An ERL-Driven Intense Compton Source Above 100 keV and Other ERL Application

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For the CBETA ICS team

CBETA

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Brookhaven National Laboratory — a passion for discovery

Office of Science, U.S. Department of Energy

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

UKRI Science and Technology Facilities Council

Credit and References

- Intense monochromatic photons above 100 keV from an inverse Compton source, ***K. Deitrick***, G.H. Hoffstaetter, C. Franck, B.D. Muratori, P.H. Williams. G.A. Krafft, B. Terzić, ***J. Crone***, H. Owen, Phys. Rev. AB 24, 050701 (2021)

- Measurement of the per cavity energy recovery efficiency in the single turn Cornell-Brookhaven ERL Test Accelerator configuration, C. Gulliford , N. Banerjee , ***A. Bartnik***, J. Crittenden , K. Deitrick , J. Dobbins , G. H. Hoffstaetter , P. Quigley, and K. Smolenski, J. S. Berg , R. Michnoff, S. Peggs, ***D. Trbojevic***, Phys. Rev. AB 24, 010101 (2021)

- CBETA: First Multipass Superconducting Linear Accelerator with Energy Recovery, A. Bartnik, N. Banerjee , D. Burke, J. Crittenden , K. Deitrick , J. Dobbins , C. Gulliford , G. H. Hoffstaetter , Y. Li, W. Lou, P. Quigley, D. Sagan , and K. Smolenski, J. S. Berg, S. Brooks , R. Hulsart, G. Mahler, F. Meot, R. Michnoff, S. Peggs, T. Roser , D. Trbojevic , N. Tsoupas, Phys. Rev. Letters 125, 044803 (2020)

Some material provided by K. Deitrick and J. Crone

Abstract

This talk will specify the ***x-ray characteristics that can be achieved by Compton scattering*** off a high-brightness electron beam that ERLs make available. These are important parameters for x-ray users as well as for nuclear physics applications. The use of the ***Cornell BNL ERL Test Accelerator (CBETA)*** as an example layout for such a Compton source will be presented, including some accelerator physics details of CBETA's design, construction, and commissioning. The talk will also highlight other ***applications that are enabled by unique features of ERLs***.

High Beam Current at Reduced Cost

By **recovering the Energy** of accelerated beams, Energy Recovery Linacs (ERLs) make **large beam powers** possible that would otherwise be prohibitively expensive.

Linacs produce **high beam qualities** for scientific experiments and for industrial applications, but their **beam power is limited** by the available electrical power.

ERLs surpass this power limit: much larger beam currents and beam powers become available because the beam energy is recaptured.

How do ERLs compare to other accelerators?

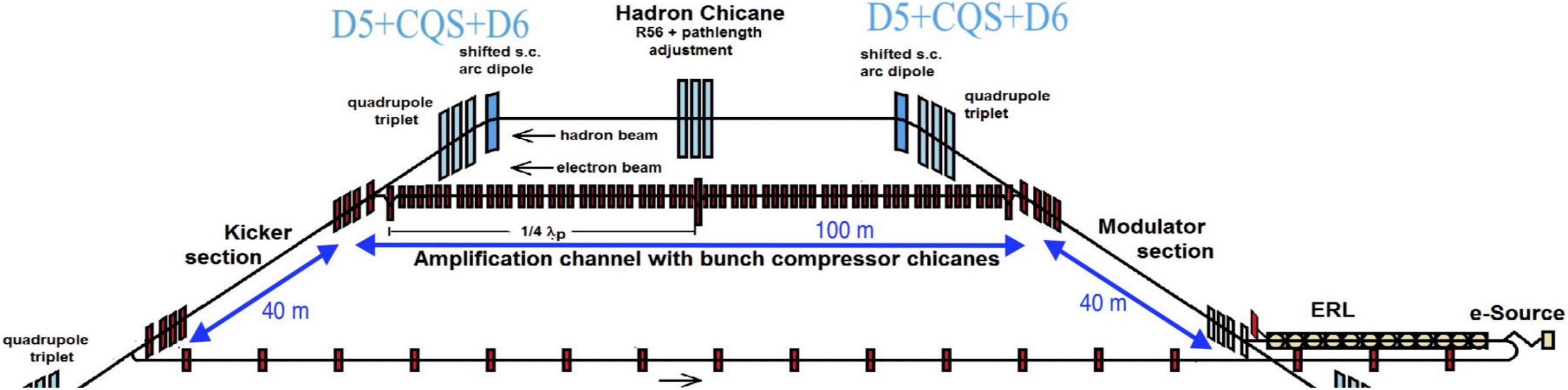
(a) high currents, like storage rings, because the energy is recovered,

(b) high beam quality (low emittance, bunch length, and energy spread) like linacs, because each bunch traverses it only once,

(c) tolerates beam disruption as each bunch is used only once before it’s discarded.

All these strengths of ERLs are beneficial to EIC cooling!

Application: EIC Hadron Cooler ERL



- 400kV DC gun for 100 mA of beam and 4 MeV SRF injector
- Dogleg ERL merger
- 149 MeV Super conducting Energy Recovery LINAC (in existing RHIC tunnel)
- e Beam transport to merge hadron beam
- Amplification section with chicanes for electrons
- Hadron chicane (existing magnets) path length matching & R56 adjust
- Return transport of electron beam to ERL.
- Detailed design in Bmad

ERL Application overview

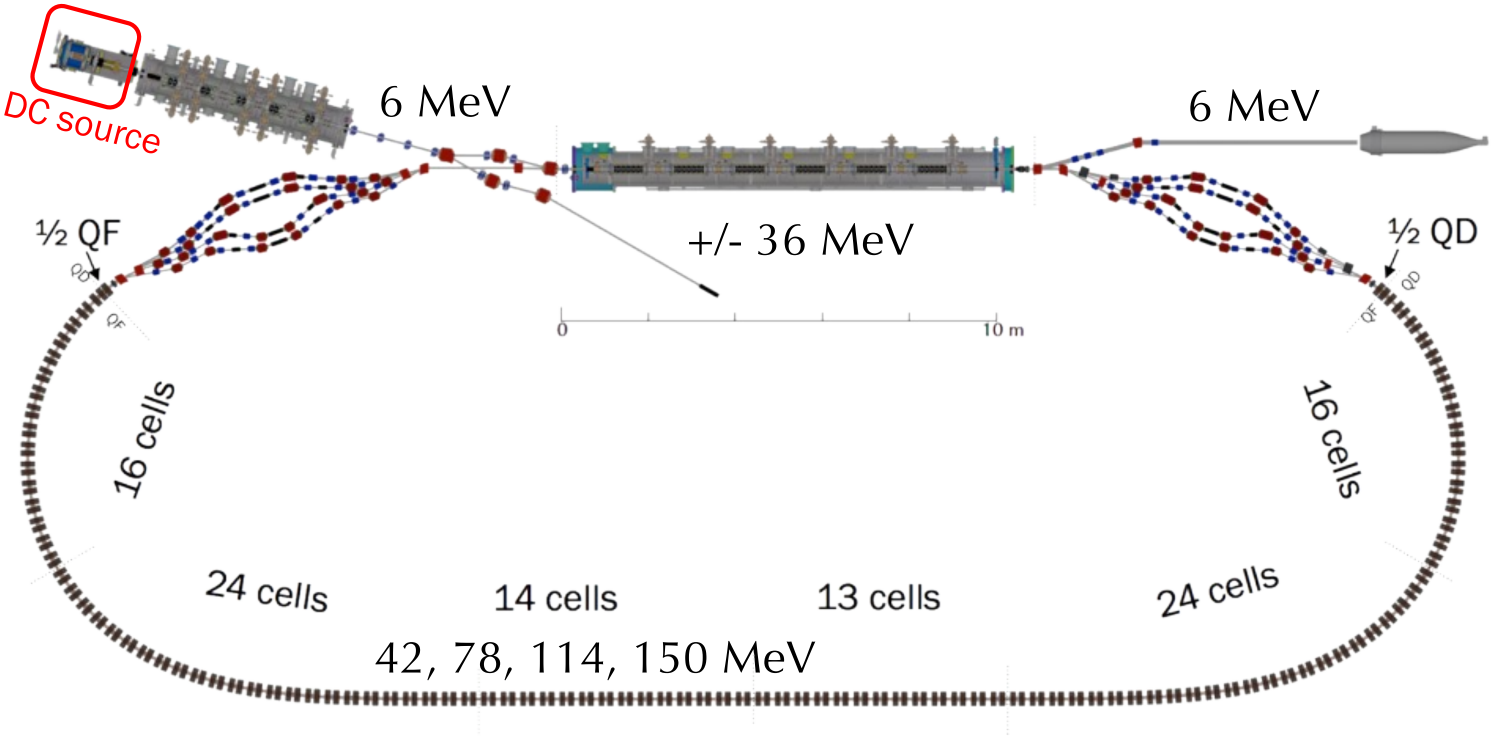
- Coherent (fast) hadron coolers and incoherent hadron coolers.
- High-power FELs
- Coherent light sources
- Lithography for chip production
- Nuclear Physics Colliders (from DarkLight to an ERL eRHIC)
- Compton-Scattering gamma source for Nuclear physics
- Medical isotope production, transmutation of nuclear waste,
- High Energy Physics ERLs:
  - LHeC
  - CERC (FCC-ee as an ERL)
  - ERLC (ILC as an ERL)
- Compton-Scattering X-ray sources

Described in soon to come:
Submission to JINST of
The Development of Energy-Recovery Linacs
240 page paper, 44 authors from 19 institutions.

