

# FFA Return Loop in the 4-turn ERL CBETA

Georg Hoffstaetter (Cornell)  
presented by Scott Berg (BNL)



**CBETA**  
CORNELL-BNL ERL TEST ACCELERATOR

**BROOKHAVEN**  
NATIONAL LABORATORY  
*a passion for discovery*



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

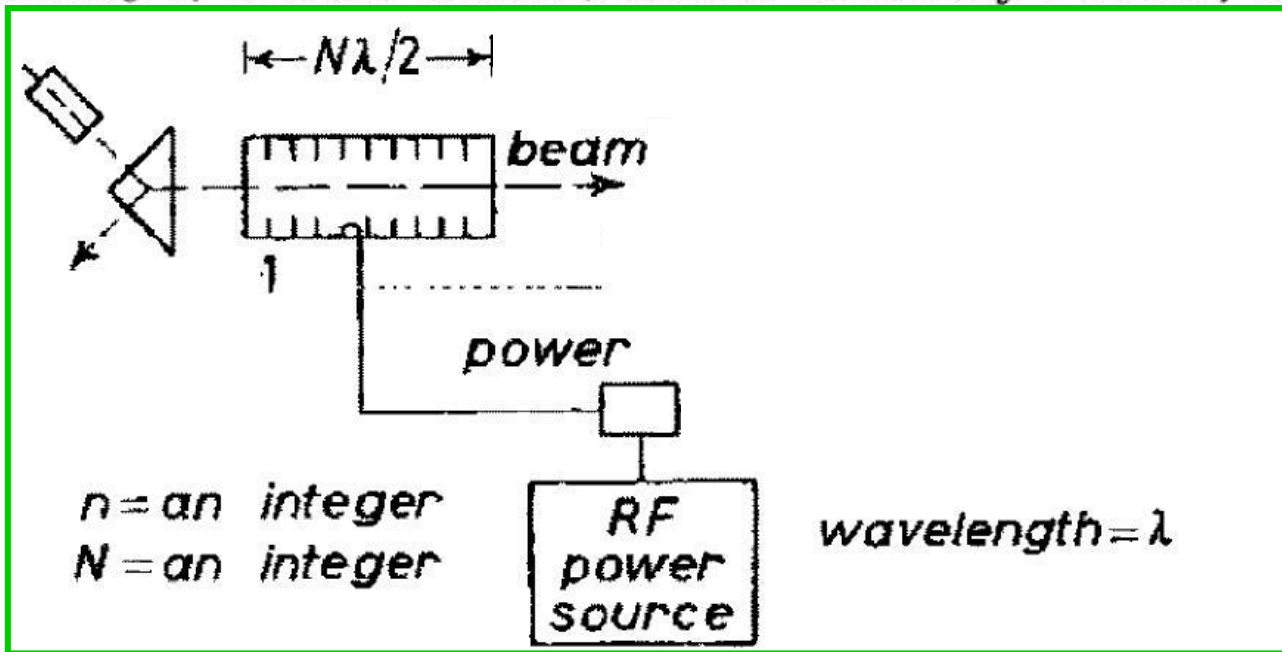
[Georg.Hoffstaetter@cornell.edu](mailto:Georg.Hoffstaetter@cornell.edu)



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

M. TIGNER

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

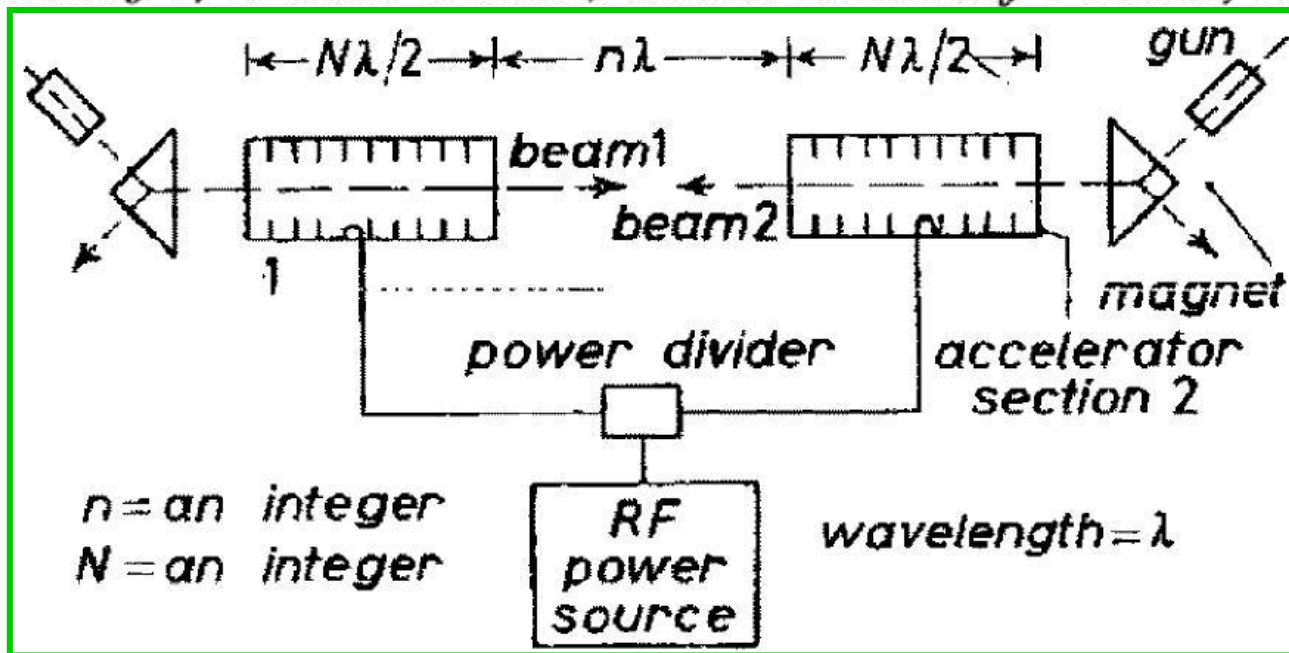


- Linacs produce **very high bunch quality** (narrow, short, low energy spread)
- Remaining beam energy is discarded (wasted energy).

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

M. TIGNER

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

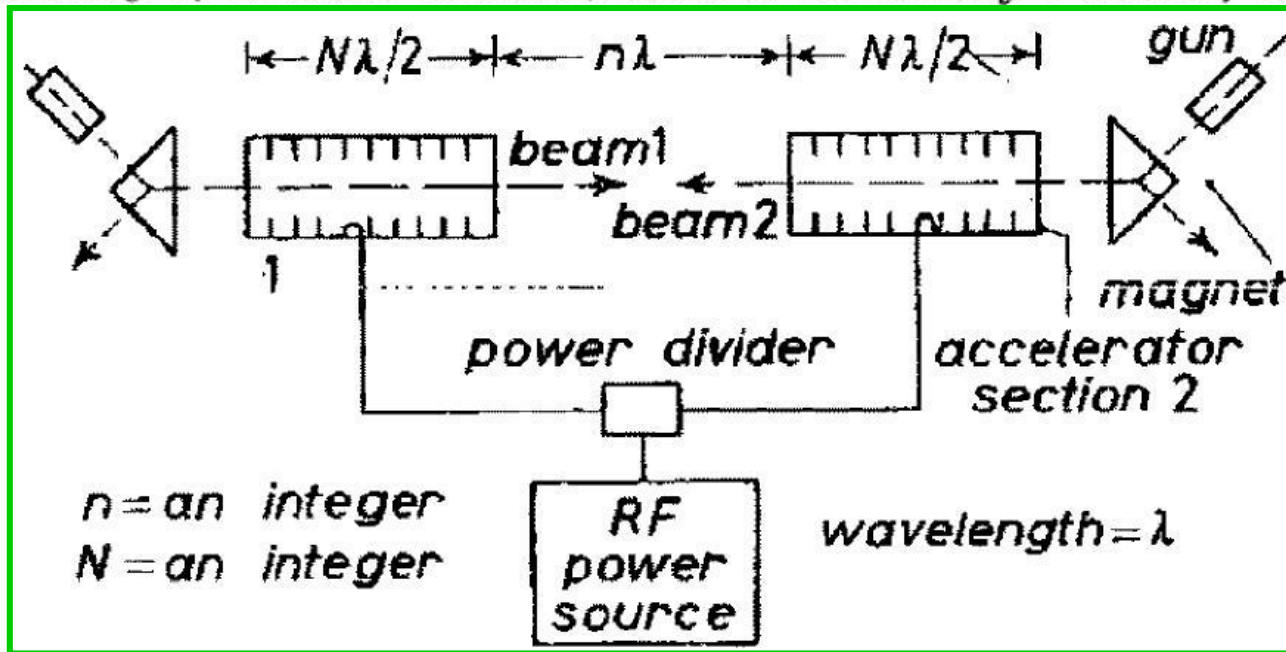


- Energy Recovery Linacs recapture the beam power in Super-Conducting (SRF) Accelerating structures to accelerate more beam.
- This energy saving allows for **unprecedented beam powers** from Linacs.

## 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.



Under Cornell PI ship (Sol Gruner and Georg Hoffstaetter):

- 2005 Start of construction of DC photo-emitter gun; to world record current (75mA)
- 2012 PD-Design Report on a hard x-ray 5GeV ERL; no construction.
- 2013 Achieved world record brightness

Under joint PI ship of Cornell (Georg Hoffstaetter) and BNL (Dejan Tobojevic):

- 2014 White paper for CBETA with collaborators at BNL.
- 2016 Construction funding by NYS begins.
- 2017 CBETA Design Report
- 2018 1<sup>st</sup> beam thorough SRF chain, one separator and one PMA unit.

