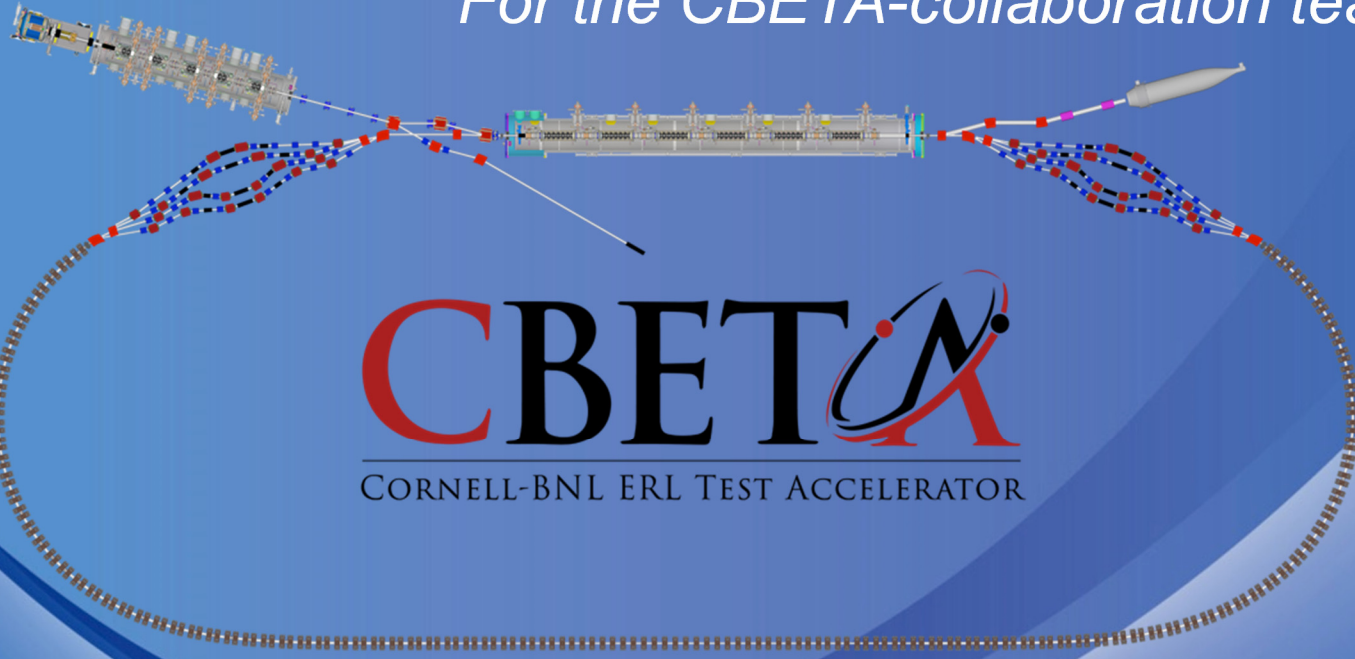


CBETA, the 4-Turn SRF ERL with Single Return Loop

IPAC18, 1 May 2018

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





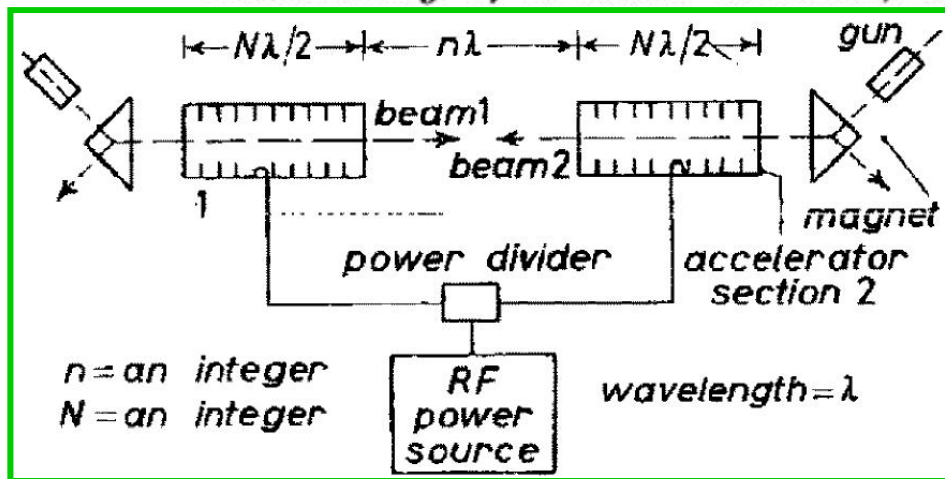
Cornell Laboratory for
Accelerator-based Sciences and
Education (CLASSE)



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

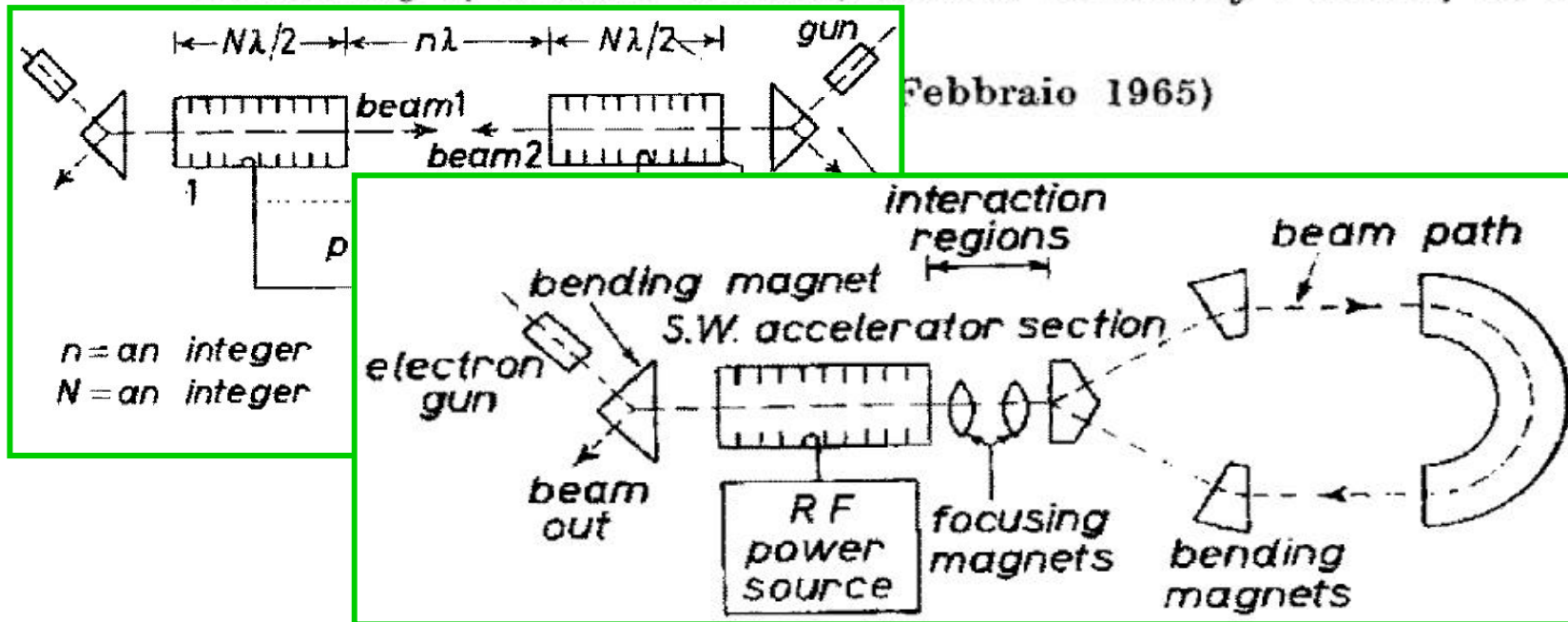
- Normal conducting high field cavities can get too hot.
- Superconducting cavities used to have too low fields.

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

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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.



ERLs store the energy in SRF cavities, but they do not the beam.

They can have

- (a) **high currents**, like storage rings, b/c the energy is recovered,
- (b) **high beam quality** (low emittance, bunch length, and energy spread) like linacs, b/c each bunch traverses it only once,
- (c) **higher luminosity** than ring colliders, b/c bunches can be damaged more by the beam beam force.

Their current is not limited by the available power, as in linacs, but by

- (a) HOM heating
- (b) HOM-driven Beam-Brakeup Instability



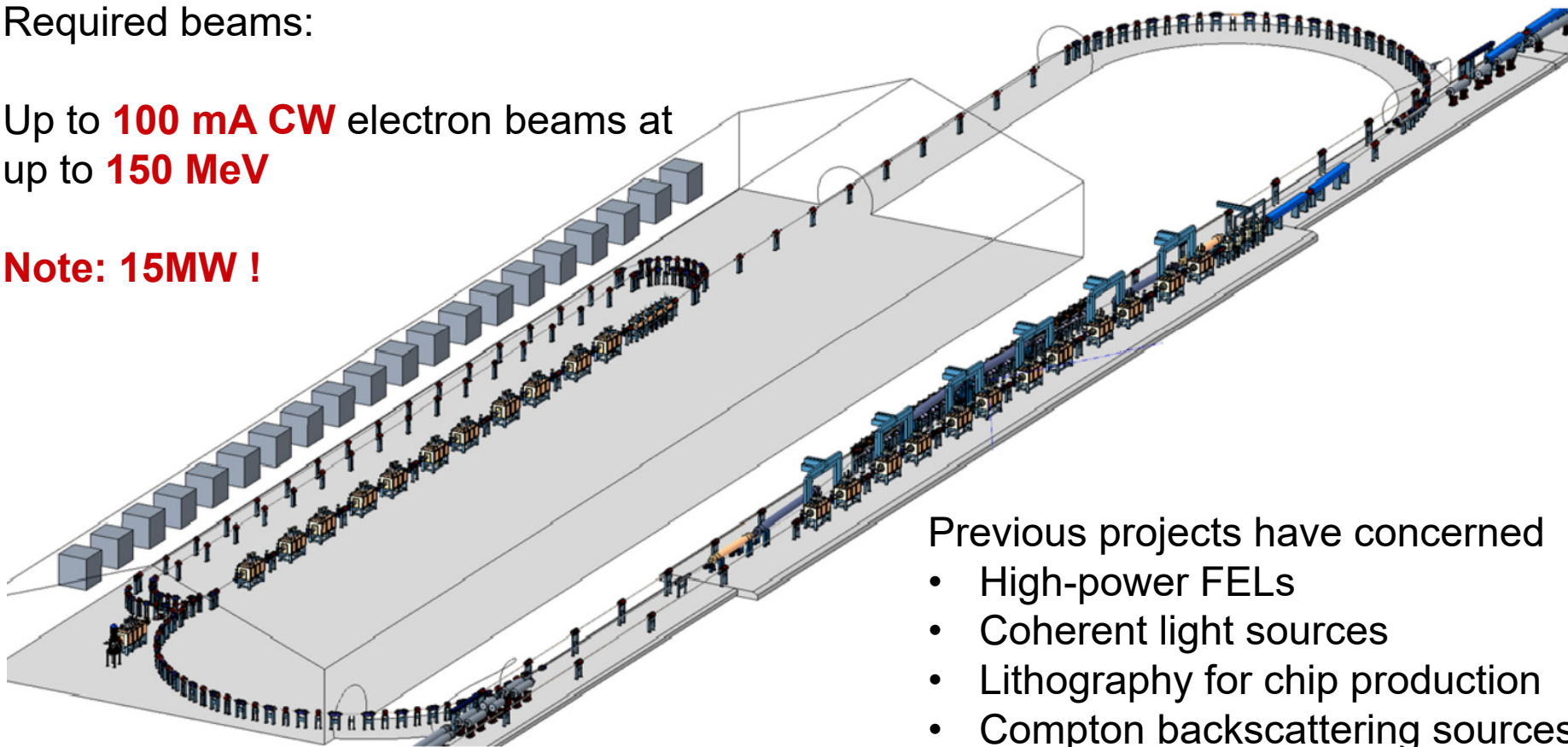
Strong Hadron Cooling for EICs

Both EIC projects, the one at BNL and the one at JLAB, plan to cool the hadron beam with electrons.

Required beams:

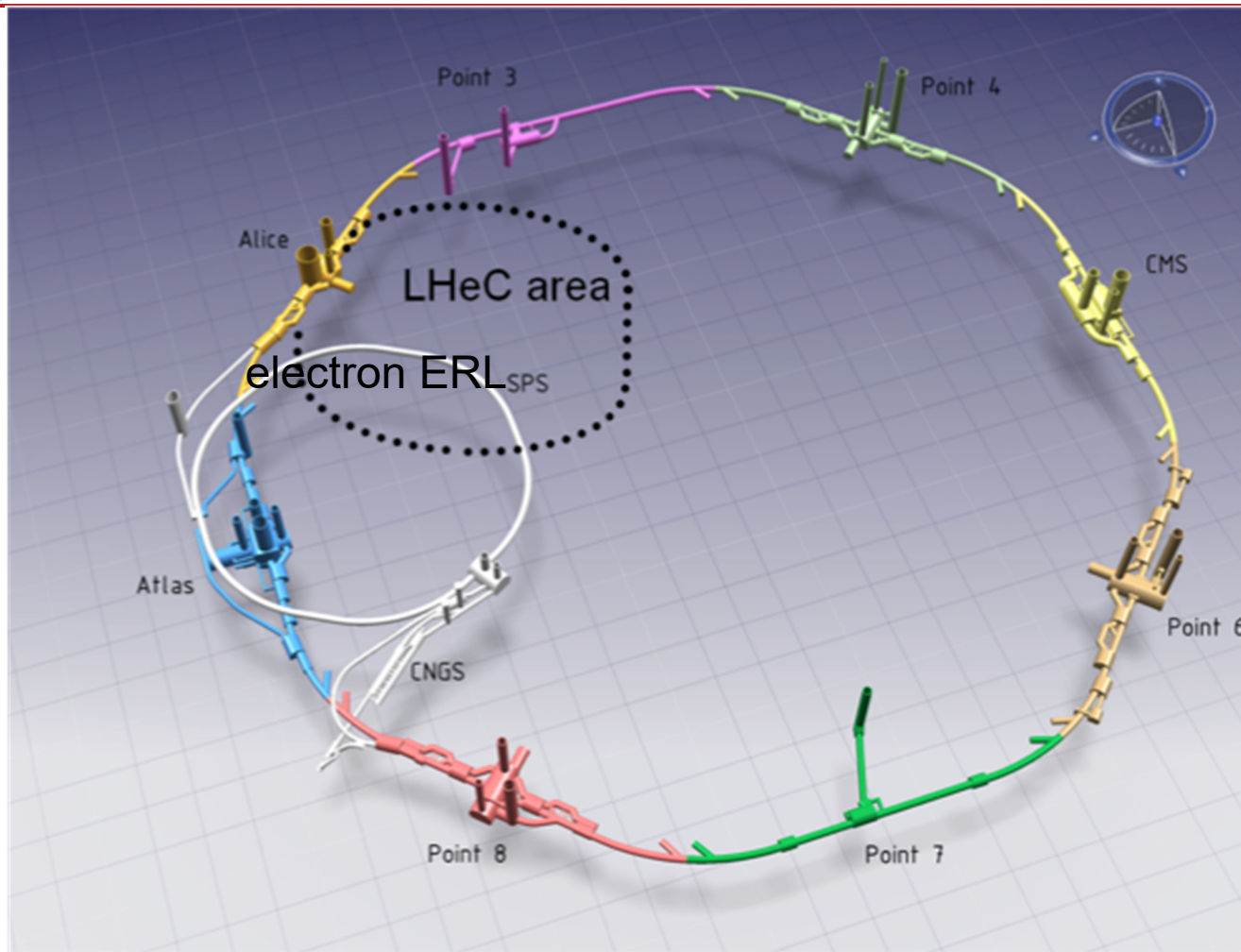
Up to **100 mA CW** electron beams at
up to **150 MeV**

Note: 15MW !



