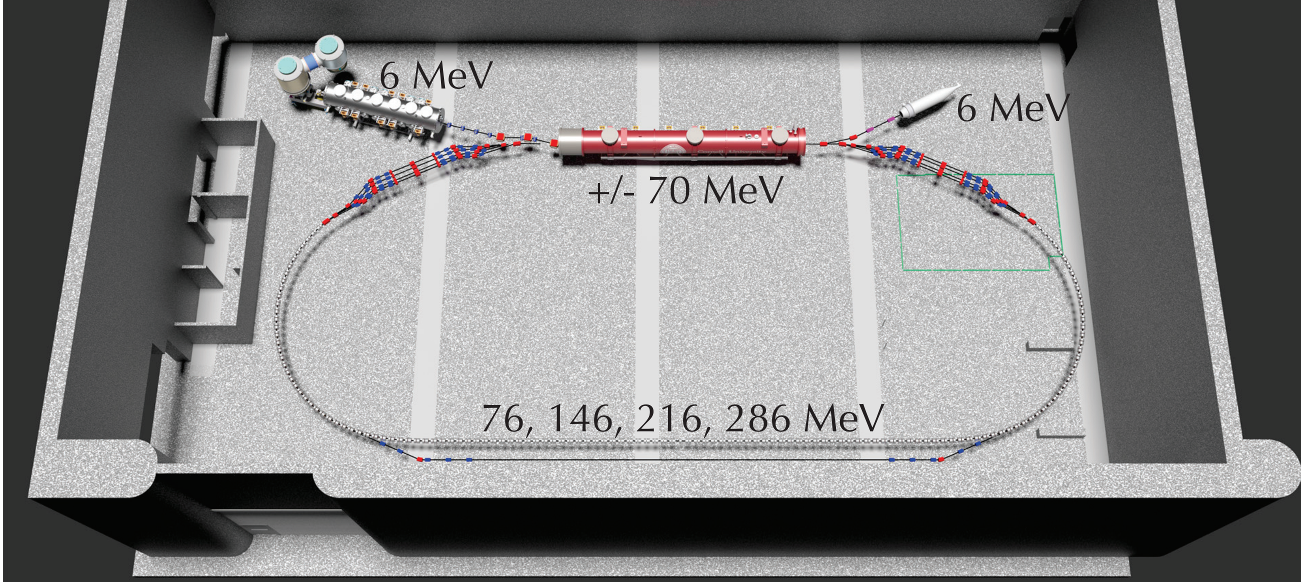
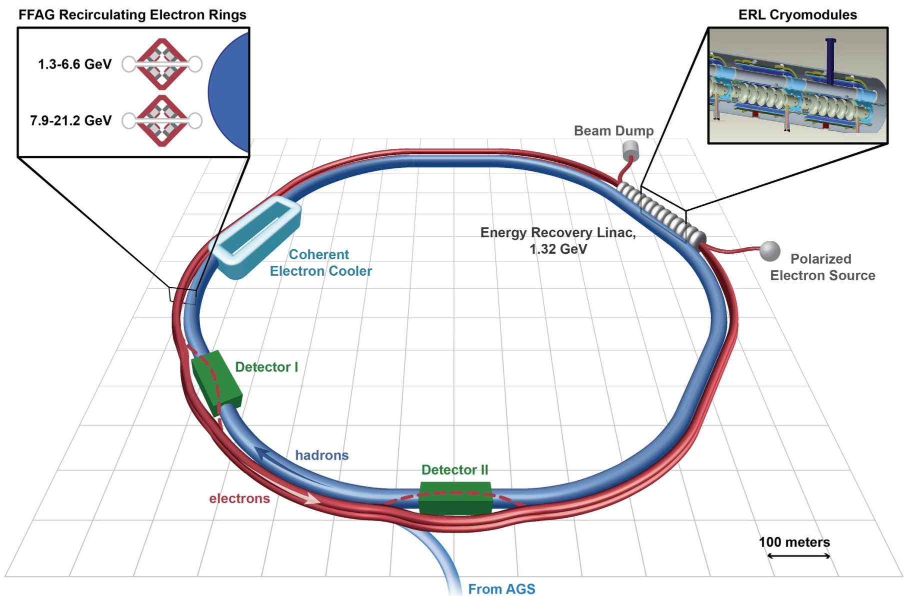
# A FFAG-ERL at Cornell,
# a BNL/Cornell Collaboration

Georg Hoffstaetter (Cornell) for the Cβ collaboration

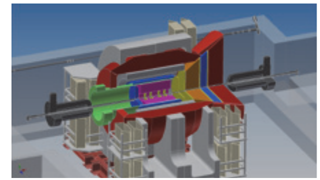


# eRHIC Design – requires an ERL !

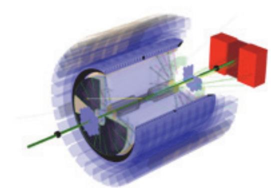




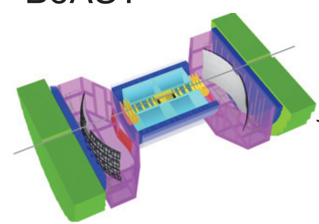

ePHENIX



eSTAR



BeAST

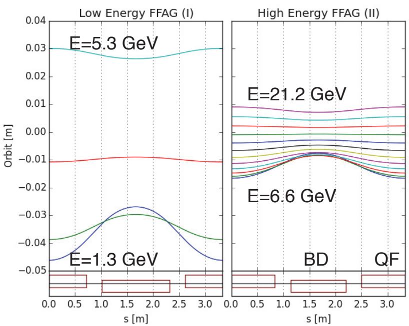


- $1.7 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ for $\sqrt{s}$ = 127 GeV (15.9 GeV e↑ on 255 GeV p↑)
- × 10 luminosity with modest improvements (coating of RHIC vacuum chamber)
- × 100 luminosity with shorter bunch spacing (ultimate capability)

courtesy Thomas Roser

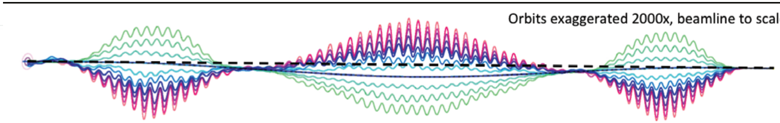
# eRHIC ERL has 16 turns in only 2 NS-FFAG arcs !



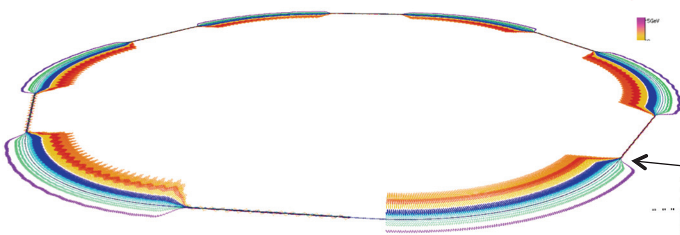



- eRHIC uses two FFAG beamlines to do multiple recirculations. (FFAG-I: 1.3-5.4 GeV, FFAG-II: 6.6-21.2 GeV)
- All sections of a FFAG beamline is formed using a same FODO cell. Required bending in different sections is arranged by proper selection of the offsets between cell magnets (or, alternatively,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

*@S.Brooks, D.Trbojevic*

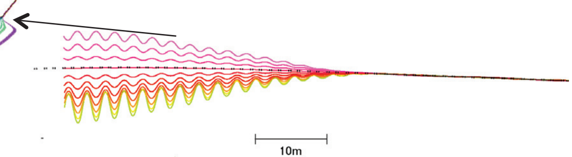



Orbits in Detector bypass section



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:

