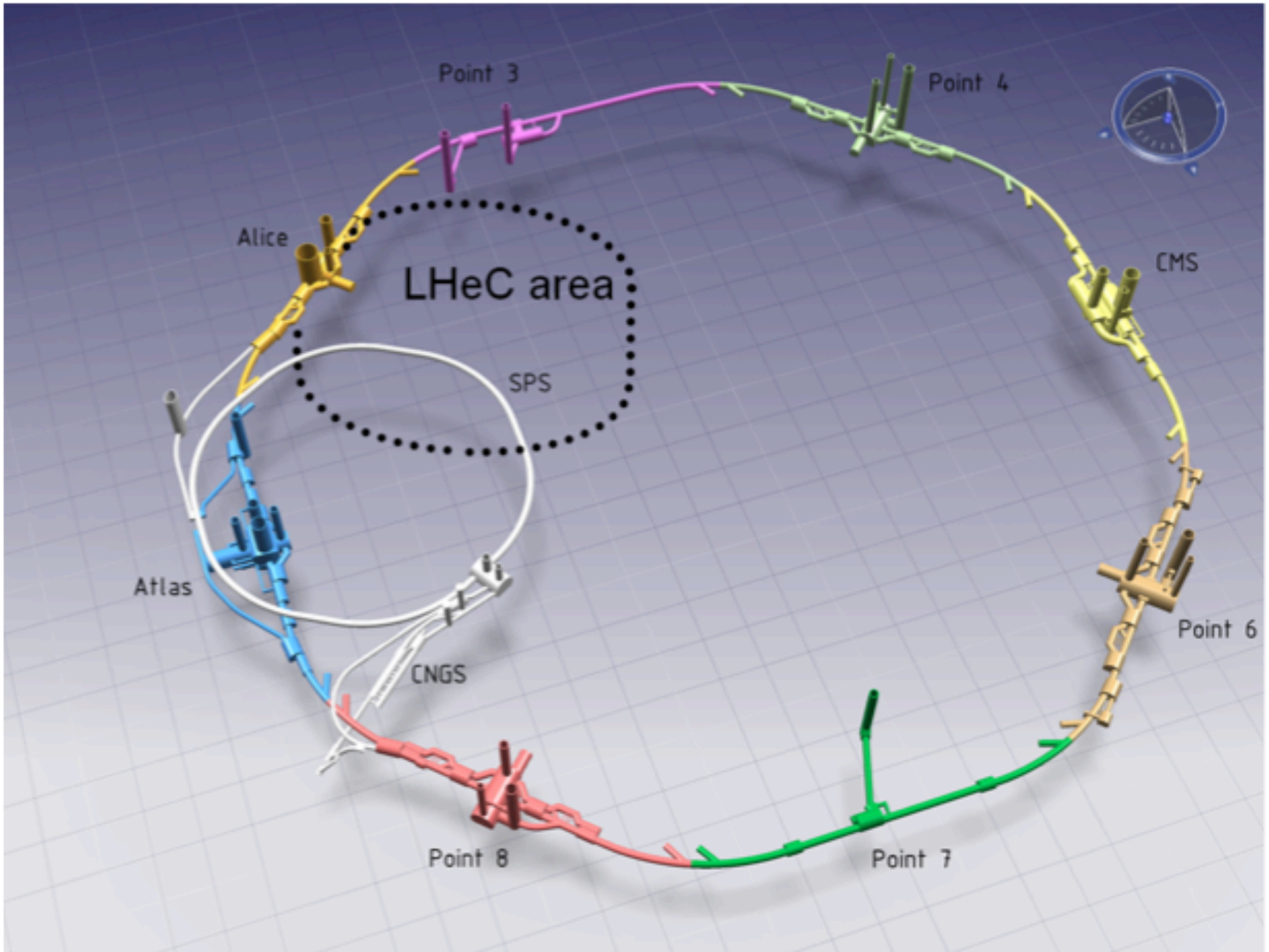
(c) **tolerates beam disruption** as each bunch is used only once before it's discarded.

The limit to the beam current is beam loss and heating!

Recent ERL developments

- The cERL at KEK
- LAL is promoting PERLE, an ERL in support of the LHeC and has already committed a hall and infrastructure. A collaboration works on a TDR and an MOU is in preparation.
- TUD has put out a white paper of a multi-turn ERL in the SDALINAC hall, also supporting the LHeC.
- The NAS report mentions ERLs as the only credible path to election calling at an EIC.
- 1-turn Energy recovery has been achieved at CBETA.
- CBETA is commissioning toward 4-turn ERL during the rest of 2019, offering commissioning experience to collaborating laboratories.

AnERL for LHeC (e-hadron collisions)



courtesy Oliver Bruening

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."

Hadron Cooling

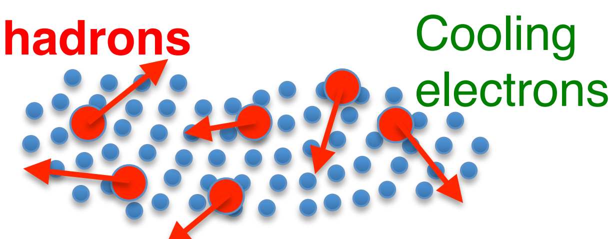
Higher bunch charges lead to more luminosity,
but also to more beam-size growth through internal scattering and nonlinear dynamics.

Solution: cool hadron beams or replace frequently.

Both 1.E34 luminosity designs for the EIC need cooling.

(A) Scattering Cooling:

(both magnetized or not, and storage ring cooling)

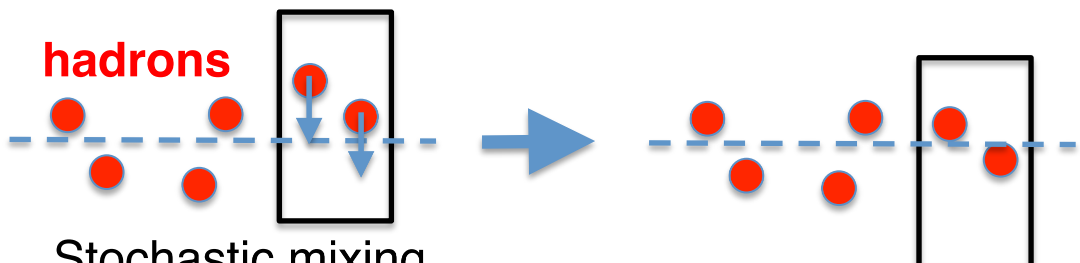


In the rest frame of both beams

Both need ERL-type currents!

(B) Stochastic cooling:

(Coherent eC, micro bunching, optical SC)



Stochastic mixing of who is in the slice.

Correct the dipole moment of slices.

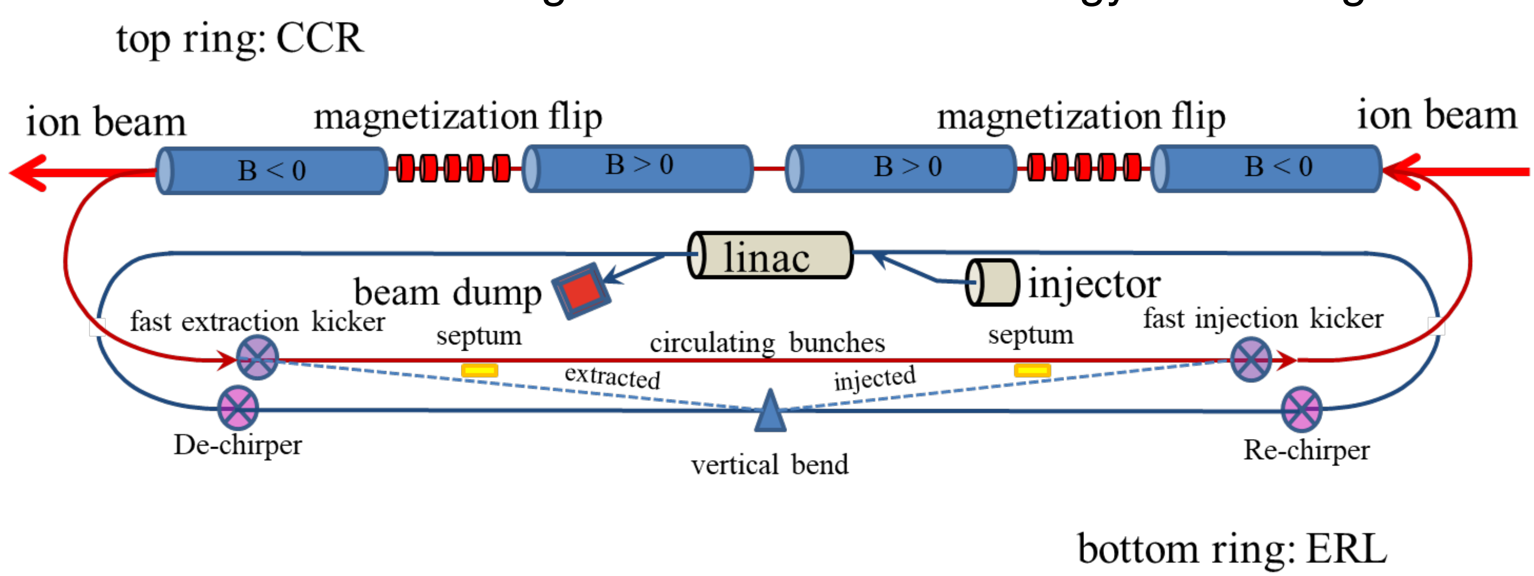
The correcting kick is done by an electron beam.

High Electron Currents are needed

Both cooling methods need **very high current** electron beam with **very little divergence** to be effective.

As the NAS study maintains, such beam can only be produced by Energy Recovery Linacs (**ERLs**)

(A) Scattering cooling with keeping electrons parallel in a B field: **1 Ampere**
Fast harmonic kicker fills a ring for 11 turns before energy recovering that beam.



(B) Stochastic cooling has designs for : **0.1 Ampere of the 150MeV beam => 15MW**
Factor of 10 more than what was done before.

CBETA capabilities for EICs

- 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 with world-wide support, incl. JLAB, KEK, HZB, TU Darmstadt, JG-University Maiz, ASTEC.

- It has applications beyond EIC research

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.

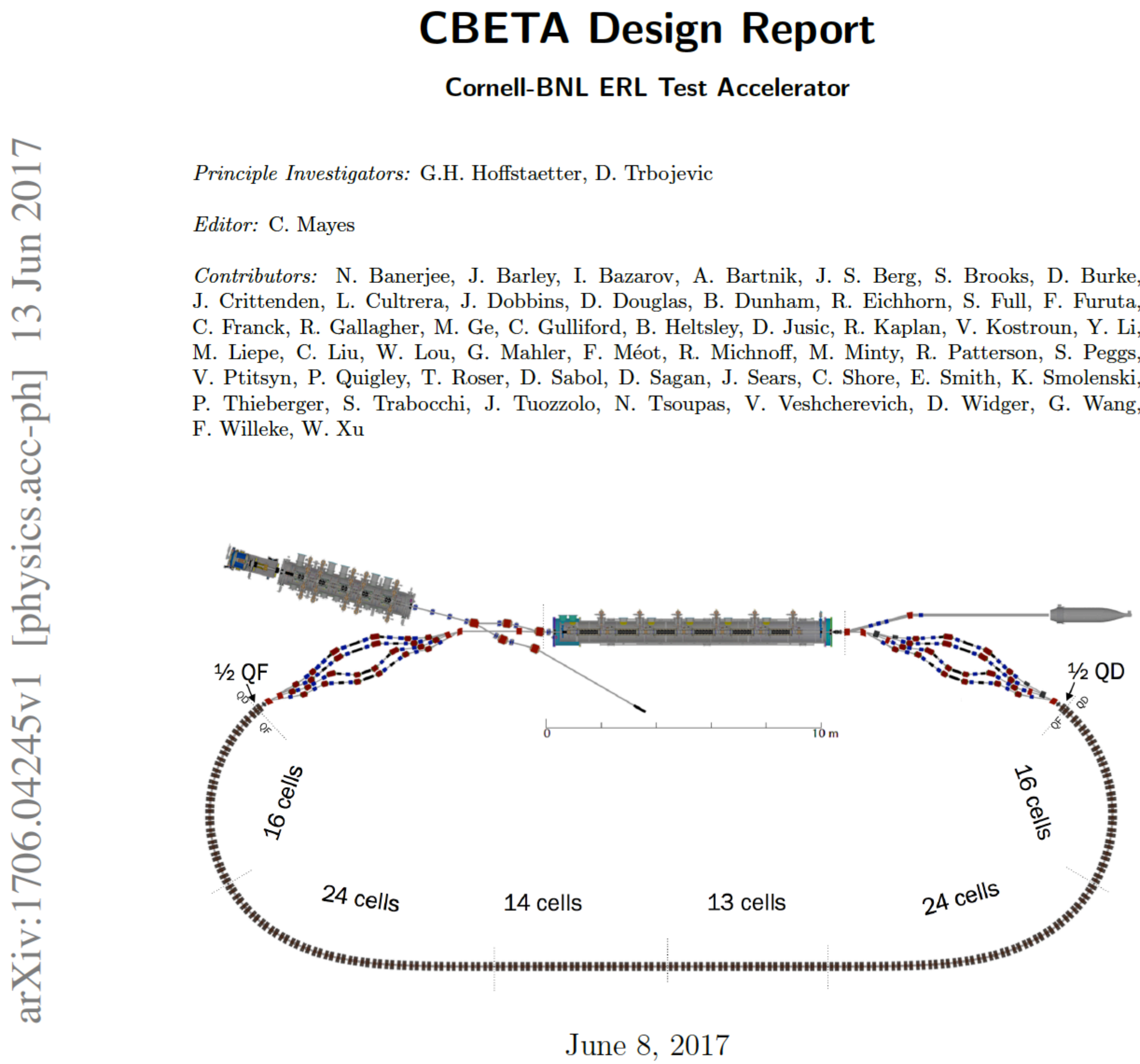
2016 Construction funding by NYS

2017 CBETA Design Report

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

2019 1st energy recovery with 1 turn.

