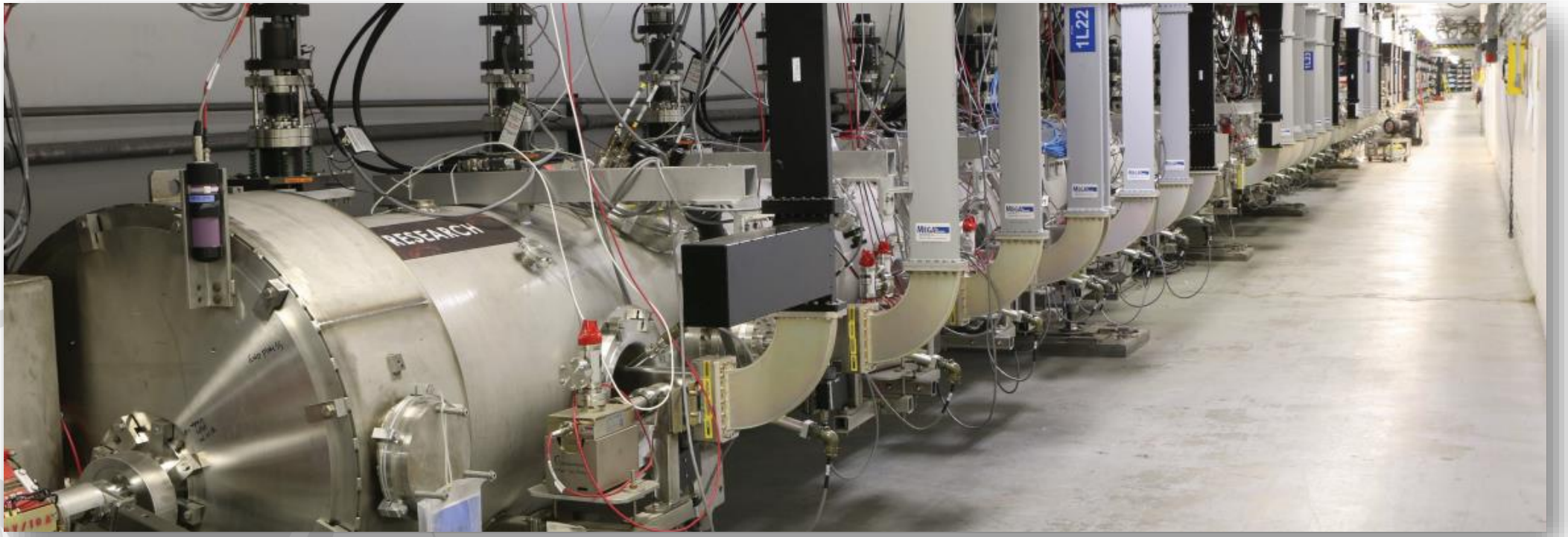
CEBAF Overview

Continuous Electron Beam Accelerator Facility



Andrei Seryi

Jefferson Lab Associate Director for Accelerator Operations and R&D

The 2022 Workshop on Fixed Field Alternating Gradient Accelerators

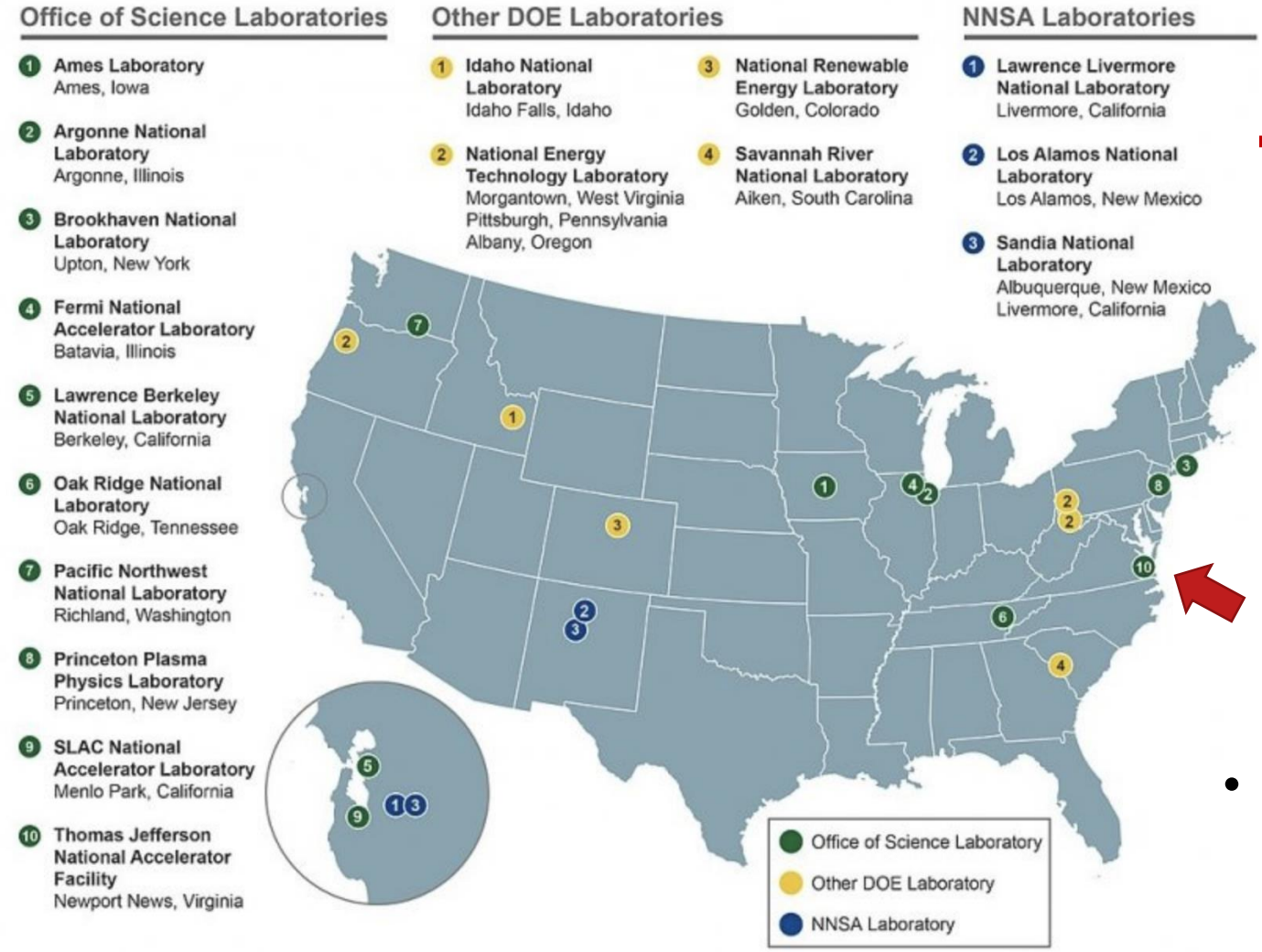
25-30 September 2022

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Jefferson Lab



- Jefferson Lab was created to build and operate the Continuous Electron Beam Accelerator Facility (CEBAF), a unique user facility for Nuclear Physics
- Managed for DOE by Jefferson Science Associates, LLC

- **Jefferson Lab by the numbers:**
  - **~ 800 employees**
  - **– 1,694 Active Users worldwide**
  - **– 26 Joint faculty with 12 universities**
  - **– 731 PhDs granted to-date (175 in progress)**
  - **– 184 patents (28 license agreements)**

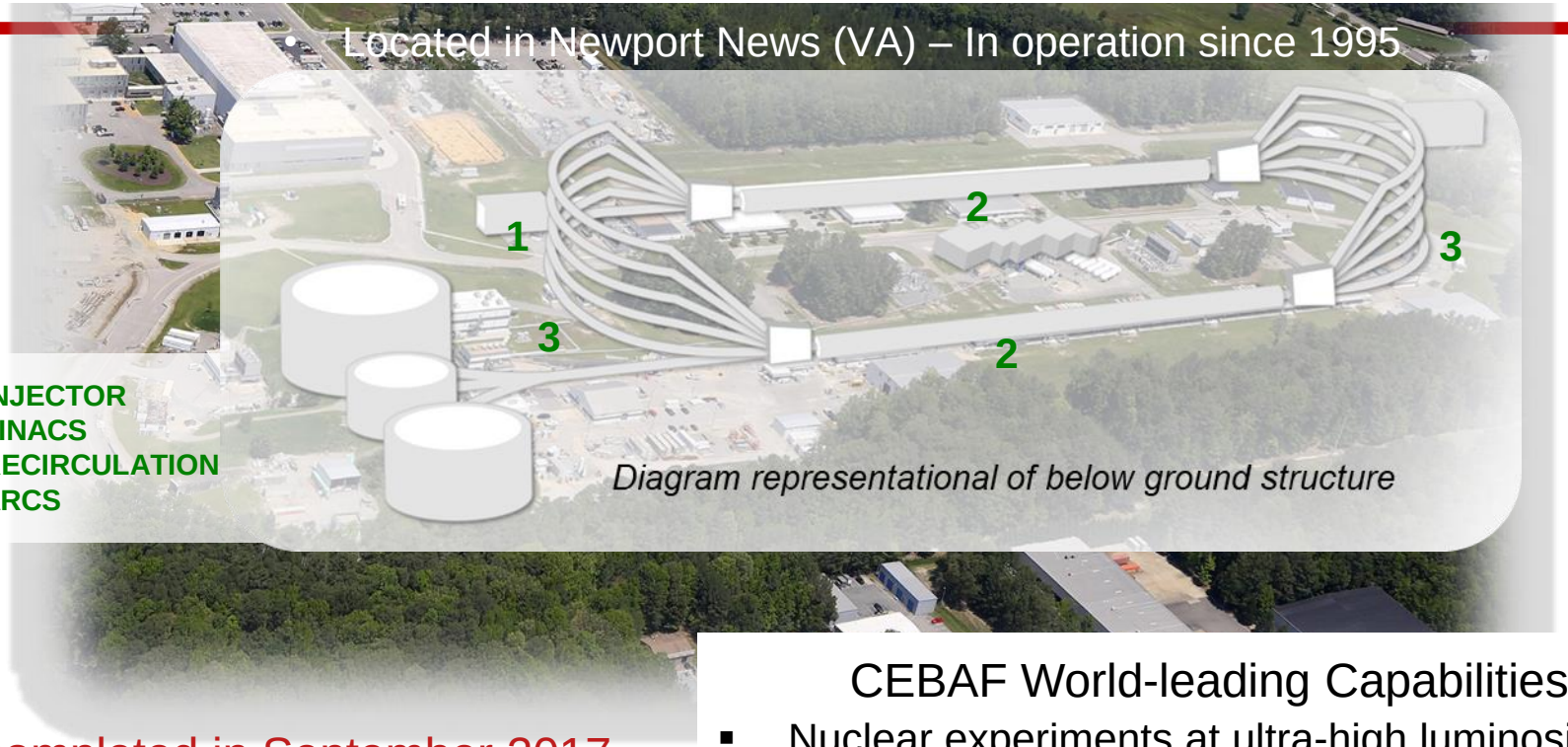
Location and History

- Thomas Jefferson National Accelerator Facility, or JLab, is located in Newport News, Virginia, next to many historical landmarks
- 1984-1987 – funding, selection of SC RF, start of construction
- 1995 – start of CEBAF operation at 4 GeV
- 2000 – CEBAF reached 6 GeV
- 2017 – completion of 12 GeV upgrade project

Fort Monroe. 20min drive from JLab

Jefferson Lab's Scientific Mission

Our mission is to understand the subatomic constituents of protons and neutrons and the force that holds them together – the strongest force in the Universe

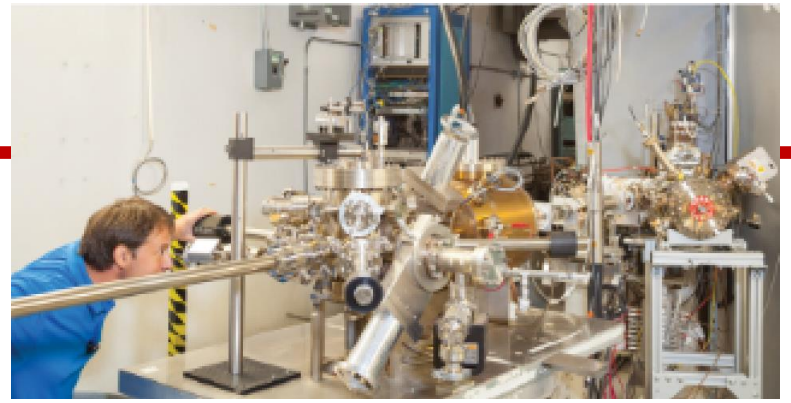


Our primary research tool is CEBAF - a superconducting high-energy electron particle accelerator

- CEBAF Upgrade completed in September 2017
  - CW electron beam
  - E_{max} = 12 GeV
  - I_{max} = 90 μA
  - Pol_{max} ~ 90%
- Physics Operation
  - 4 halls running simultaneously since January 2018

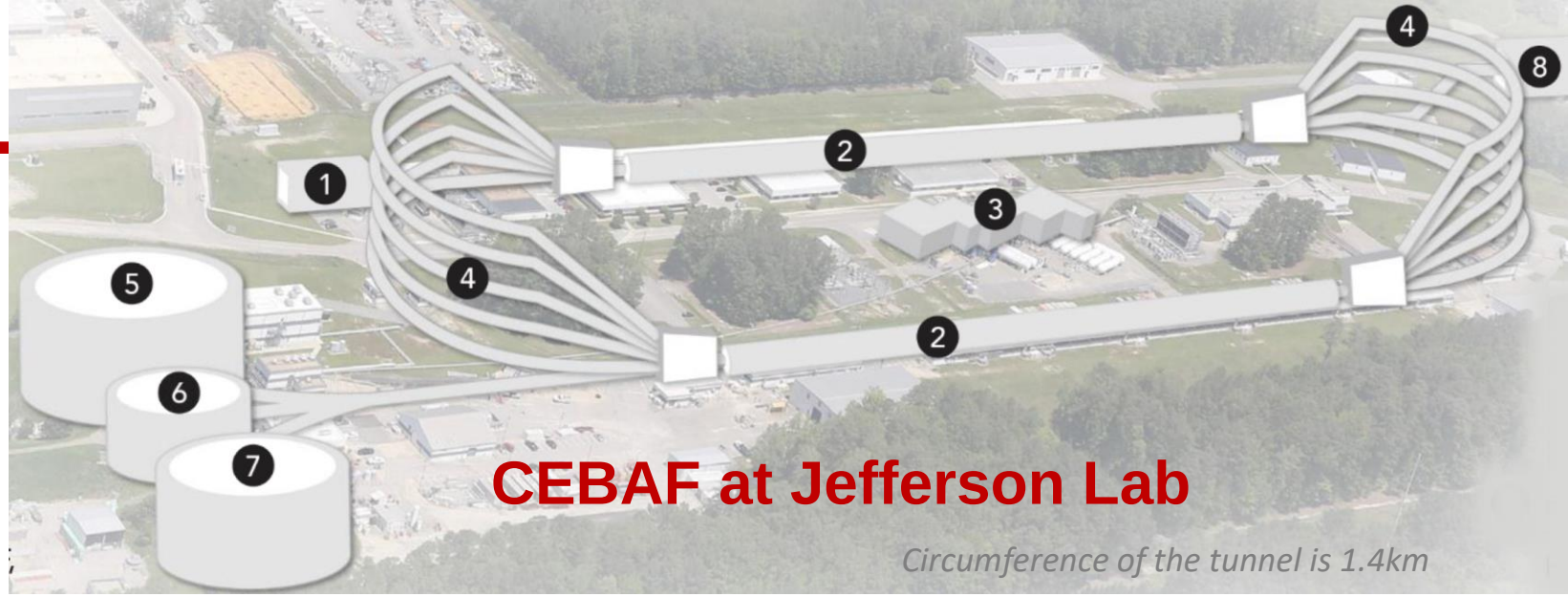
CEBAF World-leading Capabilities

- Nuclear experiments at ultra-high luminosities, up to 10^{39} electrons-nucleons /cm^2/ s
- World-record polarized electron beams
- Highest intensity tagged photon beam at 9 GeV
- Unprecedented stability and control of beam properties ➔ Excellent for low energy Standard Model tests
- Ability to deliver a range of beam energies and currents to multiple experimental halls simultaneously



1 Polarized injector

The injector produces polarized electron beams for the experiments



CEBAF at Jefferson Lab

Circumference of the tunnel is 1.4km

2 Linear accelerators 1497 MHz

Straight sections have 25 cryomodules each. Beam travels up to 5.5 passes through linacs to get to 12 GeV

3 Central Helium Liquefier

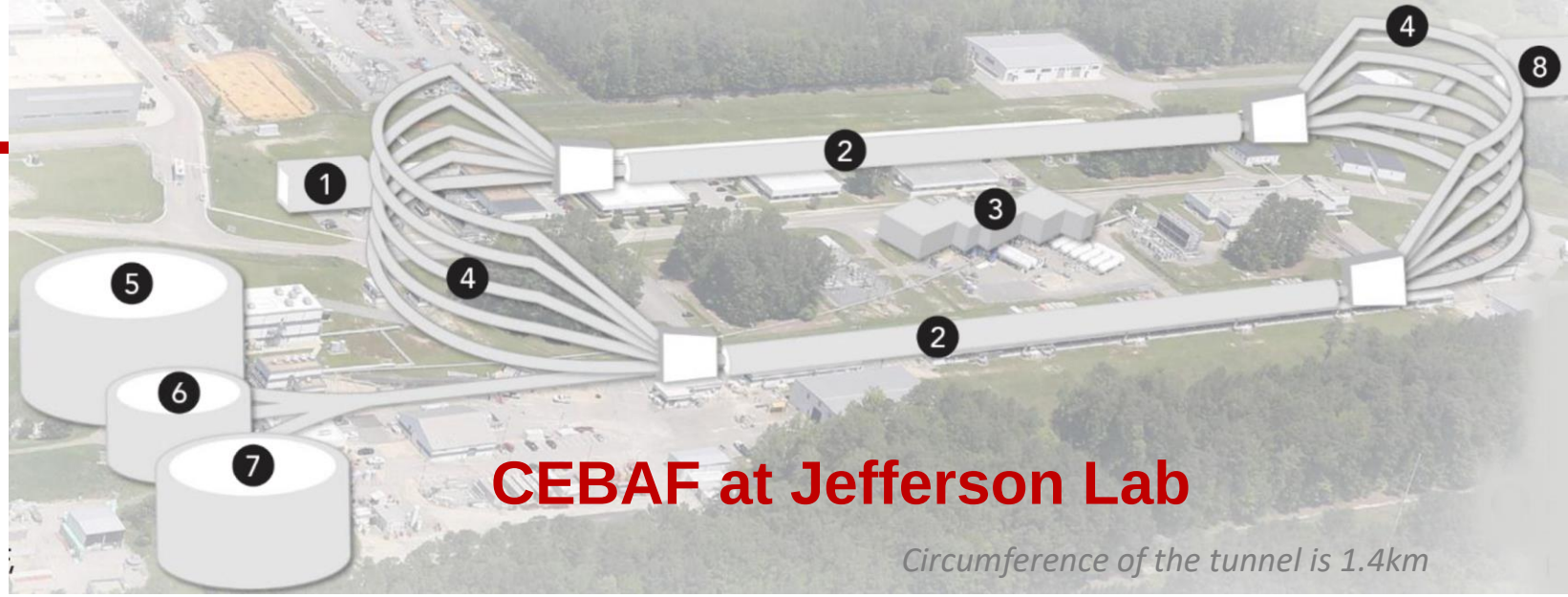
CHL keeps SRF cavities at 2K temperature

4 Recirculation magnets

Dipoles and quadrupole magnets to focus and steer beam as it pass along each arc

5 Experimental Hall A

Two High Resolution Spectrometers for precise measurements of nuclei inner structure



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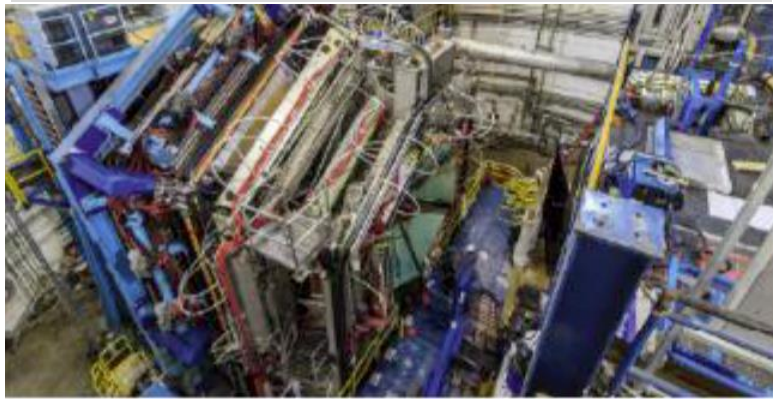
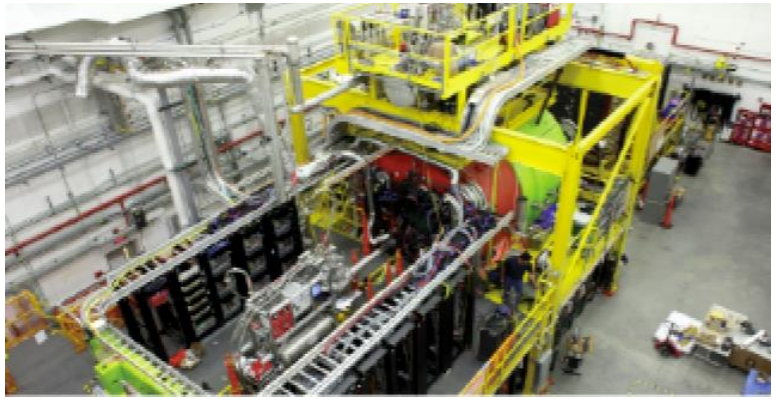