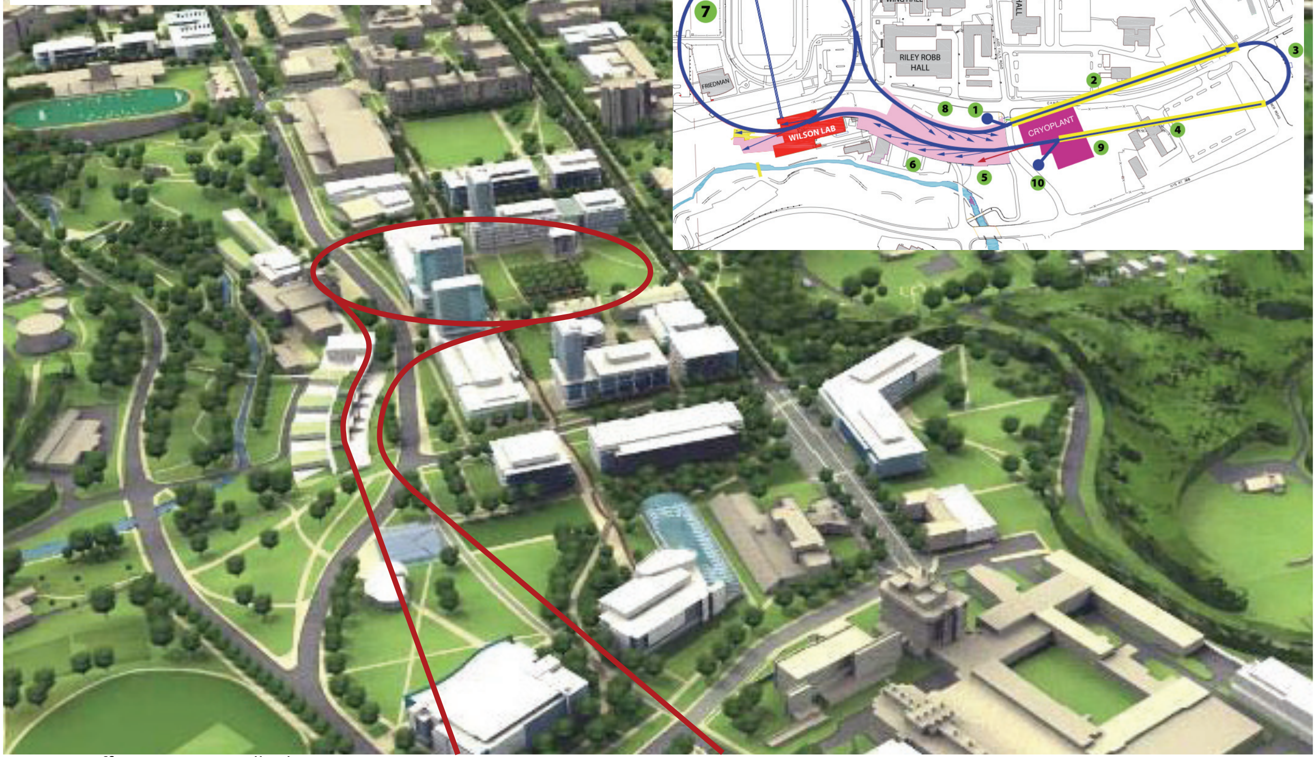
1) FFAG loops with a factor of 4 in momentum aperture.
   a) Precision, reproducibility, alignment during magnet and girder production.
   b) Stability of magnetic fields in a radiation environment.
   c) Matching and correction of multiple simultaneous orbits.
   d) Matching and correction of multiple 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

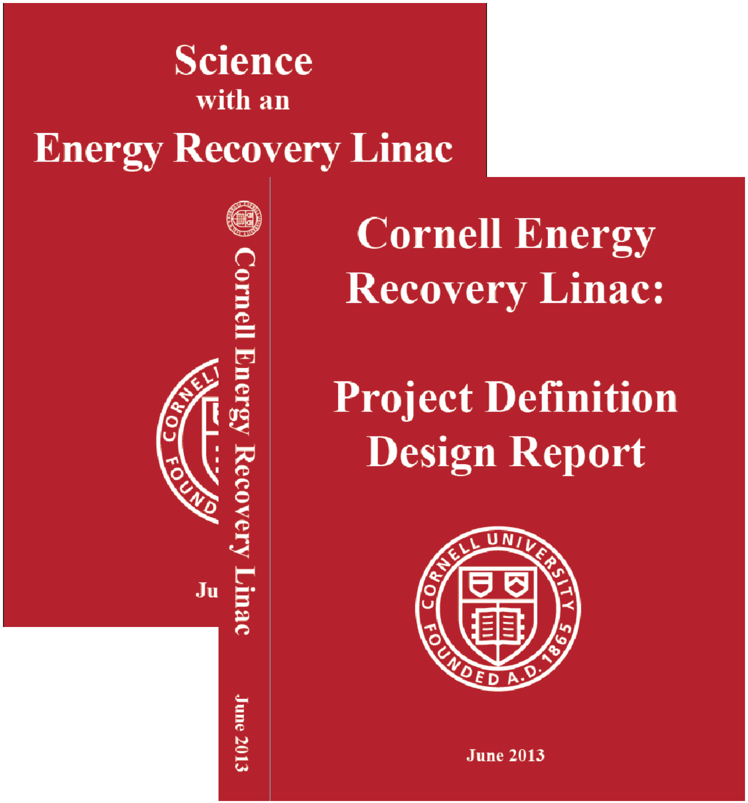


## ERL@CESR, Cornell



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



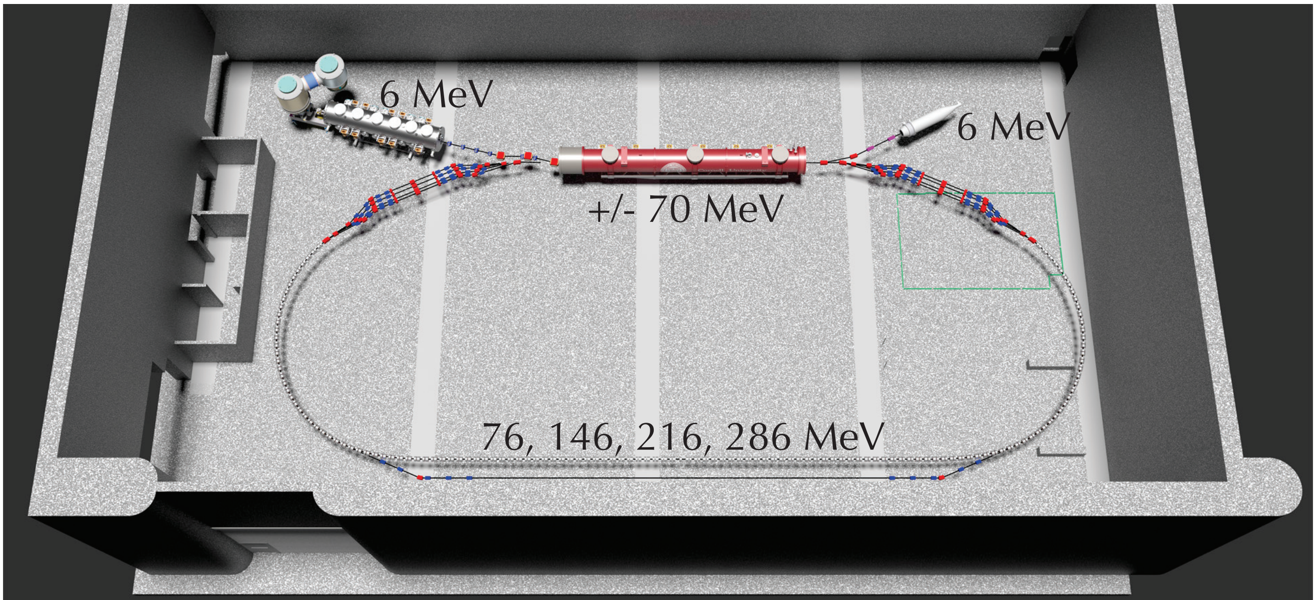



- Science case gathered in international workshops
- Design report
  - 530 pages between conceptual design and engineering design
  - Access at www.classe.cornell.edu/ERL/PDDR
- Also
  - Electron beam construction (from RI)
  - Cryoplant (from Linde and Air Liquide)

