Electron RLA and ERL FFA Applications

Kirsten Deitrick

Monday, September 11, 2023

Outline

- Introduction
- ERL Designs
  - CBETA
  - CBETA ICS
  - Generic FFA ERL
- RLA Designs
  - FFA@CEBAF
  - Generic FFA RLA
- Conclusions

DOI numbers throughout, references at the end

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  - CBETA
  - CBETA ICS
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  - FFA@CEBAF
  - Generic FFA RLA
- Conclusions

A lot of material from past presentations – contributors will be recognized throughout

DOI numbers throughout, references at the end

Introduction

- With the success of CBETA, more focus has been turned to designing future accelerators with a similar approach – namely, multi-turn recirculating linacs (RLAs) or energy recovery linacs (ERLs) with permanent magnet FFA arcs

- This talk will cover the CBETA design, demonstrated successes during operation, and similar designs with possible applications

- Moving into RLA FFA design concepts, the FFA@CEBAF energy upgrade will be introduced, and how this approach could be beneficial for both existing and future facilities

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]

(1) BNL (2) Cornell University (3) STFC (4) HZB (5) KEK

Material in this section taken from presentations by A. Bartnik, K. Deitrick, and C. Gulliford

CBETA: An Introduction

- CBETA stands for Cornell-BNL ERL Test Accelerator

- Multi-turn SRF Energy Recovery Linac 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

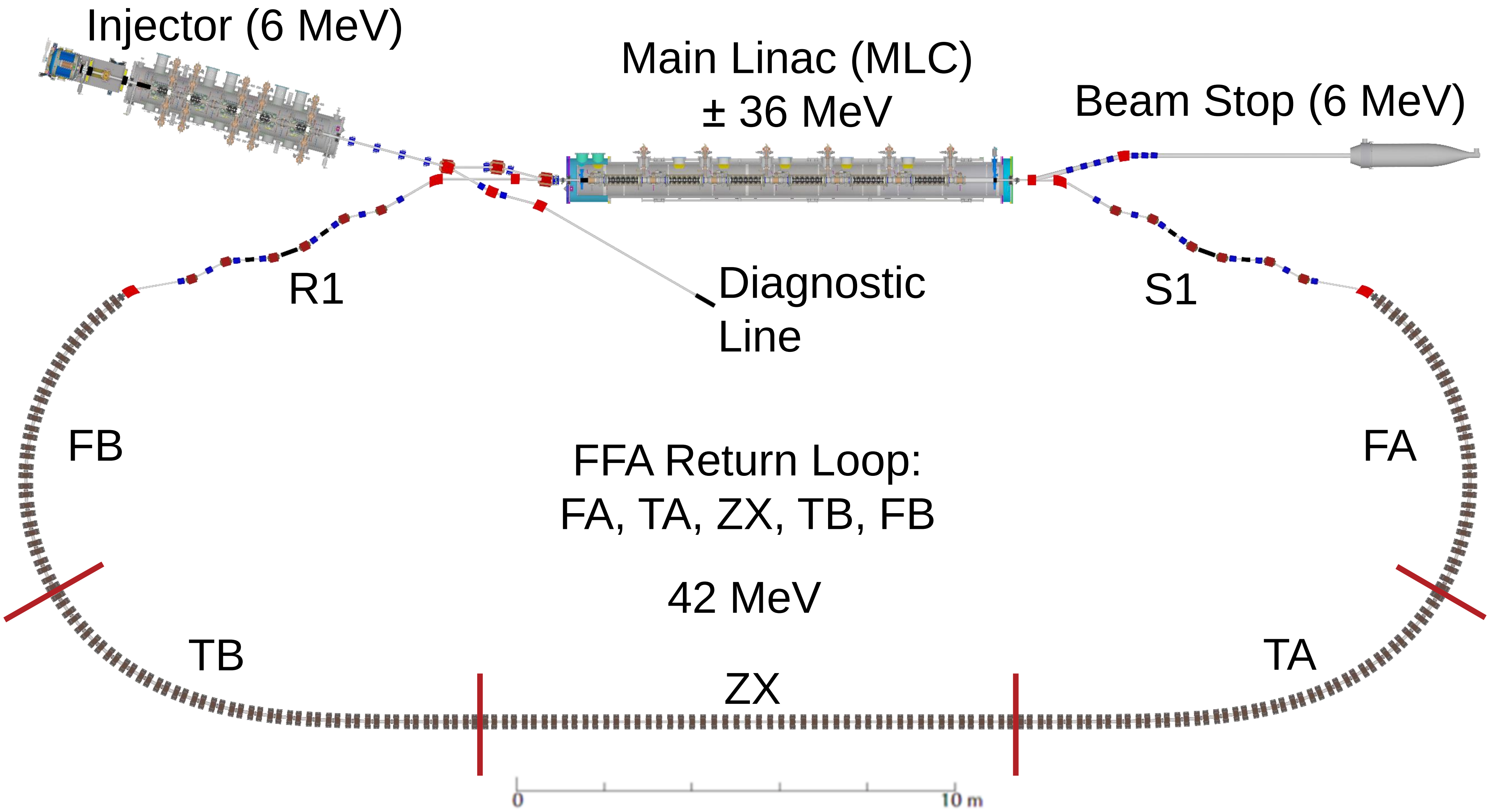
DOI: 10.48550/arXiv.1706.04245

CBETA: Nomenclature

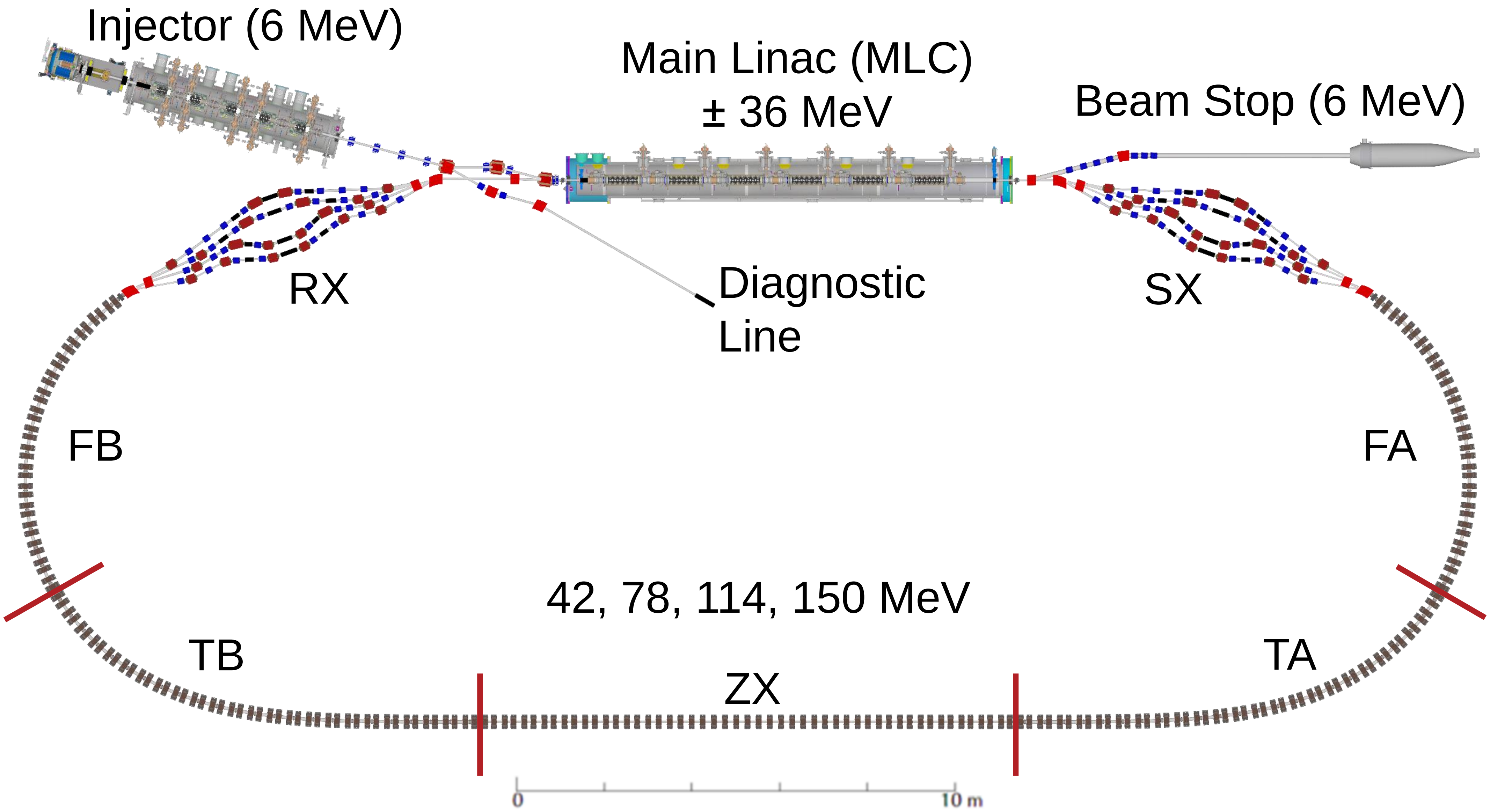
- One-turn configuration
  - One accelerating pass, one decelerating pass
  - Two passes through the MLC
  - One pass through the FFA

- Four-turn configuration
  - Four accelerating passes, four decelerating passes
  - Eight passes through the MLC
  - Seven passes through the FFA

CBETA: One-Turn Configuration



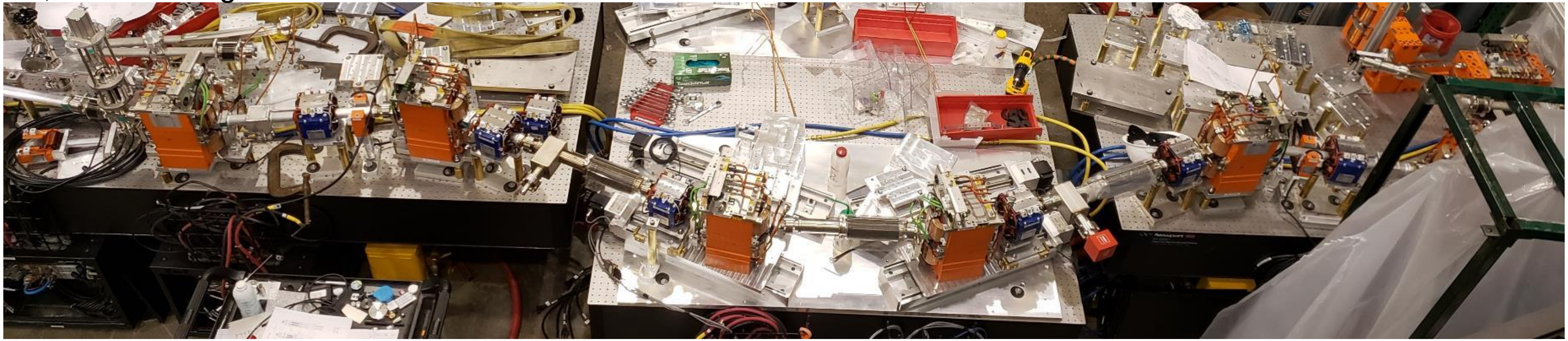
CBETA: Four-Turn Configuration



CBETA: 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 / R_{56} / orbit

S1, 1-turn configuration



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Jefferson Lab

CBETA: Splitter Lines

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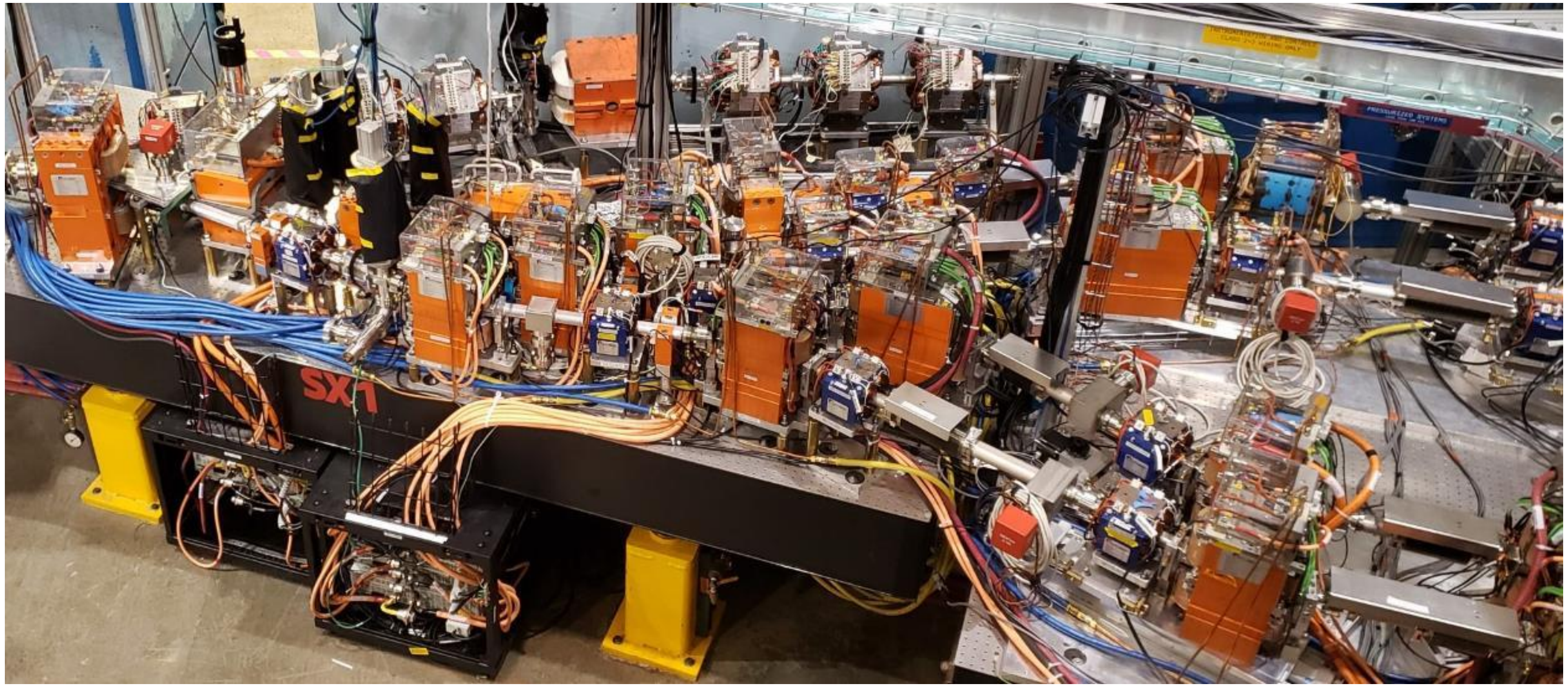

