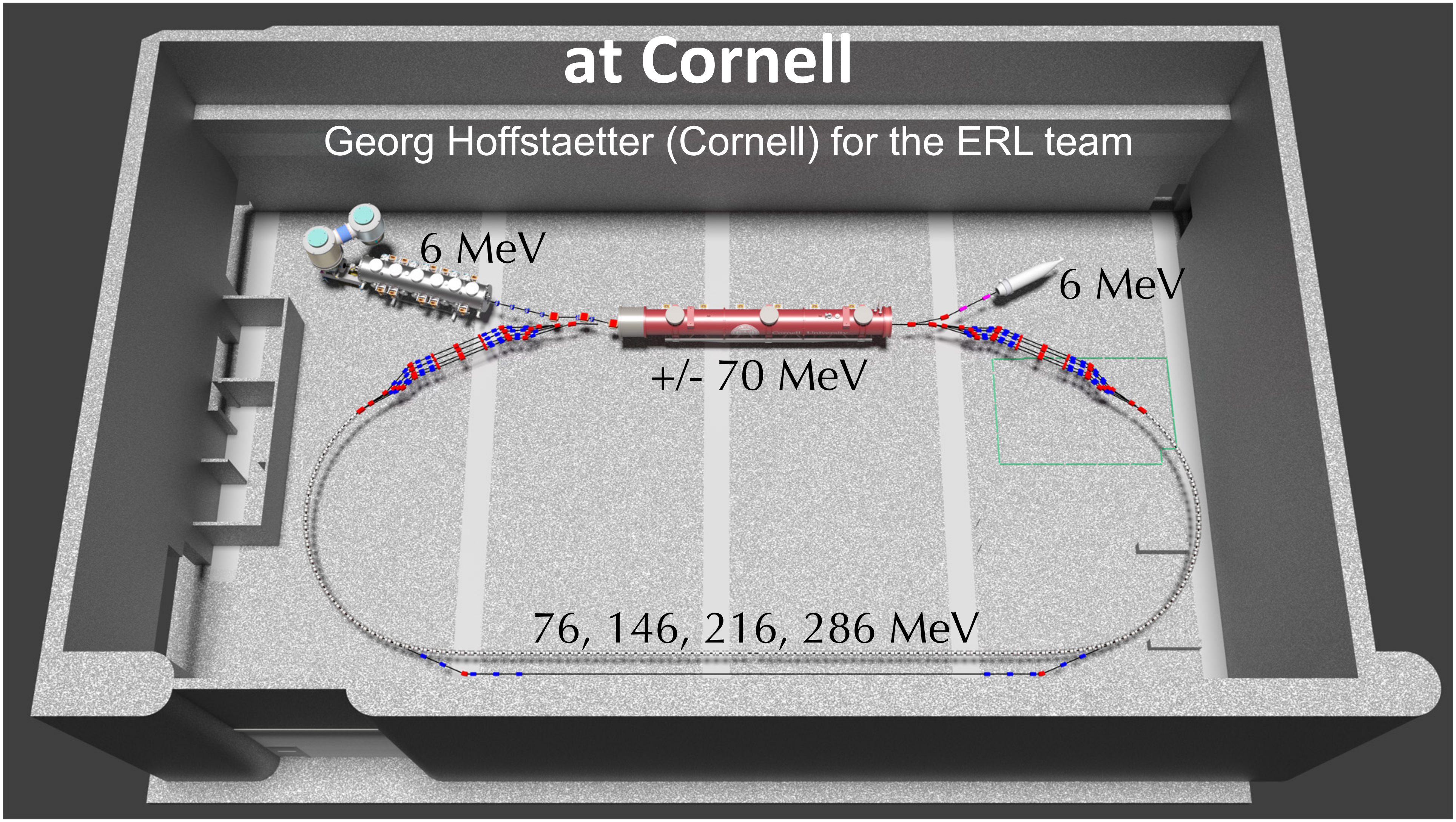
A 4-turn ERL for Intense Electron Beams at Cornell

Georg Hoffstaetter (Cornell) for the ERL team



Domains of accelerator types

Synchrotron: Repetitive acceleration to high energy, low repetition rate and therefore low current.

➔ Fixed target experiments, high energy, low current, relatively large beam size.

Storage rings: Rare filling at high energy and storage for millions of turns, high current, requires very low loss rates.

➔ Internal target experiments, high energy, high current, relatively large beam size.

Linacs: Linear acceleration to moderately high energies that are limited by the available length. Current*Energy is limited by the available power.

➔ Fixed target experiments, moderately high energies, low current, small beam size.

Cornell's 12GeV Synchrotron

And

Cornell's storage ring CESR

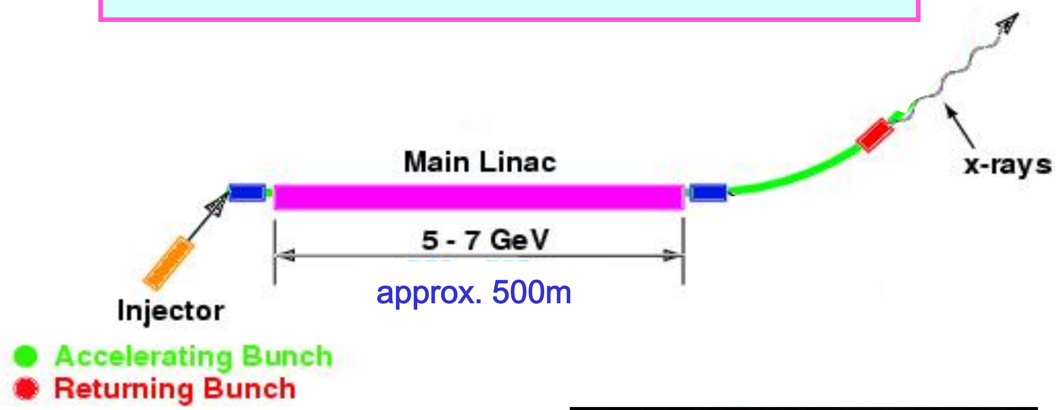
Linac beams

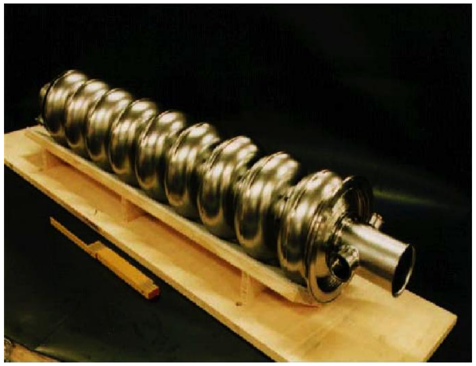
- Small beam sizes, Low energy spread, Shorter pulses
- But current limited by available power

Power limit of Linac beams

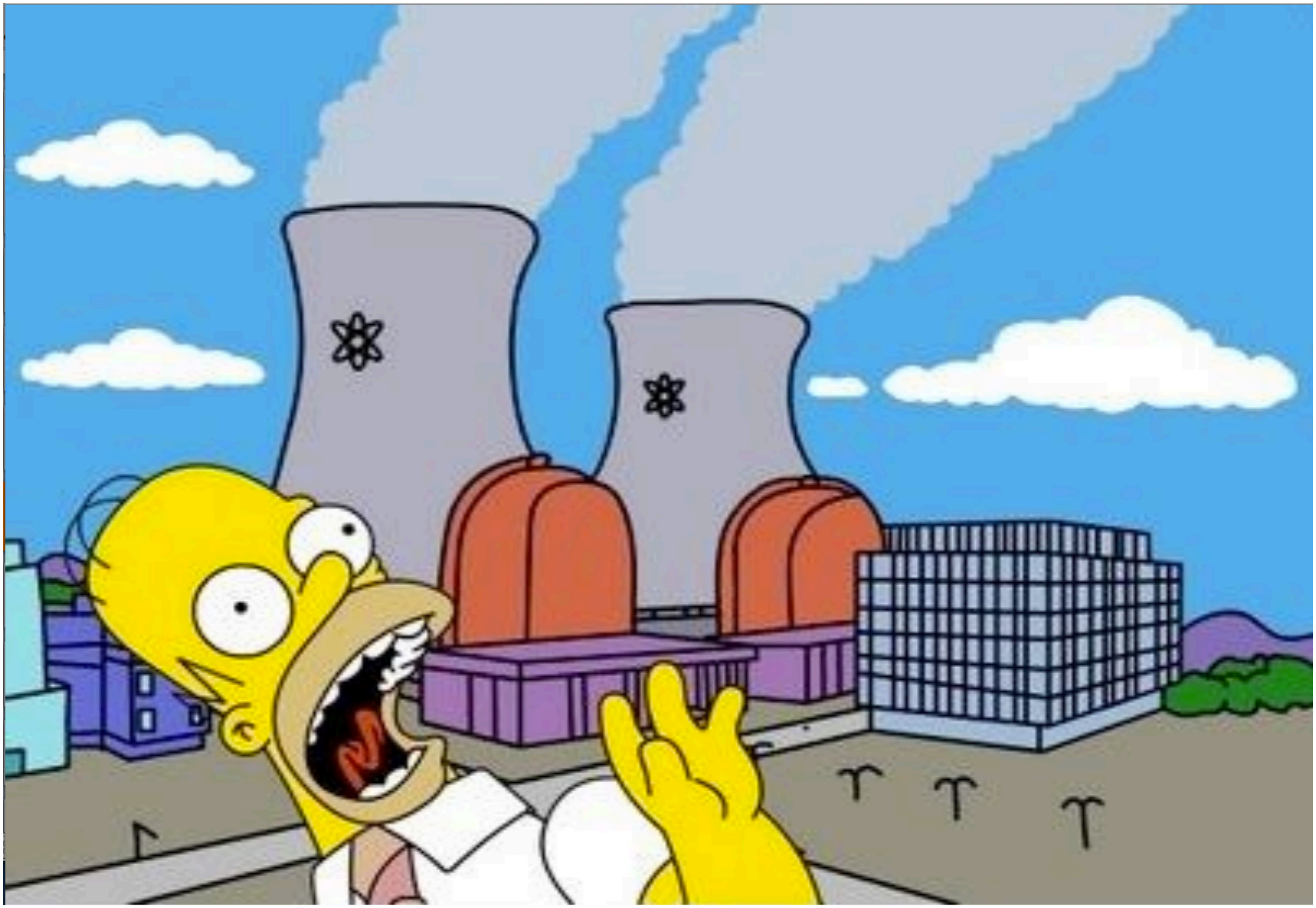
- Small beam sizes, Low energy spread, Shorter pulses
- But current limited by available power

5GV*100mA = 0.5GW
(good size power plant)



