Accelerator Physics Lessons from CBETA

The First Multi-turn SRF ERL

Kirsten Deitrick

Monday, August 8, 2022

NAPAC 2022

Outline

- Introduction to CBETA
- Design Concepts
- Commissioning Results
- Green Accelerators
- Applications
- CBETA ICS
- FFA@CEBAF
- Conclusion

DOI numbers throughout,

References at the end

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Material taken from previous talks by

K. Deitrick, A. Bartnik, and C. Gulliford

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References at the end

CBETA Collaboration

D. Trbojevic[1], G. Hoffstaetter[2], R. Michnoff[1], N. Banerjee[2], J. Barley[2], A. Bartnik[2], I. Bazarov[2], J.S. Berg[1], L. Borak[1], S. Brooks[1], D. Burke[2], J. Crittenden[2], J. Crone[3], L. Cultrera[2], K. Deitrick[2], J. Dobbins[2], C. Franck[2], R. Gallagher[2], C. Gulliford[2], B. Heltsley[2], R. Hulsart[1], J. Jones[3], D. Jusic[2], R. Kaplan[2], D. J. Kelliher[3], G. Mahler[1], F. Meot[1], V. Kostroun[2], B. Kuske[4], Y. Li[2], M. Liepe[2], W. Lou[2], M. McAteer[4], T. Miyajima[5], K. Ming[5], B. Muratori[3], S. Peggs[1], P. Quigley[2], J. Renta[1], T. Roser[1], D. Sabol[2], D. Sagan[2], J. Sears[2], C. Shore[2], E. Smith[2], K. Smolenski[2], C. Stoll[1], S. Thomas[1], S. Trabocchi[1], N. Tsoupas[1], J. Tuozzollo[1], V. Veshcherevich[2], J. Völker[4], D. Widger[2], H. Witte[1]

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BROOKHAVEN NATIONAL LABORATORY

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

UKRI Science and Technology Facilities Council

HZB Helmholtz Zentrum Berlin

KEK

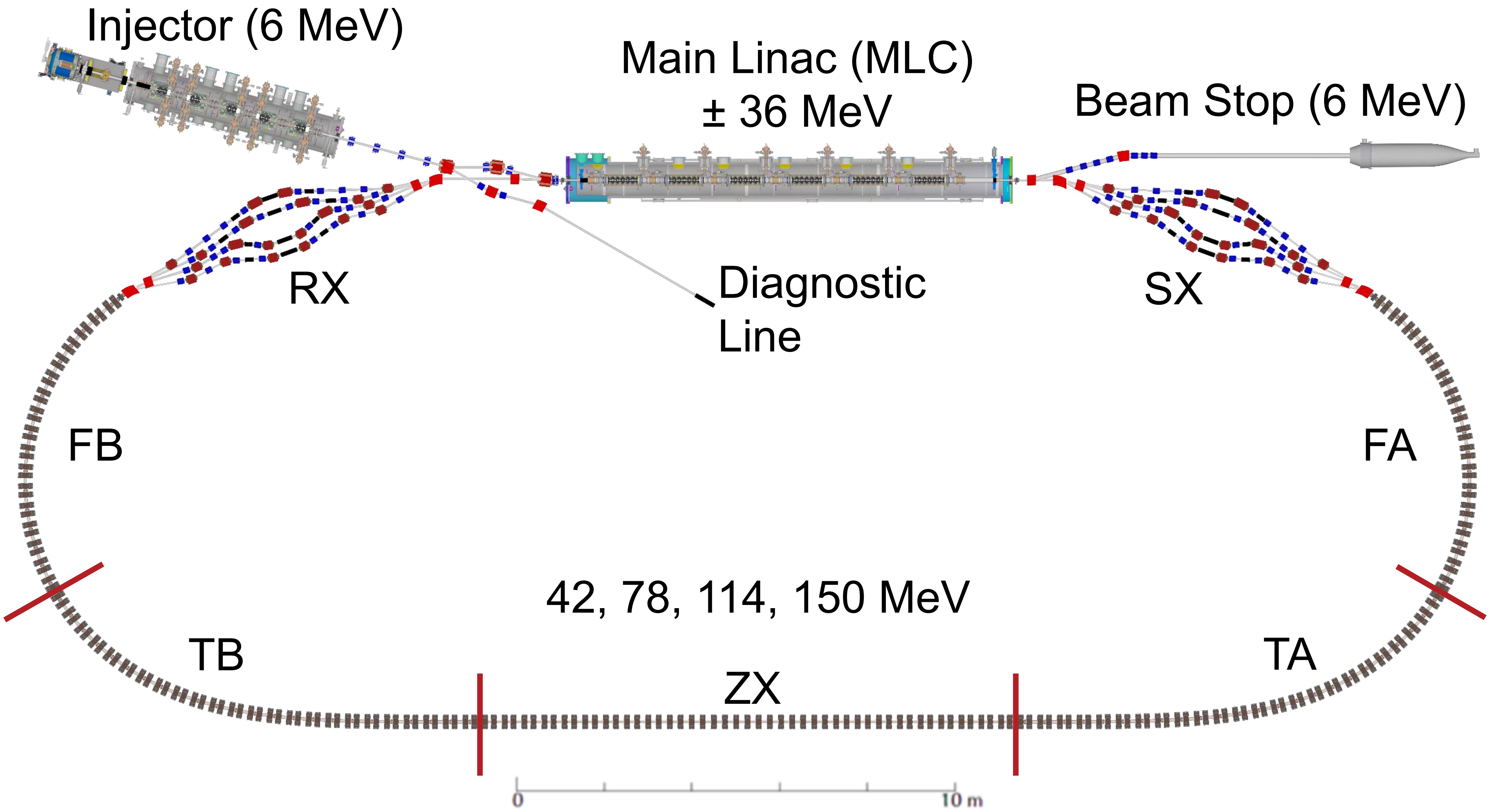
This project was supported by NSF award DMR0807731, DOE grant DE-AC02-76F00515, and NYSERDA agreement number 102192

Introduction to CBETA

- CBETA stands for Cornell-BNL ERL Test Accelerator
- Multi-turn SRF Energy Recovery Linac (ERL) utilizing a Fixed Field Alternating-gradient (FFA) permanent magnet return loop
  - Configuration of 1 - 4 turns with a maximum energy of 150 MeV
- FFA return loop has a wide energy acceptance – all 4 energies in the same pipe
- ERLs are characterized by the acceleration and deceleration of a bunch with the same SRF linac; the energy recovered by the deceleration is used to accelerate subsequent bunches

DOI: 10.48550/arXiv.1706.04245

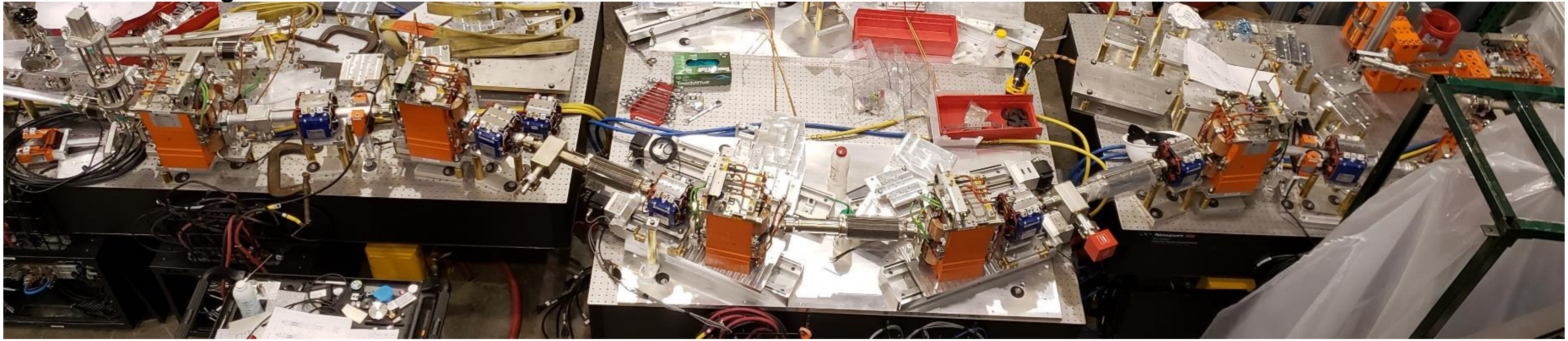
CBETA: Four-Turn Configuration



Design Concepts: Splitter Lines

- SX section has four lines (S1, S2, S3, S4) of increasing energy; similar set up in RX section
- Each line in SX and RX sections provides control of
  - Path length, using sliding joints
  - Twiss parameters / dispersion / dispersion prime / orbit

S1, 1-turn configuration



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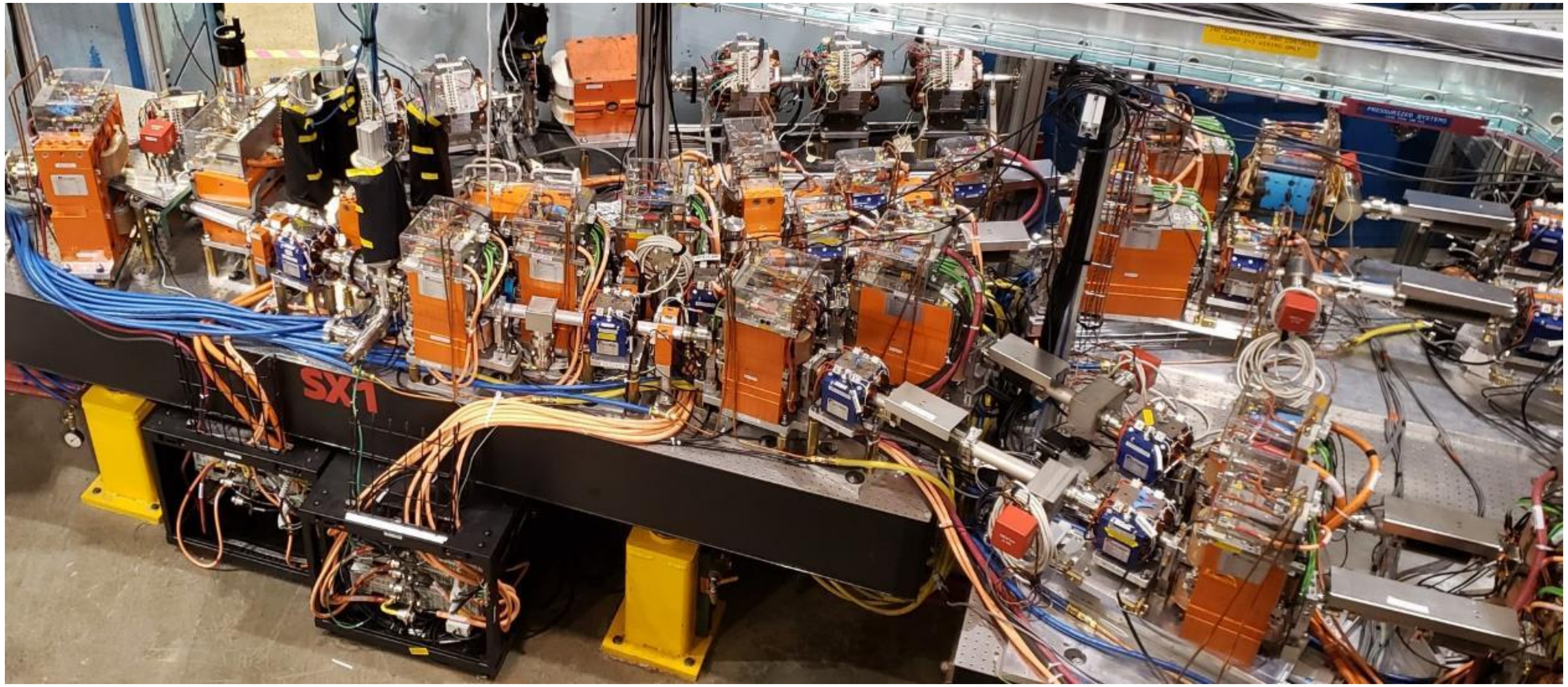