6 Experimental Hall B

CEBAF Larch Acceptance Spectrometer (CLAS12) surrounds the target to measure many angles simultaneously

7 Experimental Hall C

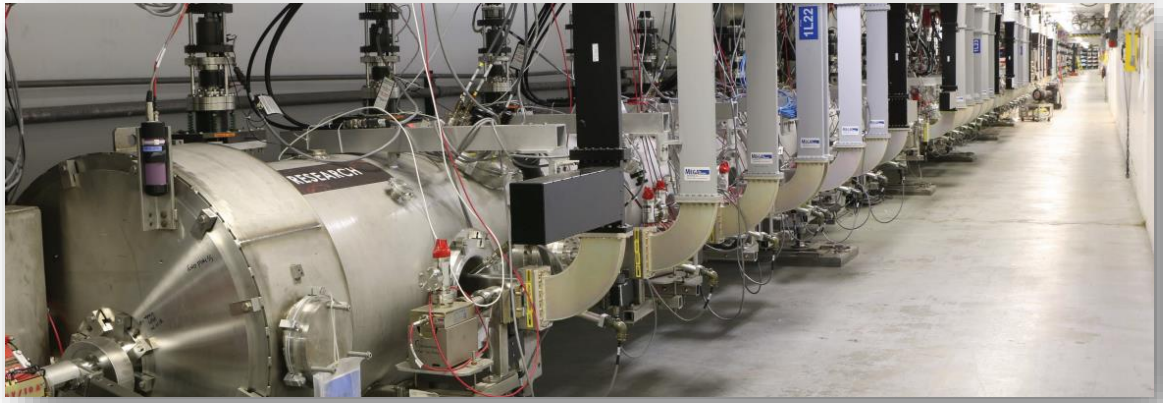
High Momentum Spectrometer measures nuclei structure at high energy and high beam current



8 Experimental Hall D

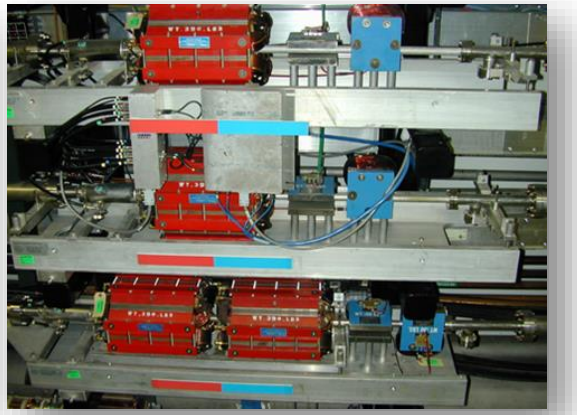
Equipped with SC magnet and detector to study strong force that binds quarks together

CEBAF Accelerator – Technical Scope

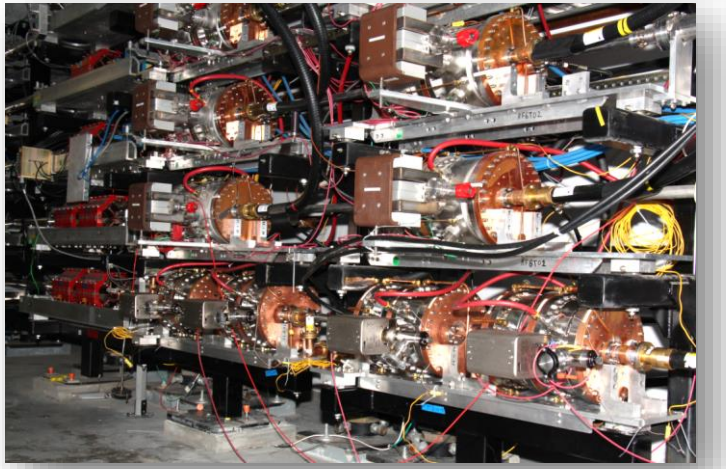


52-1/4 Cryomodules with 418 SRF Cavities to Accelerate Electrons in CEBAF

~500 Large Dipoles powered by >40 HVPS

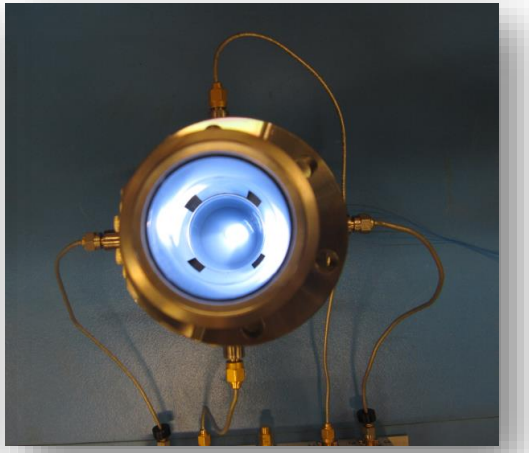


>2800 Magnets to Focus and Steer Beam



16 RF Deflectors for Extracting Beams

418 Klystrons for 52.25 Cryomodules

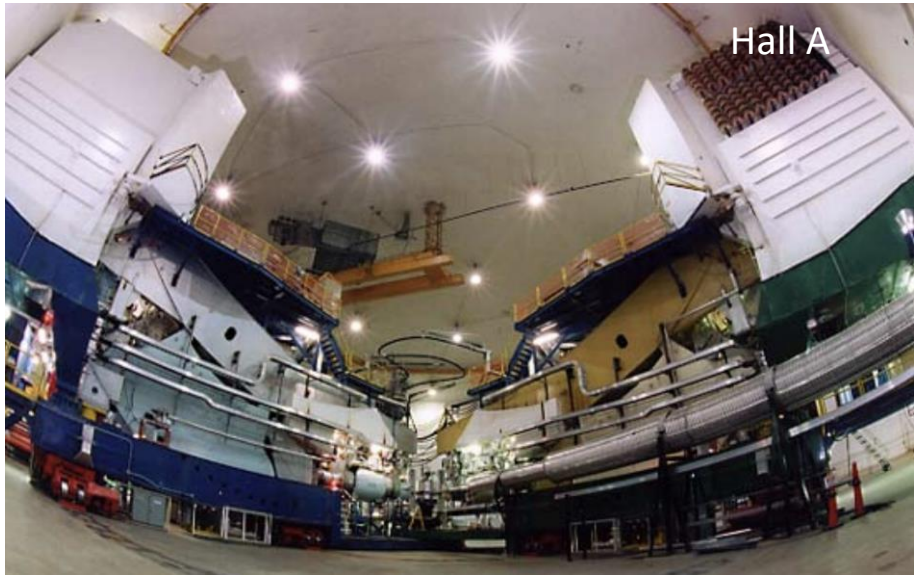


>800 Beam Position Monitors

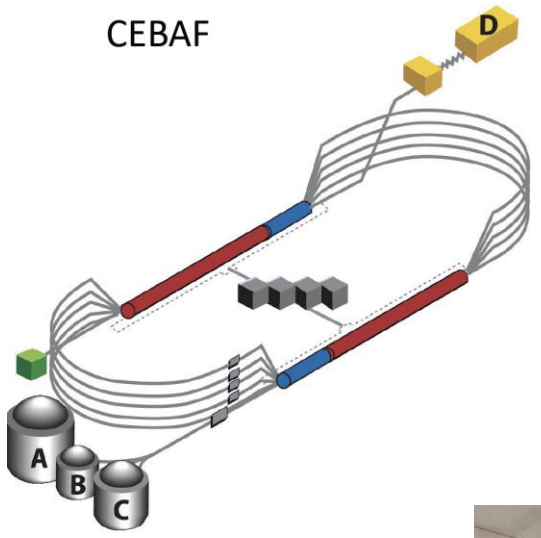
High Power Exp Hall Beam Dump

- Capable of delivering 4 independent CW polarized electron beams simultaneously to experiment Halls.
- Over 7 km of beamline ~800 BPMs, 60 harps, 150 viewers, and 7 synchrotron light monitors.
- >580,000 data channels on a distributed network of over 600 local computers with 200 kHz data rate.

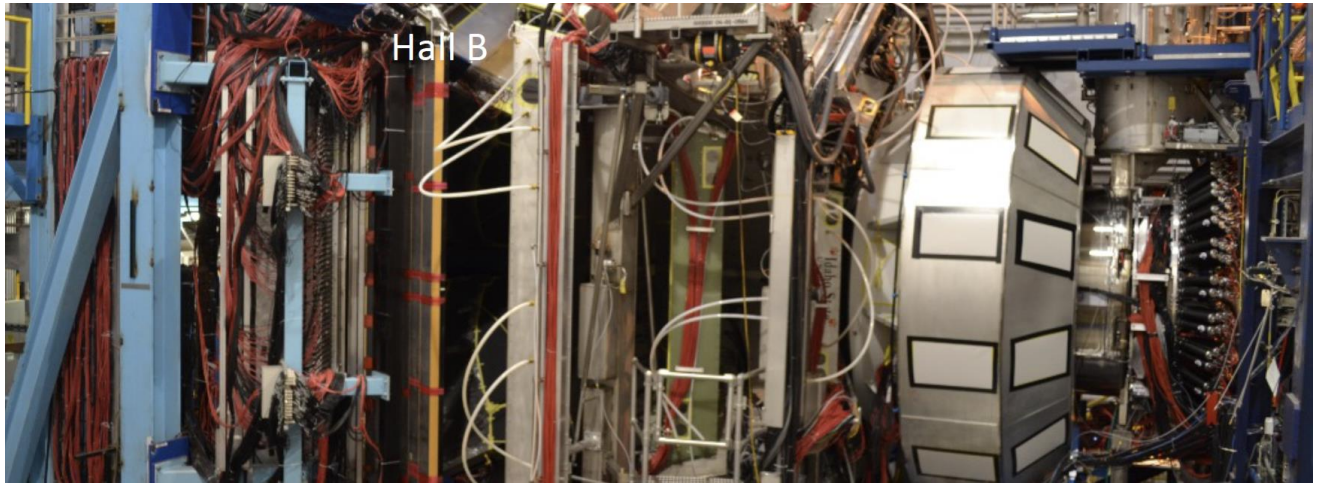
CEBAF Halls and Experiments



Hall A (HRS, SBS)



Hall D (Glue X)



Hall B (CLAS12)

Hall C (HMS and SHMS)

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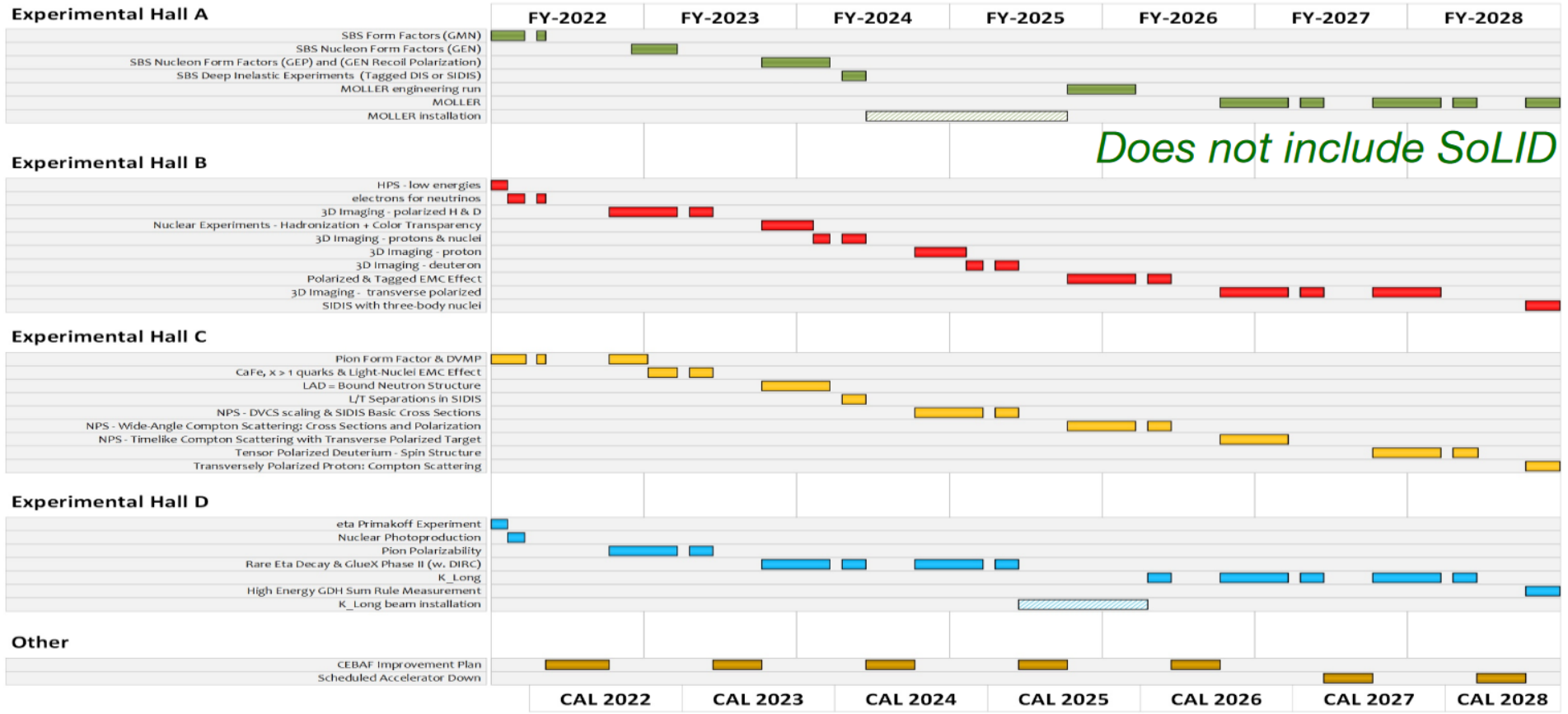
CEBAF 12 GeV Science is Exciting and Impactful

Current CEBAF Experiment Schedule



57 approved experiments now, ≈8 years at ≈30 weeks per year, more PAC's to come

QCD Town Meeting 2022: The Jefferson Lab 12 GeV Program 14 Jim Napolitano, Temple University, 24 Sept 2022

See 2022 Town Hall Meeting on Hot & Cold QCD, Sep 23-25, 2022, https://indico.mit.edu/event/538/

CEBAF Construction

- Construction started ~1987
- Cut and cover tunnel construction
- Tunnel is below water table
- Good ground water protection

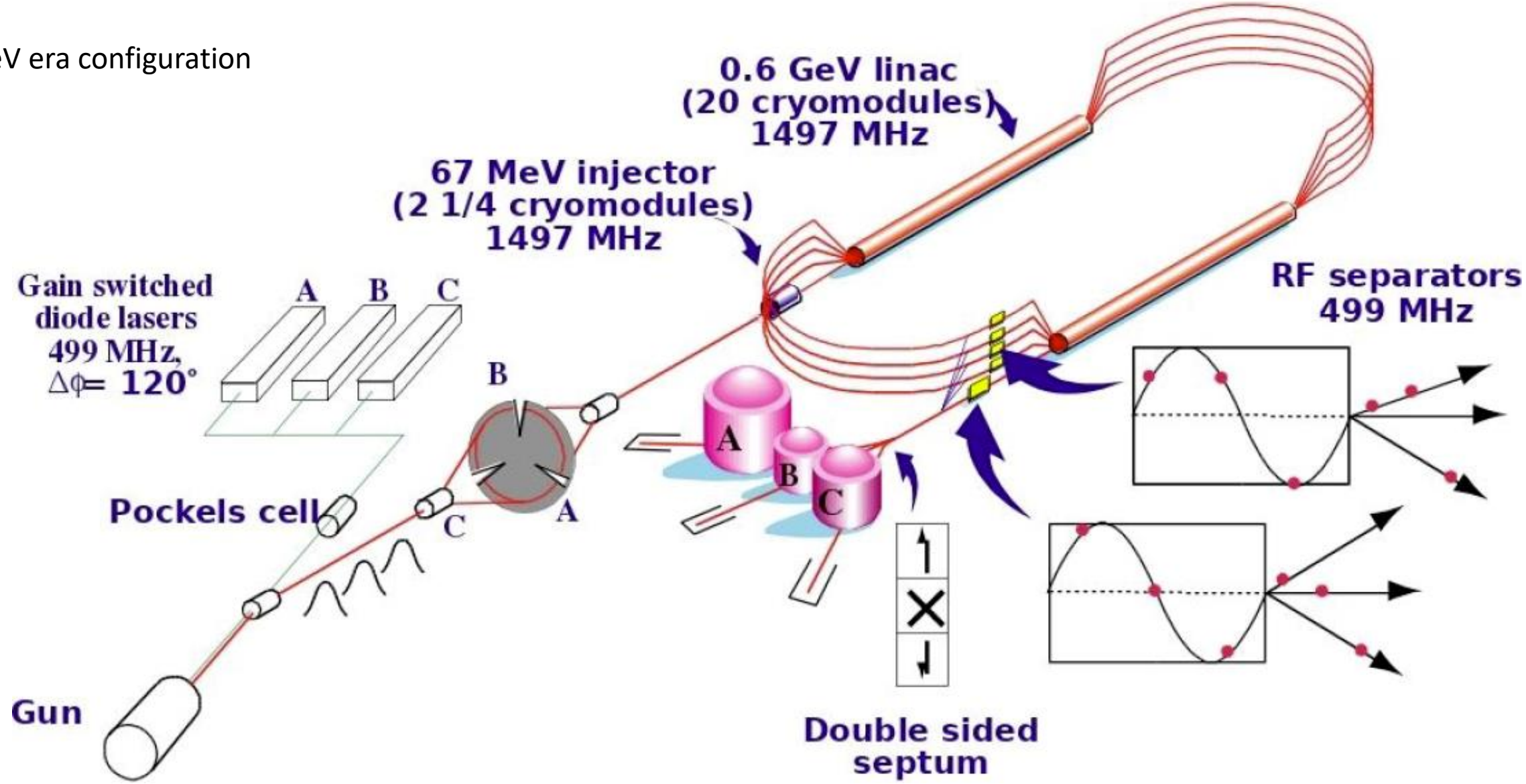
CEBAF Construction

Tunnels before hardware installations

Arcs in 6 GeV era (four beamlines)