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

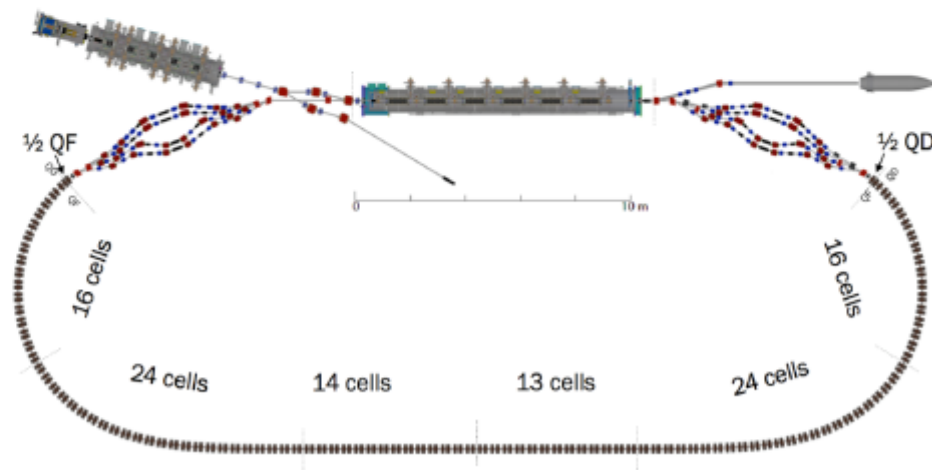
## CBETA Design Report

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



Under Cornell PI ship (Sol Gruner and Georg Hoffstaetter):

- 2005 Start of construction of DC photo-emitter gun; to world record current (75mA)
- 2012 PD-Design Report on a hard x-ray 5GeV ERL; no construction.
- 2013 Achieved world record brightness

Under joint PI ship of Cornell (Georg Hoffstaetter) and BNL (Dejan Tobojevic):

- 2014 White paper for CBETA with collaborators at BNL.
- 2016 Construction funding by NYS begins.
- 2017 CBETA Design Report
- 2018 1<sup>st</sup> beam thorough SRF chain, one separator and one PMA unit.

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

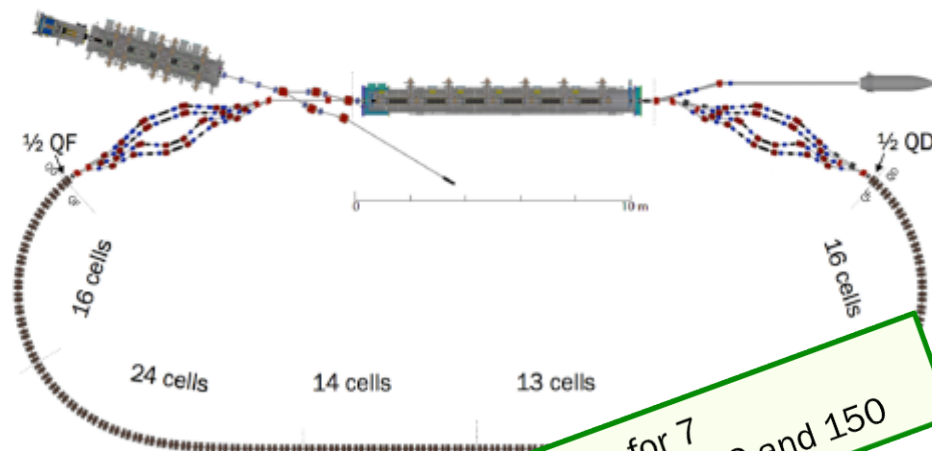
## CBETA Design Report

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



Note the FFAG return loop for 7 simultaneous beams between 42 and 150 MeV!



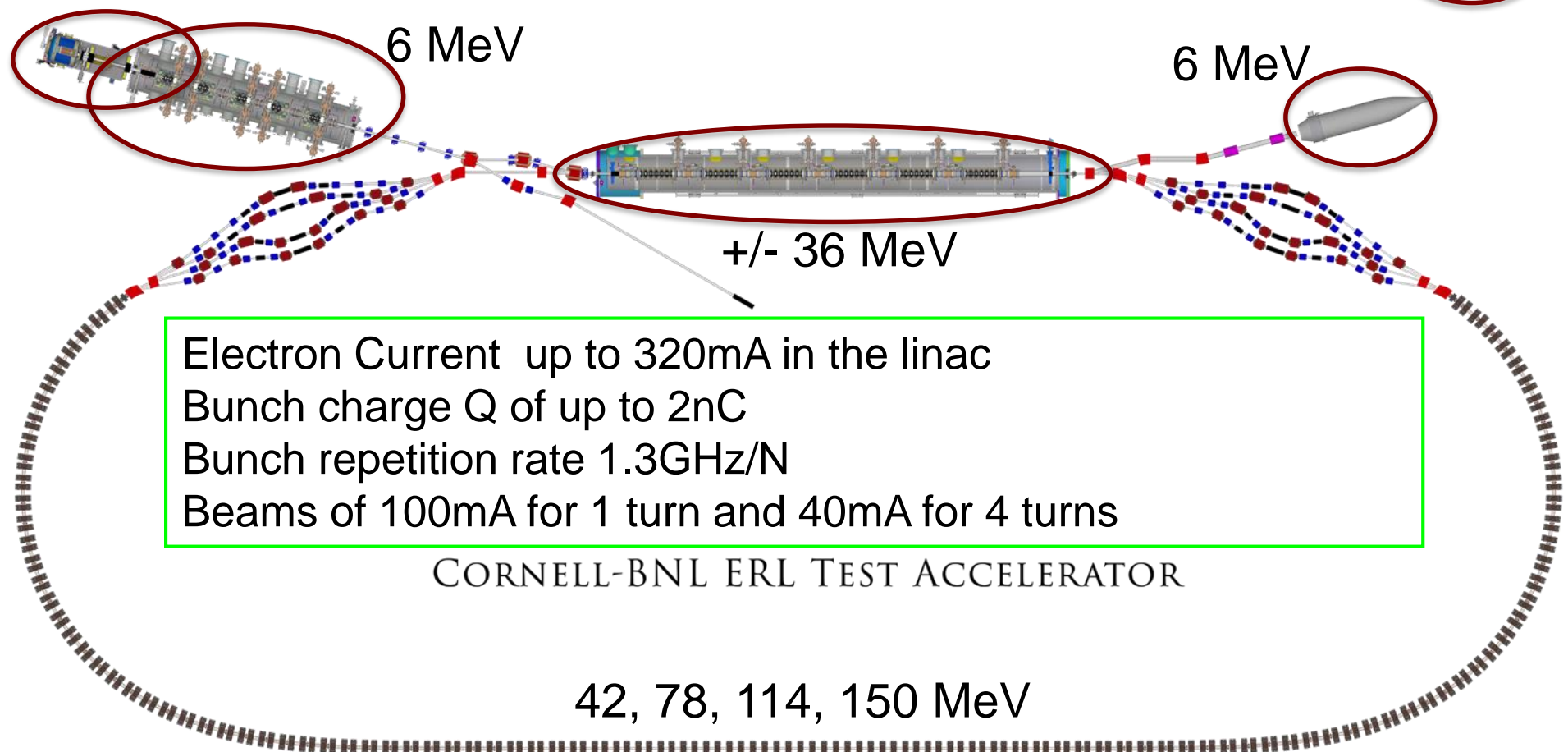
CBETA study of beam dynamics important for eRHIC:

- 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.**
  - e) **Beam parameters of EIC electron coolers**



- 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

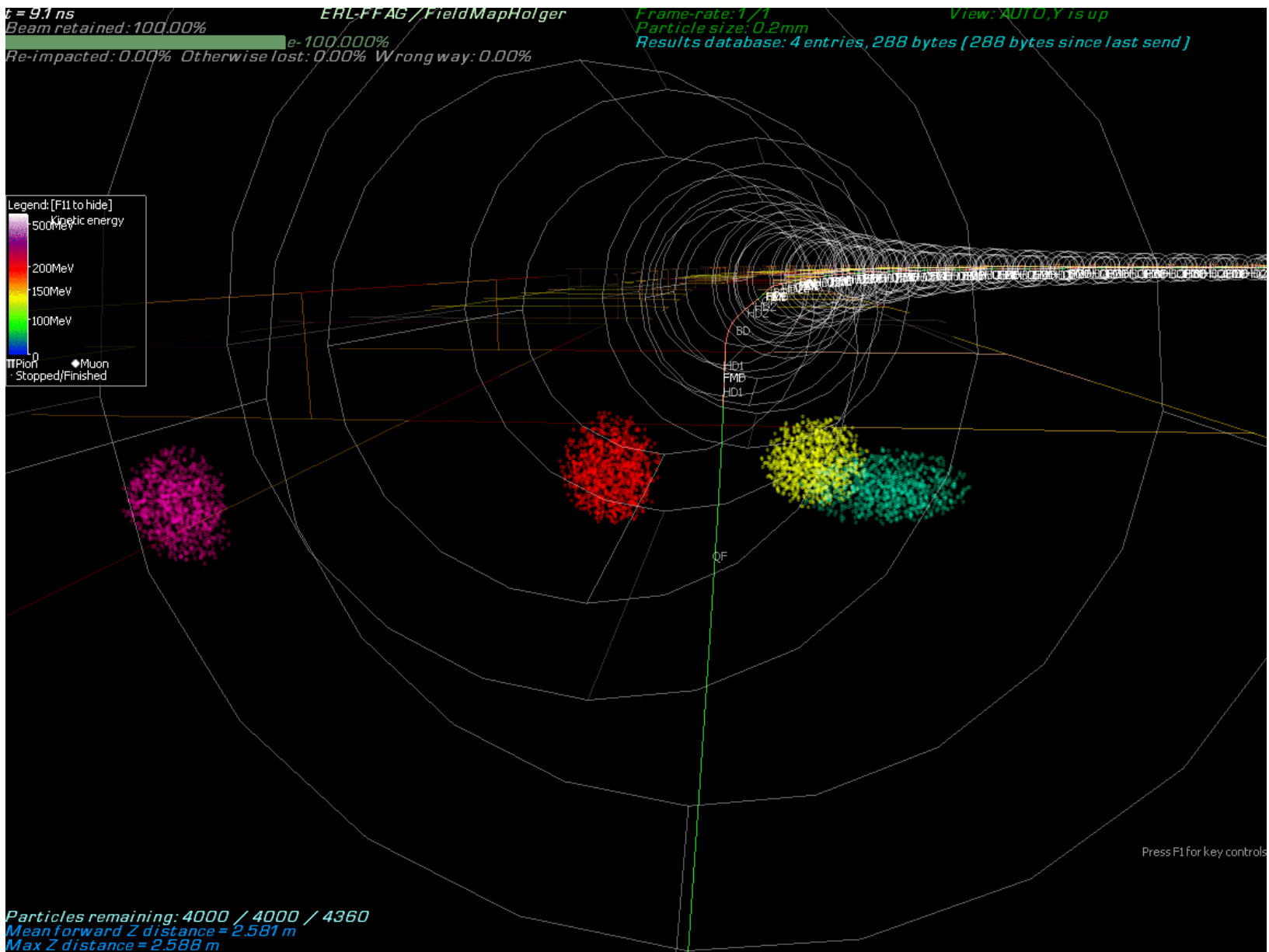
CORNELL-BNL ERL TEST ACCELERATOR

42, 78, 114, 150 MeV





<b>Parameter</b>	<b>Unit</b>	<b>KPP</b>	<b>UPP (Stretch)</b>
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





