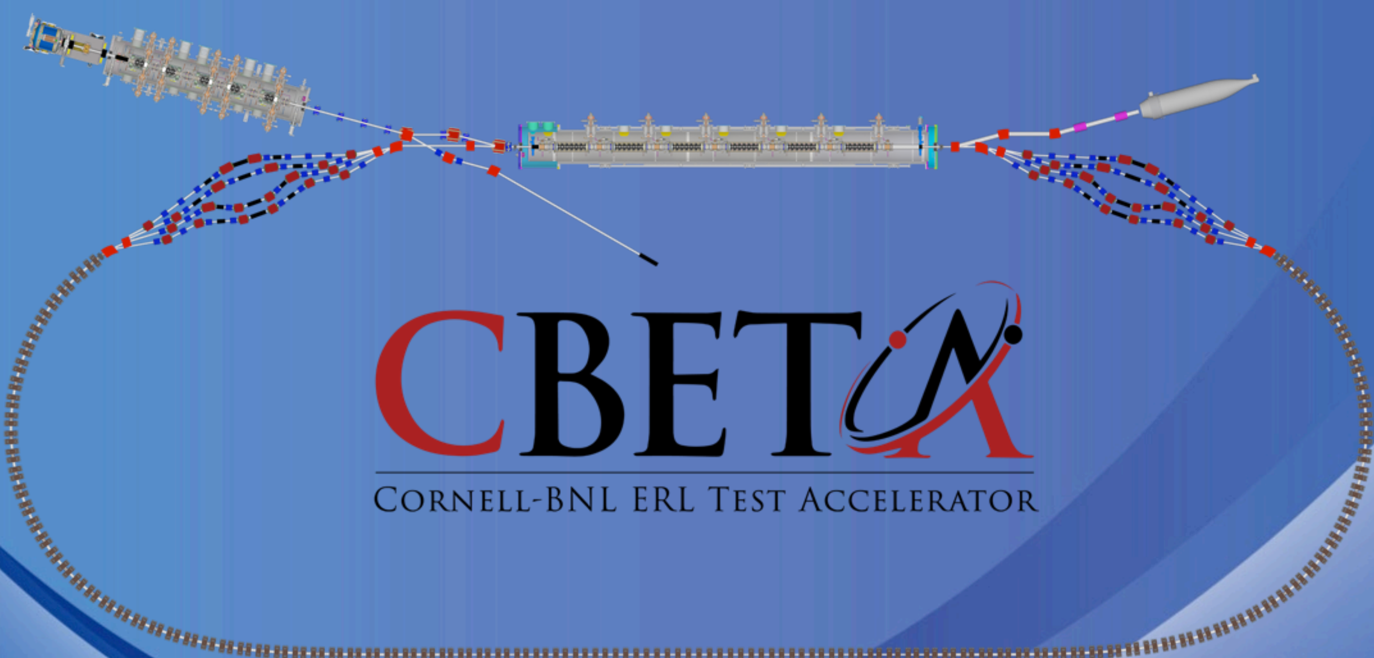
Applications for CBETA at Cornell

ERL workshop 07/19/2017

Georg Hoffstaetter (Cornell)



BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

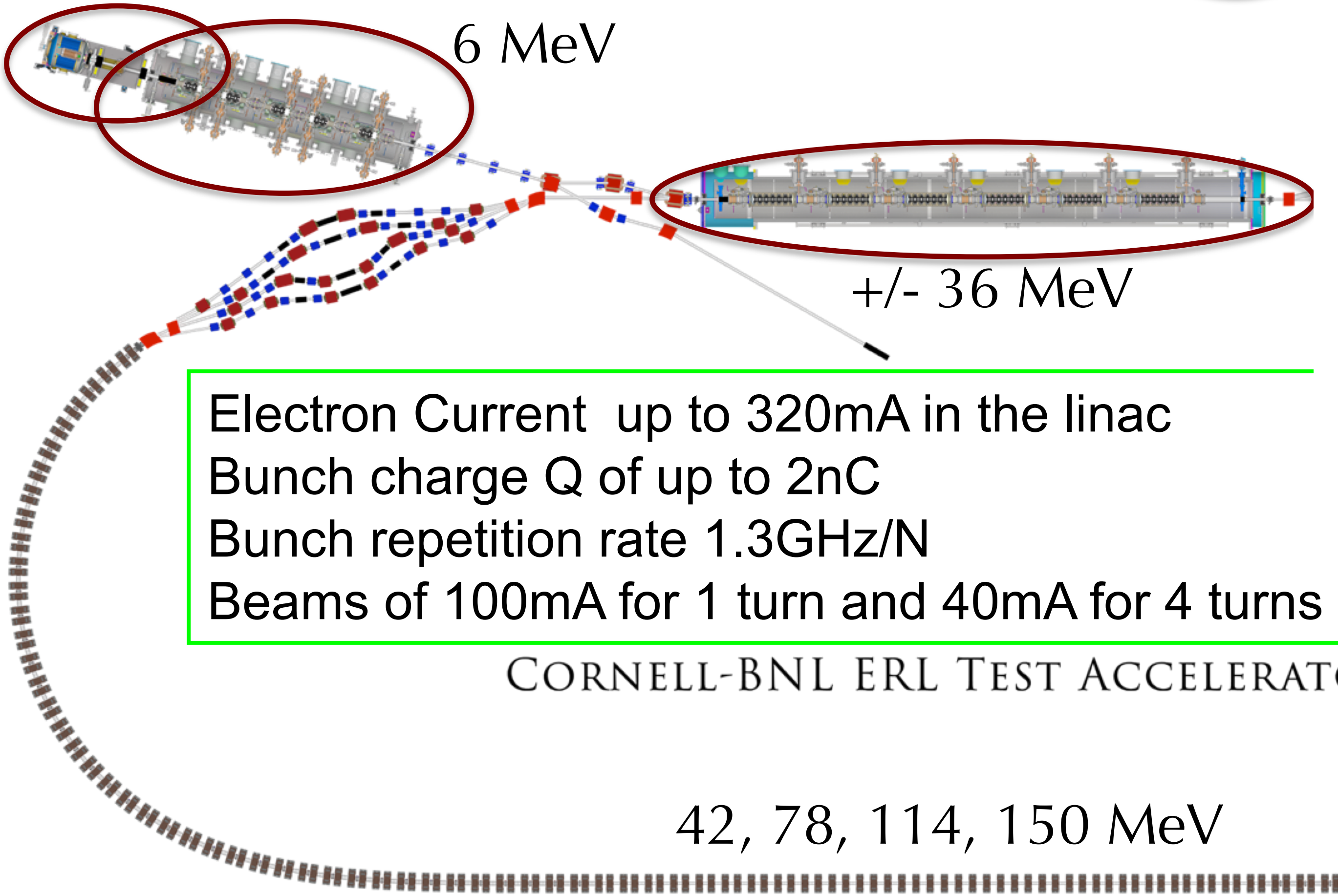
Office of Science
U.S. DEPARTMENT OF ENERGY

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

Beam through accelerator test

- Cornell DC gun
- 100mA, 6MeV SRF injector (ICM)
- 600kW beam dump
- 100mA, 6-cavity SRF CW Linac (MLC)

Tested



Electron Current up to 320mA in the linac
Bunch charge Q of up to 2nC
Bunch repetition rate 1.3GHz/N
Beams of 100mA for 1 turn and 40mA for 4 turns

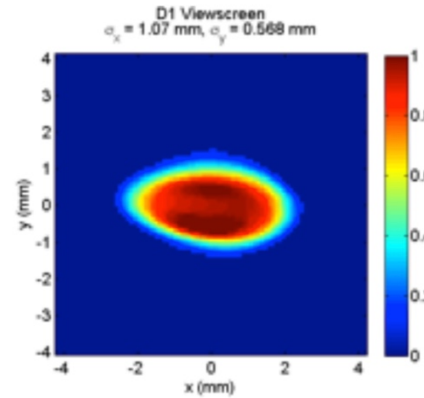


Image of first 12 MeV beam, delivered through MLC

The CBETA Collaboration

Background for CDR

Wrote PDDR for hard X-ray ERL at Cornell in 2012.

Start of CBETA July 2014 White paper December 2014

Defined CBETA in a white paper in December 2014.

CDR for CBETA in with Hybrid permanent magnets in July 2016.

