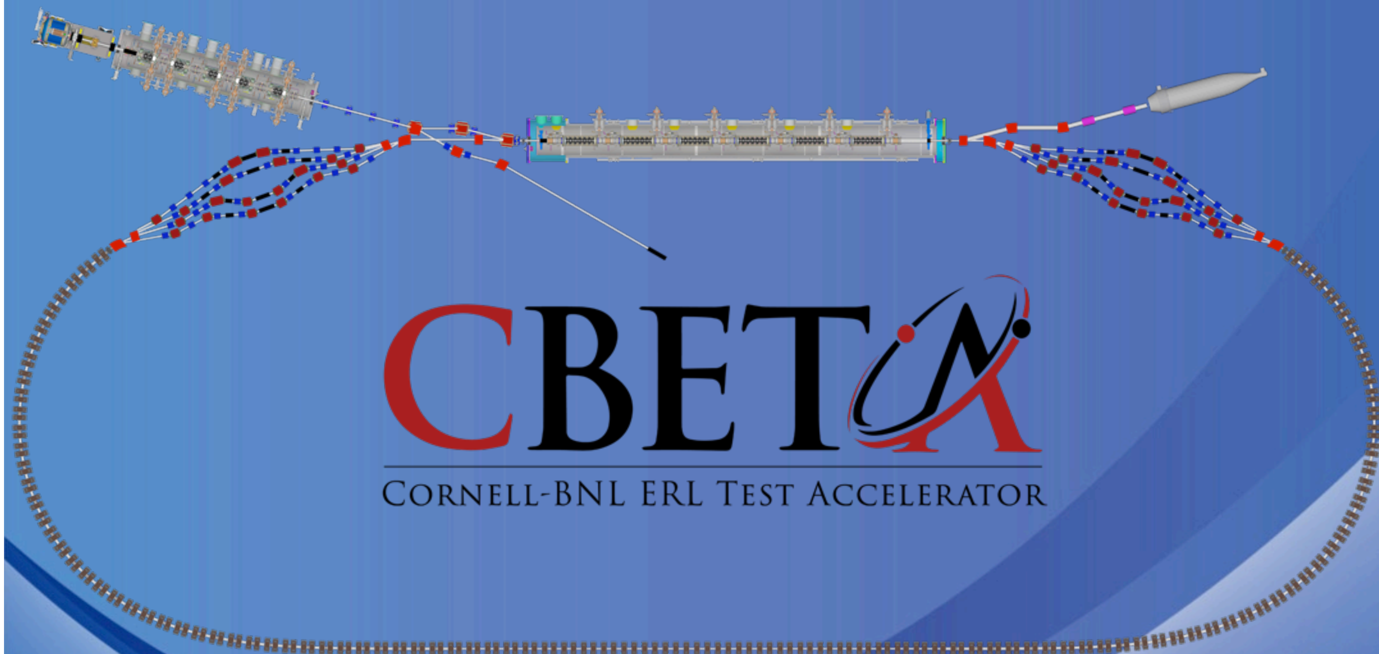
CBETA, a 4-turn ERL with FFAG arc

FFAG workshop 09/08/2017

Georg Hoffstaetter (Cornell)

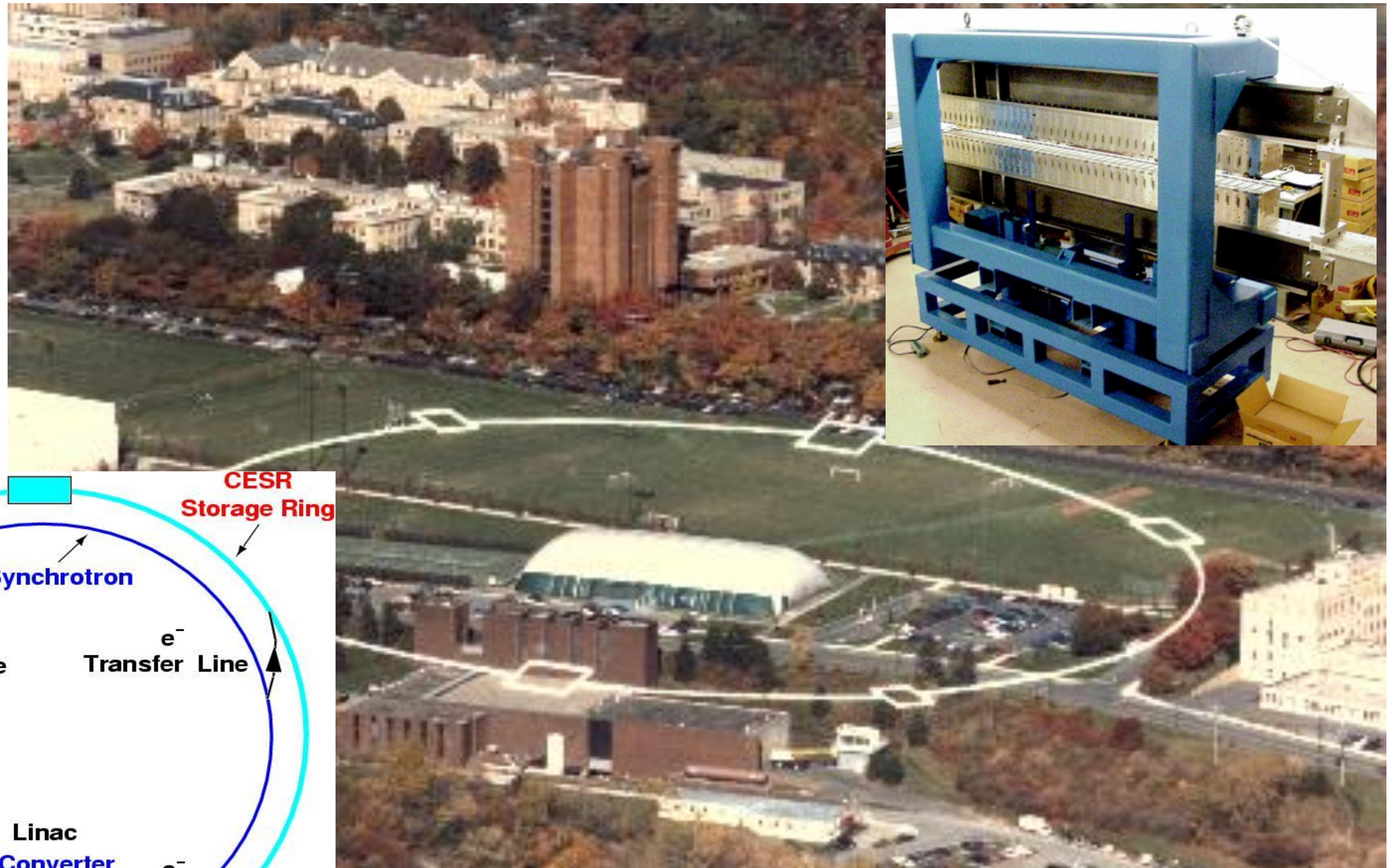


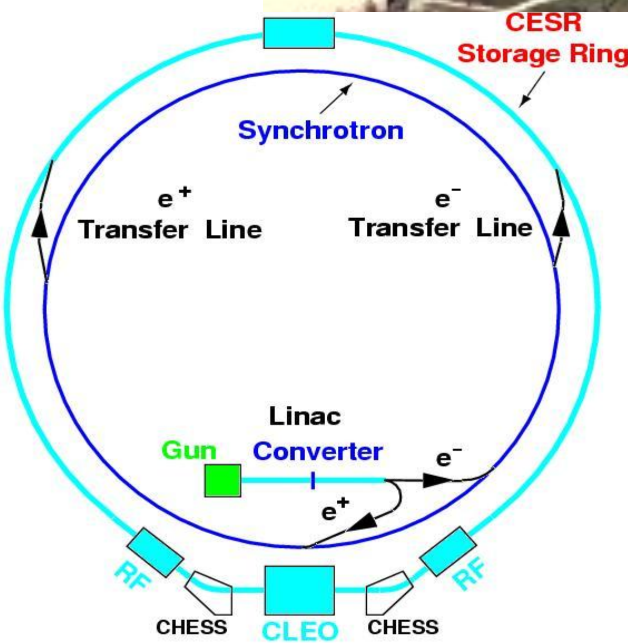
Cornell Laboratory for
Accelerator-based Sciences and
Education (CLASSE)

BROOKHAVEN
NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

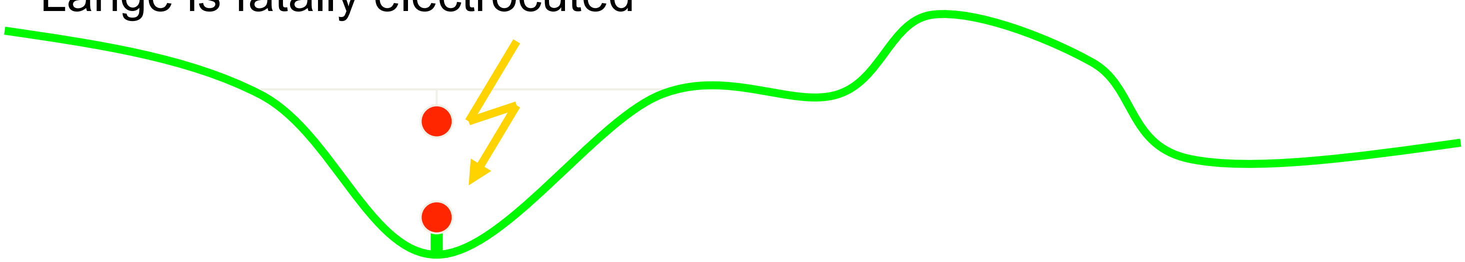
Cornell's synchroton and storage ring





Accelerator physics at Cornell

- 1932: Brasch and Lange use potential from lightening, in the Swiss Alps, Lange is fatally electrocuted



- 1934: Livingston builds the first Cyclotron away from Berkely (2MeV protons) at Cornell (in room B54)
- 1949: Wilson et al. at Cornell are first to store beam in a synchtotron (later 300MeV, magnet of 80 Tons)
- 1954: Wilson et al. build first synchrotron with strong focusing for 1.1GeV electrons at Cornell, 4cm beam pipe height, only 16 Tons of magnets.
- 1979: 5GeV electron positron collider CESR (designed for 8GeV)

- Currently:

CESR operation and optimization for the CLEO experiment
CESR operation and optimization for CHESS
ERL prototyping facility (ERL e-source and injector linac)
ERL and CESR upgrade to an ERL
ILC design, simulations, damping ring studies with CESR

Accelerator history at Cornell

Cornell accelerators:

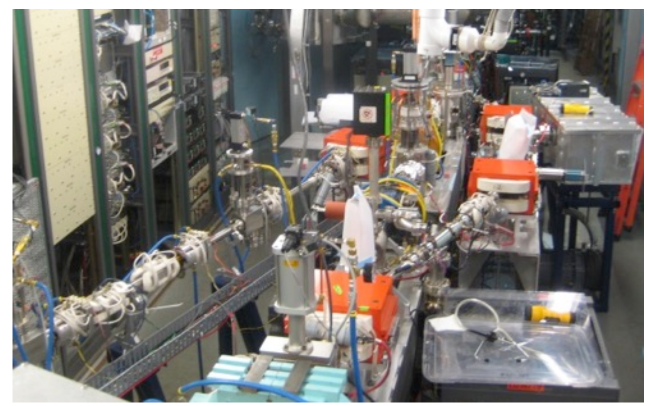
1930 1940 1950 1960 1970 1980 1990 2000 2010 2015

Cornell is a world leader in accelerators

Superconducting acceleration.

Bright electron sources. World record high current, low emittance.

Multi-turn FFAG ERL. A new accelerator paradigm.



Cornell's academic program in accelerator science is the strongest in the U.S.

Most faculty, most PhD's, most high-impact accomplishments.

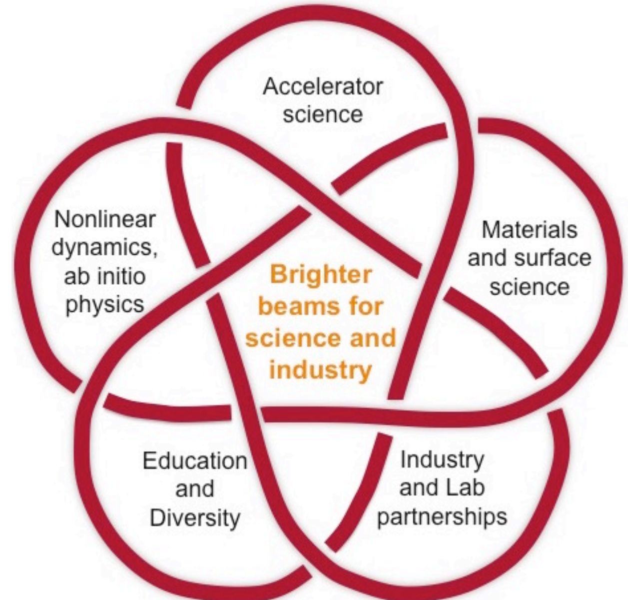
Center of Bright Beams (CBB)

CBB Vision:

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

CBB Mission:

Transform the reach of electron beams by increasing their brightness x100 and reducing the cost and size of key enabling technologies.
Transfer the best of these technologies to national labs and industry.



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

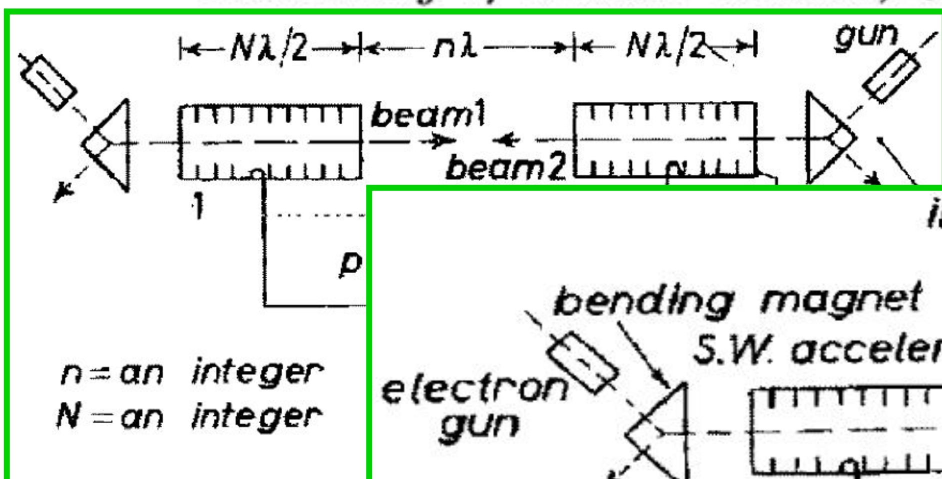
ERLs, invented at Cornell

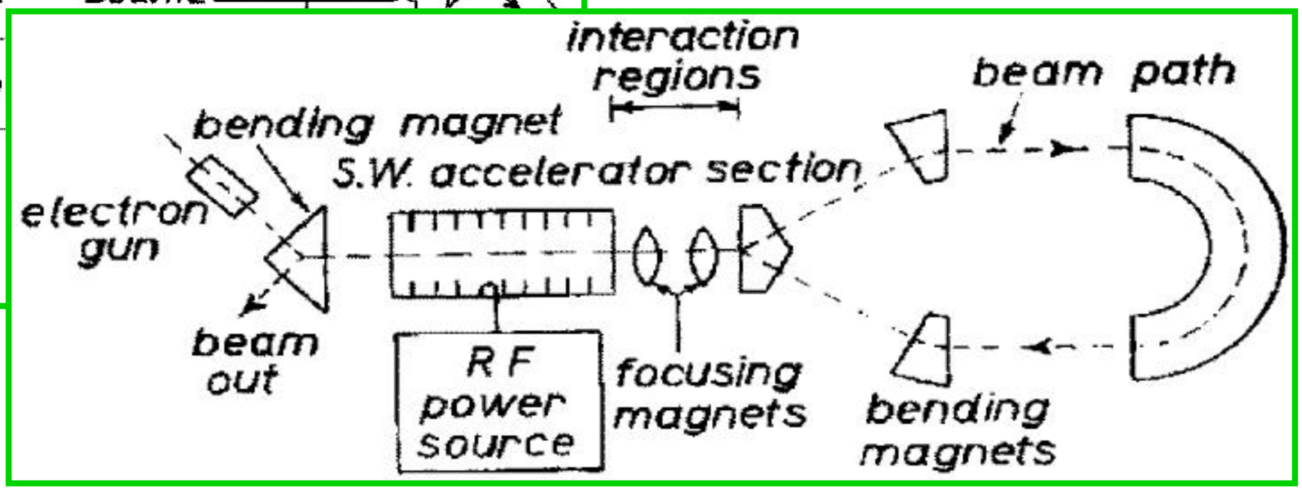
A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. TIGNER

