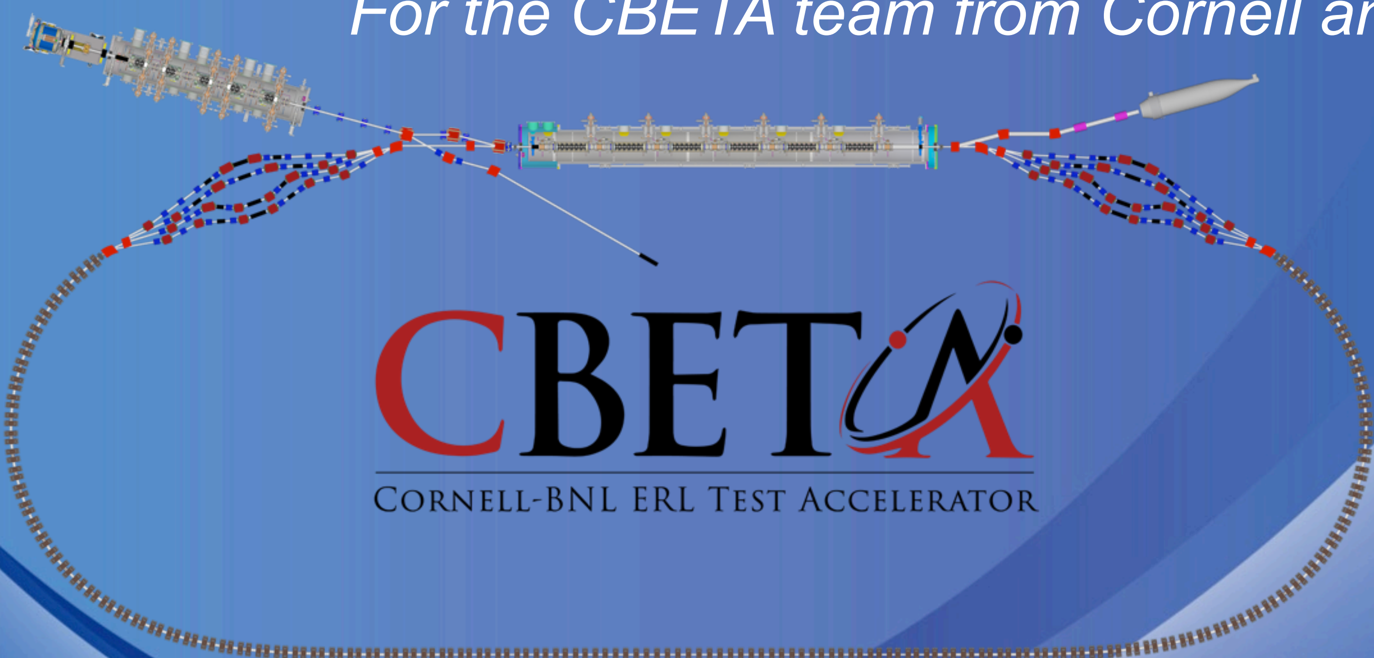
CBETA, a 4-turn ERL with FFAG arc

ERL workshop 07/19/2017

Georg Hoffstaetter (Cornell)

For the CBETA team from Cornell and BNL



CBETA

CORNELL-BNL ERL TEST ACCELERATOR

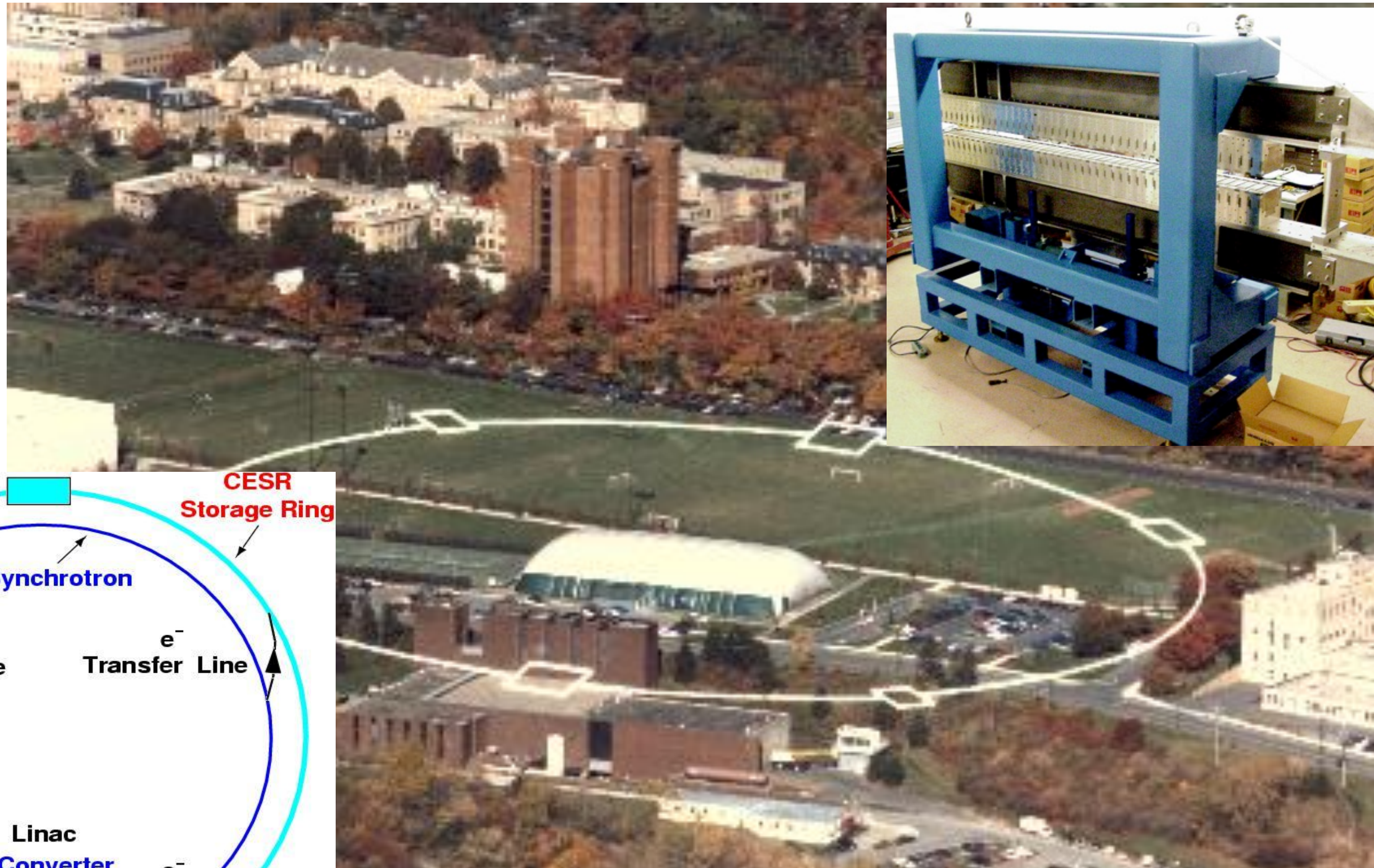
BROOKHAVEN NATIONAL LABORATORY

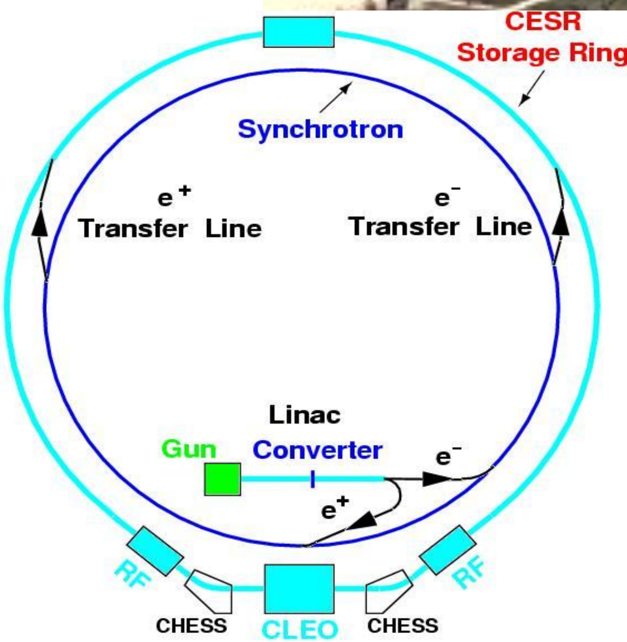
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