Secured funding October 2016

DR for CBETA with Halbach magnets in February 2017

CBETA Design Report

Cornell-Brookhaven ERL Test Accelerator

Principal Investigators: G. Hoffstaetter and D. Trbojevic

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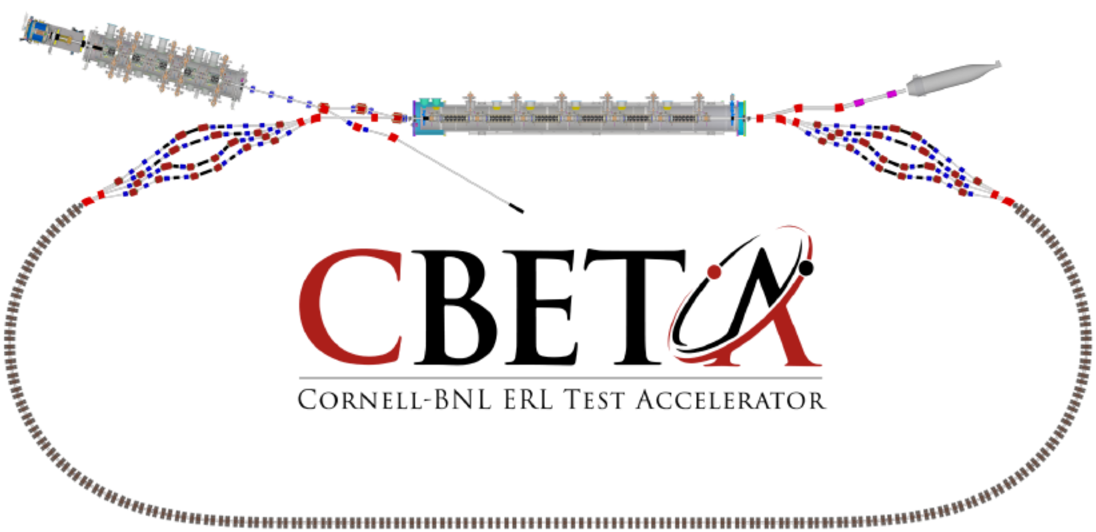
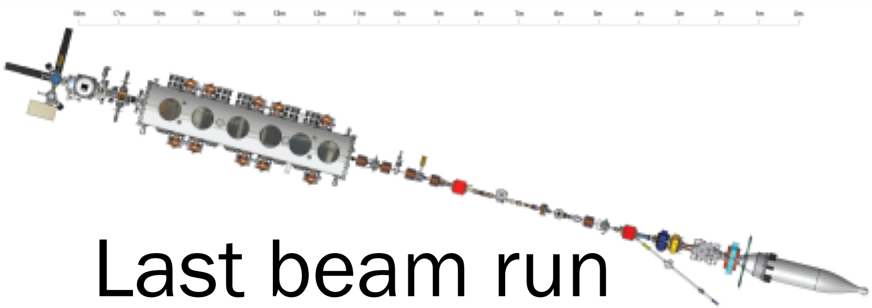


Past first technical (Jan 31st) and financial (Feb 6) review!

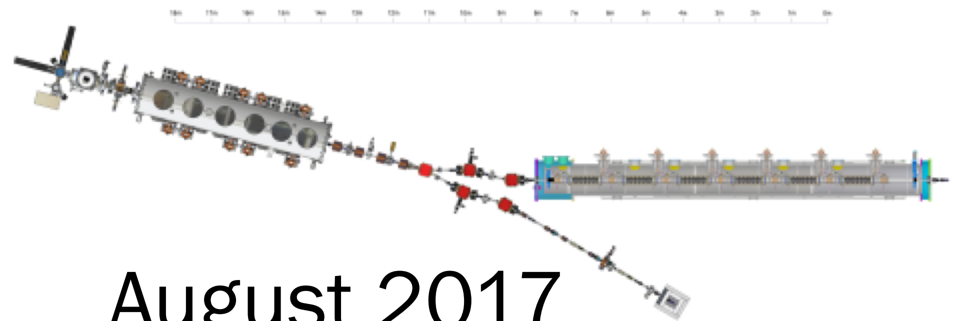
The path is free for CBETA

#	**Milestone** (at the end of months)	**Baseline**	**Actual**
	Funding start date		Oct-16
1	Engineering design documentation complete	Jan-17	
2	Prototype girder assembled	Apr-17	
3	Magnet production approved	Jun-17	
4	**Beam through Main Linac Cryomodule**	**Aug-17**	
5	First production hybrid magnet tested	Dec-17	
6	**Fractional Arc Test: beam through MLC & girder**	**Apr-18**	
7	Girder production run complete	Nov-18	
8	Final assembly & pre-beam commissioning complete	Feb-19	
9	**Single pass beam with factor of 2 energy scan**	Jun-19	
10	**Single pass beam with energy recovery**	Oct-19	
11	**Four pass beam with energy recovery (low current)**	Dec-19	
12	Project complete	Apr-20	

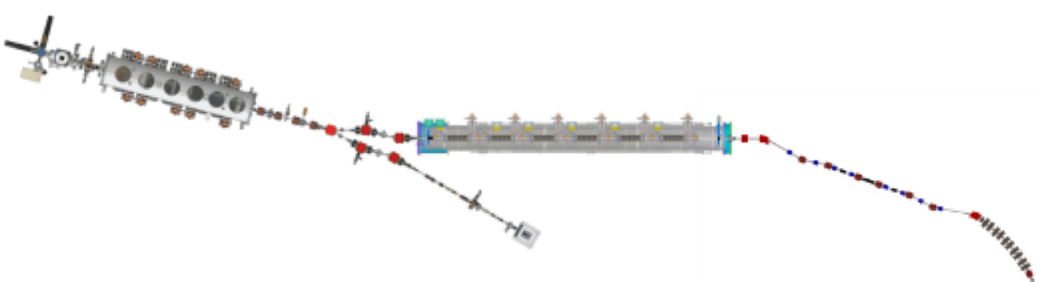
Beam Commissioning



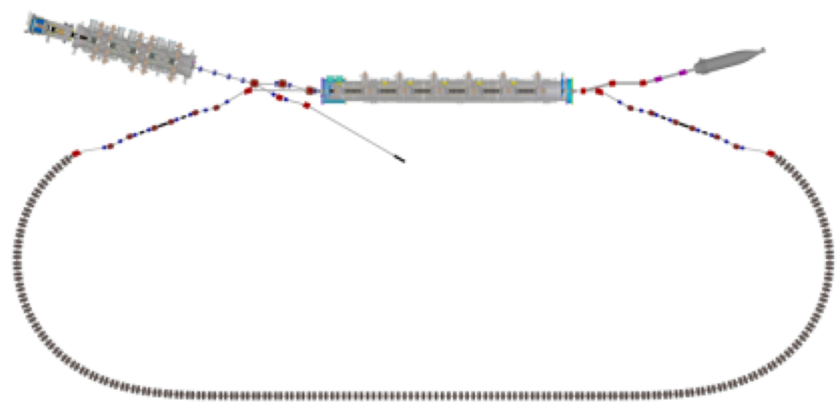
Last beam run



August 2017



April 2018



August 2019

Push toward 4-tunr ERL thereafter (April 2020)

Applications of CBETA

- DarkLight – **an experiment to find dark matter particles**
- Compact Compton source for hard x-rays – complementing CHESS' range
- THz laser – complementing CHESS' range
- Beam for time-resolved electron diffraction from 1-6MeV
- Beam for **Plasma Wakefield Acceleration with High Transformer Ratio**
- eRHIC accelerator testing – more detailed eRHIC R&D
- eRHIC cavity testing with beam
- ASML medical isotope cavity testing with beam
- Generic ERL accelerator physics
- Electron cooler tests – ERL tests for JLEIC
- Preparations for Perle
- Preparations for LHeC
- High-Power beam dynamics testing
- Permanent magnet and FFAG test bed for future accelerators

ERL – a new beam regime

Synchrotron: Repetitive acceleration to high energy, low repetition rate and therefore low current.

➔ Fixed target experiments, high energy, low current, relatively large beam size.

Storage rings: Rare filling at high energy and storage for millions of turns, high current, requires very low loss rates.

➔ Internal target experiments, high energy, high current, relatively large beam size.

Linacs: Linear acceleration to moderately high energies that are limited by the available length. Current*Energy is limited by the available power.

➔ Fixed target experiments, moderately high energies, low current, small beam size.

ERLs: Linear acceleration and deceleration to capture the energy of spent beam, like a linac but without the power limit on beam current, as spent beam provides the power. Loss rates have to be limited.

➔ **Dense internal targets, moderately high energies, high currents, small beam size.**

ERLs provide a new niche of beam parameters: What physics can they be used for?

ERL - Internal target colliders

ERLs: Linear acceleration and deceleration to capture the energy of spent beam, like a linac but without the power limit on beam current, as spent beam provides the power. Loss rates have to be limited.

➔ **Dense internal targets, moderately high energies, high currents, small beam size.**

ERLs provide a new niche of beam parameters: What physics can they be used for?

(1) Lost beam power has to be available from power sources.

(2) Target has length L, nuclei with charge Z.