Previous projects have concerned

- High-power FELs
- Coherent light sources
- Lithography for chip production
- Compton backscattering sources



Advantageous over an electron ring in the LHC tunnel:

- Less downtime of the LHC rings
- Less damage to electrons from the beam beam force => more luminosity
- Less synchrotron radiation than a ring on the same track.



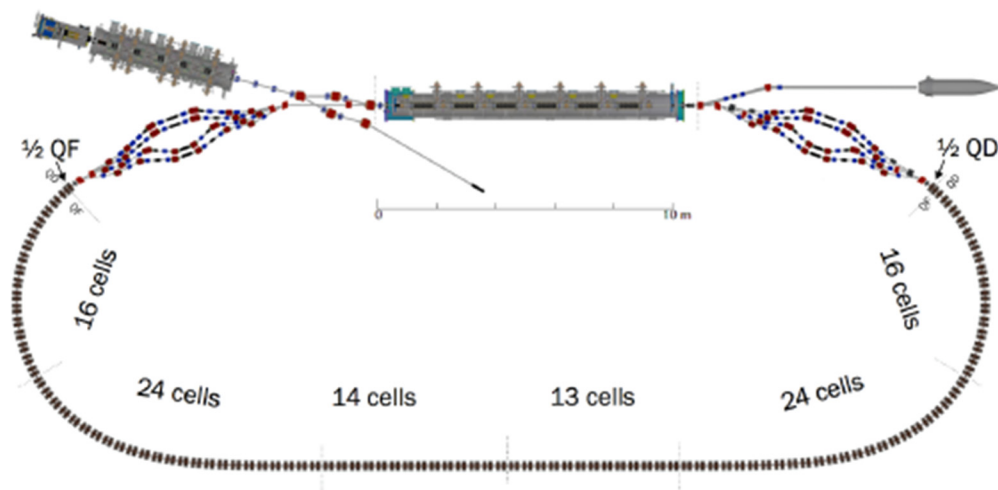
CBETA Design Report

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

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

2005 Start of construction of DC photo-emitter gun; to 75mA.

2006 Start of construction of Injector Cryo-Module (ICM); to 500kW CW.

2009 Start of commissioning of ERL injector; to 0.3 micron for bunch charges of 100mA beam.

2012 PD-Design Report on a hard x-ray 5GeV ERL; no construction.

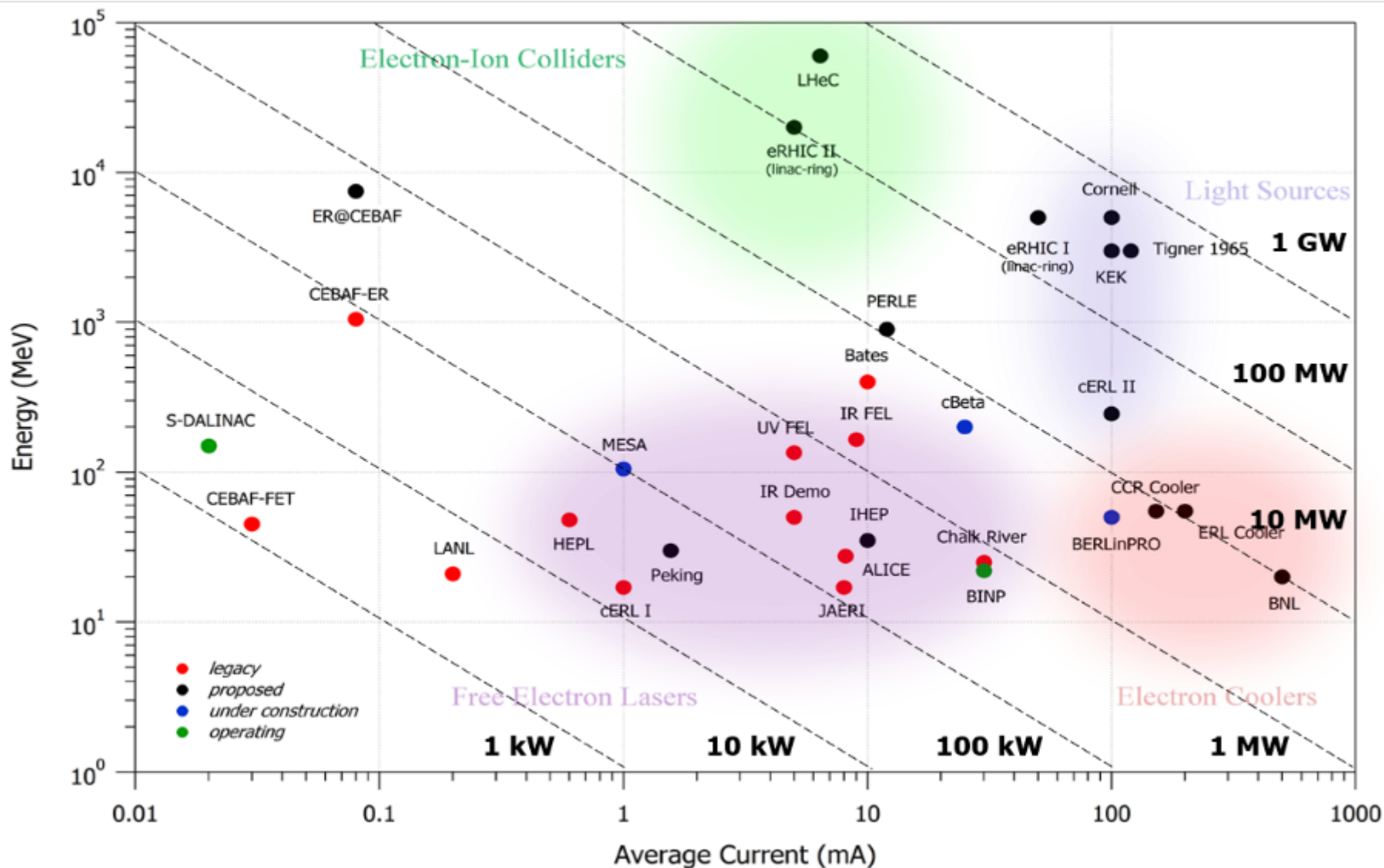
2014 White paper for CBETA with collaborators at BNL.

2016 Secured funding by NYS.

2017/05 1st beam through SRF

2017/06 DR for CBETA as 4-turn SRF ERL and permanent magnet array (PMA) with Halbachs.