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

Cornell's synchroton and storage ring





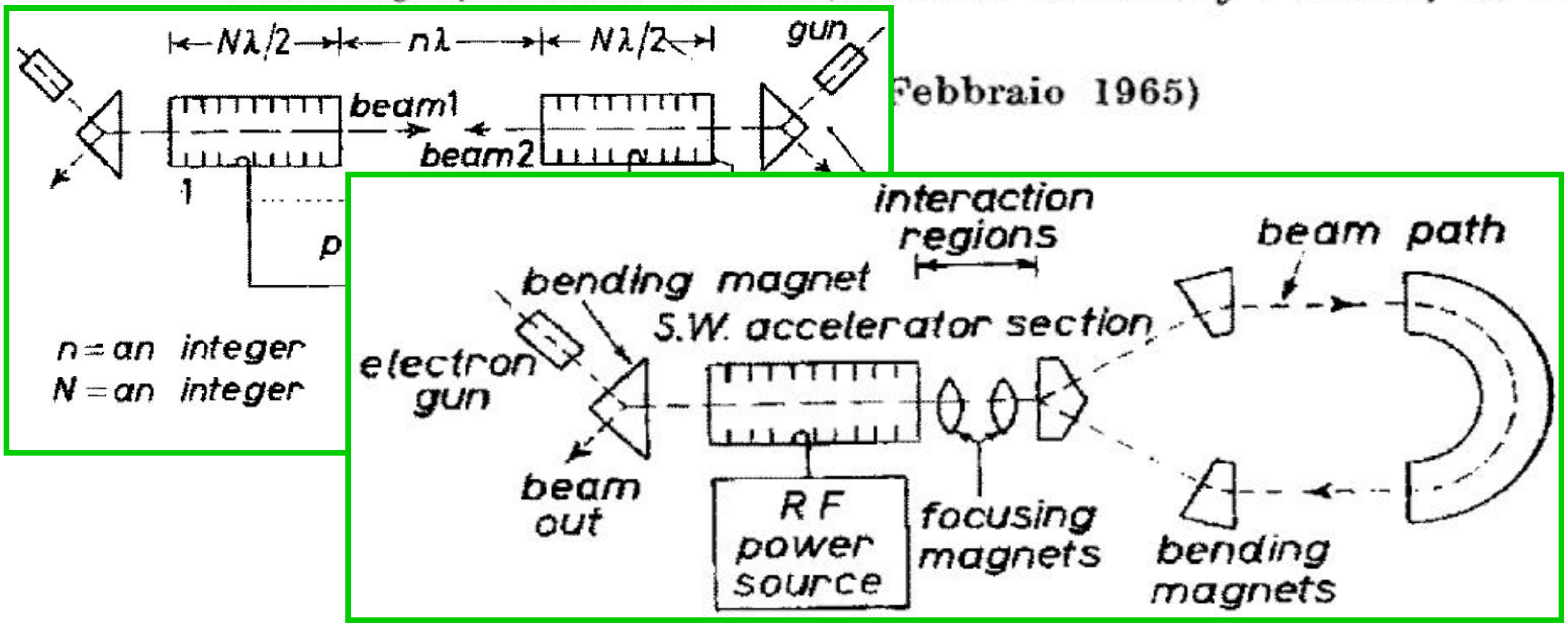
ERLs, invented at Cornell

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

M. TIGNER

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

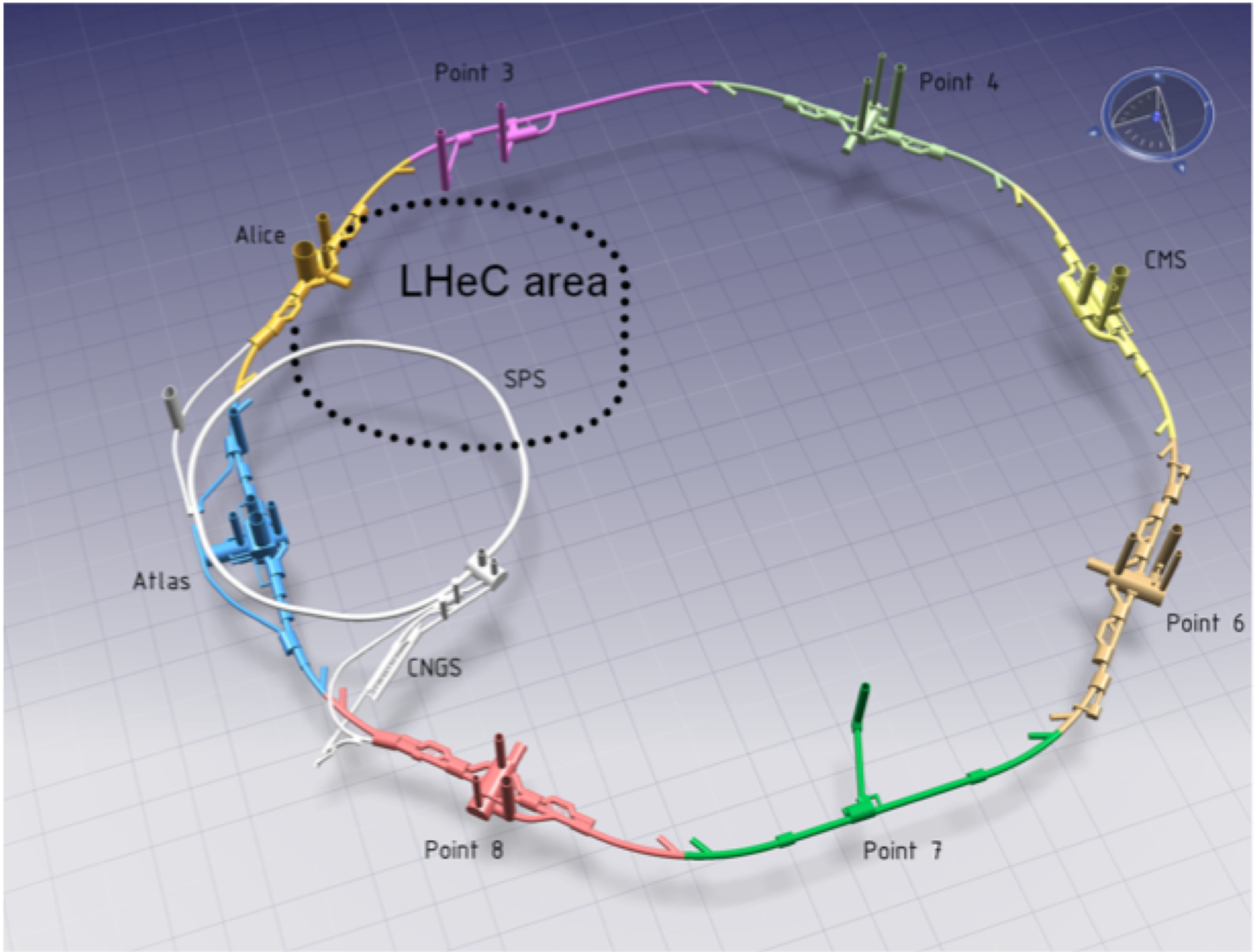
Febbraio 1965)



Energy recovery needs continuously fields in the RF structure

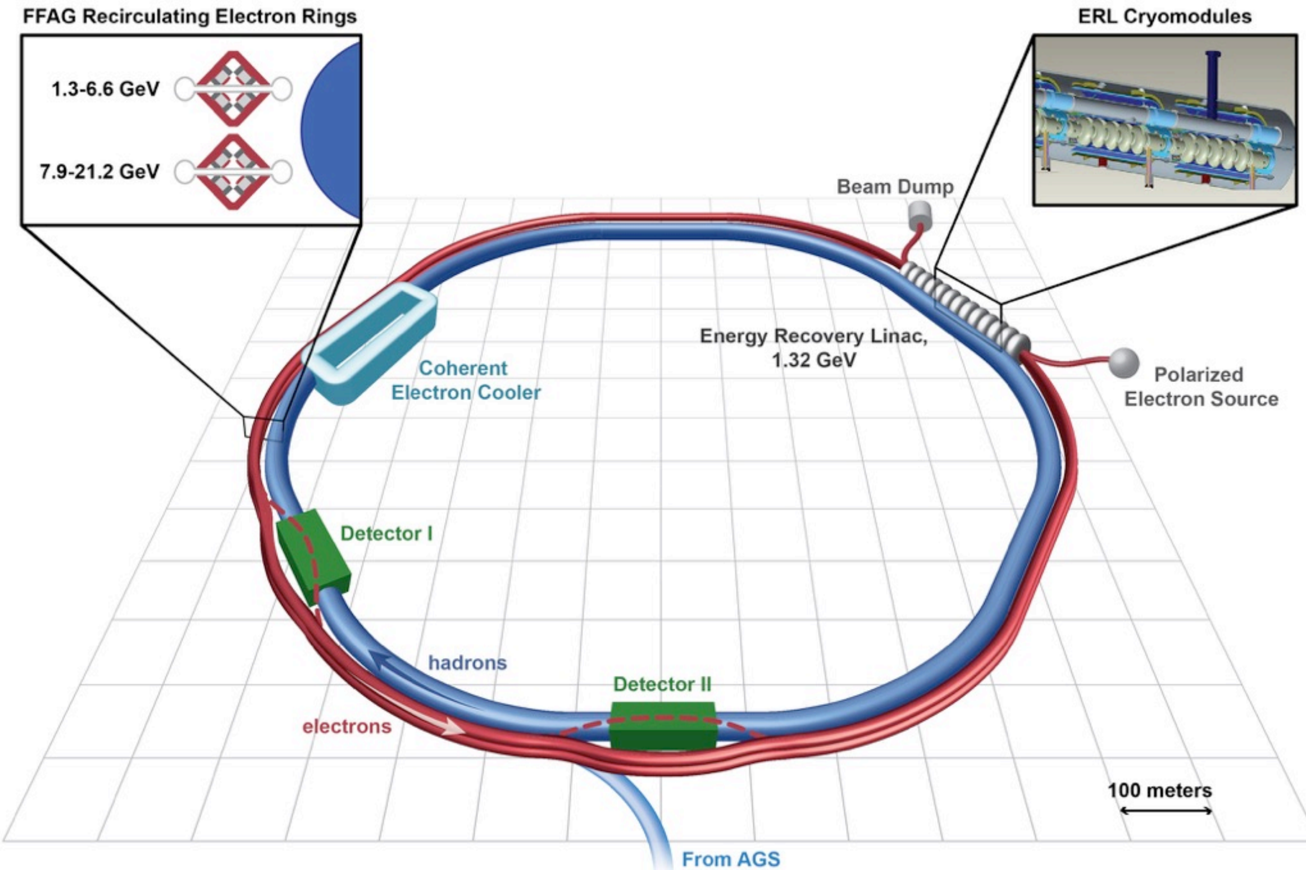
- Normal conducting high field cavities can get too hot.
- Superconducting cavities used to have too low fields.

AnERL for LHeC (e-hadron collisions)

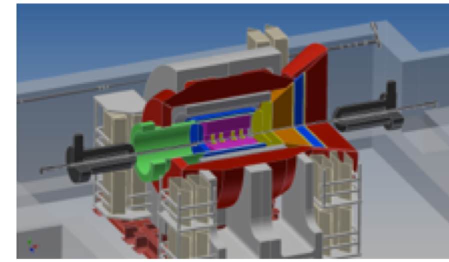


courtesy Oliver Bruening

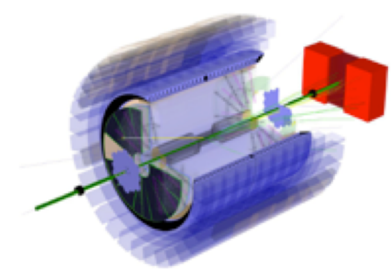
ERL for eRHIC (e-p and e-ions)



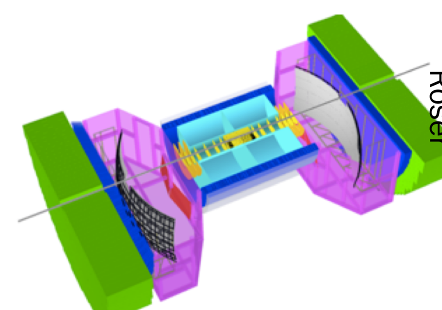
ePHENIX



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

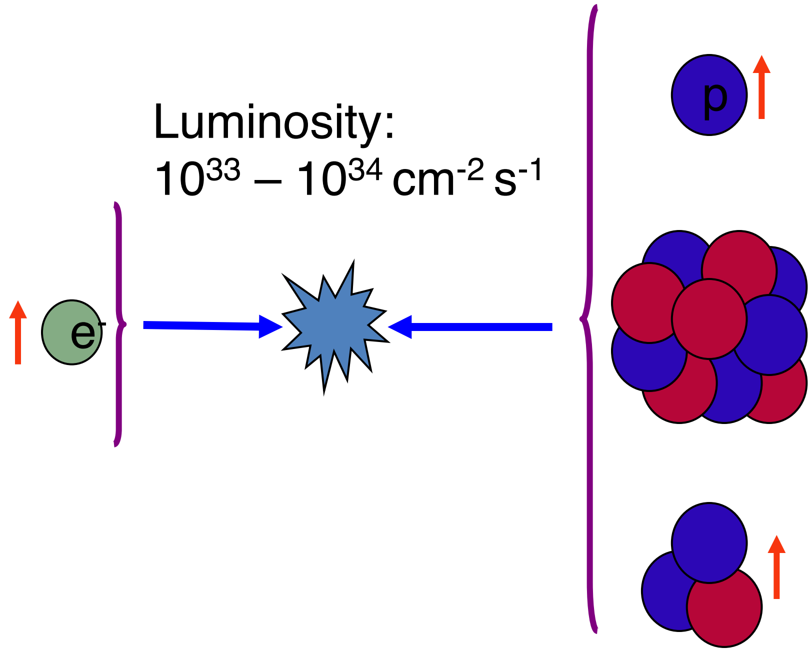
RECOMMENDATION III

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

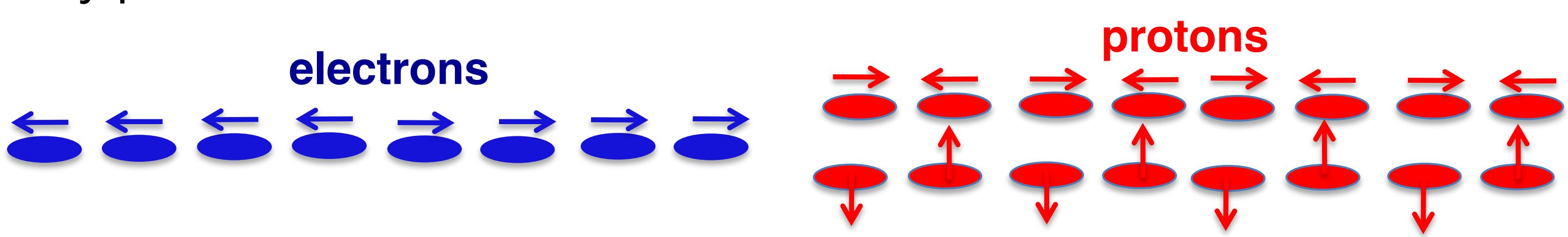
80% polarized electrons:
6.6 – 21.2 GeV



Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 - 100 (110*) GeV/u

Pol. light ions (He-3)
17 - 167 (184*) GeV/u

- 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:

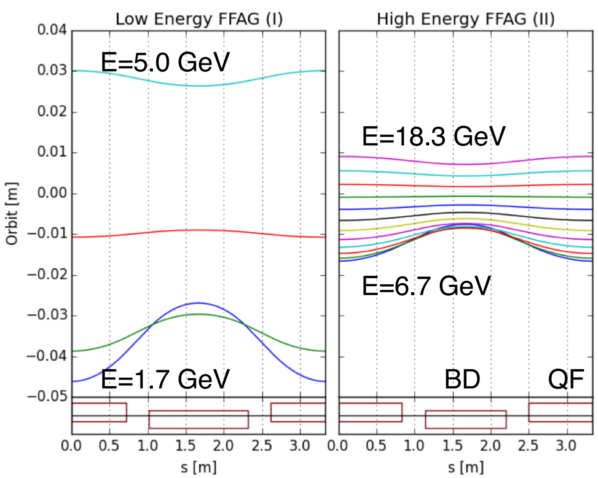
The baseline design of eRHIC has been a linac-ring collider to boost the luminosity to into the 10^{34} regime, based on a **12-turn ERL** with 2 permanent magnet **FFAG return loops**.

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.

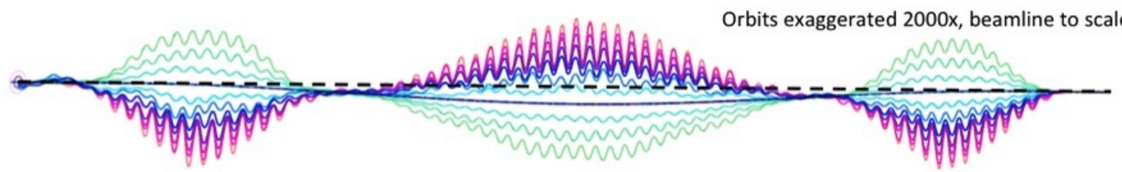
If polarization can survive acceleration in a spin-optimized rapid cycling synchrotron, a ring as injector would be a cost-saving alternative. As an option for **electron cooling**, an **ERL** is then still an important topic of study.

