Advances in Beam Dynamics at Nuclear Physics Accelerator Facilities

A. Sy

Wednesday, August 10, 2022

Disclaimer + acknowledgements

- I'm likely not the best person to ask detailed questions about the content to come
- I'm happy to direct you to others who will have better answers

- Many thanks go to:
  - A. Bogacz (JLab) and the FFA@CEBAF Working Group
  - J. Grames (JLab) and the PPB Working Group
  - B. Mustapha (ANL)
  - C. Dickerson (ANL)
  - M. Blaskiewicz (BNL)
  - F. Willeke (BNL)
  - P. Ostroumov (FRIB/MSU)

What makes an accelerator suitable for nuclear physics research?

- Nuclear physics research focuses on the understanding of nuclear matter and why it appears in the way that it does
  - Nuclear structure
  - Physics beyond the Standard Model
  - And more!
- Particle accelerators are often described as microscopes because they allow us to "see" very small things
  - Energy range: de Broglie wavelength $\lambda = \frac{h}{p}$
    - p=1 GeV/c → λ = 1.24 x 10^{-15} m ~ size of a proton
  - Particle choice: Electrons as clean probes; protons or heavy ions for more complex systems
  - Fixed target or collider
  - Enhanced interaction probability with current, luminosity

[https://commons.wikimedia.org/wiki/File:202002_Laboratory_instrument_microscope.svg]

Current DOE facilities

- DOE operates a number of accelerator facilities across the country for nuclear physics, high energy physics, and other research programs

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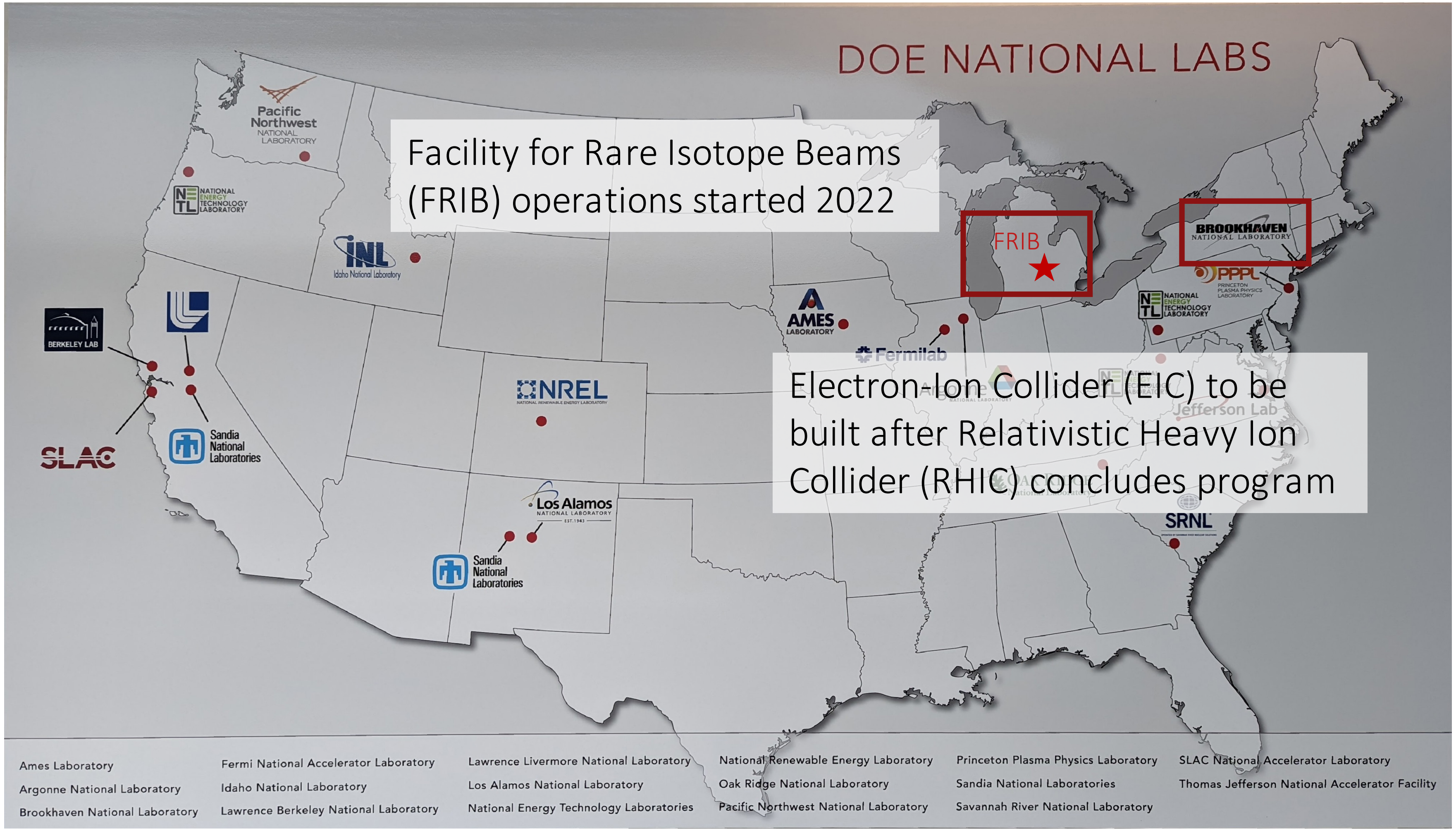

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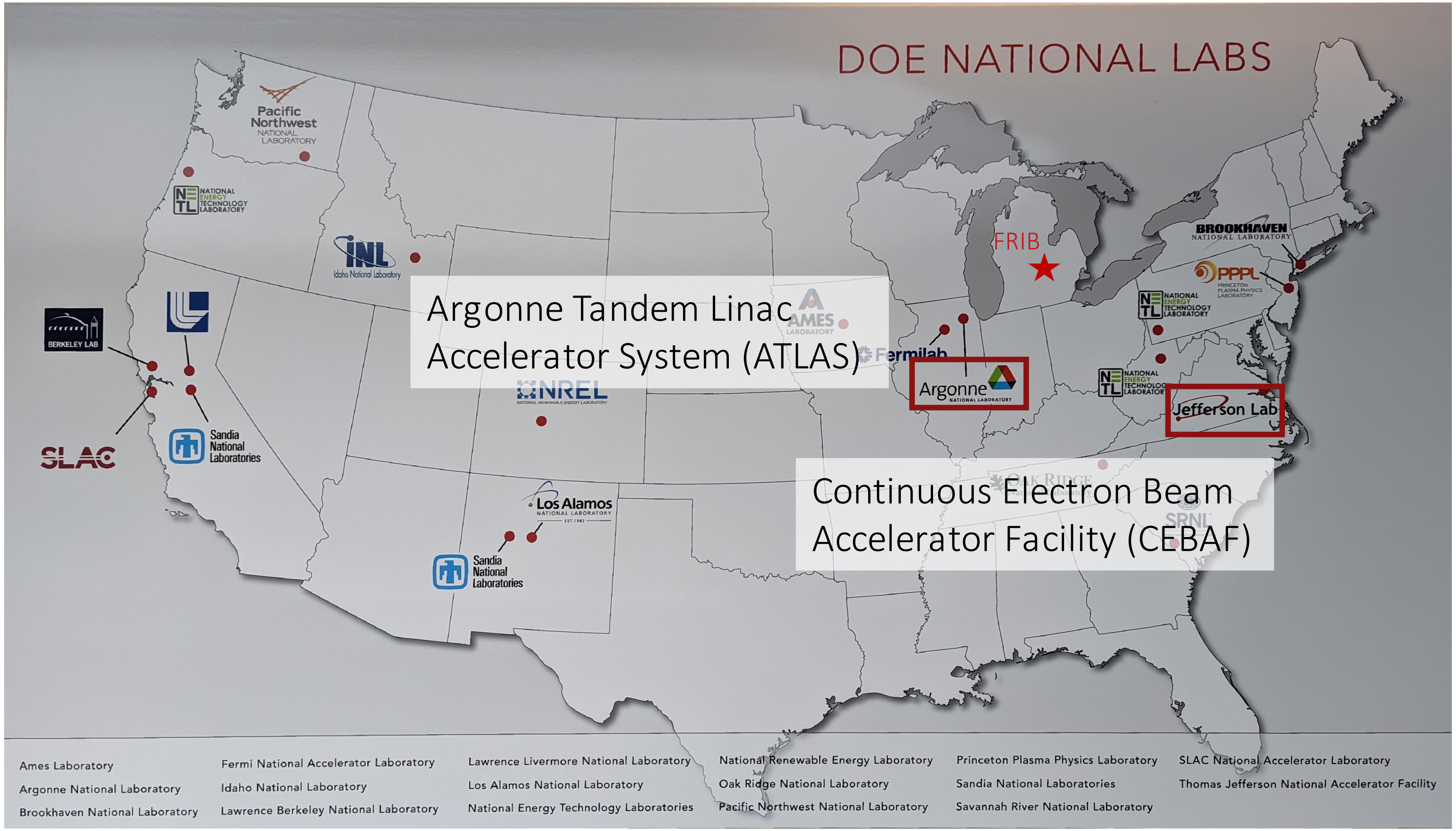


What's in store for the future?

- NSAC Long Range Plan sets priorities and makes recommendations for the direction of US nuclear physics research
- Charge for the next NSAC Long Range Plan delivered on July 13, 2022 at NSAC meeting
- The 2015 Long Range Plan recommended the construction of an EIC → 2019 CD-0 for EIC
- Meanwhile, accelerator and nuclear physicists work together to explore options for future operation of existing machines
  - RHIC → EIC
- Using an existing machine to support expanded science programs necessitates an evaluation of the beam dynamics that enable operation beyond current capabilities
  - Unique challenges arise due to constraints from existing infrastructure

Excerpt from the charge:

The new NSAC LRP should articulate the scope and the scientific challenges of nuclear physics today, what progress has been made since the last LRP, and the impacts of these accomplishments both within and outside the field. It should identify and prioritize the most compelling scientific opportunities for the U.S. nuclear physics program to pursue over the next decade (fiscal year (FY) 2023-2032) and articulate its potential scientific impact. Further, a nationally coordinated strategy for the use of existing and planned capabilities, both domestic and international, and the rationale for new investments should be articulated. To be most helpful, the LRP should indicate what resources and funding levels would be required, including construction of new facilities, mid-scale instrumentation, and Major Items of Equipment, to maintain a world-leadership position in nuclear physics research. The LRP should also describe the potential impacts and priorities under constant level of effort budgets, 2 percent growth per year using the FY 2022 enacted funding level as a reference.

