A Novel Use of FFAGs in ERLs - in Colliders: eRHIC-LHeC and a Prototype at Cornell University

Dejan Trbojevic

Abstract:

The future Electron Ion Collider (EIC) ***LHeC*** *will be able to collide electrons with protons/ions, while the* ***eRHIC*** *will have additional ability to collide* ***polarized electron*** *with* ***polarized*** *proton/He3^{+}to study origin of the proton spin. Electron acceleration is based on a concept of Energy Recovery Linacs (**ERL**) with maximum energies of 60 GeV for LHeC and 20 GeV for eRHIC. It will almost completely recover electron energy during* ***deceleration*** *to the initial energy. We present: LHeC, eRHIC, an ERL at Cornell University the eRHIC prototype. An example of the LHeC* ***with almost doubling a reduction in size of the linac****, from* ***2 x 10 GeV*** *to* ***2 x 5.345 GeV*** *from the present LHeC solution, using two NS-FFAG's beam lines. This* ***would reduce the three beam lines to two, and*** *raise the luminosity for* ***34%*** *as the electron current of 6.6 mA → 8.9 mA, due to the synchrotron radiation limit of 15 MW. For the LHeC FFAG solution with 2x5.345 GeV linacs the total synchrotron radiation loss for 25 mA is 36.4 MW. The eRHIC NS-FFAG is as well limited by the synchrotron radiation (limit set up to up to 3 MW). The Cornell ERL with the NS-FFAG should provide energy enhancement of four times.*

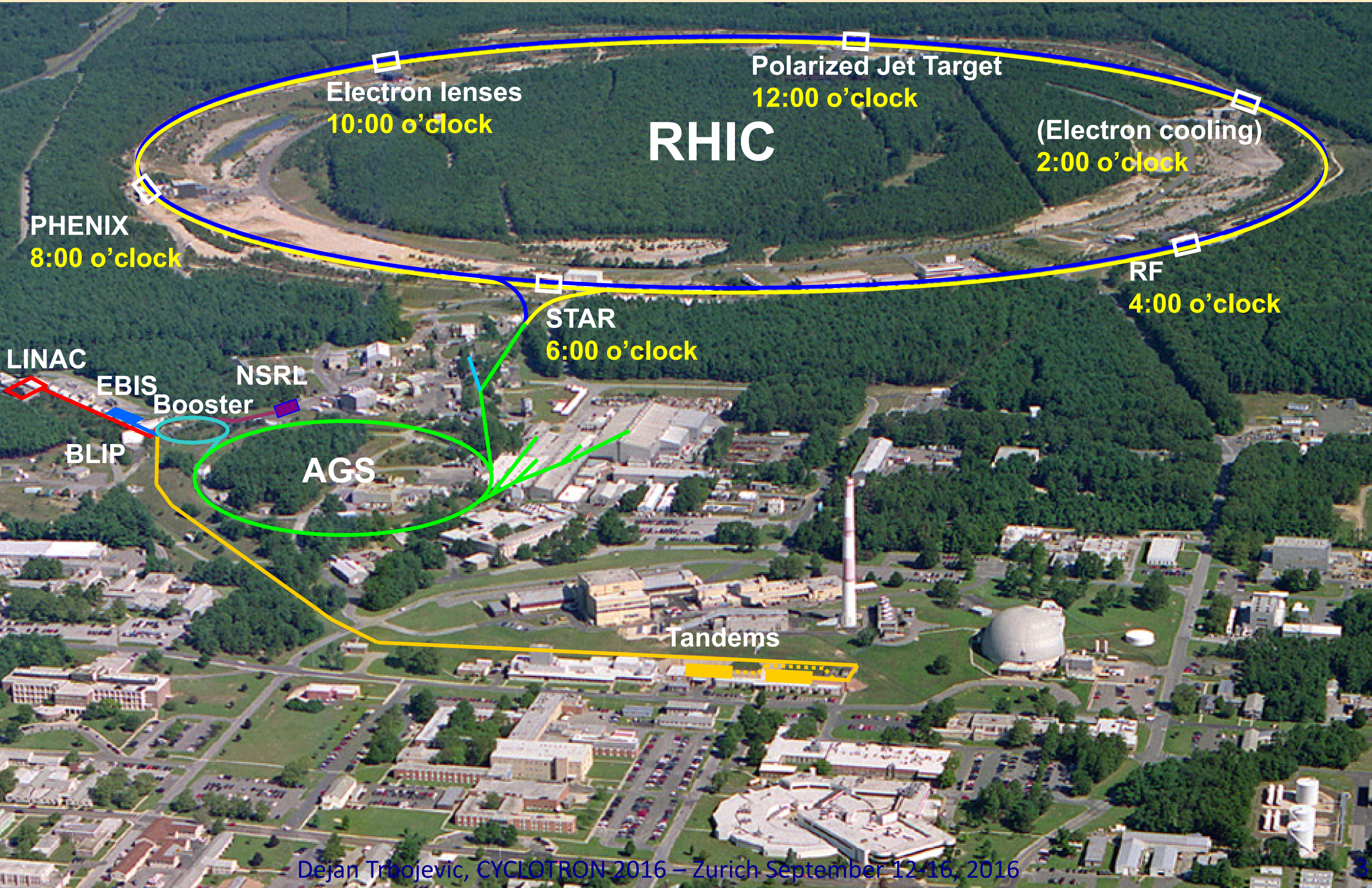
LHeC-eRHIC and CBETA

- Relativistic Heavy Ion Collider
- Why to build eRHIC and LHeC
- What is NS-FFAG?
- LHeC design and NS-FFAG proposal
- eRHIC NS-FFAG ERL proposal
- NS-FFAG eRHIC Design
- Cornell as eRHIC Proof of Principle
- Conclusion

CBETA:
Cornell
Brookhaven National Laboratory
ERL
Test
Accelerator

Relativistic Heavy Ion Collider

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



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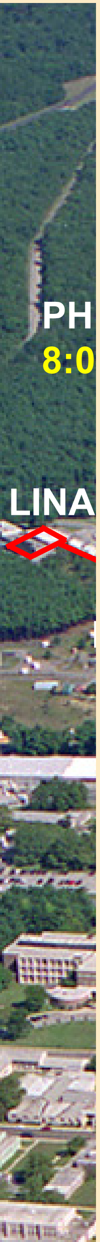
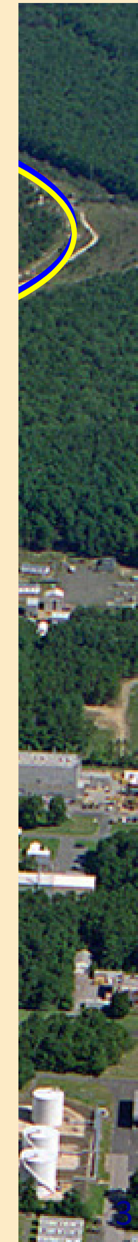


2 superconducting 3.8 km rings
2 large experiments (STAR – PHENIX)

100 GeV/nucleon ions up to U
255 GeV polarized protons

Performance defined by:

1. Luminosity *L*
2. Proton polarization *P*
3. Versatility (species, *E*)



Relativistic Heavy Ion Collider

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

Operated modes - beam energies

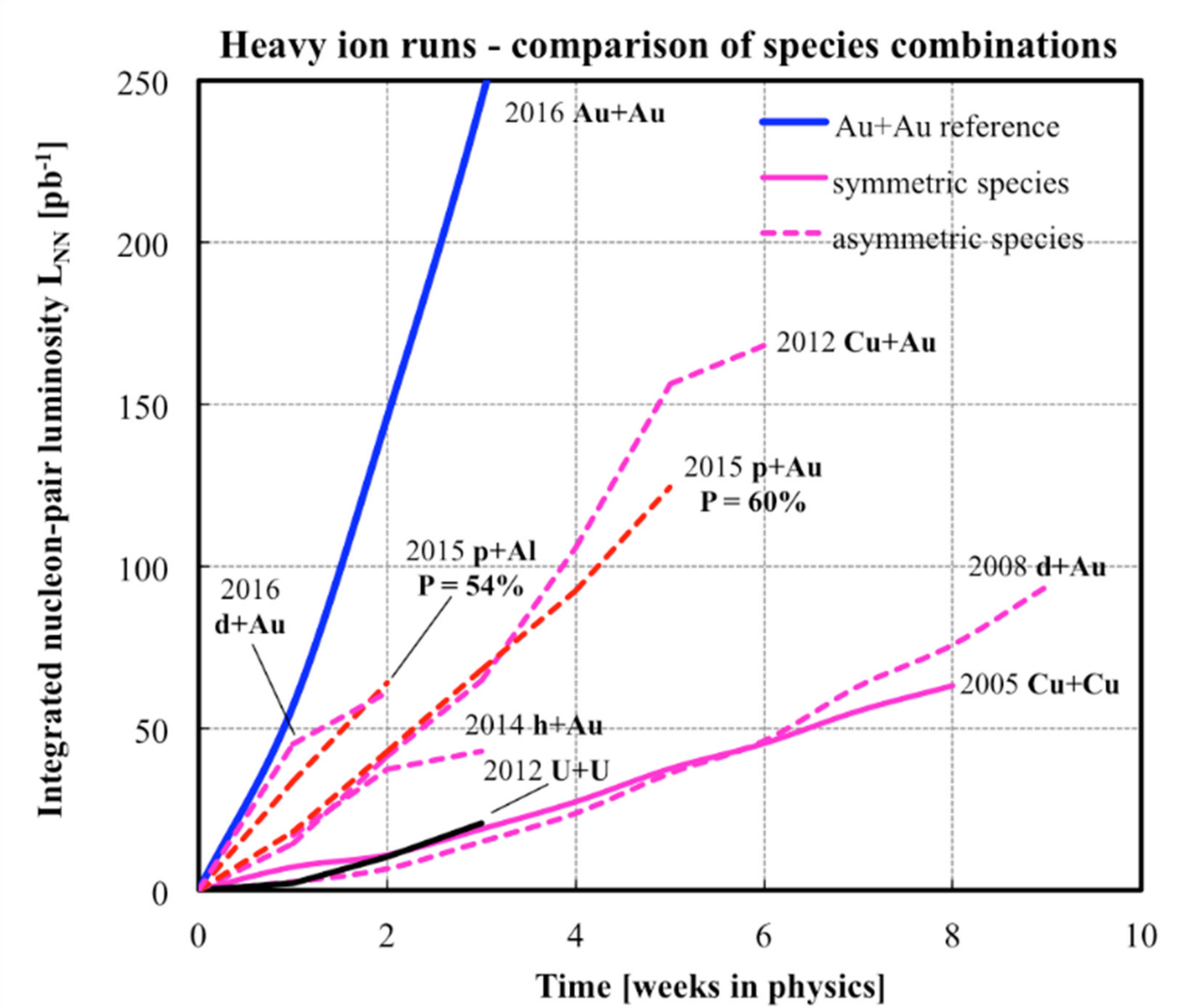
Au – Au	3.8/4.6/5.8/10/14/32/65/100 GeV/n
U – U	96.4 GeV/n
Cu – Cu	11/31/100 GeV/n
p↑ – p↑	11/31/100/205/250/255 GeV
d – Au*	100 GeV/n
Cu – Au*	100 GeV/n

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)

Relativistic Heavy Ion Collider

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



Relativistic Heavy Ion Collider

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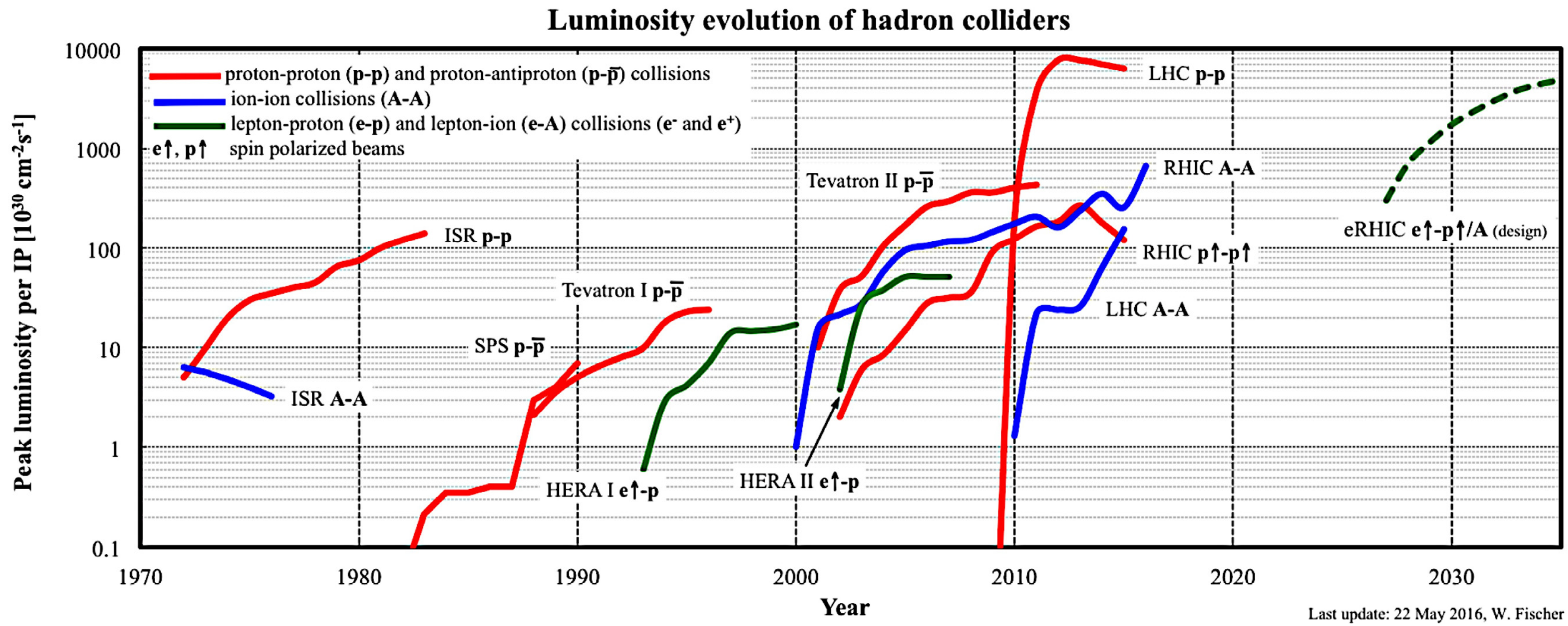
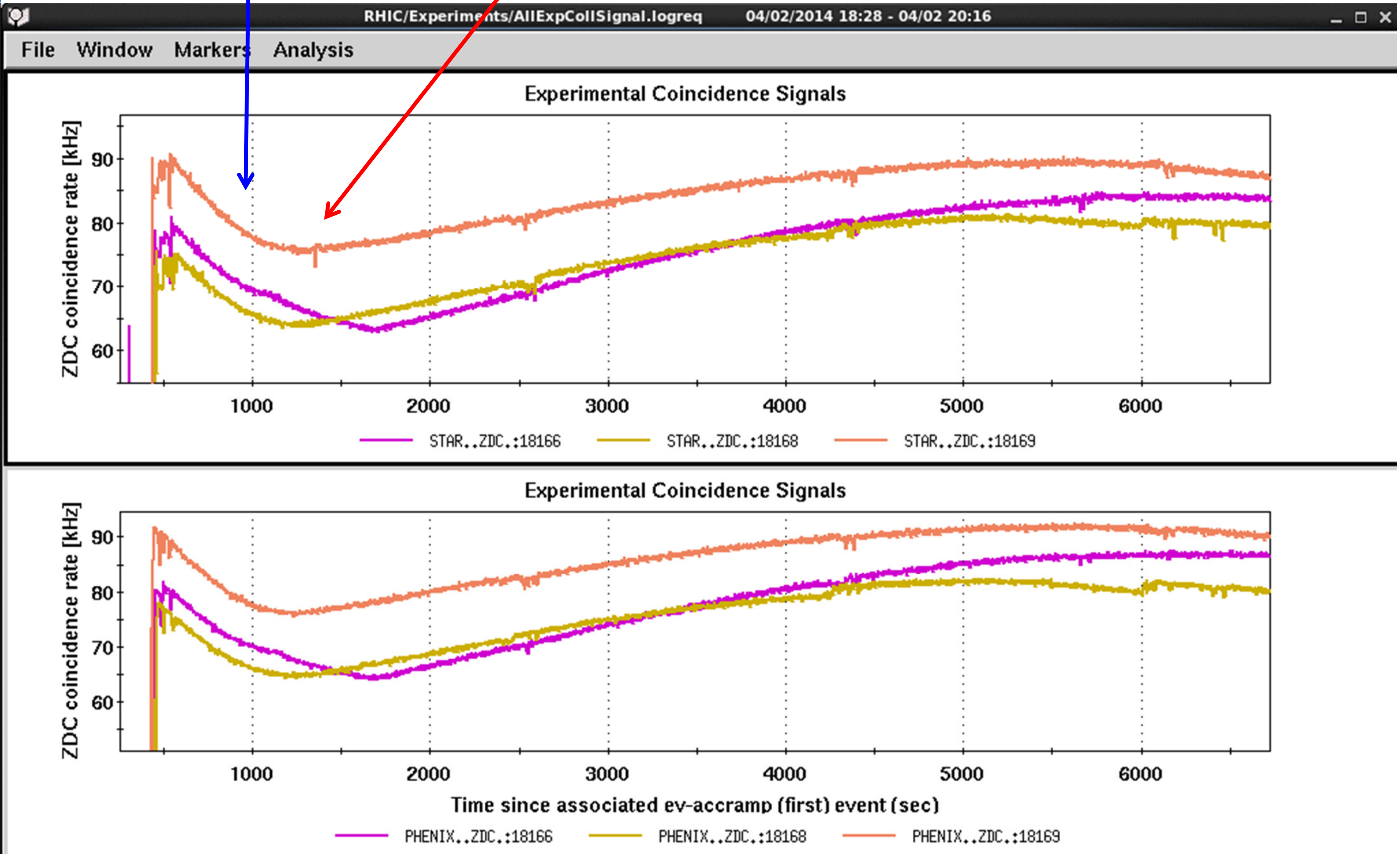


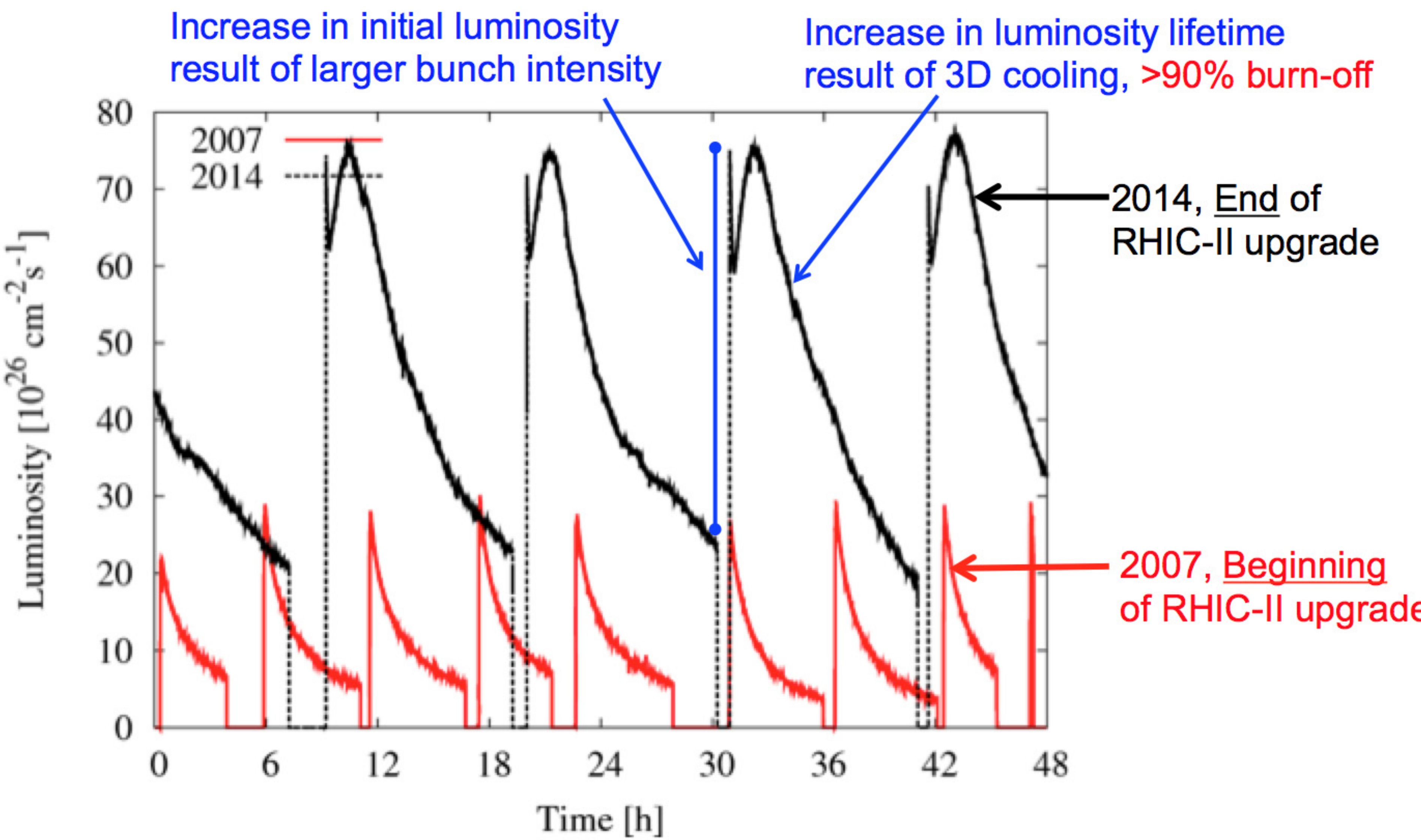
Note: For ion collisions the nucleon-pair luminosity is shown. The nucleon-pair luminosity is defined as $L_{NN} = A_1 A_2 L$, where L is the luminosity, and A_1 and A_2 are the number of nucleons of the ions in the two beam respectively. The highest energies for the machines are: ISR 31 GeV, SPS 315 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.

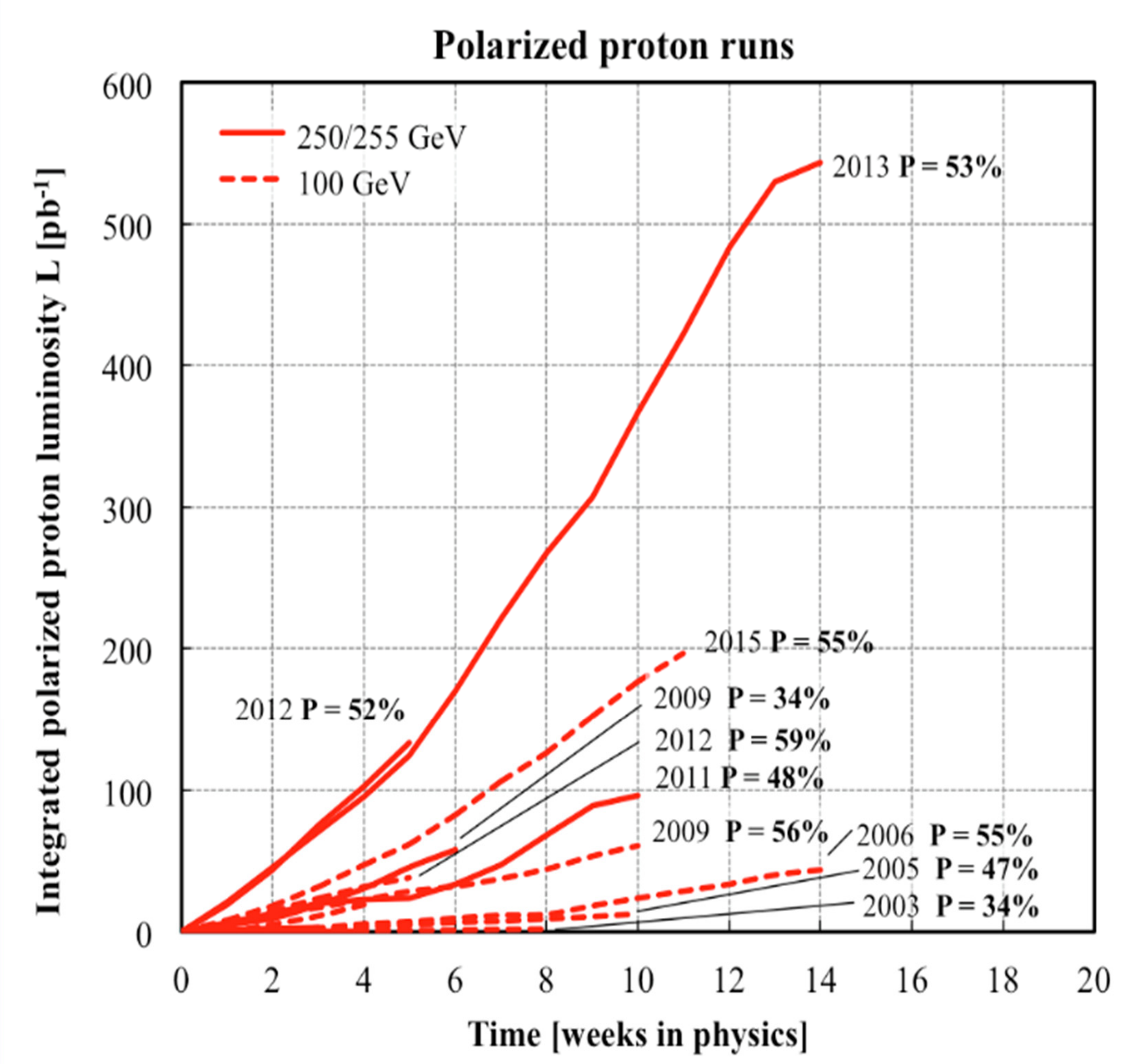
LUMINOSITY

Stochastic Cooling turned ON



RHIC Run-14 Delivering RHIC-II luminosity





Polarized proton runs
250/255 GeV
100 GeV
2013 P = 53%
2015 P = 55%
2009 P = 34%
2012 P = 59%
2011 P = 48%
2012 P = 52%
2009 P = 56%
2006 P = 55%
2005 P = 47%
2003 P = 34%
Integrated polarized proton luminosity L [pb-1]
Time [weeks in physics]
0
100
200
300
400
500
600
0
2
4
6
8
10
12
14
16
18
20

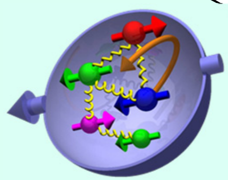
LHeC Physics

".. the LHeC there is an opportunity for energy frontier deep inelastic scattering to return to CERN in order to enrich the physics which has been made accessible by the Large Hadron Collider. Using a novel high energy electron beam scattered off LHC protons and also ions, the LHeC would represent ***the cleanest high resolution microscope in the world****, based on new principles which deserve to be developed"...*

.. "CERN with international partners is now evaluating ways of cooperation towards technical designs of the highest energy electron linac, with power recovery, and of a new detector which would enable ultra-precise, ***large acceptance deep inelastic scattering measurements****"...*

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

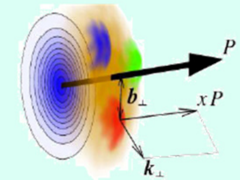
spin physics



- 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

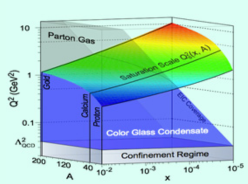


- what is the spatial distribution of quarks and gluons in nucleons/nuclei
- understand deep aspects of gauge theories revealed by k_T dep. distr'n

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

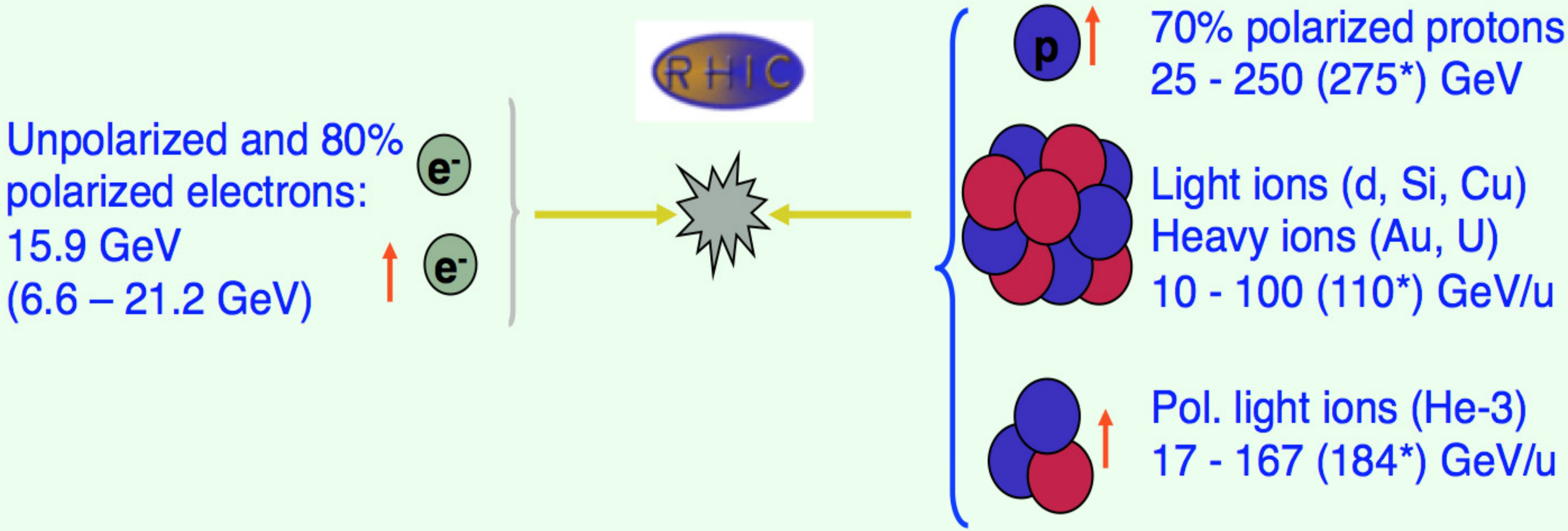
A Microscope for Gluons
AN ULTIMATE QCD LABORATORY

