CBETA: Cornell University Brookhaven National Laboratory ERL Test Accelerator:

URL:https://www.classe.cornell.edu/CBETA_PM/

Cornell University: N. Banerjee, J. Barley, A. Bartnik, I. Bazarov, D. Burke, J. Crittenden, L. Cultrera, J. Dobbins, B. Dunham[(3)], R. Eichhorn[(3)], S. Full, F. Furuta, R. Gallagher, M. Ge, C. Gulliford, B. Heltsley, G. Hoffstaetter, D. Jusic, R. Kaplan, V. Kostroun, Yulin Li, M. Liepe, W. Lou, C. Mayes[(3)], R. Patterson, P. Quigley, E. Smith, K. Smolenski, D. Sabol, D. Sagan, J. Sears, C. Shore, V. Veshcherevich, and D. Widger [[(3)]Left Cornell University and the project]

Brookhaven National Laboratory: S. Bellavia, M. Blaskiewicz, S. Brooks, K. Brown, Chuyu Liu, W. Fischer, C. Franck, Y. Hao, G. Mahler, F. Meot, R. Michnoff, M. Minty, S. Peggs, V. Ptitsyn, T. Roser, J.S. Berg, P. Thieberger, N. Tsoupas, D. Trbojevic, J. Tuozzolo, F. Willeke, and H. Witte.

Jefferson Laboratory: D. Douglas

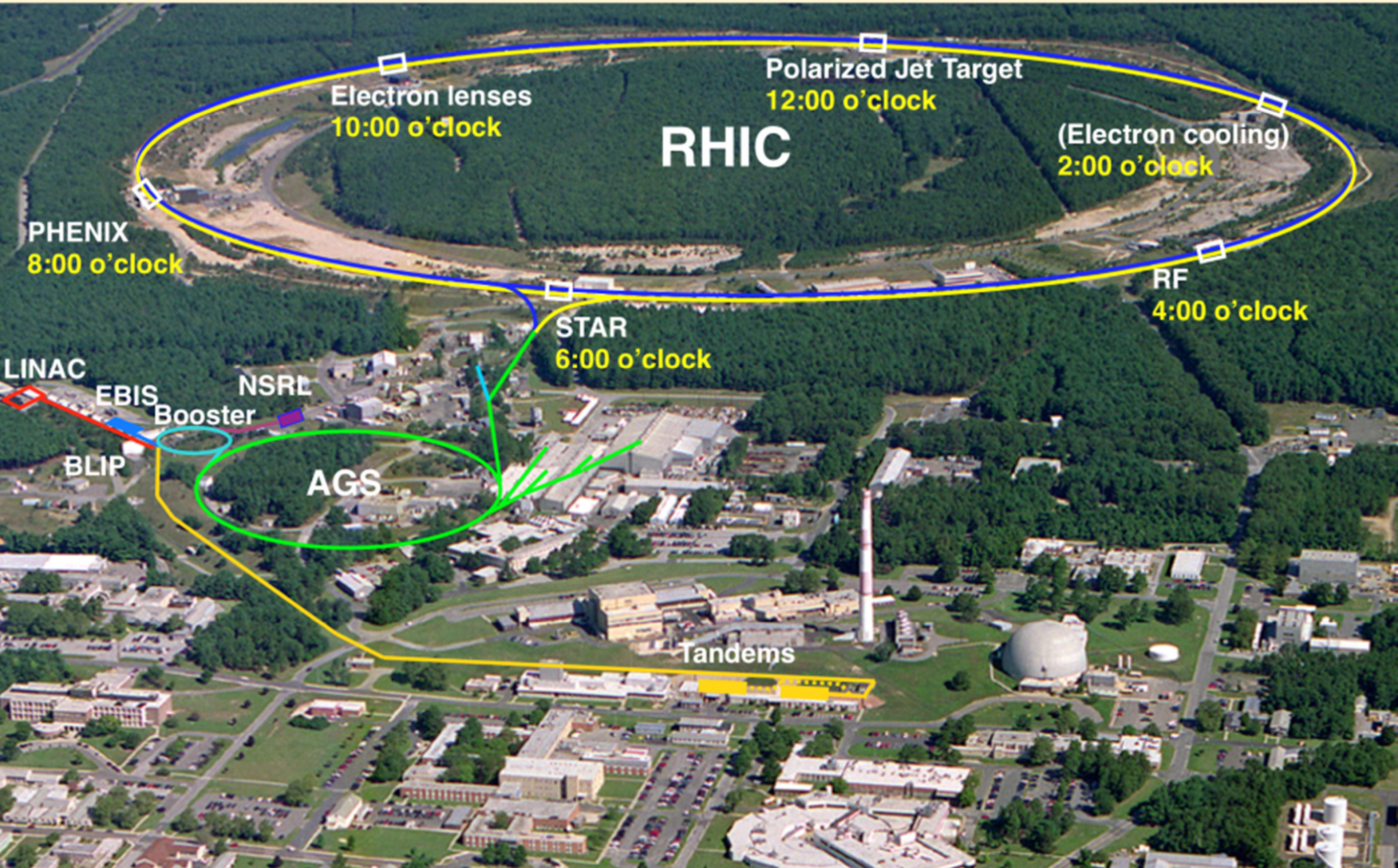
BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

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

Relativistic Heavy Ion Collider

1 of 2 ion colliders (other is LHC), only polarized p-p collider



Operated modes - beam energies

Au – Au 3.8/4.6/5.8/10/14/32/65/100 GeV/n

U – U 96.4 GeV/n

Cu – Cu 11/31/100 GeV/n

p↑ – p↑ 11/31/100/205/250/255 GeV

d – Au* 100 GeV/n

Cu – Au* 100 GeV/n

Planned or possible future modes:

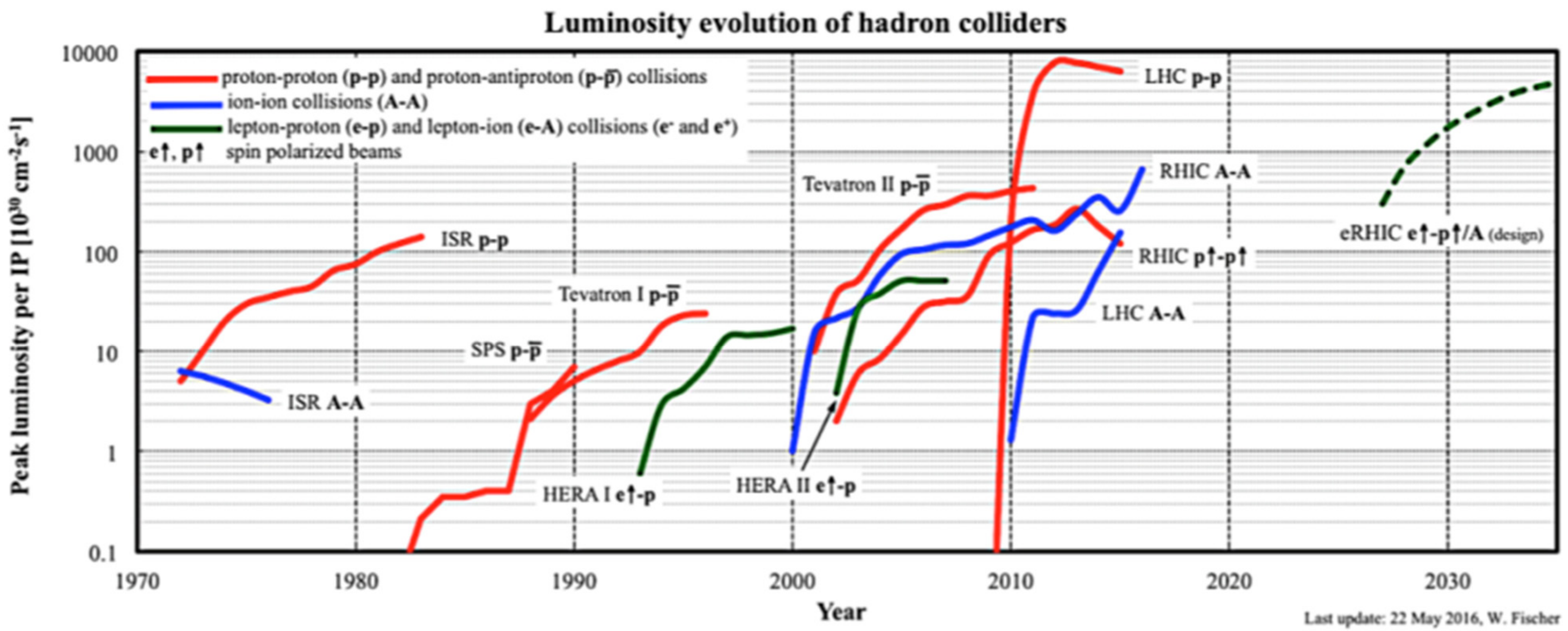
Au – Au 2.5 GeV/n

p↑ – A* 100 GeV/n (A = Au, Cu, Al)

^{3}He – A* 100 GeV/n (A = Au, Cu, Al)

p↑ – ^{3}He↑* 166 GeV/n (*asymmetric rigidity)

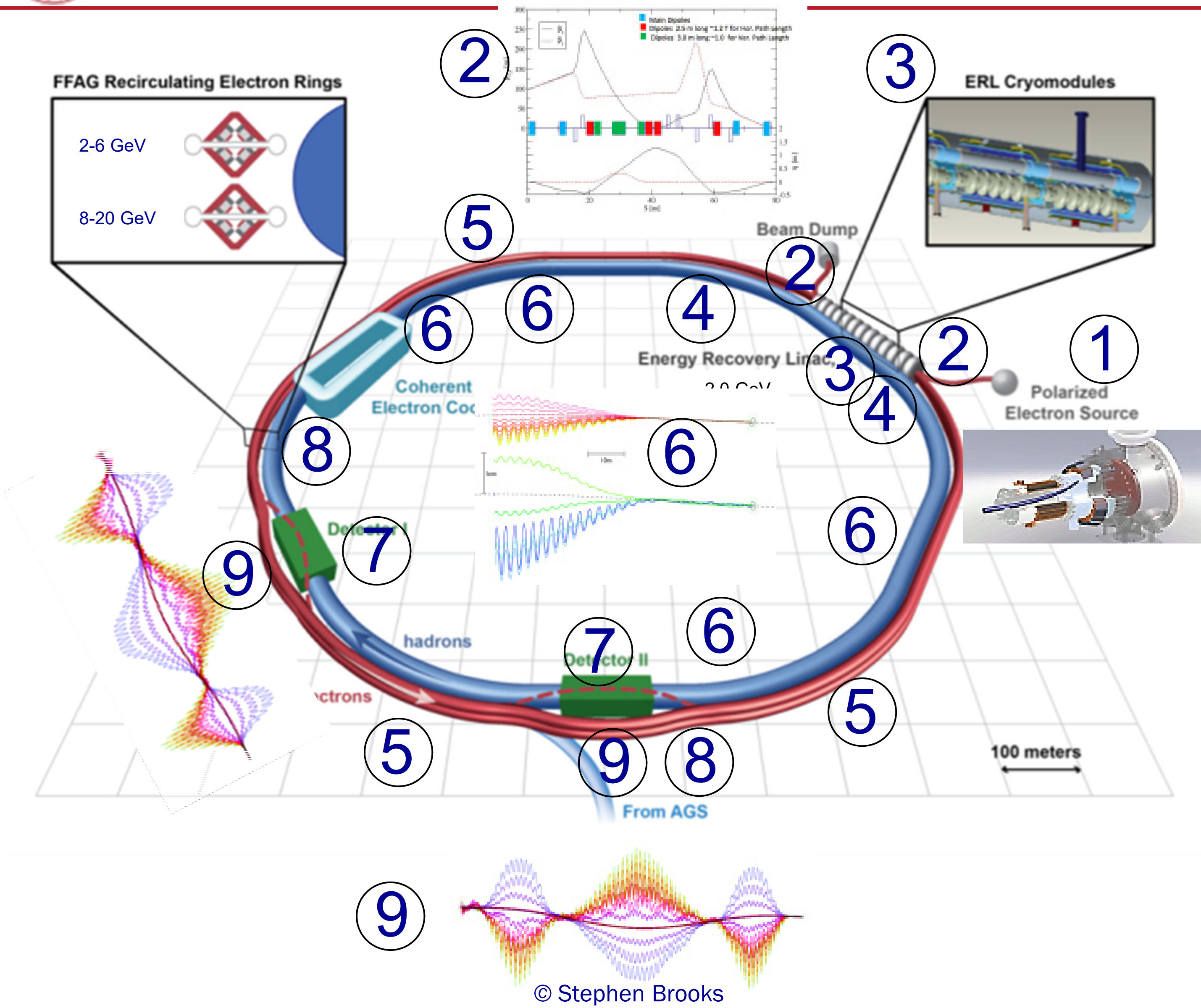
Operated modes - beam energies



Note: For ion collisions the nucleon-pair luminosity is shown. The nucleon-pair luminosity is defined as $L_{NN} = A_1 A_2 L$, where L is the luminosity, and A_1 and A_2 are the number of nucleons of the ions in the two beam respectively. The highest energies for the machines are: ISR 31 GeV, SPS 315 GeV, Tevatron 980 GeV, HERA 920 GeV (p) 27.5 GeV (e), RHIC 255 GeV, LHC 4.0 TeV. A reduction in the peak lumiosity from one year to the next (e.g. RHIC in 2015) can be the result of running at a lower energy or different species combination.

p↑ – ^{3}He↑* 166 GeV/n (*asymmetric rigidity)

LINAC-RING eRHIC SOLUTION



Major Technical Components:

① Funneling Gun

② ERL mergers

③ Superconducting Linac - ERL

④ Spreaders and Combiners

⑤ NS-FFAG arcs

⑥ Merging arcs to straight section

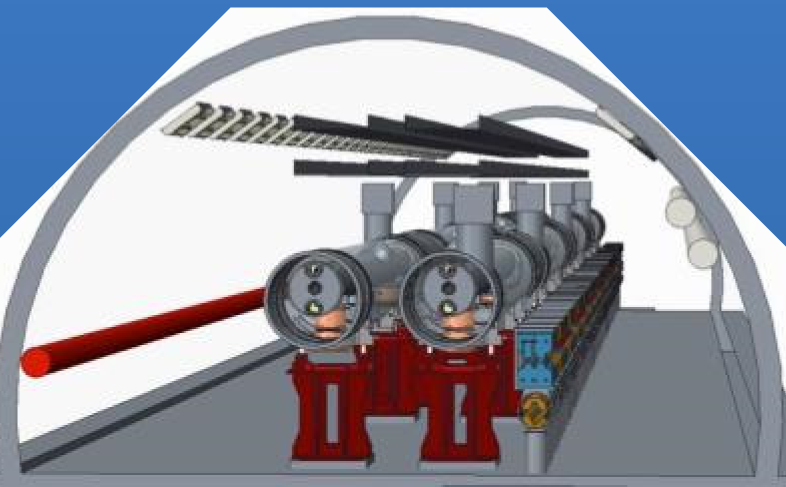
⑦ Straight section

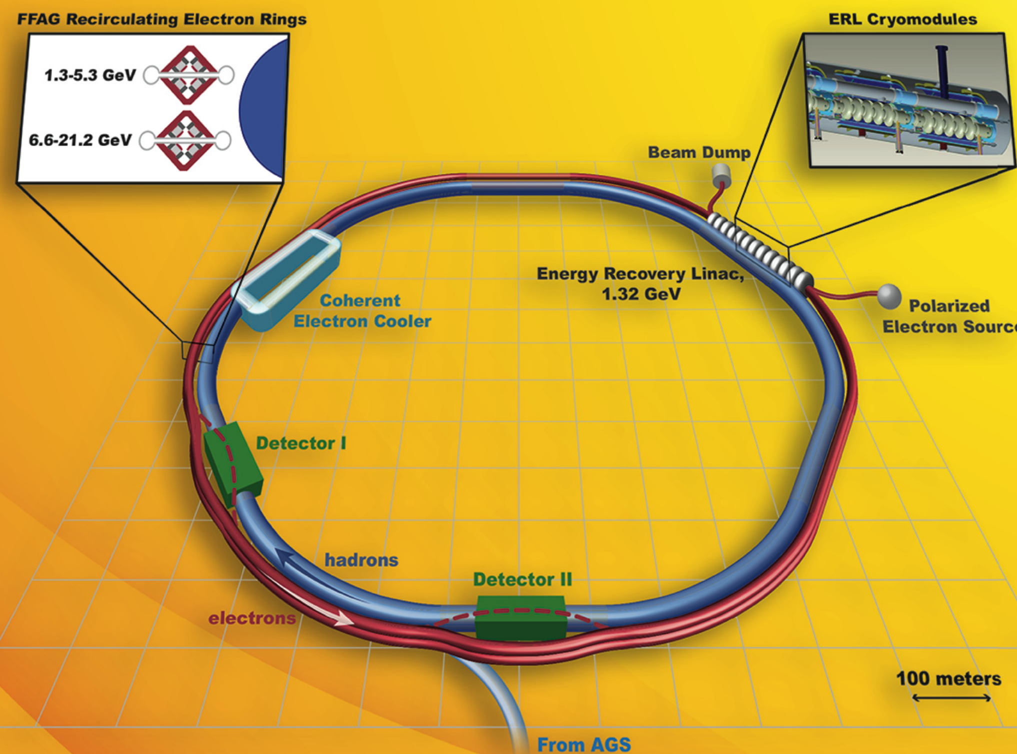
⑧ Extracted high energy beam

⑨ Detector By Passe

LINAC-RING eRHIC SOLUTION

The **Non Scaling FFAG (NS-FFAG)** lattice **enables multiple passes** of the electron beam **with different energies in a single strong focusing recirculation beam line** by using the **superconducting** RF (SRF) linac multiple times. The **FFAG-ERL** reduces significantly the overall collider and operating cost.