(3) Coulomb scattering and particle optics determine beam loss (at an aperture a with a maximal optical beta function)

ERL Target and luminosity limits:

$$\mathcal{L}_{\max} = 4.1 \times 10^{37}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\frac{1}{Z^2}\left(\frac{P_{\mathrm{loss}}}{\mathrm{kW}}\right)\left(\frac{\mathcal{E}}{100\,\mathrm{MeV}}\right)\left(\frac{a}{\mathrm{cm}}\right)^2\left(\frac{100\,\mathrm{m}}{\beta_{\max}}\right)\left(\frac{10\,\mathrm{cm}}{L}\right)$$

$$\rho = 6.6 \times 10^{18}\,\mathrm{cm}^{-3}\frac{1}{Z^2}\left(\frac{100\,\mathrm{mA}}{I}\right)\left(\frac{P_{\mathrm{loss}}}{\mathrm{kW}}\right)\left(\frac{\mathcal{E}}{100\,\mathrm{MeV}}\right)\left(\frac{a}{\mathrm{cm}}\right)^2\left(\frac{100\,\mathrm{m}}{\beta_{\max}}\right)\left(\frac{10\,\mathrm{cm}}{L}\right)^2$$

Courtesy Chris Mayes

DarkLight

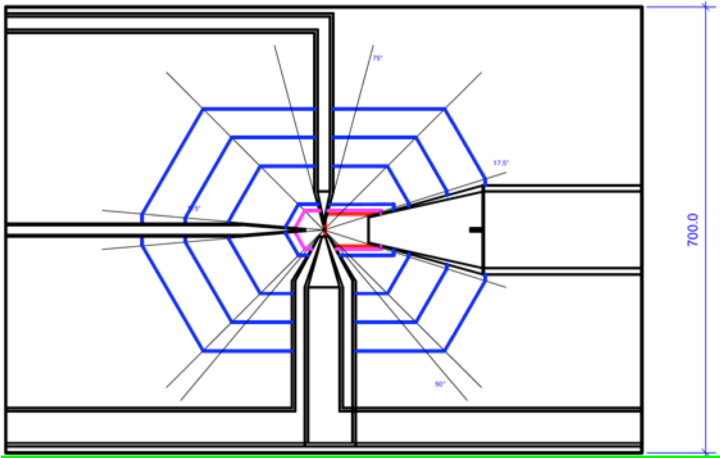
- DarkLight – **an experiment to find dark matter particles**

DarkLight @ Cornell

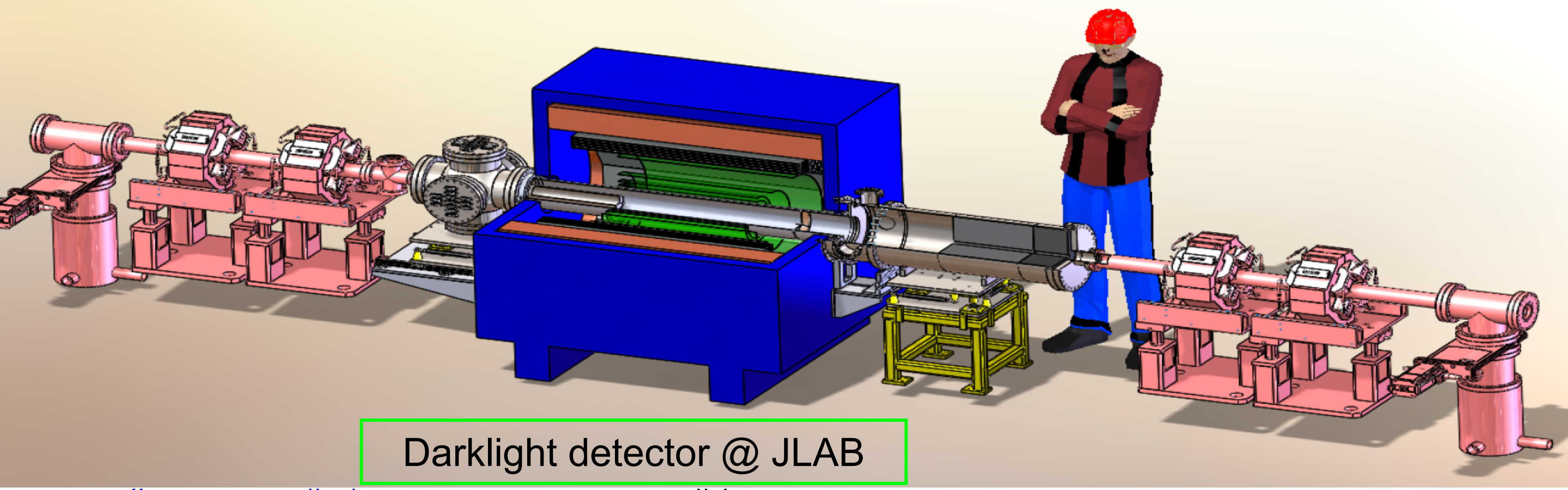
- Does CBETA have advantage over the JLAB-FEL?

=> by a factor of 10 for full CBETA performance
(40mA vs 5mA and smaller emittances for smaller gas cells).

- Detector R&D; can the JLAB Darklight detector be used?



Gas jet collision experiment.



Darklight detector @ JLAB

DarkLight

- DarkLight – an experiment to find dark matter particles

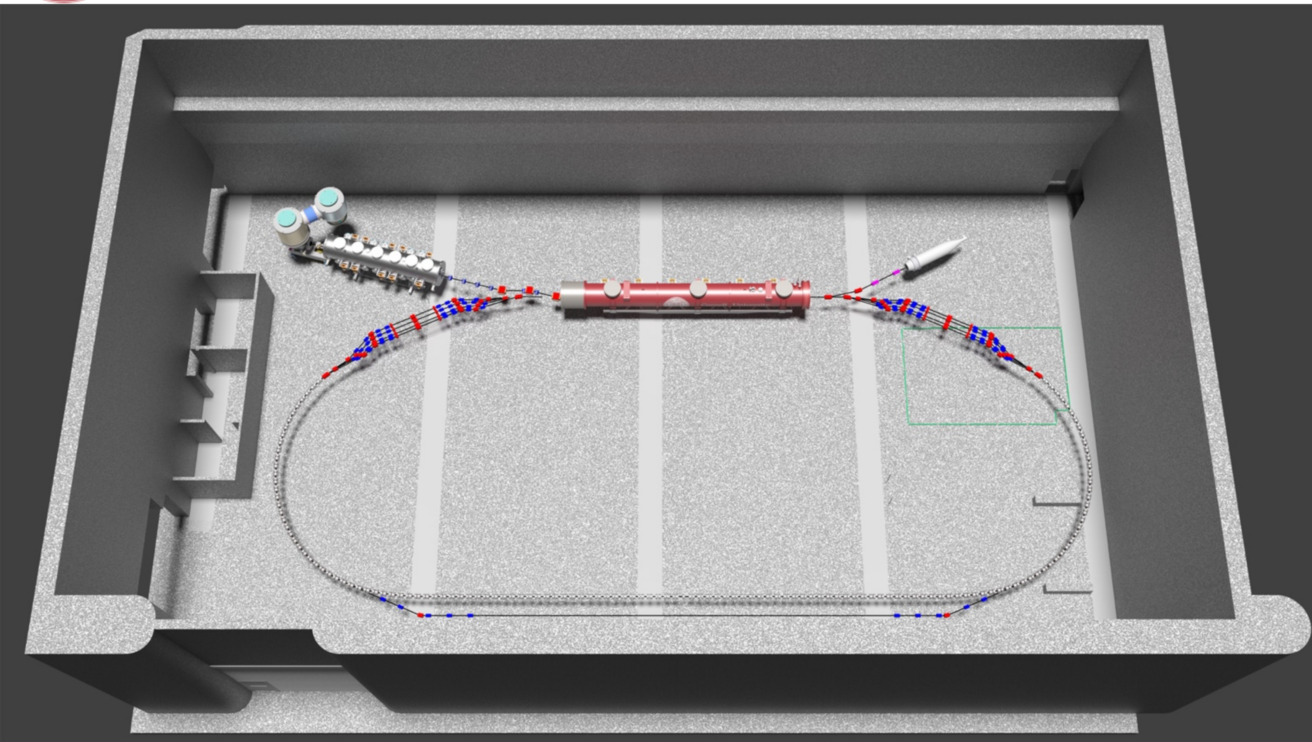
DarkLight @ JLAB test the possibility of a dark photon in the mass range 10 to 100 MeV coupling the dark sector to the Standard Model.

DarkLight precisely measures electron proton scattering using the 100 MeV electron beam of intensity 5 mA at the JLAB ERL incident on a windowless gas target of molecular hydrogen.