CEBAF three halls era

6 GeV era configuration



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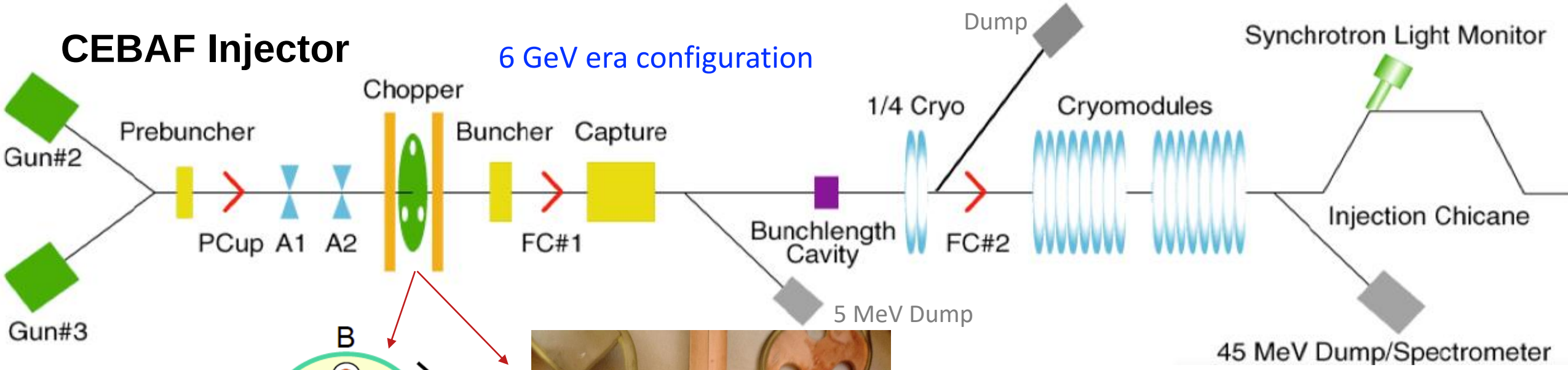
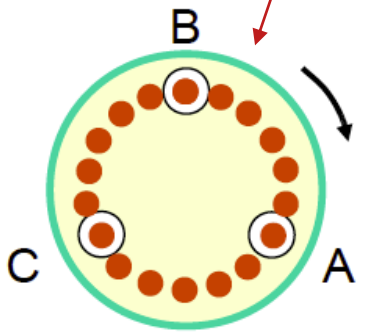
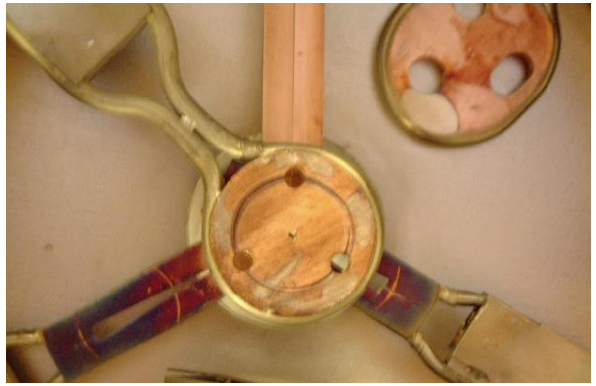
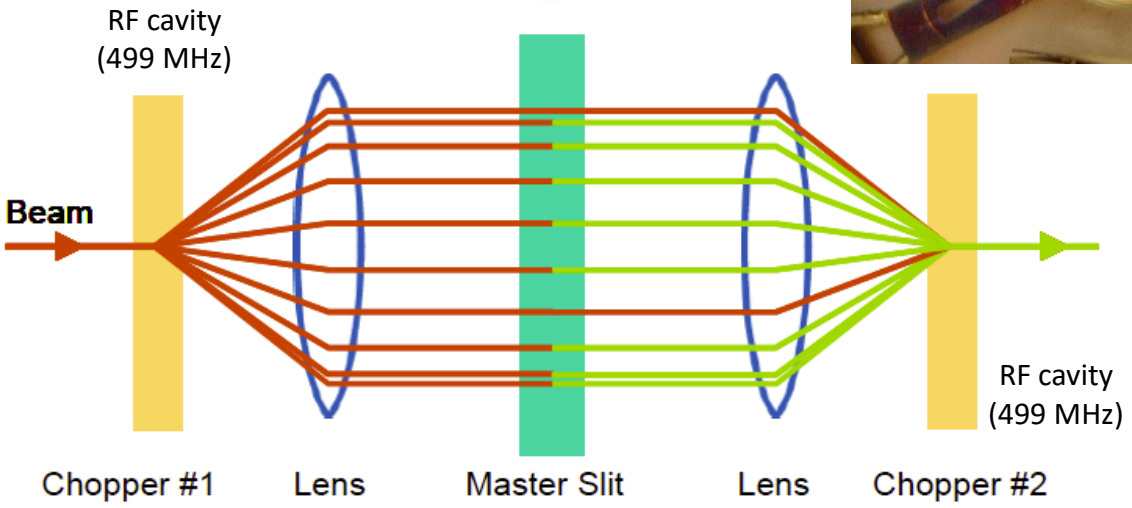
CEBAF Injector

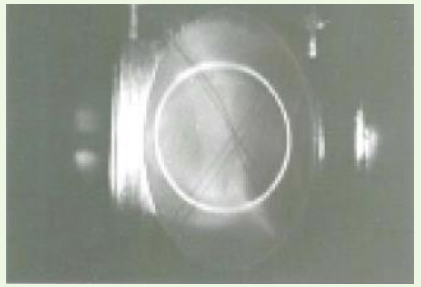
6 GeV era configuration



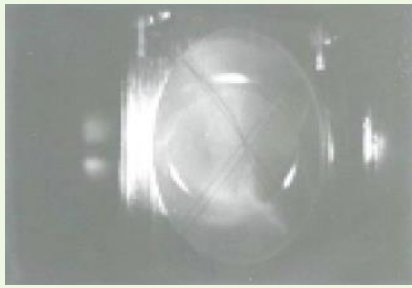




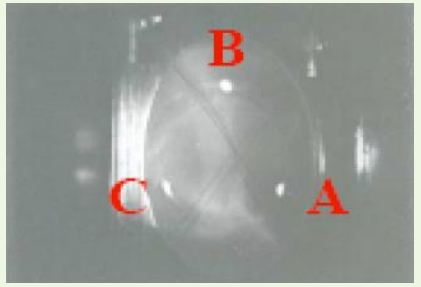




DC light, most beam thrown away

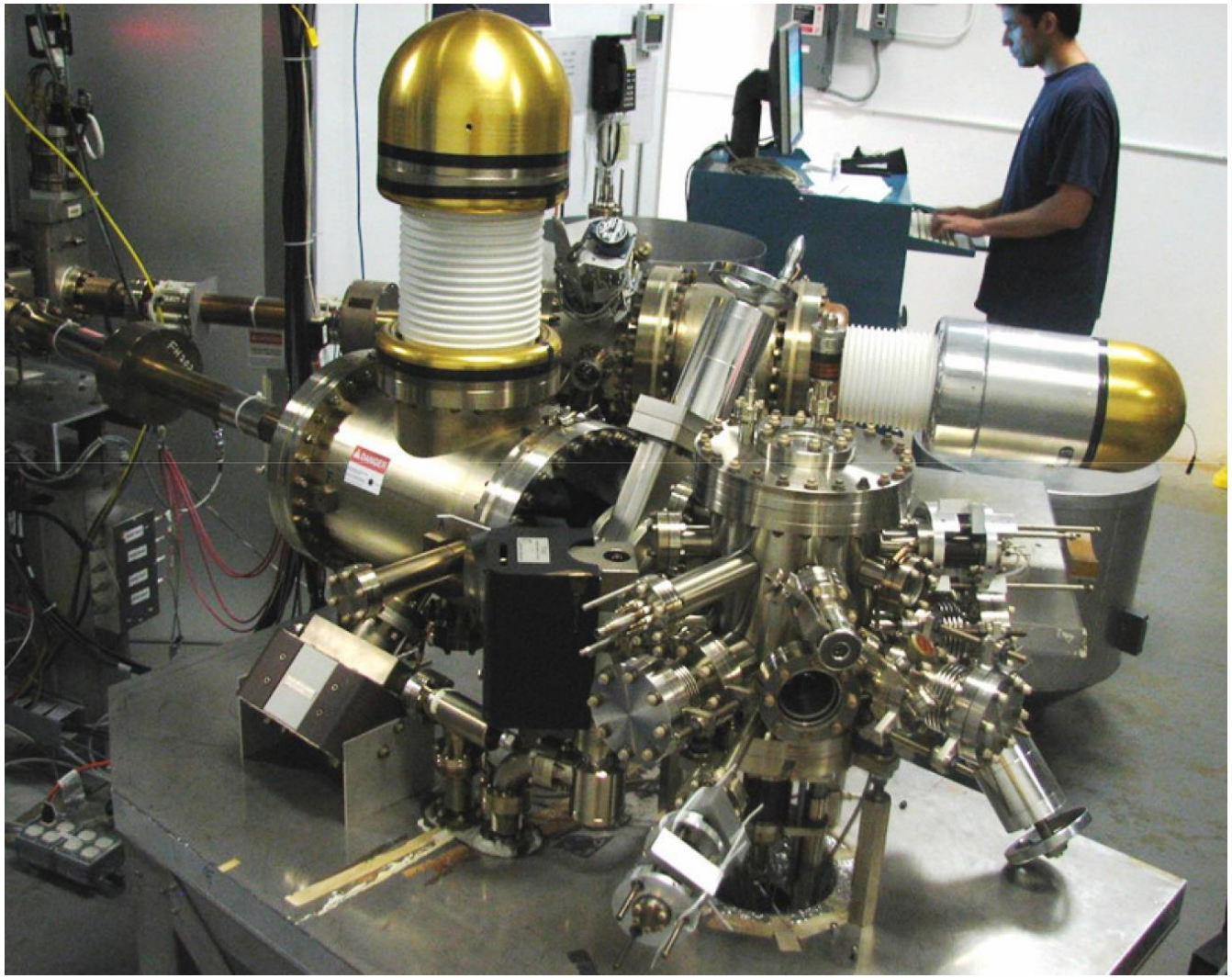


Three RF-pulsed lasers



Pre-buncher added

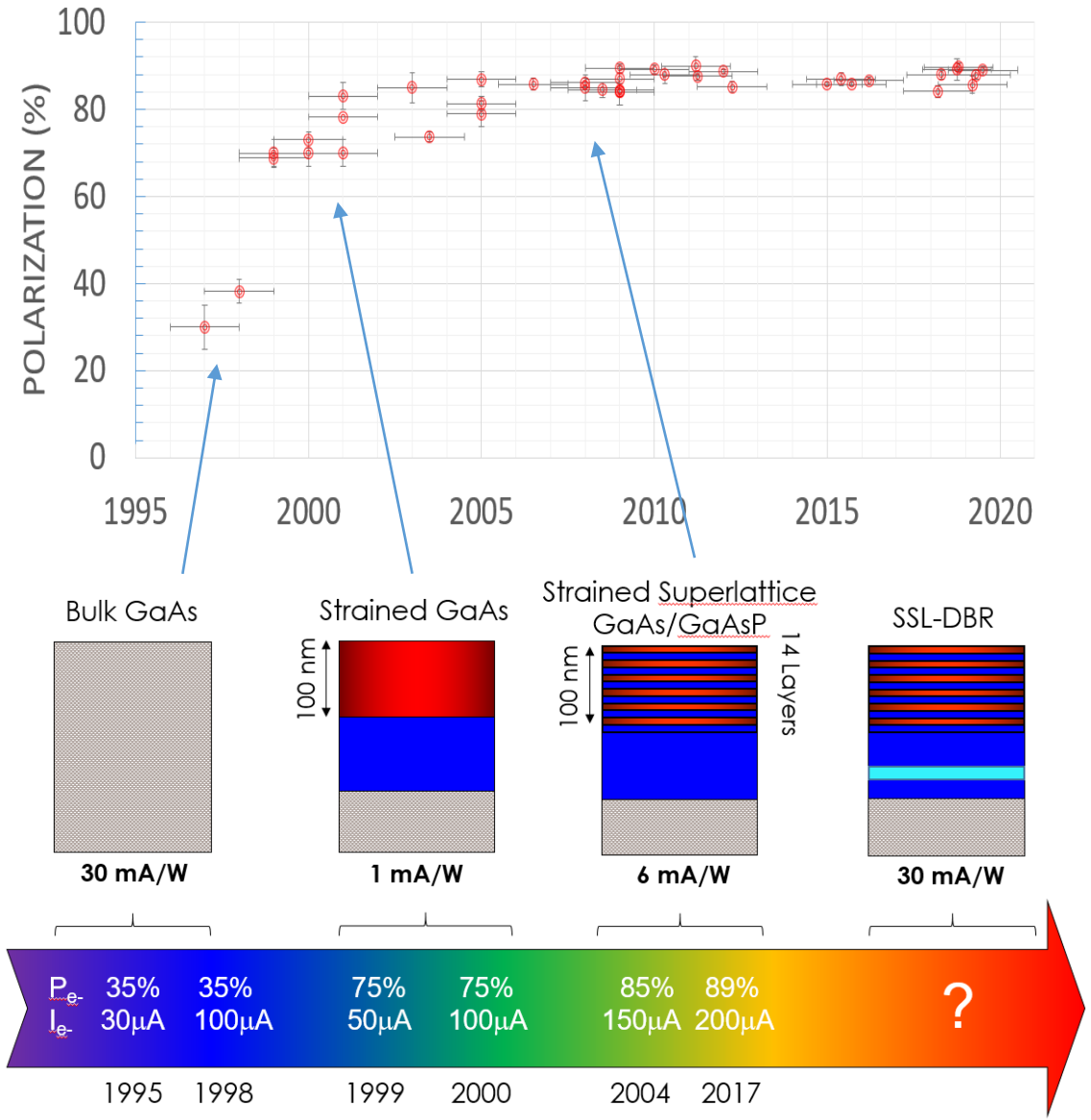
CEBAF load-lock polarized gun



- Laser light that shines on the Gallium Arsenide photocathode is RF pulsed at 499 MHz and creates an RF microstructure on the electron beam
- 499 MHz is a sub-harmonic of the fundamental accelerator operating frequency 1497 MHz
- During three-hall operations, three separate 499 MHz lasers—one for each hall—are used to generate three interlaced electron beams
- Continuous Wave Beam for Physics
- Pulsed beam for optics tuning

100kV gun (circa 2007). Lifetime limited to 30C. Path to higher lifetime and beam quality – higher voltage

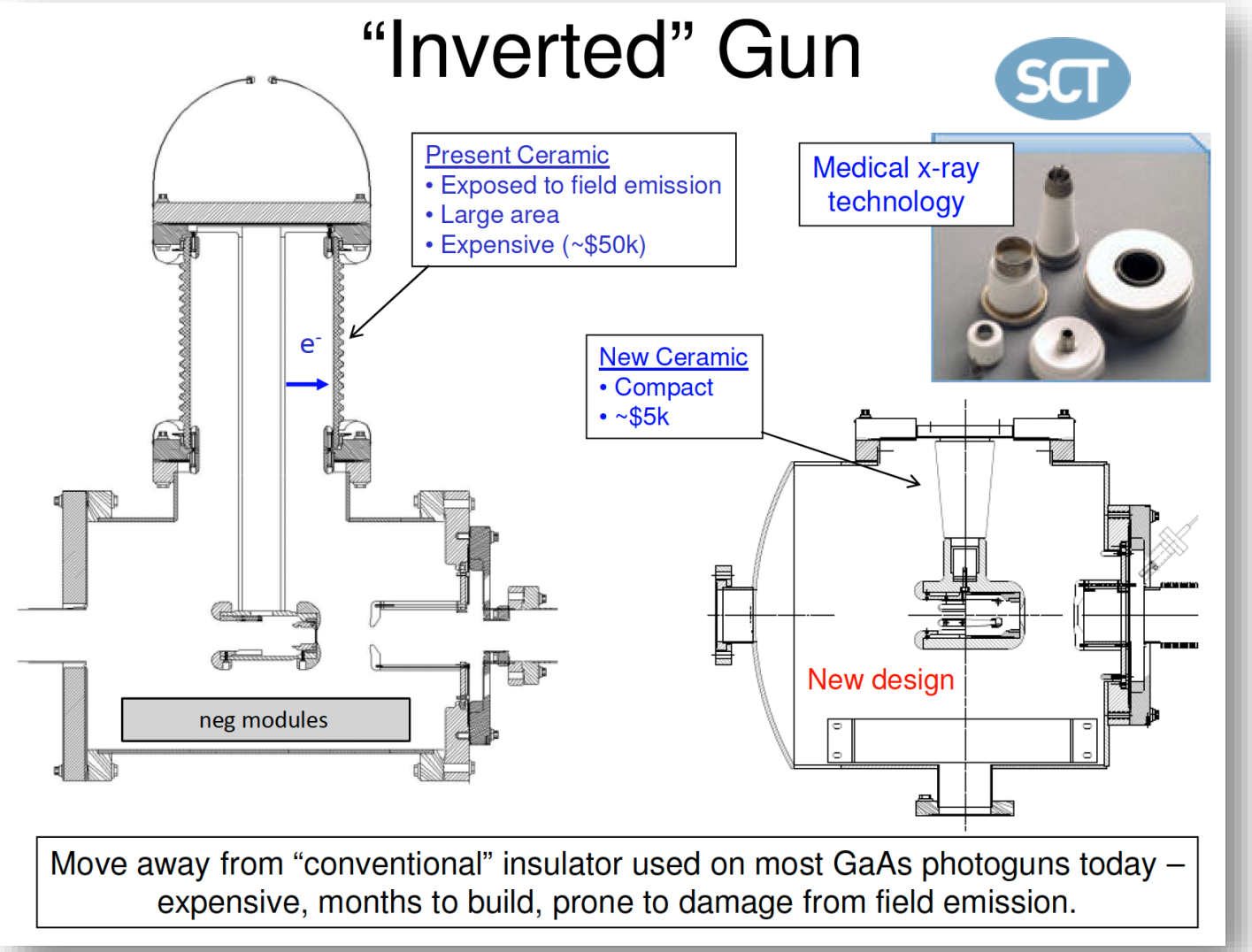
CEBAF polarized source and performance evolution

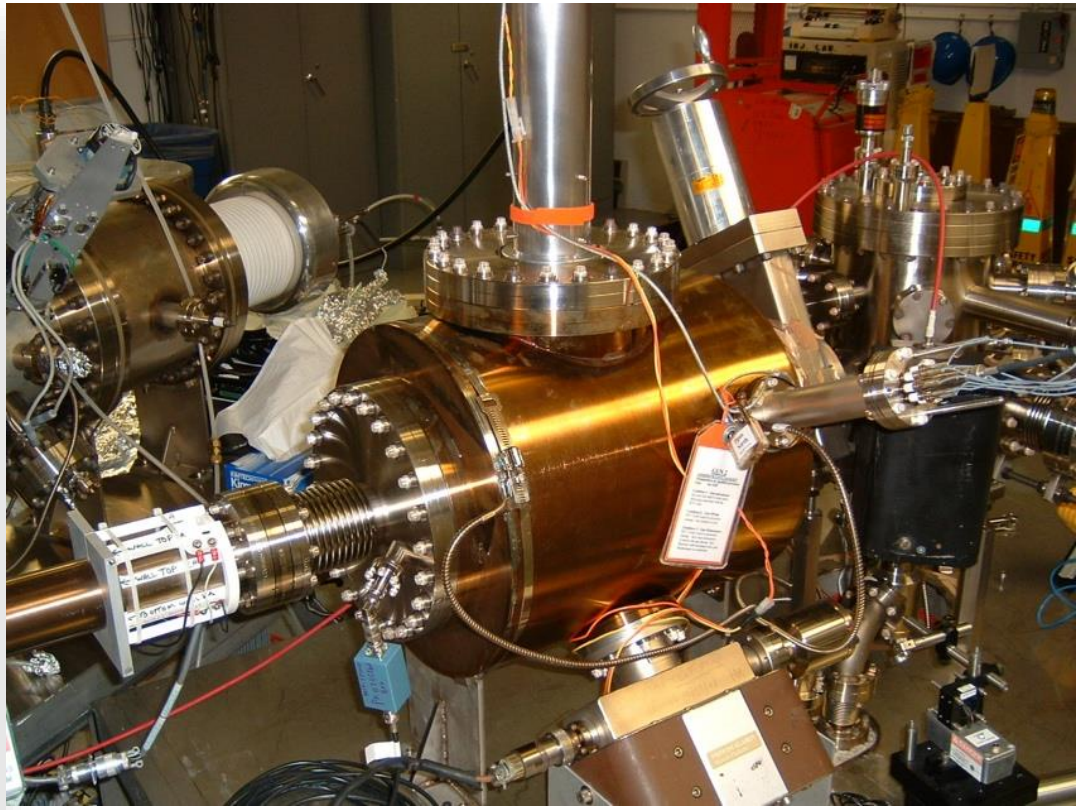


- Technology advances for e-beam polarization improvements
  - Bulk GaAs
  - Strained GaAs
  - Strained Superlattice GaAs/GaAsP
  - Strained Superlattice – Distributed Bragg Reflectors
- Polarization above 85%

- Electron gun design also advanced
- New experiments demanded longer lifetime of cathodes and new design of guns
  - ILC played a stimulating role for development of new ILC/CEBAF “Inverted gun”