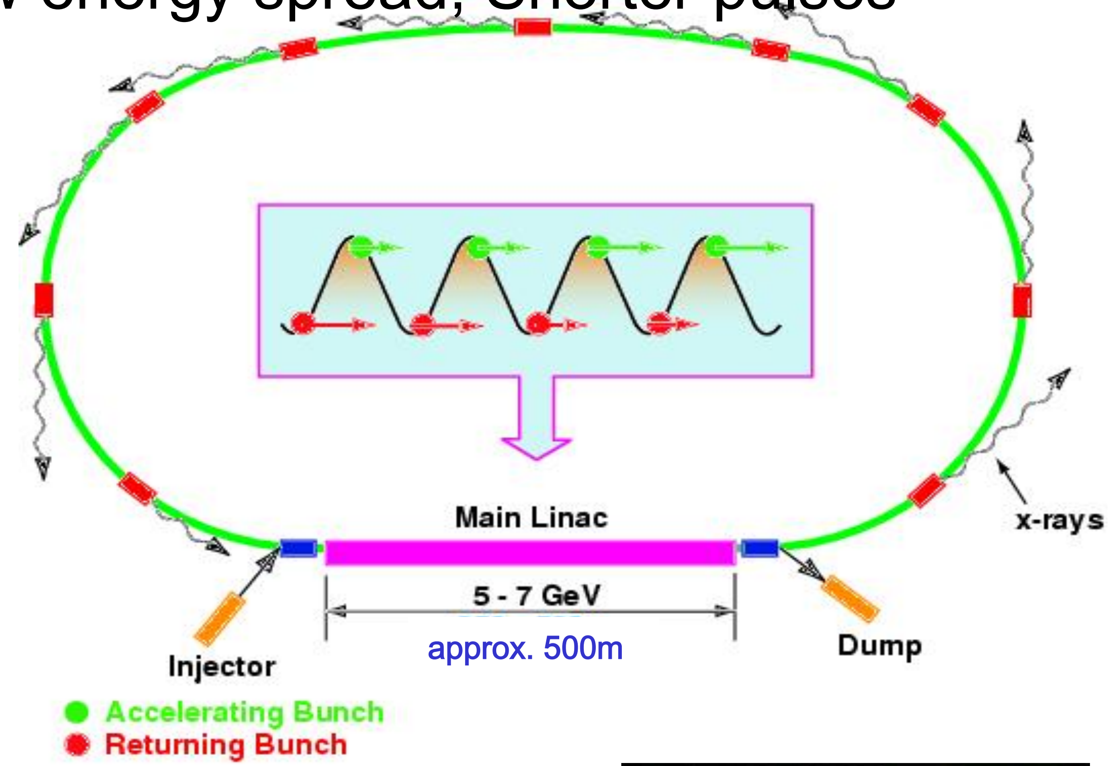


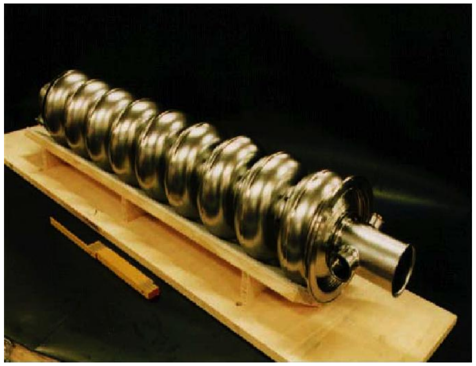
Power limit of Linac beams



Energy Recovery Linacs

- Small beam sizes, Low energy spread, Shorter pulses
- But current limited





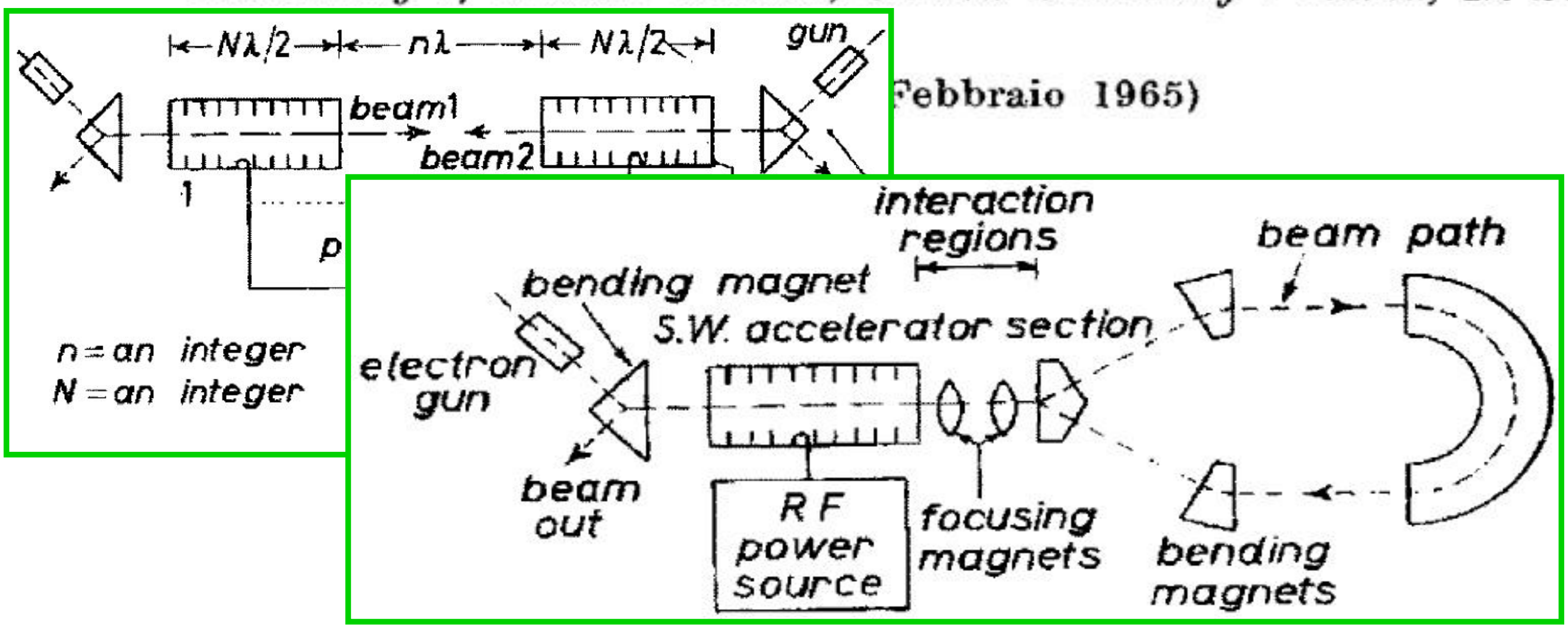
First Energy Recovery Linac idea

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.

eRHIC Design – requires an ERL !

Synchrotron: Repetitive acceleration to high energy, low repetition rate and therefore low current.

➔ Fixed target experiments, high energy, low current, relatively large beam size.

Storage rings: Rare filling at high energy and storage for millions of turns, high current, requires very low loss rates.

➔ Internal target experiments, high energy, high current, relatively large beam size.

Linacs: Linear acceleration to moderately high energies that are limited by the available length. Current*Energy is limited by the available power.

➔ Fixed target experiments, moderately high energies, low current, small beam size.

ERLs: Linear acceleration and deceleration to capture the energy of spent beam, like a linac but without the power limit on beam current, as spent beam provides the power. Loss rates have to be limited.

➔ **Dense internal targets, moderately high energies, high currents, small beam size.**

ERLs provide a new niche of beam parameters: What physics can they be used for?

Targets for ERL beams

ERLs: Linear acceleration and deceleration to capture the energy of spent beam, like a linac but without the power limit on beam current, as spent beam provides the power. Loss rates have to be limited.

➔ **Dense internal targets, moderately high energies, high currents, small beam size.**

ERLs provide a new niche of beam parameters: What physics can they be used for?

(1) Lost beam power has to be available from power sources.

(2) Target has length L, nuclei with charge Z.

(3) Coulomb scattering and particle optics determine beam loss (at an aperture a with a maximal optical beta function)

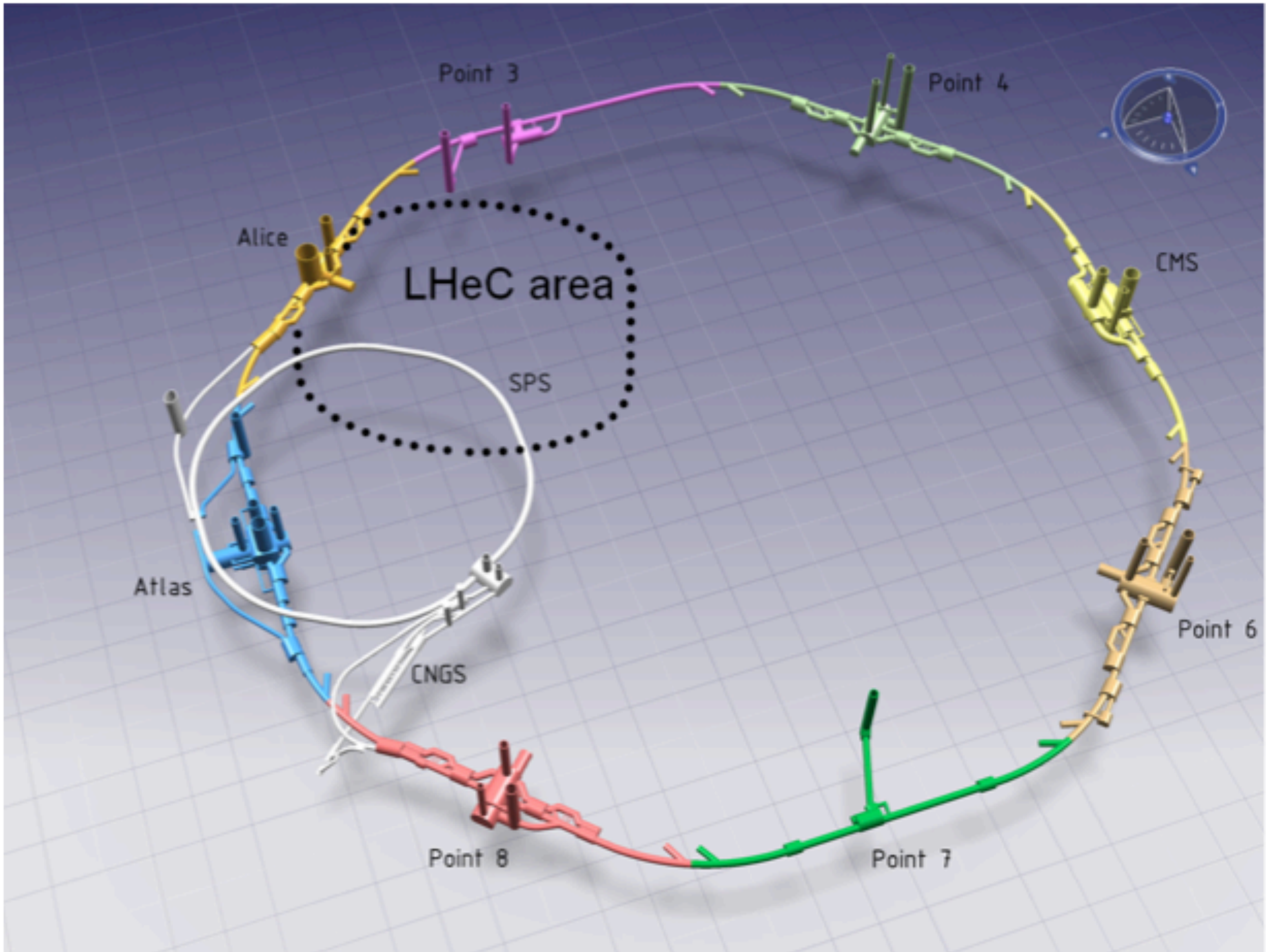
ERL Target and luminosity limits:

$$\mathcal{L}_{\rm max} = 4.1\times 10^{37}\,{\rm cm}^{-2}\,{\rm s}^{-1}\frac{1}{Z^2}\left(\frac{P_{\rm loss}}{\rm kW}\right)\left(\frac{\mathcal{E}}{100\,{\rm MeV}}\right)\left(\frac{a}{\rm cm}\right)^2\left(\frac{100\,{\rm m}}{\beta_{\rm max}}\right)\left(\frac{10\,{\rm cm}}{L}\right)$$

$$\rho = 6.6\times 10^{18}\,{\rm cm}^{-3}\frac{1}{Z^2}\left(\frac{100\,{\rm mA}}{I}\right)\left(\frac{P_{\rm loss}}{\rm kW}\right)\left(\frac{\mathcal{E}}{100\,{\rm MeV}}\right)\left(\frac{a}{\rm cm}\right)^2\left(\frac{100\,{\rm m}}{\beta_{\rm max}}\right)\left(\frac{10\,{\rm cm}}{L}\right)^2$$