CBETA: The test ERL at CBETA

CBETA

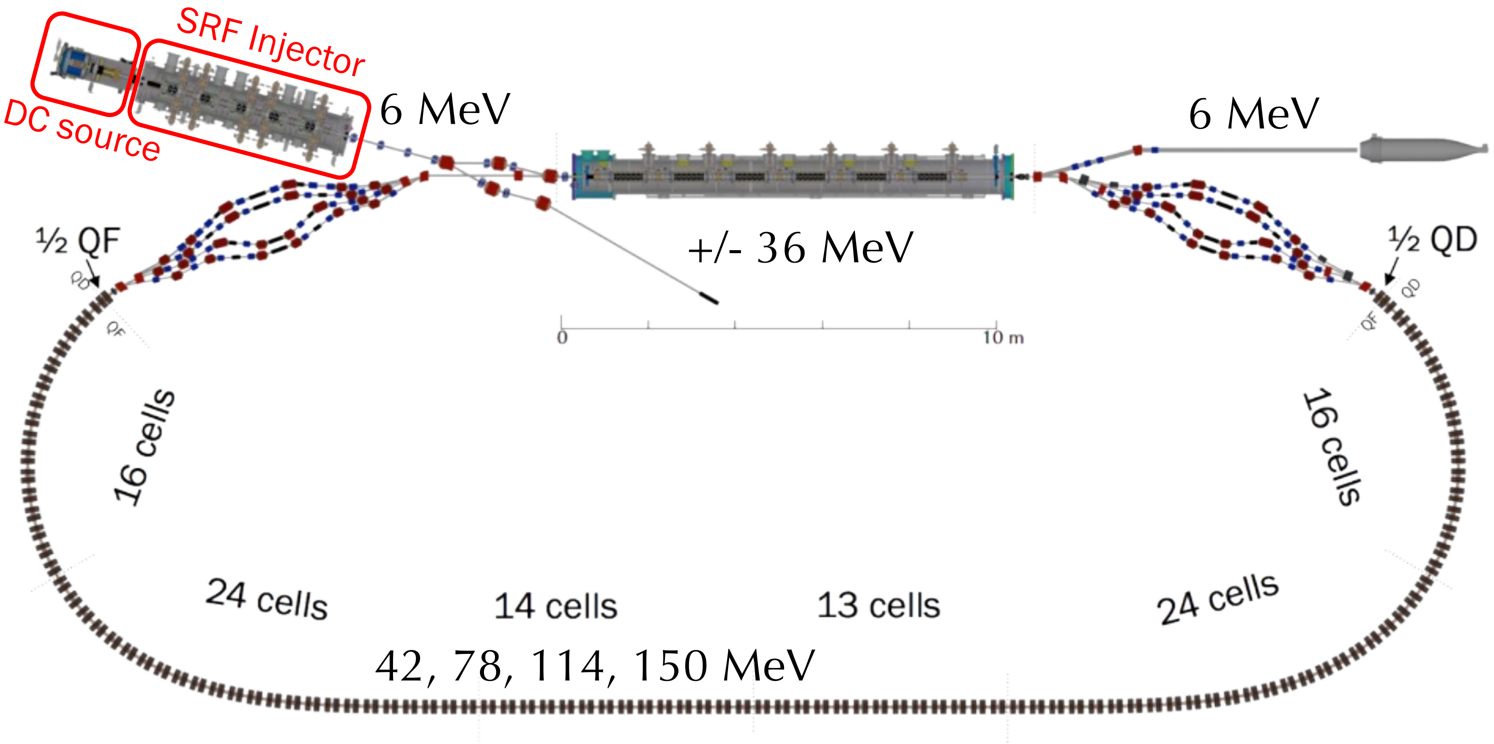
- Cornell DC gun, 2nC peak



CBETA: The test ERL at CBETA

CBETA

- Cornell DC gun, 2nC peak
- 100mA, 6MeV SRF injector (ICM), 1.3GHz



CBETA: The test ERL at CBETA

CBETA

- Cornell DC gun, 2nC peak
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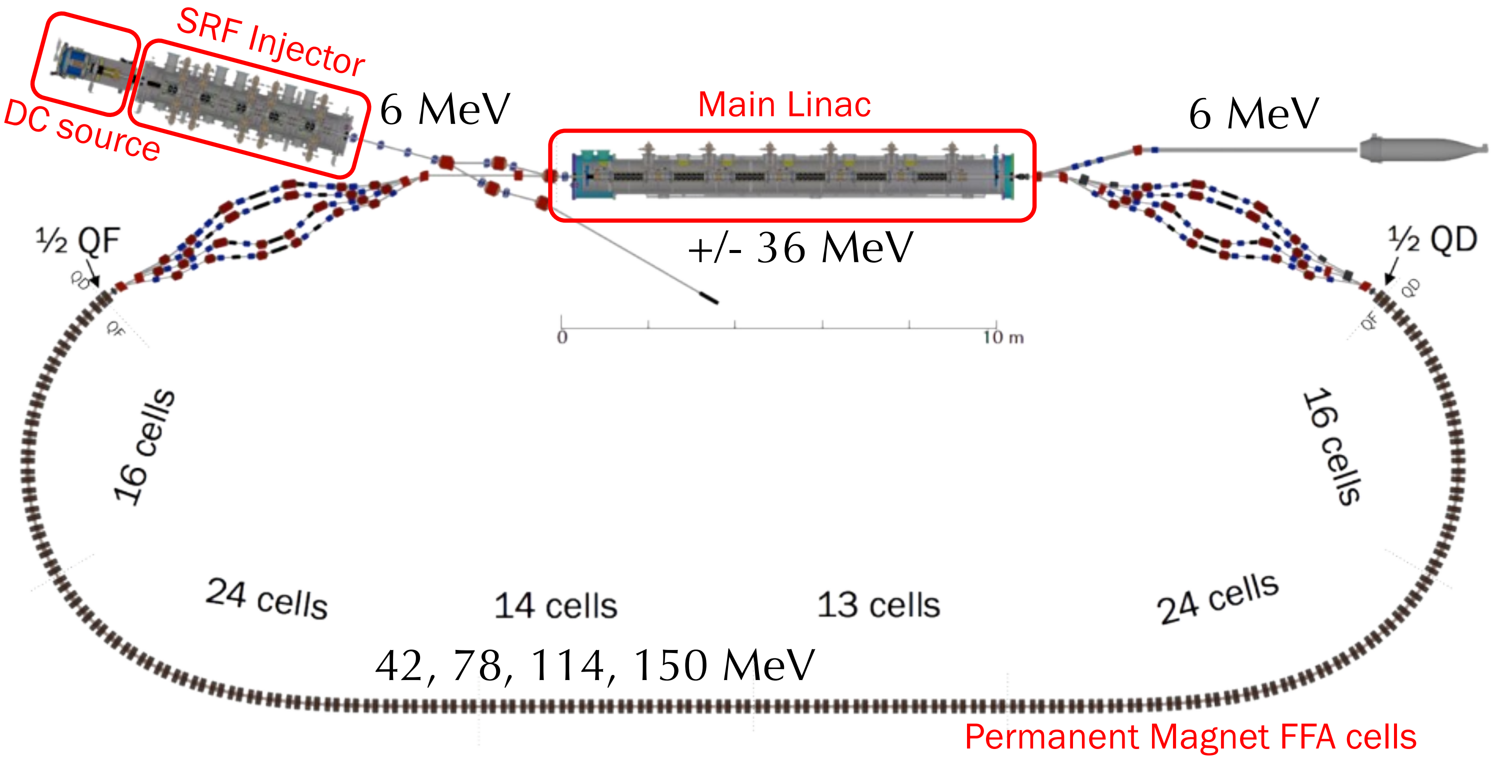
- 320mA, 6-cavity SRF CW Linac (MLC), 1.3GHz



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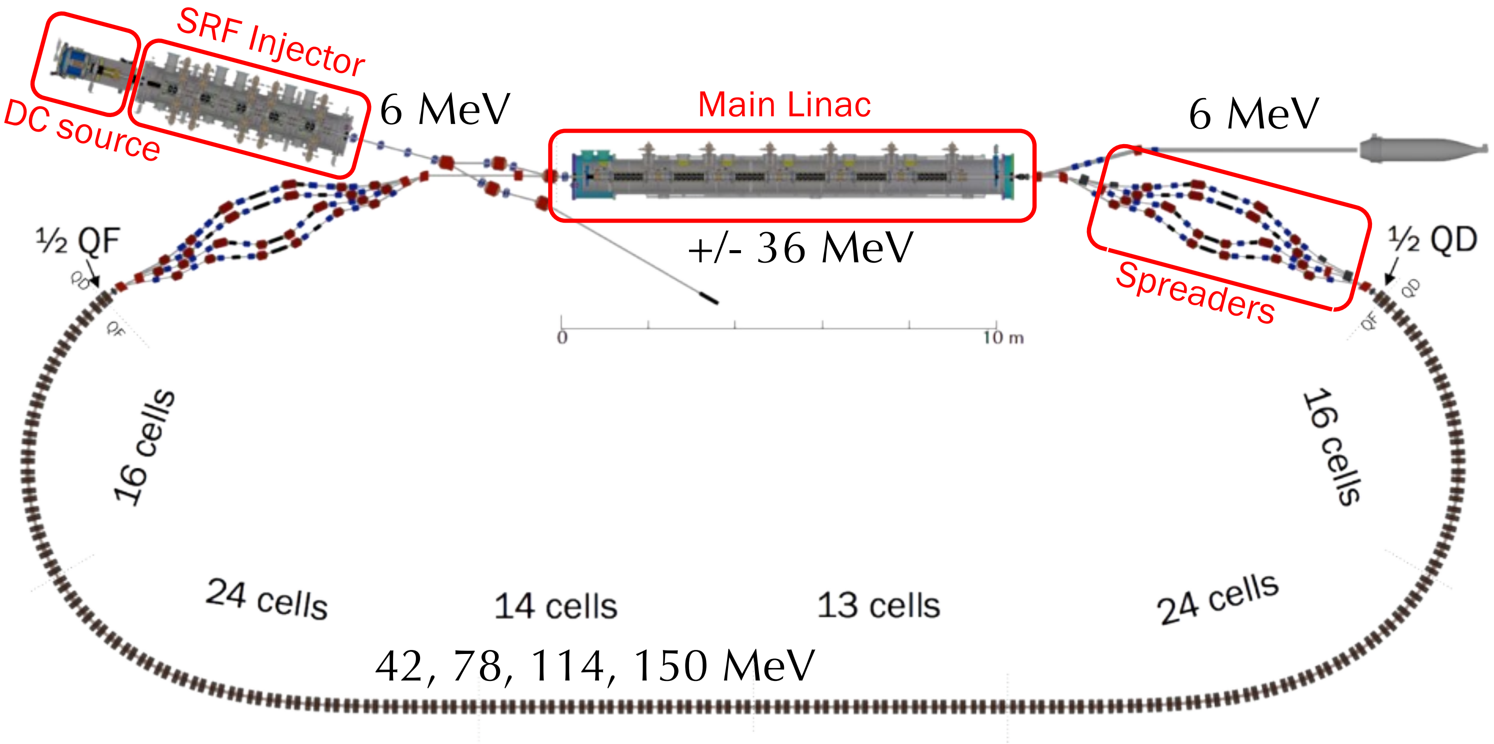
- 4 Spreaders / Combiners with electro magnets