Front half of SX,
4-turn configuration

DOI: 10.48550/arXiv.1706.04245

Design Concepts: FFA Return Loop

- Non-scaling, linear gradient FFA made of permanent Halbach magnets
- Common transport for 4 energies and 7 beams simultaneously
- Arc type of FFA cell in FA/FB sections, straight type of FFA cell in ZX section
- TA/TB sections serve as transitions

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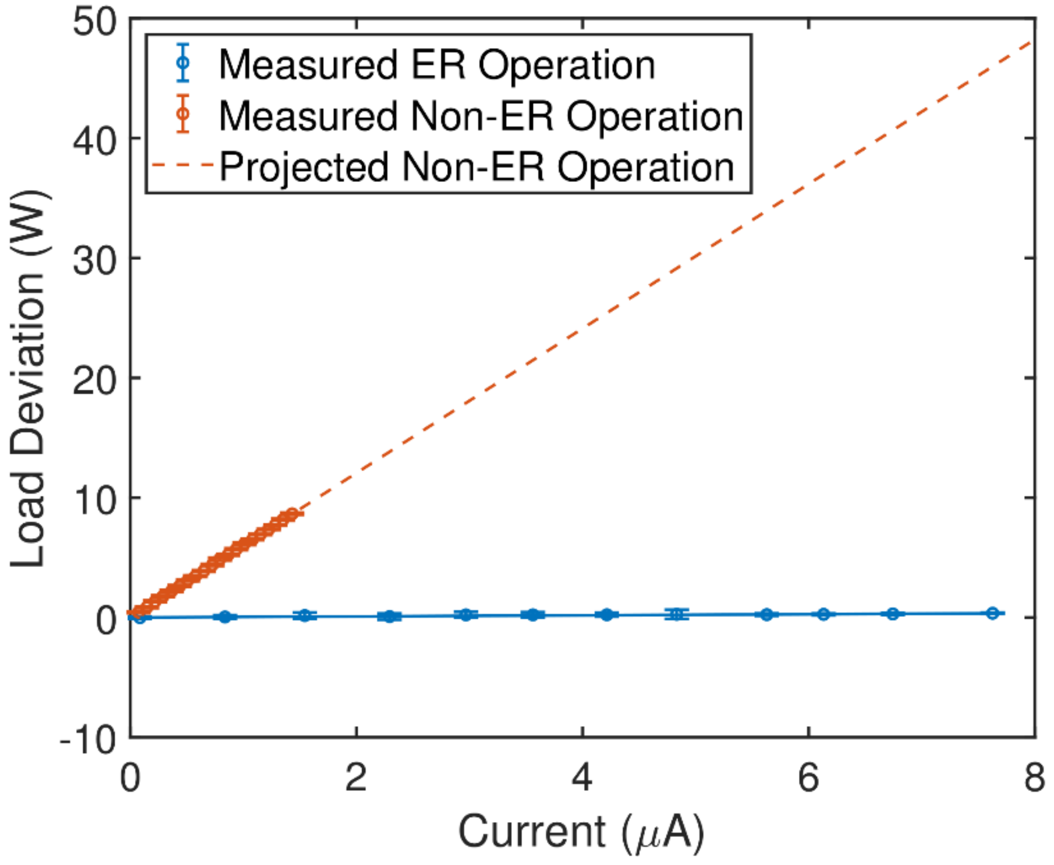
Commissioning Results: One-Turn Energy Recovery Efficiency

- Rough approximation:
  Total RF load = RF load due to cavity field + RF load due to beam
- Beam current changes is caused by changing RF load due to beam
- Load deviation ≈ beam loading
- Perfect energy recovery → no beam loading
- 99.4% one-turn power balance
- 99.9 – 101% per cavity ER efficiency

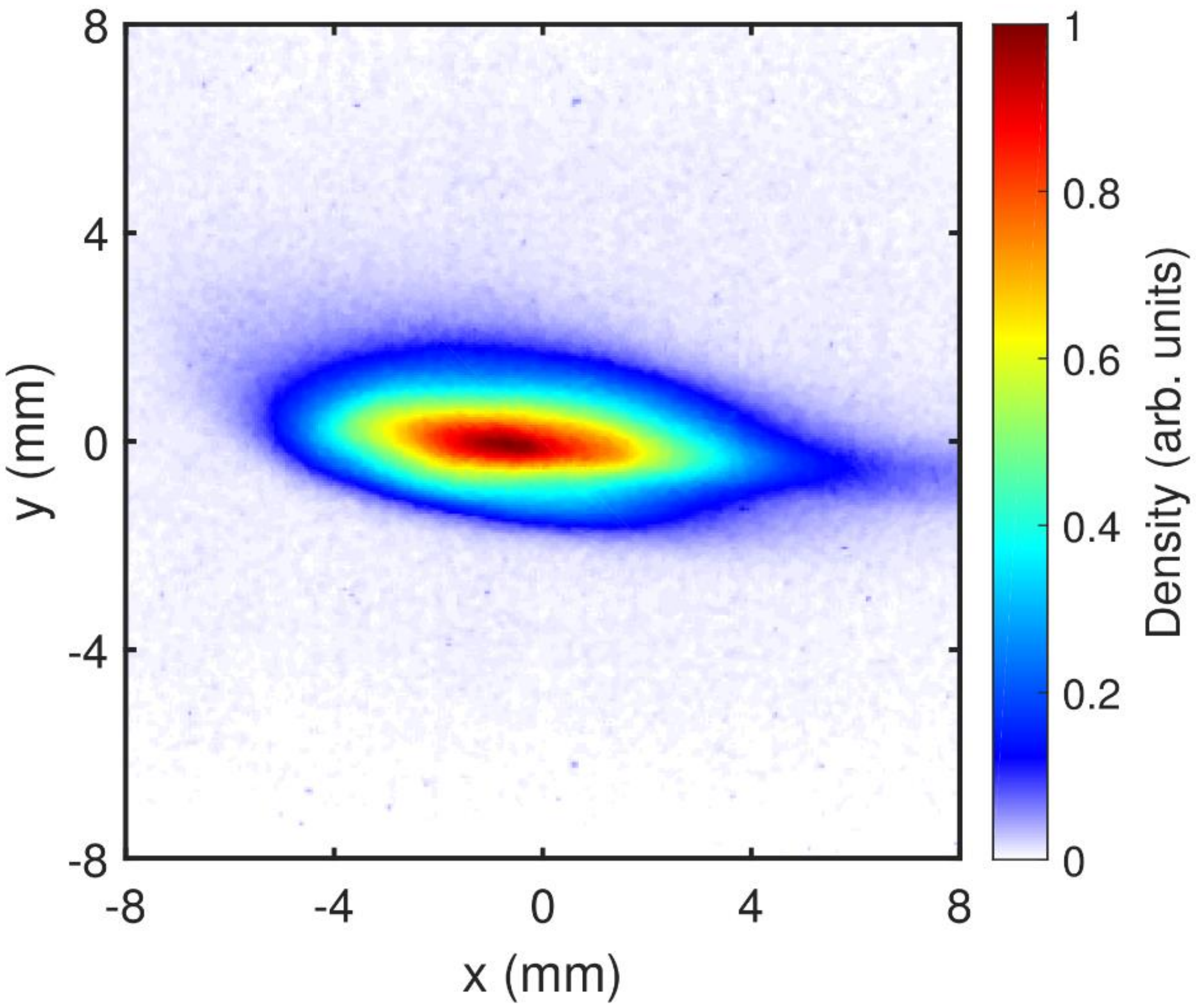


DOI: 10.1103/PhysRevAccelBeams.24.010101

Commissioning Results: Four-Turn Energy Recovery

Multi-turn energy recovery achieved on December 24, 2019!