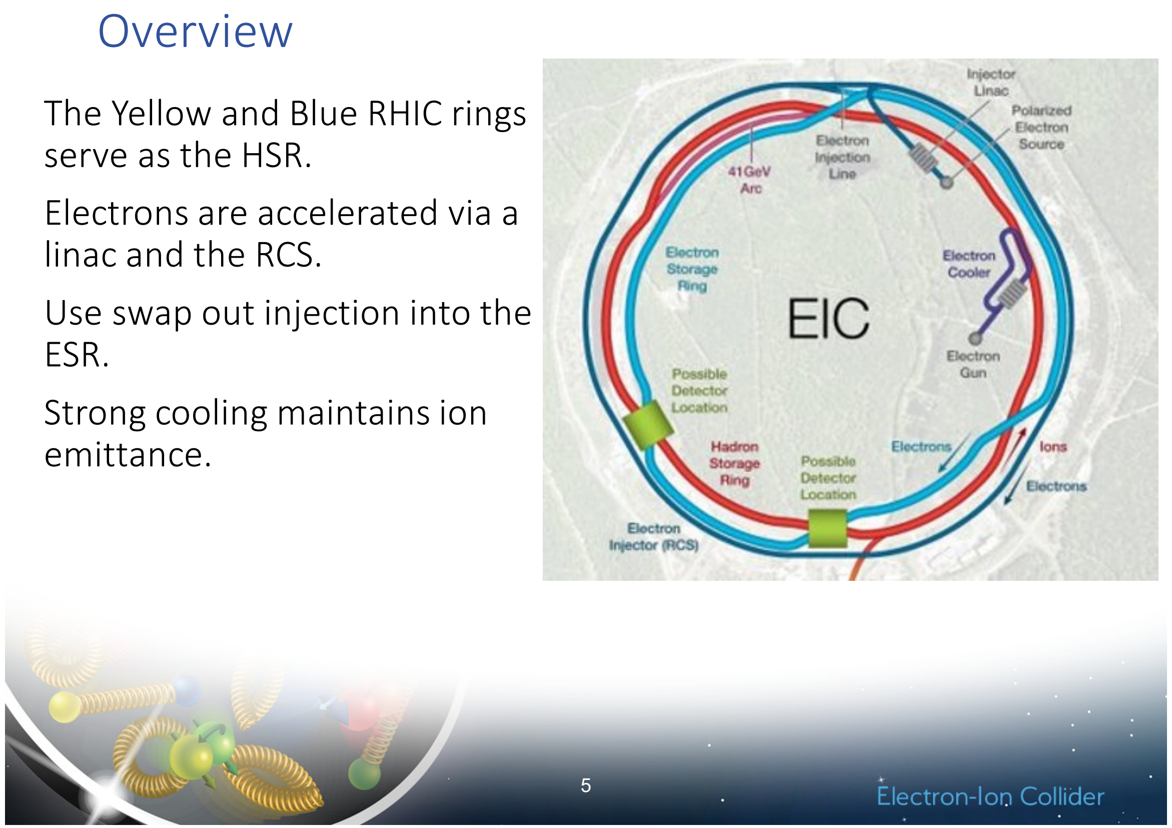
[https://science.osti.gov/np/nsac/Reports]

Why are we here today?

- Our nuclear physics accelerator facilities have planned and proposed upgrades
  - We'll focus on fixed target facilities (ATLAS and CEBAF)
- Let's discuss some of the beam dynamics topics considered for those future capabilities

RHIC upgrades: RHIC → EIC

- A bit of a misnomer, as RHIC capability isn't preserved in the EIC
- See talks MOYD1, MOYD3, MOYD4, MOYD5, MOYD6 for more detail
- Beam dynamics challenges include:
  - Dynamic aperture in ESR
  - Crab cavity related beam dynamics
  - Beam-beam interaction with crabbed beams
  - Beam polarization (electrons)
  - Beam cooling

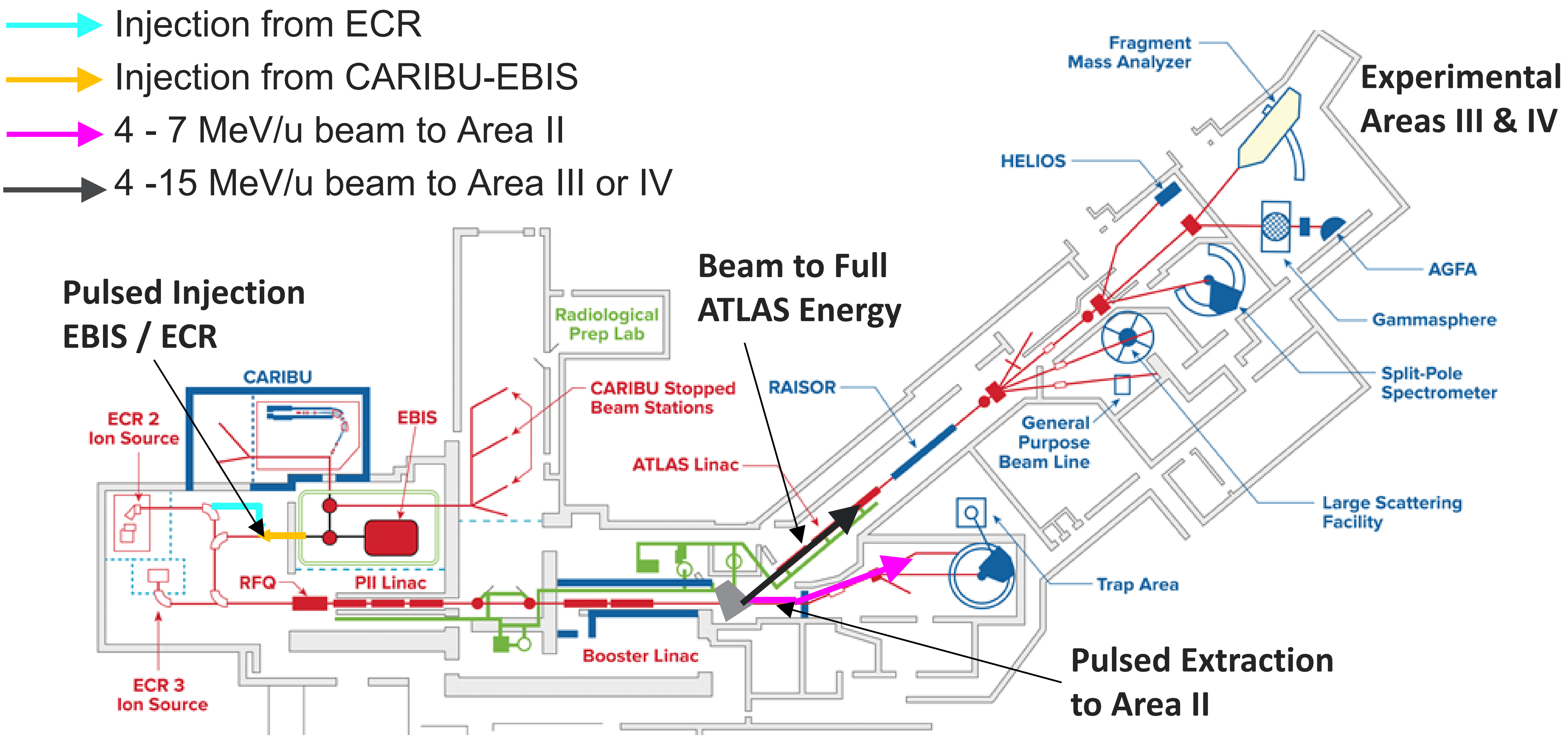


[Courtesy M. Blaskiewicz]

ATLAS upgrades

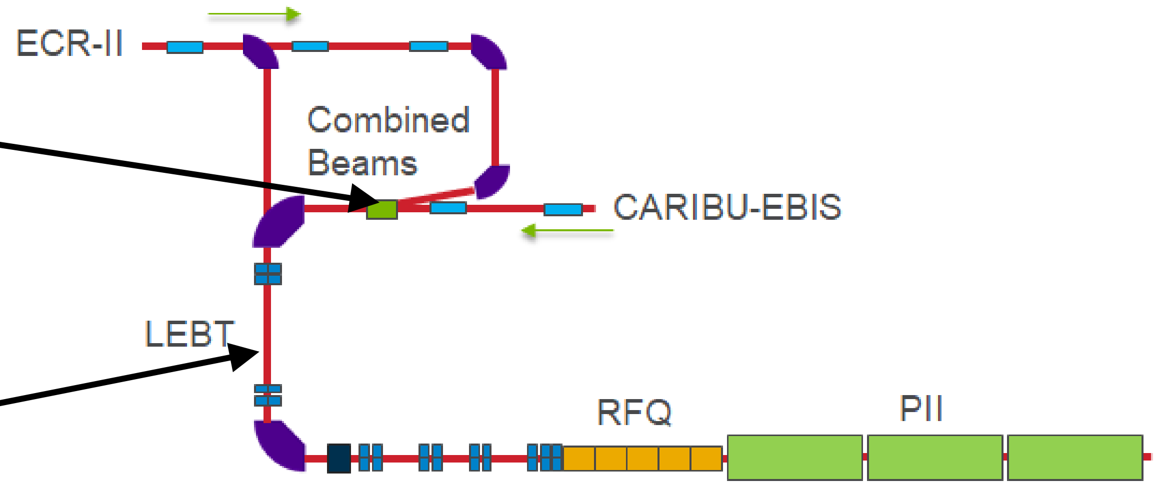
- ATLAS is a superconducting heavy ion linac
- Operating since 1985 as a user facility for low-energy nuclear physics research
- Stable and rare isotope beams available
- Multi-user upgrade recently approved: experiments requesting stable and rare isotope beams can be run simultaneously