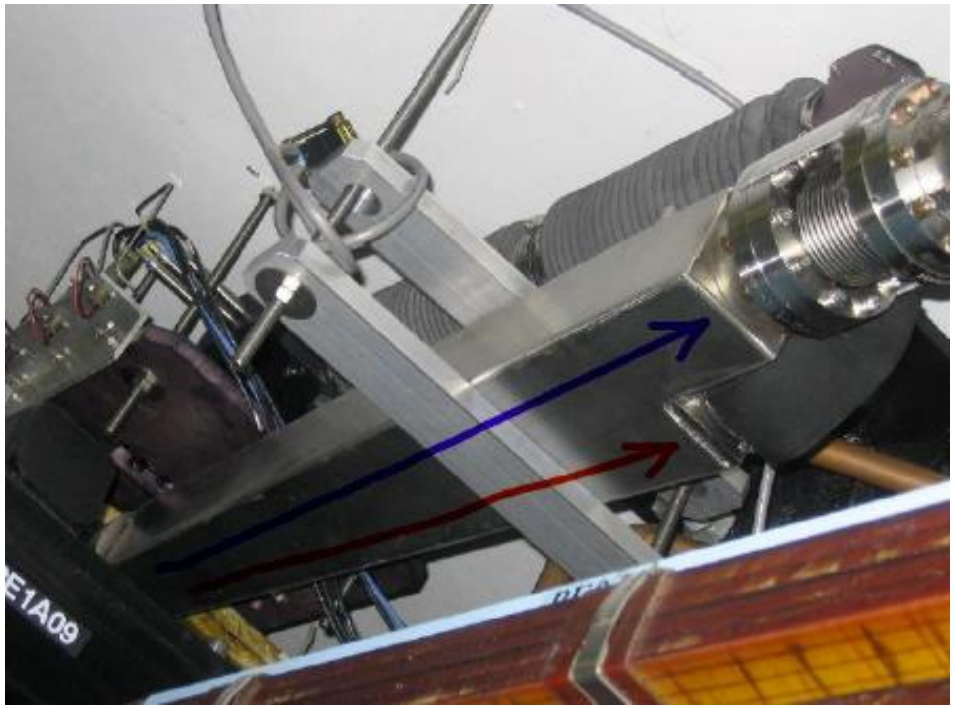
CEBAF Inverted Gun

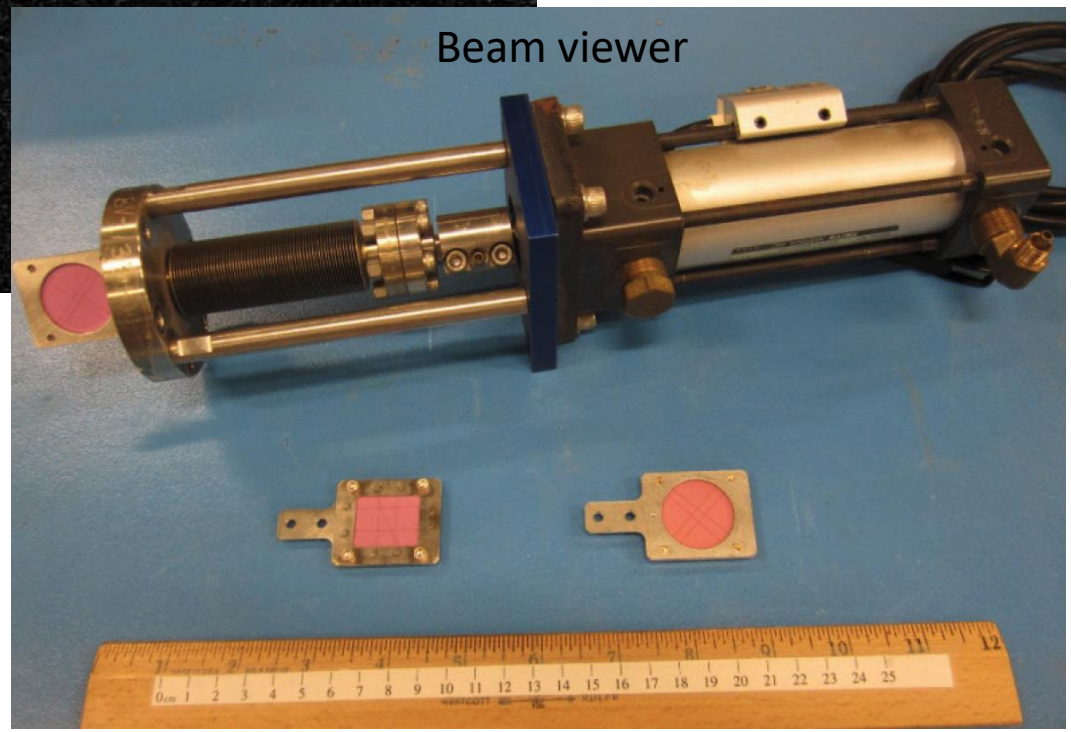




- Inverted CEBAF/ILC Gun#1 installed at CEBAF, July 2009
- Higher voltage, higher lifetime
- 200 kV for CEBAF, 350 kV for ILC

CEBAF Diagnostics

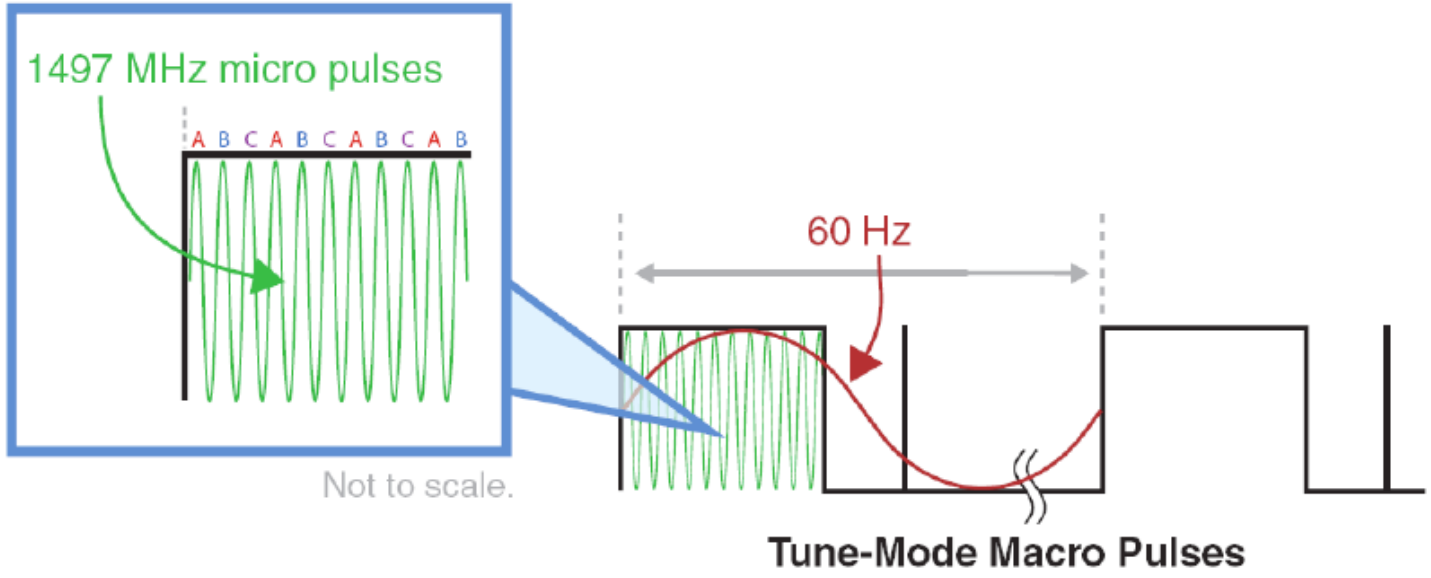


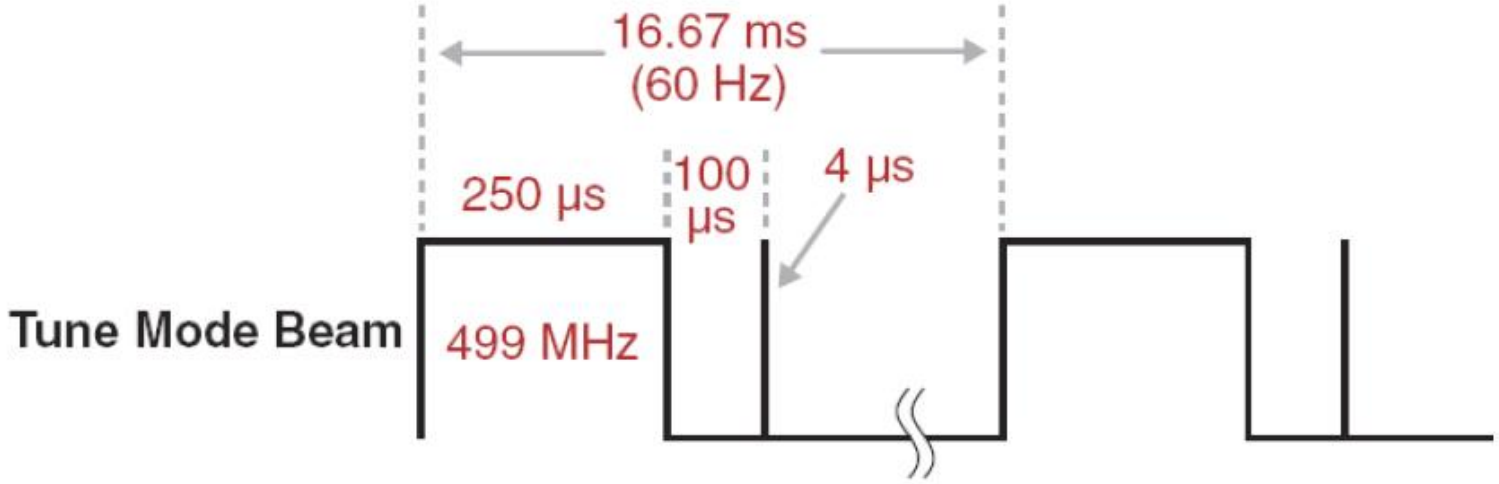


- Synchrotron Light monitors
- BPMs
- Beam size wire monitors
- Pathlength monitors
- Beam Loss monitors
- Etc.

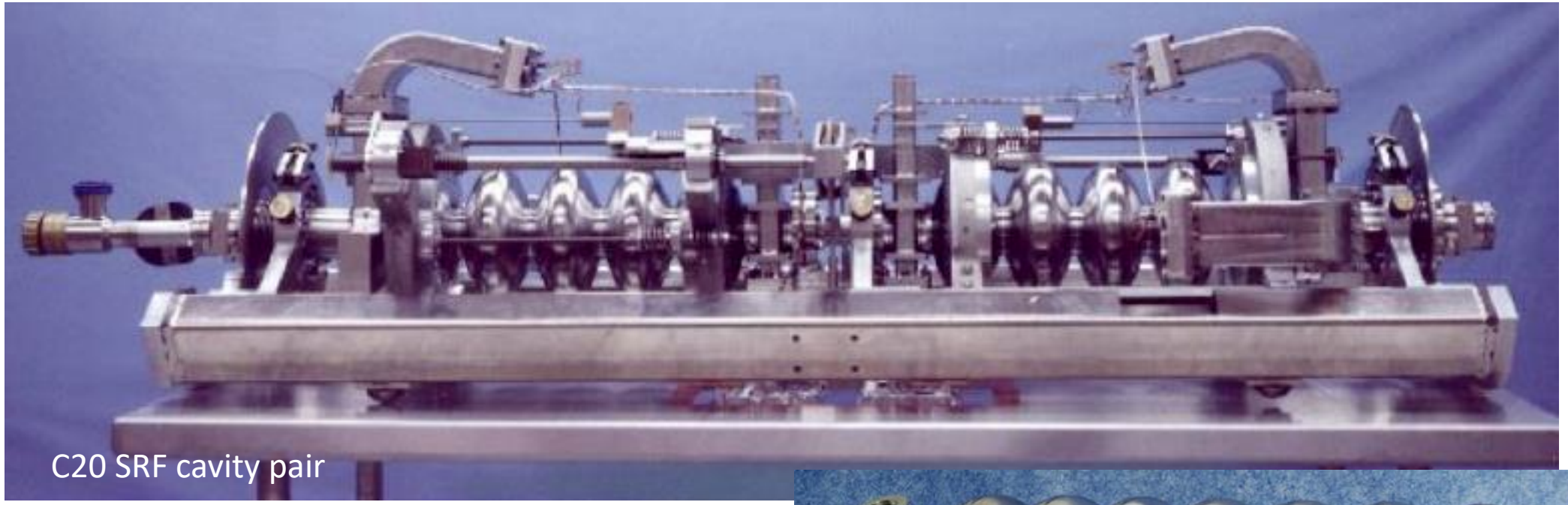
CEBAF Tune Beam

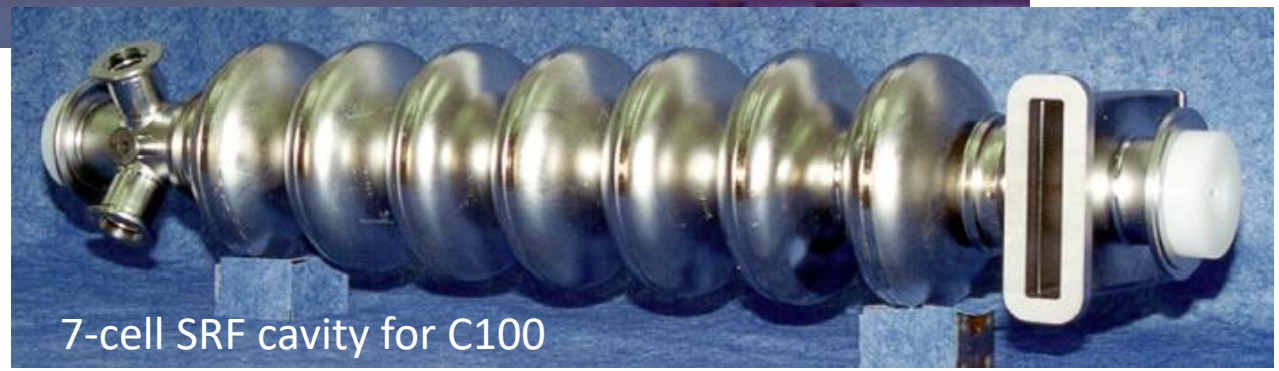
- Continuous Wave Beam for Physics
- Pulsed low power beam for accelerator optics tuning
- The 250 μs pulse width at 60 Hz provides a 1.5% duty cycle
- Nominal pulse height is 4 μA
- Beam power is 720 W for a 12 GeV beam at this duty factor
- The 4 μs trailing pulse is for measuring linac BPM orbits and linac arrival time





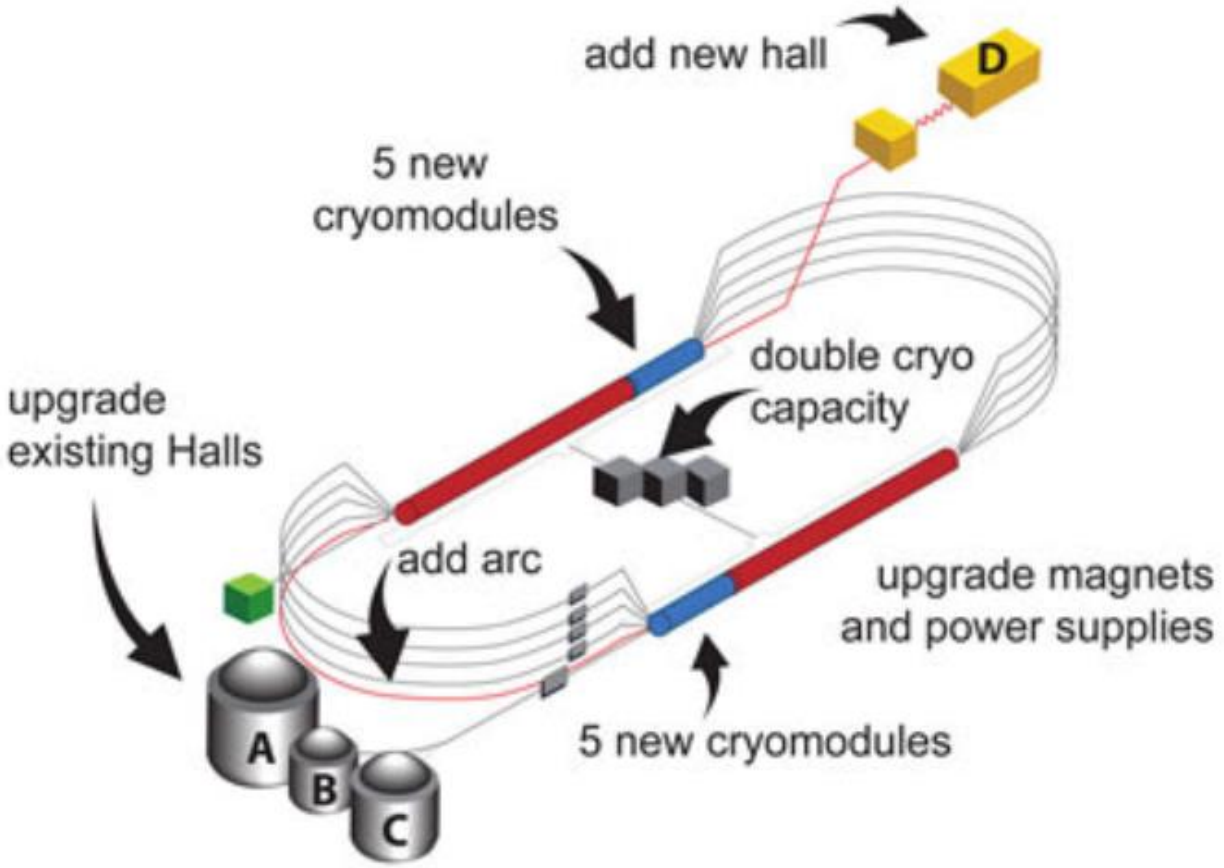
CEBAF SRF cavities and cryomodules


C20 SRF cavity pair


7-cell SRF cavity for C100

- Cryomodule types
  - C20 – has four pairs of C20 5-cell cavities
  - C50 – improved performance C20
  - C100 – eight 7-cell cavities assembled in string
    - Installed during 12 GeV upgrade, use higher power klystrons
  - C75 – upgraded C20 with new cell shape, ingot Nb, enhanced cleanness & magnetic hygiene
    - Being implemented now, to increase and maintain the energy

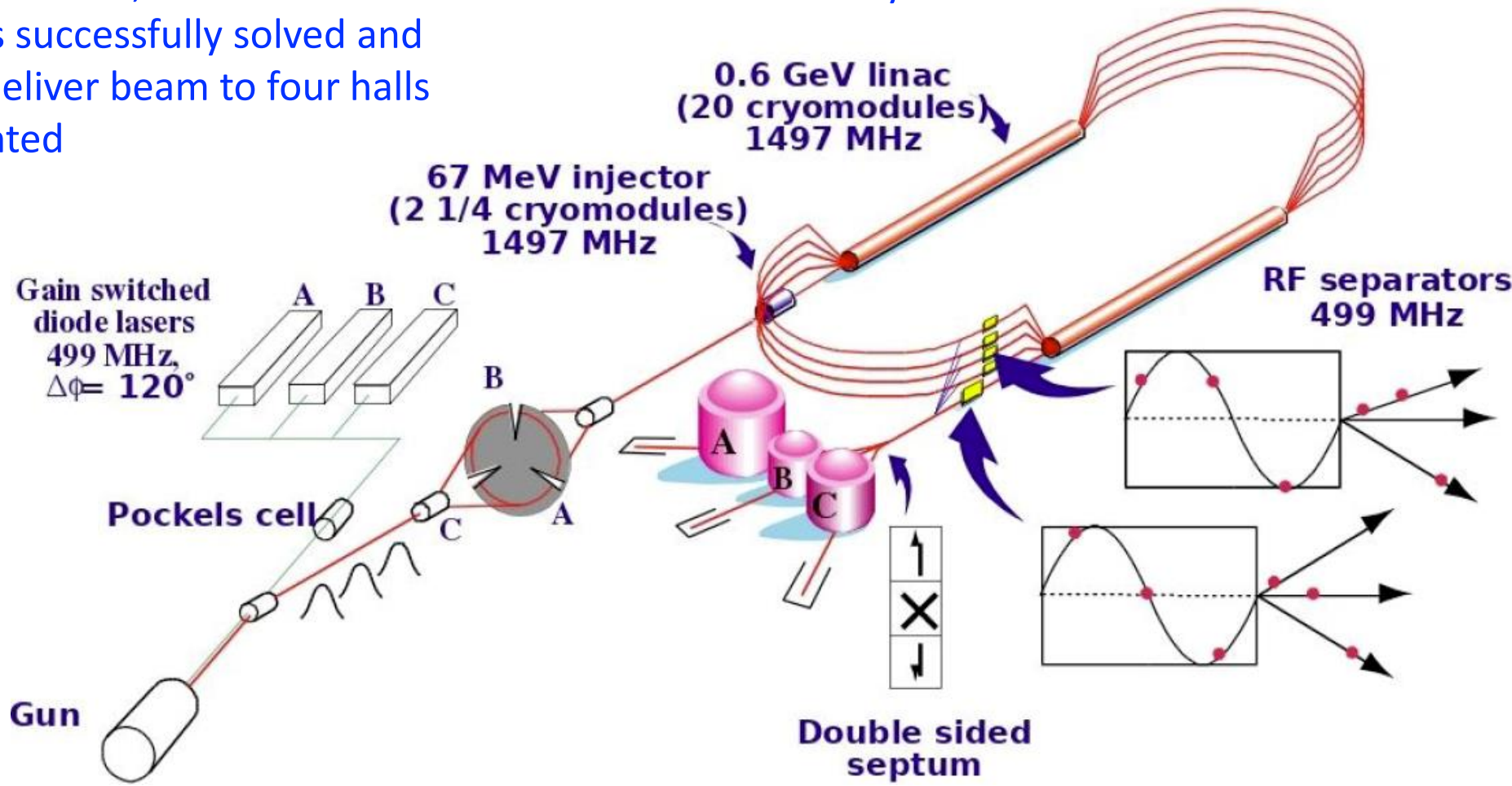
CEBAF 12 GeV Upgrade



- Double maximum accelerator energy
  - Ten new high gradient cryomodules
  - Double Helium refrigeration plant capacity
  - Civil construction and upgraded utilities
- Add 10th arc of magnets for 5.5 paths machine
- Add 4th experimental hall D
- New experimental equipment in halls B, C, D
- Project completed in September 2017