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


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

CBETA Design Report

Cornell-BNL ERL Test Accelerator

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Editor: C. Mayes

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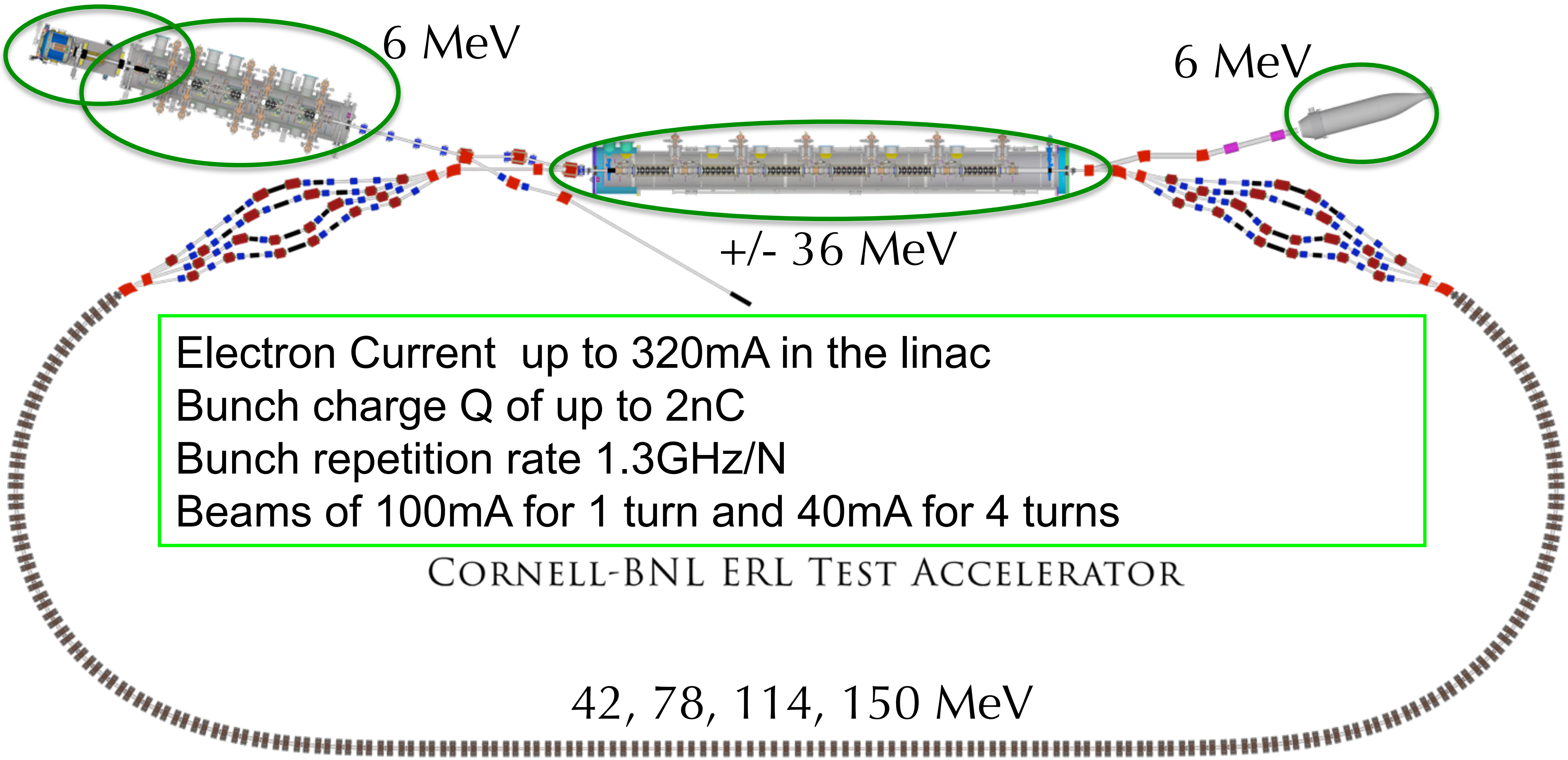
June 8, 2017

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)

Prototyped ERL 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

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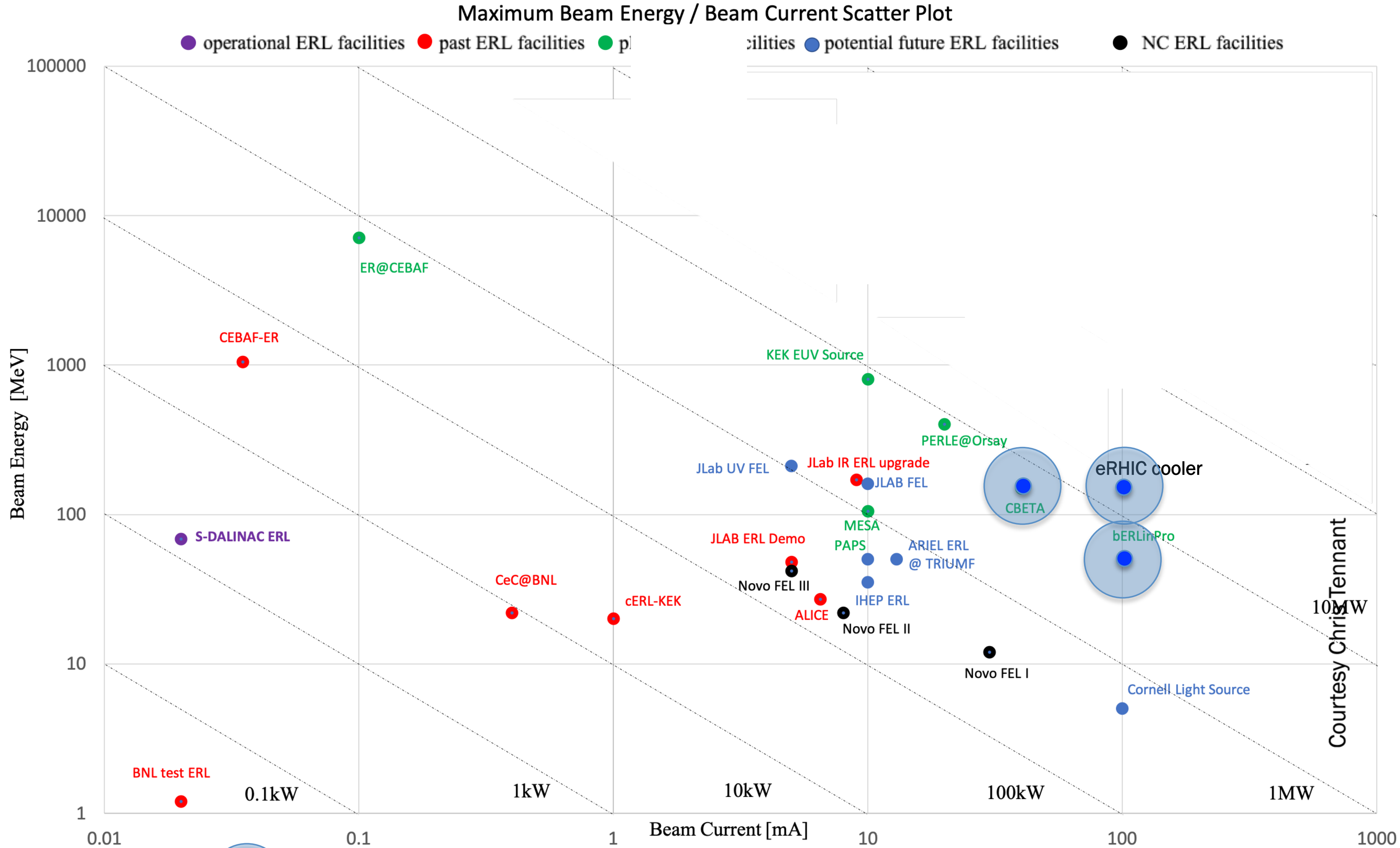
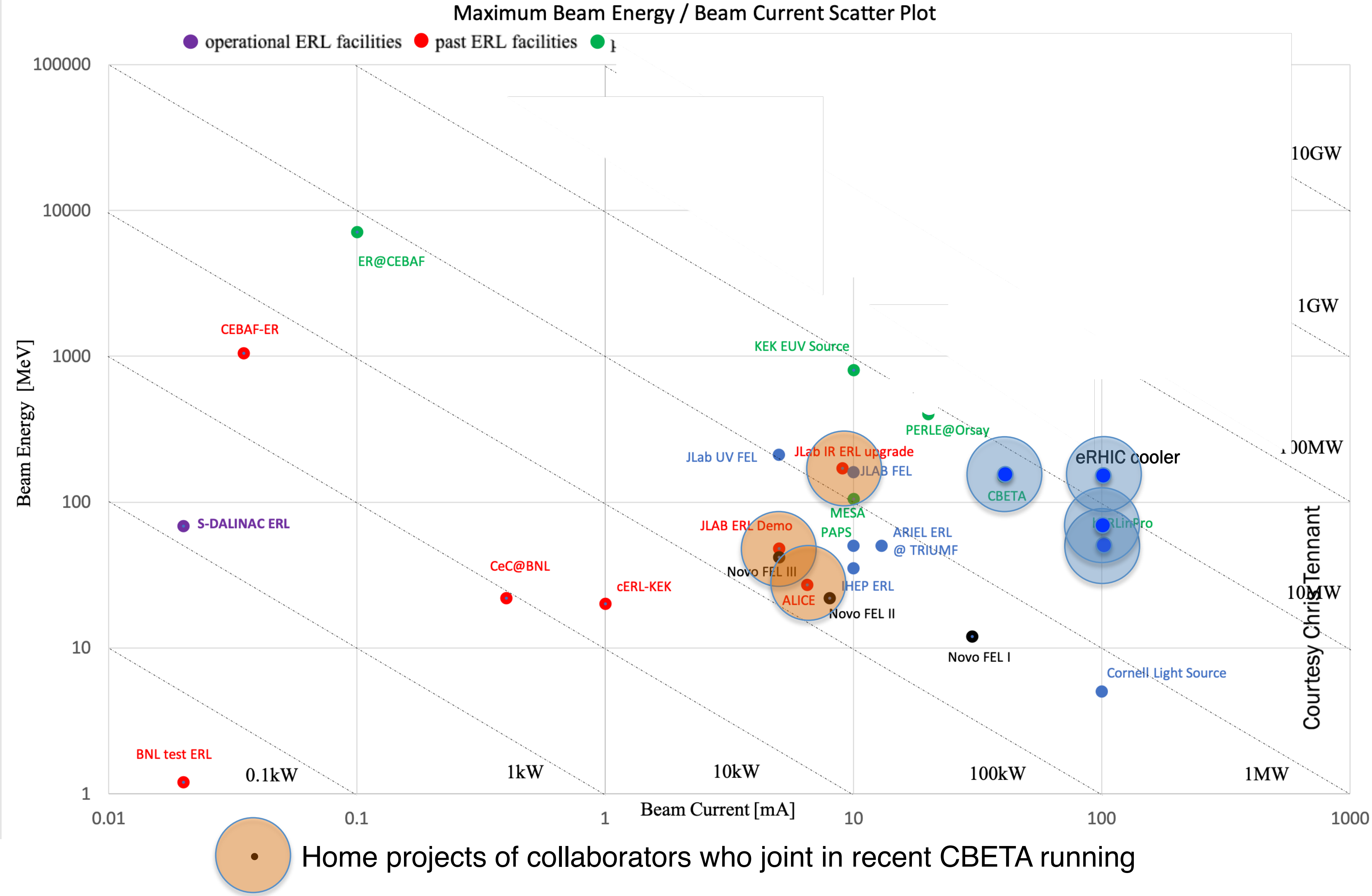
The beam power frontier



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

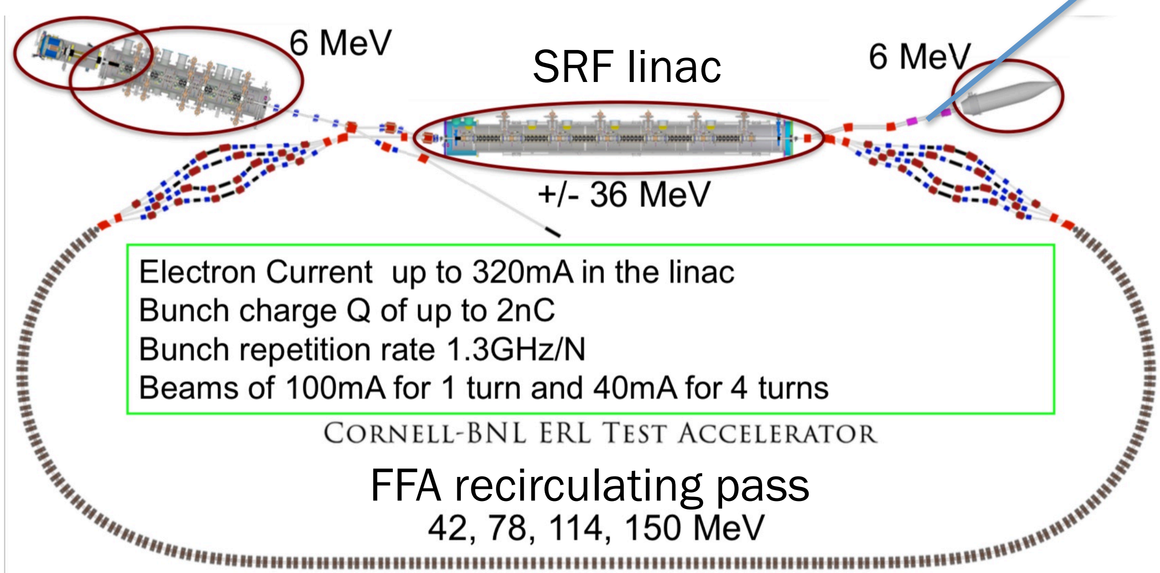
The beam power frontier

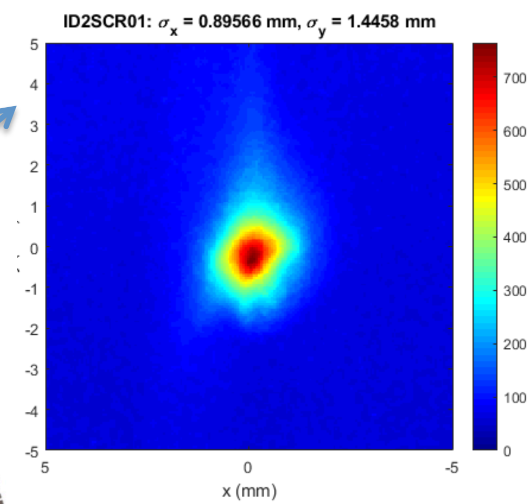


Home projects of collaborators who joint in recent CBETA running

Cornell-BNL ERL Test Accelerator

- 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 is underway.





First energy-recovered beam spot @ CBETA

Hall L0E before CBETA

L0E contained approximately 7,000 square feet of Lab and Shop space until 2014

Spring 2015

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

CBETA mid February 2019

Maury Tigner, the inventor of ERLs

CBETA mid February 2019

CBETA installation at Cornell
Magnet work at BNL before transport to Cornell

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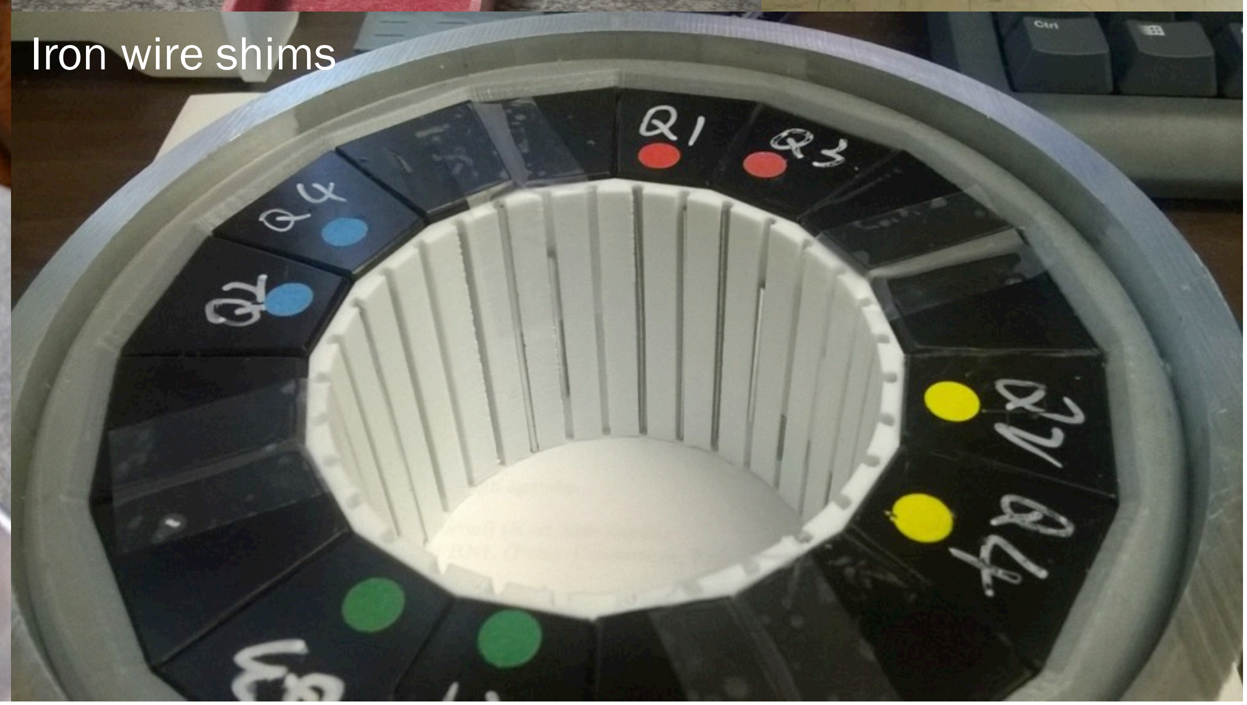
12 proof-of-principle magnets (6 QF, 6 BD) have been built as part of CBETA R&D.
Iron wire shimming has been done on 3 QFs and 6 BDs with good results.