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

ebbraio 1965)

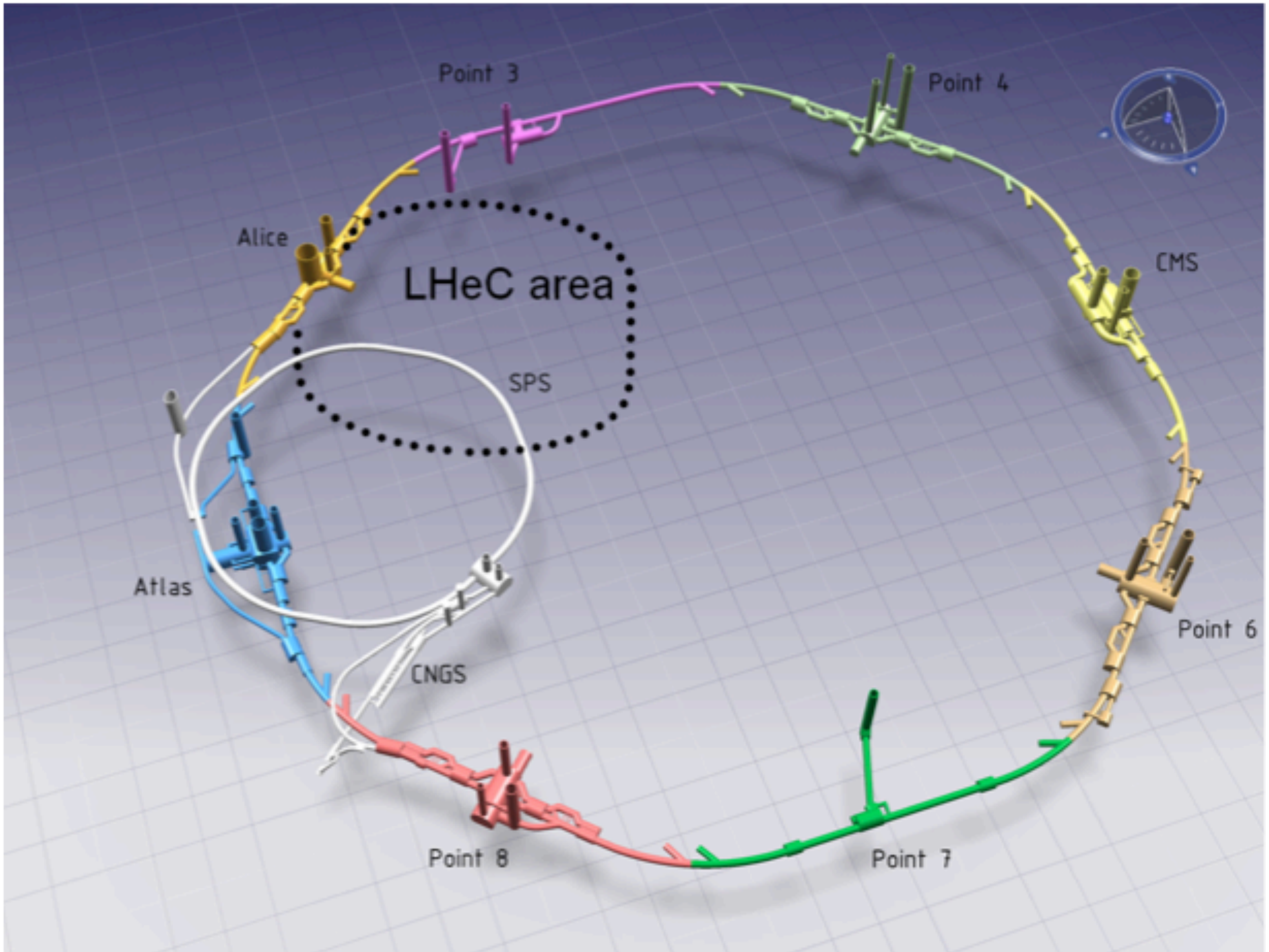




Energy recovery needs continuously fields in the RF structure

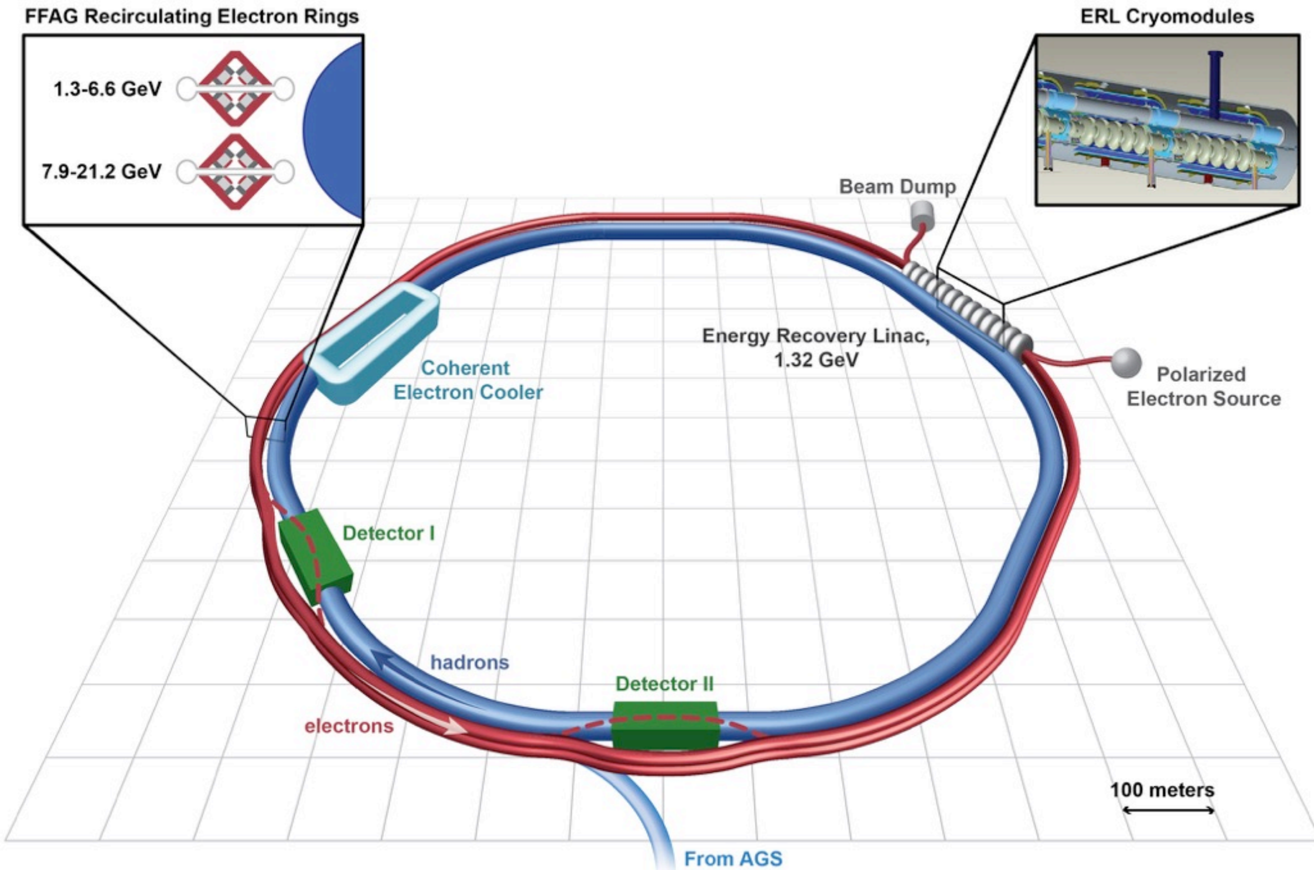
- Normal conducting high field cavities can get too hot.
- Superconducting cavities used to have too low fields.

AnERL for LHeC (e-hadron collisions)

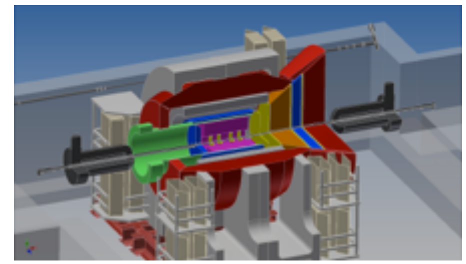


courtesy Oliver Bruening

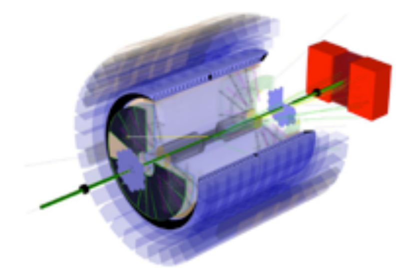
ERL for eRHIC (e-p and e-ions)



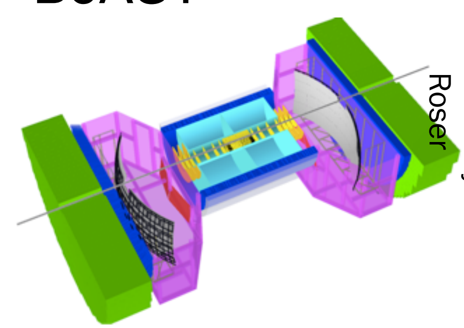
ePHENIX



eSTAR



BeAST



courtesy Thomas Roser

- 1.7 × 10^{33} cm^{-2} s^{-1} for $\sqrt{s}$ = 127 GeV (15.9 GeV e ↑ on 255 GeV p ↑)
- × 10 luminosity with modest improvements (coating of RHIC vacuum chamber)
- × 100 luminosity with shorter bunch spacing (ultimate capability)

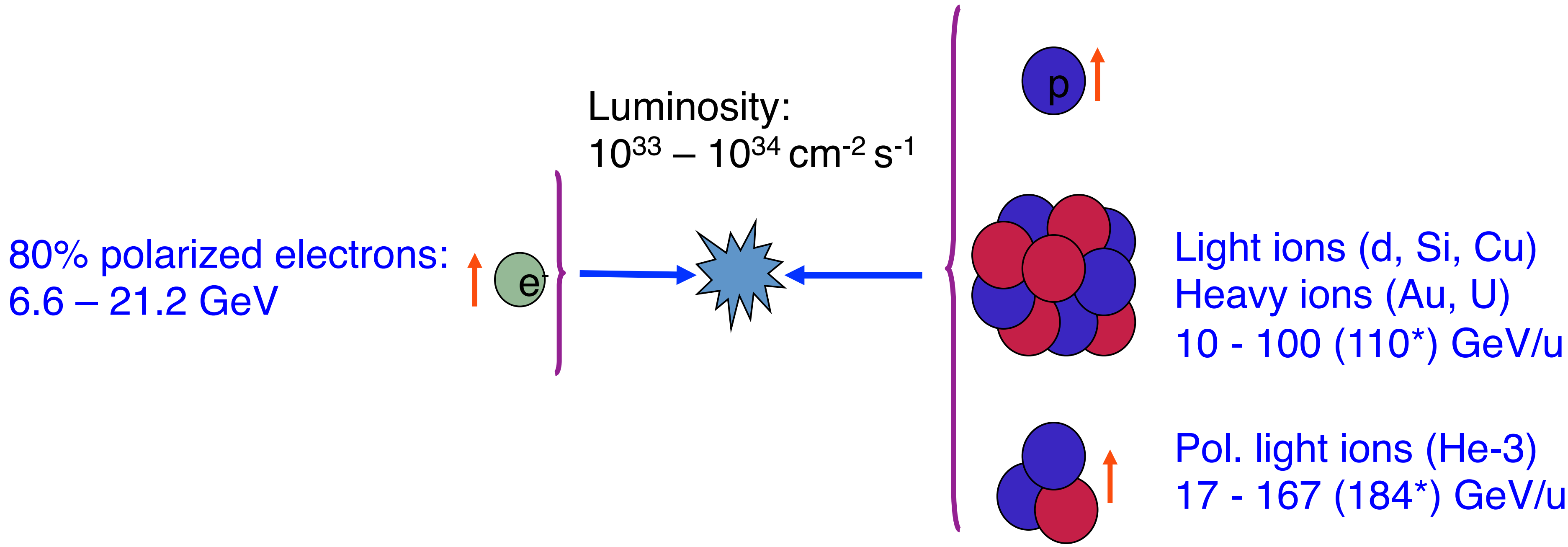
2015 NSAC Long Rang Plan

RECOMMENDATION III

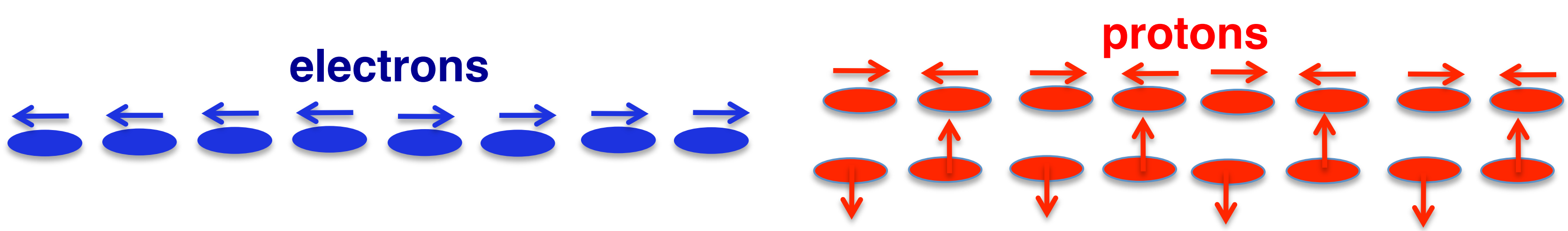
We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

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

Collisions in eRHIC



- Center-of-mass energy range: 30 – 145 GeV
- Full electron polarization at all energies
  Full proton and He-3 polarization with six Siberian snakes
- Any polarization direction in electron-hadron collisions:



Collisions in eRHIC

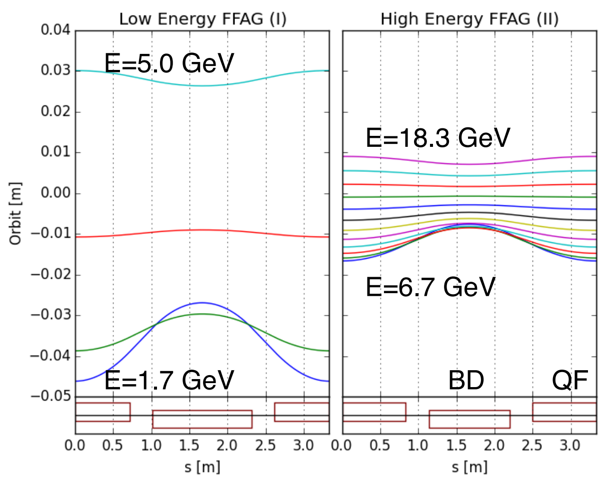
eRHIC baseline designs:

The baseline design of eRHIC has been a linac-ring collider to boost the luminosity to into the 10^{34} regime, based on a **12-turn ERL** with 2 permanent magnet **FFAG return loops**.

About 6 months ago the baseline design changed to a ring-ring collider. Luminosities in the region 10^{33} to 10^{34} regime are possible, depending on details. To provide all helicity combinations for collisions, a recirculating linac injector is chosen. **12-turn recirculation** with 2 **FFAG return loops** is a cost-saving option.