(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:

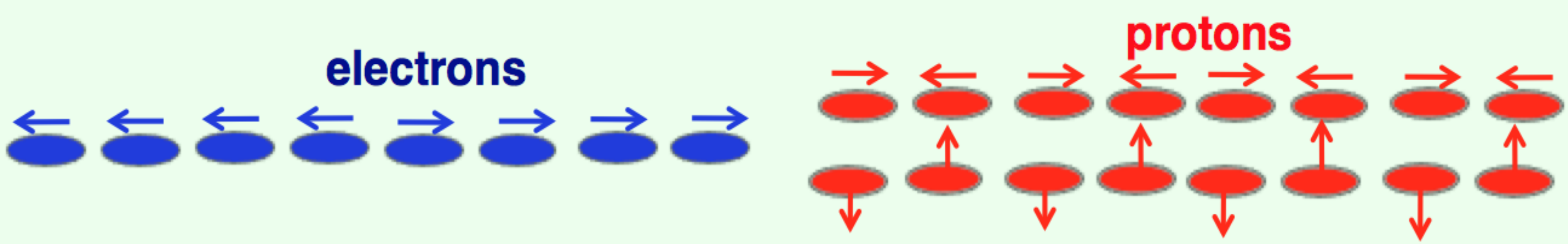
- The mass of the proton (and the visible universe)
- The spin of the proton
- The dynamics of quarks and gluons in nucleons and nuclei
- The formation of hadrons from quarks and gluons

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

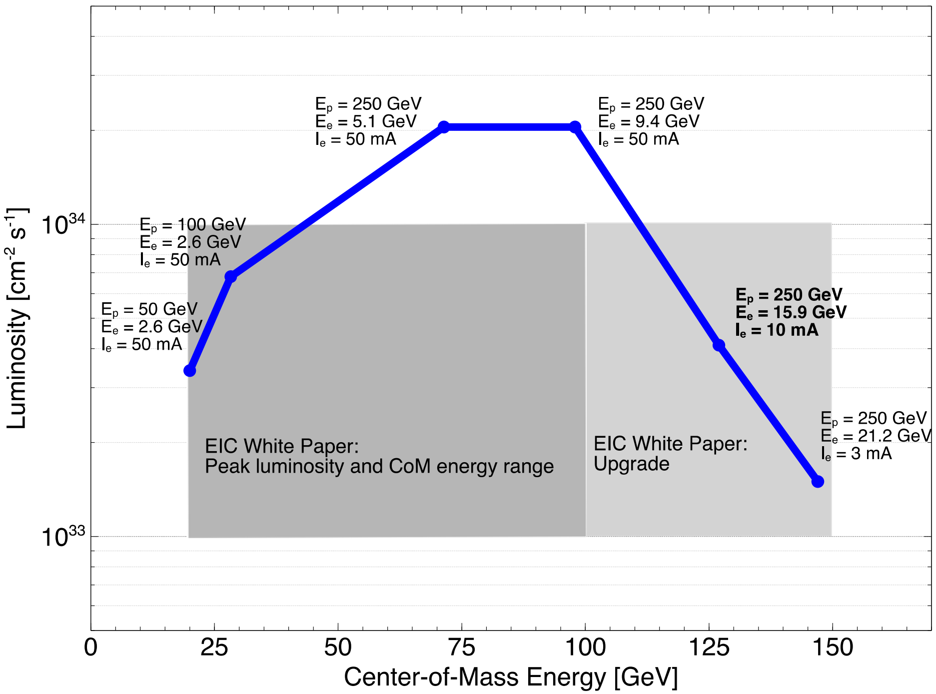


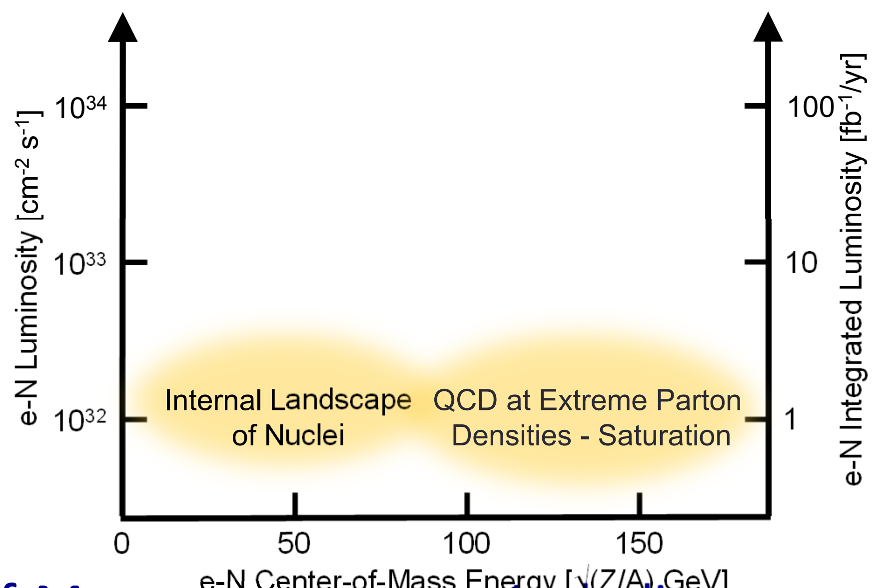
Center-of-mass energy range: 30 – 145 GeV

Any polarization direction in electron-hadron collisions



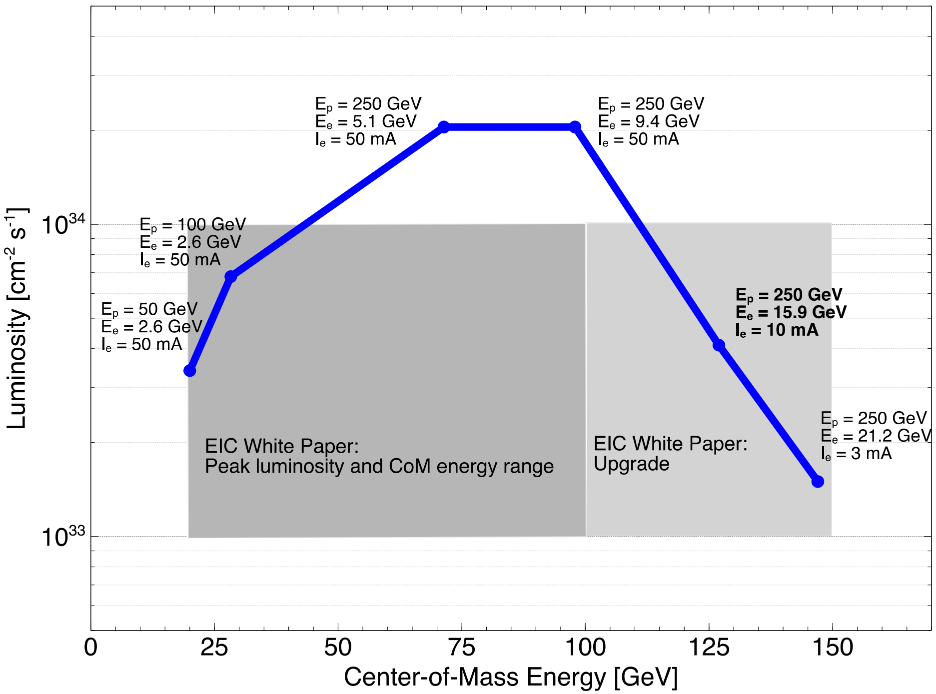
eRHIC peak luminosity vs. COM energy

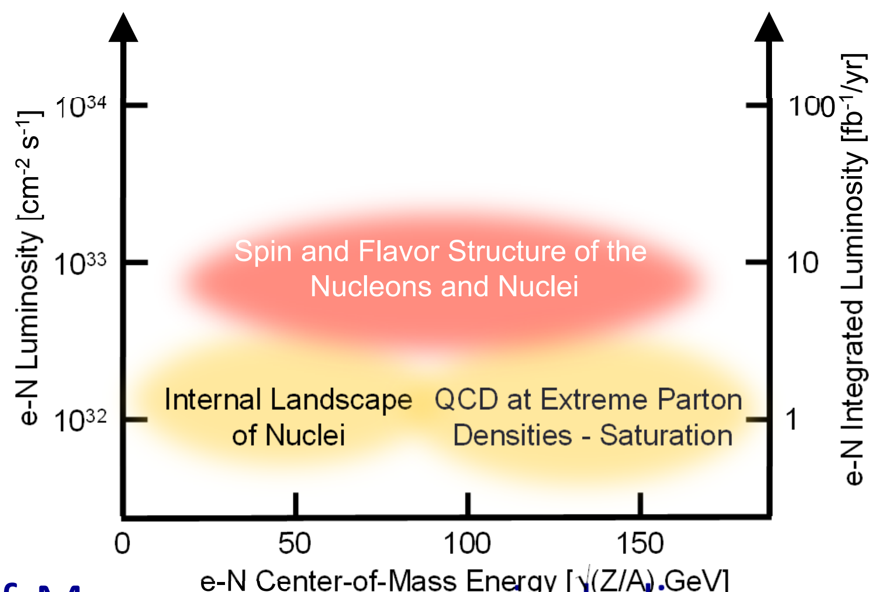




- eRHIC design covers whole Center-of-Mass energy range, including "EIC White Paper Upgrade" region
- Small beam emittances and IR design allows for full acceptance detector at full luminosity

eRHIC peak luminosity vs. COM energy





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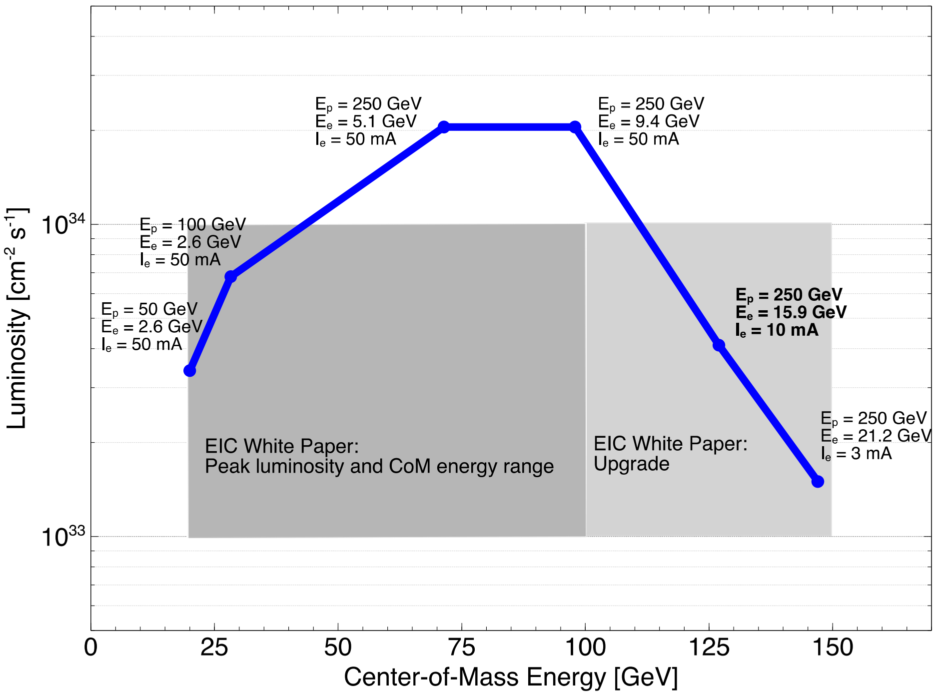

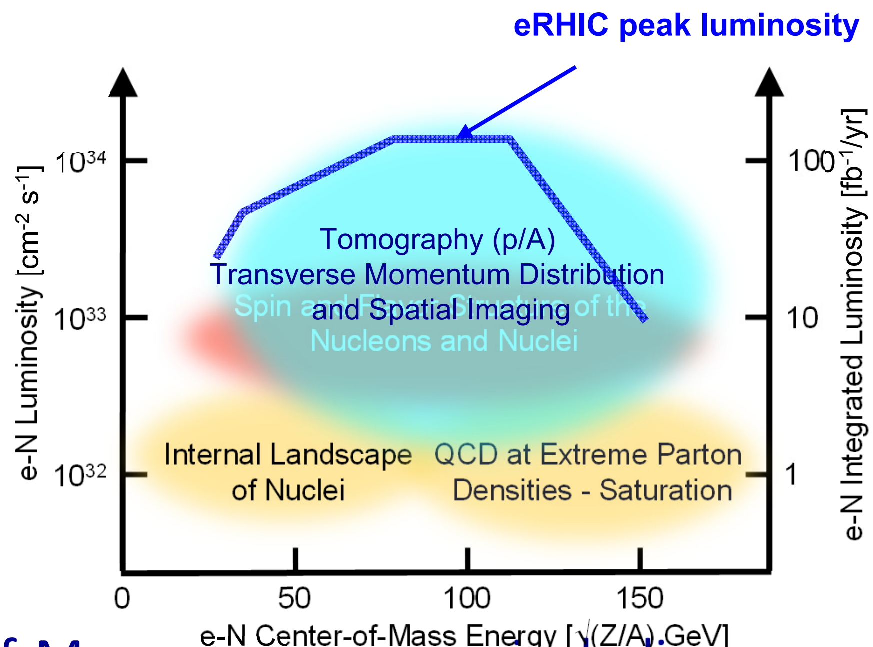

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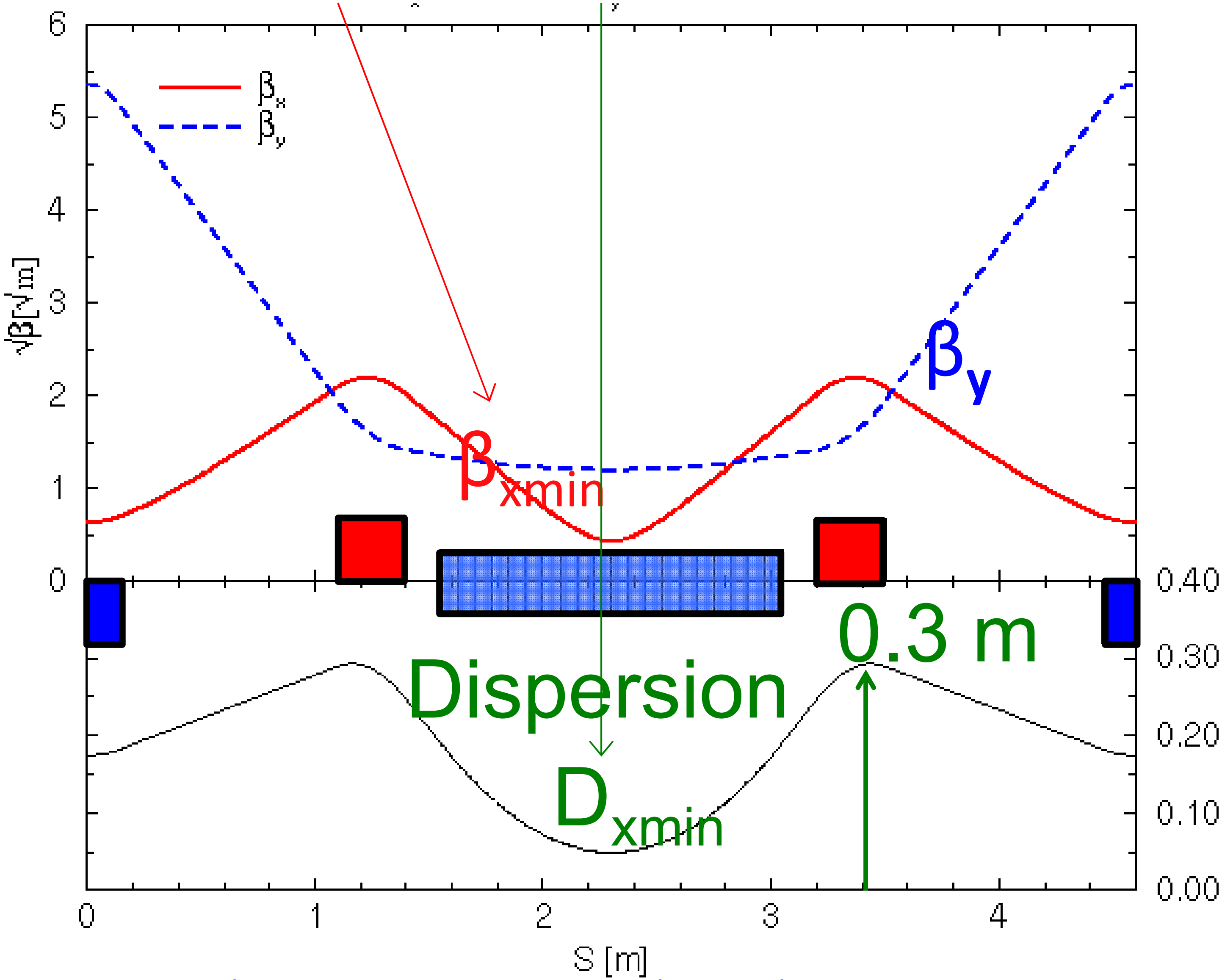
To minimize the dispersion function H the BENDING MAGNET (DEFOCUSING) should be in the centered in the cell with a minimum of $\beta_{xmin}=L_d/2\sqrt{15}$ and $D_{xmin}=\theta^* L_d/24$ @center



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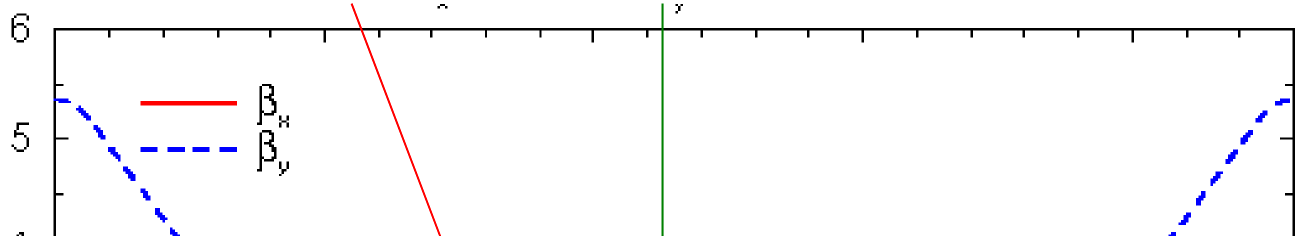
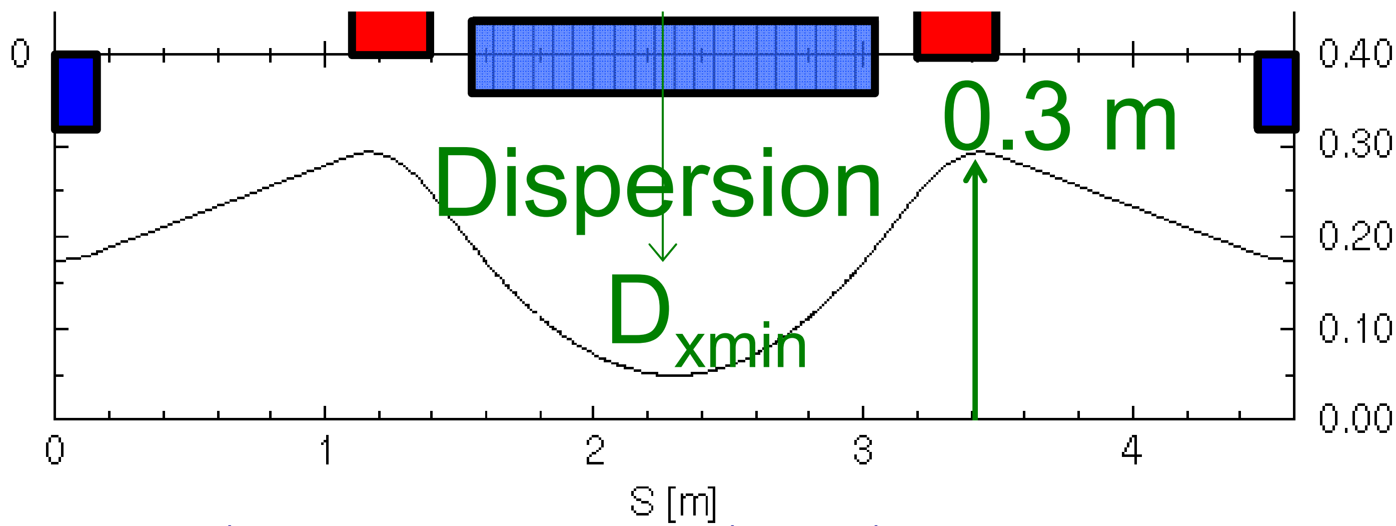


"FFAG Lattice Without Opposite Bends"

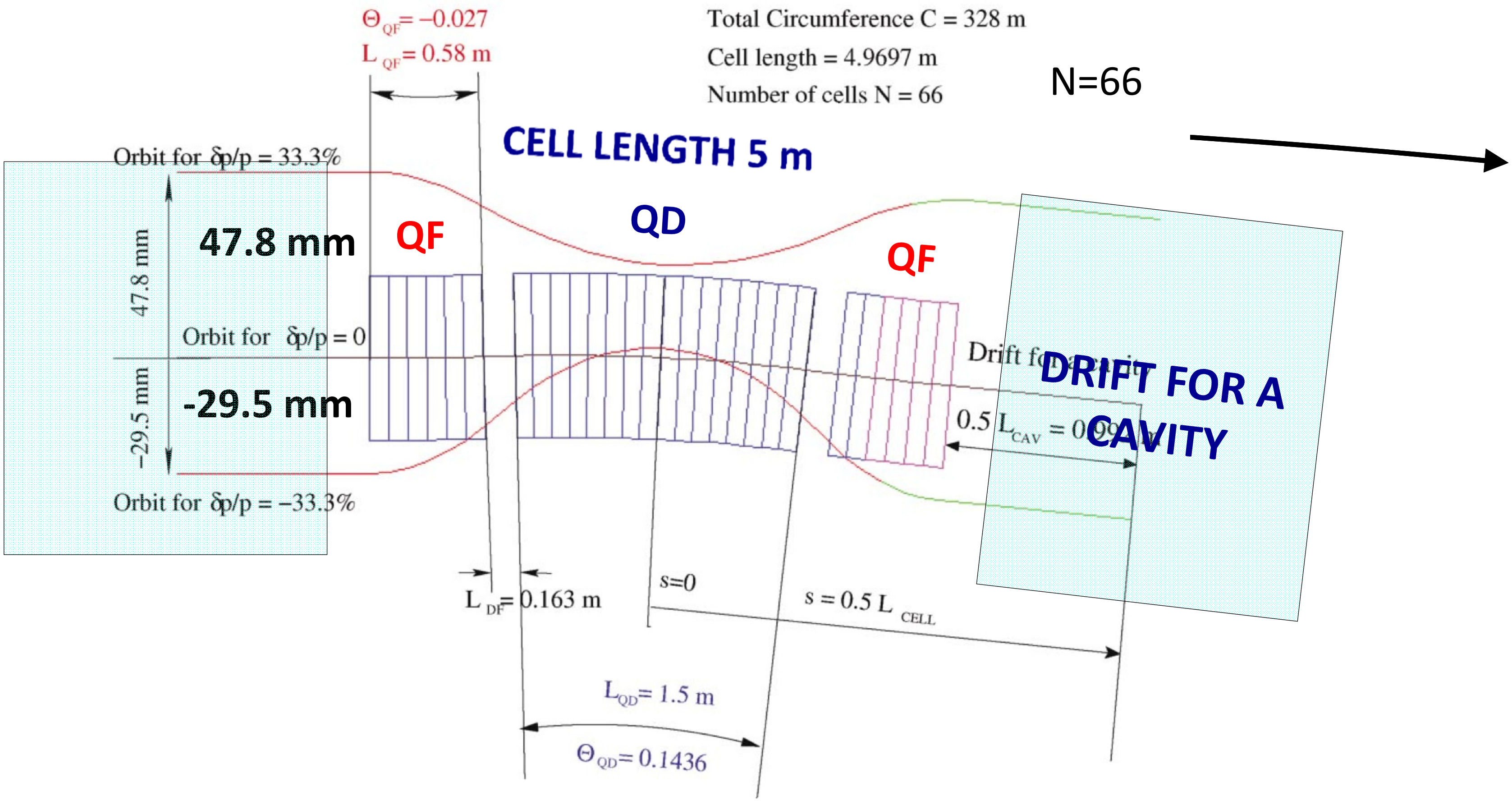
Dejan Trbojevic*, Ernest D. Courant* and Al Garren

Presented in September 1999

CP530, "Colliders and Collider Physics at the Highest Energies: HEMC'99 Workshop", edited by B. J. King



Non-scaling FFAG for Muon Acceleration

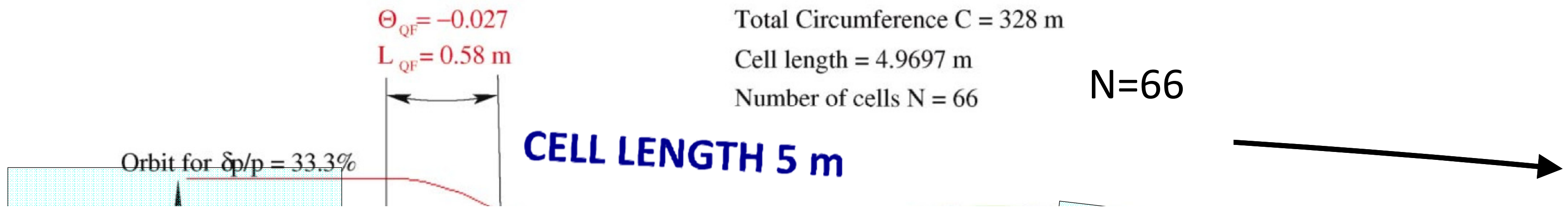


PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **8**, 050101 (2005)

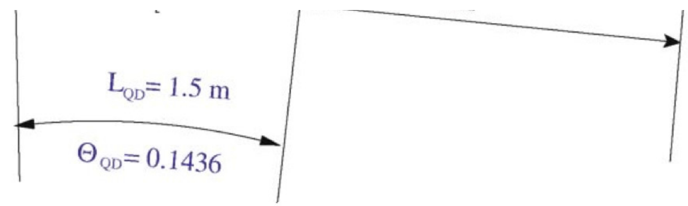
Design of a nonscaling fixed field alternating gradient accelerator

D. Trbojevic,* E. D. Courant, and M. Blaskiewicz
BNL, Upton, New York 11973, USA

Non-scaling FFAG for Muon Acceleration



- Extremely strong focusing with a small dispersion function
- Tunes vary
- Orbit offsets are small
- Magnets are small
- Large energy acceptance



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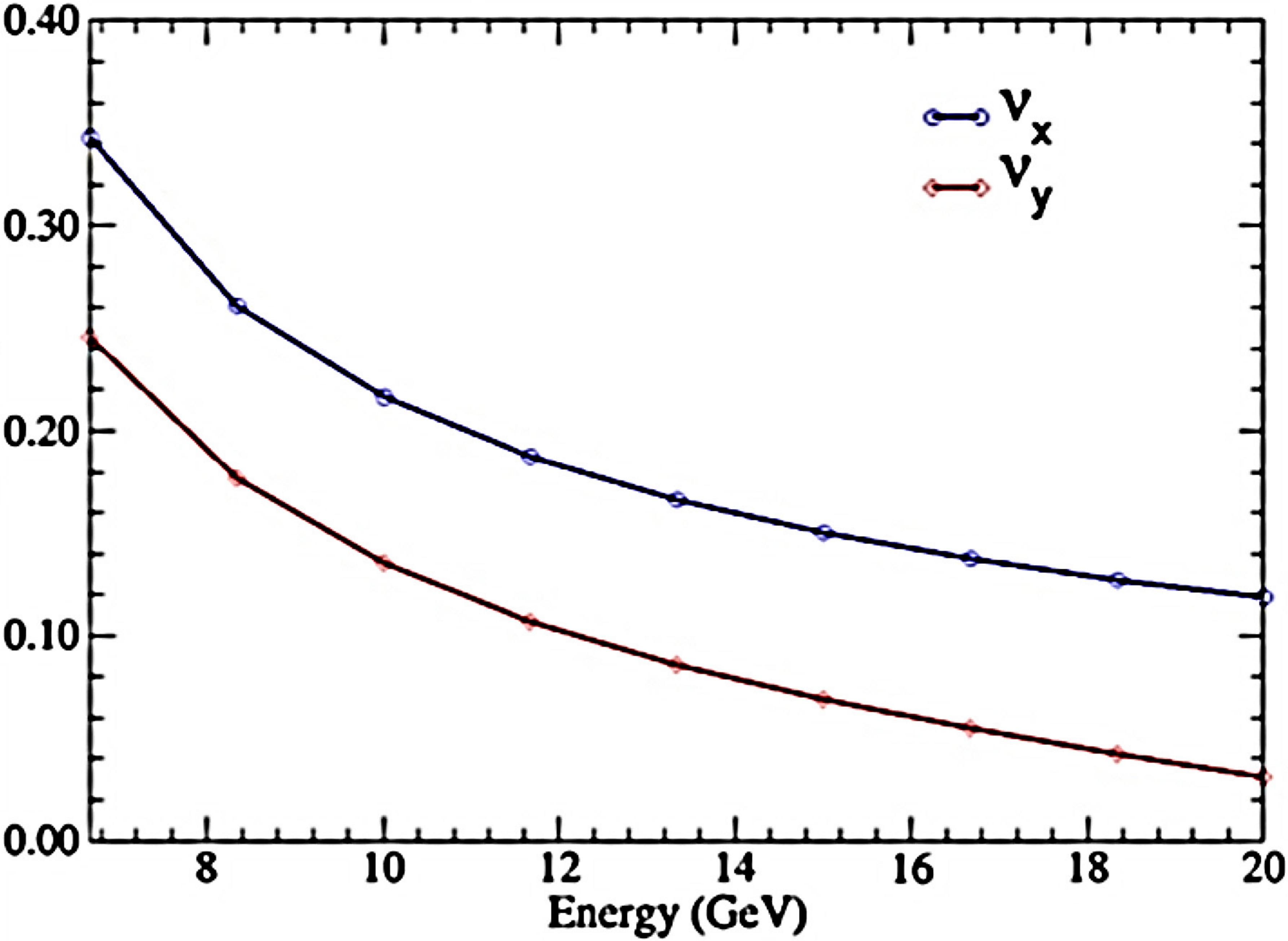