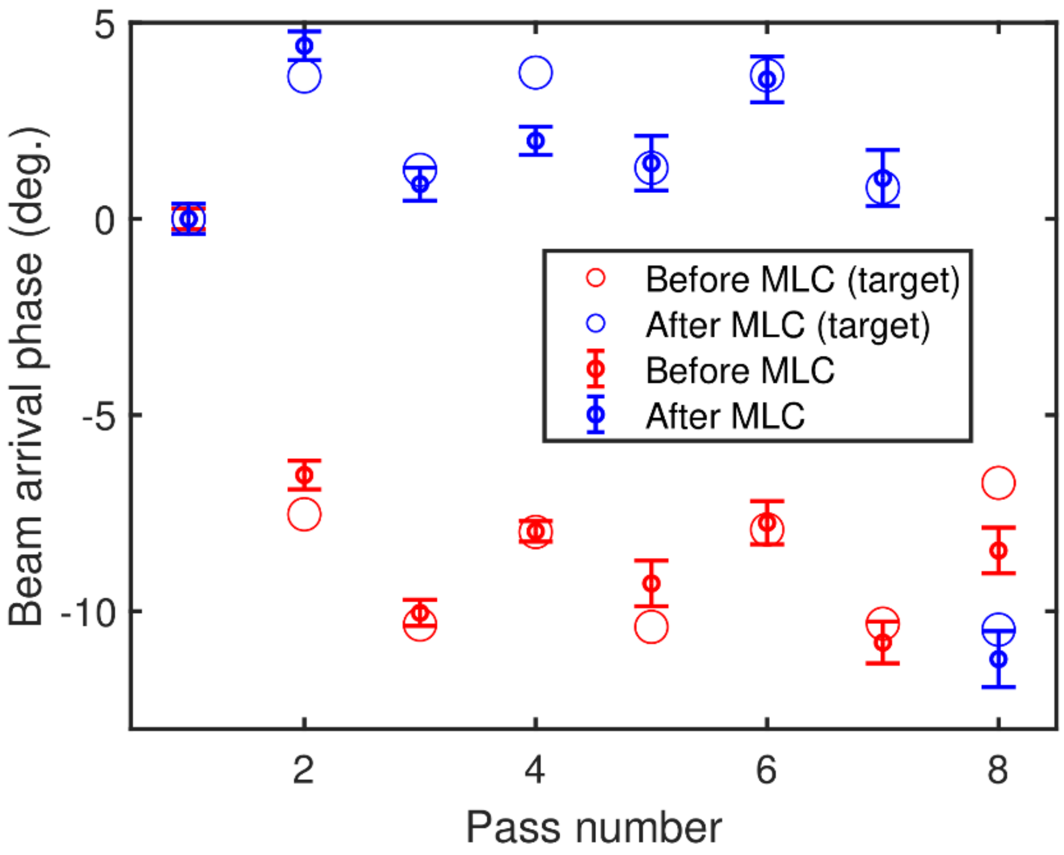
Beam on the first viewscreen in the beam stop line



DOI: 10.1103/PhysRevLett.125.044803

Commissioning Results: Four-Turn Energy Recovery

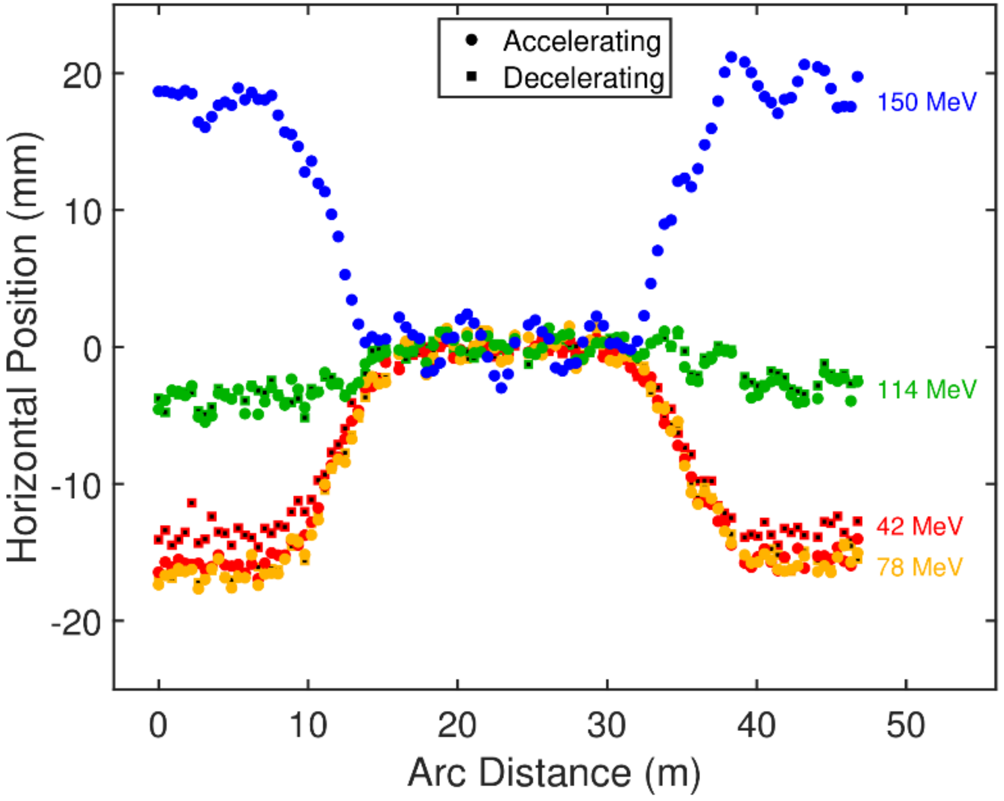
- Beam arrival time in units of RF phase before (red) and after (blue) of MLC with respect to first pass; target values (circles) are given by the design
- In the design, each MLC cavity is energy balanced (each cavity gives out as much power as it takes in)
- Good agreement between measurement and design demonstrates energy balance in each MLC cavity → energy recovery!

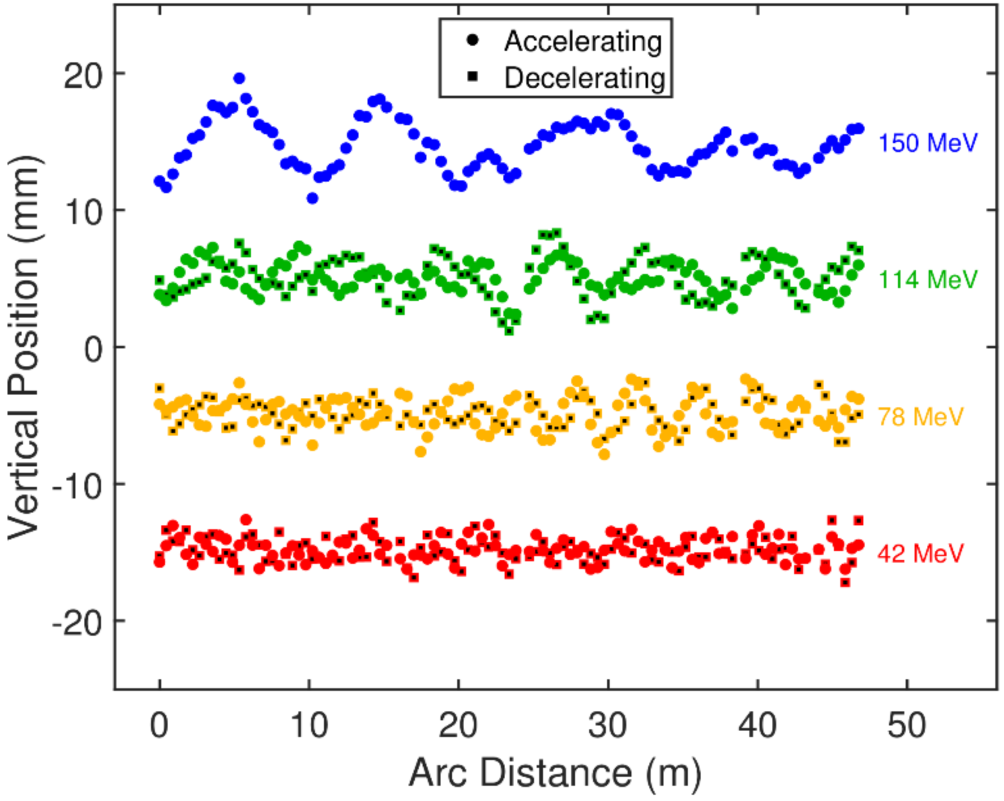


DOI: 10.1103/PhysRevLett.125.044803

Commissioning Results: Four-Turn Energy Recovery

- Horizontal (left) and vertical (right) orbits through the FFA for all seven passes
- Vertical orbits offset for clarity





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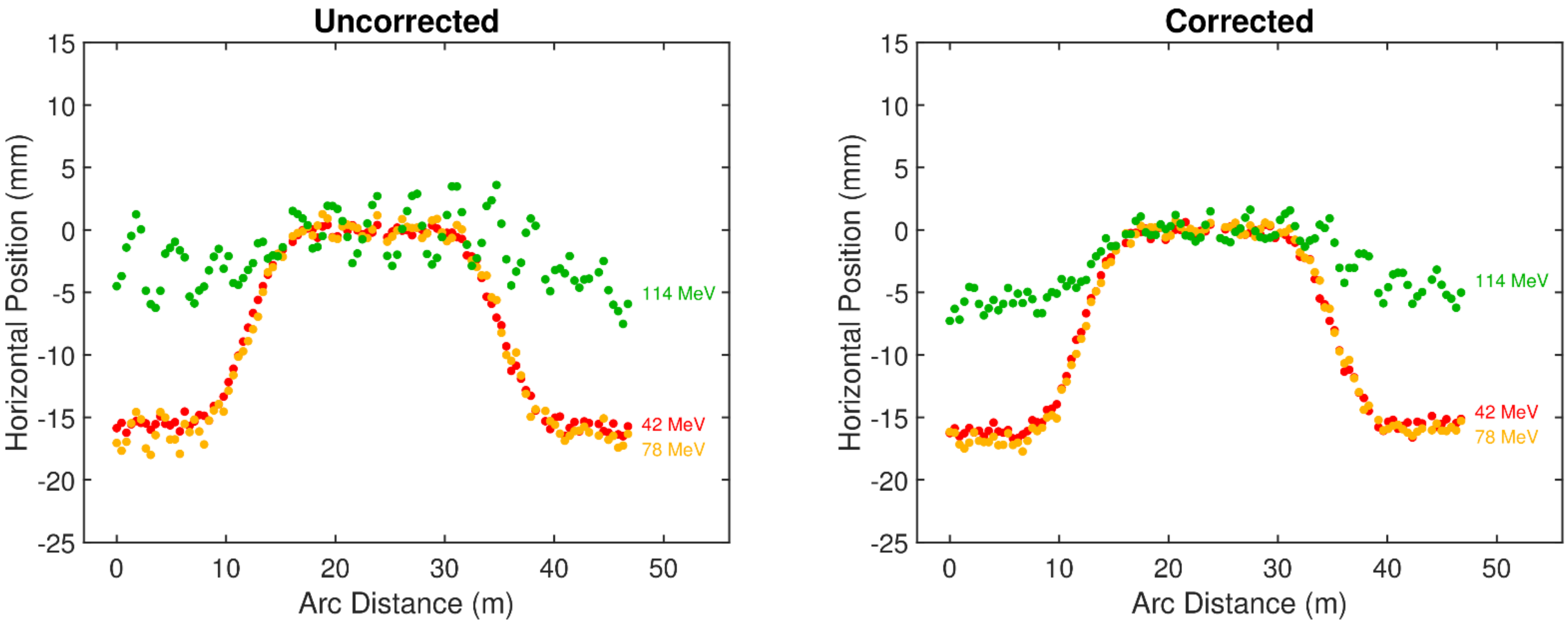
Commissioning Results: Multi-Pass Orbit Correction