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

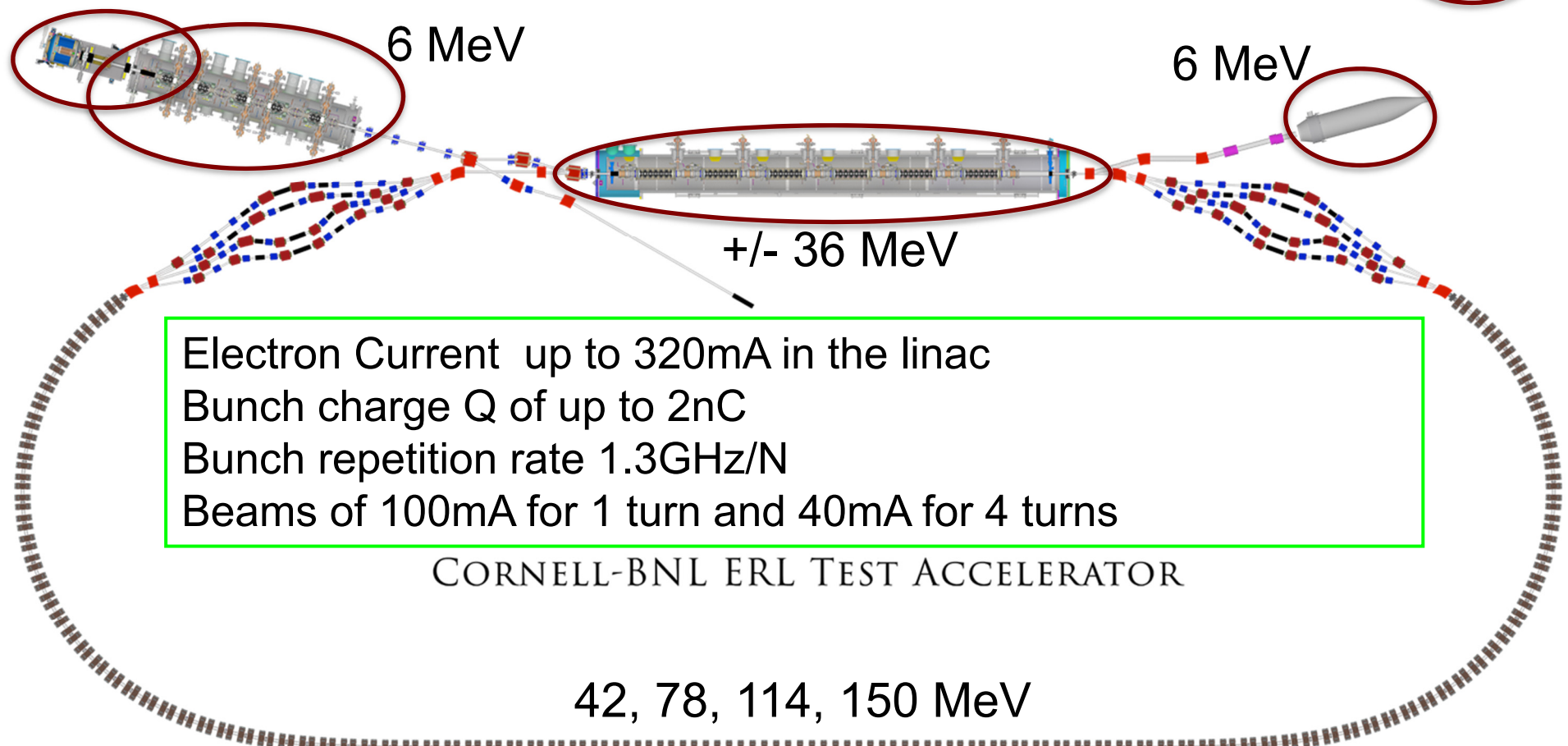


- CBETA has 150MeV and up to 40mA: 6MW beampower



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

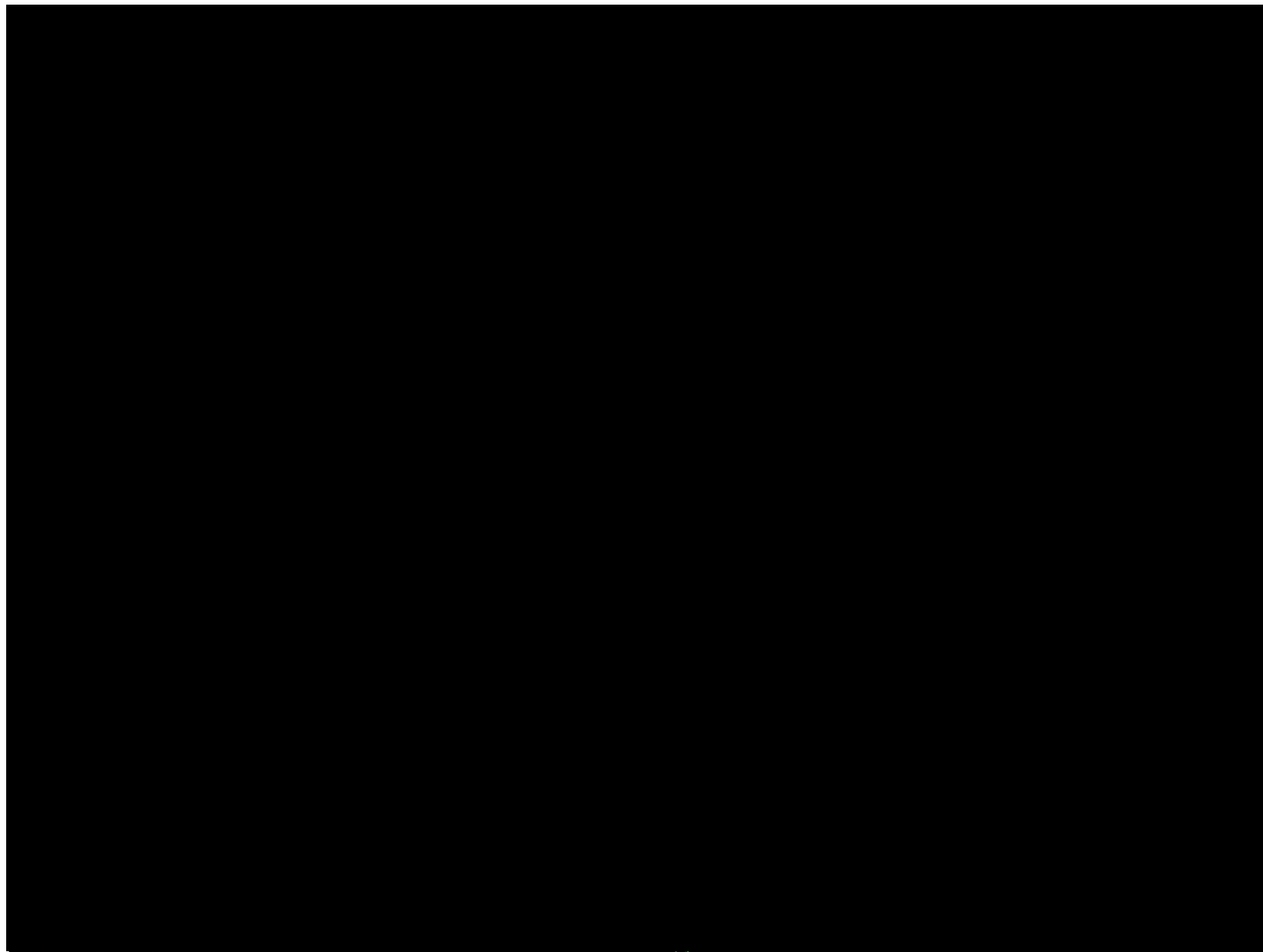
Existing components at Cornell



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

CORNELL-BNL ERL TEST ACCELERATOR

42, 78, 114, 150 MeV





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

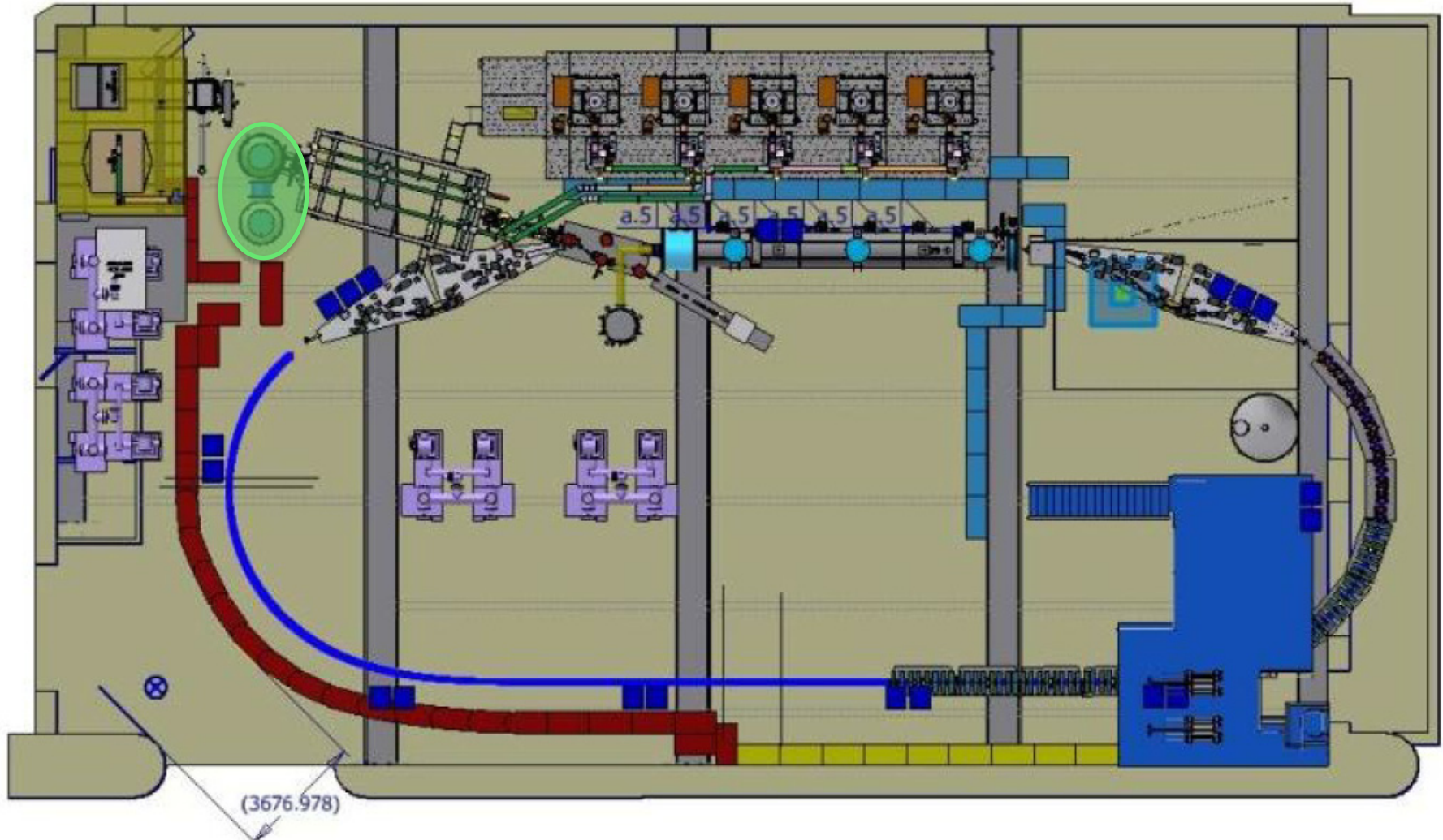


70% of the existing technical-use space was removed for the initial phase

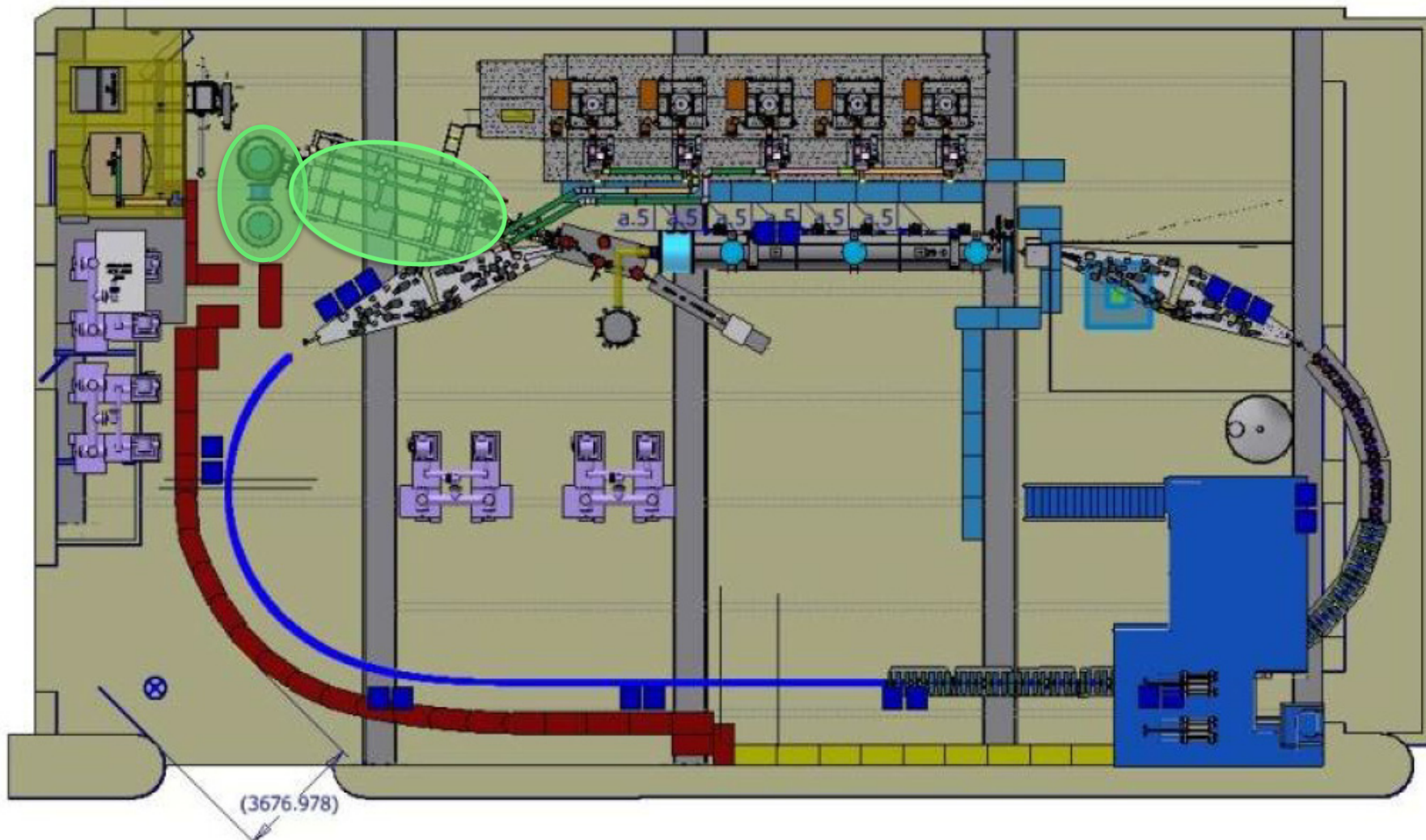




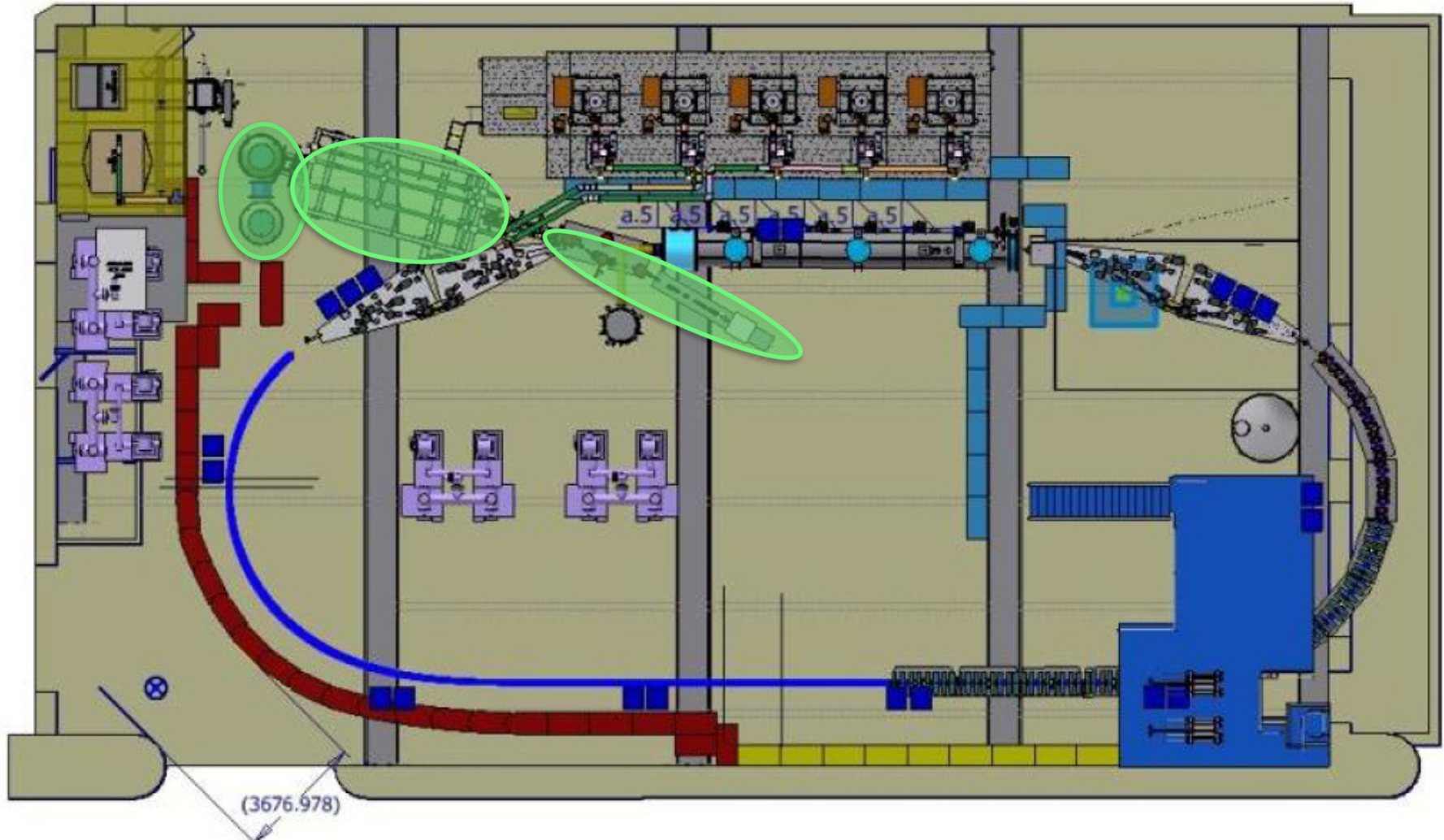
Installed: DC gun



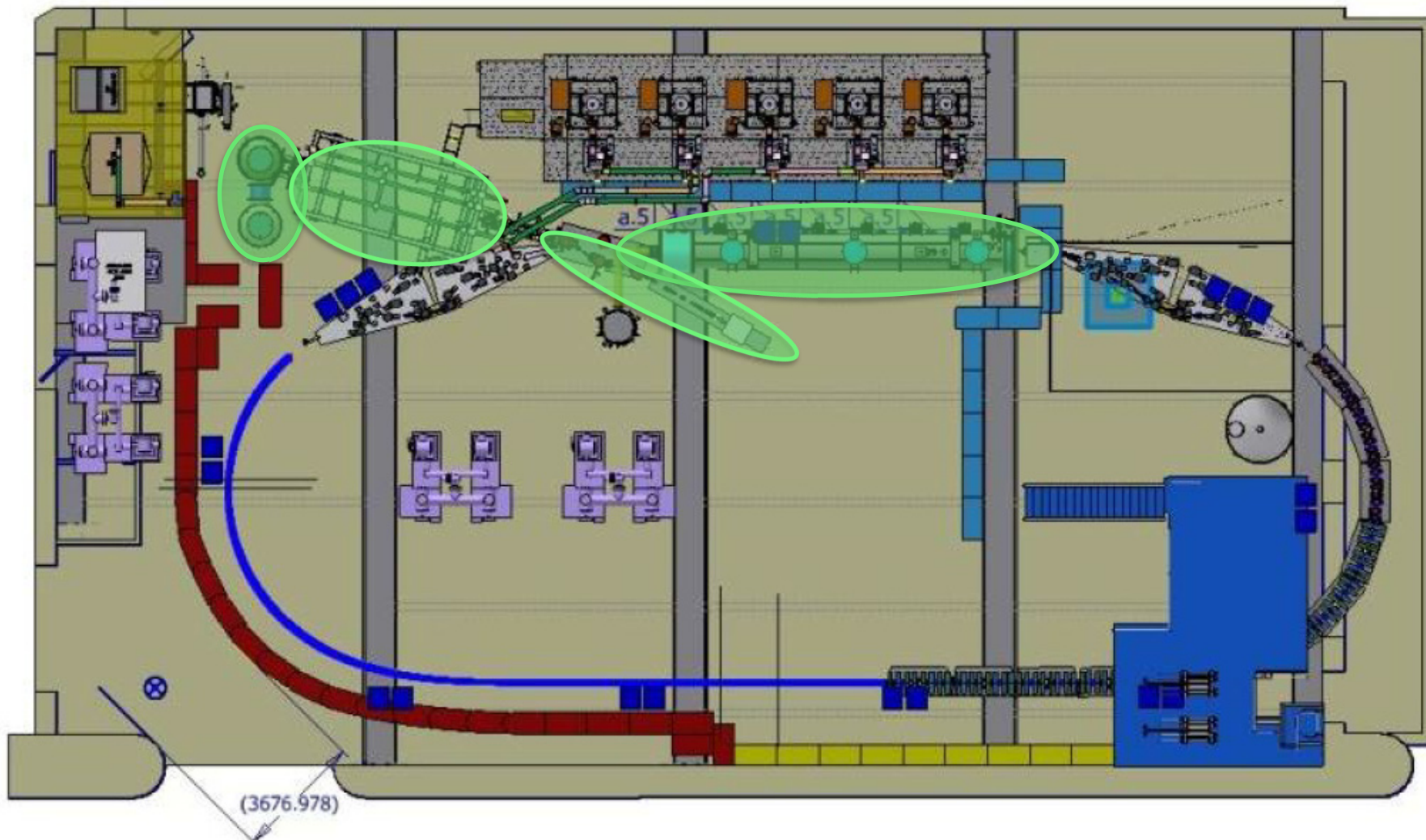
Installed: DC gun, SRF injector



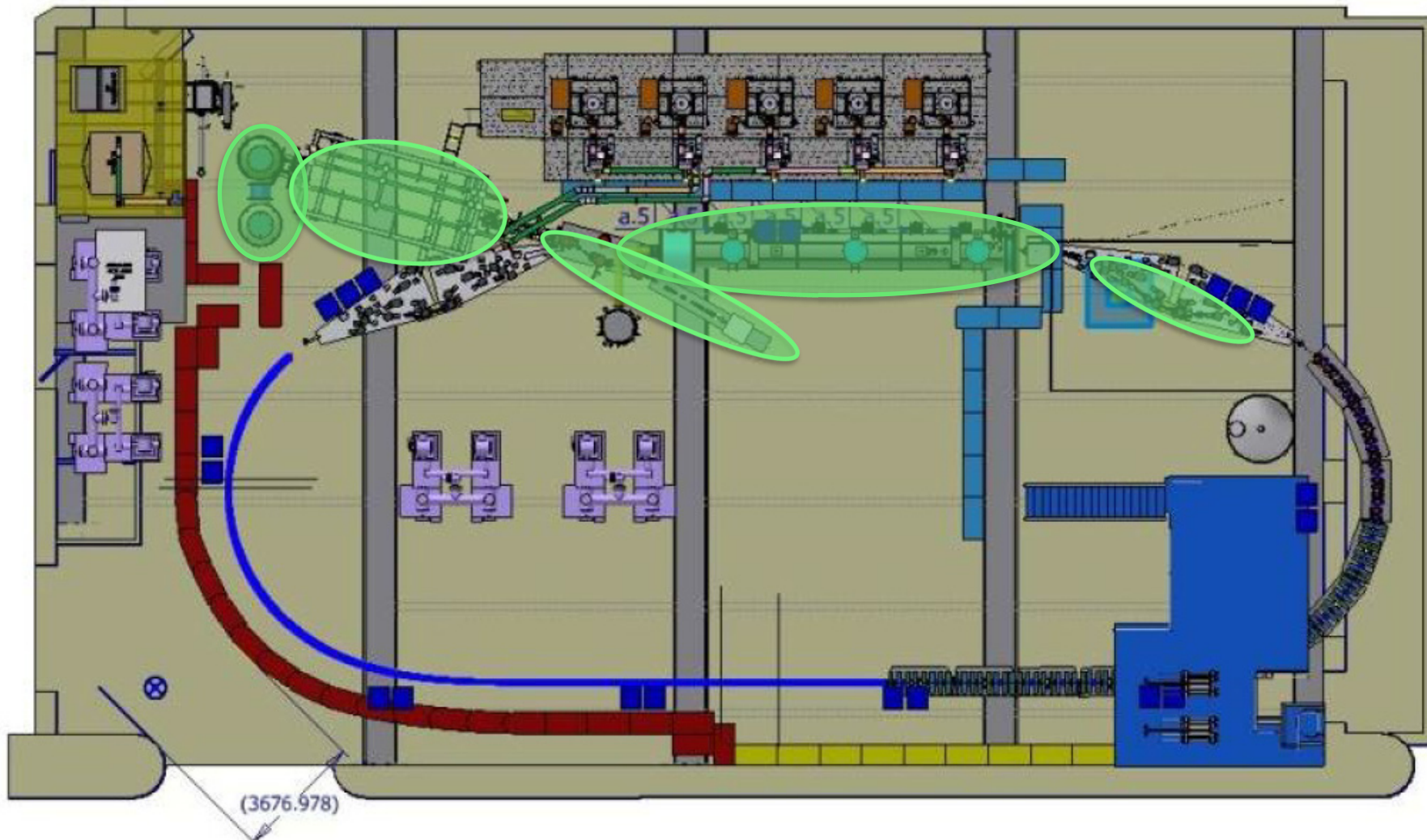
Installed: DC gun, SRF injector, mirror diagnostics line



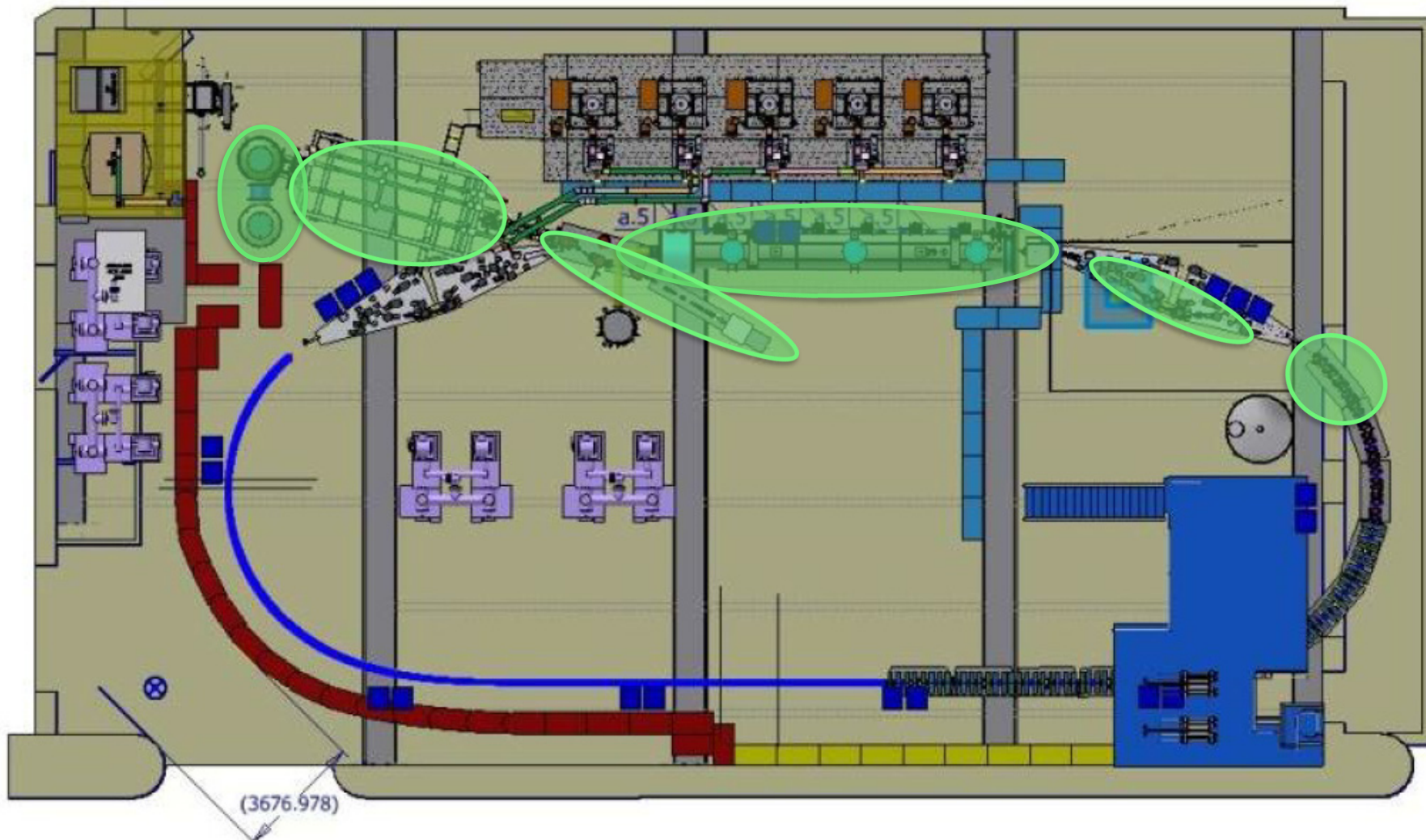
Installed: DC gun, SRF injector, mirror diagnostics line, ERL cryomodule



Installed: DC gun, SRF injector, mirror diagnostics line, ERL cryomodule
1st splitter of 8



Installed: DC gun, SRF injector, mirror diagnostics line, ERL cryomodule