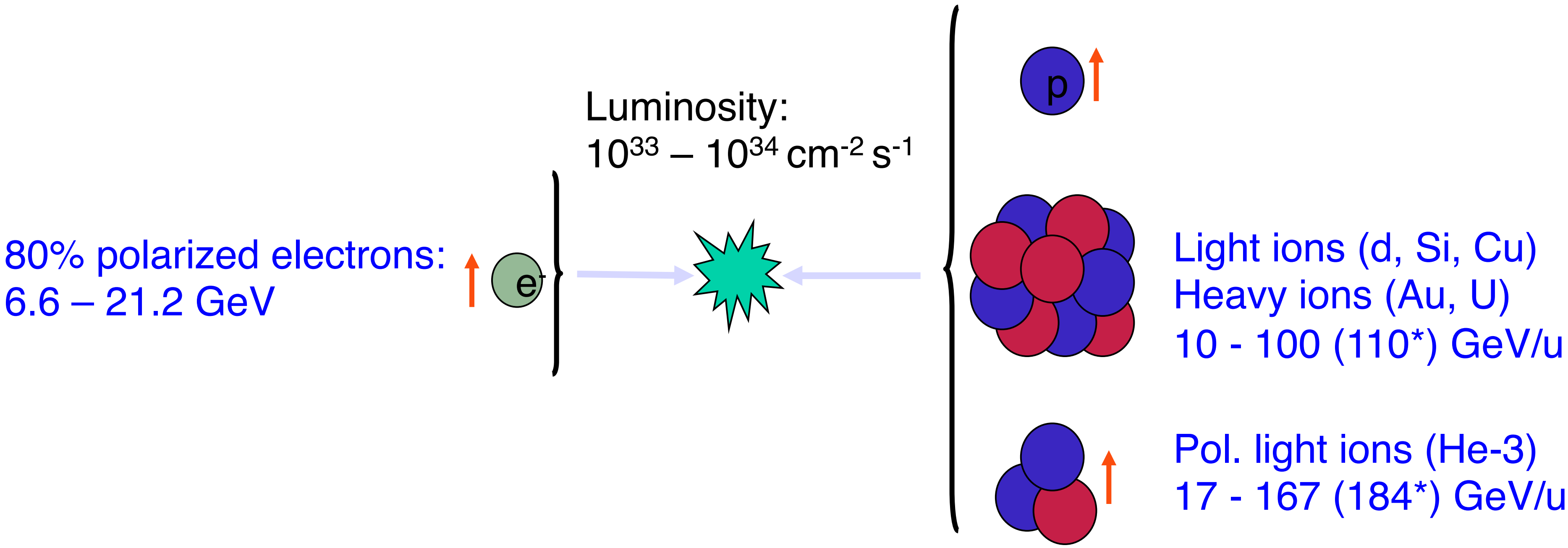
Courtesy Chris Mayes

LHeC layout – Electron Ion Collisions at the LHC

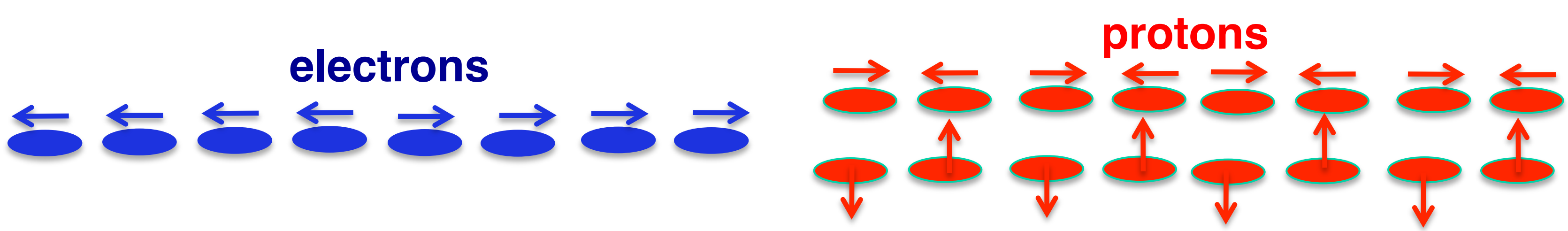


courtesy Oliver Bruening

Electron-Ion Collider eRHIC

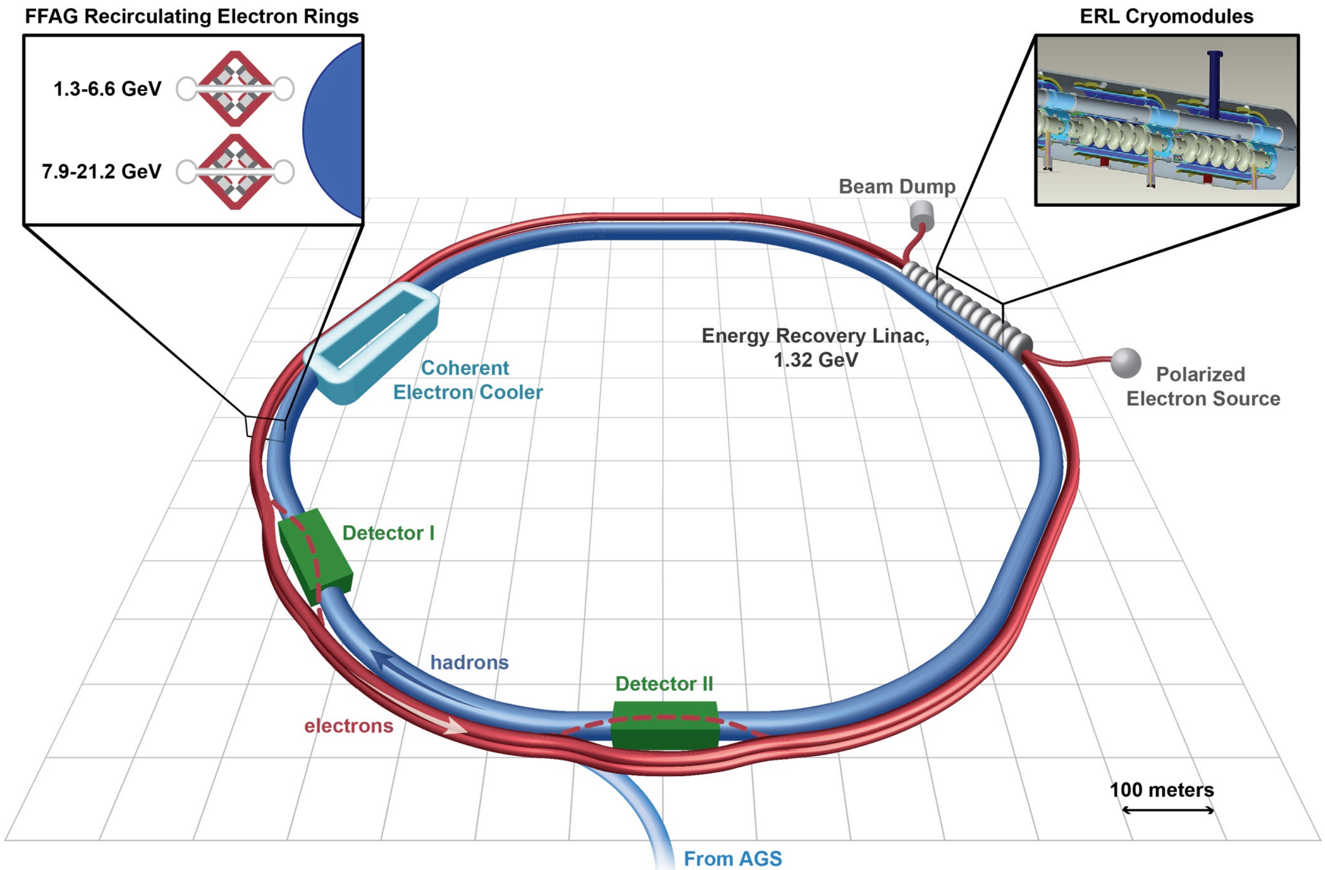


- Center-of-mass energy range: 30 – 145 GeV
- Full electron polarization at all energies
  Full proton and He-3 polarization with six Siberian snakes
- Any polarization direction in electron-hadron collisions:

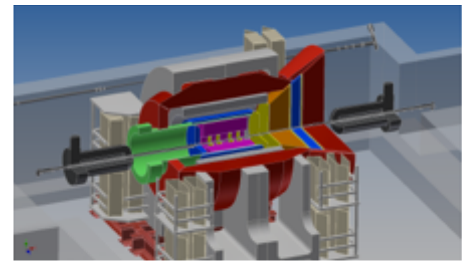


courtesy Thomas Roser

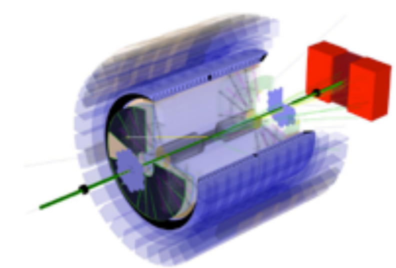
eRHIC Design – requires an ERL !



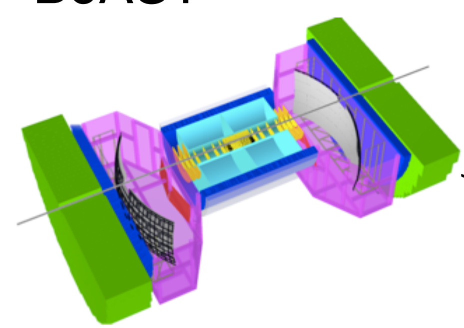
ePHENIX



eSTAR



BeAST

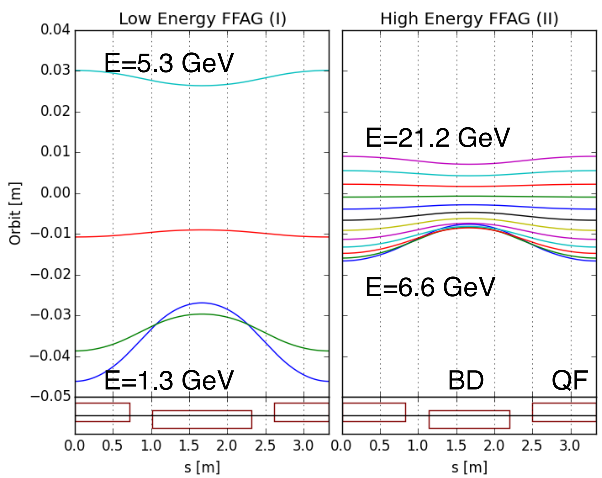


courtesy Thomas Roser

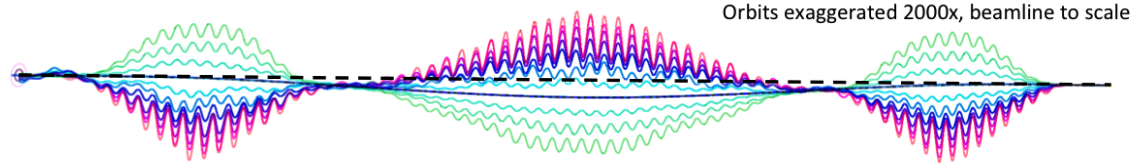
- 1.7×10^{33} cm^{-2} s^{-1} for $\sqrt{s}$ = 127 GeV (15.9 GeV e ↑ on 255 GeV p ↑)
- × 10 luminosity with modest improvements (coating of RHIC vacuum chamber)
- × 100 luminosity with shorter bunch spacing (ultimate capability)

eRHIC ERL has 16 turns in only 2 NS-FFAG arcs !

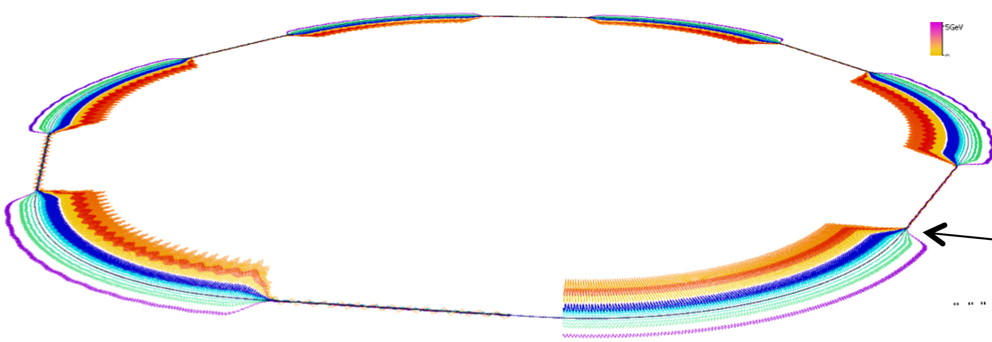
- eRHIC uses two FFAG beamlines to do multiple recirculations. (FFAG-I: 1.3-5.4 GeV, FFAG-II: 6.6-21.2 GeV)
- All sections of a FFAG beamline is formed using a same FODO cell. Required bending in different sections is arranged by proper selection of the offsets between cell magnets (or, alternatively, with dipole field correctors).
- Permanent magnets can be used for the FFAG beamline magnets (no need for power supplies/cables and cooling).



@S.Brooks, D.Trbojevic

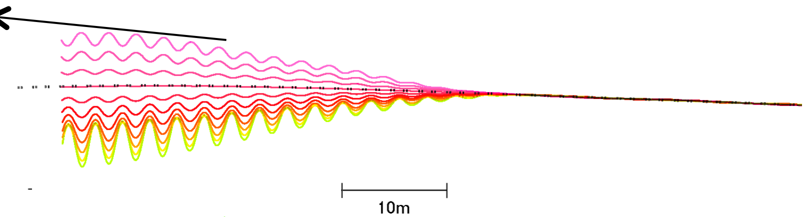


Orbits in Detector bypass section



Quad offsets evolve adiabatically

Orbits in Transition section



Each of two eRHIC FFAGs contain 1066 FFAG cells

Risk drivers for eRHIC

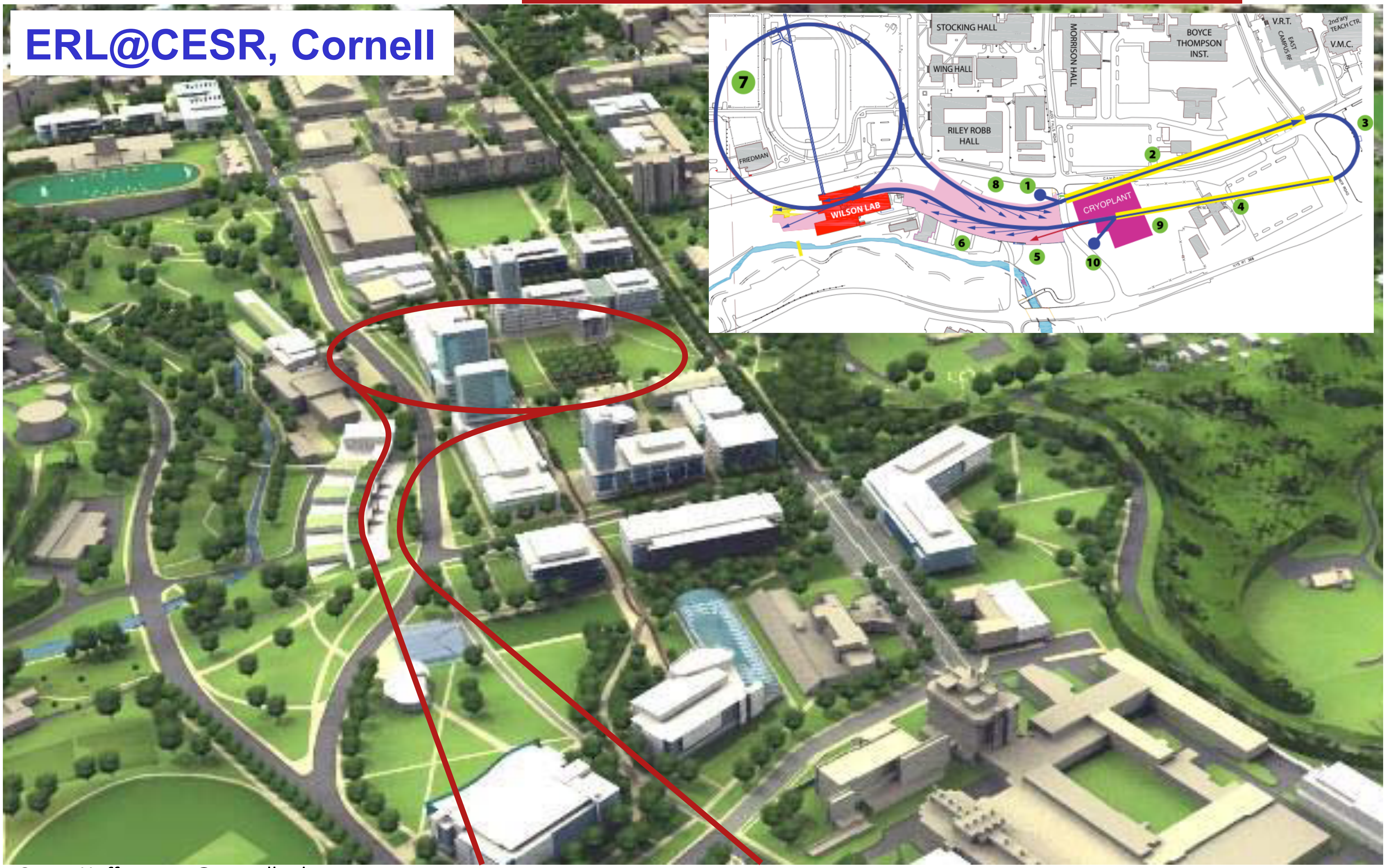
Some of the most important risk items for eRHIC:

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.

