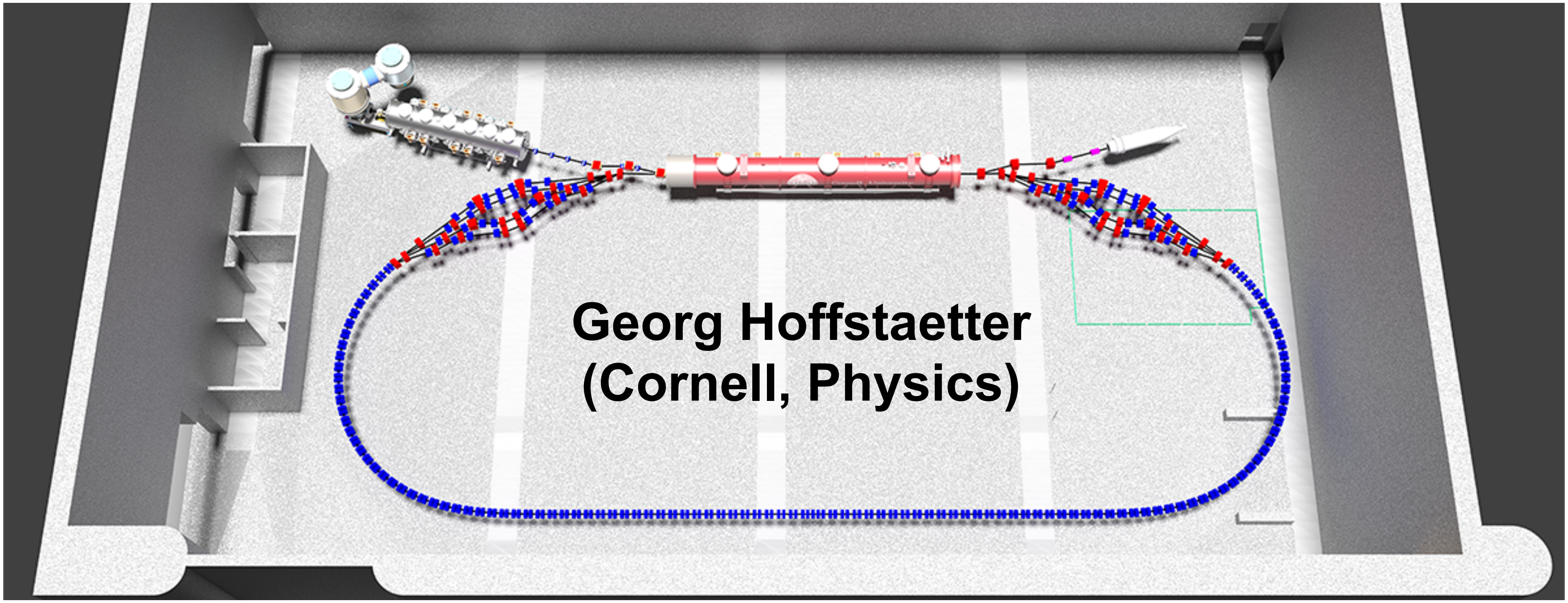
CBETA

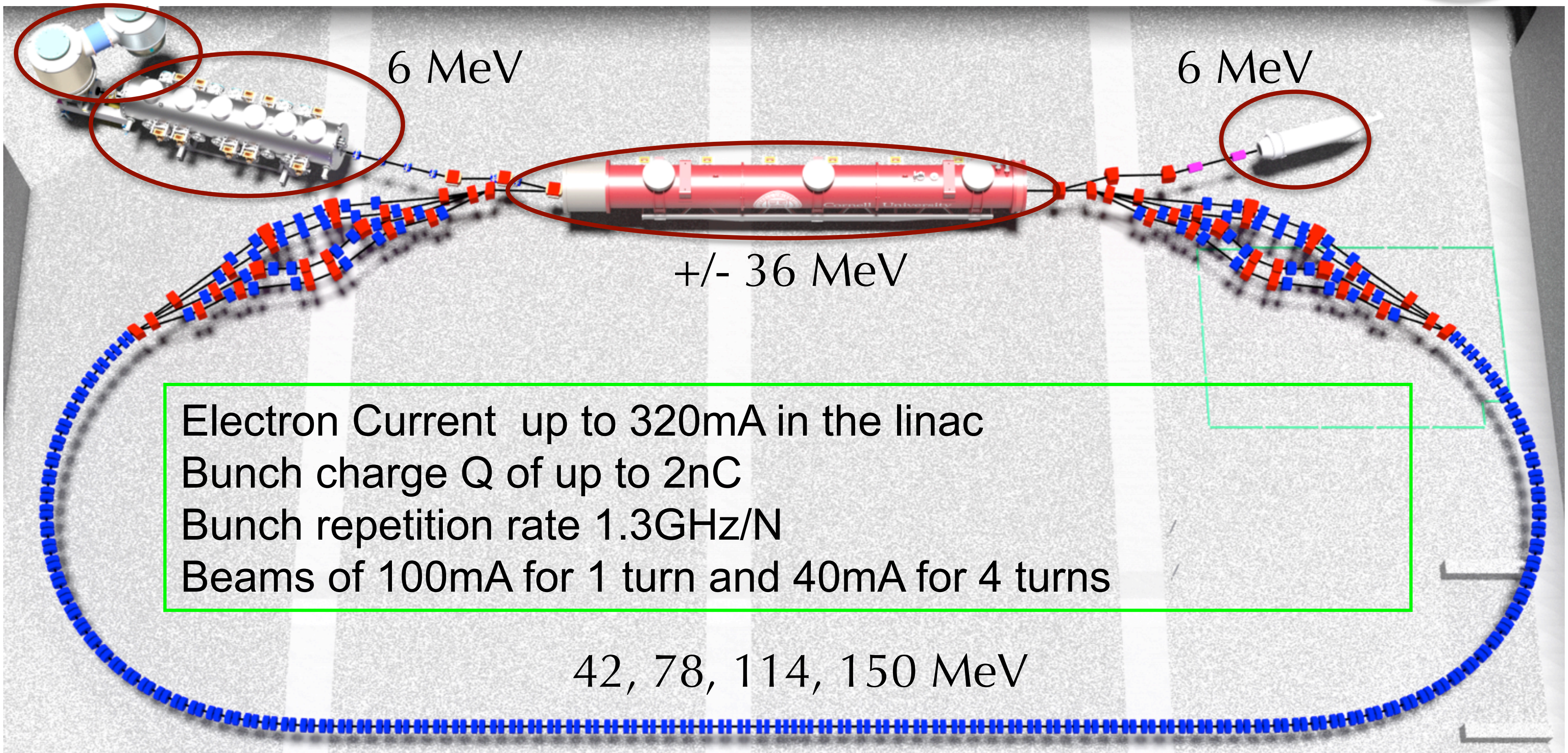
CORNELL-BNL ERL TEST ACCELERATOR



The test ERL in Cornell's hall L0E

- 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

Performance Parameters

Table 1: Key Performance Parameters (KPPs) and Design Parameters (UPPs)

Parameter	KPP	Design / UPP	Unit
Electron beam energy		200	MeV
Electron bunch charge		246	pC
Gun’s current	1	40	mA
Gun’s bunch-repetition rate		162.5	MHz
RF frequency	1300	1300	MHz
Injector energy		6	MeV
RF operation mode		CW	
Number of ERL turns	0 - 4	0 - 4	
Energy aperture of FFAG	2	4	

Project scope in the management plan

Clean out Cornell's former extracted-beam hall (L0E)

Move Cornell's ERL equipment into this hall

Design a layout for a 4-turn ERL with FFAG return loop based on this equipment.

Provide electrical infrastructure, cryogenic infrastructure, RF sources and controls.

Install the magnets and vacuum chambers on girders, equip with power and controls.

Install diagnostic systems used for optimizing the beam emittance, optics, and trajectory.

Provide controls to operate the RF system, the laser systems and the diagnostic systems

Design and install appropriate radiation shielding, including components from BNL.

Design and install equipment protection systems.

Obtain authorization to commission and operate.

Commission with the goal of reaching the Key Performance Parameters (KPPs)

Push toward the Ultimate Performance parameters (UPPs)

Other operation modes are also interesting for eRHIC, e.g. 10MHz and 1nC

CBETA for risk drivers of eRHIC

Some of the most important risk items 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.

The CBETA CDR

Background for CDR

Wrote PDDR for hard X-ray ERL at Cornell in 2012.

Start of CBETA July 2014 White paper December 2014

CDR scheduled for magnet prototypes.

Planed for completion of optics and layout for CDR.

Scheduled this Review to include advise on CDR.

Plan to include committee advise by the end of July.

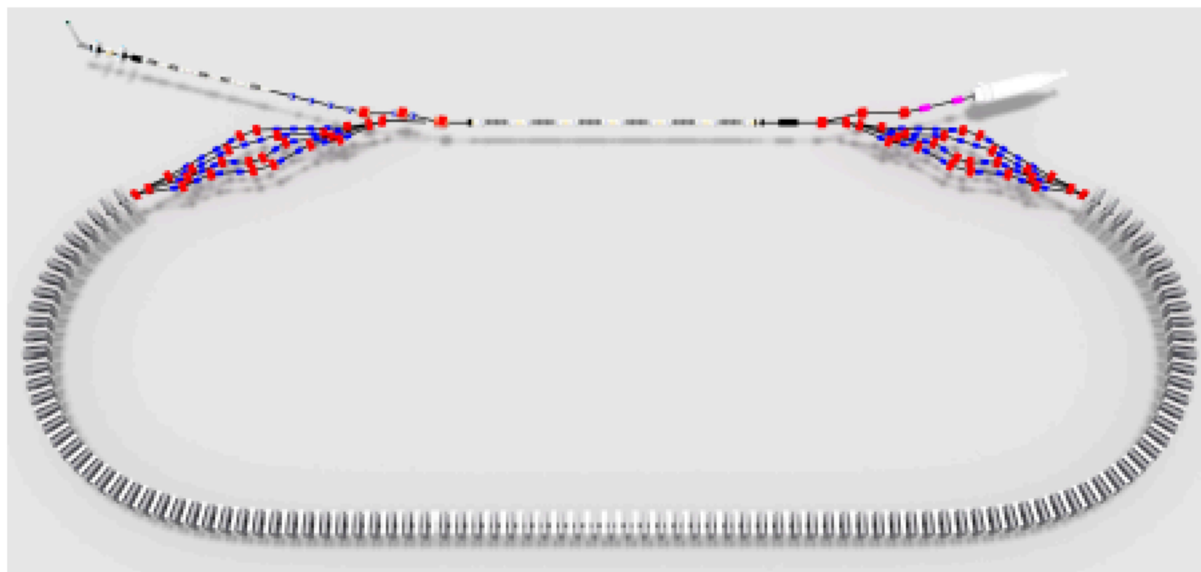
DRAFT

CBETA Conceptual Design Report

Cornell-Brookhaven ERL Test Accelerator

Editors: G. Hoffstaetter and D. Trbojevic

Contributors: J. Barley, I. Bazarov, A. Bartnik, I. Ben-Zvi, J. S. Berg, S. Brooks, D. Douglas, J. Dobbins, B. Dunham, R. Eichhorn, R. Gallagher, C. Gulliford, G. Hoffstaetter, Y. Li, M. Liepe, W. Lou, G. Mahler, C. Mayes, F. Méot, M. Minty, R. Patterson, S. Peggs, V. Ptitsyn, T. Roser, D. Sabol, E. Smith, J. Tuozzolo, D. Trbojevic, N. Tsoupas, H. Witte



June 7, 2016

CDR content

The draft CDR has been distributed to the committee.