Front half of SX,
4-turn configuration

DOI: 10.48550/arXiv.1706.04245

CBETA: 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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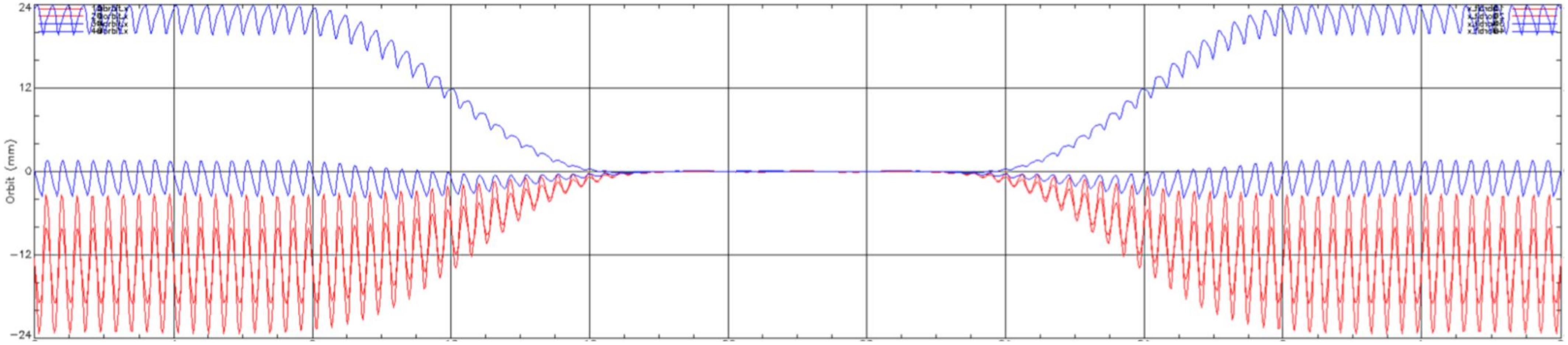

42 MeV, 78 MeV, 114 MeV, 150 MeV

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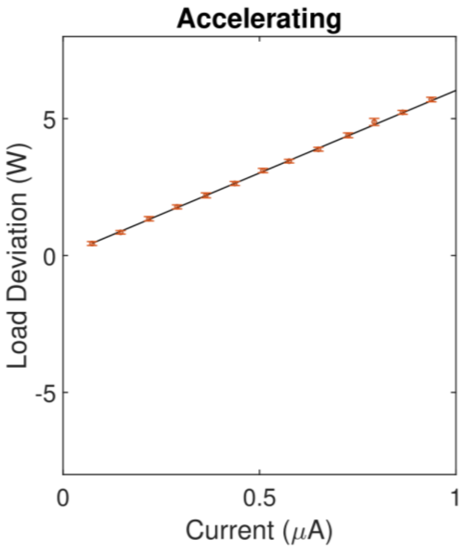
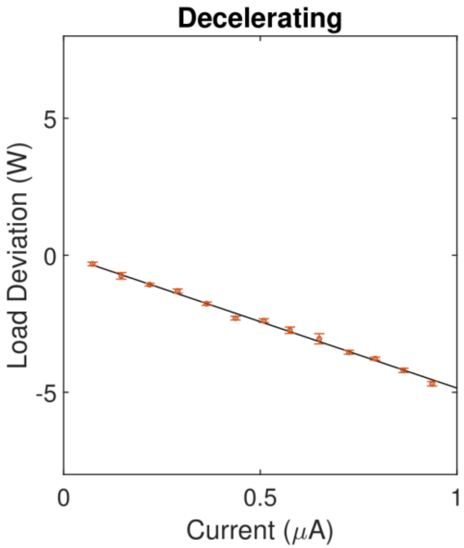
CBETA: One-Turn Energy Recovery

- Rough approximation:
  Total RF load = RF load due to cavity field + RF load due to beam
- As beam current changes, the change in total RF load (load deviation) is caused by changing RF load due to beam (beam loading)

- 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

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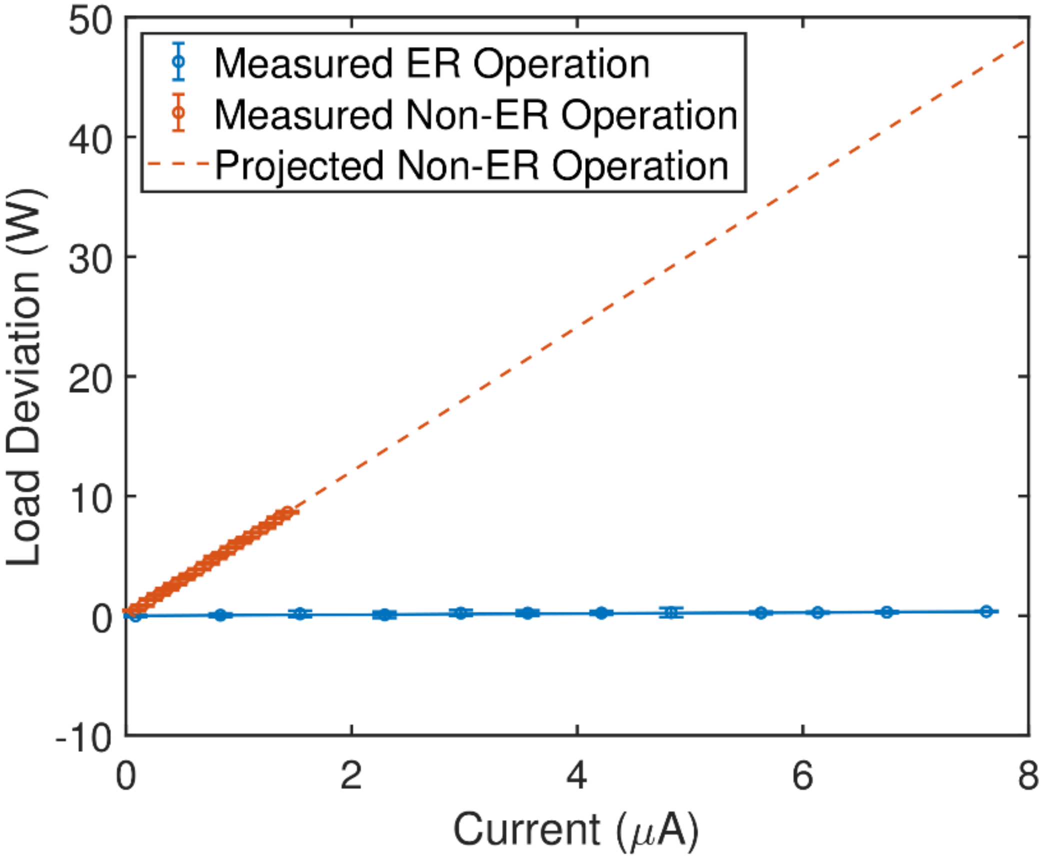
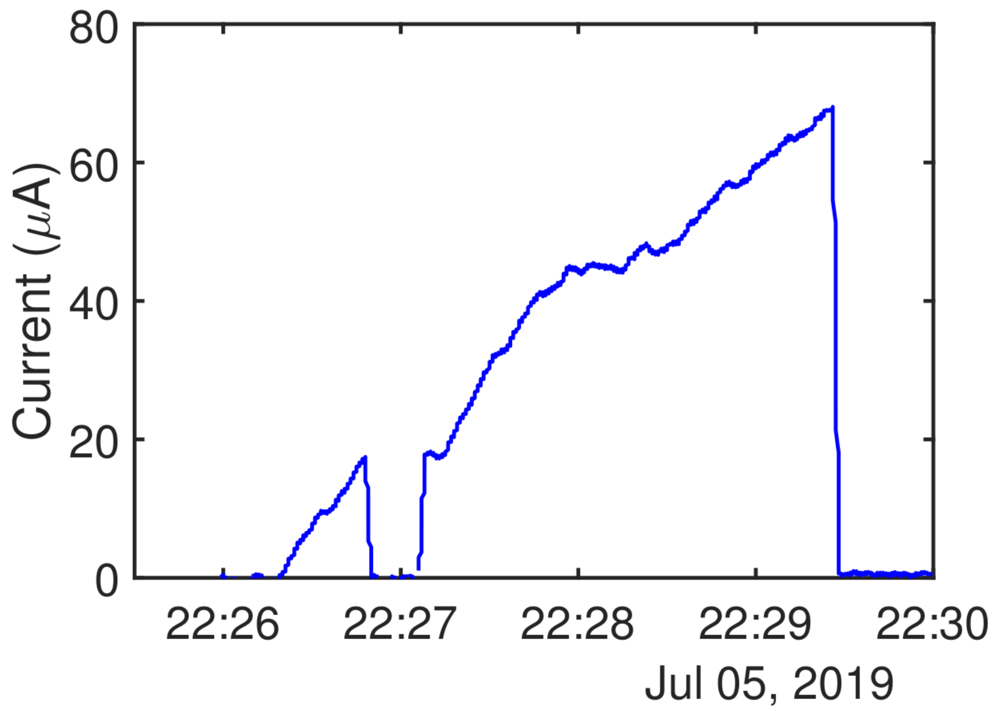


DOI: 10.1103/PhysRevAccelBeams.24.010101

CBETA: Push for Higher Current

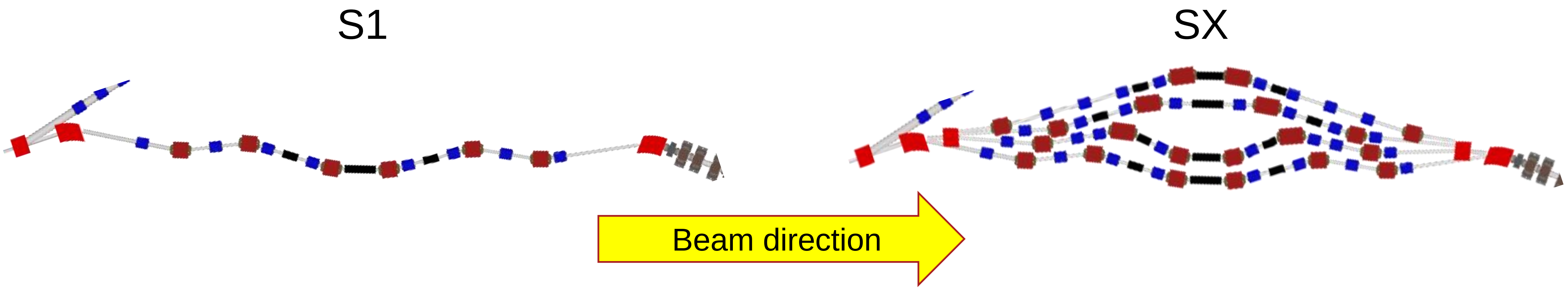
- Highest average current achieved was nearly 70 μA
- Limited by several factors:
  - Large spot cathode
  - Incomplete machine protection
    - Permanent magnets
  - Insufficient beam stop shielding
  - MLC energy instability
    - Last two concerns were significantly improved before four-turn run



DOI: 10.1103/PhysRevAccelBeams.24.010101

CBETA: Moving to Four-Turn

- Difference in SX/RX sections
  - Go from one splitter line in each section to four
  - 56 new magnets in each section; 112 new magnets total