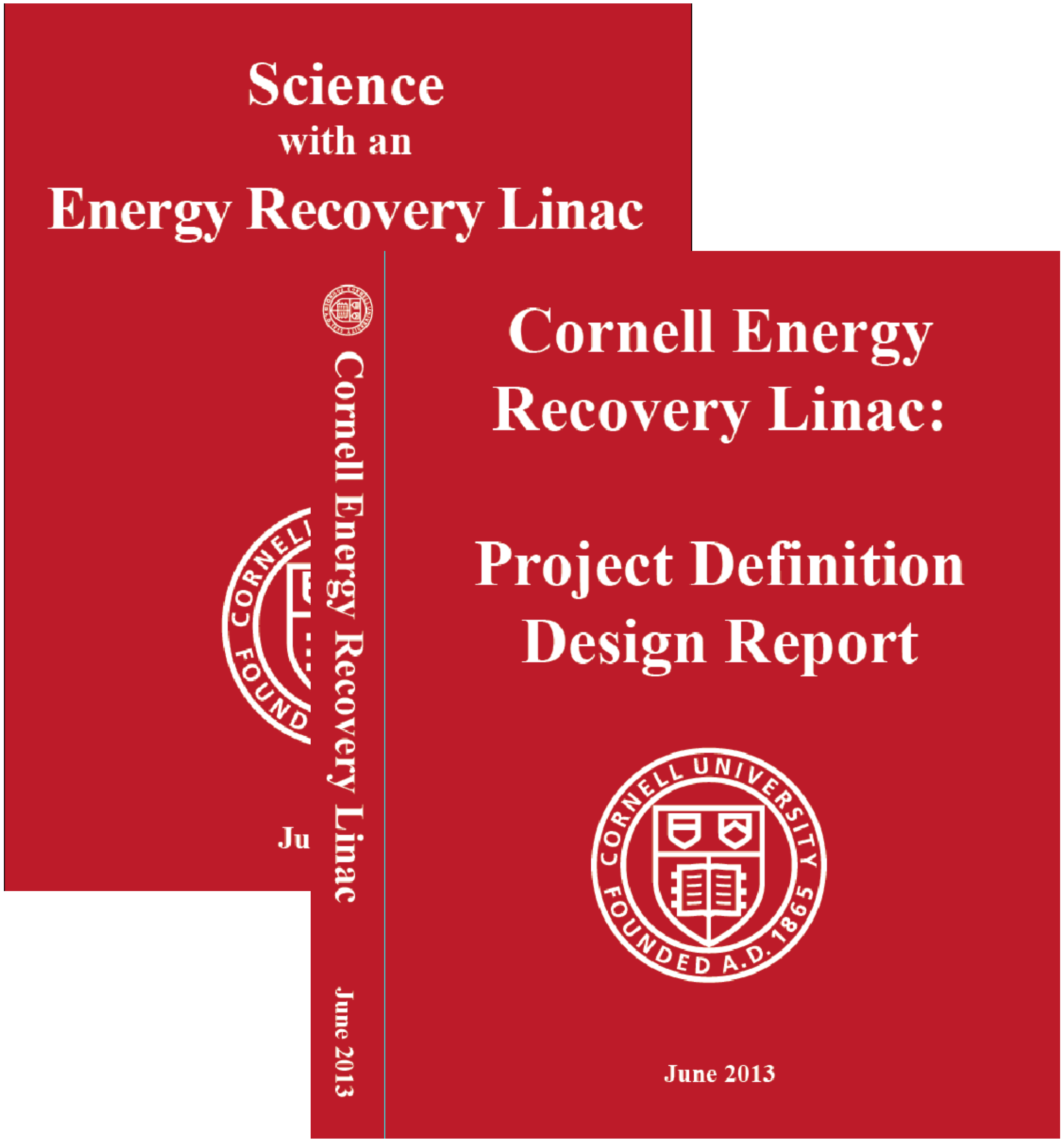
2) Multi-turn ERL operation with a large number of turns.
   a) HOM damping.
   b) BBU limits.
   c) LLRF control and microphonics.
   d) ERL startup from low-power beam.

ERL as extension of CESR

ERL@CESR, Cornell



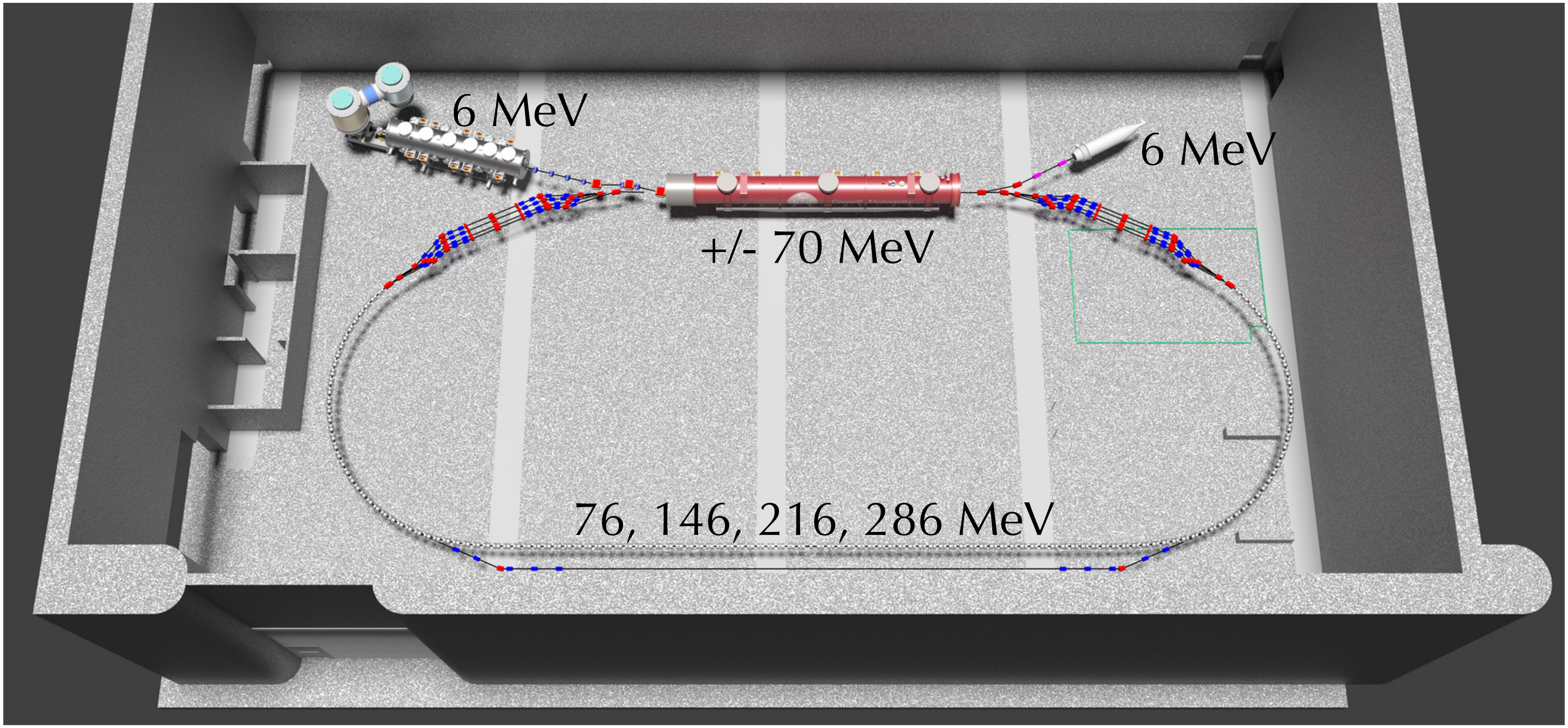
ERL documentation: (1) Science, (2) Generic design



- Science case gathered in international workshops
- Design report
  - 530 pages between conceptual design and engineering design
  - Access at www.classe.cornell.edu/ERL/PDDR
- Also
  - Electron beam construction (from RI)
  - Cryoplant (from Linde and Air Liquide)

Prototype eRHIC ERL @ Cornell

- NS-FFAG arcs, four passes (like first eRHIC loop)
- Momentum aperture of x4, as for eRHIC (EMMA achieved x1.7, planned x2)
- Uses Cornell DC gun, injector (ICM), dump, 70MeV SRF CW Linac (MLC)
- Prototyping of essential components of eRHIC design



The Cornell-BNL FFAG-ERL Test Accelerator

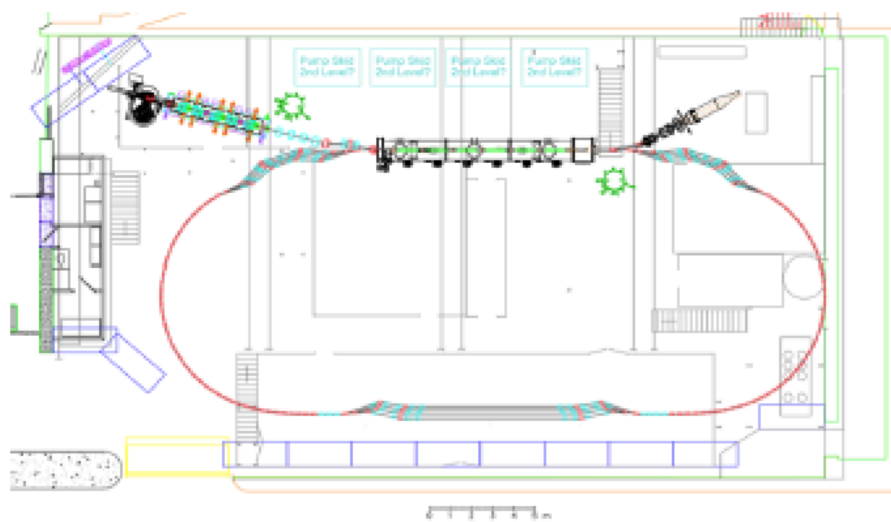
White Paper

Ivan Bazarov, John Dobbins, Bruce Dunham, Georg Hoffstaetter, Christopher Mayes, Ritchie Patterson, David Sagan

Cornell University, Ithaca NY

Ilan Ben-Zvi, Scott Berg, Michael Blaskiewicz, Stephen Brooks, Kevin Brown, Wolfram Fischer, Yue Hao, Wuzheng Meng, François Méot, Michiko Minty, Stephen Peggs, Vadim Ptitsin, Thomas Roser, Peter Thieberger, Dejan Trbojevic, Nick Tsoupas.

Brookhaven National Laboratory, Upton NY



December 16, 2014

A white paper has been written to outline the Cβ concept: arXiv:1504.00588

A Conceptual Design Report (CDR) is in preparation.

The Cβ collaboration has:

- Started collaborative discussions in July 2014.
- Weekly phone meetings.
- Three face to face collaboration meetings of about 20 participants. Next one this Mo and Tu at Stony Brook University.

Beam parameters at the FFAG-ERL

Electrons

Current I of up to 320mA in the linac (eRHIC has 700mA in the Linac)

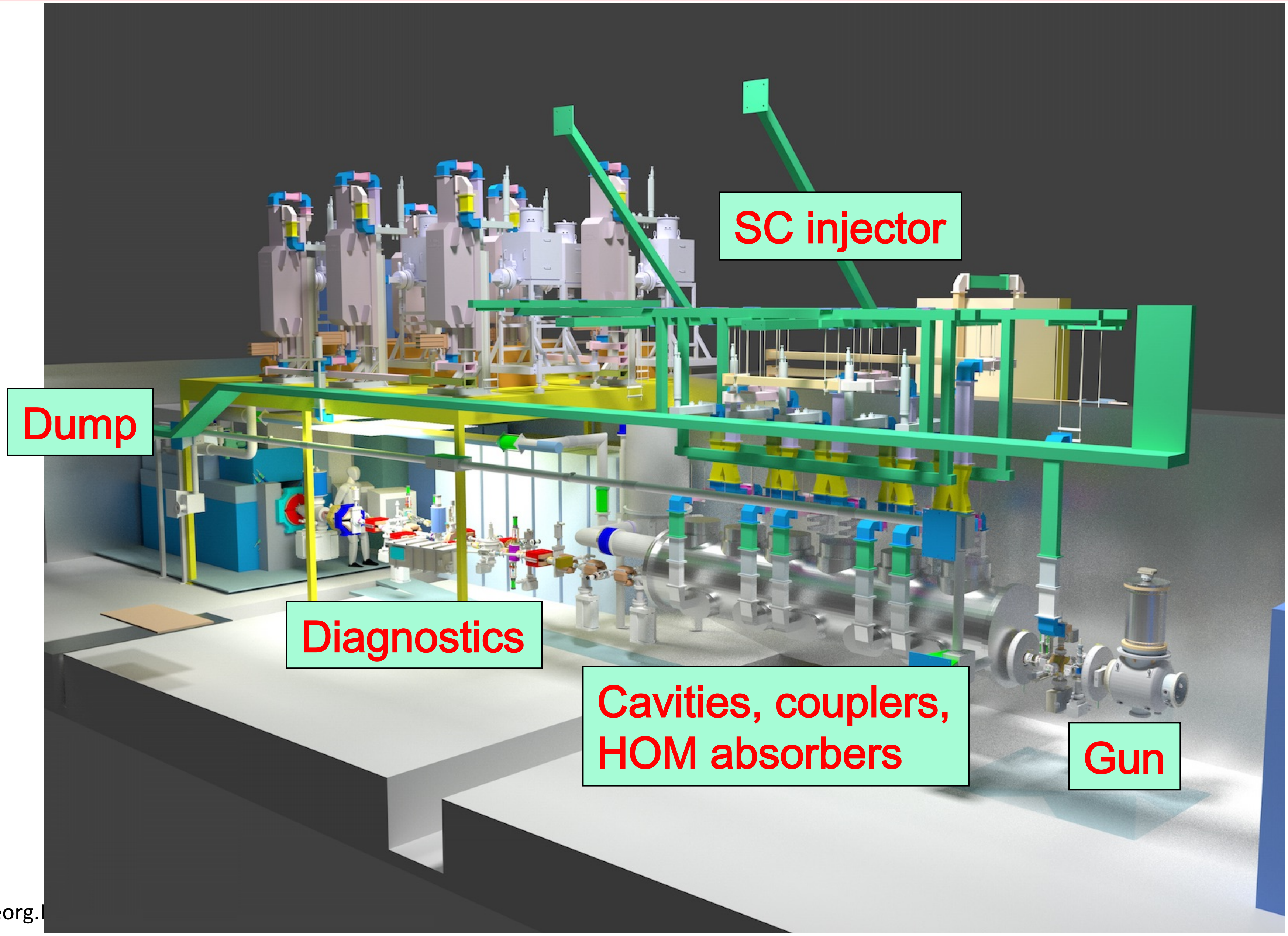
Bunch charge Q of up to 2nC [funded by DOE-NP] (eRHIC 5.3nC)
[to be copied for BNL]