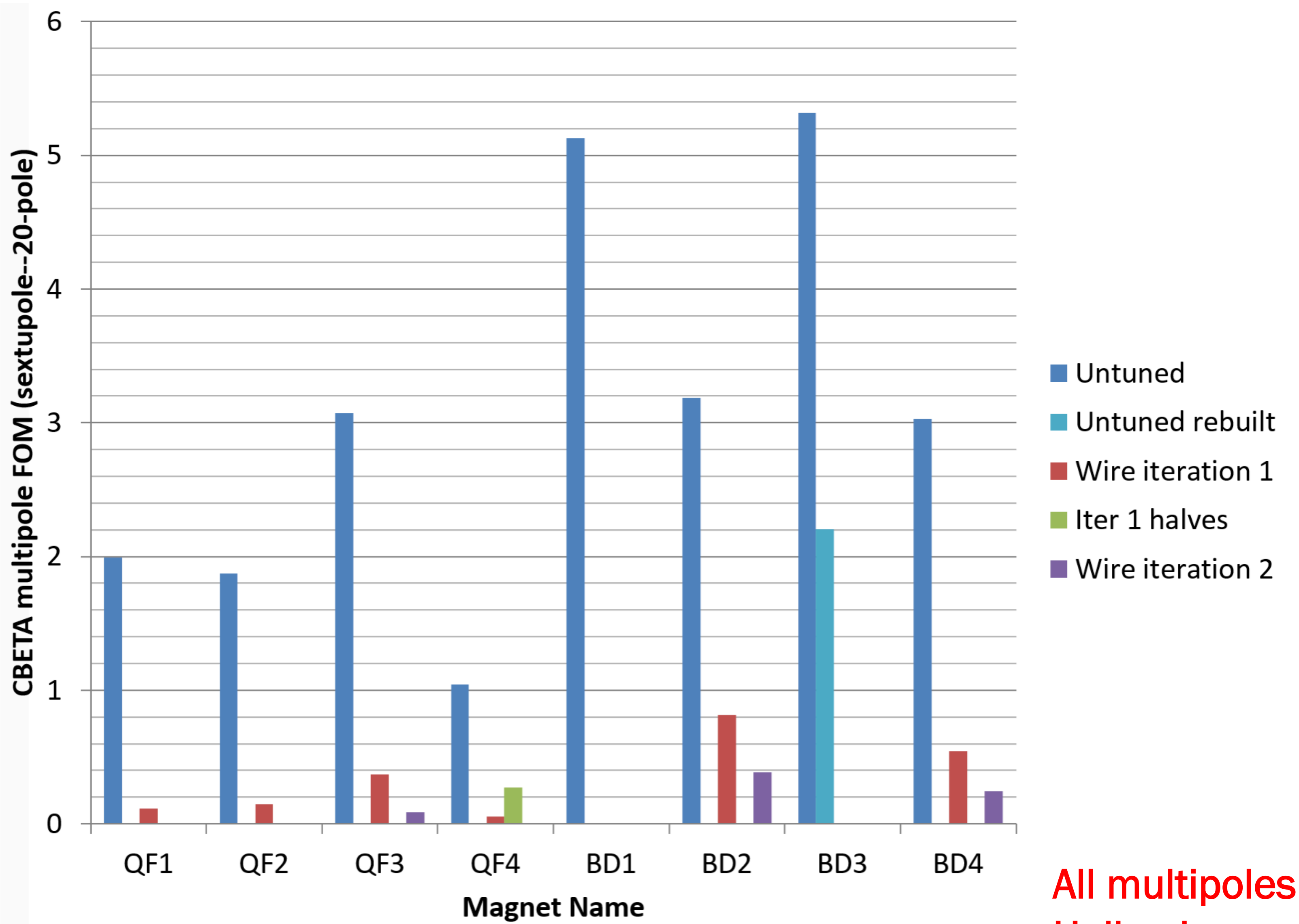

PoP QF


PoP magnet series


PoP BD

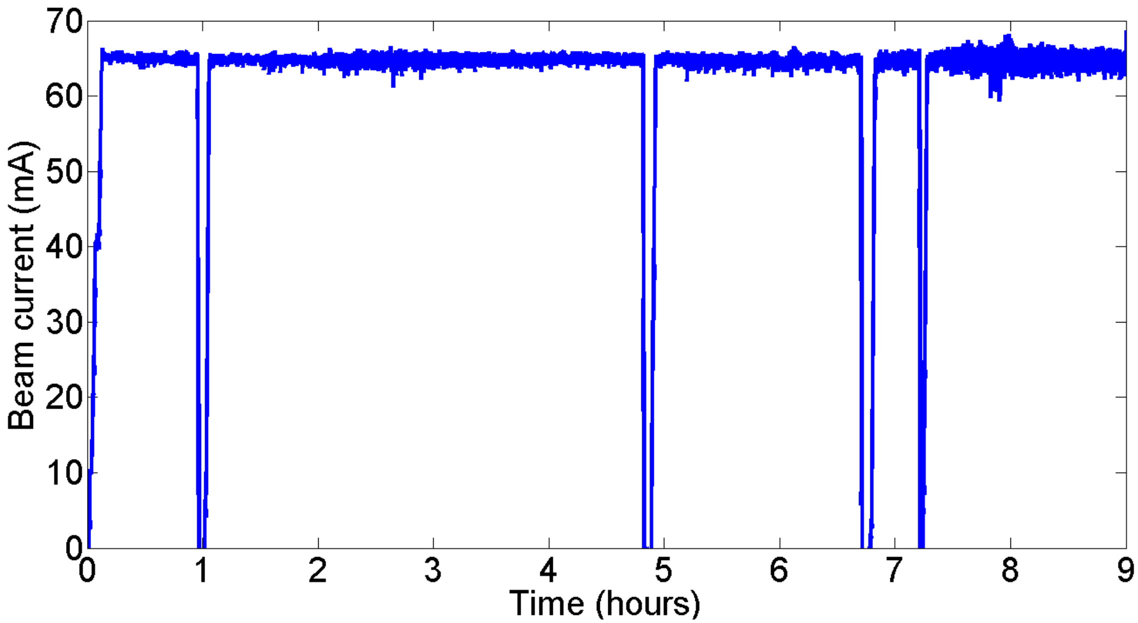

Iron wire shims

Iron Wire Shimming Improvement



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

High Current Beams



- Peak current of 75mA (world record)

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

Source achievements:

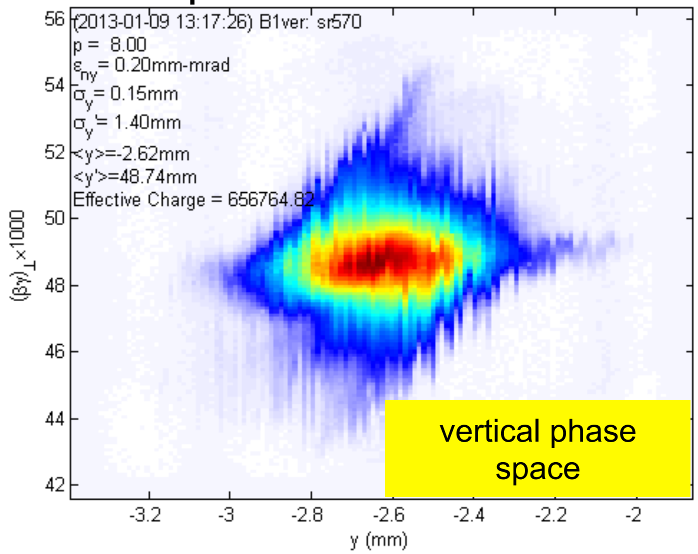
- 2.6 day 1/e lifetime at 65mA
- 8h at 65mA
- With only 5W laser power (20W are available)
- now pushing to 100mA

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

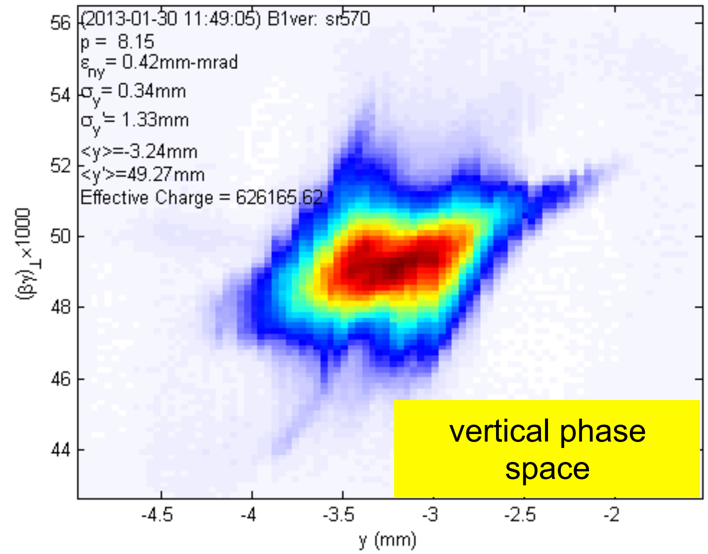
✓ Source current can meet CBETA needs

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)

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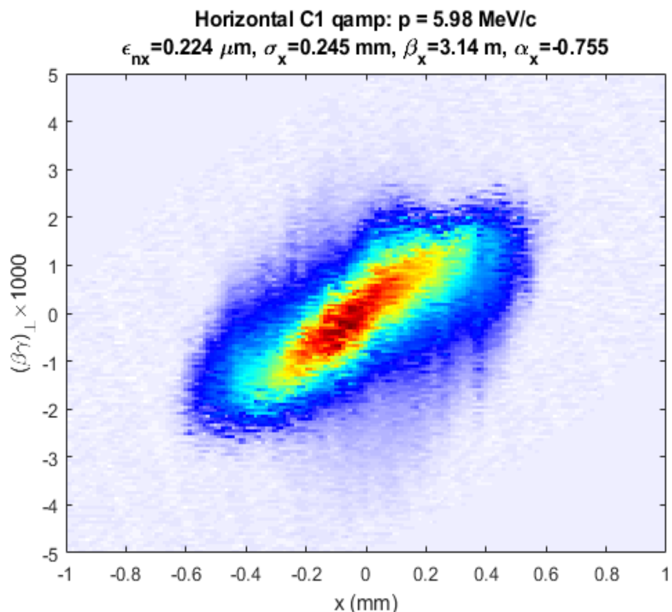
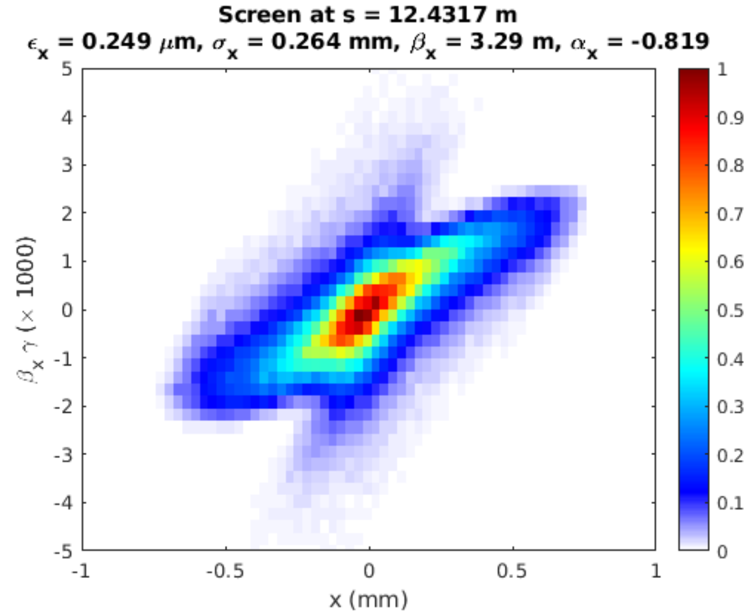
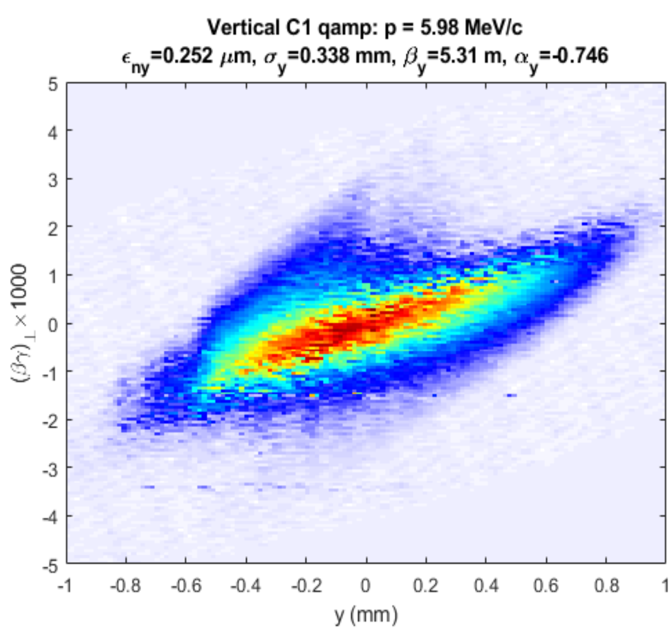
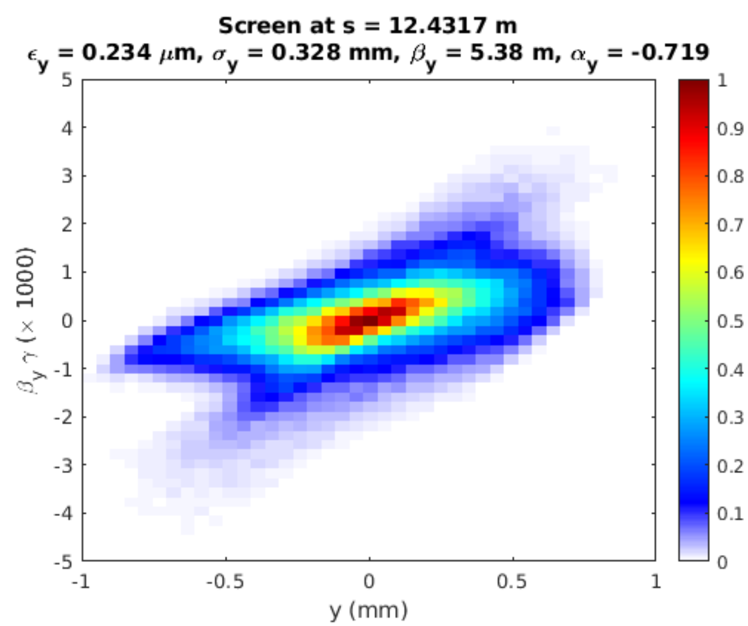
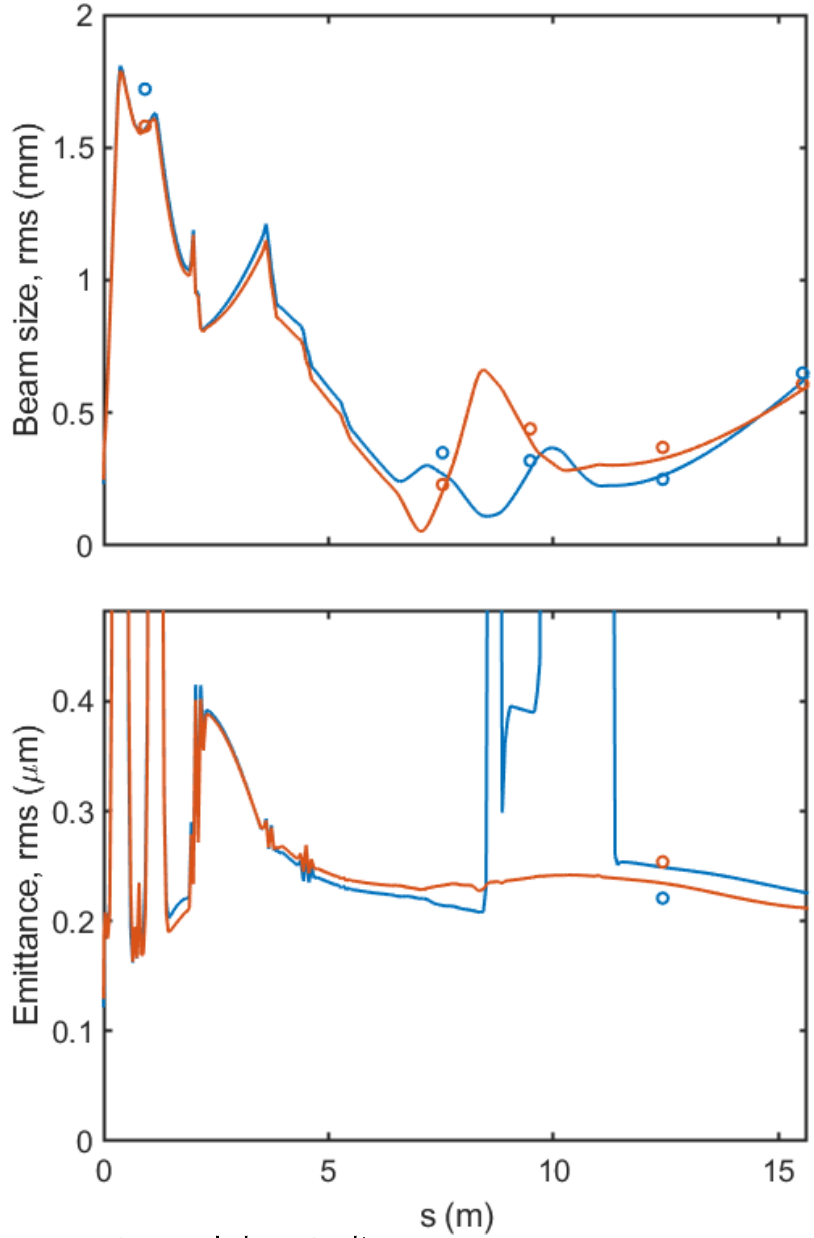
CBETA