Concept of the ATLAS Multi-User Upgrade



AMUU Technical Solution

1) Modification to the Front-end / Injection

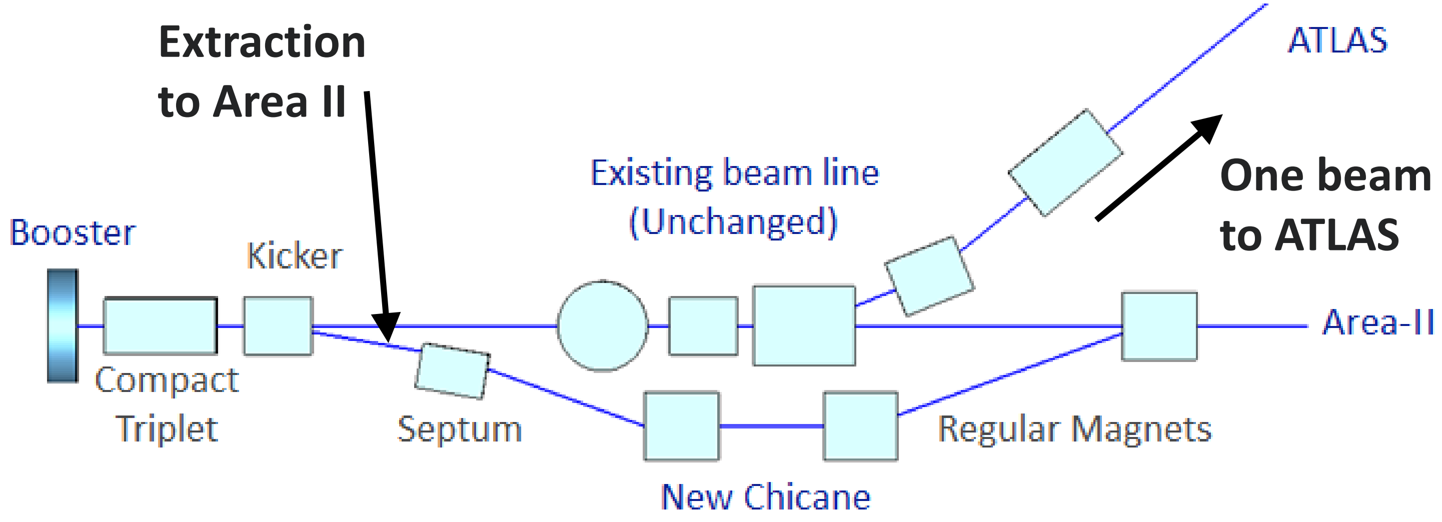


Pulsed E-Deflector

Achromatic LEBT includes 2 sextupoles

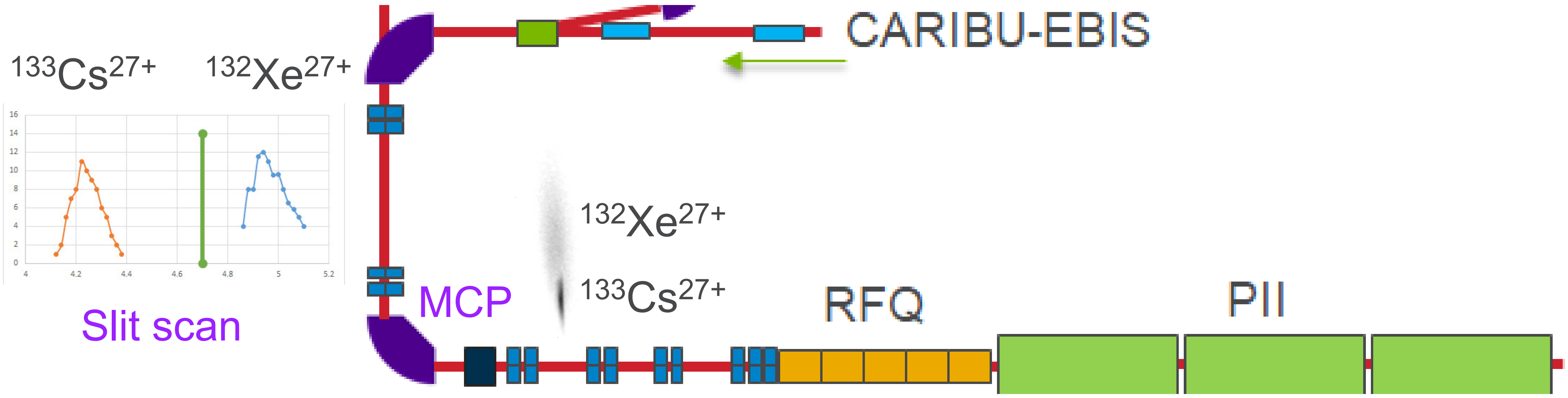
2) Extraction added after the Booster section

Extraction to Area II



One beam to ATLAS

Combining Two Beams - Recent Experiment

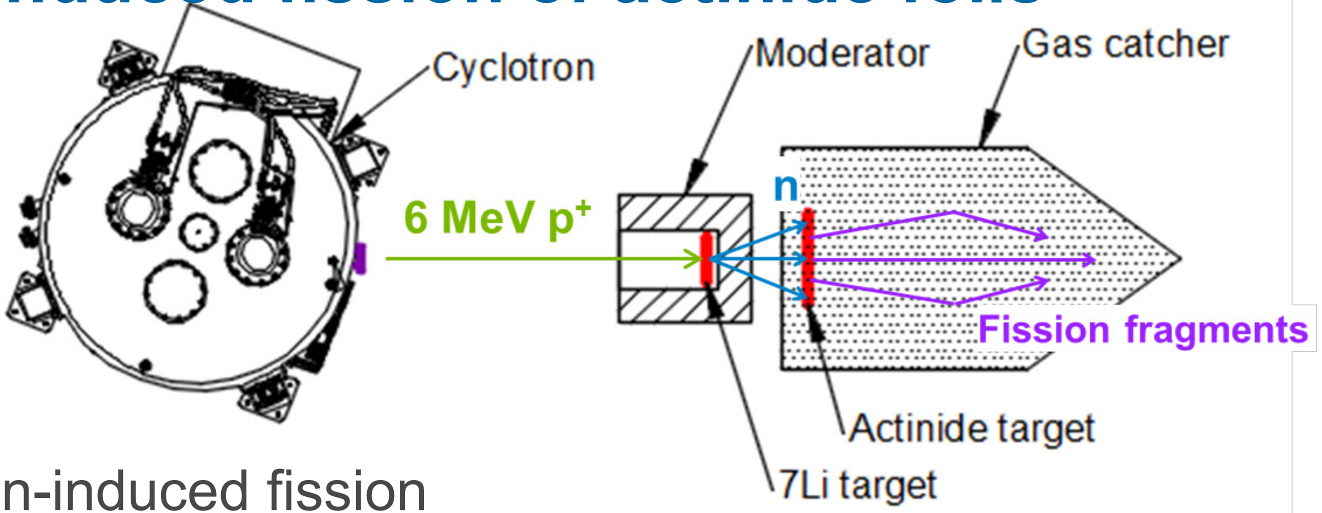


✓Since the ECR/EBIS combiner line is not available yet, the test was done using two EBIS beams: $^{133}Cs^{27+}$ and $^{132}Xe^{27+}$

✓Two beams successfully combined, injected and accelerated through RFQ, PII and Booster sections with ~ 70% total transmission

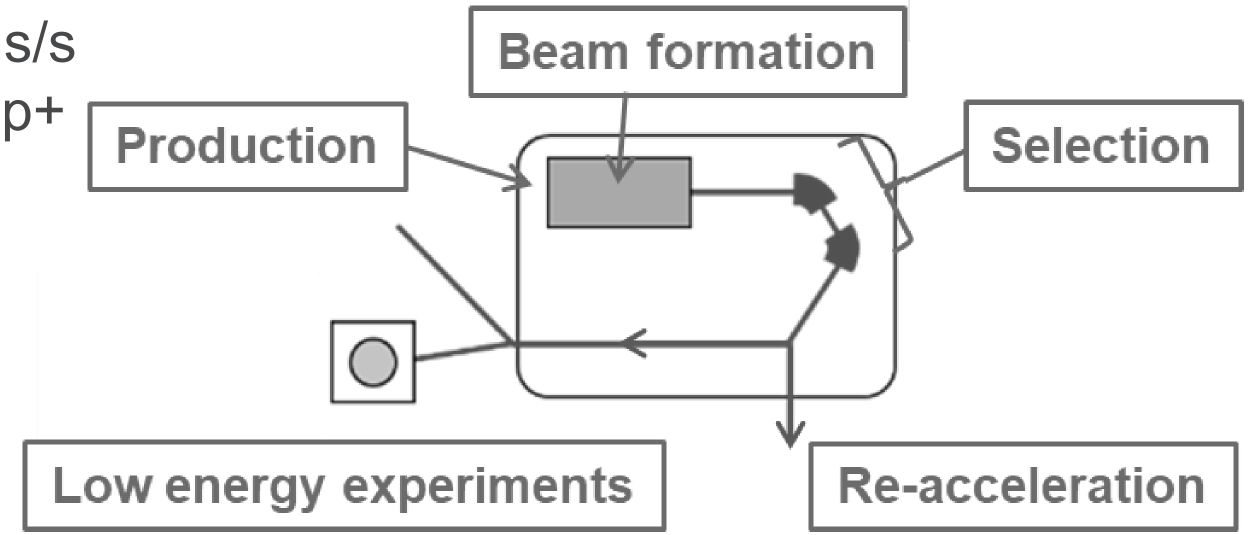
nuCARIBU PROJECT

n-induced fission of actinide foils



- n-induced fission
- ~1 x 10^9 fissions/s
- 6 MeV, 0.5 mA p+

- High purity He gas catcher
- Thermalizes fission fragments
- RF electrodes form beam