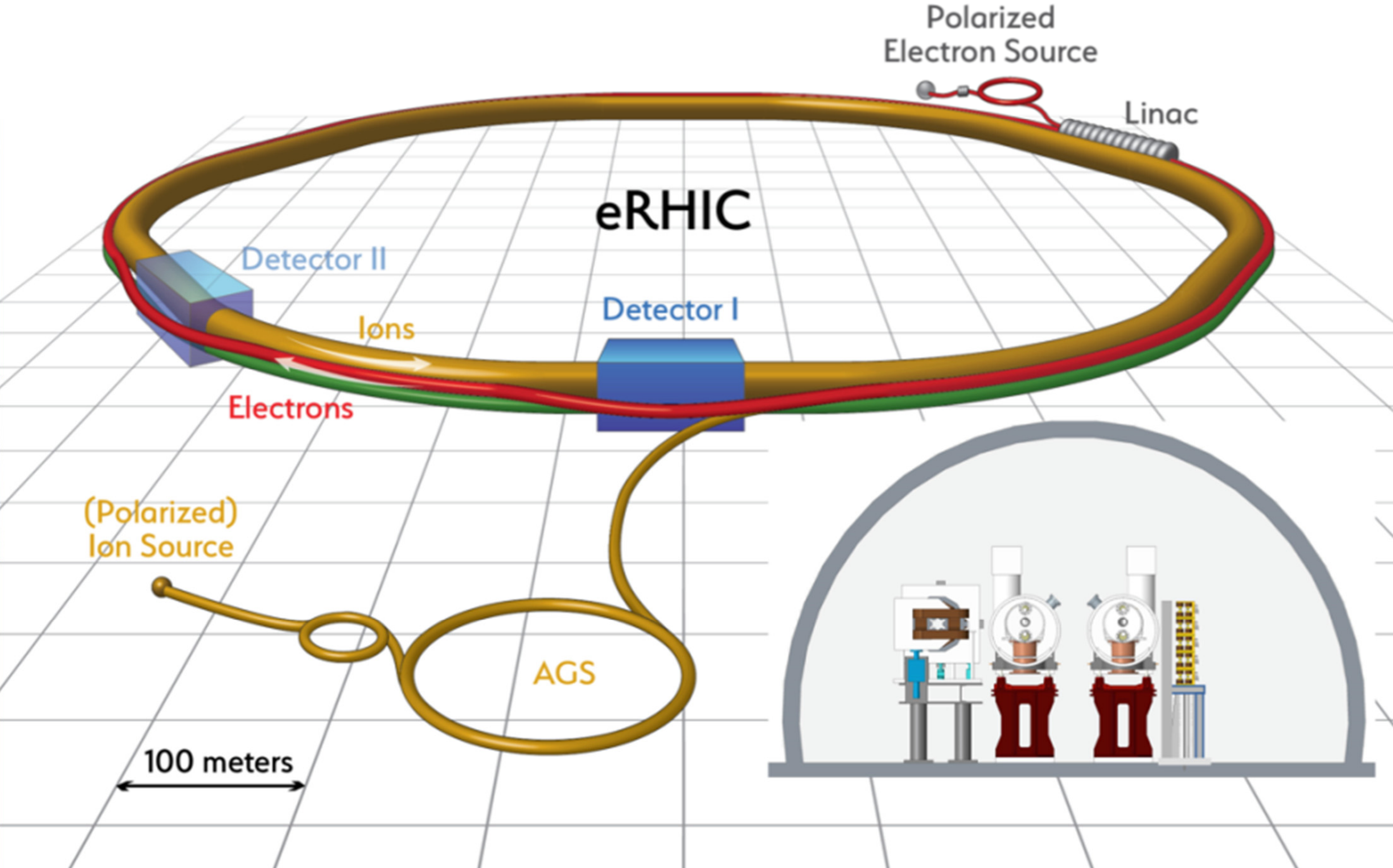


eRHIC Design Study

An Electron-Ion Collider at BNL

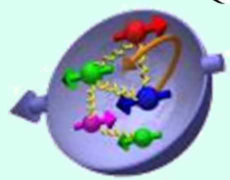
DECEMBER 2014

RING – RING DESIGN



WHY TO BUILD A NEW POLARIZED ELECTRON – PROTON/He^3 AND HEAVY ION COLLIDER (eRHIC)?

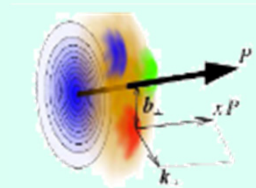
spin physics



- what is the polarization of gluons at small x where they are most abundant
- what is the flavor decomposition of the polarized sea depending on x

determine quark and gluon contributions to the proton spin at last

imaging

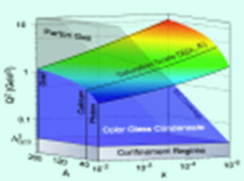


- what is the spatial distribution of quarks and gluons in nucleons/nuclei
- understand deep aspects of gauge theories revealed by k_T dep. distr'n

possible window to orbital angular momentum

physics of strong color fields

quantitatively probe the universality of strong color fields in AA, pA, and eA



- understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation
- how do hard probes in eA interact with the medium

WHY TO BUILD A NEW POLARIZED ELECTRON – PROTON/He^3 AND HEAVY ION COLLIDER (eRHIC)?

(courtesy from Thomas Roser)

Protons are fundamental to the visible universe (including us) and their properties are dominated by emergent phenomena of the self-coupling strong force that generates high density gluon fields:

- **The mass of the proton (and the visible universe)**
- **The spin of the proton**
- **The dynamics of quarks and gluons in nucleons and nuclei**
- **The formation of hadrons from quarks and gluons**

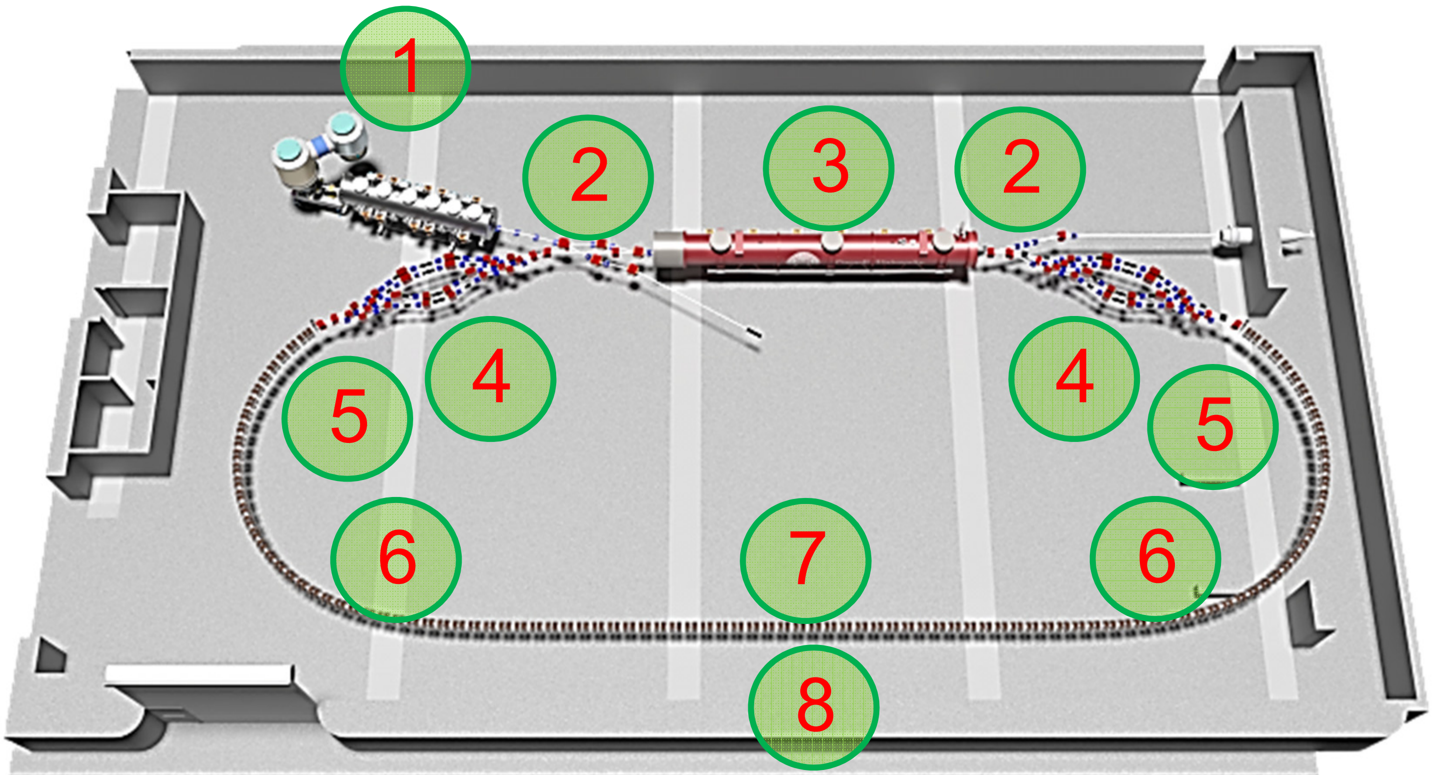
The study of the high density gluon field, which is at the center of it all, requires a high energy, high luminosity, polarized Electron Ion Collider

A femtoscope for gluons

AN ULTIMATE QCD LABORATORY

What is CBETA?

CBETA will comprise the first ever Energy Recovery Linac (ERL) based on a Fixed Field Alternating Gradient (FFAG) lattice.



Major Technical Components:

1. Electron Gun with Linac
2. ERL mergers
3. Superconducting Linac - ERL
4. Spreaders and Combiners
5. NS-FFAG arcs
6. Merging arcs to straight section
7. Straight section
8. Extracted high energy beam

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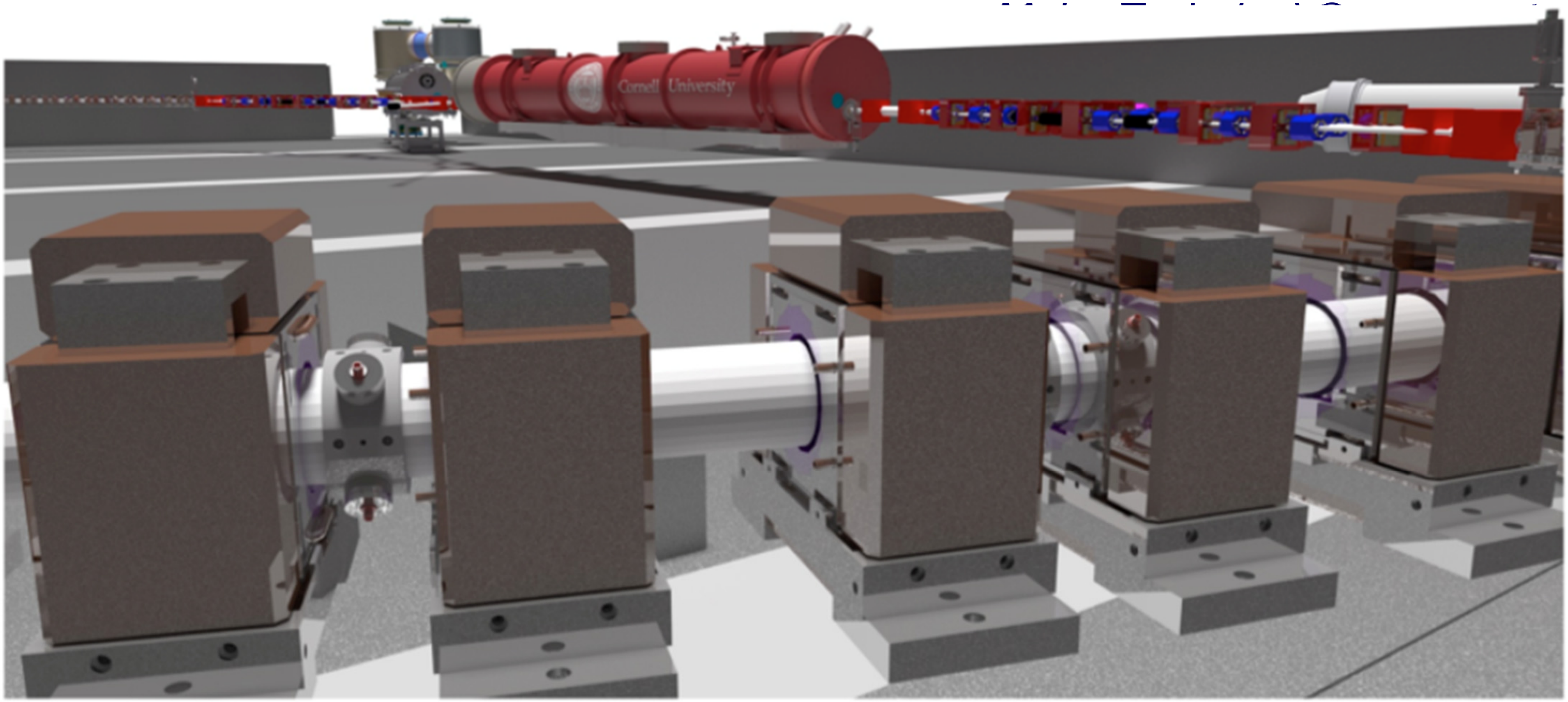
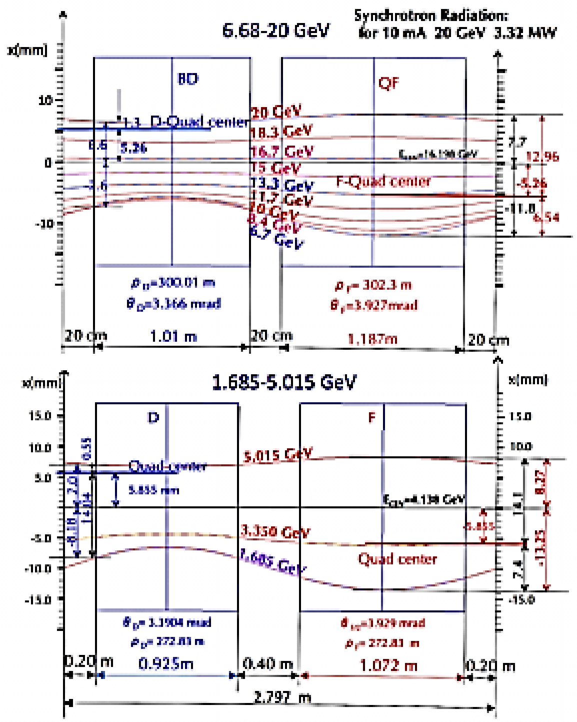
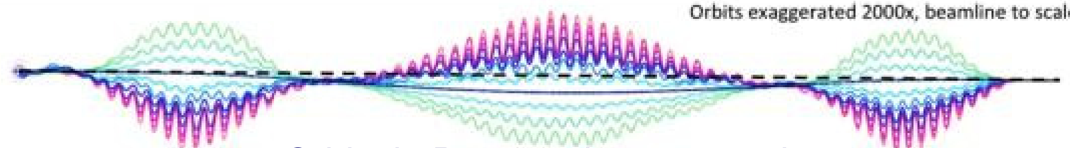


energy beam

CBETA topics to study for eRHIC

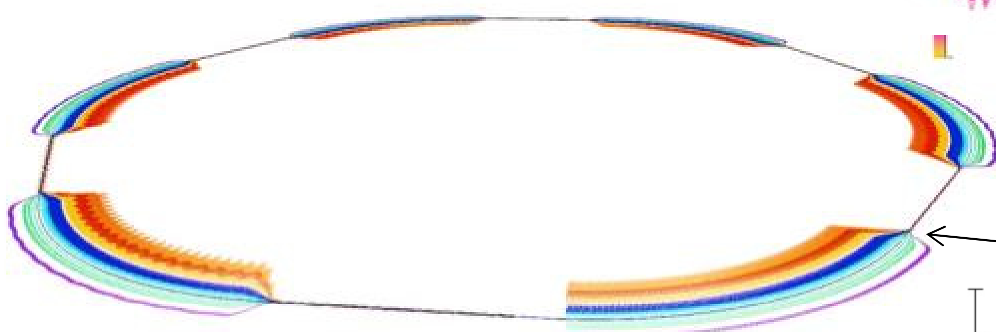


- LINAC RING solution for eRHIC uses two FFAG beam lines to do multiple recirculations.
 (FFAG-I: 1.7-5.0 GeV, FFAG-II: 6.7-18.3 GeV, 20 GeV)
- All sections of a FFAG beam line is formed using a same FODO cell. Required bending in different sections is arranged by proper selection of the offsets between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



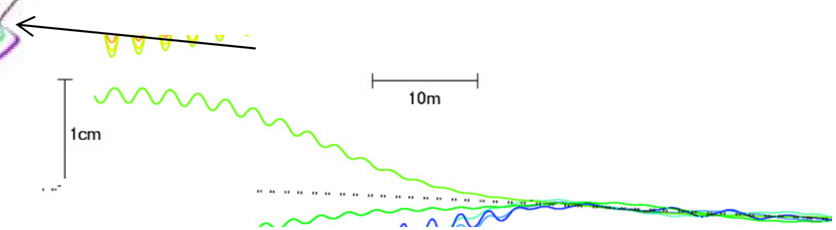
Orbits in Detector bypass section

S. Brooks



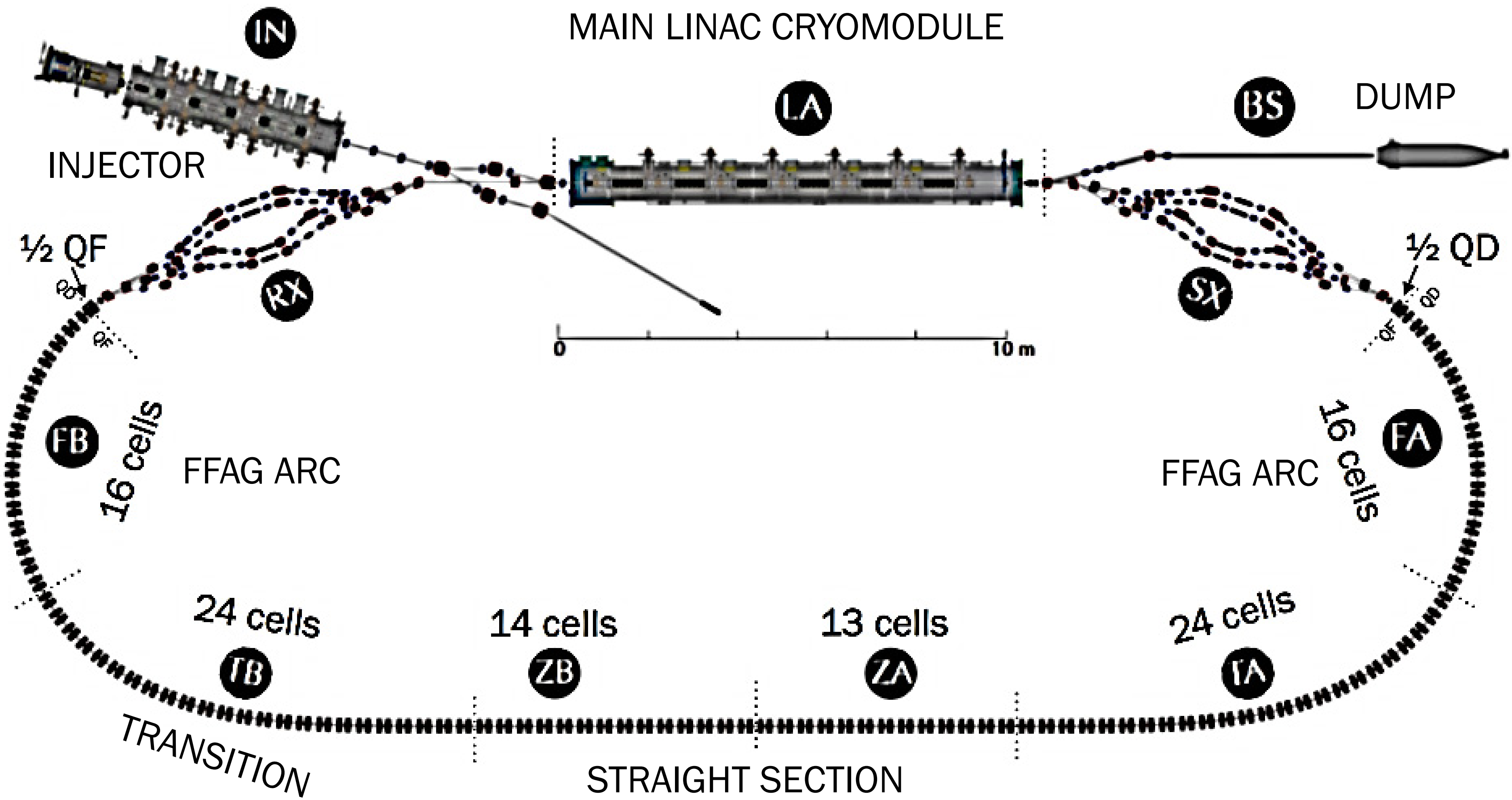
Quad offsets evolve adiabatically

Orbits in Transition section



Each of two eRHIC FFAGs contain 1066 FFAG cells

What is CBETA?