	Measured	Simulation
Horizontal		
Vertical		

High precision injector installation

Beam size

Emittance



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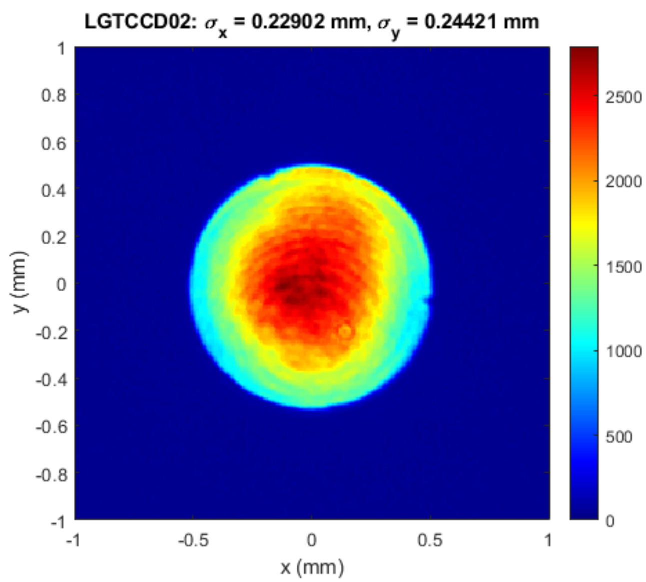
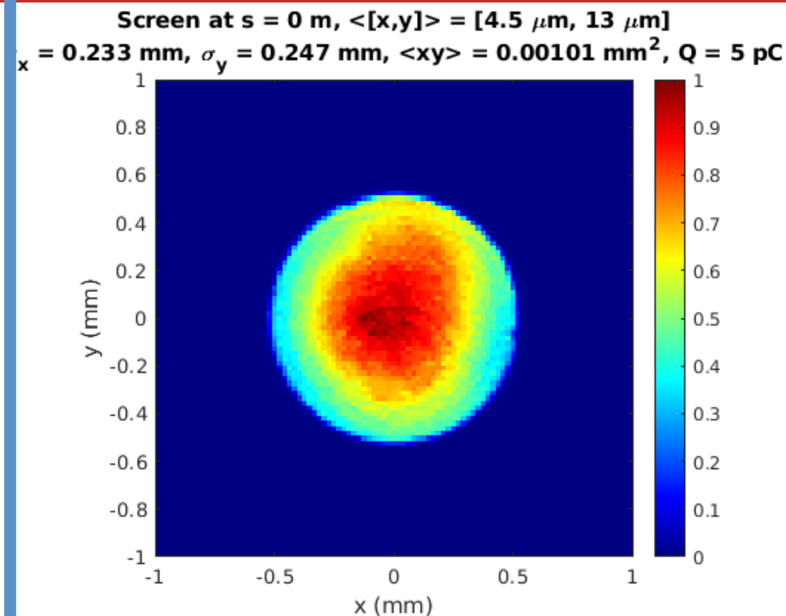
CBETA

Measured

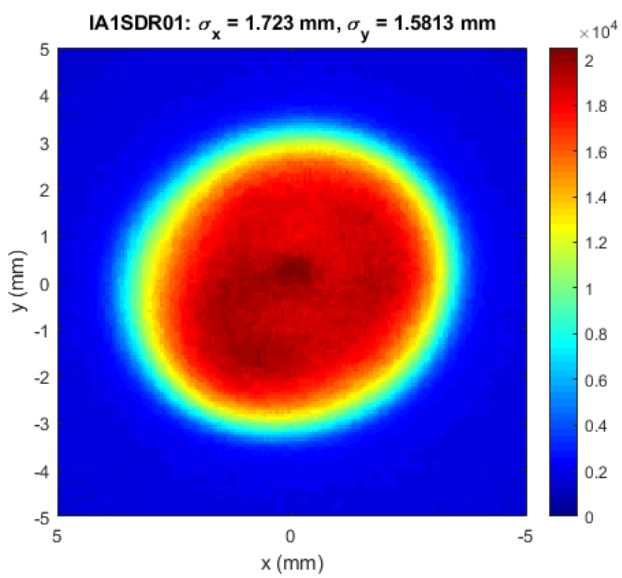
Simulation

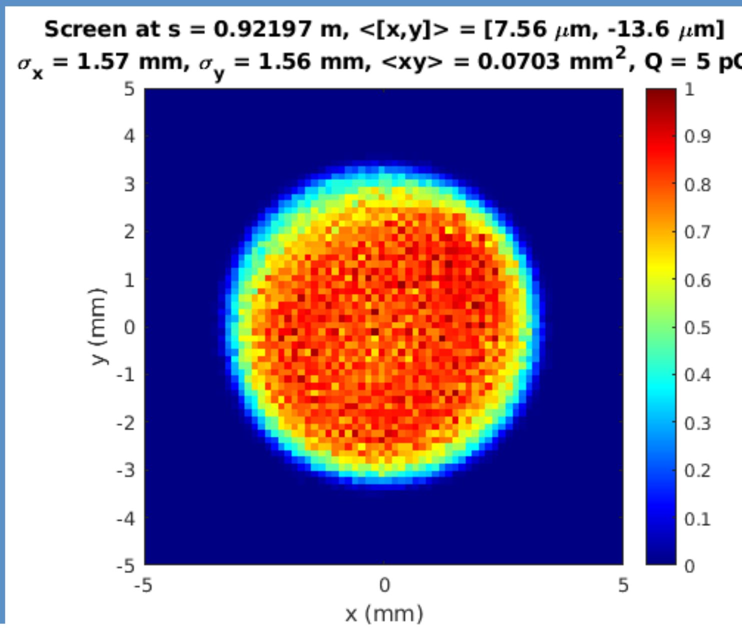
Laser





Screen A1





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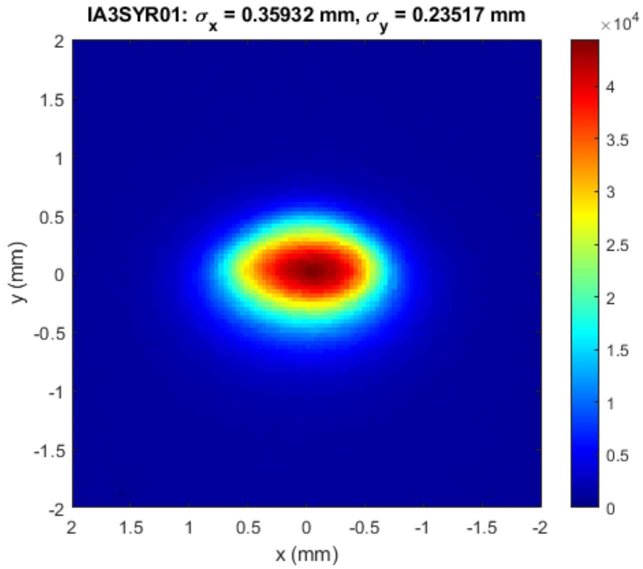
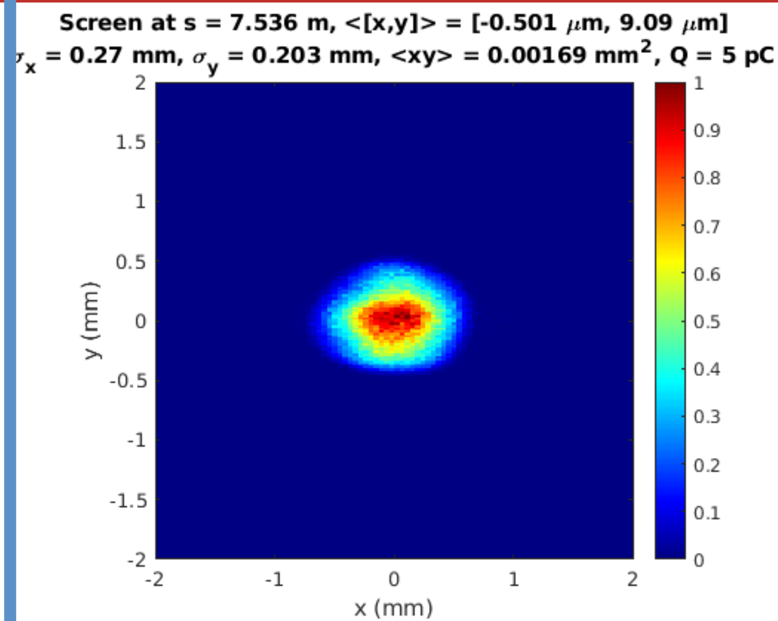
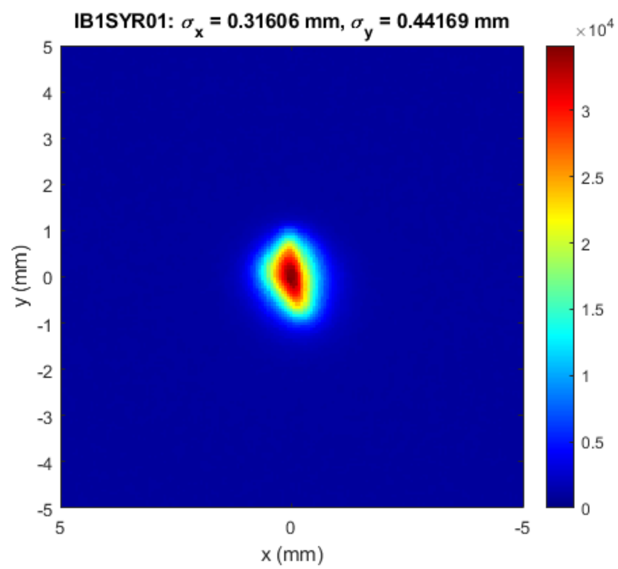
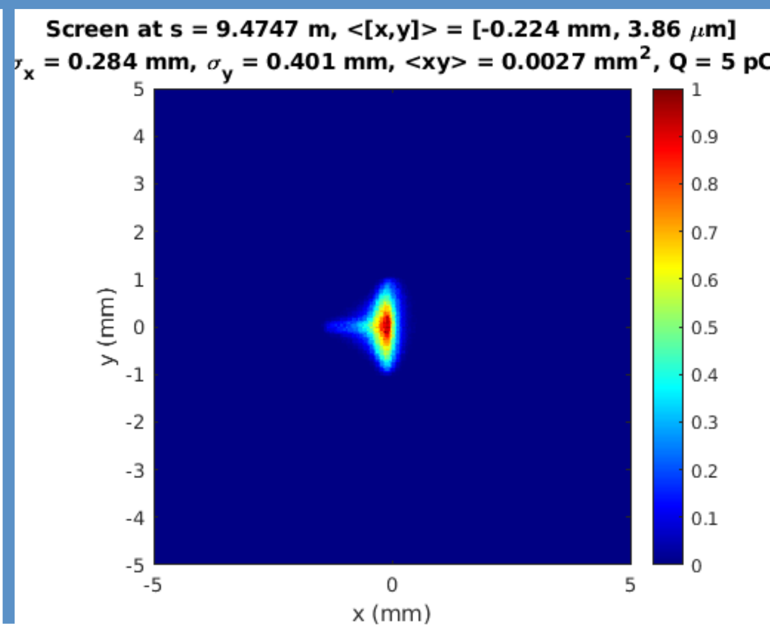
CBETA