# Prototype eRHIC ERL @ Cornell



- NS-FFAG arcs, four passes (like first eRHIC loop)
- Momentum aperture of x4, as for eRHIC (EMMA achieved x1.5, planned 1.9)
- 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

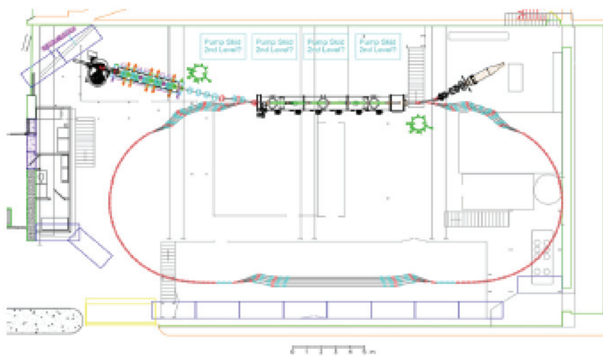
**White Paper**

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]

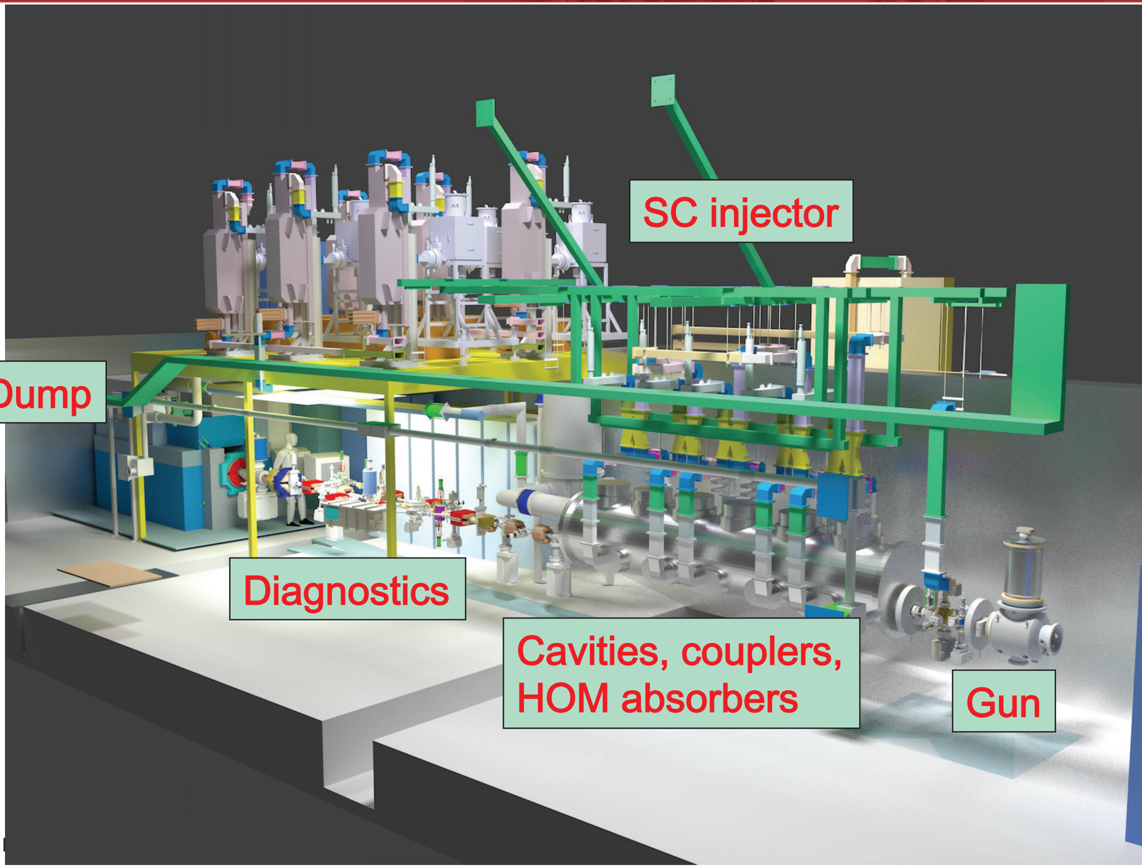
Bunch repetition rate of 1.3GHz or 433MHz (for a tuned eRHIC cavity)

Energy E up to about 300 MeV

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

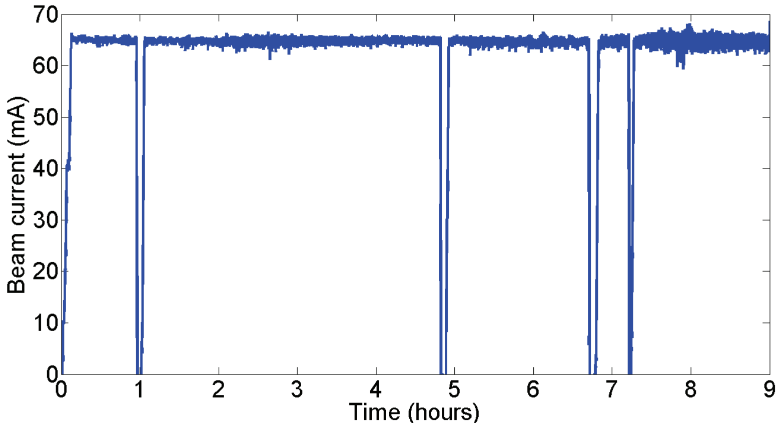
# Cornell ERL injector prototype





# 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

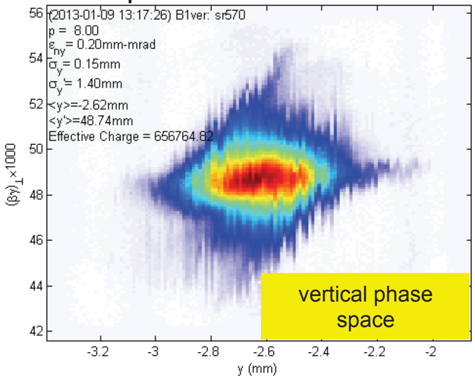
Simulations accurately reproduce photocathode performance with no free parameters, and suggest strategies for further improvement.