- The same example of the vertical uncorrected (left) and corrected (right) orbits for three passes through the FFA



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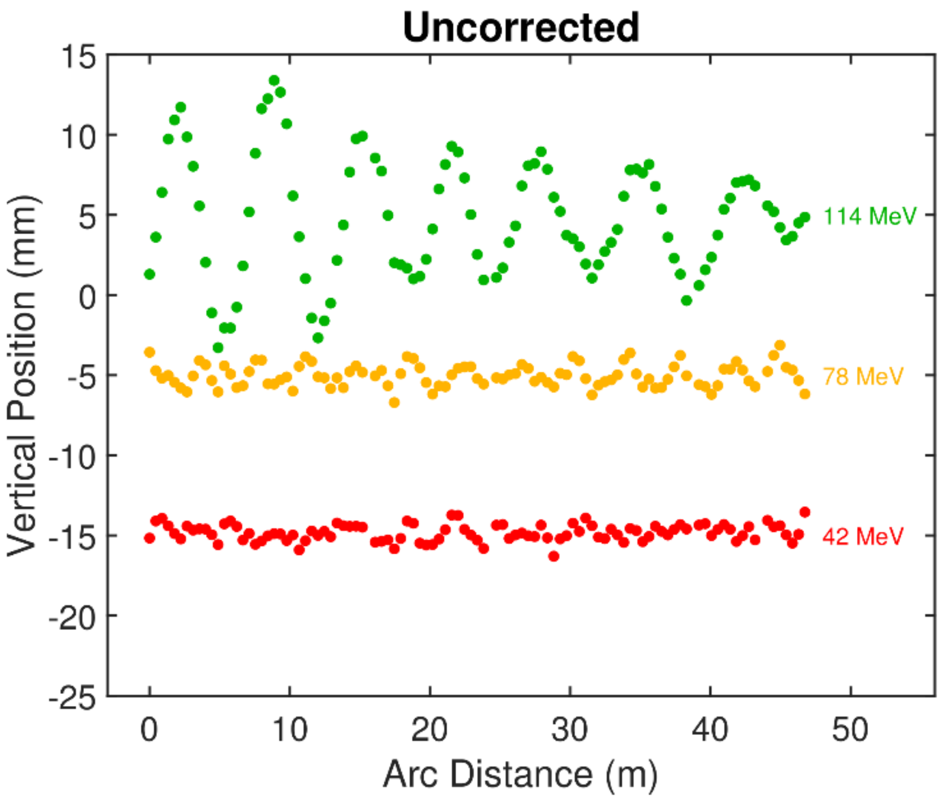

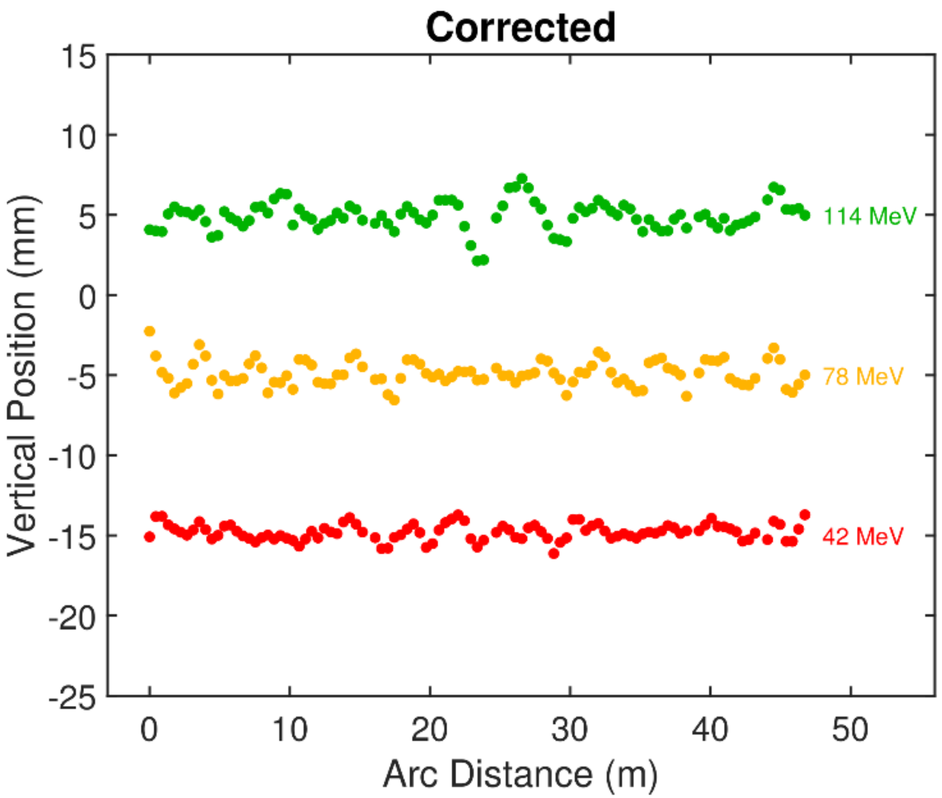

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Green Accelerators: Why?

- As projects call for higher energy and higher current, the power requirements for a linac become infeasible
- Storage rings are capable of higher beam currents, but require many, many electromagnets
- ERLs are a good solution and often have a smaller footprint
- Accelerators need to become more energy efficient for both sustainability and cost

DOI: 10.18429/JACoW-IPAC2022-TUOZSP3

Green Accelerators: How?

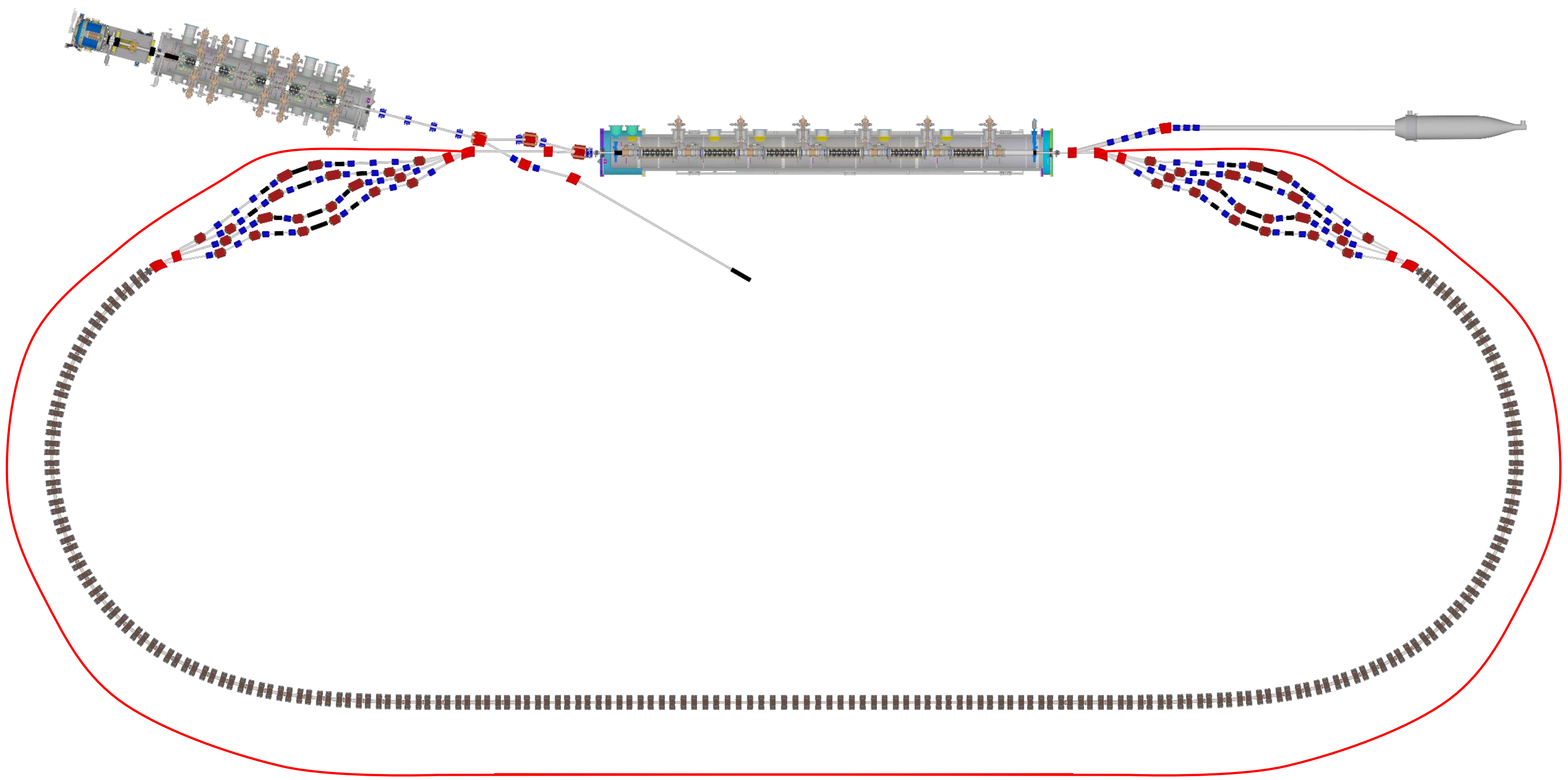
- Energy Recovery Linacs
  - Typically, smaller than a storage ring and more power efficient than a linac
  - Single-turn or multi-turn
  - ERLs can have higher beam power than installed SRF power

- Permanent Magnet FFA arcs
  - Permanent magnets → no power supplies necessary
  - Very compact way to transport multiple beams of different energies
  - Can be used for multi-turn ERLs, recirculating linacs, radiation gantries, etc…

- Very generic design:
  - Multi-turn ERL accelerates through FFA transport
  - Highest energy diverted into bypass line for relevant application