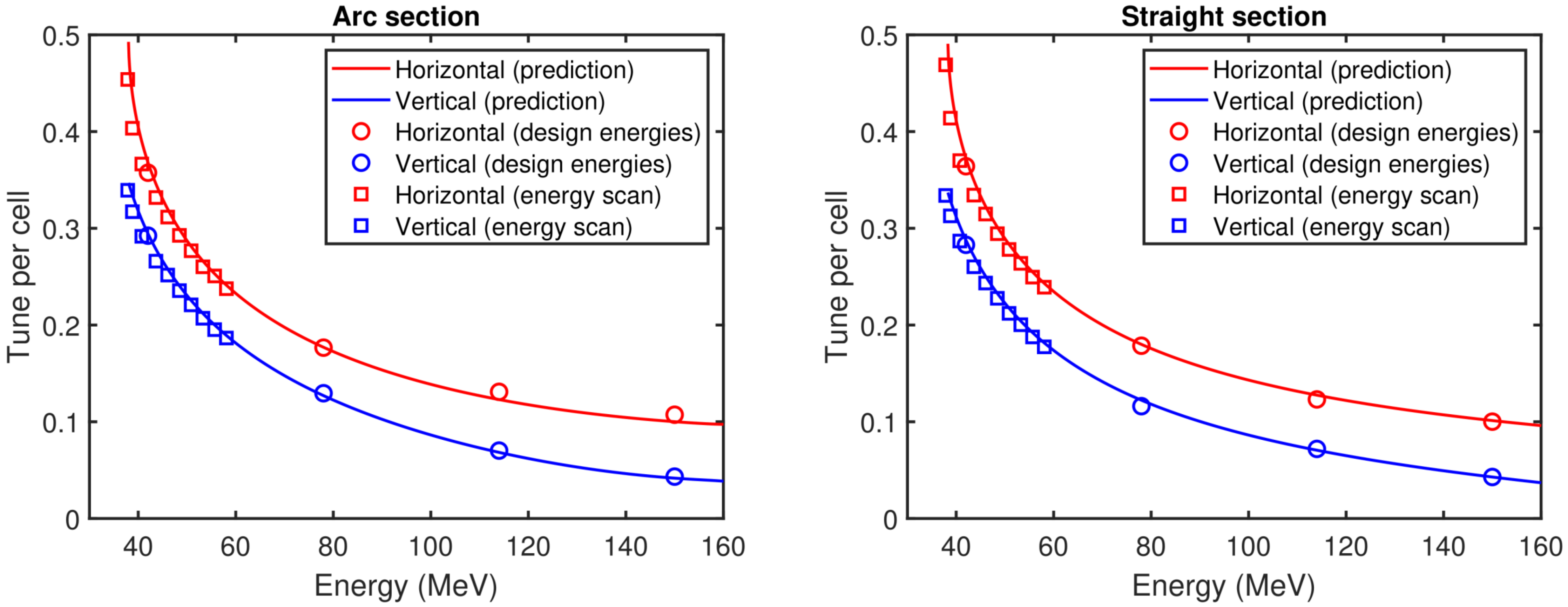


- Operation began in early October 2019
  - Milestone: 8 passes through the MLC
  - 12 weeks of operation before milestone deadline

DOI: 10.48550/arXiv.1706.04245

CBETA: FFA Tune Measurements

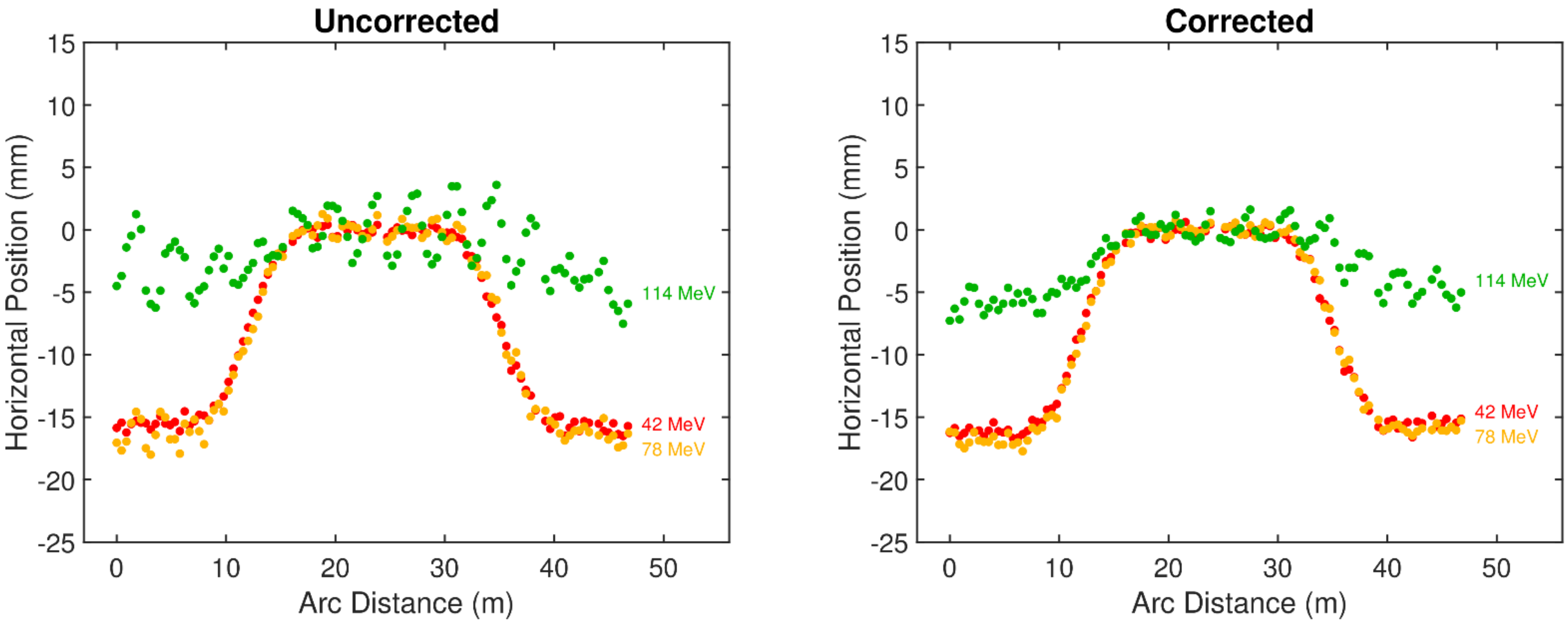
- Energy scan measured during 1-turn run (39 - 59 MeV)
- Design energies measured during 4-turn run (42, 78, 114, 150 MeV)
- Measurements show a good agreement with the model



DOI: 10.1103/PhysRevLett.125.044803
Jefferson Lab

CBETA: Multi-Pass Orbit Correction

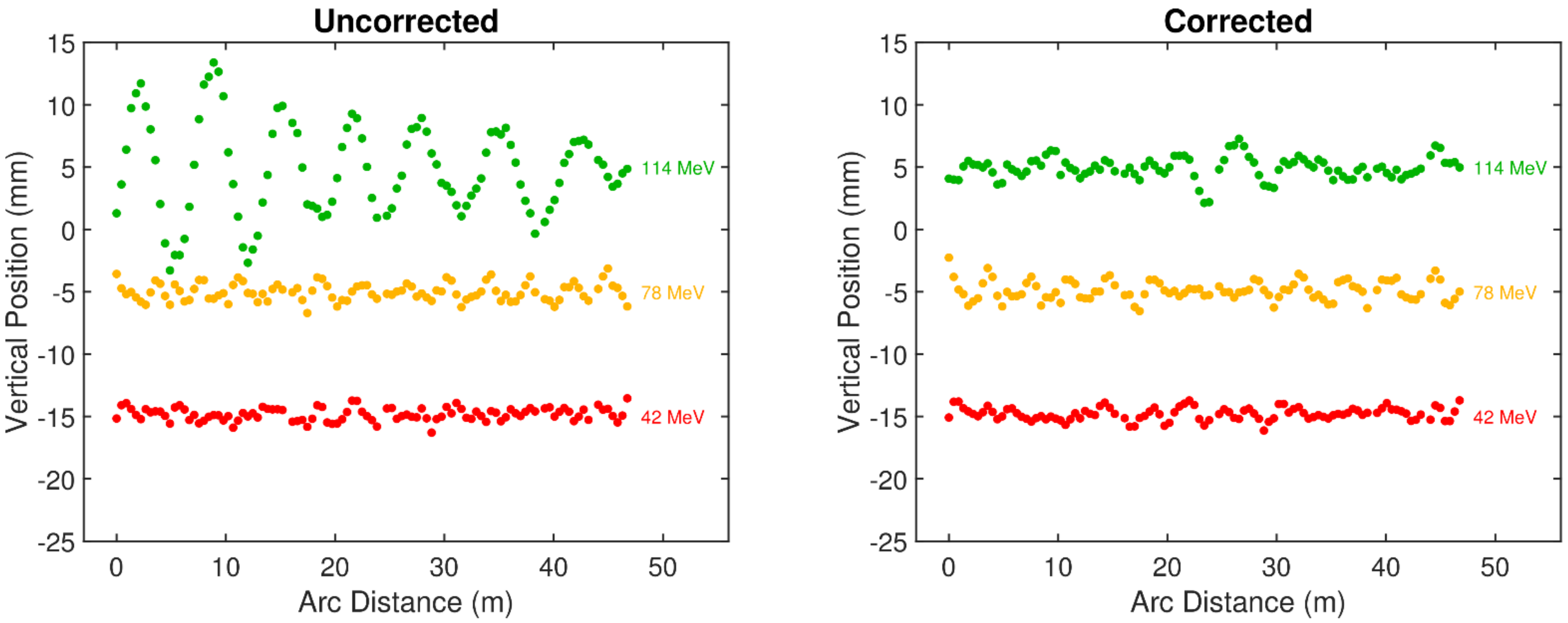
- Correcting multiple passes in the FFA involves the same set of corrector coils working on multiple beams of different energies
- An example of the horizontal uncorrected (left) and corrected (right) orbits for three passes through the FFA



DOI: 10.1103/PhysRevLett.125.044803

CBETA: Multi-Pass Orbit Correction

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



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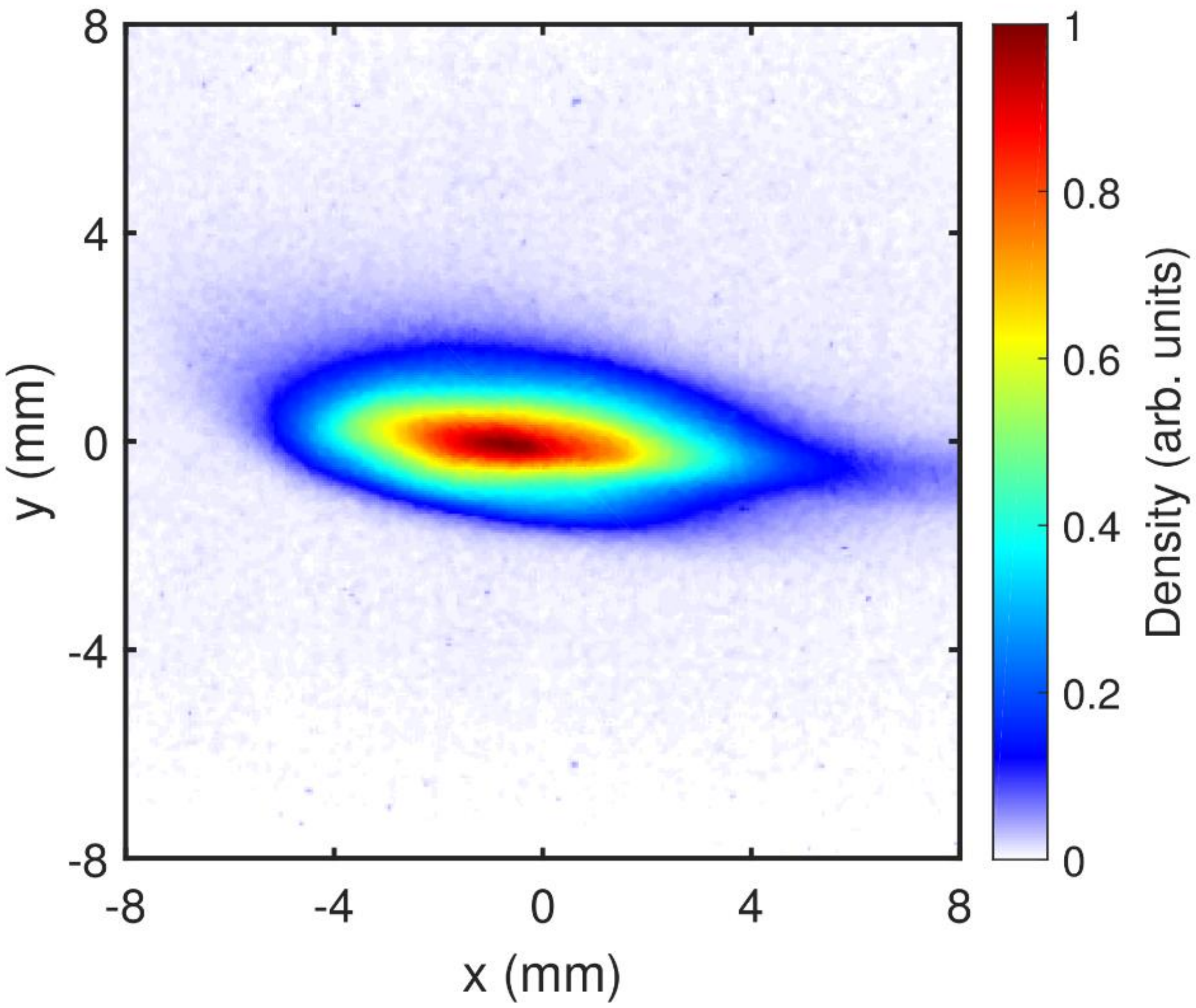
CBETA: Four-Turn Energy Recovery