✓ Source current can meet ERL needs

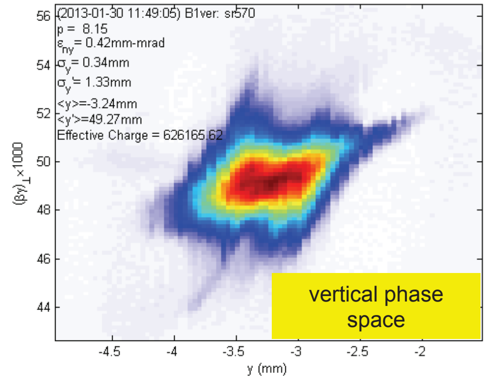
# ERL readiness: Beam brightness



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***

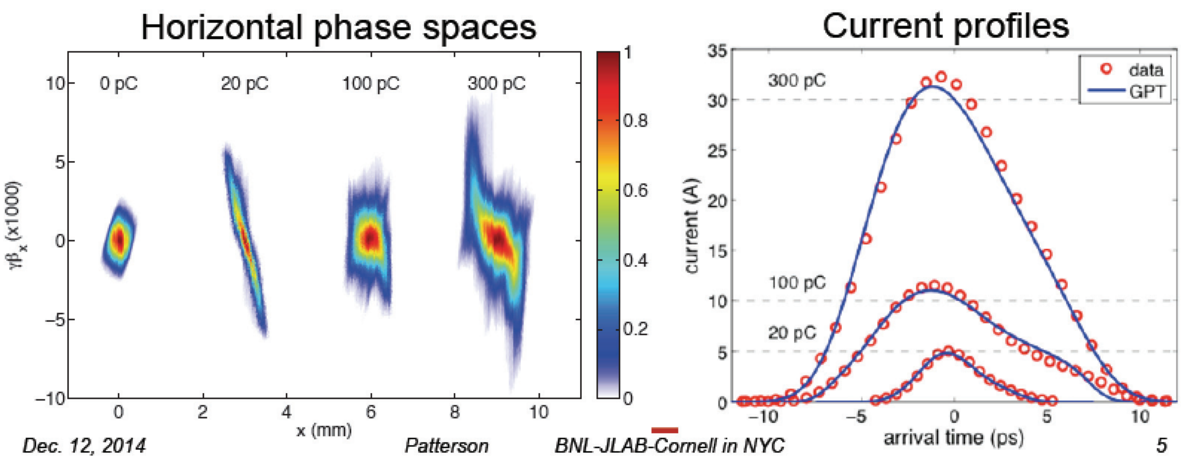
✓ At 5 GeV this gives 20x the world's highest brightness (Petra-III)

# Beam tests for LCLS-II



## Target specs:

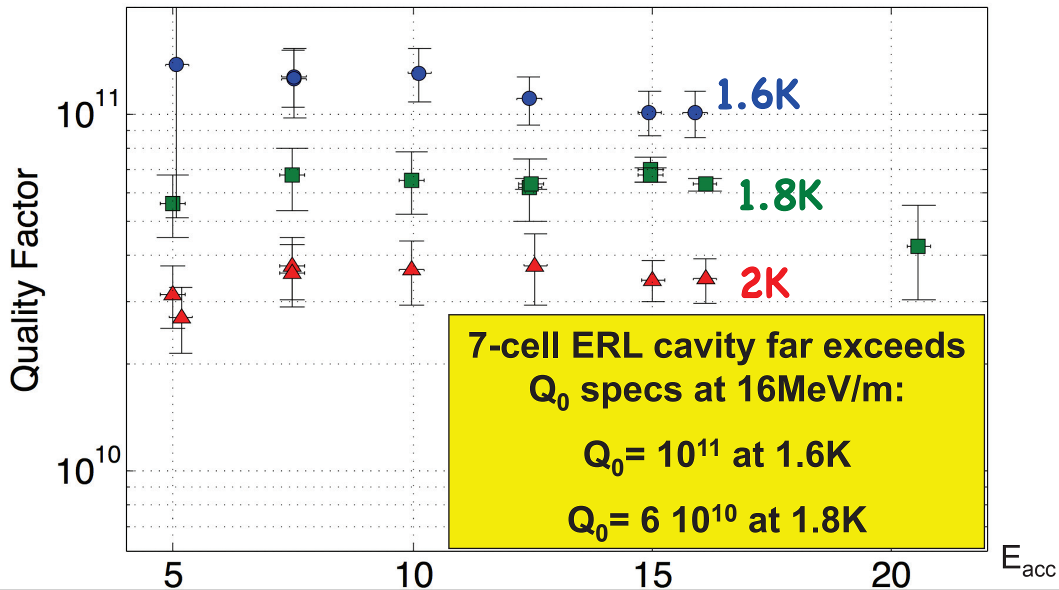
| Bunch charge (pC) | Peak current target (A) | Peak current measured (A) | Emittance Target (95%, μm) | Emittance measured (95%, μm) |
|---|---|---|---|---|
| 20 | 5 | 5 | 0.25 | H: 0.18, V: 0.19 |
| 100 | 10 | 11.5 | 0.40 | H: 0.32, V: 0.30 |
| 300 | 30 | 32 | 0.60 | H: 0.62, V: 0.60 |



# 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.




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.

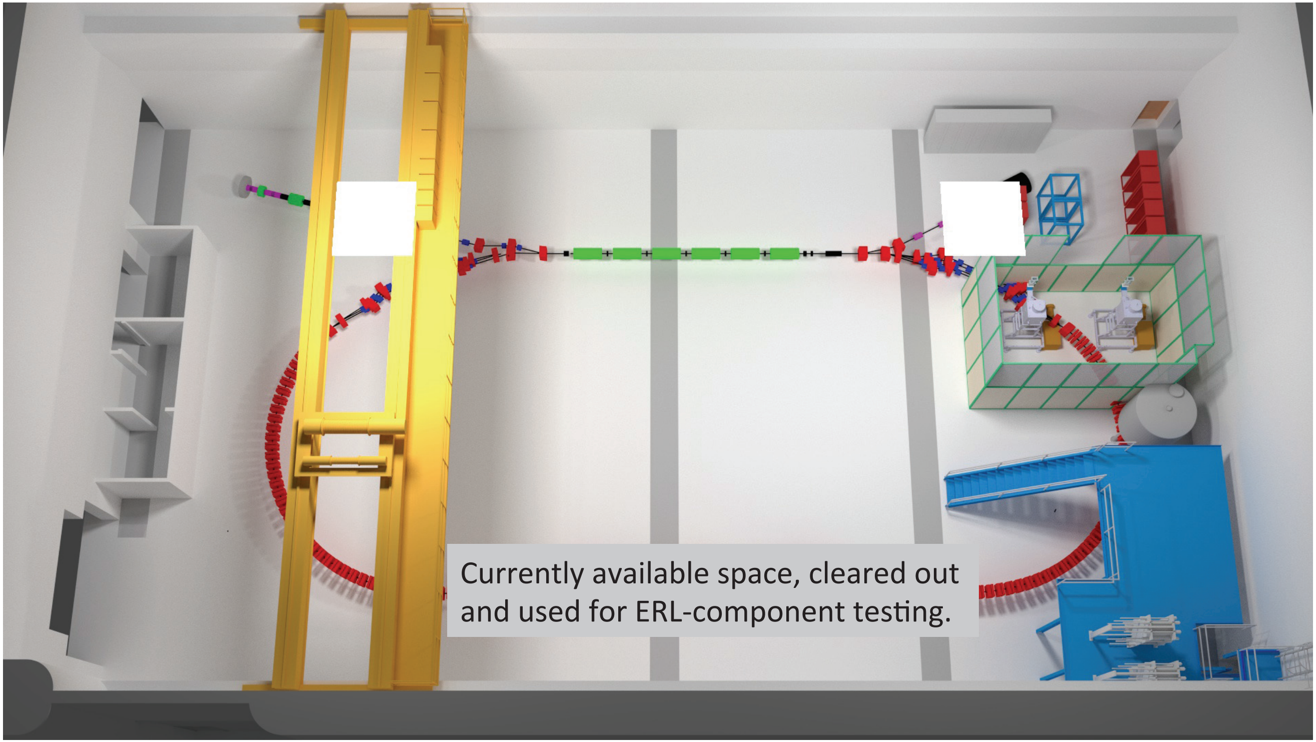
- R&D and prototyping of eRHIC systems, e.g. permanent magnets, multi-beam diagnostics possibly for pilot bunches, optics control, and feedback, mergers, timing, halo control, collimation, LLRF control, resonant extraction of the highest-energy beam, etc.
- Proof of eRHIC-cavity capabilities, e.g. current 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