- Accelerator Physics
  - Layout and Optics
  - Beam dynamics (CSR, space charge, wakes, scattering)
  - Tolerances and correction schemes
  - BBU current limits

- FFAG Magnets (Design and prototypes)

- Injector (as it exists)

- Linac and RF system (as they mostly exist)

- Cryogenics (as it partially exists)

- Vacuum System

- Diagnostics and Control
- Personnel Safety
- Commissioning

Why is CBETA at Cornell

Track Record:

a) ERL injector with world-record current (10 times more than the next)

b) ERL injector with world-record emittance (5 times less than the next)

c) SRF cavity shape for high current (30 times more than the next)

d) SRF R&D for ERL Light Sources with world-record low loss

e) High Brightness Beam Physics (first full hard x-ray ERL design)

Facilities and Capabilities:

- About 120 accelerator-related employees with decades of experience in accelerator building and operation at the worlds forefront.
- Facilities and experience for building full SRF accelerators and DC guns.
- Space for a 100mA, > 60MeV per turn ERL.

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

Fall 2015

The initial installation was completed for the MLC and ERL beamline

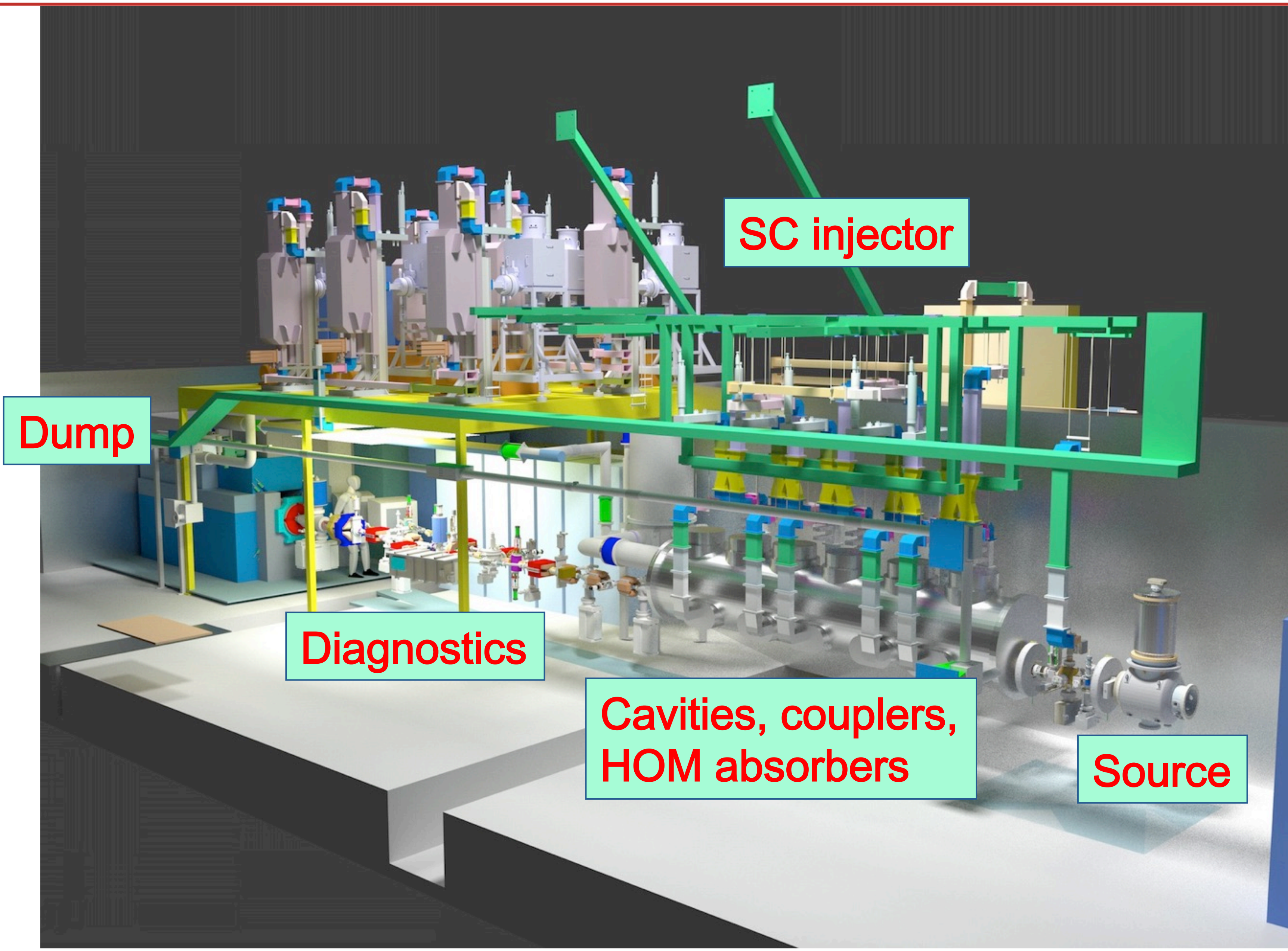
Spring 2016

The second phase will accommodate the new loop-layout

Summer 2016

The second phase is almost complete

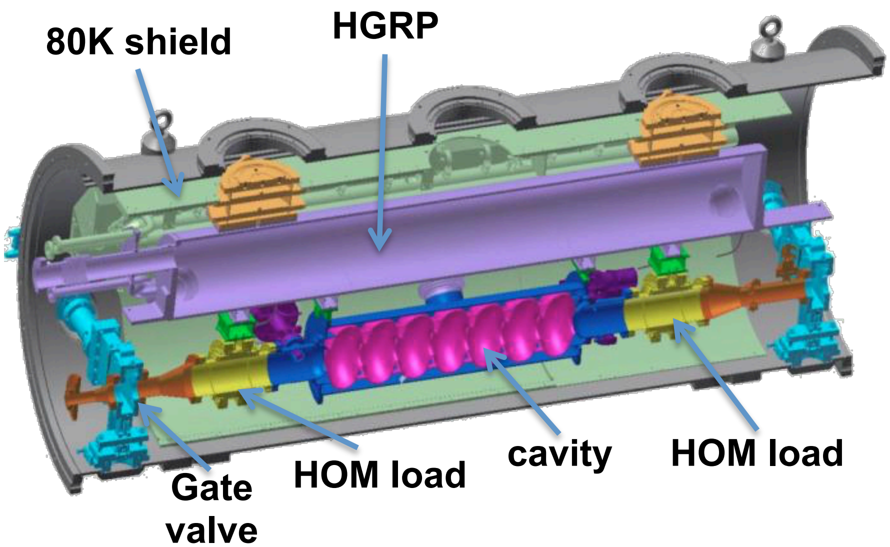
ERL injector at Cornell



Main linac cryomodule assembly for CW beams

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

Horizontal tests of 1st ERL cavity

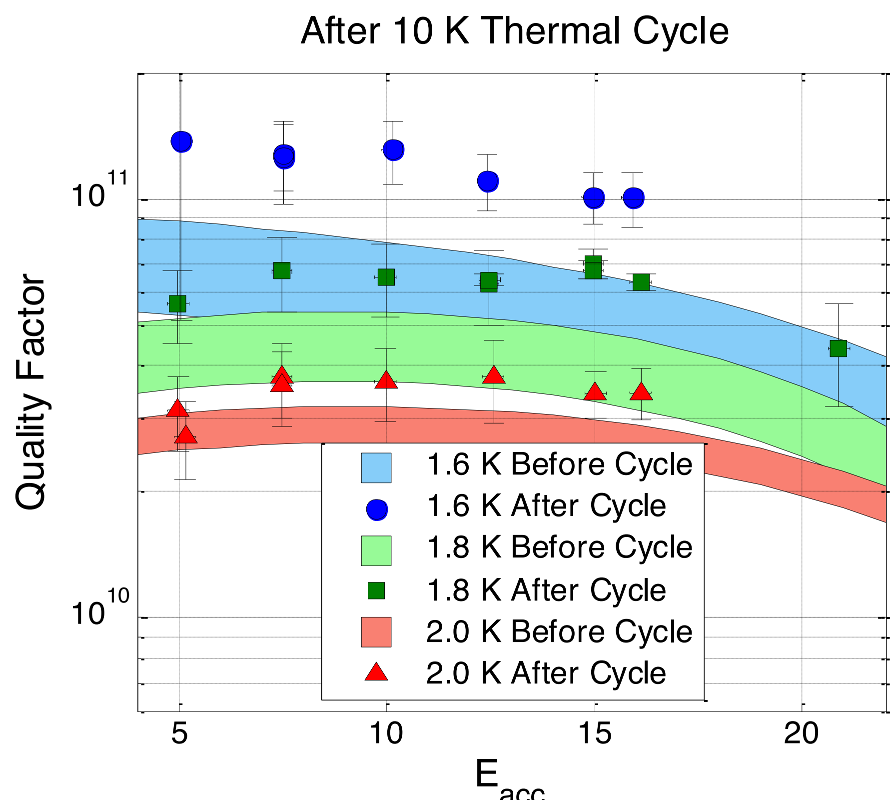


Horizontal Test Cryostat:
16MV/m, 1.8K: Q_0 = 2.E10
(reached with coupler)

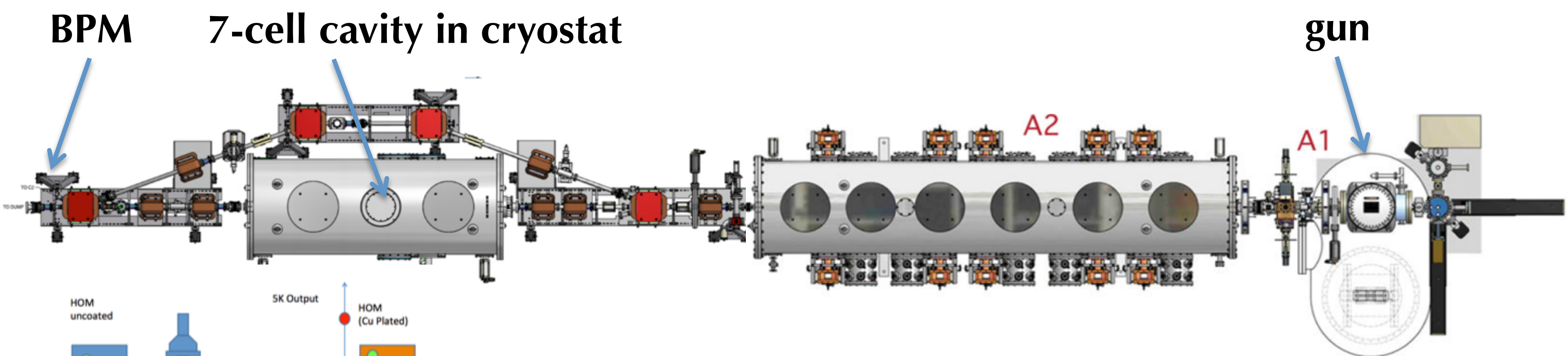
Q_0 = 3.5E10 without coupler

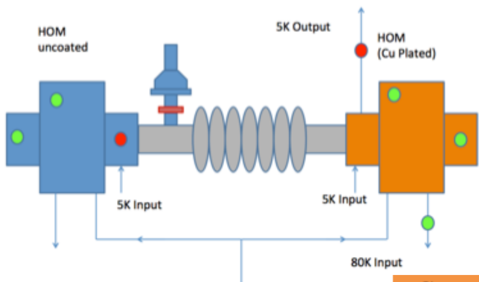
Q_0 = 6E10 with coupler and HOM absorbers (held the world record)

- Much better Q0 than the ERL spec.
- Increased state of the art expectations for other projects, e.g. LCLS-II.
- Became essential for high-Q cavity research, incl. for N-doped cavities.