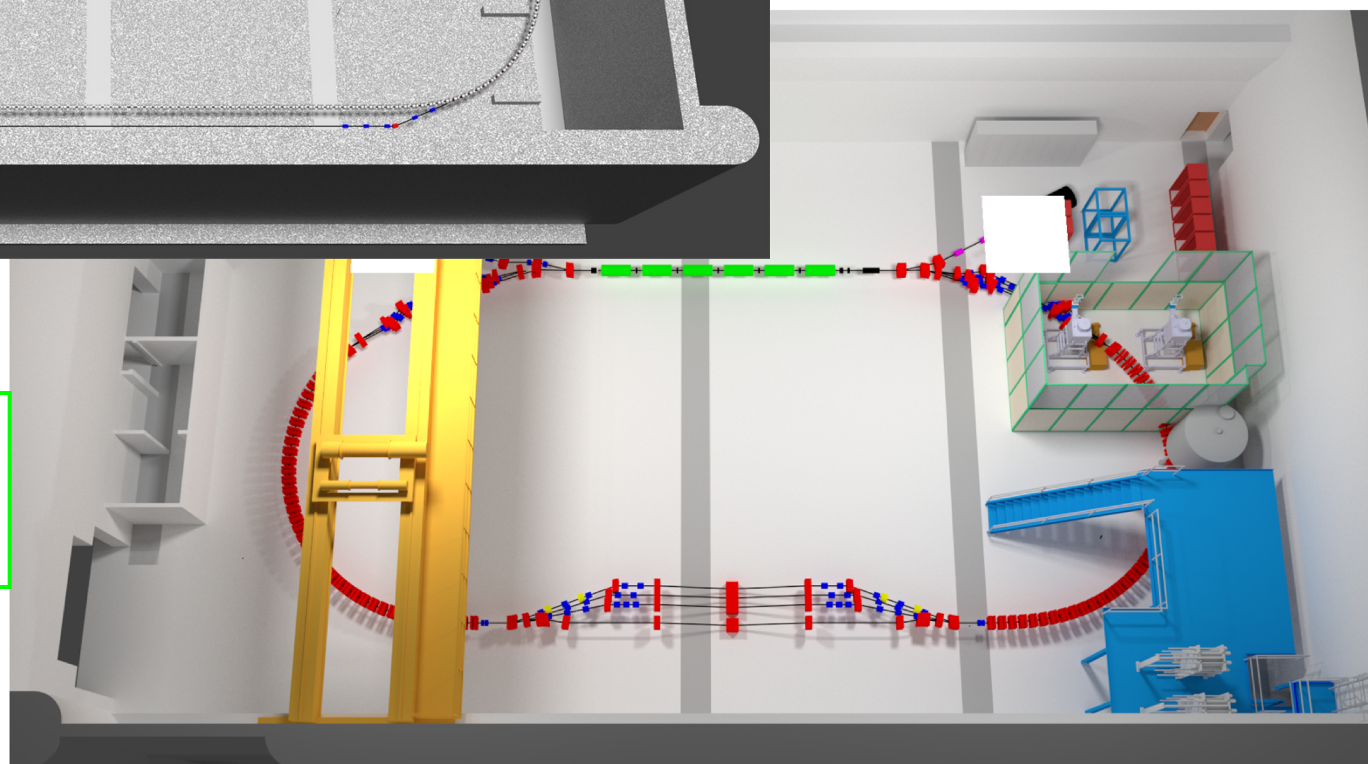
The complete initial state including scattered electron, recoil proton, and e+/e- pair that could come from the decay of a dark photon will be detected.

The DarkLight experiment drives development of new technology for beam, target, and detector and provides a new means to carry out electron scattering experiments at low momentum transfers. This technology would be ready to be applied at CBETA.

Resonantly extracted beam



Resonant extraction:
Use correctors that cancel for three energies but add for the highest energy.

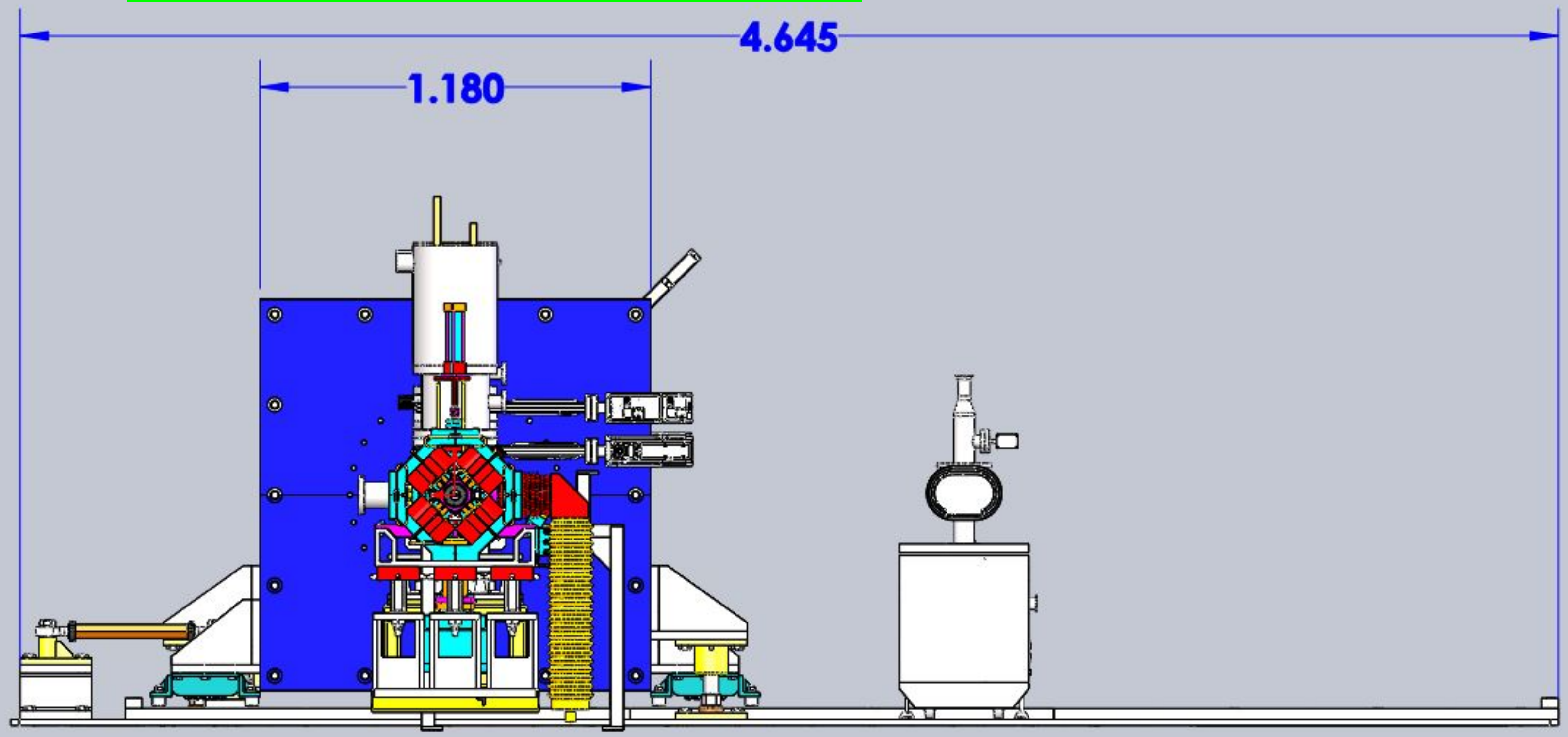


Beam separation:
Use septa magnets to separate each energy.

DarkLight

- DarkLight – an experiment to find dark matter particles

The Darklight detector at JLAB

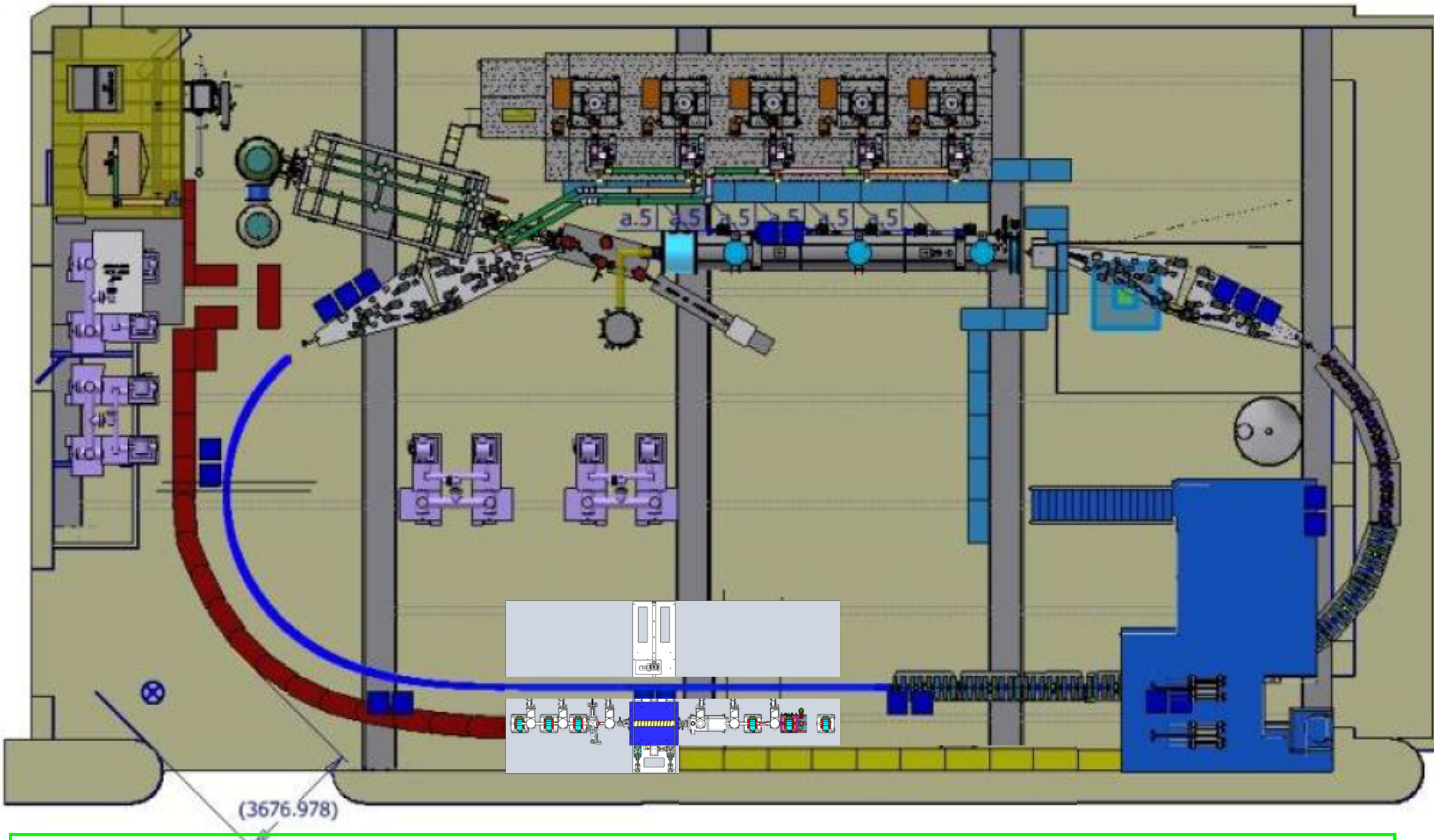


Movable support

Movable support

Pump station for the gas jet.