Topics of eRHIC to be studied in CBETA

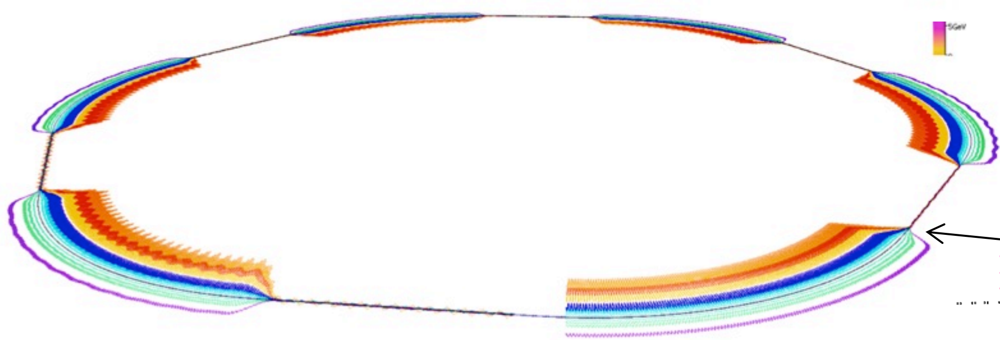
- eRHIC uses two FFAG beamlines to do multiple recirculations.
  (FFAG-I: 1.7-5.0 GeV, FFAG-II: 6.7-18.3 GeV, 20 GeV)
- All sections of a FFAG beamline is formed using a same FODO cell. Required bending in different sections is arranged by proper selection of the offsets between cell magnets (or, alternatively, 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

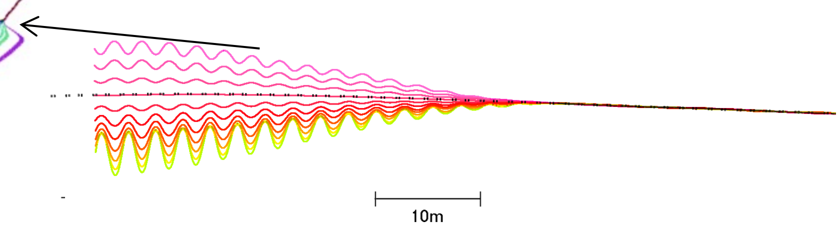


Orbits in Detector bypass section



Quad offsets evolve adiabatically

Orbits in Transition section



Each of two eRHIC FFAGs contain 1066 FFAG cells

CBETA topics to support eRHIC

CBETA study topics important for eRHIC:

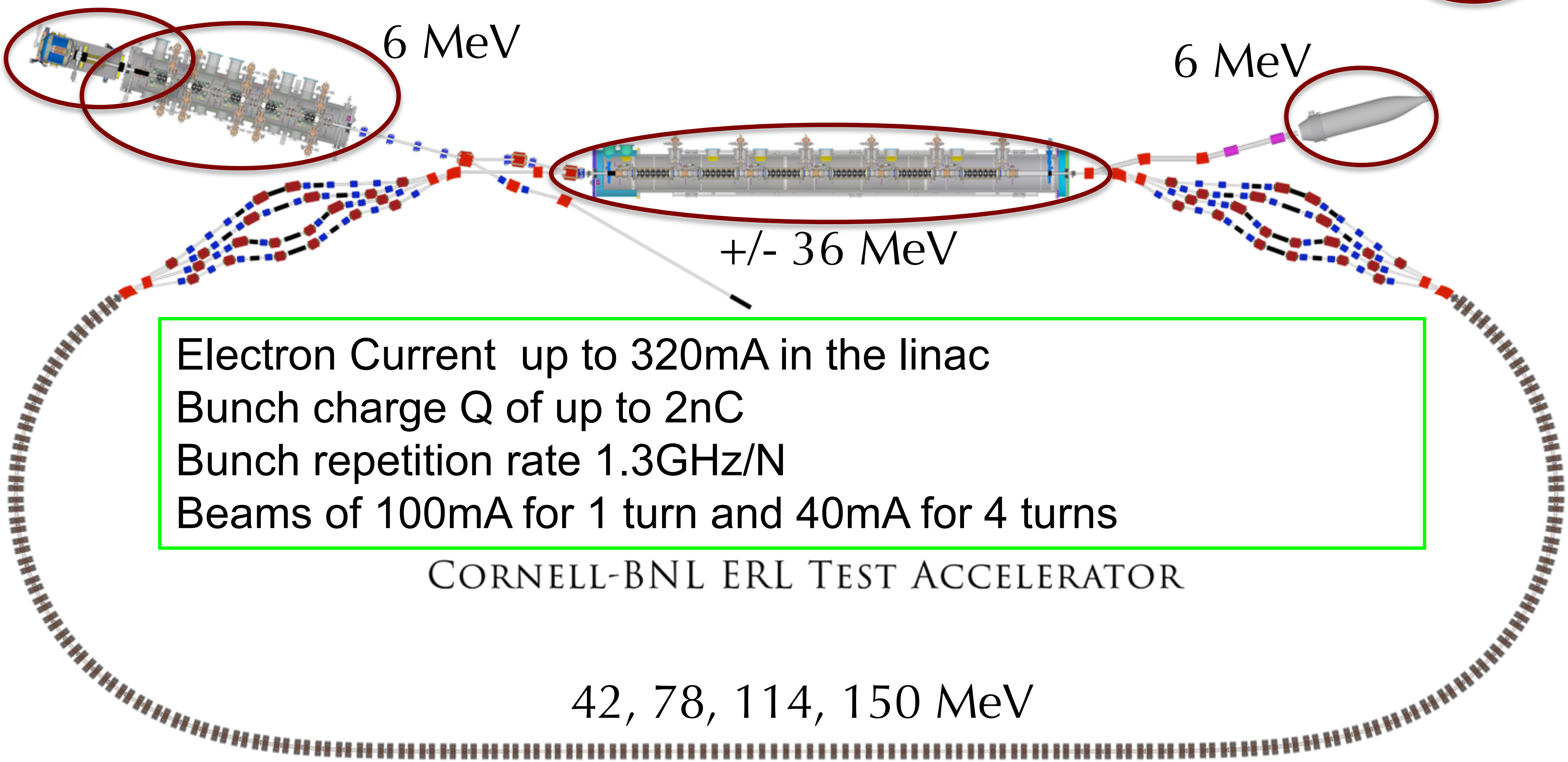
1) **FFAG** loops with a factor of 4 in momentum **aperture**.
   a) Precision, reproducibility, alignment during magnet and girder production.
   b) Stability of magnetic fields in a radiation environment.
   c) **Matching** and correction of multiple simultaneous **orbits**.
   d) **Matching** and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



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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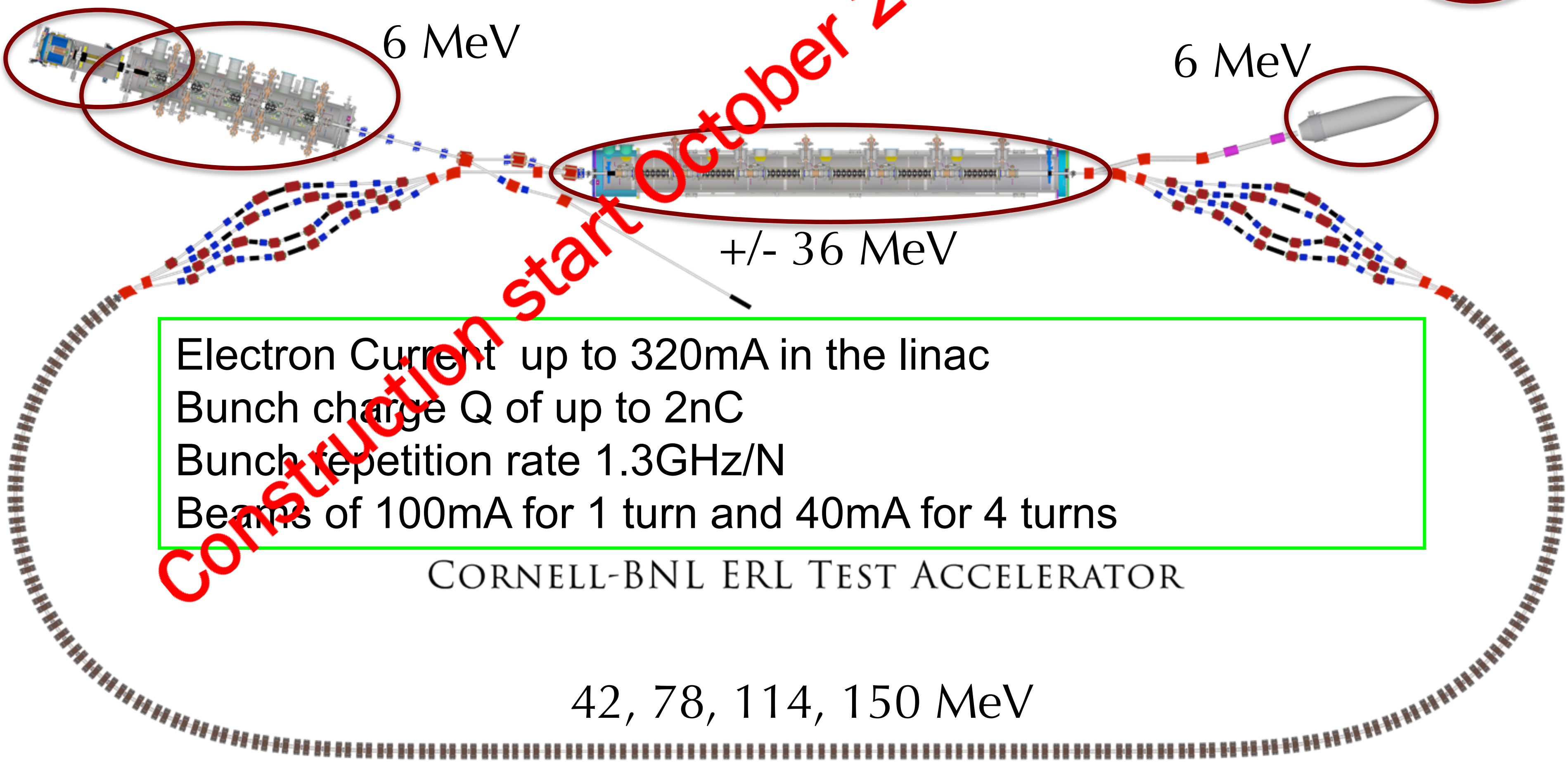
Construction start October 2016



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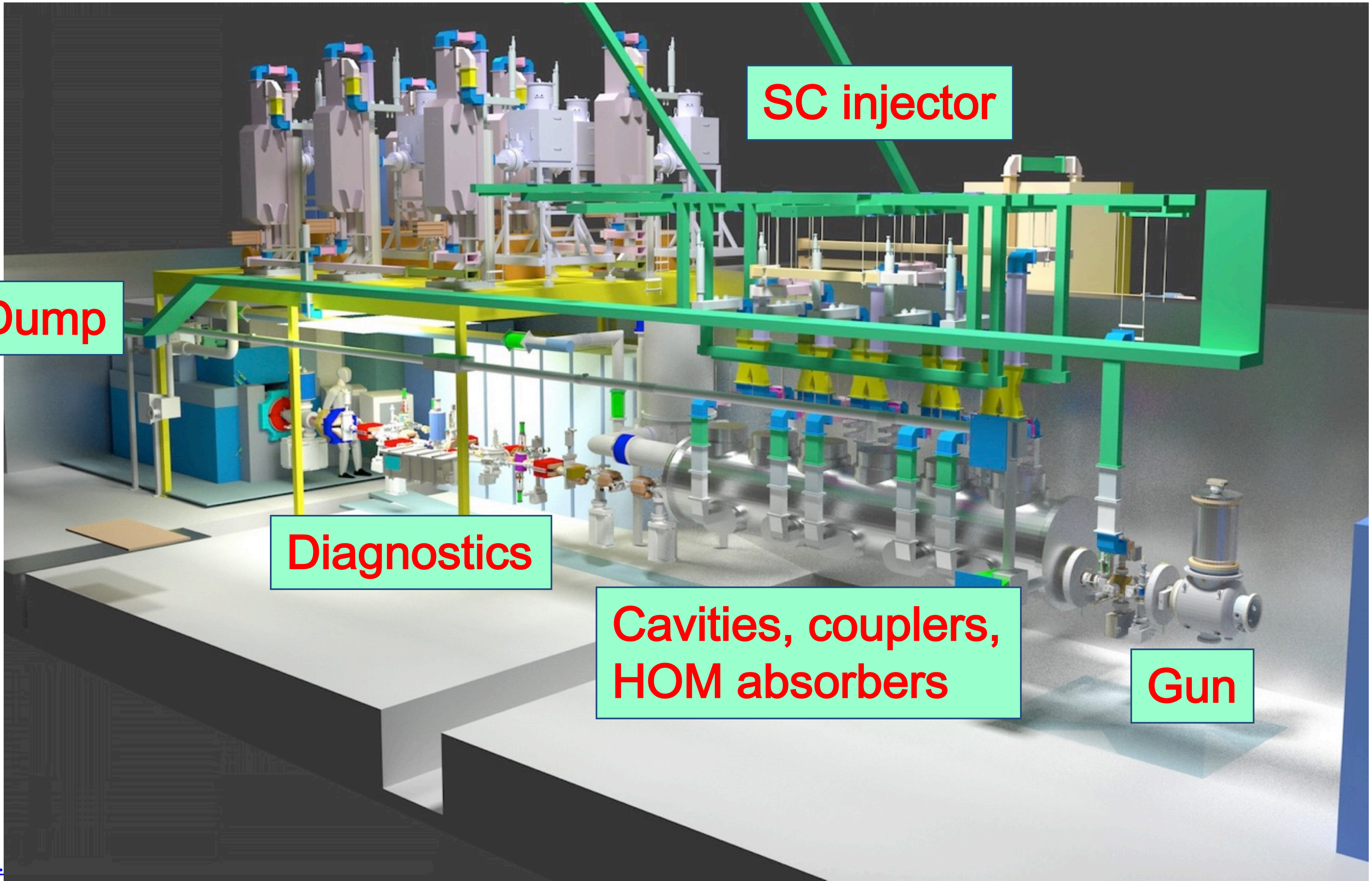
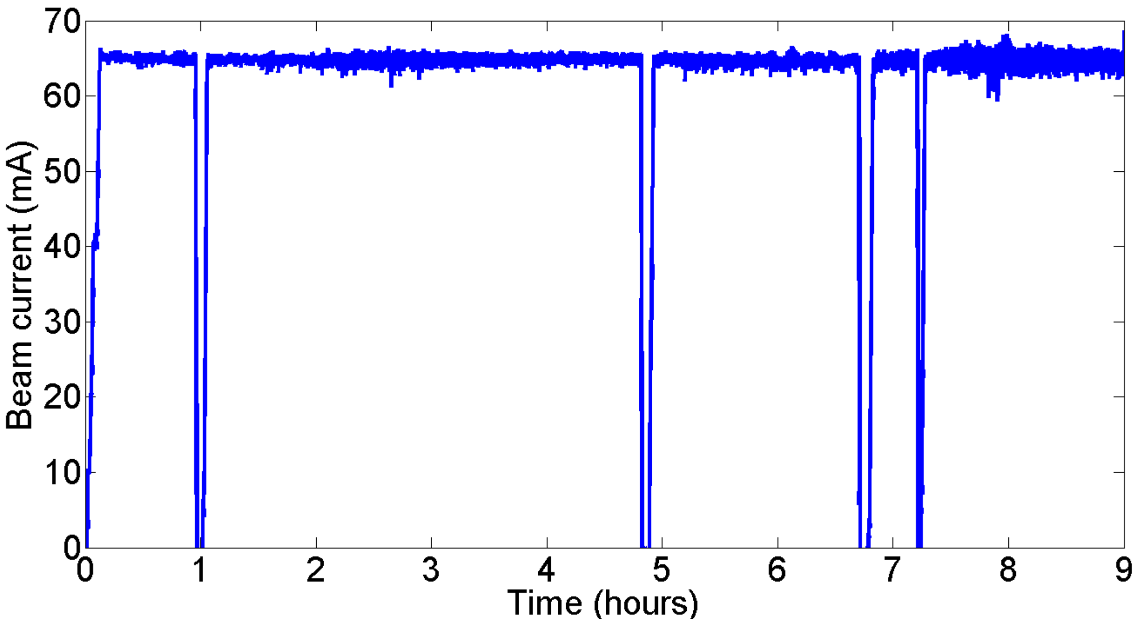
Cornell ERL injector prototype