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

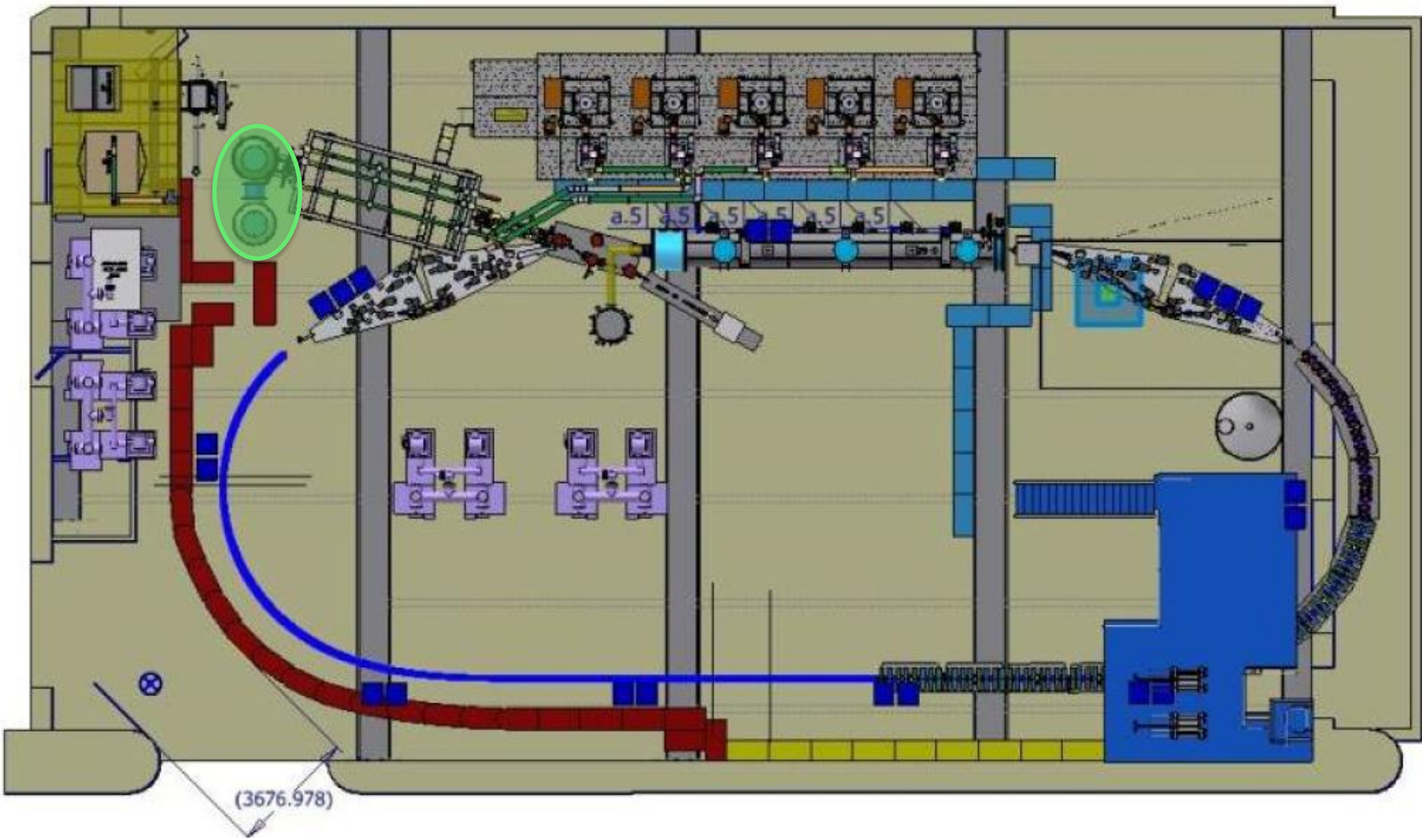


*70% of the existing technical-use space was removed for the initial phase*

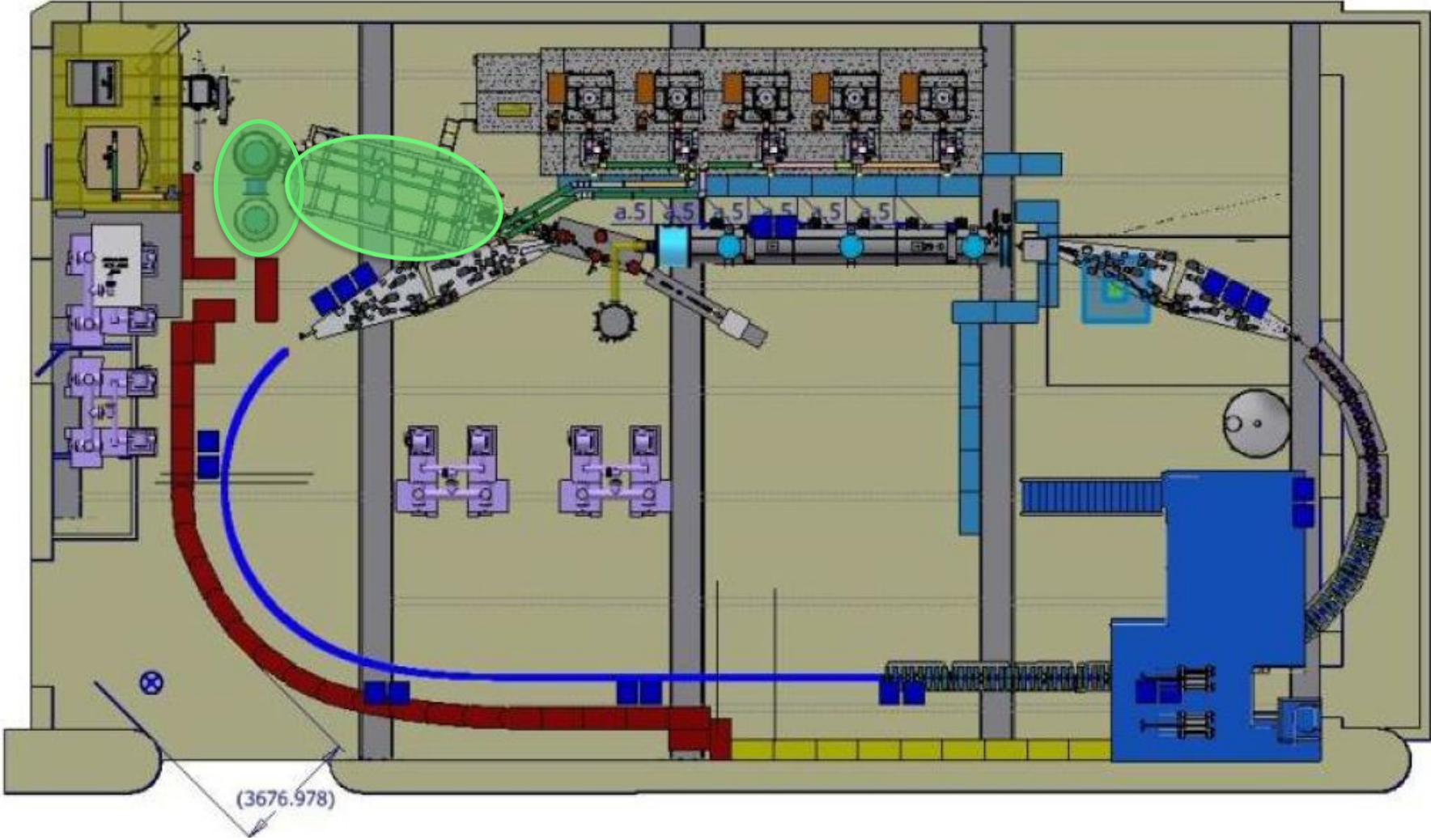




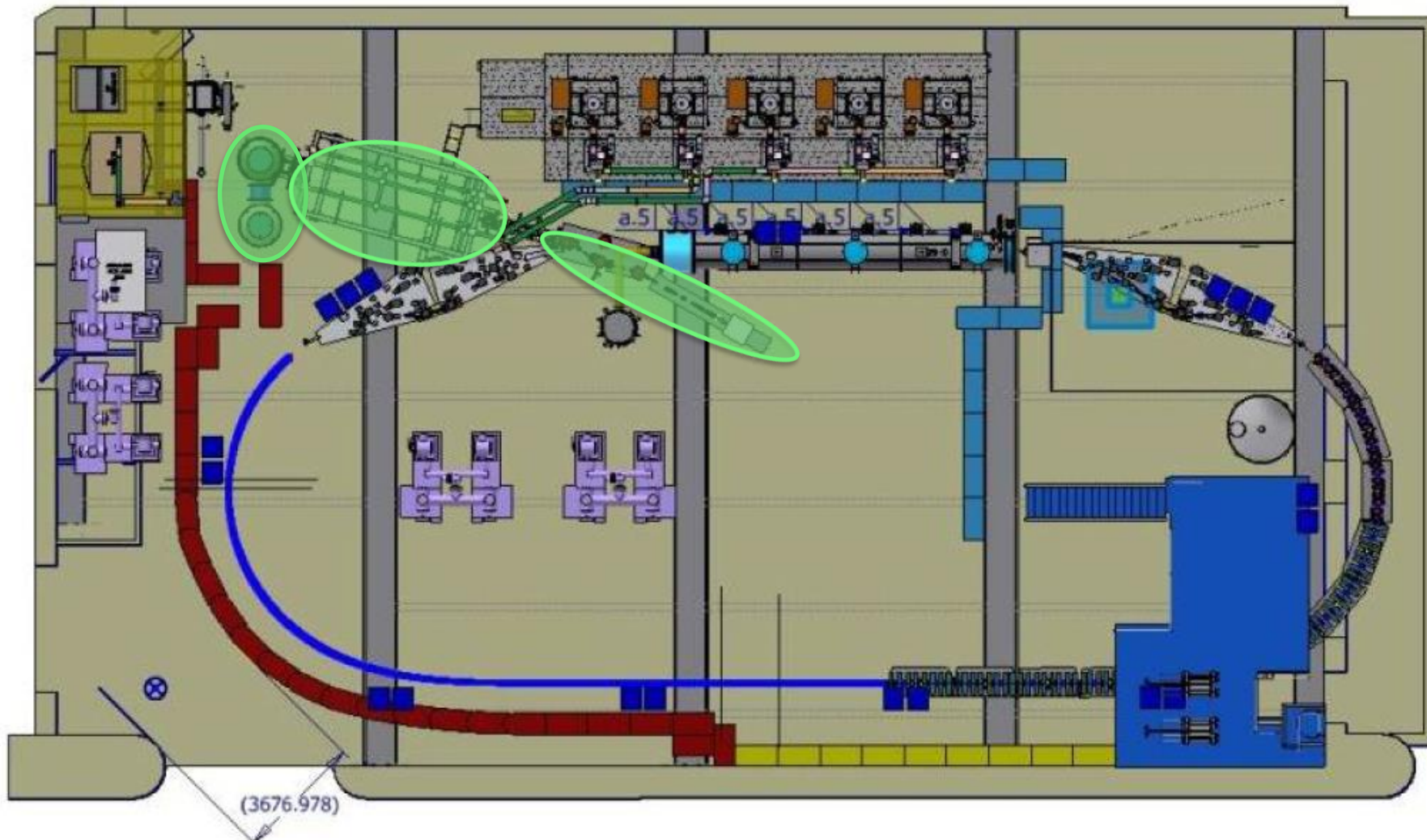
Installed: DC gun



Installed: DC gun, SRF injector

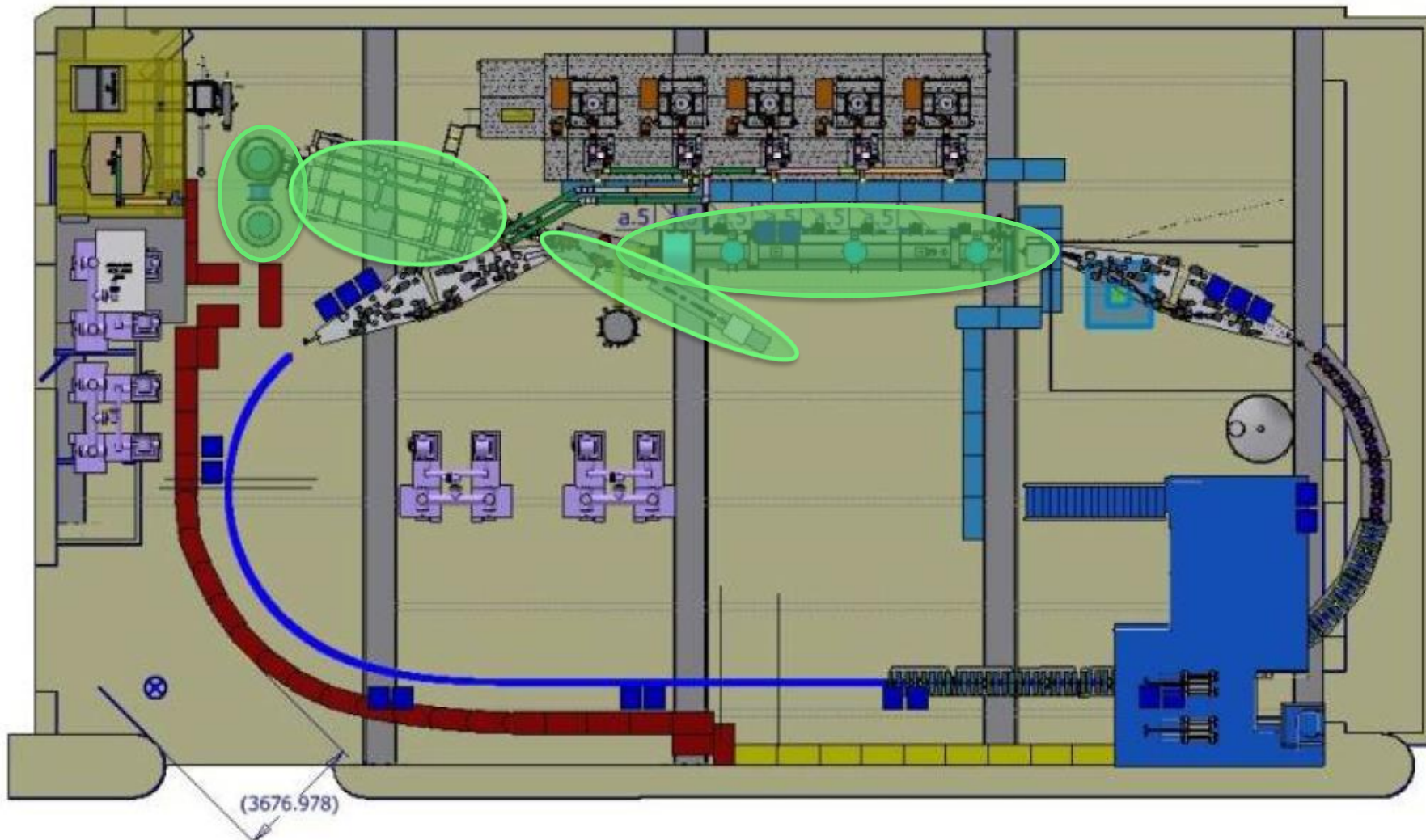


Installed: DC gun, SRF injector, mirror diagnostics line

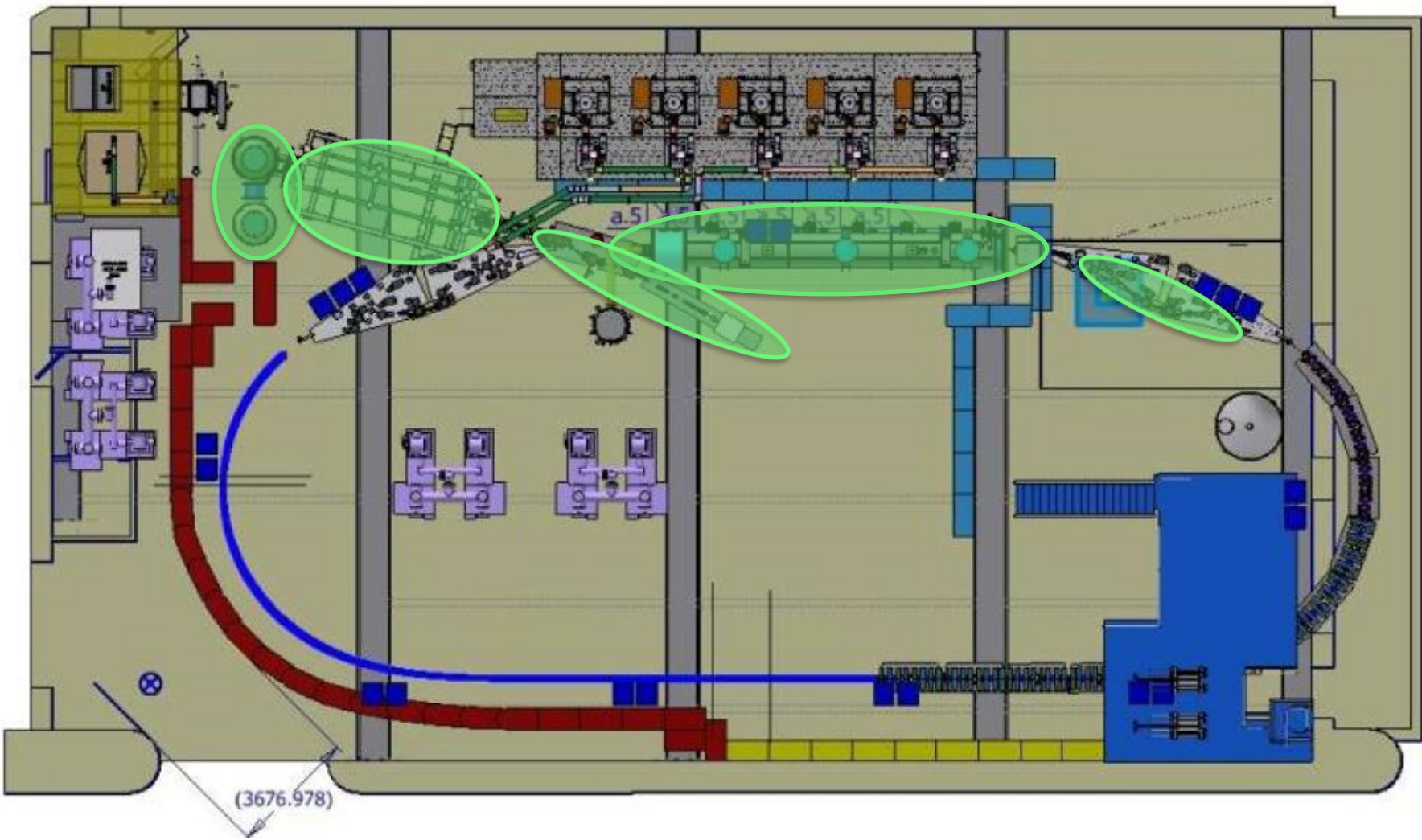




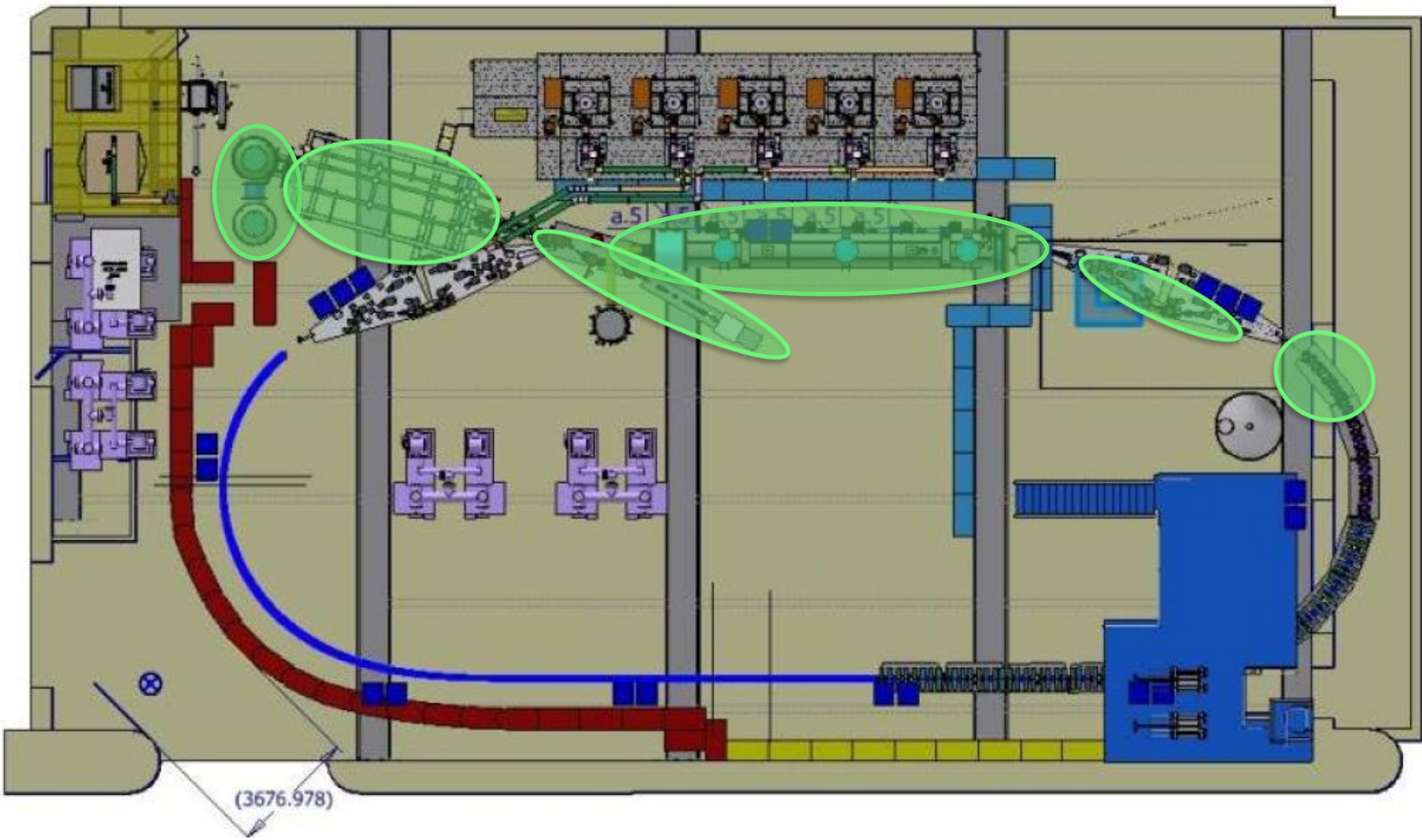
Installed: DC gun, SRF injector, mirror diagnostics line, ERL cryomodule



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



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





## CERN COURIER



ADVANCED DIAGNOSTICS  
FOR CHARGED PARTICLE BEAMS

Latest Issue | **Archive** | Jobs | Links | Buyer's guide | White papers | Events | Contact us

Search

### LATEST CERN COURIER ARTICLES

- ▶ Beams back in LHC for final phase of Run 2
- ▶ DESY sets out vision for the future
- ▶ Gamma-ray lasing
- ▶ First hints of ultra-rare kaon decay
- ▶ Antihydrogen spectroscopy enters precision era

### SHARE THIS

- E-mail to a friend
- StumbleUpon
- Twitter
- Facebook
- CiteUlike

SHARE

### RELATED PRODUCTS

### 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

### DIGITAL EDITION

CERN Courier is now available as a regular digital edition. **Click here** to read the digital edition.