(A) DarkLight



The Darklight detector will fit around the resonantly extracted CBETA beam, if the movable support is redesigned.

Cornell is in contact with the DarkLight collaboration to submit a joint proposal.

(B) Compact Compton Source

- Compact Compton source for hard x-rays – complementing CHESS' range

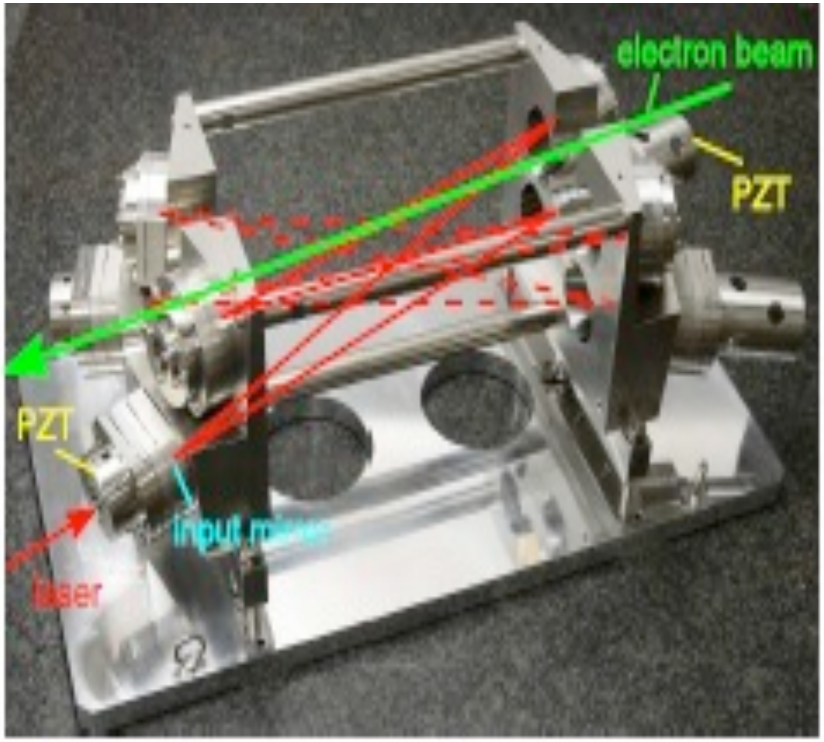
Extrapolating from the recent demonstration of an ERL-based laser Compton source by T. Akagi et al., Phy. Rev. Accelerators and Beams **19**, 114701 (2016). Assuming the same laser source and photon pulse – electron bunch collider

Expected maximum X-ray energy: **412 keV with 0.4% bandwidth, 0.14 mrad divergence**

Anticipated flux on sample of **2×10^{10} photons/ sec**

This is 13 times more than at a 3rd generation synchrotron radiation source: the current Cornell wiggler at CHESS's F2 line with the upgraded CESR storage ring (to be completed in the next few years)

From a collaboration with Carl Franck (Cornell)



The electron/photon collisions would occur within an optical cavity that intensifies the optical bunch intensity. The base design is due to Akagi et al. (2016)

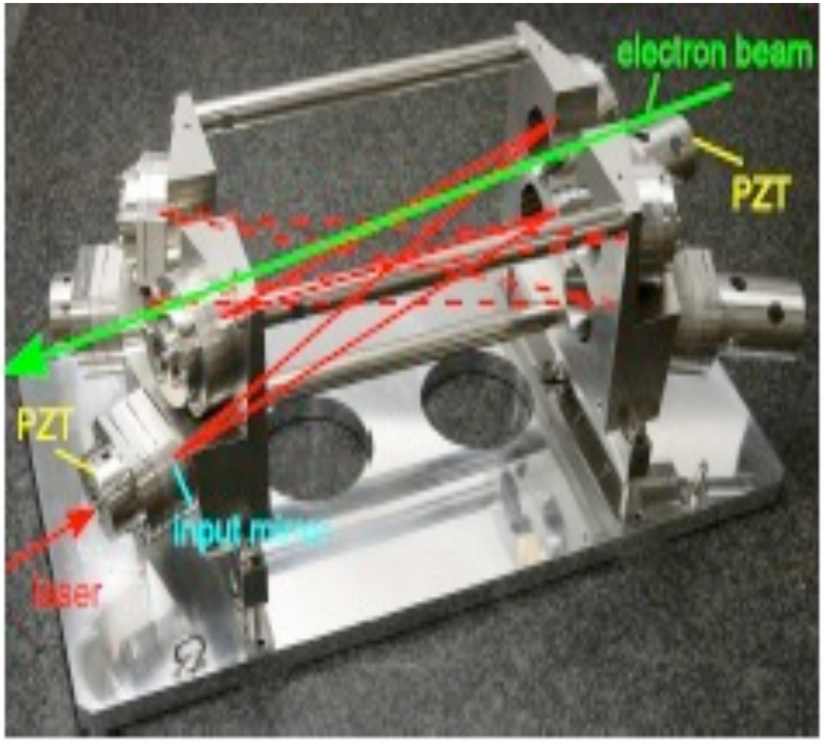
(B) Compact Compton Source

- Compact Compton source for hard x-rays – complementing CHESS' range

A proposal is envisioned for

- Develop laser storage cell
- Establish collisions in CBETA
- Develop an x-ray beamline

For after commissioning of CBETA with current funding by summer 2020 and possible stage II accelerator R&D.



THz Laser

- THz laser – complementing CHESS' range

European XFEL Workshop

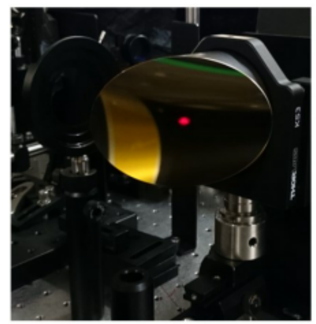
Terahertz science at European XFEL

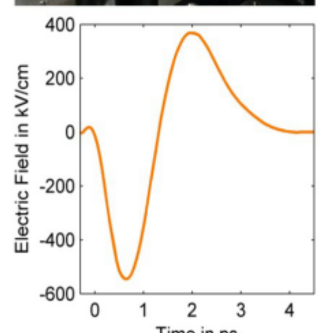
European XFEL

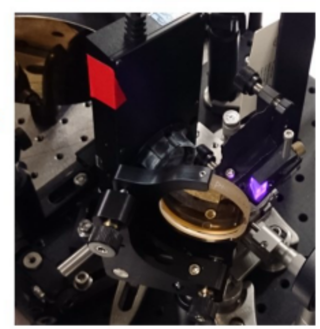
01–02 June 2017 / European XFEL, Schenefeld, Germany

The **interaction of terahertz radiation with matter** excites novel states with unique properties. These non-equilibrium states will benefit from ultrafast characterization using the ultrashort and highly brilliant X-ray pulses available at FELs. With this in mind, we are pleased to announce a terahertz workshop, with the aim to find the most scientifically promising strategies to combine terahertz radiation with the unique X-ray pulses generated at European XFEL.

The 2 day workshop will be led by 18 presentations from invited international scientists. The first day will explore the **scientific motivation for THz - X-ray experiments**. The second day will focus on the **two main routes to THz generation in the frequency range from 0.1 to 20 THz** (3 mm to 15 μm): On the one hand, state of the art laser-based sources; and on the other, undulator sources based on a second, smaller accelerator. Specific aspects will be compatibility with the MHz repetition rate of the European XFEL and novel opportunities for coherent control in the multi-THz regime. We intend to discuss how individual research projects can benefit from a combination of these sources.