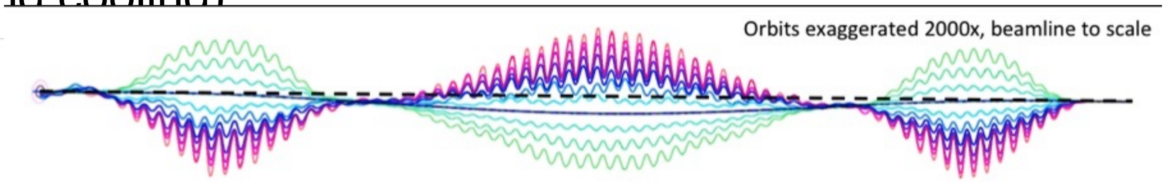
If polarization can survive acceleration in a spin-optimized rapid cycling synchrotron, a ring as injector would be a cost-saving alternative. As an option for **electron cooling**, an **ERL** is then still an important topic of study.

Topics of eRHIC studied in CBETA

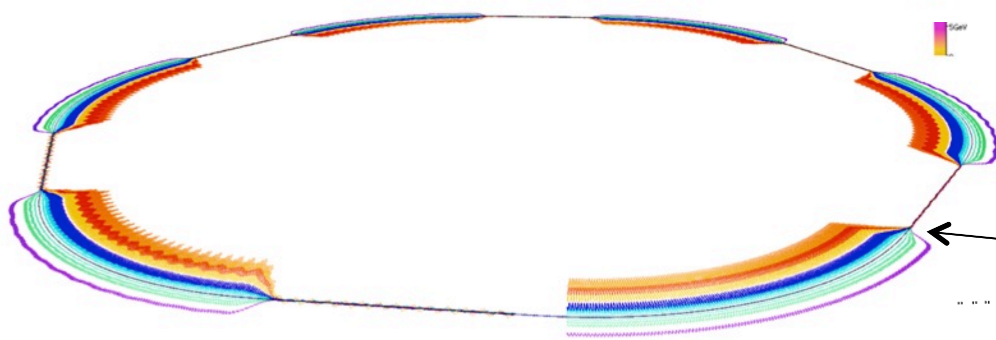


- eRHIC uses two FFAG beamlines to do multiple recirculations.
  (FFAG-I: 1.7-5.0 GeV, FFAG-II: 6.7-18.3 GeV, 20 GeV)
- All sections of a FFAG beamline is formed using a same FODO cell. Required bending in different sections is arranged by proper selection of the offsets between cell magnets (or, alternatively, with dipole field correctors).
- Permanent magnets can be used for the FFAG beamline magnets (no need for power supplies/cables and cooling)

@S.Brooks, D.Trbojevic

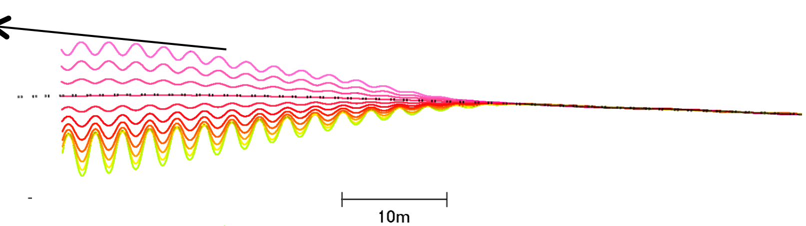


Orbits in Detector bypass section



Quad offsets evolve adiabatically

Orbits in Transition section



Each of two eRHIC FFAGs contain 1066 FFAG cells

CBETA study topics important for eRHIC:

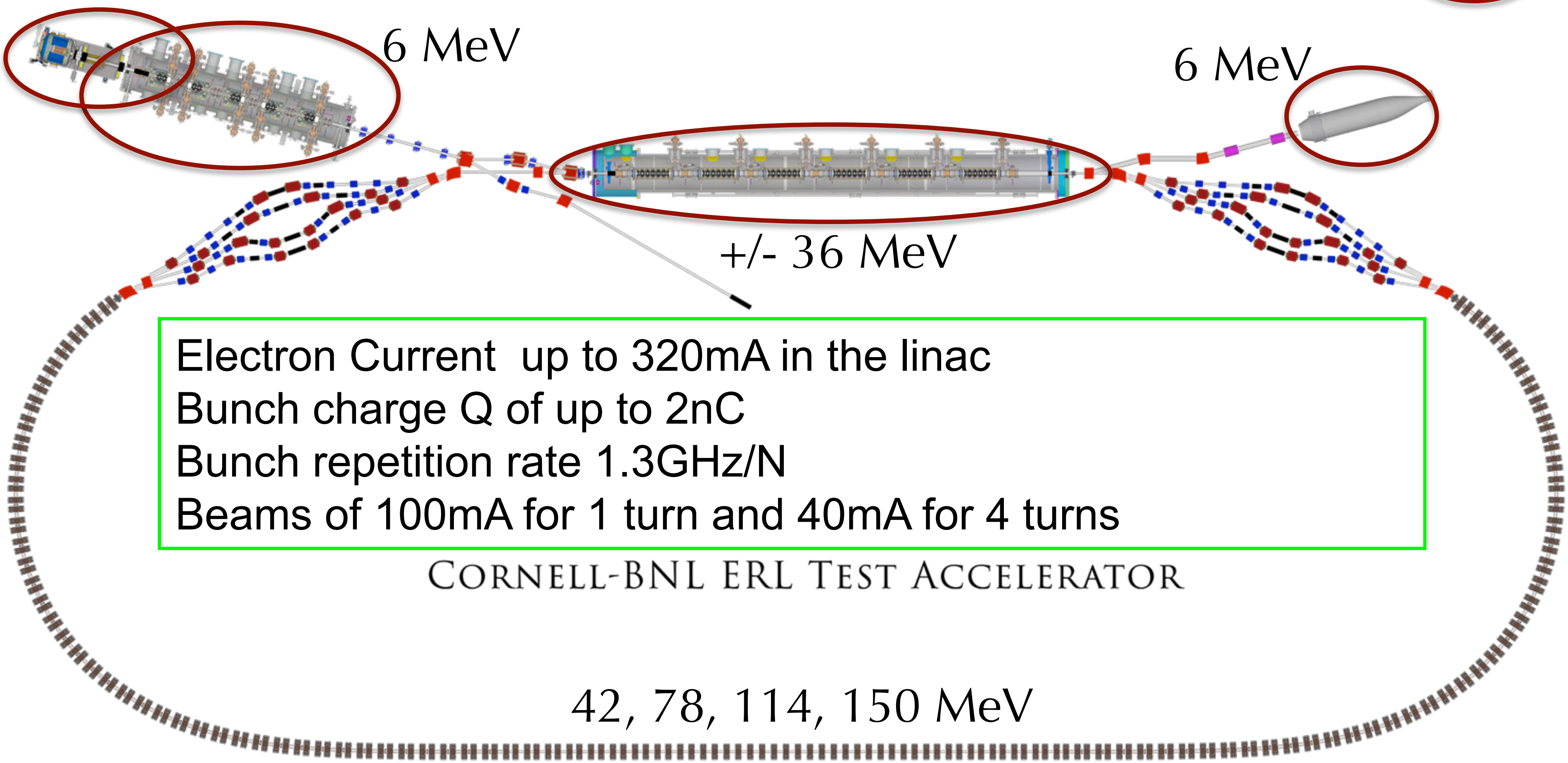
1) **FFAG** loops with a factor of 4 in momentum **aperture**.
   a) Precision, reproducibility, alignment during magnet and girder production.
   b) Stability of magnetic fields in a radiation environment.
   c) **Matching** and correction of multiple simultaneous **orbits**.
   d) **Matching** and correction of multiple simultaneous **optics**.
   e) **Path length control** for all orbits.

2) Multi-turn ERL operation with a large number of turns.
   a) **HOM damping.**
   b) **BBU limits.**
   c) **LLRF control and microphonics.**
   d) **ERL startup from low-power beam.**

The test ERL in Cornell's hall LOE

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

Existing components at Cornell



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The test ERL in Cornell's hall LOE

CBETA

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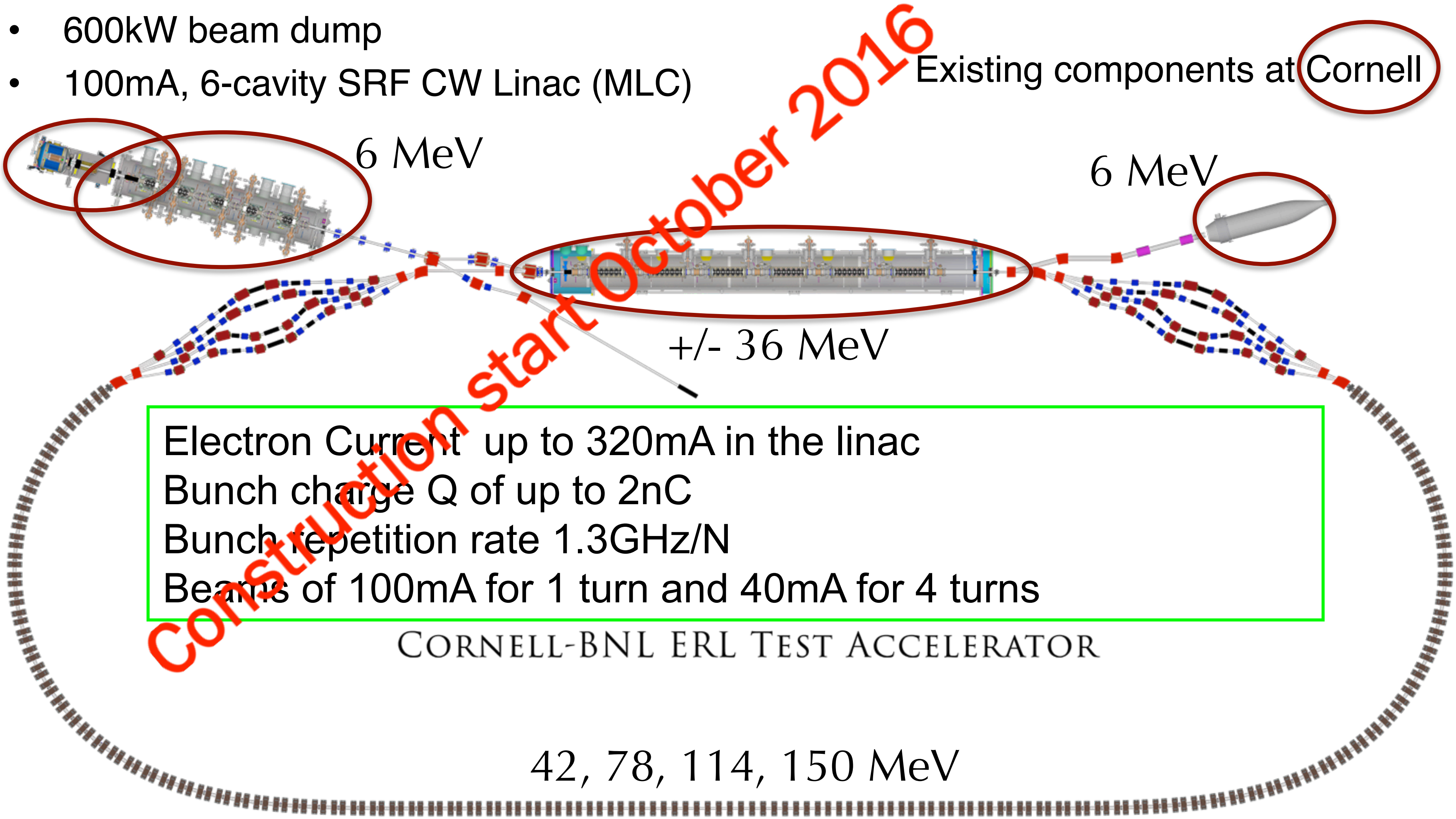
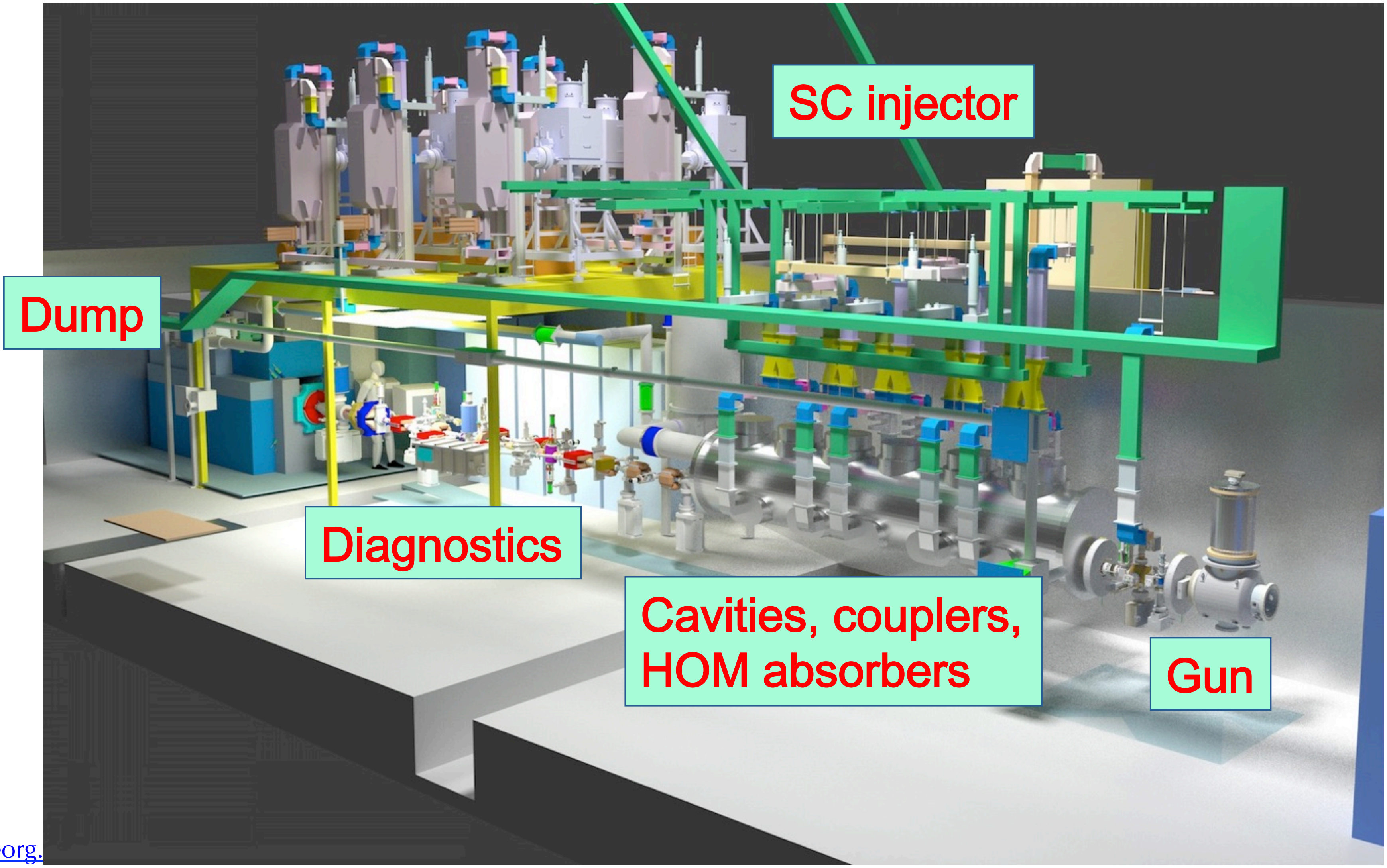
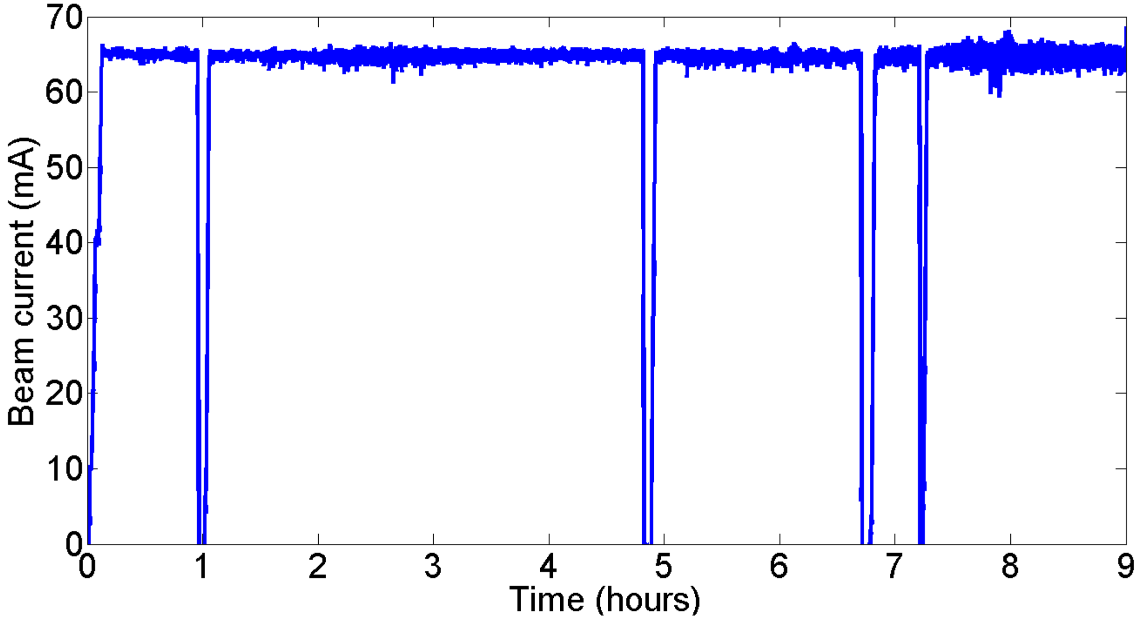


Cornell ERL injector prototype

- DC photo-emitter electron source with highest current (75mA)
- SRF injector linac with up to 0.5MW, 12MeV, larges bunch brightness for high current
- Full 6-D beam diagnostics for low-emittance studies.