### KEY SUPPLIERS

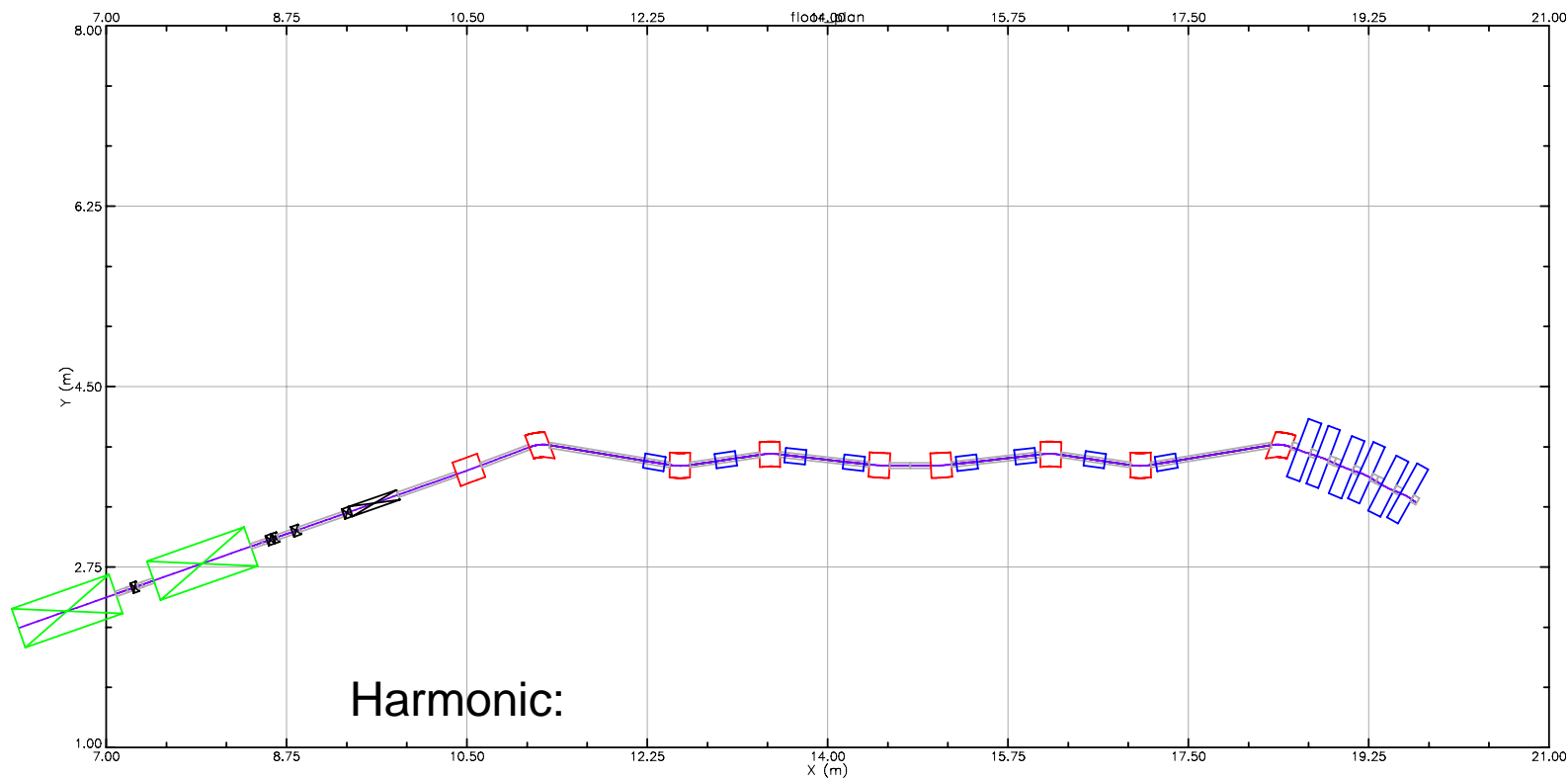
HuihongFiber



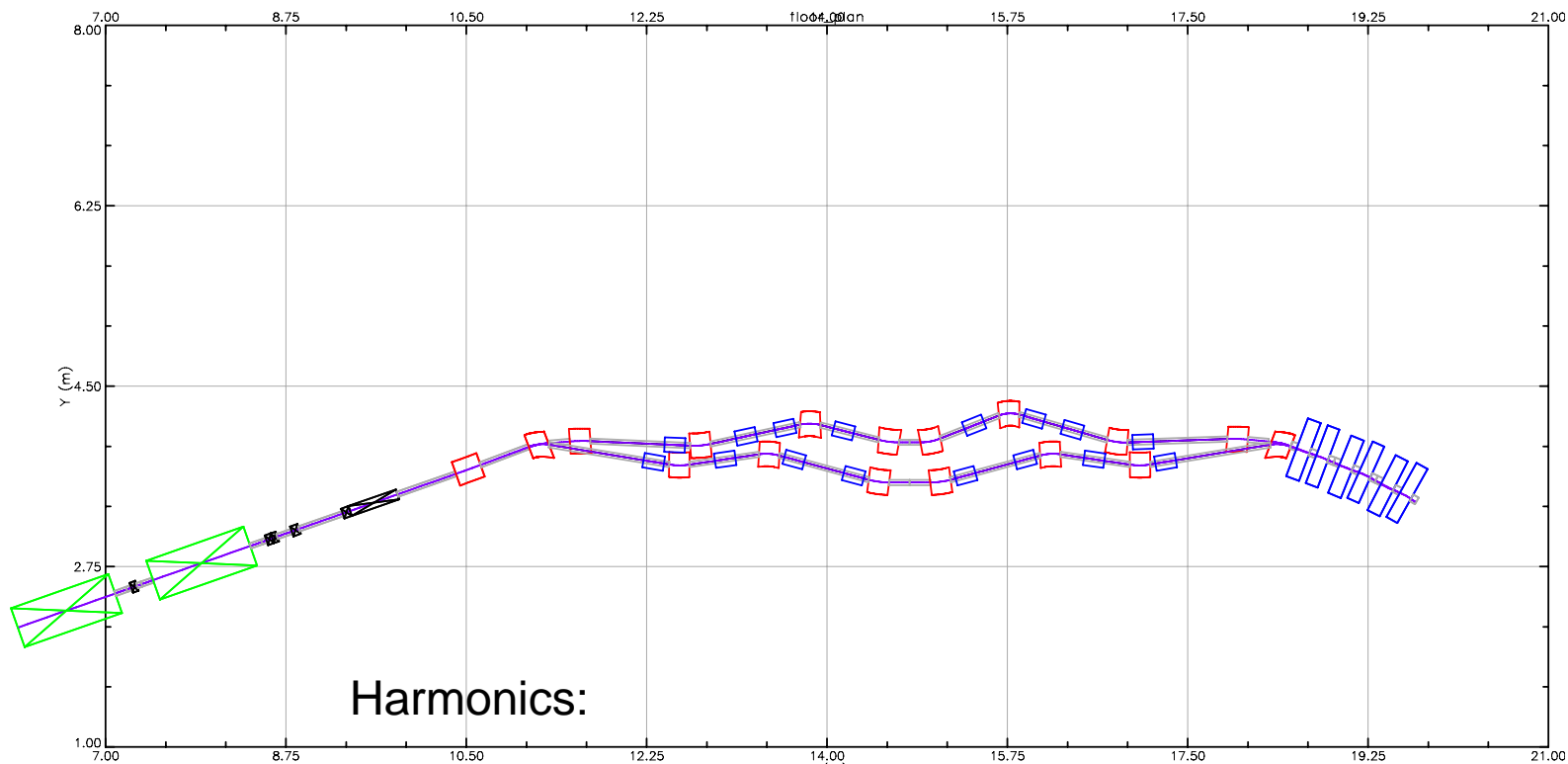
More companies ▶

### FEATURED COMPANIES



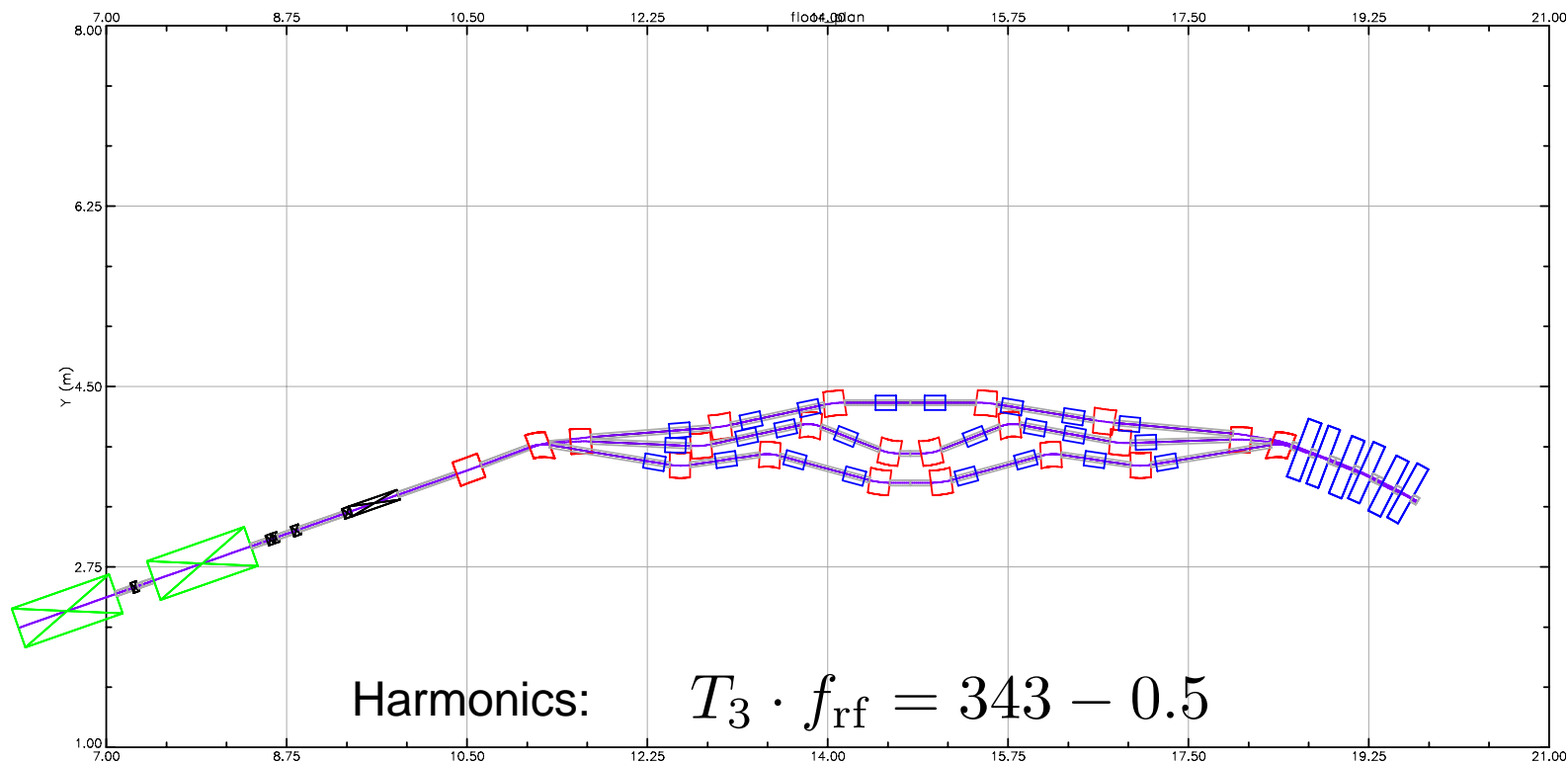


$$T_1 \cdot f_{\text{rf}} = 343 - 0.5$$