HOM measurements with beam

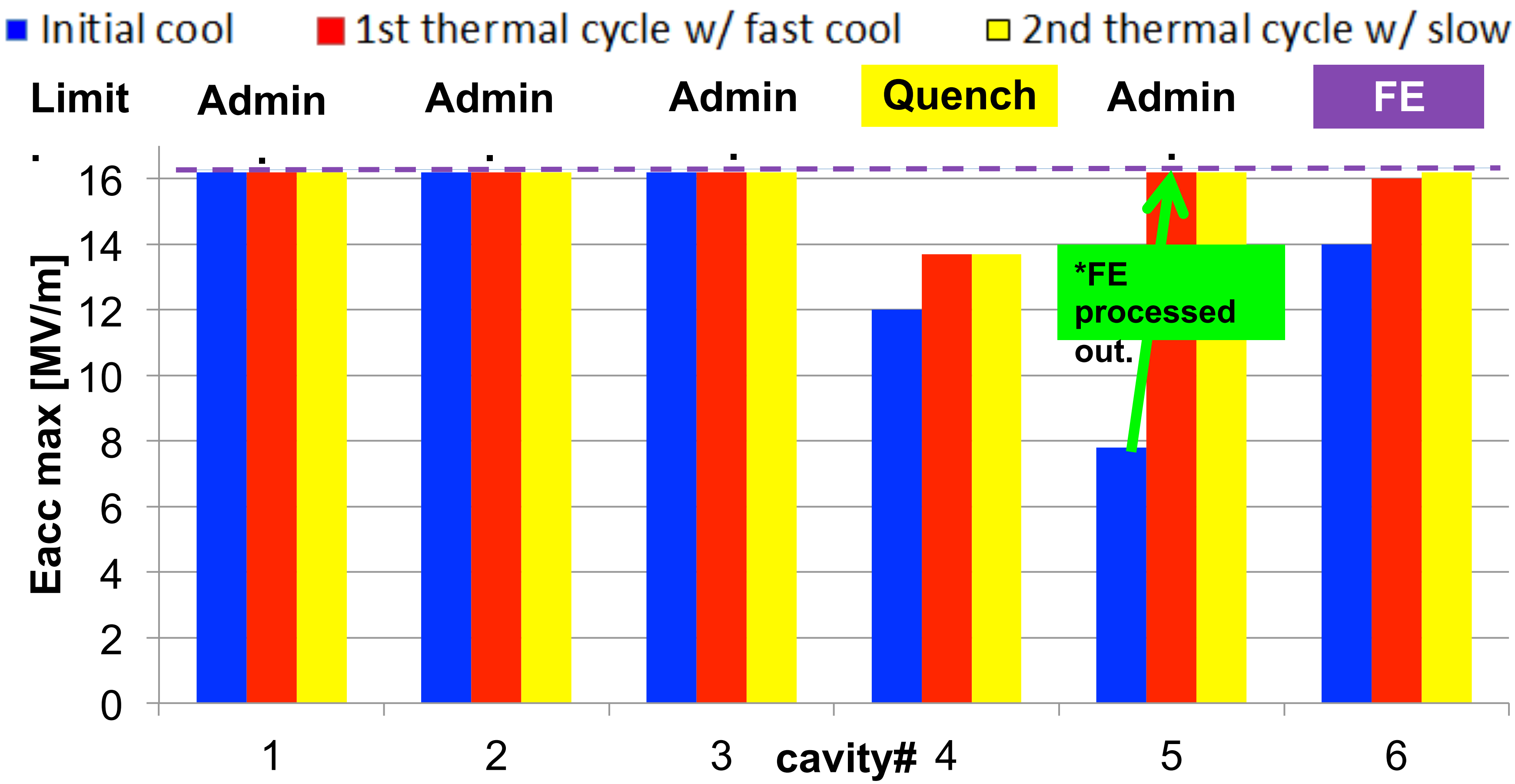




Current, bunch length	ΔT (beam pipe behind Abs.) coated/uncoated	ΔT (80K gas temp) coated/uncoated	ΔT (80K absorber temp) coated/uncoated	ΔT (5K flange next to cavity) coated	ΔT, beam pipe to cavity coated/uncoated
25 mA, 3.0 ps	0.075/0.075	1.14/0.82	1.02/0.975	0.007	0.076/-.005
40 mA, 3.4 ps	0.2475/0.335	2.95/2.16	2.72/2.53	0.021	0.179/0.009
40 mA, 2.7 ps	0.2975/0.425	3.00/2.22	2.772/2.63	0.027	0.203/0.014

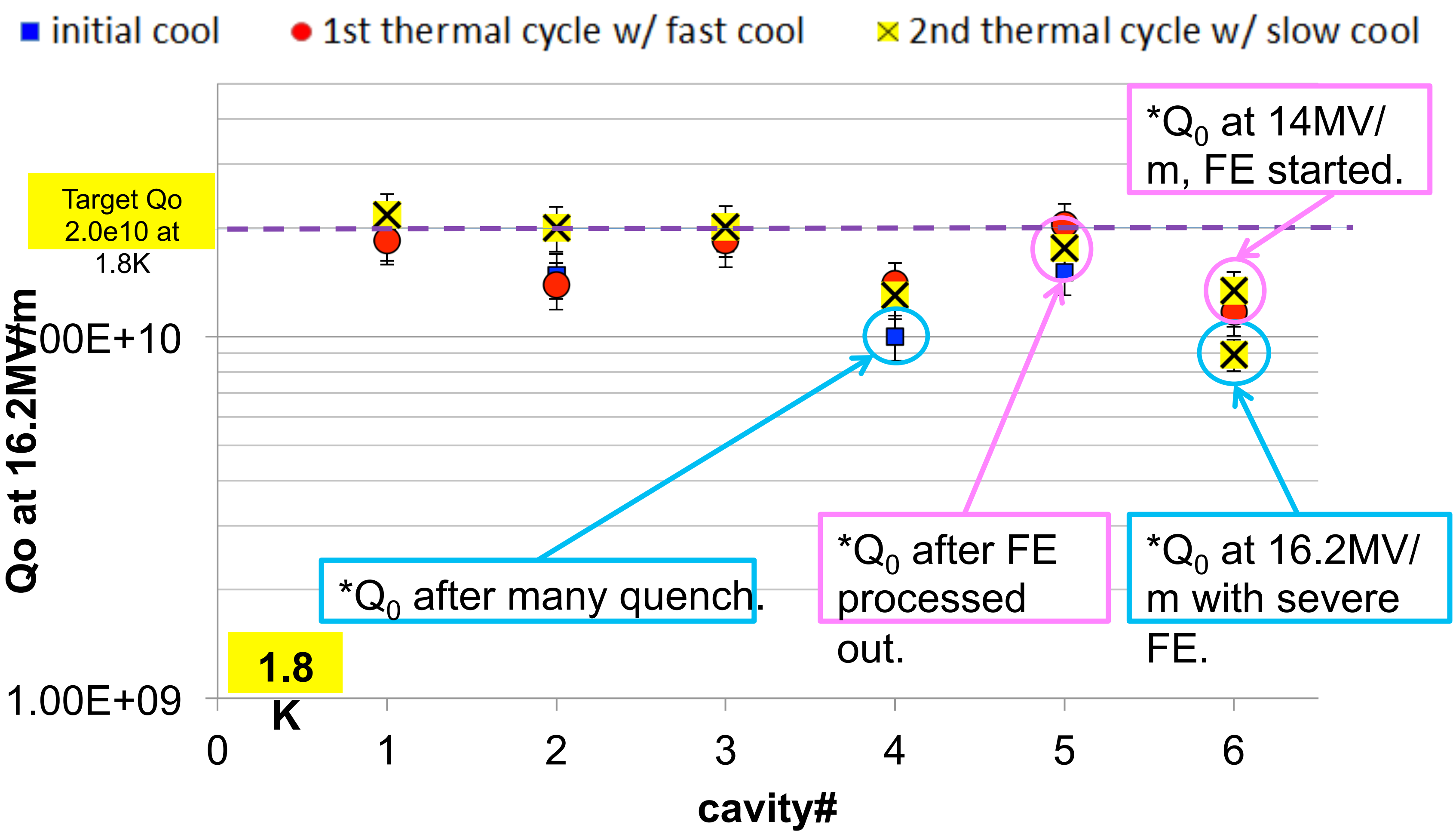
- No charge-up of the HOM absorber observed.
- HOM heating was less than expected, limits to 400mA total ERL current.
- **This establishes the current limit of 40mA for the 4-turn CBETA ERL**

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)**

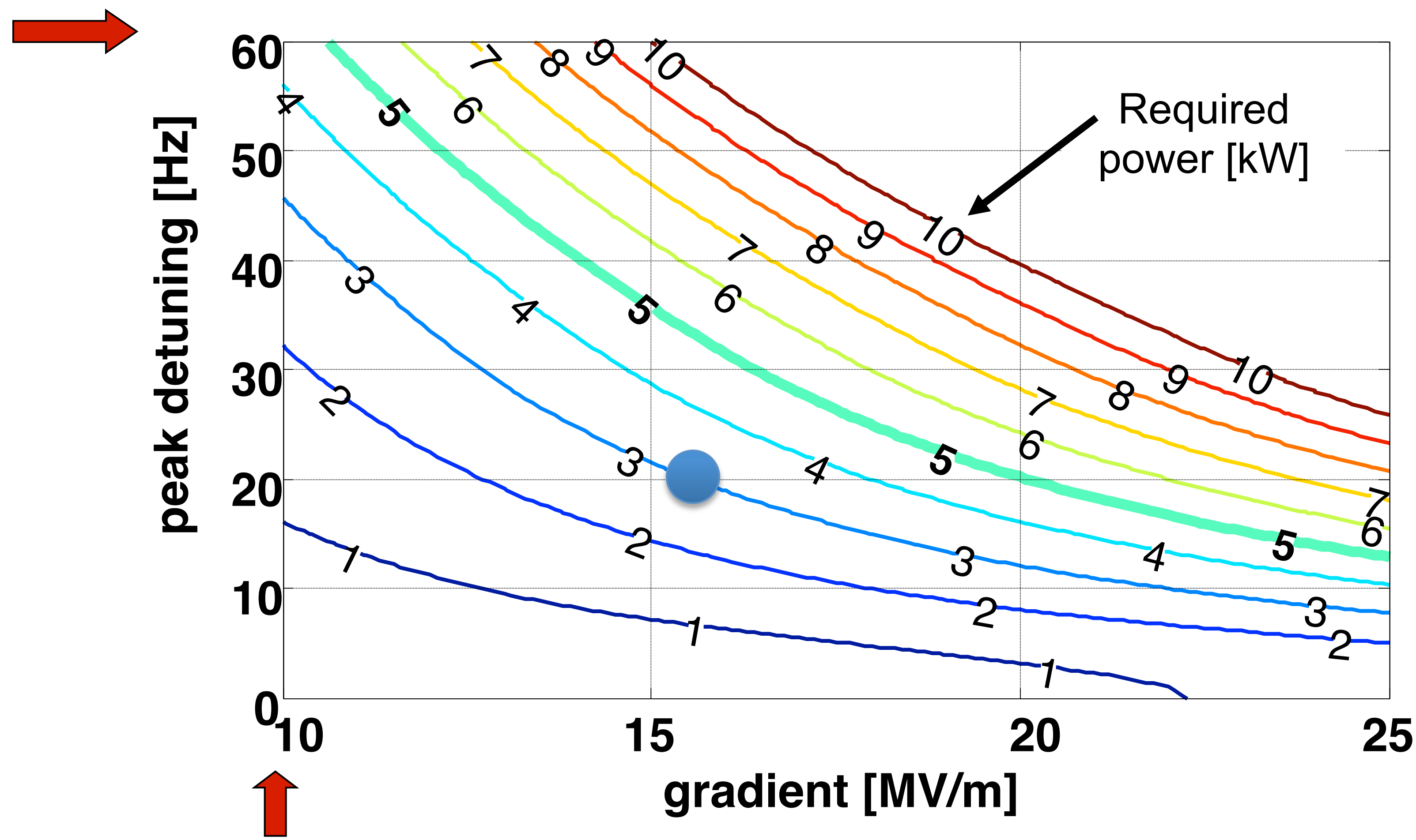
Main linac cryomodule (MLC) achieved surface losses (Q0)