- 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.



ERL Readiness: high current beam



- Peak current of 75mA (world record)

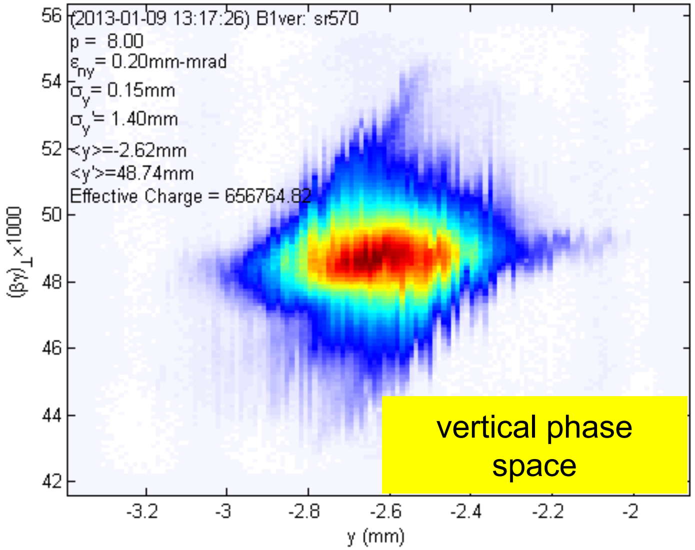
- NaKSb photocathode
- High rep-rate laser
- DC-Voltage source

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

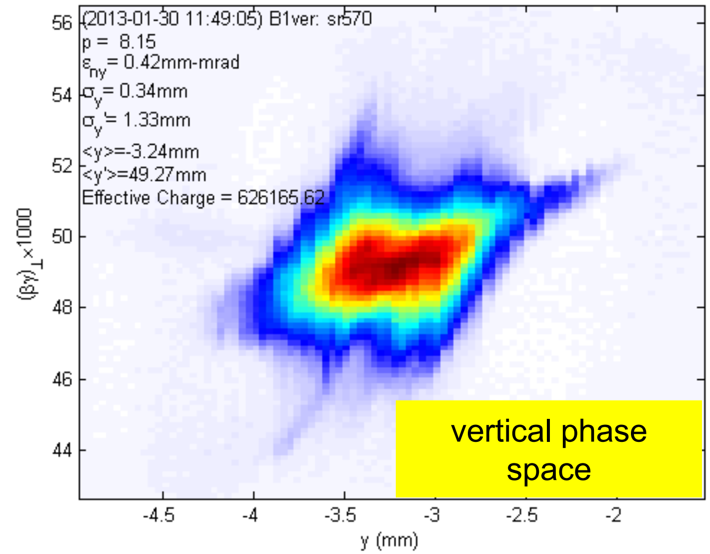
Simulations accurately reproduce photocathode performance with no free parameters, and suggest strategies for further improvement.

✓ Source current can meet ERL needs

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 (%)

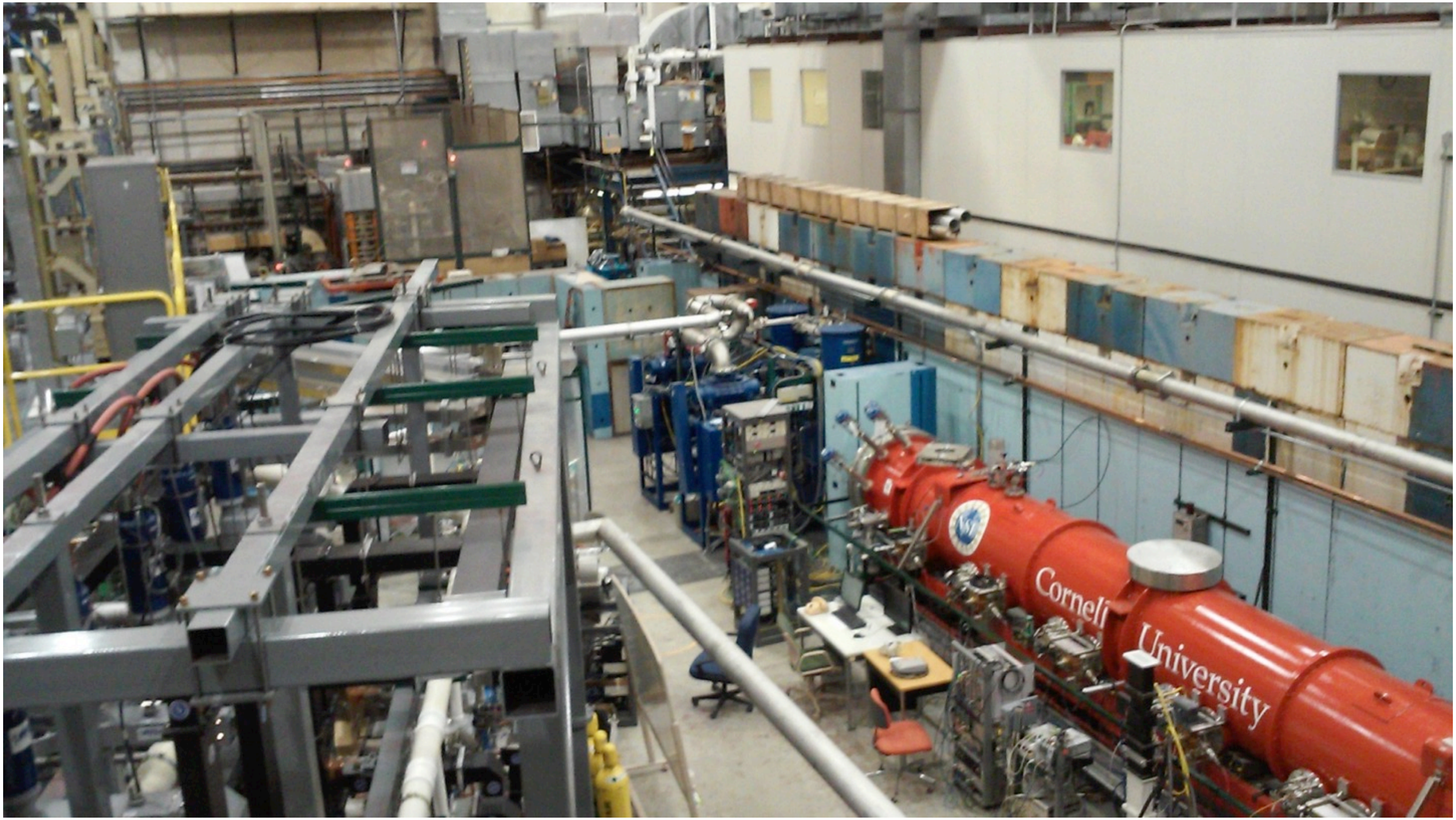
0.14/0.09 mm-mrad @ 68% 0.24/0.18 mm-mrad @ 61%

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

The CBETA Collaboration

Background for CDR

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CBETA Design Report

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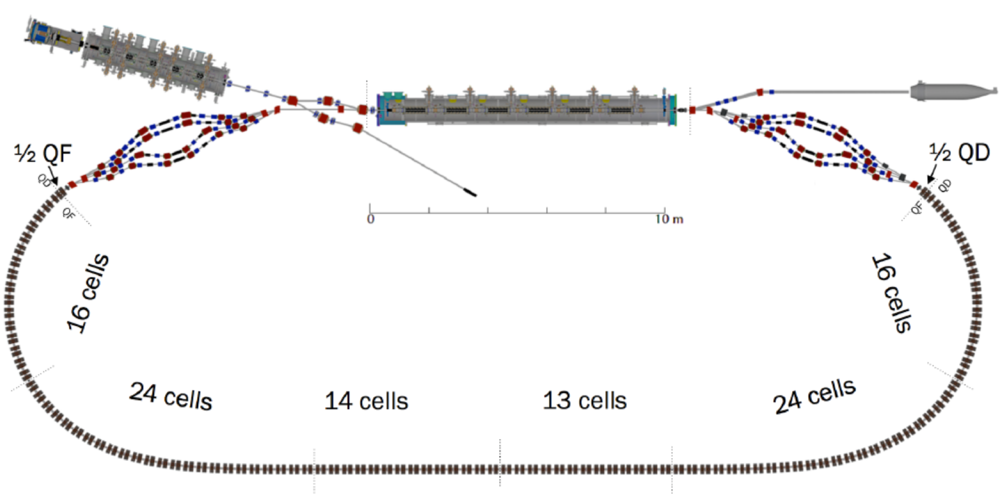
Editor: C. Mayes