High Current Beams



- Peak current of 75mA (world record)

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

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

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

✓ Source current can meet ERL needs

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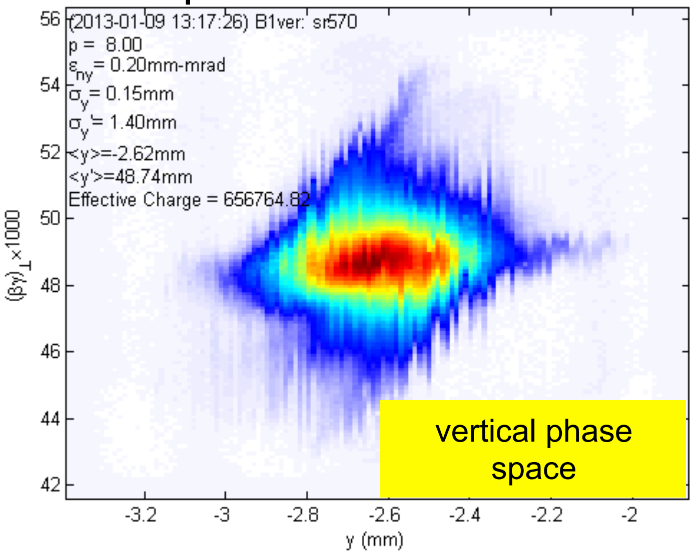
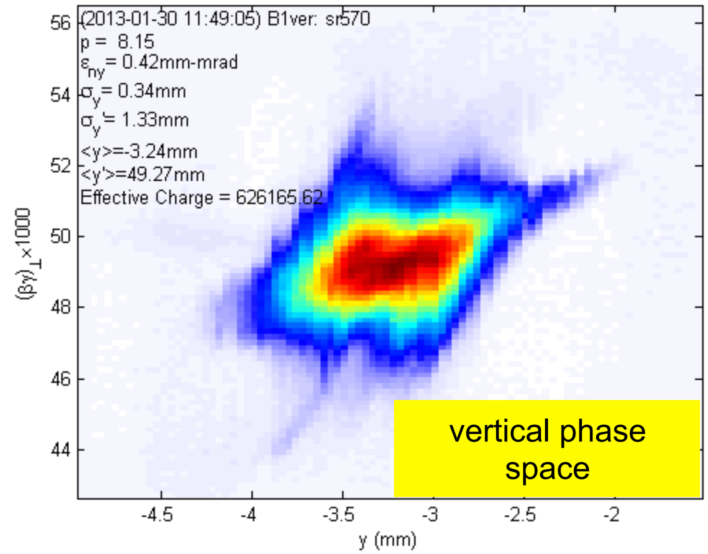
Beam Brightness

CBETA

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 (%)

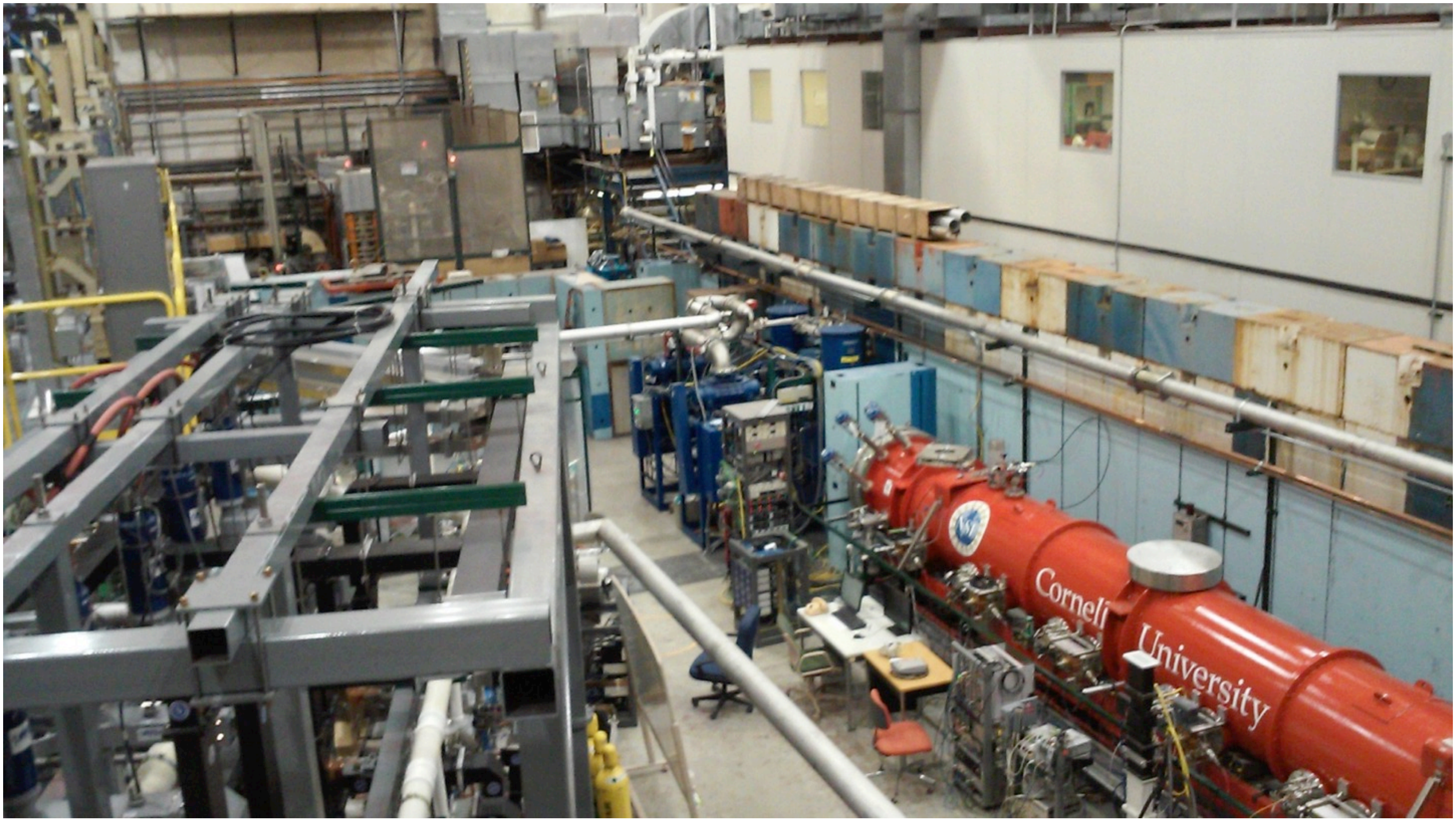
0.14/0.09 mm-mrad @ 68% 0.24/0.18 mm-mrad @ 61%

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

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

MLC construction at Cornell

- 1.3GHz, 6 cavities, 7 cells, a SiC beampipe HOM absorber next to each cavity.
- 5 kW solid-state amplifiers for each coupler (capable of 10kW)



Key Performance Parameters and Ultimate Performance Parameters

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

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The CBETA Collaboration

Background for CDR

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

Start of CBETA July 2014 White paper December 2014

Defined CBETA in a white paper in December 2014.

CDR for CBETA in with Hybrid permanent magnets in July 2016.

Secured funding October 2016

Passed design and finance review, January 2017

DR for CBETA with Halbach magnets in February 2017

Prototype FFAG girder, April 2017

1st beam through MLC, May 2017

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

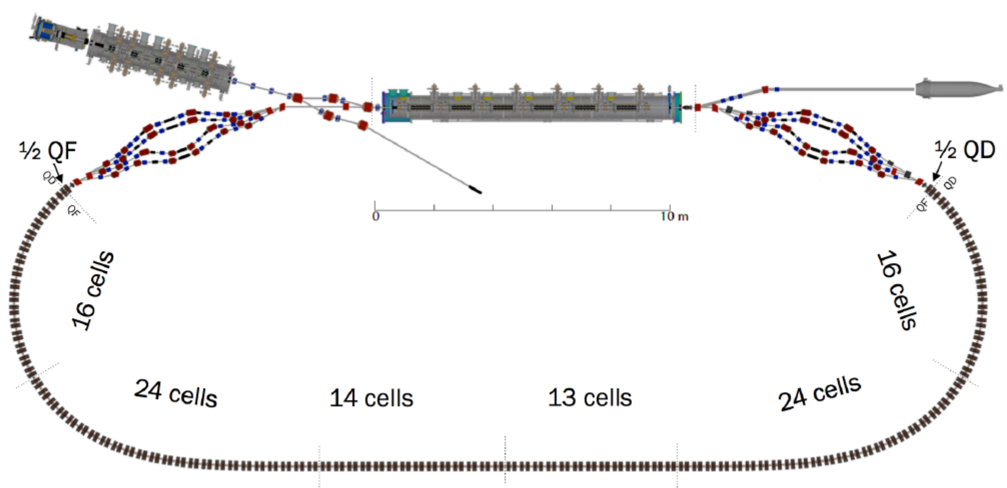
CBETA Design Report

Cornell-BNL ERL Test Accelerator

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

Editor: C. Mayes

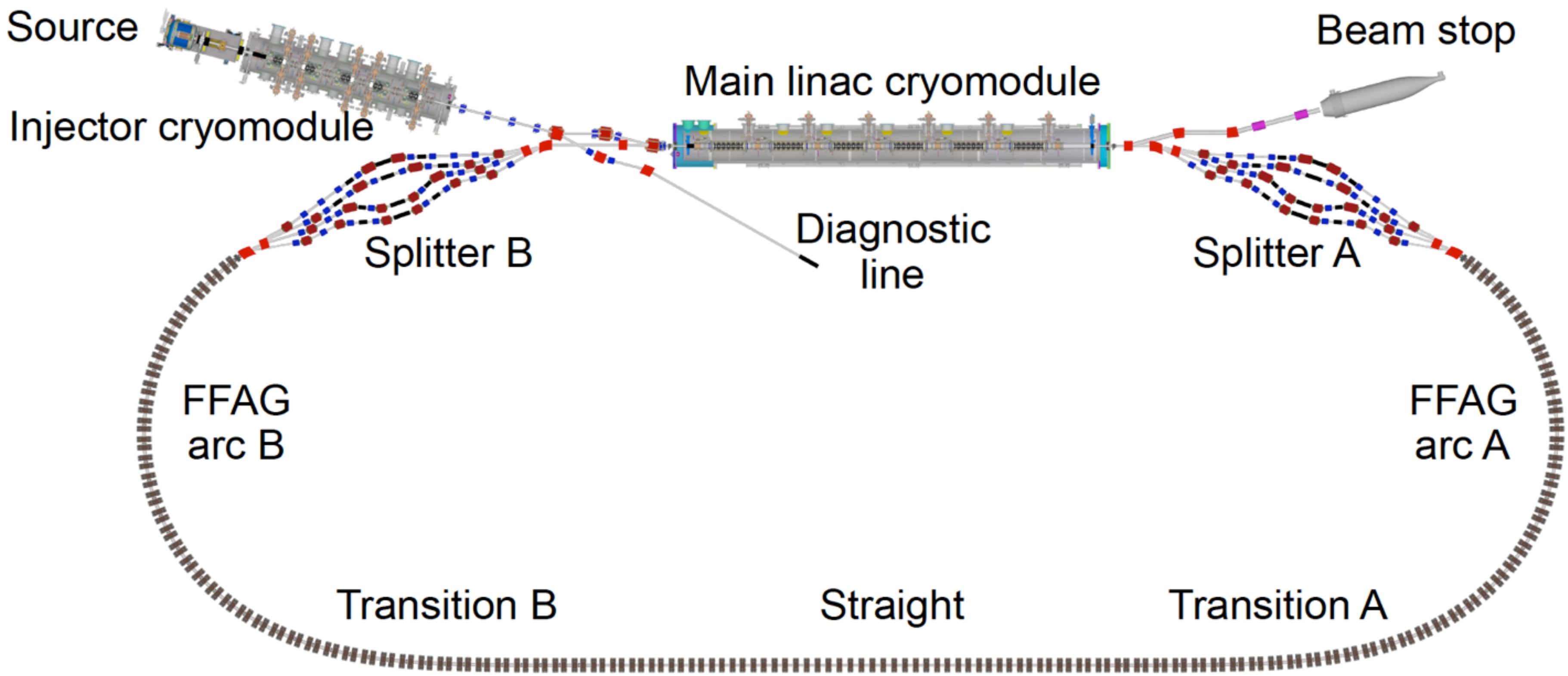
Contributors: N. Banerjee, J. Barley, I. Bazarov, A. Bartnik, J. S. Berg, S. Brooks, D. Burke, J. Crittenden, L. Cultrera, J. Dobbins, D. Douglas, B. Dunham, R. Eichhorn, S. Full, F. Furuta, C. Franck, R. Gallagher, M. Ge, C. Gulliford, B. Heltsley, D. Jusic, R. Kaplan, V. Kostroun, Y. Li, M. Liepe, C. Liu, W. Lou, G. Mahler, F. Méot, R. Michnoff, M. Minty, R. Patterson, S. Peggs, V. Ptitsyn, P. Quigley, T. Roser, D. Sabol, D. Sagan, J. Sears, C. Shore, E. Smith, K. Smolenski, P. Thieberger, S. Trabocchi, J. Tuozzolo, N. Tsoupas, V. Veshcherevich, D. Widger, G. Wang, F. Willeke, W. Xu