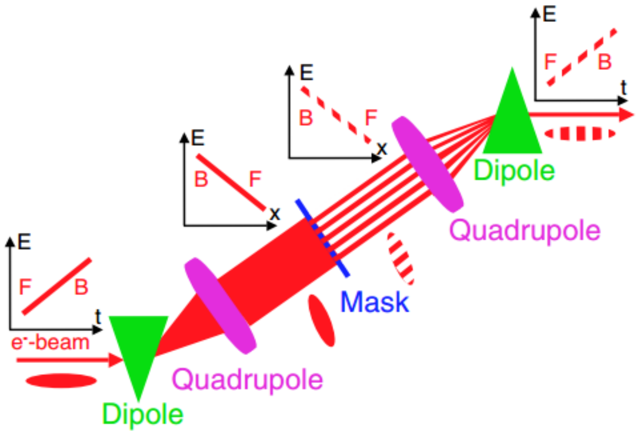




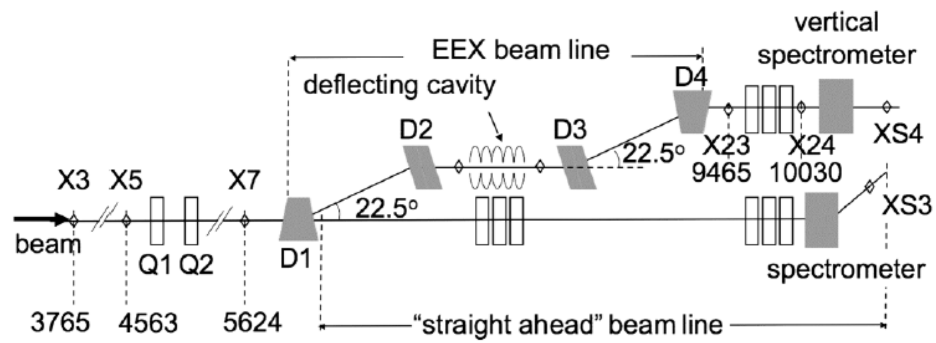


Accelerator based narrow-band THz schemes

- Exchange transverse modulation to longitudinal distribution

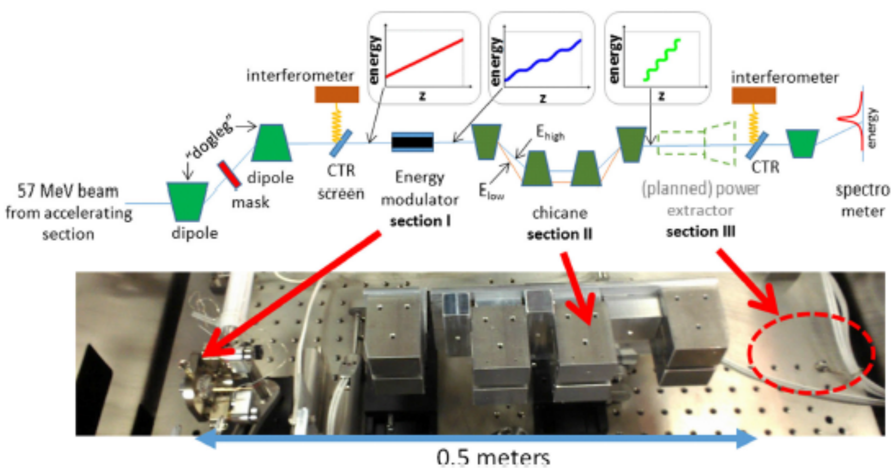


P. Muggli et al., PRL 101, 054801 (2008)



Y. E. Sun et al., PRL 105, 234801 (2010)

- Exchange wake-induced energy modulation to density bunching



K. Bane and G. Stupakov, NIM-A 677, 67 (2012)

S. Antipov et al., PRL 108, 144801 (2012)

S. Antipov et al., PRL 111, 134802 (2013)

G. Stupakov, PRST-AB 18, 030709 (2015)

K. Bane et al., NIMA 844, 121 (2017)

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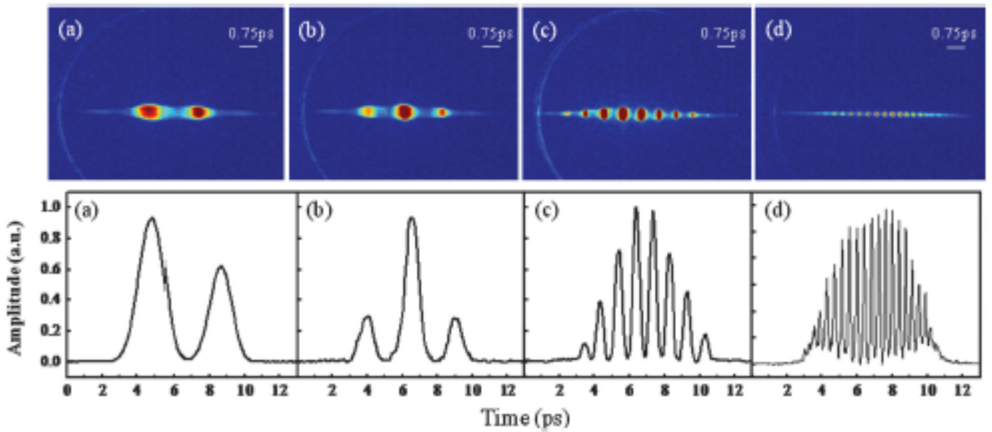
Accelerator based narrow-band THz schemes

- Direct modulate the drive laser of the gun



Y. Li et al., APL 92, 014101 (2008)

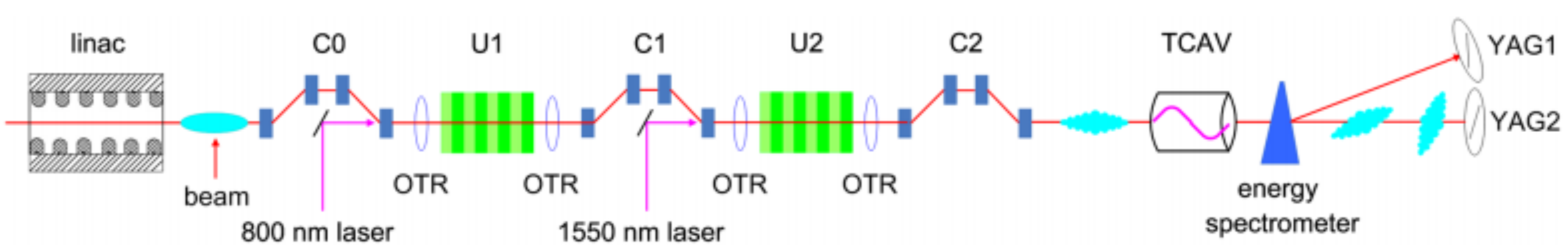
P. Musumeci et al., PRL 106, 184801 (2011)

Y. Shen et al., PRL 107, 204801 (2011)

P. Musumeci et al., PRST-AB 16, 100701 (2013)

Z. Zhang et al., PRL 116, 184801 (2016)

- Frequency beating of laser-induced density bunching



D. Xiang et al., PRST-AB 12, 080701 (2009) *M. Dunning et al., PRL 109, 074801 (2009)*

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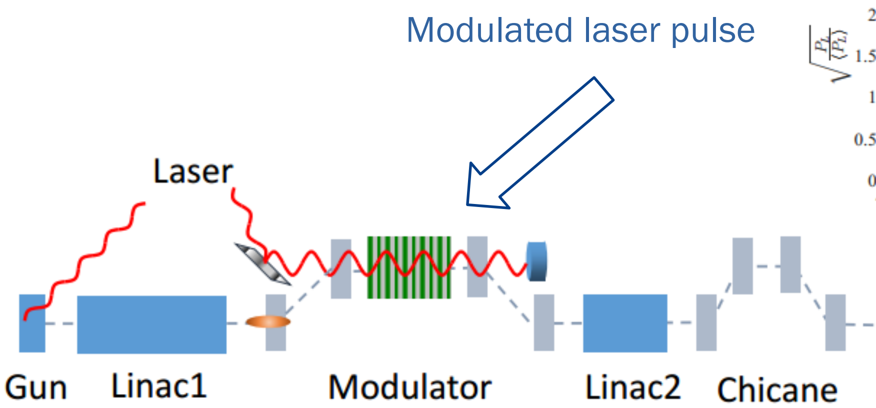
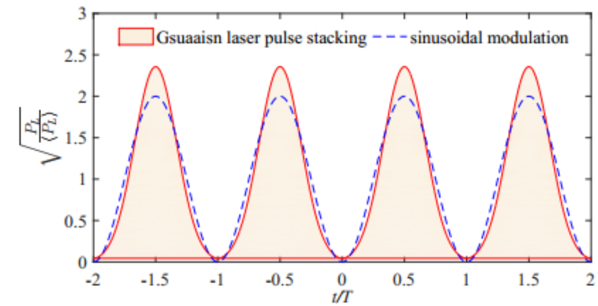
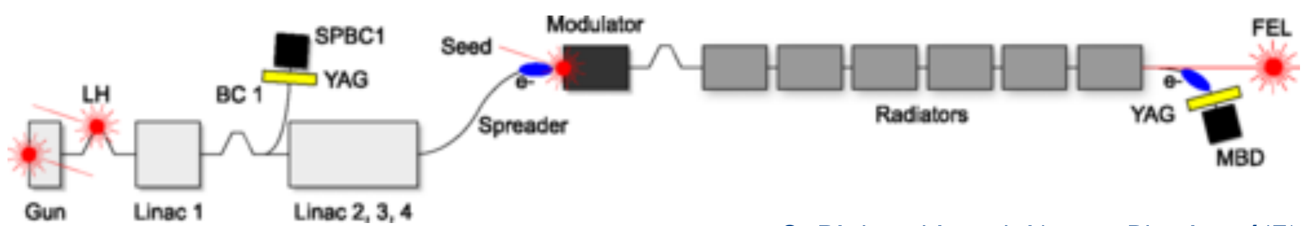
New method
(Z. Zhang et al., Phys. Rev. AB 20, 050701, 2017)

- We propose a method based on the slice energy spread modulation to generate density bunching in a relativistic electron beam (a la **laser heater setup**)





- Similar method has been used in storage ring and FERMI FEL (for two-color FEL).