PI
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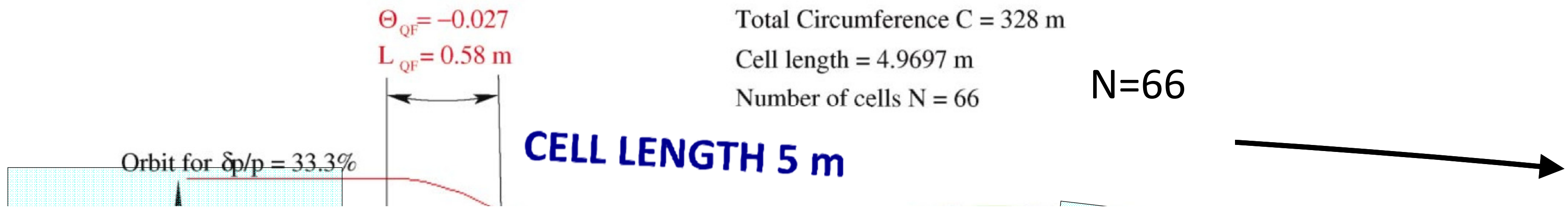
NATION

Non-scaling FFAG for Muon Acceleration



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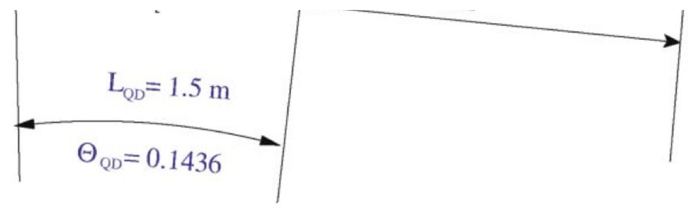

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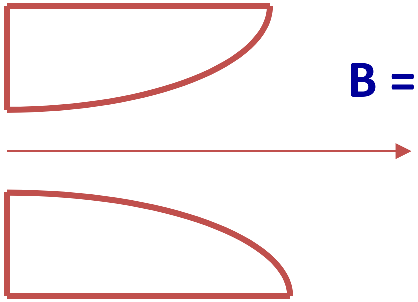
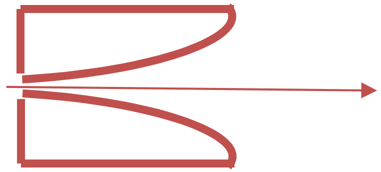
Scaling FFAG – Non scaling FFAG



$B = B_o(r/r_o)^k$

$B = B_o + r\,G_o$



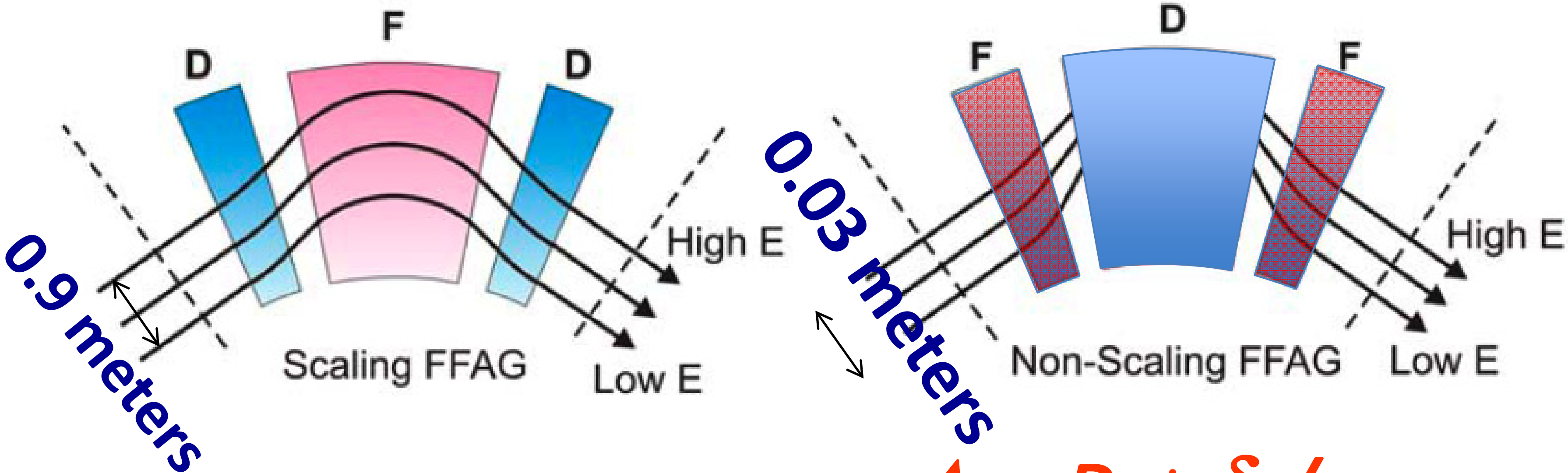
Scaling FFAG properties:

- Zero chromaticity.
- Orbits parallel for different $\delta p/p$
- Relatively large circumference.
- Relatively large physical aperture (80 cm – 120 cm).
- RF - large aperture
- Tunes are fixed for all energies no integer resonance crossing.
- Negative momentum compaction.
- $B = B_o(r/r_o)^k$ non-linear field
- Large acceptance
- Large magnets
- Very large range in $\Delta p/p = \pm 90\%$
- could be isochronous CW operation

Non-Scaling FFAG properties:

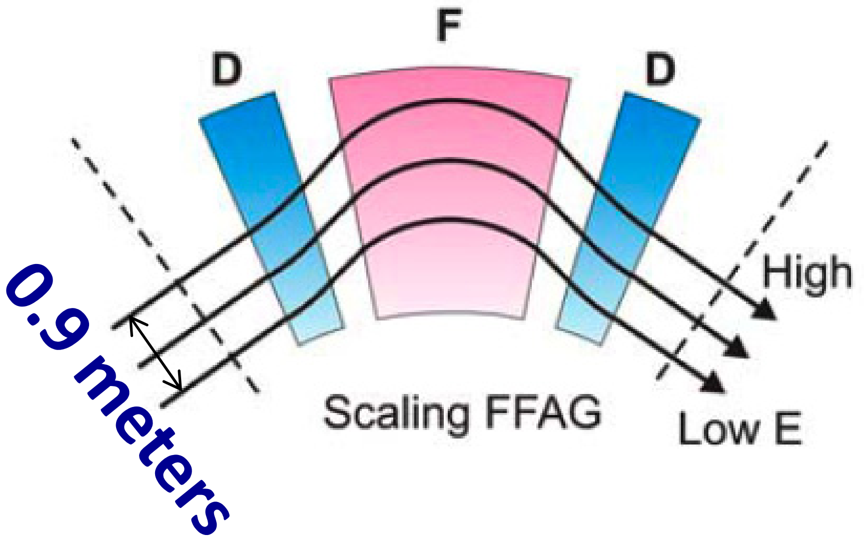
- Chromaticity is changing.
- Orbits are not parallel.
- Relatively small circumference.
- Relatively small physical aperture (0.50 cm – 10 cm).
- RF - smaller aperture.
- Tunes move 0.4-0.1 in basic cell resonance crossing for protons
- Momentum compaction changes.
- $B = B_o + x\,G_o$ linear field
- Smaller acceptance
- Small magnets
- Large range in $\Delta p/p = \pm 60\%$
- Very difficult to be isochronous

SCALING VS. NON-SCALING FFAG



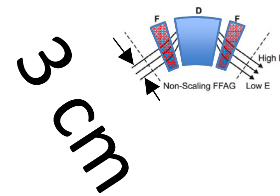
$\Delta x = D_x * \delta p/p$

SCALING VS. NON-SCALING FFAG



Linear magnetic field:

$$B = B_o + r\,G_o$$



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

D magnet = reverse bend

Magnetically inefficient

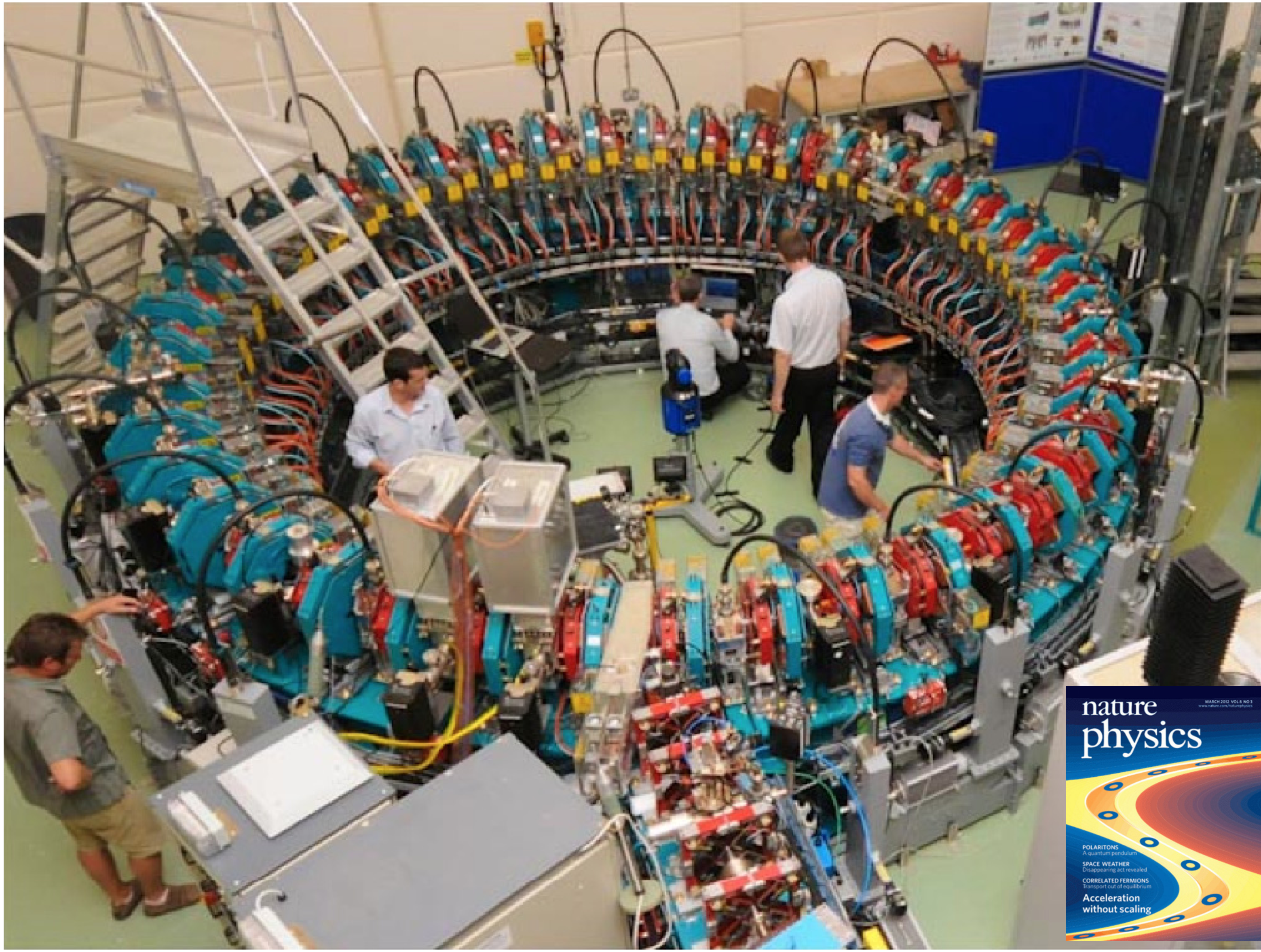
VERY BAD for synchrotron radiation (10MW)

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

$$D_x \sim 4\ \text{cm} / 0.5 = 8\ \text{cm}$$

EMMA the first NS-FFAG

"Electron Model for Many Applications" built at Daresbury Laboratory



ELECTRON ENERGY RANGE 10-20 MeV

Kaon Factory FFAG proposal
Rick Baartman and Mike Craddock (1979)

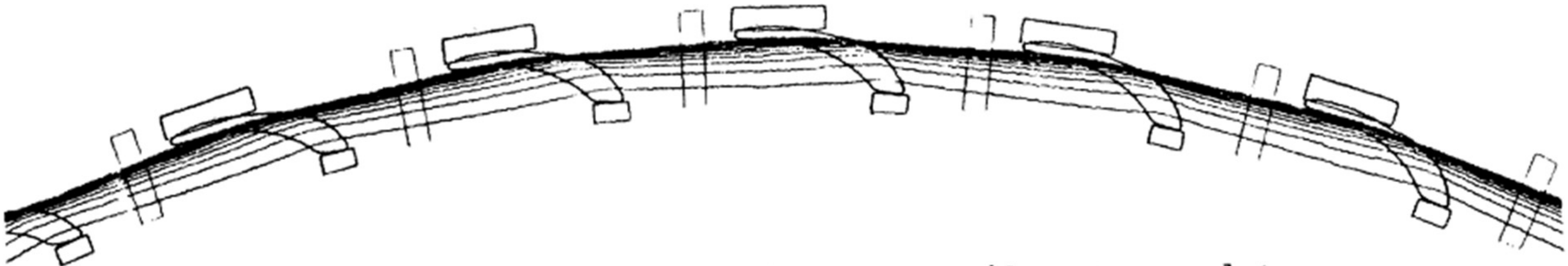
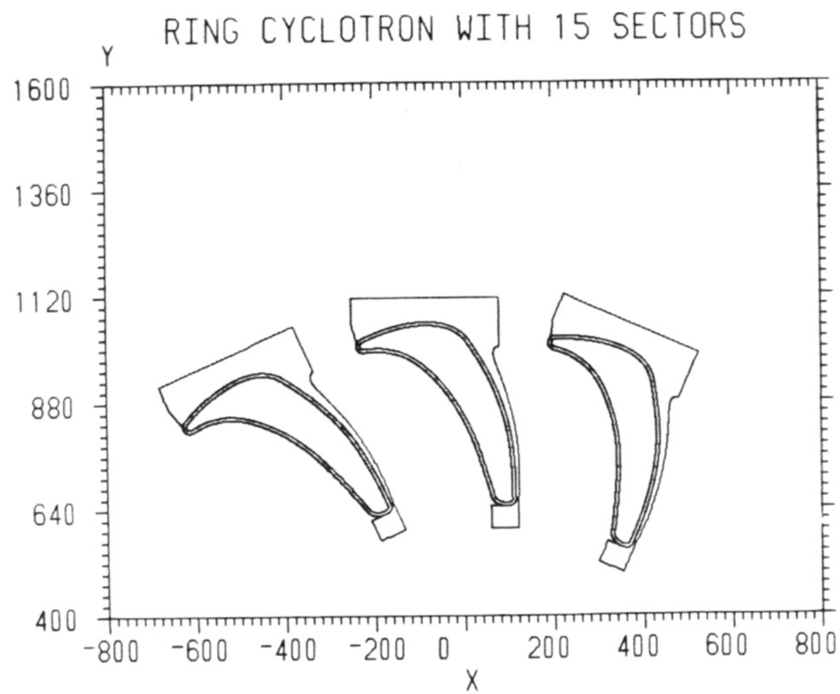
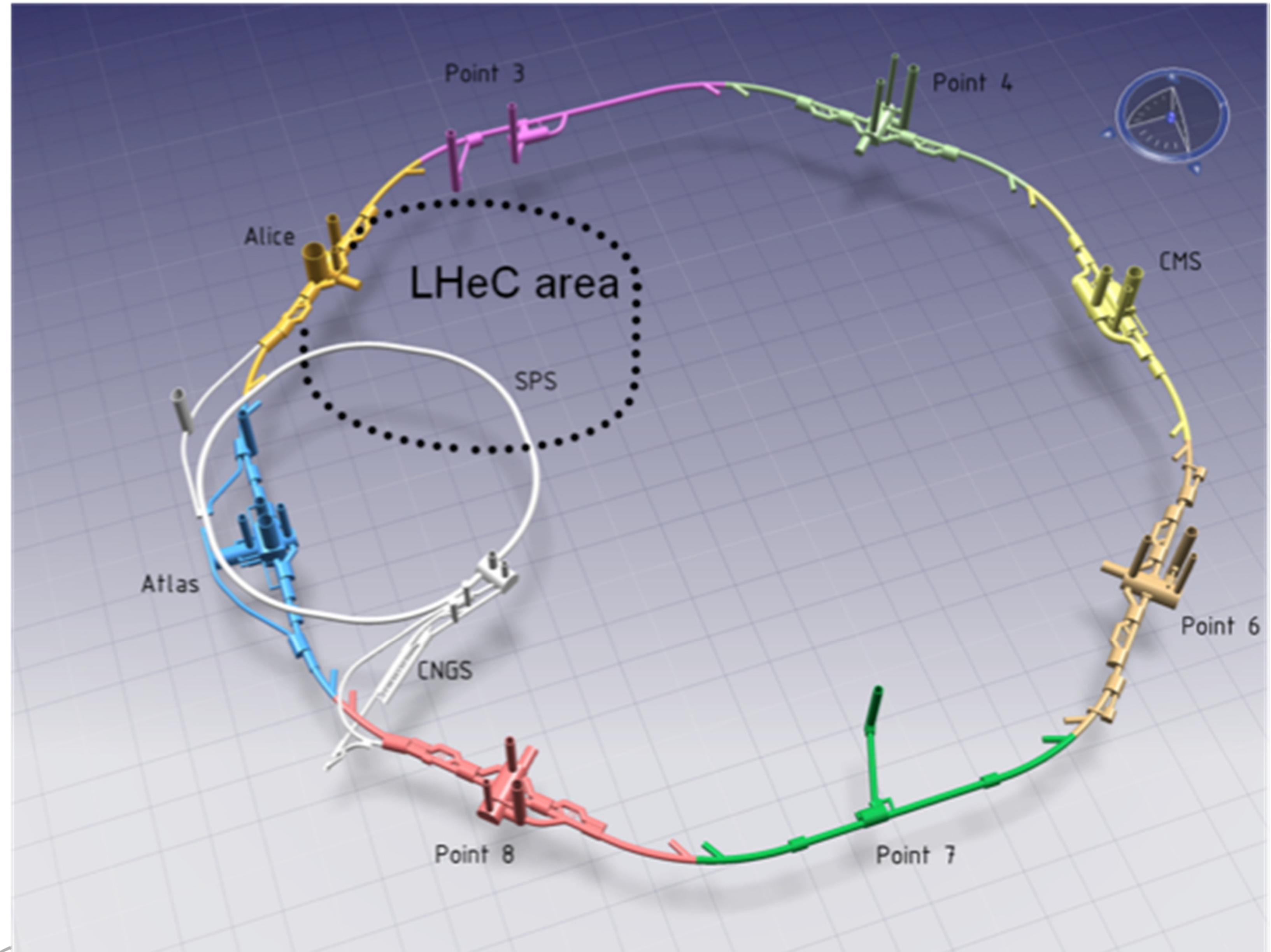


Fig. 1. Five sectors from the 40 m radius 42 sector cyclotron showing magnets, RF cavities and proton orbits.

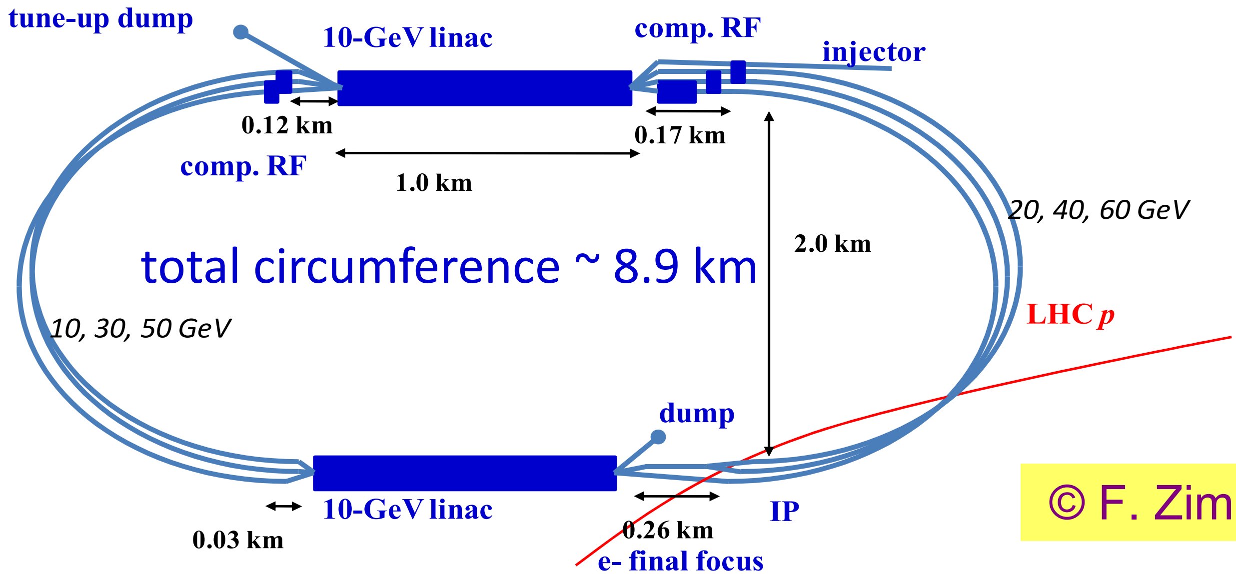


From Oliver Brüning

Layout of the LHeC-LHC-SPS



Linac-Ring Option – LHeC Recirculator



© F. Zimmermann

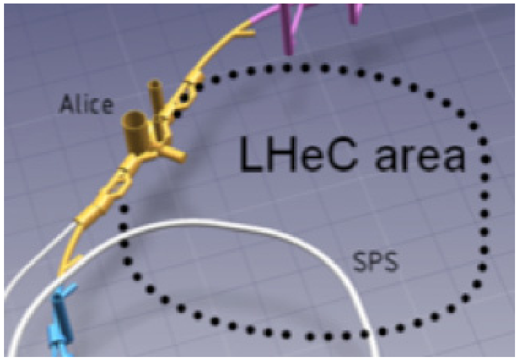
RECIRCULATOR COMPLEX

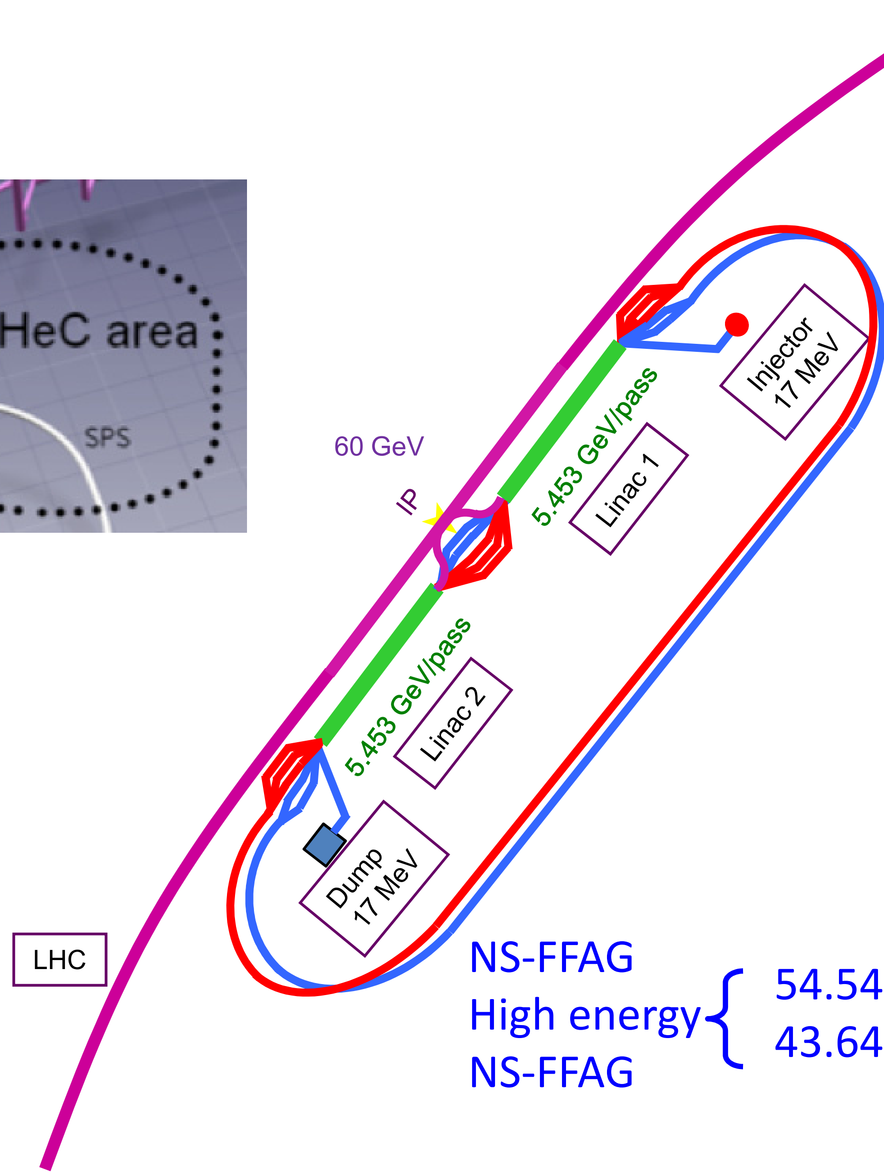
1. 0.5 Gev injector
2. Two SCRF linacs (10 GeV per pass)
3. Six 180° arcs, each arc 1 km radius
4. Re-accelerating stations
5. Switching stations
6. Matching optics
7. Extraction dump at 0.5 GeV

	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	50
Beta Function $\beta^*_{x,y}$ [m]	0.10	0.12
rms Beam size $\sigma^*_{x,y}$ [μm]	7	7
rms Divergence $\sigma'_{x,y}$ [μrad]	70	58
Beam Current [mA]	(860) 430	6.6
Bunch Spacing [ns]	25 (50)	25 (50)
Bunch Population	$1.7*10^{11}$	$(1*10^9)$ $2*10^9$

The baseline 60 GeV ERL option proposed can give an e-p luminosity of 10^{33} cm^{-2}s^{-1} (extensions to 10^{34} cm^{-2}s^{-1} and beyond are being considered)

NS-FFAG LHeC Recirculator with ERL



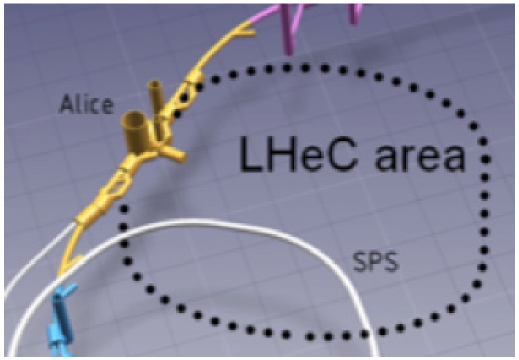


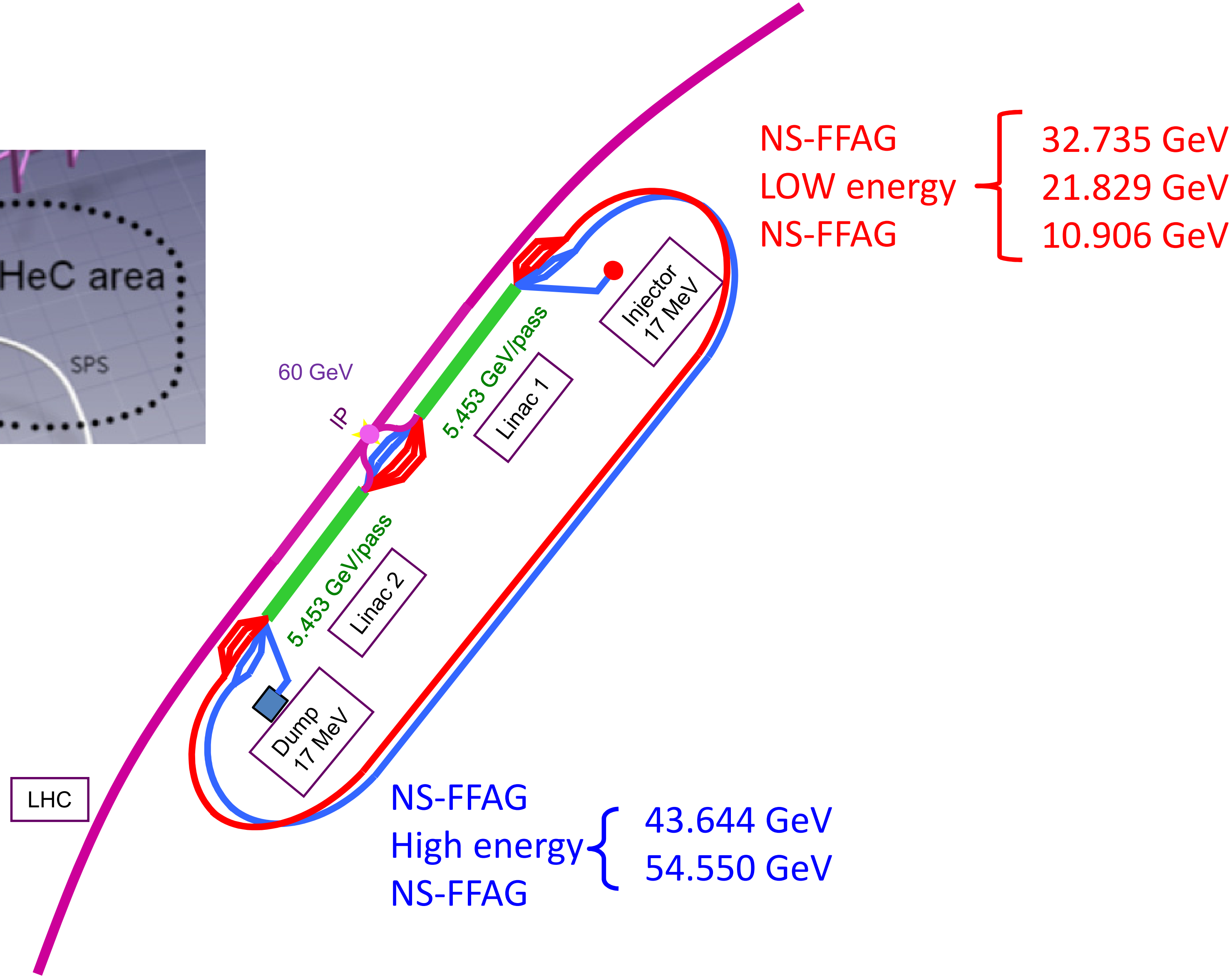
NS-FFAG LOW energy NS-FFAG: 10.906 GeV, 21.829 GeV, 32.735 GeV