- 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)**

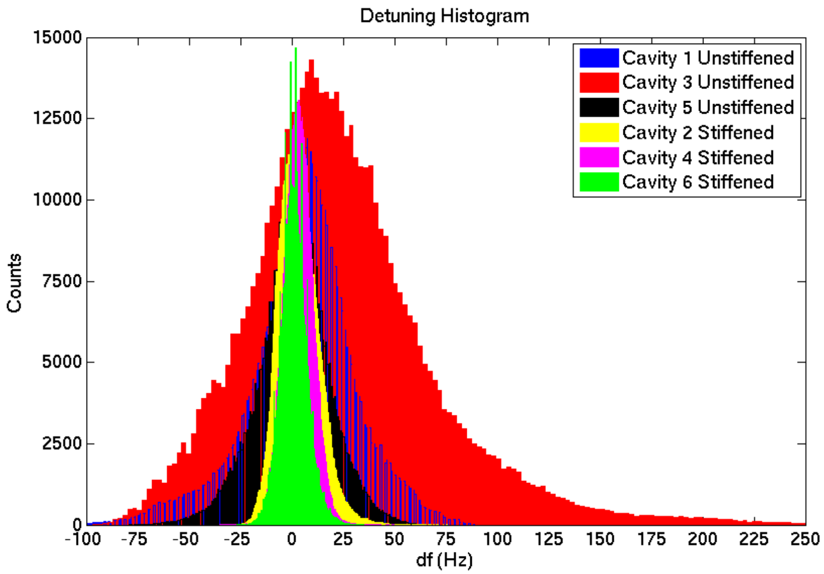
Required Peak Power (Q_L=2·10^7 … 1·10^8)

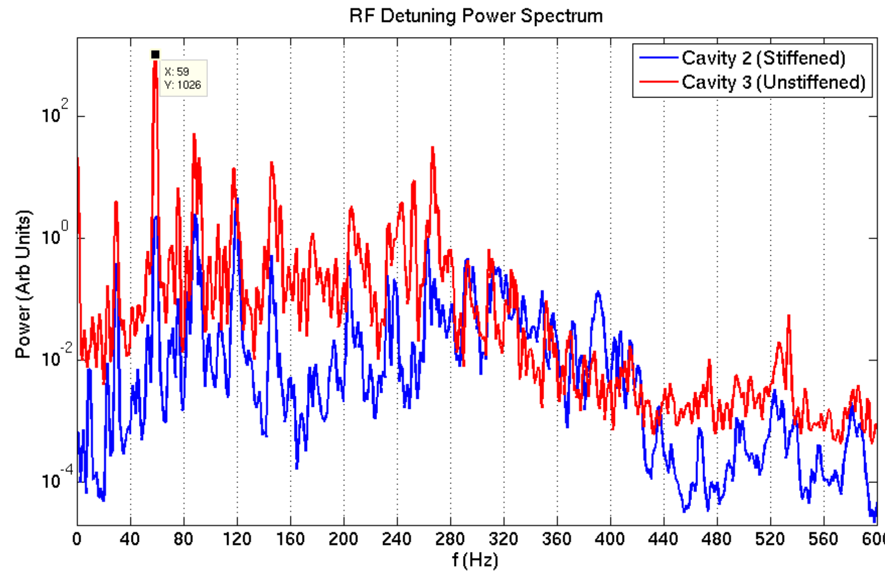
CBETA



5 kW RF power gives sufficient overhead for 8MV/m cavity operation with up to 90 Hz peak detuning (50 Hz if Q_L is not adjusted)

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)**

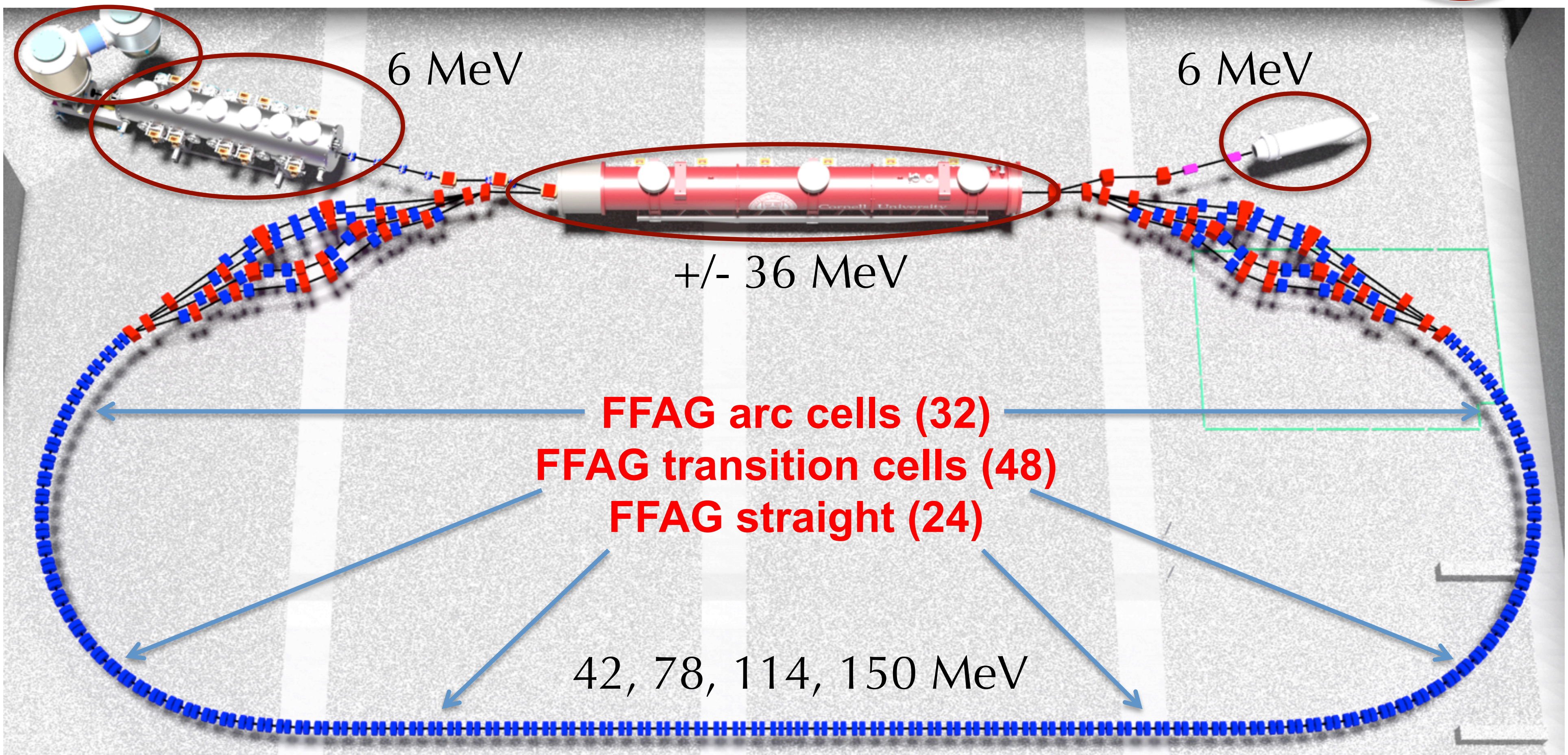
But much remains to be done …

1. Prototyping FFAG return loops
   - Prototyping permanent magnets (similar to eRHIC) with required precision
   - Prototyping orbit and optics control
2. Prototyping multi-turn ERL components
   - timing and synchronization systems
   - halo diagnostics, halo control, and collimation systems
   - multi-beam diagnostics and control, possibly with pilot bunches
   - splitters and path-lenth adjusters, develop low-emittance injection
   - ion clearing
3. Prove recirculative BBU for 4turn ERL.
4. Prove operational stability, incl. halo, ions, tolerances, etc.