June 8, 2017

Existing & new equipment

CBETA



Much equipment & infrastructure exists — 32 M$

Major new equipment: — 25 M$ new funding

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

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

L0E for the Injector test

The gun and ICM were tested with beam

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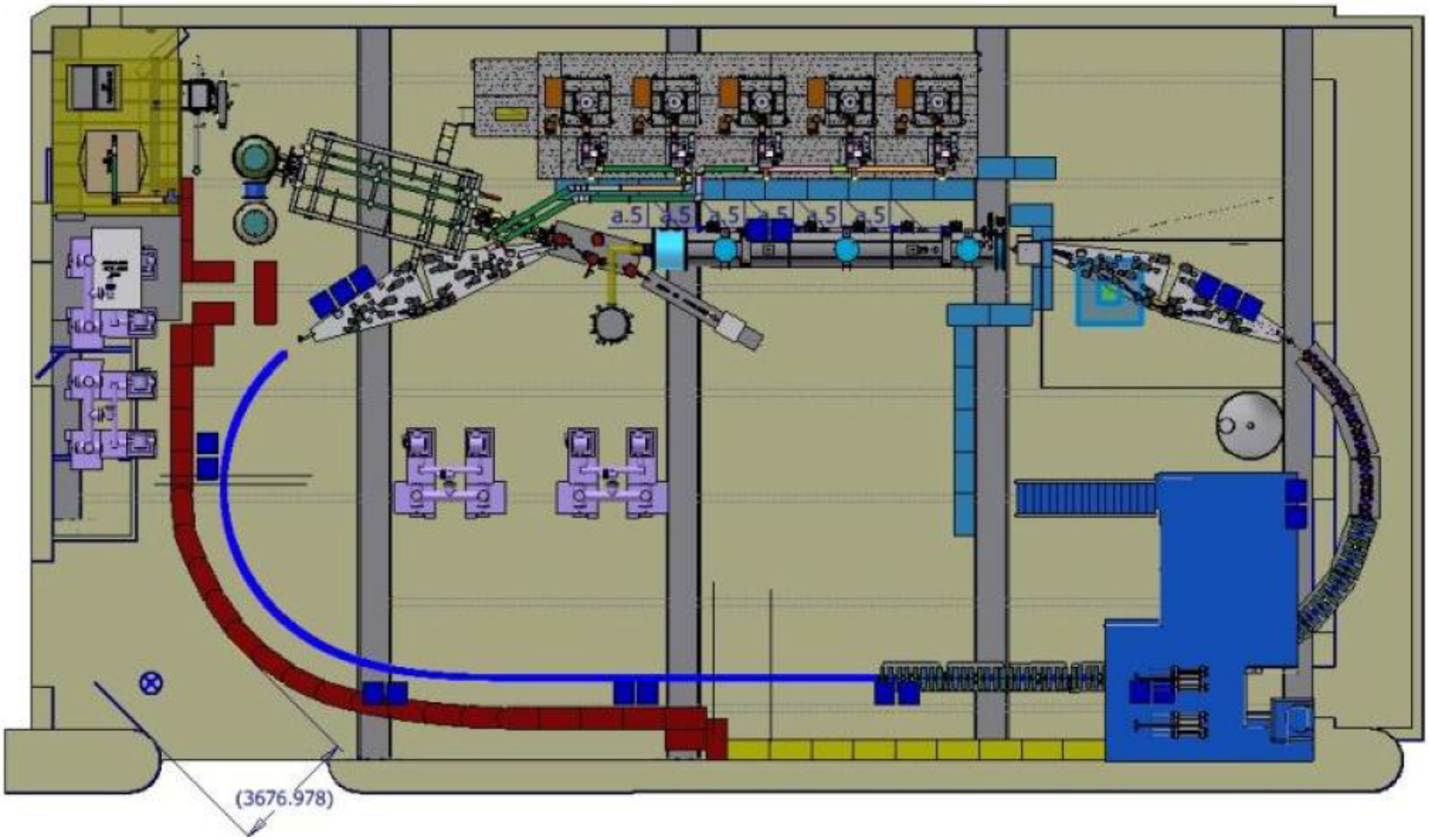
L0E with space for the return loop

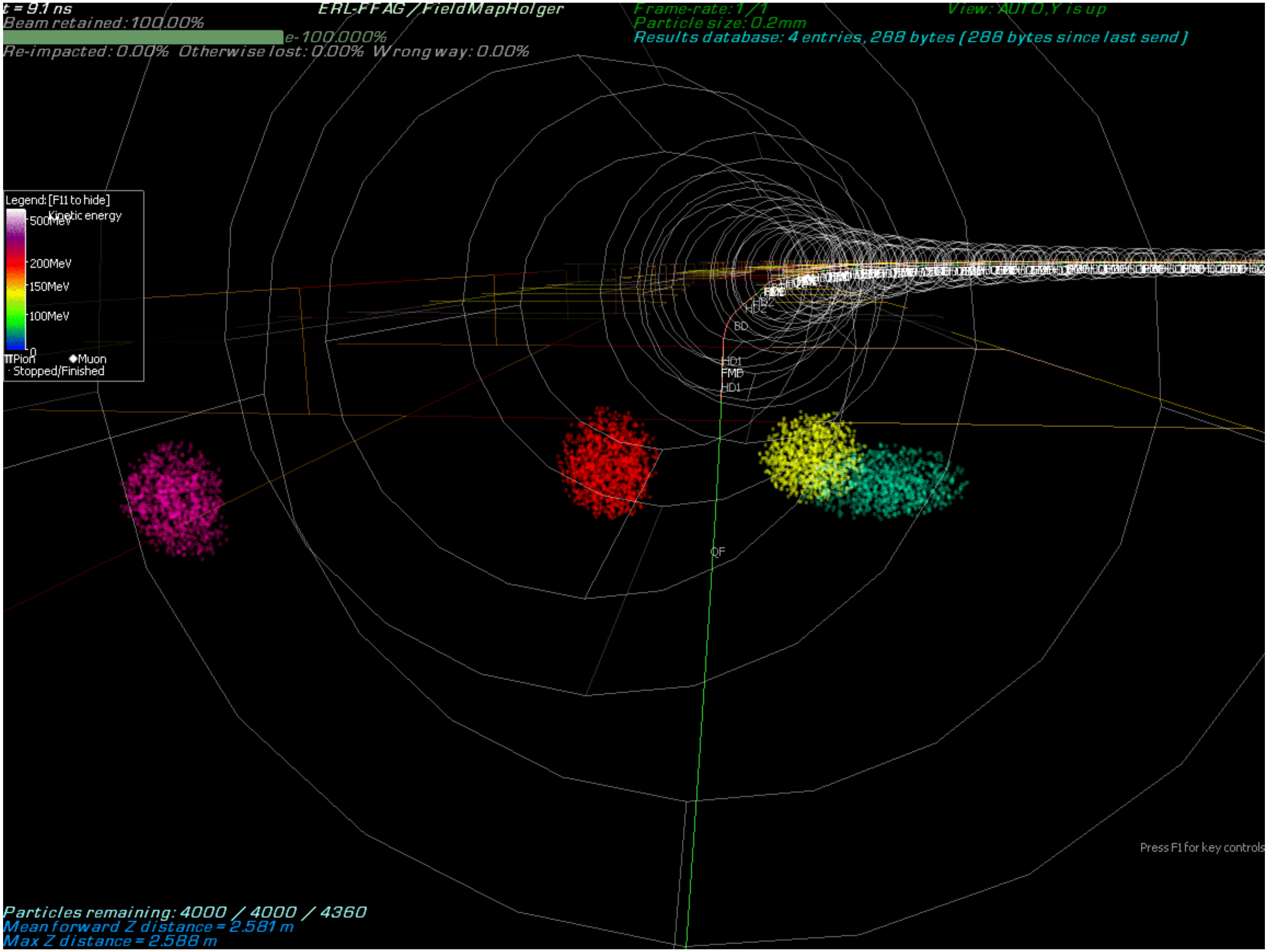
CBETA

Before and After of the Vacuum Lab in Wilson Laboratory

2019 Layout



Bunche dynamics in 3D field maps



RF sourses

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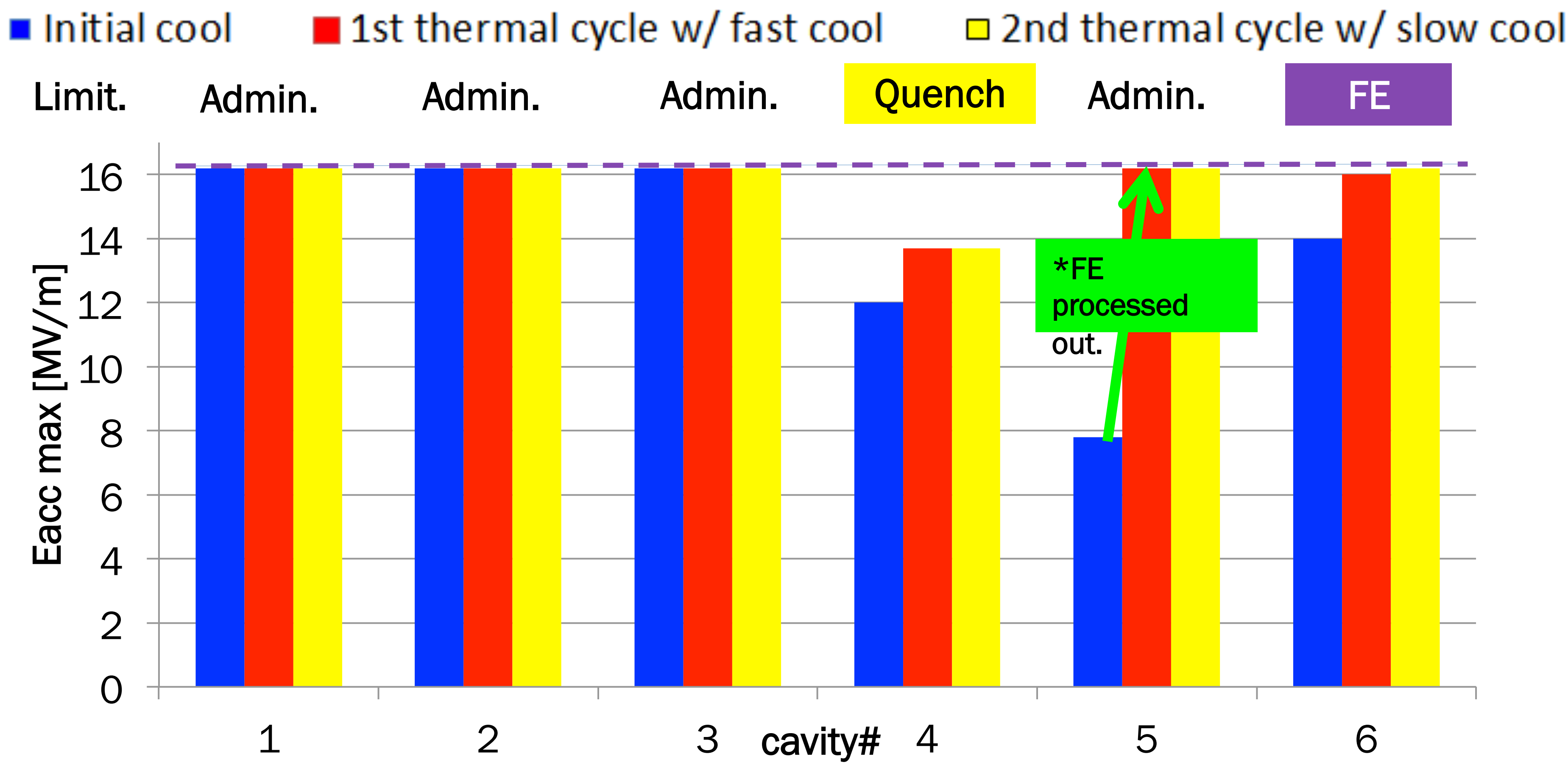
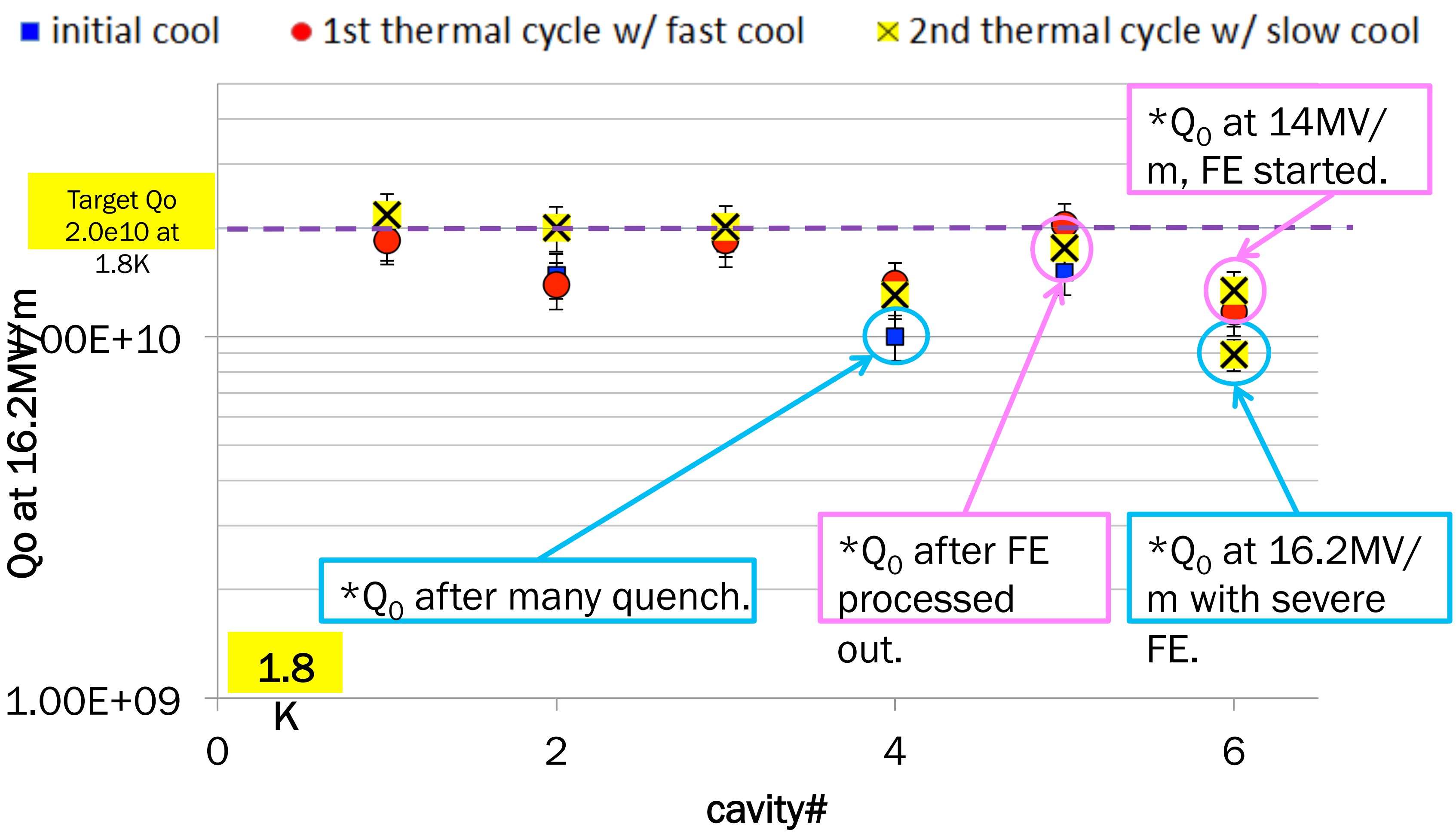
Main linac cryomodule (MLC) achieved accelerating gradients