Thomas Roser's idea

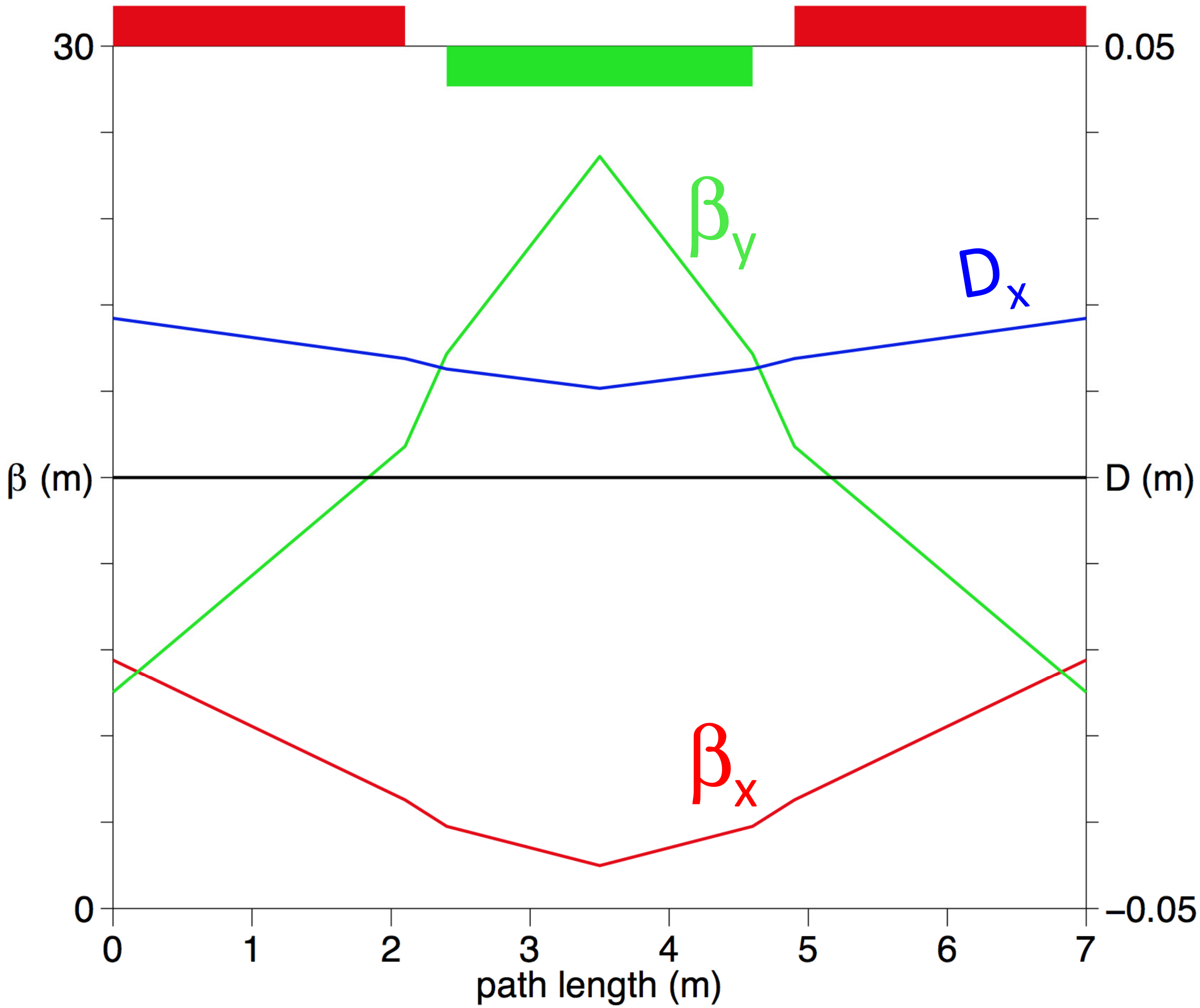
NS-FFAG High energy NS-FFAG: 54.547 GeV, 43.641 GeV

NS-FFAG LHeC ERL

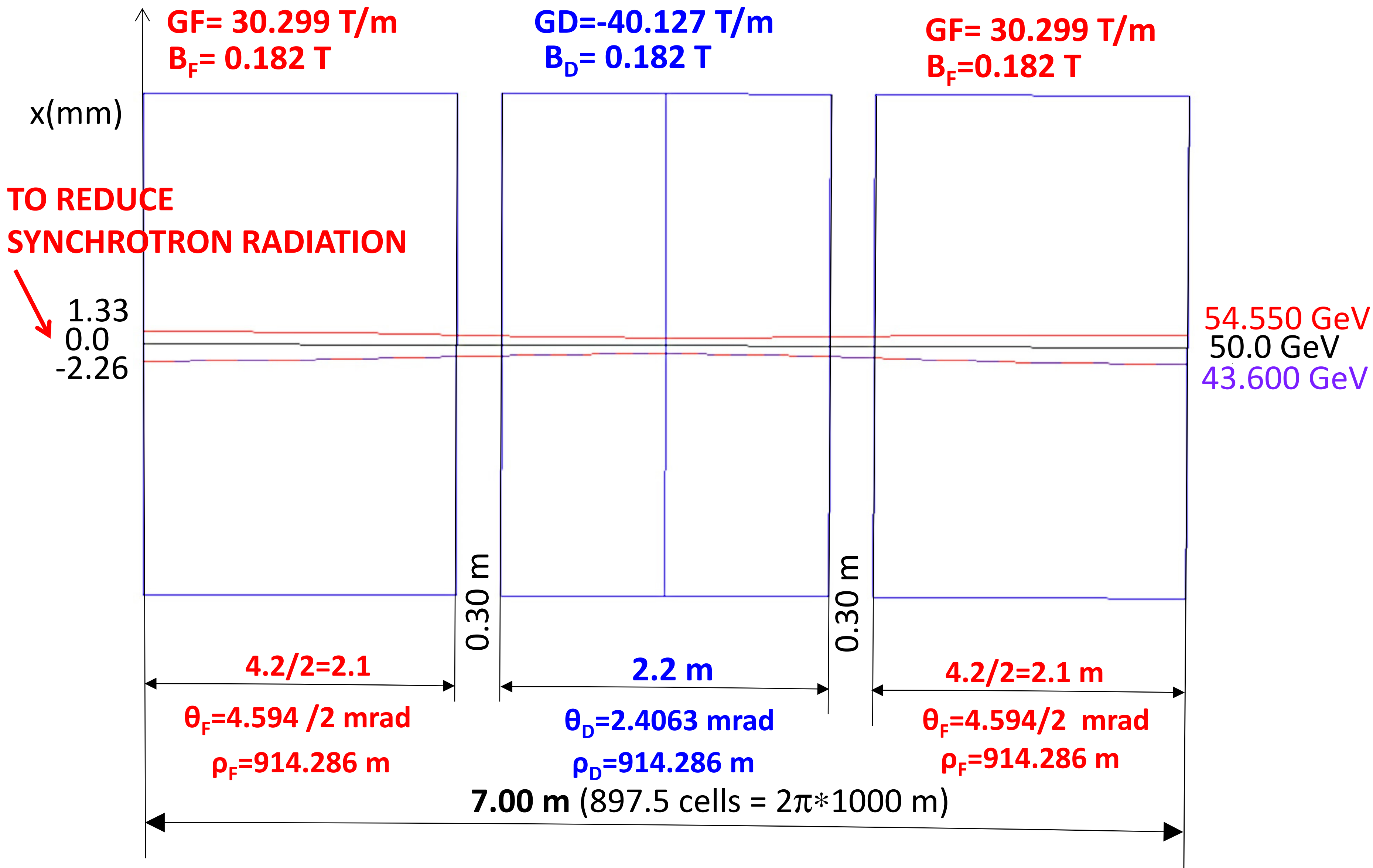




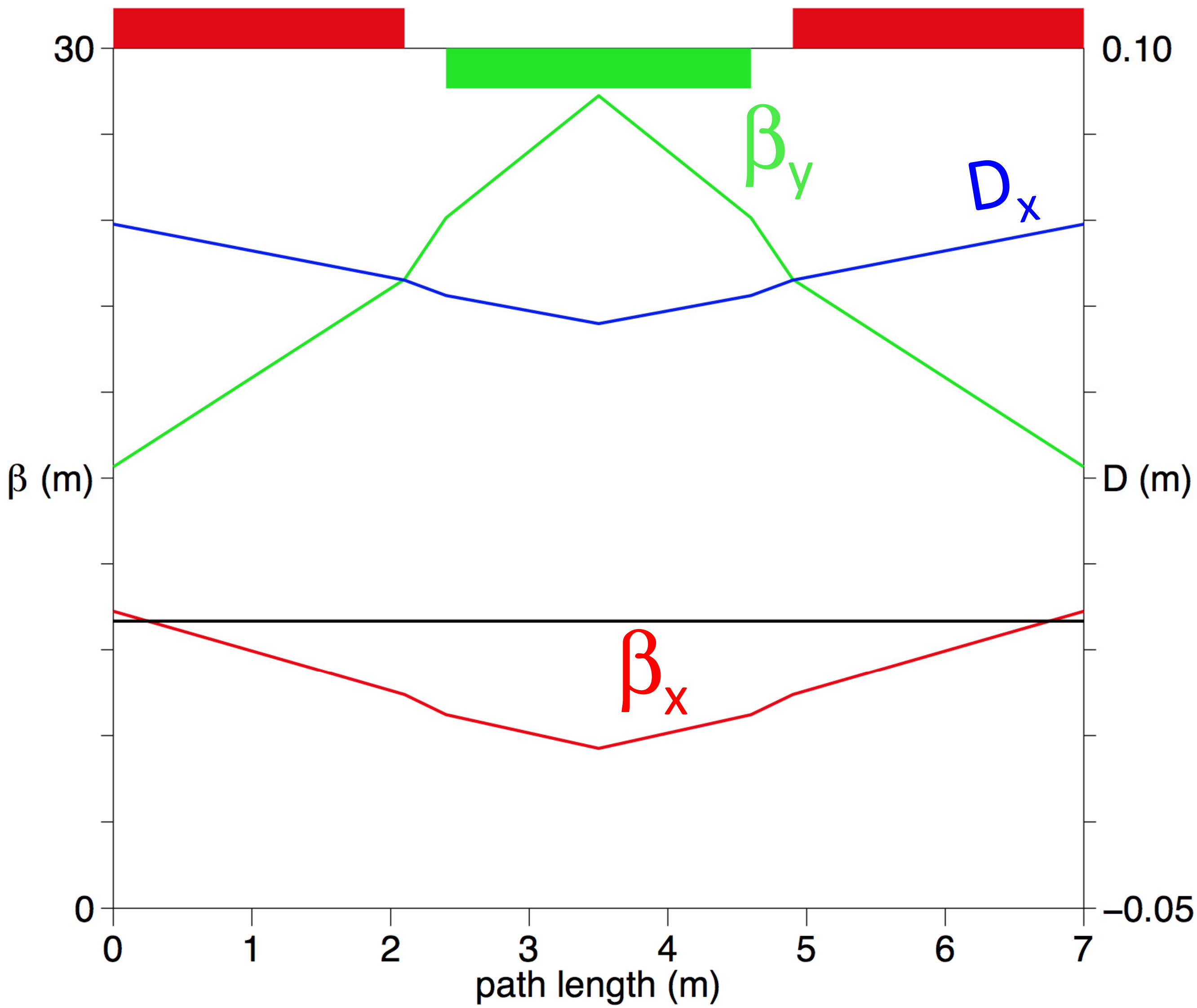
Betatron Functions for E_c=50 GeV, 2 x 5.453 GeV linacs



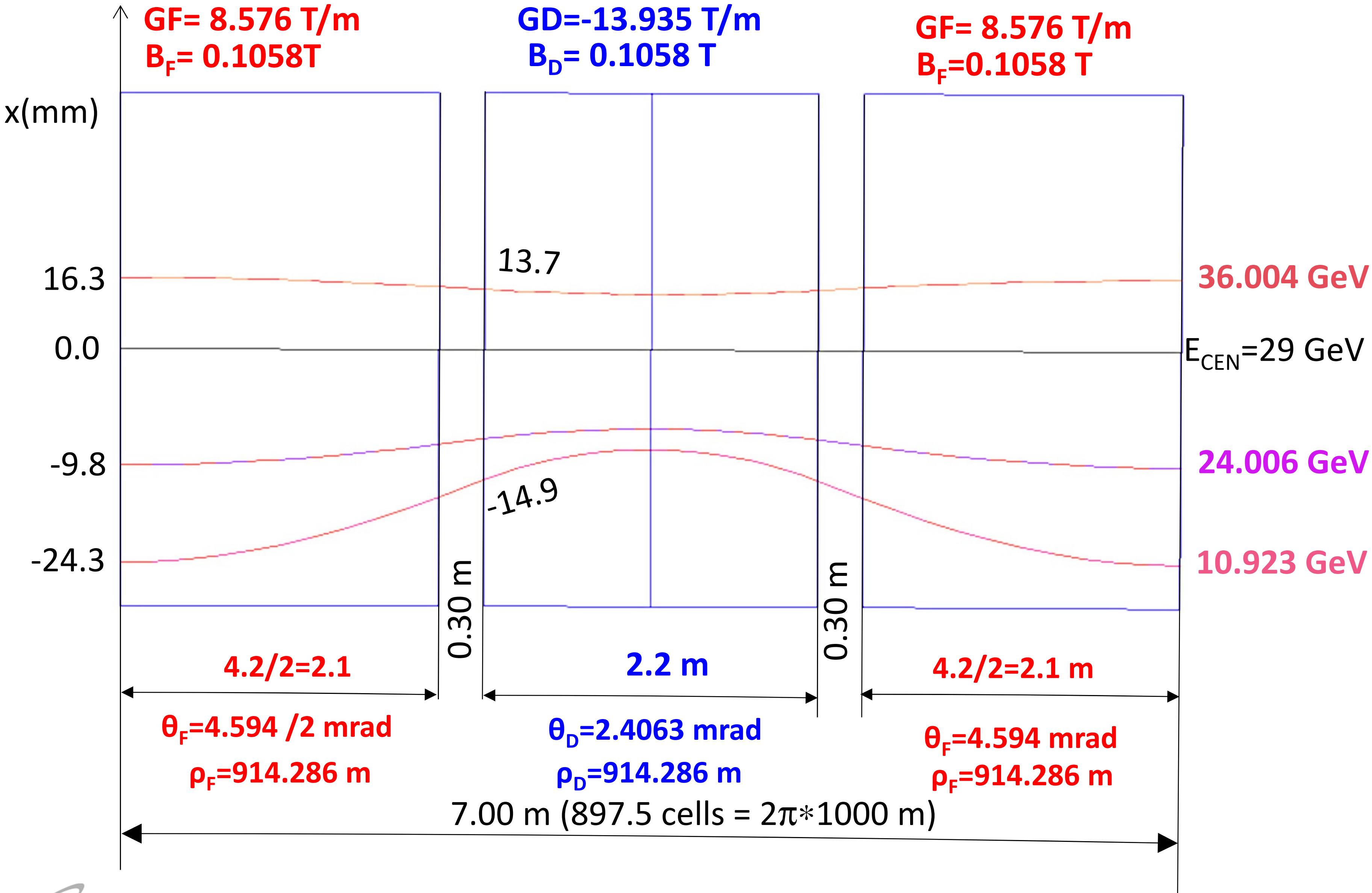
LHeC ARC– 2 x 5.453 GeV linacs: Orbits in the basic cell of the High energy NS-FFAG **54.55 - 43.644** GeV



Betatron Functions for E_c=29 GeV, 2 x 5.453 GeV linacs



LHeC-ERL with 2 x 5.453 GeV linacs
Orbits in the basic cell of the Low energy NS-FFAG **10.923 - 32.735** GeV

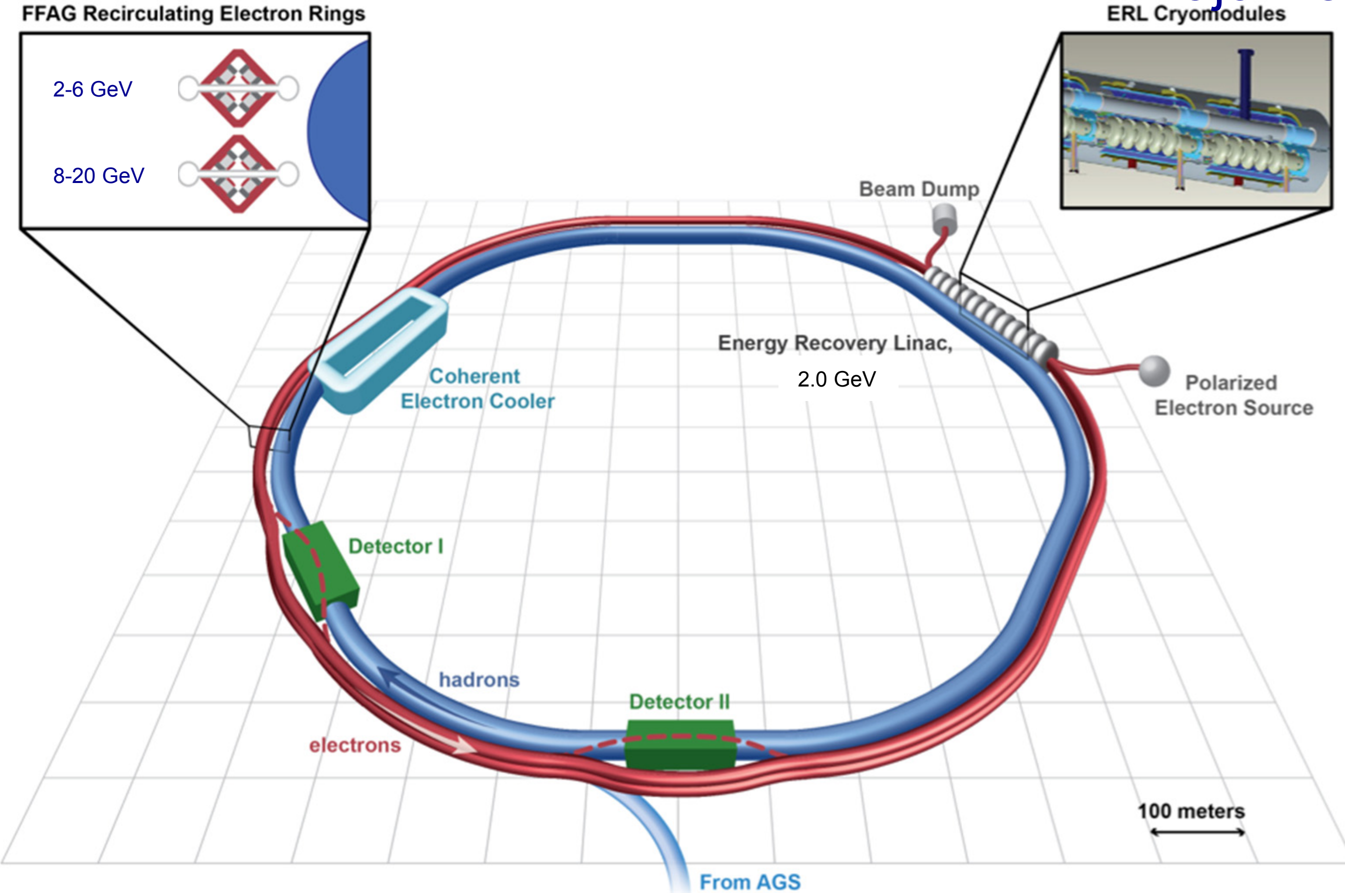


Synchrotron Radiation in LHeC with 2 x 5.453 GeV linacs Two NS-FFAG 43.6-54.6 GeV and 10.9-32.7 GeV Maximum Collision Energy 60 GeV

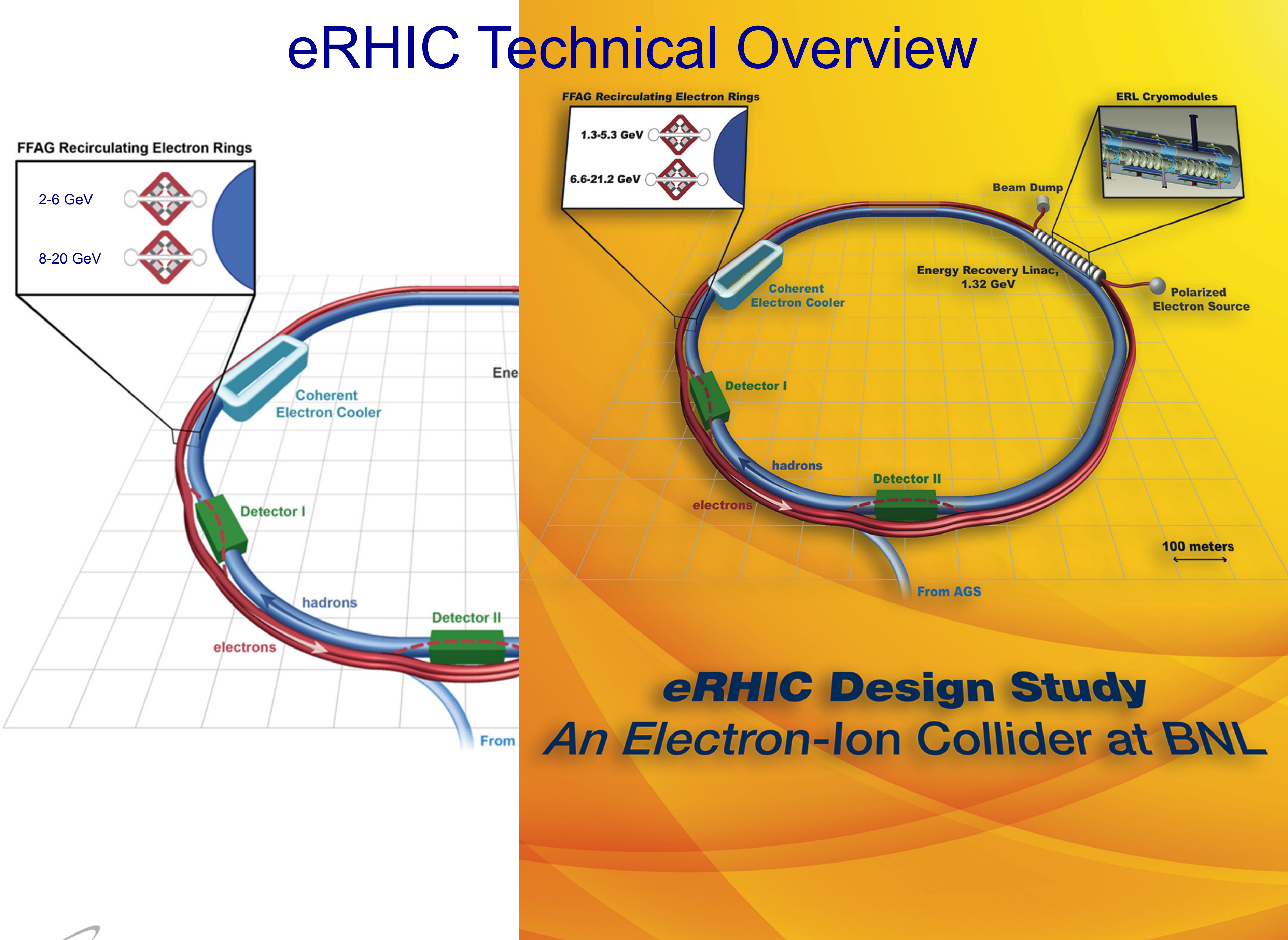
E(GeV)	Total Power (MW) 8.87 mA	Total Power (MW) 6.6 mA
54.550	7.5779	5.6383
43.644	4.2080	3.1310
32.735	1.3902	1.0344
21.829	1.2881	0.9584
10.923	0.5359	0.3987
TOTAL	**15.000**	**11.1608**

eRHIC Technical Overview

Major Technical Components:

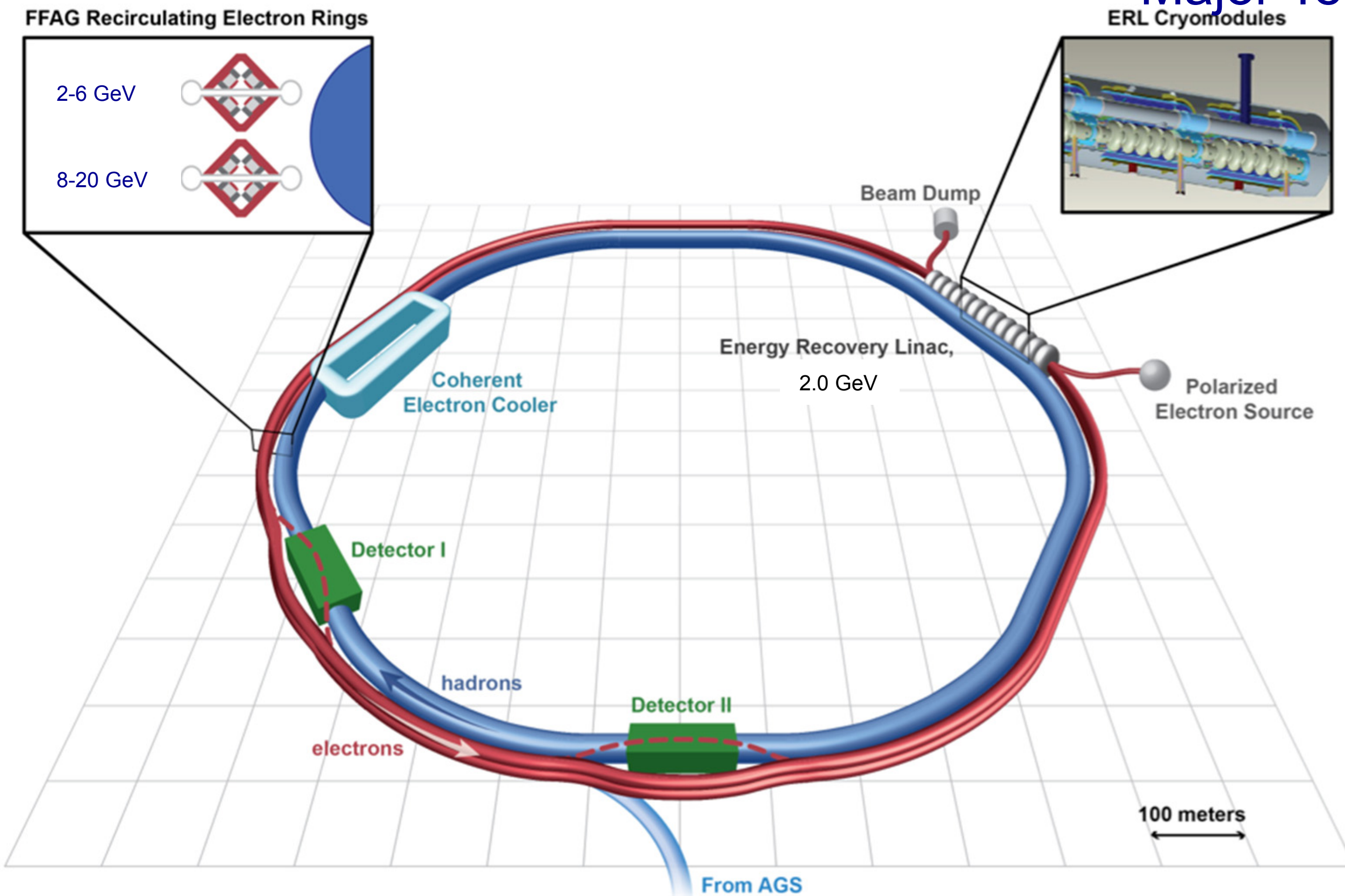


eRHIC Technical Overview

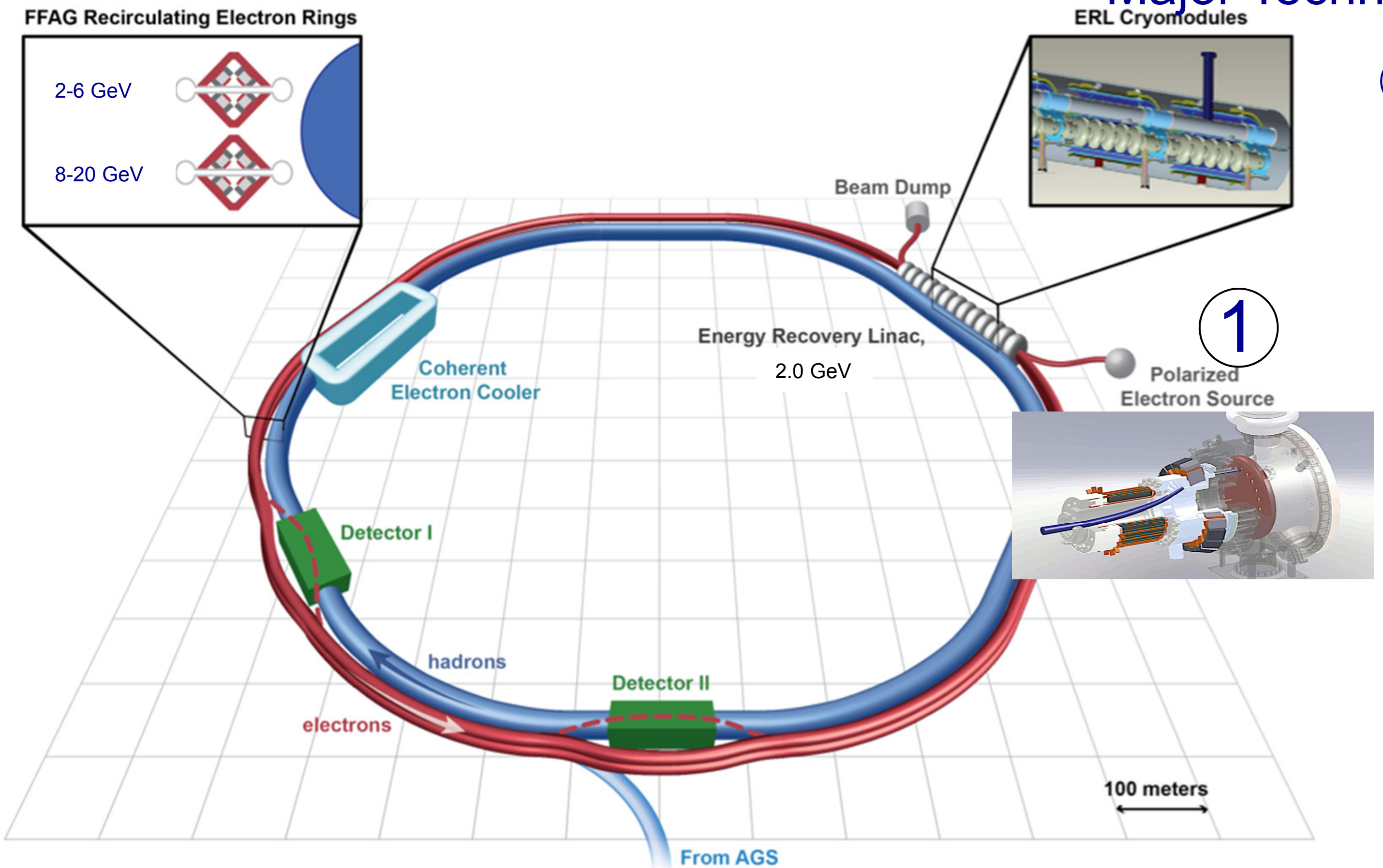


eRHIC Technical Overview

Major Technical Components:



eRHIC Technical Overview



Major Technical Components:

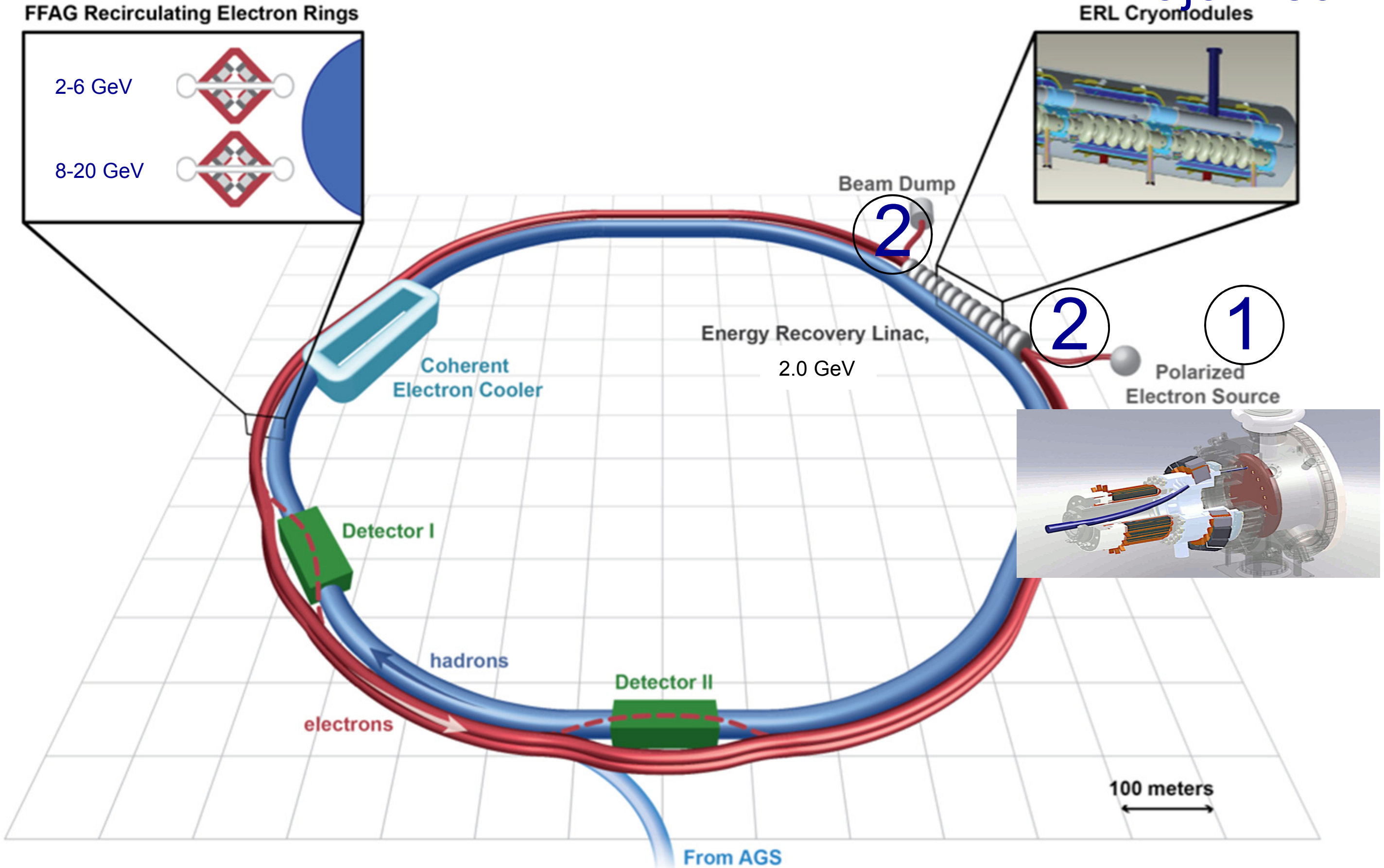
① Funneling Gun

eRHIC Technical Overview

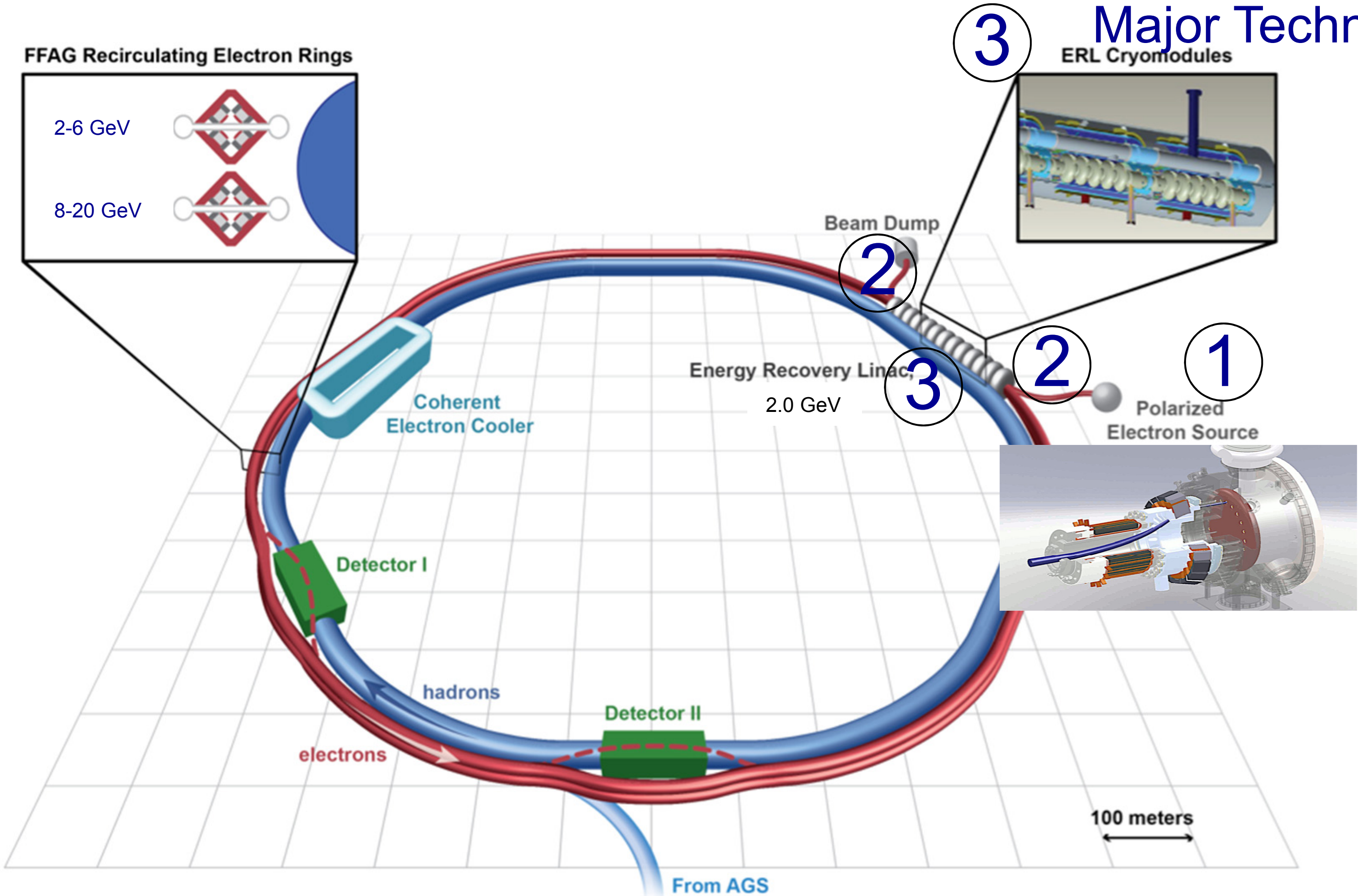
Major Technical Components:

① Funneling Gun

② ERL mergers



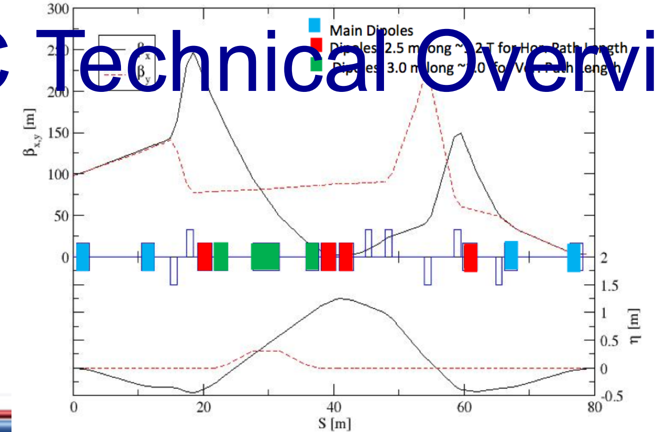
eRHIC Technical Overview

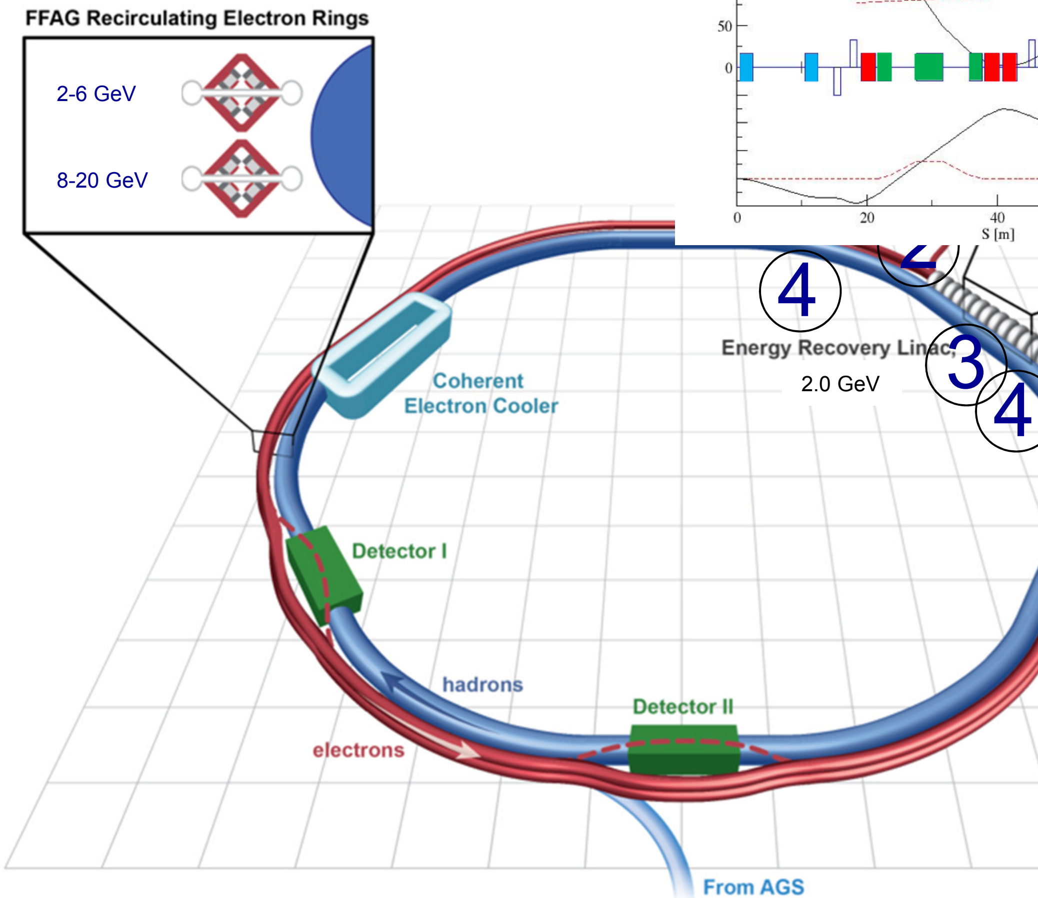


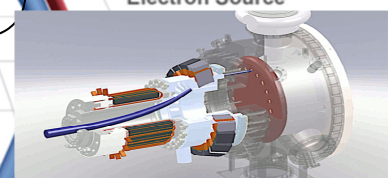
Major Technical Components:

① Funneling Gun
② ERL mergers
③ Superconducting Linac - ERL

eRHIC Technical Overview







echnical Components:

① Funneling Gun
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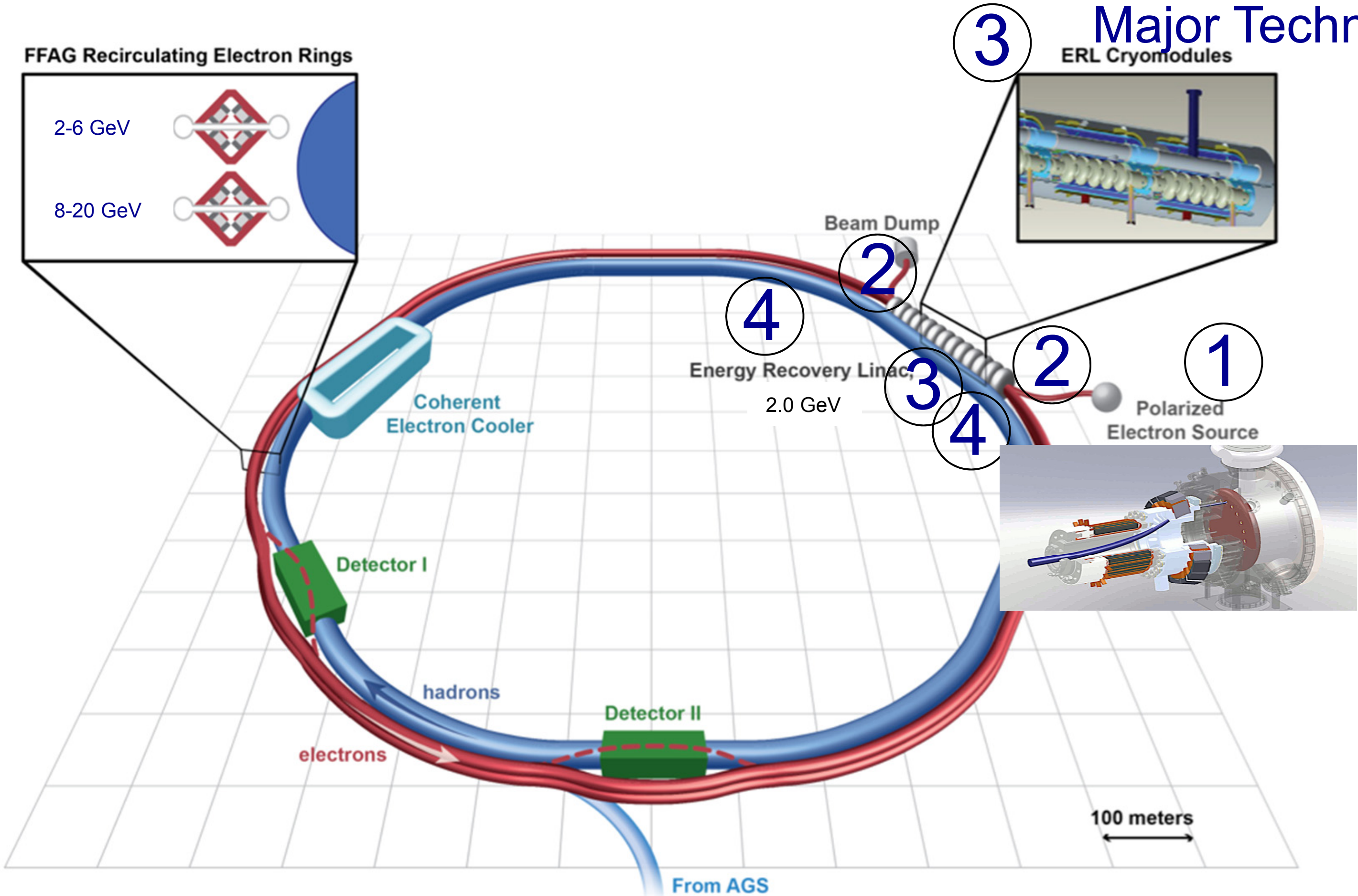
③ Superconducting Linac - ERL
④ Spreaders and Combiners

eRHIC Technical Overview



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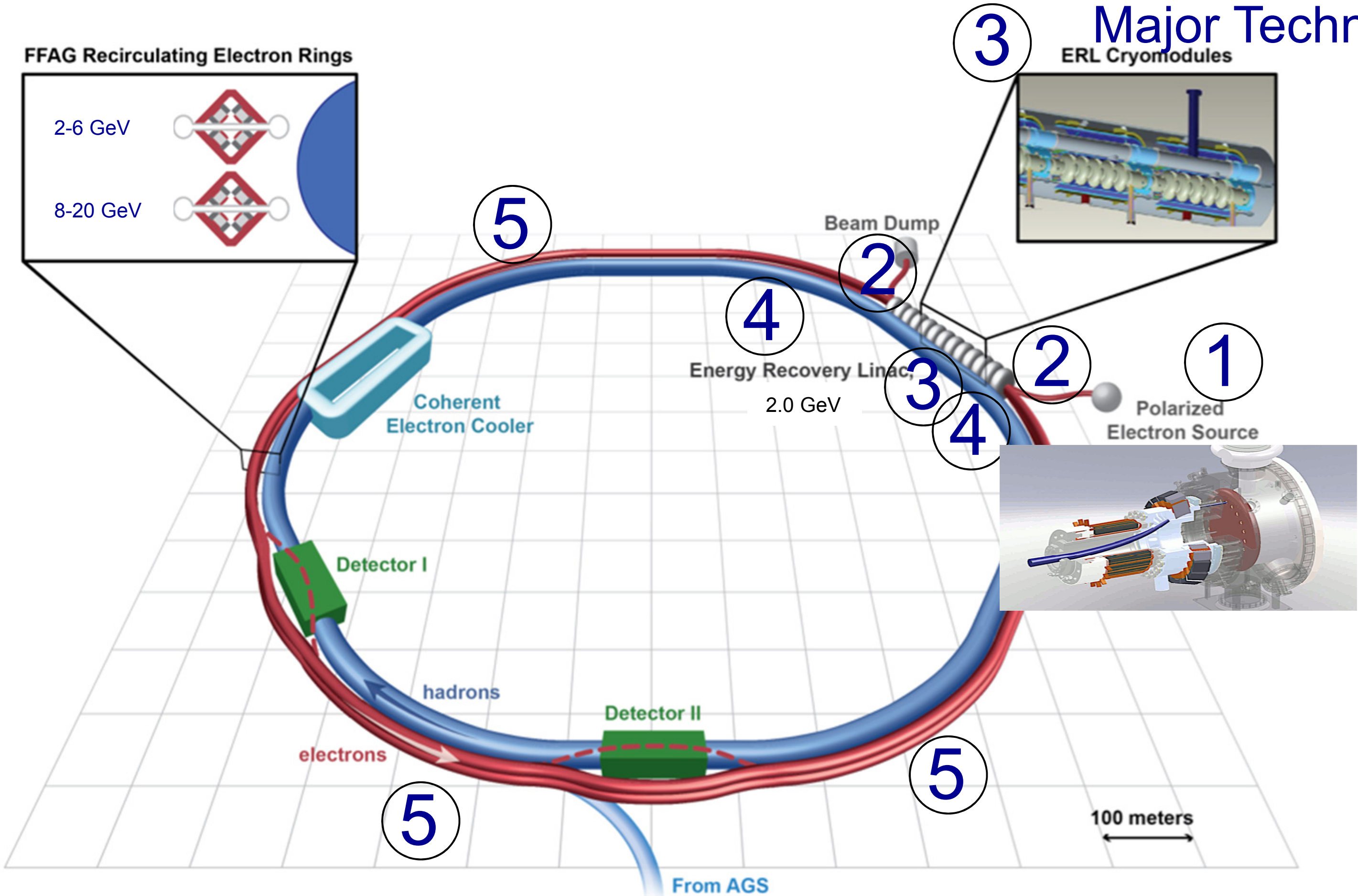
eRHIC Technical Overview



Major Technical Components:

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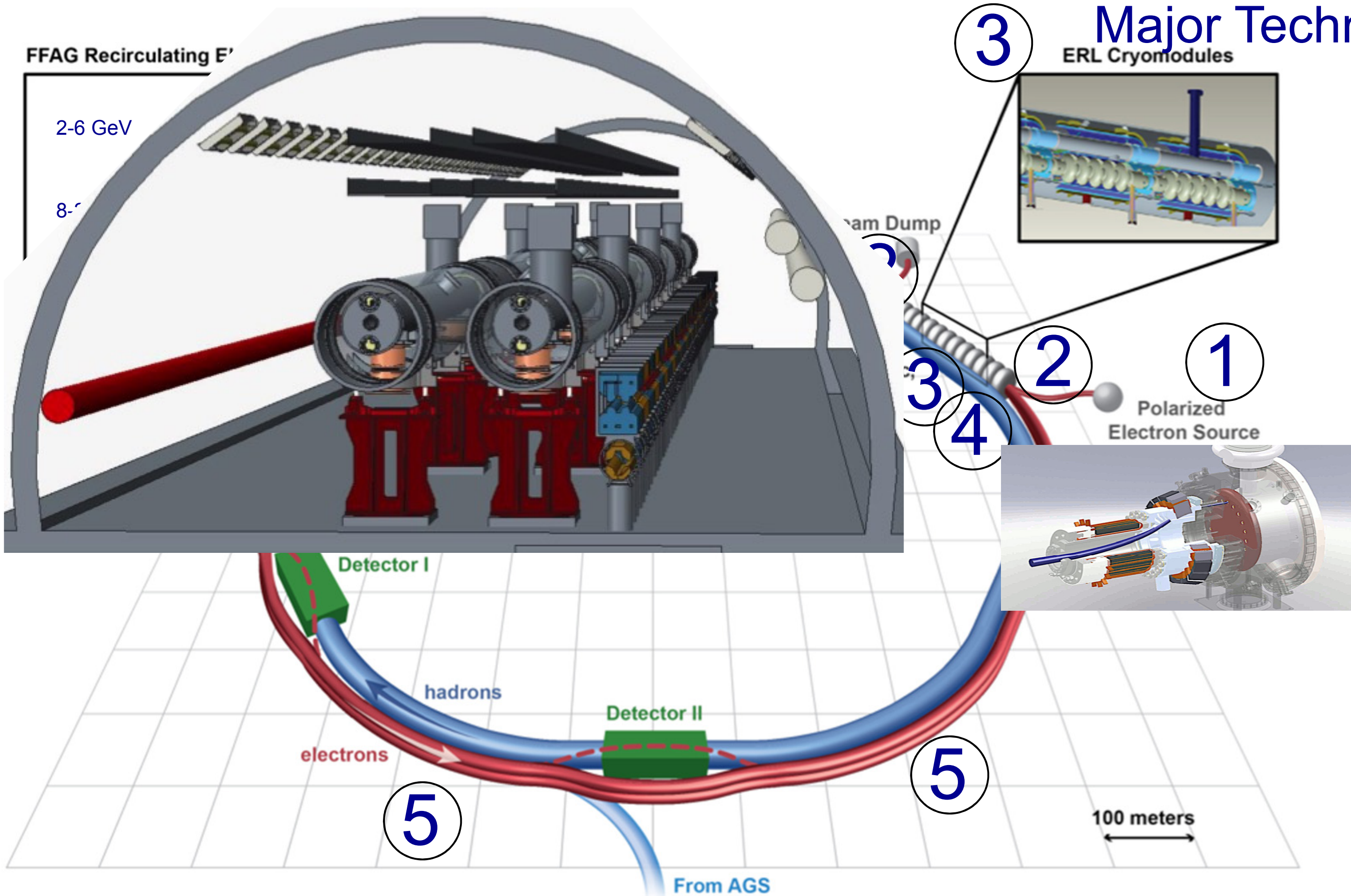
② ERL mergers
③ Superconducting Linac - ERL
④ Spreaders and Combiners
⑤ NS-FFAG arcs

eRHIC Technical Overview



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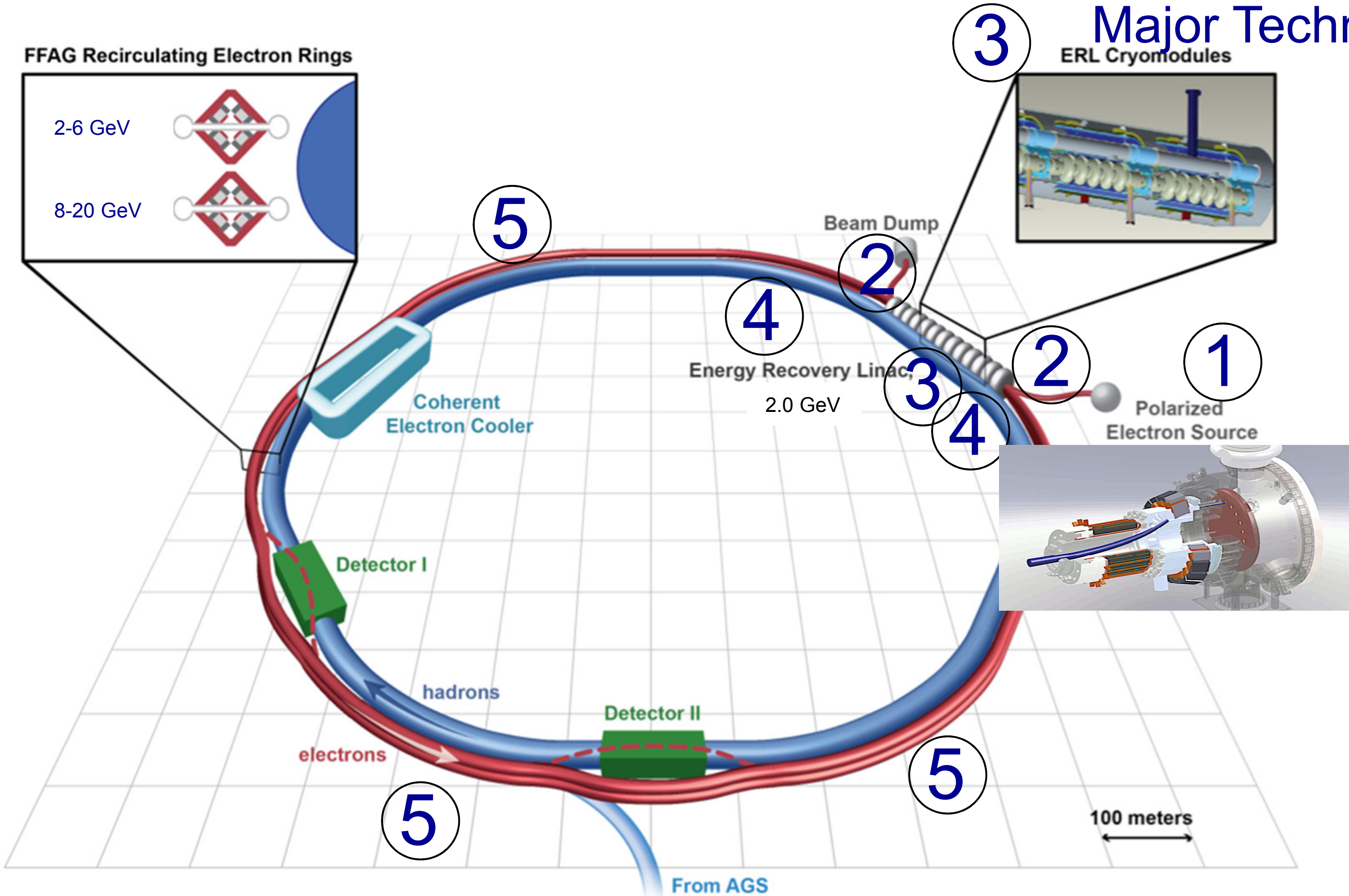