	Measured	Simulation
Screen A3		
Screen B1		

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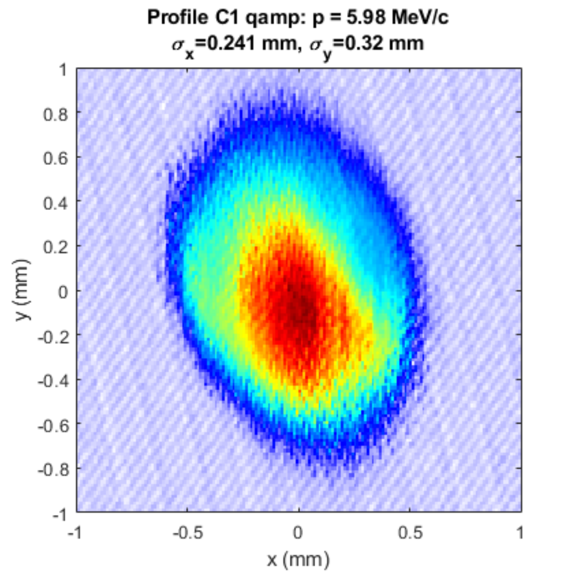
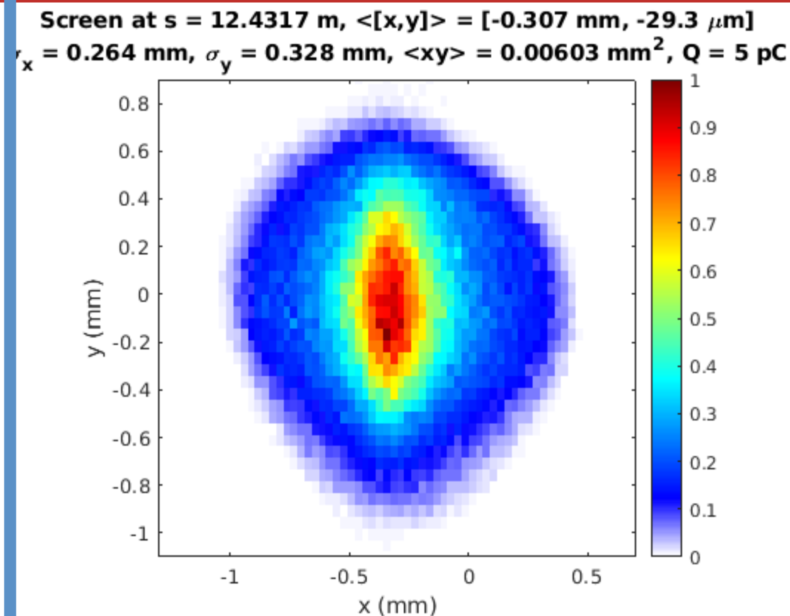
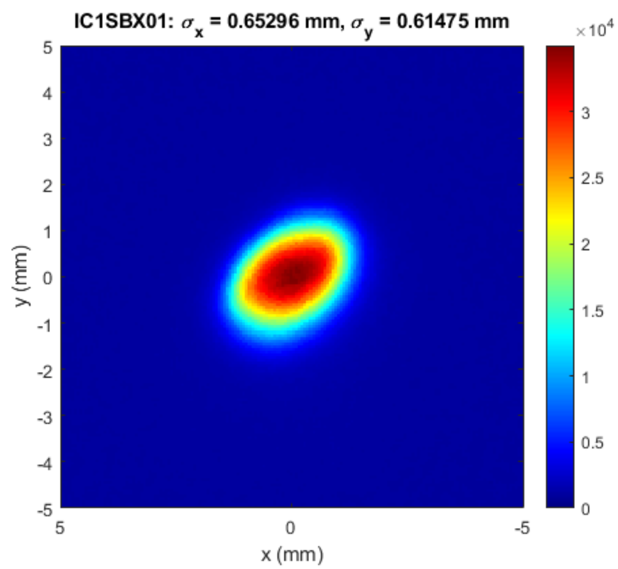
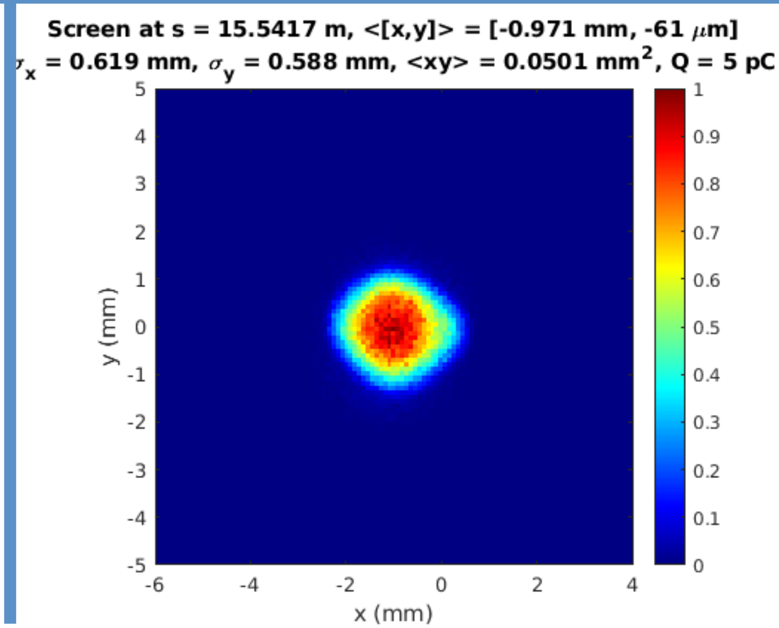
CBETA

	Measured	Simulation
Slits		
C1		



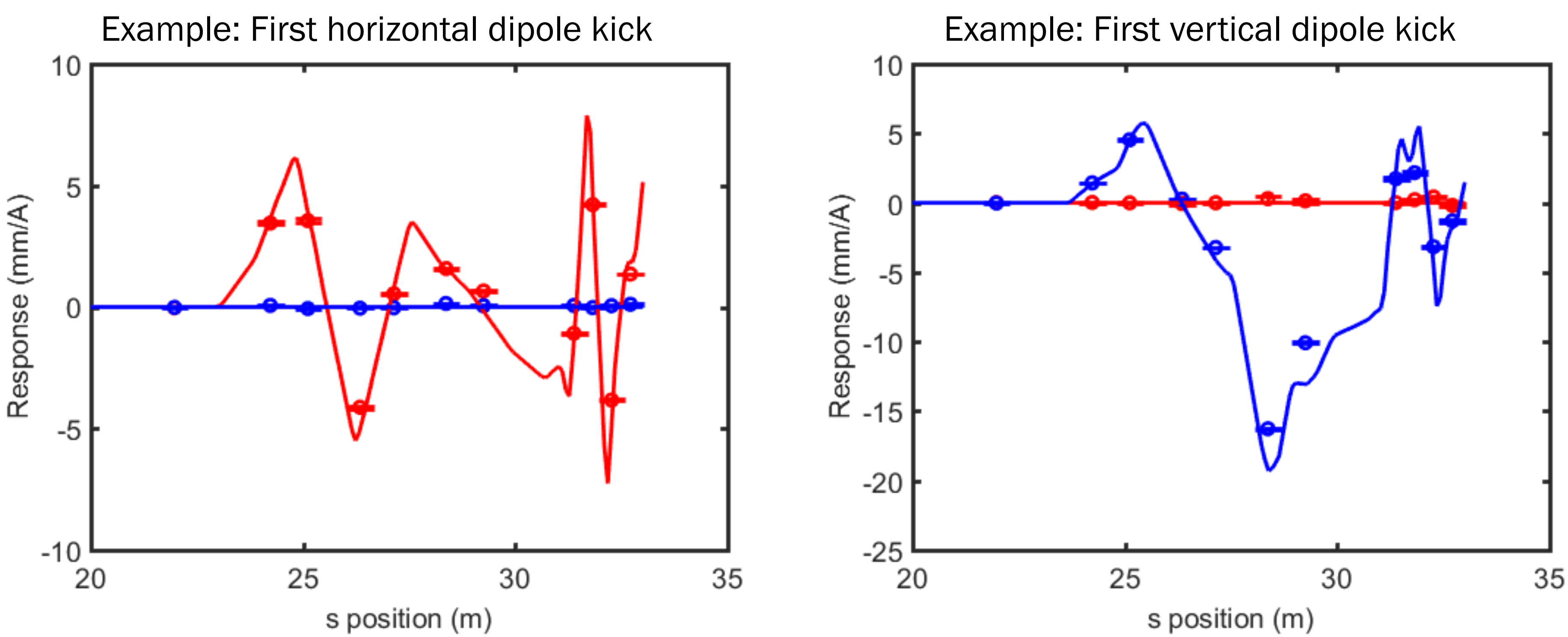






Orbit Response at 42 MeV

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



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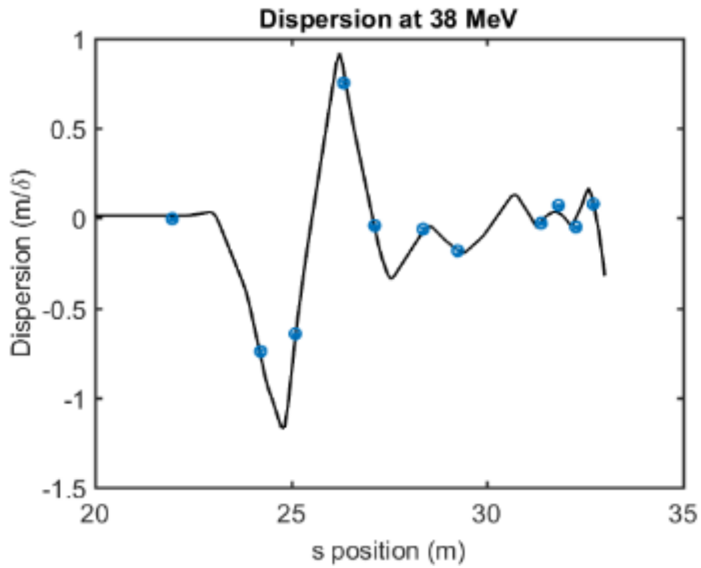
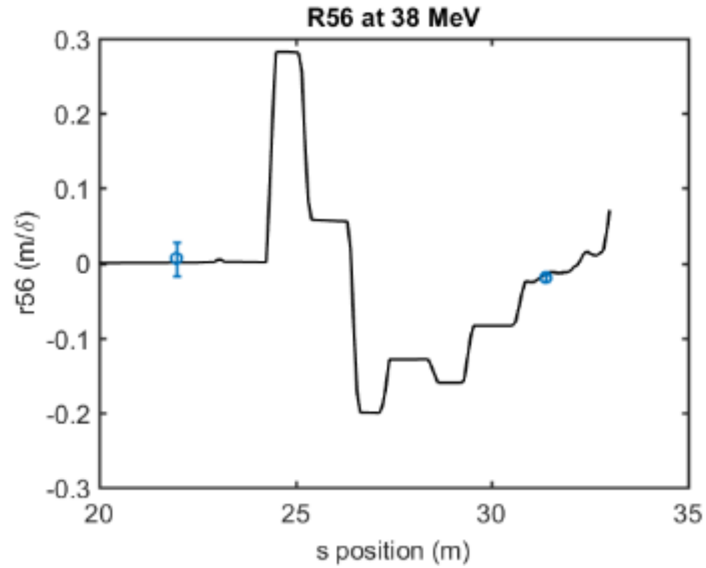
Dispersion and R56 vs. Energy