1st splitter of 8, 1st Fixed Field Alternating-gradient (FFA) girder of 25.





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CERN COURIER

Feb 16, 2018

Small accelerator promises big returns

Under construction in the US, the CBETA multi-turn energy-recovery linac will pave the way for accelerators that combine the best of linear and circular machines.



The main linac cryomodule

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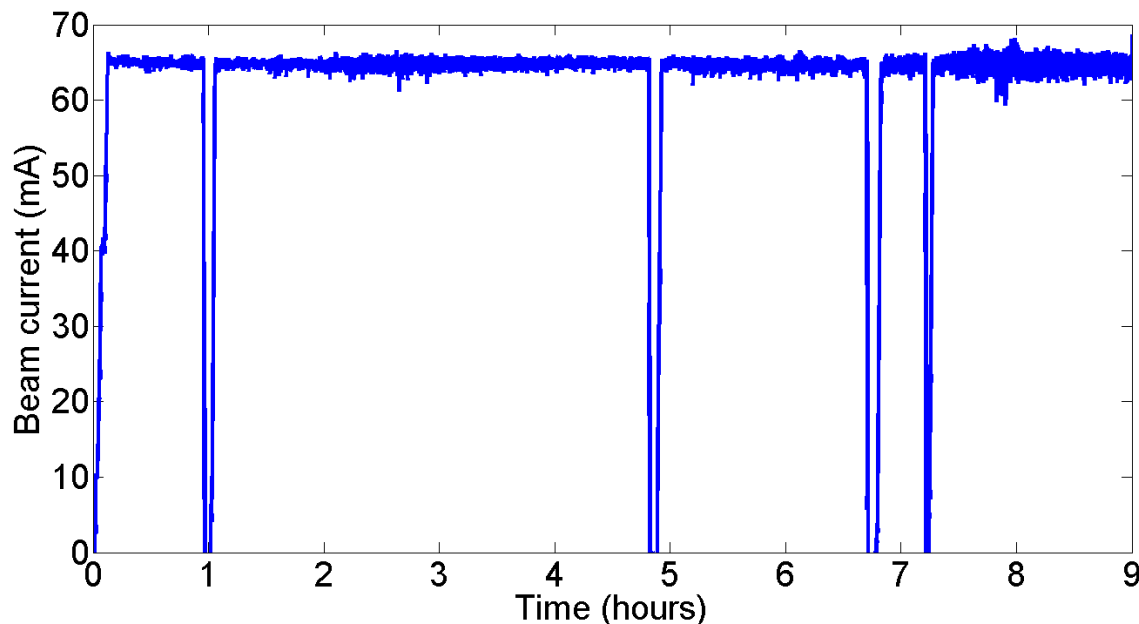


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FEATURED COMPANIES







- Peak current of 75mA (world record)
- NaKSb photocathode
- High rep-rate laser
- DC-Voltage source

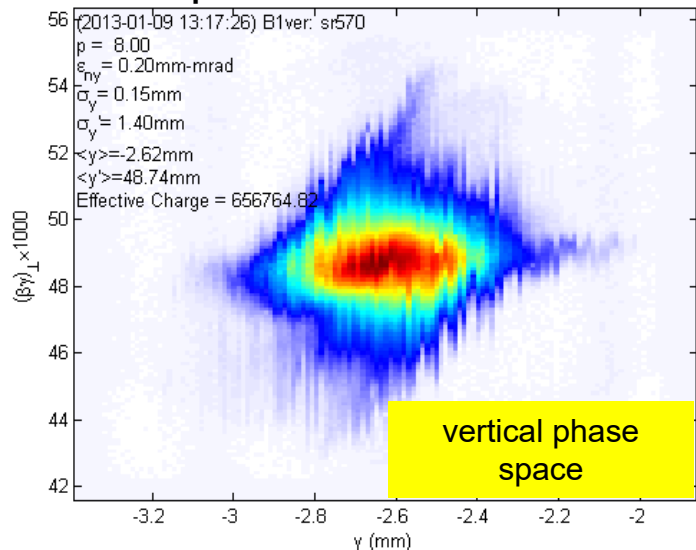
Source achievements:

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

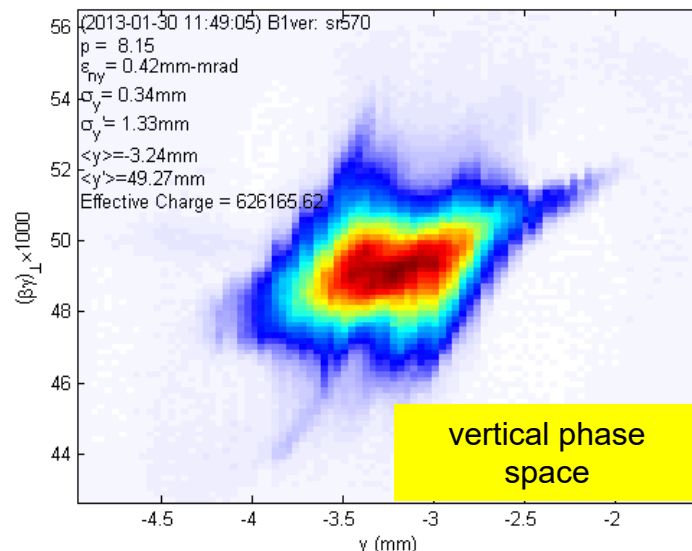
Simulations accurately reproduce photocathode performance with no free parameters, and suggest strategies for further improvement.

✓ Source current can meet ERL needs

20 pC/bunch



80 pC/bunch



Normalized rms emittance (horizontal/vertical) 90% beam, $E \sim 8$ 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%