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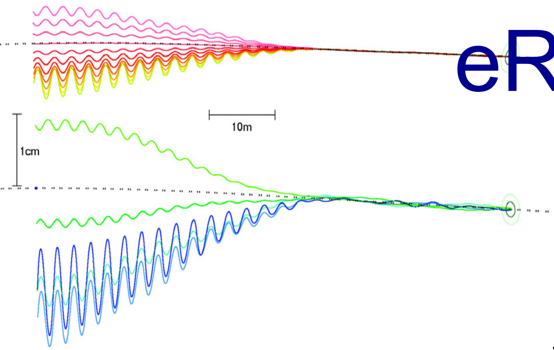

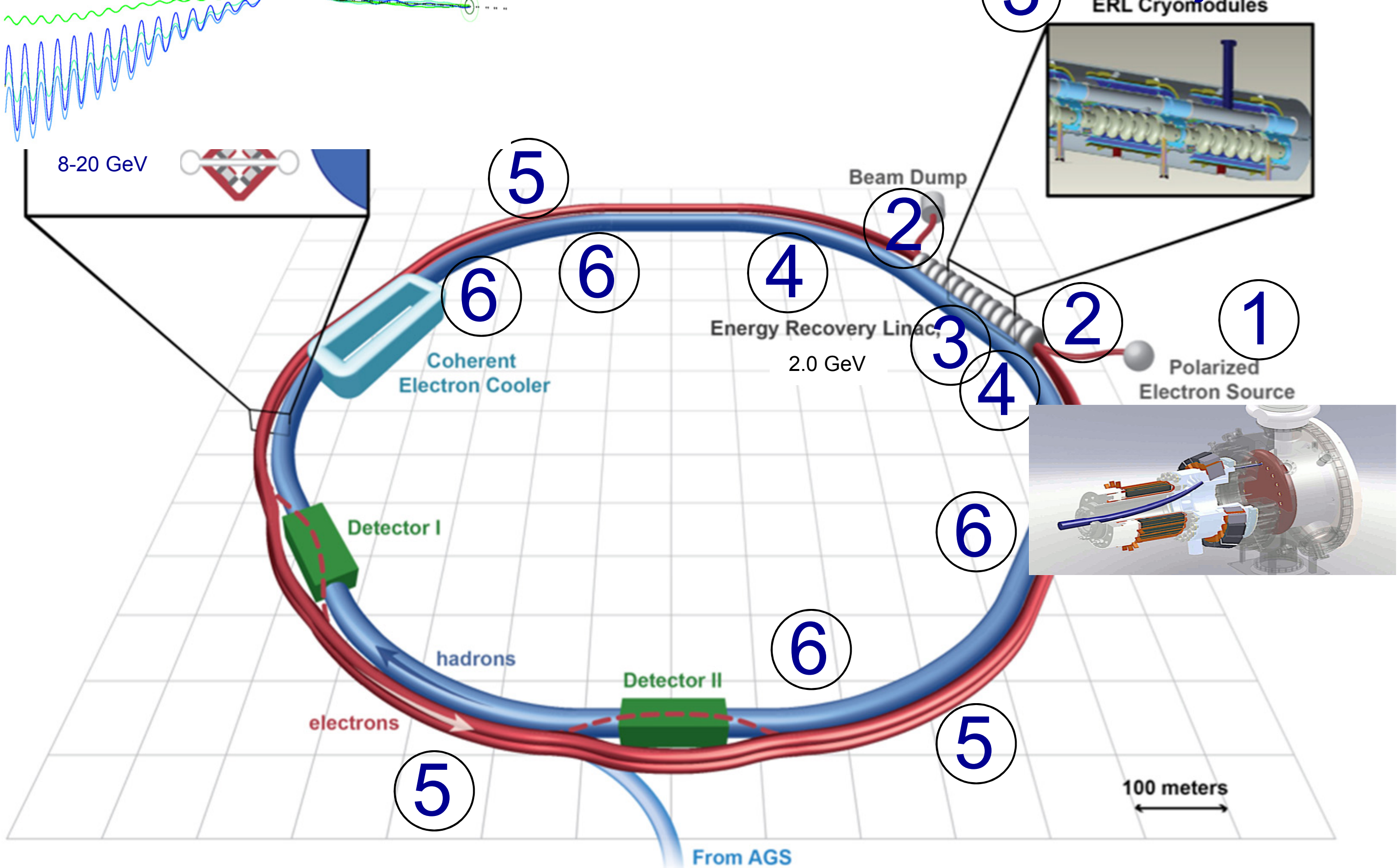

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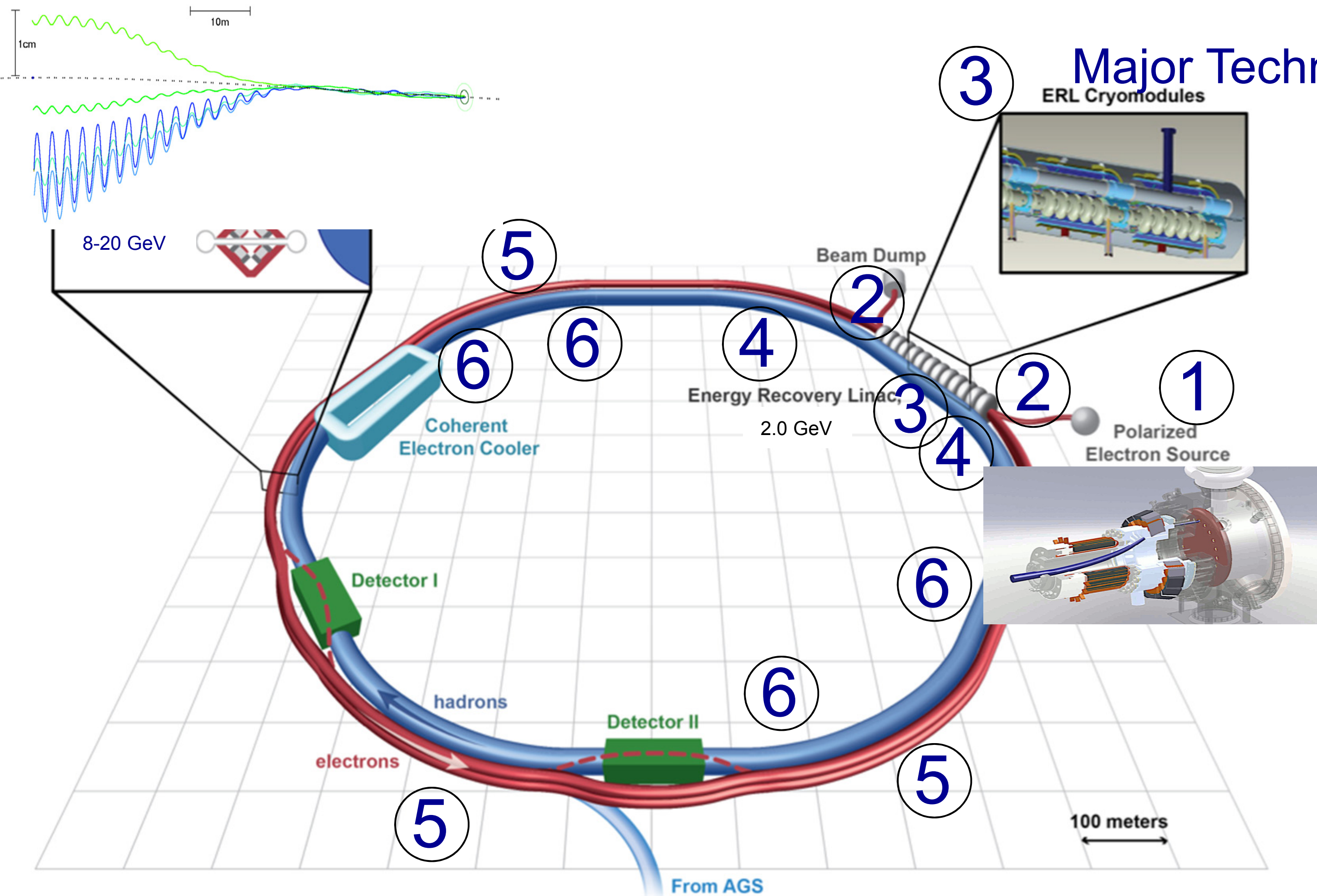
④ Spreaders and Combiners

⑤ NS-FFAG arcs

⑥ Merging arcs to straight section

eRHIC Technical Overview



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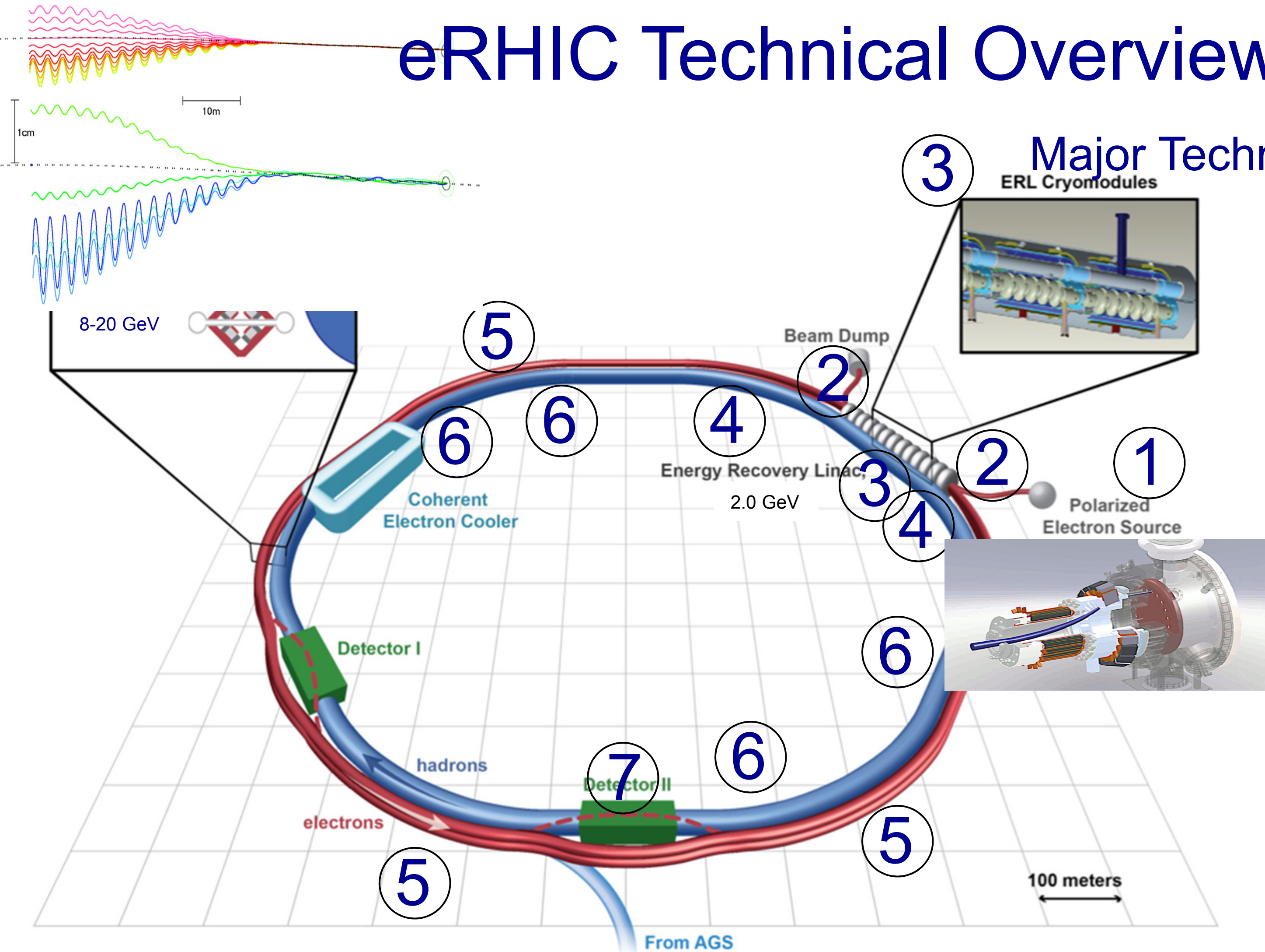

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⑦ Straight section
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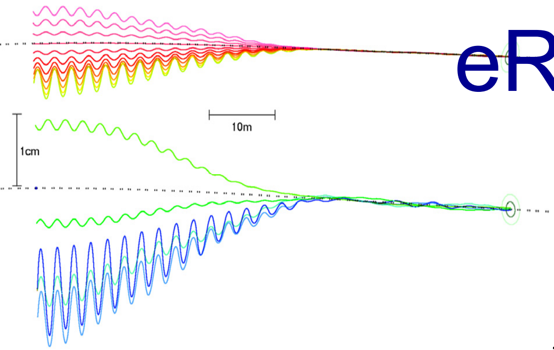
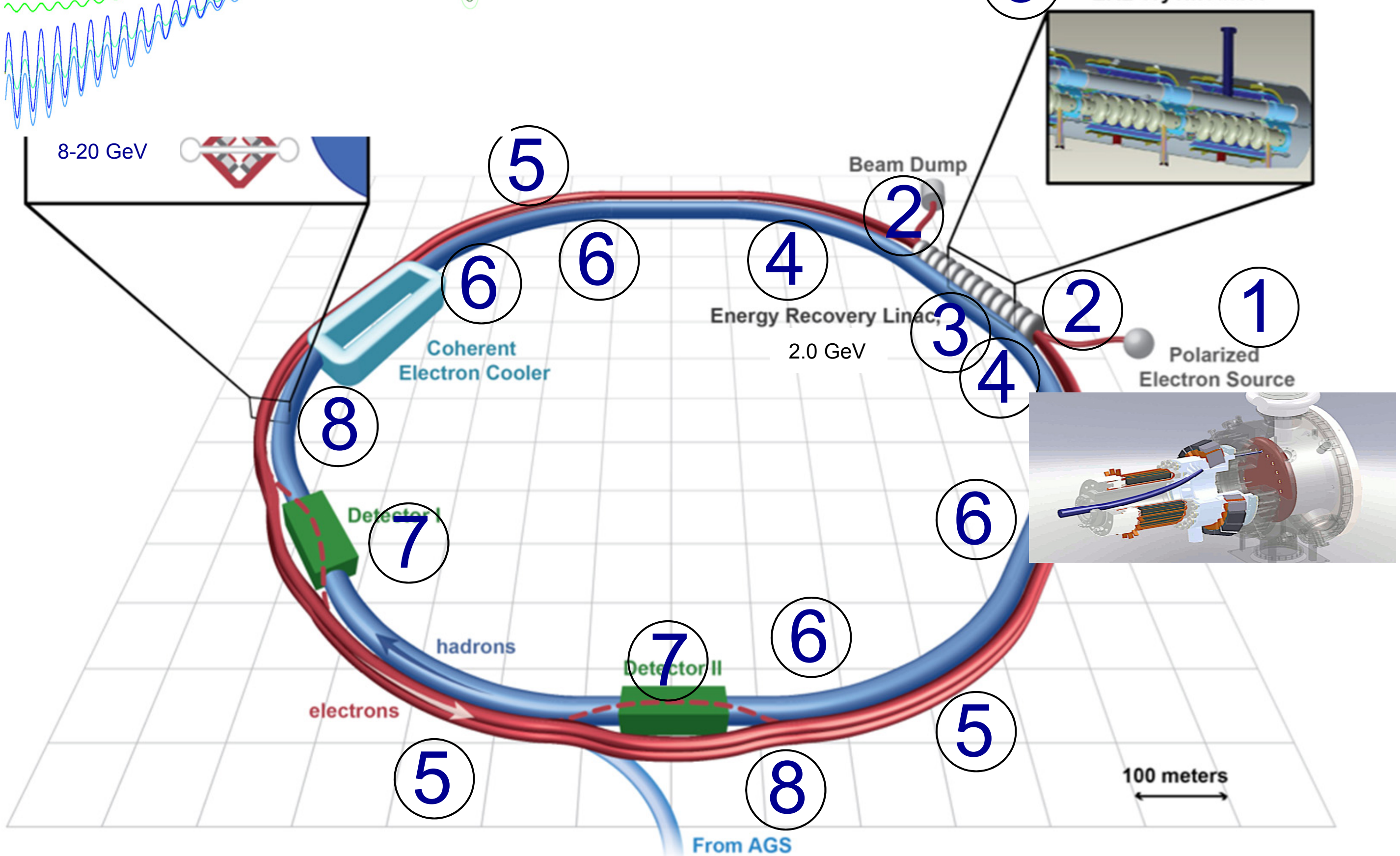
eRHIC Technical Overview





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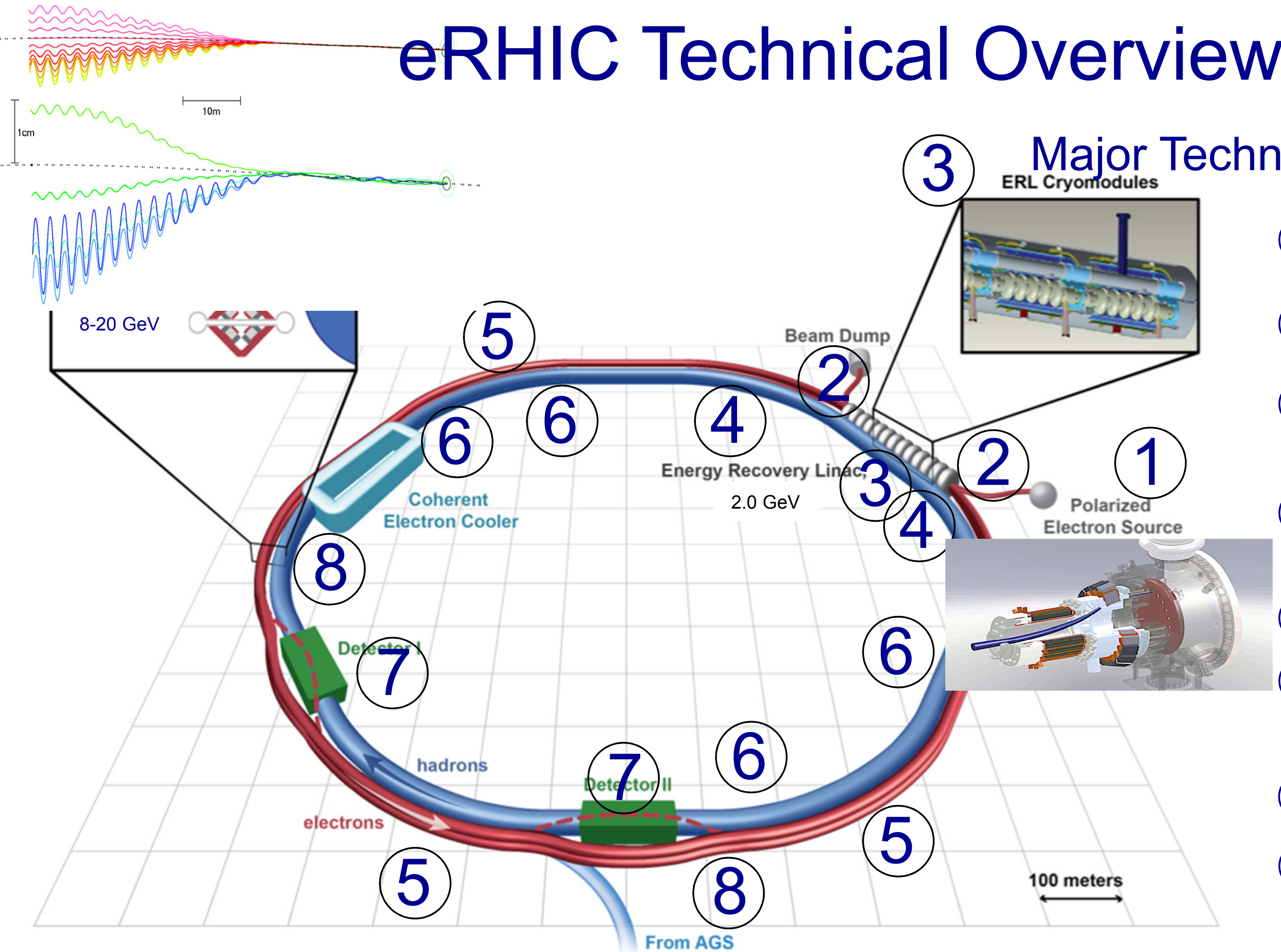

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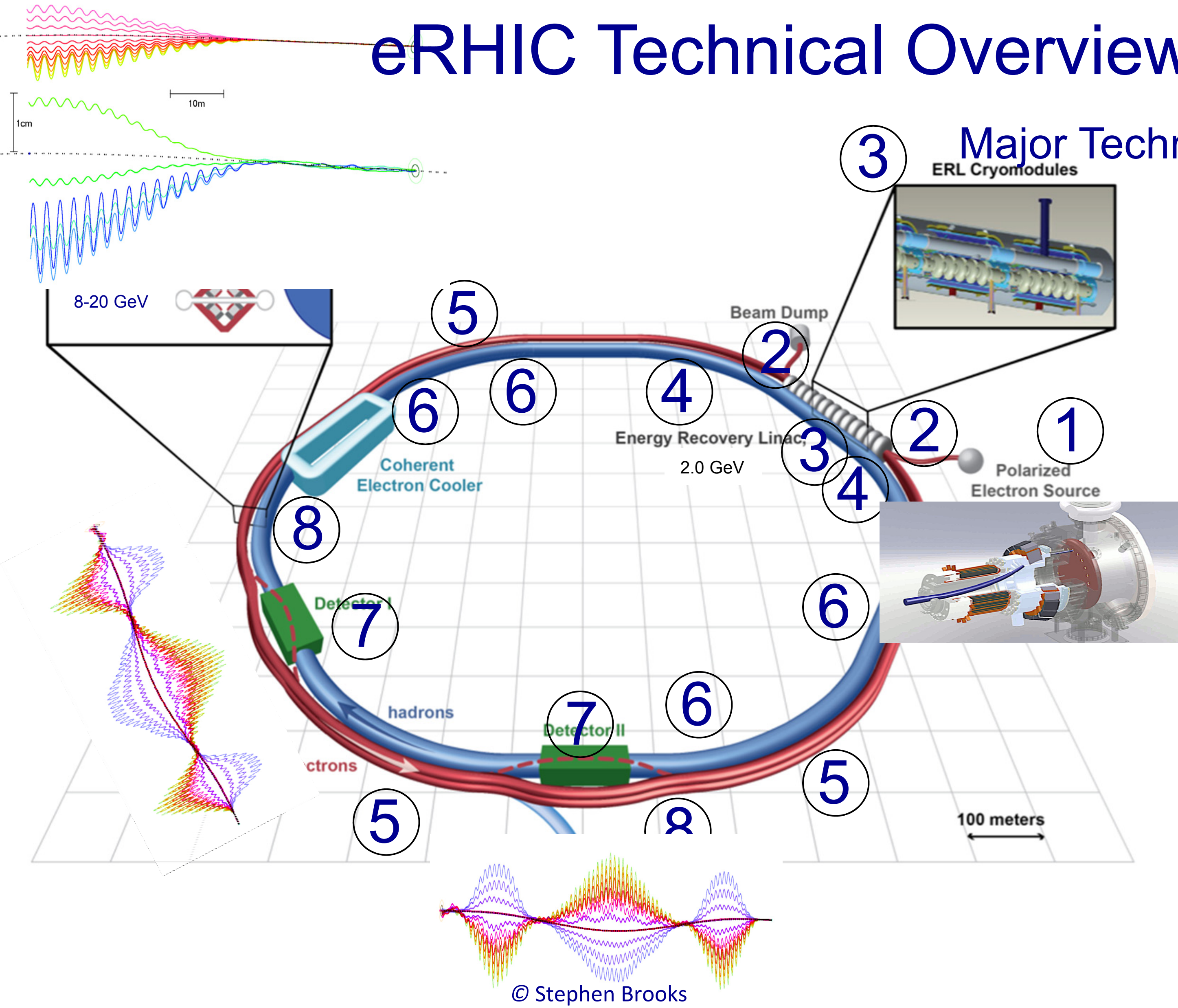
⑨ Detector By Passe

eRHIC Technical Overview



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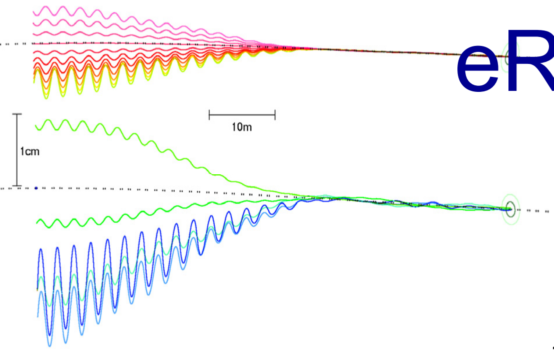
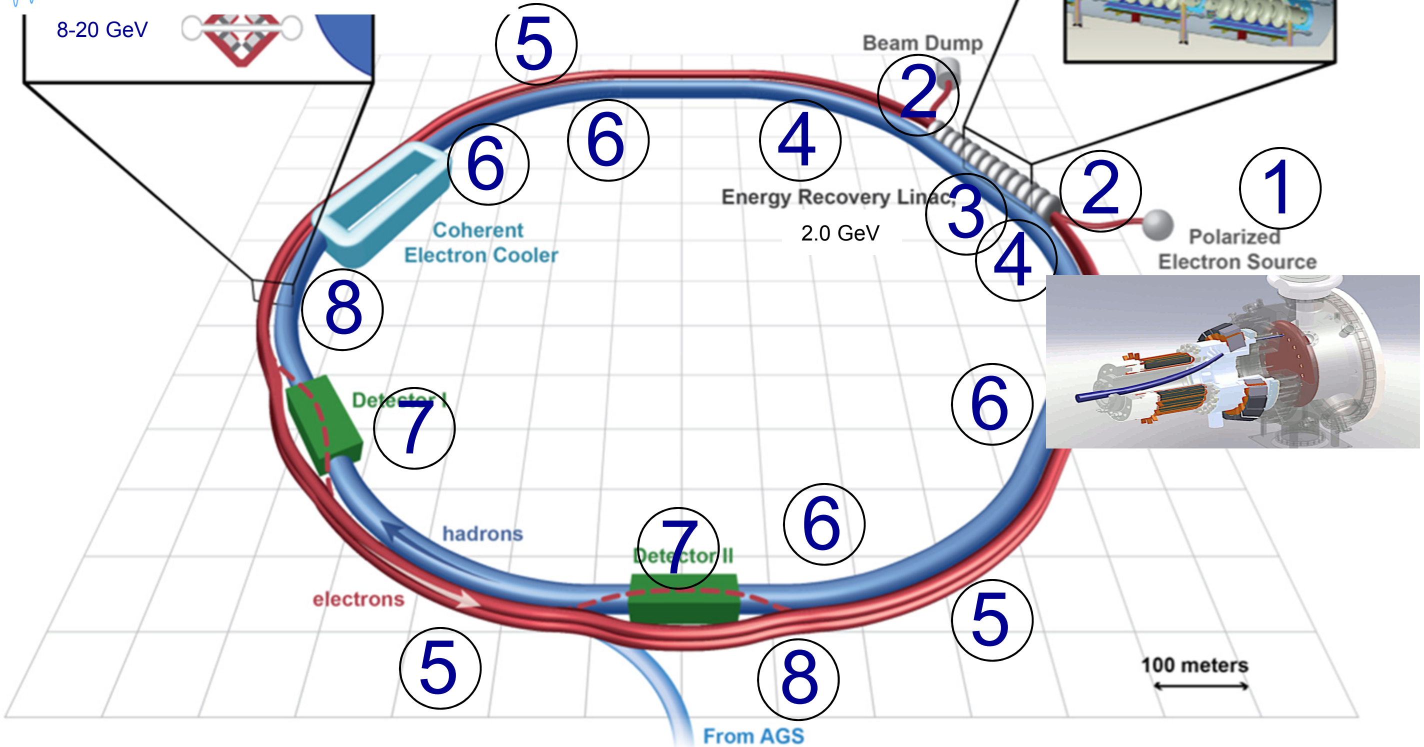
BROOKHAVEN NATIONAL LABORATORY

eRHIC Technical Overview





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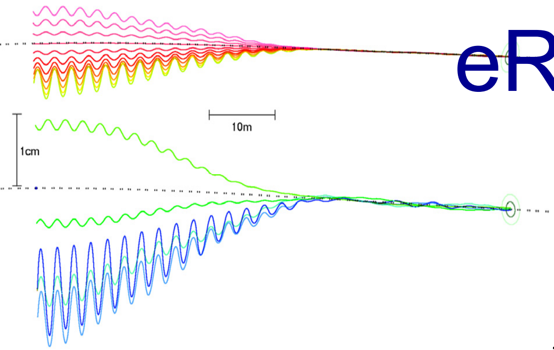