S. Bielawski et al. Nature Physics, 4(5), 390-393 (2008)
E. Roussel et al. Phys. Rev. Lett. 115, 214801(2015).

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Simulation parameters fit very well to CBETA

Parameter	Value	Units
Electron beam		
Charge	500	pC
Beam energy	135	MeV
Current Profile	flat-top	/
Bunch length	~ 10	ps
Intrinsic slice energy spread	10^{-4}	/
Norm. emittance	1	mm-mrad
rms beam size	200	μm
Modulator		
Laser wavelength	800	nm
Undulator period	5	cm
Period number	10	/
Laser waist size	1.5	mm
Laser stacking separation	0.5 (0.25*)	ps
rms laser pulse length	60 (30)	fs
Laser power	1 (0.26)	GW

* The numbers in brackets are the parameters for 4 THz case.

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High-rep. Rate Stand-alone THz source

A stand alone THz source has been designed for the LCLS-II are

- Stand-alone THz source at the experimental area (XFEL, LCLS-II)
- Use LCLS-II spare gun + accel. cryomodule (50 MeV) for a high-rep. rate compact accelerator
- E-beam power is similar to LCLS-I (5-10 kW) and requires LCLS-I type of shielding
- Leverage OPCPA laser at LCLS-II R&D (800 nm, 0.1 -1 MHz, 100 W)
- Expect good synchronization with hutch lasers (both through OPCPA)
- Strong THz field may be used in the LCLS(-II) TimeTool to cross-correlate with optical signals (and X-rays) for jitter corrections

- THz pulse form can be controlled by both laser and e-beam techniques (narrowband, chirped, a few cycle pulses, all possible)
- Flexible, powerful, high-rep. rate THz, well-synchronized with X-rays.

Similar parameters could be achieved at CBETA.
This application is under discussion, no planning has been started.

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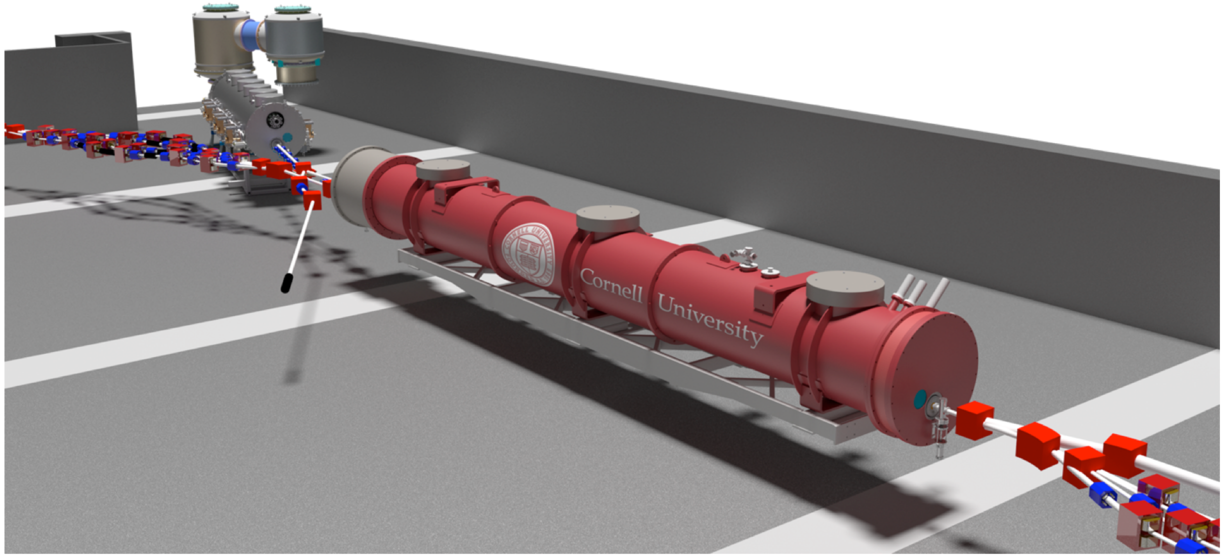
Fast electron diffraction

- Beam for time-resolved electron diffraction from 1-6MeV

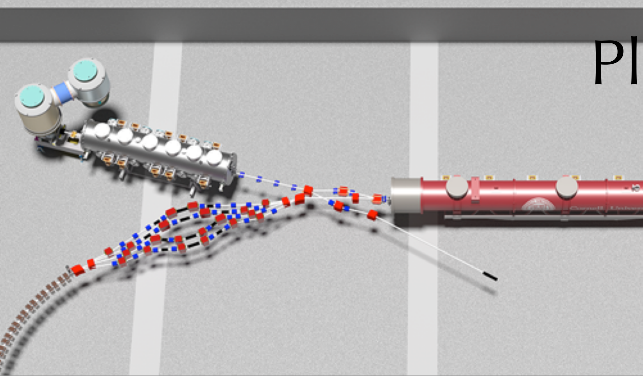


CBETA has a 6MeV line that is mirror symmetric to the line that leads into the Main Linac Cryomodule (MLC). It is for injector optimization, because optimization in the MLC lacks detectors.

The full beam brightness can be optimized in this region between 1 and 6 MeV and can be used for various beam applications.

Together with David Muller (Cornell) an application for fast electron diffraction is being prepared.

Plasma Wakefield Acceleration



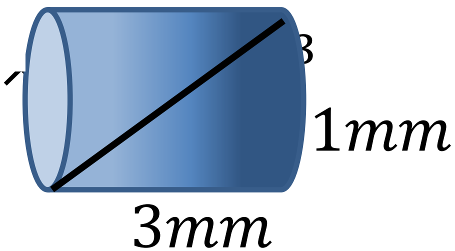
- Beam for **Plasma Wakefield Acceleration**

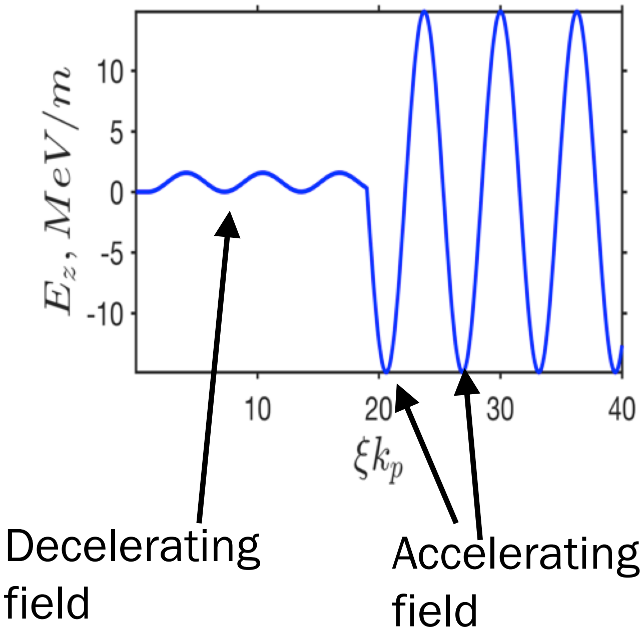
  with High Transformer Ratio

beam parameter:

$Q = 1nc$

$n_{max} = 5.5\times$

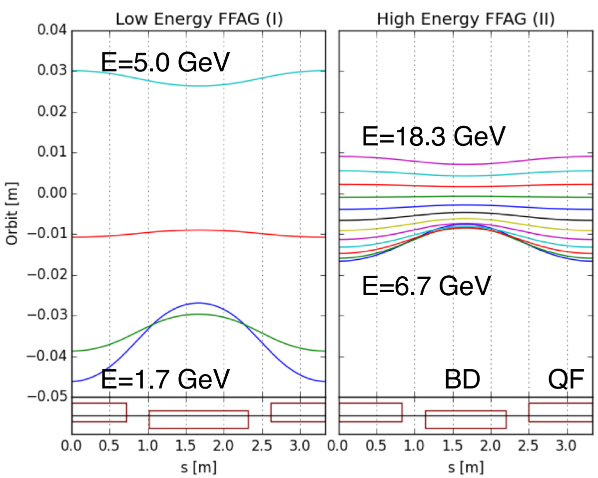


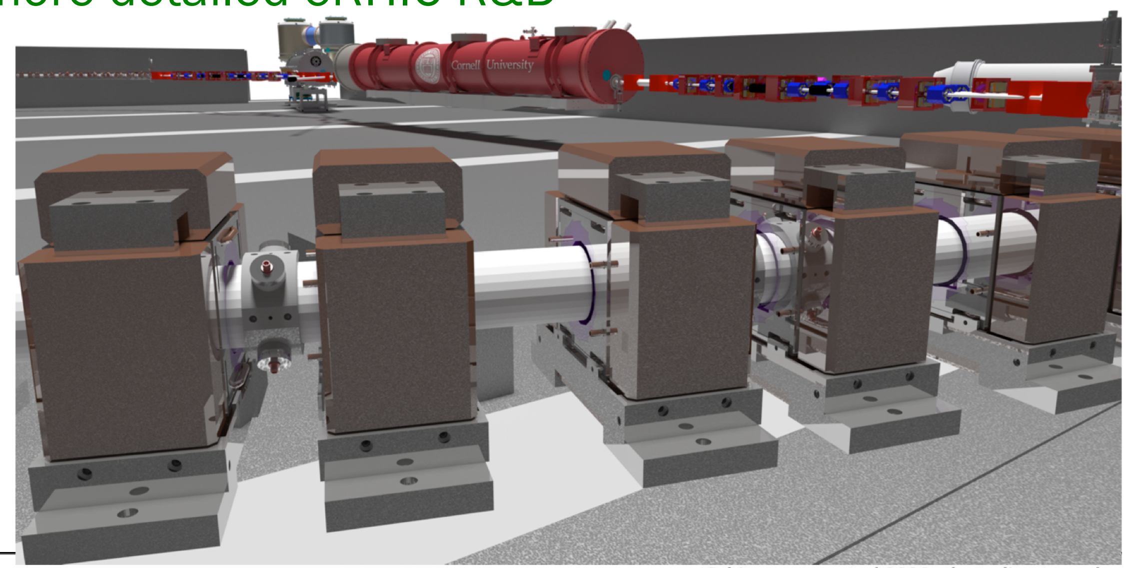


- Key challenge for PWFA: low transformer ratio
- A Gaussian driver bunch is experiencing a **decelerating field that is ½ of the peak accelerating field** experienced by the witness bunch
- Shaped bunches → large transformer ratio → never demonstrated before
- CBETA could generate triangular shaped driver bunches and time-delayed witness bunches (Collaboration with Gennady Shvets)

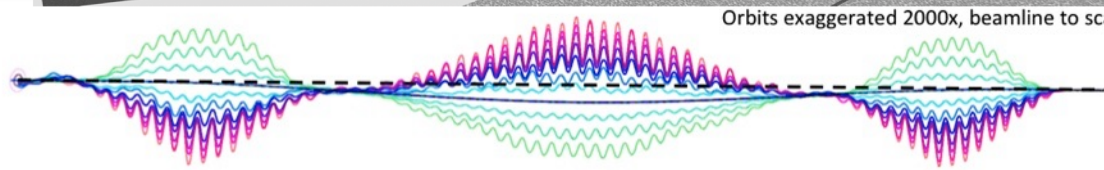
Continued eRHIC prototyping

- eRHIC accelerator testing – more detailed eRHIC R&D



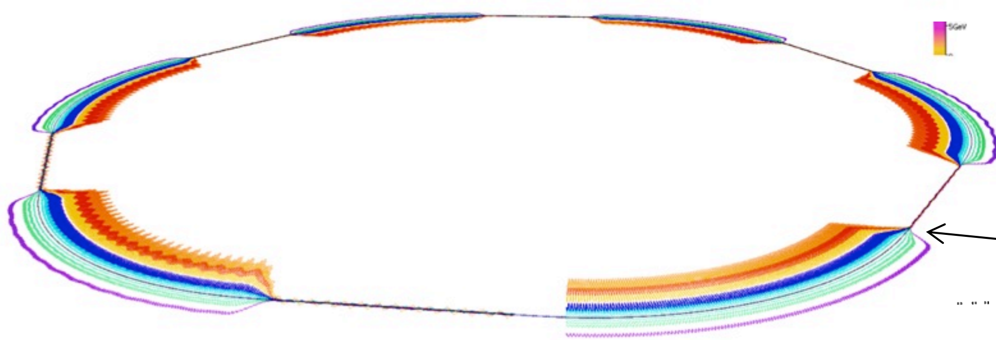


Orbits exaggerated 2000x, beamline to scale



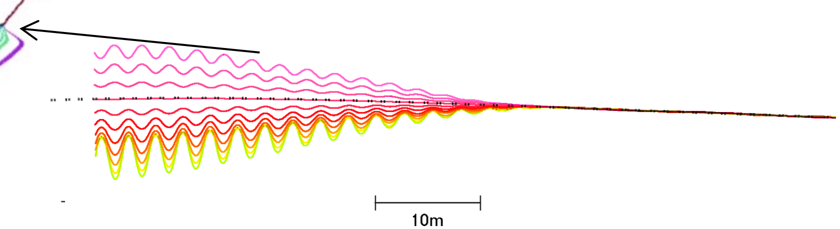
@S.Brooks, D.Trbojevic

Orbits in Detector bypass section



Quad offsets evolve adiabatically

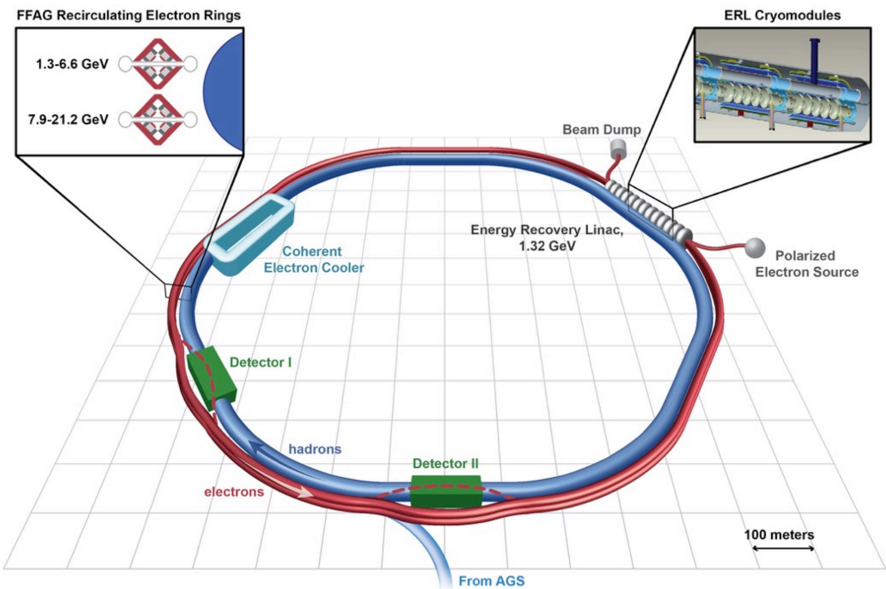
Orbits in Transition section



Each of two eRHIC FFAGs contain 1066 FFAG cells

Cavity testing with beam

- eRHIC cavity testing with beam
- ASML medical isotope cavity testing with beam

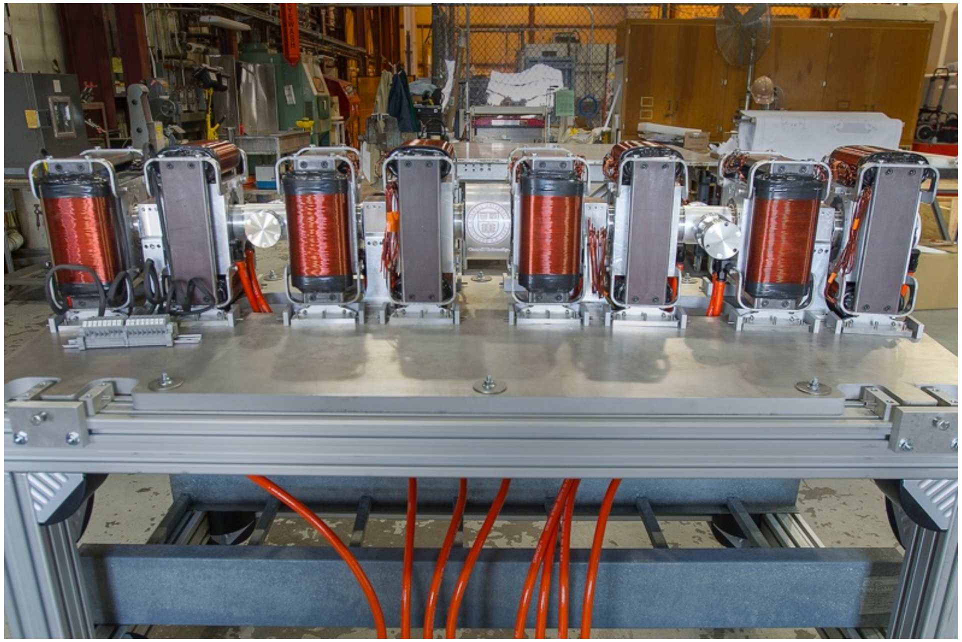


eRHIC's first test cavity has 650MHz and can be tested in CBETA setup with beam:
- Remove MLC, adjust cryo and RF systems
- Insert eRHIC test-cryomodule with 2 5-cell cavities

The company ASML has a grant for electron-beam production of medical isotopes with an CW SRF linac. Interest in beam test of the linac (650MHz or 1.3GHz) in CBETA has been discussed.

ERL accelerator physics

- Generic ERL accelerator physics
- Electron cooler tests – ERL tests for JLEIC
- Preparations for Perle @ ORSAY
- Preparations for LHeC
- High-Power beam dynamics testing
- Permanent magnets for future accelerators
- FFAG test bed for future accelerators



CBETA's prototype girder with 4 FFAG cells of permanent Halbach magnets.

Questions?