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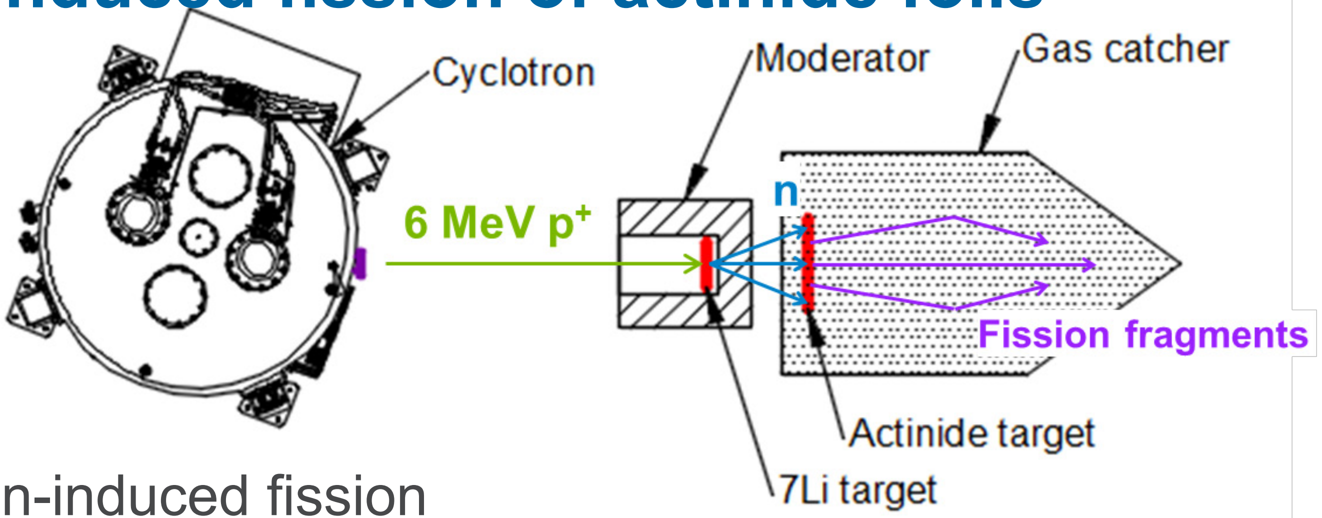
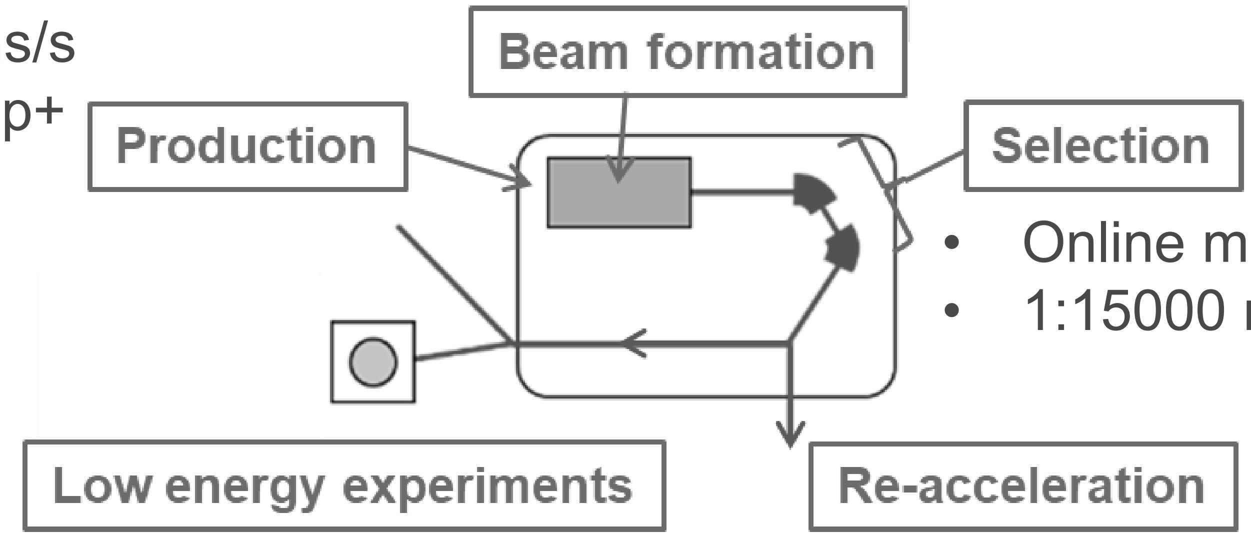


Goals
- x10 total intensity
- Reliability
- Safety
- Consistency

- High purity He gas catcher
- Thermalizes fission fragments
- RF electrodes form beam

- n-induced fission
- ~1 x 10^9 fissions/s
- 6 MeV, 0.5 mA p+



- Online magnetic separation
- 1:15000 resolution

[Courtesy C. Dickerson]

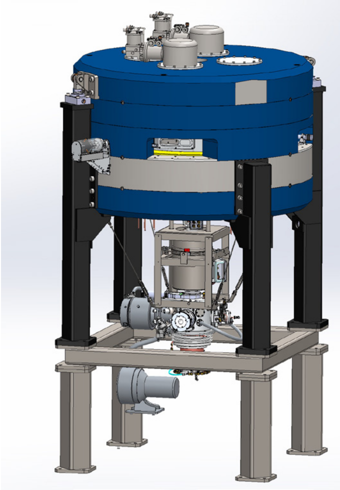
nuCARIBU CHALLENGES

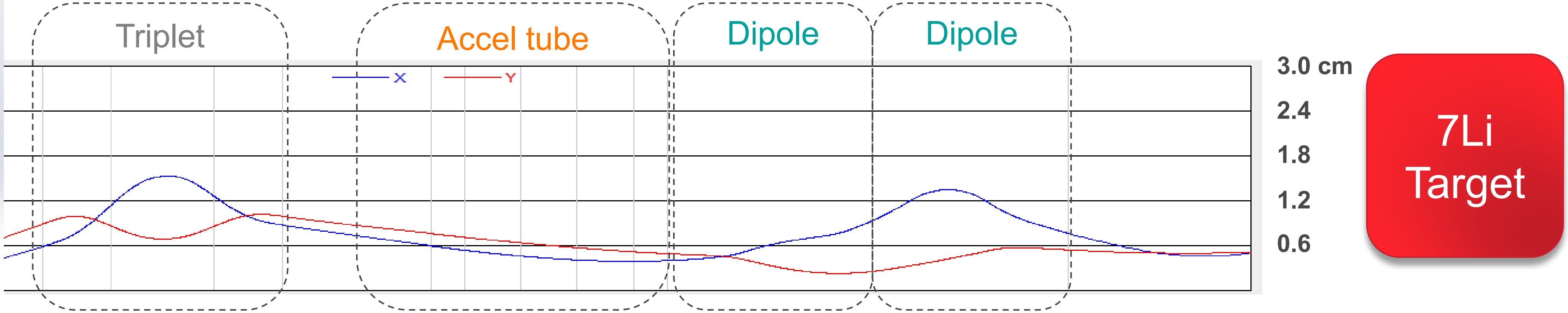
Optics

- Beam from cyclotron is much lower quality than typical ATLAS beams
  - $e_{x,y}$ 99%, normalized ≈ 25p mm-mrad
  - Energy: 6.13 MeV average
  - DE, 99% ≈ 1 MeV
- Minimize losses during transport to avoid radiation
- A chicane enables shielding of back-streaming neutrons

[Courtesy C. Dickerson]

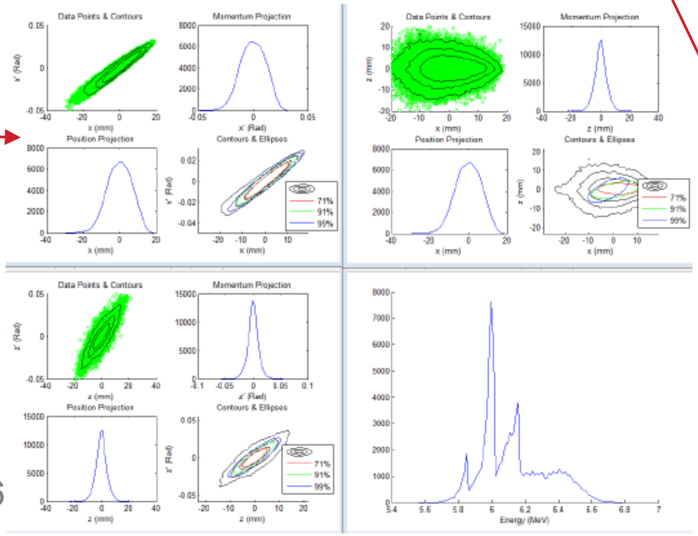
BEAMLINE – SIMULATION RESULTS

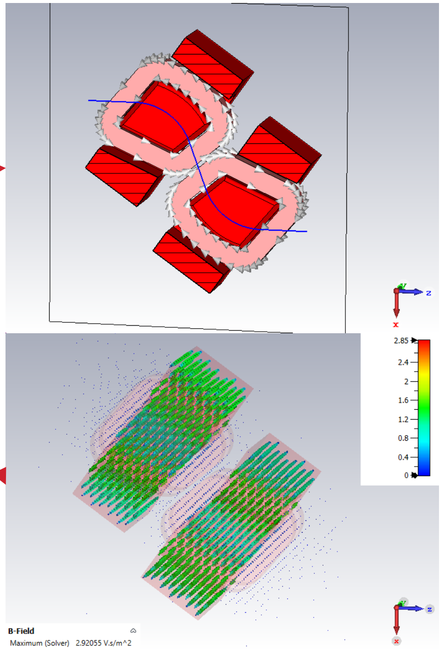




X and **Y** RMS radii

- Simulations performed with TRACK
- Chicane fields calculated and extracted from CST Studio
- Used extracted particles from cyclotron vendor simulations