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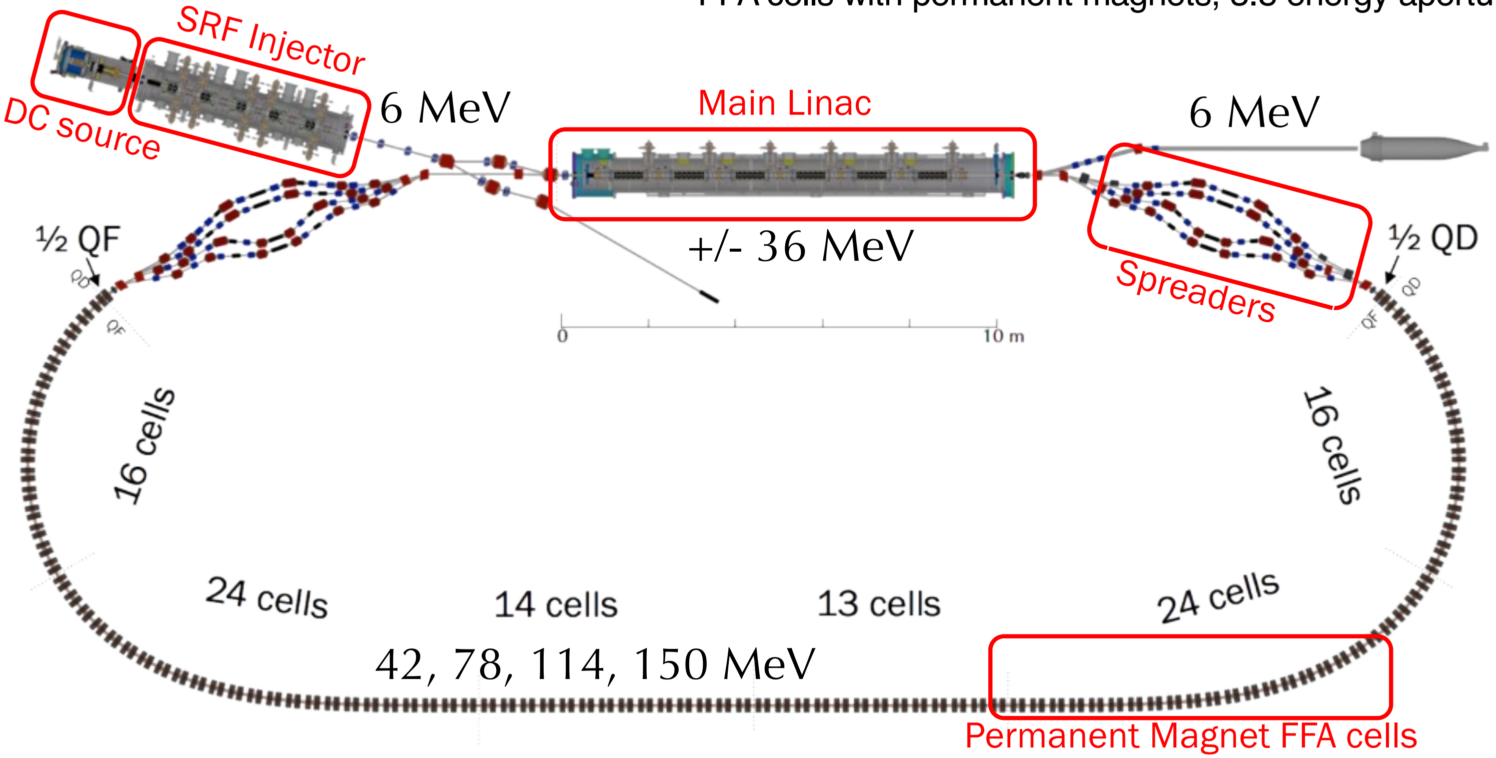
- FFA cells with permanent magnets, 3.8 energy aperture, 7 beams



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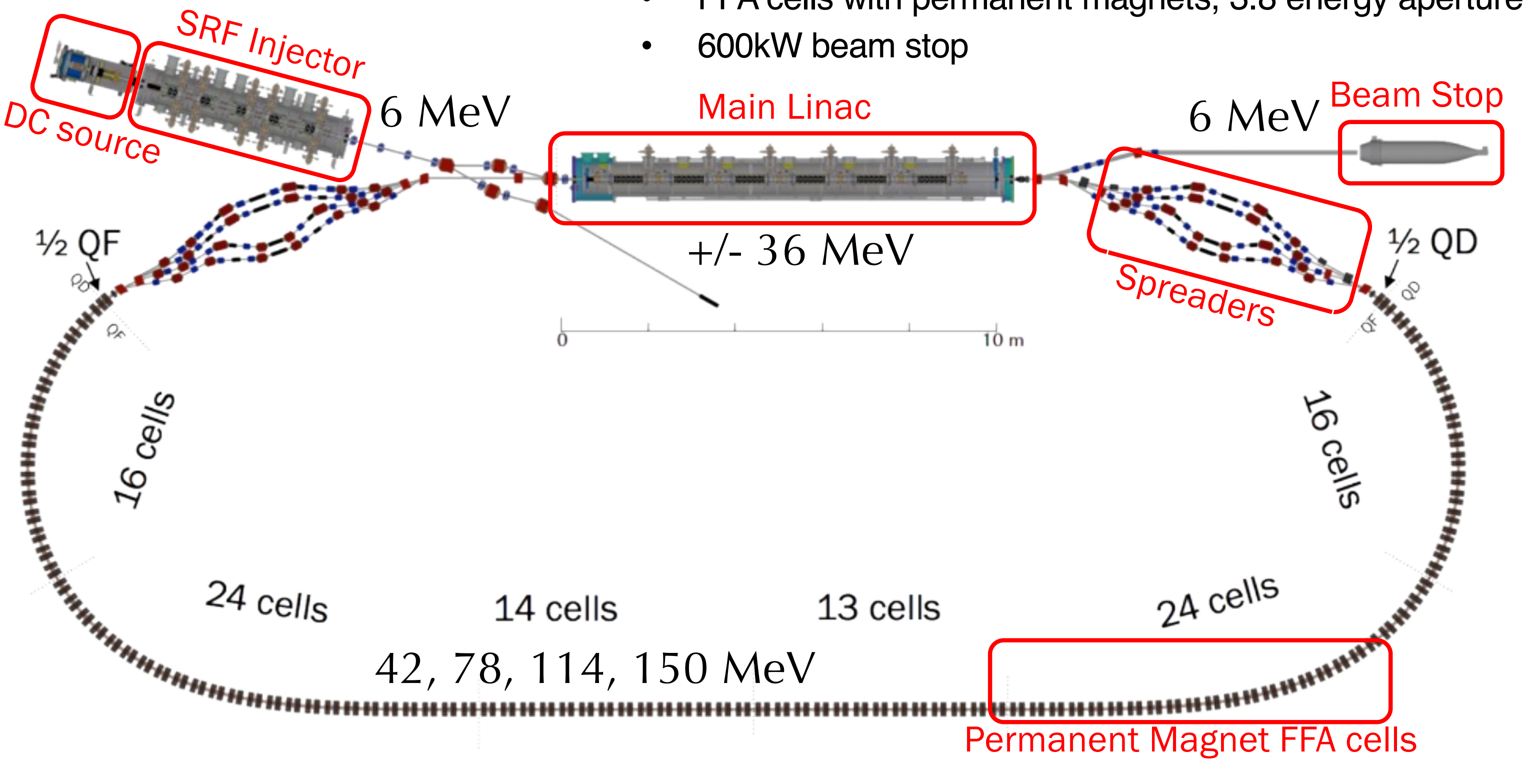
- 600kW beam stop



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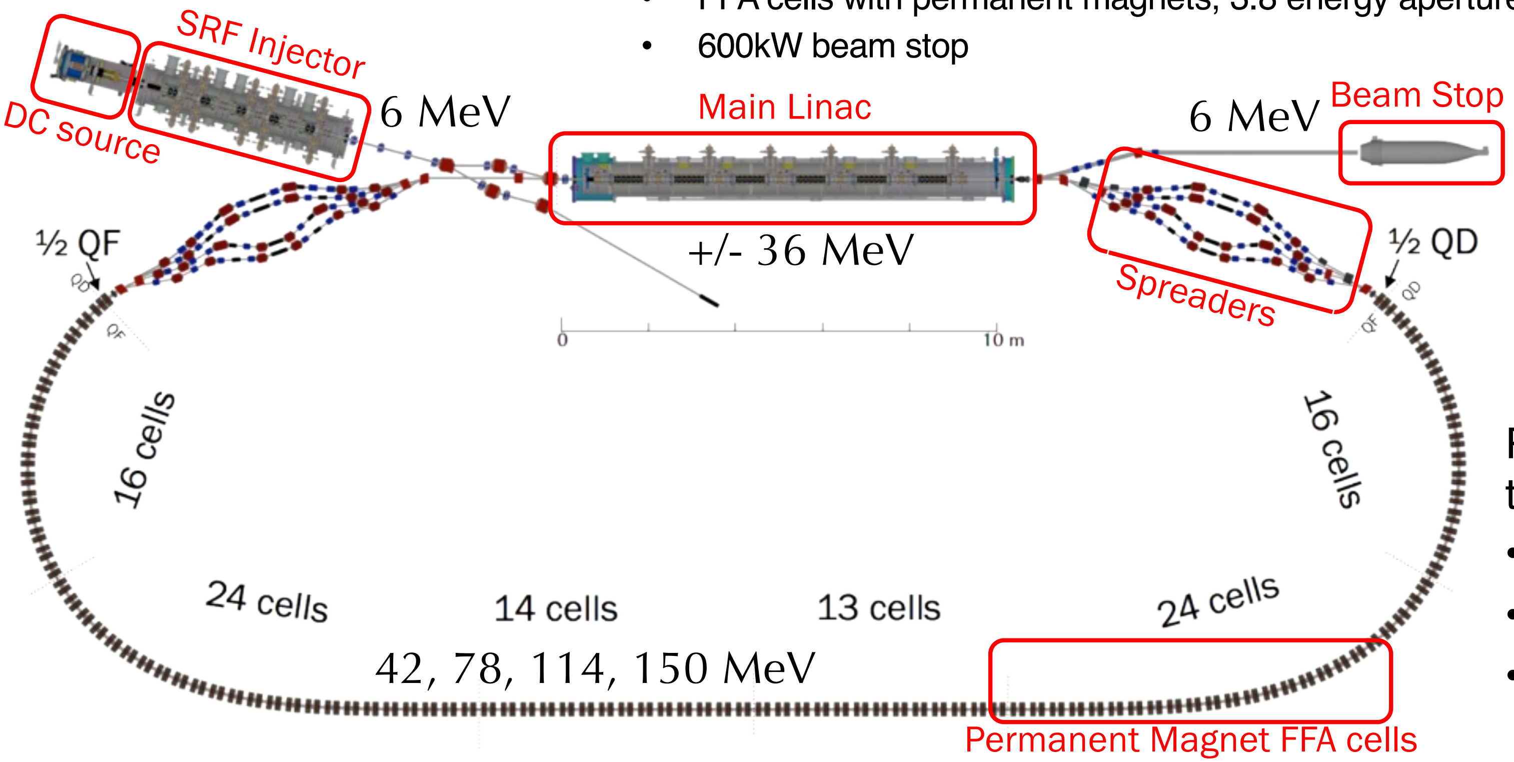
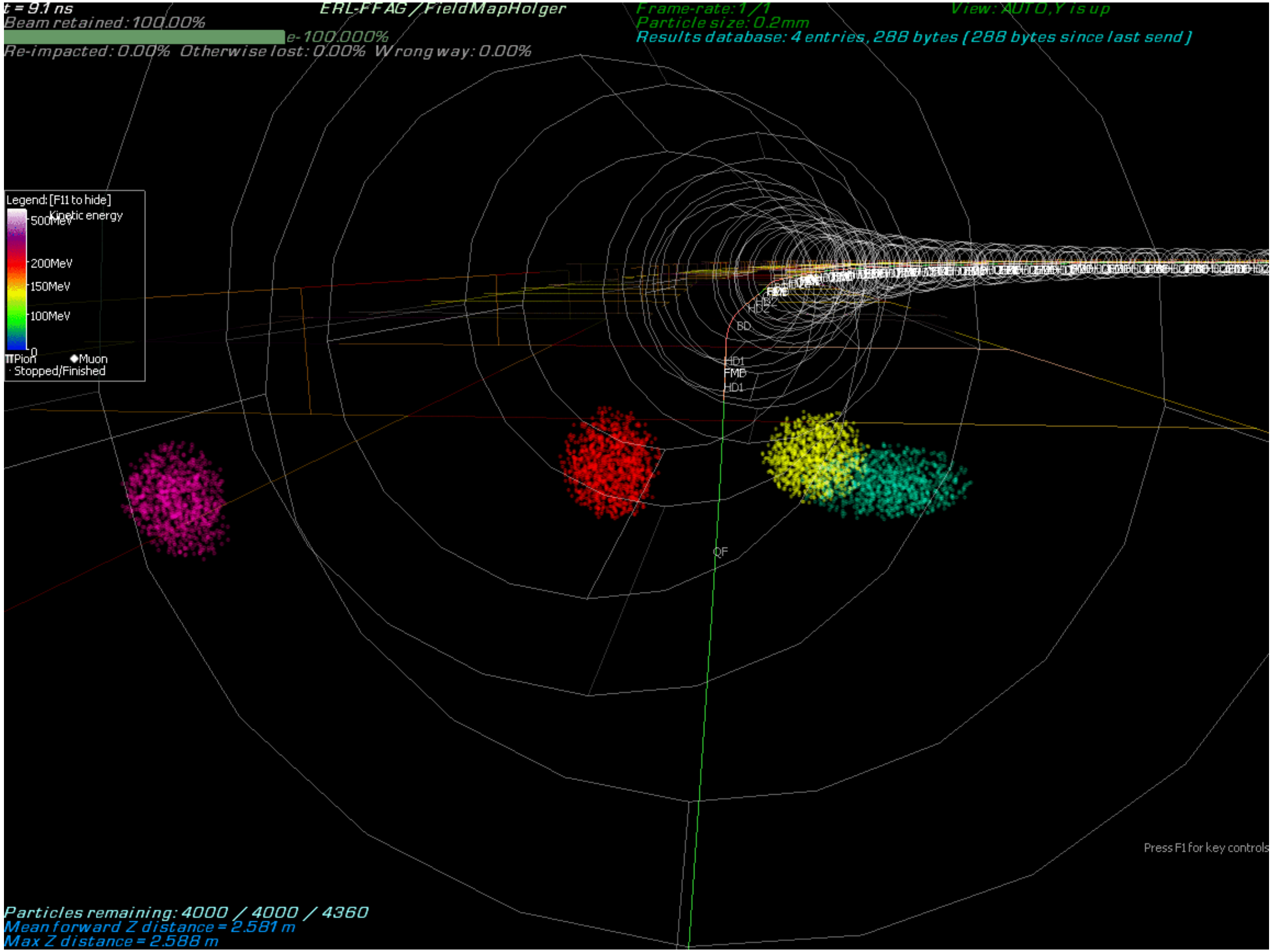