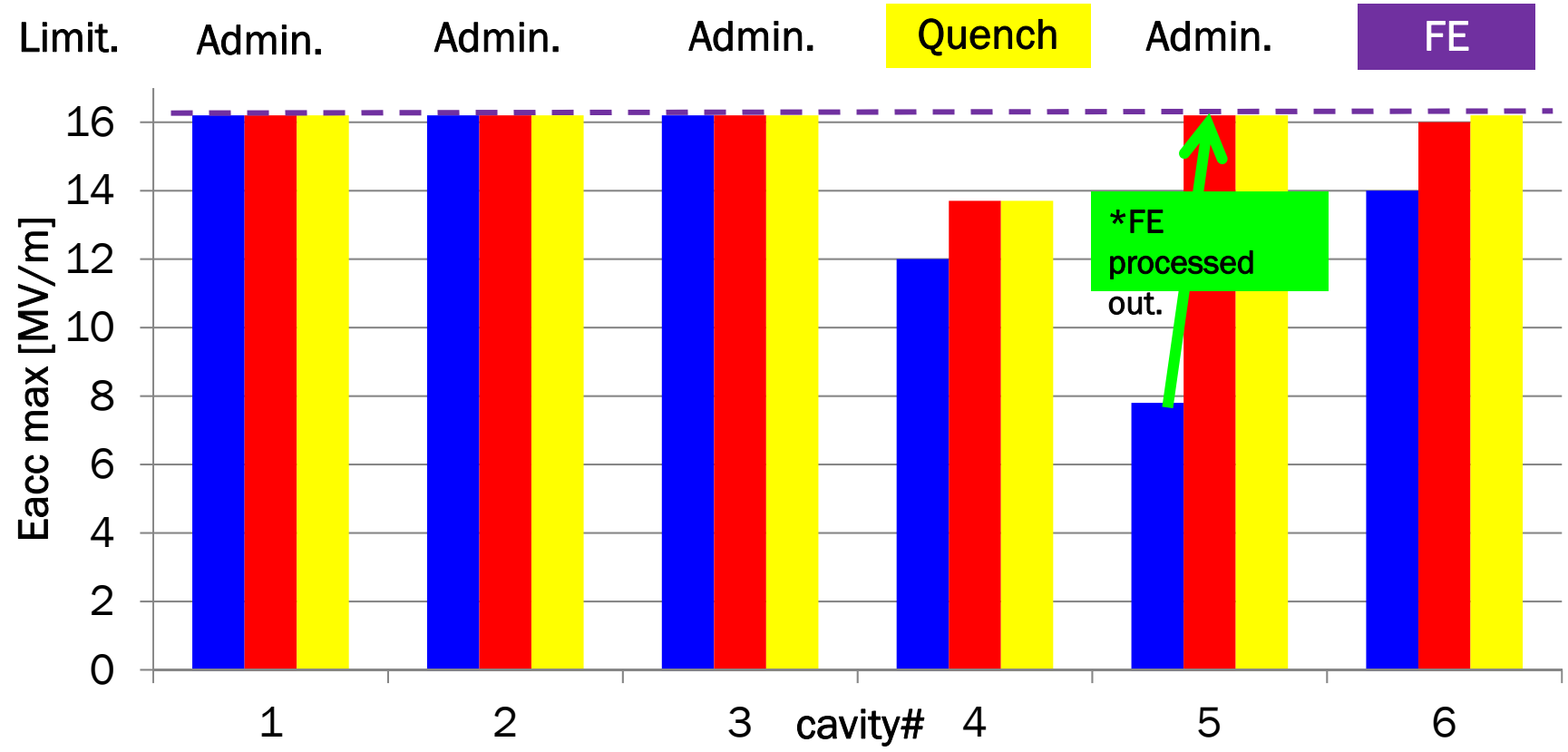
0.24/0.18 mm-mrad @ 61%

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

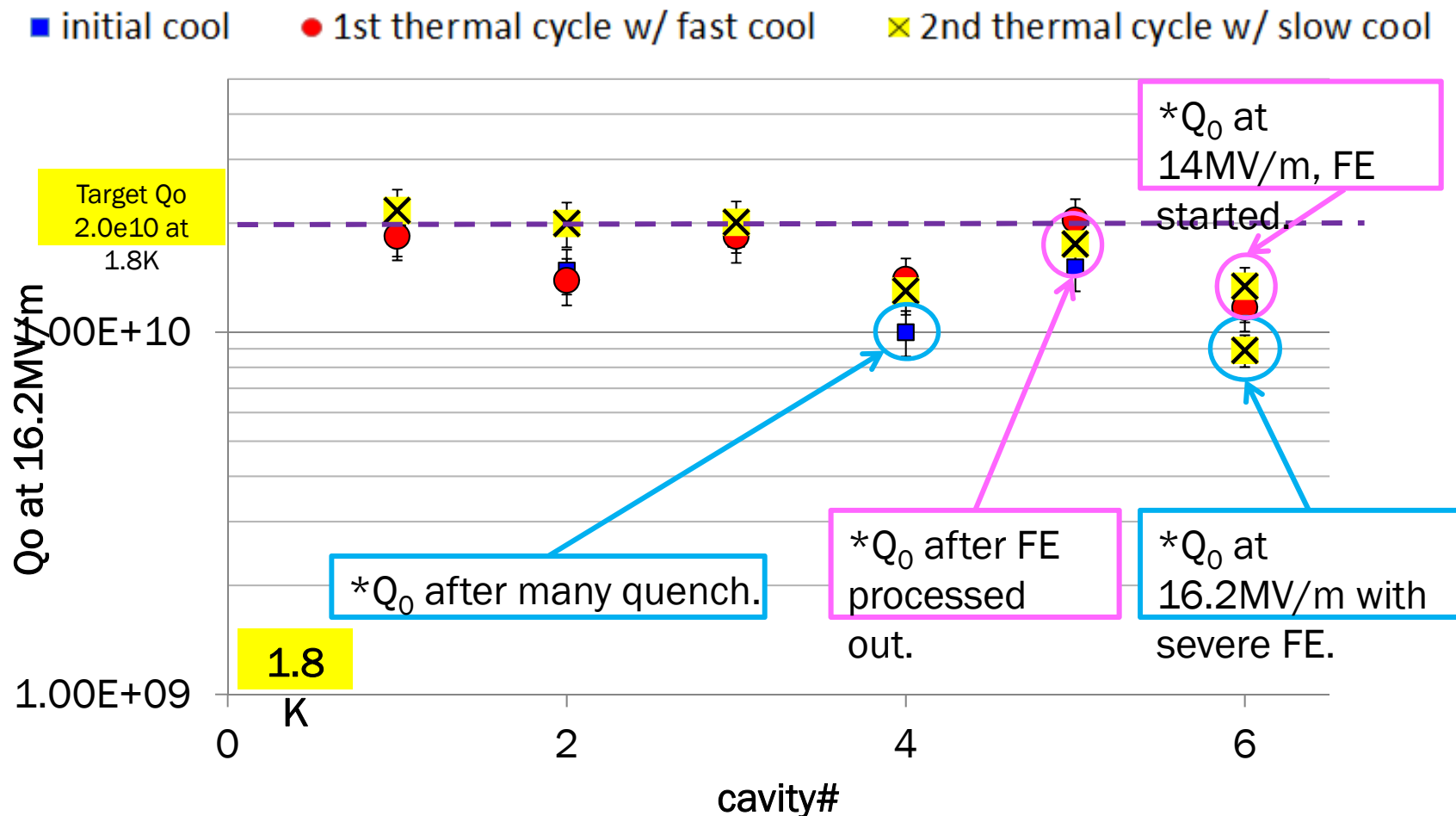
✓ At 5 GeV this gives 20x the world's highest brightness (Petra-III)



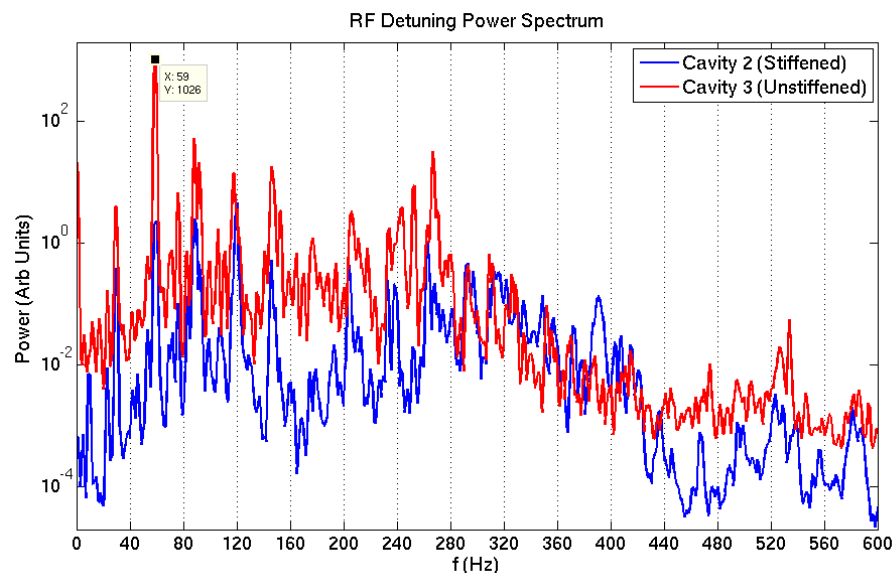
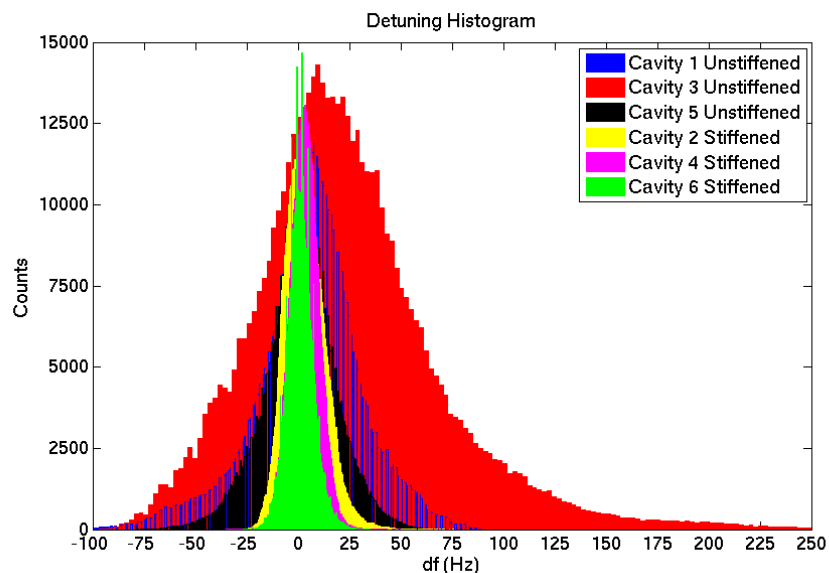
■ Initial cool ■ 1st thermal cycle w/ fast cool ■ 2nd thermal cycle w/ slow cool



- 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)**

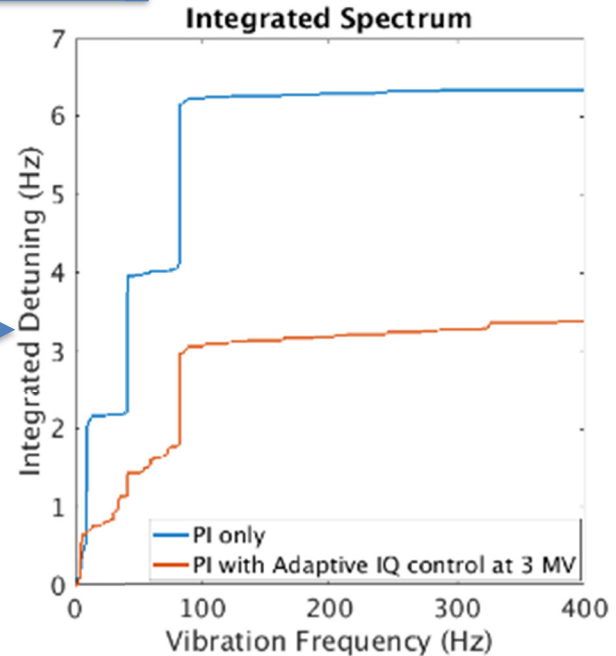
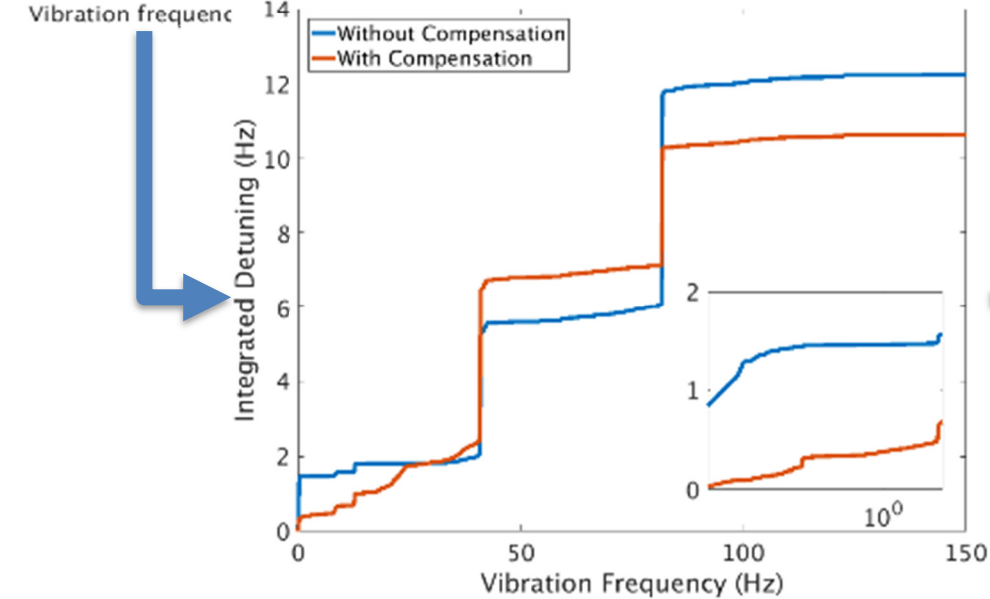
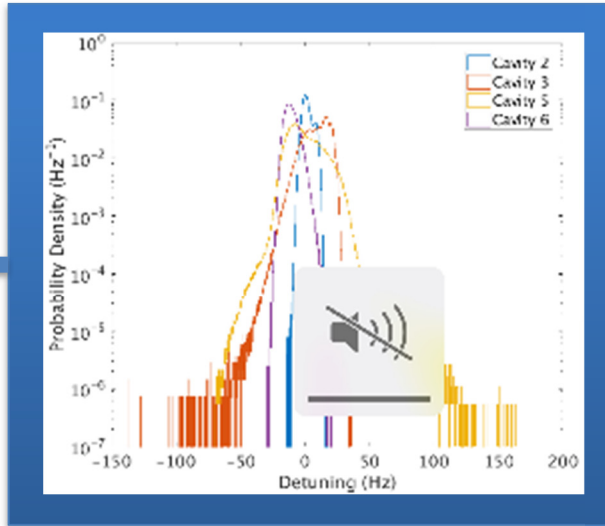
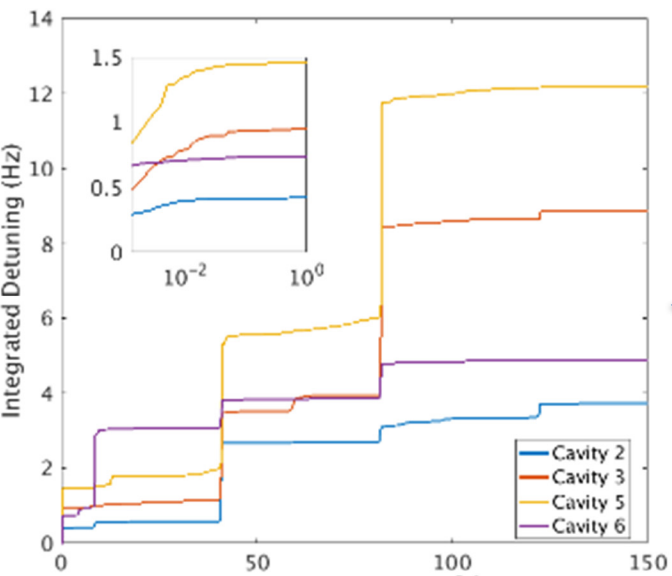


- 4 of 6 cavities had achieved design Q_0 of $2.0E+10$ at 1.8K.
- Q_0 of Cavity#6 had severe FE at 16MV/m.
- **Enough cooling for 73MV per ERL turn (where 36MeV are needed)**



Preliminary results:

- Stiffened cavities have ~ 30 Hz detuning, Un-stiffened cavities have ~ 150 Hz detuning.
- Design specs are ~ 20 Hz.
- 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)



Algorithm is stable! Reduced peak detuning by about a factor of 2.



PoP QF

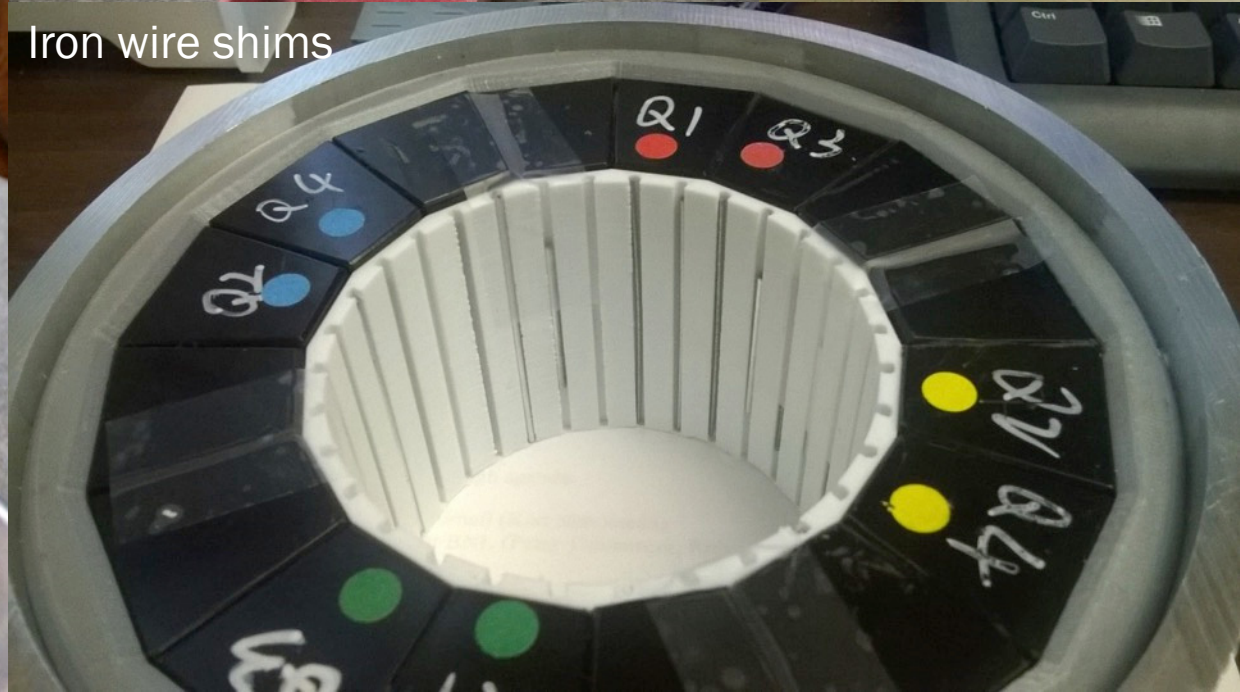
12 **proof-of-principle magnets** (6 QF, 6 BD) have been built as part of CBETA R&D.
Iron wire shimming has been done on 3 QFs and 6 BDs with good results.