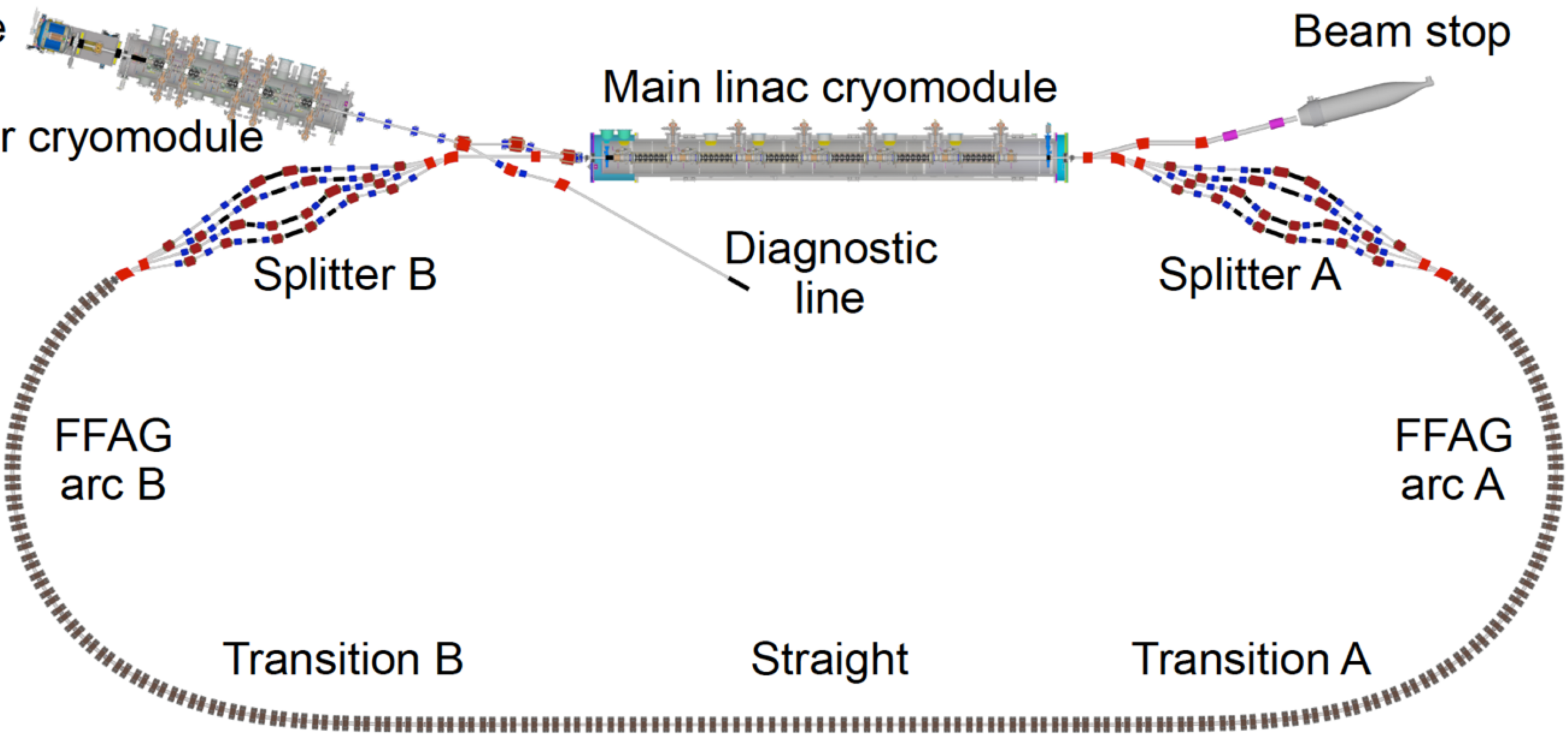
Contributors: N. Banerjee, J. Barley, I. Bazarov, A. Bartnik, J. S. Berg, S. Brooks, D. Burke, J. Crittenden, L. Cultrera, J. Dobbins, D. Douglas, B. Dunham, R. Eichhorn, S. Full, F. Furuta, C. Franck, R. Gallagher, M. Ge, C. Gulliford, B. Heltsley, D. Jusic, R. Kaplan, V. Kostroun, Y. Li, M. Liepe, 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