CBETA



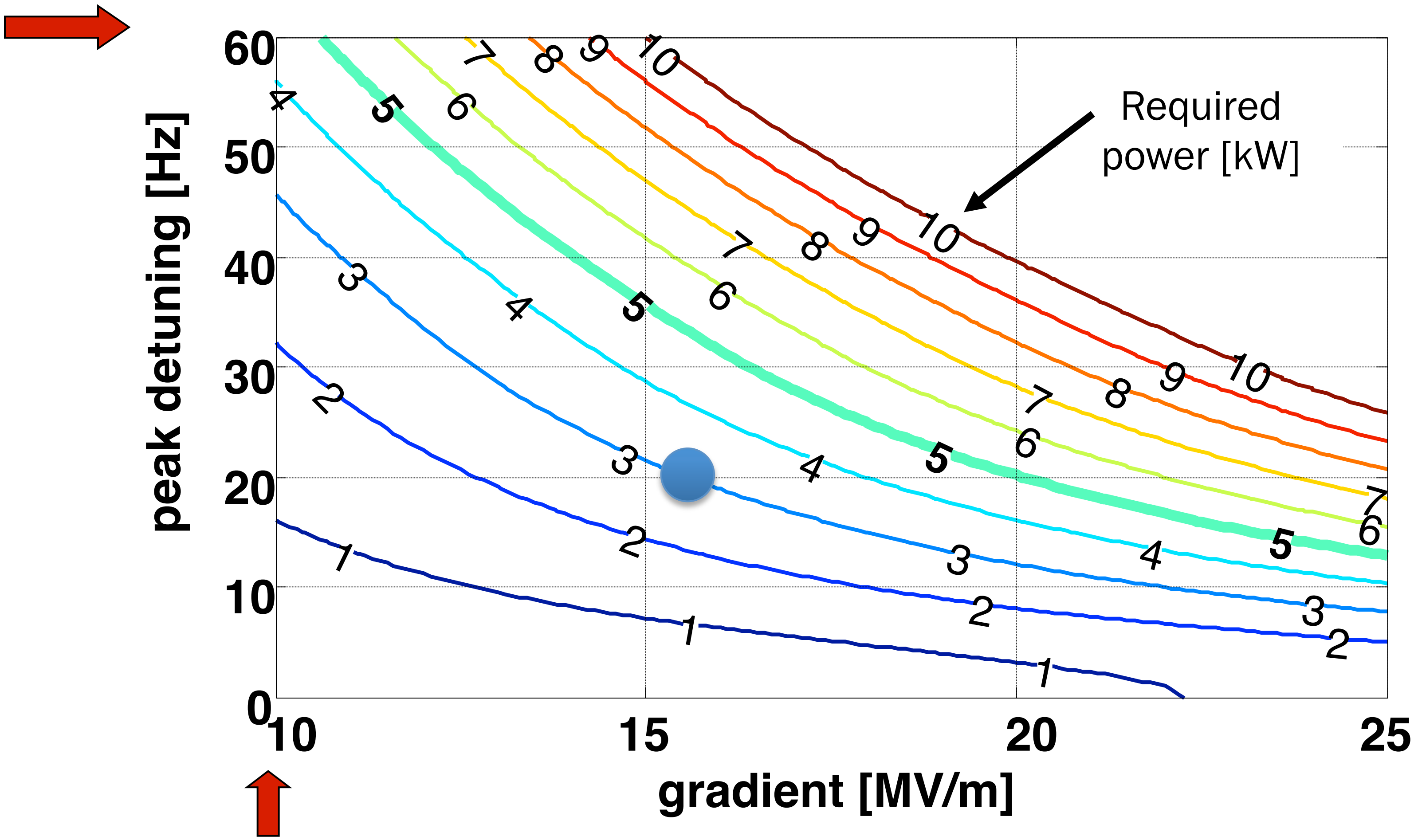
- 5 of 6 cavities had achieved design gradient of 16.2MV/m at 1.8K in MLC.
- Cavity#4 is limited by quench so far, no detectable radiation during test.
- Enough Voltage for 76MeV per ERL turn (where 36MeV are needed)

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



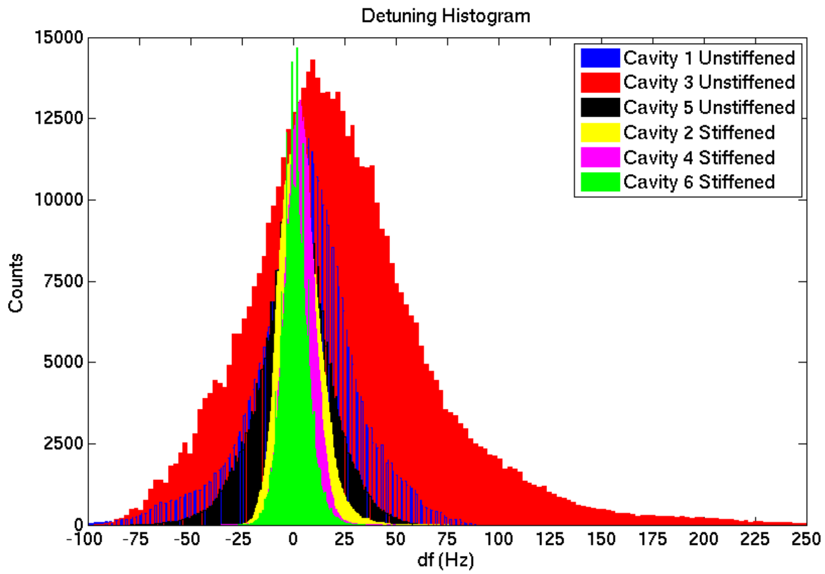
- 4 of 6 cavities had achieved design Q_0 of 2.0E+10 at 1.8K.
- Q_0 of Cavity#6 had severe FE at 16MV/m.
- **Enough cooling for 73MV per ERL turn (where 36MeV are needed)**

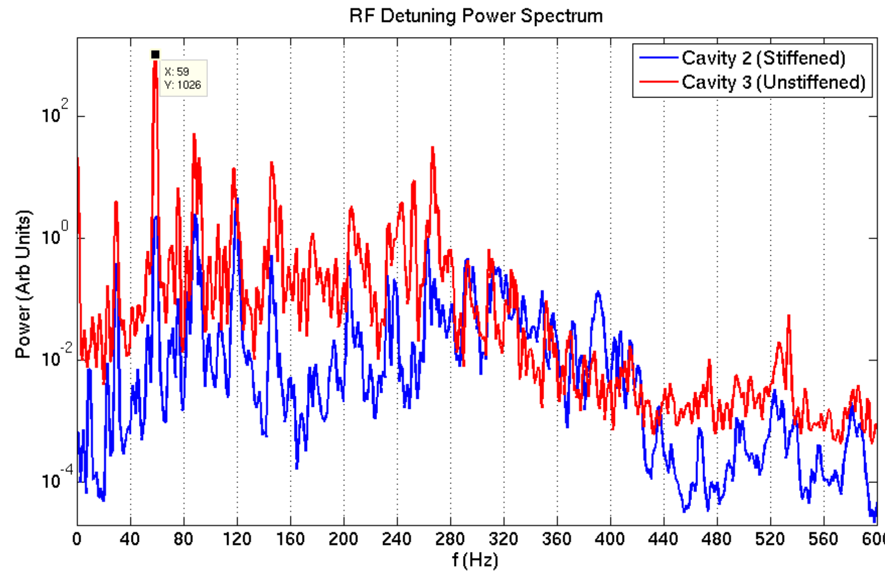
Required Peak Power (Q_L=2·10 [7])



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



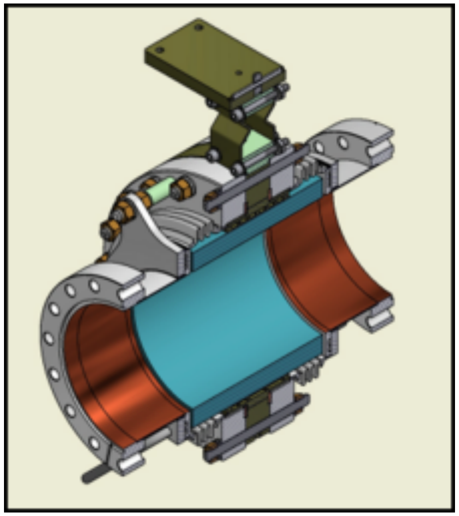


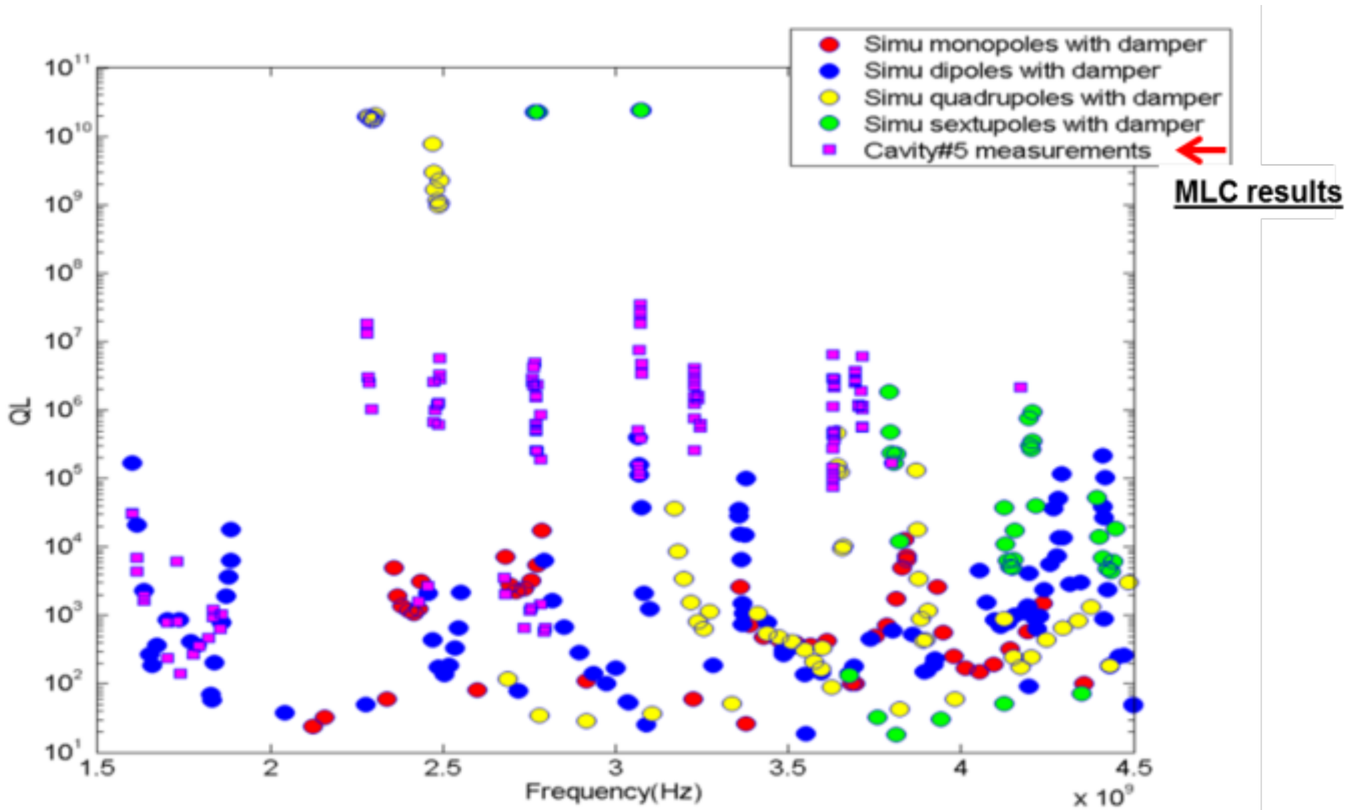
Preliminary results:

- 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)**

Current limits from HOMs



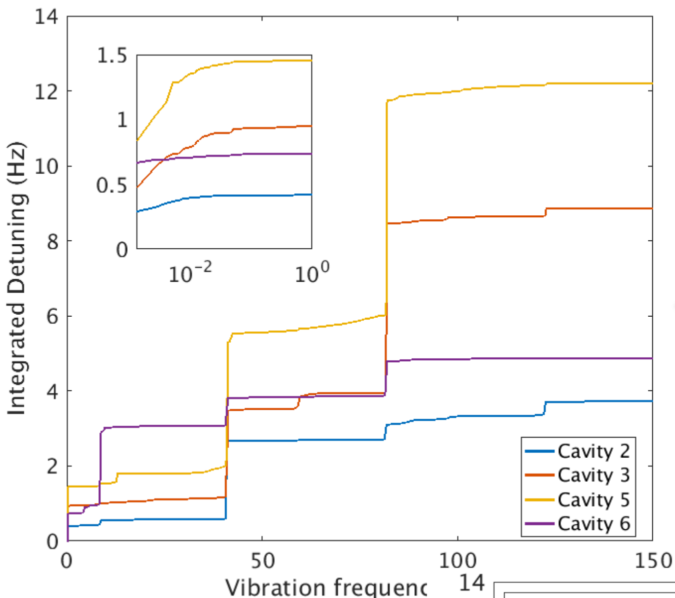


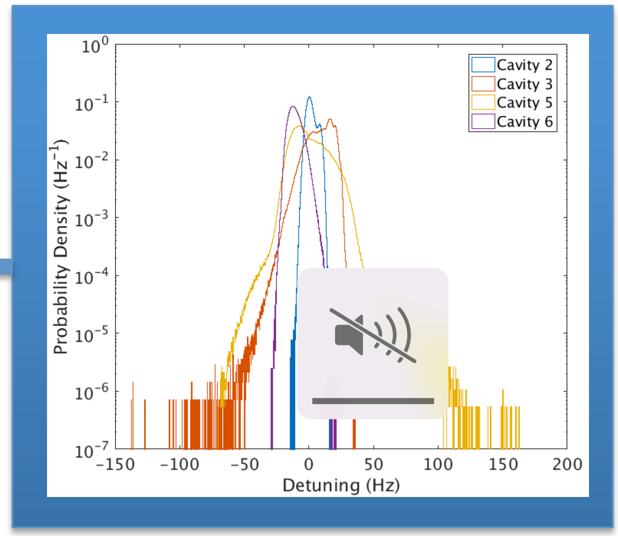
Dipole HOMs on MLC were strongly damped below $Q\sim10^4$.
Consistent with HTC and simulation results.

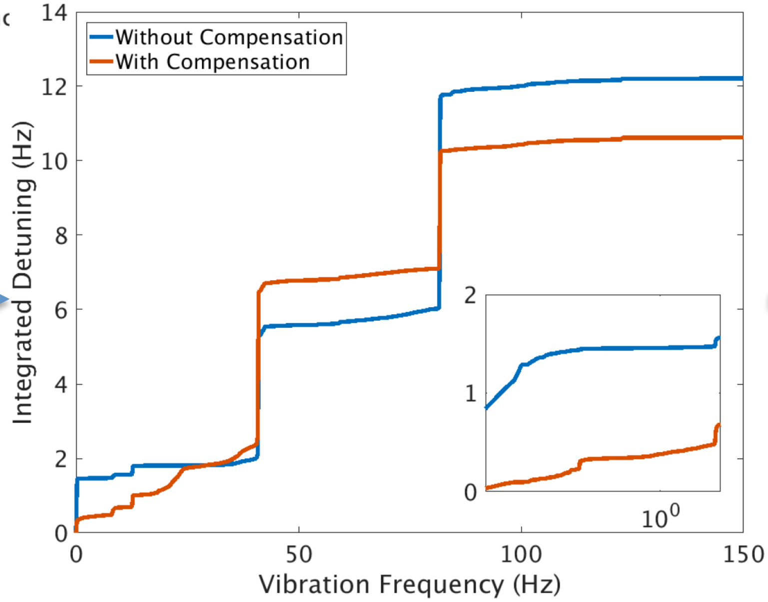
HTC results were:

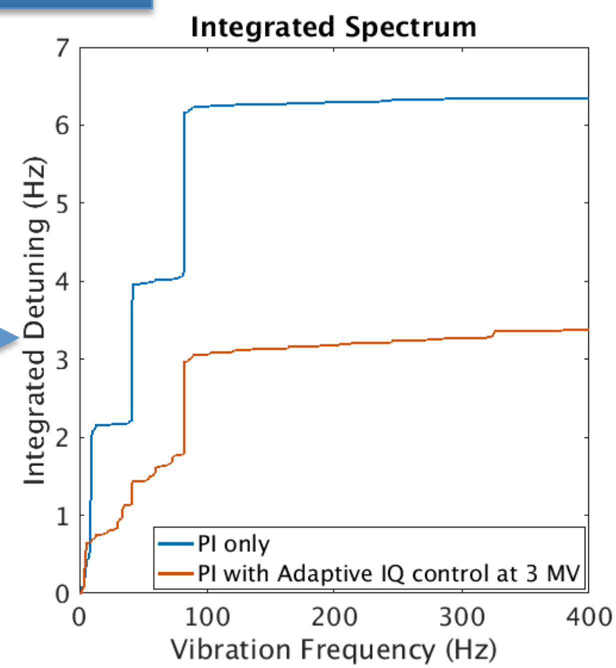
- HOM heating: currents are limited to < 40mA in CBETA
- BBU no HOM limits BBU to below 100mA in one turn