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

Beam on the first viewscreen in the beam stop line



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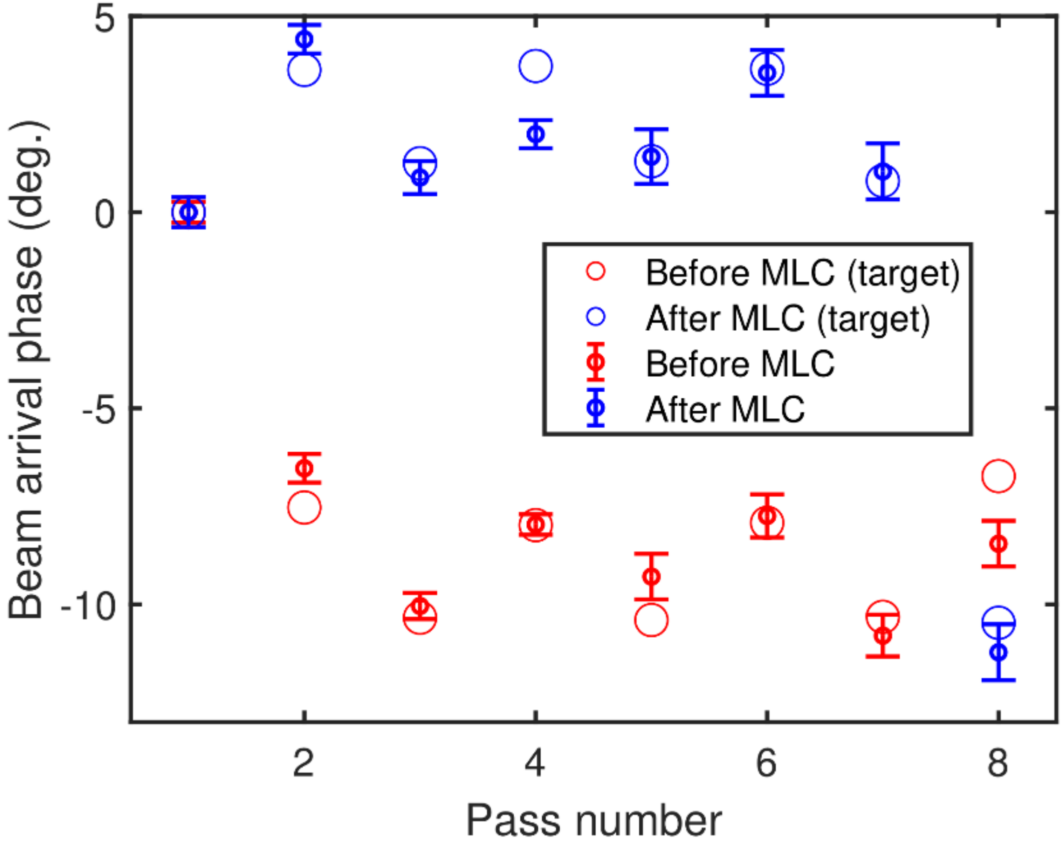
CBETA: Four-Turn Energy Recovery

- 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!



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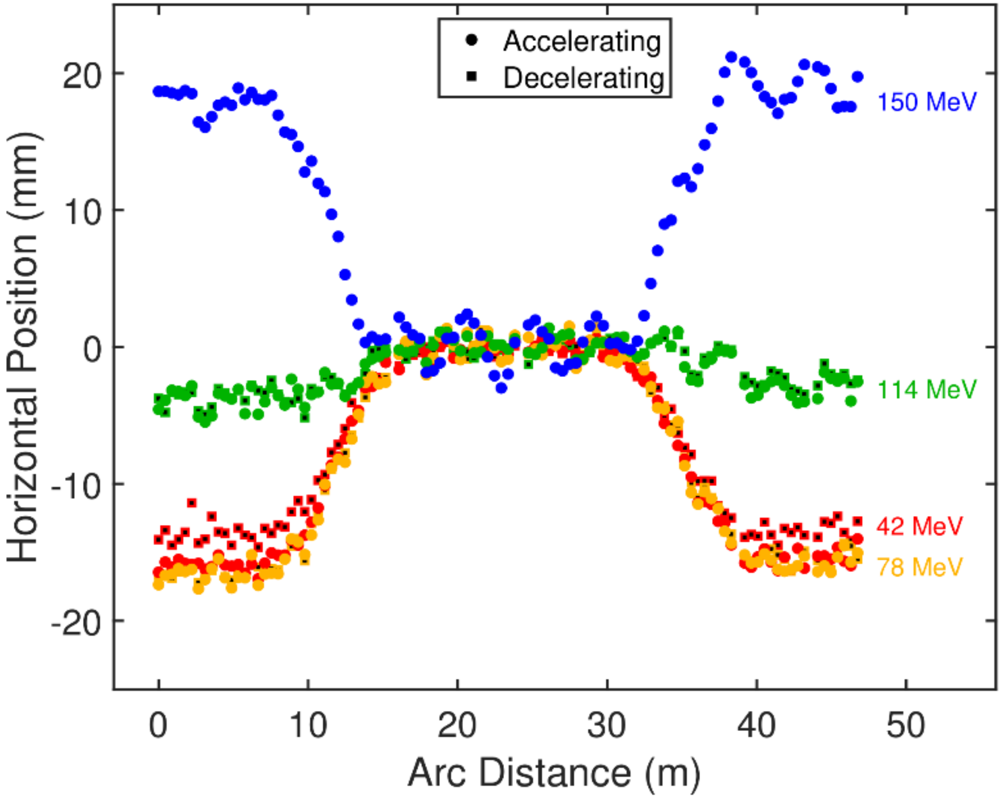
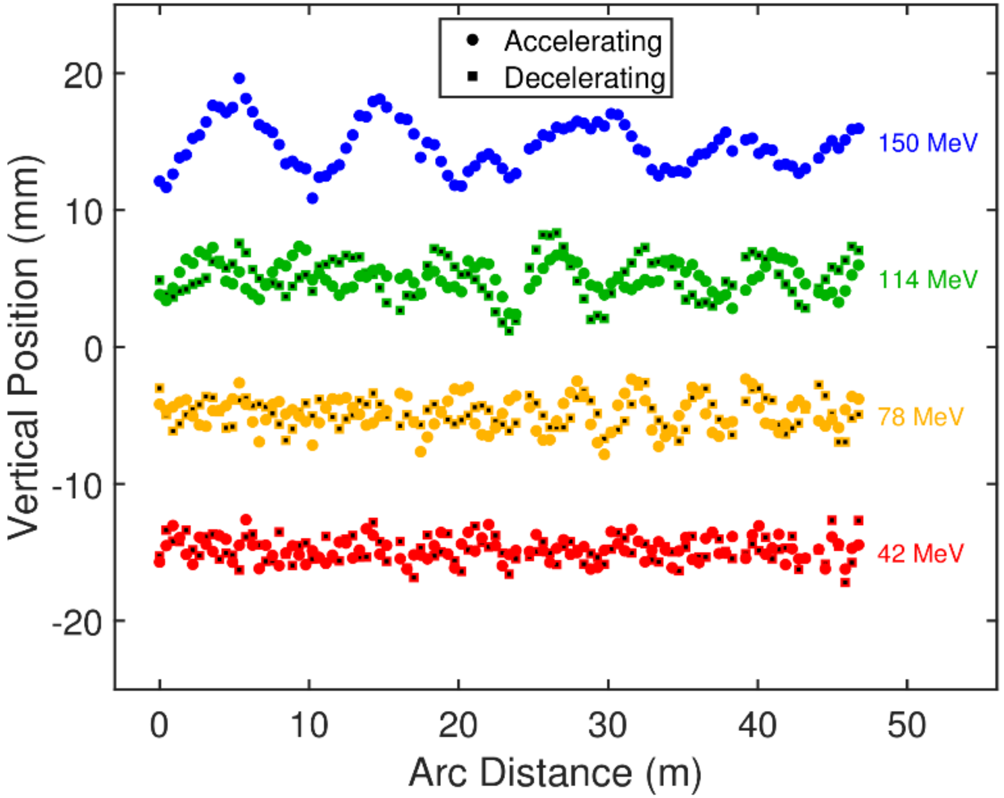
CBETA: Four-Turn Energy Recovery

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





DOI: 10.1103/PhysRevLett.125.044803

CBETA ICS Collaboration

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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)

UKRI Science and Technology Facilities Council

MANCHESTER 1824 The University of Manchester

OLD DOMINION UNIVERSITY

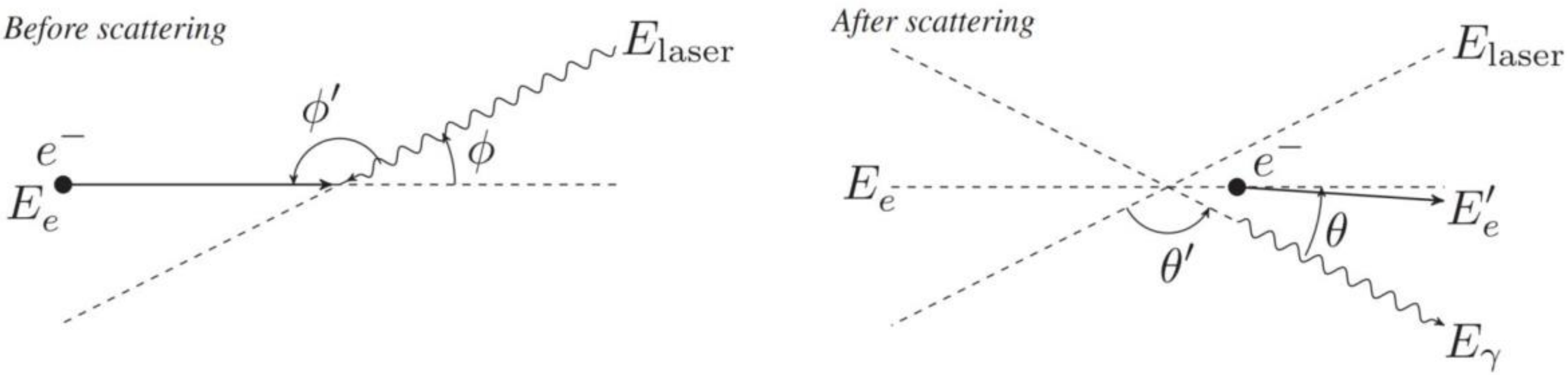
Jefferson Lab Thomas Jefferson National Accelerator Facility