$$T_2 \cdot f_{\text{rf}} = 343 - 0.5$$

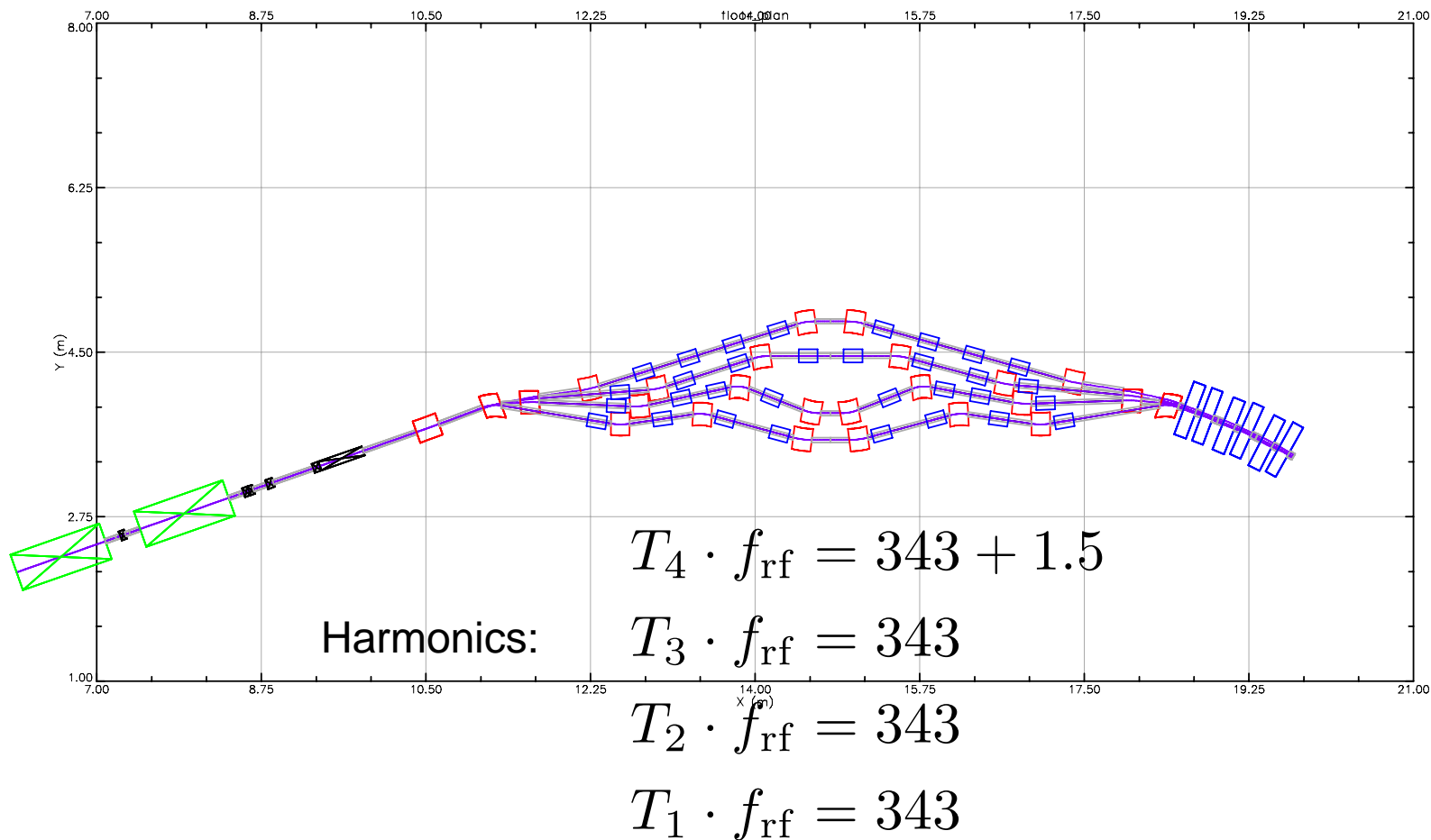
$$T_1 \cdot f_{\text{rf}} = 343$$



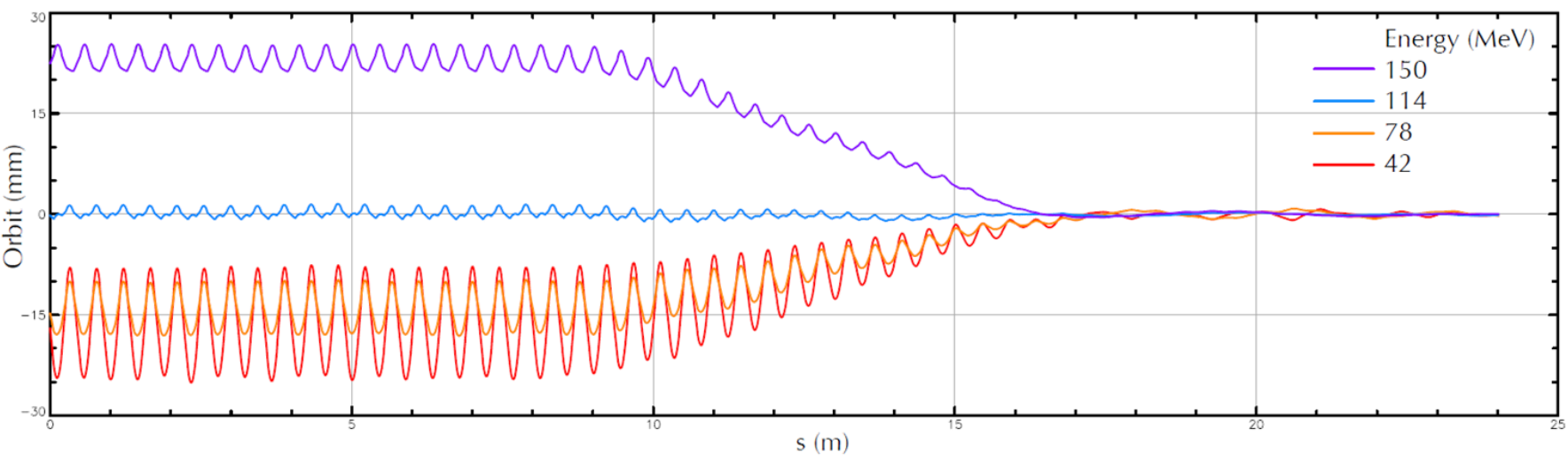
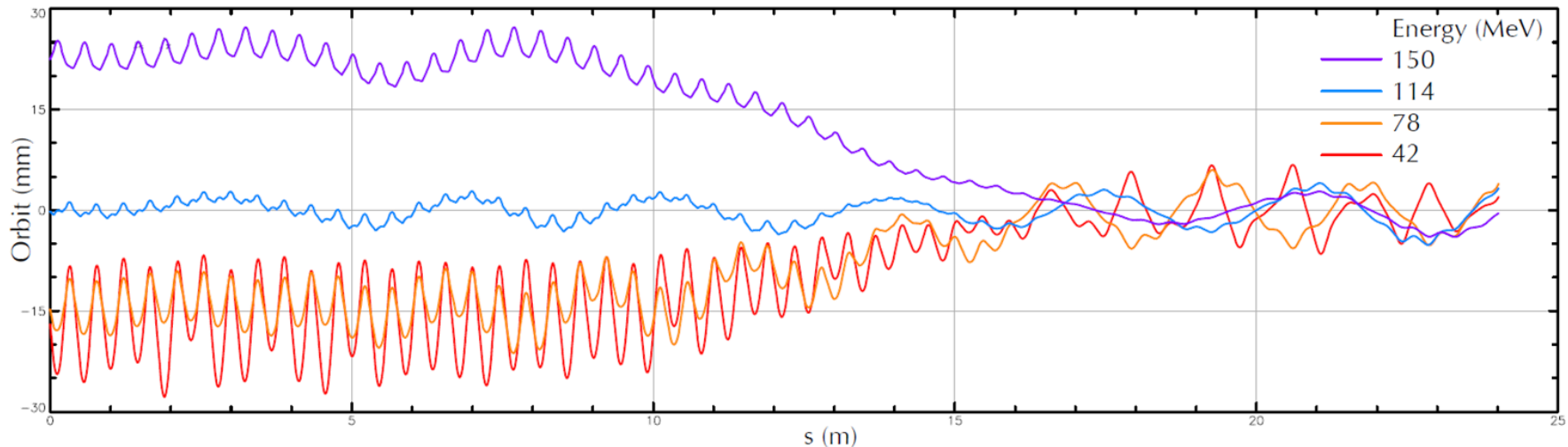
Harmonics:  $T_3 \cdot f_{\text{rf}} = 343 - 0.5$