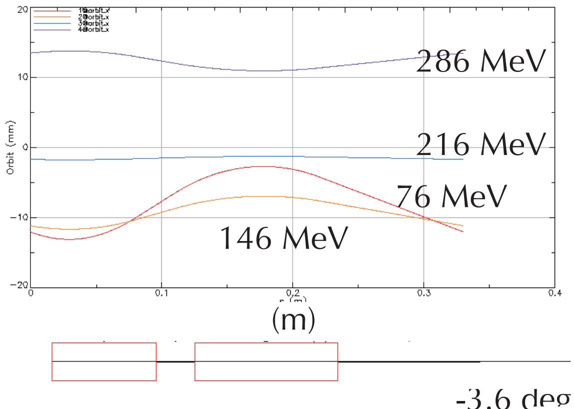
**Many of the design criteria are identical to those of eRHIC**

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

# Example study: Orbits for different energies



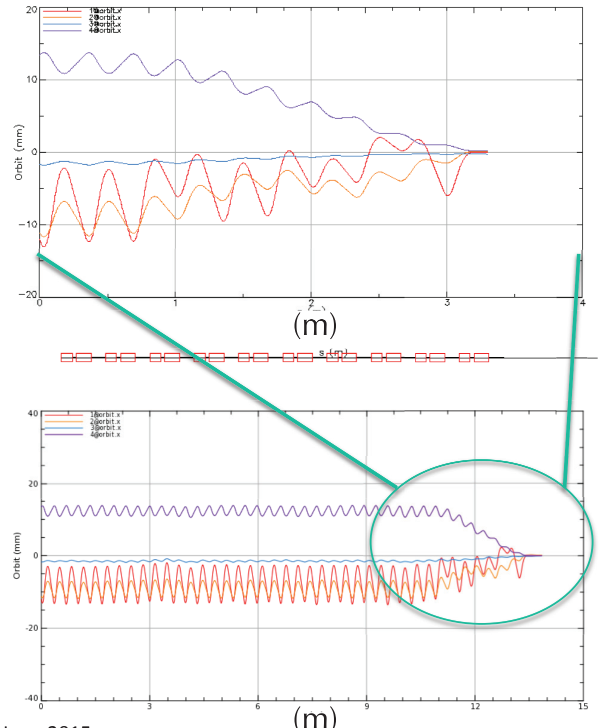
## Cell




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

(Orvigt ….XXXXX

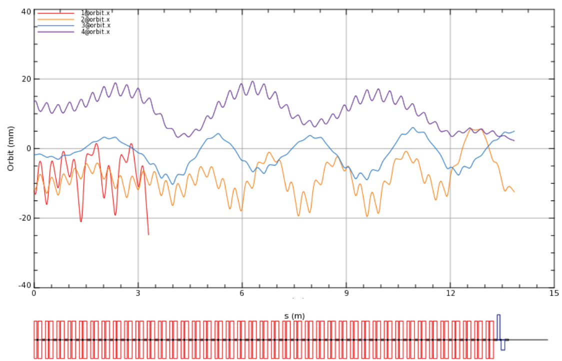
## Arc-to-Straight (10 cells)



# Example study: FFAG ERL orbit corrections

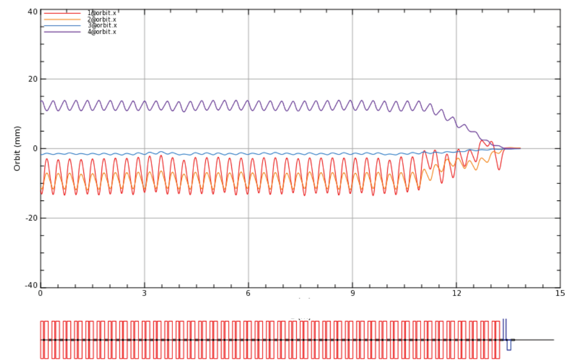


500 um rms x offset errors




Full FFAG arc

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




Full FFAG arc

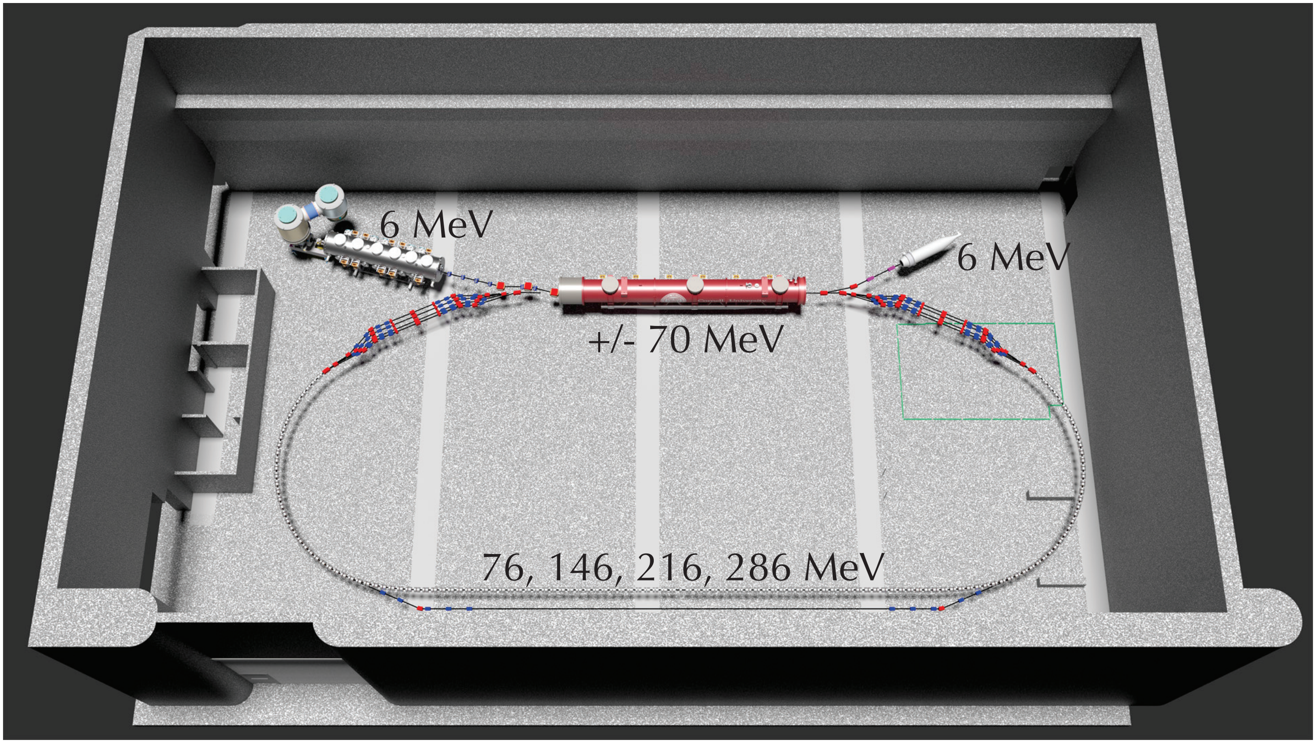
# R&D and Prototyping for eRHIC at the Cβ FFAG-ERL