DOI: 10.18429/JACoW-IPAC2021-THPAB007

Green Accelerators: Cartoon Diagram



Bypass Line for Interactions

Jefferson Lab

Applications

- Free Electron Laser
- Hadron Cooler
- EUV Lithography
- Nuclear and HEP Colliders
- X-ray and Gamma-ray Inverse Compton Scattering Sources
- Medical Isotope Production
- Transmutation of Nuclear Waste
- And Many More

DOIs: 10.18429/JACoW-IPAC2021-THPAB007
10.18429/JACoW-IPAC2022-TUOZSP3
10.18429/JACoW-IPAC2022-TUIZGD1

CBETA ICS Collaboration

Kirsten Deitrick[1], Georg Hoffstaetter[1], Carl Franck[1], Bruno D. Muratori[2], Peter H. Williams[2], Geoffrey A. Krafft[3,4], Balša Terzić[4], Joe Crone[5], Hywel Owen[5]

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(3) Jefferson Lab (4) Old Dominion University
(5) University of Manchester and Cockcroft Institute

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

Science and Technology Facilities Council

The University of Manchester

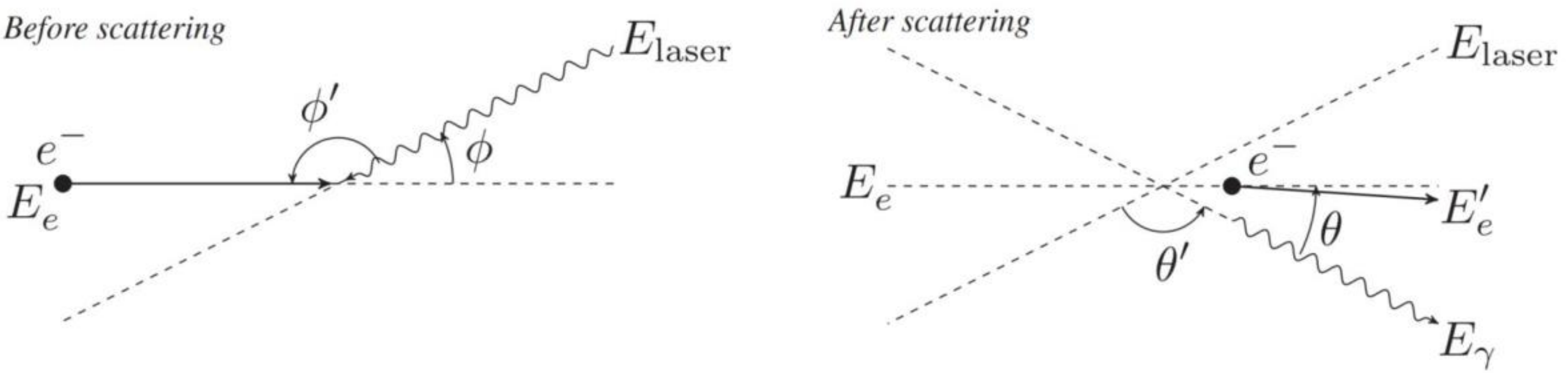
Thomas Jefferson National Accelerator Facility

The Cockcroft Institute of Accelerator Science and Technology

Some material taken from prior presentations by K. Deitrick and J. Crone

CBETA ICS

- Inverse Compton scattering is the collision of relativistic electrons and photons at the interaction point (IP) which produces radiation – i.e., x-rays or gamma rays
  - Relativistic electrons generally accelerated by linacs or ERLs

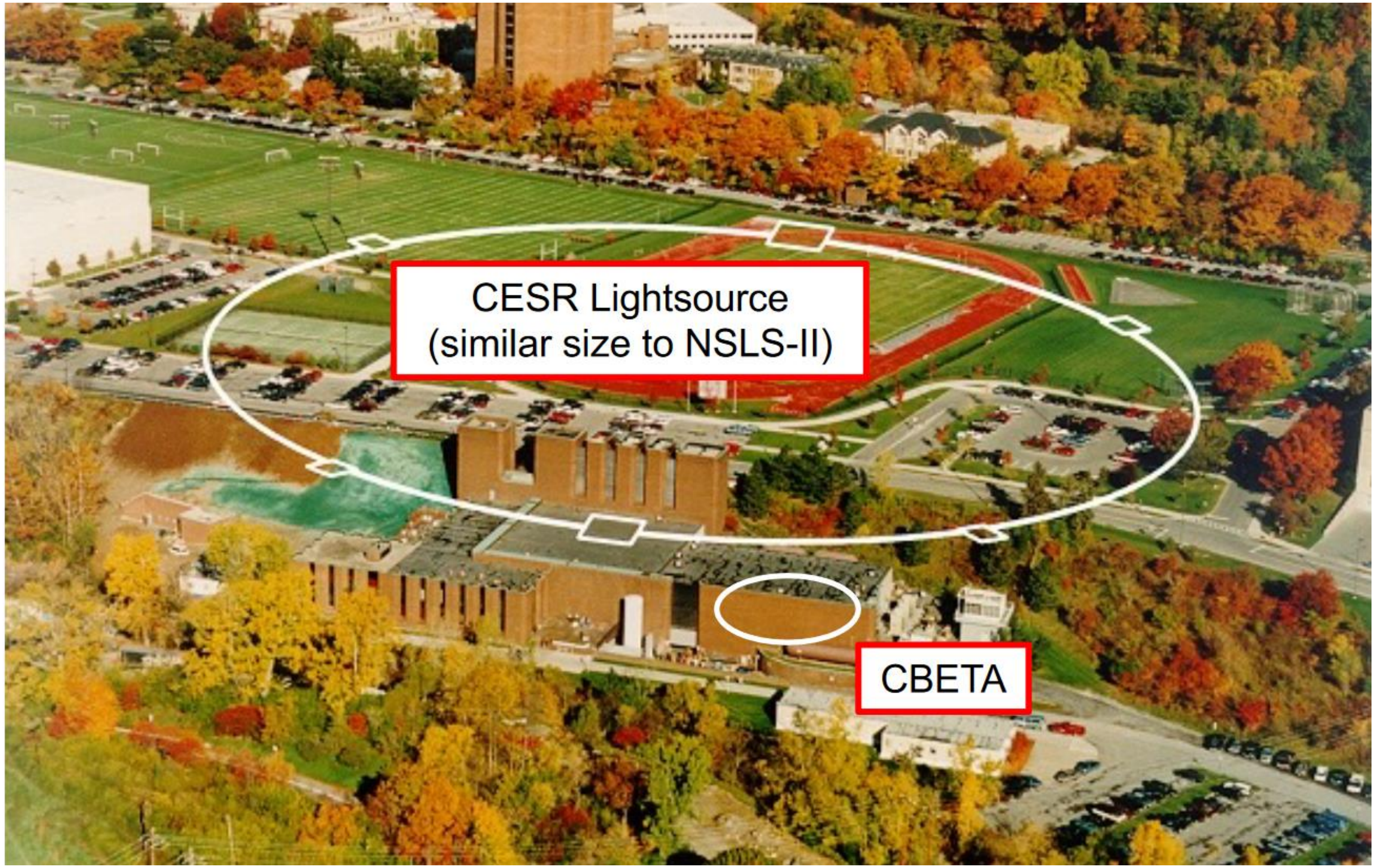


DOI: 10.1103/PhysRevAccelBeams.24.050701

CBETA ICS

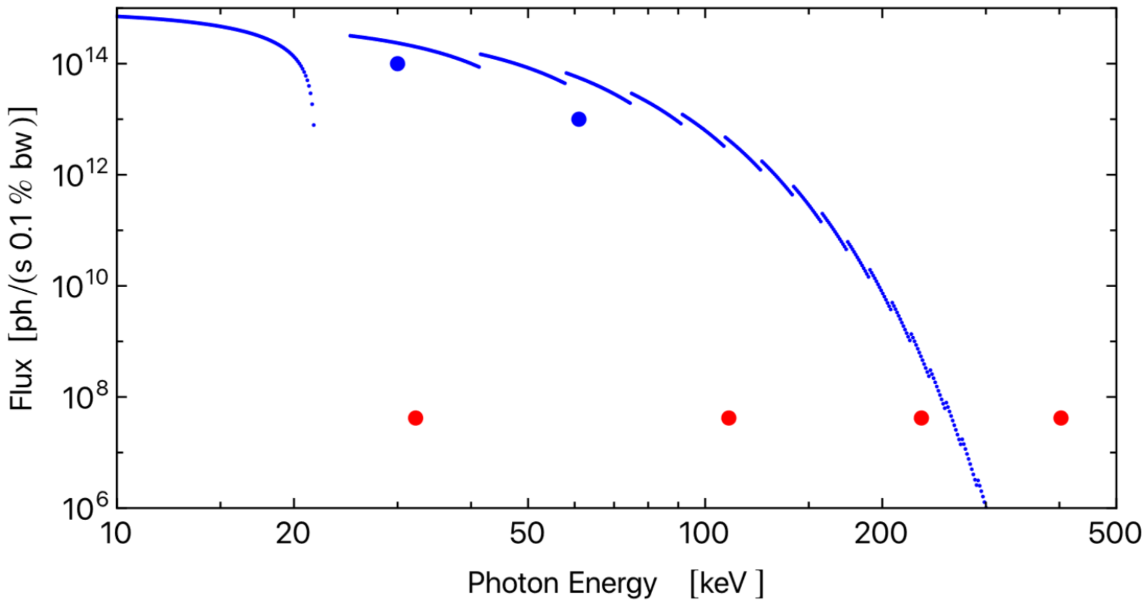
- Undulators typically have greater flux and brilliance for a given x-ray energy