What is CBETA?

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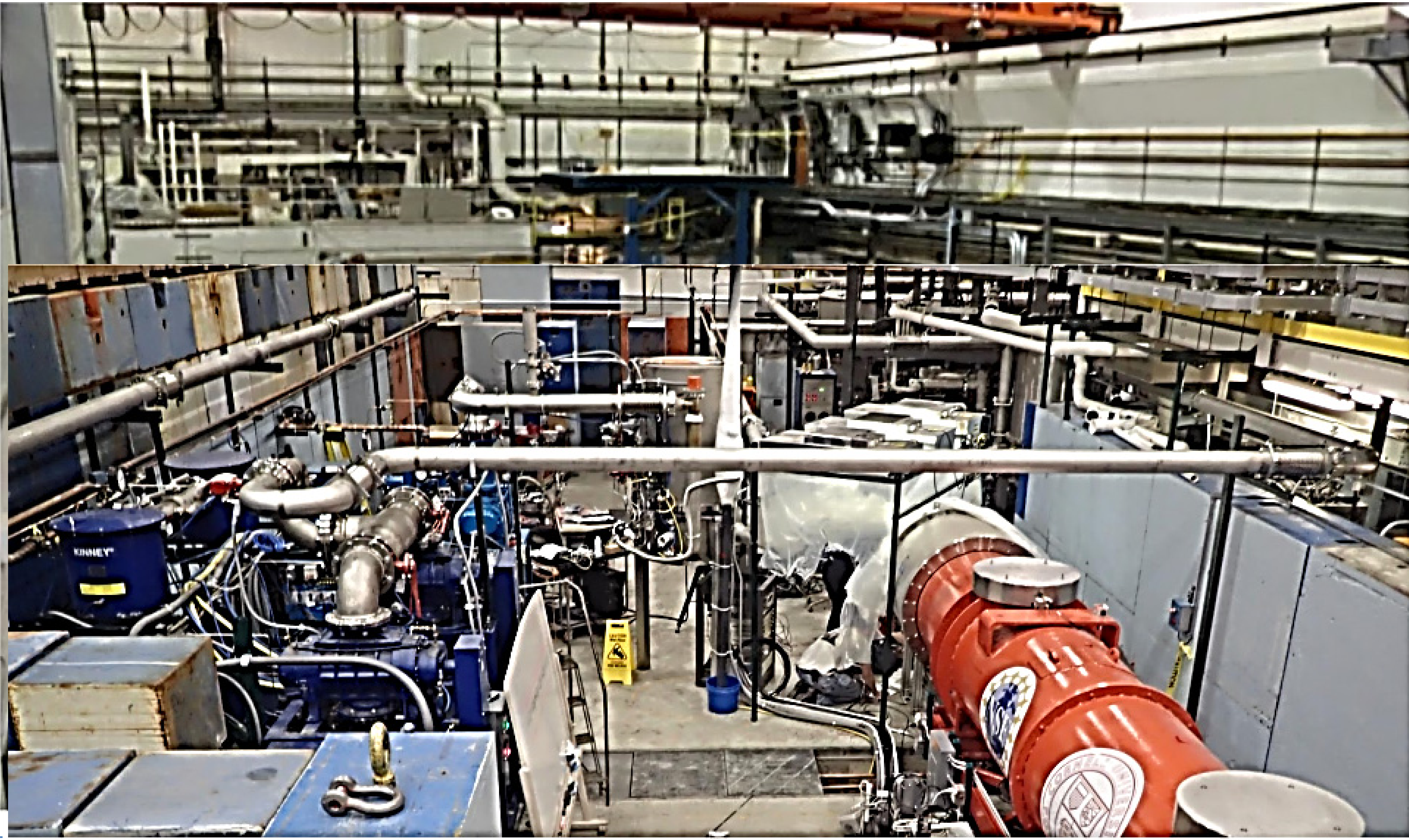
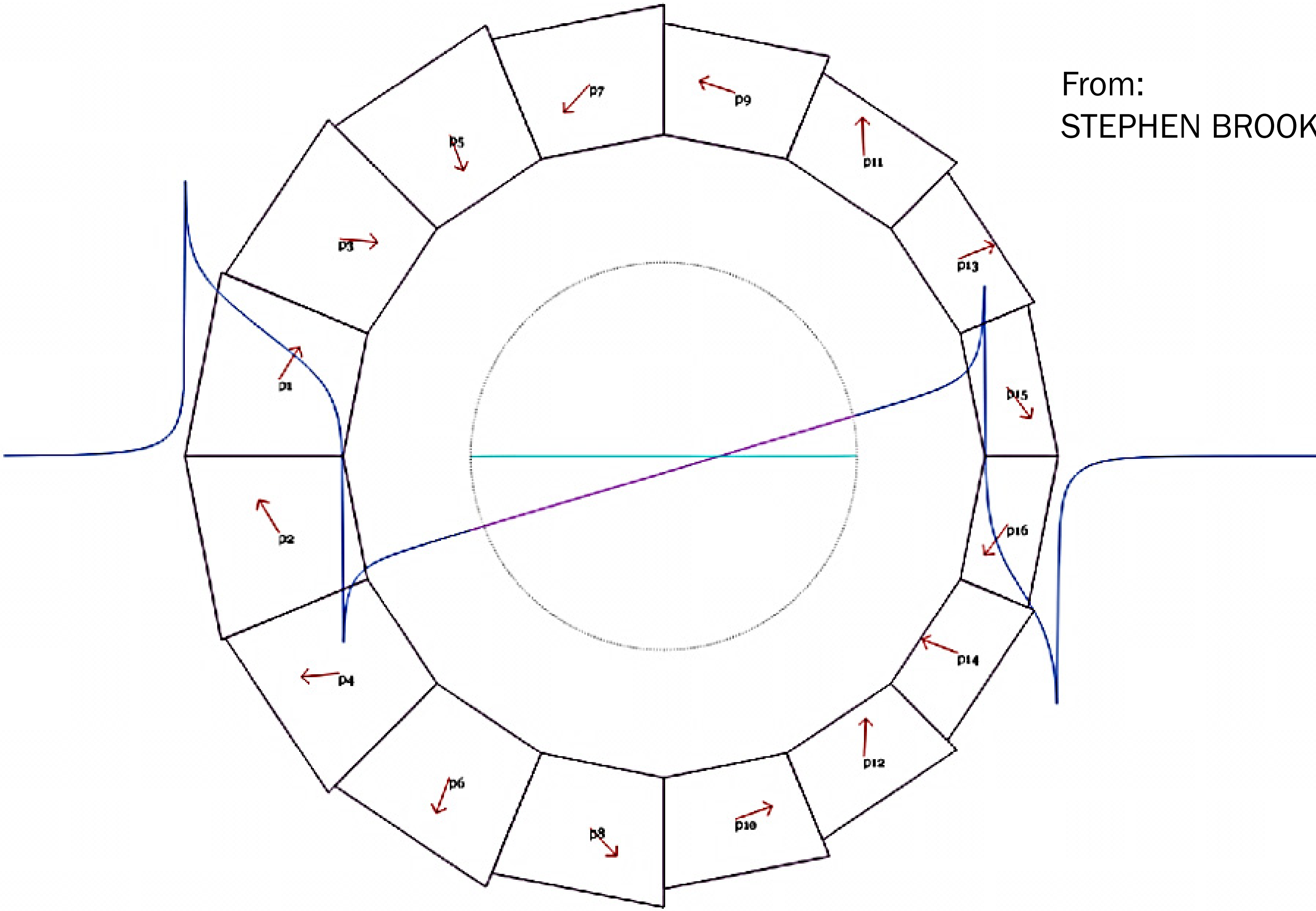


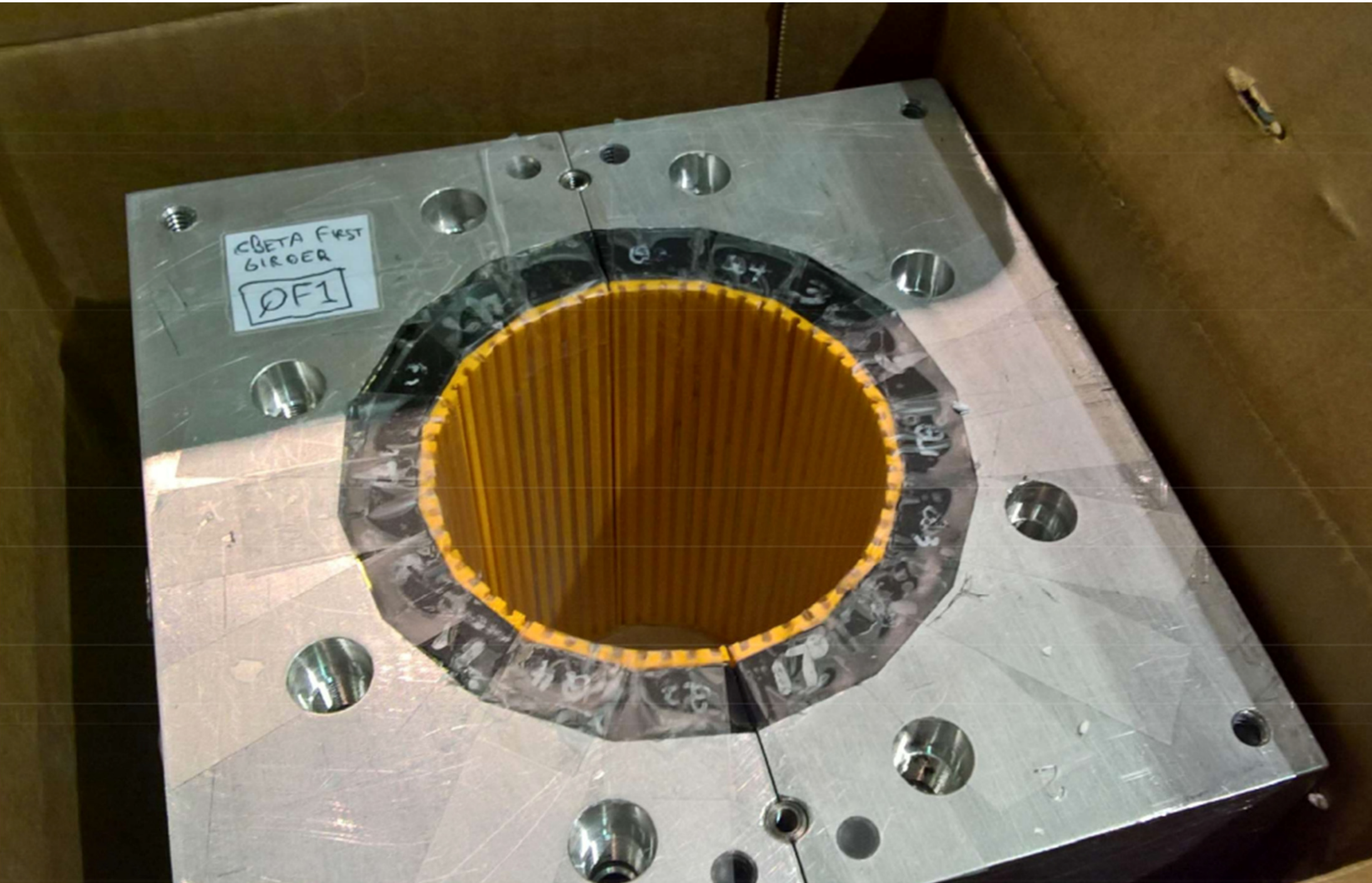
What is CBETA?

NEW WAY TO MAKE COMBINED FUNCTION MAGNET

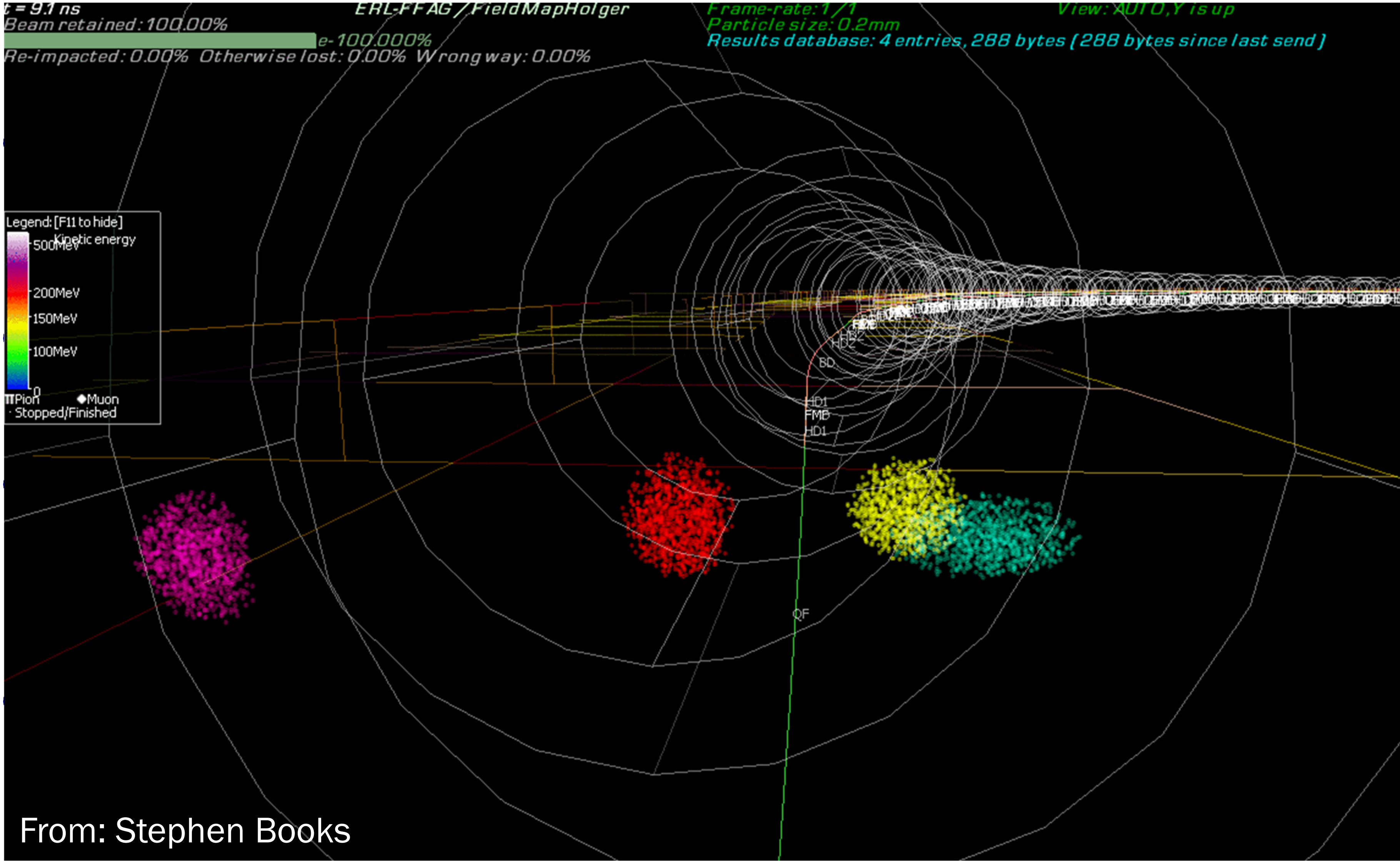
From:
STEPHEN BROOKS



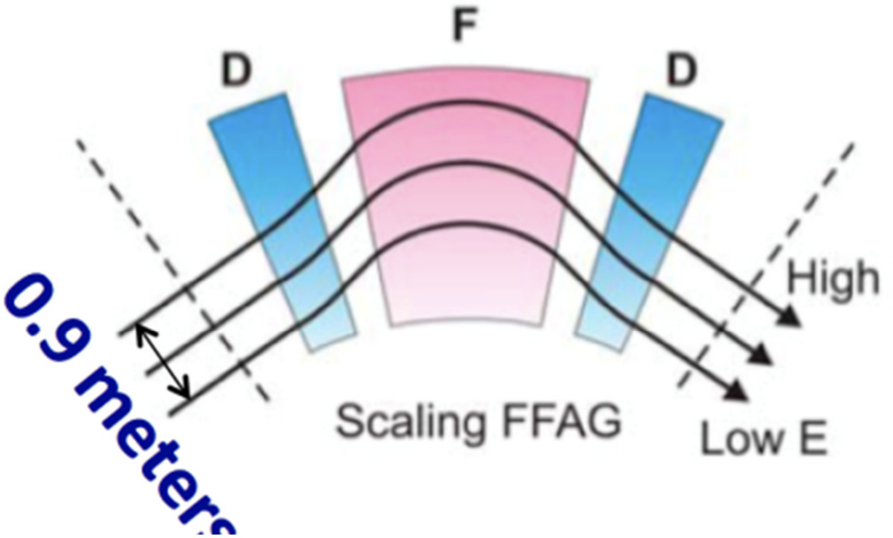
NEW WAY TO MAKE COMBINED FUNCTION MAGNET