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





# L0E cleanout for Cβ ERL

# L0E cleanout for Cβ ERL


# L0E cleaned out for Cβ ERL

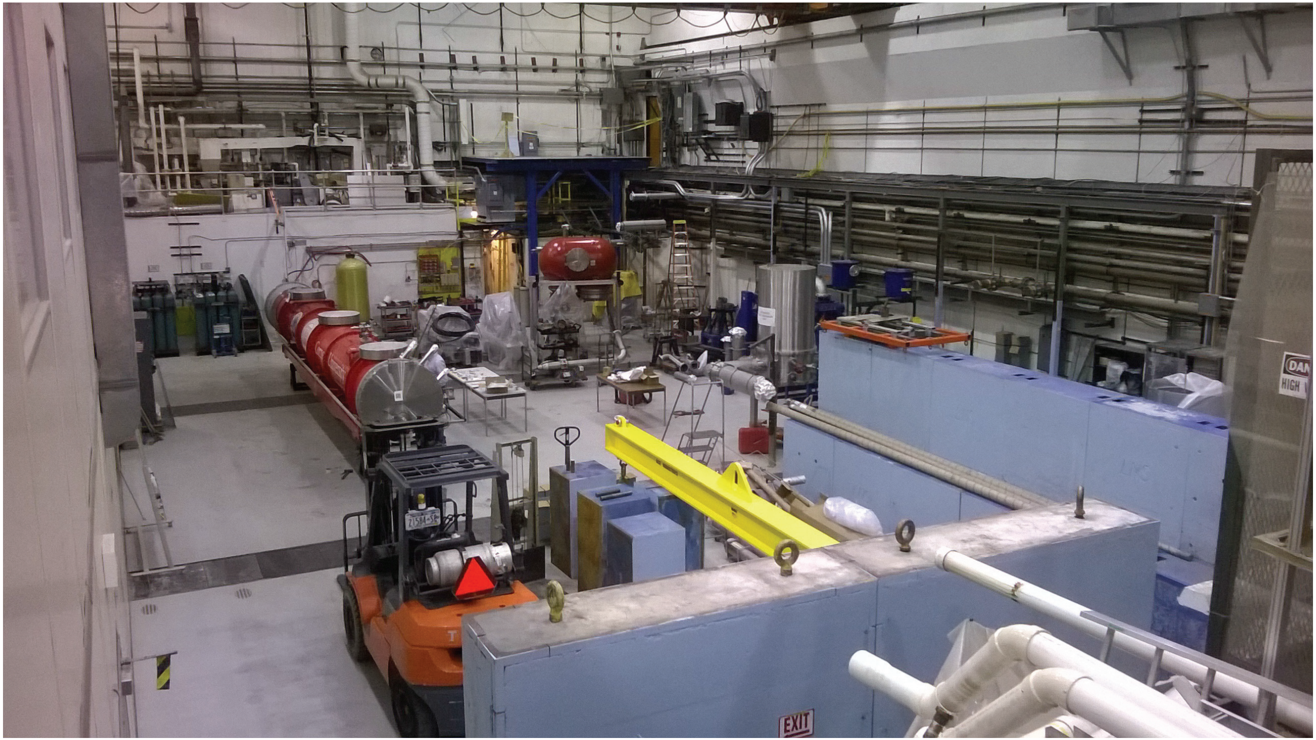


# L0E cleaned with Cβ ERL



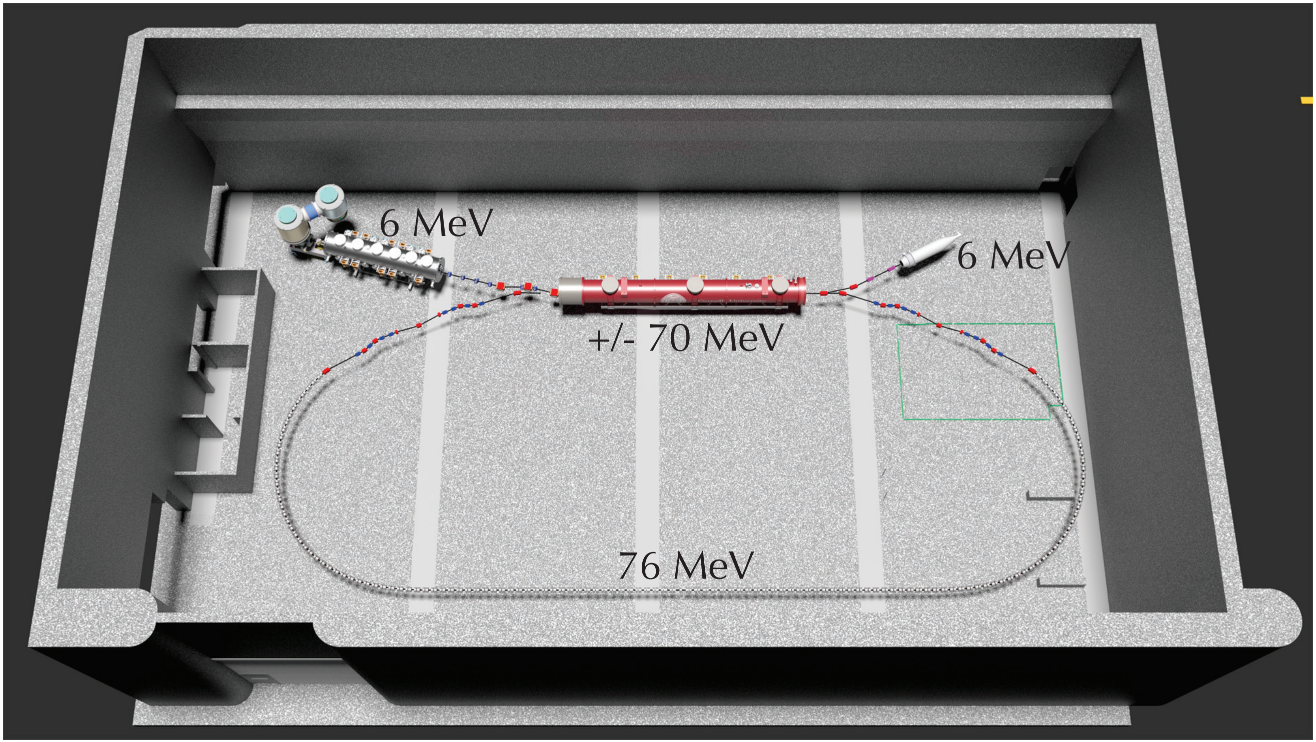
# L0E for current ERL injector and MLC test