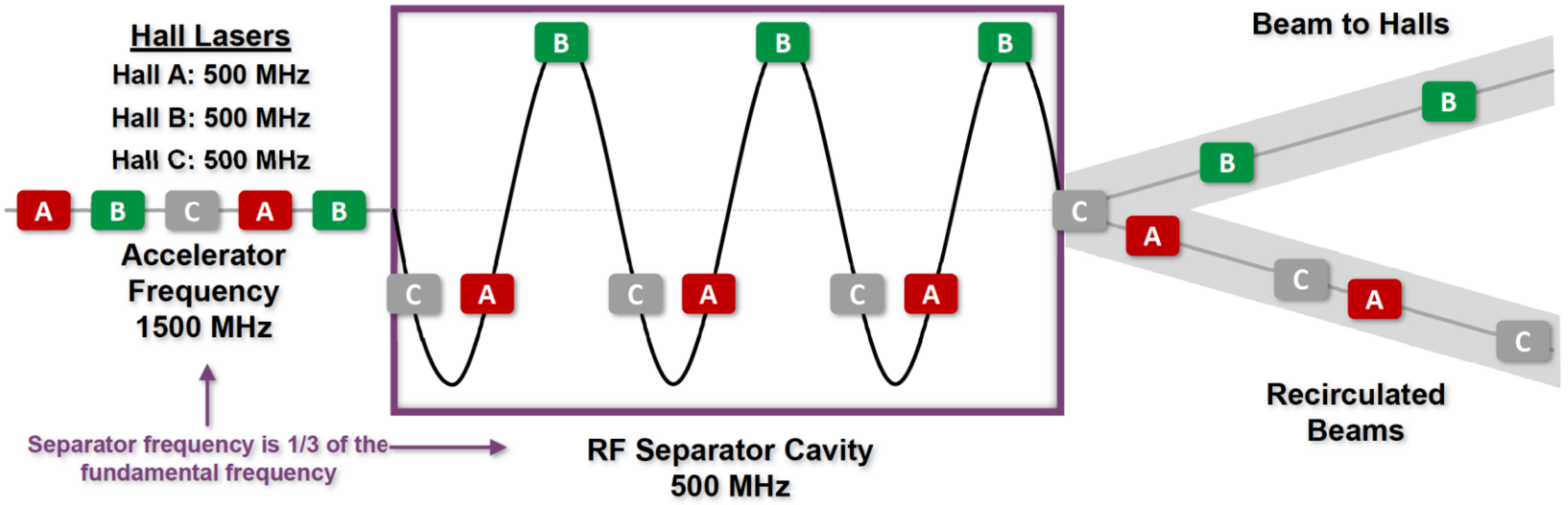
Enabling simultaneous four hall availability in 12 GeV

- The scheme with 1.5GHz RF and 500MHz rate to three halls shown here for 6 GeV three halls era is naturally only suitable for sending beam to three halls
  - E.g., after upgrade to four halls, beam could be sent to new hall D and only two other halls
- However, this challenge was successfully solved and scheme to simultaneously deliver beam to four halls was invented and implemented

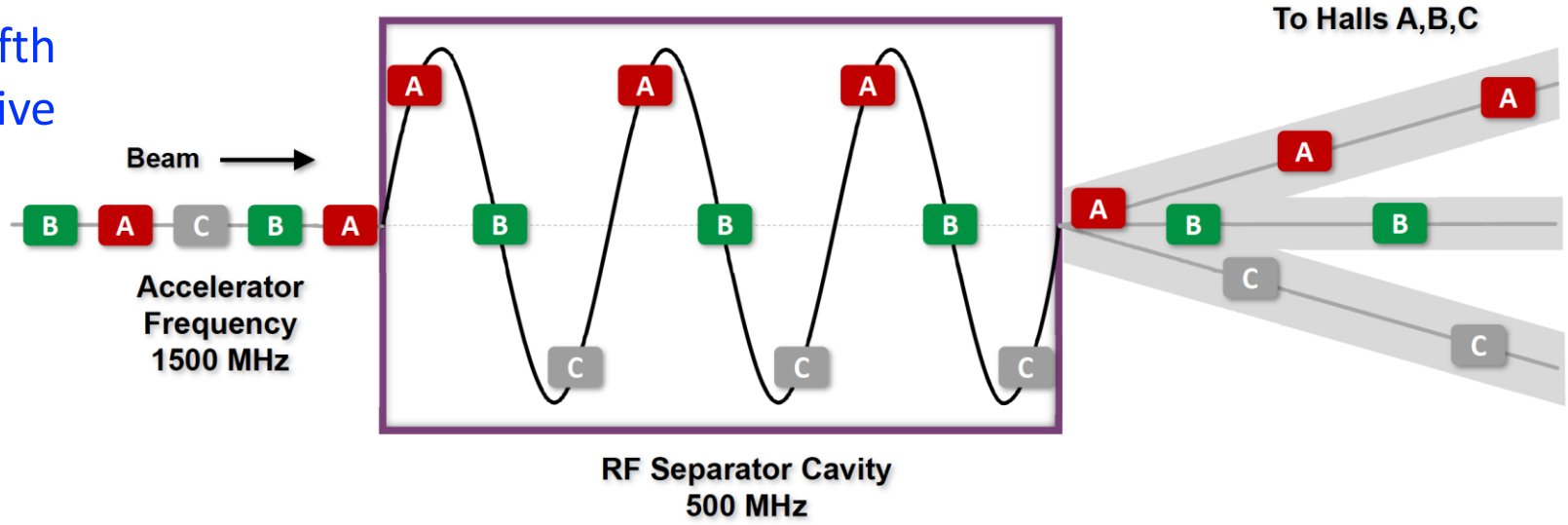


Sending beam to three halls

The 500 MHz separation scheme kicks one beam out and recirculate two. This is the configuration for the first four passes.

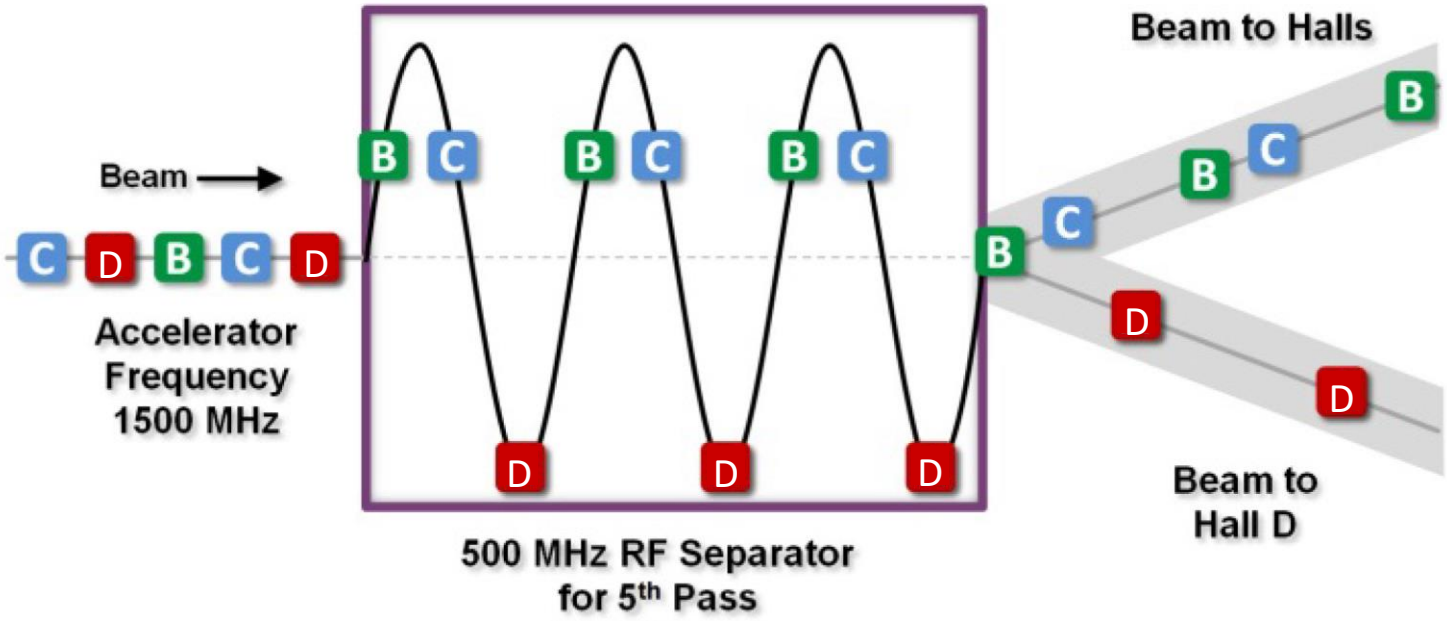


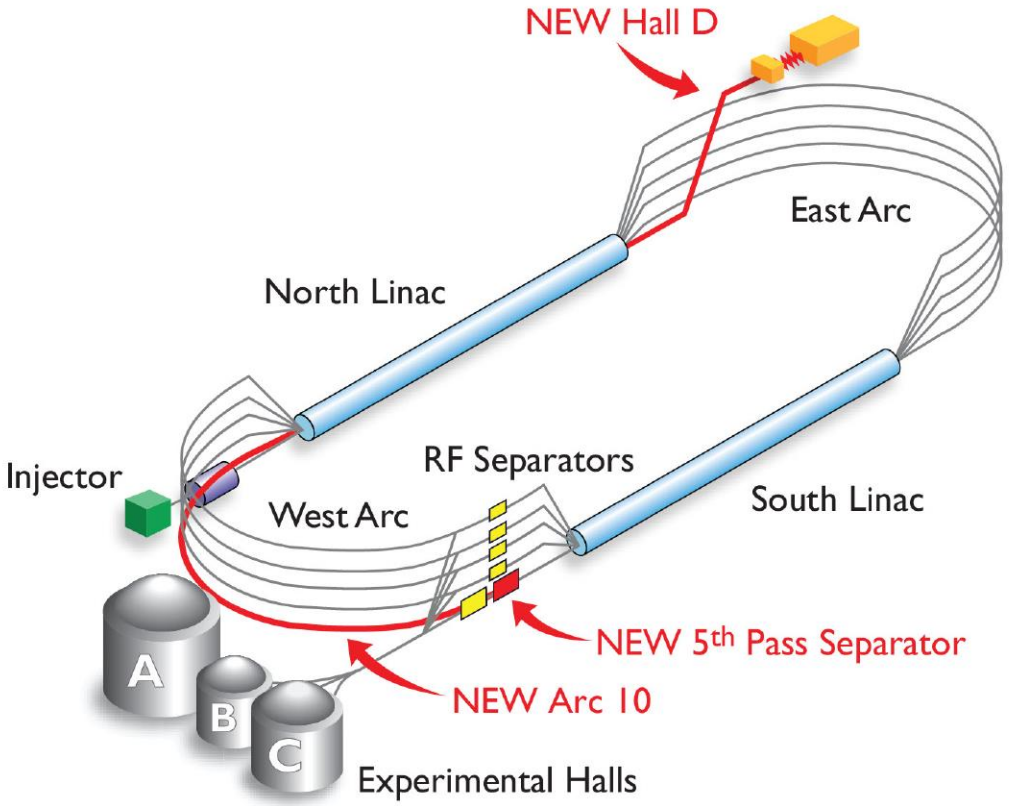
The 500 MHz separation triple split for fifth pass which allows the three halls to receive beam simultaneously at the highest pass (highest energy) if they choose



Sending beam to new hall D – the initial idea

- With addition of the new Hall D and new Arc 10, there was a need to re-configure the separation system to allow sending the beam to hall D too





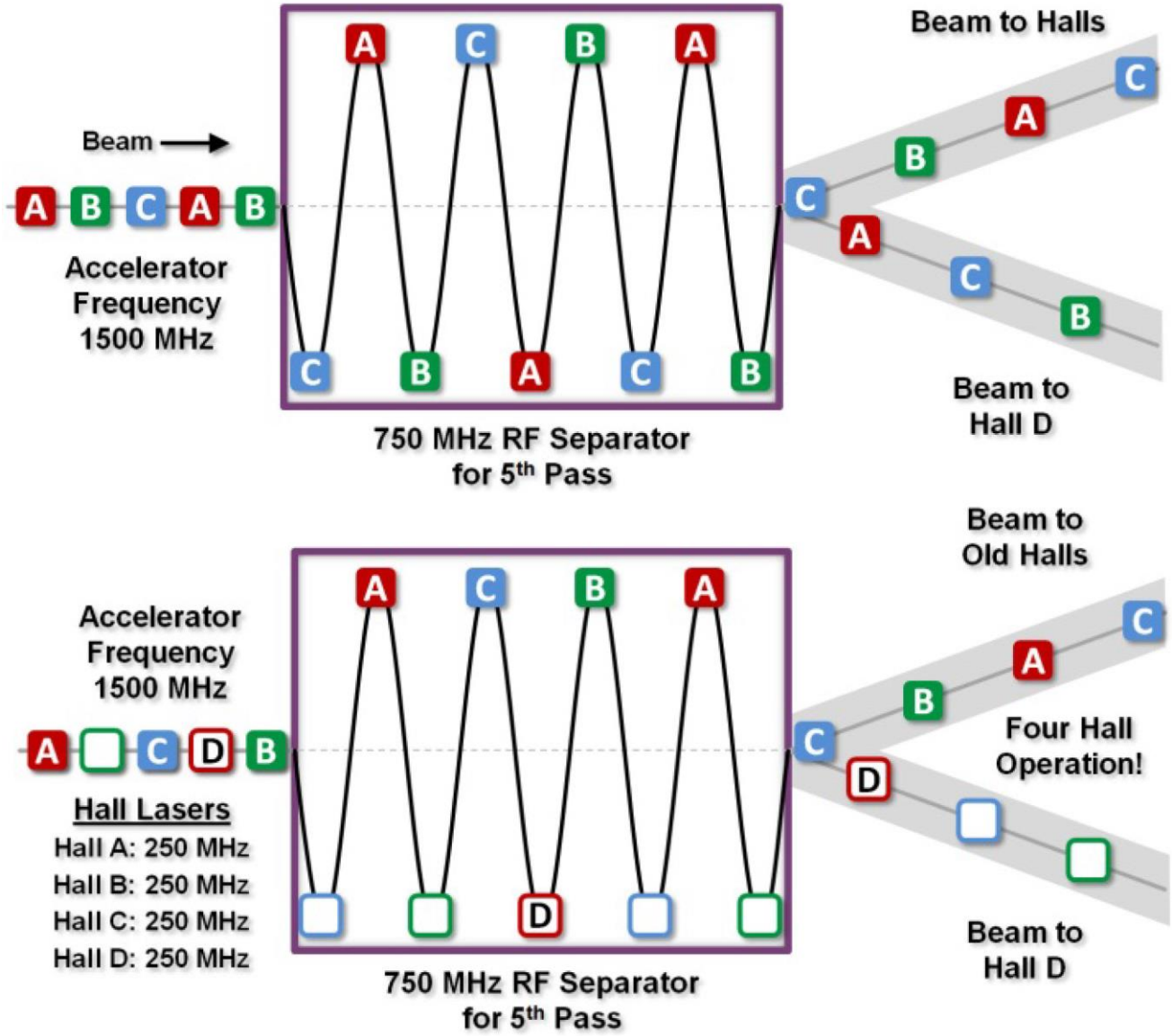
- The initial idea was to install a new 500 MHz separation system in the new arc, to separate beam to the new Hall D, and send another two to the existing halls
- However, this would be “Hall D + 2” solution, when only three halls could receive beam simultaneously

Sending beam to four halls simultaneously

- Instead of 500MHz system, use 750 MHz (half of fundamental frequency) separator for 5th pass
- It will separate odd end even bunches

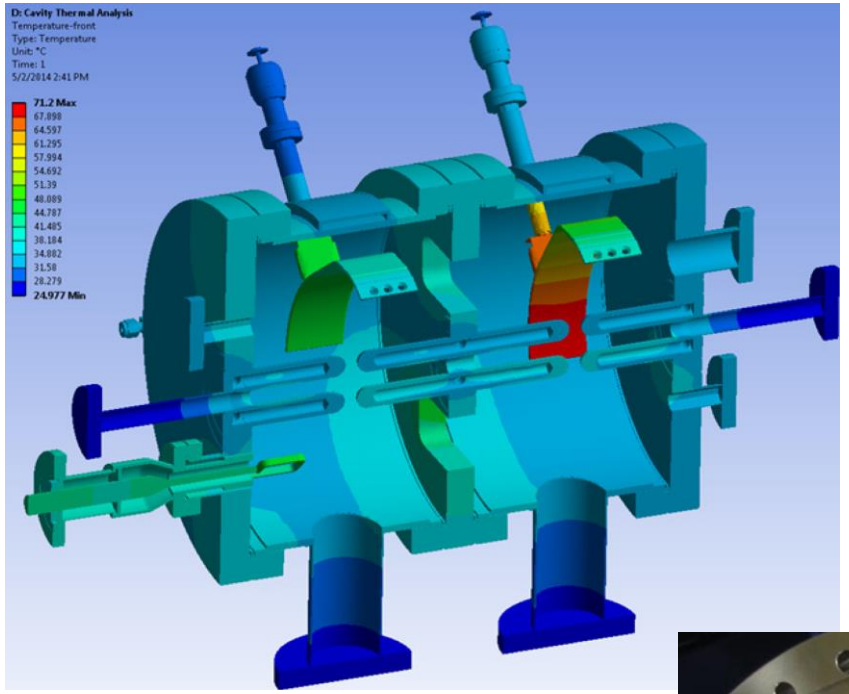
- Empty, e.g., all even buckets, but reduce the laser rate from 500MHz to 250MHz
  - (To keep same current, can double the charge per bunch)

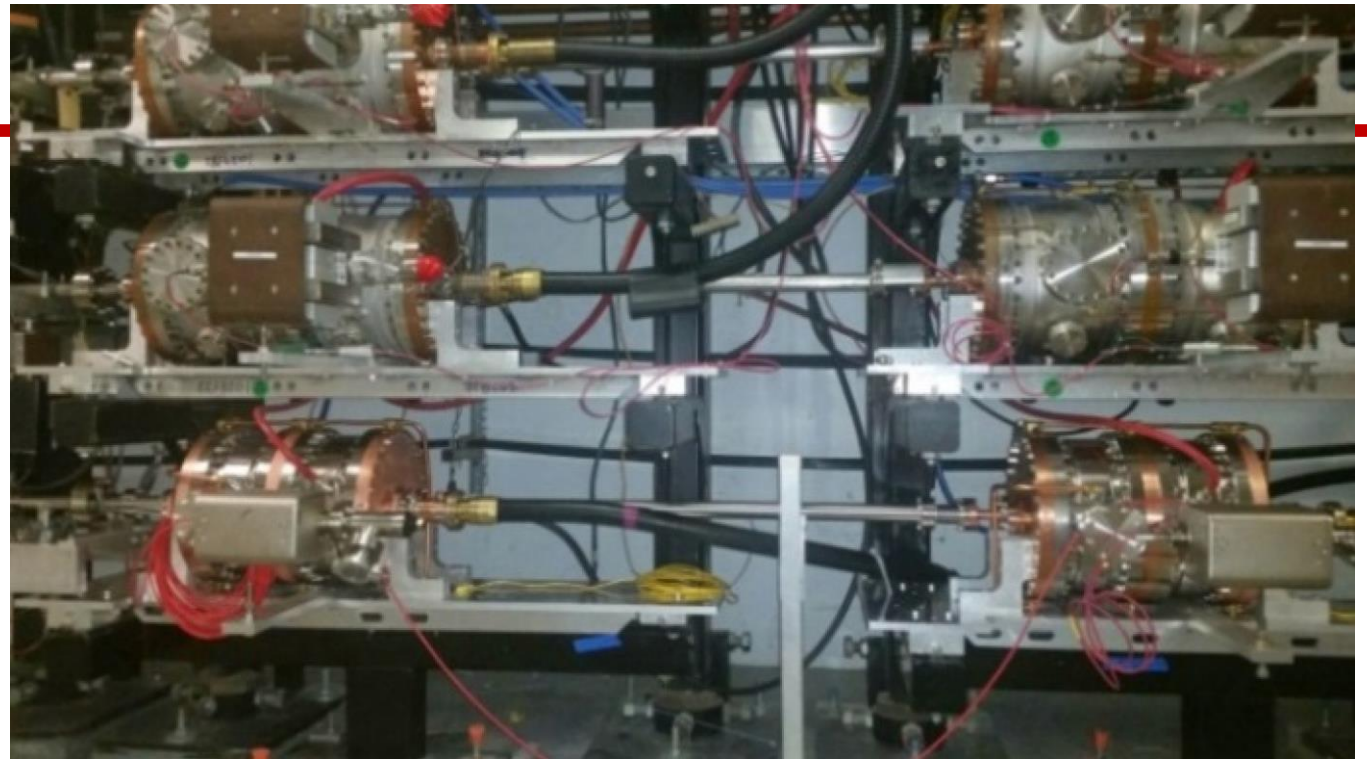
- Fill some empty buckets with bunches for the Hall D