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

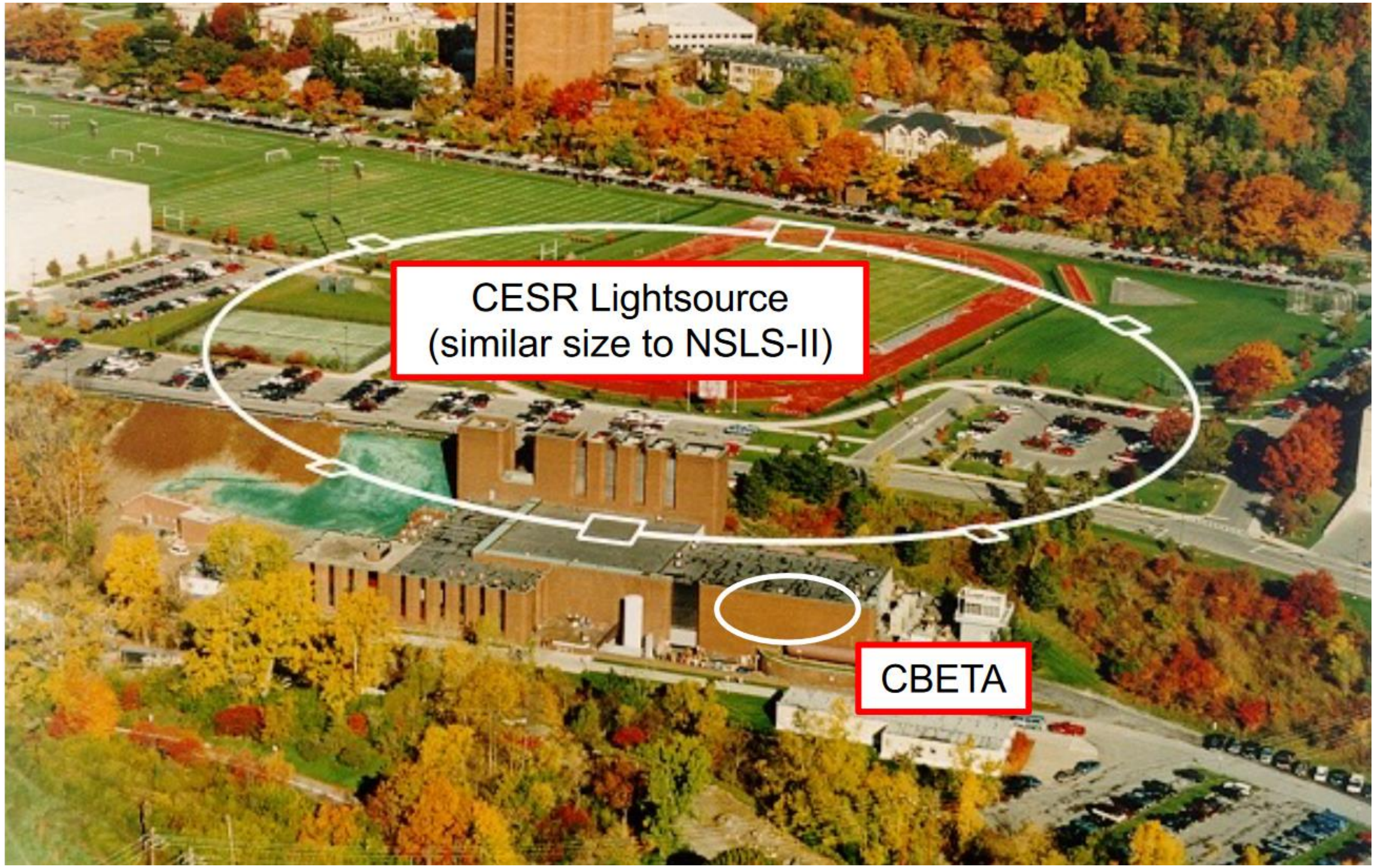


DOI: 10.1103/PhysRevAccelBeams.24.050701

CBETA ICS

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

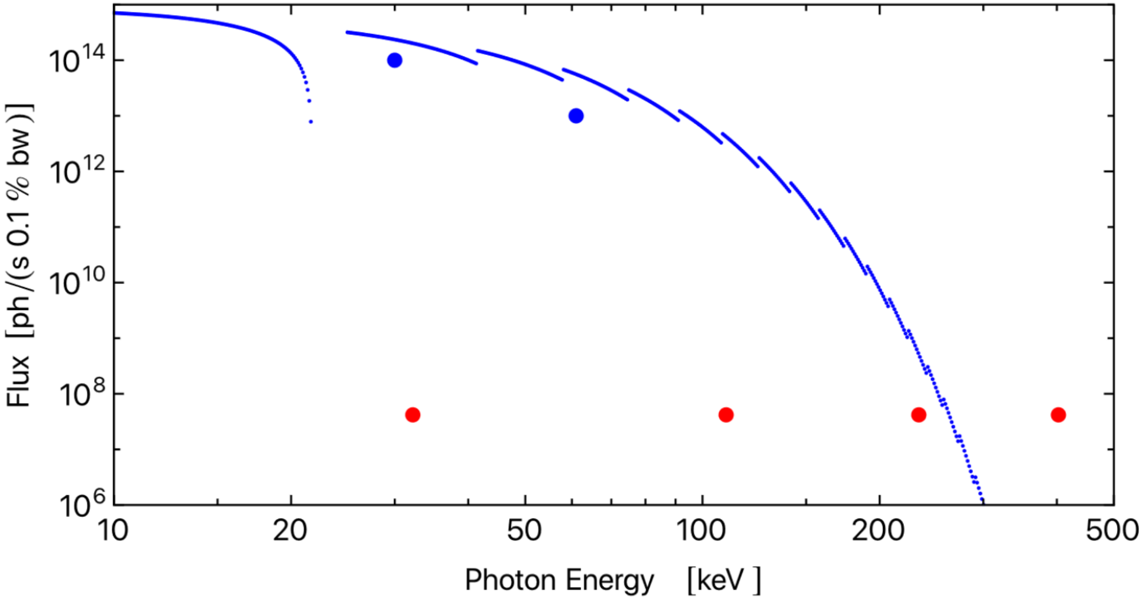
- But:
  - Cost more
  - Bigger footprint
  - Limited availability
  - Higher energy spread x-rays

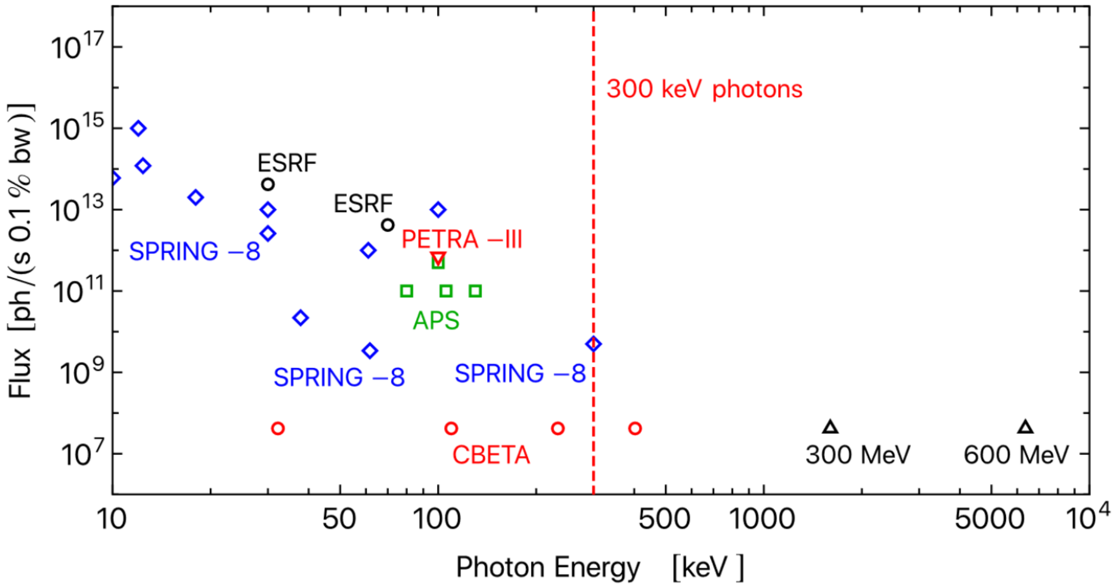


Picture from DOI: 10.18429/JACoW-IPAC2022-TUIZGD1

DOI: 10.1103/PhysRevAccelBeams.24.050701

CBETA ICS





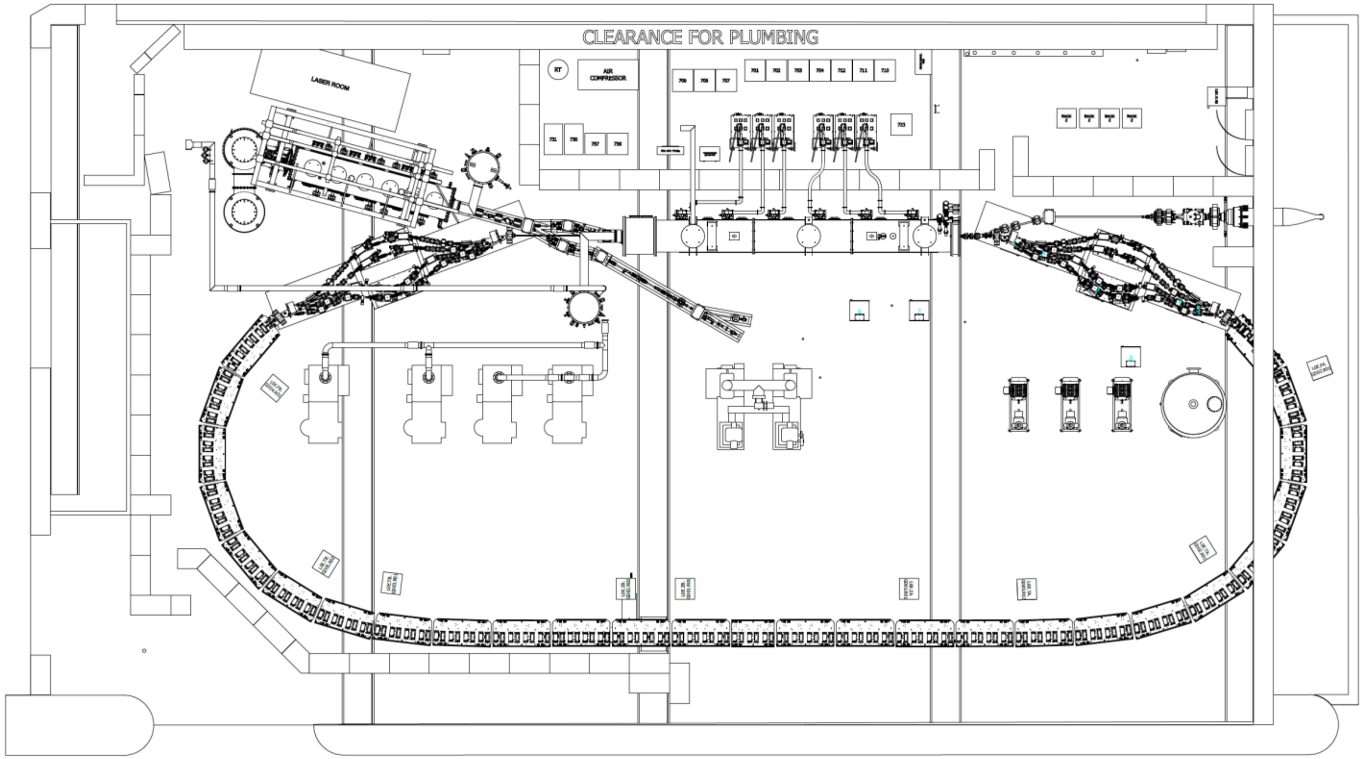
Left: Flux per 0.1% BW of the CBETA ICS (red) against the harmonic curves and data (blue) of the Spring-8 high energy undulator. Right: Flux per 0.1% BW of the CBETA ICS (red) against a collection of the major high energy storage ring undulators across the globe.

- 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

DOI: 10.1103/PhysRevAccelBeams.24.050701

CBETA ICS

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

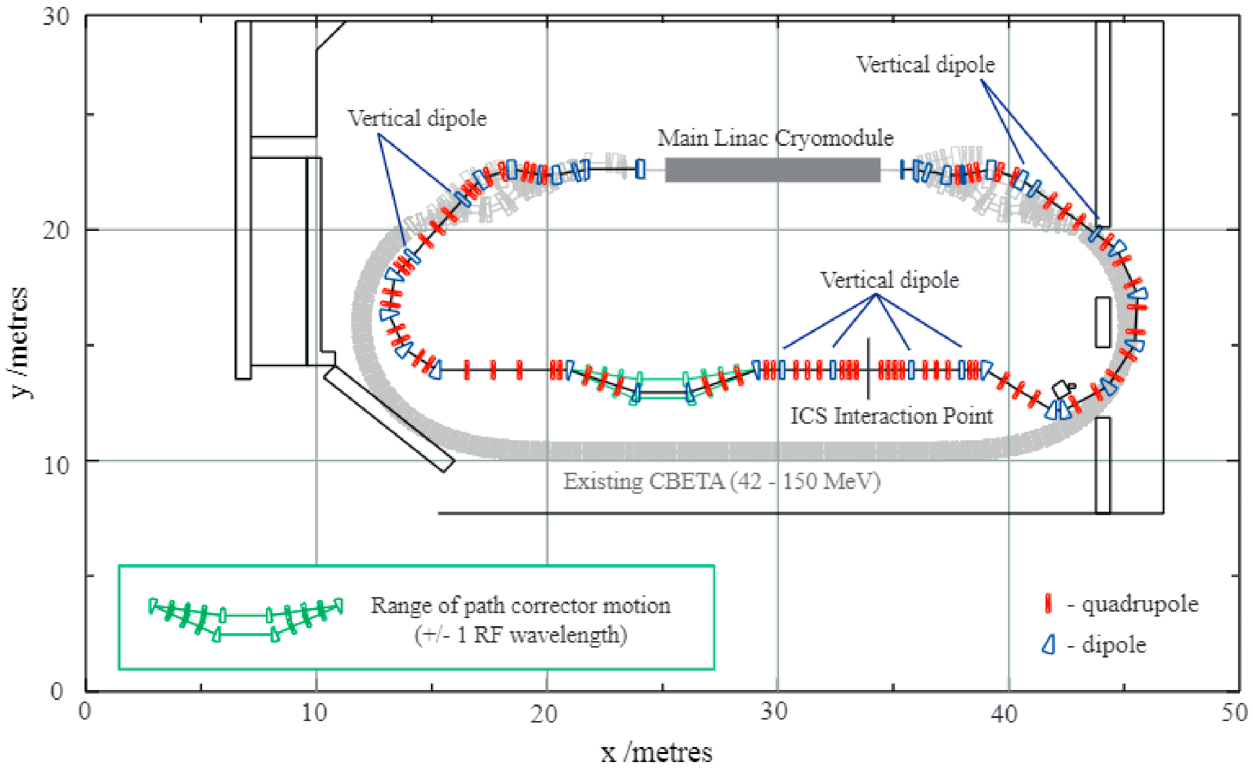


Schematic of the CBETA enclosure. MLC ~10 m for scale.