Bunch repetition rate of 1.3GHz or 433MHz (for a tuned eRHIC cavity)

Energy E up to about 300 MeV

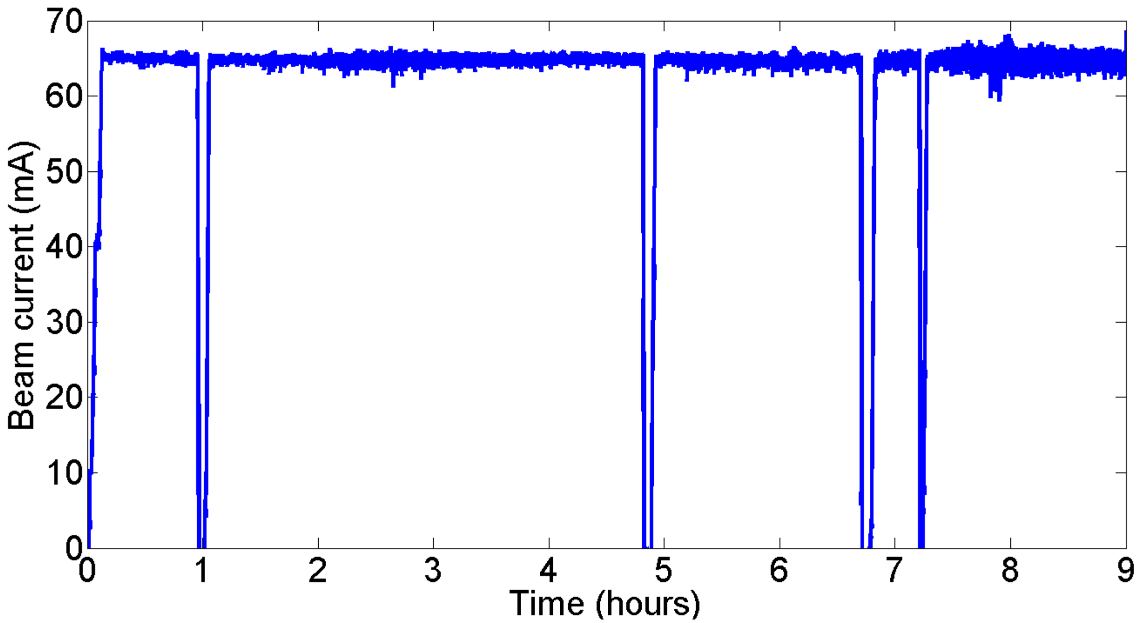
Beams of 100mA at 76MeV, 80mA at 146MeV, 40mA at 286MeV

Cornell ERL injector prototype



ERL Readiness: high current beam

CLASSE



- Peak current of 75mA (world record)

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

Source achievements:

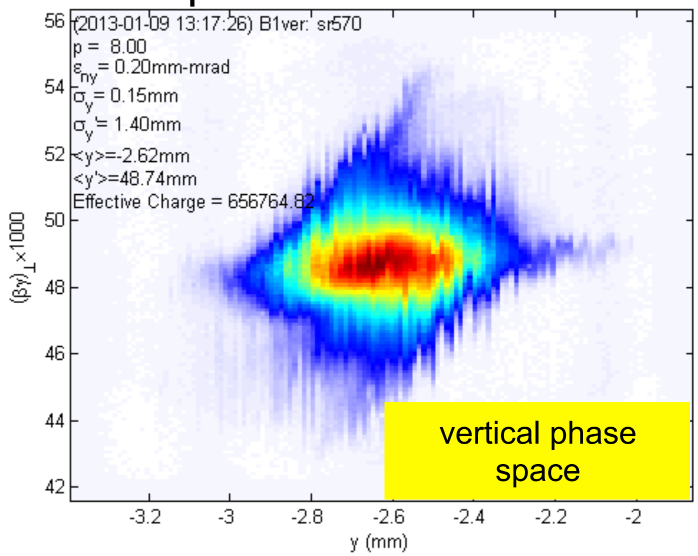
- 2.6 day 1/e lifetime at 65mA
- 8h at 65mA
- With only 5W laser power (20W are available)
- now pushing to 100mA

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

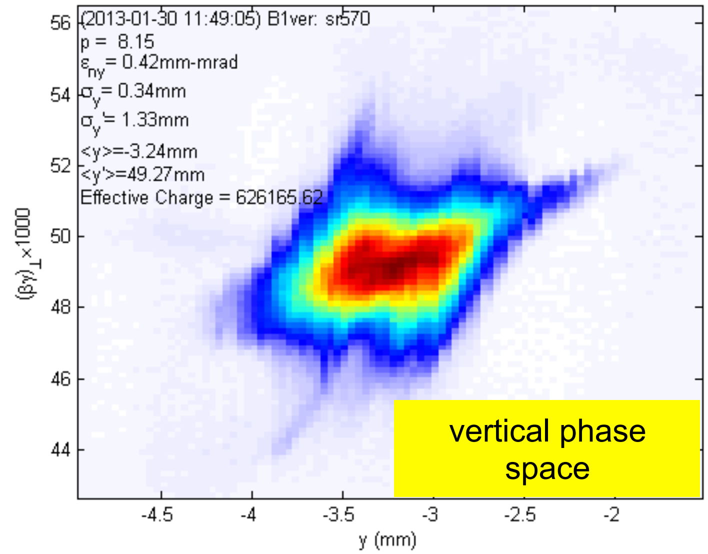
✓ Source current can meet ERL needs

ERL readiness: Beam brightness

20 pC/bunch



80 pC/bunch



Normalized rms emittance (horizontal/vertical) 90% beam, E ~ 8 MeV, 2-3 ps

0.23/0.14 mm-mrad   0.51/0.29 mm-mrad

Normalized rms core* emittance (horizontal/vertical) @ core fraction (%)

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

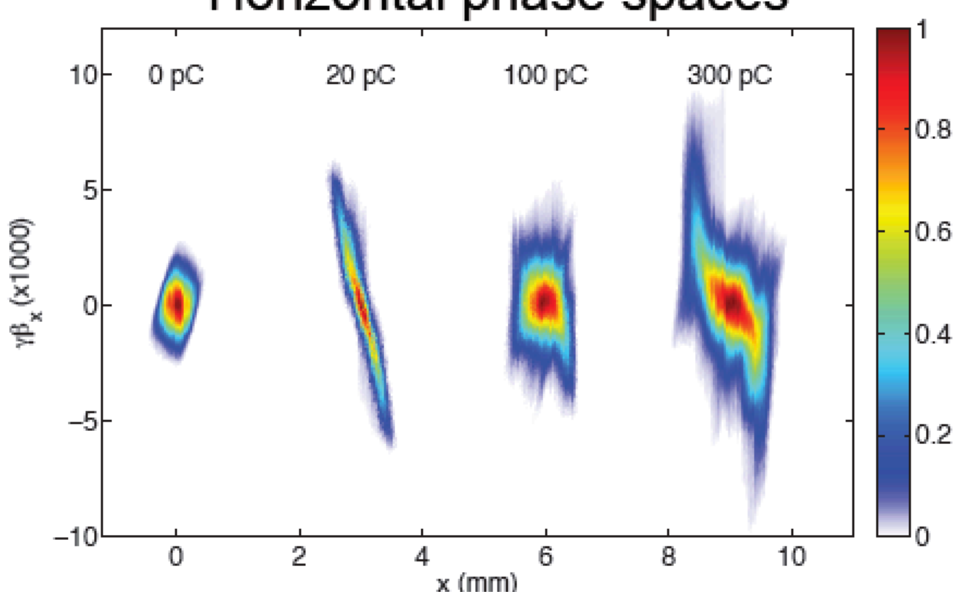
***Phys. Rev. ST-AB 15 (2012) 050703**
ArXiv: 1304.2708

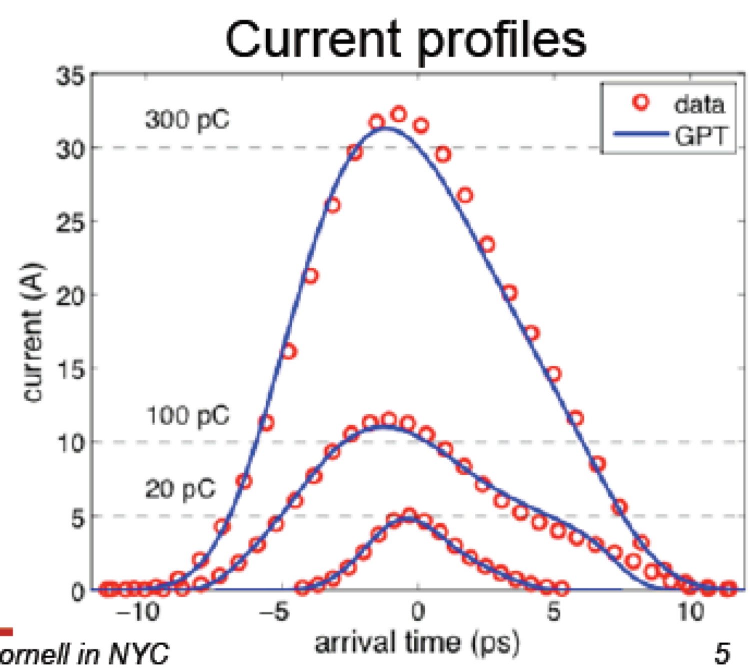
✓ At 5 GeV this gives 20x the world's highest brightness (Petra-III)

Beam tests for LCLS-II

Target specs:

Bunch charge (pC)	Peak current target (A)	Peak current measured (A)	Emittance Target (95%, μm)	Emittance measured (95%, μm)
20	5	5	0.25	H: 0.18, V: 0.19
100	10	11.5	0.40	H: 0.32, V: 0.30
300	30	32	0.60	H: 0.62, V: 0.60

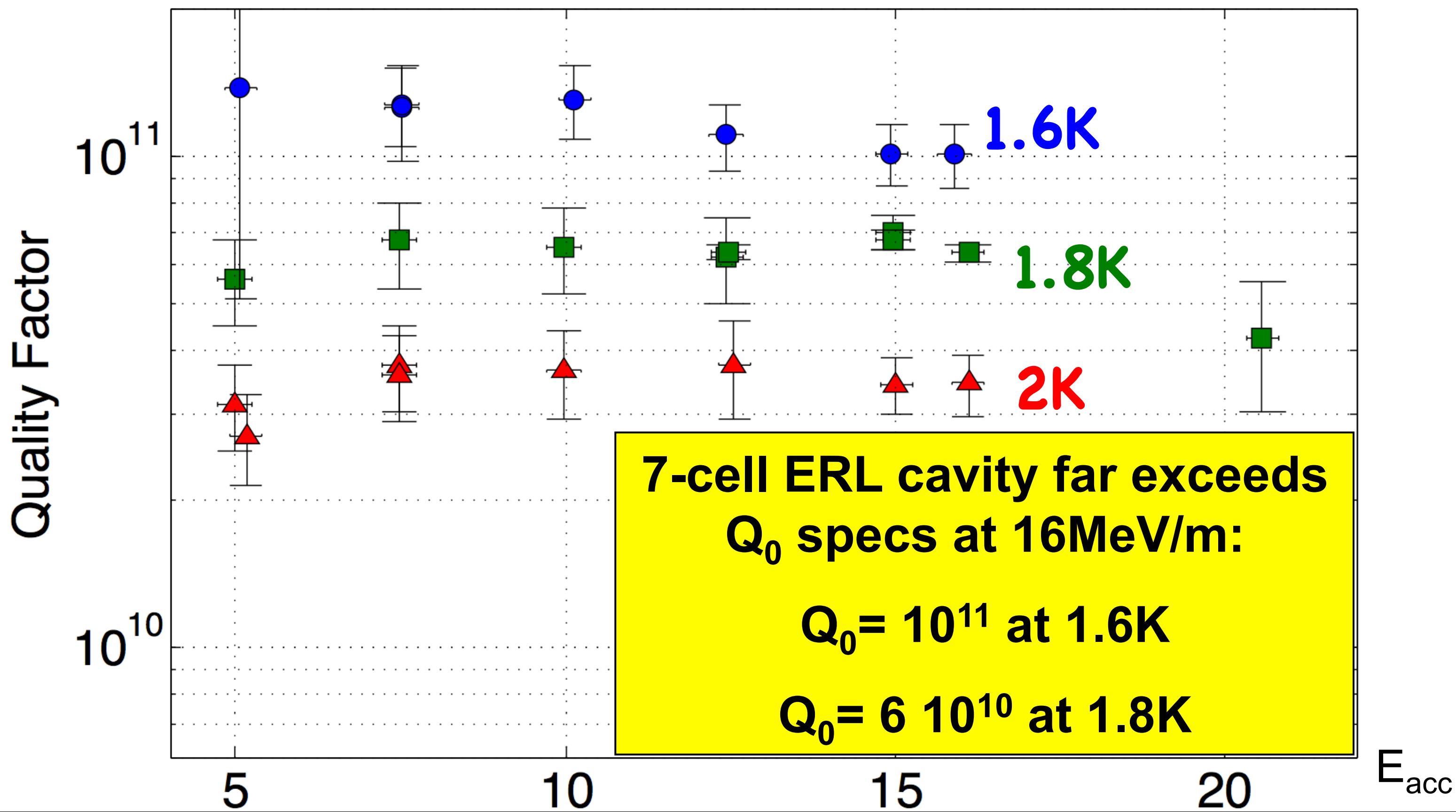




Dec. 12, 2014 *Patterson* *BNL-JLAB-Cornell in NYC* *5*

Low-loss SRF cavities for CW linacs: High Q0

Cavity surface was prepared for high Q_0 while keeping it as simple as possible: bulk BCP, 650C outgassing, final BCP, very uniform 120C bake, HF rinse.