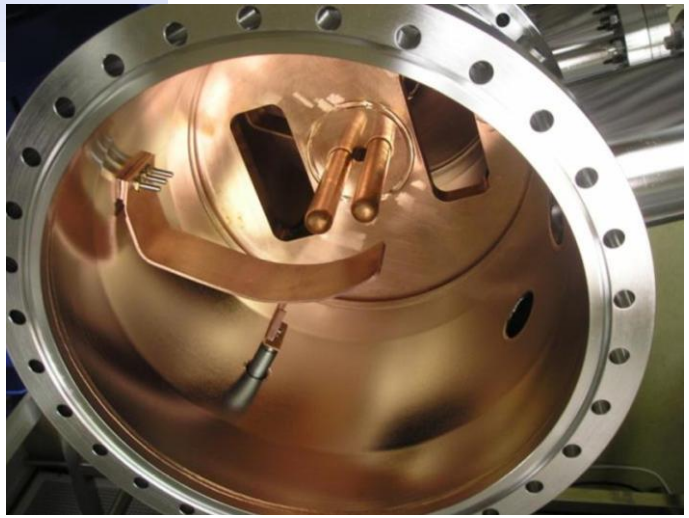


R. Kazimi, IPAC 2013, https://accelconf.web.cern.ch/IPAC2013/papers/thpfi091.pdf

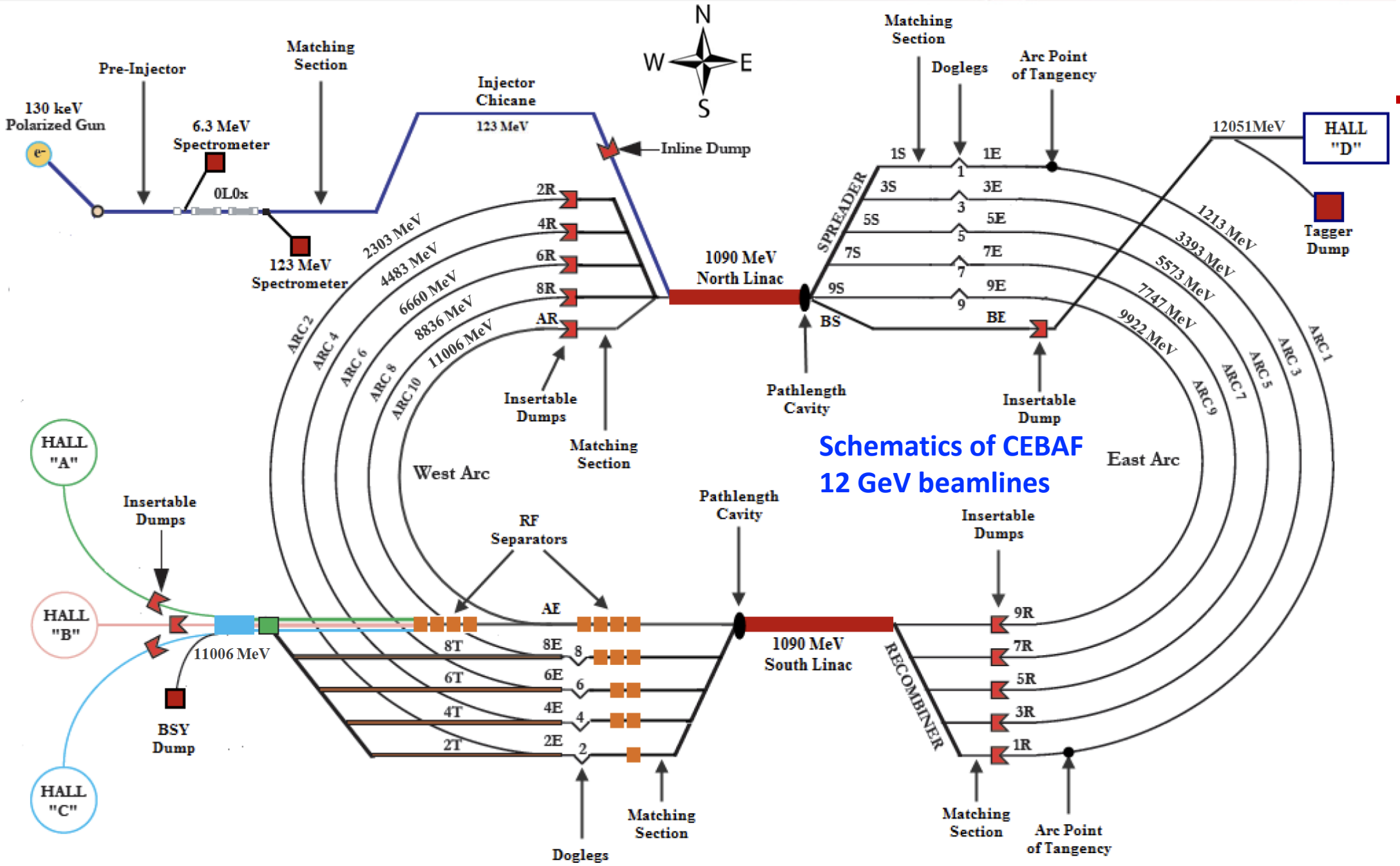
750MHz separator hardware







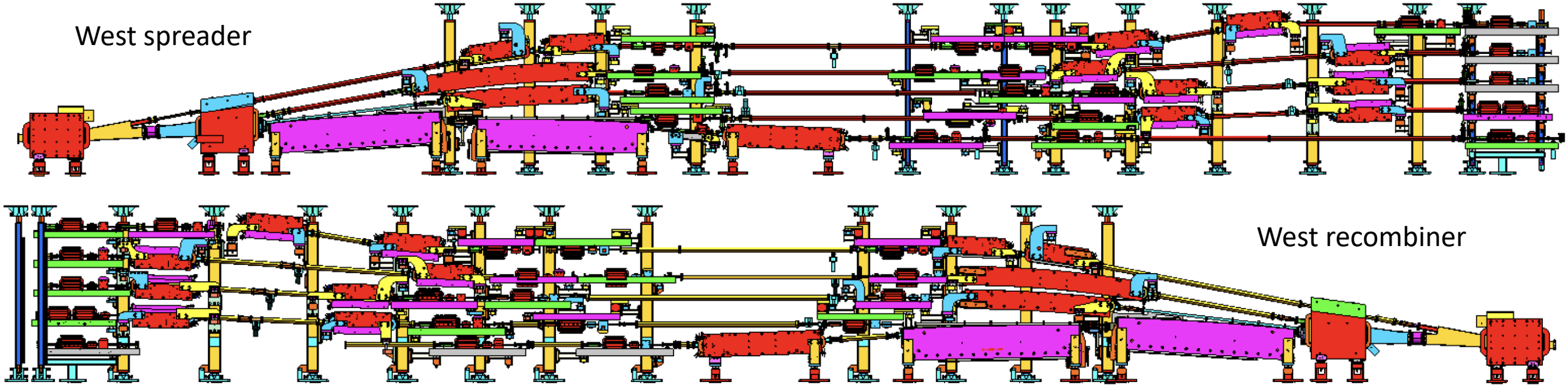
500MHz RF separator cavities (two higher beamlines) and the new 750 MHz separator cavity (lowest beamline)



Jefferson Lab

Spreaders and recombiners

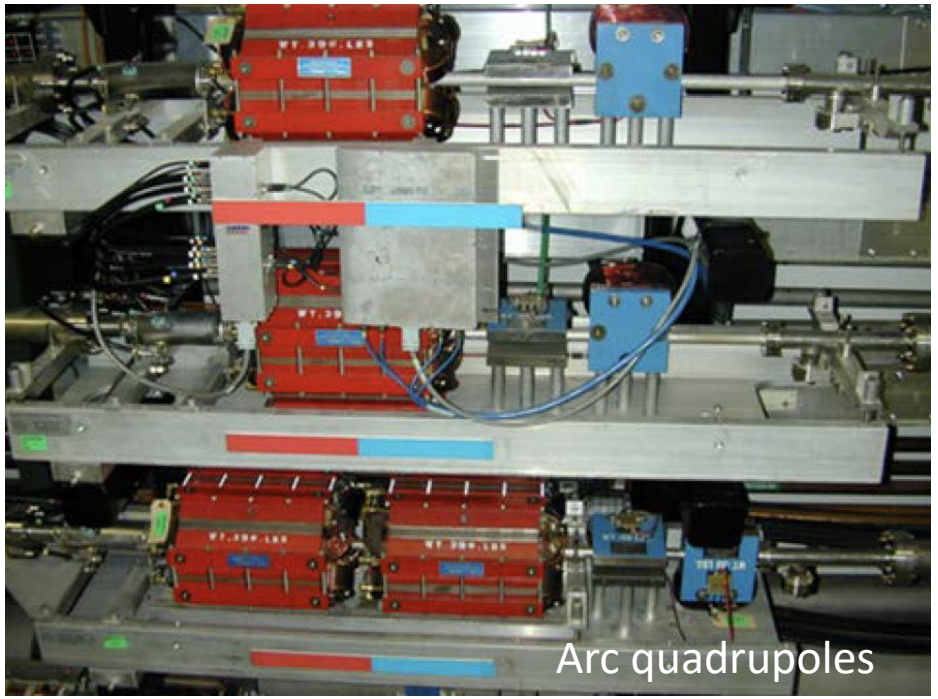
- Vertically achromatic system designed to accept broad range of multi-pass input parameters for recirculation transport
- Recombiner is mirror-symmetric to the Spreader

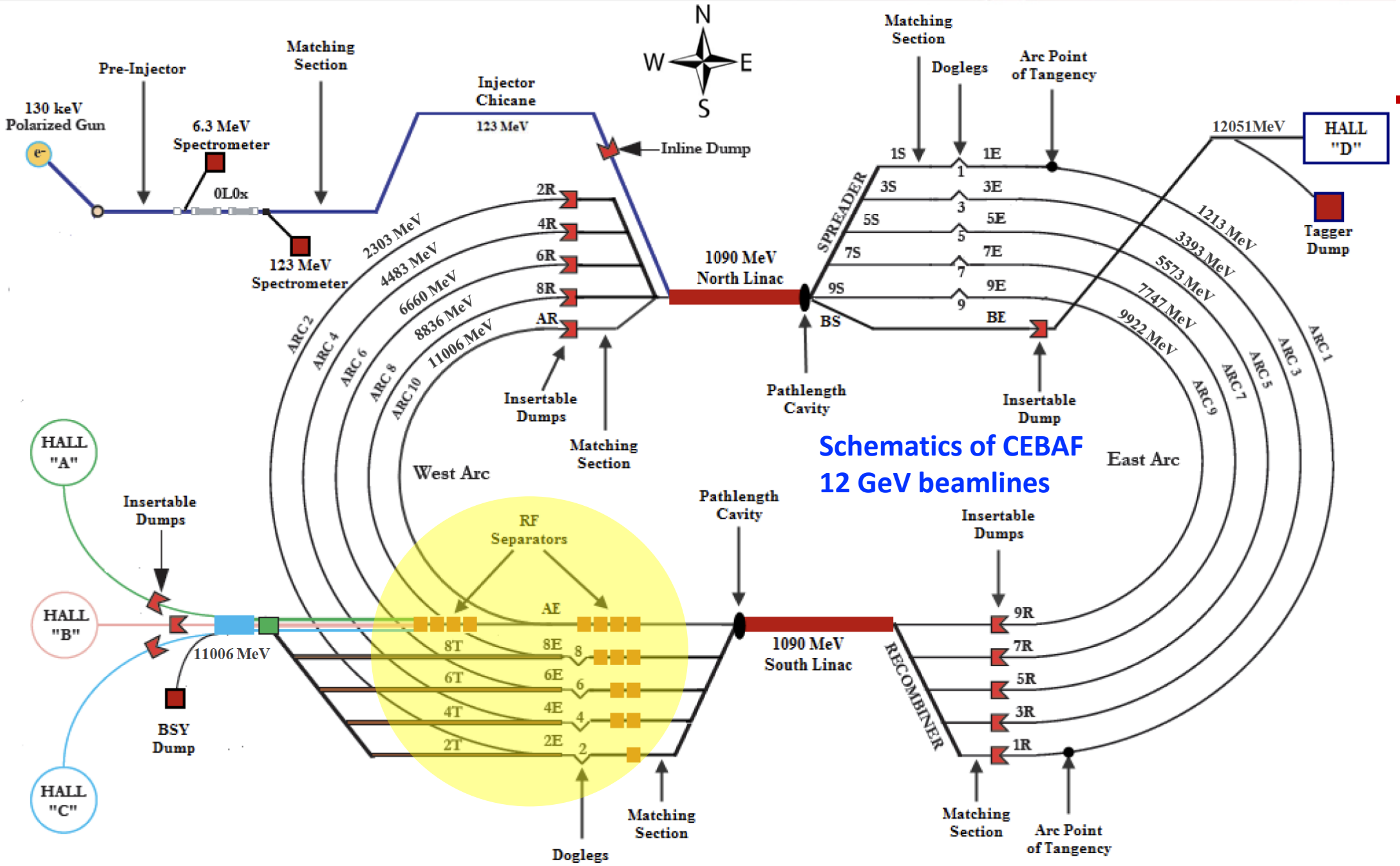


Recirculation arcs

- Sixteen dipoles for Arc 1 and Arc 2 and thirty-two dipoles for Arc 3-10
- The arcs radius is 80 m
- Each Arc has 32 quadrupole girders grouped in 4 families to control achromaticity, momentum compaction and the betatron tune


Arc dipoles


Arc quadrupoles



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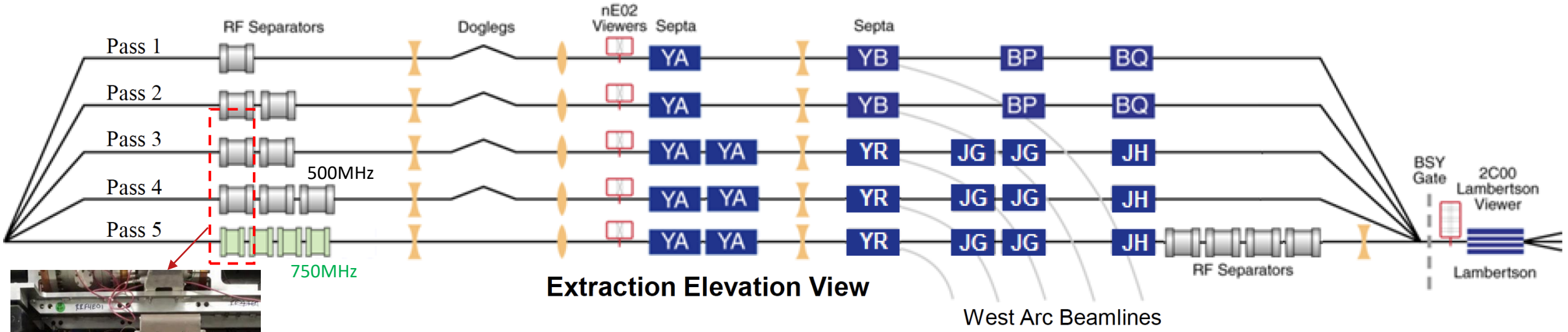
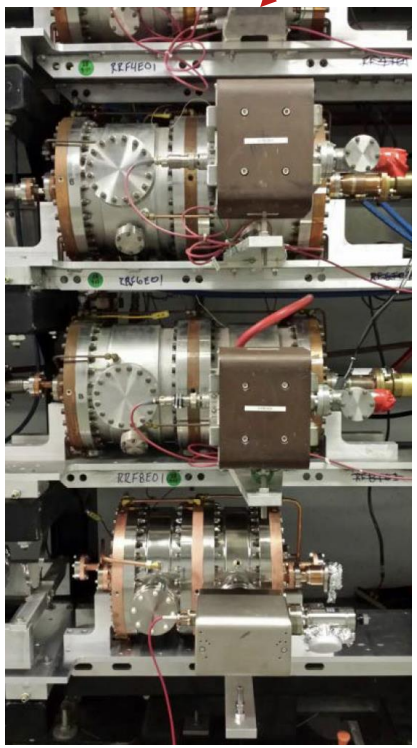
Extraction system

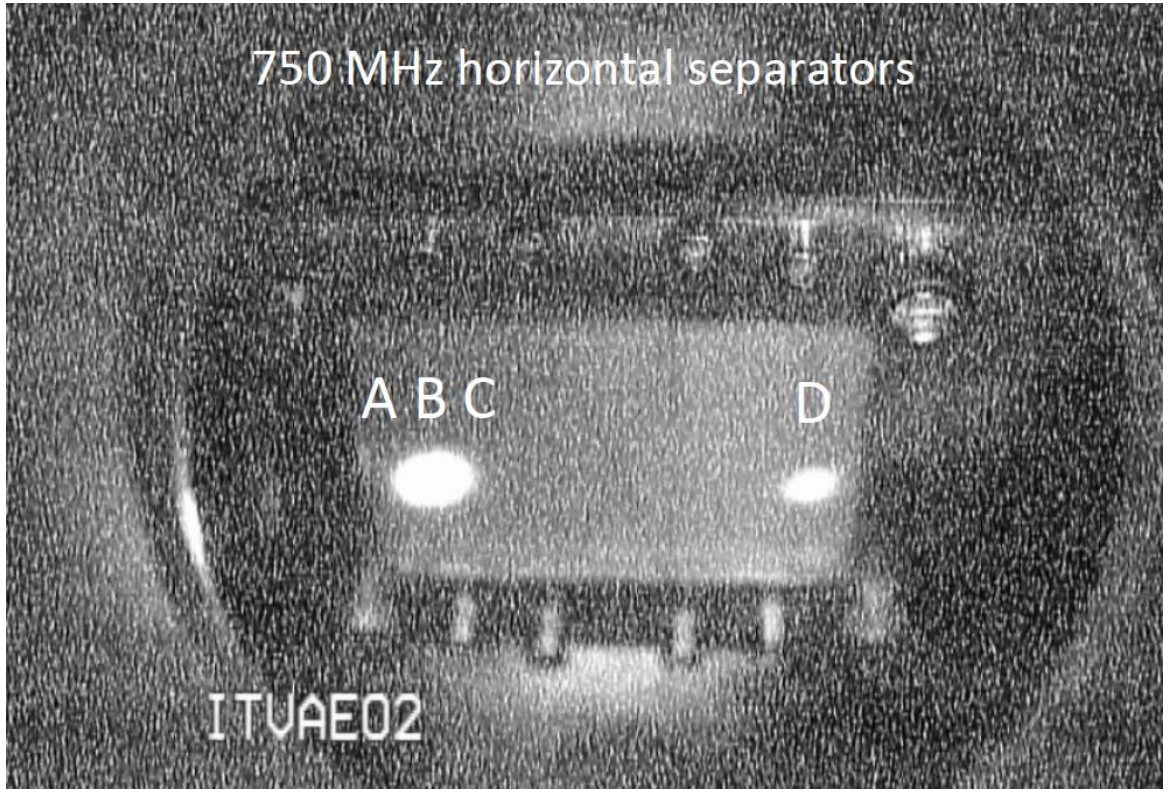




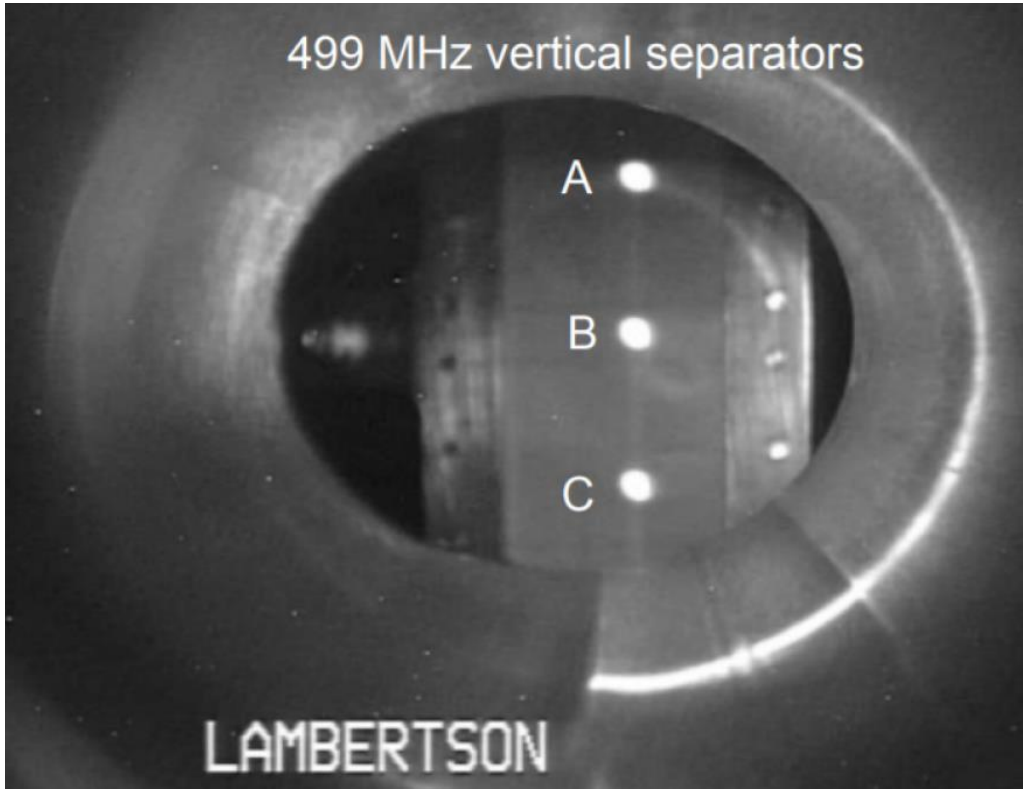
- Horizontal extraction systems at 500 MHz for 1st through 4th pass
- Vertical extraction system at 500 MHz for 5th pass
- Horizontal extraction system at 750 MHz for 5th pass to enable simultaneous four hall operation

Simultaneous four halls capability

- 5th Pass Horizontal Extraction at 750 MHz with three beams left and one beam right
- 5th Pass Vertical Extraction at 500 MHz showing A, B, C beams