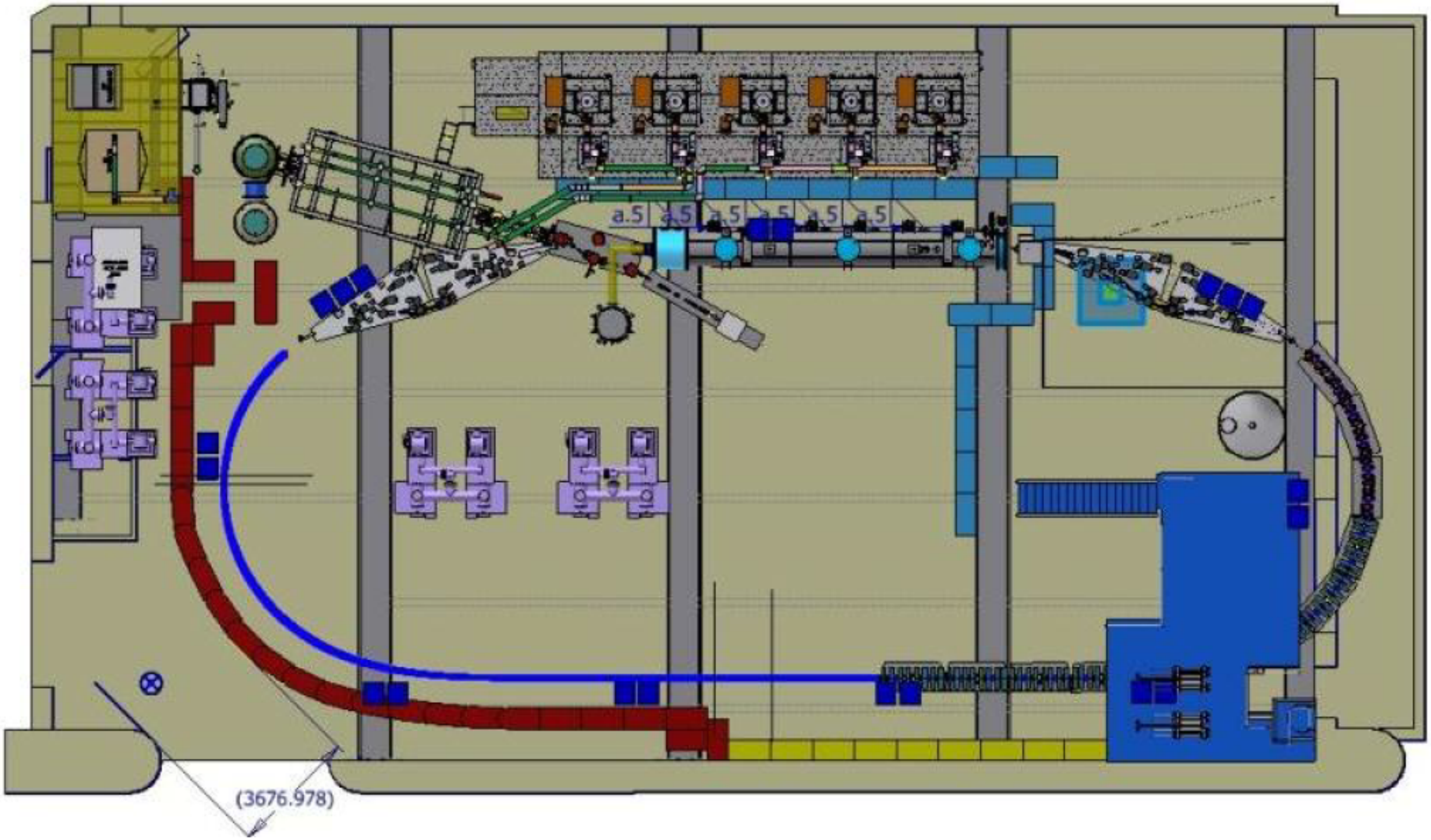
L0E for the Injector test

The gun and ICM were tested with beam

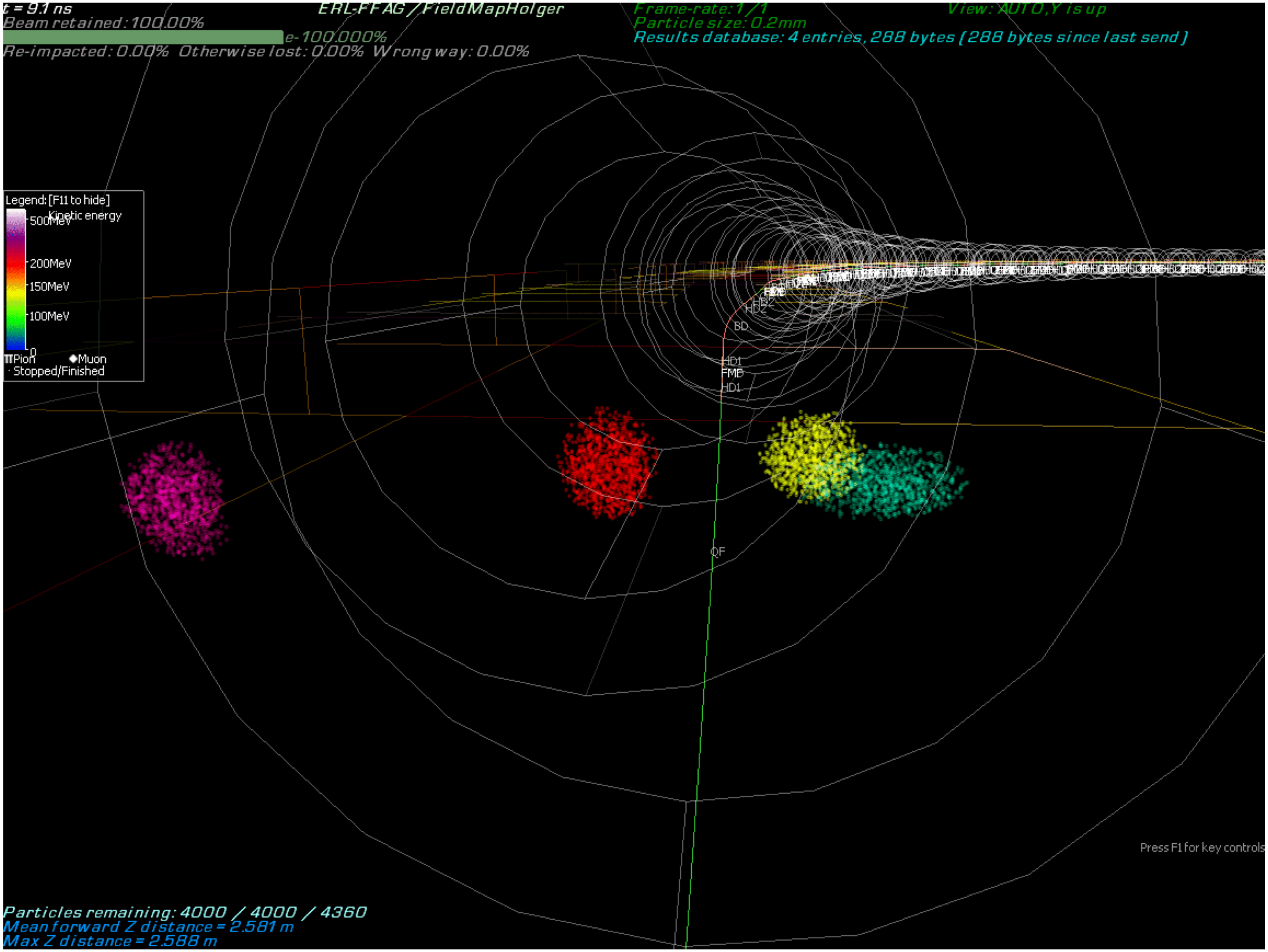
L0E with space for the return loop

Before and After of the Vacuum Lab in Wilson Laboratory

2019 Layout

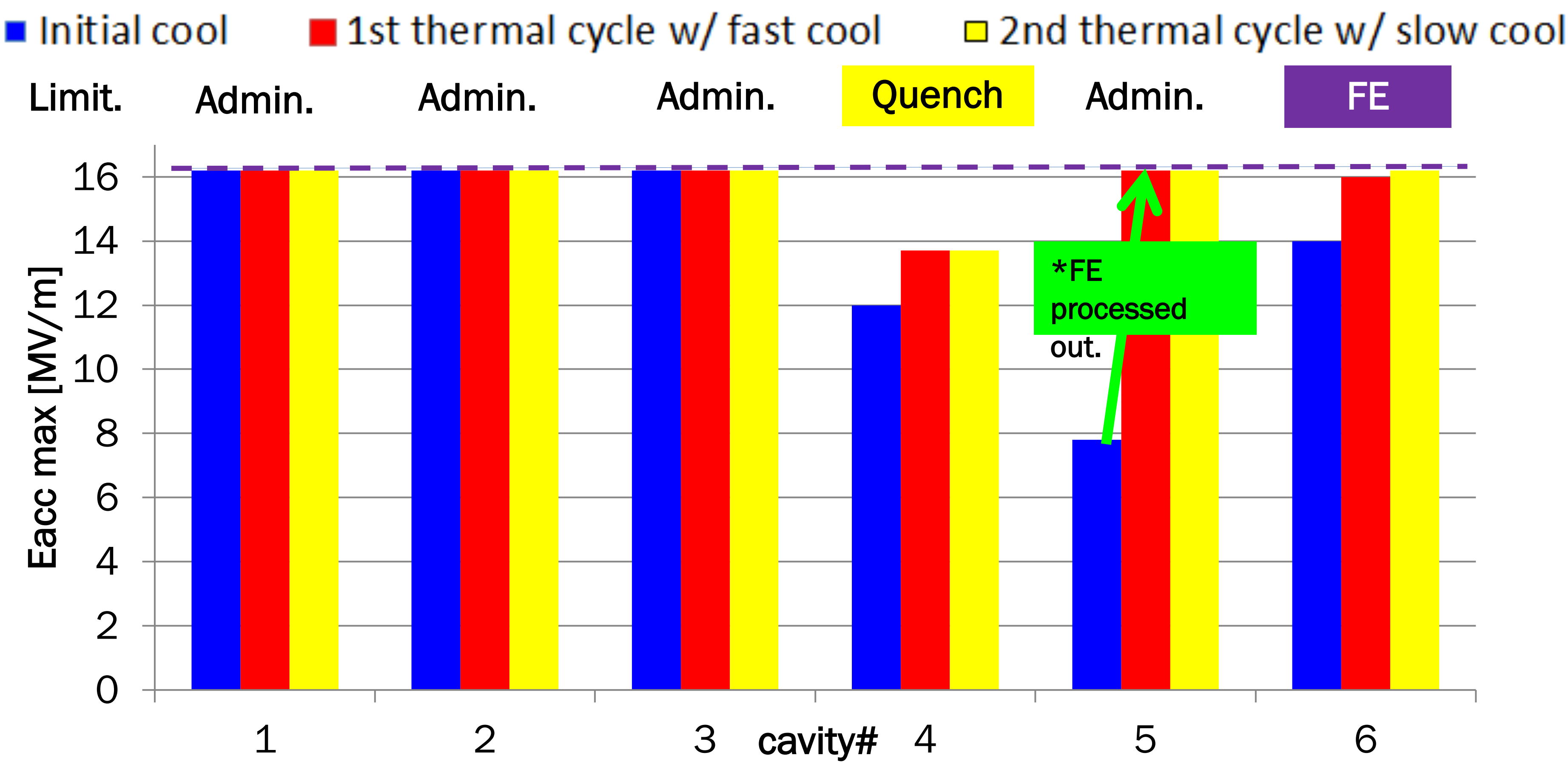


Bunche dynamics in 3D field maps



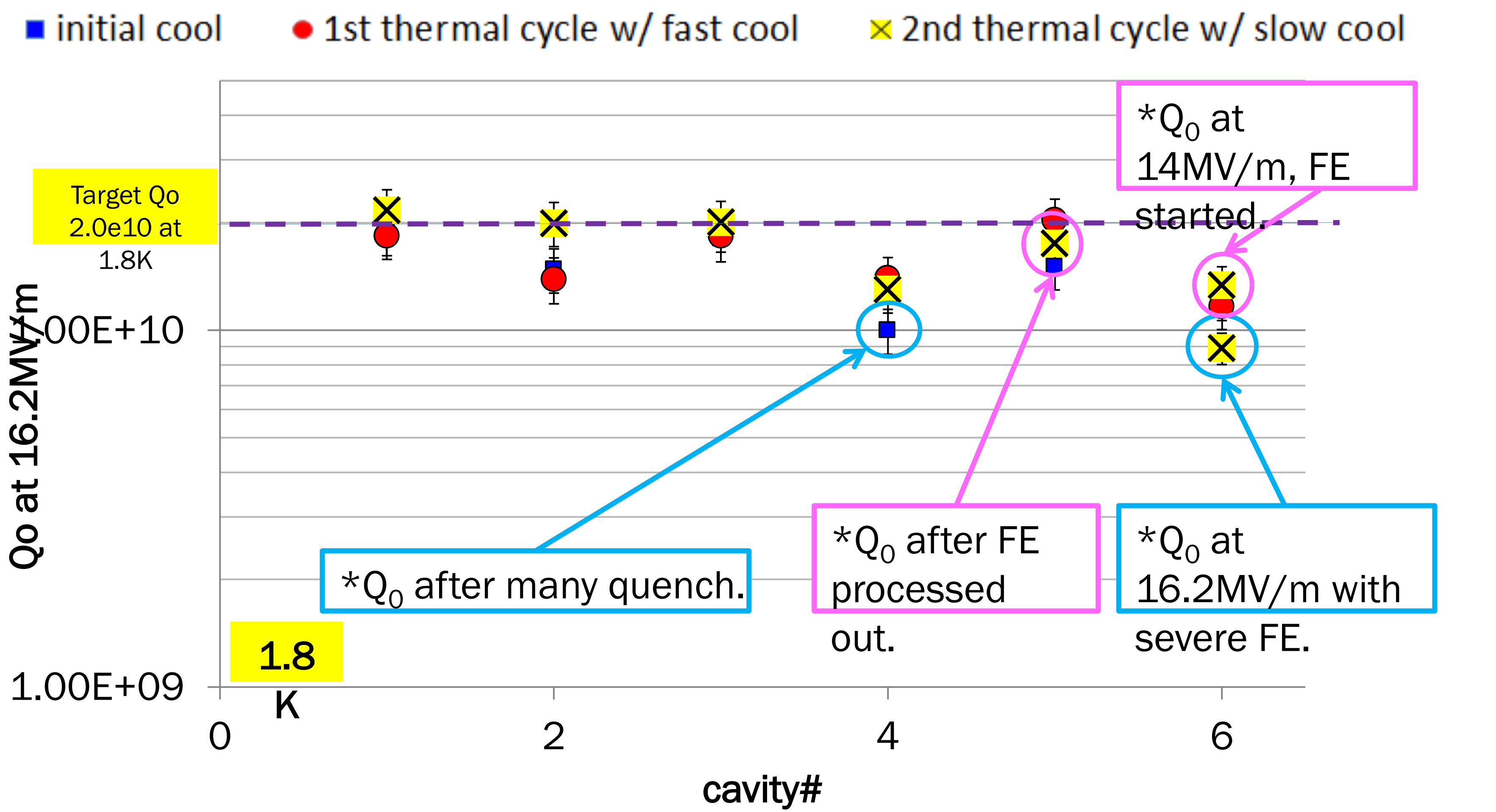
RF sourses

Main linac cryomodule (MLC) achieved accelerating gradients



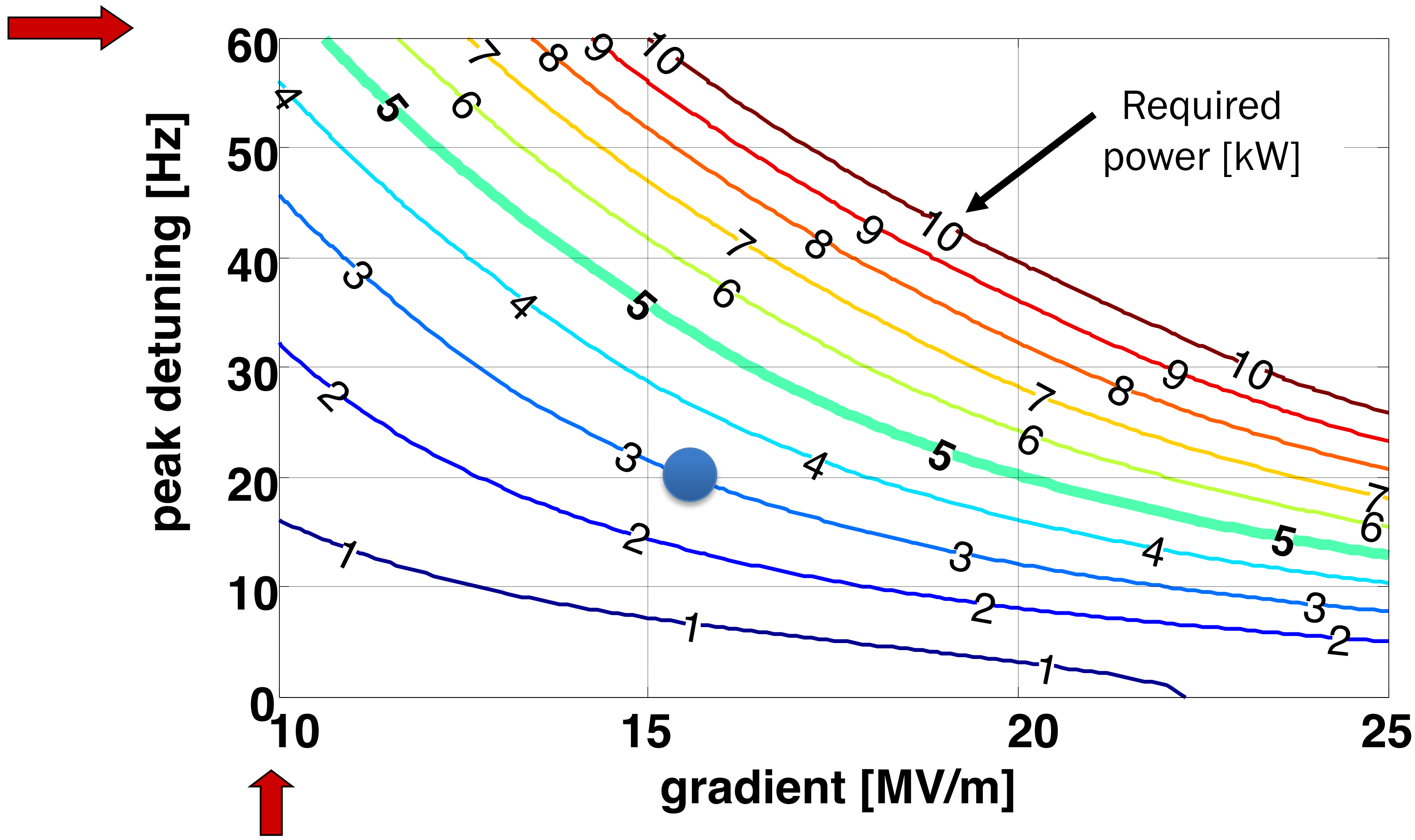
- 5 of 6 cavities had achieved design gradient of 16.2MV/m at 1.8K in MLC.
- Cavity#4 is limited by quench so far, no detectable radiation during test.
- Enough Voltage for 76MeV per ERL turn (where 36MeV are needed)

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



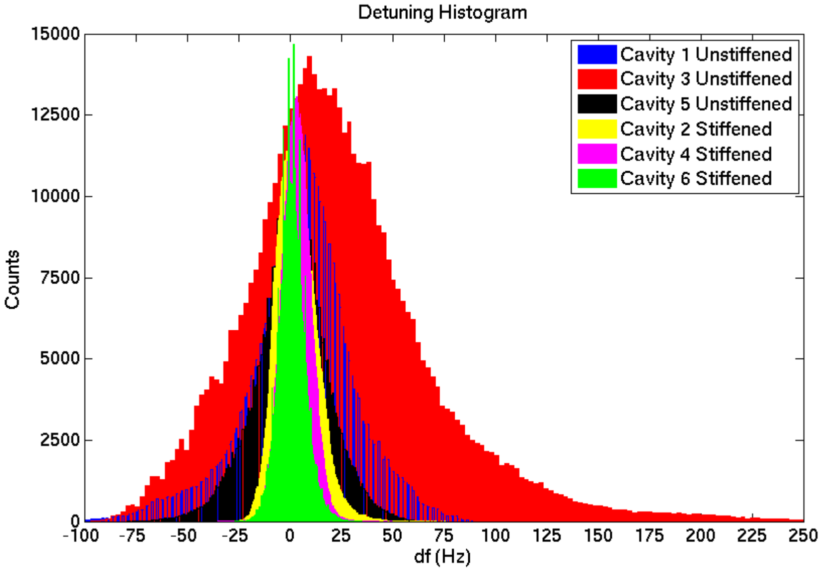
- 4 of 6 cavities had achieved design Q_0 of 2.0E+10 at 1.8K.
- Q_0 of Cavity#6 had severe FE at 16MV/m.
- **Enough cooling for 73MV per ERL turn (where 36MeV are needed)**

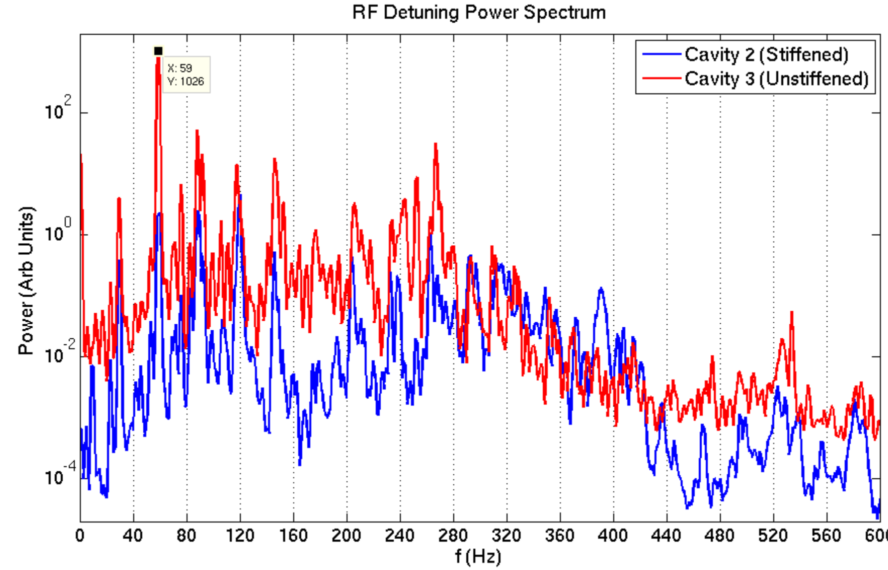
Required Peak Power (Q_L=2·10 ^{7})