Current limits from HOMs



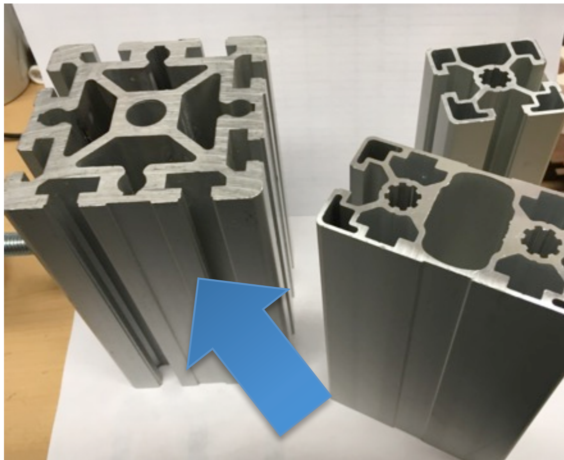




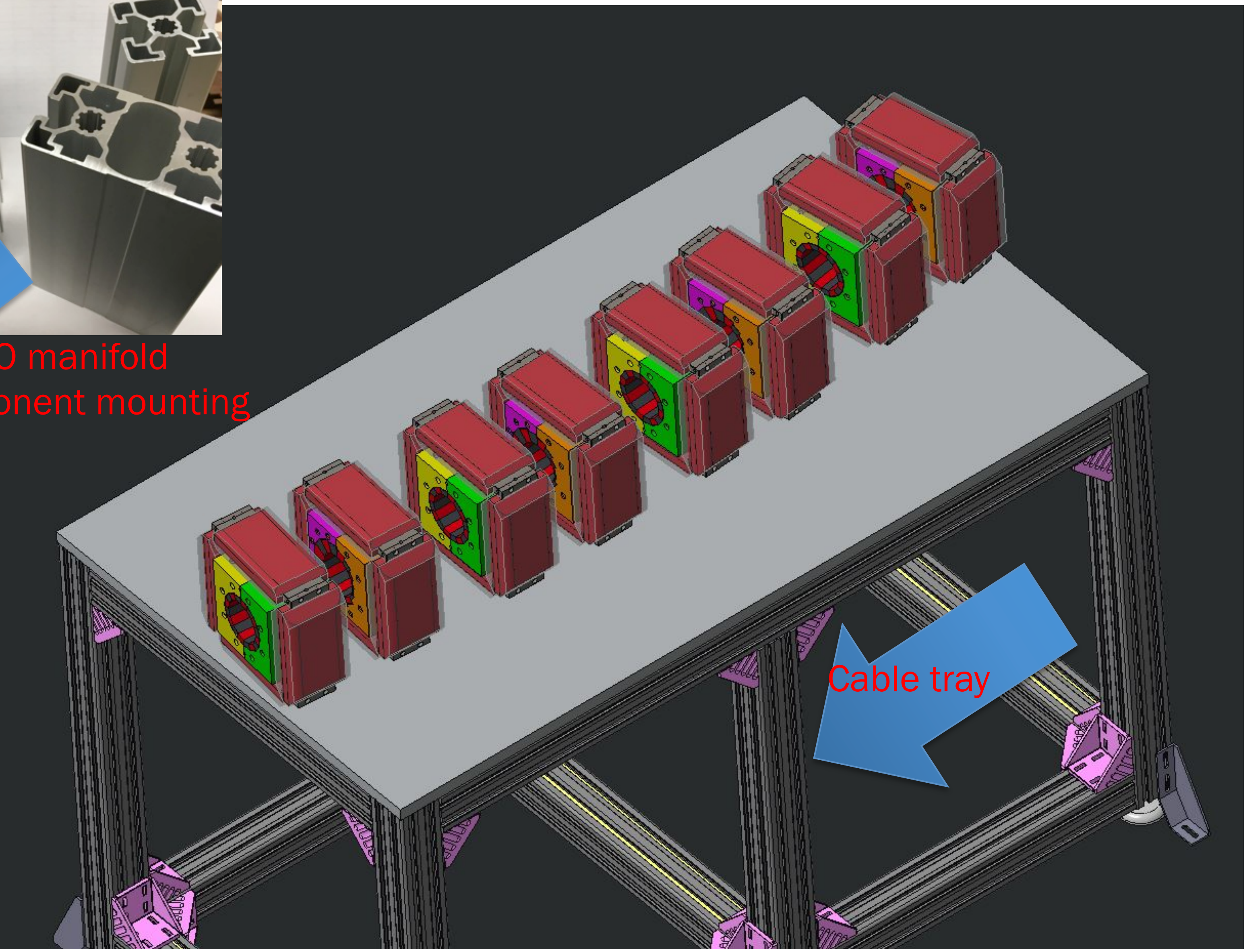


Algorithm is stable! Reduced peak detuning from 30.2Hz to 15.5Hz.

Girder Types and Positions



Integrated H20 manifold
Flexible component mounting



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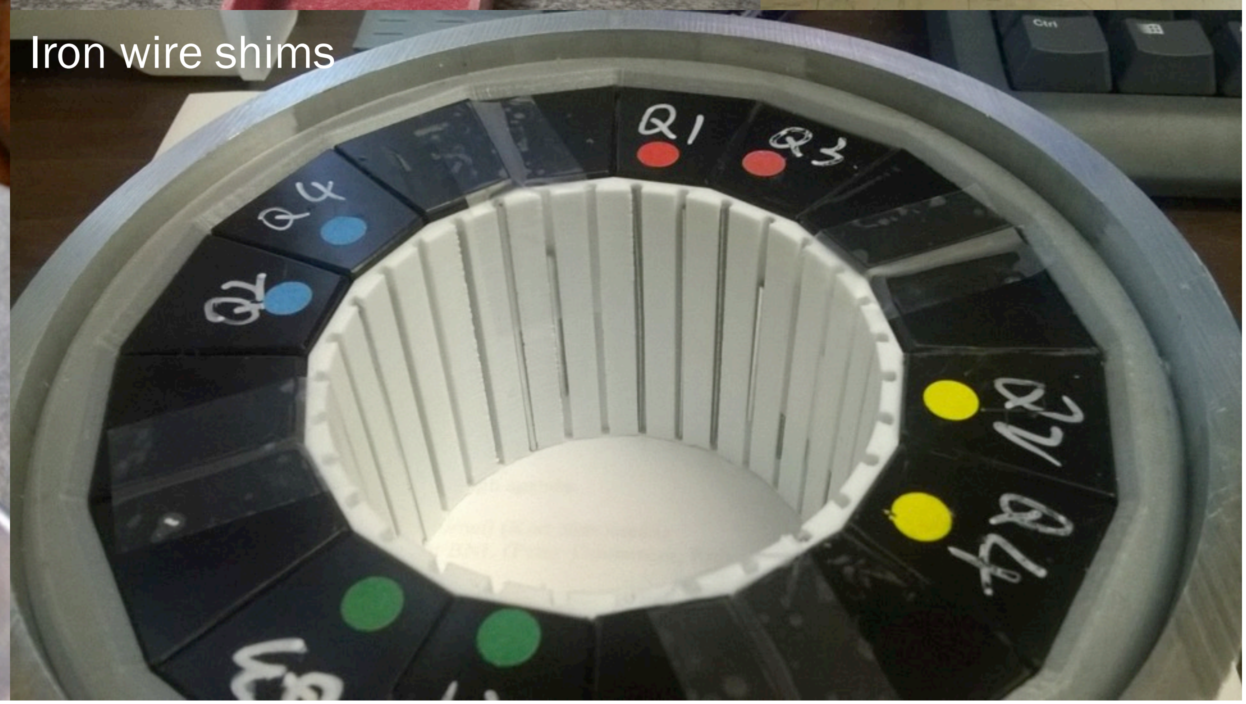
12 proof-of-principle magnets (6 QF, 6 BD) have been built as part of CBETA R&D.
Iron wire shimming has been done on 3 QFs and 6 BDs with good results.


PoP BD

PoP QF

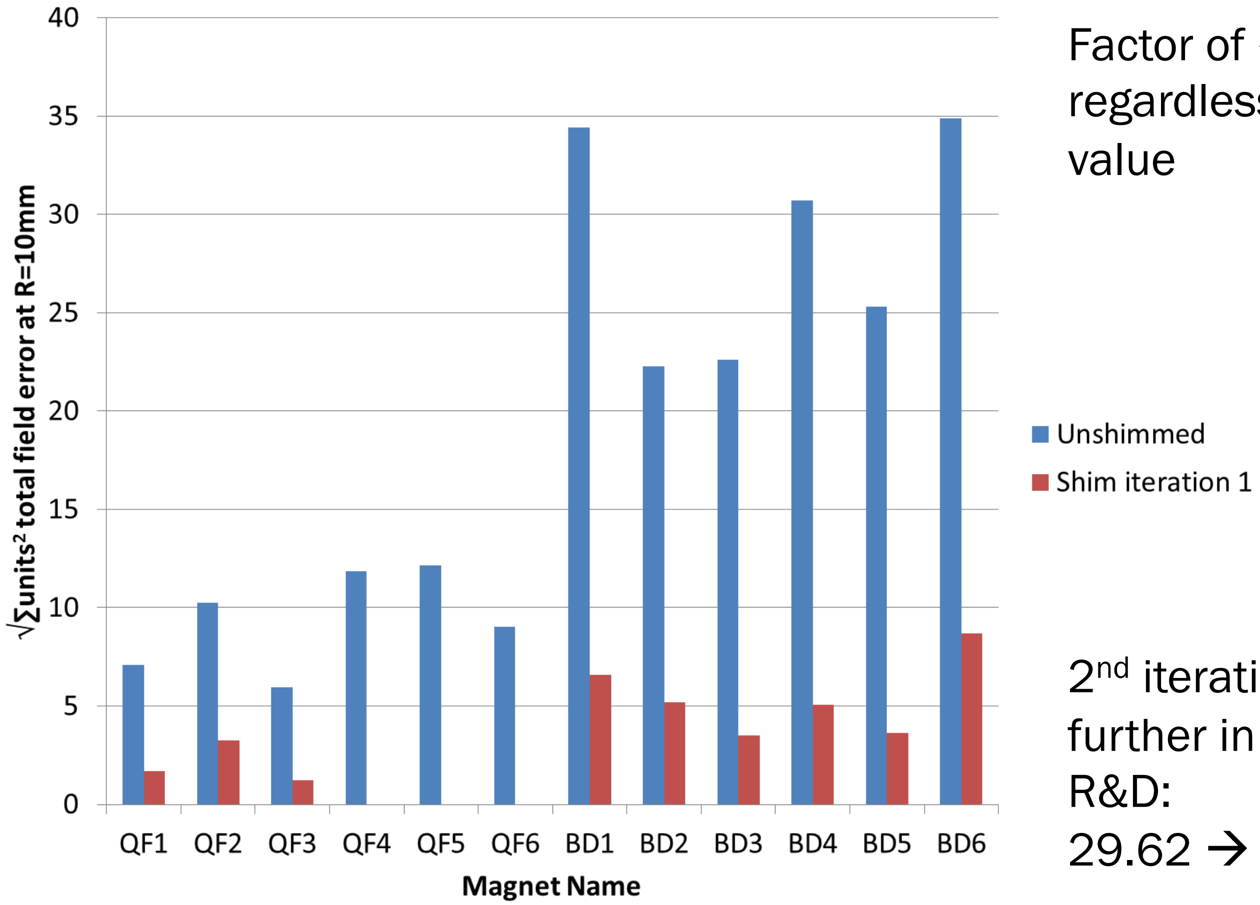

PoP magnet series



Iron wire shims

Iron Wire Shimming Improvement

DR3.1.4



Factor of ~4 reduction regardless of starting value

2nd iteration improved further in previous R&D:
29.62 → 6.69 → 1.94

Multipole tolerances in the FFAG

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

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

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

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

Multipole limits:

For < 10% emittance and beam-size growth

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

First Girder Construction

Beam through accelerator test

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

Tested

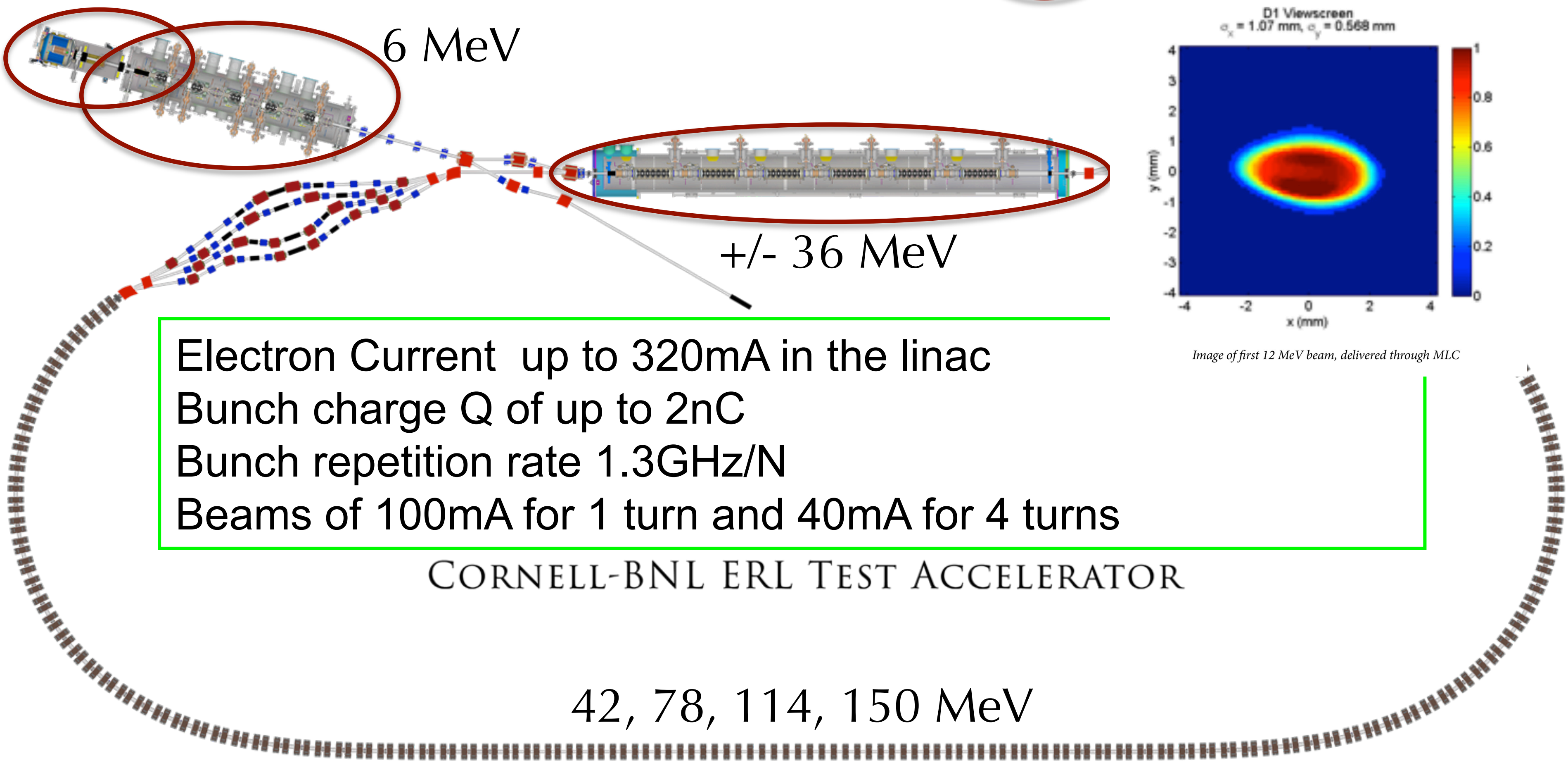
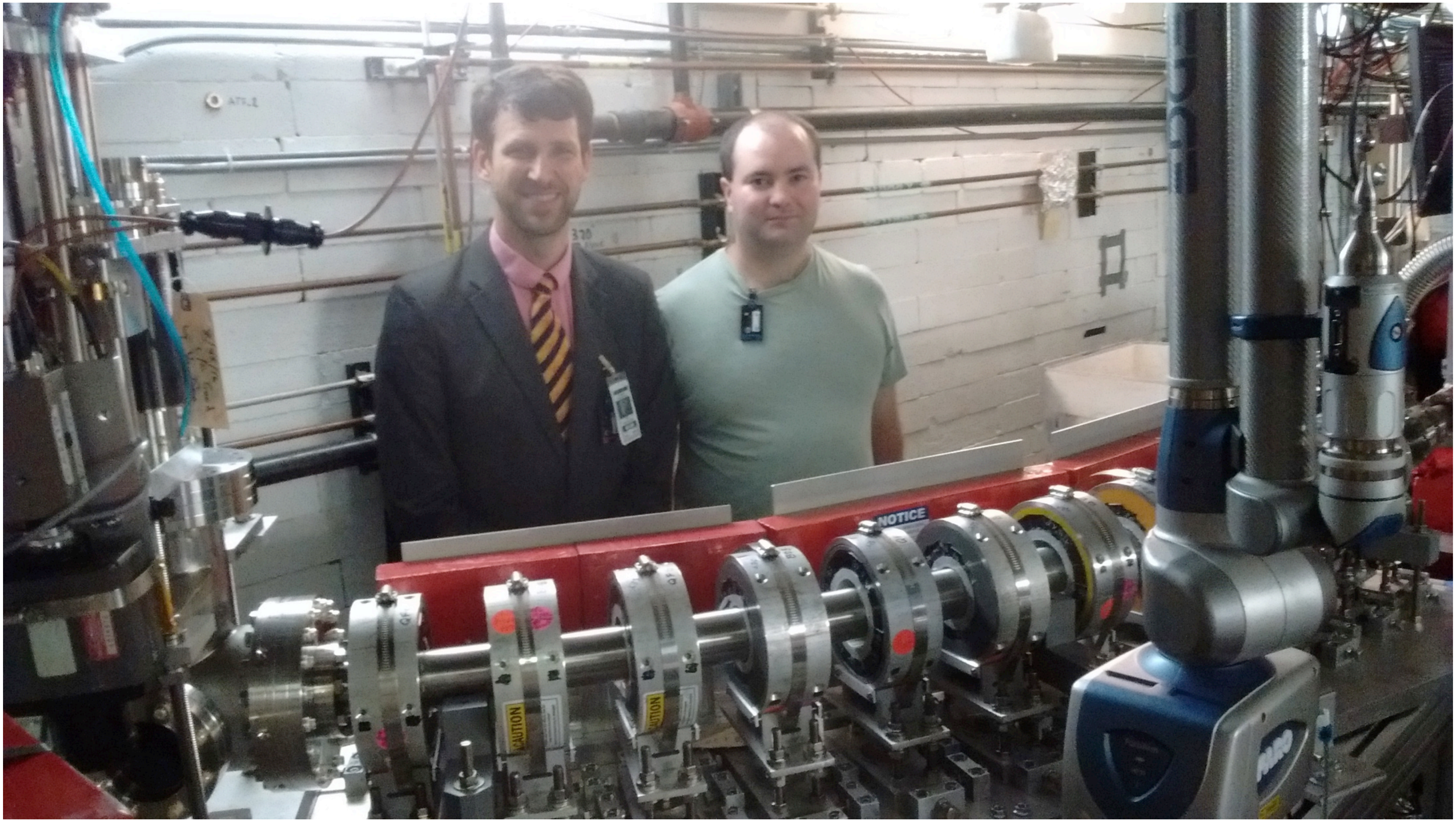