Viewer at Entrance of Extraction Septum

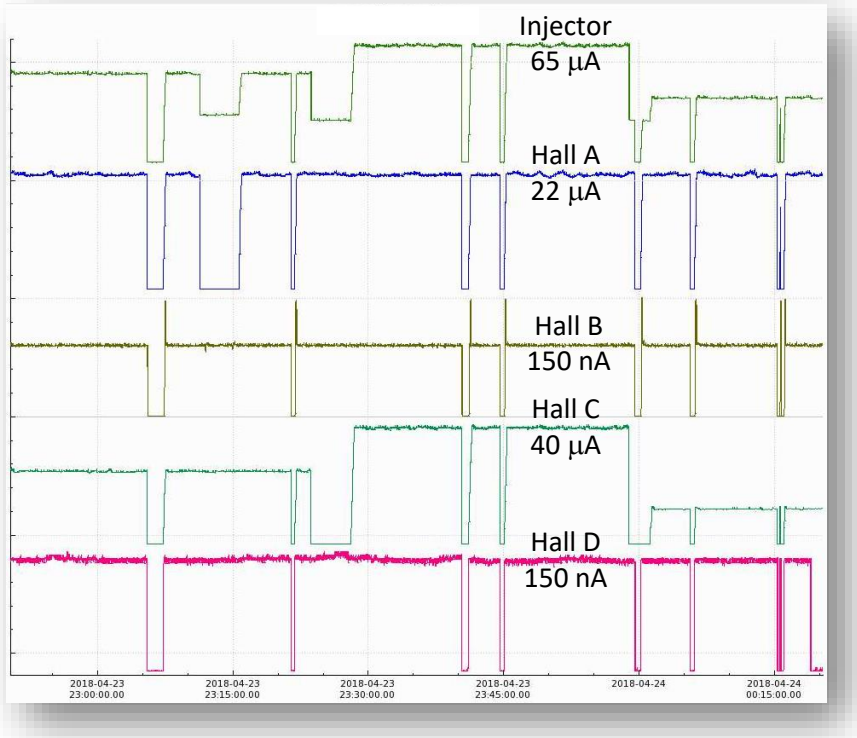


Viewer at Entrance of Beam Switchyard

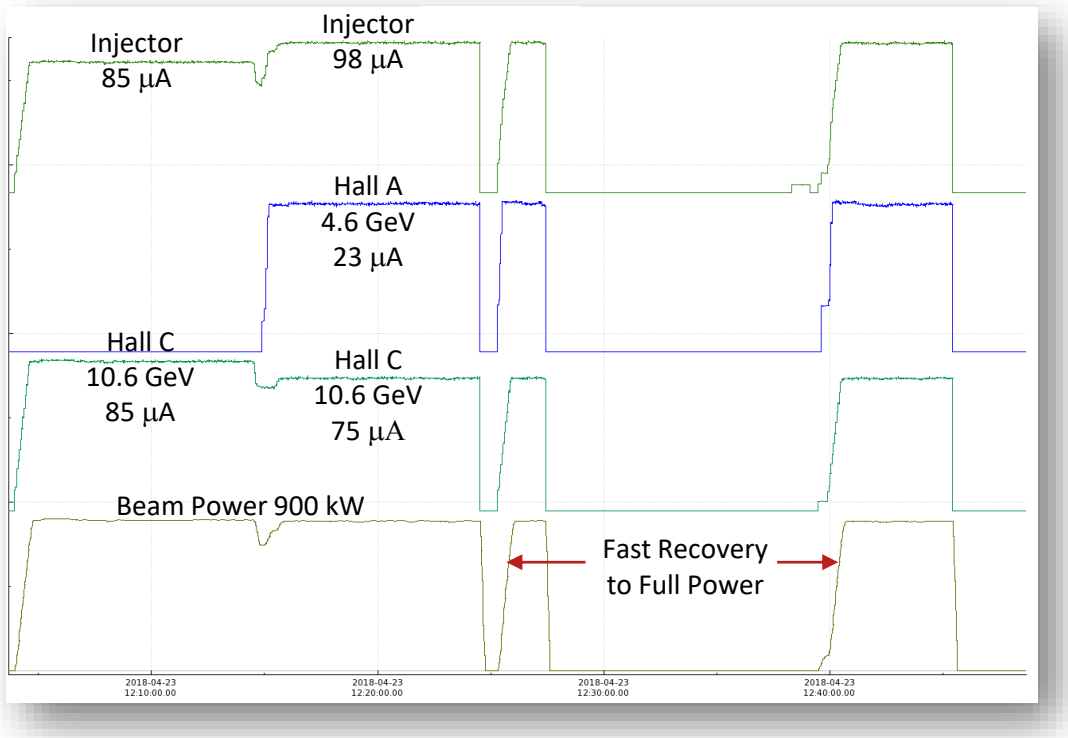
CEBAF four hall operations

Four-Hall and Full Power Operations

- Stable Full Power Operation demonstrated on April 23rd 2018
- Routine 4-Hall Operations from Spring 2018 Run and beyond



Simultaneous 4-Hall Beam Delivery (~90 minute time slice)



Full Power Beam Delivery (~45 minute time slice)

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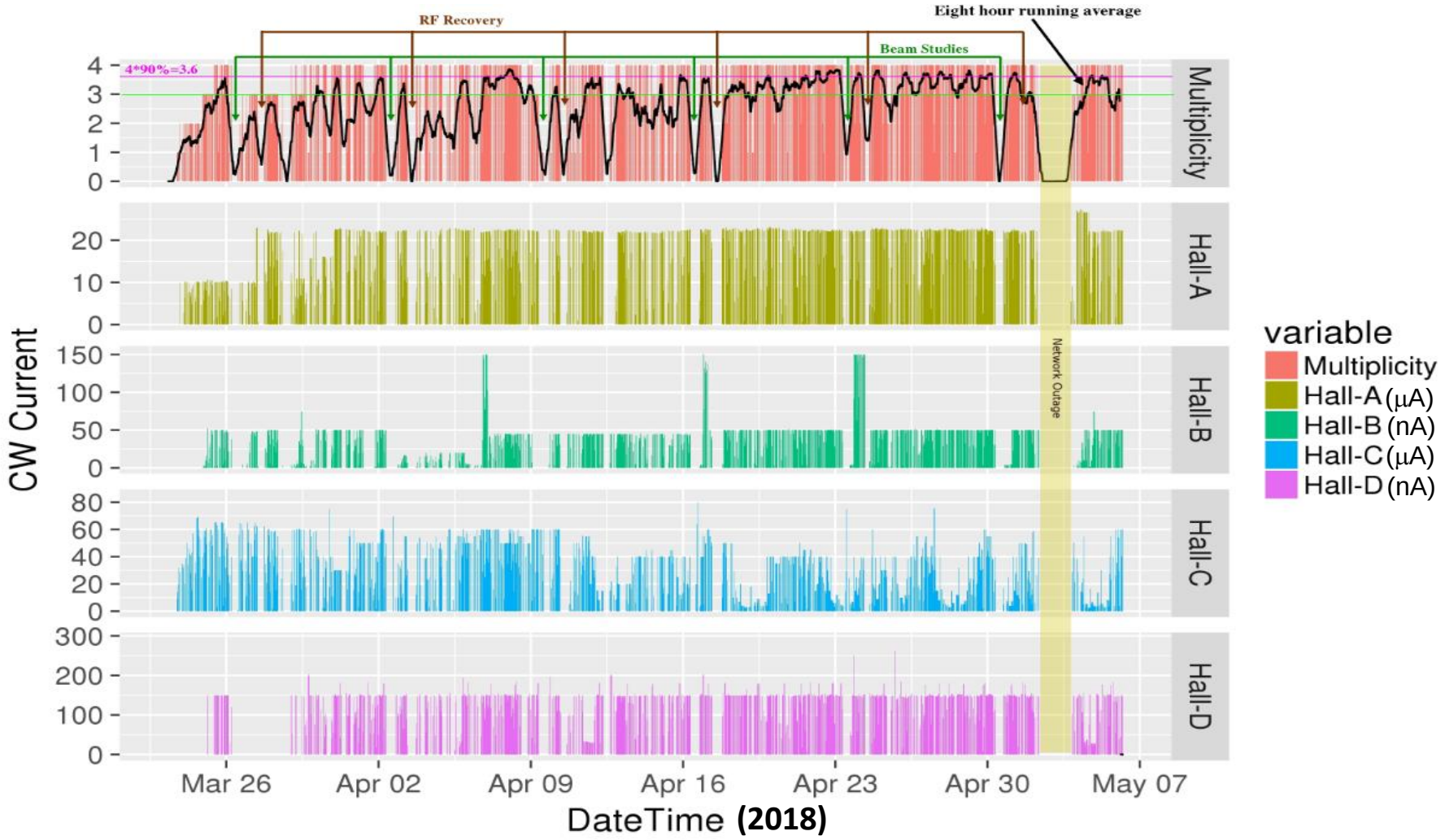
CEBAF four hall operations & reliability

- Reliability goal > 90%
- Goal of less than 5 minutes/hour lost to Fast Shutdown trips
- Multiplicity – sum of each of four halls availability (max is 4)
- Multiplicity is the multiplier for physics output

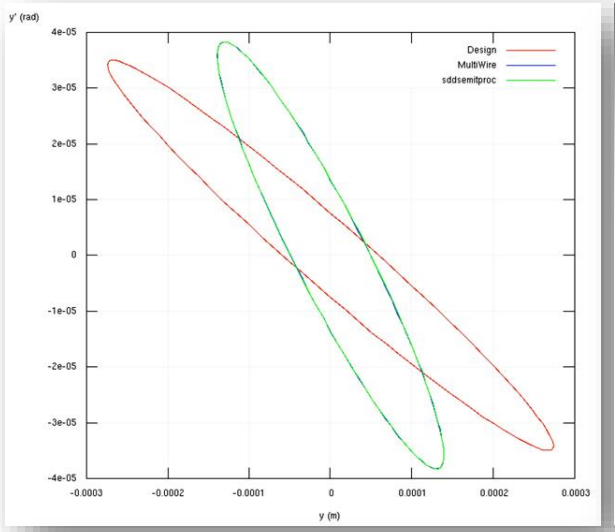
Average Multiplicity Peak at 3.6

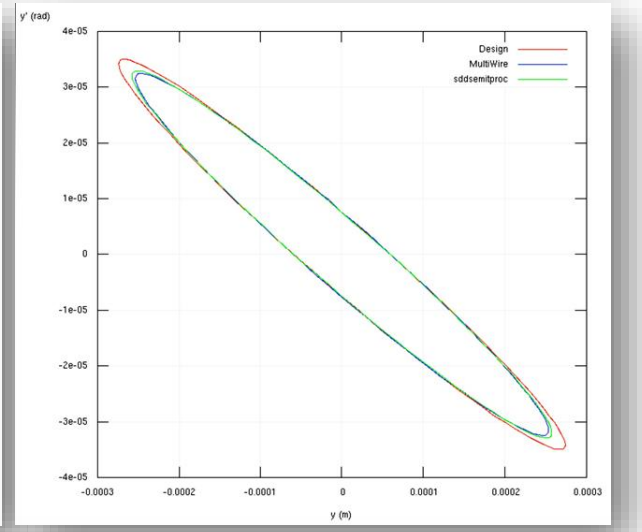


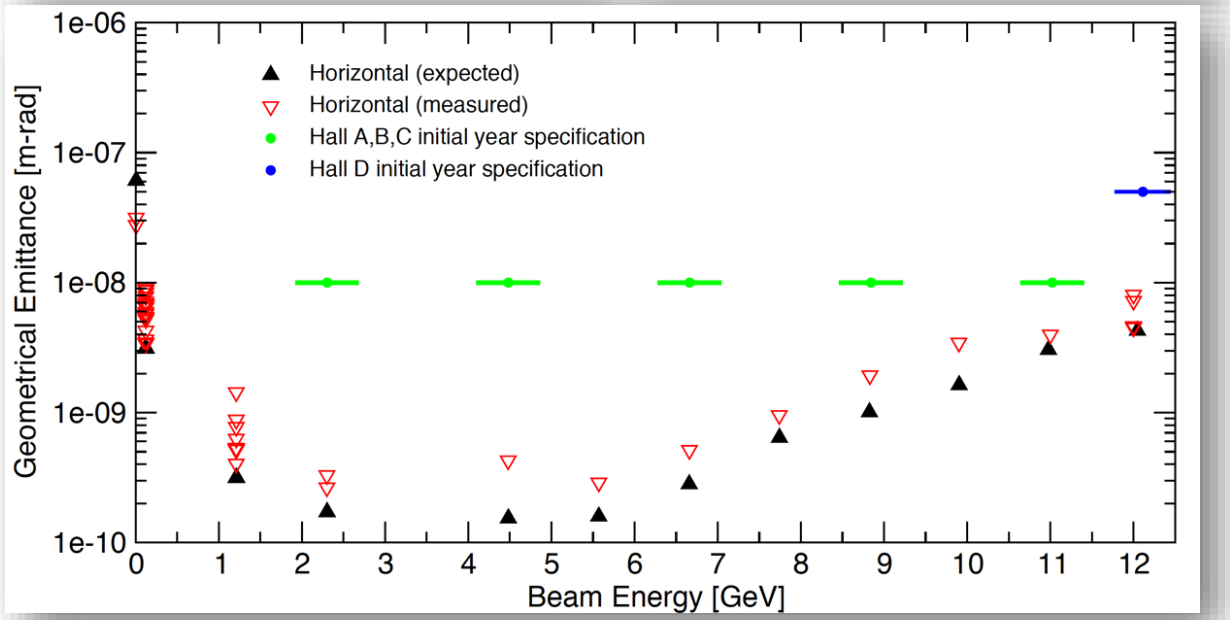
CEBAF beam quality and NP program demands

- Beam performance is meeting specifications for the Nuclear Physics Program
- Increased demands for parity beam quality for future runs and Moller
- Upgraded QCM (now in UITF will be installed in CEBAF next year)
- New diagnostics being developed and tested (BNNT screens, cameras)
- New operation approaches based on Machine Learning are in development

Parameter	Value
Max. Energy ABC	11 GeV
Max. Energy D	12 GeV
Max. Beam Power	1 MW
Bunch Charge Range	0.004 fC – 1.3 pC
Hall Repetition Rate	31.2 – 499 MHz
Nominal Bunch Charge	0.36 pC
Nominal Hall Repetition Rate ABC	499 MHz
Nominal Hall Repetition Rate D	249.5 MHz
Geometric Emittance at Full Energy	3nm-rad(X) 1 nm-rad(Y)
Energy Spread at Full Energy	0.018%
Polarization	>85%

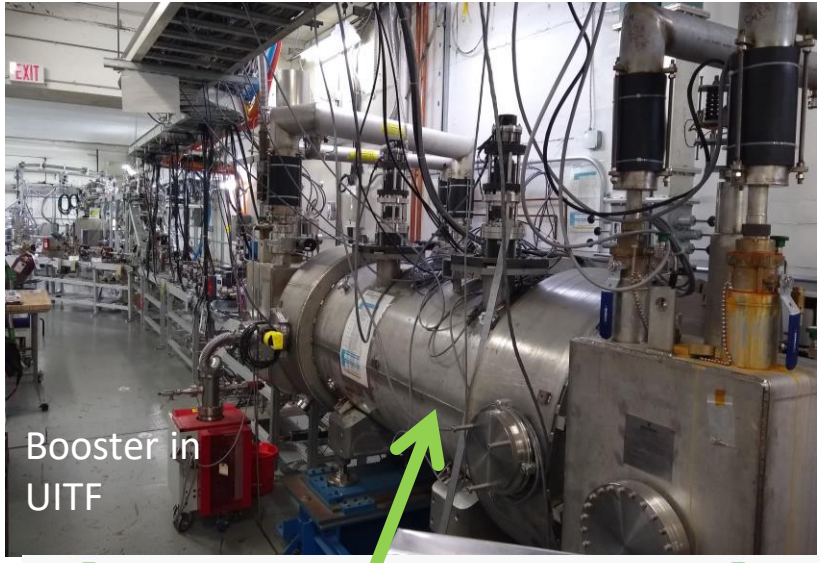


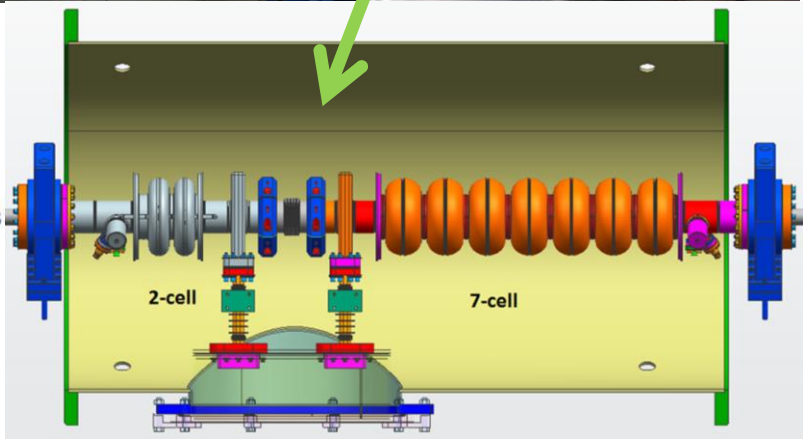




BNNT – Boron Nitride NanoTube

- **CEBAF Polarized electron Injector upgrade**
  - Aimed at improving beam quality
  - beamline rebuilt with improved vacuum & 200 KV magnets & Wien filters
  - A 10 MeV SRF Booster commissioned at UITF





200 kV w/o field emission
(building gun at UITF in 2022)

Additional NEG coated BPM
(PQB position/angle, mapped)

New 200 keV solenoids (3)
(less astigmatism)

New 200 keV 15 deg bend
(install Winter SAD 2022)

New A1/A2 cubes
- 200 keV coils
- Remote A1 (full out)
- GP-100 NEG @ aperture

Upgrade 200 keV Wien Filters
- Magnet upgrade
- HV upgrade (+/- 20kV)
- HVPS upgrade

YAG/Harp combo
(new fast match)

Phase 1 ends here

New Y-chamber design
- NEG coated beam line
- Massive NEG pumping arrays
- 44% larger aperture
- Split 15 deg (min. edge focus)

New laser window (UVa)
(min. birefringence)

New 200 keV Wien quad (4)
- Improved air-core design
- Captured bakable coils
- GP-100 NEG @ Wien aperture

New 200 keV prebuncher designed
- After both Wiens
- New copper cavity (vs SS)
- New 100W amp

New 200 keV PSS kicker
(improve reliability)

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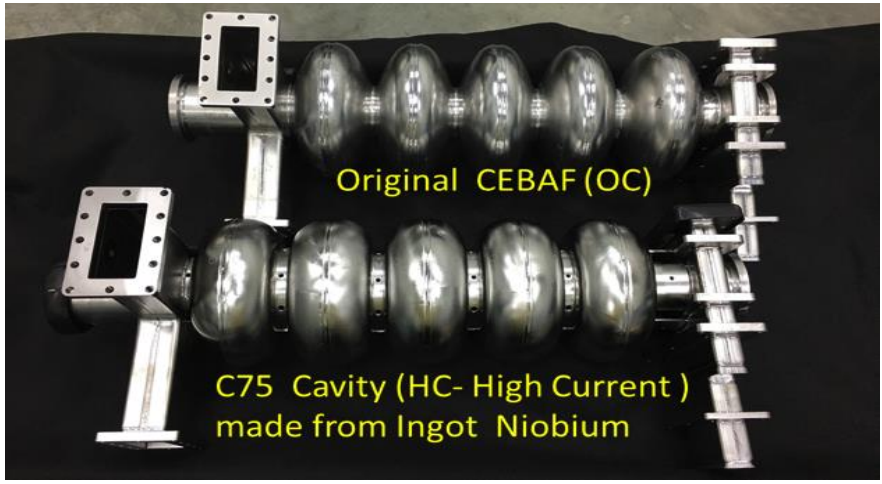
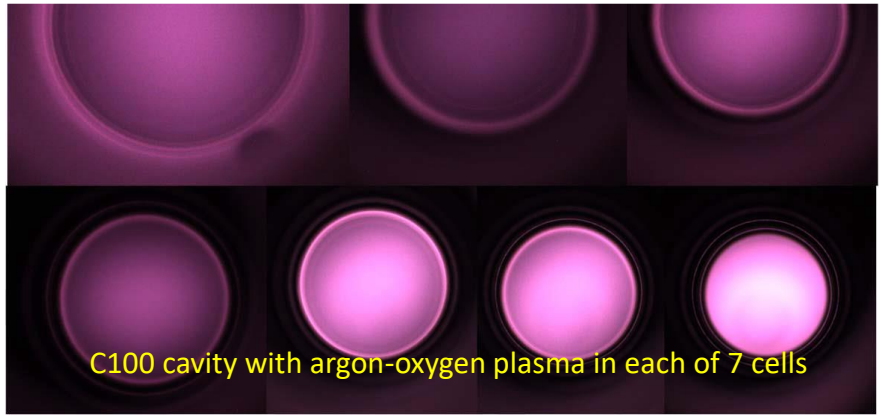
CEBAF operations and CPP