Novelties in CBETA



NON-SCALING FFAG



$$p = p_o \left(\frac{r}{r_o}\right)^{k+1} \quad B(r) \approx B_o \left(\frac{r}{r_o}\right)^{k}$$

D magnet = reverse bend
Magnetically inefficient
VERY BAD for synchrotron radiation (10MW)

Linear magnetic field:
$B = B_o + r\, G_o$

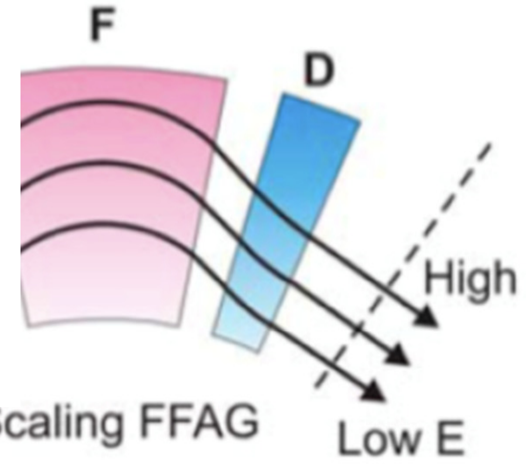
$$\Delta x = D_x * \delta p/p$$

To reduce the **orbit offsets to ±4 cm range**, for momentum range of **$\delta p/p$ ~ ± 50 %** the dispersion function D_x has to be of the order of:

$$D_x \sim 4\ cm / 0.5 = 8\ cm$$

NON-SCALING FFAG

EMMA "Electron Model for Many Applications" the first NS-FFAG built at Daresbury Laboratory



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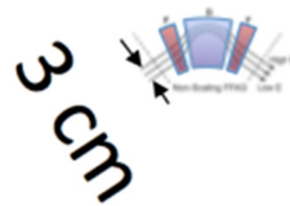

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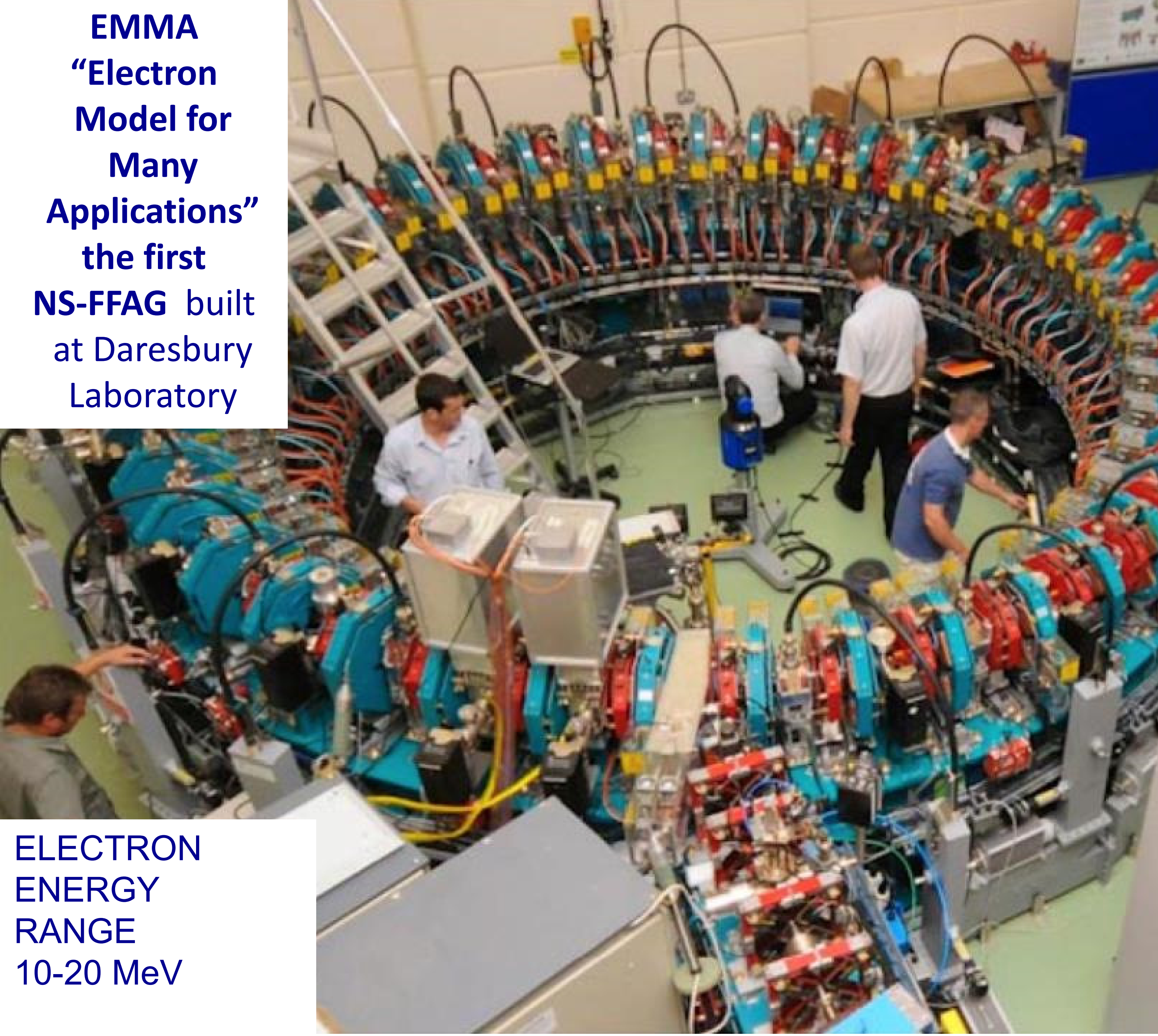
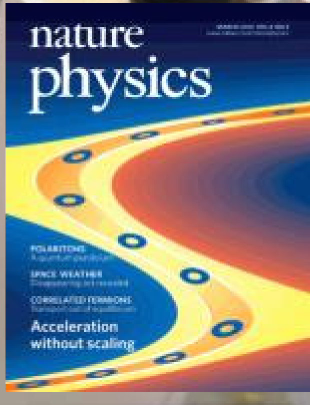




ELECTRON ENERGY RANGE 10-20 MeV

Key Performance Parameters and Designed Performance Parameters

Circumference = 111.86092 m

Parameter	Unit	KPP	Design
Electron beam energy	MeV	42	150
Electron bunch charge	pC	3	123
Gun current	mA	1	40
Bunch repetition rate (gun)	MHz	325	325
RF frequency	MHz	1300	1300
Injector energy	MeV	6	6
RF operation mode		CW	CW
Number of ERL turns		1	4
Energy aperture of arc		2	4

CBETA topics to support eRHIC

1) **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.**

2) **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.

An “FFAG ERL” is not by Coincidence at Cornell University with BNL collaboration

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

M. Tigner

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

(ricevuto il 2 Febbraio 1965)

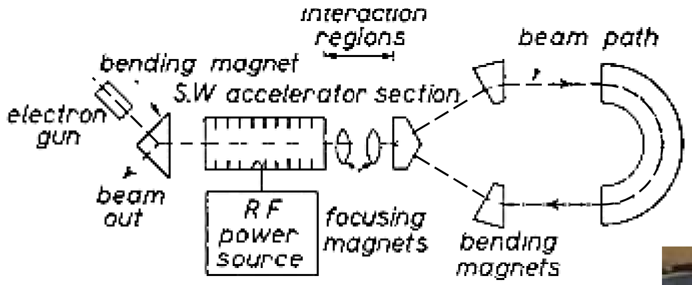


Fig. 3.

- **The first ERL was proposed 1965 by Maury Tigner (Cornell University)**

- Cornell University has been very successfully developing the superconducting RF technology through more than three decades.

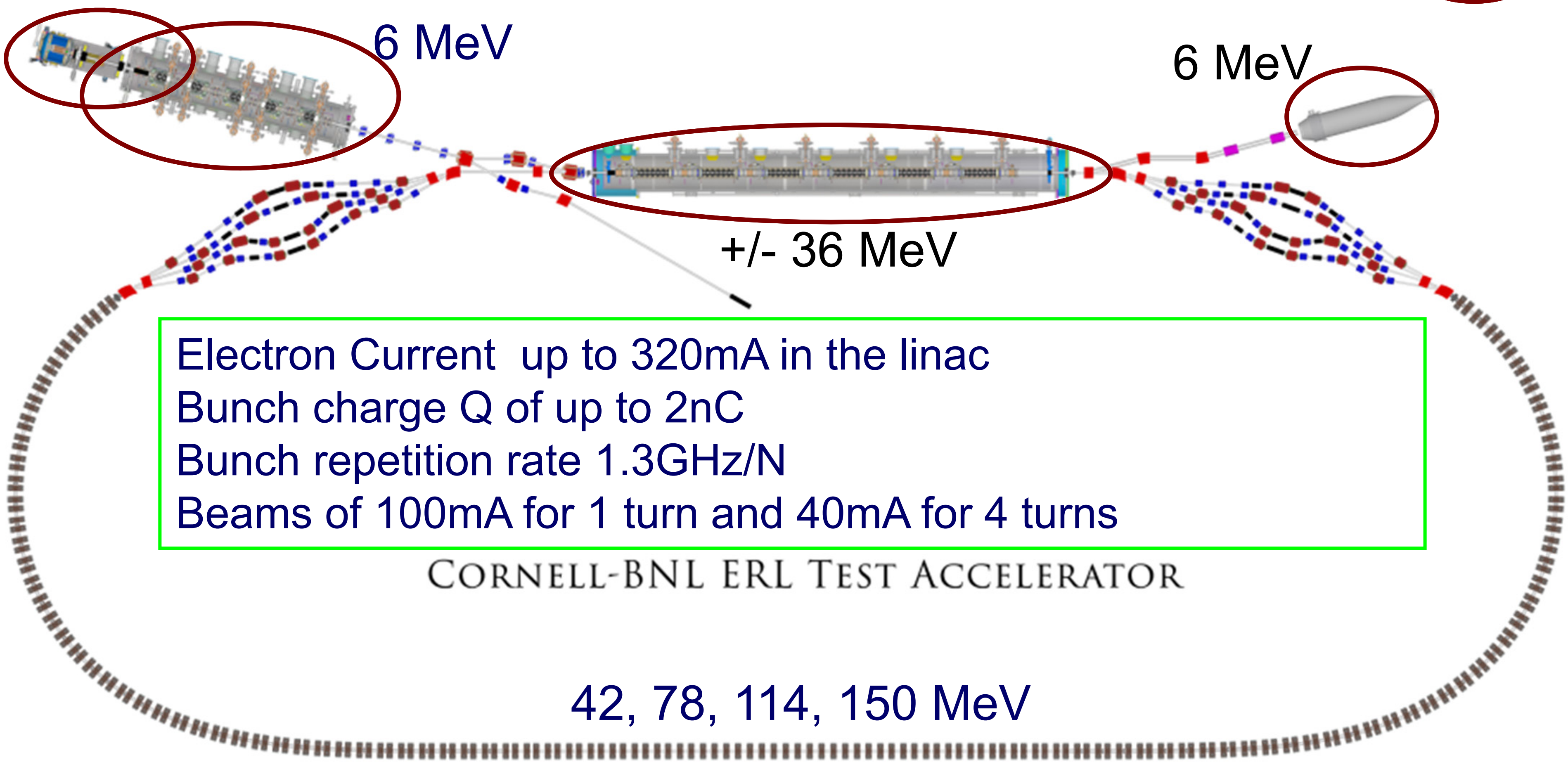
Commissioning of the CBETA Main Superconducting Linac

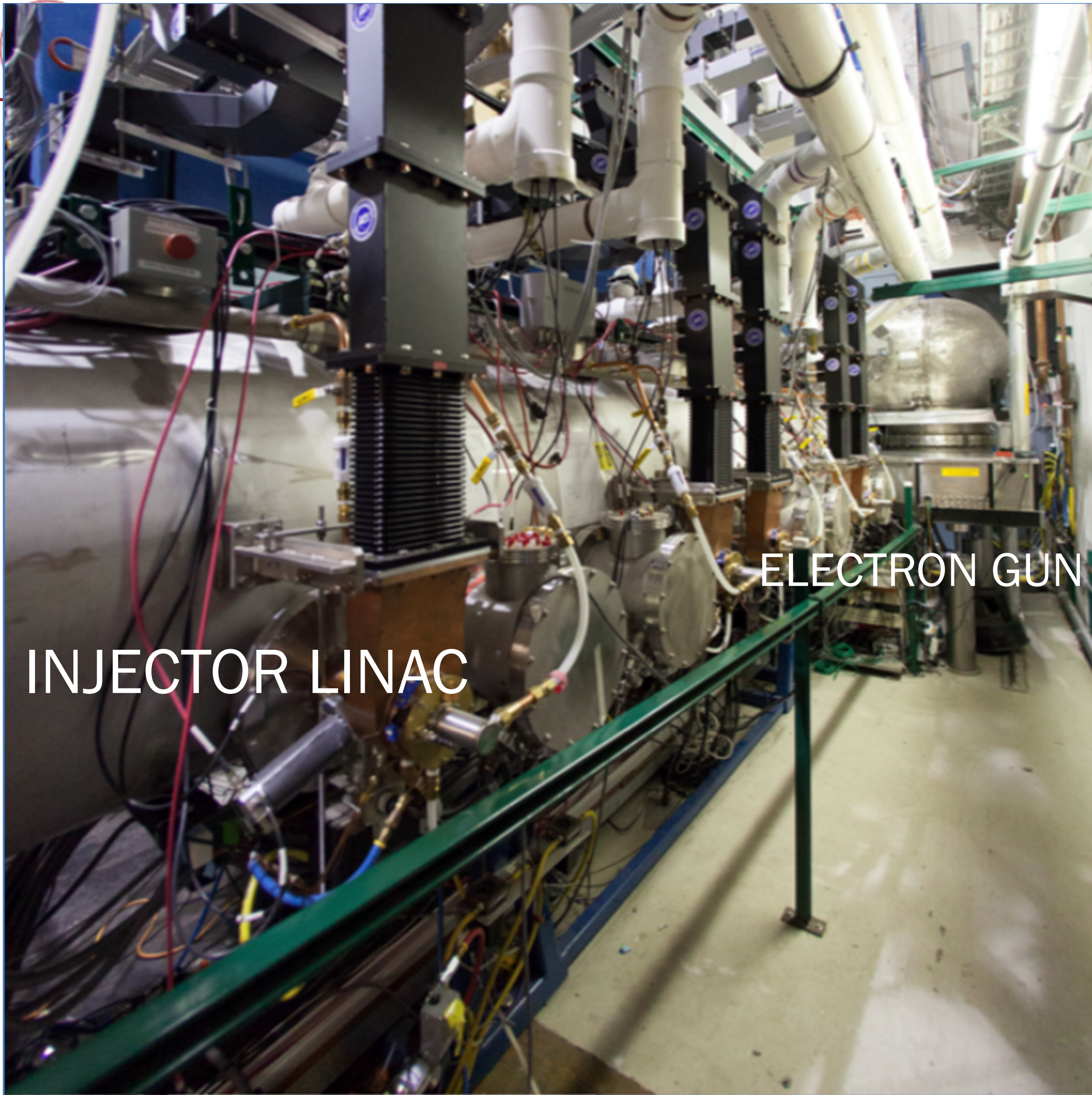
The BNL has a team of experts in Fixed Field Alternating Gradient accelerators FFAG: D. Trbojevic, S. Berg, F. Meot, S. Brooks, and E. D. Courant

(in 1999 D. Trbojevic, E. D. Courant and A. A. Garren proposed Non-Scaling FFAG: “FFAG Lattice Without Opposite Bends” - published at **“Colliders and collider physics at the highest energies: Muon colliders at 10 TeV to 100 TeV” : HEMC '99 Workshop, Montauk, New York, 27 September-1 October 1999 - editor, Bruce J. King)**