7-cell ERL cavity far exceeds Q_0 specs at 16MeV/m:

$Q_0 = 10^{11}$ at 1.6K

$Q_0 = 6\ 10^{10}$ at 1.8K

The achievement of high Q is relevant not only to Cornell's ERL but also to Project-X at Fermilab, to the Next Generation Light Source, to Electron-Ion colliders, spallation-neutron sources, and accelerator-driven nuclear reactors.

MLC construction at Cornell

Main Linac Cryomodule

Assembly completed November 20, 2014. Ready for testing.

Synergy between Cornell and BNL

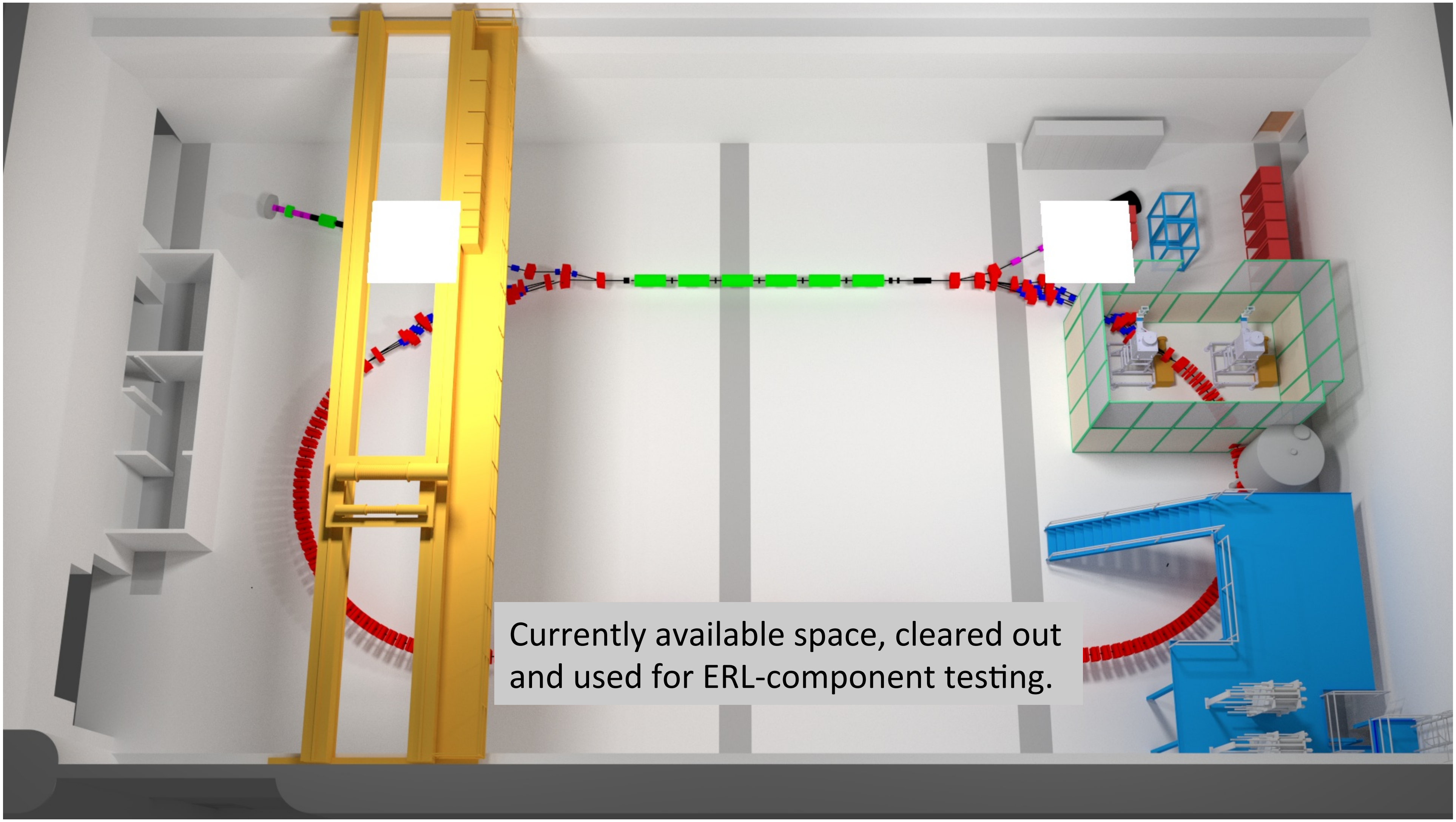
BNL gets out of the collaboration: Risk reduction and prototyping.

- R&D and prototyping of eRHIC systems, e.g. permanent magnets, multi-beam diagnostics possibly for pilot bunches, optics control, and feedback, mergers, timing, halo control, collimation, LLRF control, resonant extraction of the highest-energy beam, etc.
- Proof of eRHIC-cavity capabilities, e.g. current limits, RF stability, microphonics control, HOM heating, etc.
- Proof of FFAG capabilities, e.g. momentum acceptance of x4, orbit and optics correction with real tolerances, reproducibility of magnet construction, etc.

Cornell gets out of the collaboration:

- Forefront research in ERL physics.
- Excellent opportunities to educate accelerator physics students.
- A high-brightness beam of moderate energy for physics experiment.

The Cβ FFAG ERL in L0E



Currently available space, cleared out and used for ERL-component testing.

Topic to complete the Cβ FFAG ERL setup

- Complete lattice design, including resonant extraction at high energy.
- Study tolerances, prototype suitable permanent magnets and girders.
- Design collimation for halo from ghost pulses, field emission, Touschek, and gas scattering
- Work out a commissioning plan and required diagnostics
- Work out an accelerator physics plan and required diagnostics
- Design radiation shielding and safety systems

Many of the design criteria are identical to those of eRHIC

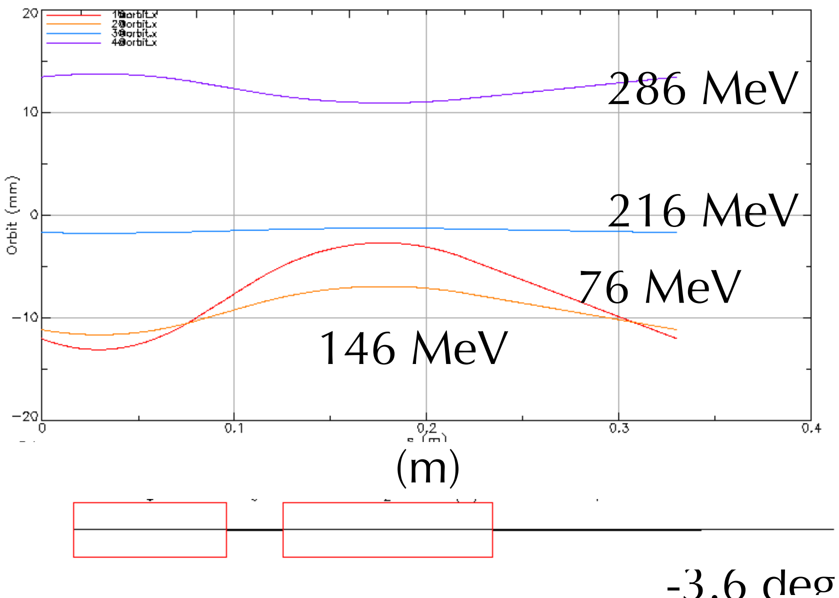
- These topics are currently worked out and documented in a Conceptual Design Report (CDR)
- WBS for costing and planning is being produced simultaneously.

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

Example study: Orbits for different energies

CLASSE

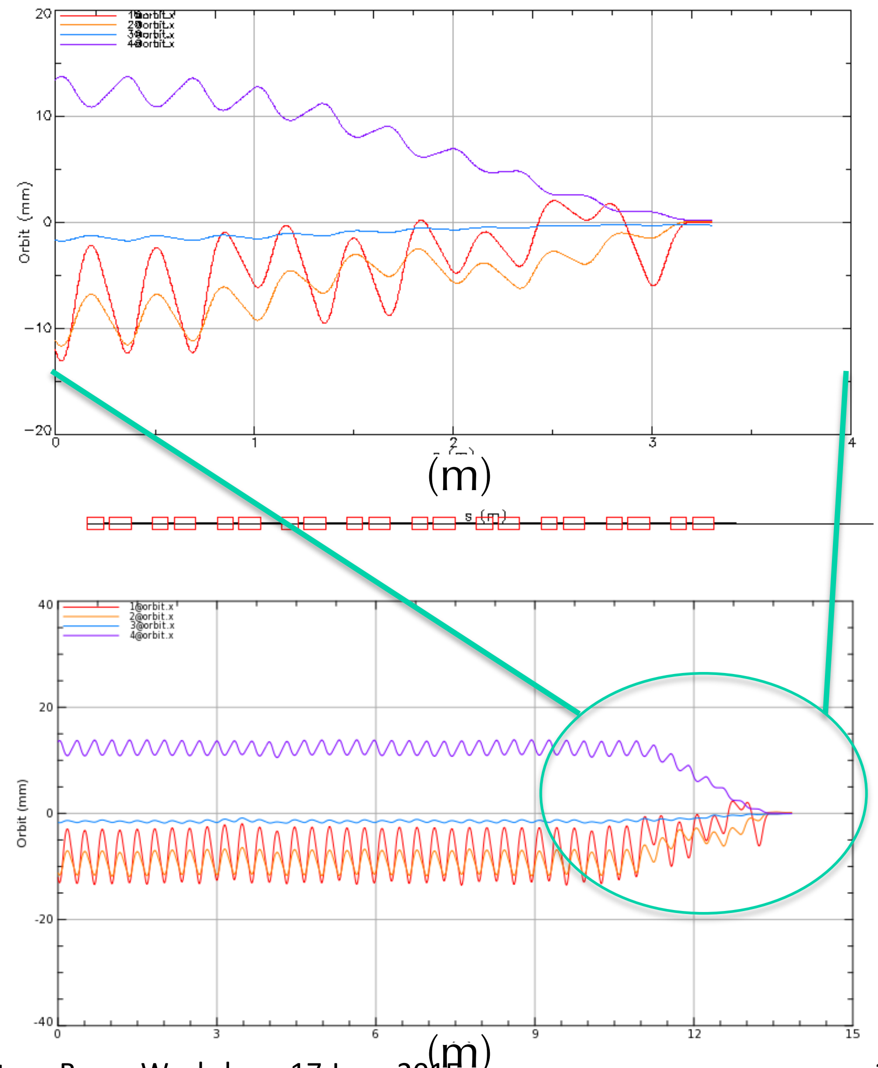
Cell



Focus	Defocus
8 cm	11 cm
42.5 T/m	-27.5 T/m
-0.104 T	-0.5044 T

(Orvigt ….XXXXX

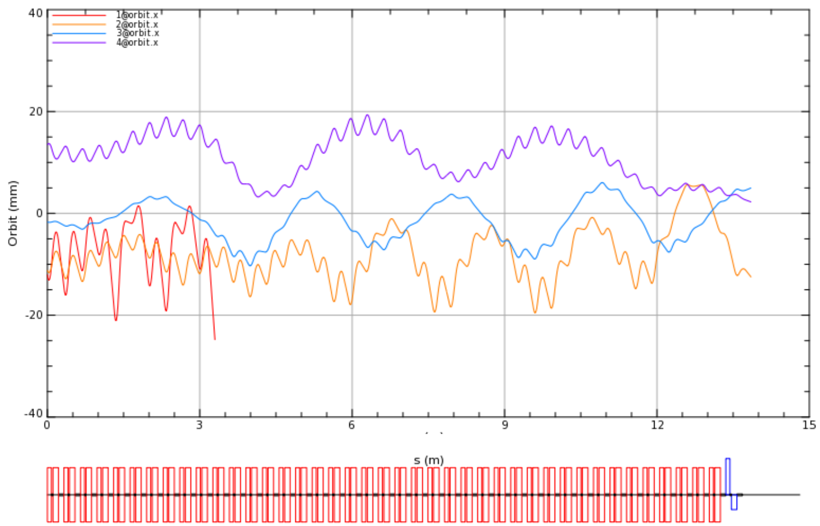
Arc-to-Straight (10 cells)