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



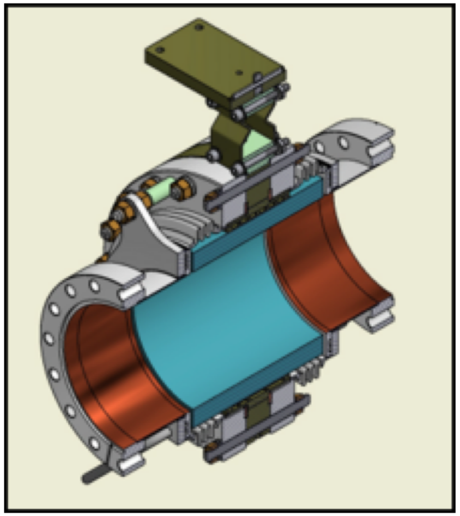


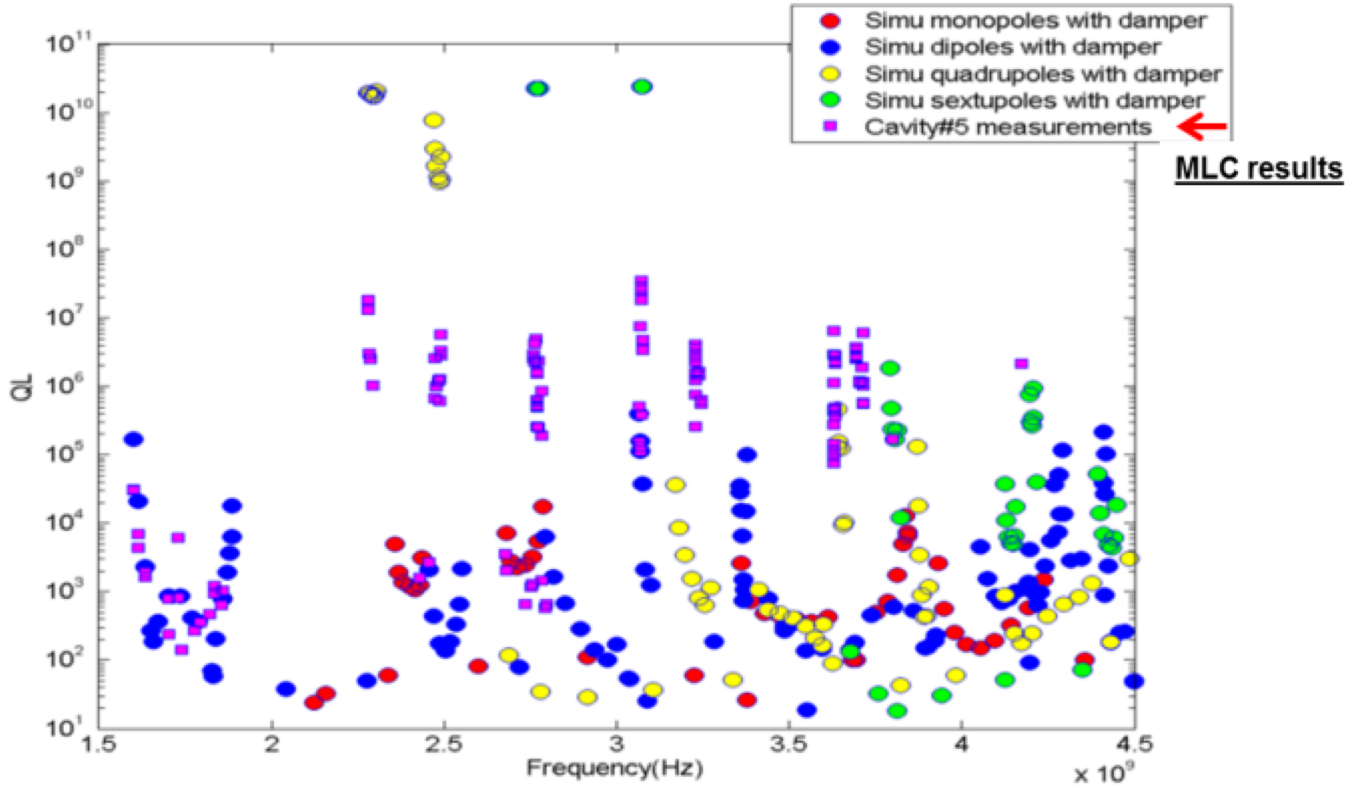
Preliminary results:

- 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



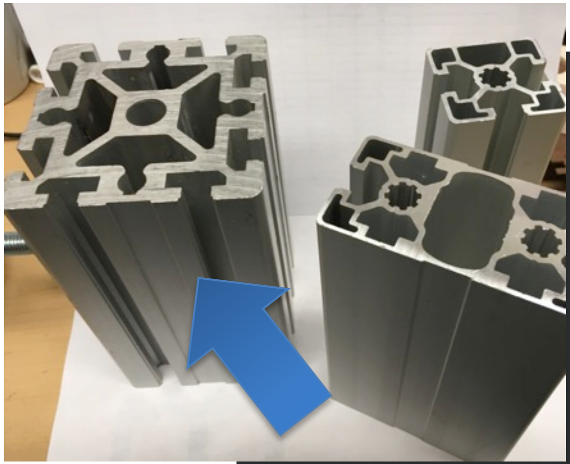


Dipole HOMs on MLC were strongly damped below $Q\sim10^4$.
Consistent with HTC and simulation results.

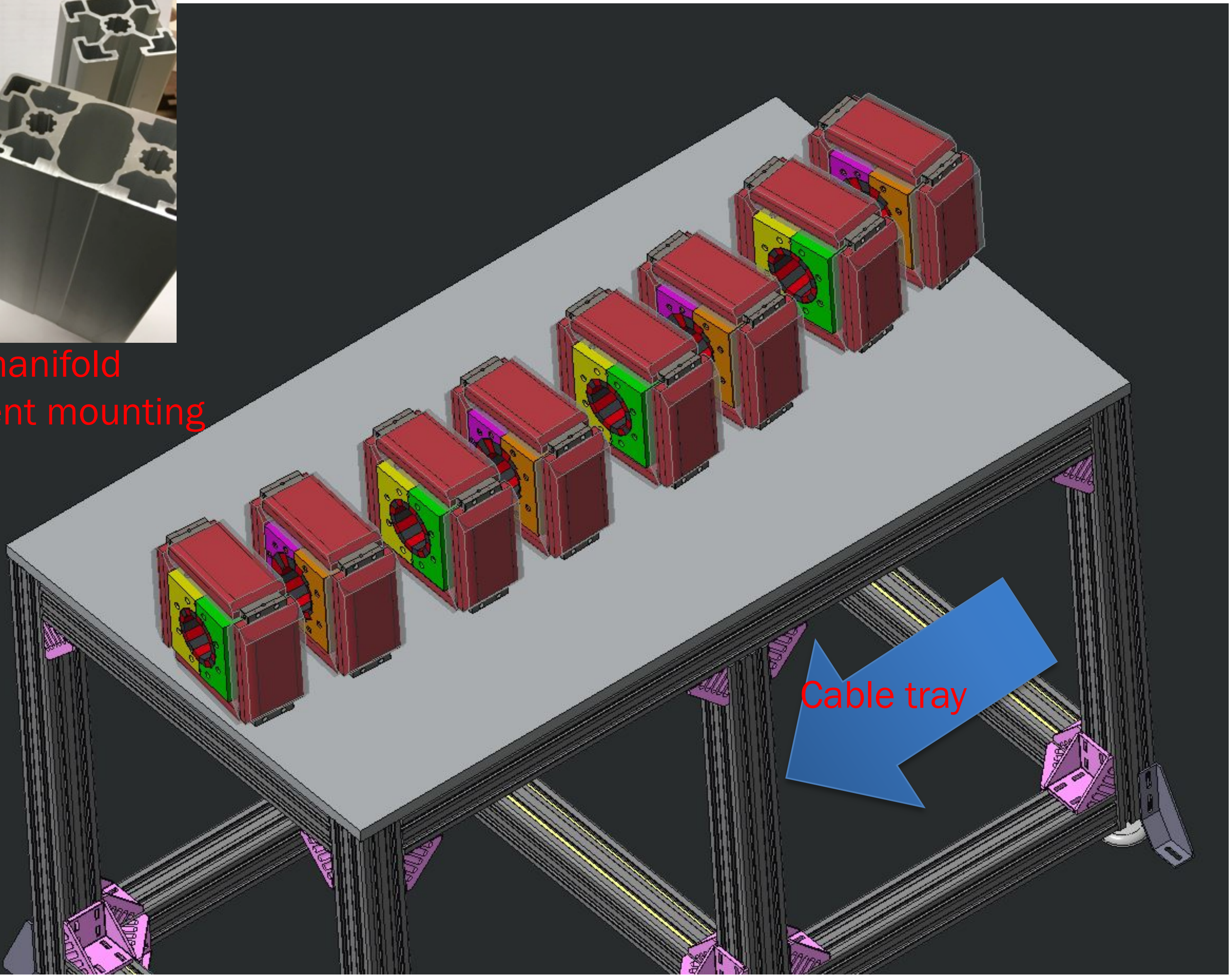
HTC results were:

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

Girder Types and Positions



Integrated H2O manifold
Flexible component mounting



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.