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

Existing components at Cornell

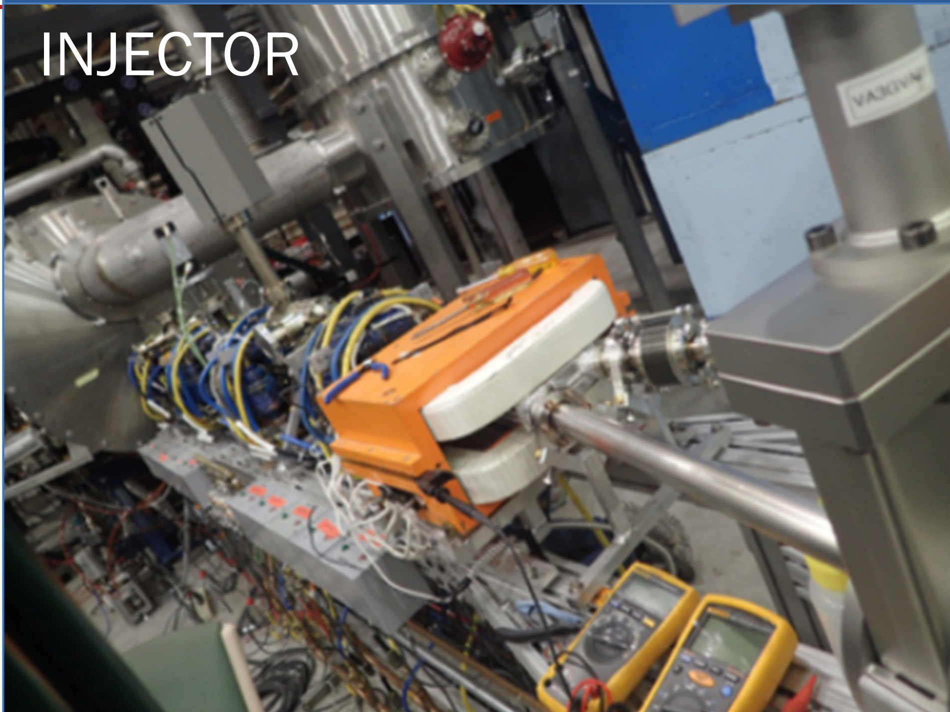


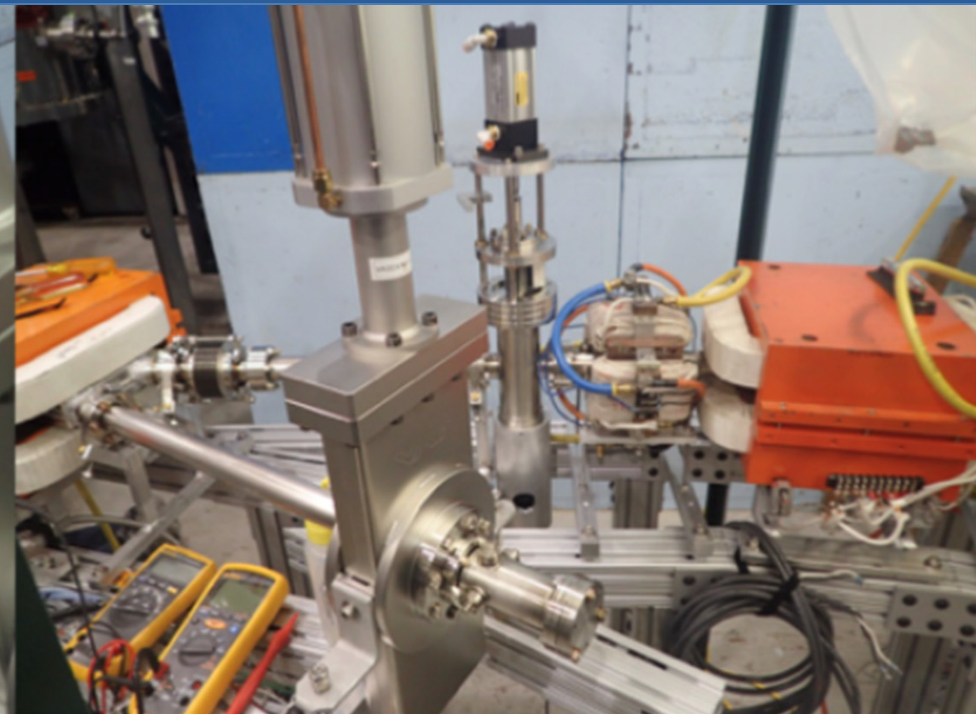

ELECTRON GUN
INJECTOR LINAC


LINAC INSTALLED AND
CONNECTED TO THE
INJECTOR

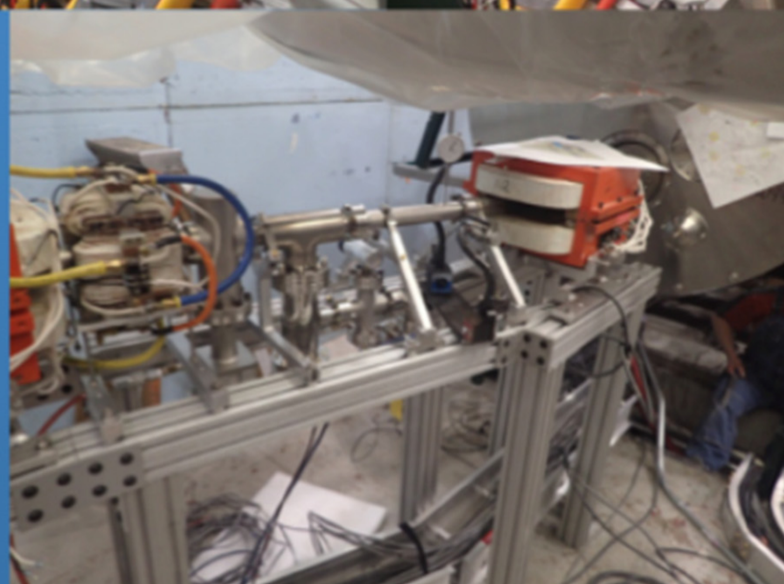
Connections of the Injector to the Main Linac