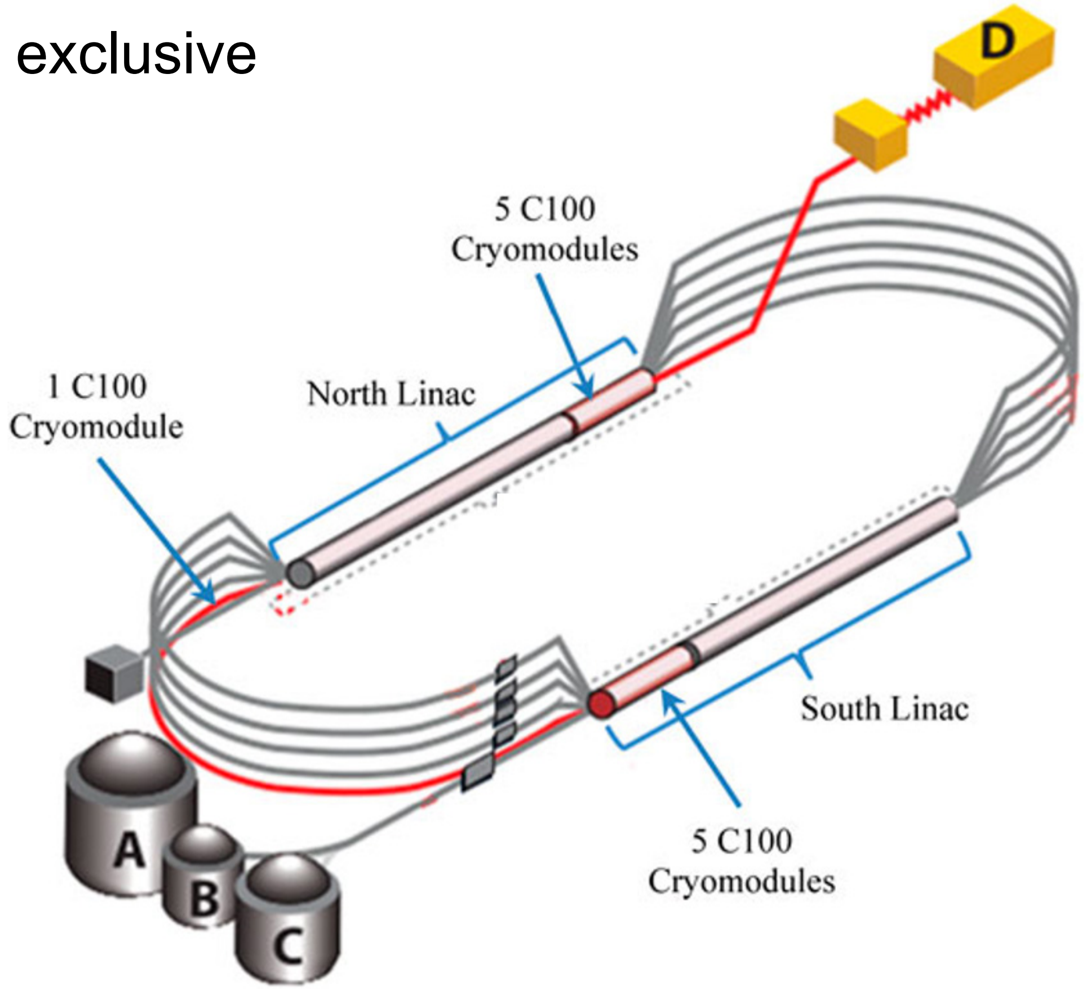


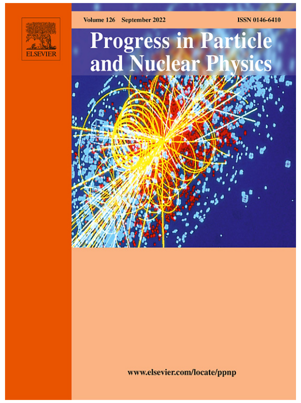
CEBAF upgrade options

- Positrons at CEBAF (Ce+BAF) and an energy upgrade are being considered for physics beyond the current 12 GeV program, for operation beyond ~2030
- The two options are not mutually exclusive

High duty factor/CW electron beam
1.1 GeV design per linac
Recirculating up to 5 passes (5.5)
4 experimental Halls
Polarized and unpolarized beams

Design energy of 11 GeV to Halls A, B, C; 12 GeV to Hall D

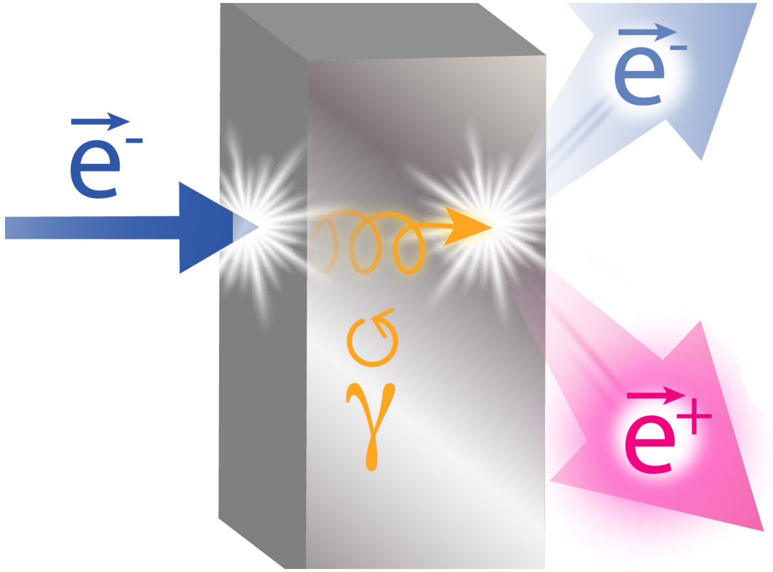


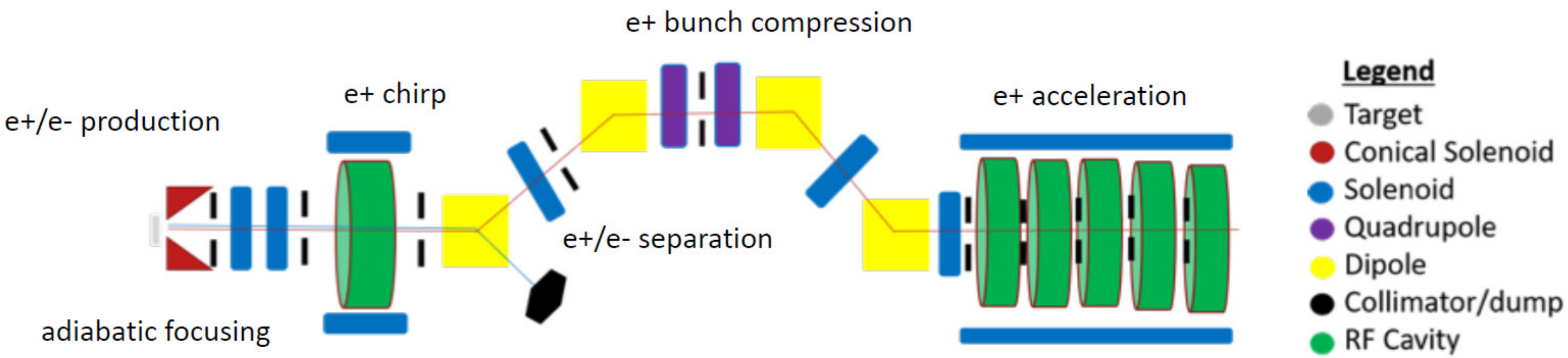


[https://doi.org/10.1016/j.ppnp.2022.103985]

CEBAF upgrade option 1: positron capability

- Opportunities to explore aspects of two photon exchange physics, nuclear structure, and more using both polarized and unpolarized positrons
- A new polarized positron injector based on the PEPPo method [Phys. Rev. Lett., **116**, 214801 (2016)]
- Beam dynamics issues include: positron capture at the source, transport to and in CEBAF, CEBAF acceptance limits

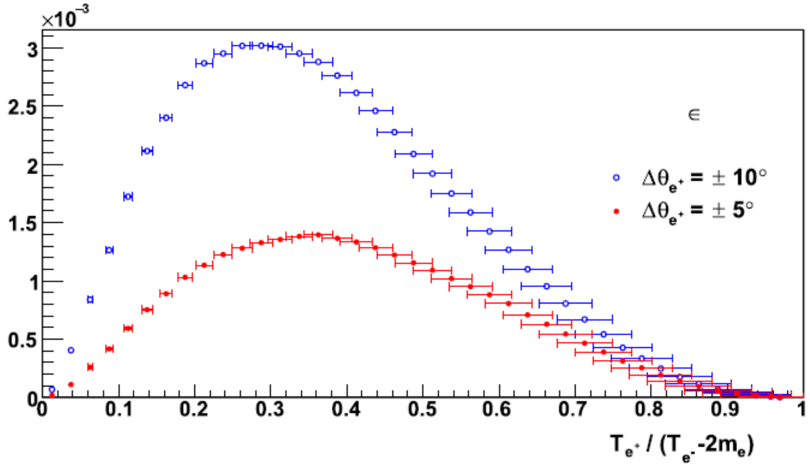




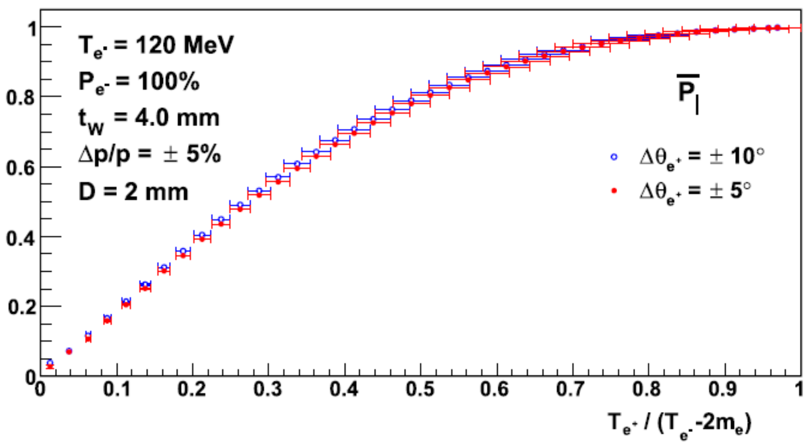
CEBAF upgrade option 1: positron capability

- Positron capture and manipulation: the positron production method creates a highly divergent positron beam
- The positron collection system must balance yield, polarization, and momentum
- Solenoid based systems that can be mimicked with angular and momentum acceptance cuts

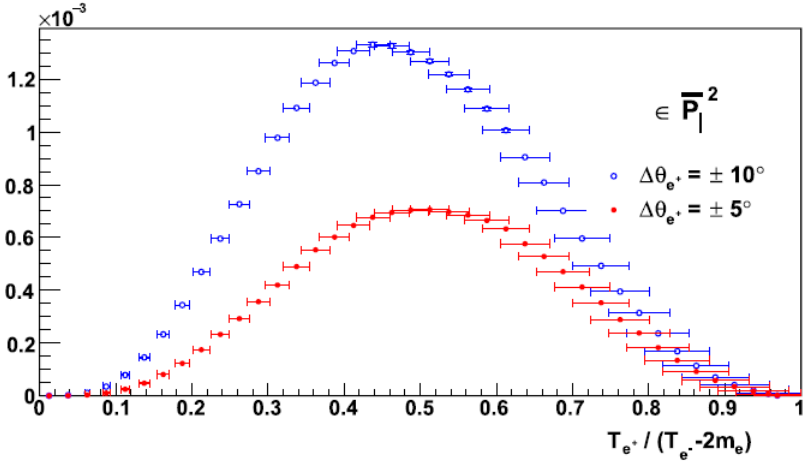
Yield



Polarization



FoM = Yield x Polarization^2

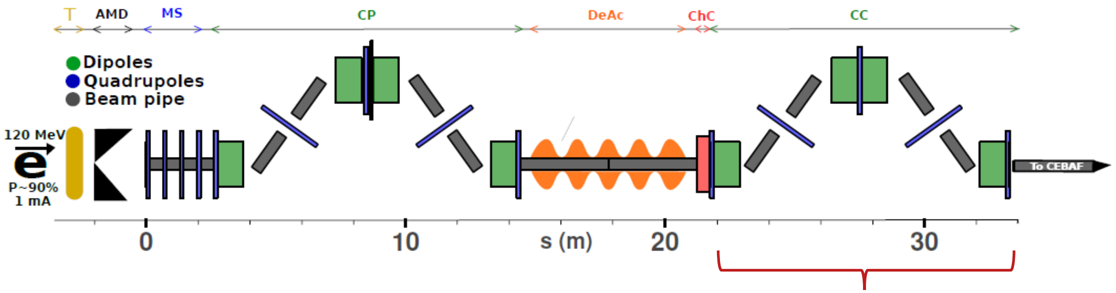


[Eur. Phys. J. A (2021) 57:261]