CBETA: The FFAG loop

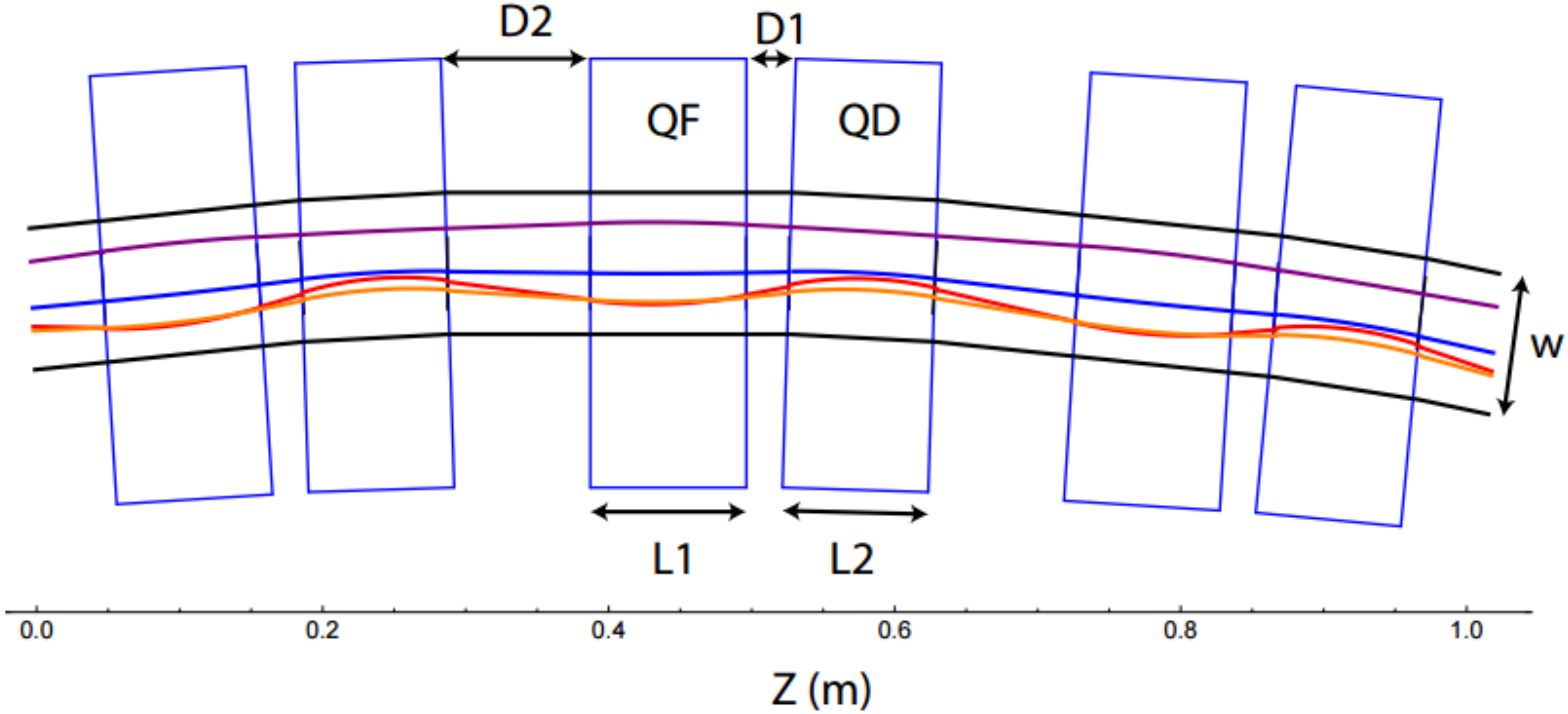
- Cornell DC gun
- 100mA, 6MeV SRF injector (ICM)
- 600kW beam dump
- 100mA, 6-cavity SRF CW Linac (MLC)

Existing components at Cornell



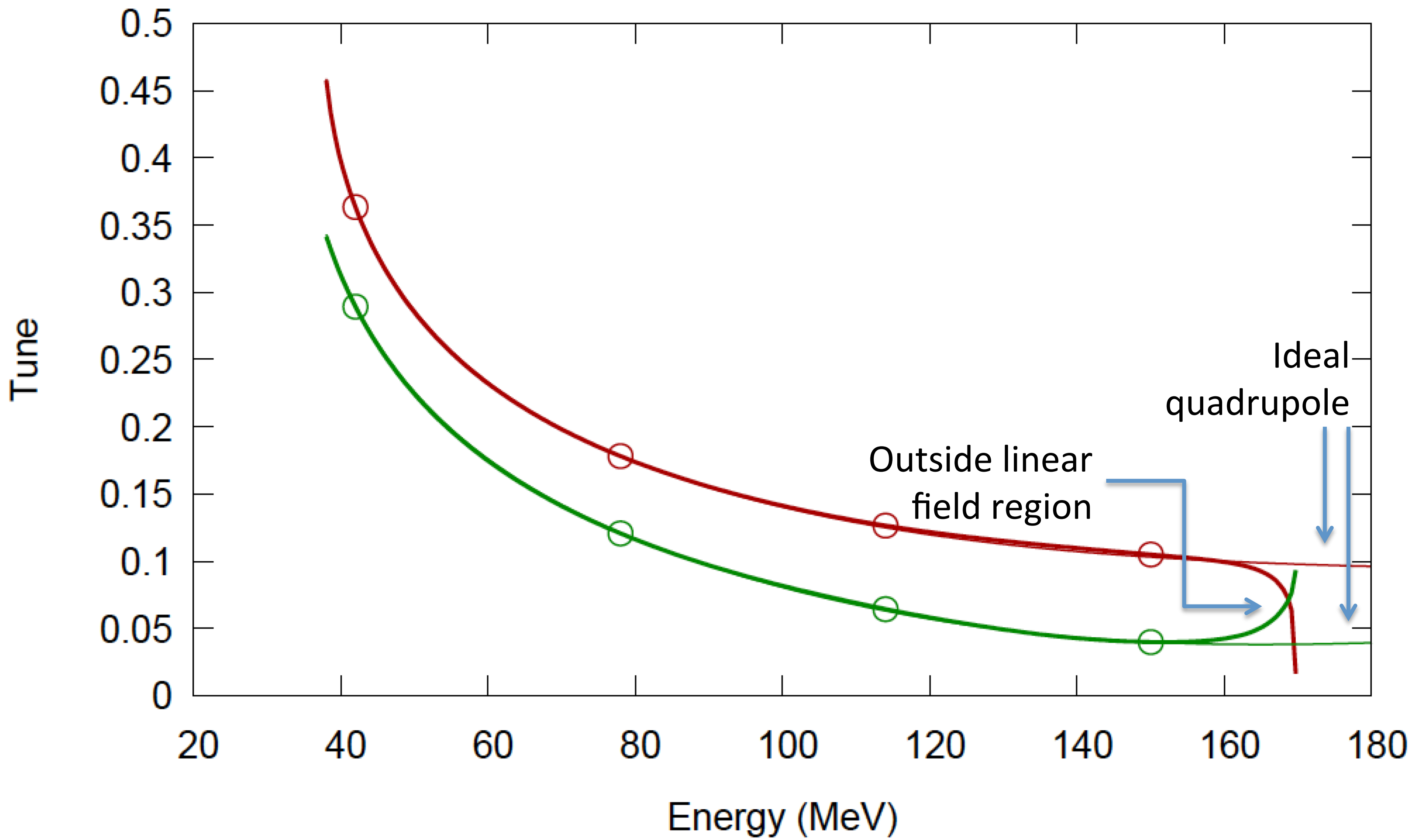
The FFAG principle

A periodic FODO channel can have a periodic solution for a large range of energies, with the phase advance going toward 0 for large energies.



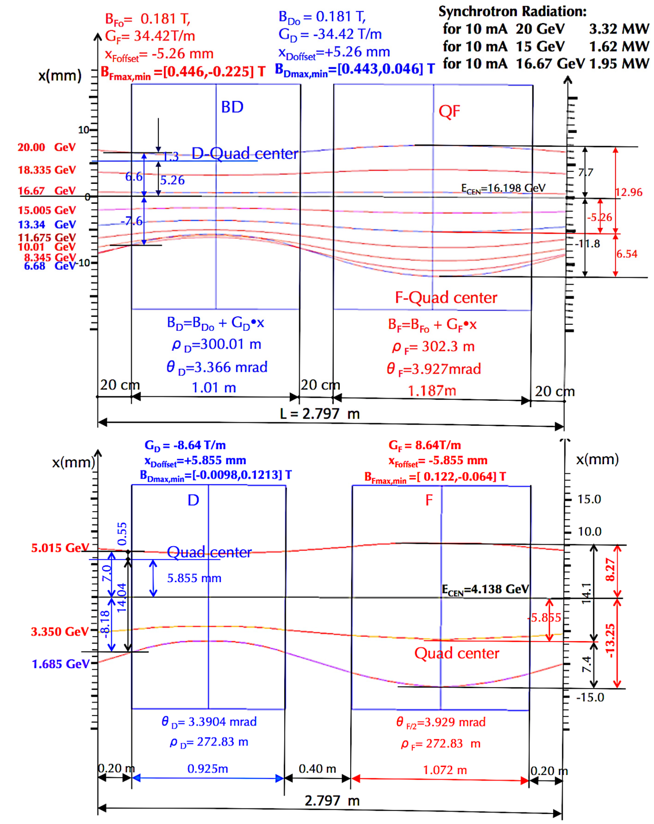
A dipole component or a lateral shift of quadrupoles leads to a bent FODO channel.

Cell tune with realistic magnets

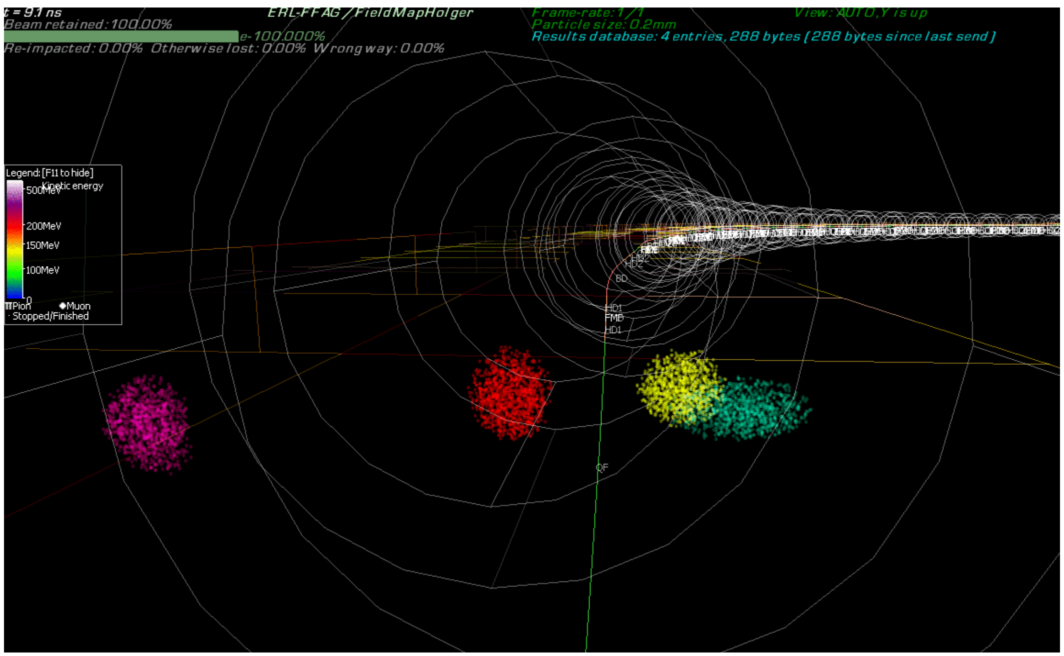


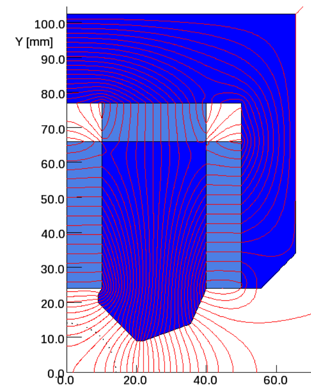
FFAG cell for CBETA

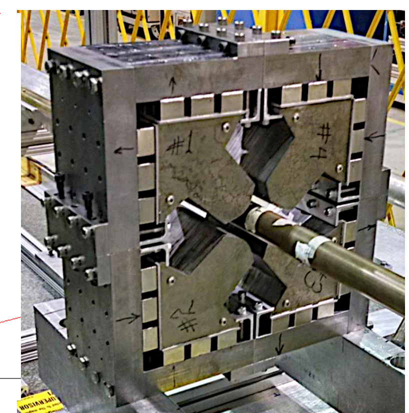
- Up to 4 re-circulations through one beam line using novel FFAG lattice, needing energy acceptance of nearly a factor 4.
- Only a factor 1.7 has been achieve so far.
- Permanent magnet technology is used, similar to what is planned for eRHIC. Prototypes are in construction.
- A suitable backup solution exists (Halbach magnets).