DOI: 10.1103/PhysRevAccelBeams.24.050701

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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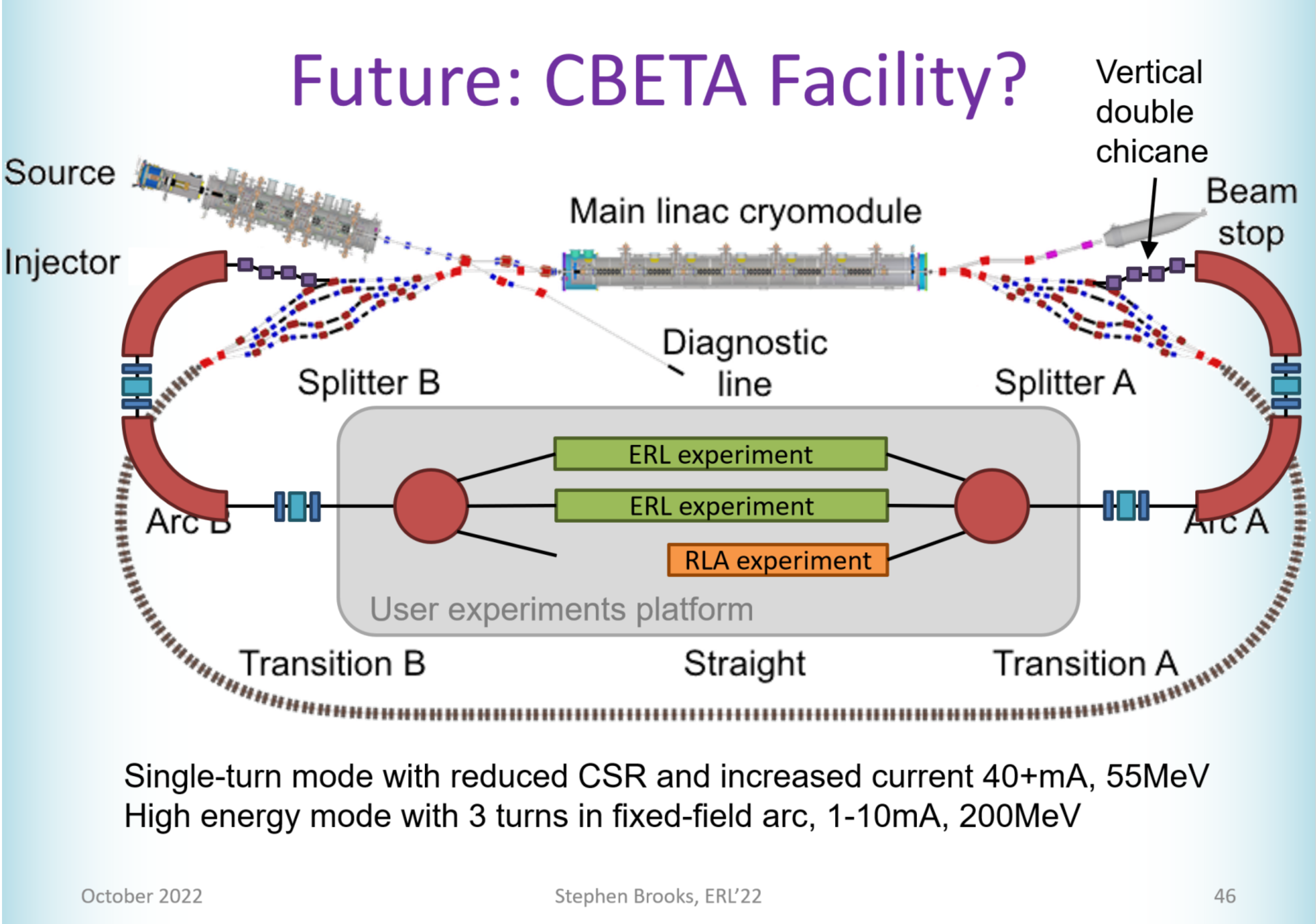
CBETA: Other Applications

- First proposed by Stephen Brooks in 2019
- Similar design concept – vertical extraction to a bypass line
- Flexibility of multiple experiments set up simultaneously



Generic FFA ERL: 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

DOIs: 10.18429/JACoW-IPAC2022-TUOZSP3
10.18429/JACoW-NAPAC2022-MOZD6

Generic FFA ERL: Why?

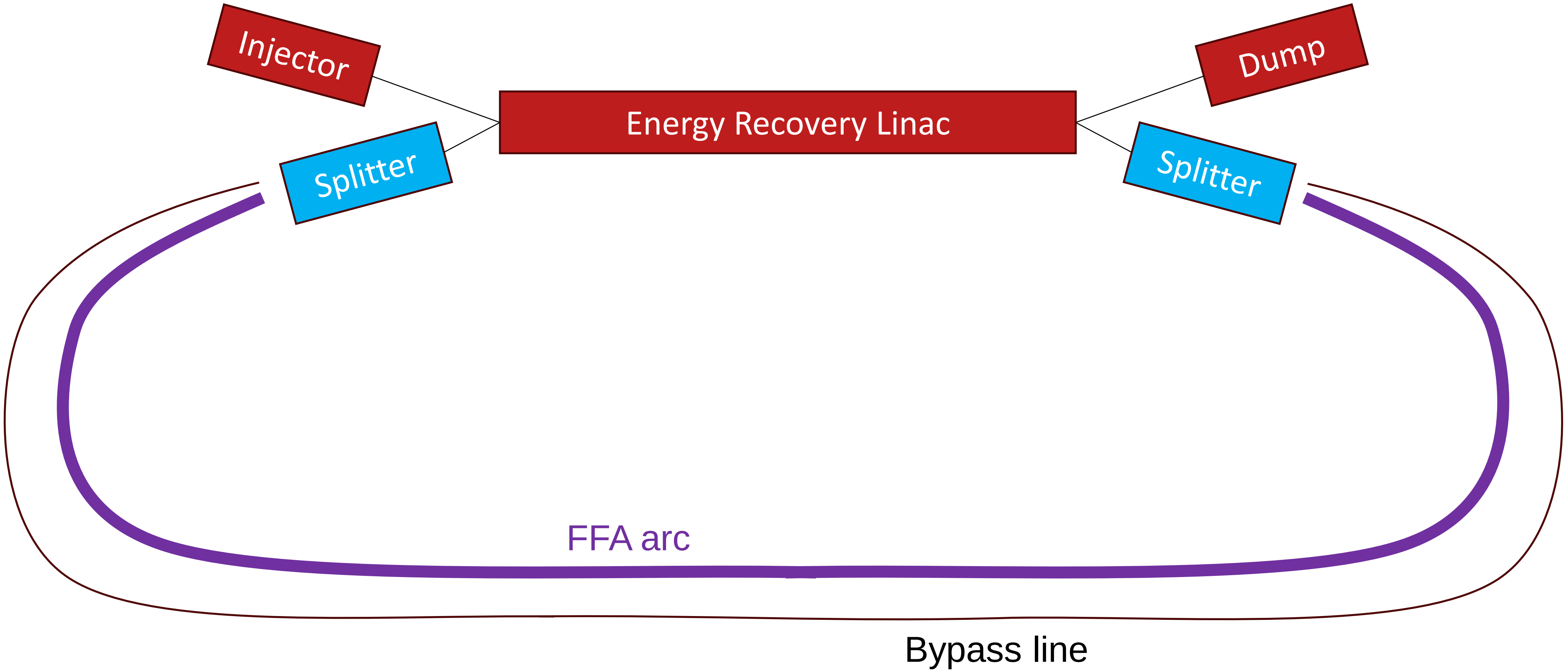
- Energy Recovery Linacs
  - Typically, smaller than a storage ring and more power efficient than a linac
  - Single-turn or multi-turn
  - ERLs can have higher beam power than installed SRF power

- 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, reducing the number of cryomodules for a given beam energy

- Very generic design:
  - Multi-turn ERL accelerates through FFA transport
    - Highest energy diverted into bypass line for relevant application OR
    - All or some energies have dedicated experimental lines between FFA arcs

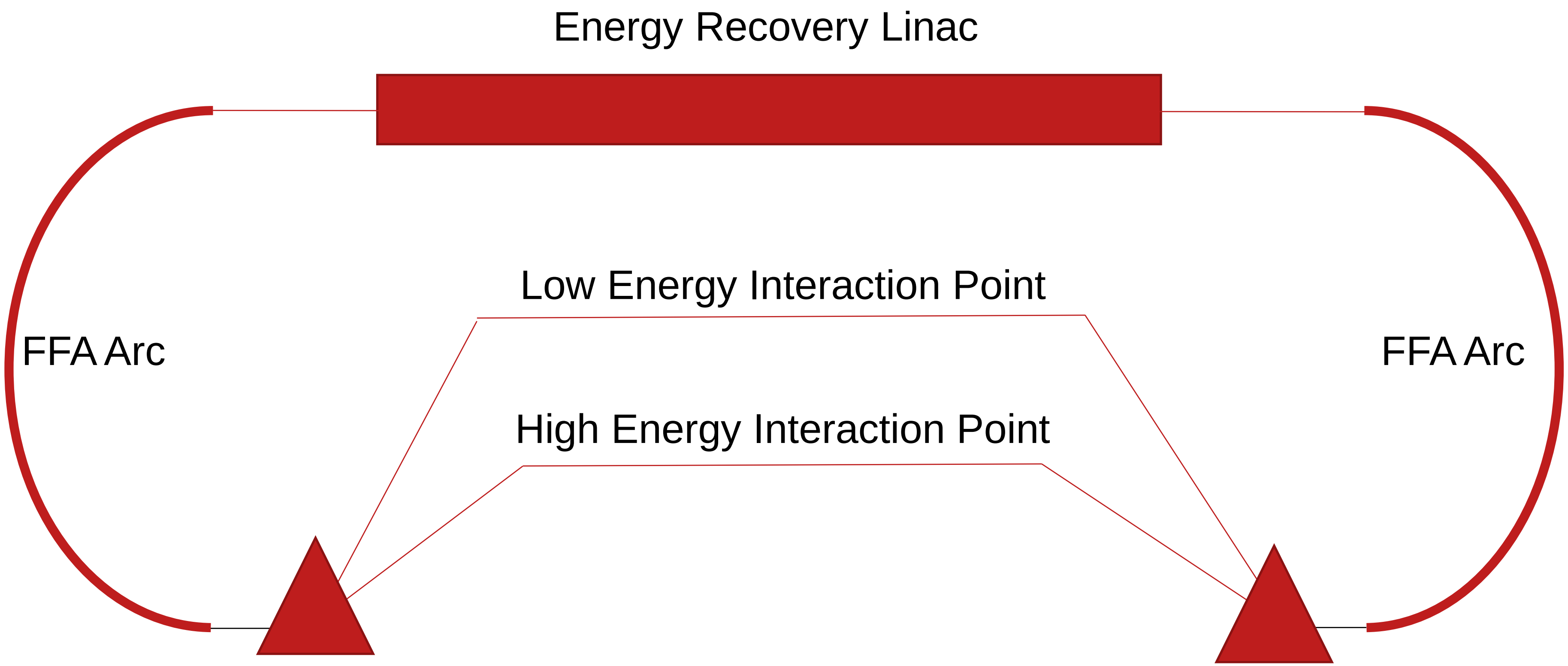
DOIs: 10.18429/JACoW-IPAC2022-TUOZSP3
10.18429/JACoW-NAPAC2022-MOZD6