CEBAF upgrade option 1: positron capability

- Positron capture and manipulation: the positron production method creates a highly divergent positron beam
- Compression of positron bunch length for efficient acceleration – chicane design for desired compression, compression using CEBAF arcs

[doi:10.18429/JACoW-IPAC2022-MOPOTK012]



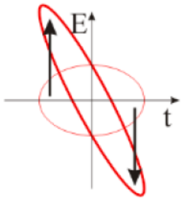
Compression chicane

- $\textbf{Compression factor} = \frac{Bunchlength_{z0}}{Bunchlength_{zf}}$

$$C = \frac{1}{1 + [R_{56} \times \kappa]}$$

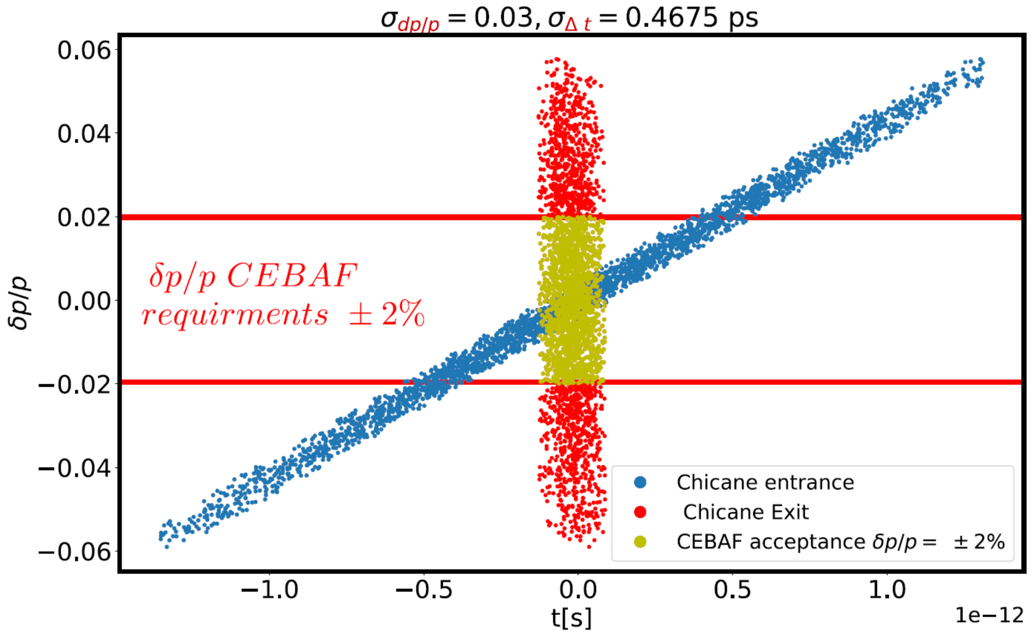
- **Using z & $\frac{\delta P}{P}$ space, we have:**

$$\kappa = \frac{d\delta_p}{dz} = \frac{-keV_0}{E0 + eV0\cos\phi}\sin\phi$$



- $R_{56} = -25\ cm$
- Chirp : $\kappa = 3.81\ m^{-1}$
- Full compresion factor : $C = \frac{1}{1+\kappa \times R_{56}} = 23.3$

[S. Habet]



CEBAF upgrade option 1: positron capability

- Positron transport in CEBAF and acceptance: synchrotron radiation-induced emittance growth

Adiabatic damping

Synch. rad. growth

	Electrons			Positrons		
Area	δp/p [x 10^{-3}]	ε_x [nm]	ε_y [nm]	δp/p [x 10^{-3}]	ε_x [nm]	ε_y [nm]
Chicane	0.5	4.00	4.00	10	500	500
ARC1	0.05	0.41	0.41	1	50	50
ARC2	0.03	0.26	0.23	0.53	26.8	26.6
ARC3	0.035	0.22	0.21	0.36	19	18.6
ARC4	0.044	0.21	0.24	0.27	14.5	13.8
ARC5	0.060	0.33	0.25	0.22	12	11.2
ARC6	0.090	0.58	0.31	0.19	10	9.5
ARC7	0.104	0.79	0.44	0.17	8.9	8.35
ARC8	0.133	1.21	0.57	0.16	8.36	7.38
ARC9	0.167	2.09	0.64	0.16	8.4	6.8
MYAAT01	--	--	--	0.18	9.13	6.19
ARC10	0.194	2.97	0.95	--	--	--
Hall D	0.18	2.70	1.03	--	--	--

$$\Delta E = \frac{2\pi}{3} r_0\, mc^2 \,\frac{\gamma^4}{\rho}$$

$$\Delta\epsilon_N = \frac{2\pi}{3} C_q r_0 < H > \frac{\gamma^6}{\rho^2},$$

$$\frac{\Delta\epsilon_E^2}{E^2} = \frac{2\pi}{3} C_q r_0 \frac{\gamma^5}{\rho^2},$$

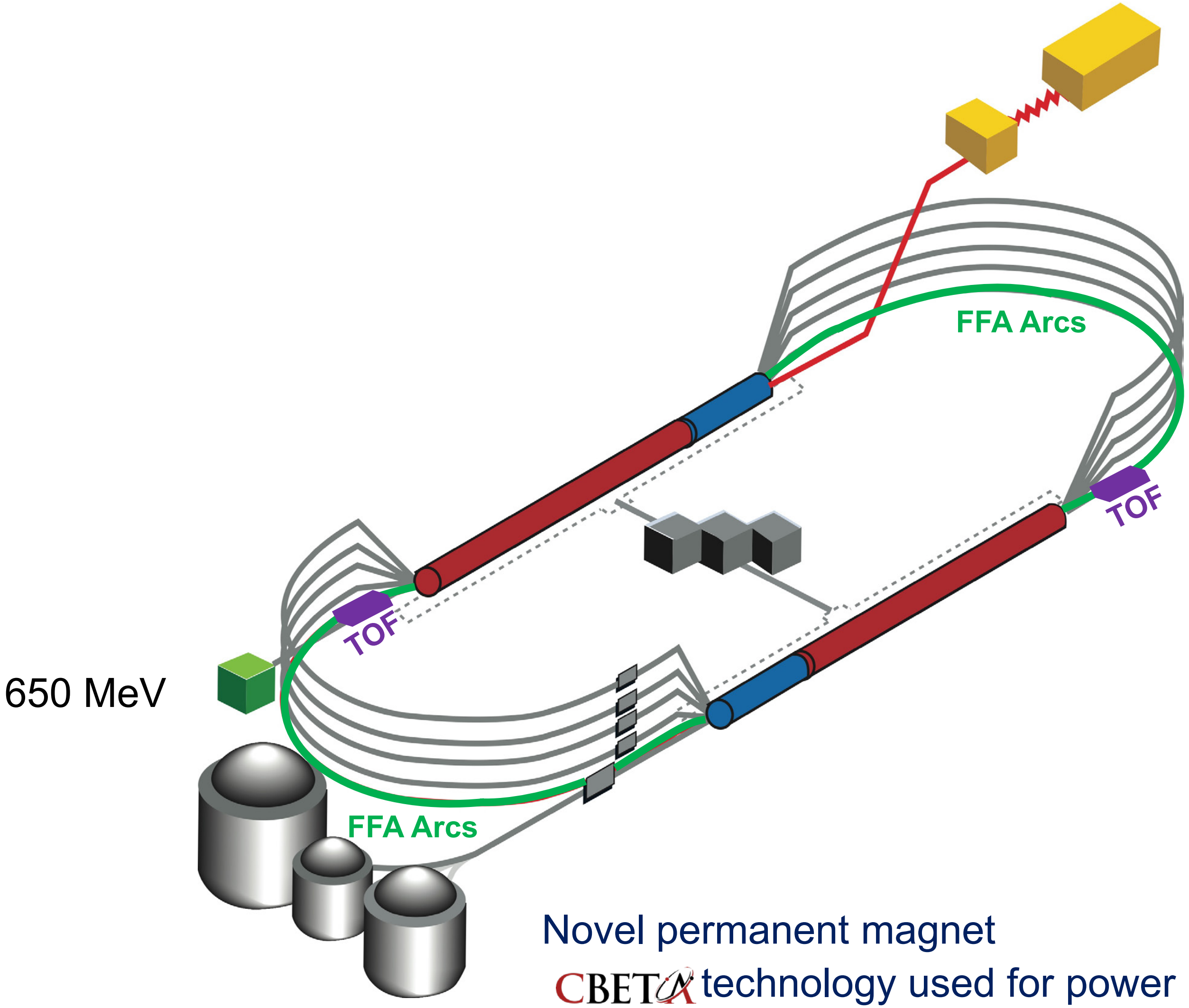
$$H_x = \gamma_x D_x^2 + 2\alpha_x D_x D'_x + \beta_x D'^2_x$$

$$C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc}$$

[JLAB-TN-21-043]

CEBAF upgrade option 2: energy upgrade to 22-24 GeV

- Energy upgrade from 12 GeV to 22-24 GeV is being explored using multiple passes in new fixed field, alternating-gradient (FFA) arcs
- Adiabatic, non-scaling FFA arcs replace high energy CEBAF arcs, allowing for more recirculation → higher energy
- A new 650 MeV electron injector
- Beam dynamics issues include: beam optics in FFA lattice, multi-pass linac optics, synchrotron radiation impact on beam quality at higher energy