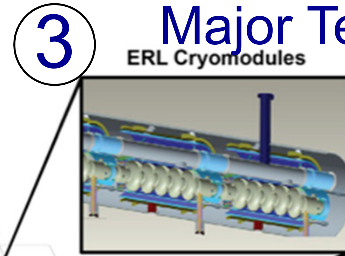

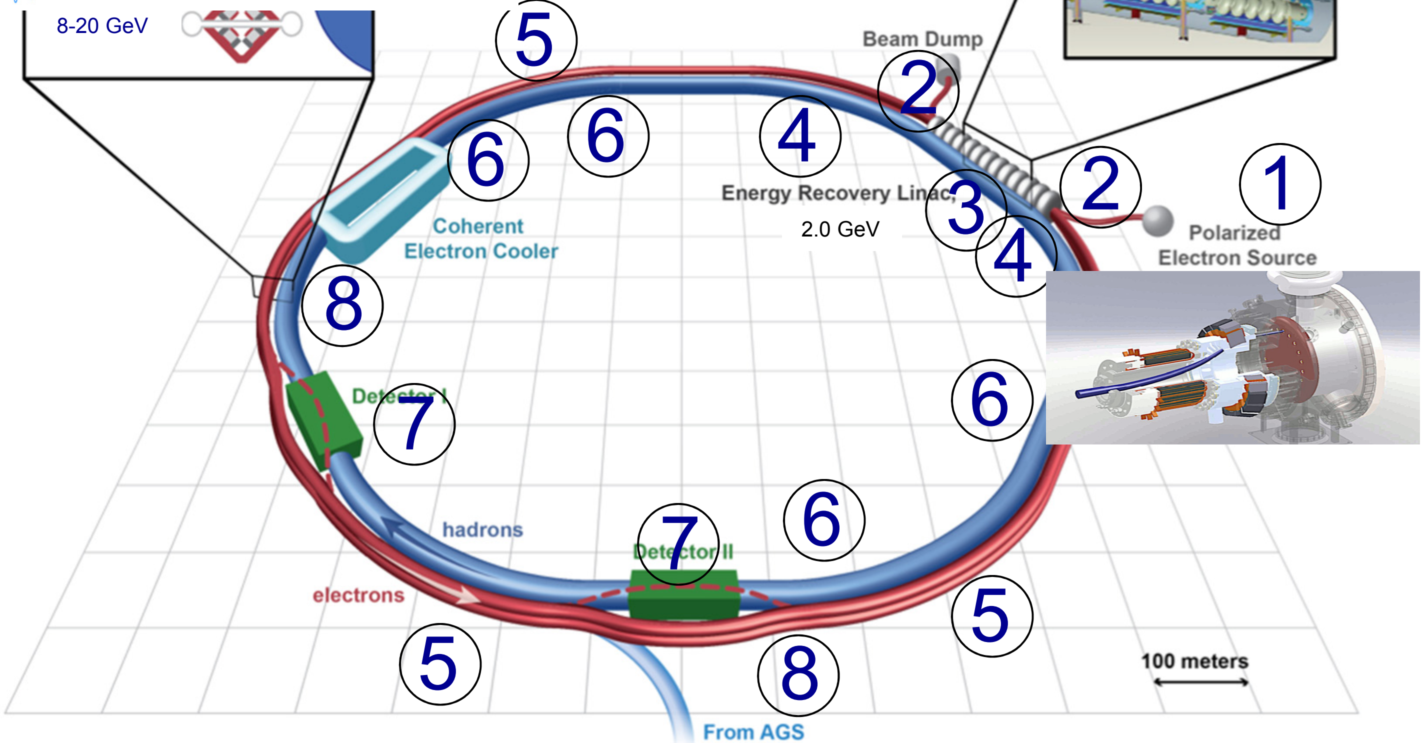

Major Technical Components:

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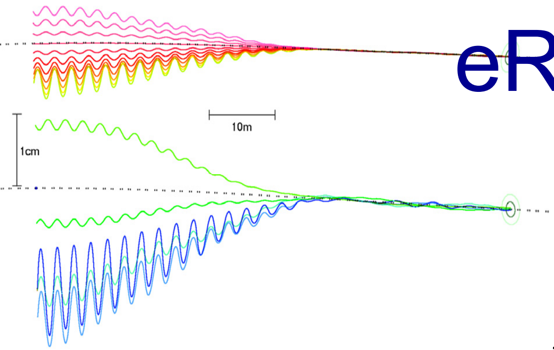
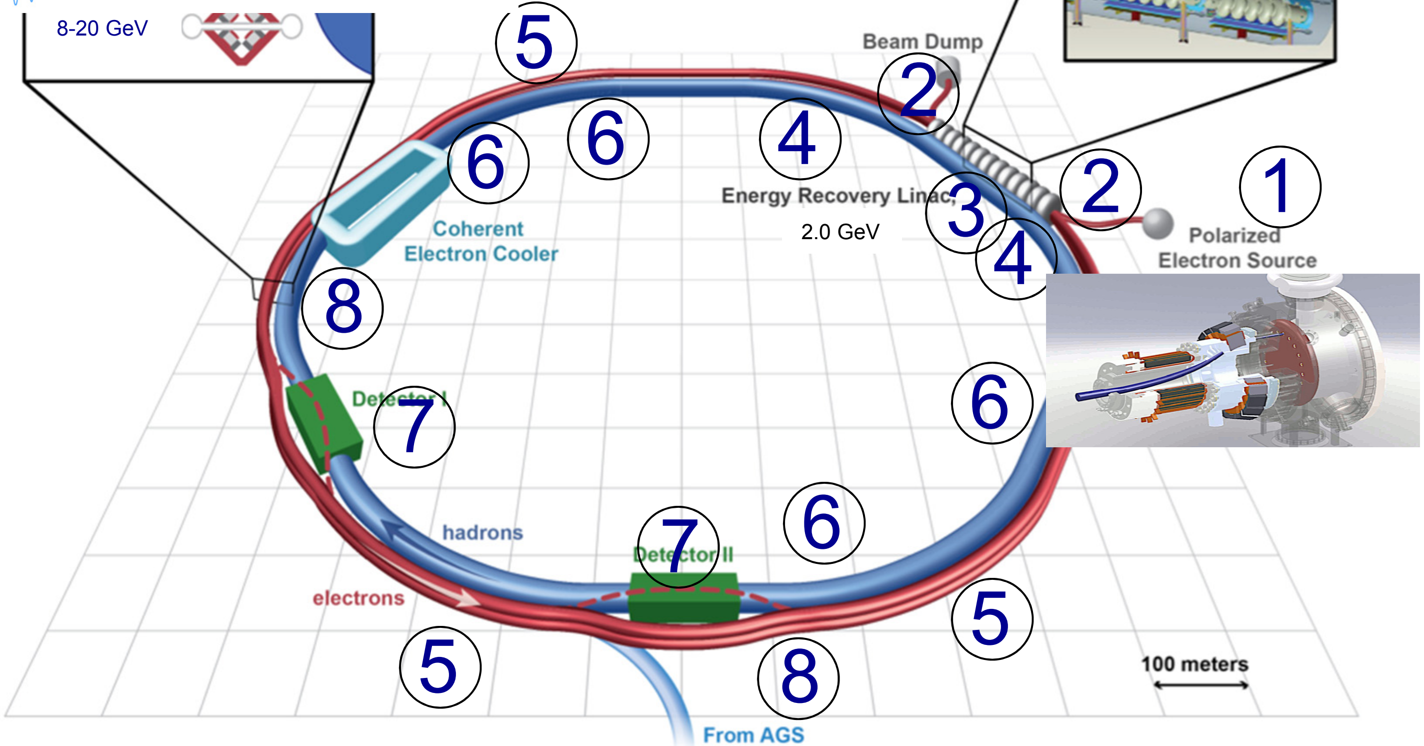
2. ERL mergers
3. Superconducting Linac - ERL
4. Spreaders and Combiners
5. NS-FFAG arcs
6. Merging arcs to straight section
7. Straight section
8. Extracted high energy beam

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 moves the cost optimized linac and recirculation lattice to a dramatically better optimum.

eRHIC Technical Overview





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⑤ NS-FFAG arcs

⑥ Merging arcs to straight section

⑦ Straight section

⑧ Extracted high energy beam

The Non Scaling FFAG (NS-FFAG) lattice enables multiple passes of the electron beam

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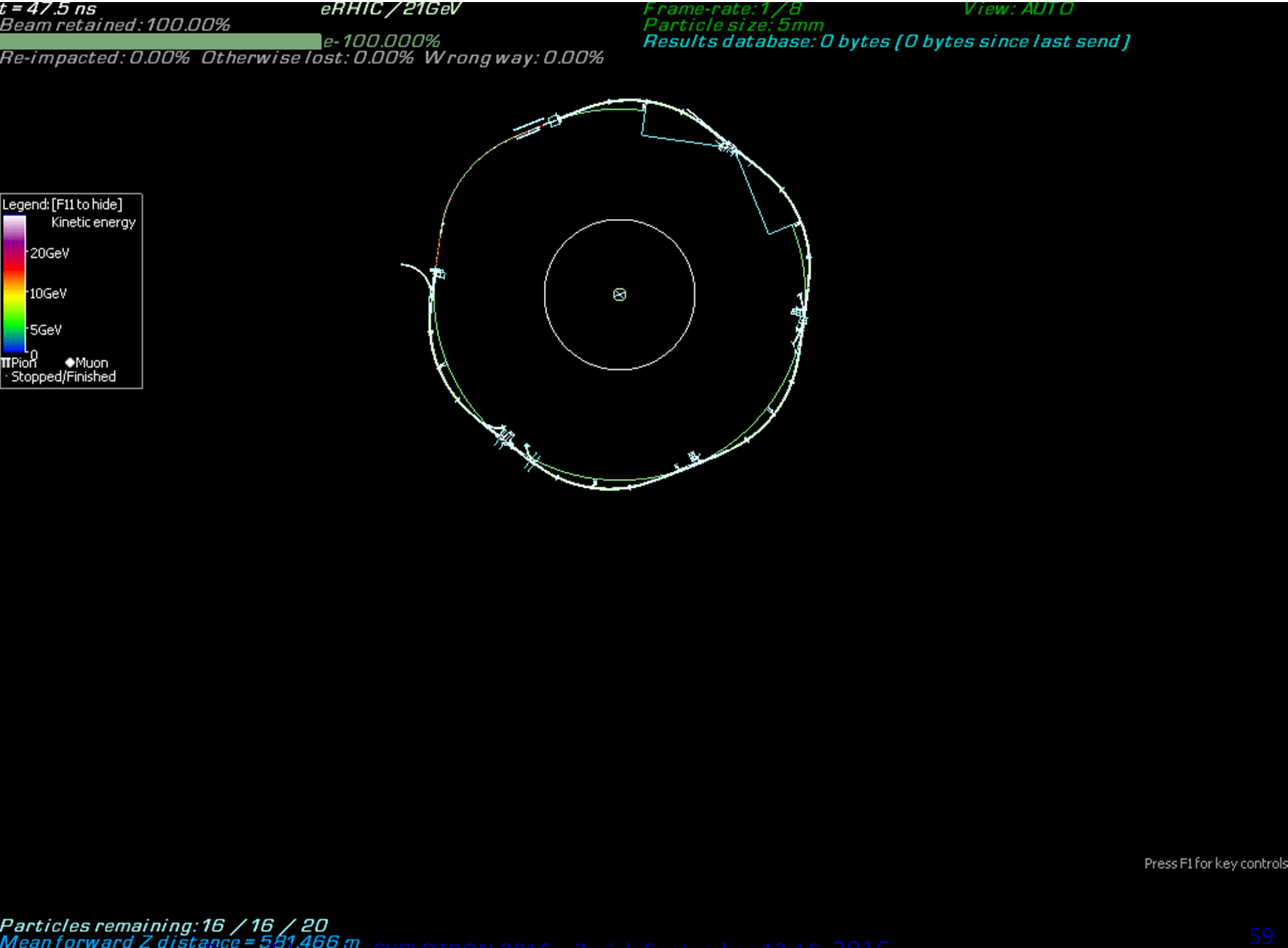
Proceedings of EPAC 2004, Lucerne, Switzerland

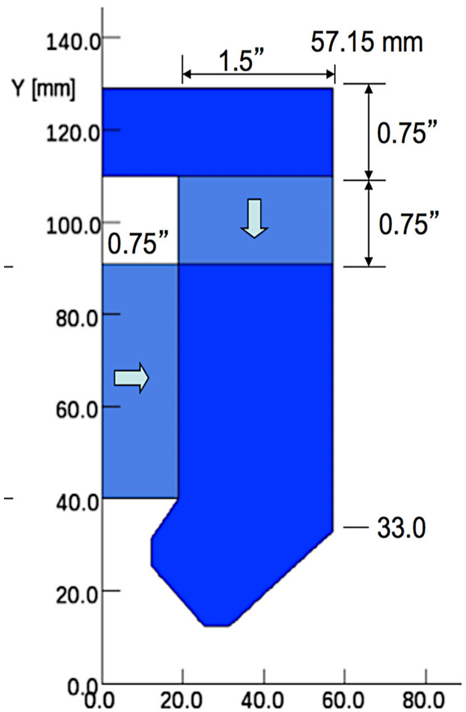
ELECTRON ACCELERATION FOR E-RHIC WITH NON-SCALING FFAG*

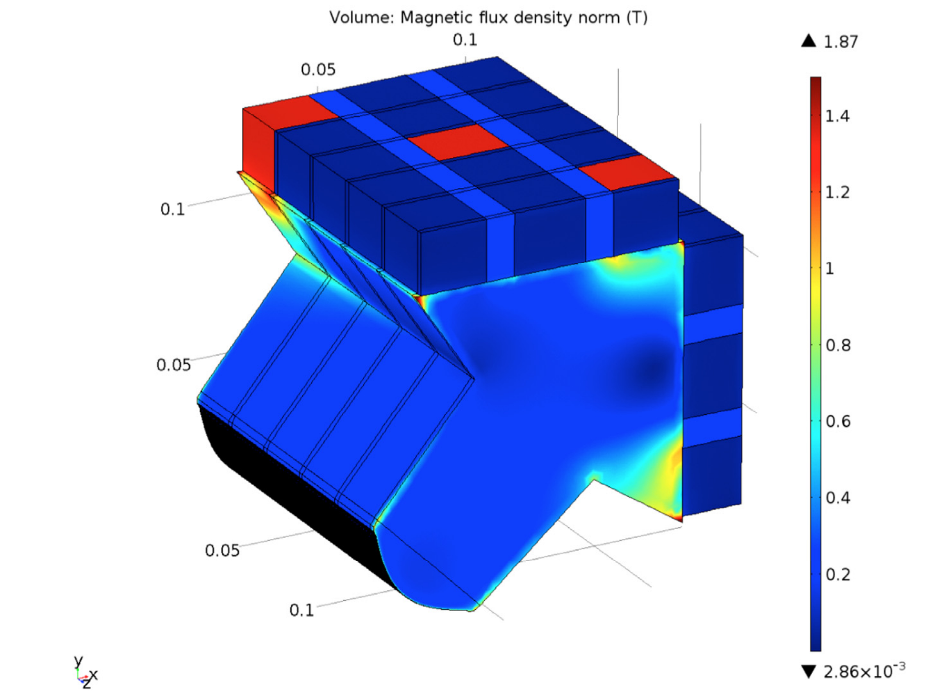
D. Trbojevic, M. Blaskiewicz, E. D. Courant, A. Ruggiero, J. Kewisch, T. Roser, and N. Tsoupas, BNL, Upton, N.Y. 11973, USA



t = 47.5 ns
eRHIC / 21GeV
Frame-rate: 1 / 8
View: AUTO
Beam retained: 100.00%
Particle size: 5mm
e- 100.000%
Results database: 0 bytes (0 bytes since last send)
Re-impacted: 0.00% Otherwise lost: 0.00% Wrong way: 0.00%
Legend: [F11 to hide]
Kinetic energy
20GeV
10GeV
5GeV
0
Pion
Muon
Stopped/Finished
Press F1 for key controls
Particles remaining: 16 / 16 / 20
Mean forward Z distance

eRHIC Magnet Design

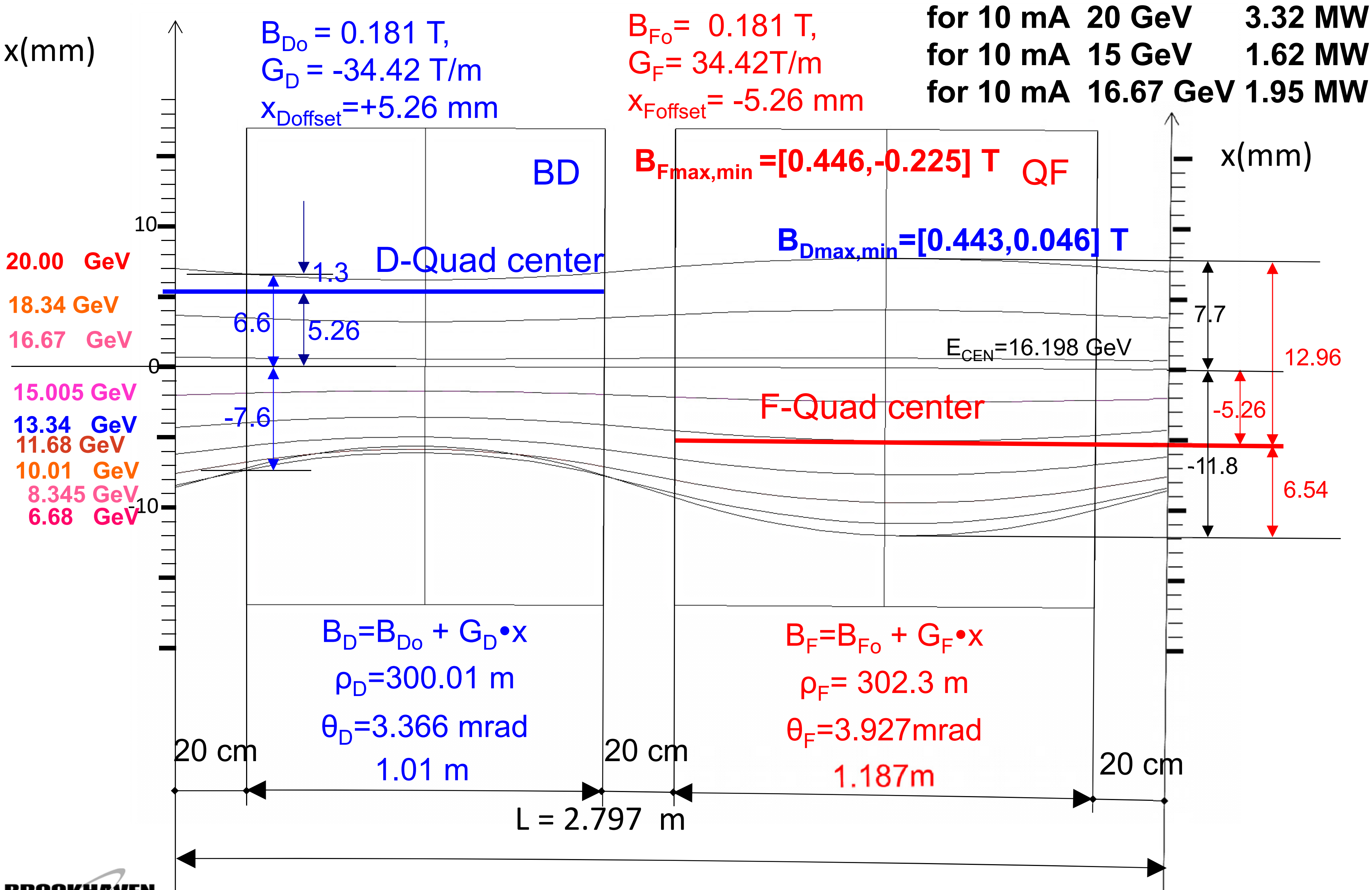




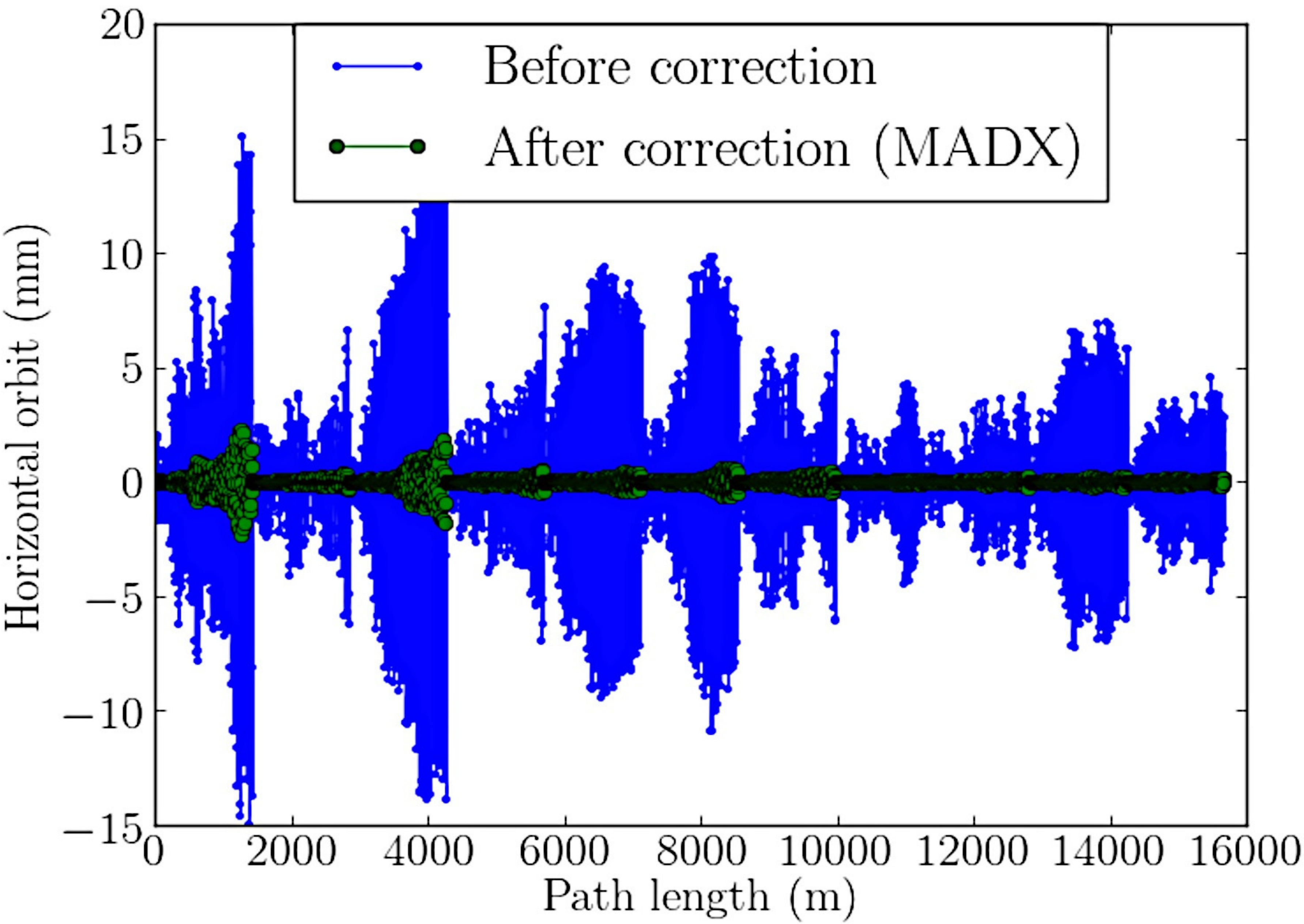
High Energy eRHIC NS-FFAG Cell

Synchrotron Radiation:

for 10 mA	20 GeV	3.32 MW
for 10 mA	15 GeV	1.62 MW
for 10 mA	16.67 GeV	1.95 MW



Chuyu Liu

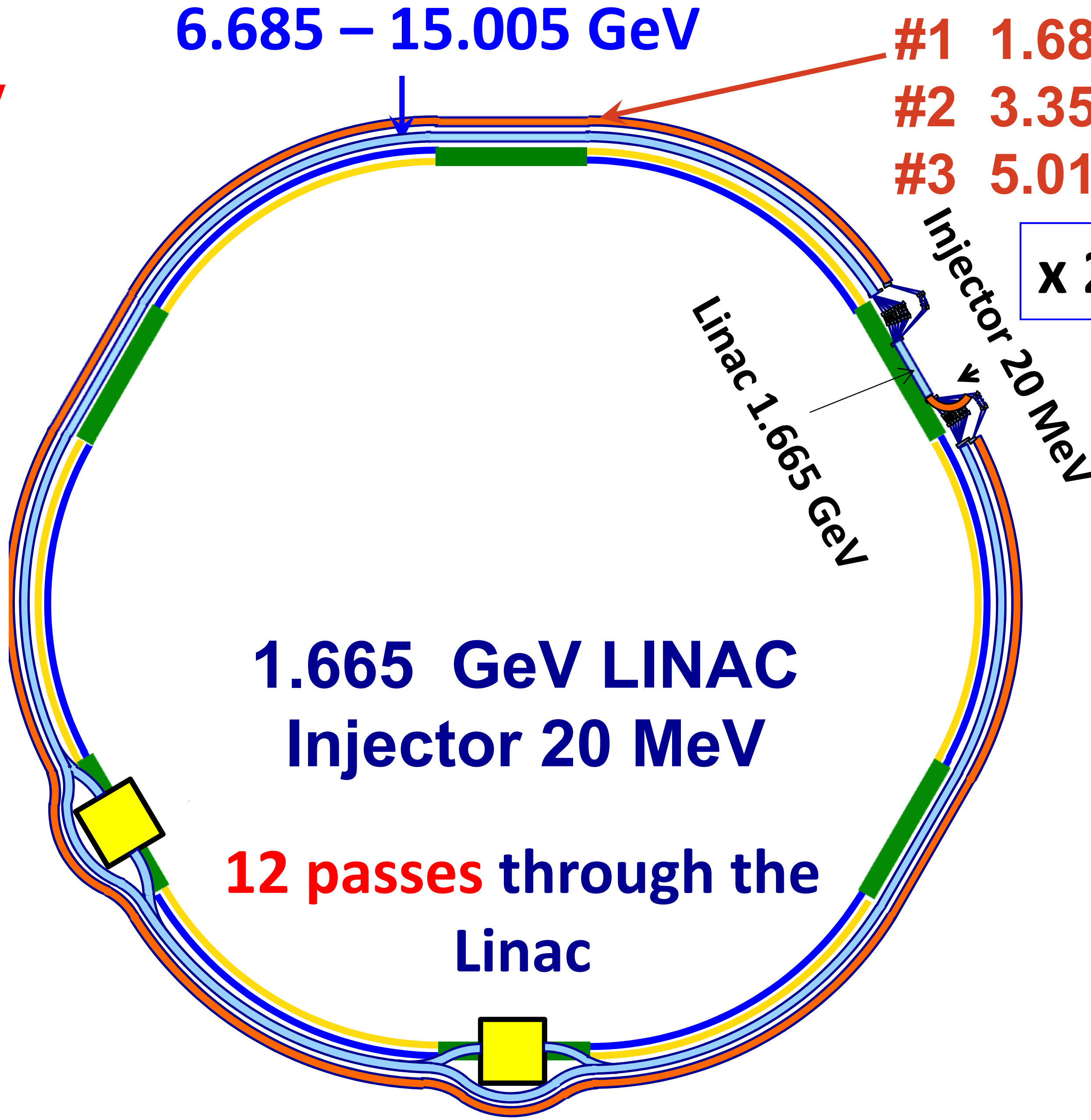

Before correction
After correction (MADX)
Horizontal orbit (mm)
Path length (m)
20
15
10
5
0
−5
−10
−15
0
2000
4000
6000
8000
10000
12000
14000
16000