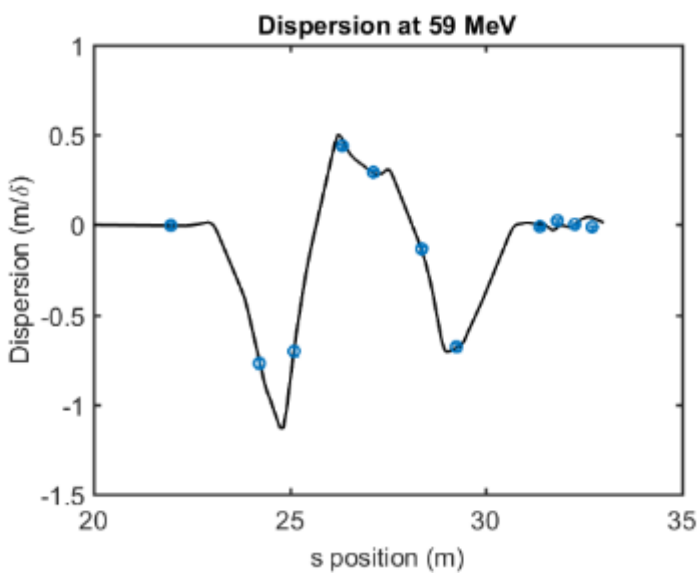
CBETA

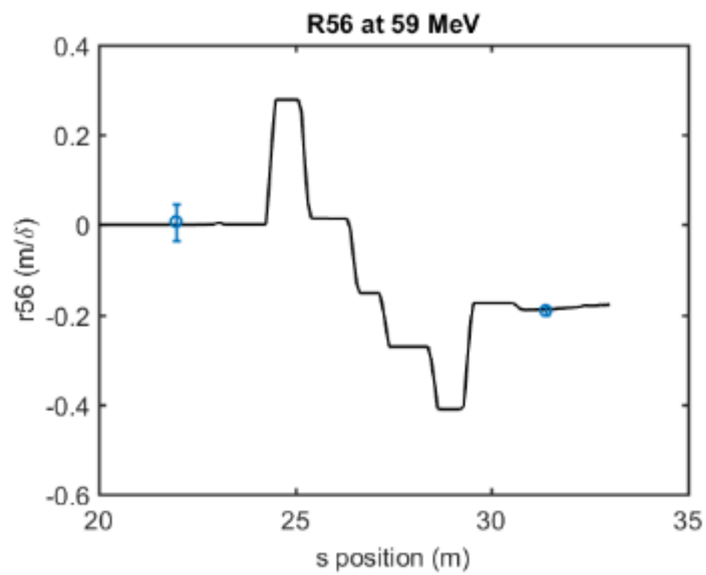
38 MeV



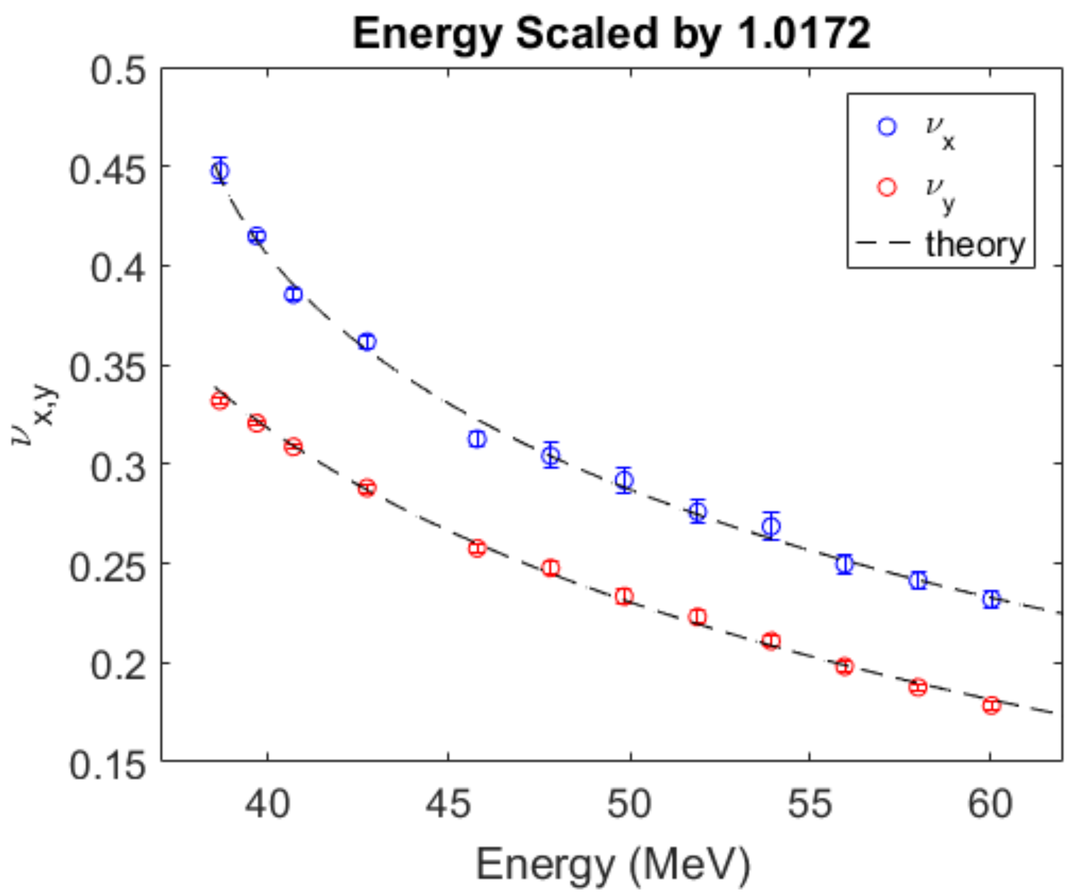


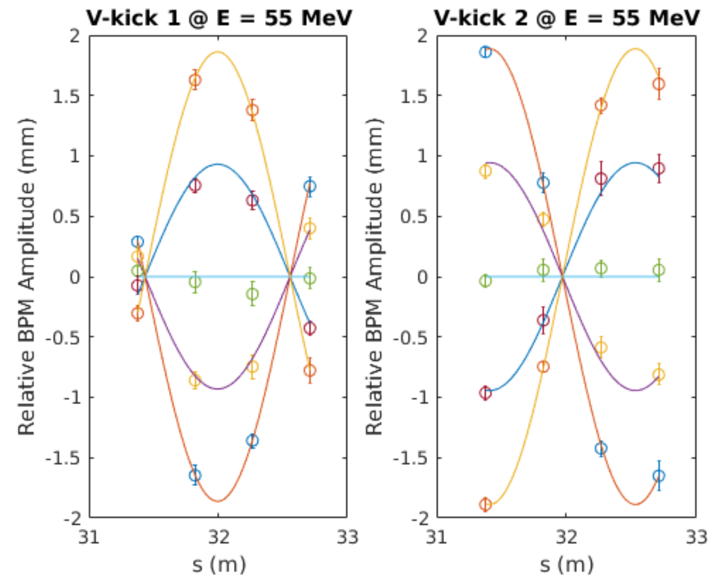
59 MeV

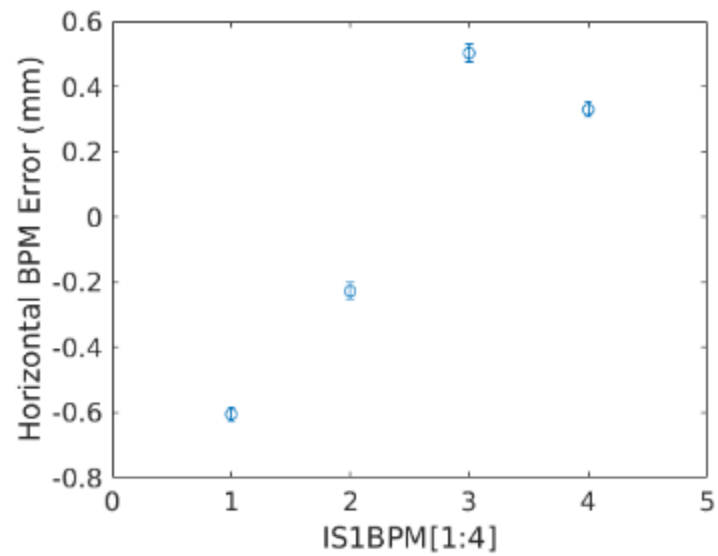




Tune Measurements vs. Energy

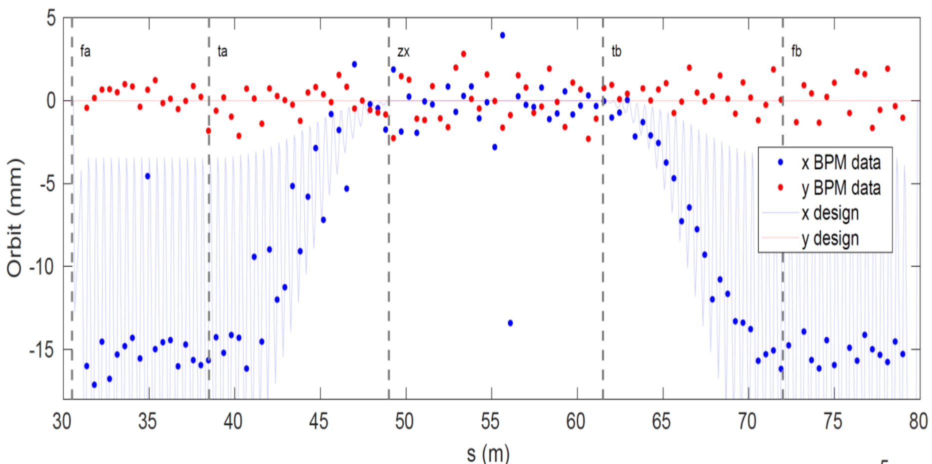




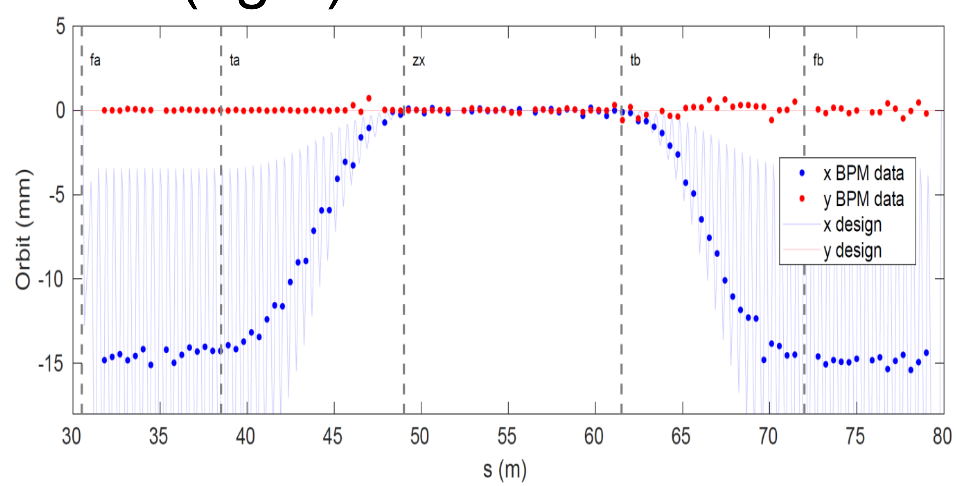


Orbit Correction

- CBETA-V and virtual machine
- Orbit correction script
  - Works using response matrix from virtual machine

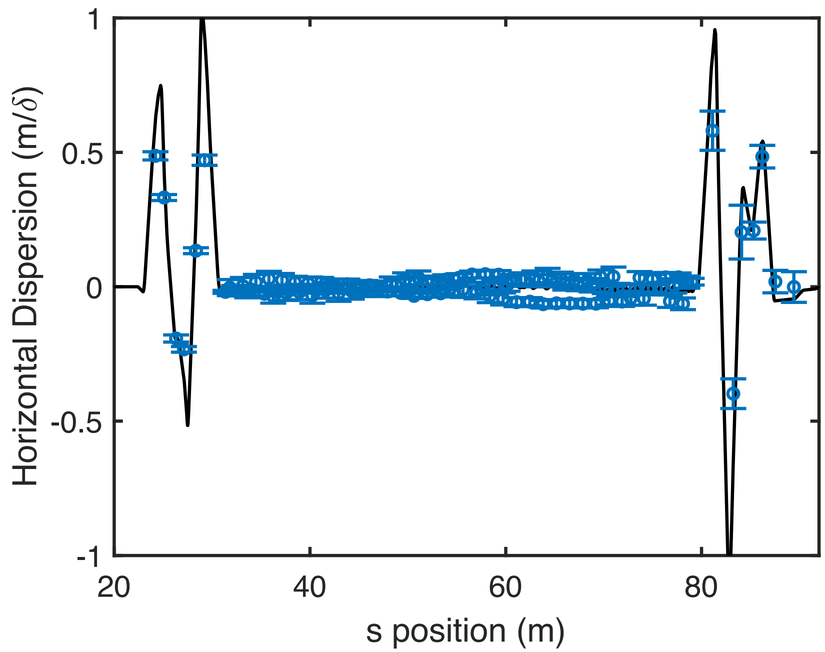


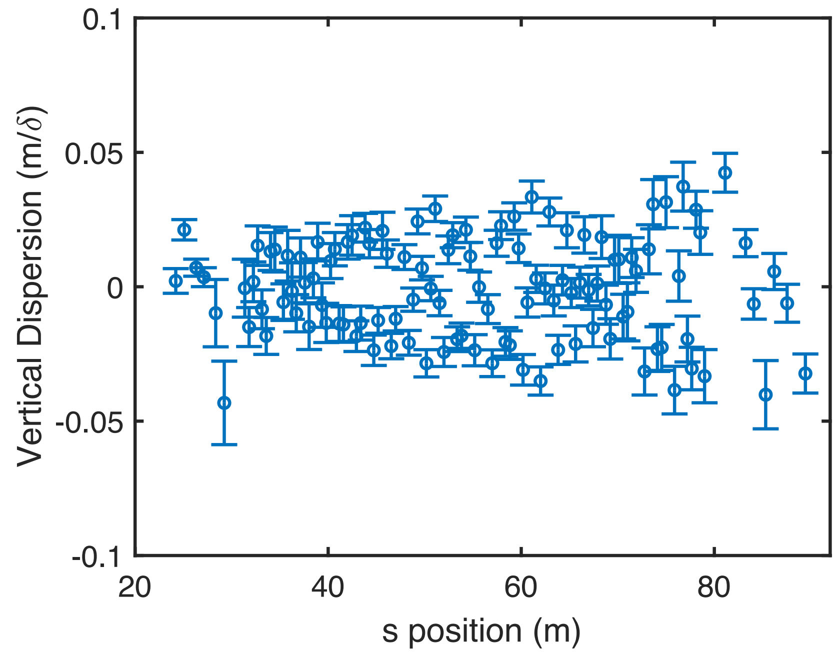
Horizontal and vertical positions on BPMs through the FFA arc for initial orbit (left) and corrected orbit (right)