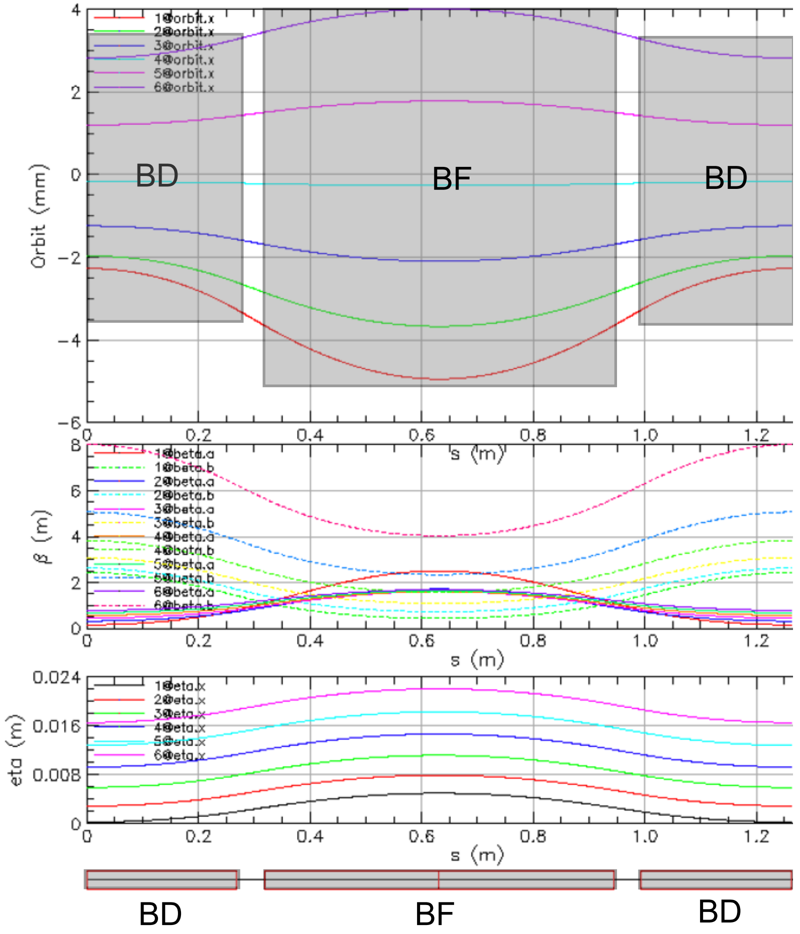


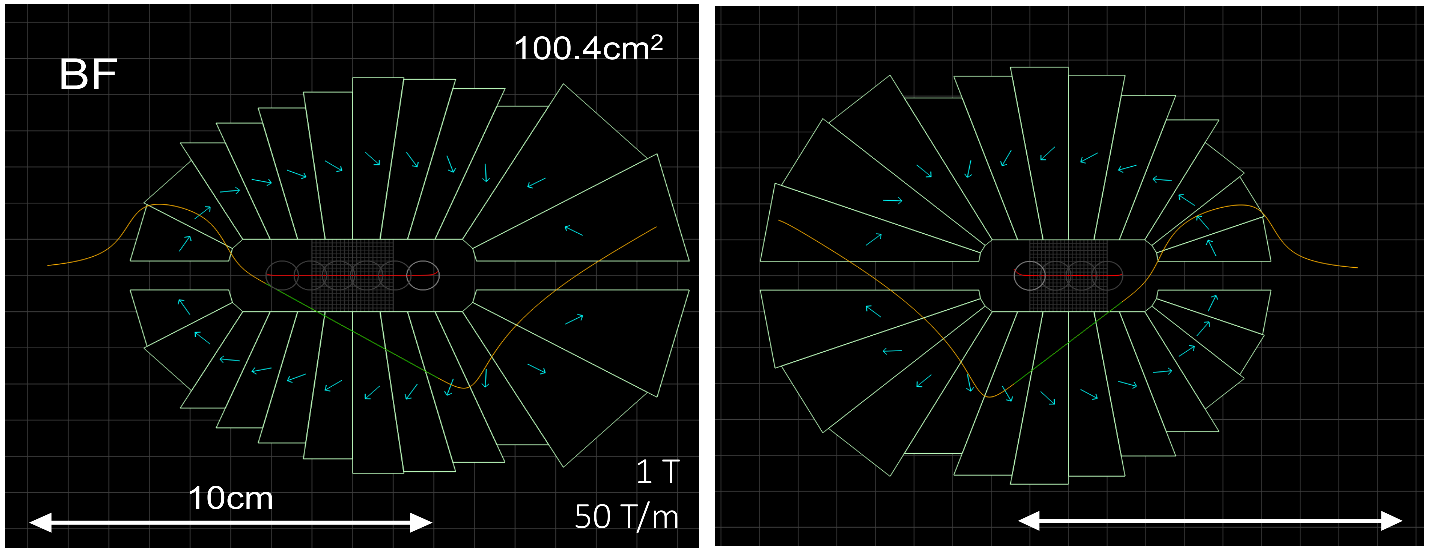
Novel permanent magnet CBETA technology used for power and cost savings

[A. Bogacz and FFA@CEBAF Working Group]

CEBAF upgrade option 2: energy upgrade to 22-24 GeV

- FFA lattice optics: compact FFA FODO cell with large momentum acceptance and combined function magnets → multiple energy beams can be transported through the same string of permanent magnets



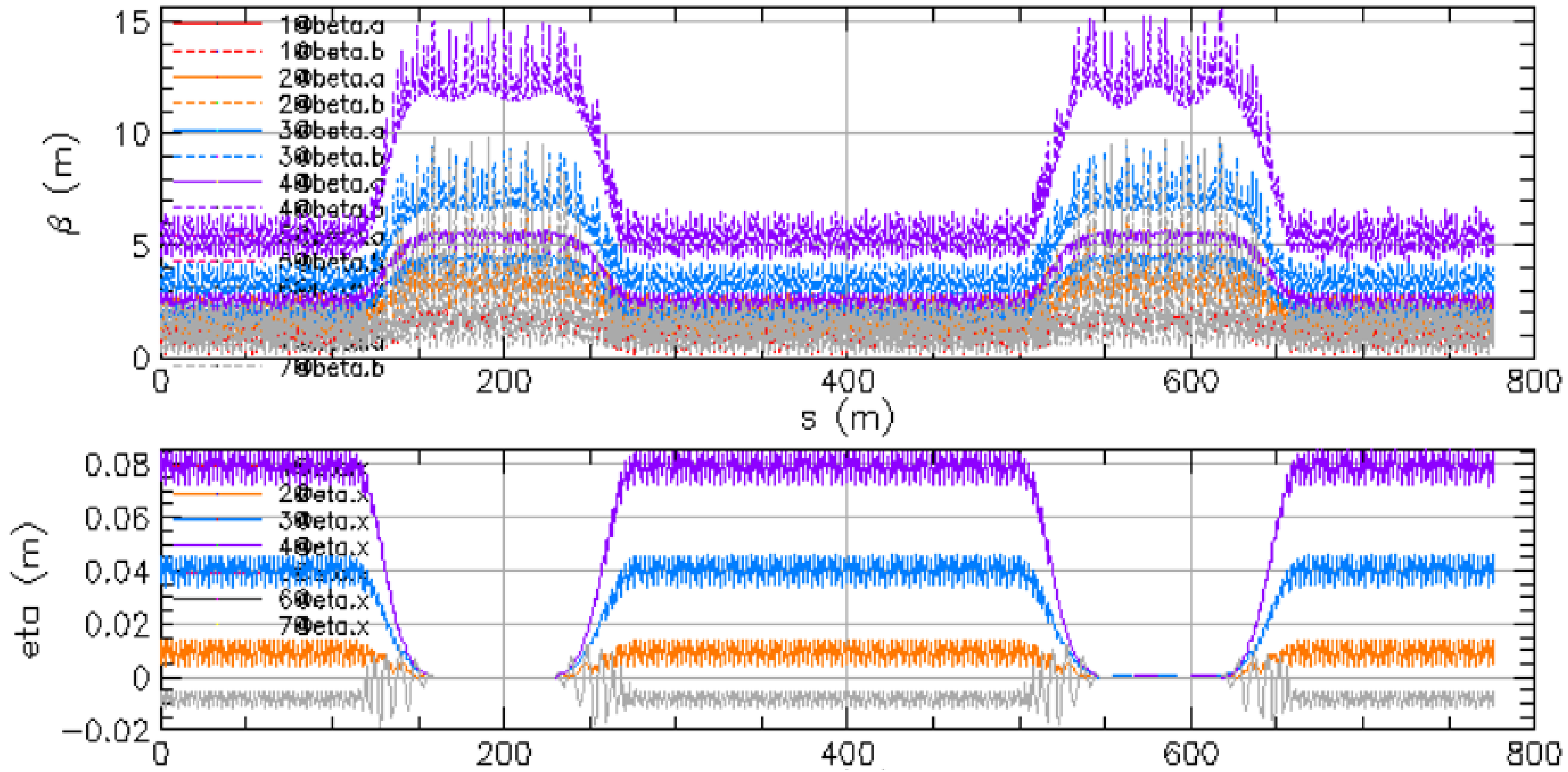


CBETA magnets: from 38cm² to 78cm²

[S. Brooks]