PoP BD



PoP magnet series

Iron wire shims





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

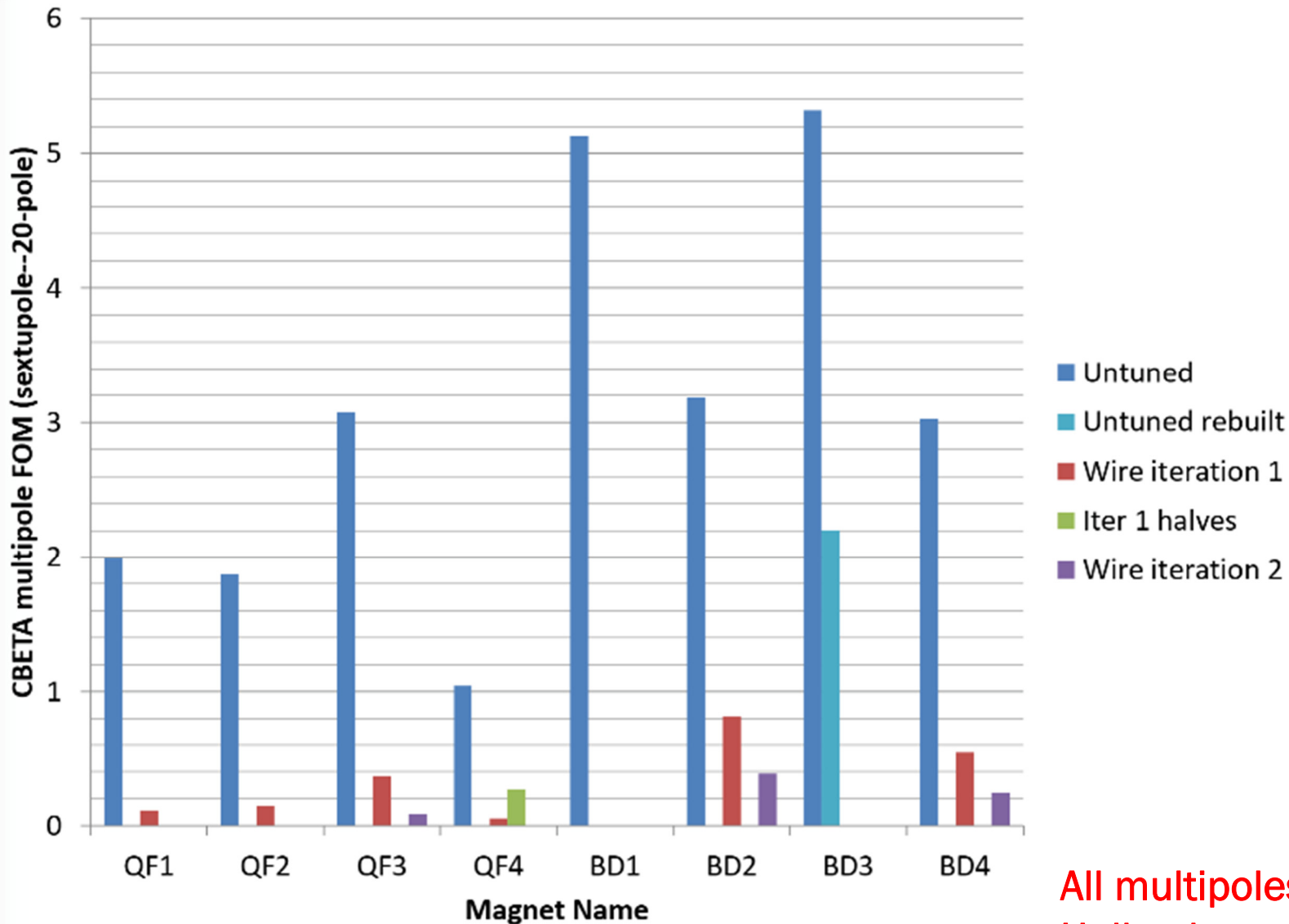
$$B_x + iB_y = \frac{b_n + ia_n}{L} (x + iy)^n$$

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

Multipole limits:

For < 10% emittance and beam-size growth

$$\sqrt{\sum_n \left(\frac{b_n}{\lim_b_n} \right)^2 + \left(\frac{a_n}{\lim_a_n} \right)^2} < 0.75$$



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



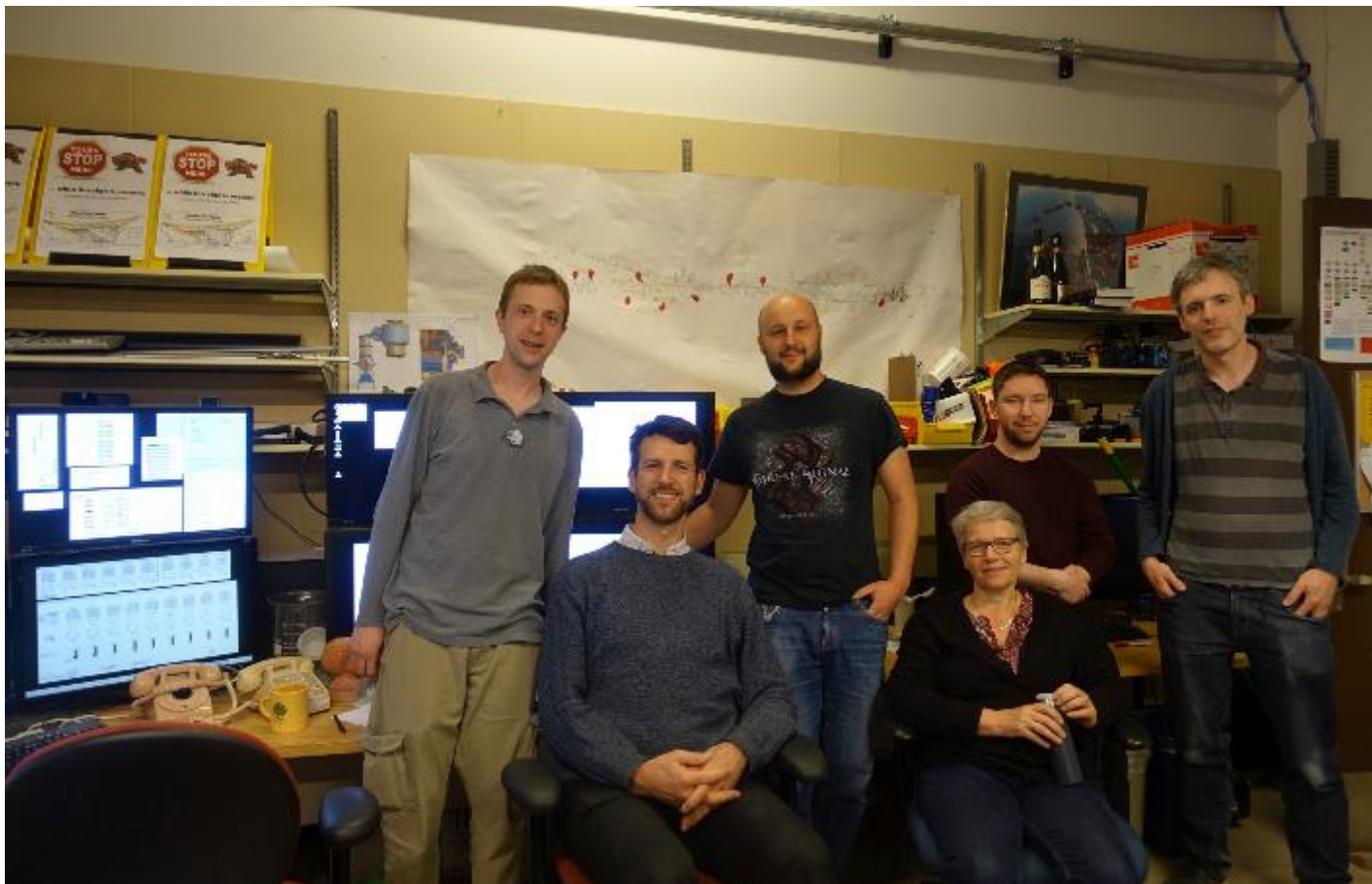


#	Milestone (at the end of months)	Baseline	Actual
	Funding start date		Oct-16
1	Engineering design documentation complete	Jan-17	
2	Prototype girder assembled	Apr-17	
3	Magnet production approved	Jun-17	
4	Beam through Main Linac Cryomodule	Aug-17	
5	First production hybrid magnet tested	Dec-17	
6	Fractional 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	



We are forming a **collaboration interested in CBETA or generic ERL research.**

As a first step, visitors from 4 labs are participating in the current commissioning run:
3 from HZB/Germany, 2 from Daresbury/UK, 3 from JLAB, 5 from BNL.

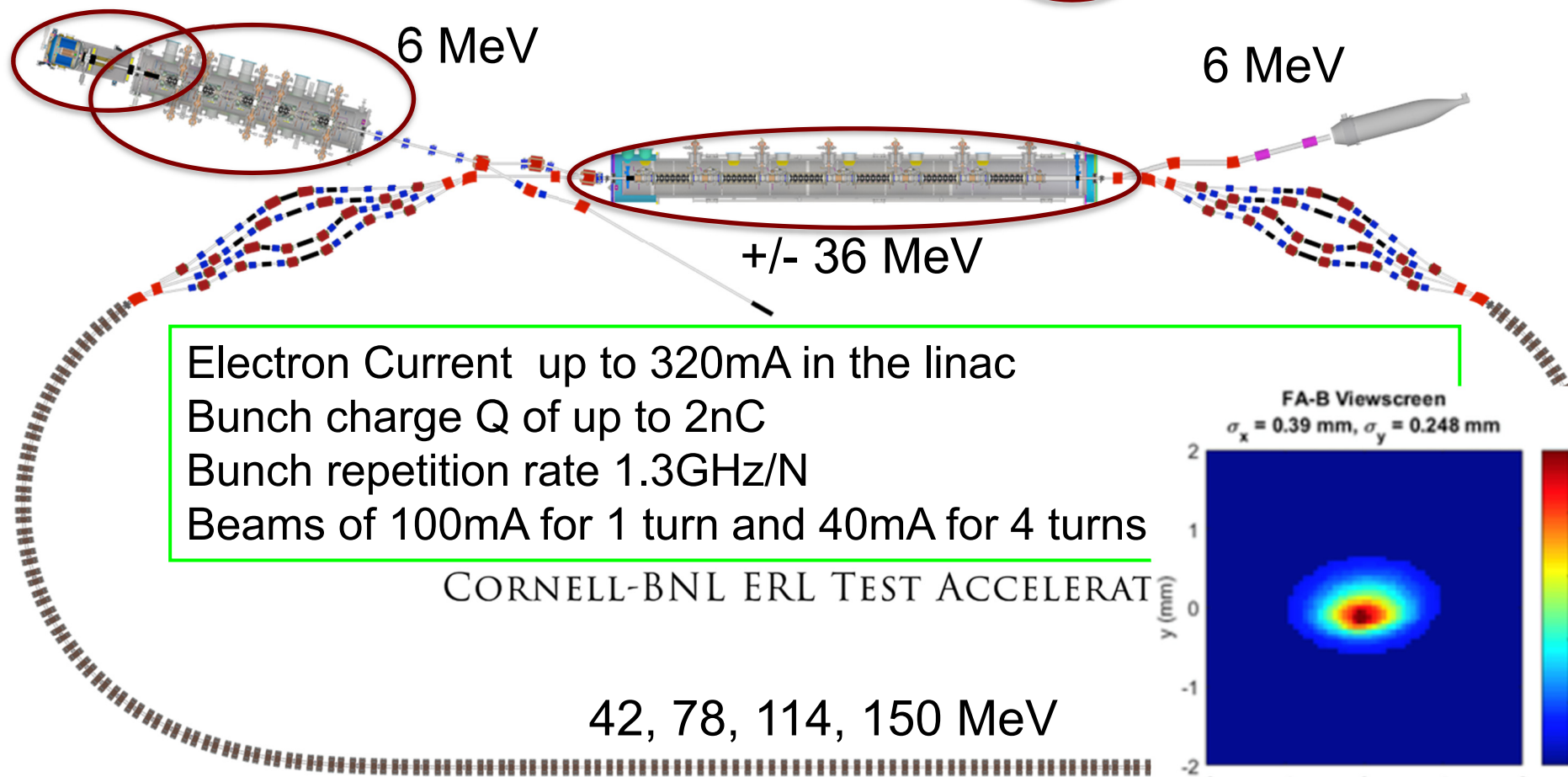


1st set of international visitors for Commissioning (r to l): D. Kelliher & J. Jones (Daresbury), B. Kuske & J. Völker (HZB).