Pursuing **green** technology:

- Energy Recovery
- Low loss SRF
- Permanent magnets

Bunch dynamics in 3-D fields

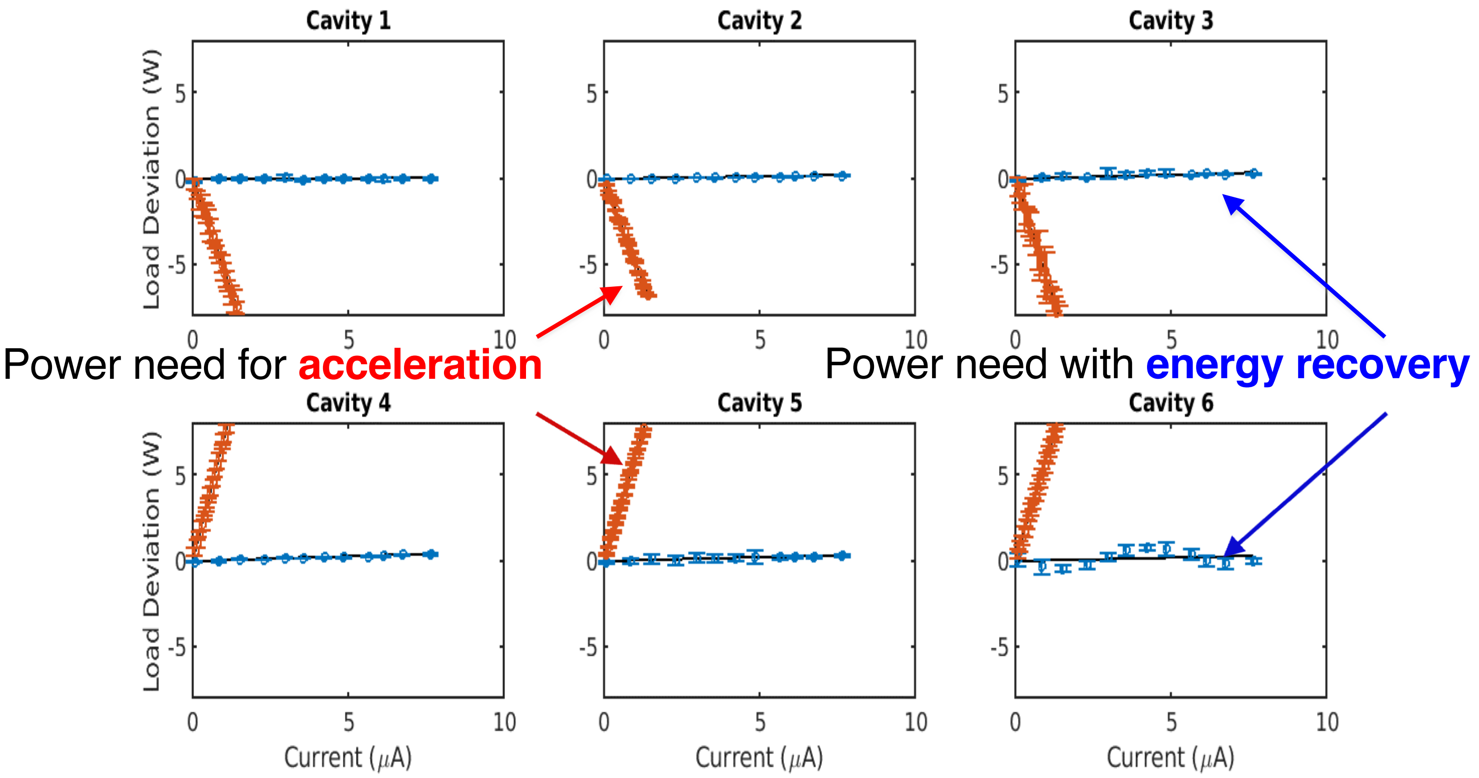
CBETA



Permanent FFA magnets

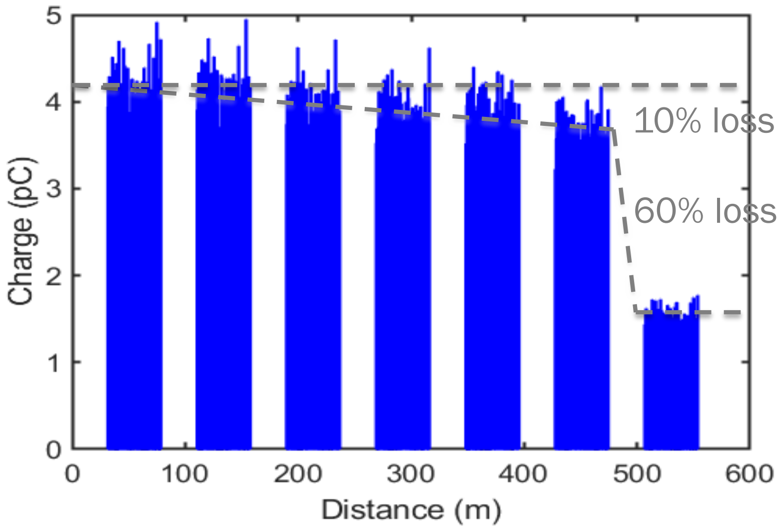
Energy Recovery in every Cavity

- Transmission 99.6 ± 0.1% ; energy recovery > 99.8%
- Measured up to 8 μA
- Each cavity accelerates beam **without** receiving **external power** for it.



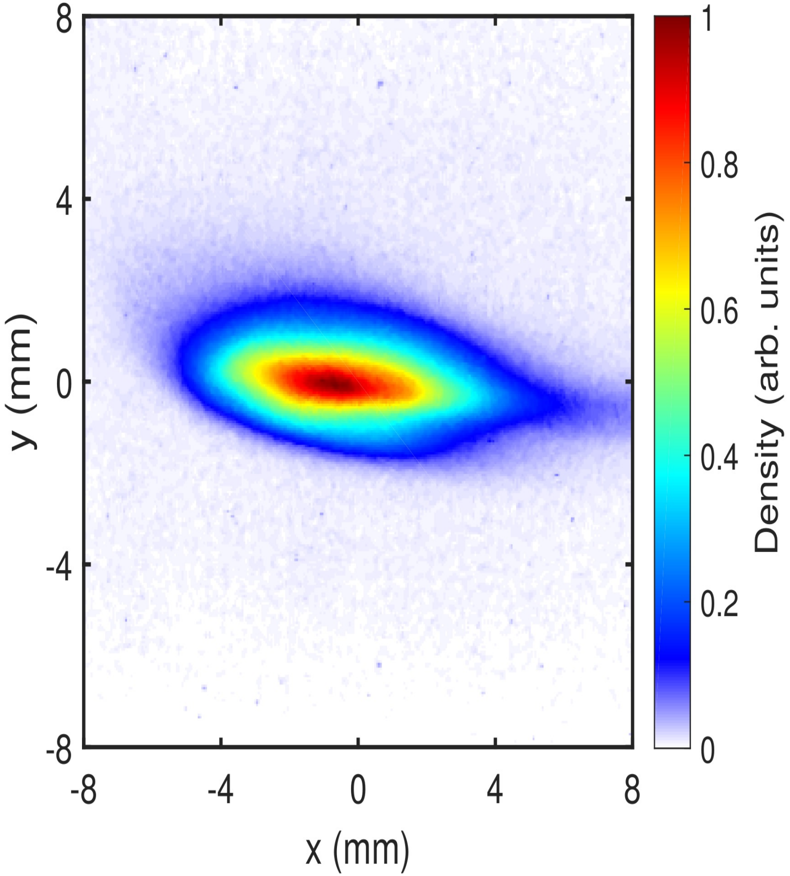
1st multi-turn SRF ERL

First beam Dec. 24, 2019. Multi-turn energy recovery achieved on operated until February 2020.