Simulation and animation by Stephen Brooks

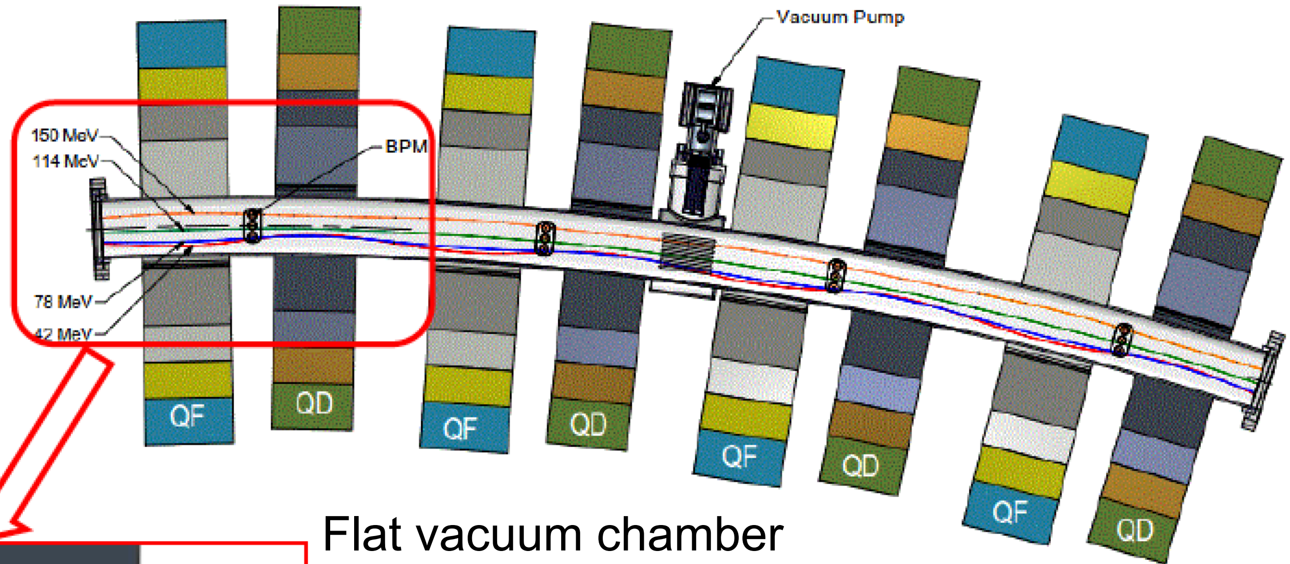


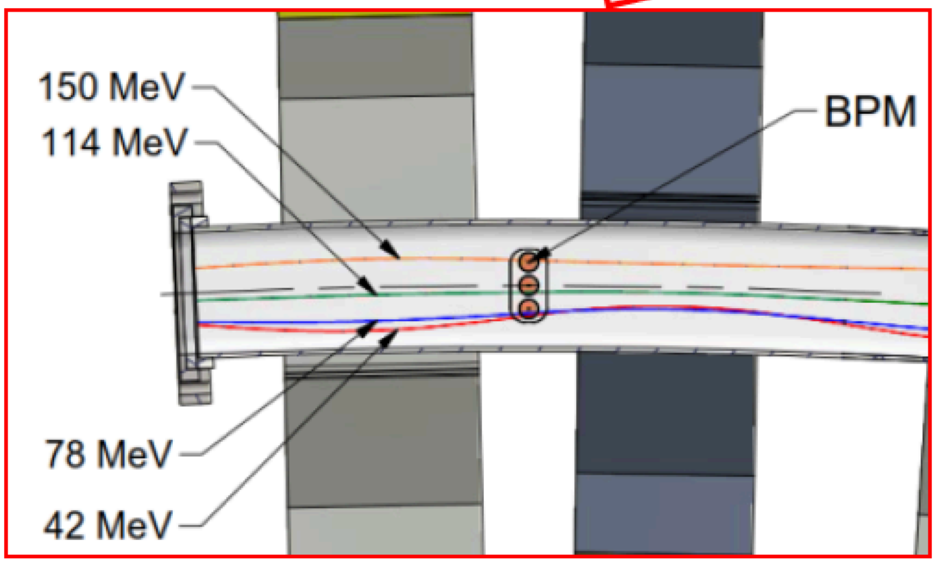




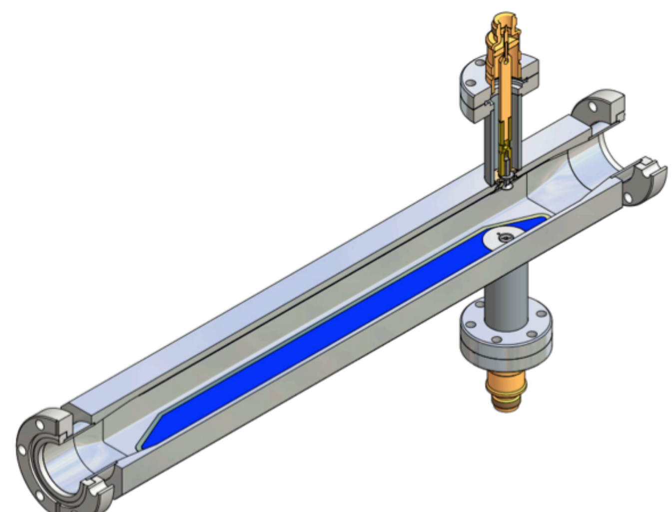
The vacuum pipe with BPM and ion clearing

- *Closest beam approach ~ 12-mm*
- *Clearance to magnet (QD) >2.0mm*
- *Flat beampipe allows space for correctors*





Flat vacuum chamber
24X84mm (inner), needing 6-button BPMs

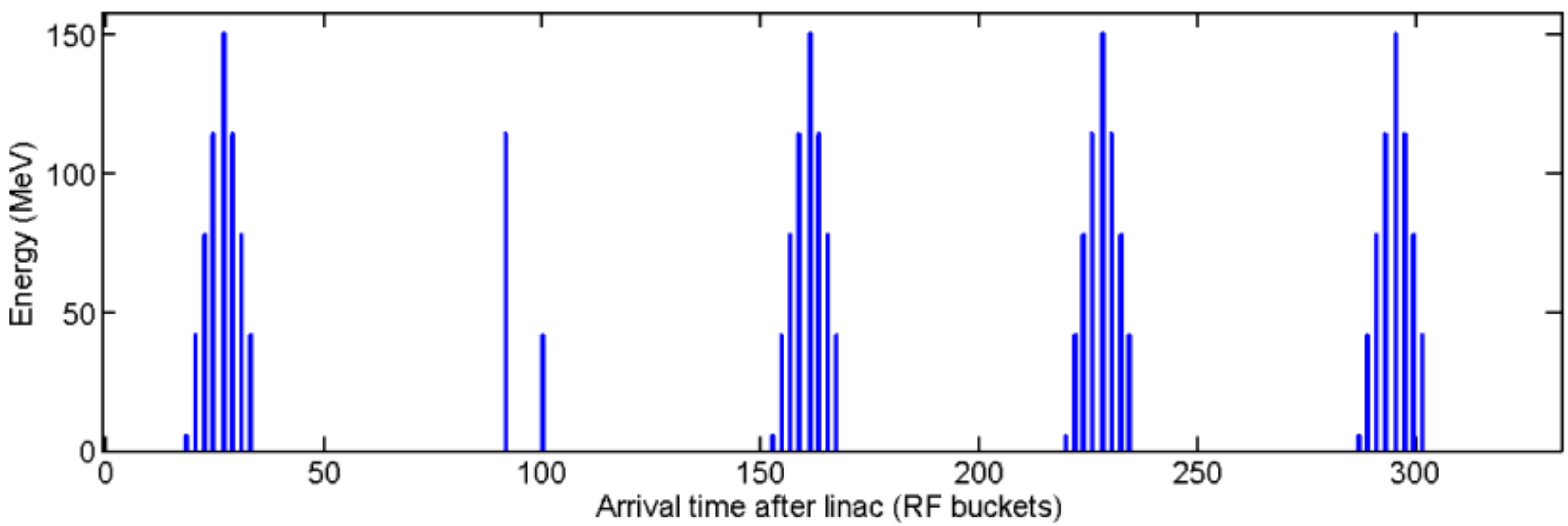


Ion-clearing electrodes next to each bpm

Bunch patterns for single pulse resolution

Table 2.8.1: Operational Modes

	Commissioning	eRHIC	High-current	
Injection Rate	0.97	19.4	325	MHz
Max Bunch Charge	125	125	125	pC
Max Current	0.12	2.4	40	mA
Probe Bunch Rate	N/A	$\leq$0.97	$\leq$0.43	MHz



Two probe pulses are separated by 7.5 RF cycles. ~ 5.8 ns
With each turn the probe pulses have a new energy.

Diagnostic needs for Commissioning

Beam loss monitors
- Crude steering, machine protection
- Evidence of halo at high currents

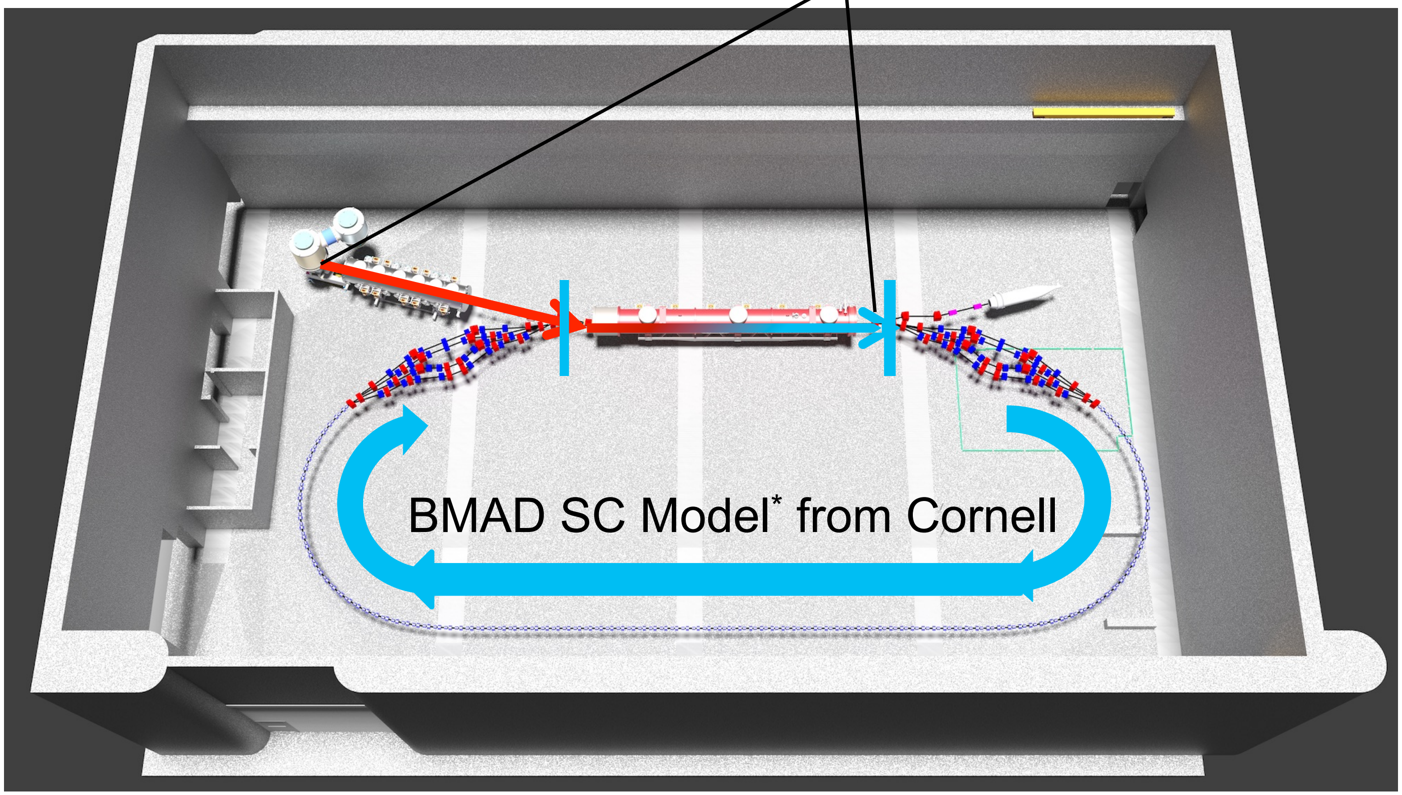
Viewscreens
- Stair-step structure in FFAG allows “many” beams to be seen
- Linear, low-current beam position
- Beam size (… roughly)

BPM
- (Likely) nonlinear, high current beam position
- Two designs
  1. Frequency based- gives beam phase
  2. Time-domain based- can resolve many beams

Space-Charge: Is 150MeV ok?