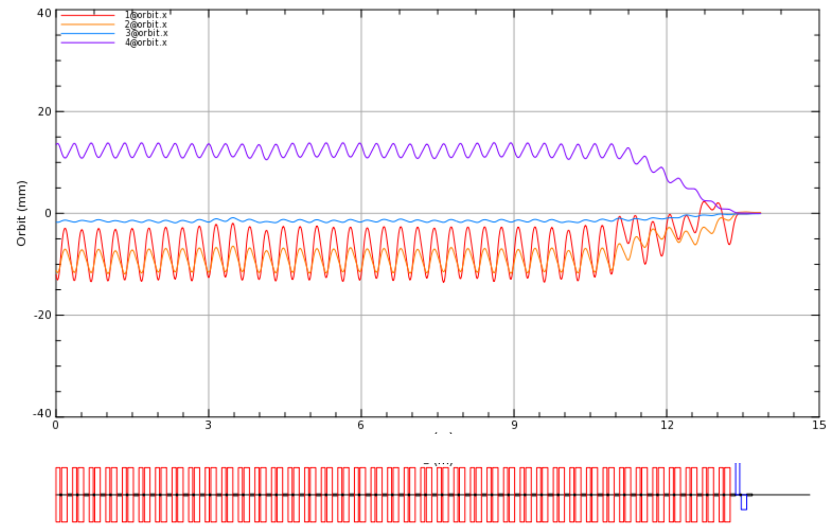
Example study: FFAG ERL orbit corrections

500 um rms x offset errors

SVD correction given BPM readings for separate beams and correction coils on every other dipole



Full FFAG arc

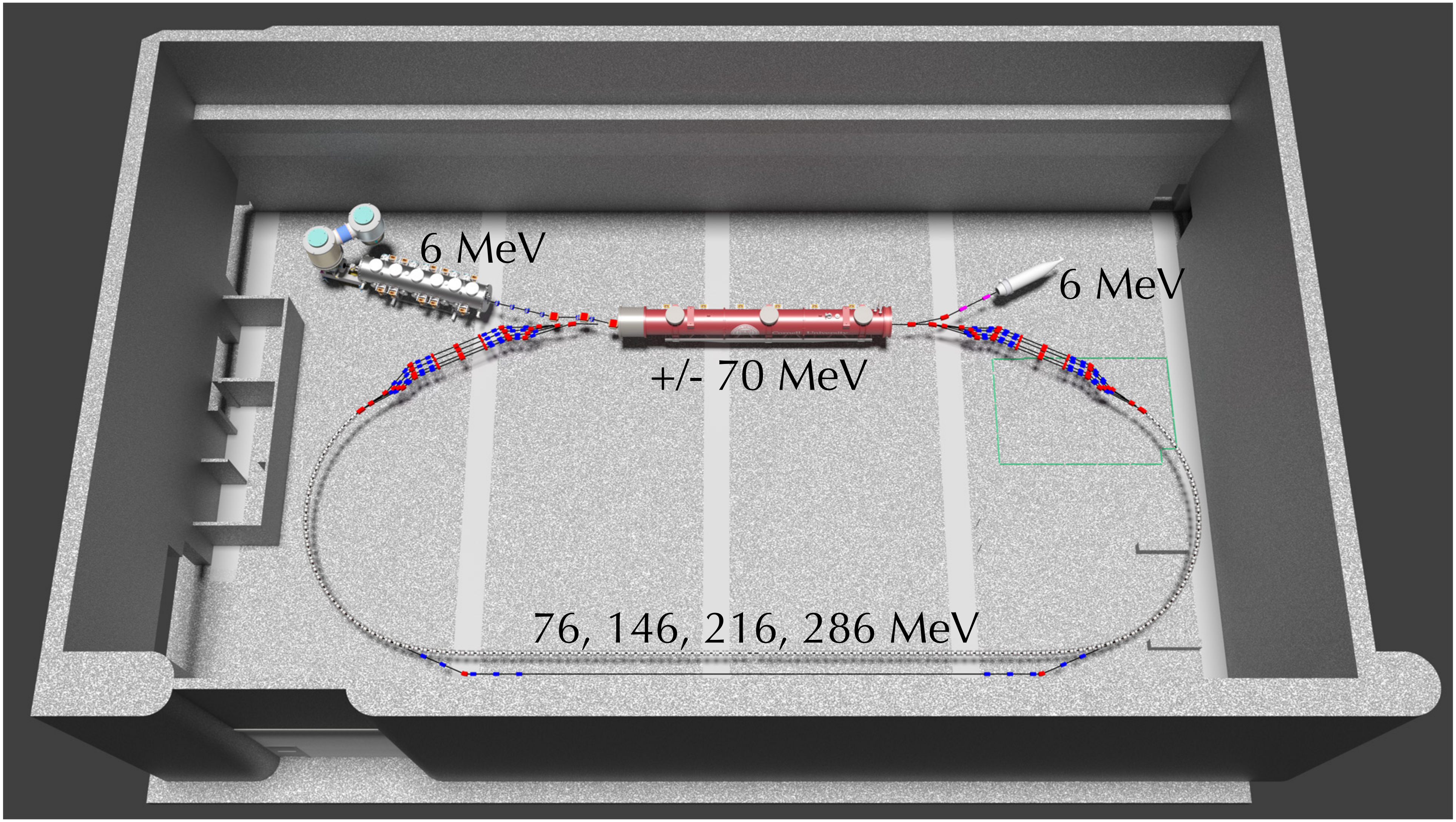


Full FFAG arc

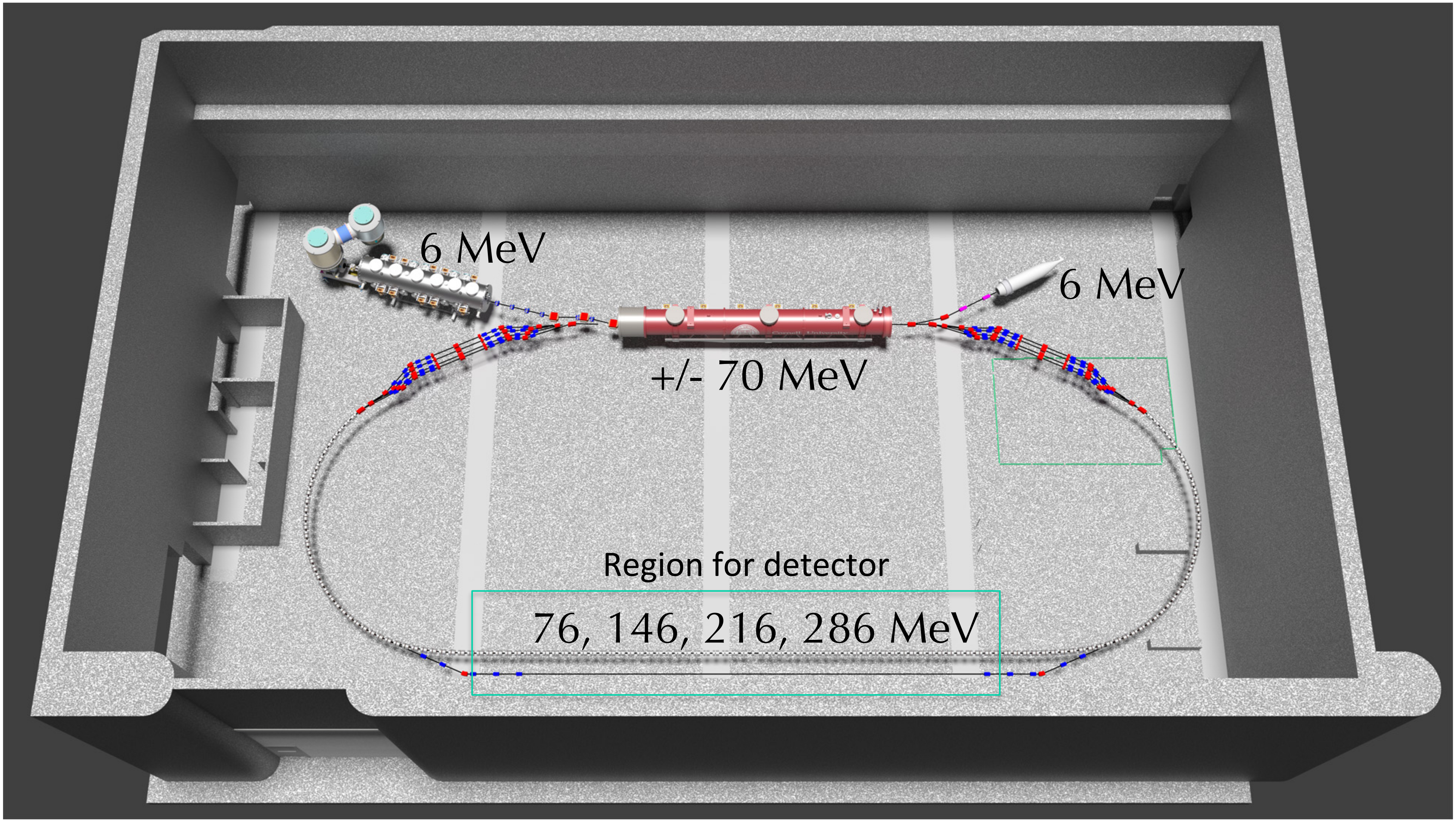
R&D and Prototyping for eRHIC at the Cβ FFAG-ERL

1. Prototyping FFAG return loops for eRHIC (or LHeC)
   - Prototyping eRHIC permanent magnets with required precision
   - Prototyping orbit and optics control
2. Prototyping multi-turn ERL components
   - timing and synchronization systems for eRHIC
   - halo diagnostics, halo control, and collimation systems
   - multi-beam diagnostics and control, possibly with pilot bunches
   - eRHIC splitters and path-lenth adjusters, develop low-emittance injection
   - eRHIC ion clearing
3. Prove recirculative BBU for 16turn eRHIC is tolerable for eRHIC cavities.
4. Prove operational stability, incl. halo, ions, tolerances, etc.

Goal: 4-turn FFAG ERL at 16MV/m



Goal: 4-turn FFAG ERL at 16MV/m



L0E cleanout for Cβ ERL

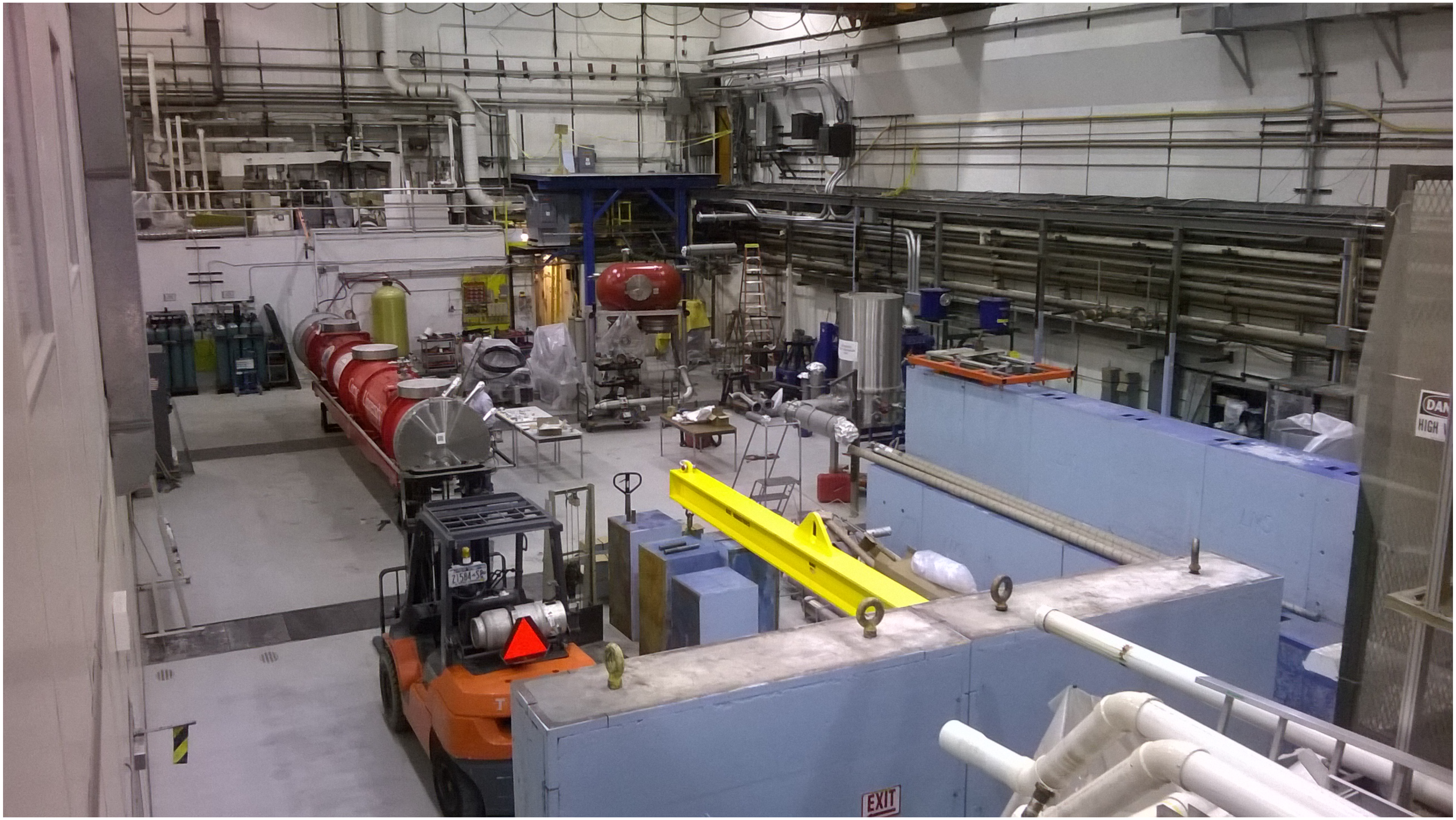
Cornell Laboratory fo
Accelerator-based Scie
Education (CLASSE)