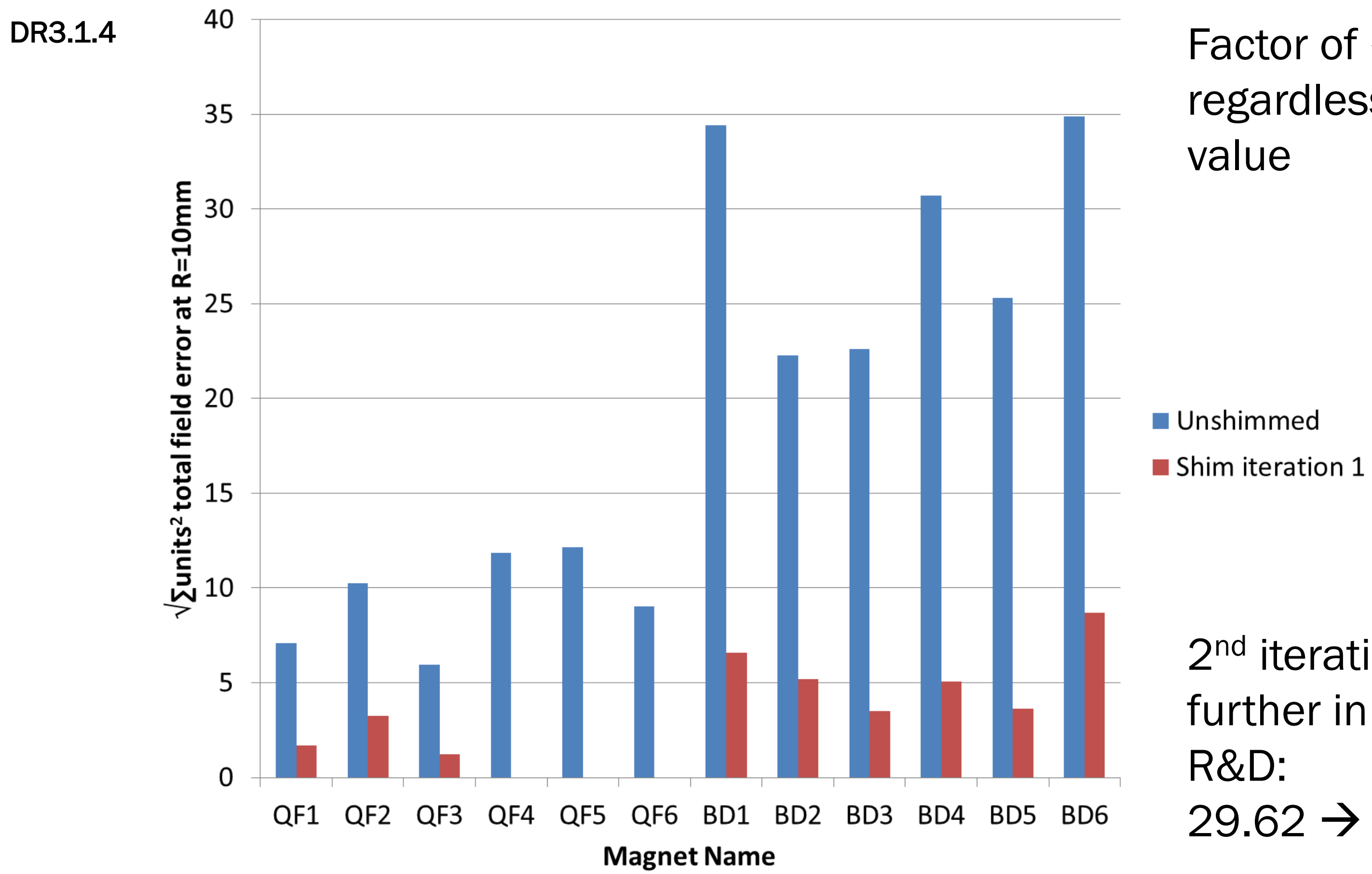

PoP BD


PoP QF


PoP magnet series


Iron wire shims

Iron Wire Shimming Improvement



Factor of ~4 reduction regardless of starting value

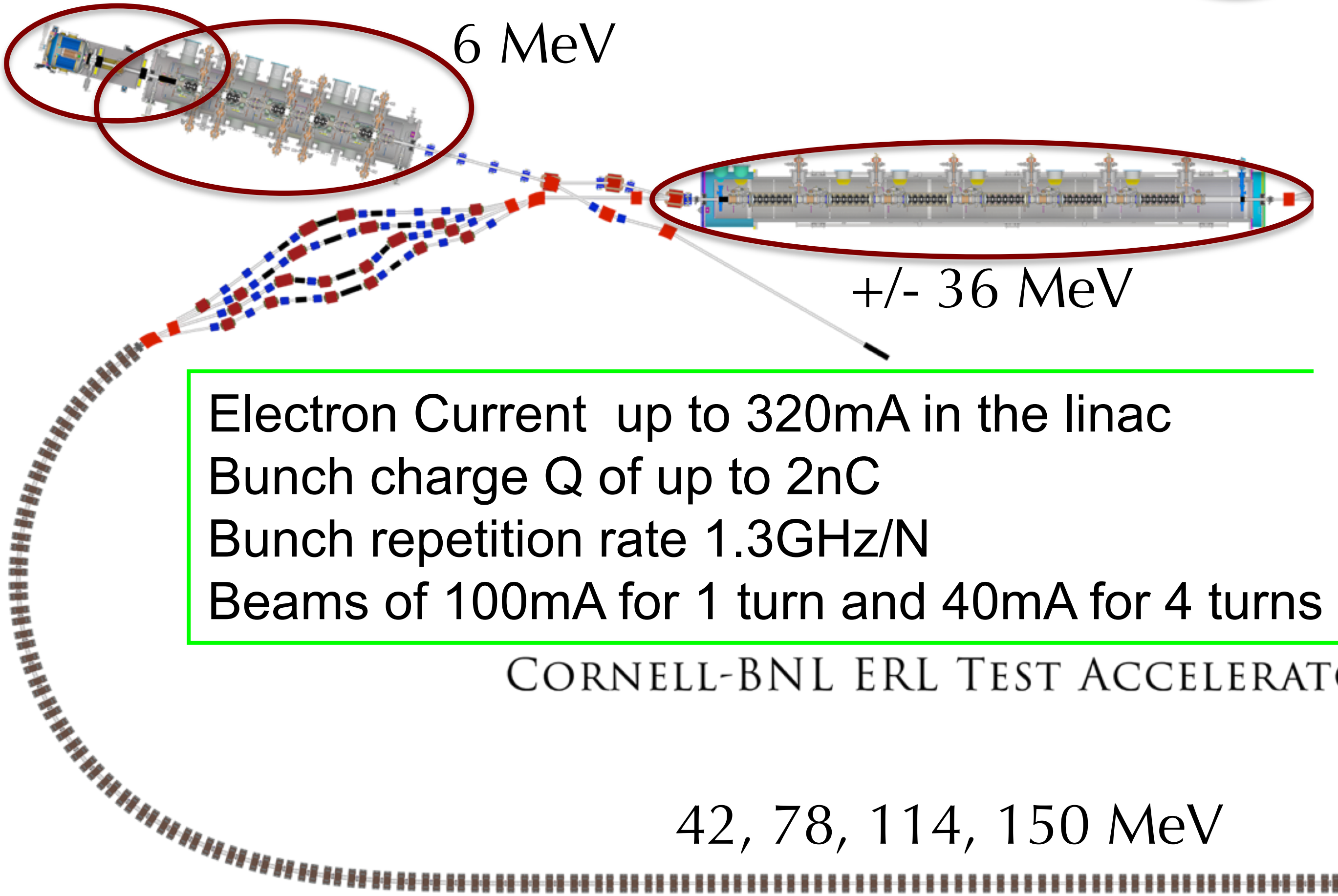
2nd iteration improved further in previous R&D:
29.62 → 6.69 → 1.94

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



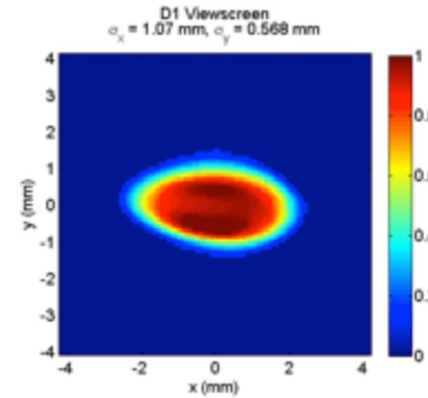
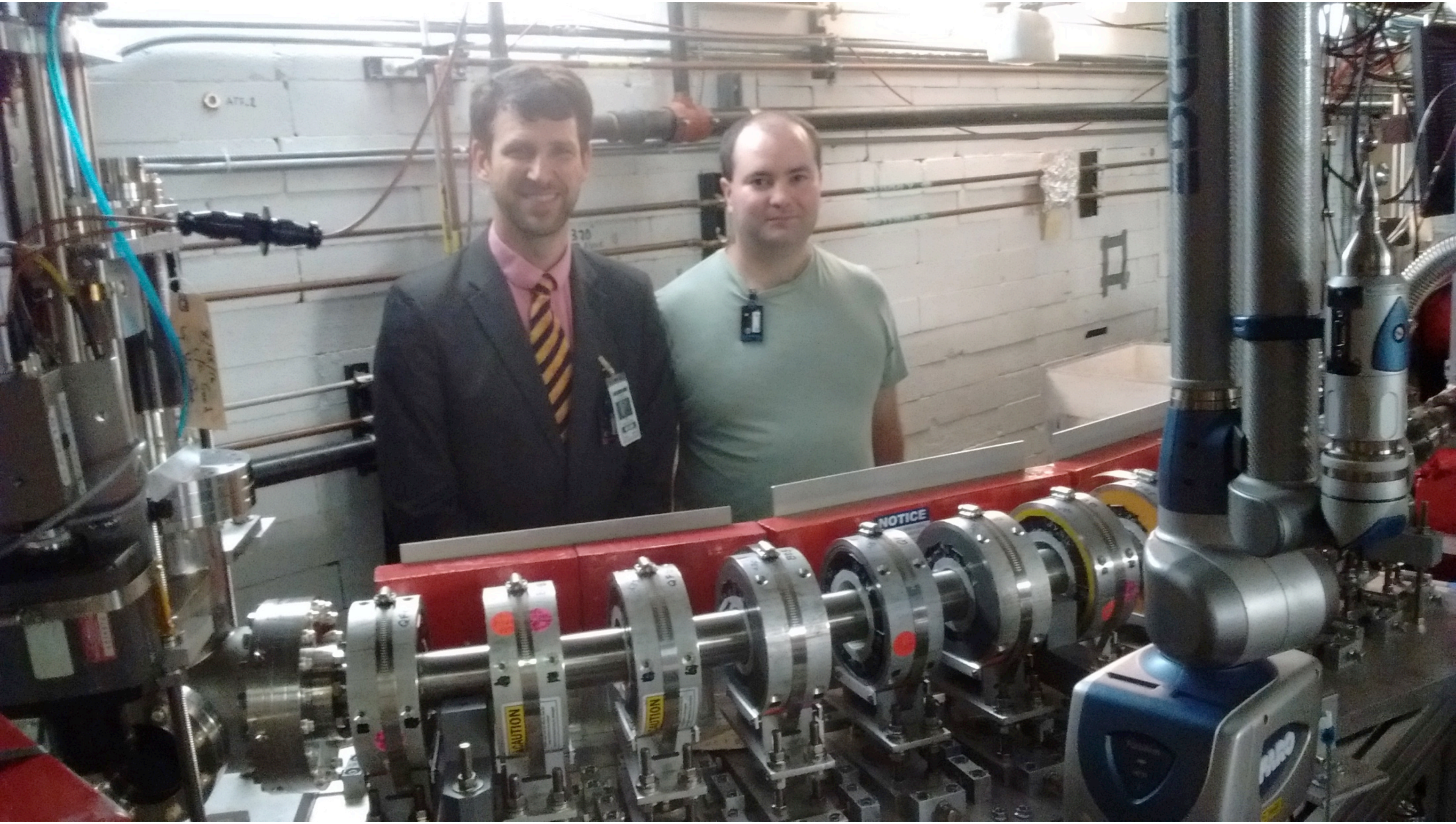


Image of first 12 MeV beam, delivered through MLC

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

CORNELL-BNL ERL TEST ACCELERATOR

FFAG test with beam



Courtesy Stephen Brooks

Scaled down Halbach FFAG with beam at BNL's ATF

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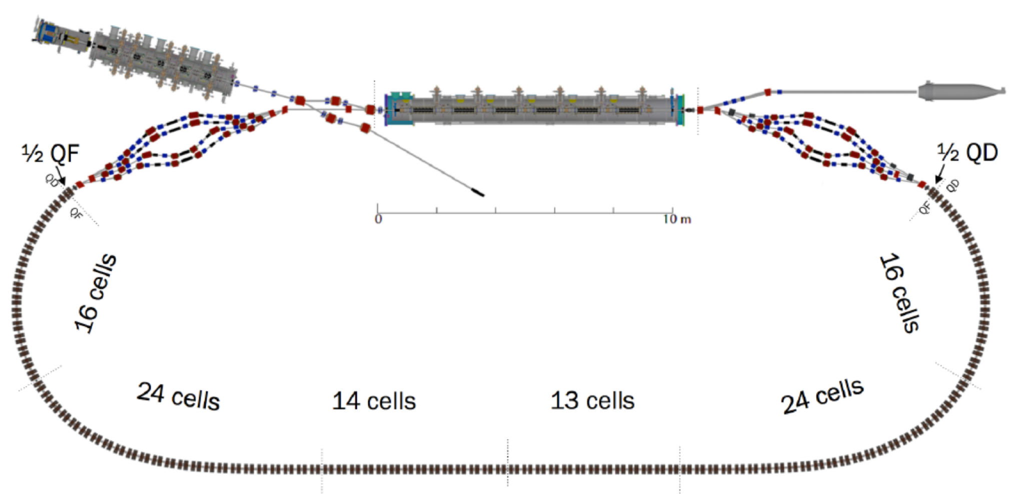
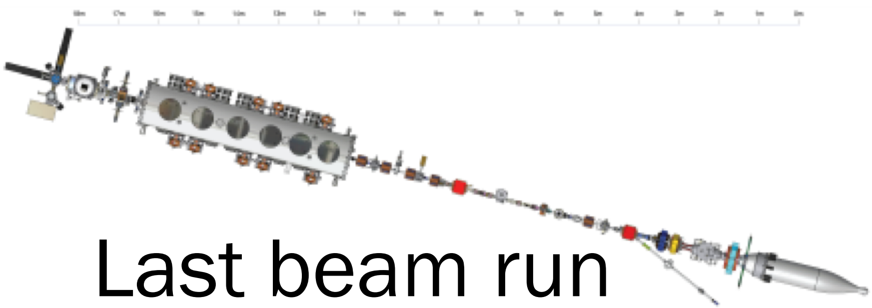


June 8, 2017

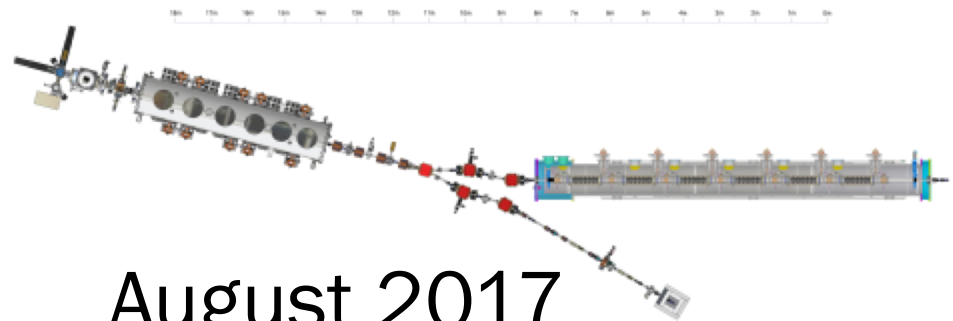
The path is free for CBETA

#	**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	

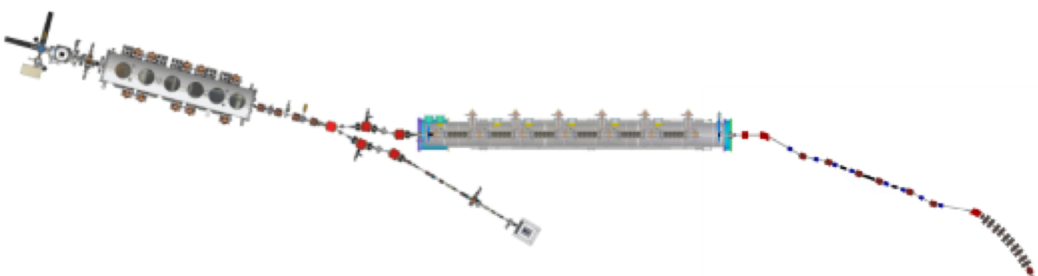
Beam Commissioning



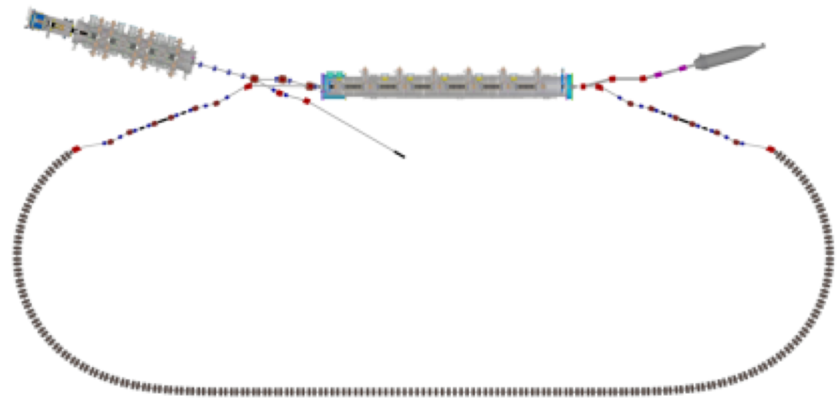
Last beam run



August 2017



April 2018



August 2019

Push toward 4-tunr ERL thereafter (April 2020)

Questions?