Most relevant in the injector and 1st pass through linac and recirculation arc, as well as final deceleration and into the dump.

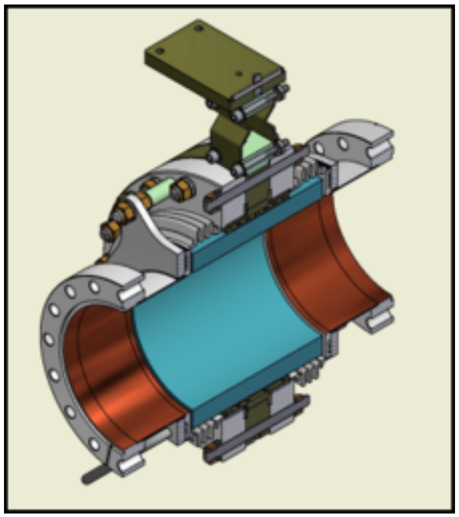
For 1st part, use 3D space charge code GPT + MOGA optimization:

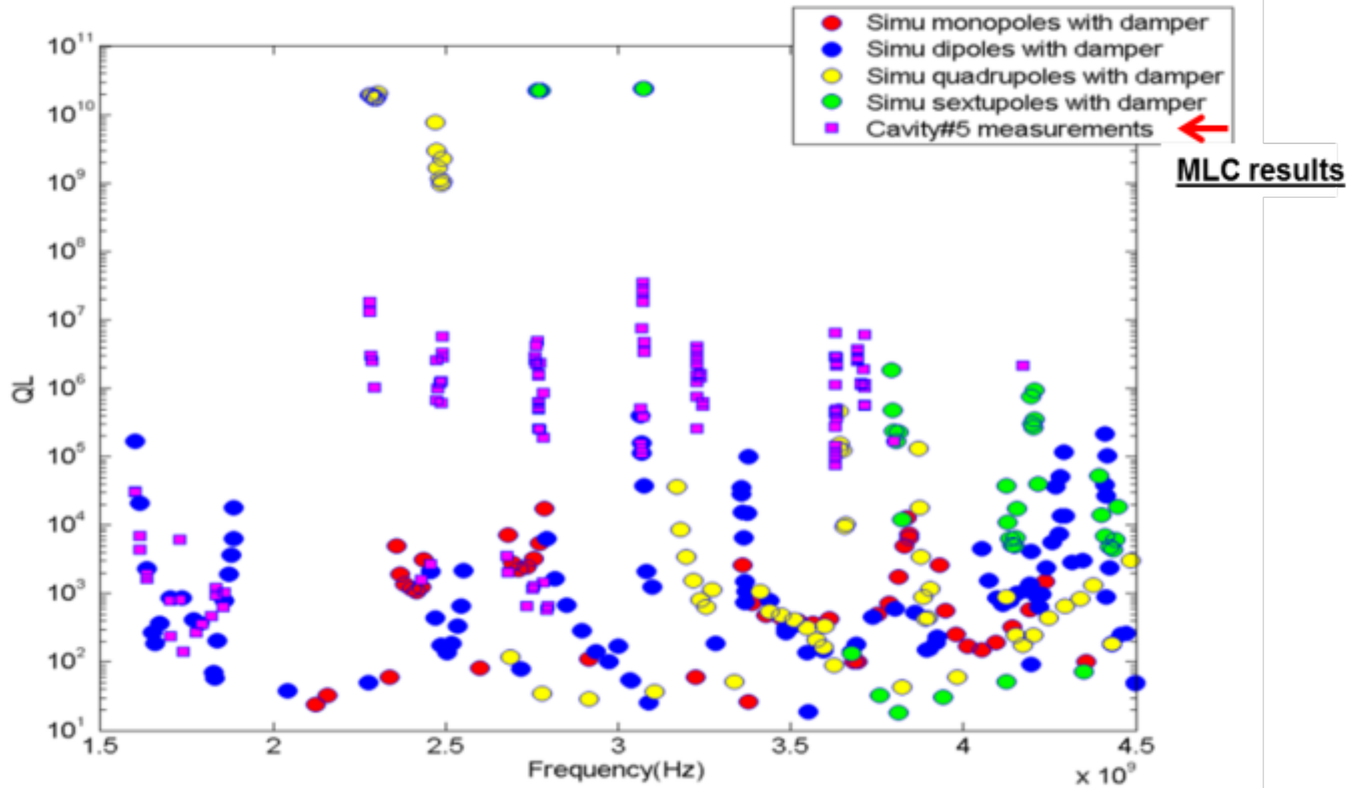


* BMAD SC Model from Cornell is the non-radiative part of its well-tested CSR program.

Space charge emittance growth is sufficiently small to allow a first turn at 42MeV, and thefore a top energy of 150MeV.

Current limits from HOMs



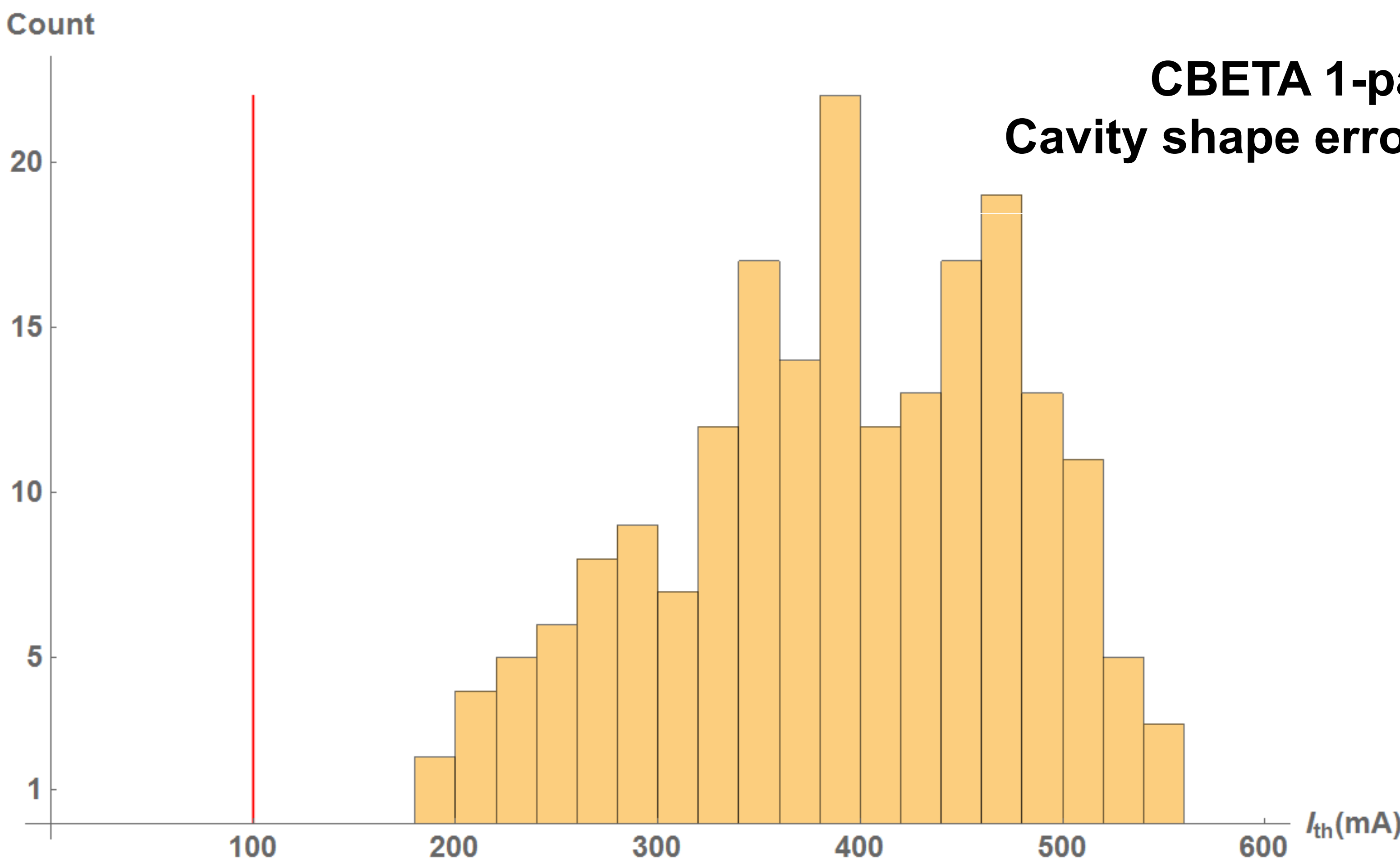


Dipole HOMs on MLC were strongly damped below Q~10^4.
Consistent with HTC and simulation results.