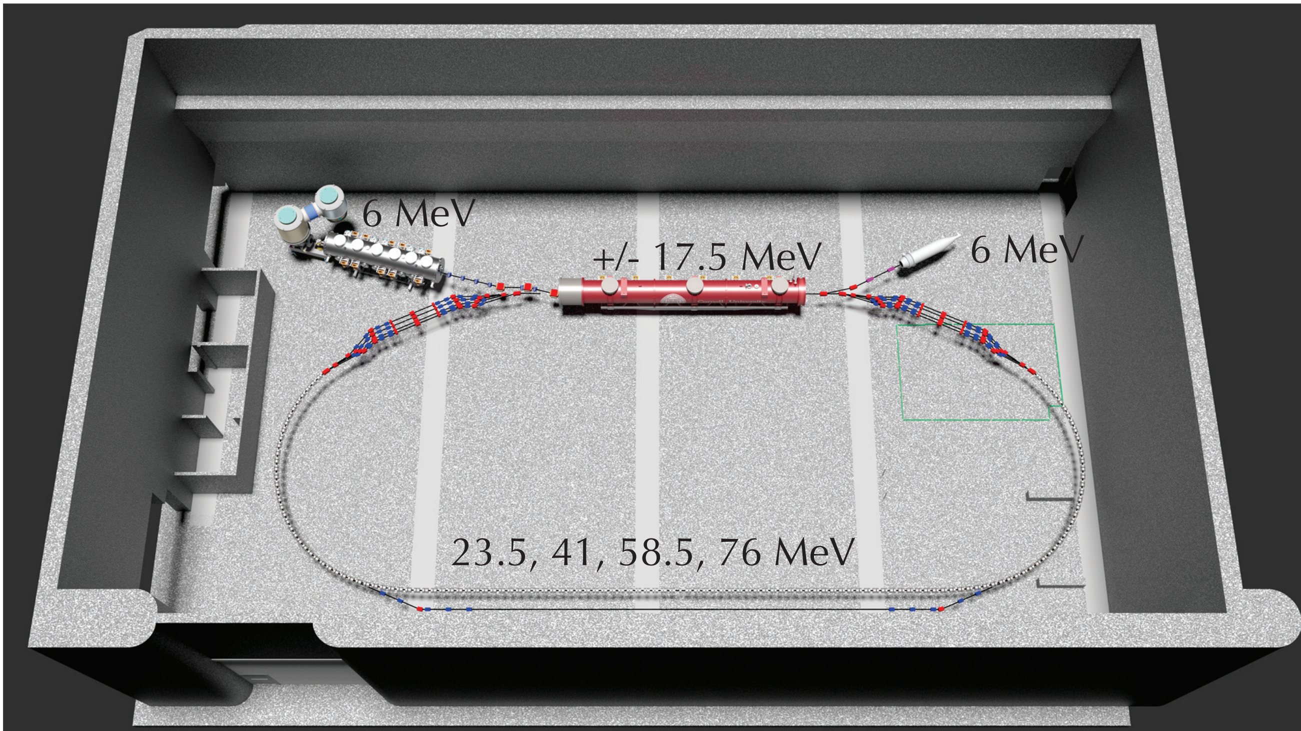
# 1$^{st}$ stage: 1-turn ERL for 76 MeV





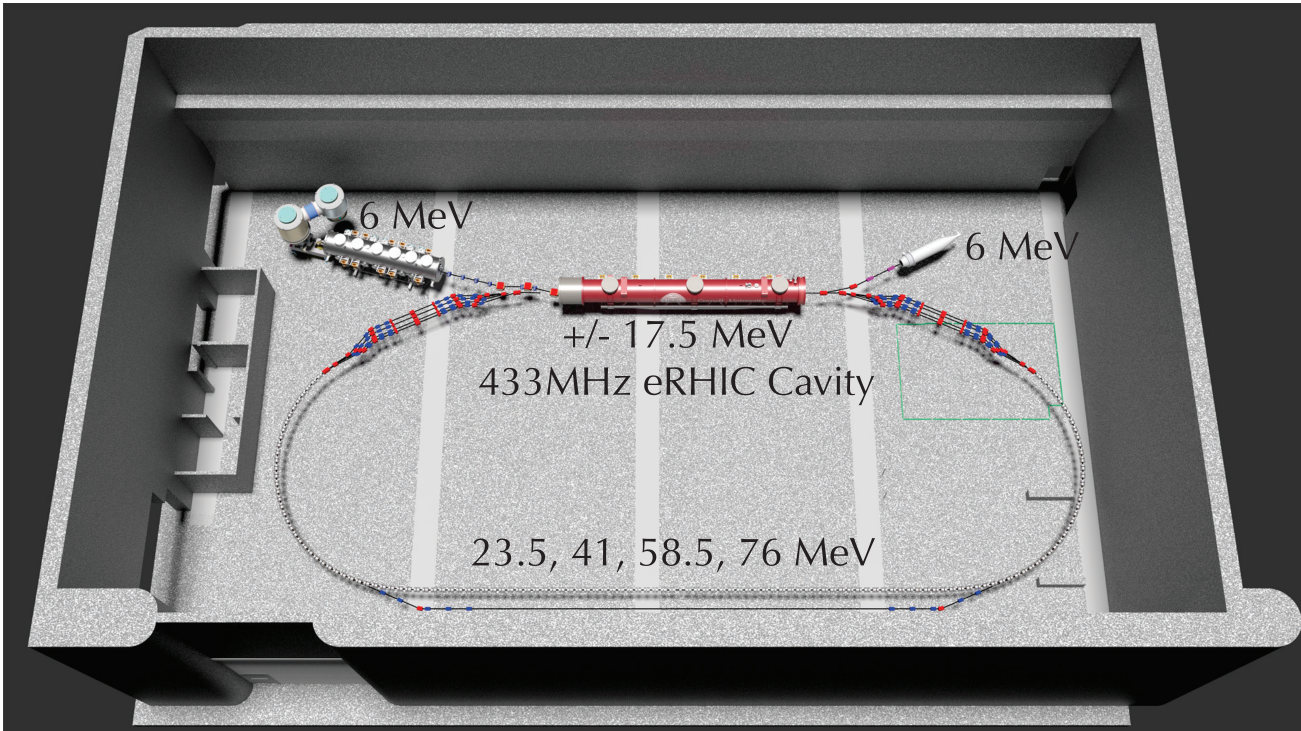
# 2nd stage: 4-turn ERL for 76 MeV





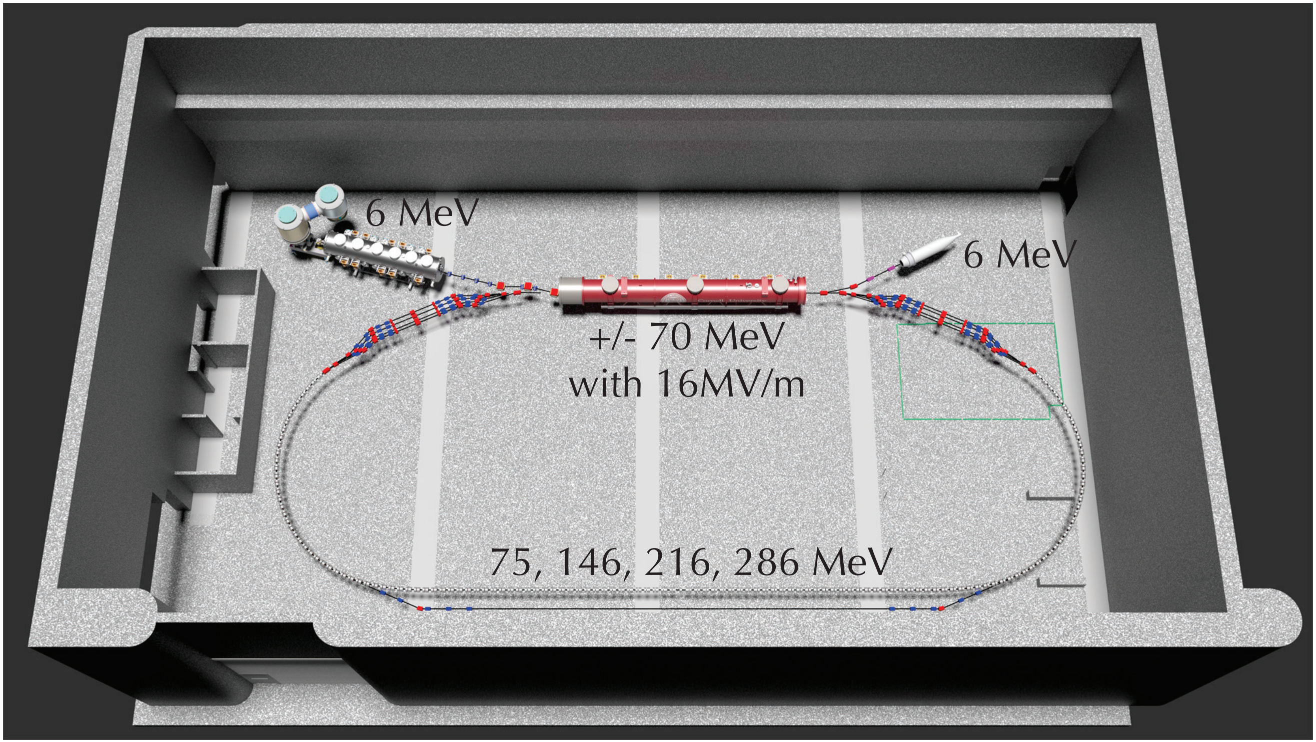
# 3rd stage: 4-turn ERL for 76MeV with an eRHIC cavity





# 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. Here the 433MHz cavity would be replaced by the 1.3GHz MLC and the FFAG magnets would be strengthened for a peak energy of 286 MeV. 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 the
**Intense Electron Beams Workshop at Cornell University, June 17-19, 2015.**

# Unique capabilities of Cβ, essentail for eRHIC risk reduction



- Cβ will be the first accelerator in the world to include any of the following things, which are all required by the eRHIC design
  - ERL using FFAG recirculating arcs
  - Linear field FFAG with momentum range of 4x
  - Adiabatic transition from curved to straight FFAG
  - Permanent magnets (PMs) used in an FFAG
  - NdFeB PMs used for main beam steering
  - PMs used in ERL return arcs
  - Multi-pass superconducting ERL

$\}$ Phase 1&2

← Phase 3&4

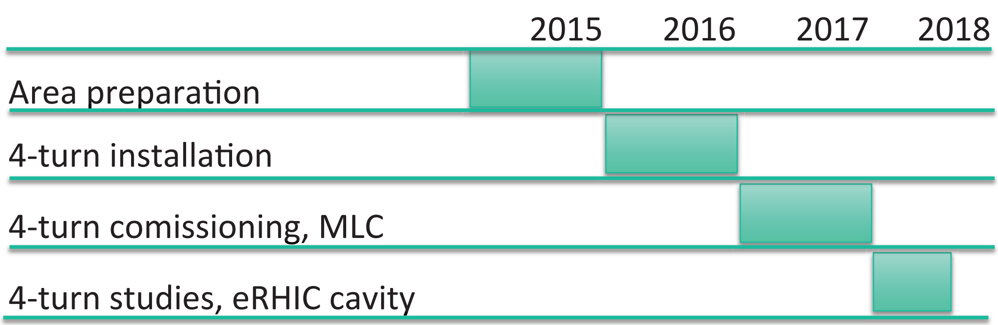
# A possible draft schedule



Start 2015 – Start 2016: Cleaning out of experimental area, and injector and MLC test

Start 2016 – Start 2017: Install 4-turn ERL-FFAG for 23.5, 41, 58.5, and 76 MeV.

Start 2017 – Mid 2018: Commissioning of 1 to 4 turn ERL and accelerator physics studies. Replace Cornell's MLC with BNL's eRHIC prototype cavity, tuned to 433MHz. Perform high-current experiments, including HOM heating studies. Study the multi-turn BBU threshold for eRHIC cavities.



# 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 !**

# Questions ?

# A possible draft schedule 12 months of 1st year



| | |
|---|---|
| Complete magnet designs for 3 competing options<br>Optics design<br>Clear out remainder of experimental hall<br>Construct cryo lines for MLC | Cooldown MLC and test RF<br>Vacuum and support structure design<br>specify and design diagnostic systems |
| Optics design, uild prototypes for 3 magnet types<br>Clear out remainder of experimental hall<br>Construct cryo lines for MLC | Complete MLC RF tests<br>Vacuum and support structure design<br>Design diagnostic systems |
| Optics design, Test prototype magnets<br>Clear out remainder of experimental hall<br>Move MLC to final position, connect cryogenics | Prepare for low current beam tests through MLC<br>Design diagnostic systems |
| Optics design, Test prototype magnets<br>Experimental hall ready<br>Complete MLC cryogenics | Low current beam tests through MLC<br>Complete vacuum chamber design<br>Complete support girder design |