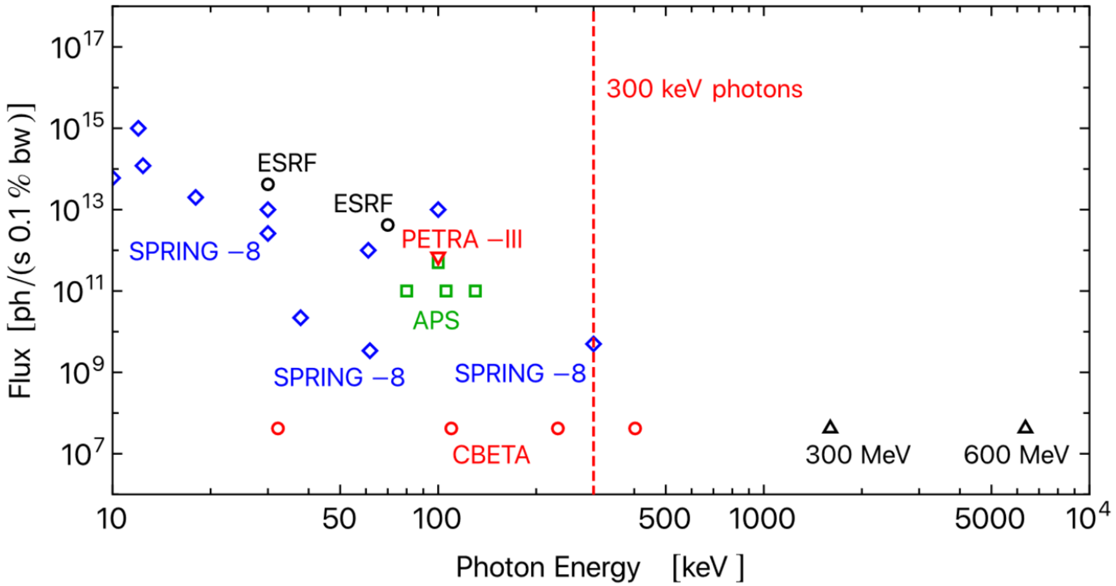
- But:
  - Cost more
  - Bigger footprint
  - Limited availability
  - Higher energy spread x-rays



Picture from DOI: 10.18429/JACoW-IPAC2022-TUIZGD1

CBETA ICS





Left: Flux per 0.1% BW of the CBETA ICS (red) against the harmonic curves and data (blue) of the Spring-8 high energy undulator. Right: Flux per 0.1% BW of the CBETA ICS (red) against a collection of the major high energy storage ring undulators across the globe.

- Beyond ~300 keV, undulator radiation production is difficult due to high harmonics and undulator phase errors
- ICS footprint for MeV-scale γ-ray sources significantly smaller than synchrotron, while performing better

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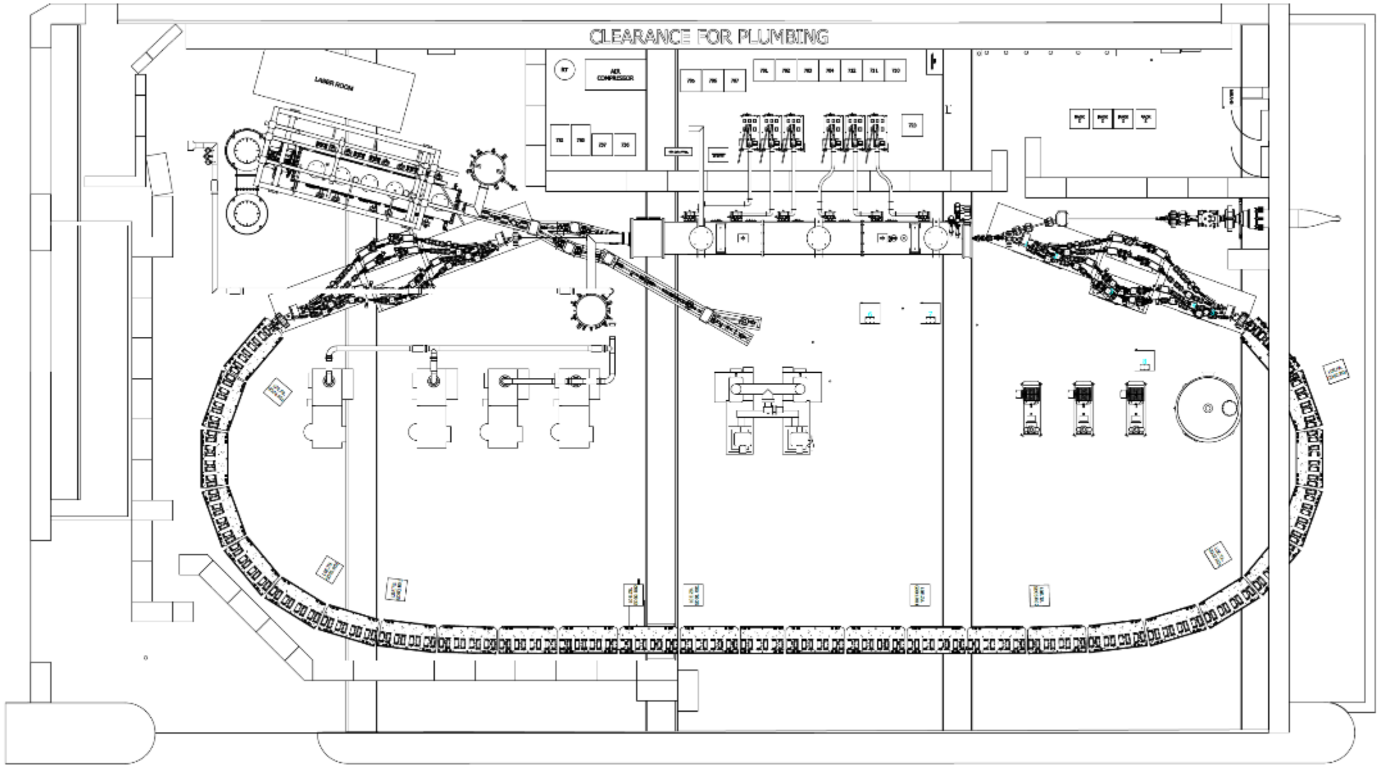
CBETA ICS

- As is, there's no room in the FFA arc for the IP



Schematic of the CBETA enclosure. MLC ~10 m for scale.

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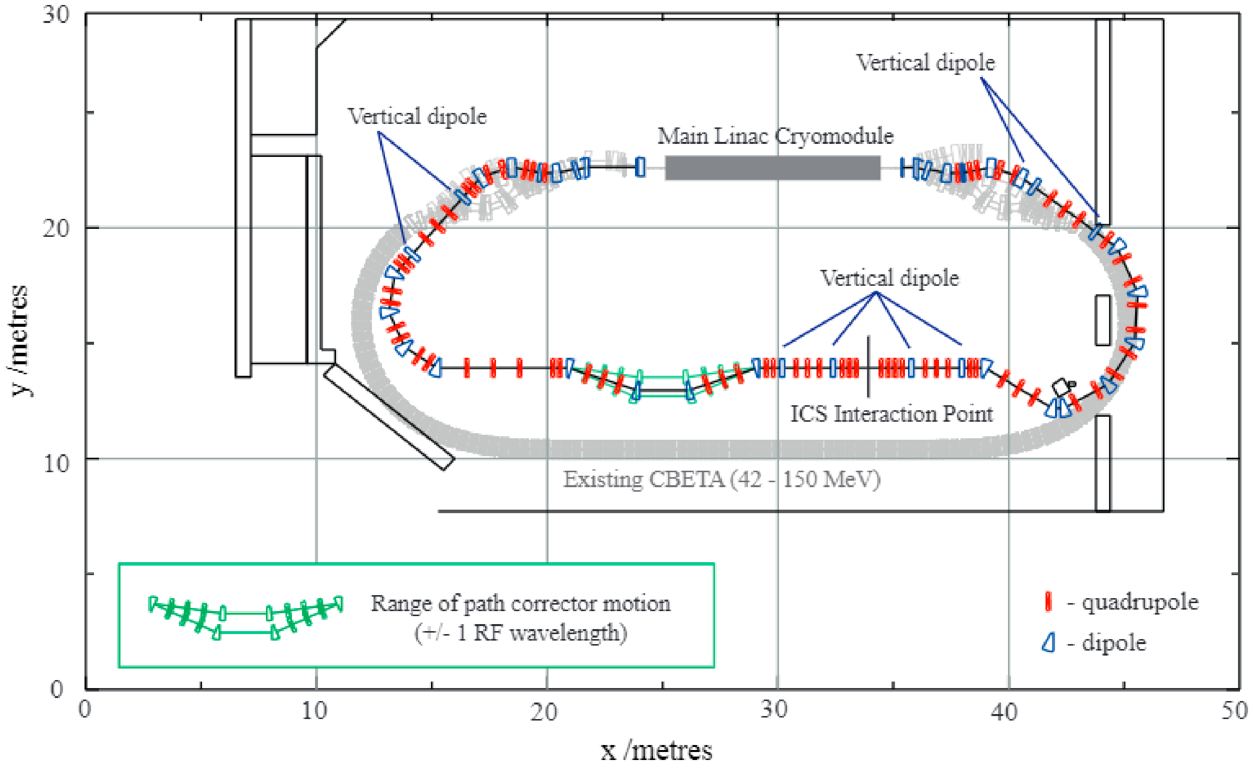
CBETA ICS

- As is, there’s no room in the FFA arc for the IP
- Bypass line is elevated above existing plane by 30 cm; IP is further elevated by another 50 cm
- Optics are set such that the parameters going into the MLC for the fifth pass match CBETA design parameters



Floor plan schematic of the ICS bypass to CBETA. The existing CBETA return loop is shown in grey. The configurations of the path length correction system are shown in green. Vertical dipoles are indicated.