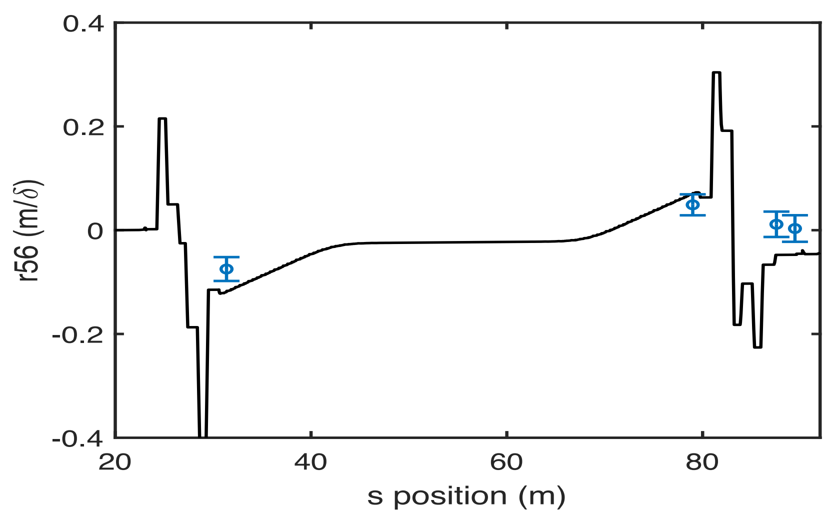


Dispersion and R56

- CBETA-V and virtual machine measure and compare with simulation

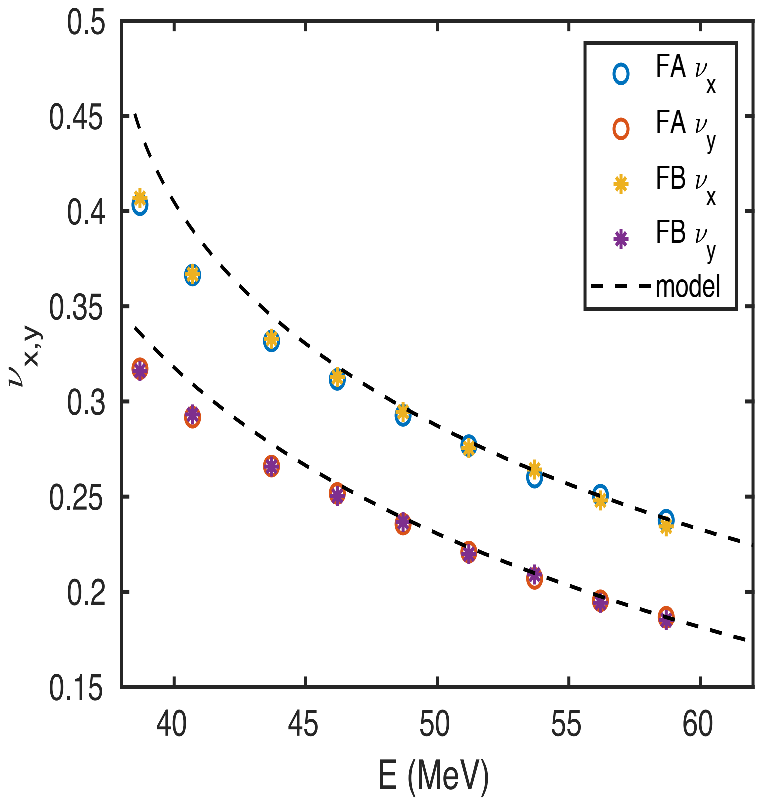


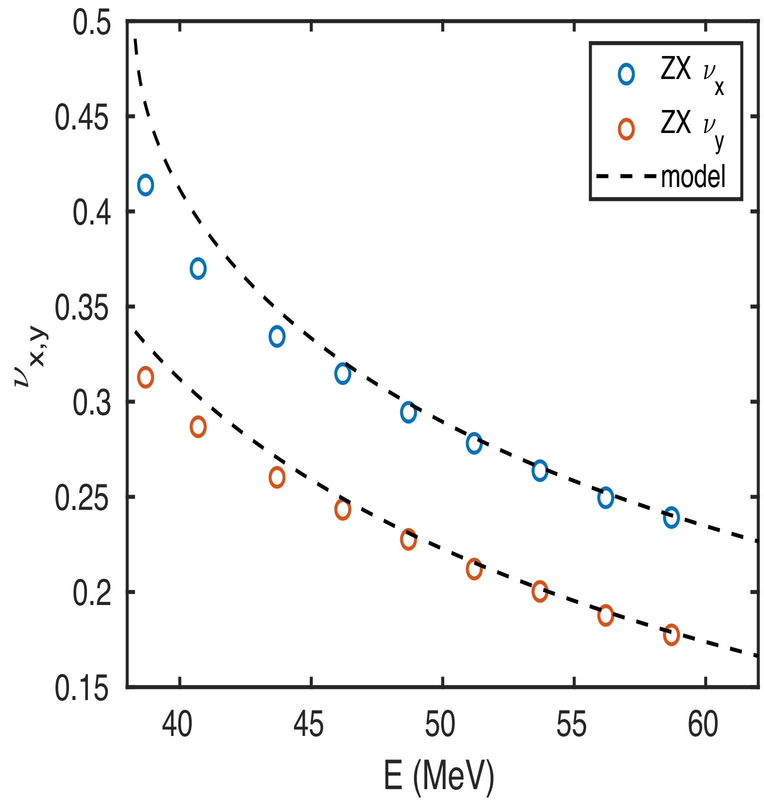




High acceptance lattice

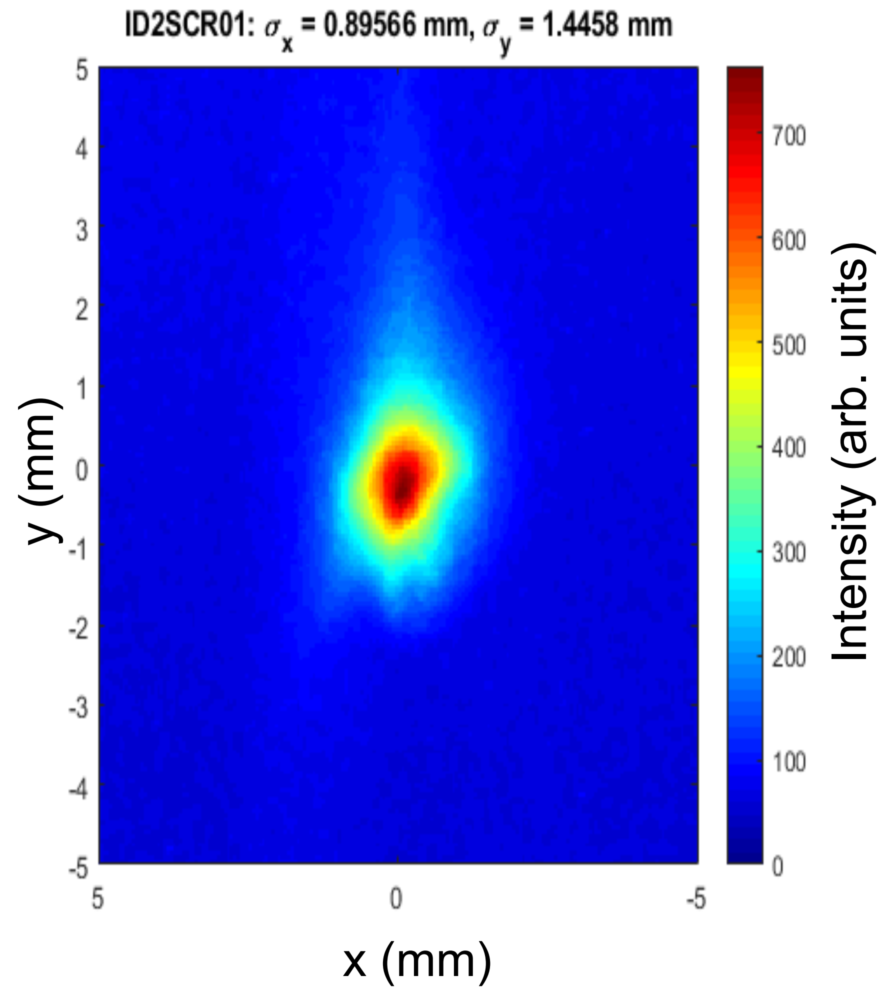
- Beam energy into the permanent magnet arc: 39 - 59 MeV (same B field)
- Energy dependent phase advances agrees well with the model
- Permanent magnet region is very clean - beam losses are hardly measurable, far dominated by other regions.





First Recirculation

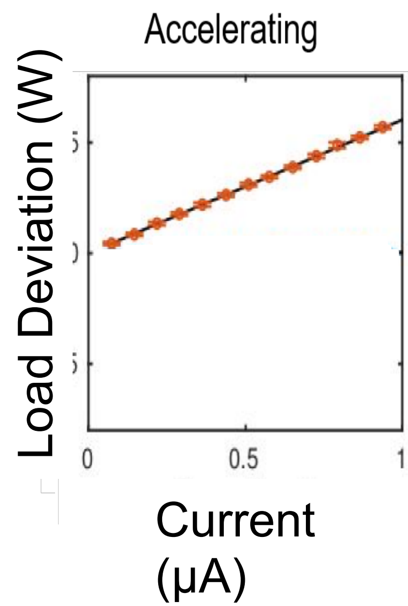
- June 10, first recirculated beam back through the MLC into the beam stop
- Beam energy at roughly 6.1 MeV (injected energy of 6 MeV)
- Beam on first viewscreen in beam stop line, shown on right

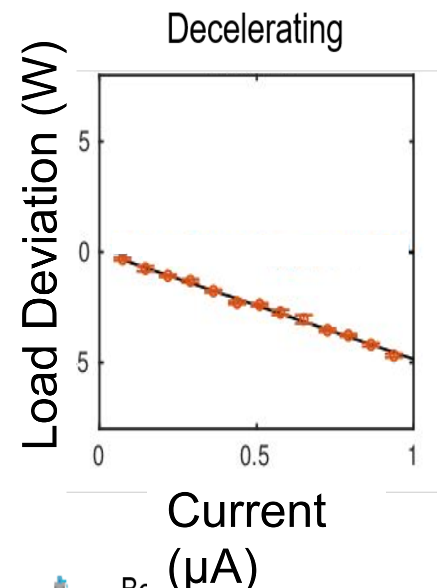


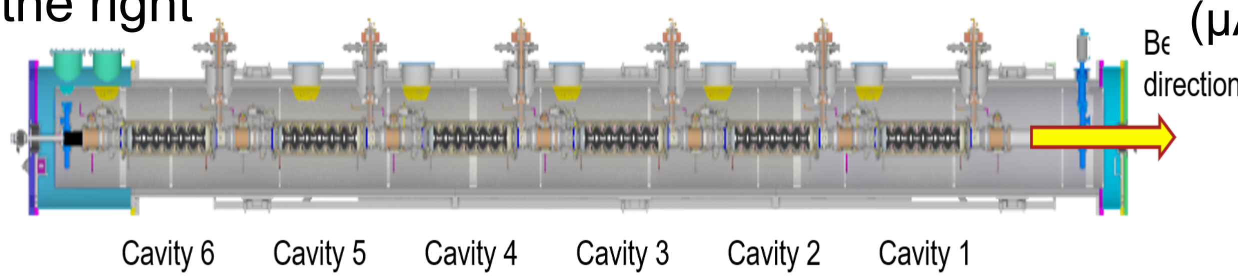
Energy Recovery

- To demonstrate load deviation in MLC cavity, the each cavity was set up near typical field – but the last three cavities decelerated the beam, sending it directly into the beam stop

- MLC labeled layout shown below, typical beam loading plots for accelerating (cavities 4-6) and decelerating (cavities 1-3) shown to the right

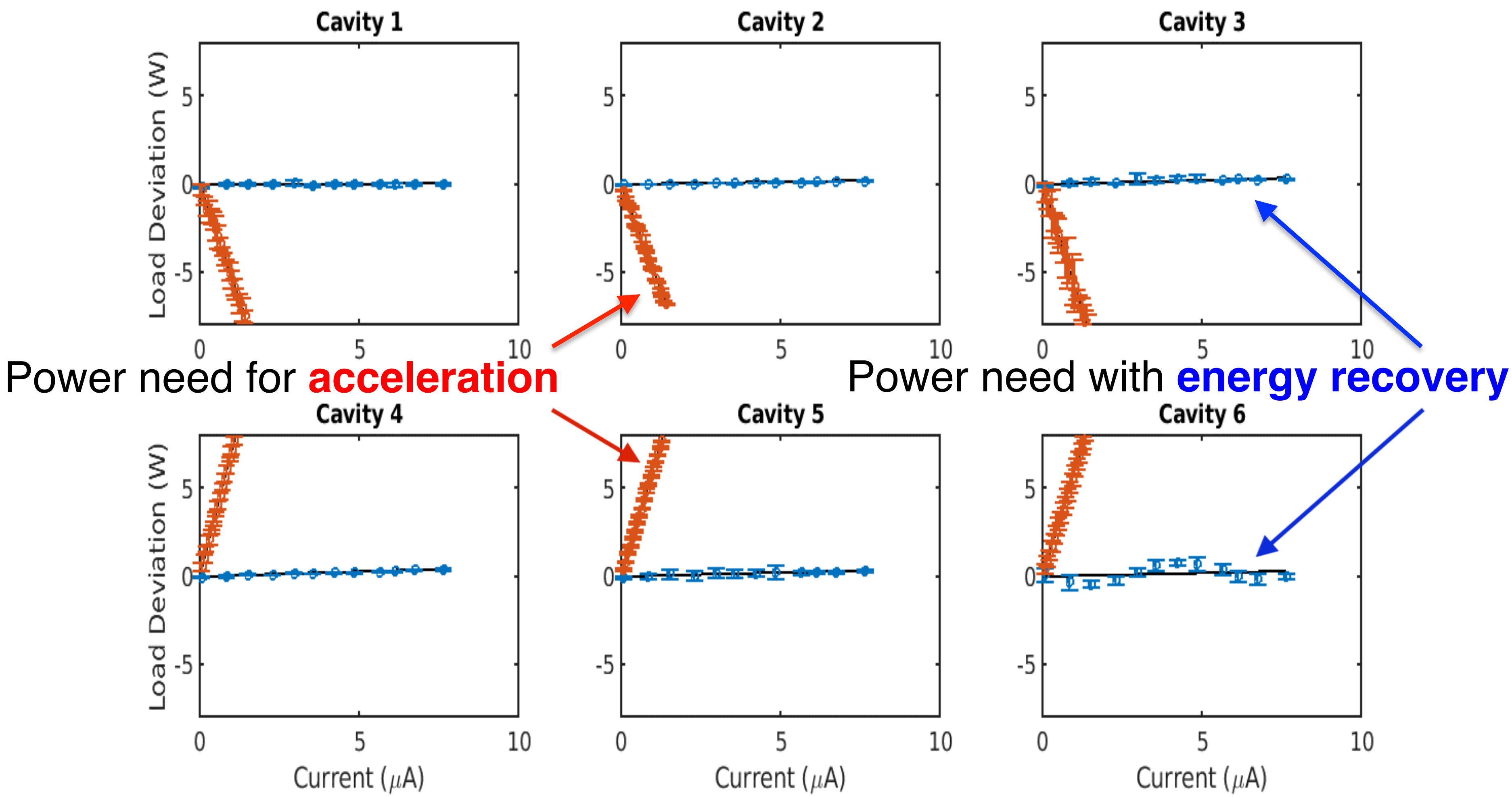




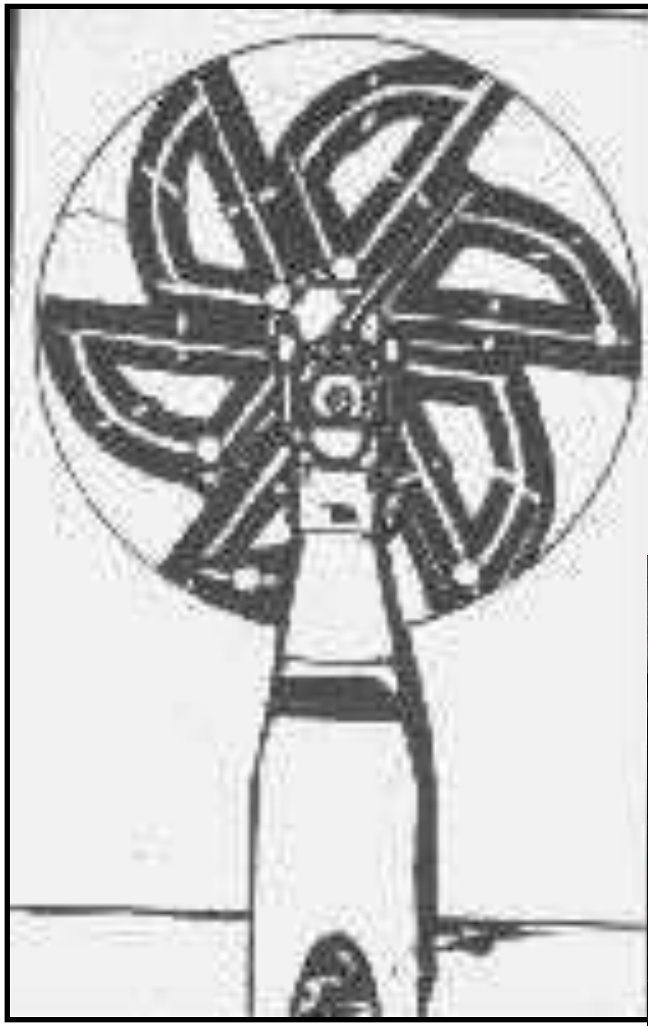


Energy Recovery in every cavity

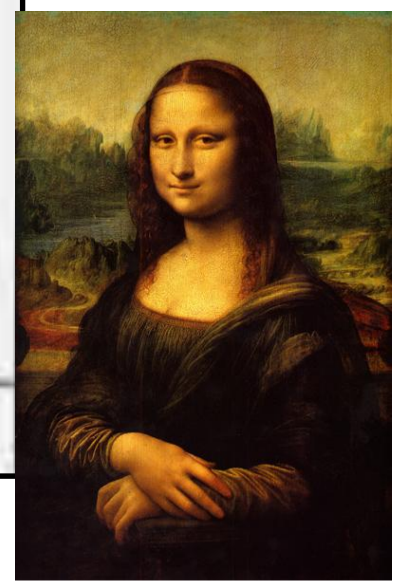
- Transmission 99.6 ± 0.1% ; energy recovery > 99.8%
- Measured up to 8 µA
- Each cavity accelerates beam **without** receiving **external power** for it.



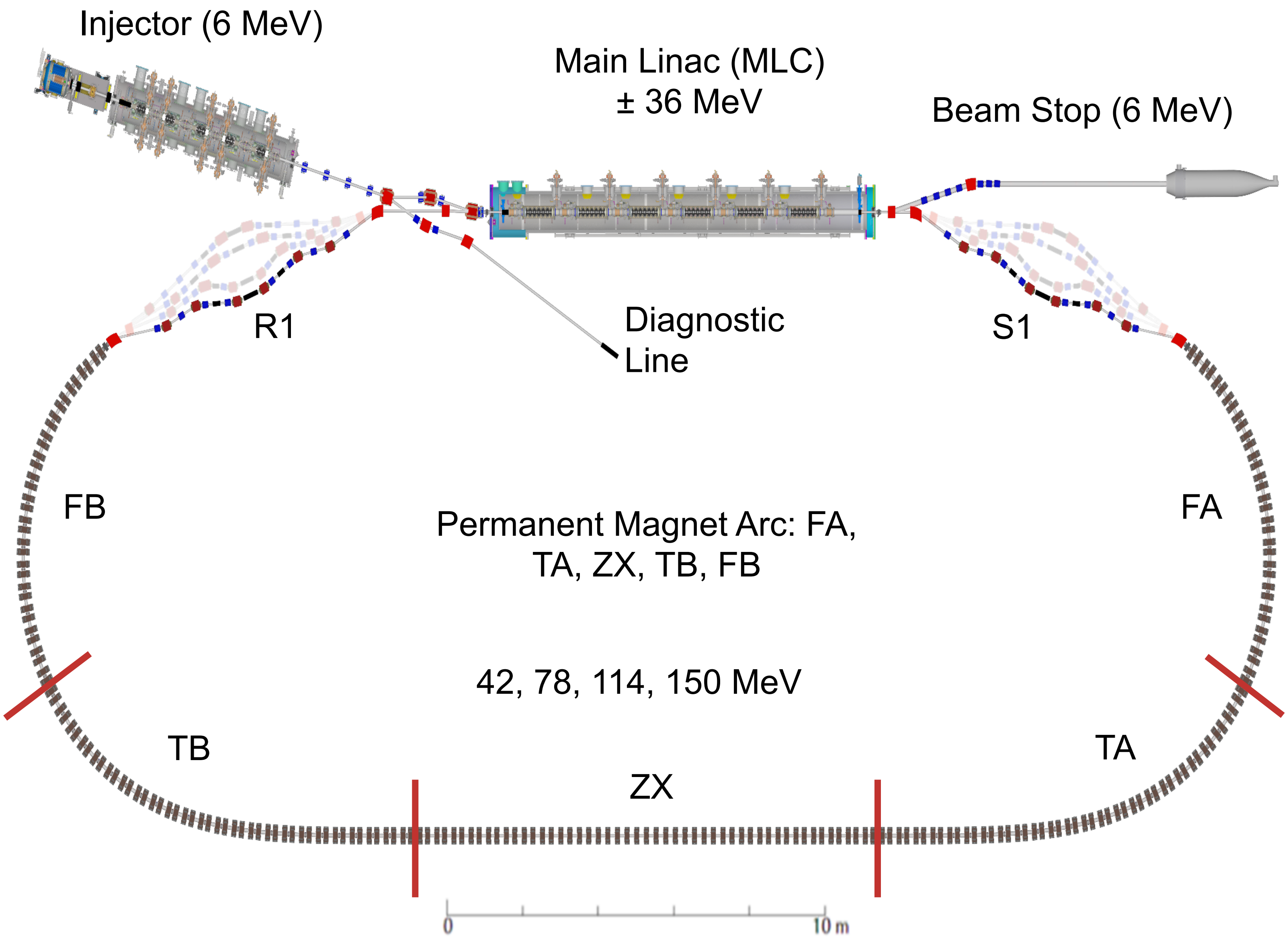
A good idea … ?