Image of first 12 MeV beam, delivered through MLC

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

FFAG test with beam



Courtesy Stephen Brooks

Scaled down Halbach FFAG with beam at BNL's ATF

The CBETA Collaboration

Background for CDR

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

Start of CBETA July 2014 White paper December 2014

Defined CBETA in a white paper in December 2014.

CDR for CBETA in with Hybrid permanent magnets in July 2016.

Secured funding October 2016

Passed design and finance review, January 2017

DR for CBETA with Halbach magnets in February 2017

Prototype FFAG girder, April 2017

1st beam through MLC, May 2017

CBETA Design Report

Cornell-BNL ERL Test Accelerator

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Editor: C. Mayes

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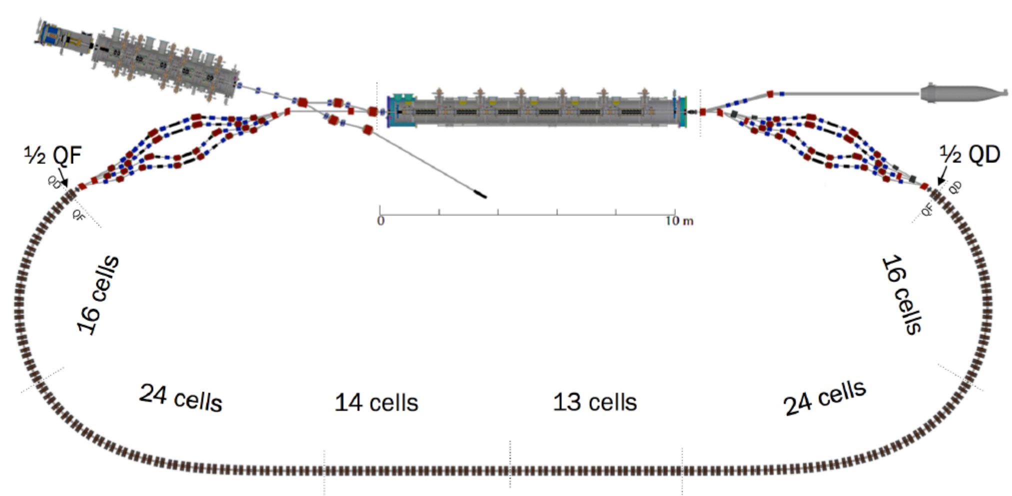
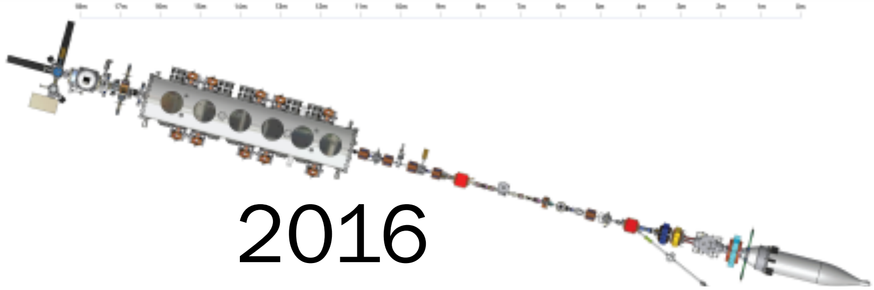


June 8, 2017

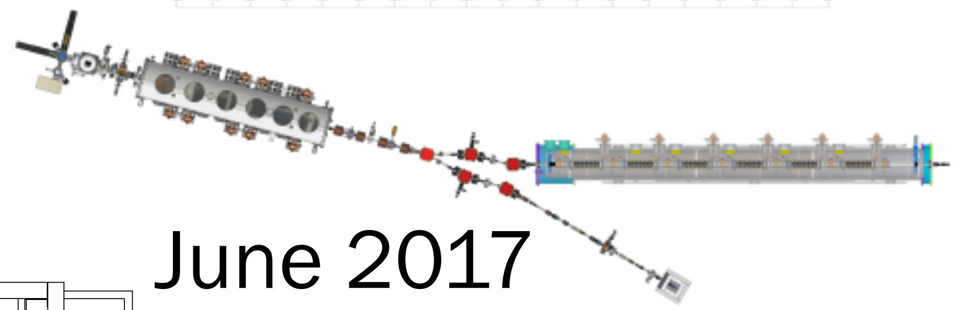
The path is free for CBETA

#	**Milestone** (at the end of months)	**Baseline**	**Actual**
	Funding start date		Oct-16
1	Engineering design documentation complete	Jan-17	
2	Prototype girder assembled	Apr-17	
3	Magnet production approved	Jun-17	
4	**Beam through Main Linac Cryomodule**	**Aug-17**	
5	First production hybrid magnet tested	Dec-17	
6	**Fractional Arc Test: beam through MLC & girder**	**Apr-18**	
7	Girder production run complete	Nov-18	
8	Final assembly & pre-beam commissioning complete	Feb-19	
9	**Single pass beam with factor of 2 energy scan**	Jun-19	
10	**Single pass beam with energy recovery**	Oct-19	
11	**Four pass beam with energy recovery (low current)**	Dec-19	
12	Project complete	Apr-20	

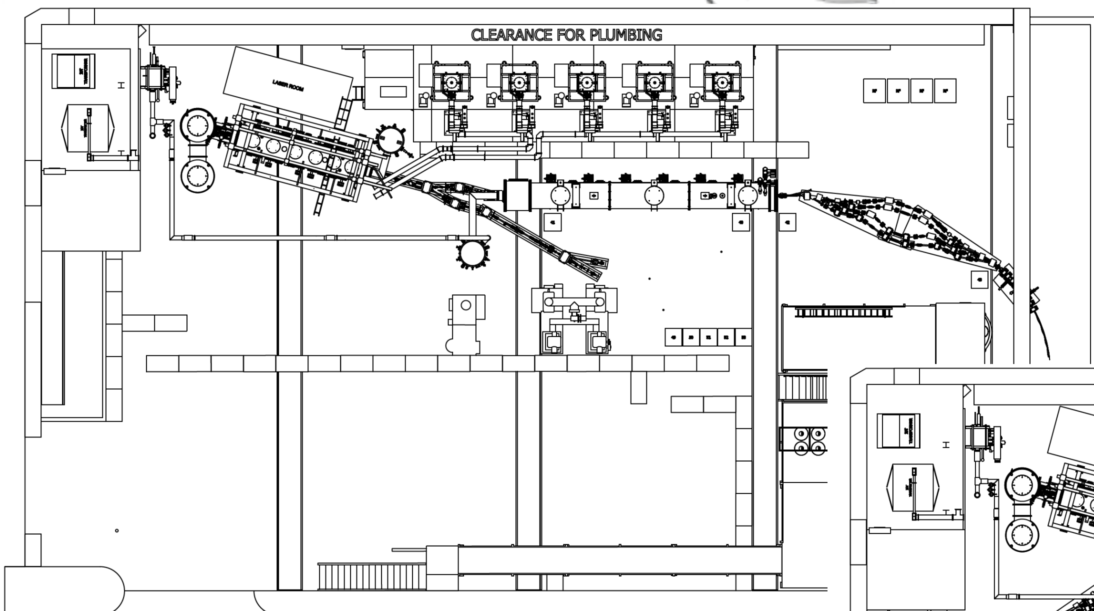
Beam Commissioning



2016

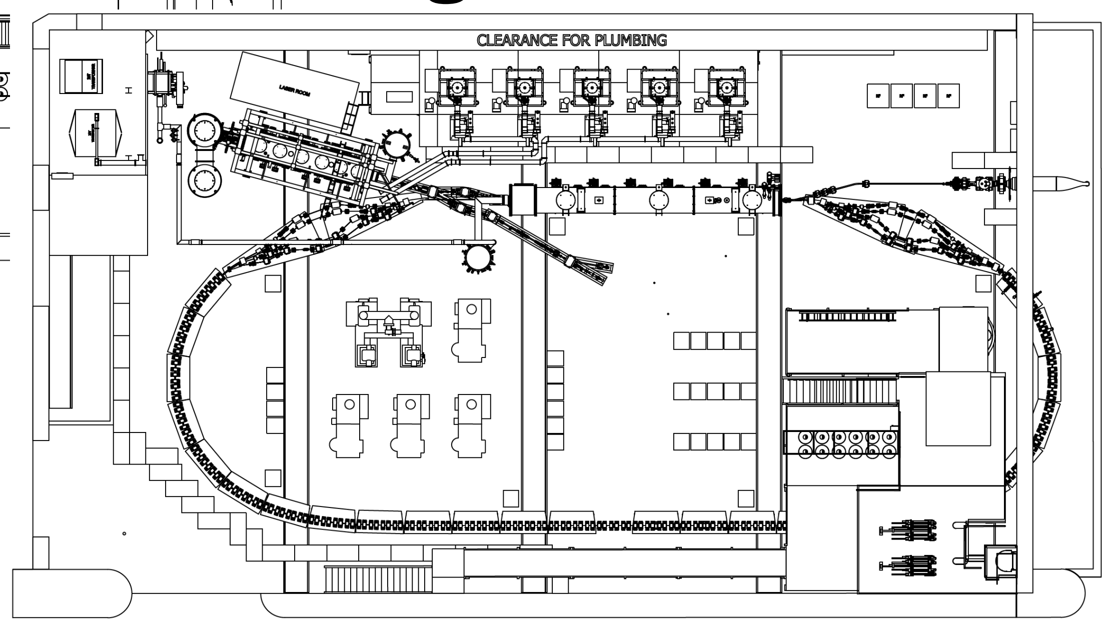


June 2017



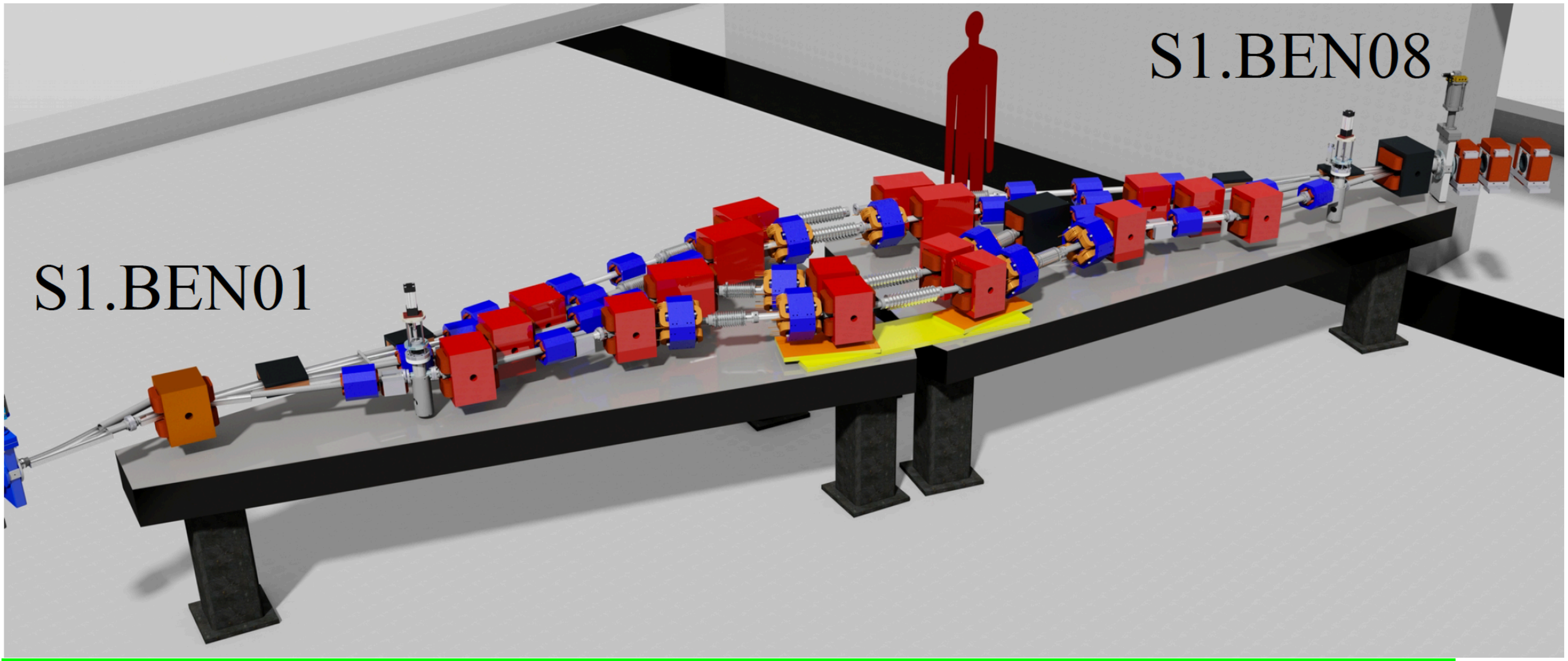
April 2018: FAT

August 2019: 1-turn



Push toward 4-tunr ERL until April 2020

Preparations for the FAT



- Tables are designed.
- Dipoles and Quadrupoles are ordered, power supplies are ordered.
- Common magnets are designed and about to be ordered.
- All but one FFAG quad are built.
- Space is nearly cleared out.
- Much infrastructure preparation remains, e.g. wholes in the east wall and placement of beam stop and FFAG table.
- The next major milestone April 30 seems achievable.

Questions?