Option #2
10 mA
Linac 1.67 GeV
#1 6.680 GeV
#2 8.345 GeV
#3 10.010 GeV
#4 11.675 GeV
#5 13.340 GeV
#6 15.005 GeV
#7 16.670 GeV
#8 18.335 GeV
#9 20.000 GeV

x 2.99

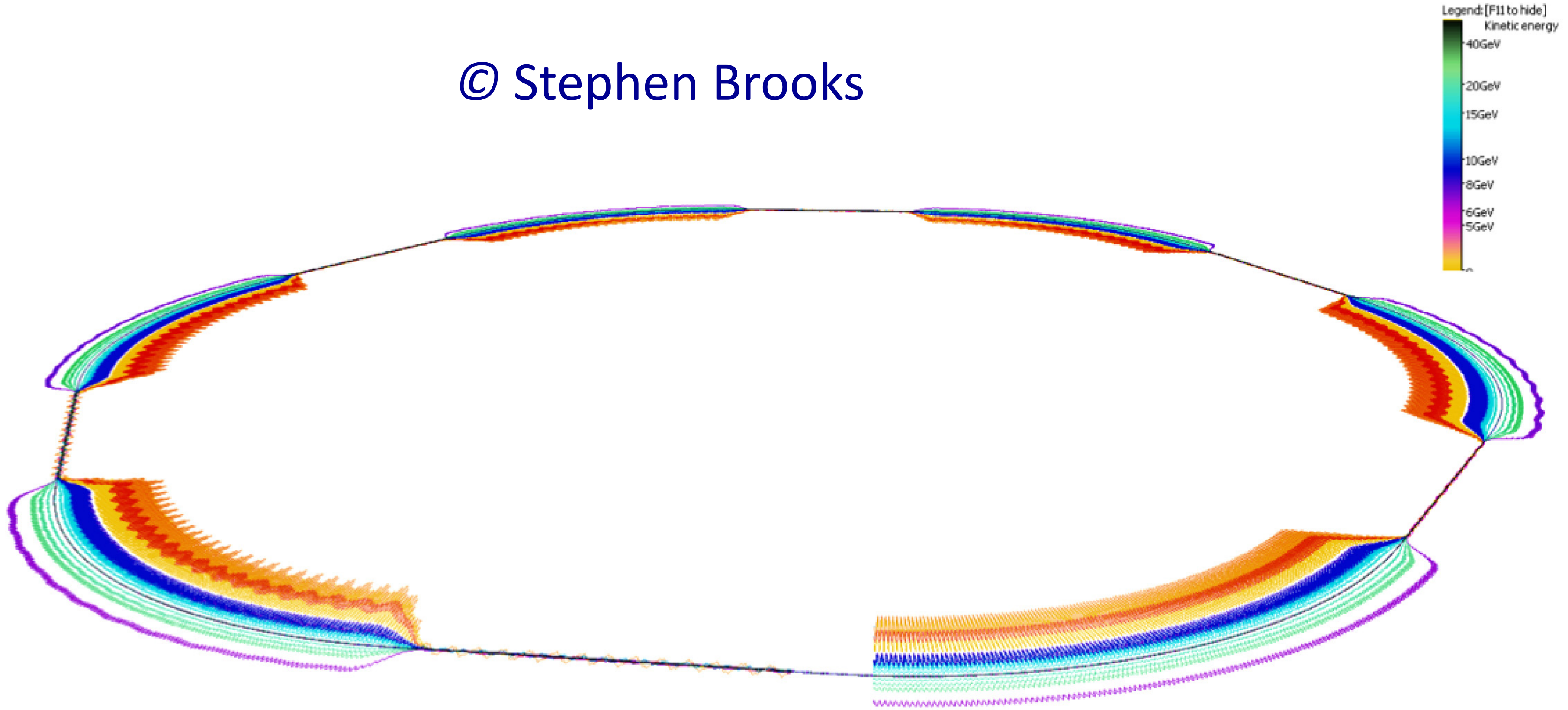
Energy
#1 1.685 GeV
#2 3.350 GeV
#3 5.015 GeV

x 2.976

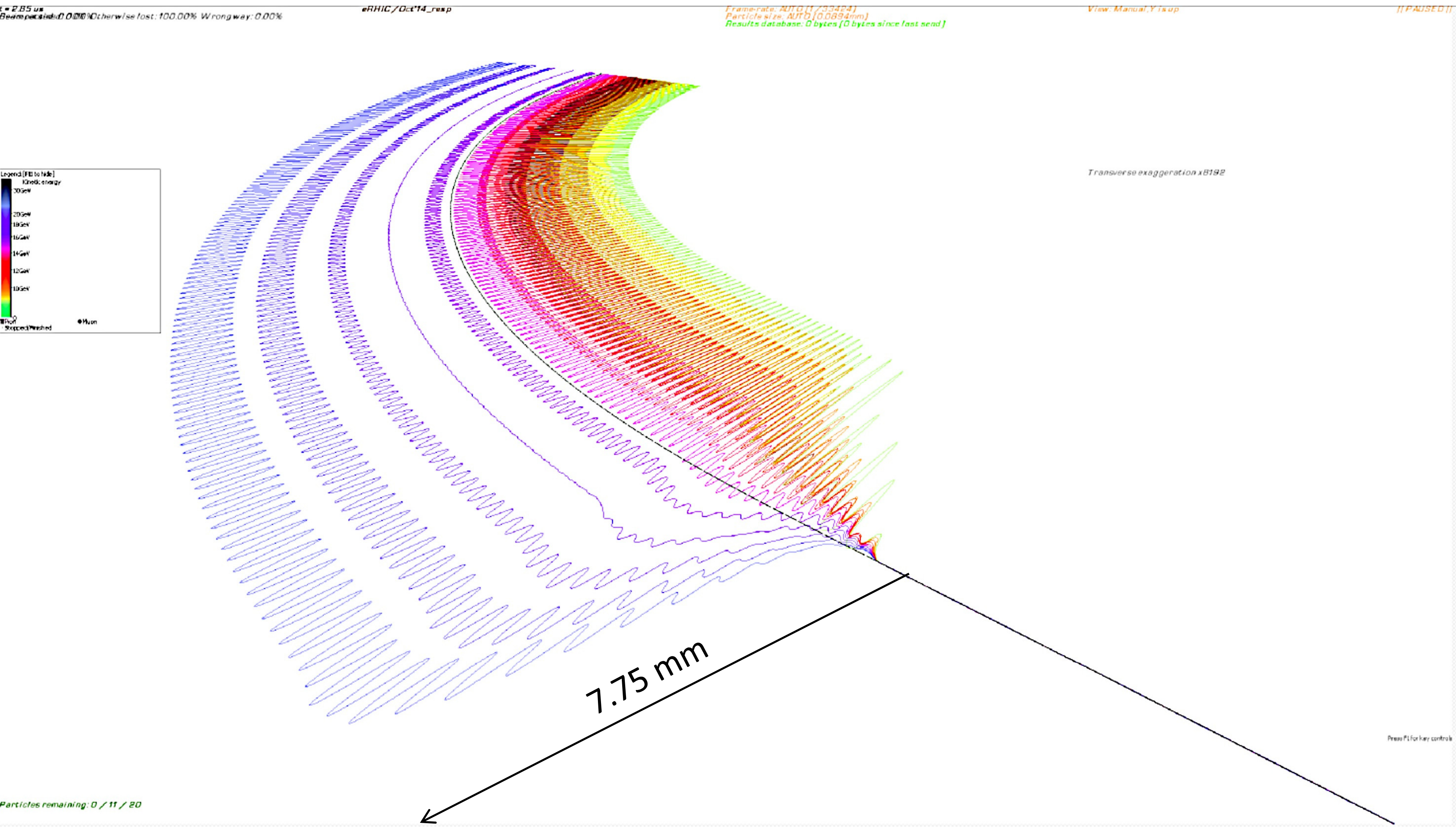


eRHIC FFAG Orbits Magnified x1000

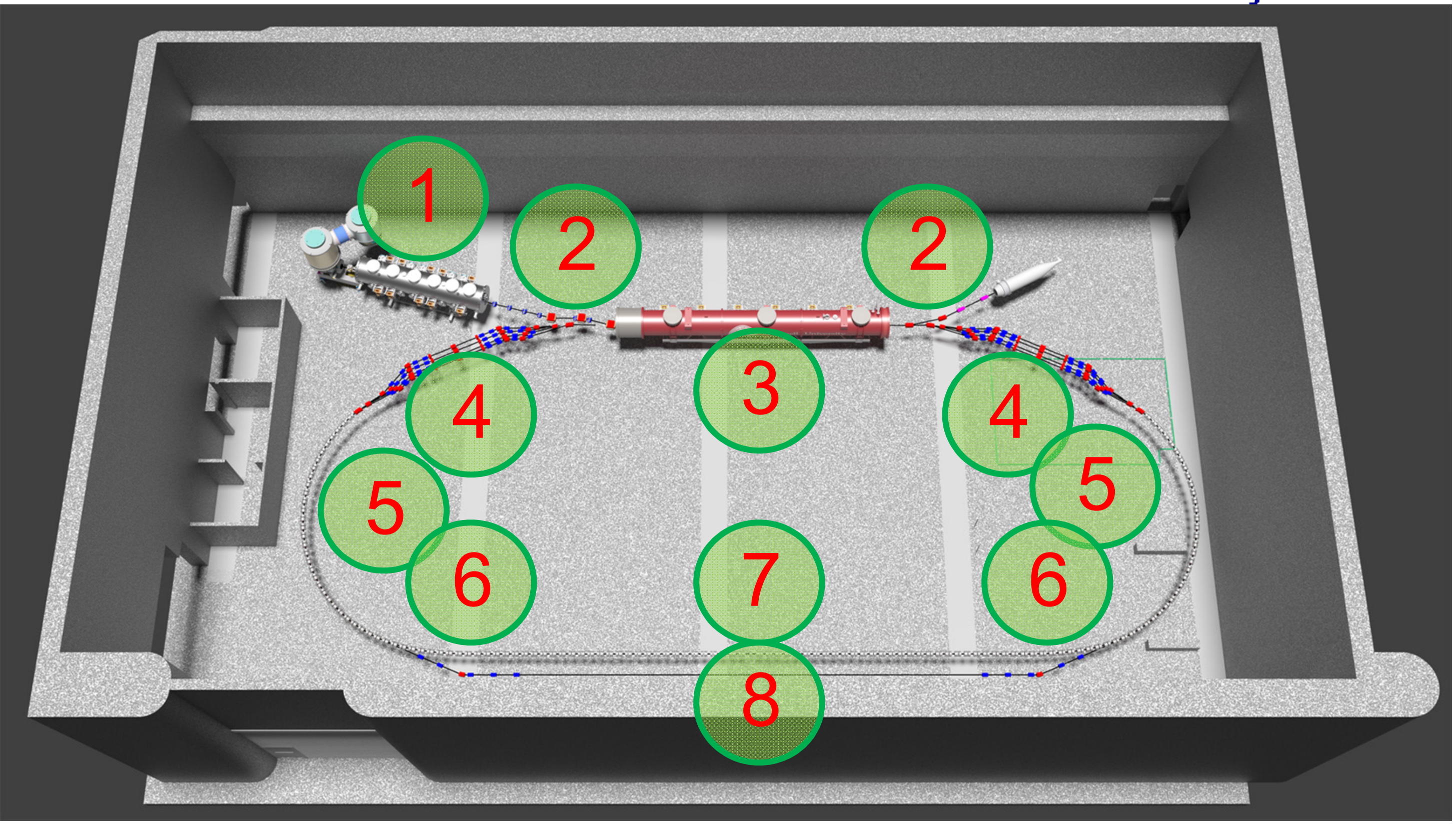
© Stephen Brooks



Merging FFAG arcs to the straight section in eRHIC



eRHIC prototype: NS-FFAG ERL at Cornell



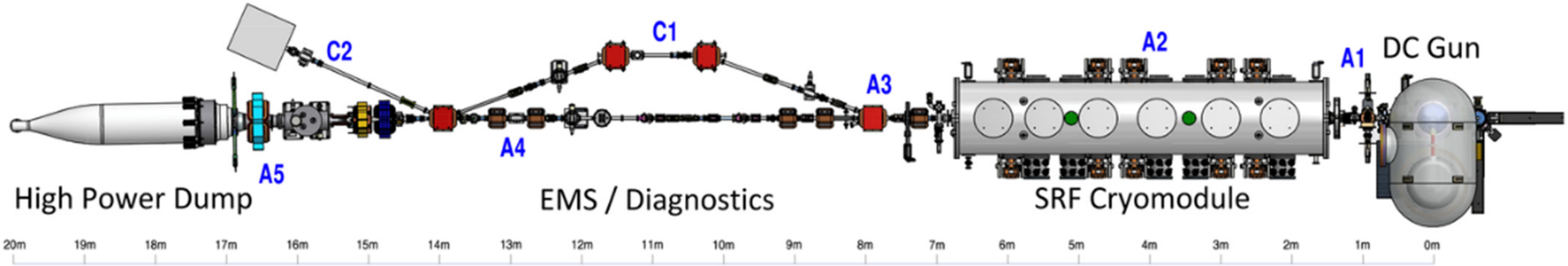
Major Technical Components:

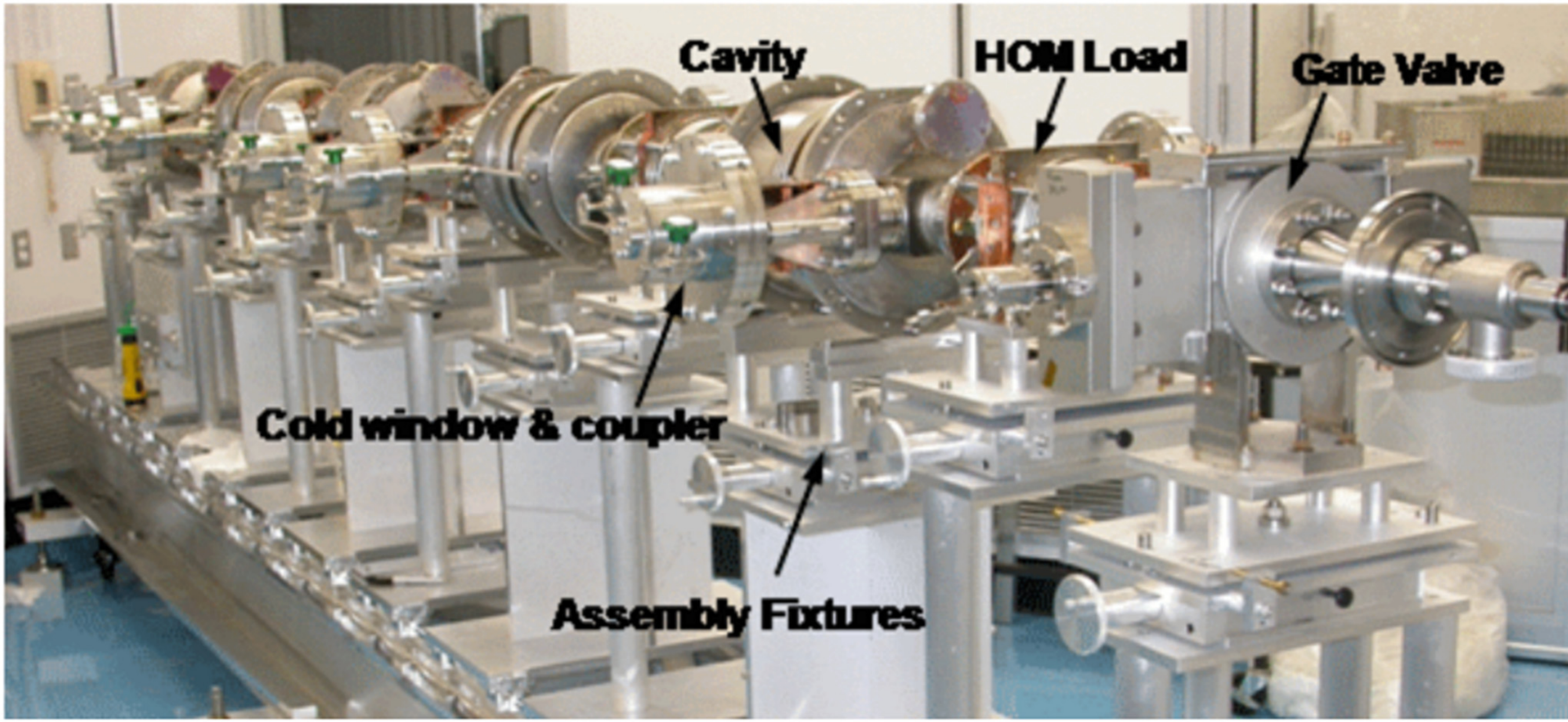
① Electron Gun with Linac
② ERL mergers
③ Superconducting Linac - ERL
④ Spreaders and Combiners
⑤ NS-FFAG arcs
⑥ Merging arcs to straight section
⑦ Straight section
⑧ Extracted high energy beam

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

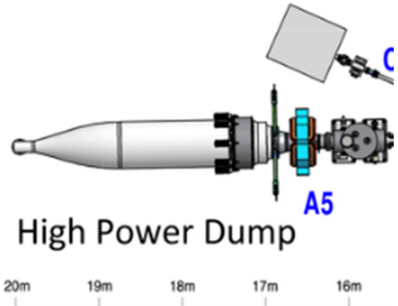
Tracking electron beams with four different energies through the Cornell Demonstration NS-FFAG ERL (by Stephen Brooks)

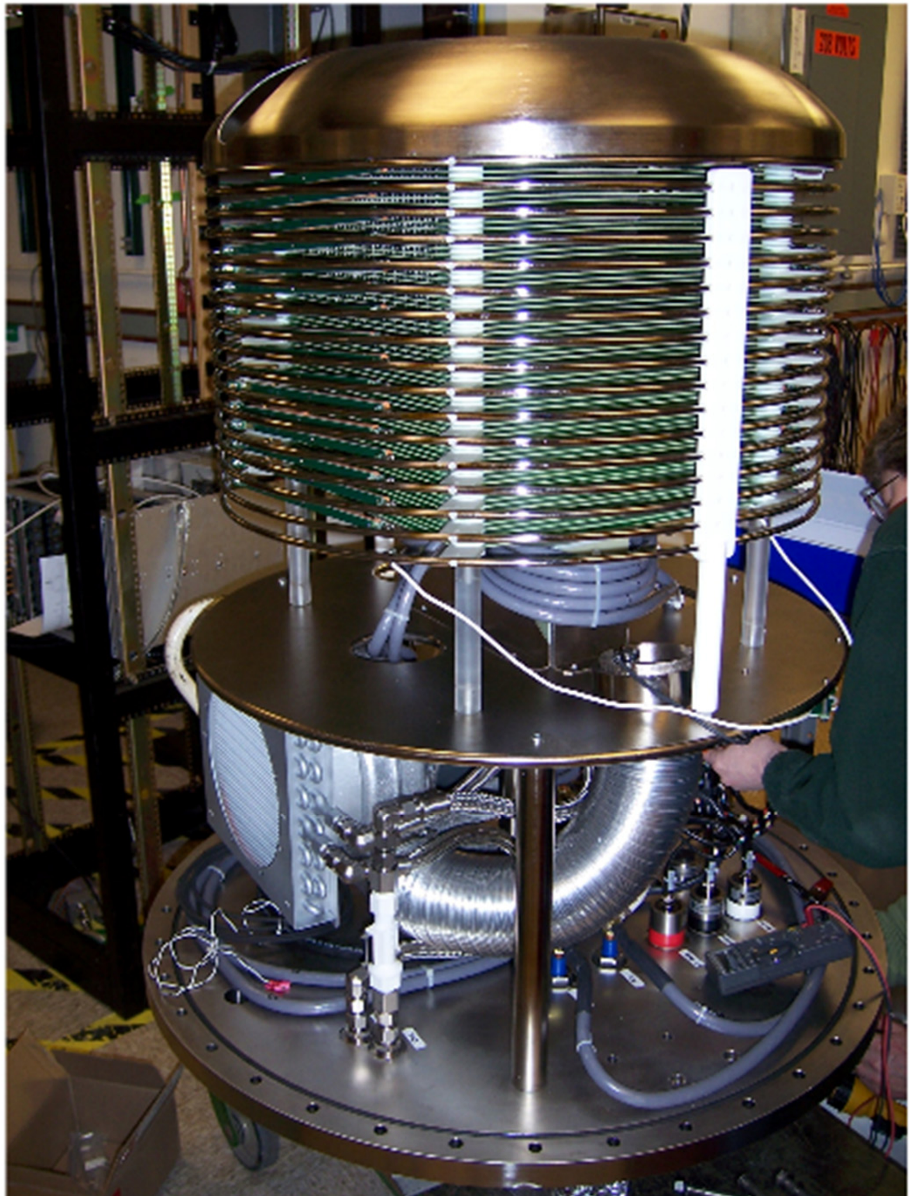
Cornell Injector

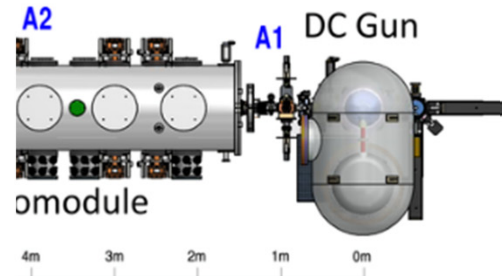




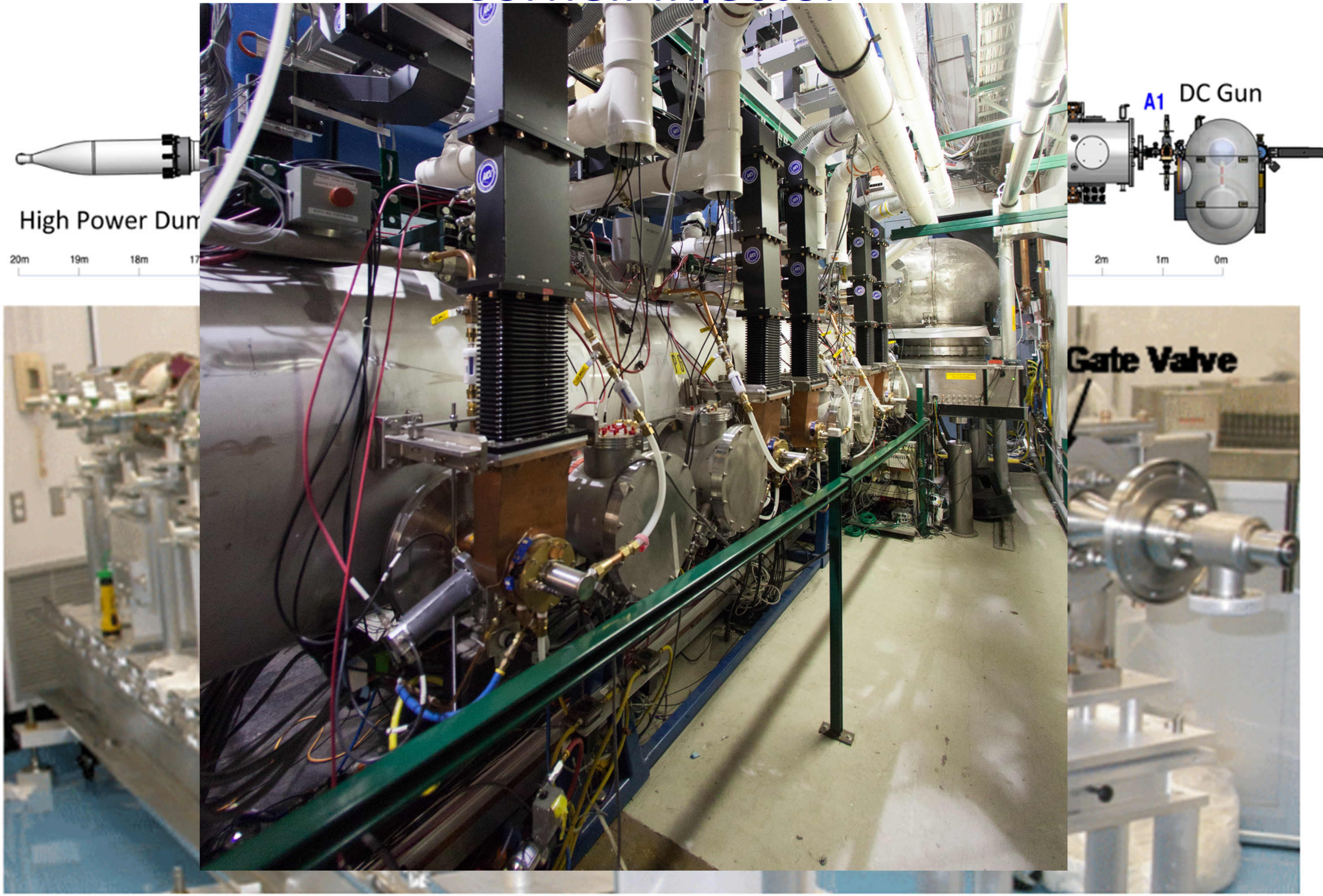
Cornell Injector



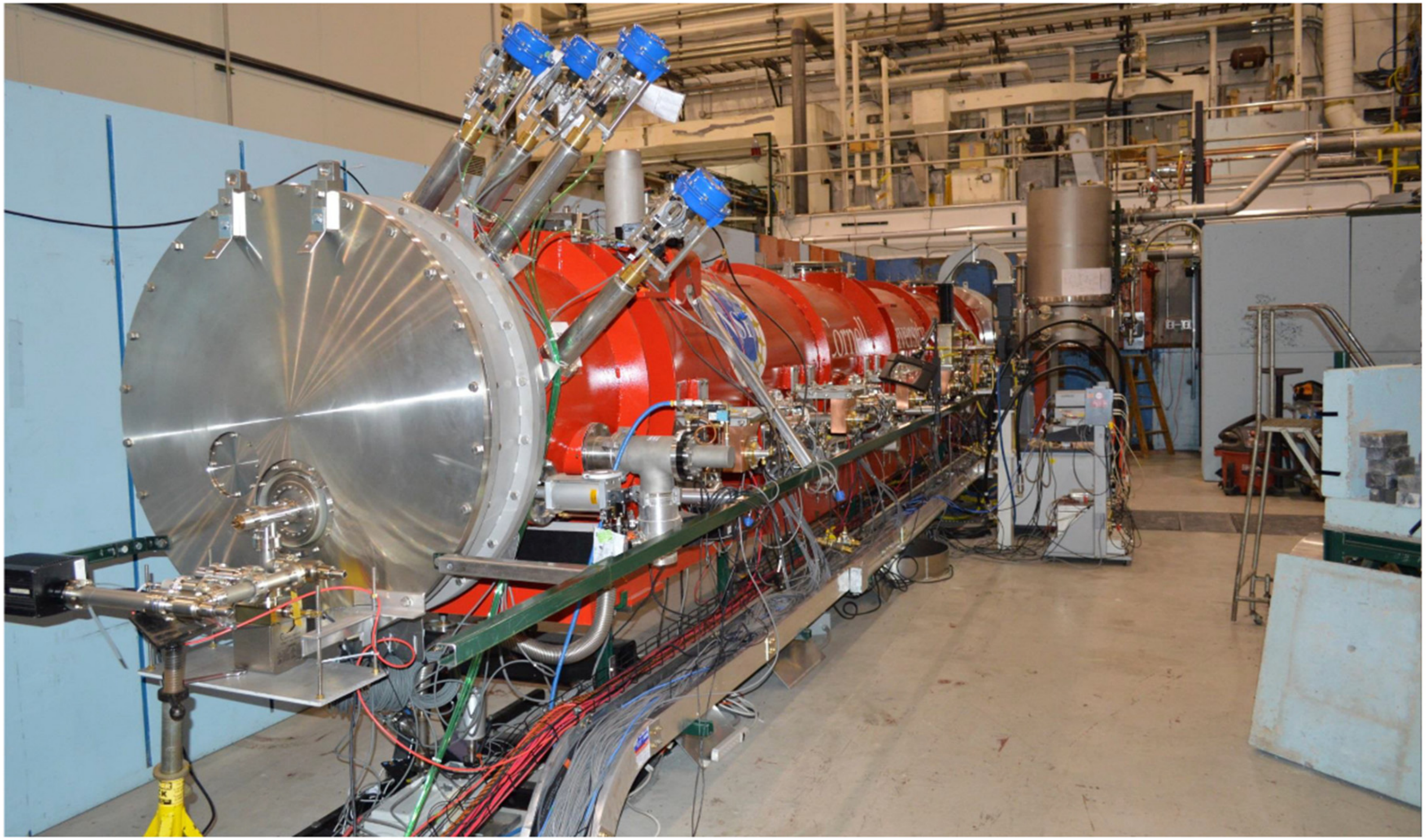




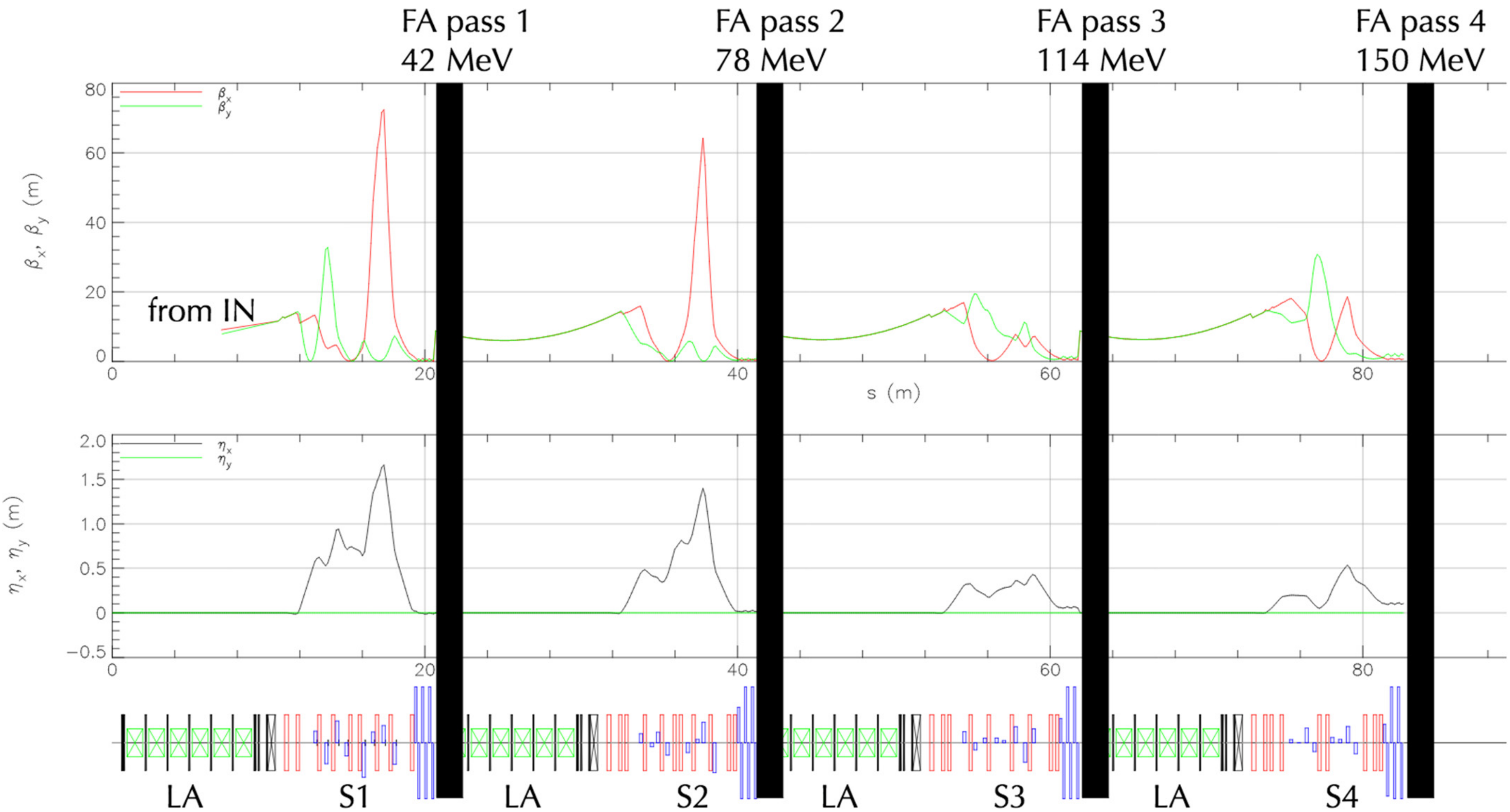
Cornell Injector



Cornell superconducting Linac



Betatron functions for 4 energies in CBETA



The prototype of eRHIC will be built at Cornell

Some of the most important risk items 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.
   d) ERL startup from low-power beam.

CONCLUSION

- A cost effective LHeC (almost twice reduction of the proposed linac size with enhanced luminosity) and eRHIC designs with 1.6 GeV linac and maximum energy of 20 GeV, as well as the 250 and 150 MeV ERL with NS-FFAG at Cornell University, are shown.

- At LHeC a proposal for replacement of the 2 x 10 GeV linacs and three arcs, with 2 x 5.453 GeV linacs and two NS-FFAG arcs, respectively. This would be a cost-effective solution with lower synchrotron radiation, hence 34 % larger luminosity for the same limit on the value of 15 MW for the total loss from synchrotron radiation.

- At eRHIC the previous 6 separate beam lines are replaced with two NS-FFAG lines reducing the linac energy and with permanent magnets more effective power consumption makes additional savings in operating cost and price.

- The ERL with NS-FFAG arcs at Cornell University will be a first ERL of that type. Advantages at Cornell University are already existing 6 MeV injector, superconducting linac 45-70 MeV making possible to obtain with the NS-FFAG maximum energies of 150-250 or higher MeV. This will be a proof of principle fot the new concept: merging FIXED FIELD ALTERNATING GRADIENT beam lines with the Energy Recovery Principle.