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FFA@CEBAF Collaboration

J.F. Benesch[1], R.M. Bodenstein[1], **S.A. Bogacz**[1], A.M. Coxe[1], K.E. Deitrick[1], B.R. Gamage[1], G.A. Krafft[1], K.E. Price[1], Y. Roblin[1], A. Seryi[1], J.S. Berg[2], S.J. Brooks[2], D. Trbojevic[2], V.W. Morozov[3], G.H. Hoffstaetter[2,4], D. Douglas[5]

(1) Jefferson Lab (2) BNL (3) Oak Ridge National Lab (4) Cornell University
(5) Douglas Consulting

Jefferson Lab Thomas Jefferson National Accelerator Facility

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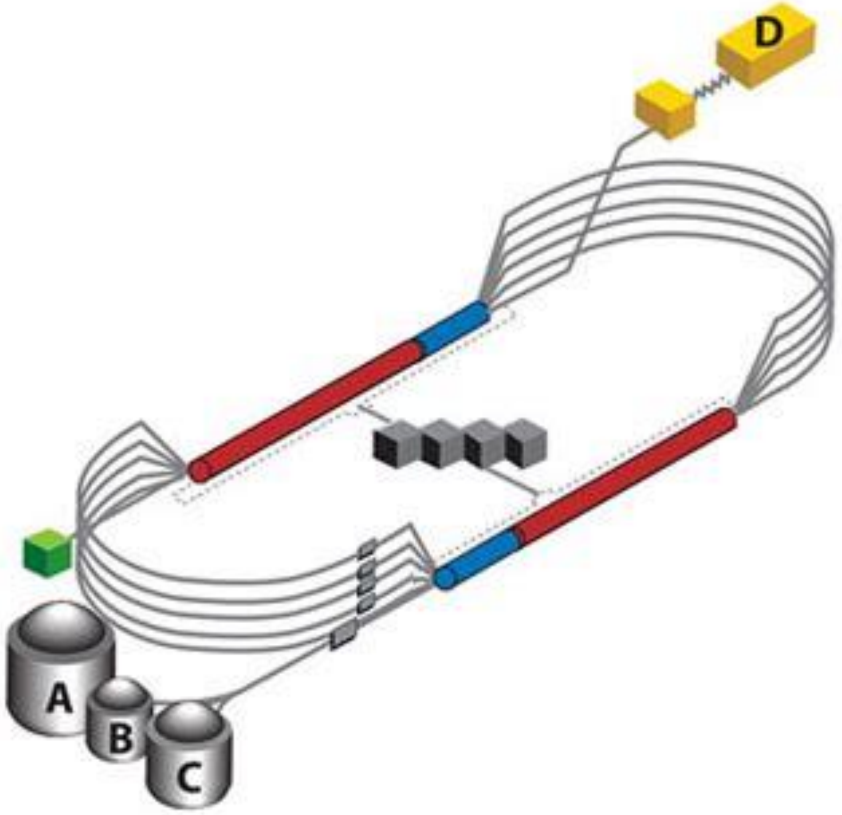
OAK RIDGE National Laboratory

FFA@CEBAF

- Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab
- Recirculating linac
- Two SRF linacs (north and south) and electromagnetic arcs between them

- Energy upgrade completed in 2017 from 6 GeV to 12 GeV by installing more SRF cavities



FFA@CEBAF

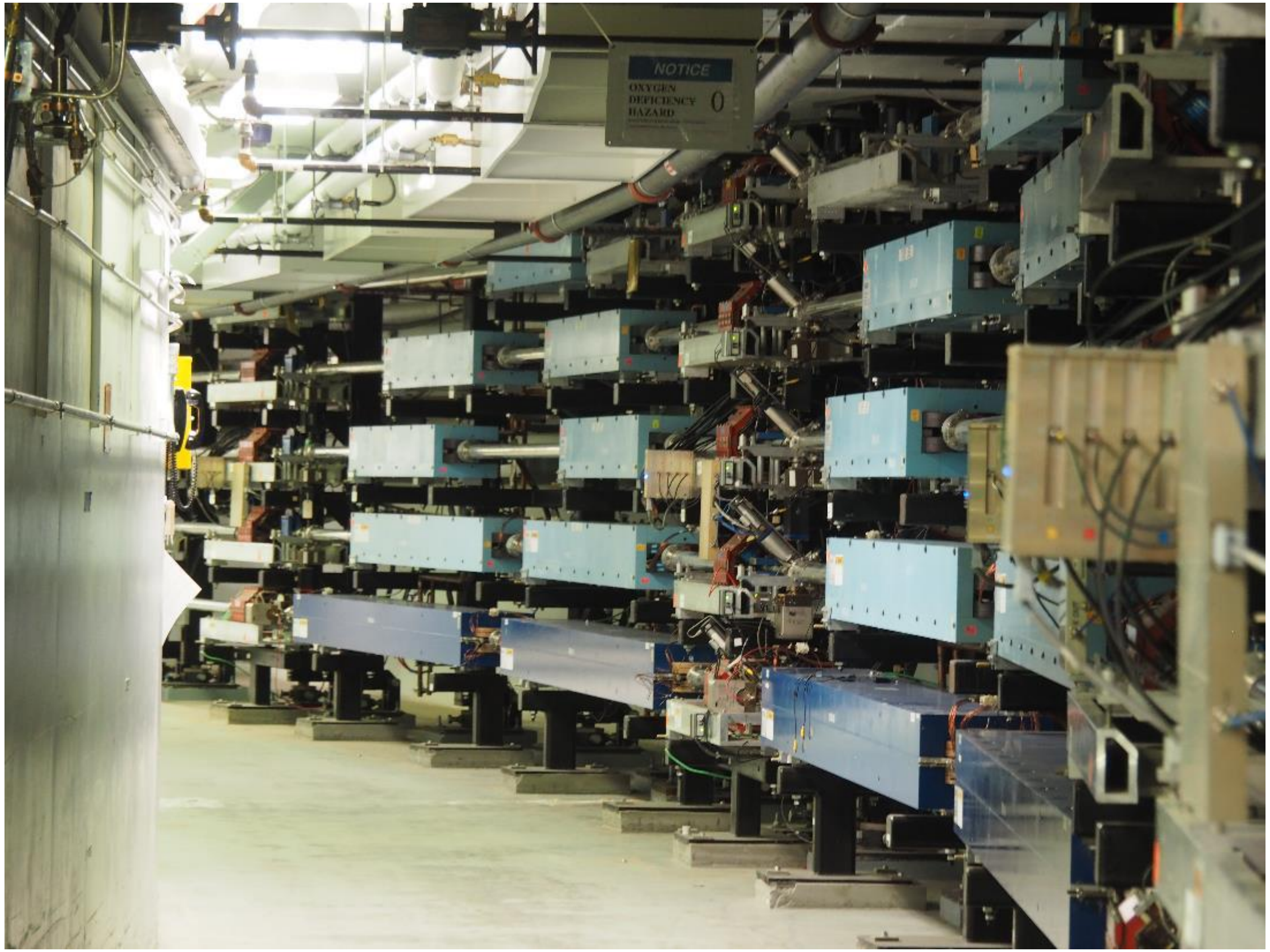
- While last energy upgrade was achieved by adding additional cavities, there is no more room for cavities in existing footprint

- So, instead look to increasing number of recirculation passes

- Just one problem…

FFA@CEBAF

- While last energy upgrade was achieved by adding additional cavities, there is no more room for cavities in existing footprint
- So, instead look to increasing number of recirculation passes
- Just one problem – there's very limited room in the arcs for additional passes



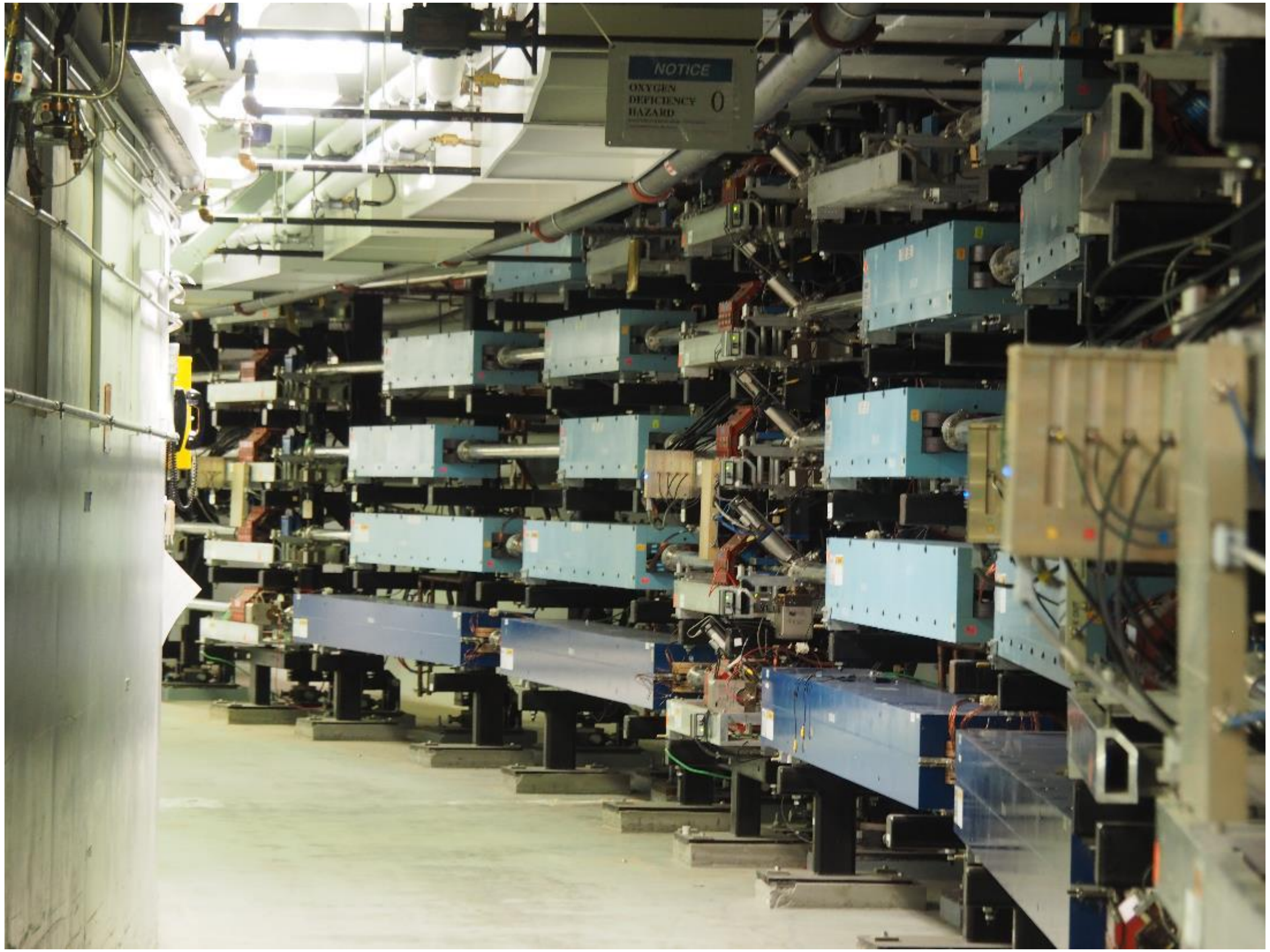
FFA@CEBAF

- While last energy upgrade was achieved by adding additional cavities, there is no more room for cavities in existing footprint

- So, instead look to increasing number of recirculation passes

- Just one problem – there's very limited room in the arcs for additional passes

- But FFAs transport multiple energies in one beam pipe



DOI: 10.18429/JACoW-IPAC2022-THPOST023

FFA@CEBAF

- Current concept is to remove highest energy arc and replace with FFA transport and time of flight correction (splitter section)

- Expected energy upgrade to 20 GeV or greater

 DOI: 10.18429/JACoW-IPAC2022-THPOST023

Conclusions

- CBETA is the first accelerator to successfully operate as a multi-turn SRF ERL
- The combined technologies of energy recovery and permanent magnet FFA transport demonstrate high energy efficiency critical for future accelerators of high performance and high beam power
- Applications of these future accelerators range from basic research, industrial and medical uses, cultural heritage applications, and more
- The CBETA ICS and FFA@CEBAF collaborations demonstrate how these technologies can be applied moving forward to new designs

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- K. Deitrick *et al.*, “Intense monochromatic photons above 100 keV from an inverse Compton source’”, *Physical Review Accelerators and Beams*, vol. 24, p. 050701, May 2021. doi:10.1103/PhysRevAccelBeams.24.050701

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Questions?