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

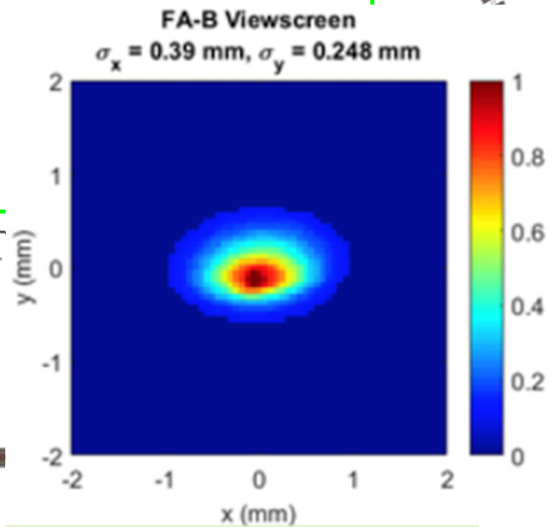
Tested

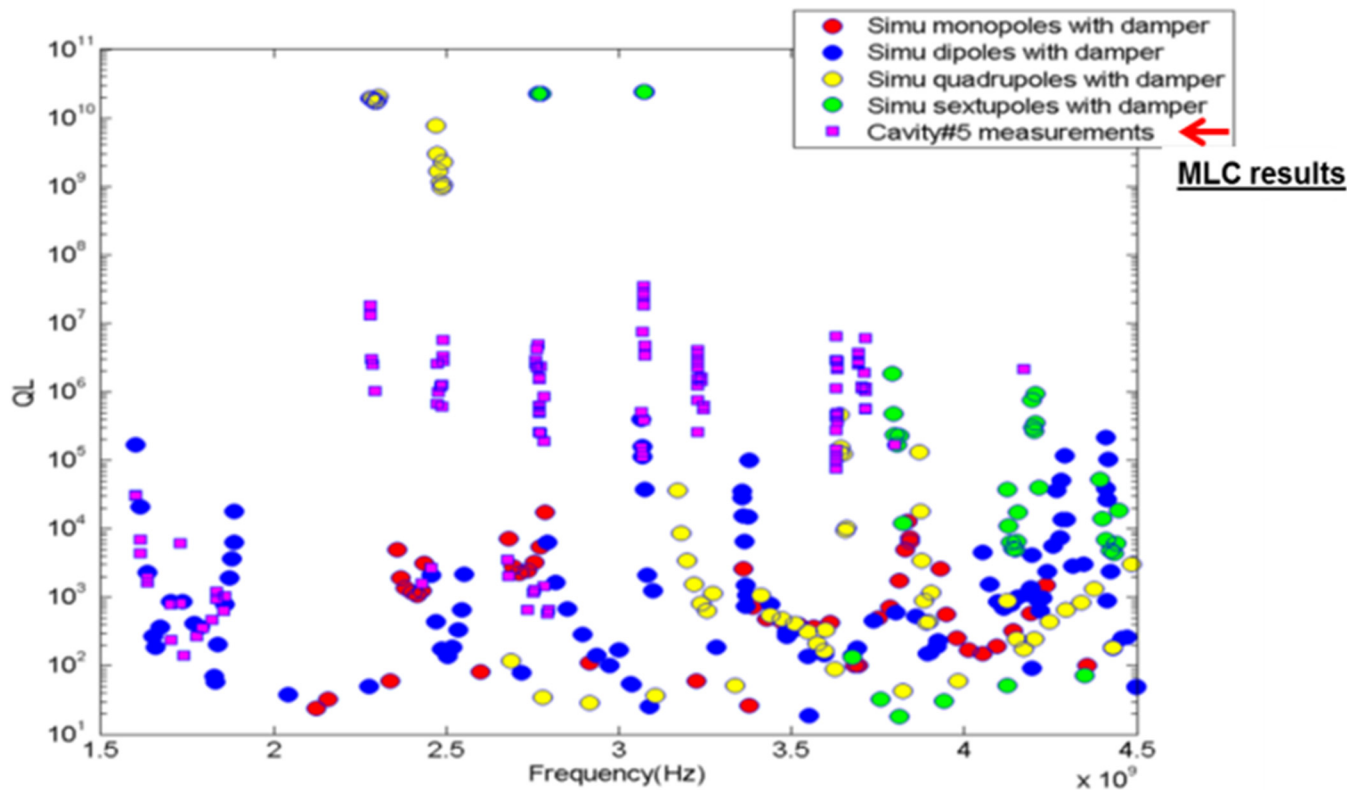
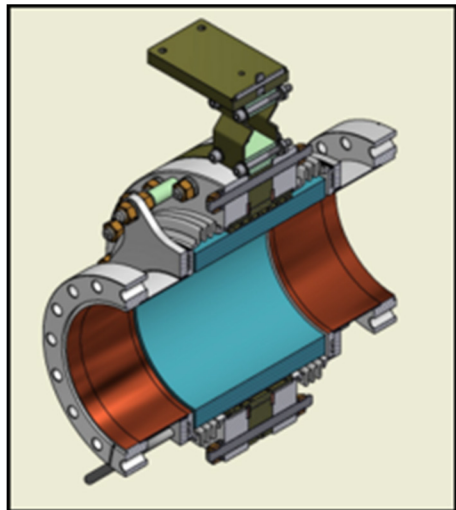


Electron Current up to 320mA in the linac
 Bunch charge Q of up to 2nC
 Bunch repetition rate 1.3GHz/N
 Beams of 100mA for 1 turn and 40mA for 4 turns

CORNELL-BNL ERL TEST ACCELERATOR

42, 78, 114, 150 MeV





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

HTC results were:

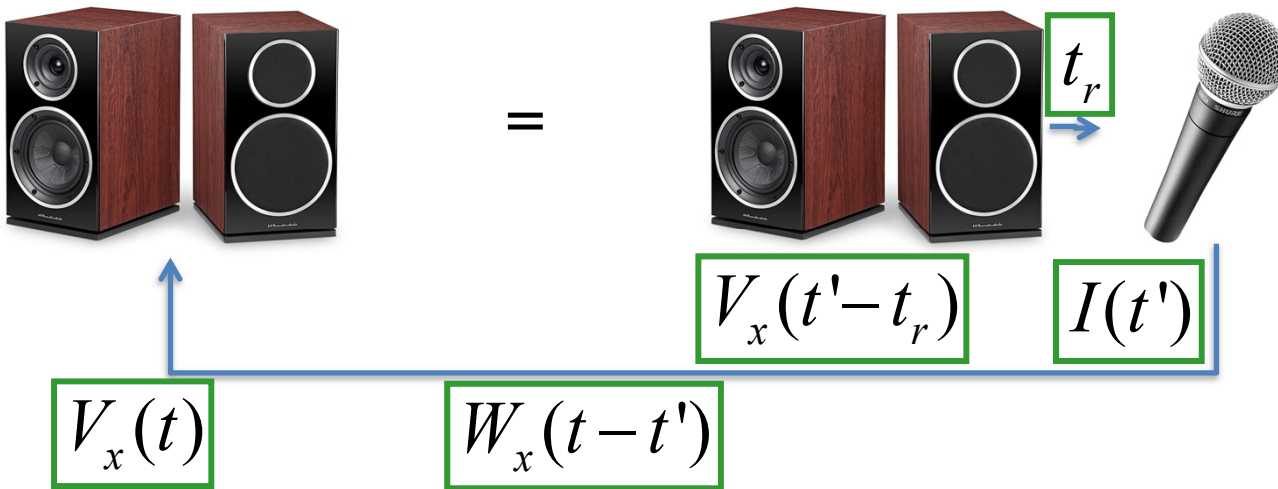
- HOM heating: currents are limited to $< 40\text{mA}$ in CBETA
- BBU no HOM limits BBU to below 100mA in one turn

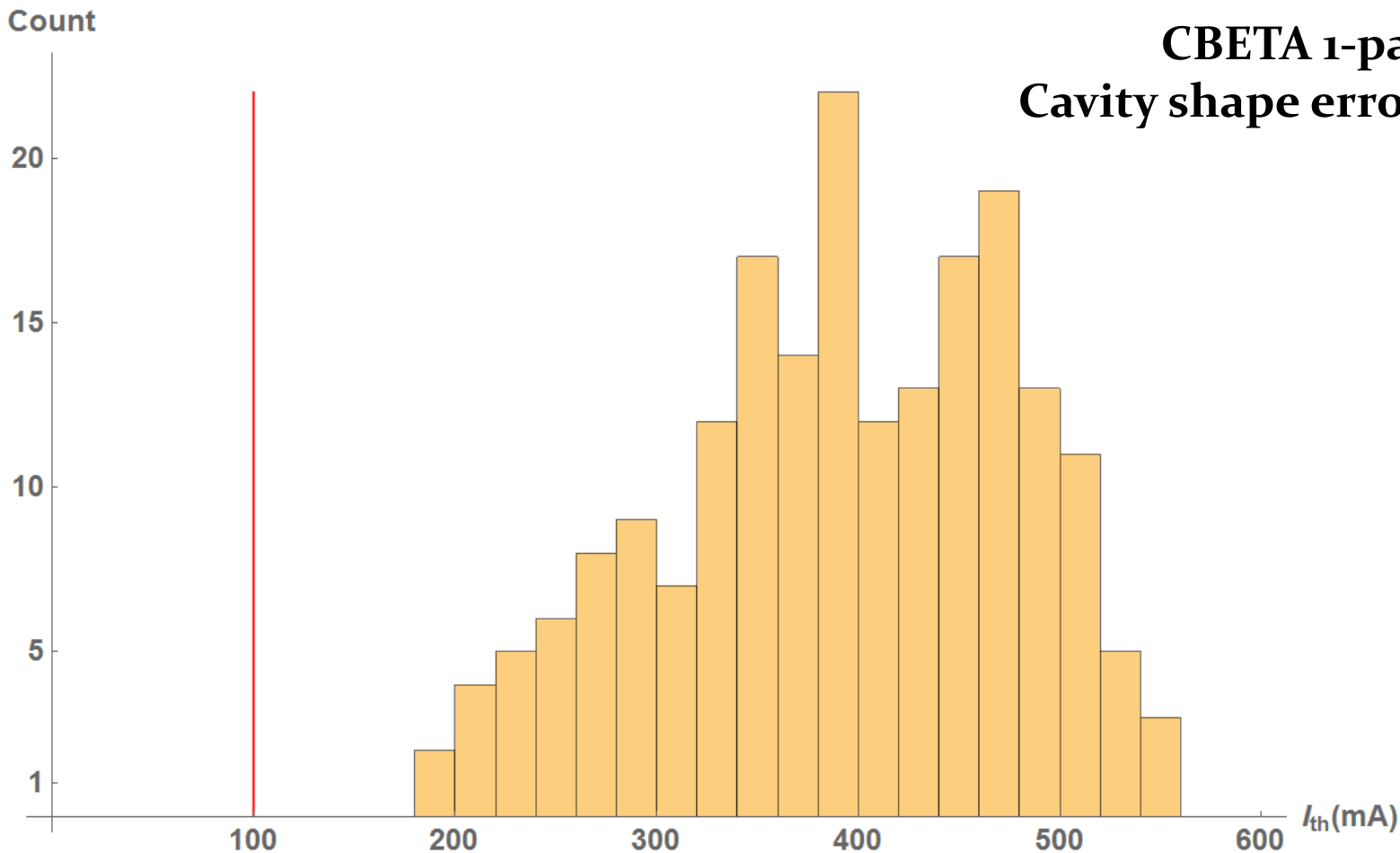
Beam break up: a potential limit to ERL currents