| Optics design complete<br>Choose magnet type<br>Prototype complete FFAG arc cell structure<br>Install MLC RF systems | Prepare for magnet QA<br>Low current beam tests through MLC<br>Build/order vacuum components<br>Build/order support girders |
| Order permanent magnets<br>Order conventional magnets & PS<br>Complete MLC RF system installation<br>Start vacuum system design | Prepare for magnet QA<br>Low current beam tests through MLC |

# A possible draft schedule 12 months of 2nd year



| | |
|---|---|
| PM magnet acceptance and QA<br>Conventional magnet acceptance and QA<br>Support girder acceptance | Construct magnet girder assemblies<br>Control system installation<br>Safety system installation |
| PM magnet QA<br>Conventional magnet QA<br>Assemble/test FFAG girder | Construct magnet girder assemblies<br>Install magnet girders<br>Install magnet power supplies<br>Control system installation |
| Vacuum chamber acceptance/testing<br>Order bpm electronics | Install magnet girders<br>Install magnet power & water & controls<br>Subsystem tests: vacuum, magnets, diagnostics<br>Control system installation |
| Vacuum chamber acceptance/testing | Install magnet girders<br>Install magnet power & water & controls<br>Subsystem tests: vacuum, magnets, diagnostics<br>Control system installation |
| Construct magnet girder assemblies | Install magnet girders<br>Install magnet power & water & controls<br>Subsystem tests: vacuum, magnets, diagnostics |
| Construct magnet girder assemblies<br>Control system installation<br>Safety system installation | Safety system testing<br>Subsystem tests: vacuum, magnets, diagnostics<br>Safety system certification |

# A possible draft schedule 12 months of 3RD year



Initial beam commissioning
1 pass and energy recovery

1 pass at different energies - energy acceptance

2, 3 and 4 pass setup
Beam quality measurements

High current operations
BBU measurements

Remove MLC and install BNL cavity
Prepare laser for lower frequency

Initial beam commissioning
1 pass and energy recovery

2, 3 and 4 pass setup
High current operations

BBU measurements

Chromaticity and emittance growth measurements

Test beam extraction concepts

Other beam tests

Other beam tests

**Accelerator physics experiments**

Snergy acceptance
Multi-pass beam breakup - CU cavities
Multi-pass beam breakup - BNL cavities
Chromaticity and emittance growth
Beam extraction from FFAG
Multi-beam diagnostics
Multi-beam orbit correction

# Upgrade options to 600MeV with an 8-turn ERL