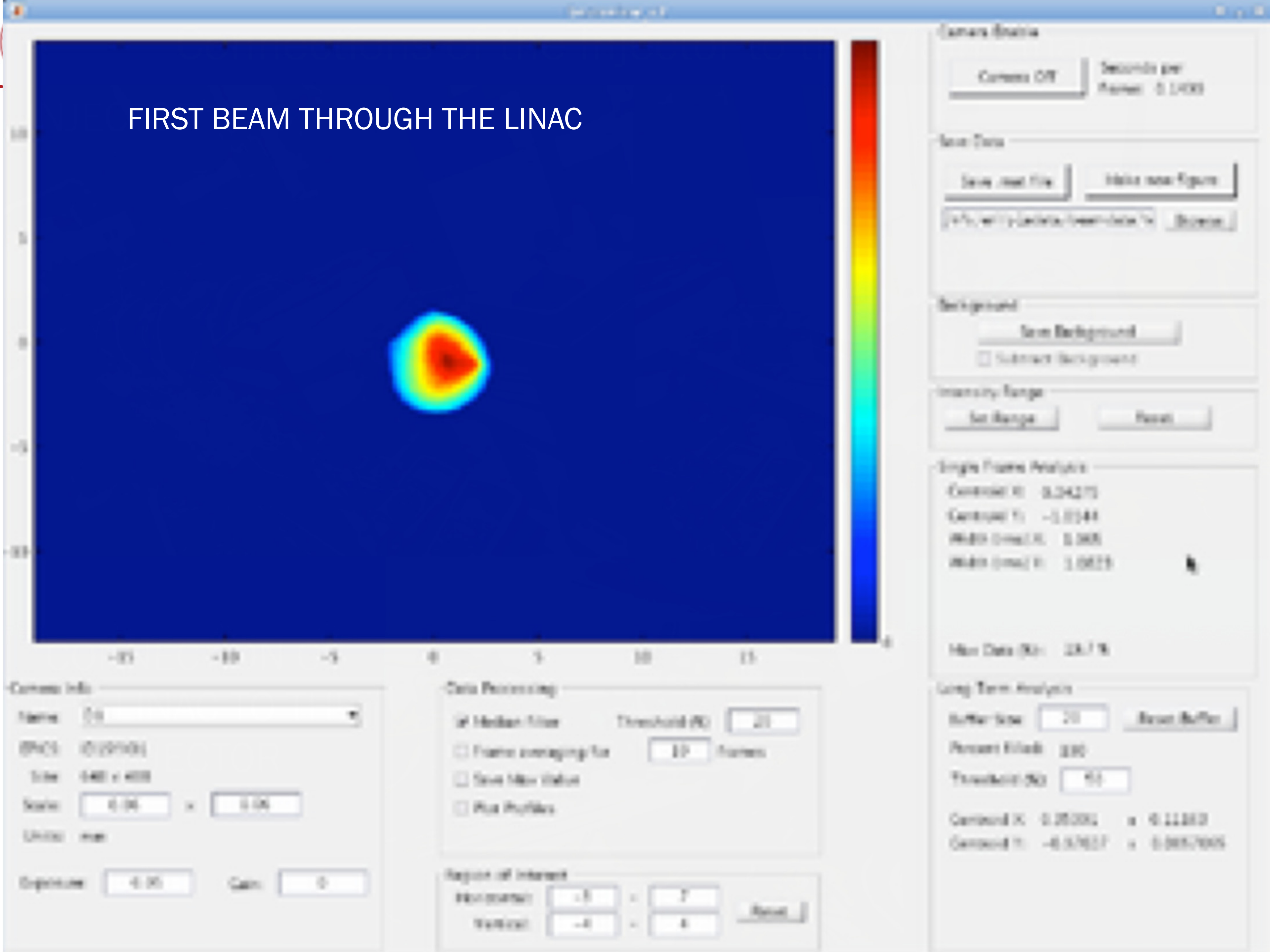
INJECTOR





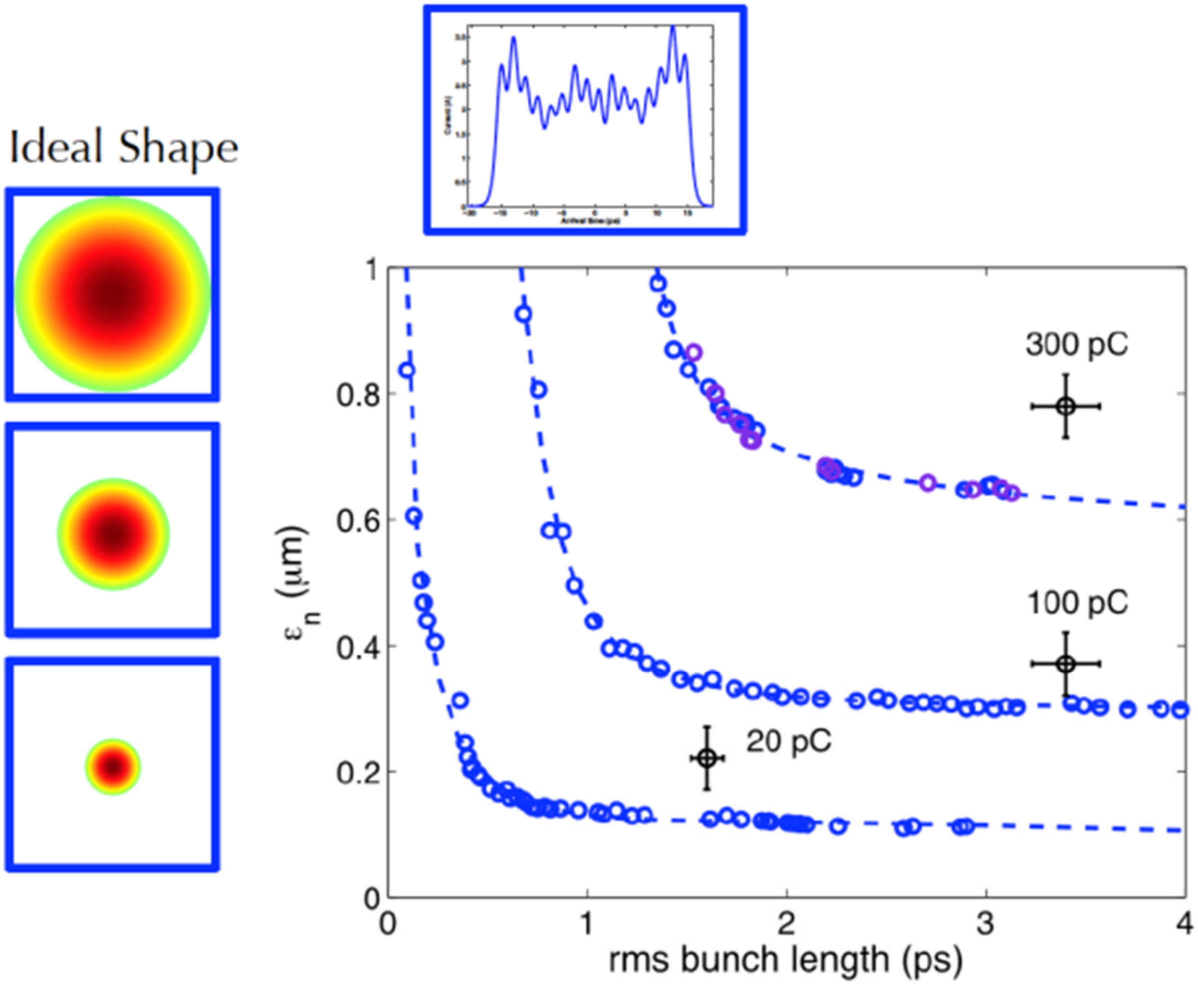
CONNECTION OF THE LINAC TO THE INJECTOR




FIRST BEAM THROUGH THE LINAC

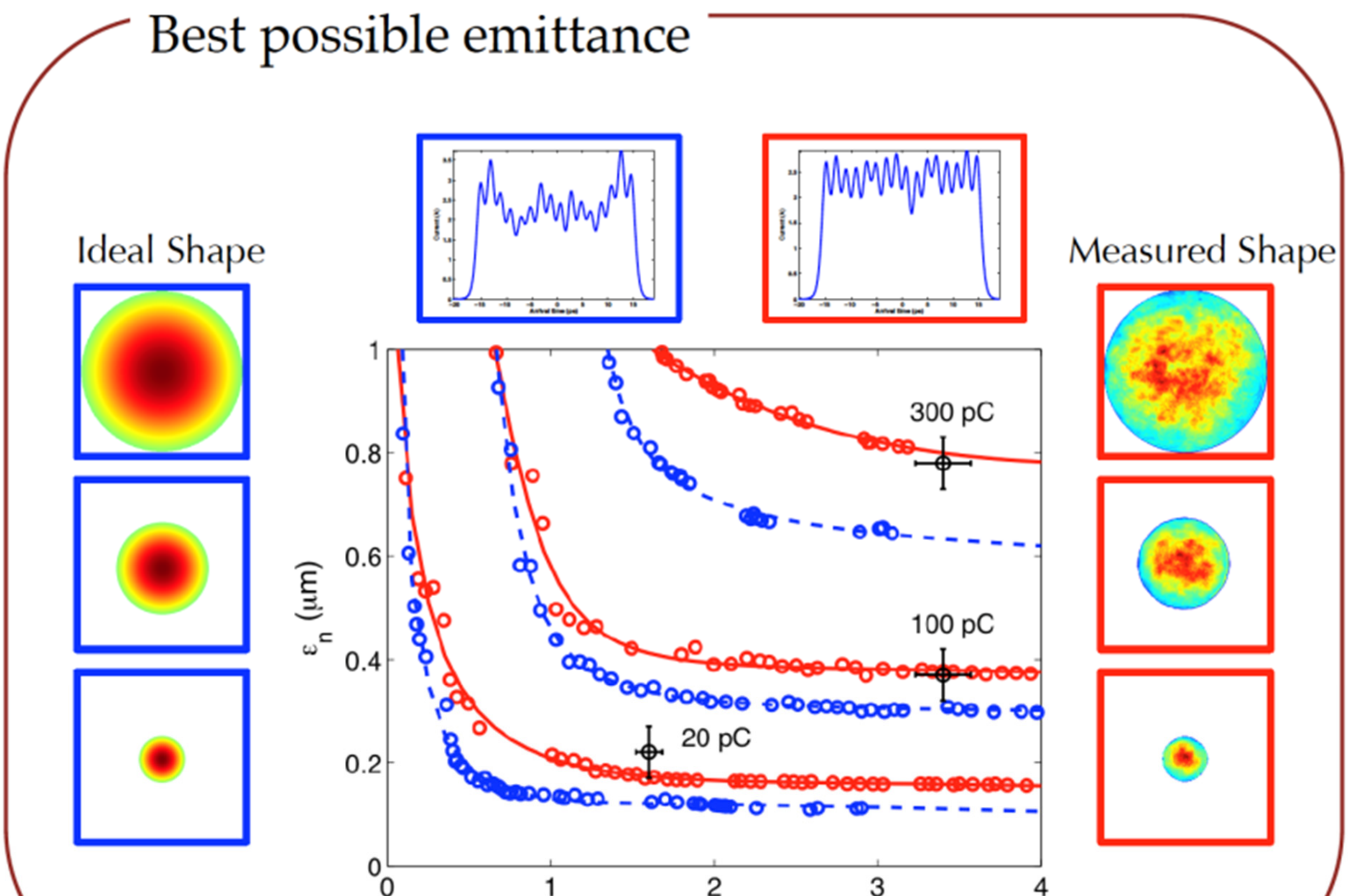
Previous Injector Results

Best possible emittance



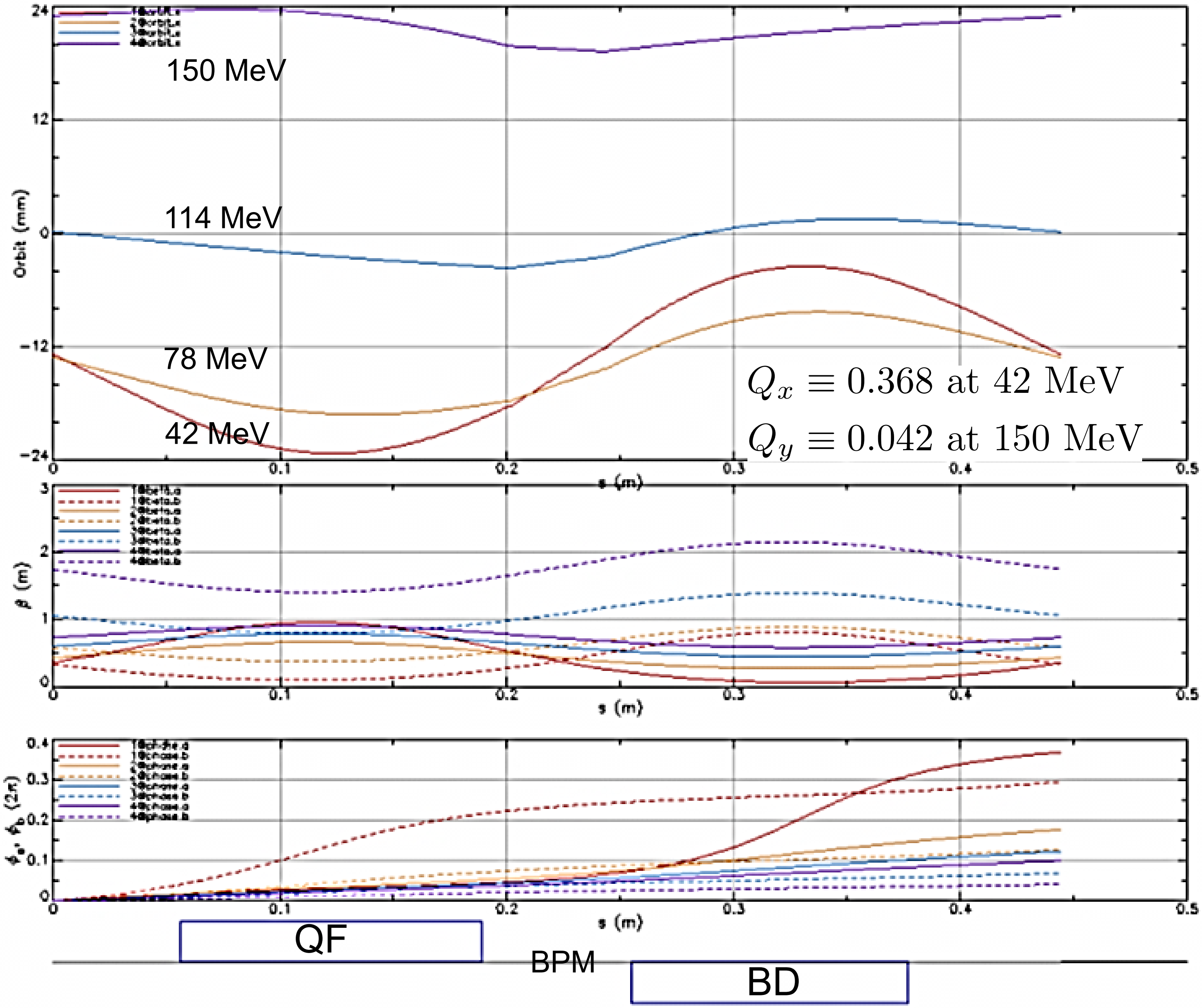
Christopher Mayes – June 25, 2015

Previous Injector Results

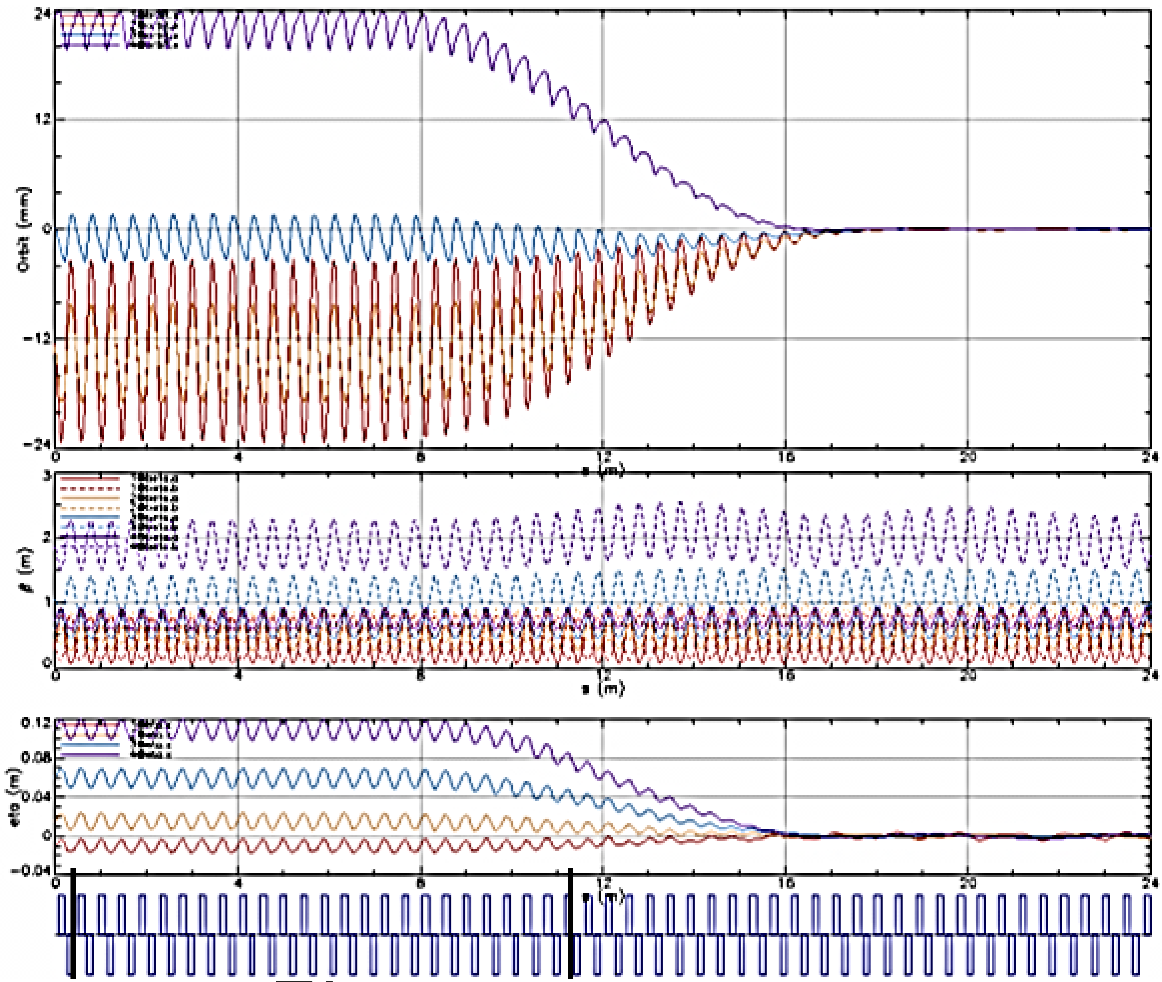


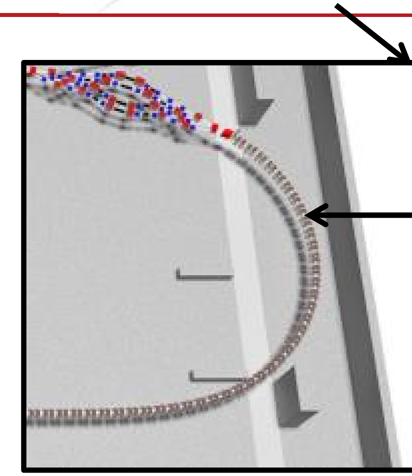
The Cornell gun holds the world record in sustained current of up to 75mA.

FFAG Arc Cell (5 deg)



Designed FFAG Arc, transition, straight



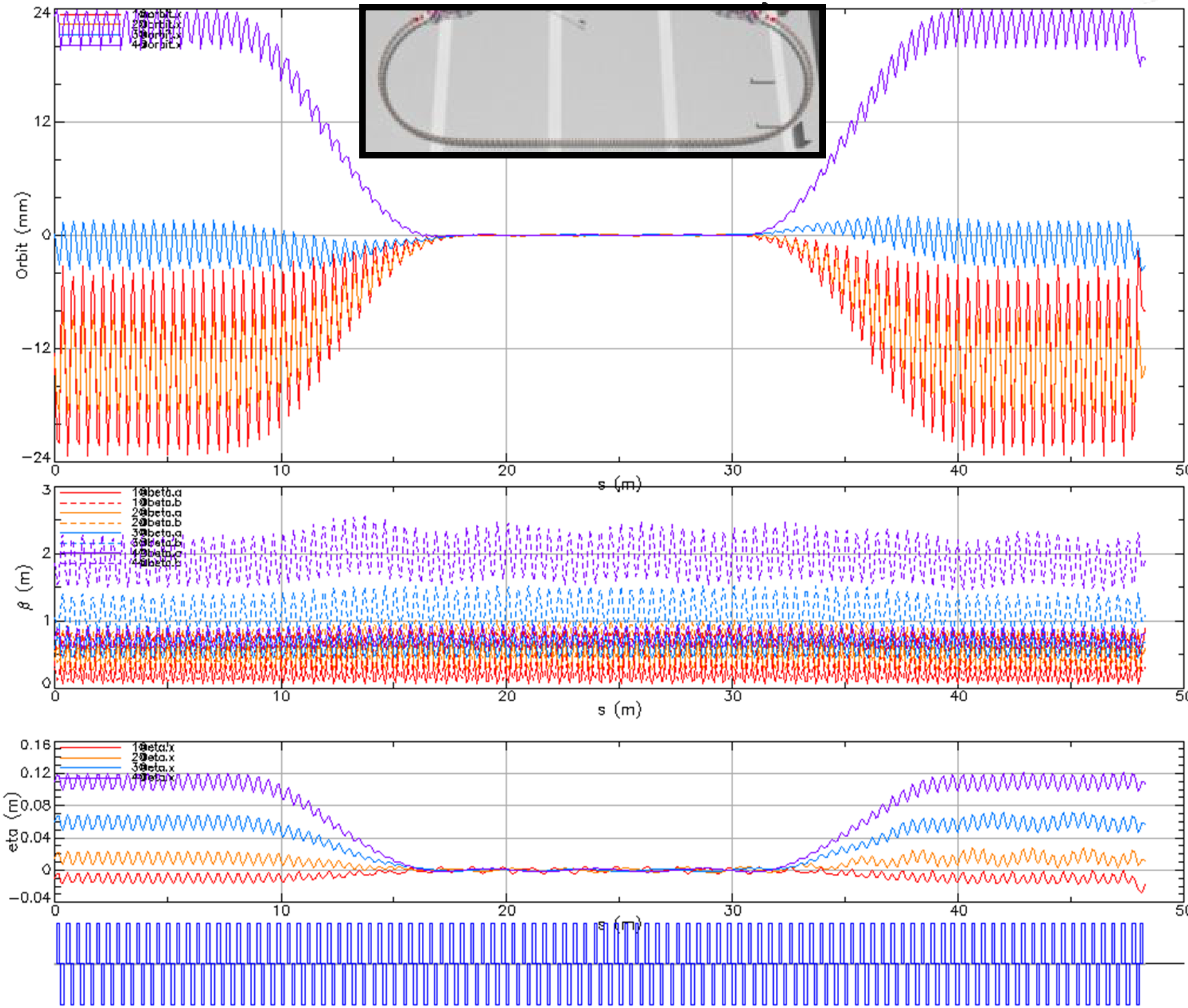


FA TA ZA

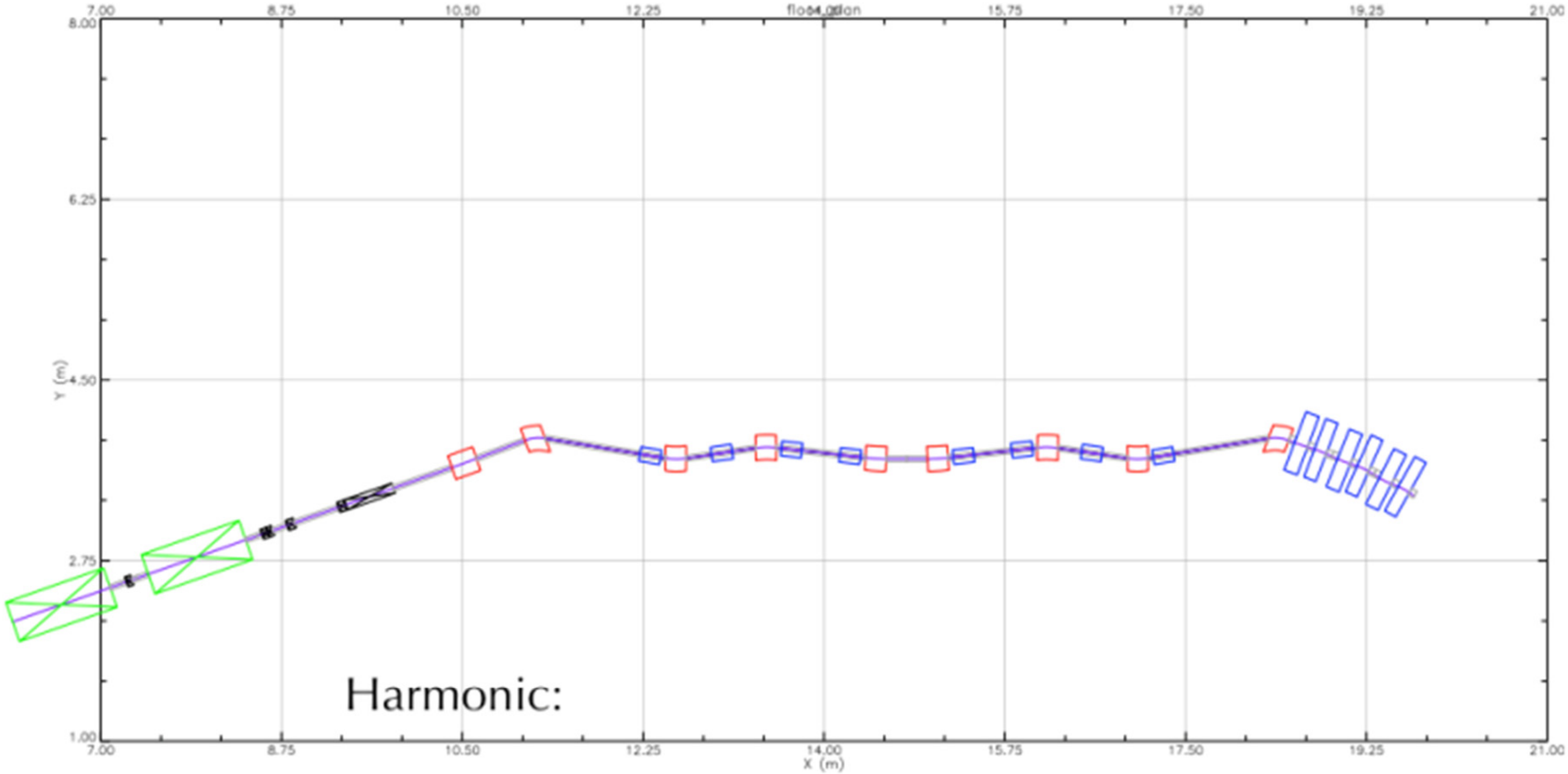
Offsets, angles scaled by factor:

$$f(x) = 1 - x + (1/2 - x)x(1-x)[1.788 + 3.954x(1-x) + 6.58x^2(1-x)^2]$$

Full FFAG Arc

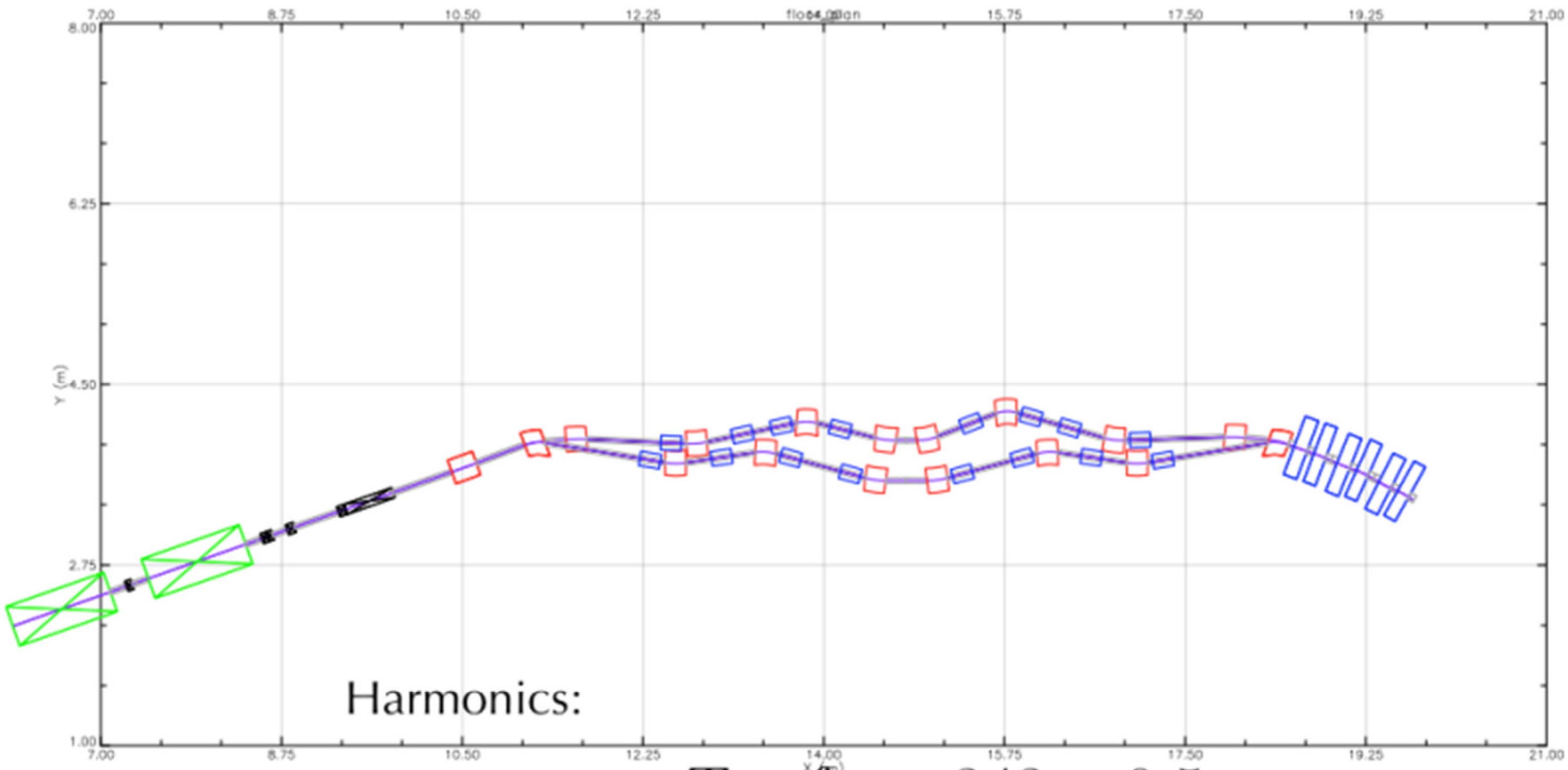


SPLITTER: Path length: 1-pass



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

SPLITTER: Path length: 1-pass

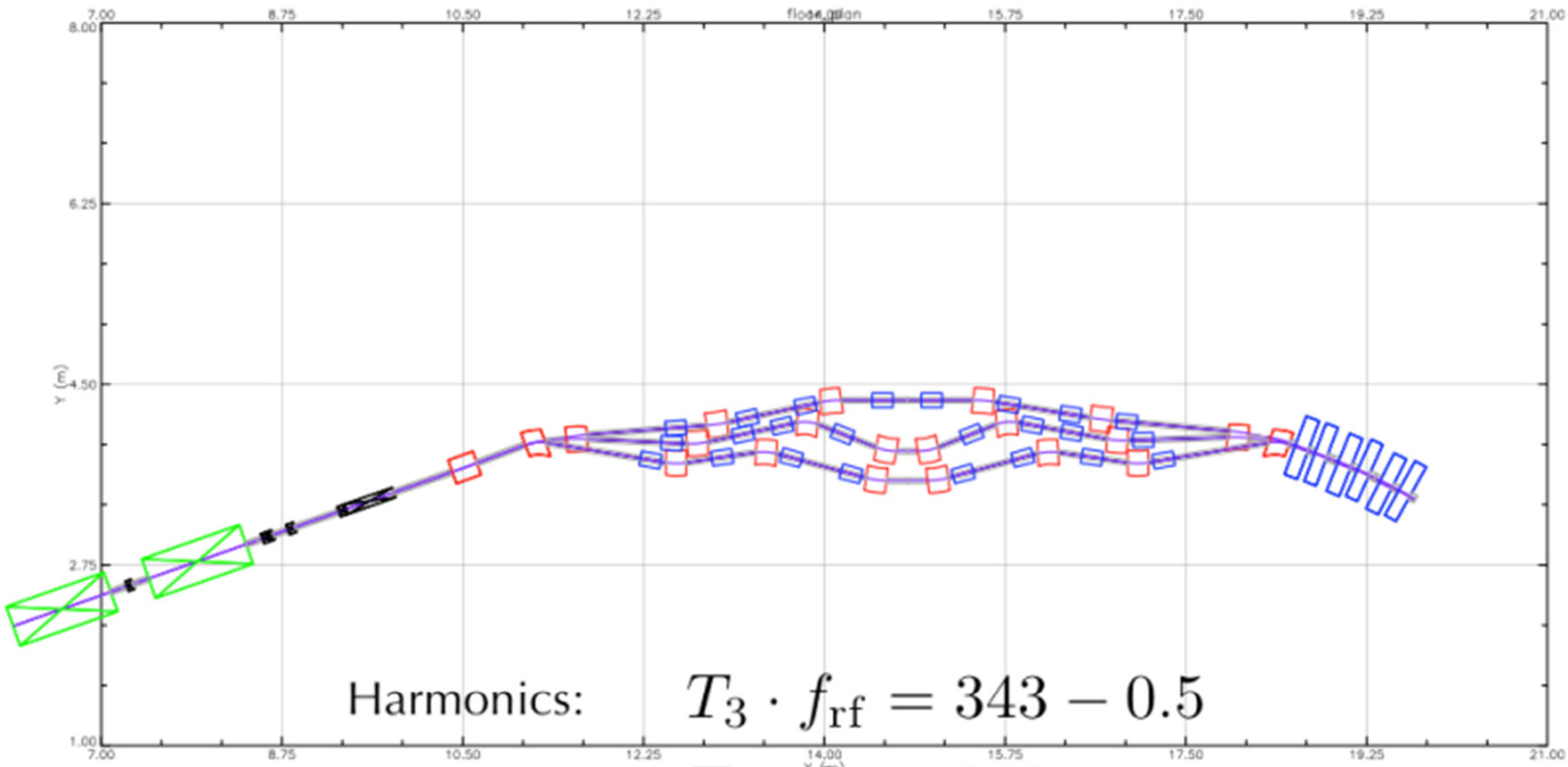


Harmonics:

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

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

SPLITTER: Path length: 1-pass



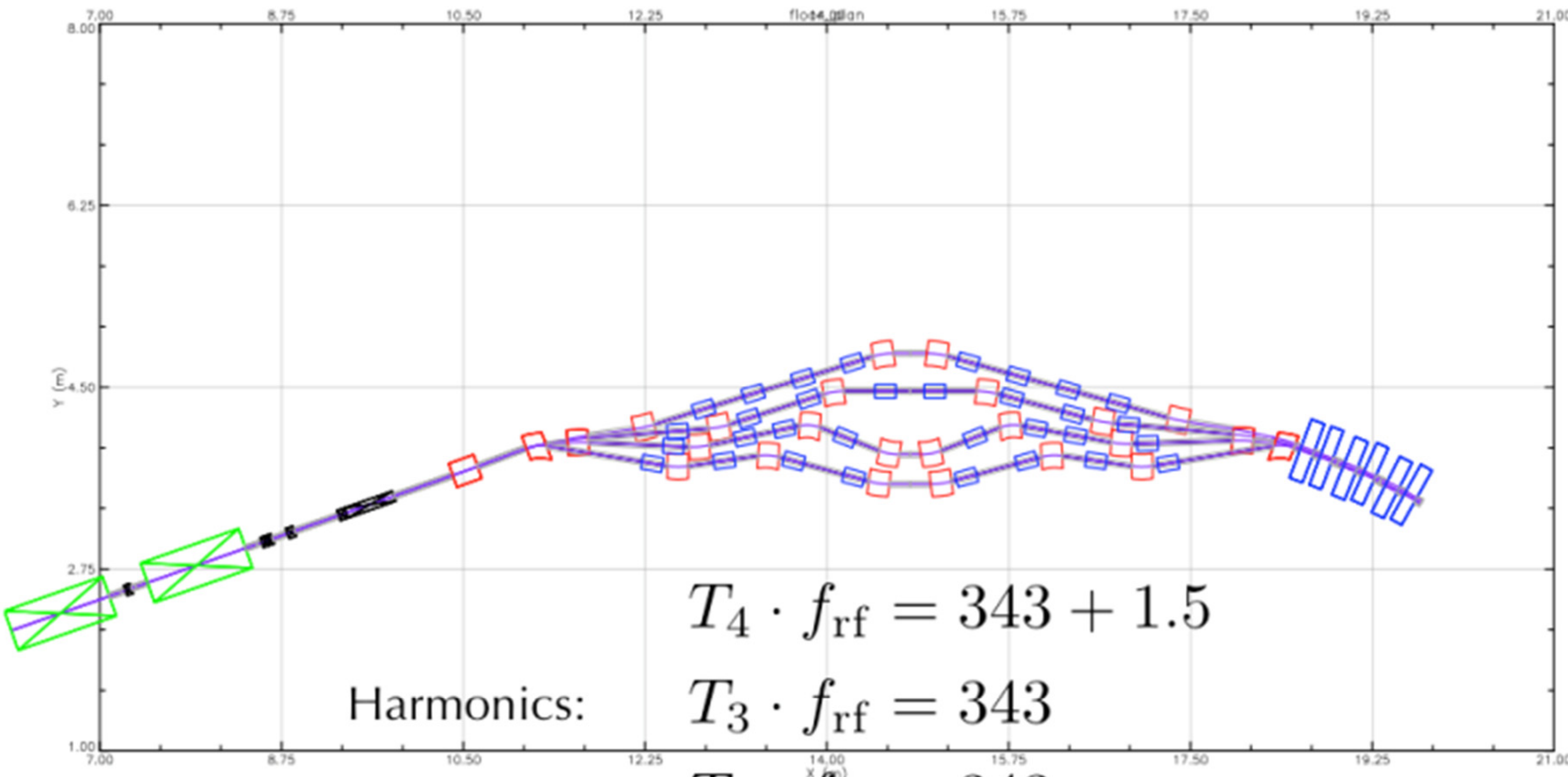
Harmonics:

$$T_3 \cdot f_{\mathrm{rf}} = 343 - 0.5$$

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

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

SPLITTER: Path length: 1-pass



Harmonics:

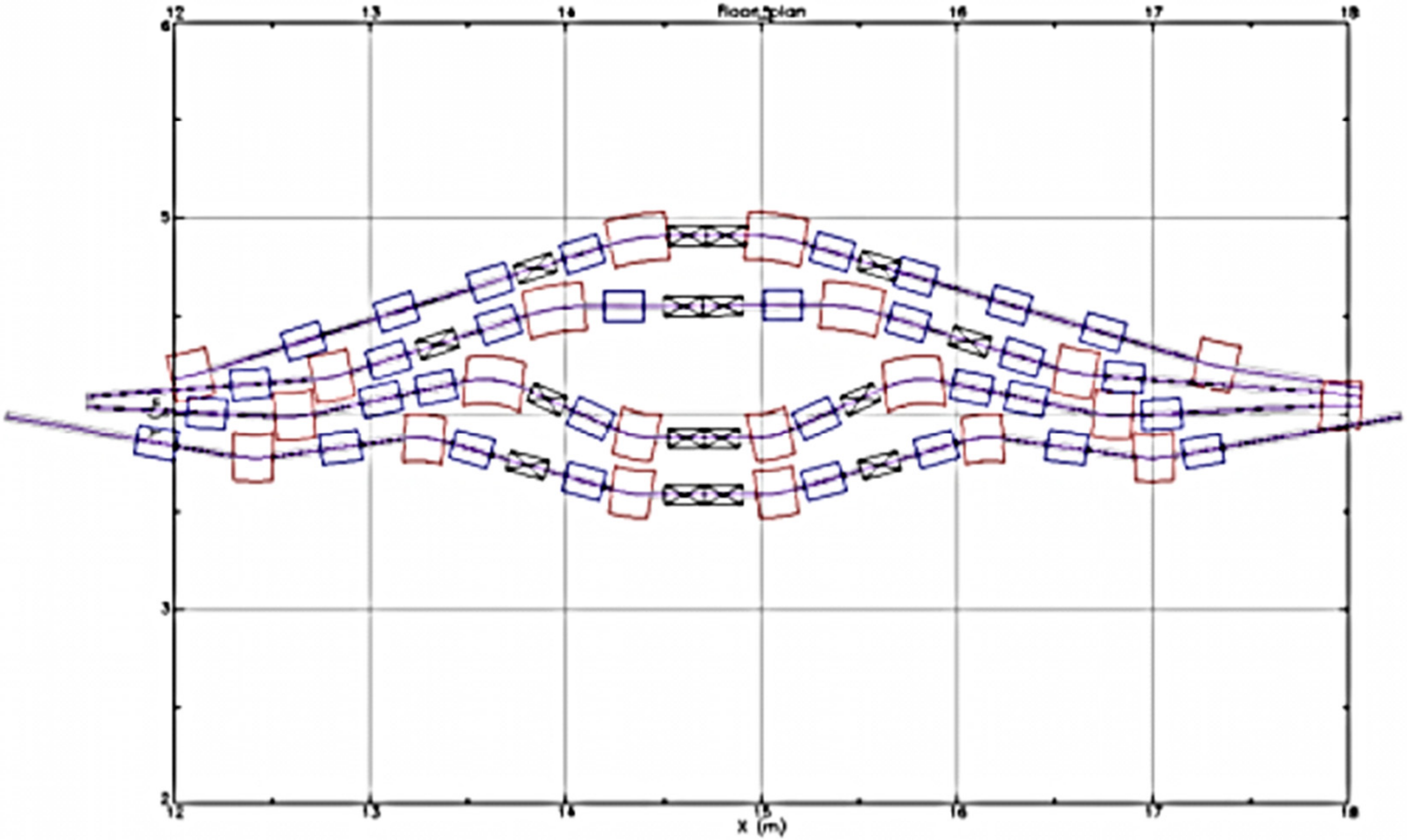
$$T_4 \cdot f_{\mathrm{rf}} = 343 + 1.5$$