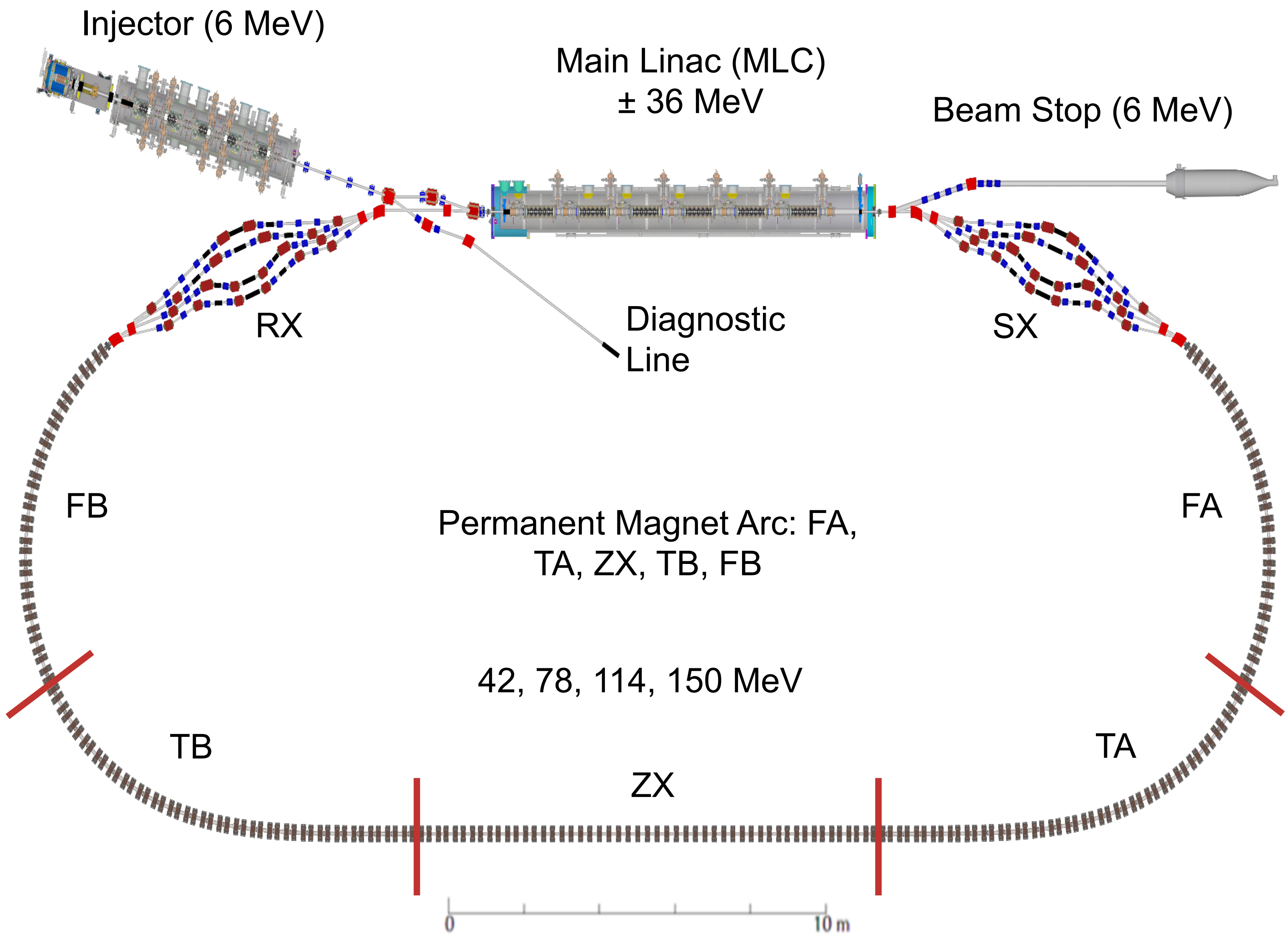
Leonardo da Vinci
(1452-1519)
France from 1516



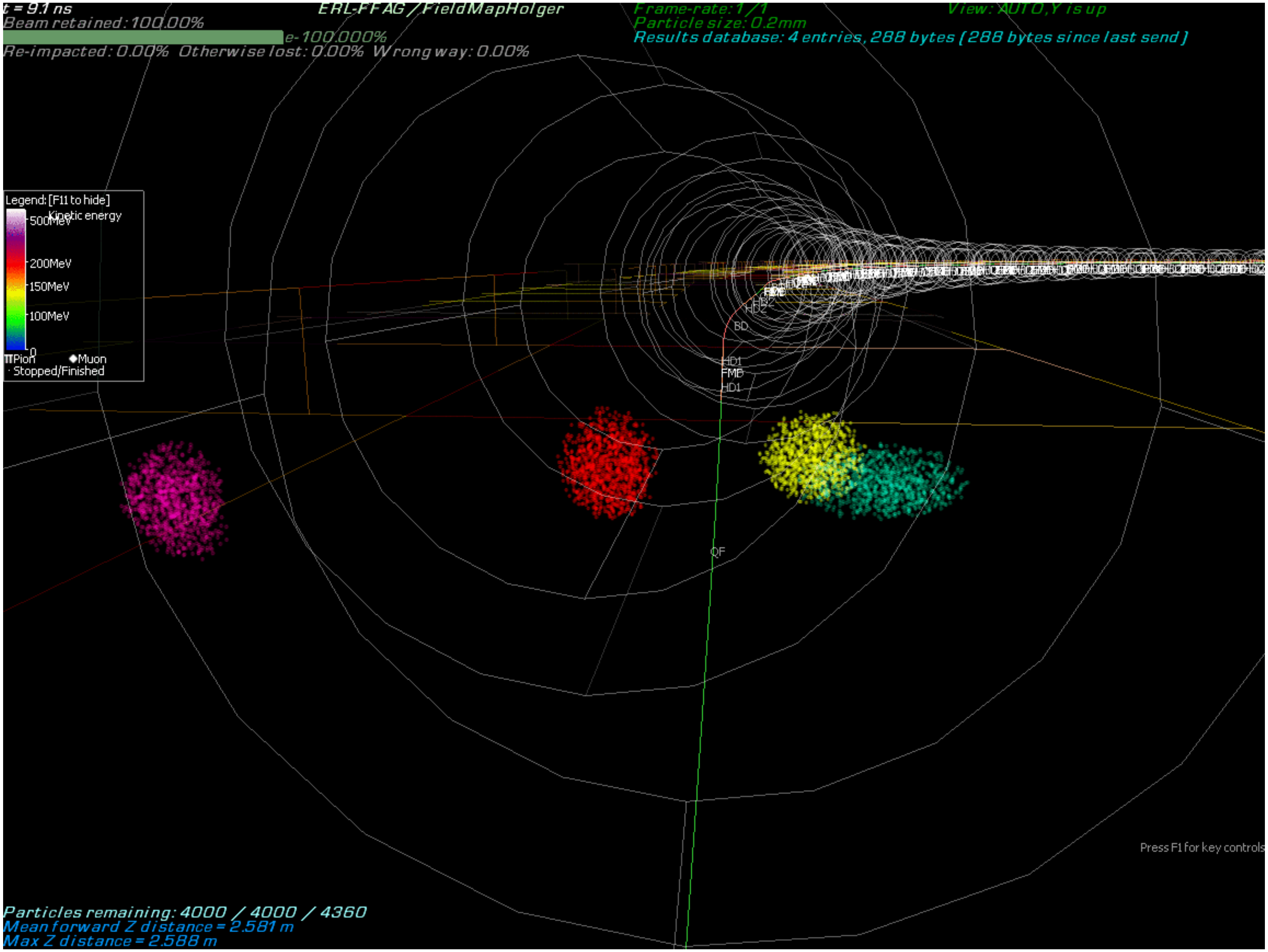
CBETA One-Pass Layout



CBETA Four-Pass Layout



Bunche dynamics in 3D field maps



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	

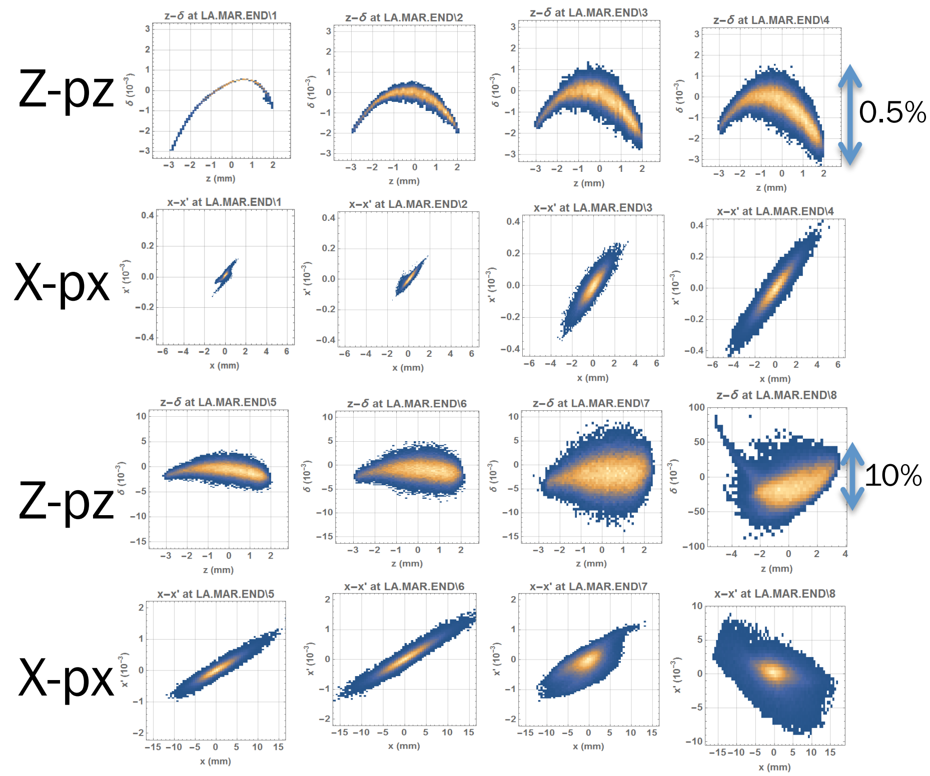
CSR energy spread and microbunching

Even for 5pC, correlated energy spread is very significant after 4 turns.

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.

Important contributions of CBETA:

- **4-turn RCL to measure CSR damage.**
- **4-turn ERL for increase sensitivity to CSR damage**
- **1-turn ERL for high currents**



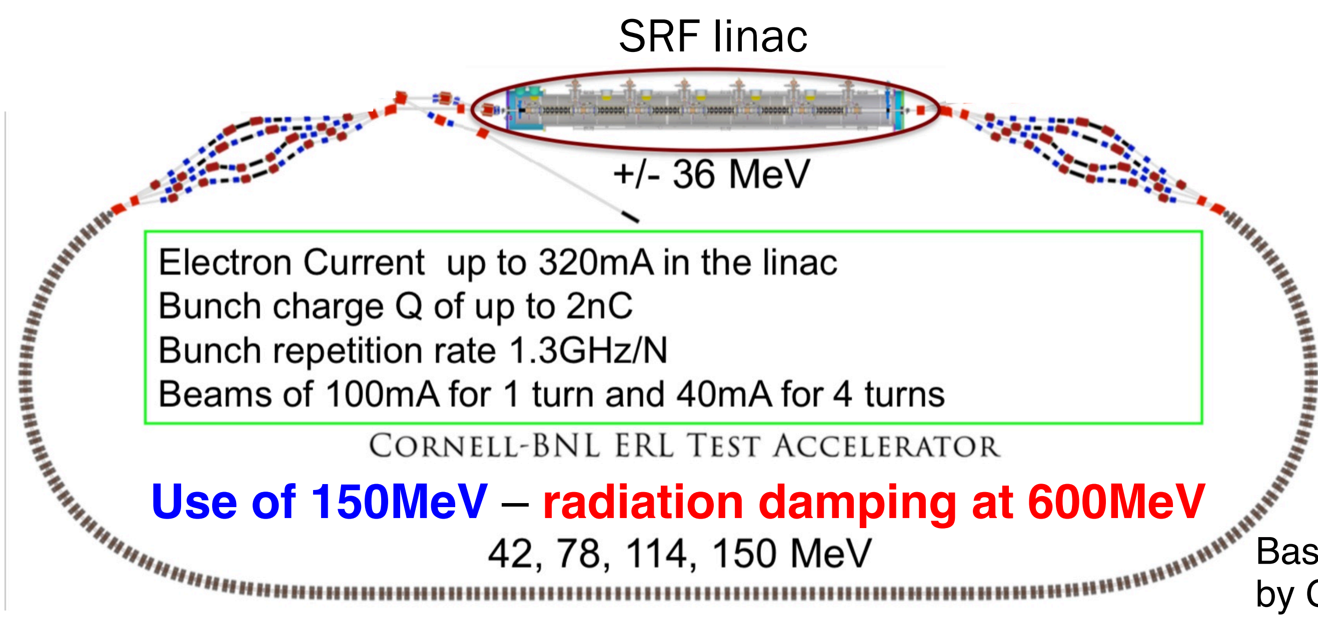
Final energy spread ≈ ± 5.0%

Weaker storage-ring cooling

Solutions without cooling have less luminosity, e.g. 0.44E34 at BNL, and the luminosity decay becomes faster as well.

Weaker cooling (e.g. storage ring) could help to at least keep the luminosity constant at this level, e.g. by storage ring cooling.

New thoughts being discussed: Storage ring cooling could be increase by 1-2 orders of magnitude by increased damping in an ERL.



For 150MeV cooling, one would radiation damp at about 600MeV, with 64 times more radiation damping.

Based on a related idea by Geoff Kraft (JLAB)

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
- Compton backscattering source
- Gas-jet collider for NP, dark light
- Lithography for chip production
- High energy colliders, e.g. LHeC
- Coherent light sources

Questions?