$T_2 \cdot f_{\text{rf}} = 343$

$T_1 \cdot f_{\text{rf}} = 343$







Courtesy C. Mayes



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

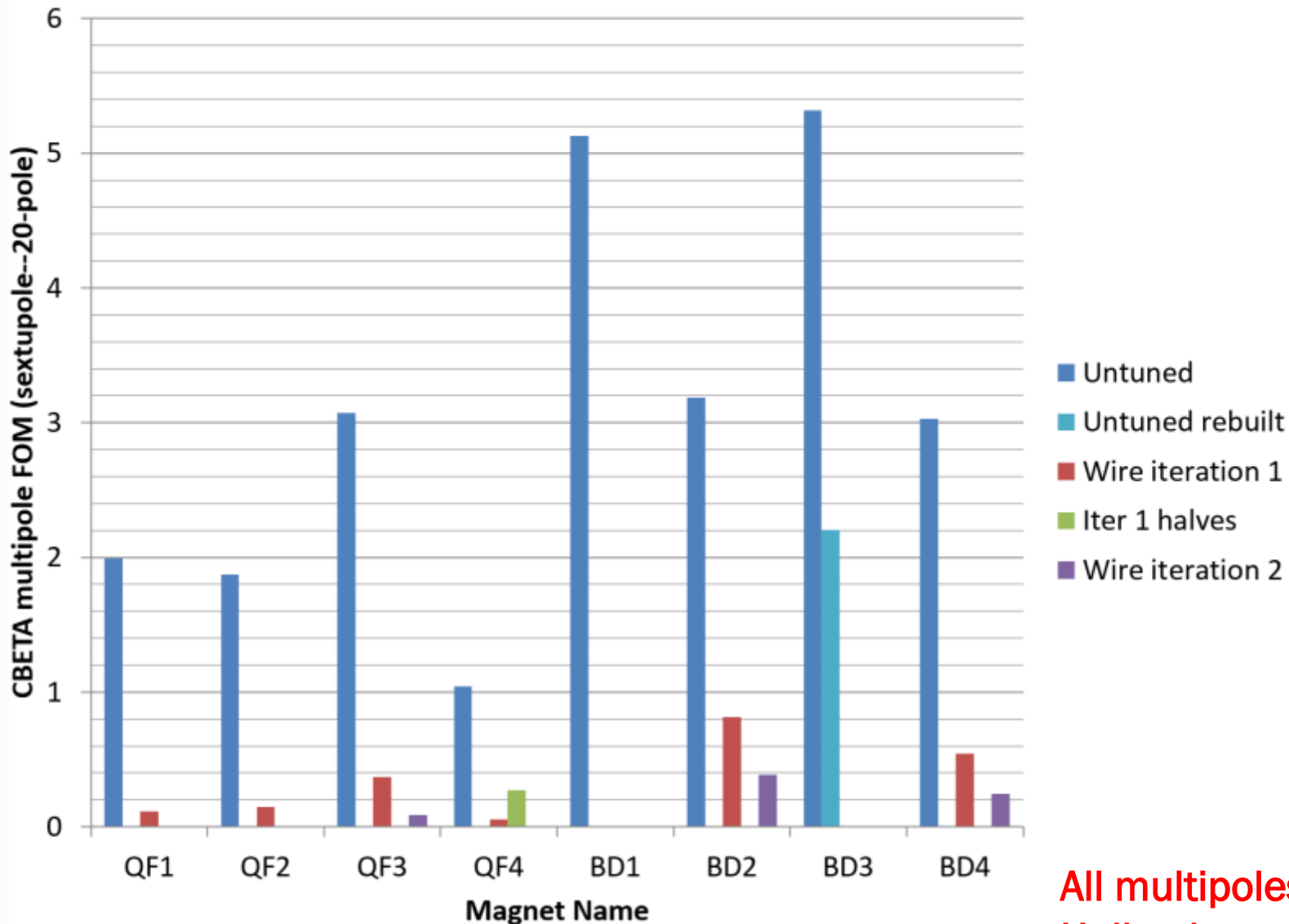
$$B_x + iB_y = \frac{b_n + ia_n}{L} (x + iy)^n$$

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

## Multipole limits:

For  $< 10\%$  emittance and beam-size growth

$$\sqrt{\sum_n \left( \frac{b_n}{\lim\_b_n} \right)^2 + \left( \frac{a_n}{\lim\_a_n} \right)^2} < 0.75$$



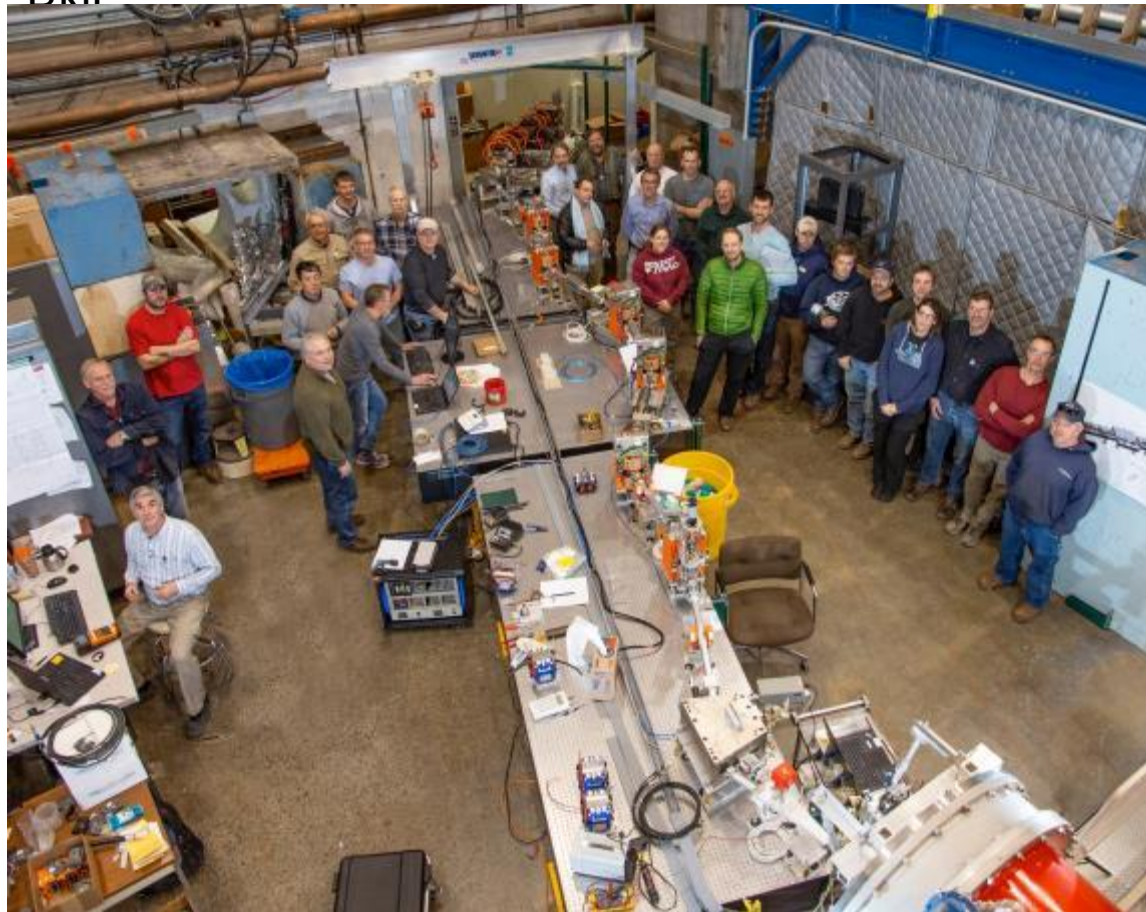
**All multipoles of the Halbach magnets can be corrected as required.**