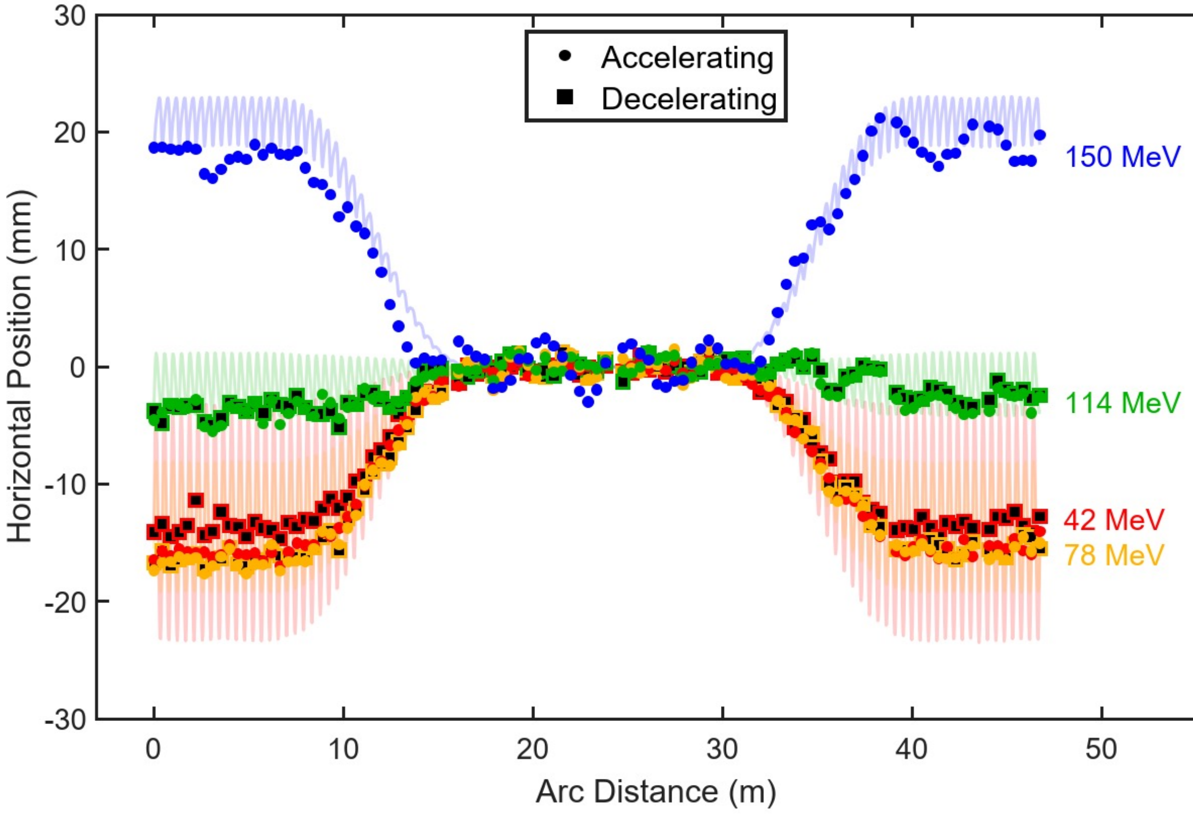


- Before the 7th FFA pass there remains an unresolved 60% loss

Beam in the beam stop line



7 orbits simultaneous orbits in FFA



Reports appeared in Nature, Phys. Rev. Letters, Forbes Magazine, IEEE Spectrum, reddid.com, and others.

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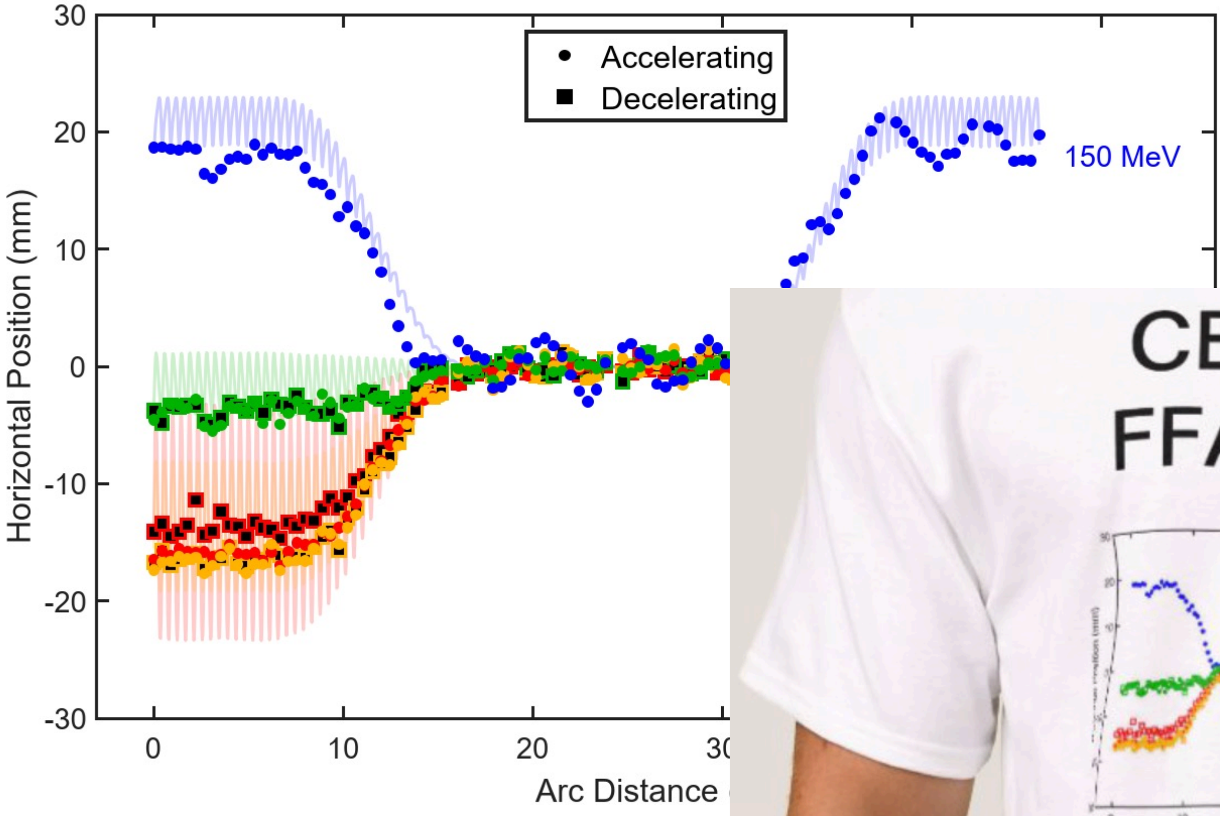
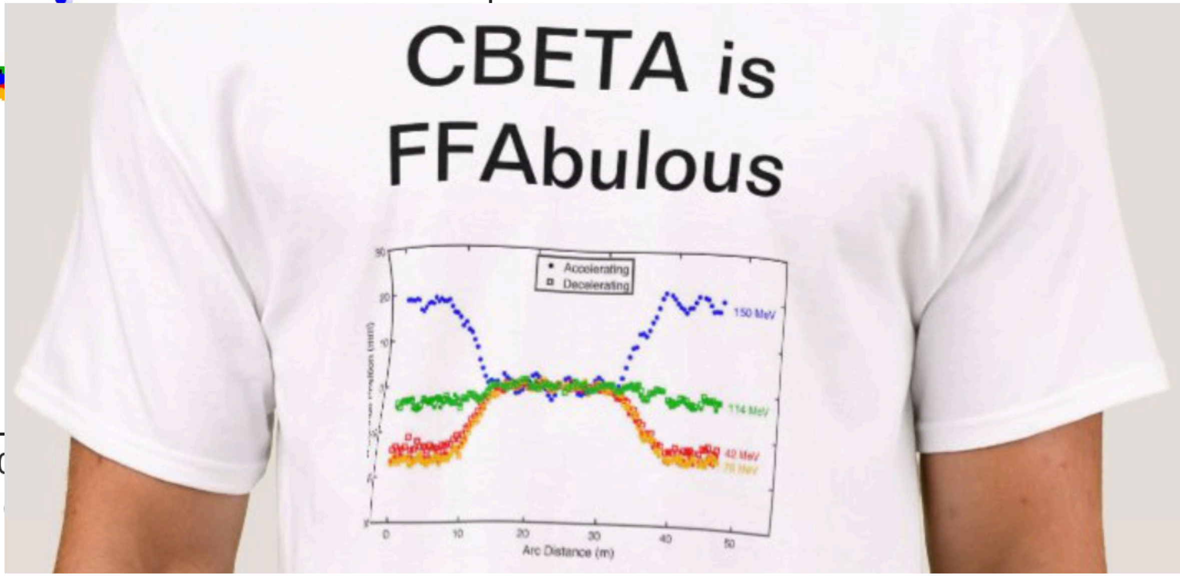


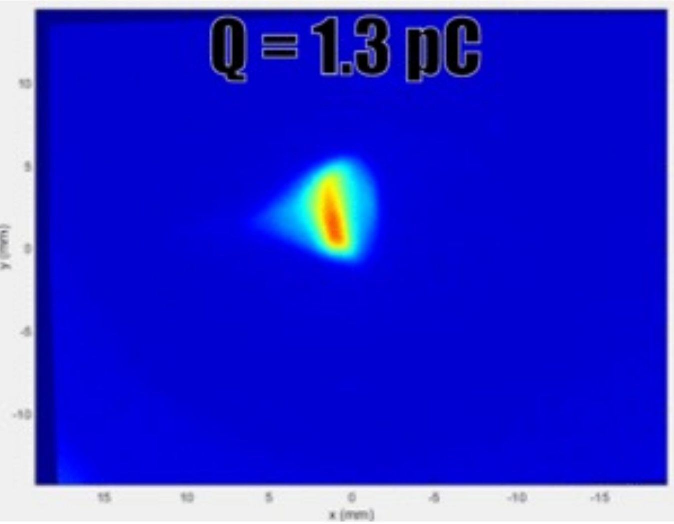


Reports appeared in Nature, Phys. Rev. Letters, Forbes Magazine, IEEE Spectrum, reddid.com, and others.

Potential for Microbunching

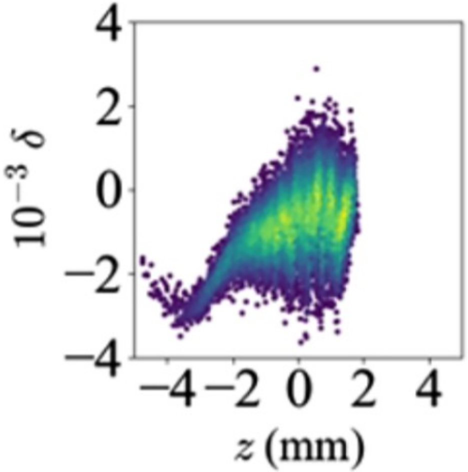
During multi-pass commissioning the transverse charge distribution of the beam profile as observed an a 78 MeV viewscreen after the linac show a microbunching structure.