L0E cleanout for Cβ ERL

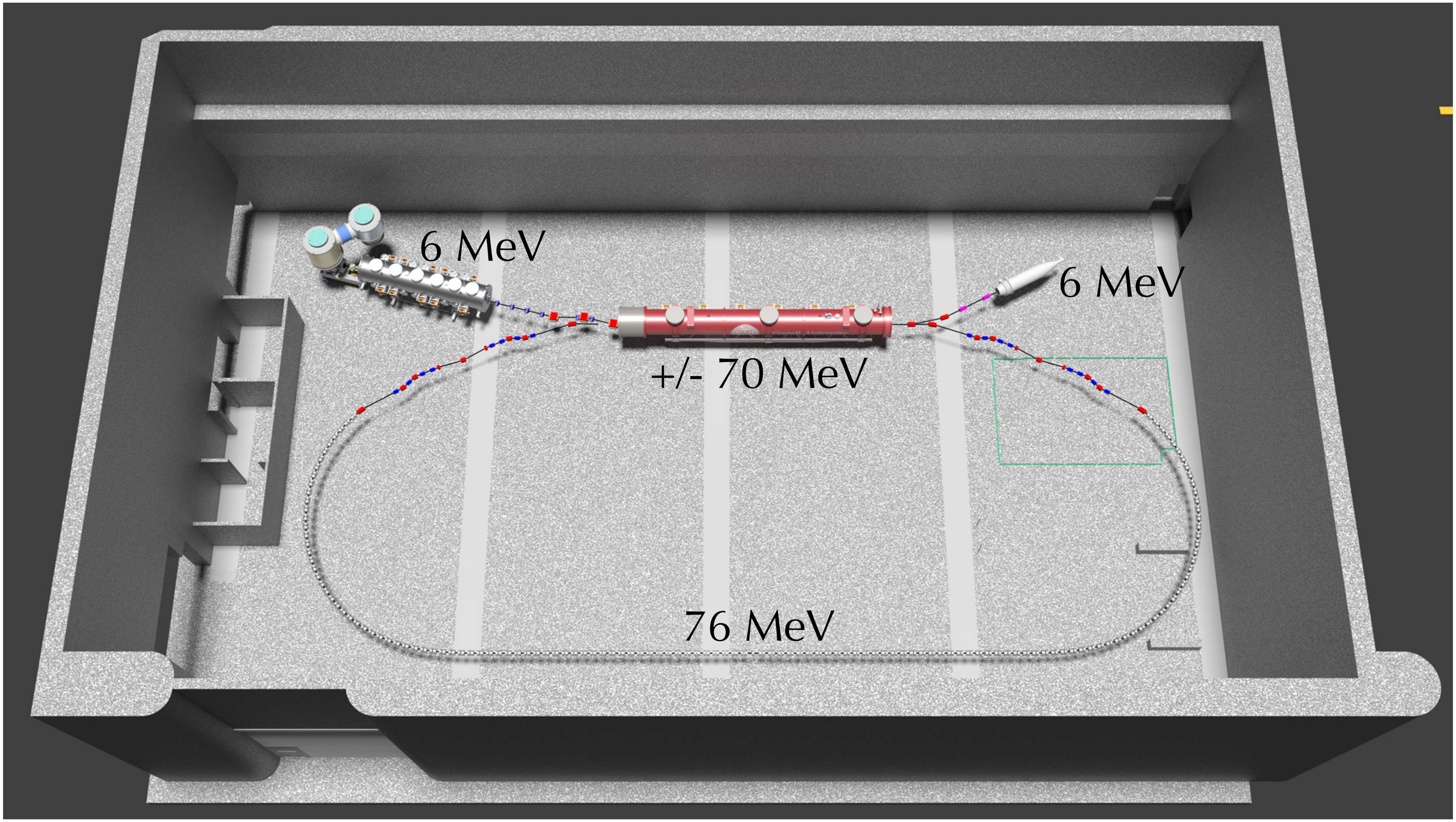
L0E cleaned out for Cβ ERL

L0E cleaned with Cβ ERL

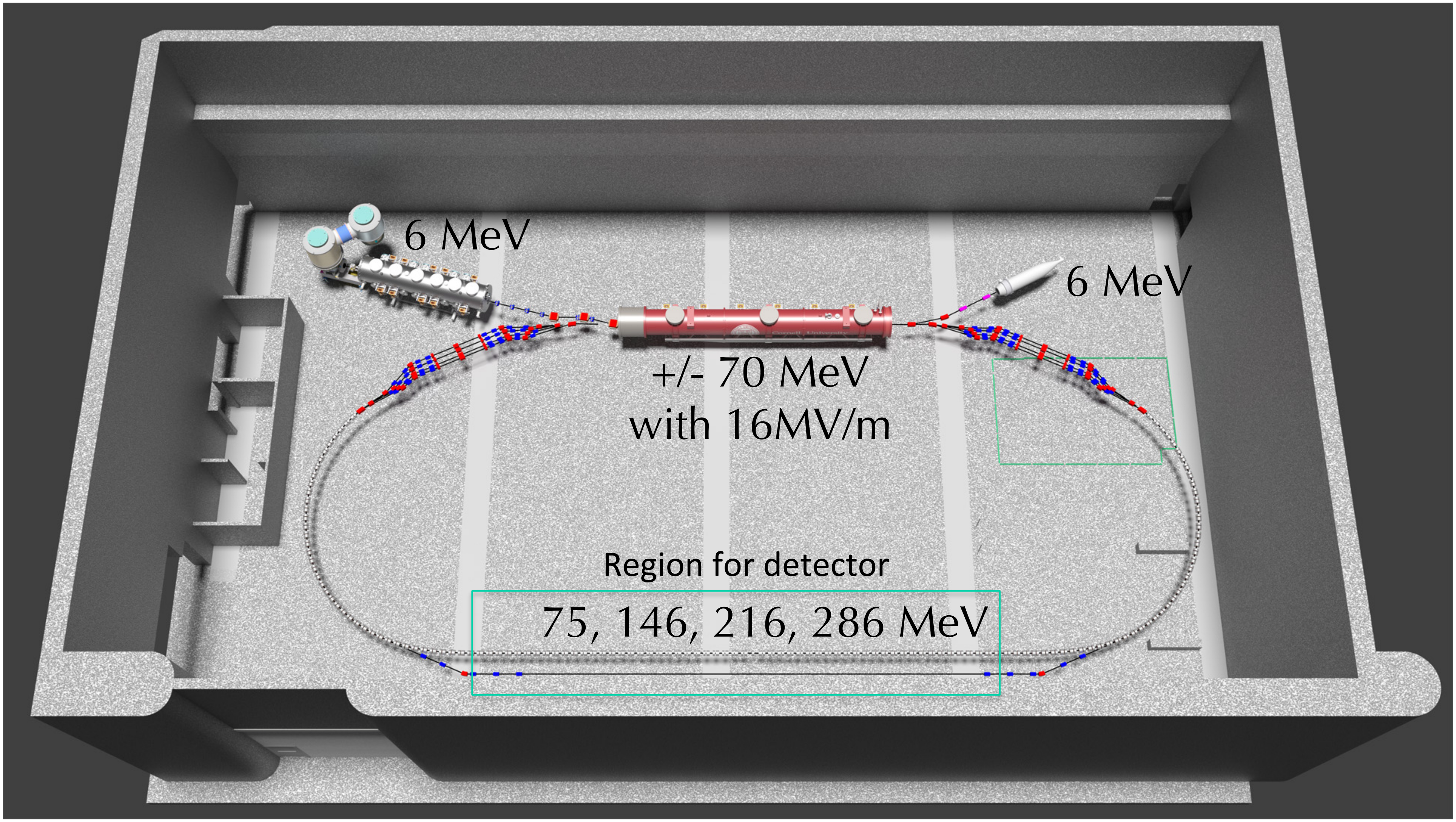
L0E for current ERL injector and MLC test



1st stage: 1-turn ERL for 76 MeV



4nd stage: 4-turn ERL for 286 MeV with eRHIC accelerating gradients



Final stage: 4-turn ERL for 286 MeV for eRHIC and physics experiments

Accomplish the full design for the full energy gain in the MLC.

Important results will be:

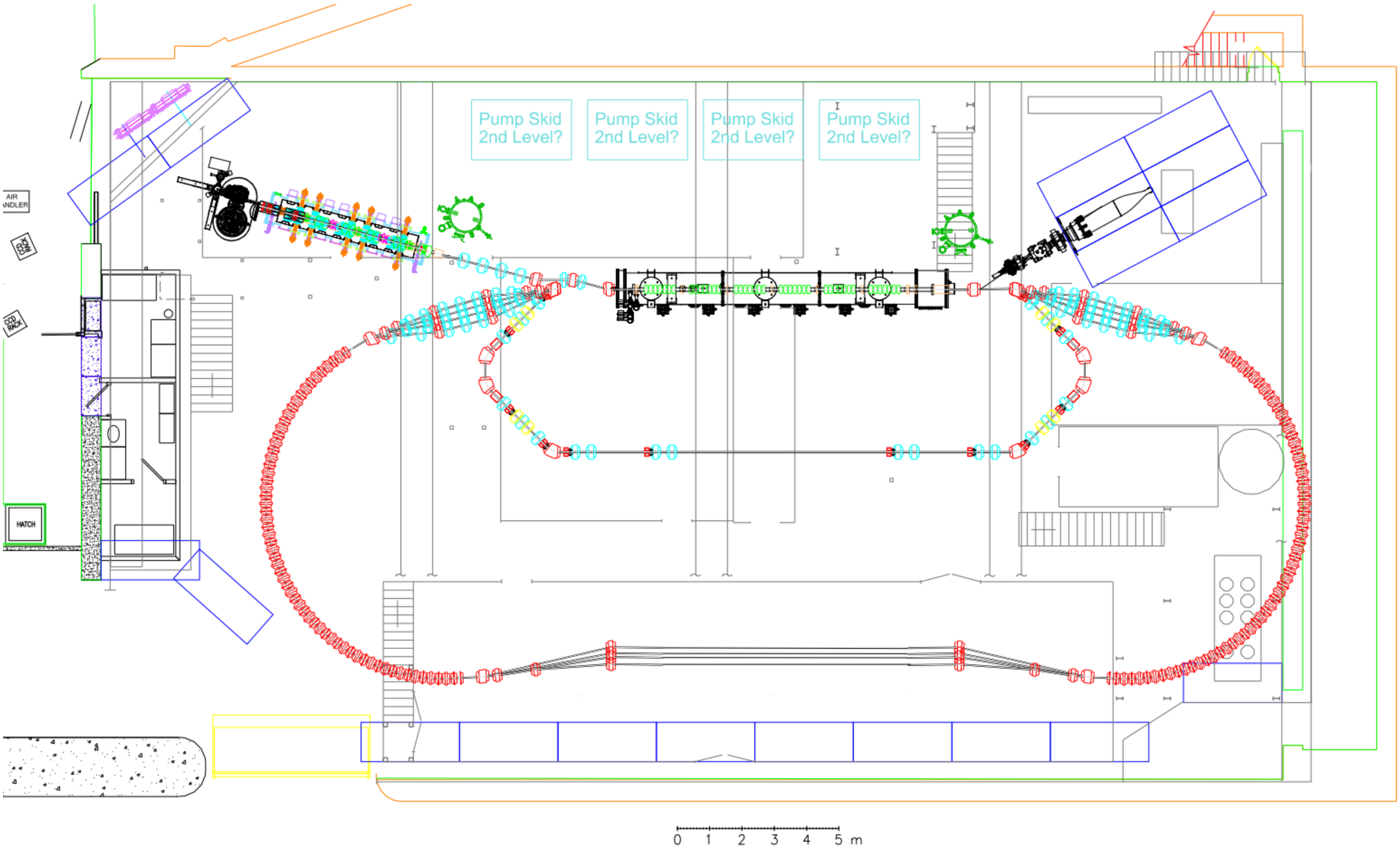
- 4-turn ERL operation at the eRHIC design gradient of 16MV/m.
- Providing energy of at least 286MeV for physics experiments.

Finally, the Cβ FFAG ERL provides an accelerator for nuclear physics and continued use for eRHIC prototyping and commissioning of eRHIC components.

The nuclear physics experiments would likely be unrelated to eRHIC and we are looking for funding.

Suitable experiments are to be addressed at this workshop.

Upgrade options to 600MeV with an 8-turn ERL – not planned



Summary

Neither an FFAG loop with a factor of 4 momentum acceptance nor a multi-turn ERL has been built before. **The Cbeta FFAG ERL at Cornell will address both of these risk factors for eRHIC** adequately and rather completely.

Cornell and BNL have started to collaborate on the creation of this prototyping facility at Cornell, using ERL components from Cornell

- A DC electron gun
- A low-emittance and high-current injector linac,
- An ERL-merger
- A 10m long CW SRF accelerator module
- A beam stop.

The collaboration has become rather active clearing space, testing components, produceing WBS for detailed costing and timeline, and providing an organizing structure.

Important eRHIC-ERL prototyping results can be available before 2018 !

Then this accelerator can be used for Physics experiments.

Questions ?