Higher Order Modes

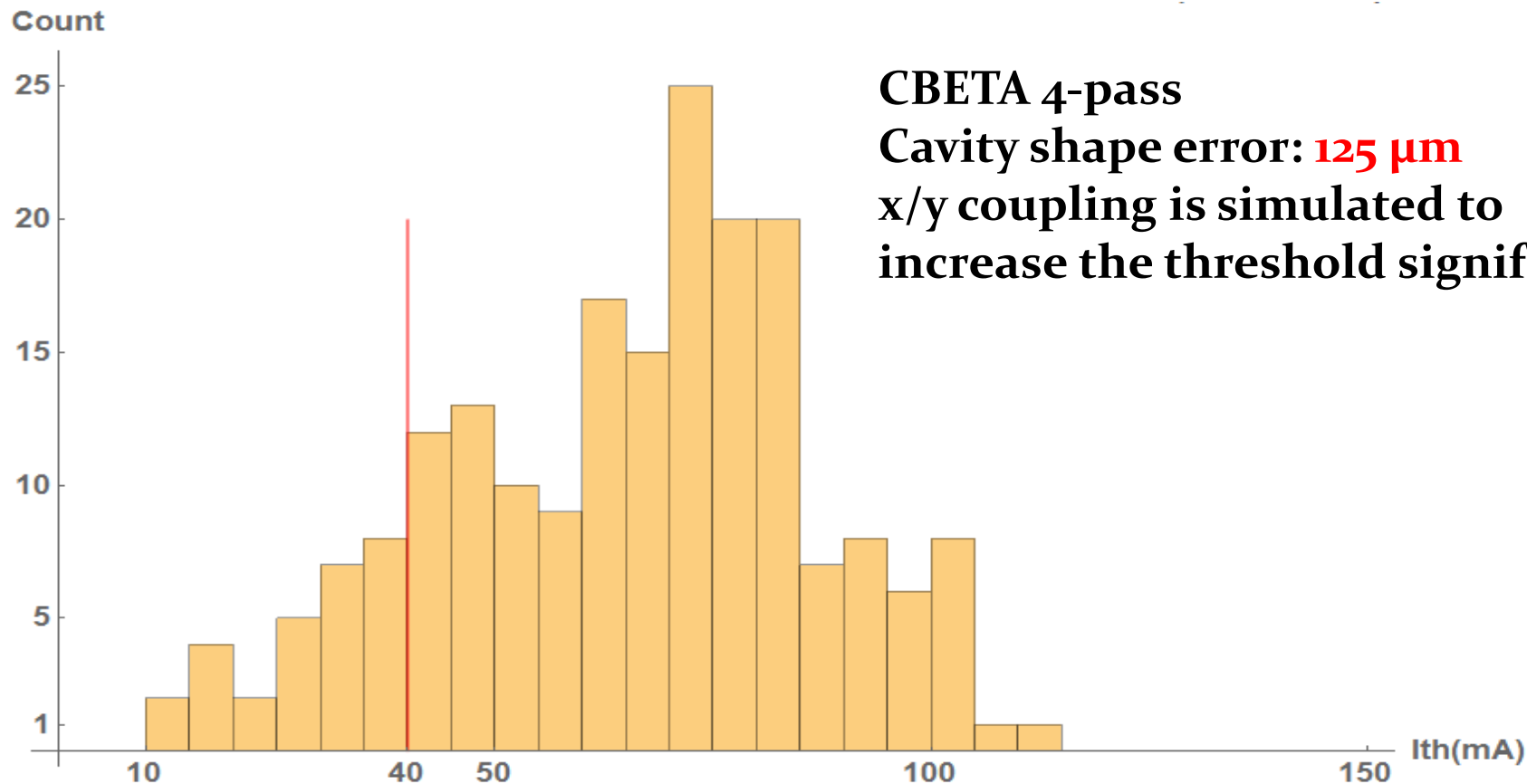


$$V_x(t) = T_{12} \frac{e}{c} \int_{-\infty}^t W_x(t-t') V_x(t'-t_r) I(t') dt'$$





100% of simulations have $I_{th} > 100\text{mA}$

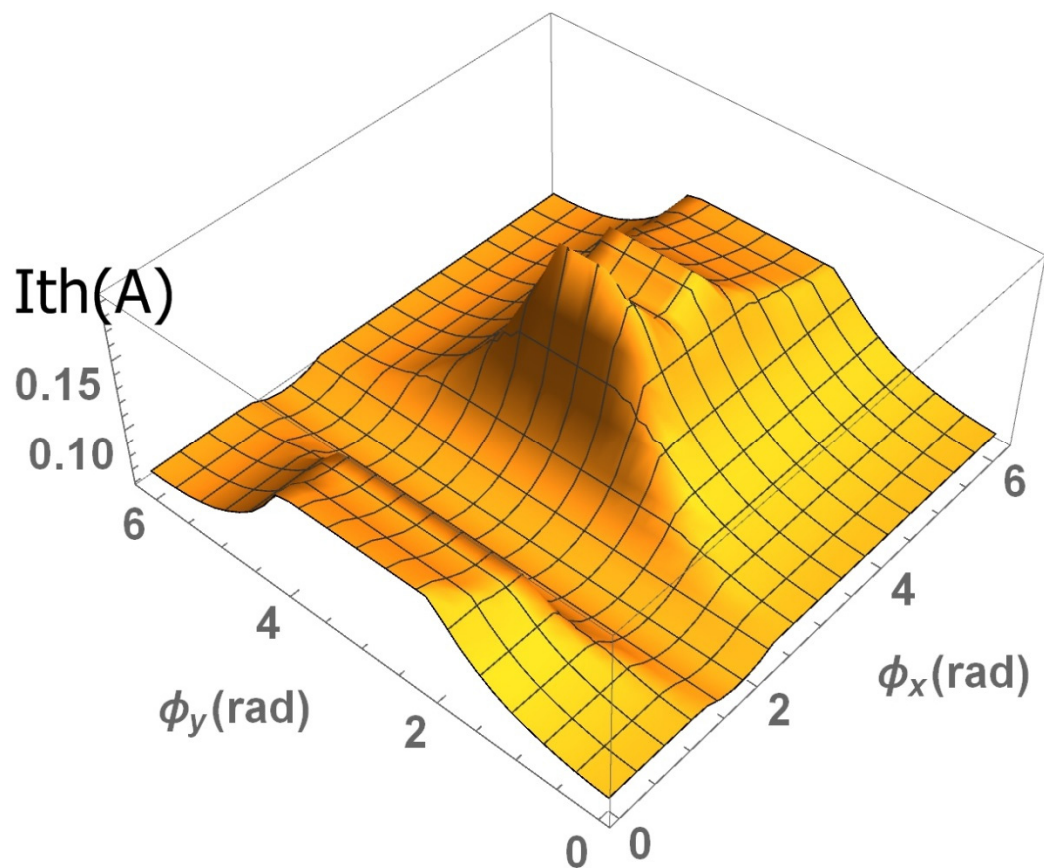


100% of simulations have $I_{th} > 100\text{mA}$

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

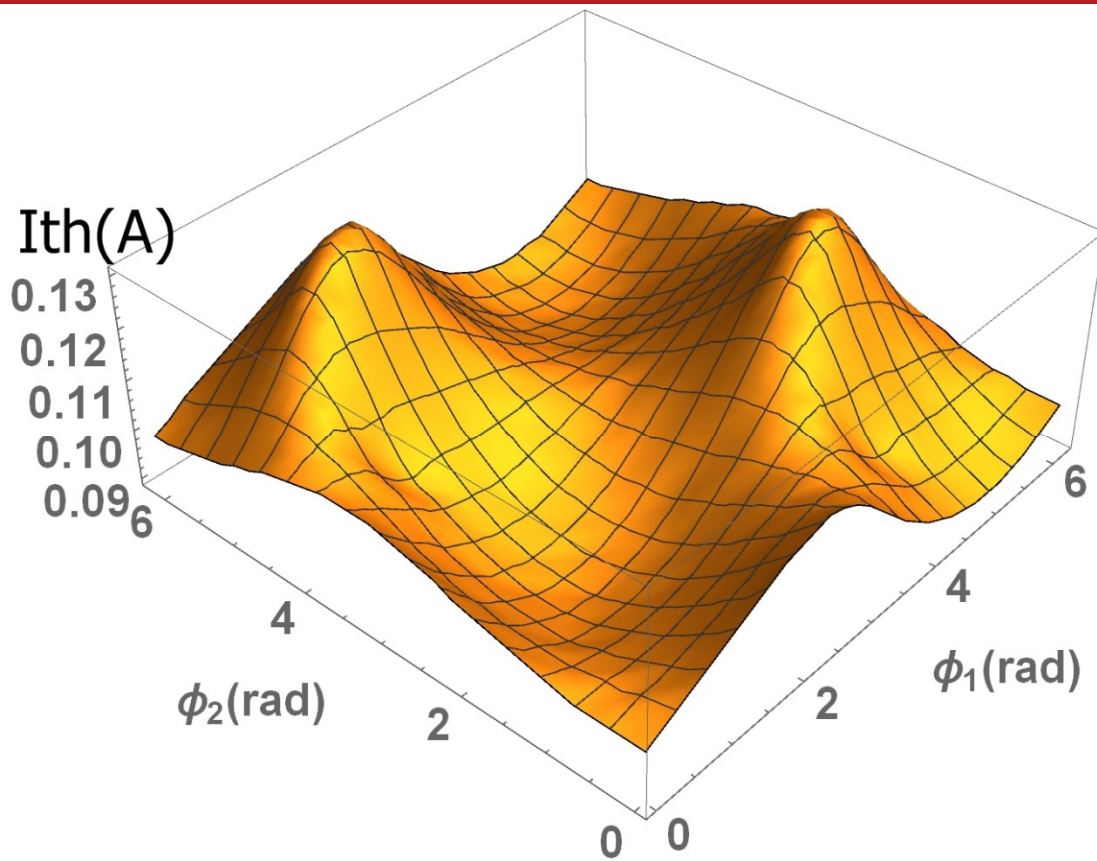


I_{th}



Min = 61 mA
Max = 193 mA
Nominal = 69 mA

I_{th} results can improve



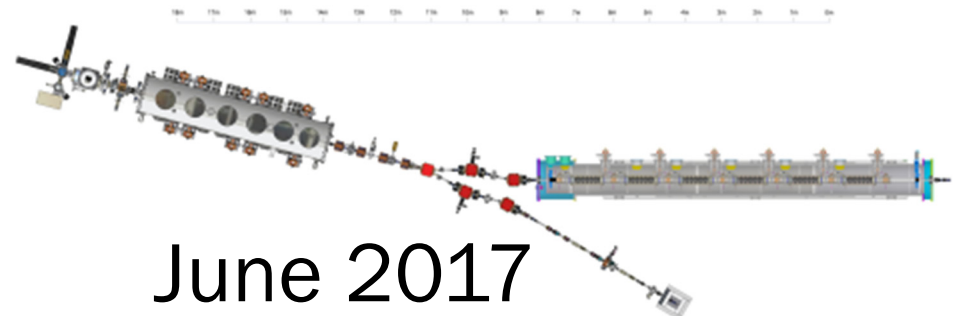
Min = 89 mA
Max = 131 mA
Nominal = 69 mA

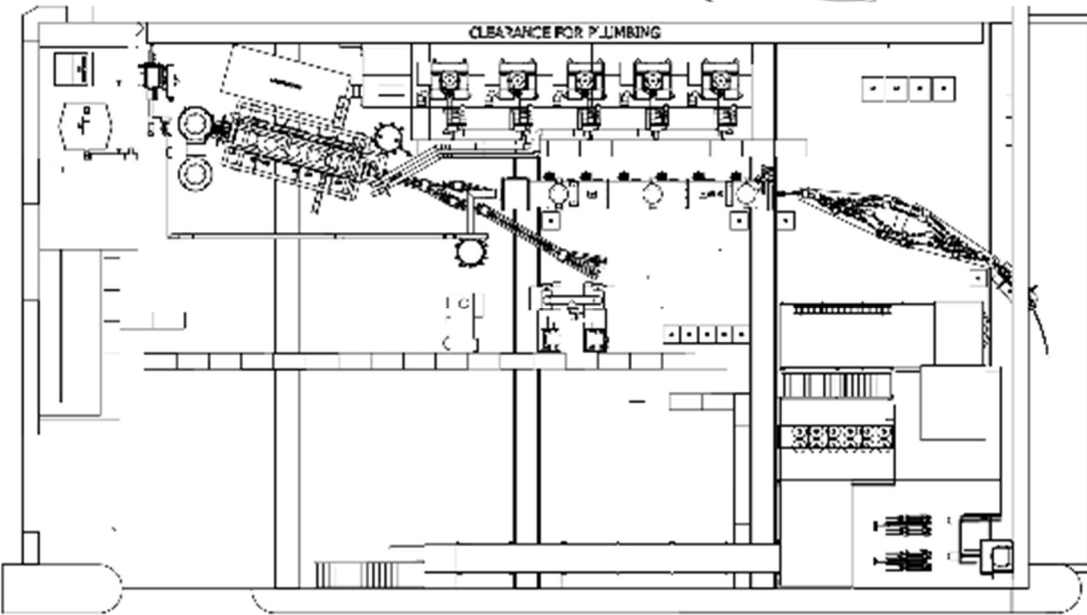
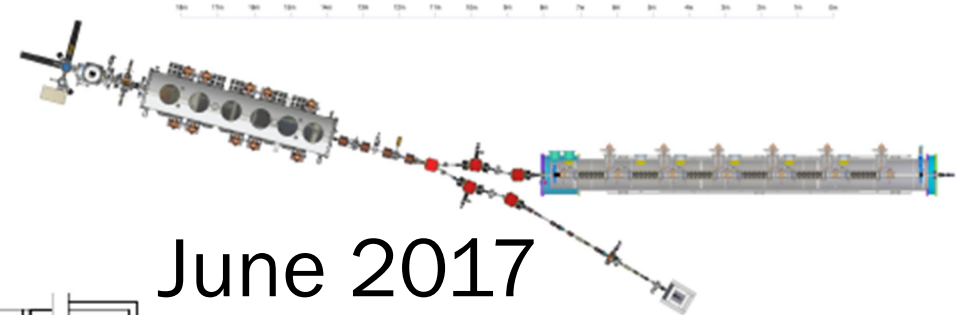
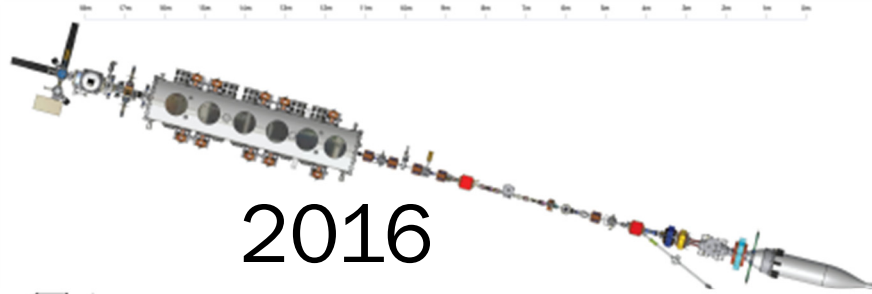
I_{th} results can improve

Conclusion: In 1-path ERLs the benefit from coupling and phase optimization can be significant. In multi-turn ERLs this benefit is much diminished.



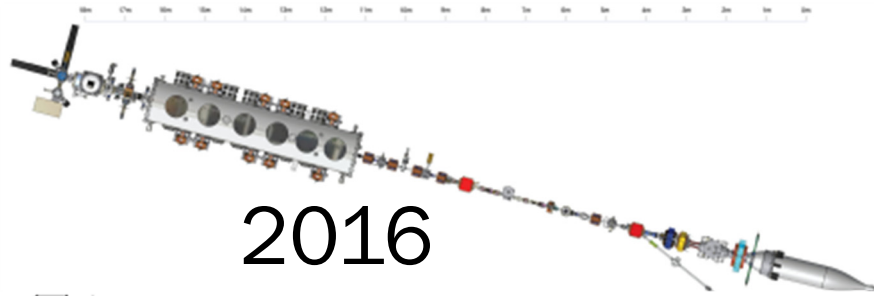
2016



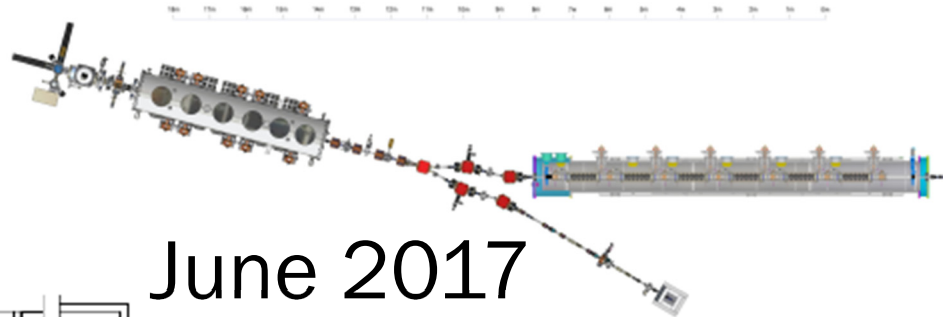


April 2018: FAT

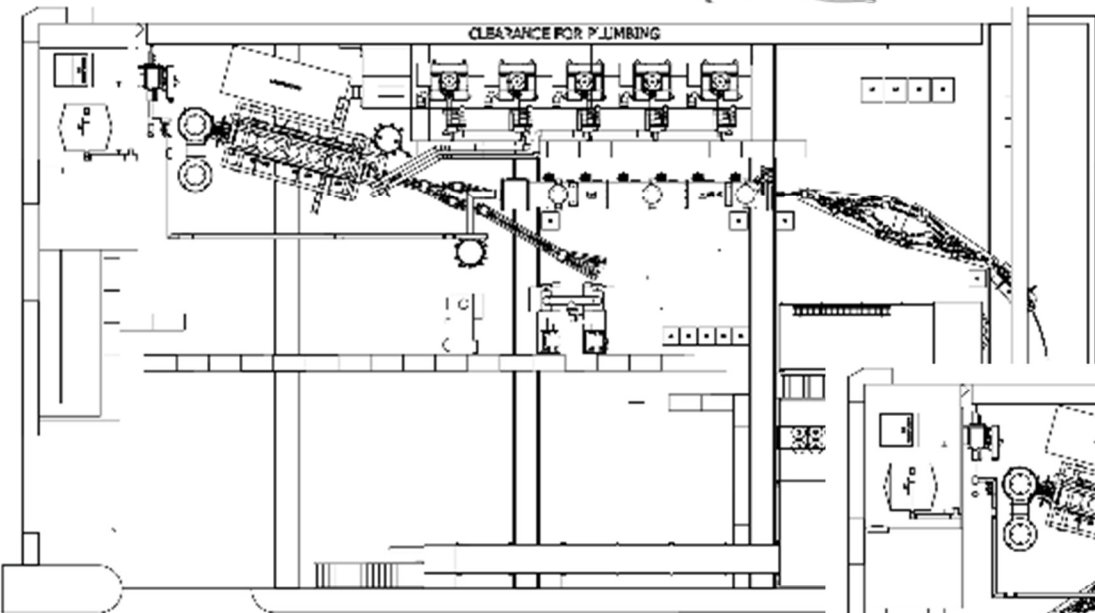
**Push toward 4-turn ERL
until April 2020**



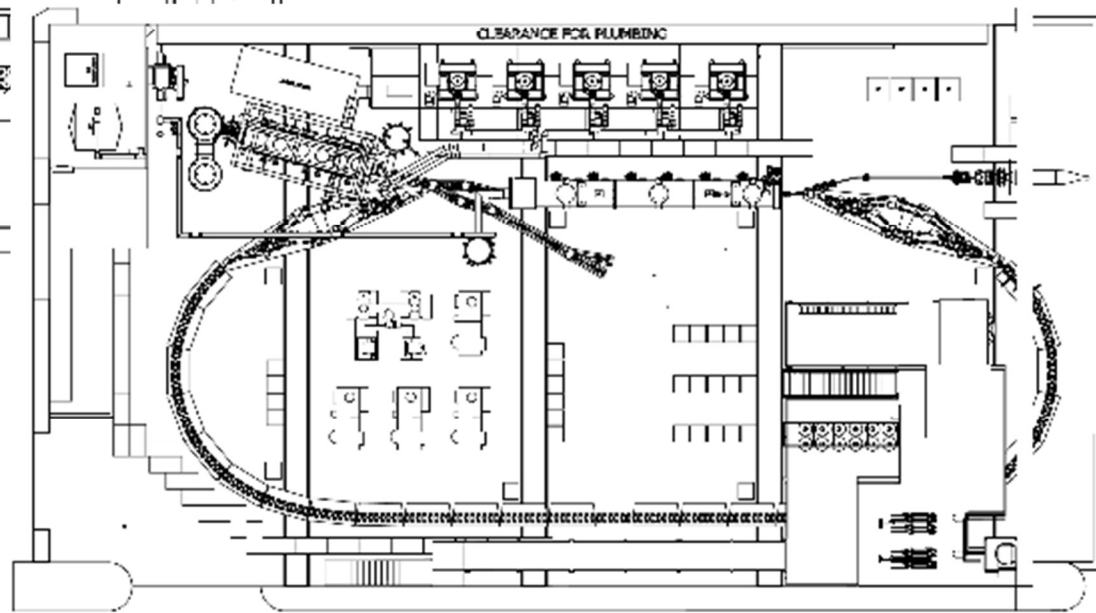
2016



June 2017



April 2018: FAT



August 2019: 1-turn

**Push toward 4-turn ERL
until April 2020**



Questions?