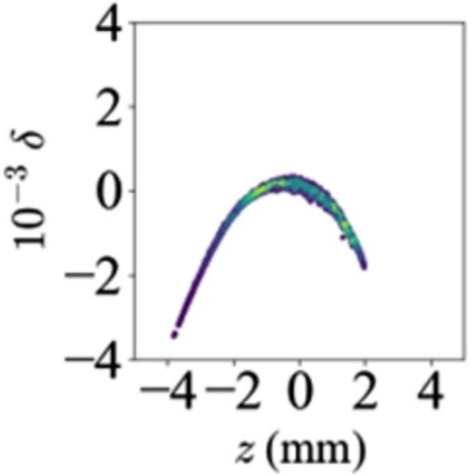
Potential for microbunching studies.



Measured transverse beam profiles for increasing bunch charges.

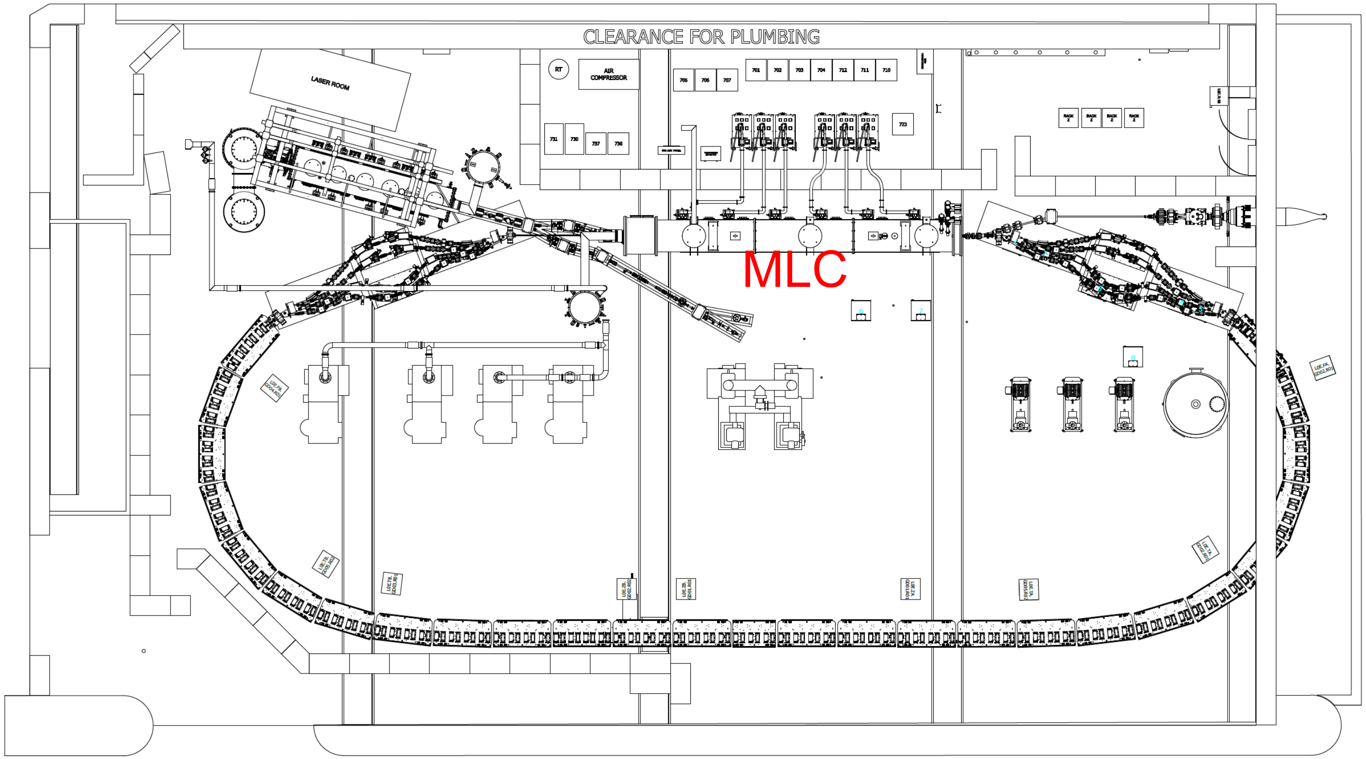
CSR simulations also showing micro-bunching instability structures.





ICS Bypass Design: Current Layout

- As is, there's no room in the FFA for the interaction
- Assume linear magnets
- Not allowed to take out existing structures
- Using 150 MeV electrons

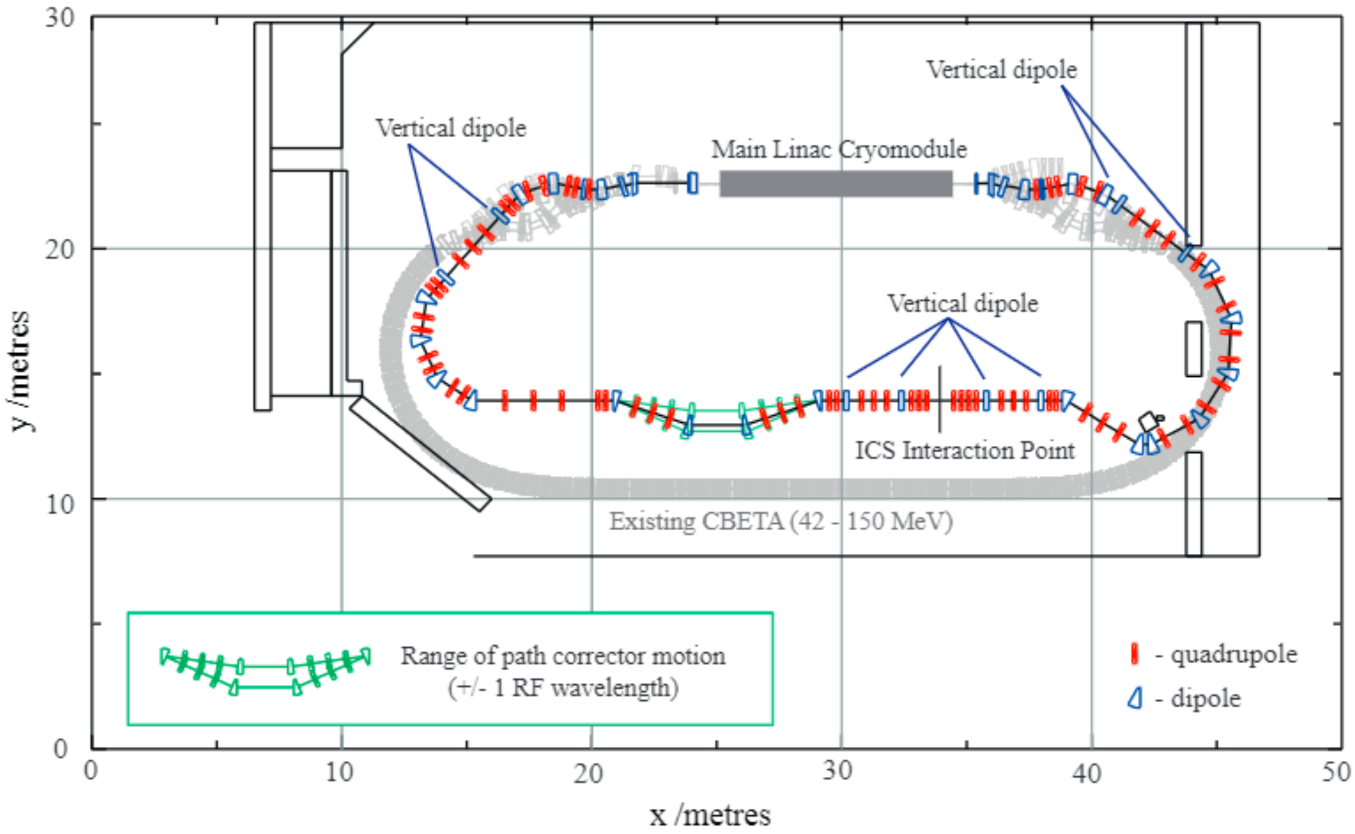


Schematic of the CBETA enclosure. MLC ~10 m for scale.

ICS Bypass Design: Overview

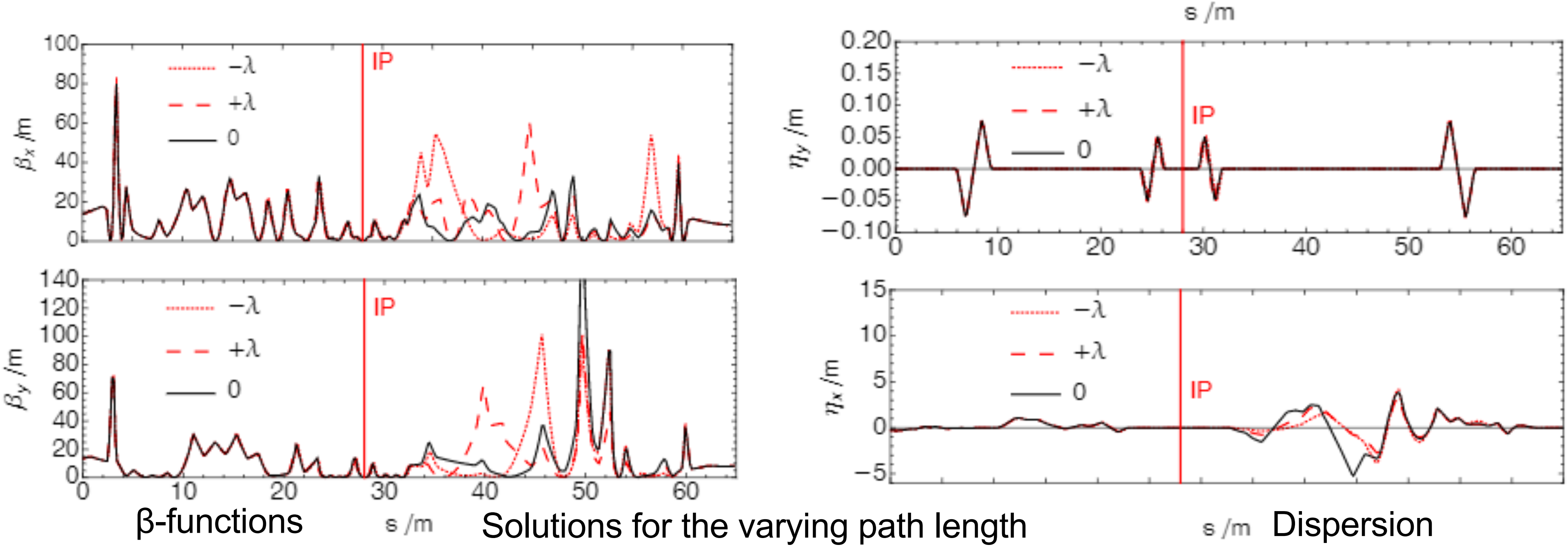
- Bypass line is elevated above existing plane by 30 cm; IP is further elevated by another 50 cm

- Optics are set such that the parameters going into the MLC for the fifth pass match CBETA design parameters



Floor plan of the ICS bypass to CBETA. The existing CBETA return loop is shown in grey. Path length correction system are in green.