We are forming a **collaboration interested in ERLs for EICs, e.g. coolers.**

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



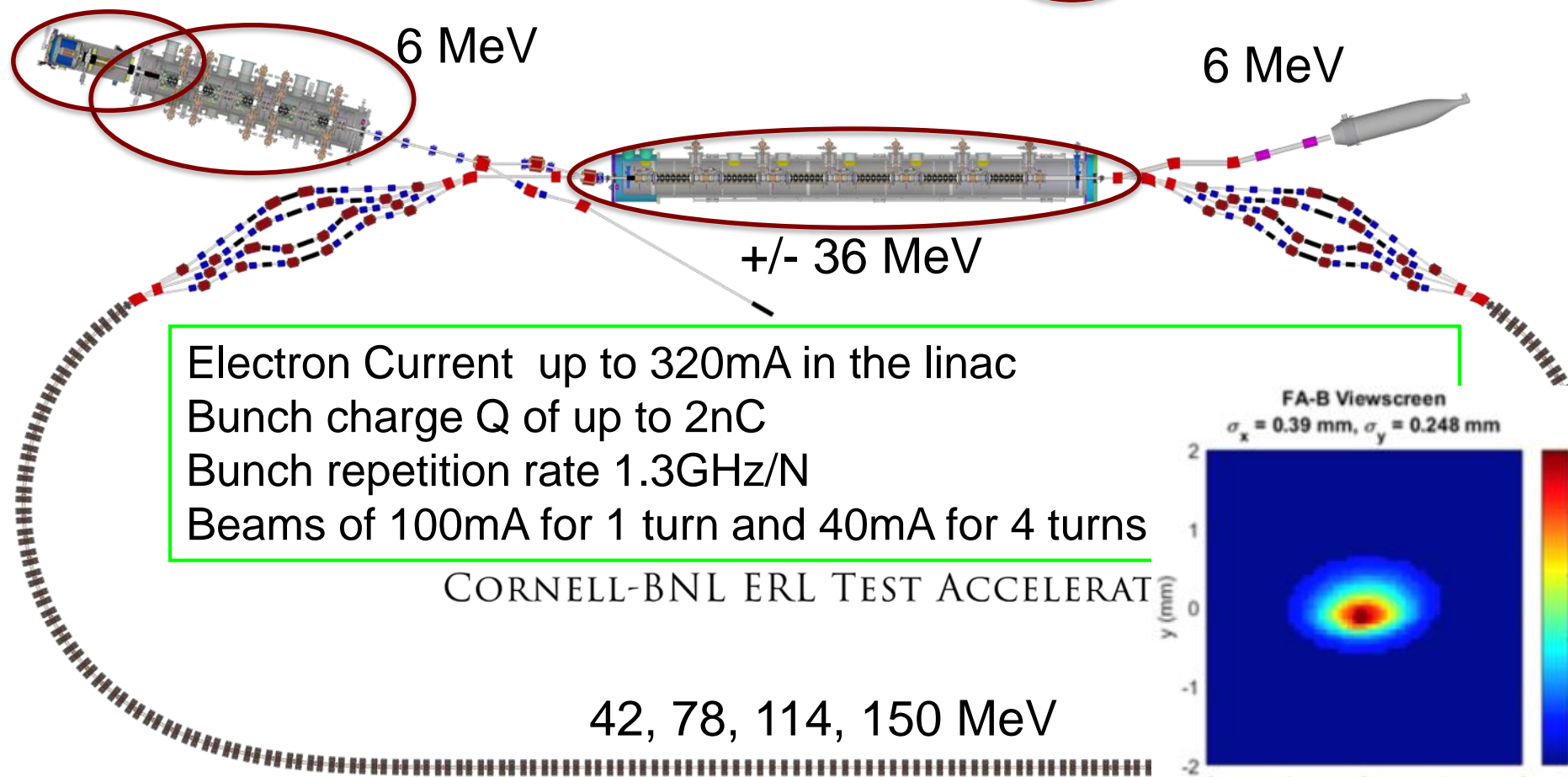
1<sup>st</sup> set of international visitors for Commissioning (r to l): D. Kelliher & J. Jones (Daresbury), B. Kuske & J. Völker (HZB).

Cornell's CBETA team with collaborators from BNL in the back: S. Peggs & S. Berg.



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

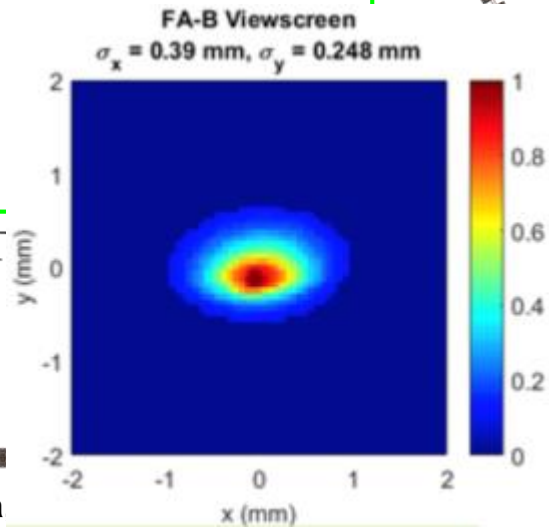
Tested



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



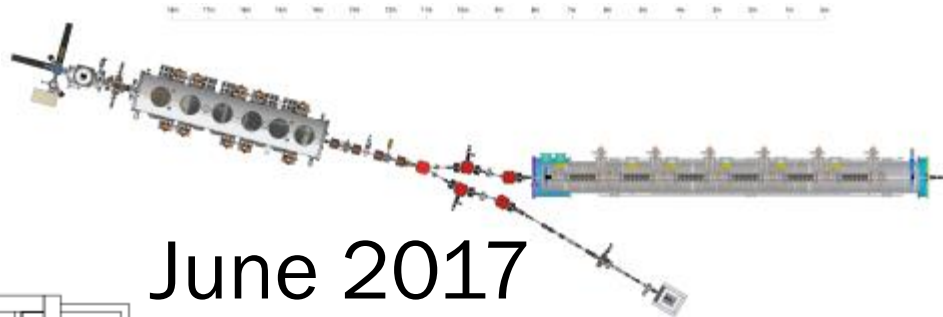


#	Milestone (at the end of months)	Baseline	Actual
	Funding start date		Oct-16
1	Engineering design documentation complete	Jan-17	
2	Prototype girder assembled	Apr-17	
3	Magnet production approved	Jun-17	
4	<b>Beam through Main Linac Cryomodule</b>	<b>Aug-17</b>	
5	First production hybrid magnet tested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

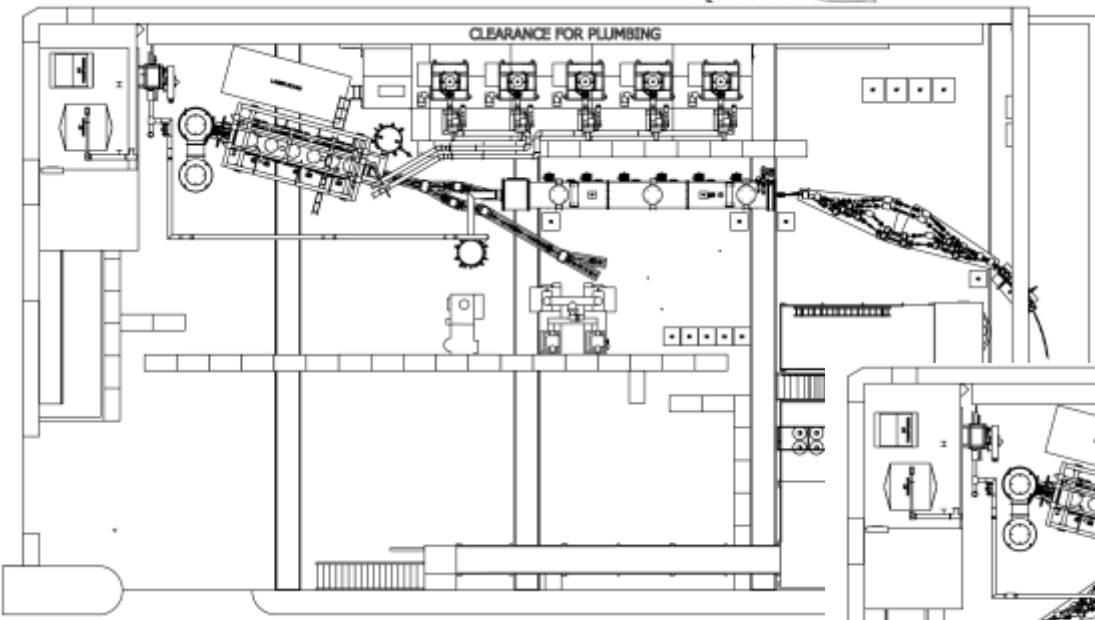




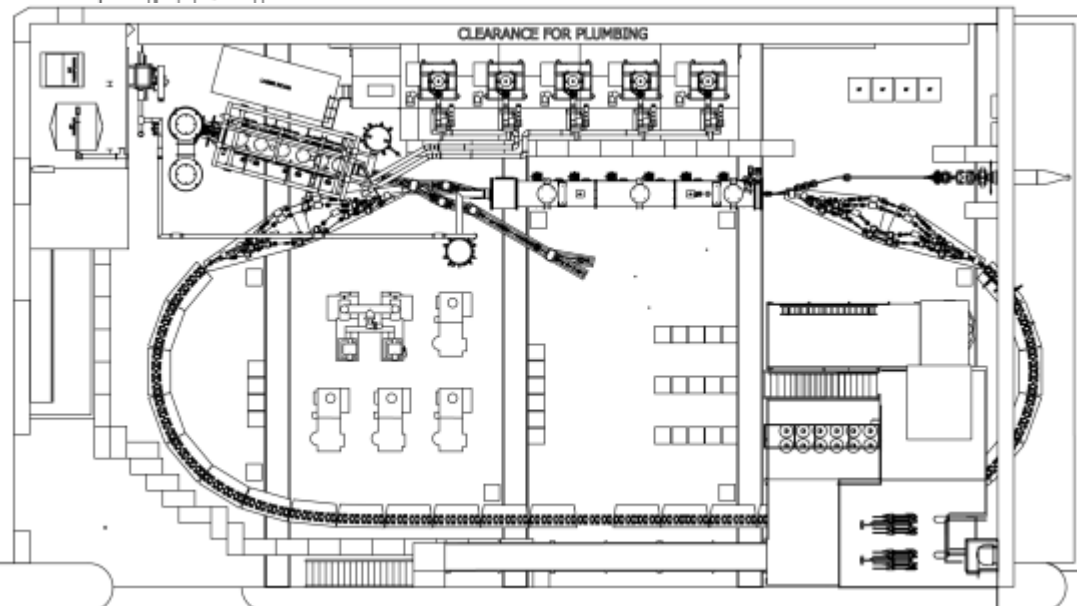
2016



June 2017



April 2018: FAT



August 2019: 1-turn

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



# Thank you for your attention!

## Questions?