Generic FFA ERL: Single Linac Highest Energy



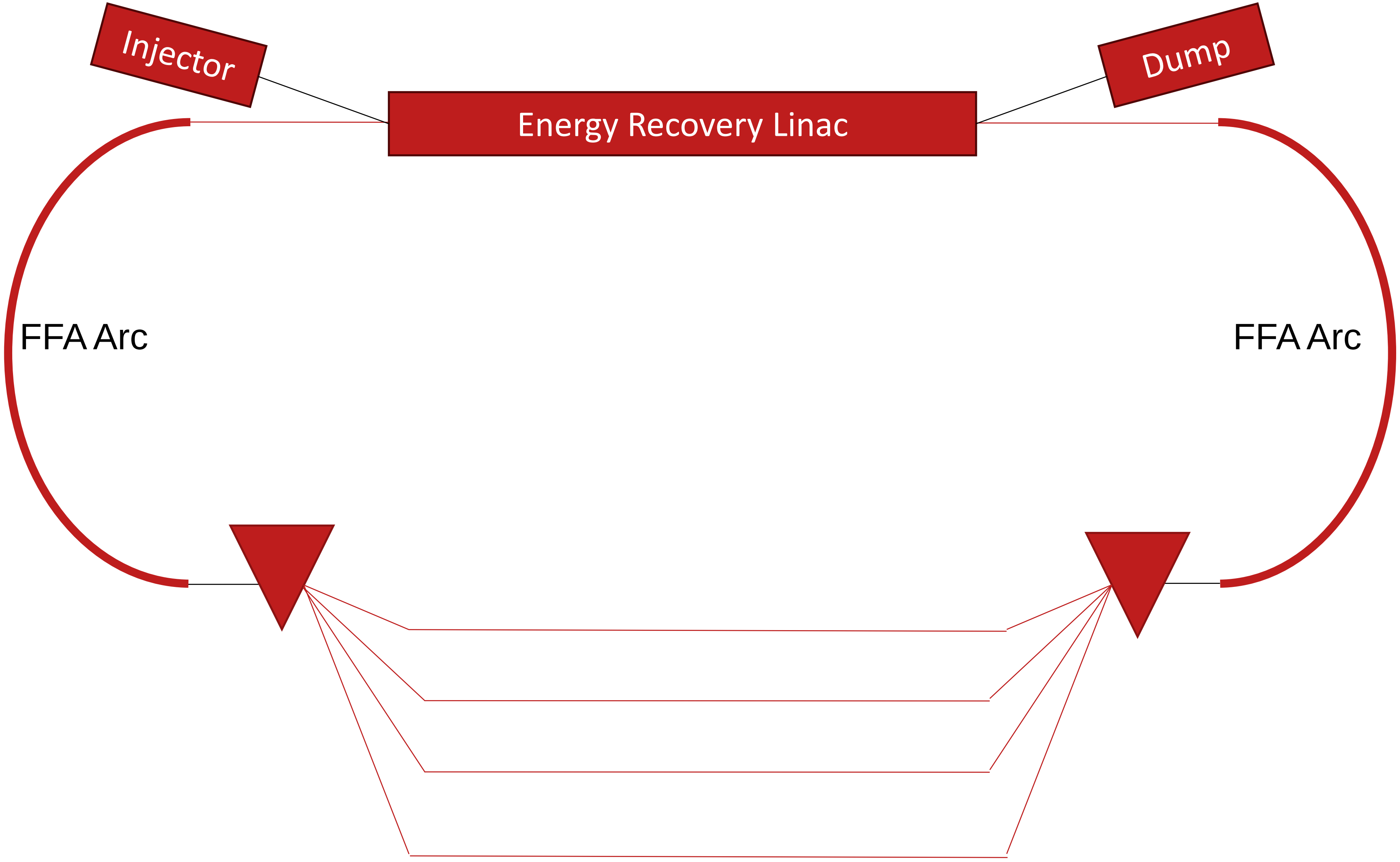
DOI: 10.18429/JACoW-NAPAC2022-MOZD6

Generic FFA ERL

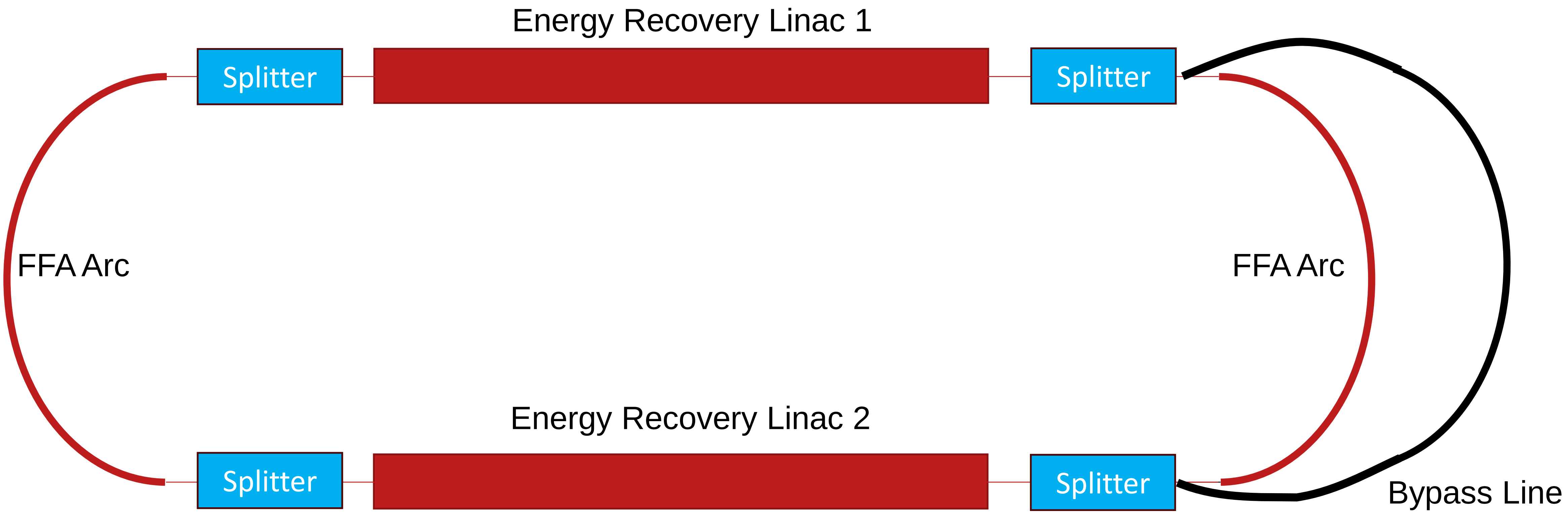


- Concept from Geoff Krafft (Jefferson Lab) for a simultaneous two-color Compton source
- Takes advantage of inherent wide-bandwidth in longitudinal direction

Generic FFA ERL: Single Linac Multiple Energies



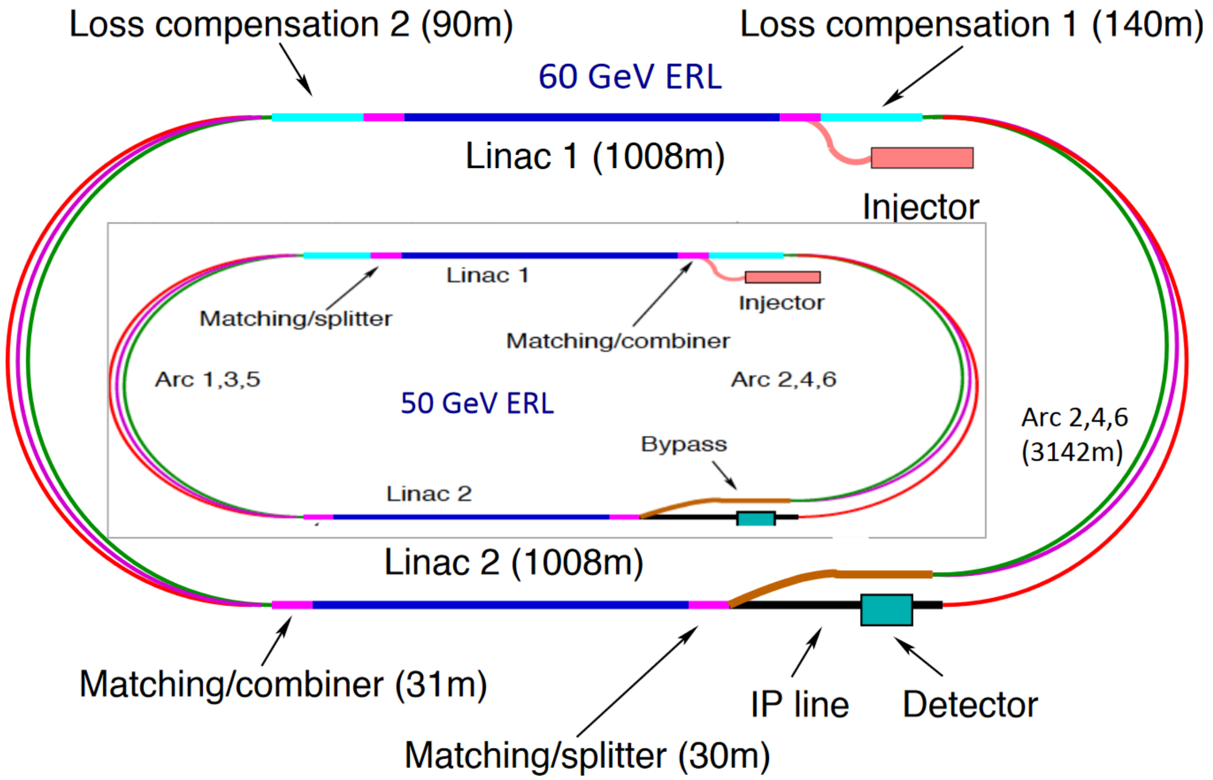
Generic FFA ERL: Two Linacs Highest Energy



Generic FFA ERL: LHeC

- Large Hadron Electron Collider

- Two potential configurations for a three-turn ERL tens of GeV



DOI: 10.1088/1361-6471/abf3ba
Jefferson Lab

Generic FFA ERL: Applications

- X-ray and Gamma-ray Inverse Compton Scattering Sources
- Free Electron Laser
- Hadron Cooler
- EUV Lithography
- Nuclear and HEP Colliders
- 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
10.18429/JACoW-NAPAC2022-MOZD6

FFA@CEBAF Working Group

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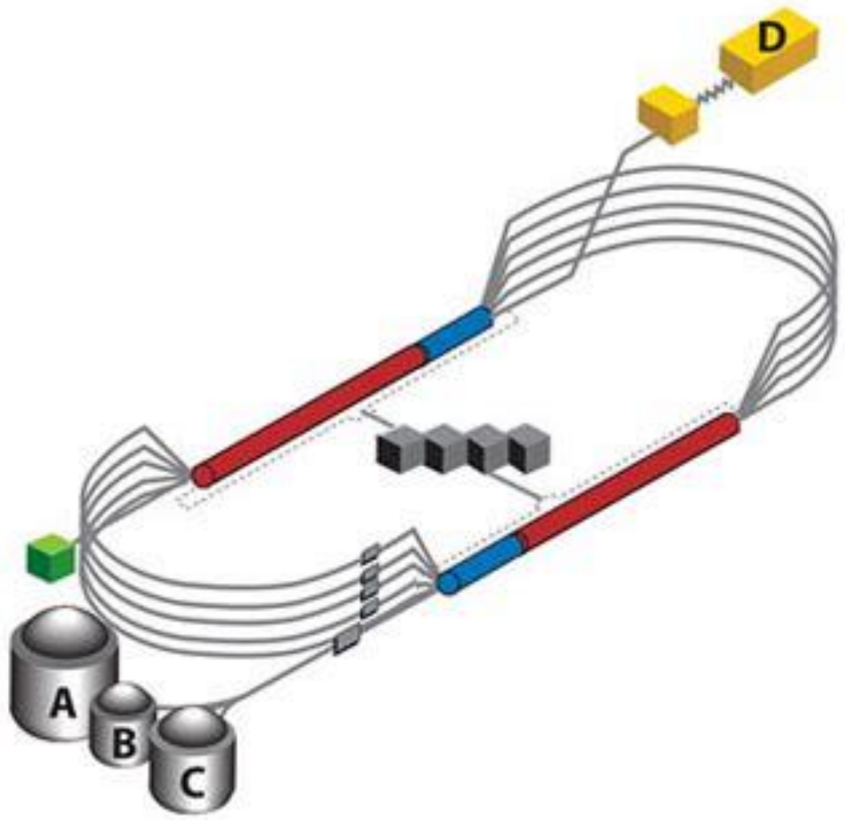
J.S. Berg, S.J. Brooks, D. Trbojevic

Cornell University and Brookhaven National Lab:
G.H. Hoffstaetter

Oak Ridge National Lab:
V.W. Morozov

FFA@CEBAF

- Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab
- Recirculating linac (RLA)
- 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

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- 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

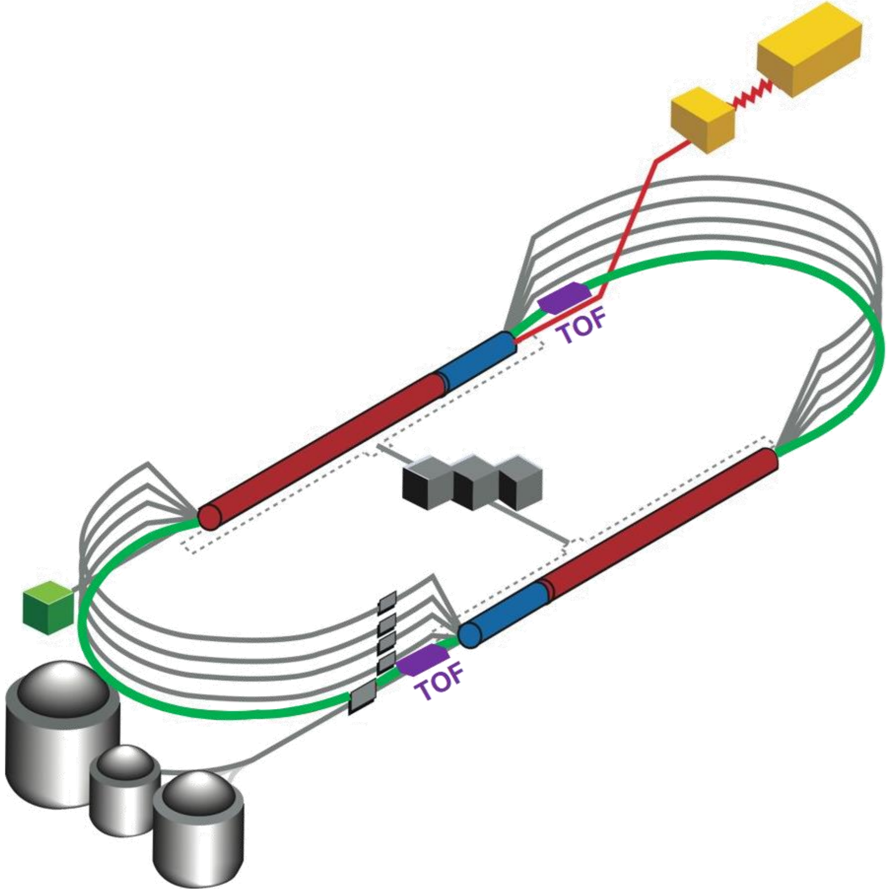
DOI: 10.18429/JACoW-IPAC2023-MOPL182

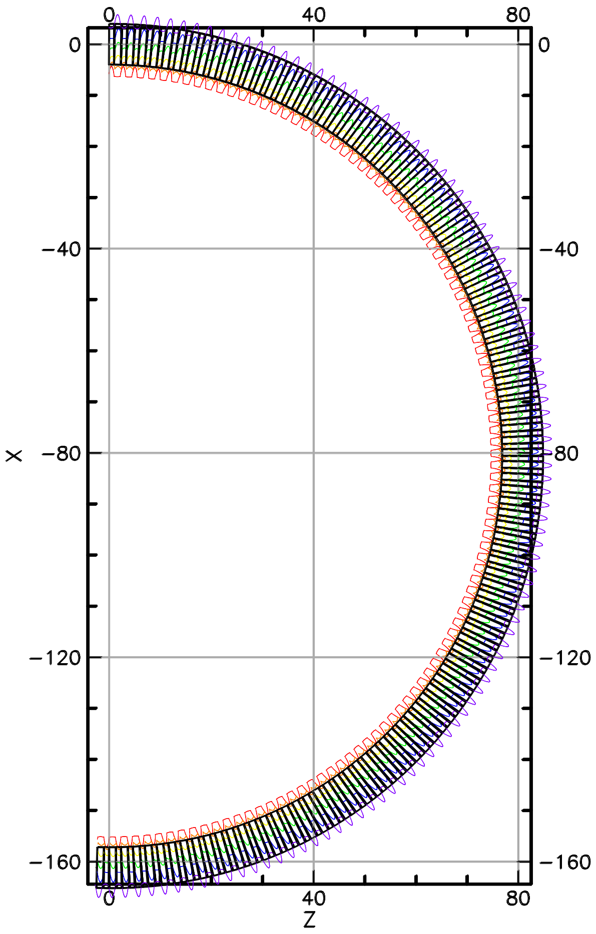
FFA@CEBAF

- Current concept is to remove highest energy arc on both sides and replace it with FFA transport and a splitter section