HTC results were:

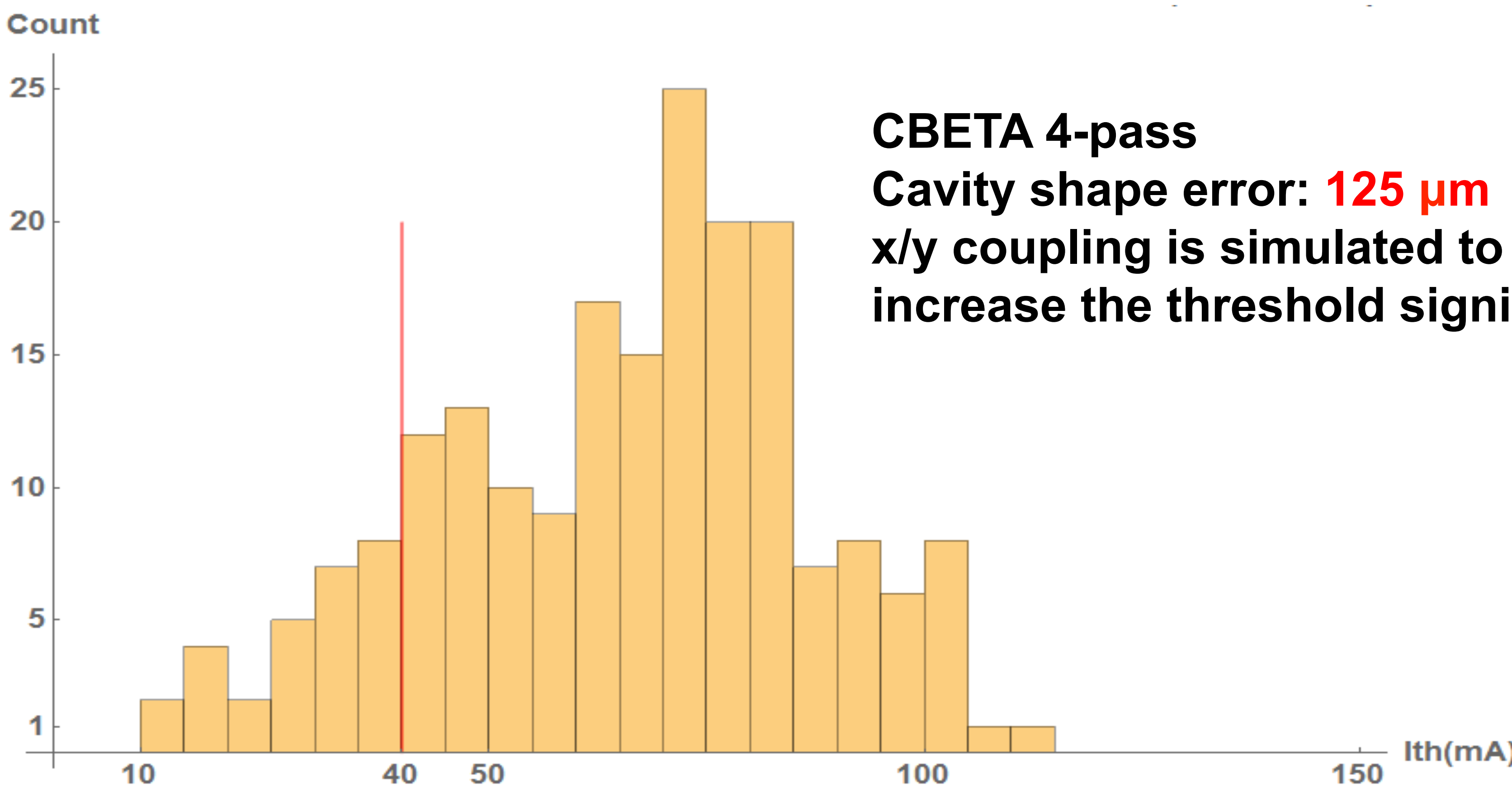
- **HOM heating: currents are limited to < 40mA in CBETA**
- **BBU no HOM limits BBU to below 100mA in one turn**

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_{th} > 100mA

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

CBETA

Tolerances in FFAG are similar to more conventional, e.g. FODO, lattices.

For FFAGs with focal length f = 1/k:

$$x \approx \beta / f \cdot \Delta x$$

Misalignments

$$x \approx \beta \cdot x_{co} \Delta k = \beta / f \cdot x_{co} \Delta k / k$$

Quad errors

$$\Delta\beta / \beta \approx \beta \cdot \Delta k = \beta / f \cdot \Delta k / k$$

Beta beat

For more conventional latices with focal length f = 1/k:

$$x \approx \beta / f \cdot \Delta x$$

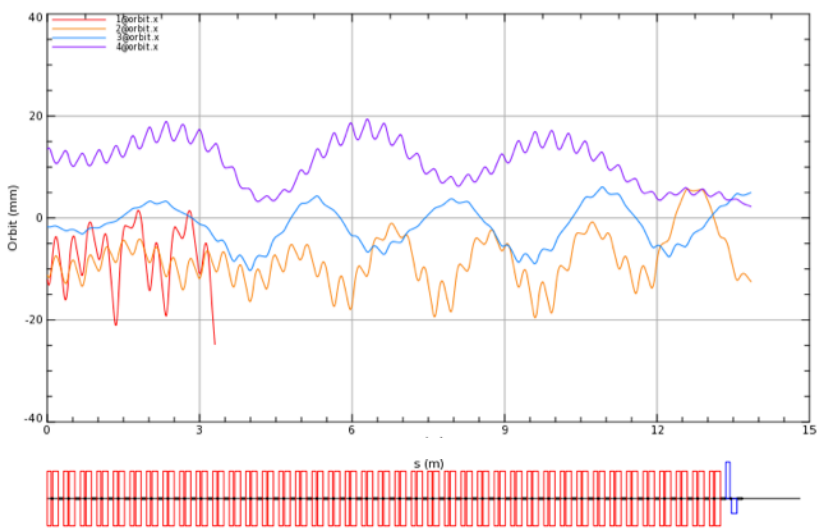
$$x \approx \beta \cdot \phi \cdot \Delta B / B \approx x_{orb} \Delta B / B$$

$$\Delta\beta / \beta \approx \beta \cdot \Delta k = \beta / f \cdot \Delta k / k$$

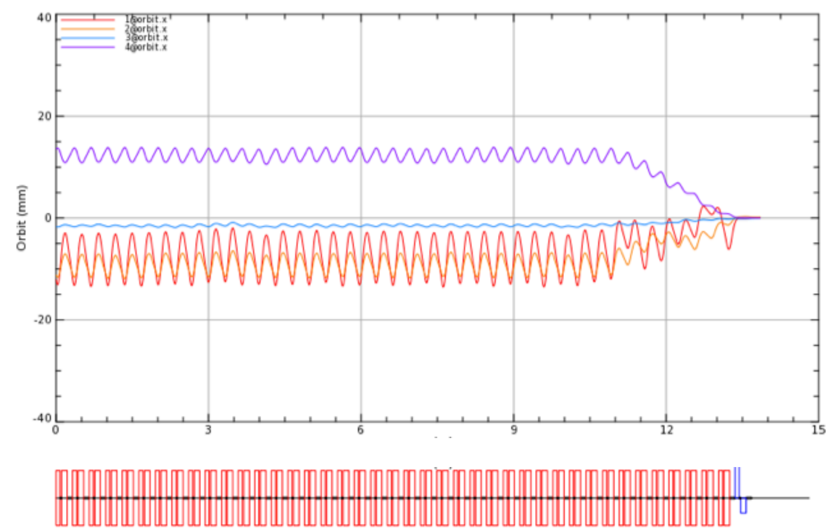
Orbit correction

500 um rms x offset errors

SVD correction given BPM readings for separate beams and correction coils on every other dipole



Full FFAG arc



Full FFAG arc

Orbit correction is possible even with 7 simultaneous beams and large misalignments.

CBETA: FFAG-ERL

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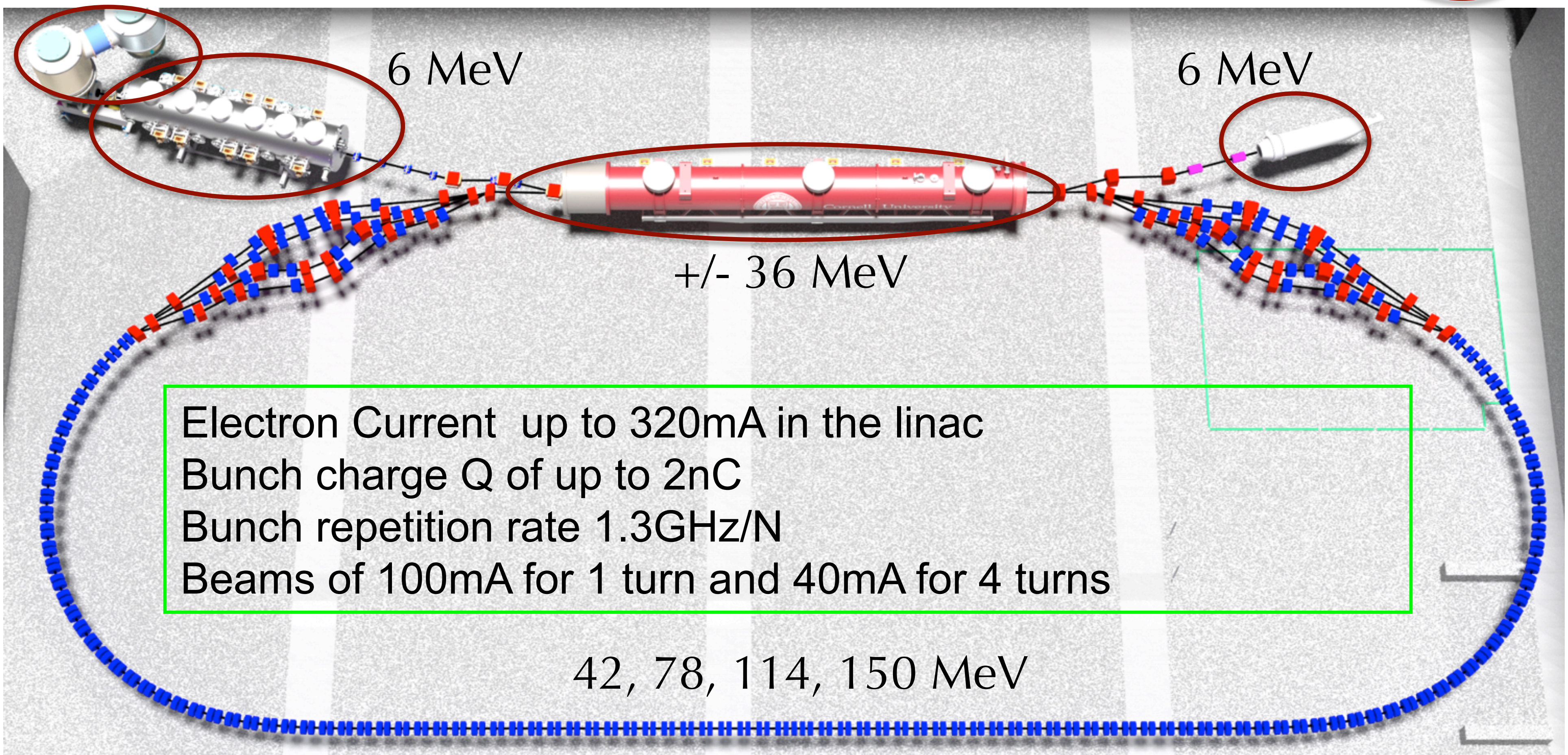
Existing components at Cornell



Summary

Neither an FFAG loop with a factor of 4 momentum acceptance nor a multi-turn ERL has been built before. **The Cbeta FFAG ERL at Cornell will address both of these risk factors for eRHIC** adequately and rather completely.

Cornell and BNL have collaborated for two years already the design of CBETA and on the creation of this prototyping facility at Cornell, using ERL components from Cornell

- A DC electron gun
- A low-emittance and high-current injector linac,
- An ERL-merger
- A 10m long CW SRF accelerator module
- A beam stop.

(Replacement and development value of about $32M)

The scope of the project contains:

- **Making space at Cornell**
- **Moving existing equipment there and bring it into operation**
- **Install 8 spreaders with electromagnets**
- **Install the ERL loop with permanent magnets**
- **Achieve the Key Performance Parameters (1mA mode)**
- **Push toward Ultimate Performance Parameters (up to 40mA)**

Questions
Discussion
?