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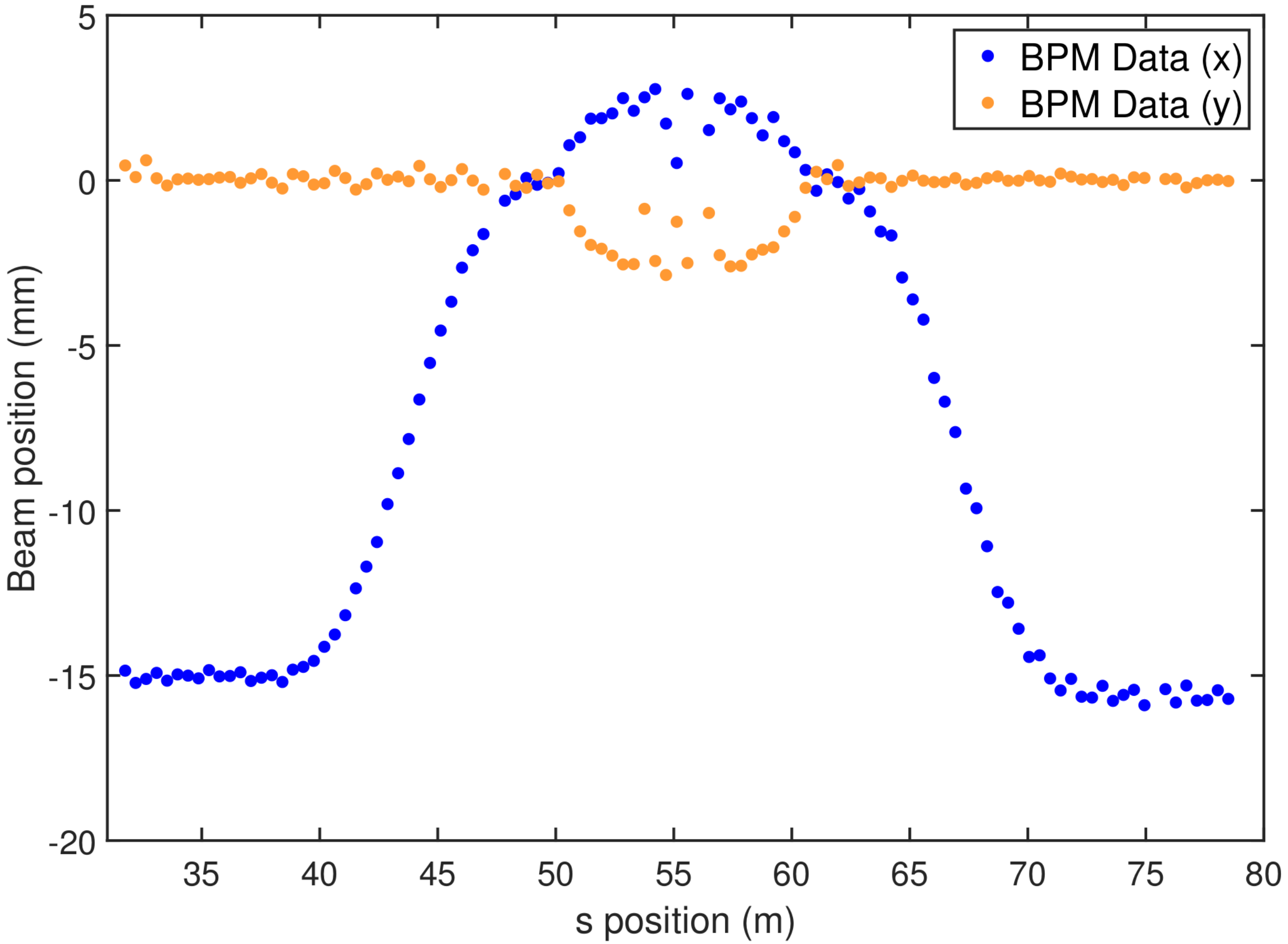
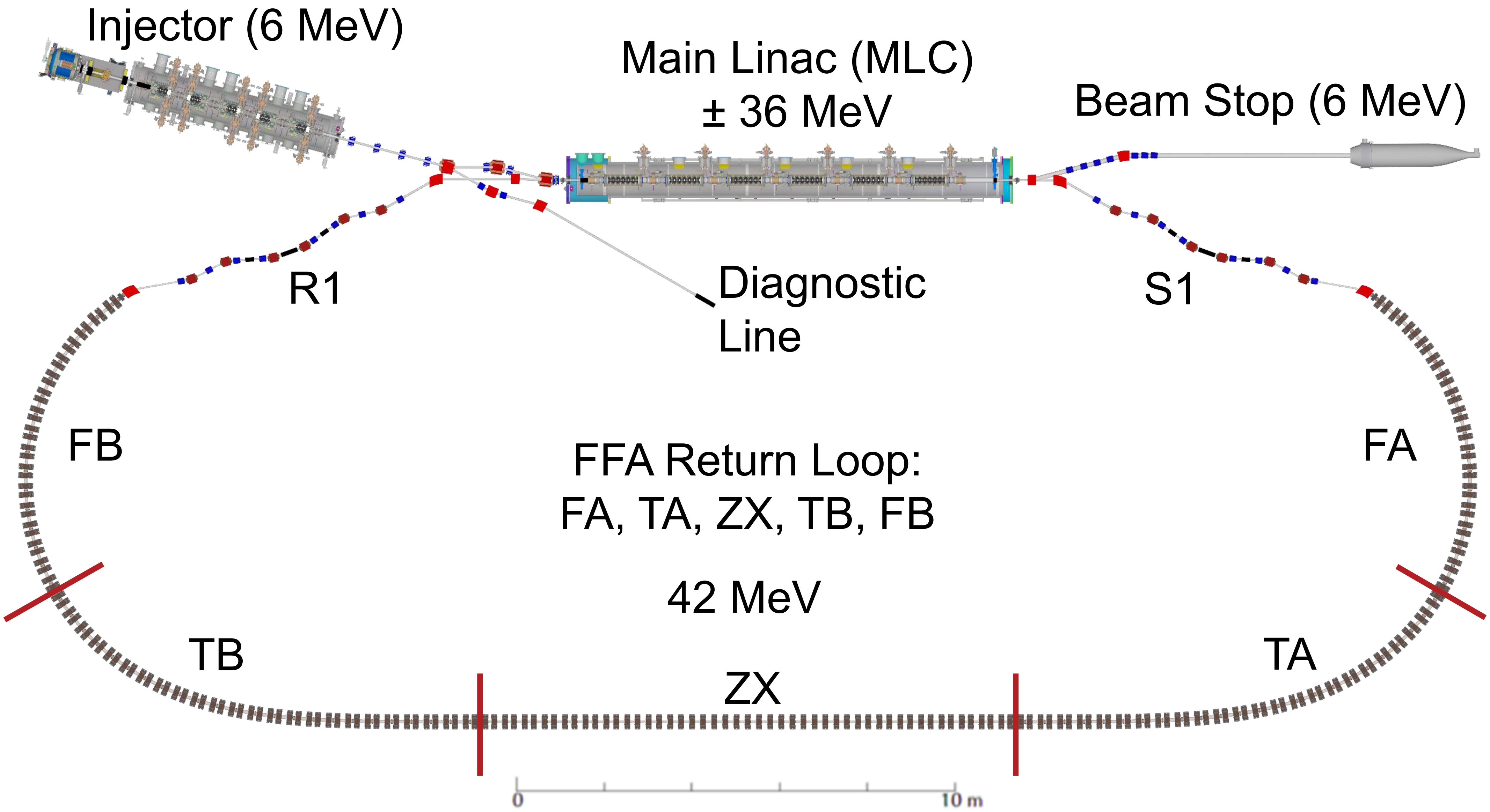
Thanks for your attention!



CBETA: One-Turn Configuration



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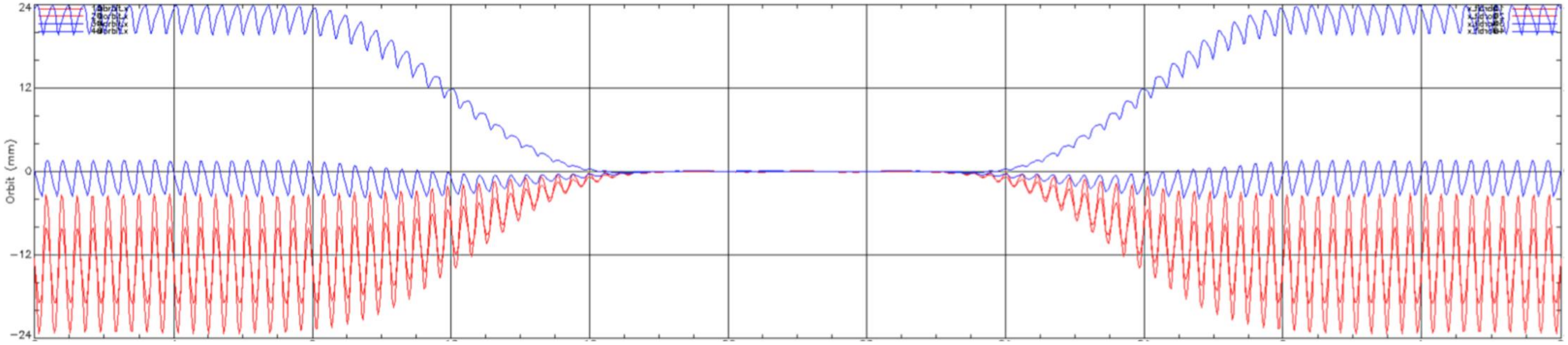

42 MeV, 78 MeV, 114 MeV, 150 MeV