- Expected energy upgrade to 20 GeV or greater

- Several talks with more details this week





DOI: 10.18429/JACoW-IPAC2023-MOPL182

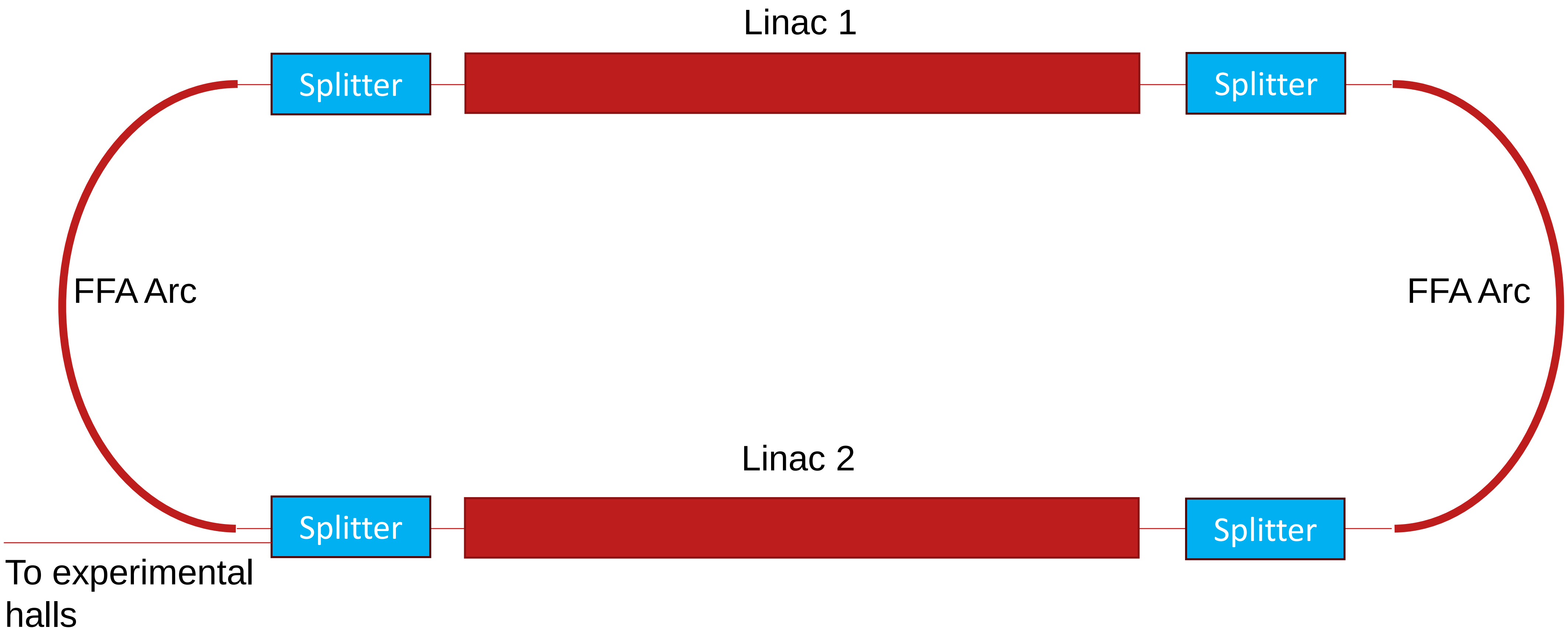
Generic FFA RLA: Why?

- While an RLA does not have the same benefit of reducing need for SRF power as an ERL does, it does reduce both the footprint and the number of cryomodules necessary to achieve a desired energy

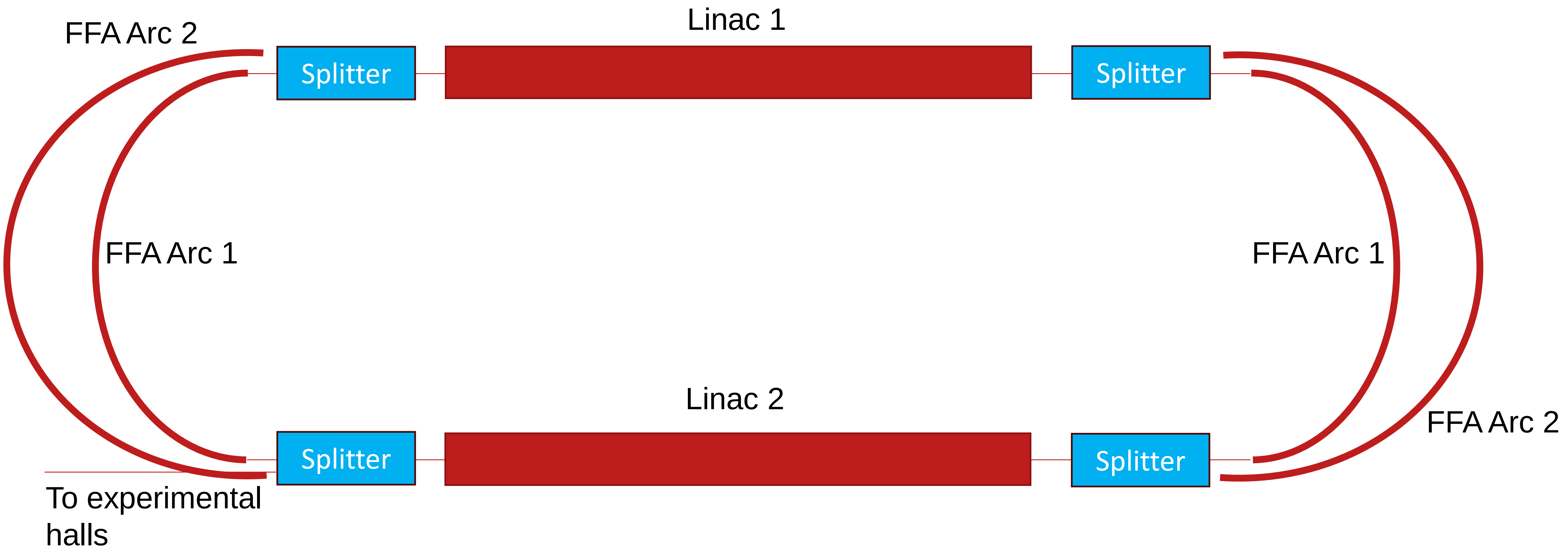
- For beam delivery to experimental halls, particularly when the beam is too perturbed to be recovered, RLAs are more useful than ERLs

- FFA arcs can be instrumental in future RLA designs as well as extending the energy reach of existing facilities

Generic FFA RLA: 1 FFA



Generic FFA RLA: 2 FFAs



Conclusion

- 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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Questions?

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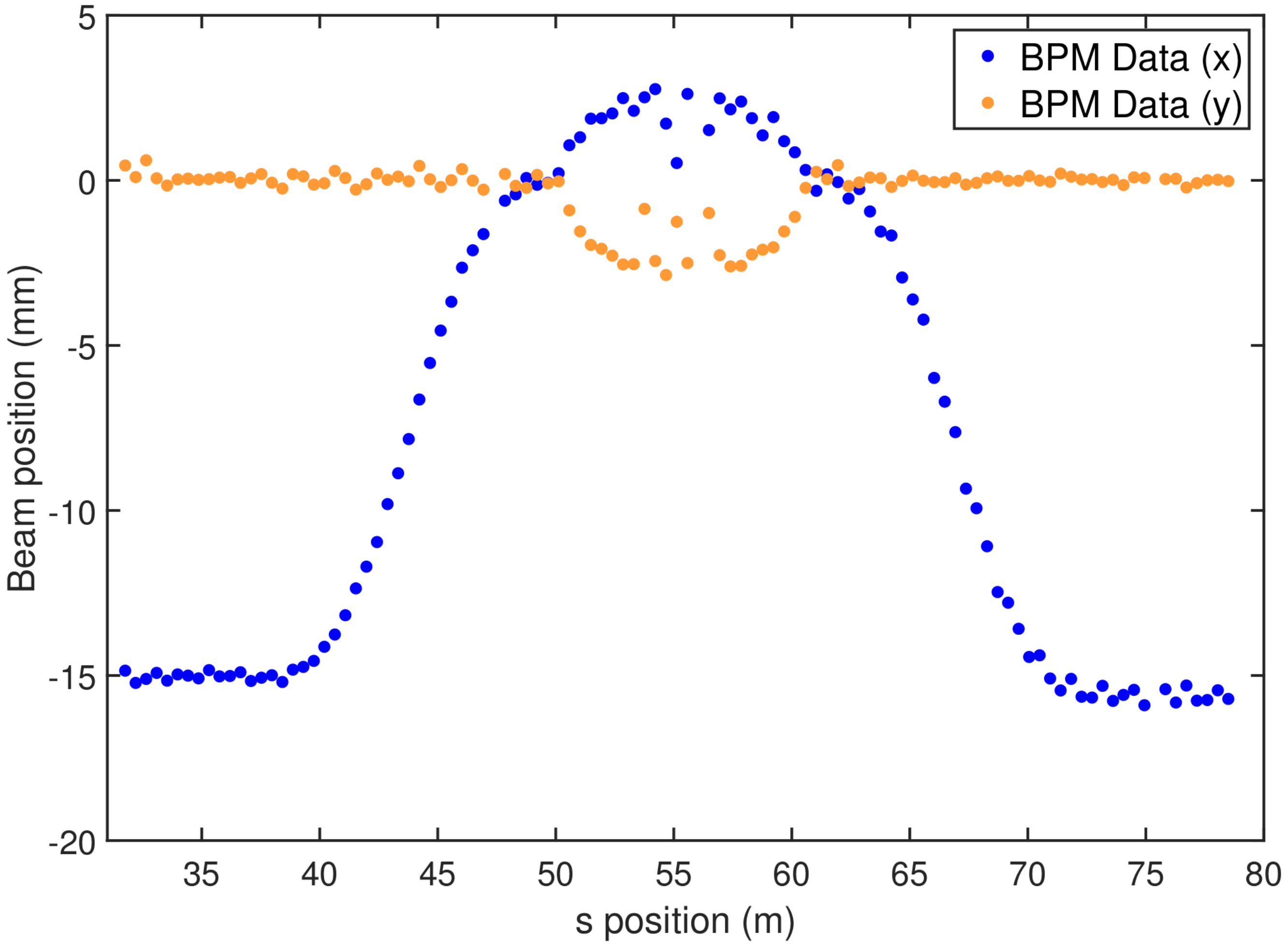
Thanks for your attention!



References

- G.H. Hoffstaetter *et al.*, “CBETA Design Report, Cornell-BNL ERL Test Accelerator”, 2017. doi:10.48550/arXiv.1706.04245

- C. Gulliford *et al.*, “Measurement of the per cavity energy recovery efficiency in the single turn Cornell-Brookhaven ERL Test Accelerator configuration”, *Physical Review Accelerators and Beams*, vol. 24, p. 010101, Jan. 2021. doi:10.1103/PhysRevAccelBeams.24.010101

- A. Bartnik *et al.*, “CBETA: First Multipass Superconducting Linear Accelerator with Energy Recovery”, *Physical Review Letters*, vol. 125, p. 044803, Jul. 2020. doi:10.1103/PhysRevLett.125.044803

- G. H. Hoffstaetter, “An ERL-Driven Intense Compton Source Above 100 keV and Other ERL Applications” presented at IPAC'22, Bangkok, Thailand, Jun. 2022 doi:10.18429/JACoW-IPAC2022-TUIZGD1

- 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

References, continued

- A. Hutton, M. Klein, and B.C. Kuske, “The European ERL Roadmap” in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 831—83 doi:10.18429/JACoW-IPAC2022-TUOZSP3

- K.E. Deitrick and G.H. Hoffstaetter, “Accelerator Physics Lessons from CBETA, the First Multi-Turn SRF ERL”, *in Proc. NAPAC'22*, Albuquerque, NM, USA, Aug. 2022, pp. 41-44. doi:10.18429/JACoW-NAPAC2022-MOZD6

- K.E. Deitrick *et al.*, “Technology Spinoff and Lessons Learned from the 4-Turn ERL CBETA” in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 3762--3764. doi:10.18429/JACoW-IPAC2021-THPAB007

- P. Agnostini *et al.*, “The Large Hadron-Electron Collider at the HL-LHC”, *J. Phys. G: Nucl. Part. Phys.,* vol. 48 110501. doi: 10.1088/1361-6471/abf3ba

- K. Deitrick *et al.*, “CEBAF 22 GeV FFA Energy Upgrade” in *Proc. IPAC’23*, Venice, Italy, May 2023 doi:10.18429/JACoW-IPAC2023-MOPL182

CBETA: Four-Turn Energy Recovery

- Transmission in the FFA arc for each pass
- Potential contributors to abrupt transmission drop have been identified, but none have proven to be the sole cause
- Transmission loss prevented beam loading measurement