CEBAF upgrade option 2: energy upgrade to 22-24 GeV

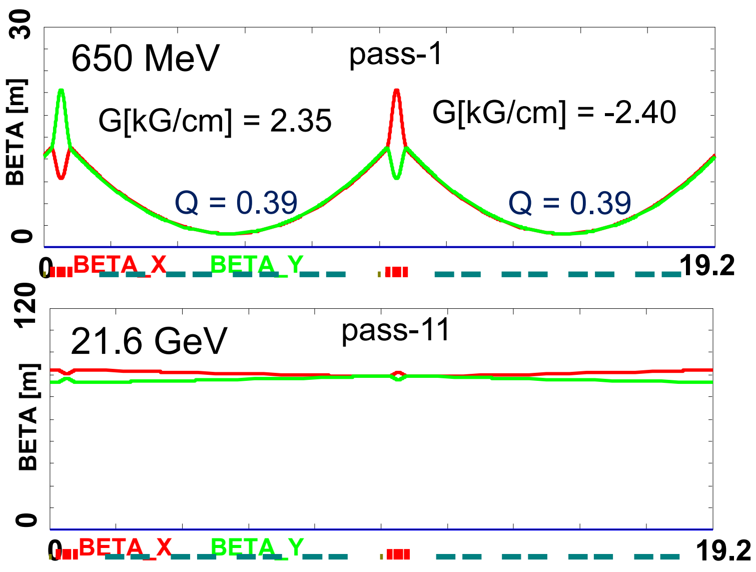
- FFA lattice optics



Optical functions for the entire 10-22 GeV (6-pass) FFA racetrack

CEBAF upgrade option 2: energy upgrade to 22-24 GeV

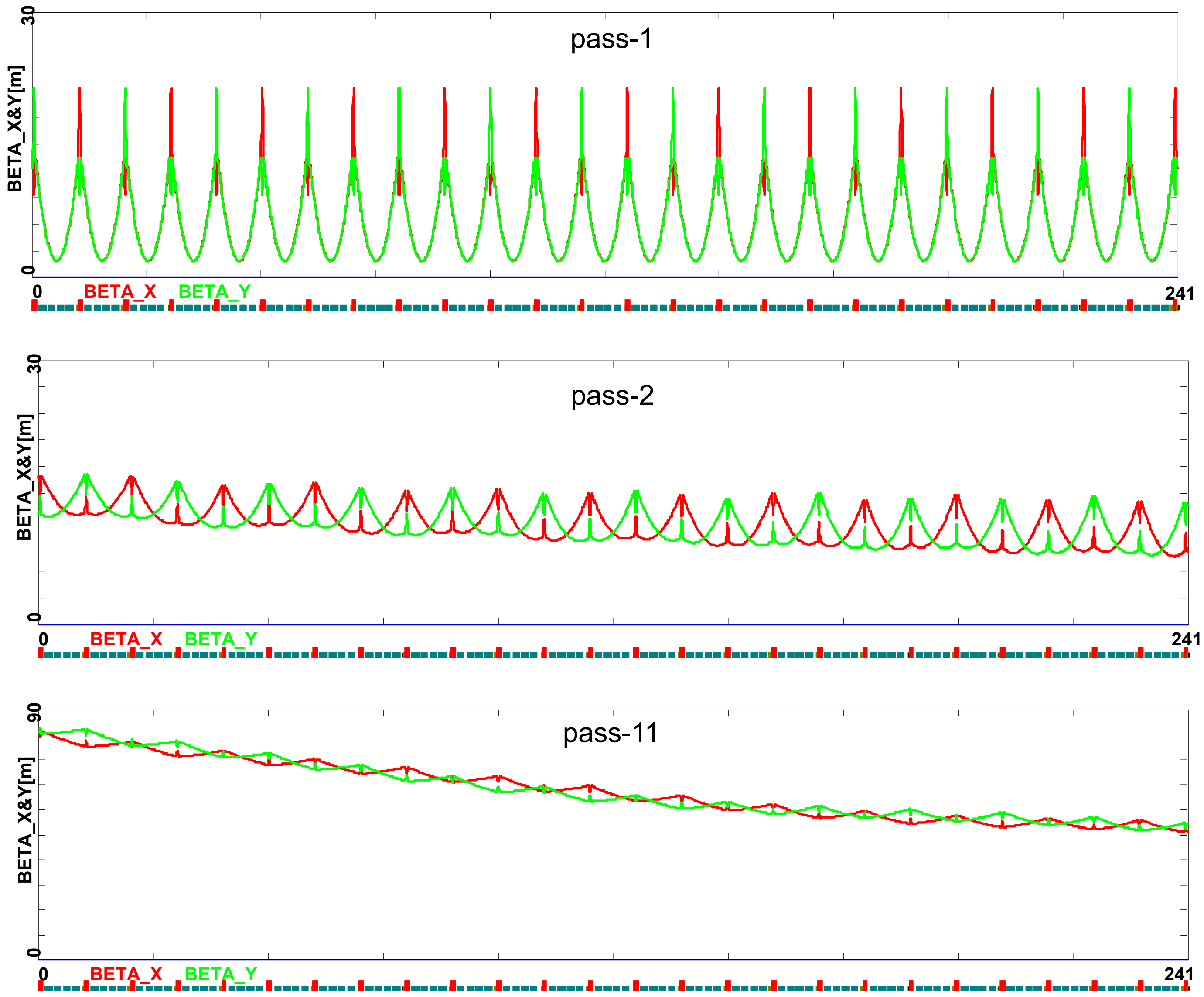
- Multi-pass linac optics: current linac optics are periodic for lowest energy pass, with large beta-beating for higher passes
- Incompatible with small beta functions in FFA arcs
- New ‘twin cell’ triplet for the linacs:



650 MeV

2.83 GeV

21.6 GeV



CEBAF upgrade option 2: energy upgrade to 22-24 GeV

- Synchrotron radiation effects at higher energy: present status

	E [GeV]	Fill factor	ρ [m]	ΔE [MeV]	<H> [m]	$\Delta\epsilon_N$ [m rad]	$\Delta\sigma_{\Delta E/E}$
arc 1	1.2	0.063	5.1	0	1.8E-01	2.8E-09	2.6E-06
arc 2	2.3	0.127	10.2	0	1.8E-01	3.6E-08	8.9E-06
arc 3	3.4	0.126	10.2	1	1.8E-01	3.7E-07	2.6E-05
arc 4	4.5	0.253	20.4	1	1.8E-01	8.2E-07	4.3E-05
arc 5	5.6	0.253	20.4	2	1.8E-01	1.6E-06	7.1E-05
arc 6	6.7	0.253	20.4	4	9.0E-02	4.0E-06	1.2E-04
arc 7	7.7	0.379	30.6	5	9.0E-02	6.7E-06	1.6E-04
arc 8	8.8	0.379	30.6	9	9.0E-02	1.2E-05	2.2E-04
FFA 9	9.91	0.876	70.6	6	4.0E-03	1.3E-05	2.6E-04
FFA 10	11.00	0.876	70.6	9	4.0E-03	1.3E-05	3.0E-04
FFA 11	12.08	0.876	70.6	13	4.0E-03	1.3E-05	3.6E-04
FFA 12	13.15	0.876	70.6	19	4.0E-03	1.4E-05	4.3E-04
FFA 13	14.22	0.876	70.6	26	4.0E-03	1.4E-05	5.2E-04
FFA 14	15.29	0.876	70.6	34	4.0E-03	1.6E-05	6.2E-04
FFA 15	16.34	0.876	70.6	45	4.0E-03	1.8E-05	7.5E-04
FFA 16	17.39	0.876	70.6	57	4.0E-03	2.1E-05	8.9E-04
FFA 17	18.42	0.876	70.6	72	4.0E-03	2.4E-05	1.1E-03
FFA 18	19.44	0.876	70.6	89	4.0E-03	3.0E-05	1.2E-03
FFA 19	20.44	0.876	70.6	109	4.0E-03	3.7E-05	1.5E-03
FFA 20	21.42	0.876	70.6	132	4.0E-03	4.7E-05	1.7E-03
FFA 21	22.38	0.876	70.6	157	4.0E-03	6.0E-05	2.0E-03
FFA 22	23.31	0.876	70.6	185	4.0E-03	7.6E-05	2.3E-03

$$\Delta E = \frac{2\pi}{3} r_0 \, mc^2 \, \frac{\gamma^4}{\rho}$$

$$\Delta \epsilon_N = \frac{2\pi}{3} C_q r_0 < H > \frac{\gamma^6}{\rho^2} ,$$

$$\frac{\Delta \epsilon_E^2}{E^2} = \frac{2\pi}{3} C_q r_0 \, \frac{\gamma^5}{\rho^2} ,$$

$$H_x = g_x D_x^2 + 2a_x D_x D_x' + b_x D_x'^2$$

$$C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc}$$

Geometric Arc Radius [m]	80.6

Final Energy [GeV]	24.2
Total Energy Loss [MeV]	976

CEBAF upgrade option 2: energy upgrade to 22-24 GeV

- Synchrotron radiation effects at higher energy: present status

Growth!

	E [GeV]	Fill factor	r [m]	DE [MeV]	<H> [m]	De_N [m rad]	$Ds_{DE/E}$
arc 1	1.2	0.063	5.1	0	1.8E-01	2.8E-09	2.6E-06
arc 2	2.3	0.127	10.2	0	1.8E-01	3.6E-08	8.9E-06
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arc 6	6.7	0.253	20.4	4	9.0E-02	4.0E-06	1.2E-04
arc 7	7.7	0.379	30.6	5	9.0E-02	6.7E-06	1.6E-04
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FFA 9	9.91	0.876	70.6	6	4.0E-03	1.3E-05	2.6E-04
FFA 10	11.00	0.876	70.6	9	4.0E-03	1.3E-05	3.0E-04
FFA 11	12.08	0.876	70.6	13	4.0E-03	1.3E-05	3.6E-04
FFA 12	13.15	0.876	70.6	19	4.0E-03	1.4E-05	4.3E-04
FFA 13	14.22	0.876	70.6	26	4.0E-03	1.4E-05	5.2E-04
FFA 14	15.29	0.876	70.6	34	4.0E-03	1.6E-05	6.2E-04
FFA 15	16.34	0.876	70.6	45	4.0E-03	1.8E-05	7.5E-04
FFA 16	17.39	0.876	70.6	57	4.0E-03	2.1E-05	8.9E-04
FFA 17	18.42	0.876	70.6	72	4.0E-03	2.4E-05	1.1E-03
FFA 18	19.44	0.876	70.6	89	4.0E-03	3.0E-05	1.2E-03
FFA 19	20.44	0.876	70.6	109	4.0E-03	3.7E-05	1.5E-03
FFA 20	21.42	0.876	70.6	132	4.0E-03	4.7E-05	1.7E-03
FFA 21	22.38	0.876	70.6	157	4.0E-03	6.0E-05	2.0E-03
FFA 22	23.31	0.876	70.6	185	4.0E-03	7.6E-05	2.3E-03

$$\Delta E = \frac{2\pi}{3} r_0\, mc^2 \frac{\gamma^4}{\rho}$$

$$\Delta\epsilon_N = \frac{2\pi}{3} C_q r_0 < H > \frac{\gamma^6}{\rho^2},$$

$$\frac{\Delta\epsilon_E^2}{E^2} = \frac{2\pi}{3} C_q r_0 \frac{\gamma^5}{\rho^2},$$

$$H_x = g_x D_x^2 + 2a_x D_x D_x^{'} + b_x D_x^{'2}$$

$$C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc}$$

Geometric Arc Radius [m]	80.6

Final Energy [GeV]	24.2
Total Energy Loss [MeV]	976

Optimization in progress

Summary

- Upgrades to current nuclear physics accelerator facilities extend science programs beyond present capabilities
- ATLAS multi-user upgrade and nuCARIBU are approved upgrades to ATLAS at ANL
- JLab is considering positron capability and energy upgrade to CEBAF for operation beyond 2030
- Beam dynamics topics are currently being explored for proposed options at JLab

Thanks for your attention!