$$T_3 \cdot f_{\mathrm{rf}} = 343$$

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

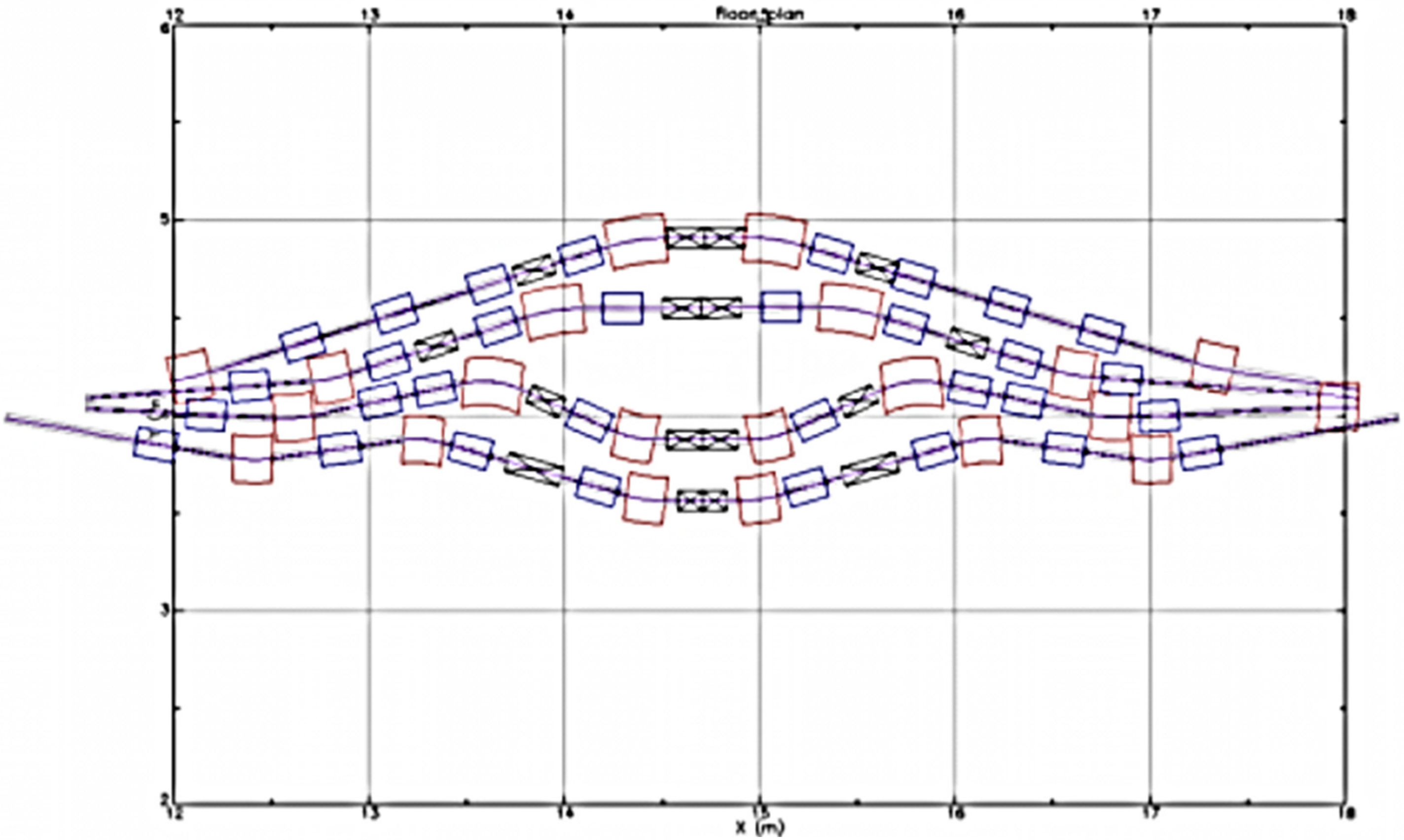
$$T_1 \cdot f_{\mathrm{rf}} = 343$$

Path length: 1-pass ERL



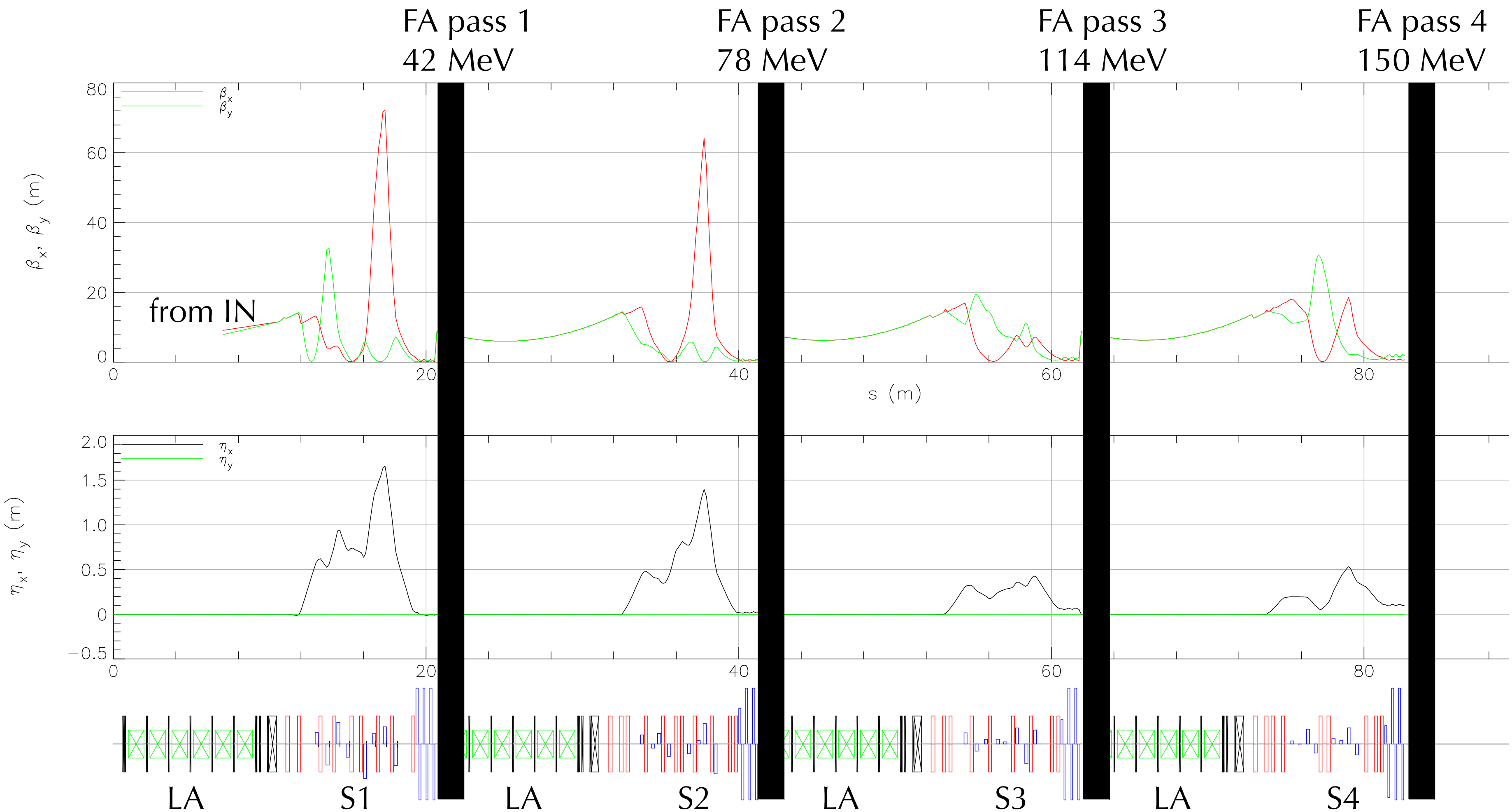
Path length: 1-pass ERL

ADJUSTMENT OF THE PATH LENGTH AFTER THE FIRST PASS IS COMMISSIONED



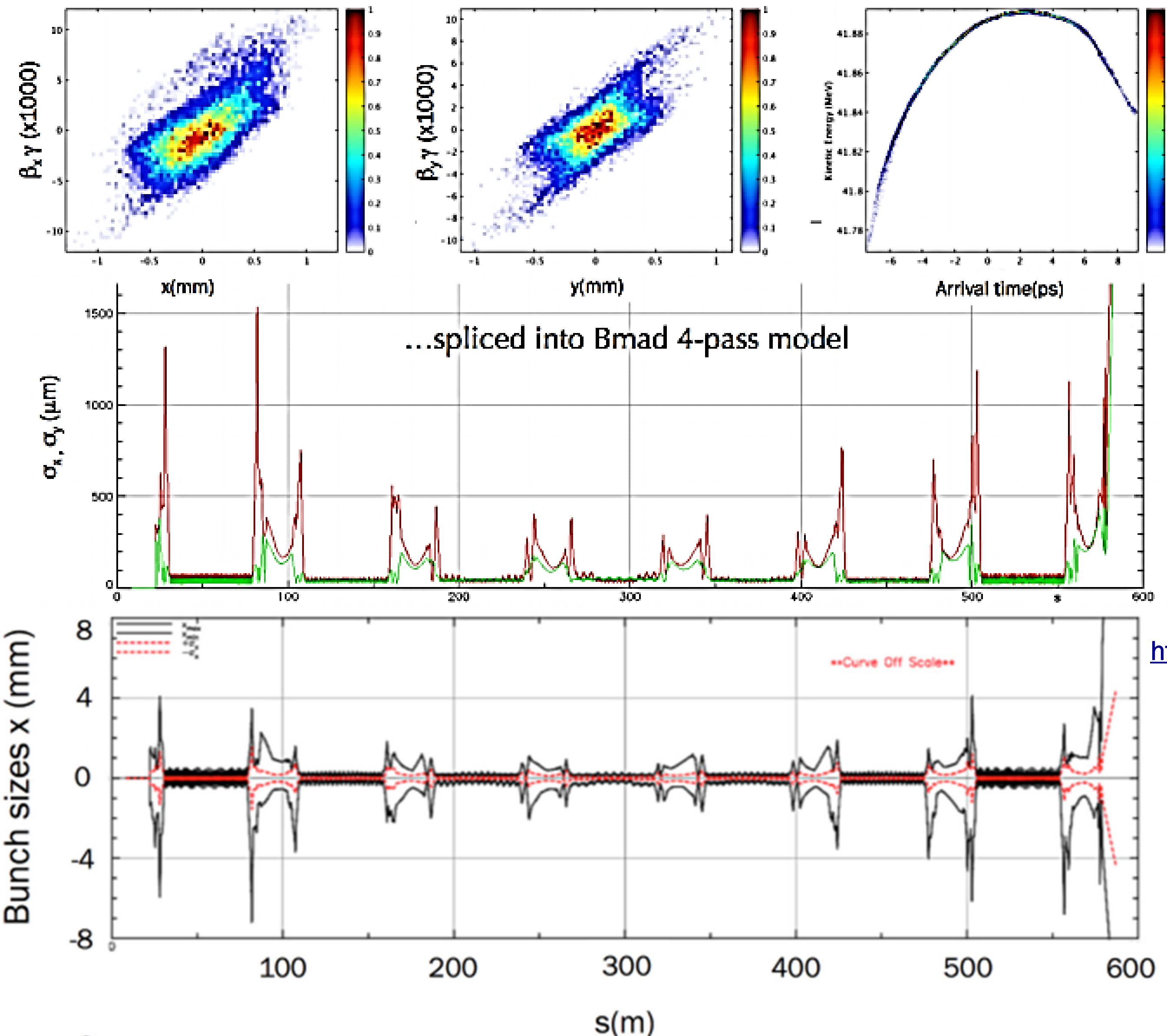
+ 10/360 * Rf wavelength

Splitter optics for each pass



Start-to-End tracking

100 pC bunch calculated from GPT with space charge



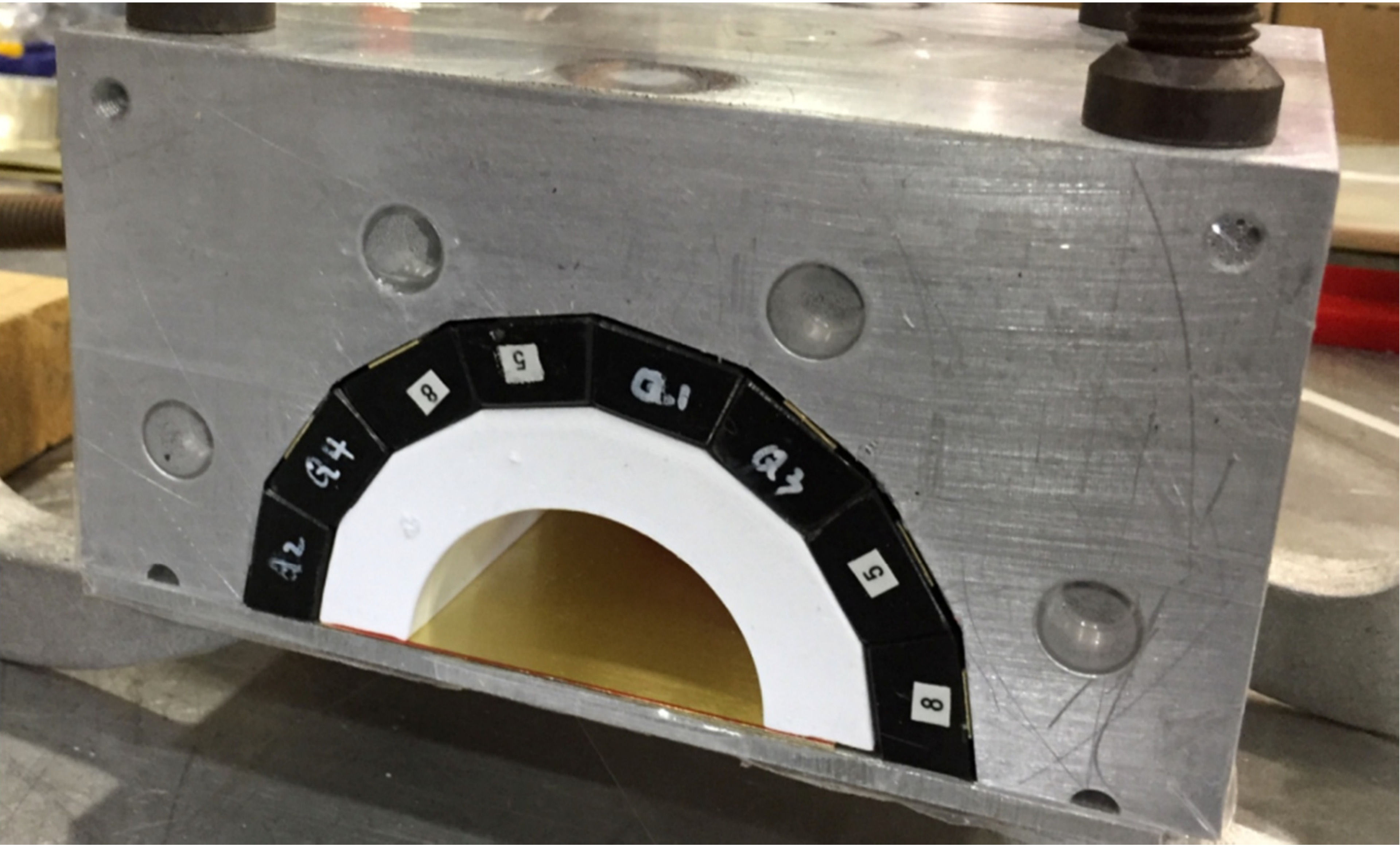
GPT -S.B. van der Geer GENERAL PARTICLE TRACER: A 3D CODE FOR ACCELERATOR AND BEAM LINE DESIGN

Bmad – David Sagan

Chris Mayes results

http://www.lepp.cornell.edu/~dcs/bmad

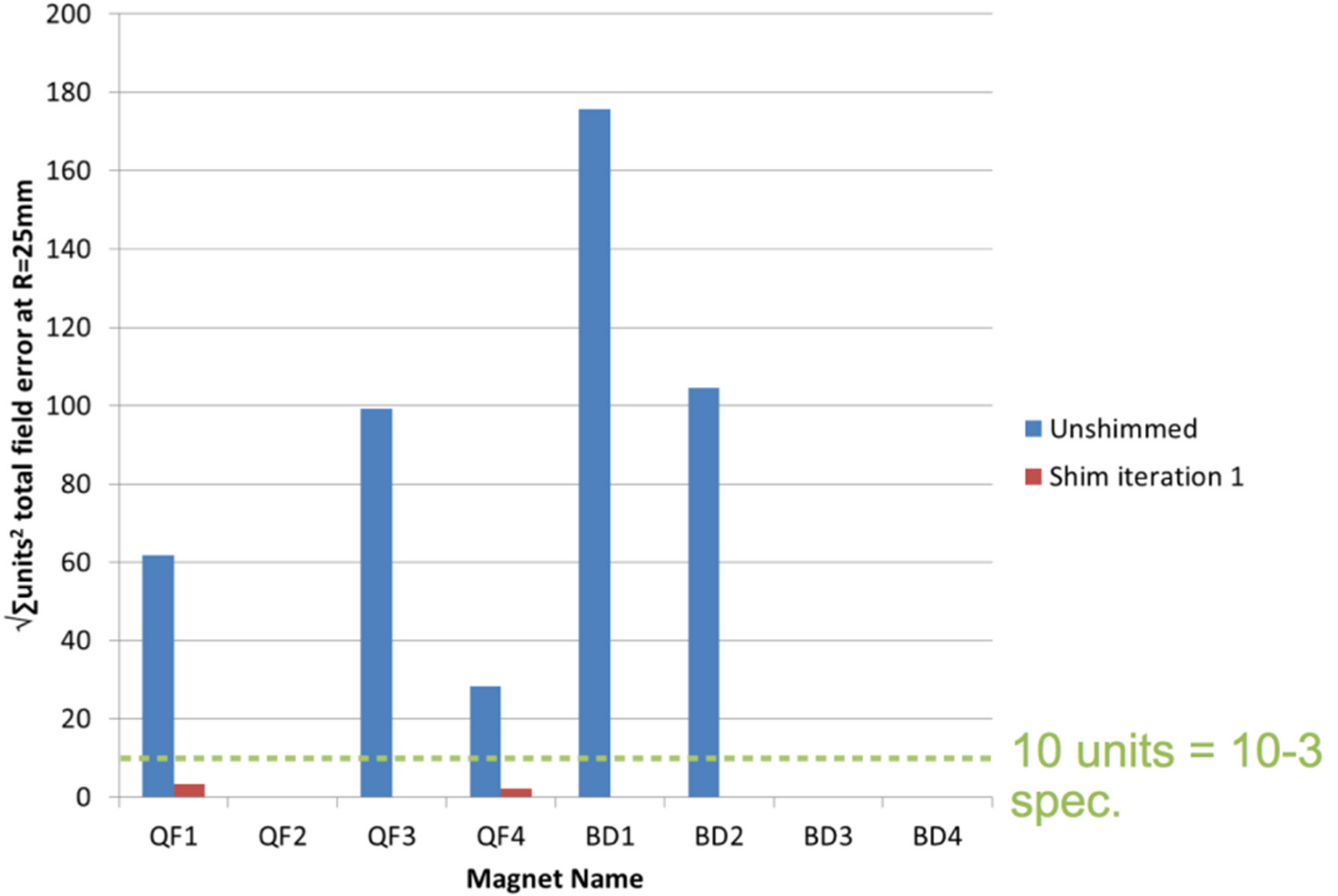
CBETA PROGRESS REPORT

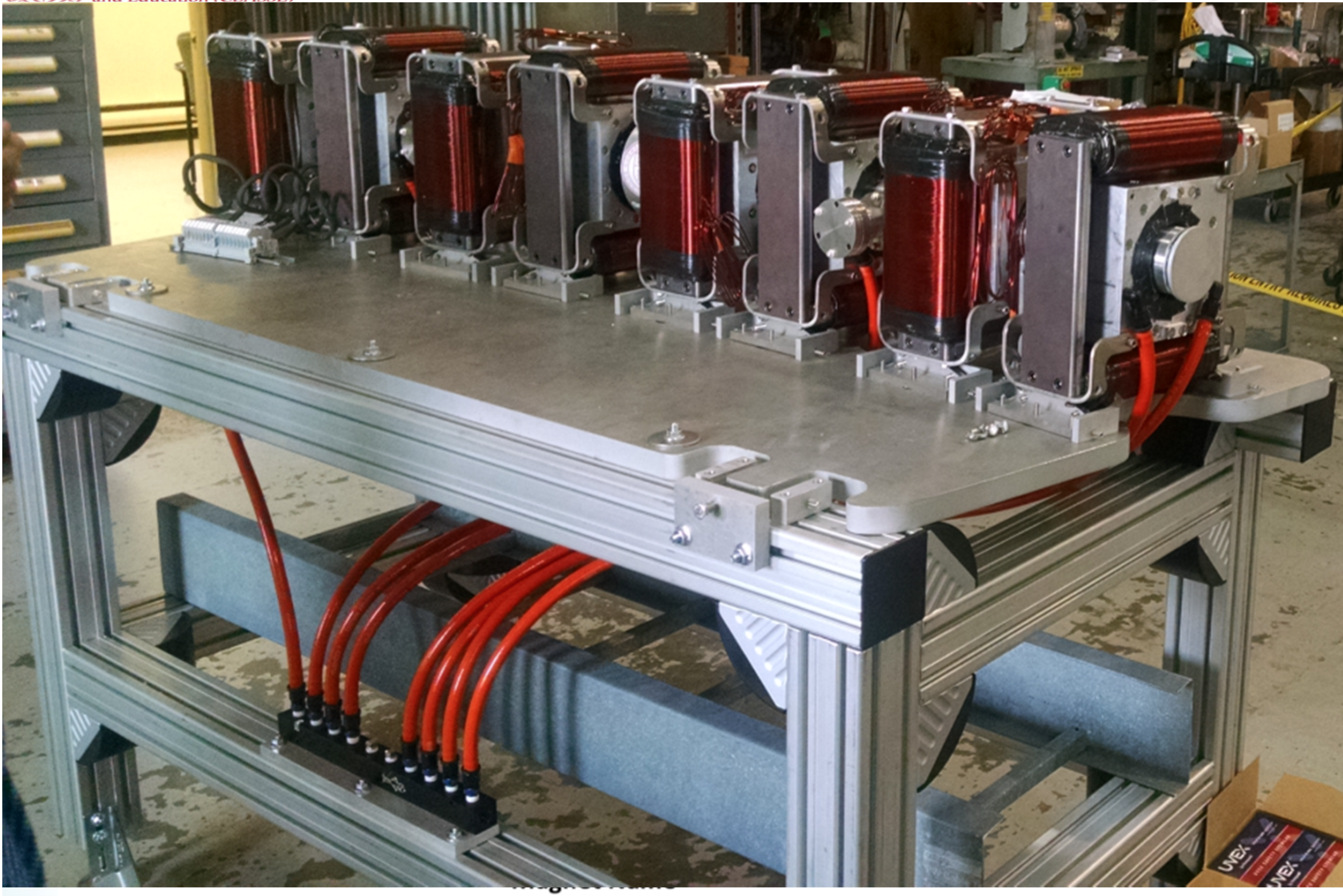


CBETA PROGRESS REPORT


CBETA First
GIRDER
QF1

CBETA PROGRESS REPORT





Technical Milestones

The 42-month timeline of milestones includes 2 "go/no-go" milestones requested by NYSERDA: 4 & 6

#	NYSERDA milestone	Baseline	Actual	Forecast
	NYSERDA funding start date		31-Oct-16	
1	Engineering design documentation complete	31-Jan-17		31-Jan-17
2	Prototype girder assembled	30-Apr-17		30-Apr-17
3	Magnet production approved	30-Jun-17		30-Jun-17
4	**Beam through Main Linac Cryomodule**	**31-Aug-17**		**31-Aug-17**
5	First production hybrid magnet tested	31-Dec-17		31-Dec-17
6	**Fractional Arc Test: beam through MLC & girder**	**30-Apr-18**		**30-Apr-18**
7	Girder production run complete	30-Nov-18		30-Nov-18
8	Final assembly & pre-beam commissioning complete	28-Feb-19		28-Feb-19
9	Single pass beam with factor of 2 energy scan	30-Jun-18		30-Jun-18
10	Single pass beam with energy recovery	31-Oct-19		31-Oct-19
11	Four pass beam with energy recovery (low current)	31-Dec-19		31-Dec-19
12	Project complete	30-Apr-20		30-Apr-20

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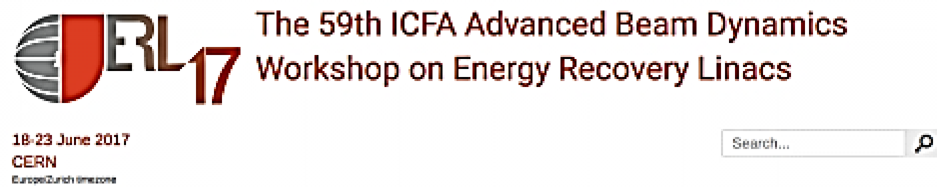
THIS IS ACTUALLY HAPPENING RIGHT NOW

ERL and FFAG Workshops

https://home.cern/cern-people/announcements/2017/01/59th-icfa-advanced-beam-dynamics-workshop-18-23-june-2017



https://www.bnl.gov/ffag17/participantinfo.php