ICS Bypass Design: Optics



β-functions   Solutions for the varying path length   Dispersion

- $\beta_{x,y}^{peak}$ < 150 m – comparable to CBETA design
- $\beta_{x,y}$ at the IP sufficiently adjustable (0.01 – 0.126 m)
- Vertical dispersion is closed, horizontal is large between IP and R4
- Bmad optimized like many ERLs, incl. the EIC cooler

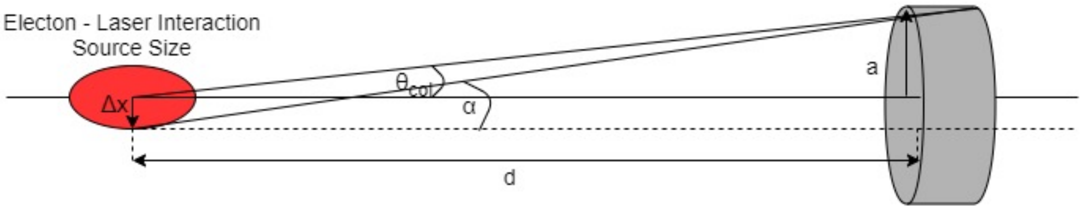
Inverse Compton Scattering (ICS)

- Collision of electron and photon at the interaction point (IP) produces radiation
- Energy of scattered radiation is given by

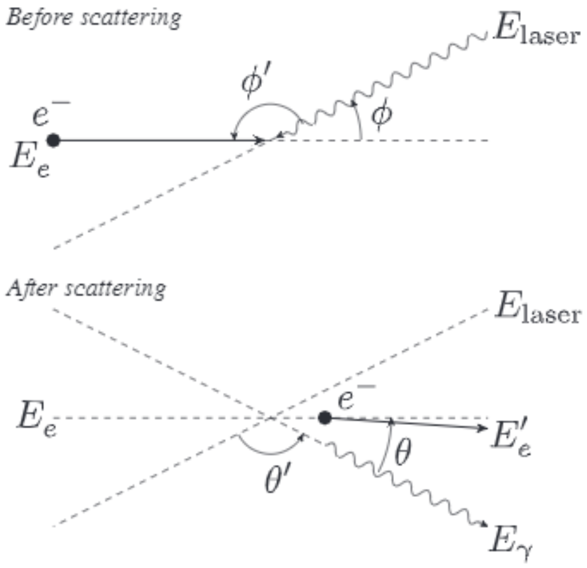
$$E_\gamma = \frac{E_{\text{laser}}\,(1-\beta\cos\phi')}{1-\beta\cos\theta+(1-\cos\theta')E_{\text{laser}}/E_e} \quad \xrightarrow{\phi'=\pi,\,\theta=0} \quad E_\gamma = \frac{4\gamma^2 E_{\text{laser}}}{1+X}$$

$$X = 4\gamma E_{\text{laser}}/m_e c^2$$

- Because E_γ is proportional to θ, a collimator can be used for energy selection and bandwidth control



Schematic of an inverse Compton source with the laser – electron convolution source size and a downstream collimator for energy selection.



Scattering geometry of an inverse Compton scattering source. The angle ϕ is the crossing angle between the laser pulse and electron bunch and the angle θ is the angle between the scattered photons and the incident electron beam.

Parameter Optimization

- Optimization of bandwidth against collimated flux is performed by adjusting β at the IP and the collimation angle
- Collimated flux

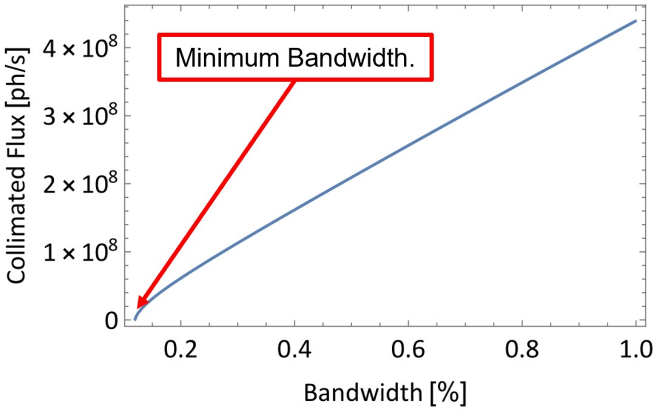
$$\mathcal{F}_\Psi \propto \frac{\left(1+\sqrt[3]{X}\Psi^2/3\right)\Psi^2}{\left[1+(1+X/2)\,\Psi^2\right](1+\Psi^2)}$$

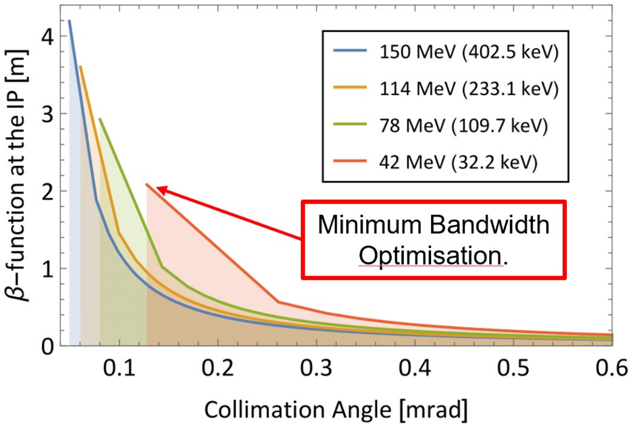
- Bandwidth of scattered radiation

$$\frac{\Delta E_\gamma}{E_\gamma} = \sqrt{\left(\frac{\sigma_\theta}{E_\theta}\right)^2 + \left(\frac{\sigma_e}{E_e}\right)^2 + \left(\frac{\sigma_L}{E_L}\right)^2 + \left(\frac{\sigma_\epsilon}{E_\epsilon}\right)^2}$$

- Minimum bandwidth

$$\lim_{\substack{\theta_{col}\to 0 \\ \beta^*_{x/y}\to\infty}} (\Delta E_\gamma/E_\gamma) = \sqrt{\left(\frac{2+X}{1+X}\frac{\Delta E_e}{E_e}\right)^2 + \left(\frac{1}{1+X}\frac{\Delta E_L}{E_L}\right)^2}$$





Top: CBETA ICS 150 MeV collimated flux – *rms* bandwidth round beam tuning curve. Recoil is small, so identical for all passes. Bottom: CBETA ICS $\theta_{col} - \beta^*$ parameter space displaying pareto front of optimised settings.

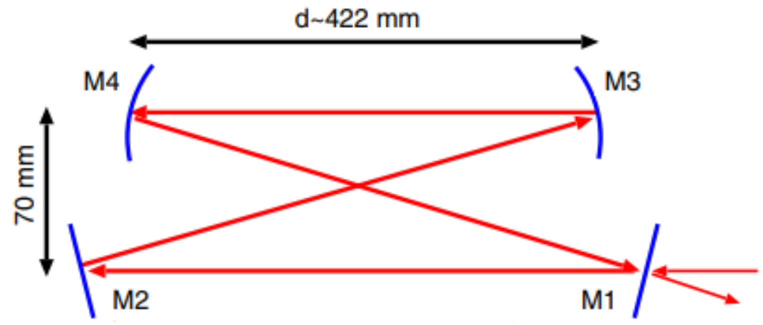
ICS @ CBETA laser parameters

The ICS is designed to operate on all passes (42-150 MeV) of the CBETA ERL with design parameters.

The laser cavity parameters are based on the demonstrated 10 kW Nd:YAG optical cavity at cERL. This is much below the state of the art optical cavity (670 kW @ 250 MHz), but accelerators are challenging environments for optical cavity operation.

Parameter	Quantity	Unit
Wavelength, λ_{laser}	1064	nm
Photon energy, E_{laser}	1.17	eV
Pulse energy	62	µJ
Number of photons, N_{laser}	3.3×10^{14}	
Repetition rate, f	162.5	MHz
Spot size at the IP, σ_{laser}	25	µm
Crossing angle, ϕ	5°	
Pulse length	10	ps
Relative energy spread, $\Delta E_{\text{laser}}/E_{\text{laser}}$	6.57×10^{-4}	

Electron beam parameters of the CBETA inverse Compton scattering source at the interaction point [10].



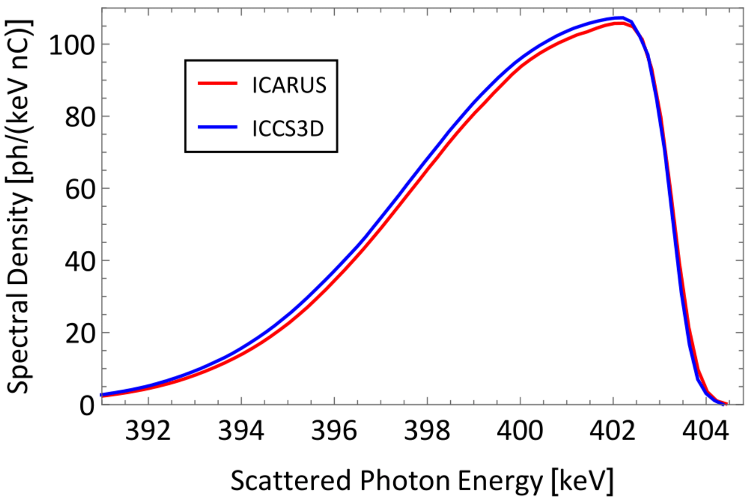
Schematic of cERL's 4 mirror bow-tie Fabry-Perot optical cavity, demonstrated at 162.5 MHz with a 5° crossing angle.

ICS @ CBETA e-parameters

Parameter	Quantity				Unit
Turn number	1	2	3	4	
Electron kinetic energy, E_e	42	78	114	150	MeV
Repetition rate, f	162.5				MHz
Bunch charge, eN_e	32				pC
Transverse normalised rms emittance, ϵ_N	0.3				mm-mrad
rms bunch length, $\Delta\tau$	1.0 (3.33)				mm (ps)
Relative energy spread	5.0×10^{-4}				
	Baseline parameters				
β^* (at the IP)	1				cm
Electron bunch spot size, $\sigma_{\mathrm{electron}}$	6.01	4.42	3.65	3.19	µm
	Optimised for 0.5% (narrow) bandwidth				
β^* (at the IP)	3.56	6.58	9.60	12.62	cm
Electron bunch spot size, $\sigma_{\mathrm{electron}}$	11.34	11.34	11.34	11.34	µm
Collimation angle, θ_{col}	1.533	0.830	0.569	0.433	mrad

Spectral Output

Right: CBETA ICS 150 MeV spectra produced by ICARUS and ICCS3D for a 0.5% BW. Note spectra are for the head-on case and therefore the position of the Compton edge is at a marginally higher energy and spectral density is not reduced by the angular crossing.



Bottom:
Spectral output parameters of the CBETA ICS. Note the peak brilliance is for a head-on collision, not the design crossing angle .

	Electron Kinetic Energy (MeV)				
	42	78	114	150	Unit
X-ray peak energy	32.2	109.7	233.1	402.5	keV
Uncollimated flux	3.16×10^{10}	3.20×10^{10}	3.21×10^{10}	3.22×10^{10}	ph/s
Spectral density	9.82×10^{5}	2.92×10^{5}	1.38×10^{5}	8.00×10^{4}	ph/s eV
Average brilliance	9.23×10^{10}	3.19×10^{11}	6.81×10^{11}	1.18×10^{12}	ph/s mm^2 mrad^2 0.1% bw
Peak brilliance	2.80×10^{15}	1.00×10^{16}	2.18×10^{16}	3.80×10^{16}	ph/s mm^2 mrad^2 0.1% bw
	0.5% bandwidth				
Collimated flux	2.09×10^{8}	2.09×10^{8}	2.09×10^{8}	2.09×10^{8}	ph/s 0.5% bw

Source Comparison: ICS

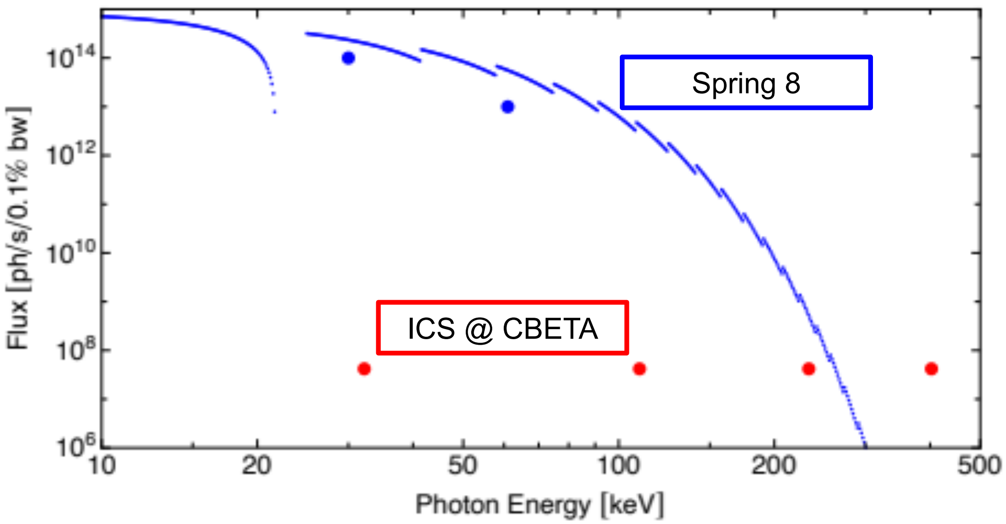
ICS	Accelerator type	Scattered photon energy (keV)	Flux (ph/s)
cERL [18]	ERL	6.95	2.6×10^7
ALICE [43]	ERL	21.5	9×10^5
MIT ICS[a] [44]	Linac	3–30	3×10^{14}
MuCLS [45]	Storage ring	15–35	$0.443 - 1.78 \times 10^{10}$
Tsinghua [46]	Linac	51.7	1×10^6
ThomX[a] [47]	Storage ring	45–90	$1 \times 10^{10} - 10^{13}$
BriXS[a] [48,49]	ERL	20–180	$1 \times 10^{10} - 10^{13}$
CBETA[a]	ERL	32.2, 109.7, 233.1, 402.5	$3.16 - 3.21 \times 10^{10}$
NIJI-IV [50]	Storage ring	1200	3.1×10^4
HIγS[b] [51]	Storage ring	1000–3000	5×10^7–5×10^8

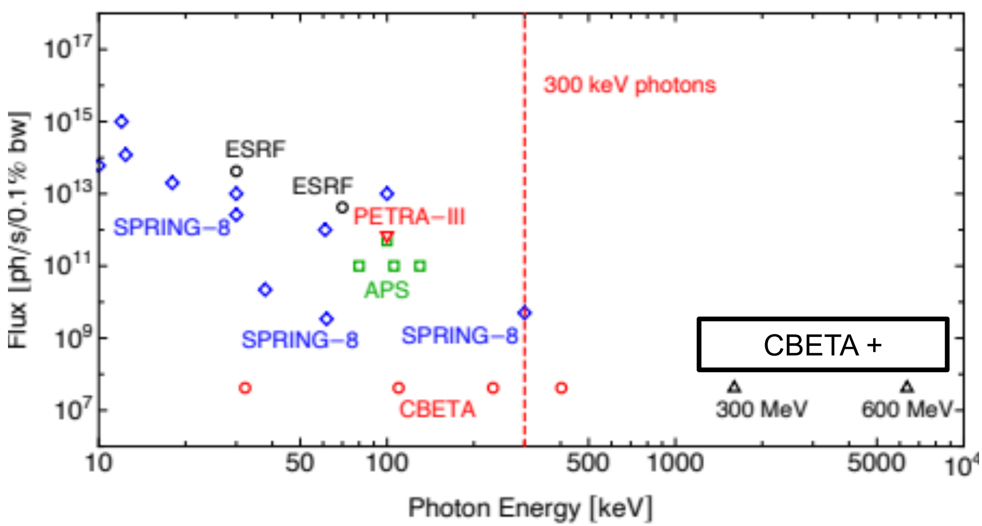
[a]Denotes design parameters for sources which are not yet demonstrated.
[b]The HIγS source is capable of scattered photon energies from 1–100 MeV with varying fluxes (see Table V of Ref. [51]). Shown is the lowest energy operational setting, most comparable to the source presented here.

Operated ERL ICS sources.

Comparison of the CBETA ICS design against other designed ICS sources driven by differing forms of accelerator. Note that CBETA is competitive with all previously operated X-ray ICS sources, but flux is lower than some other designs due to conservative laser parameters.

Source Comparison: Synchrotron





- 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

ICS - Compact Light Source

Summary Spectral Output

The CBETA ICS is a high precision (10^{-3} bandwidth) X-ray source with spectral parameters between an industrial Bremsstrahlung X-ray source and a synchrotron source, with access to higher energy X-rays.

Bandwidth is limited to $(\Delta E_\gamma / E_\gamma)_{rms} \sim$ 0.17%, due to the energy spread of the electron bunch and laser pulse.

Flux of 3.2×10^{10} ph/s makes the CBETA ICS orders of magnitude above ERL ICS demonstrations at cERL and ALICE.

Average Brilliance is favoured in this design due to the use of a low-intensity high-repetition Fabry-Perot optical cavity and the recirculated nature of a 4-turn ERL.

Angular crossing (ϕ = 5°) causes a ~5.56x reduction in flux . The hourglass effect, where the colliding bunch and pulse diverge within the length of the interaction, is negligible since the interaction length is suppressed by the angular crossing.

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	0.5% bandwidth				
Collimated flux	2.09×10^{8}	2.09×10^{8}	2.09×10^{8}	2.09×10^{8}	ph/s 0.5% bw

Applications of HE photons from ICS

- X-ray absorption spectroscopy
- X-ray fluorescence (XRF), e.g. of uranium (K-edge 116keV) and plutonium
- Nuclear resonance fluorescence (NRF), e.g. U235 detection 1ith 1.7MeV photons.

- Energy-dispersive x-ray diffraction (EDXRD) – a high-flux source for identification of minerals in mined ore samples
  - High photon energy allows for inspection of thick samples

- Non-resonant inelastic x-ray scattering (NIXS) – high incident photon energy and large flux allows to test quantum materials such as transition metal oxides, which are a testbed for theories such as the Mott-Hubbard model and high-Tc superconductors.

ERL Application overview

- Coherent (fast) hadron coolers and incoherent hadron coolers.
- High-power FELs
- Coherent light sources
- Lithography for chip production
- Nuclear Physics Colliders (from DarkLight to an ERL eRHIC)
- Compton-Scattering gamma source for Nuclear physics
- Medical isotope production, transmutation of nuclear waste,
- High Energy Physics ERLs:
  - LHeC
  - CERC (FCC-ee as an ERL)
  - ERLC (ILC as an ERL)
- Compton-Scattering X-ray sources

Described in soon to come:
Submission to JINST of
The Development of Energy-Recovery Linacs
240 page paper, 44 authors from 19 institutions.

Credit and References

- Intense monochromatic photons above 100 keV from an inverse Compton source, ***K. Deitrick***, G.H. Hoffstaetter, C. Franck, B.D. Muratori, P.H. Williams. G.A. Krafft, B. Terzić, ***J. Crone***, H. Owen, Phys. Rev. AB 24, 050701 (2021)

- Measurement of the per cavity energy recovery efficiency in the single turn Cornell-Brookhaven ERL Test Accelerator configuration, C. Gulliford , N. Banerjee , ***A. Bartnik***, J. Crittenden , K. Deitrick , J. Dobbins , G. H. Hoffstaetter , P. Quigley, and K. Smolenski, J. S. Berg , R. Michnoff, S. Peggs, ***D. Trbojevic***, Phys. Rev. AB 24, 010101 (2021)

- CBETA: First Multipass Superconducting Linear Accelerator with Energy Recovery, A. Bartnik, N. Banerjee , D. Burke, J. Crittenden , K. Deitrick , J. Dobbins , C. Gulliford , G. H. Hoffstaetter , Y. Li, W. Lou, P. Quigley, D. Sagan , and K. Smolenski, J. S. Berg, S. Brooks , R. Hulsart, G. Mahler, F. Meot, R. Michnoff, S. Peggs, T. Roser , D. Trbojevic , N. Tsoupas, Phys. Rev. Letters 125, 044803 (2020)

Some material provided by K. Deitrick and J. Crone

Questions ?

Backup: ICS spectrum codes

ICARUS

ICARUS: **I**nverse **C**ompton Scattering Semi-**A**nalytical **R**ecoil-Corrected **U**ltra-Relativistic **S**pectrum code is a 3D ICS spectrum code.

Capable of producing recoil corrected spectra of linear regime (non-intense laser) ICS interactions, considering bunch energy spread, laser energy spread, polarisation effects and emittance in 2D. Both circular and rectangular collimation can be simulated.

Currently this only operates in a head-on configuration for Gaussian modelled bunches and pulses but could be simply extended.

The code is created from a modified and corrected version of the model by C. Sun [19, 20]. The correction has enabled the arbitrary units to be dropped and the modification allows for efficient simulation of the laser pulse energy spread.

ICARUS is benchmarked against ICCS3D [17], mainly for the CBETA ICS case [10] but other cases have also been simulated with good agreement.

ICCS3D

ICCS3D: **I**mproved **C**odes for **C**ompton **S**imulation is a **3D** ICS spectrum code that computes spectra for each individual electron-photon interaction, providing statistics in the tails equal to those at the peaks [17, 21] unlike Monte Carlo codes.

Capable of producing recoil corrected spectra of linear regime ICS interactions, considering bunch energy spread, laser energy spread, polarisation effects and emittance in 2D. Both circular and rectangular collimation can be simulated.

Currently this only operates in a head-on configuration, but angular crossing is being added as an enhanced capability (in testing).

Capable of modelling bunches and pulses by numerous distributions (Gaussian, Lorentzian etc.) and by taking bunch profiles from file, enabling start to end simulations of ICS sources.

The code is created by B. Terzić and G.A. Krafft et al, an upgrade from the original ICCS [21] code by varying a_0 as a function of electron position from the centre of the interaction.