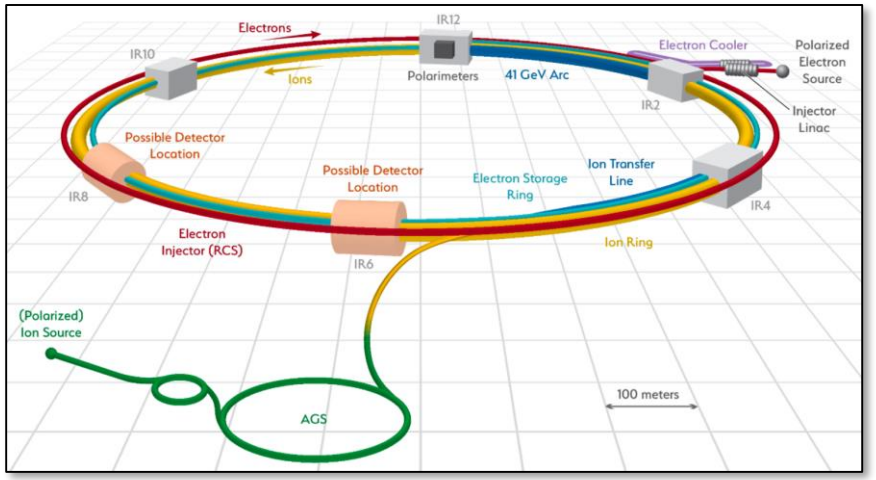
- CEBAF operations:
  - Typical run – 32 weeks per year
  - Scheduled downtime ~3 months
- CPP project – CEBAF Performance Plan
  - Significant efforts on improving reliability and beam reproducibility, as well as C75/C100 program result in steady increase of the energy and energy margin and improvements of availability
- CPP components:
  - C20 to C75 conversion – most cost-effective path for leveraging advances in RF design and SC materials (optimized cavity shape, Nb ingot material, cavities from industry) and LCLS-II lessons (clean assembly & magnetic hygiene)
  - Refurbishing low performing C100 CMs
  - Developing plasma processing of CMs for their in-situ cleaning



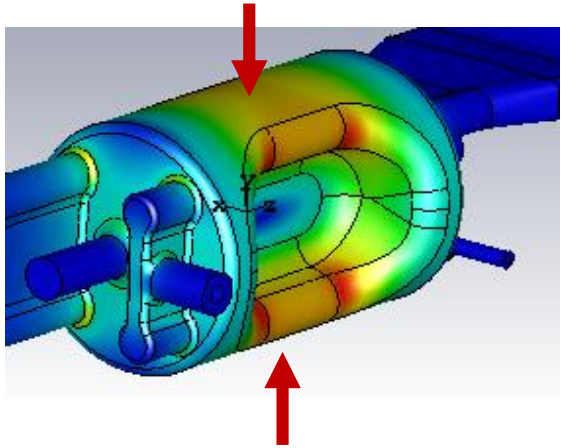


Electron-Ion Collider

- JLAB is strongly engaged in EIC
  - Lead and co-lead several L2 WBS
- Contributing to and/or Leading
  - Accelerator design – based on CEBAF design and operation
  - SRF – based on our world leading expertise
  - ERL – based on world-record ERL-based FEL
  - Cryo and magnets – based on our operation and design expertise
  - 2nd IR design, etc. – based on our collider design expertise



- CEBAF upgrade (next slides) will create complementary to EIC experimental program, boosting NP science portfolio
  - Significantly benefit from the same expertise which enabled EIC participation and leadership
    - Recirculating accelerators and ERL world-leading expertise, SRF, polarized electron sources, etc
  - The efforts on CEBAF upgrade strengthen much further our JLAB-BNL collaboration on EIC too, creating significant enthusiasm and inspiration in the team for these collaborative design efforts

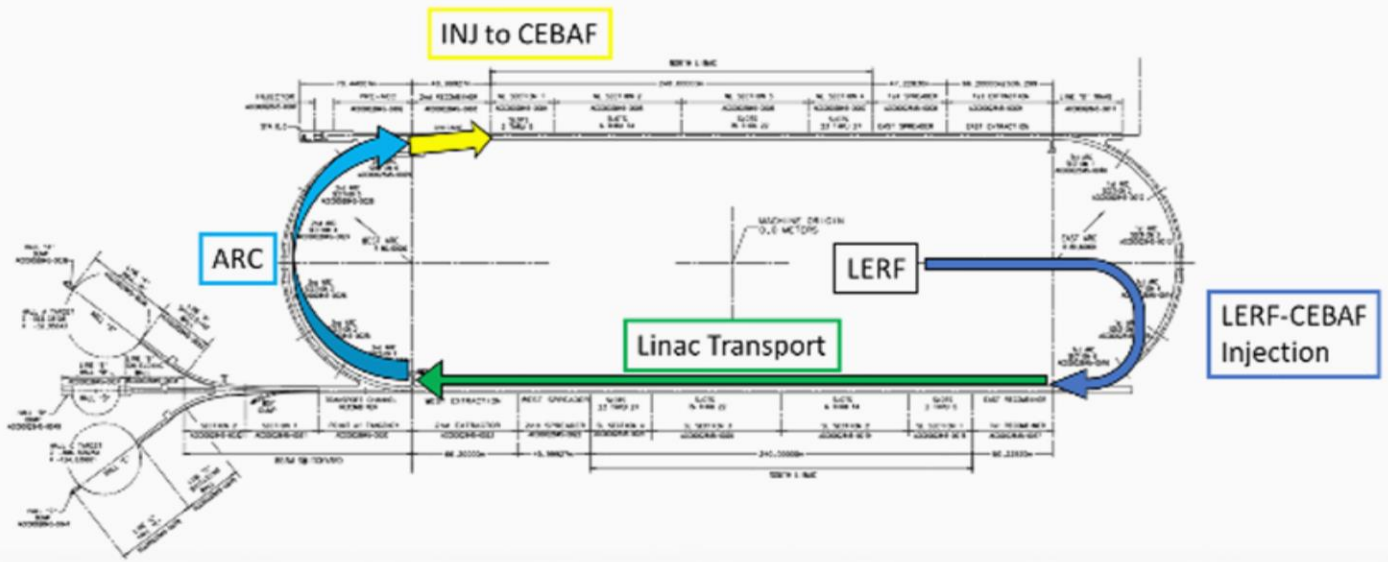


Crab cavity tuning mechanical analysis

Jefferson Lab Accelerator Upgrades, the 'Big Picture'

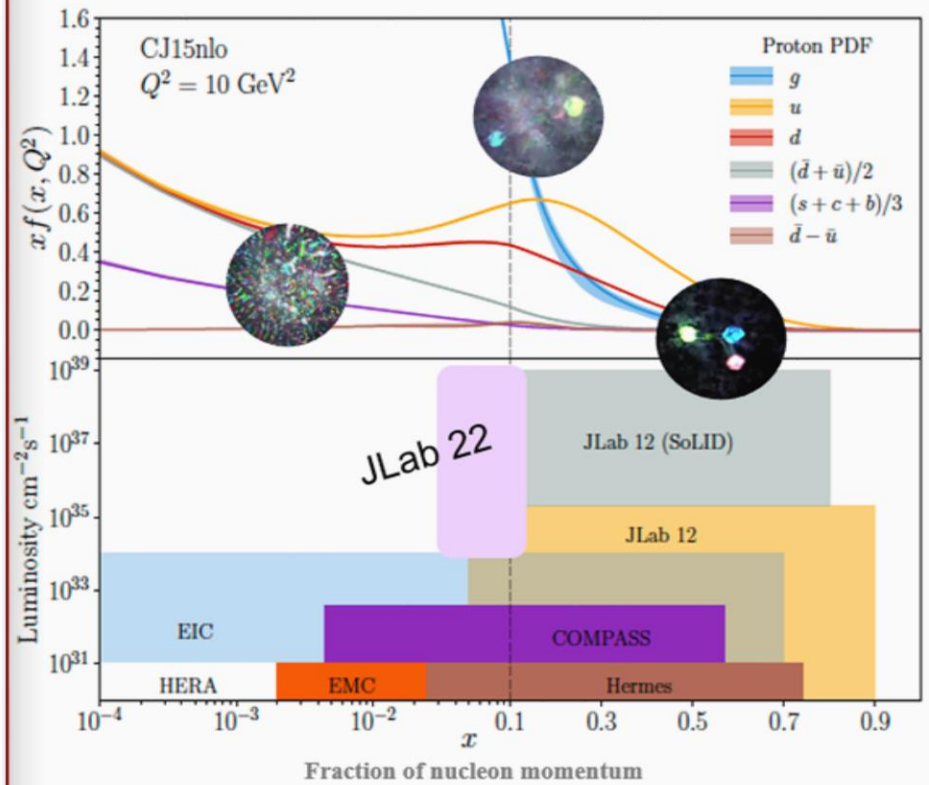
Capitalizing on recent science insights and US-led accelerator science and technology innovations, develop a staged program at the luminosity frontier

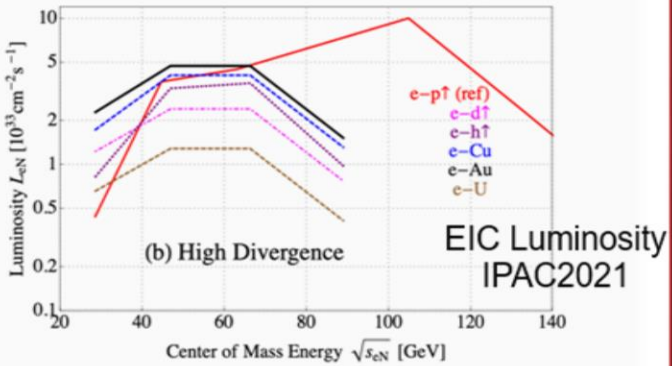
- Positrons (e+) in the LERF (former FEL) with transport to CEBAF
- Energy Upgrade for 650 MeV Electron (e-) Injection in the LERF
- Replace arcs on each side with new FFA permanent magnet arcs to upgrade to 22 GeV



See talk by Thia Keppel "JLab upgrade perspectives" presented at Sep 24 at
2022 Town Hall Meeting on Hot & Cold QCD, Sep 23-25, 2022, https://indico.mit.edu/event/538/

JLab Upgrade: Science at the Luminosity Frontier





Precision measurements in the valence quark regime requiring high luminosity are the purview of JLab12, providing overlap with EIC

The focus of the EIC will be low x, with higher luminosity than other colliders

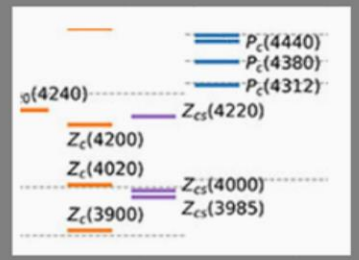
The 22 GeV upgrade will provide important overlap *into* the sea quark region.

Physics with CEBAF at 12 GeV and Future Opportunities
(Nov 30, 2021)
e-Print: 2112.00060 [nucl-ex], Accepted to Progress in Particle and Nuclear and Physics

See talk by Thia Keppel "JLab upgrade perspectives" presented at Sep 24 at
2022 Town Hall Meeting on Hot & Cold QCD, Sep 23-25, 2022, https://indico.mit.edu/event/538/

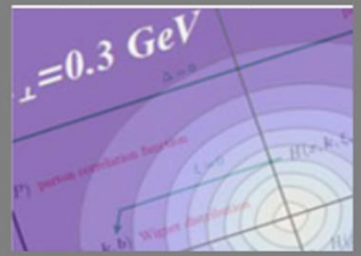
High Energy Workshop Series 2022

Hadron Spectroscopy with a CEBAF Energy Upgrade



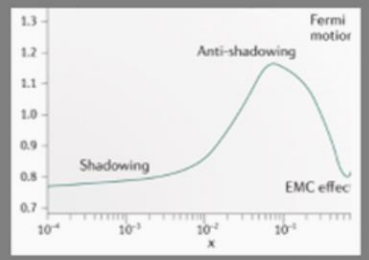
- **38** registered p.
- **8** talks

The Next Generation of 3D Imaging



- **55** registered p.
- **13** talks + Summary talk

Science at Mid x: Anti-shadowing and the Role of the Sea

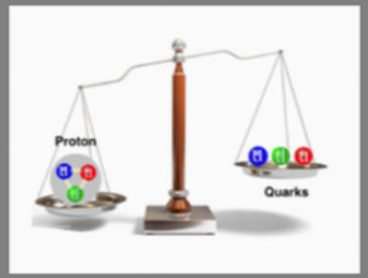


- **43** registered p.
- **14** talks

Physics Beyond the Standard Model

- **37** registered p.
- **6** talks

J/Psi and Beyond



- **38** registered p.
- **7** talks + two 1 slide pres.

- **Goal to have a first version white paper document ready in a few weeks**
- **To be discussed also at upcoming Trento workshop (September 26-30)**

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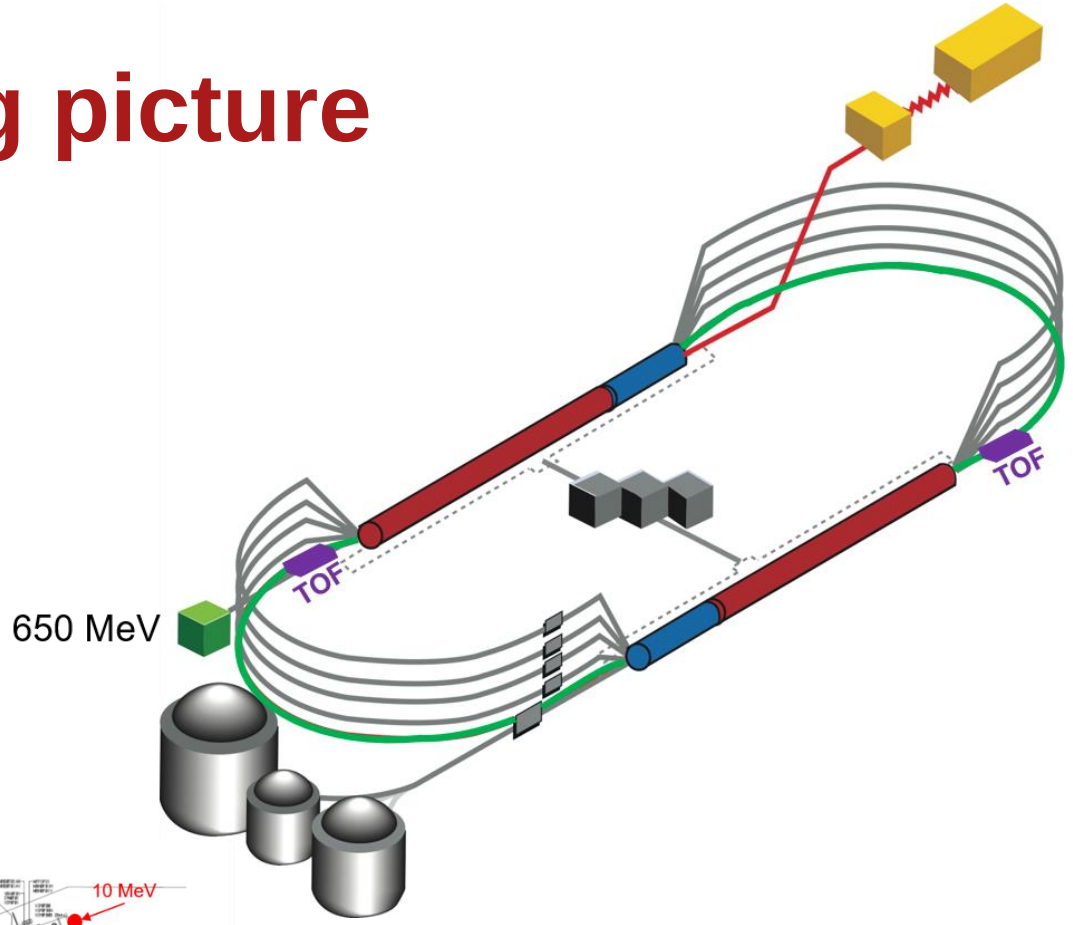
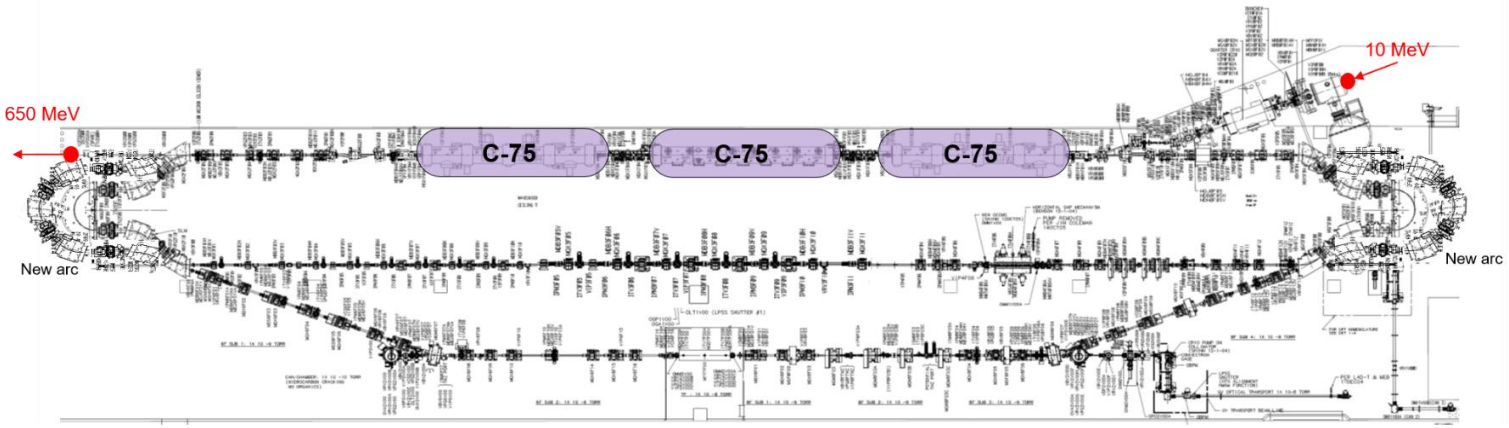
See talk by Thia Keppel "JLab upgrade perspectives" presented at Sep 24 at
2022 Town Hall Meeting on Hot & Cold QCD, Sep 23-25, 2022, https://indico.mit.edu/event/538/

Energy upgrade to 22 GeV, big picture

- Hardware needed:
  - Replace arcs on each side with new FFA permanent magnet arcs
    - (One pair of arcs to 22 GeV in 6 extra passes)
  - Add ~650MeV injector (e.g. 2-pass-recirculating compact injector)
    - LERF based recirculating injector in ~70x10m vault

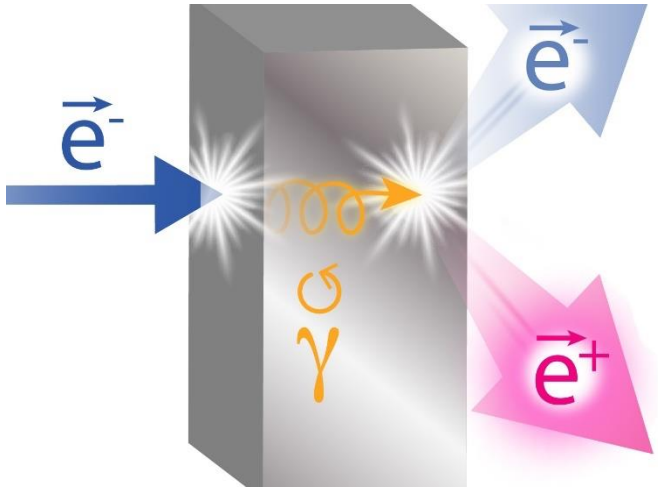


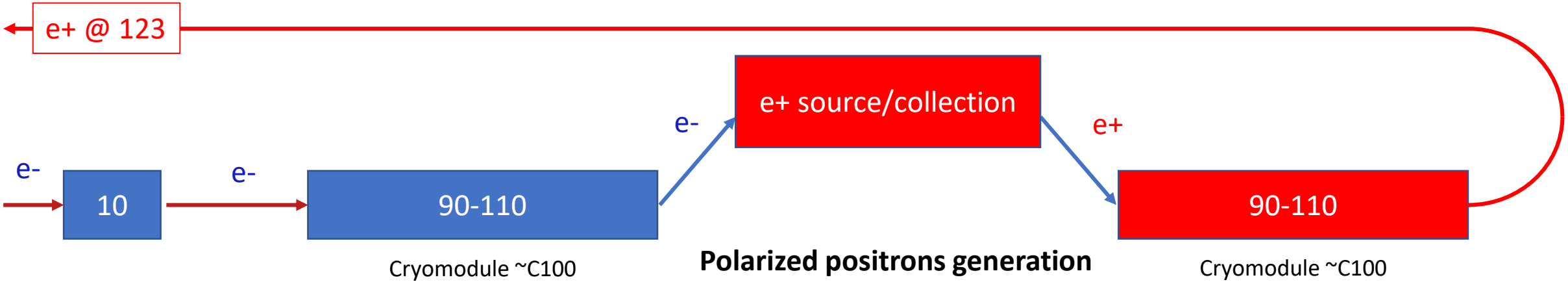


See presentation by Alex Bogacz

Polarized e+, big picture

- Hardware needed:
  - High current polarized e- source
  - A cryomodule to accelerate e-
  - An e+ target-source and collection system
  - A cryomodule to accelerate e+

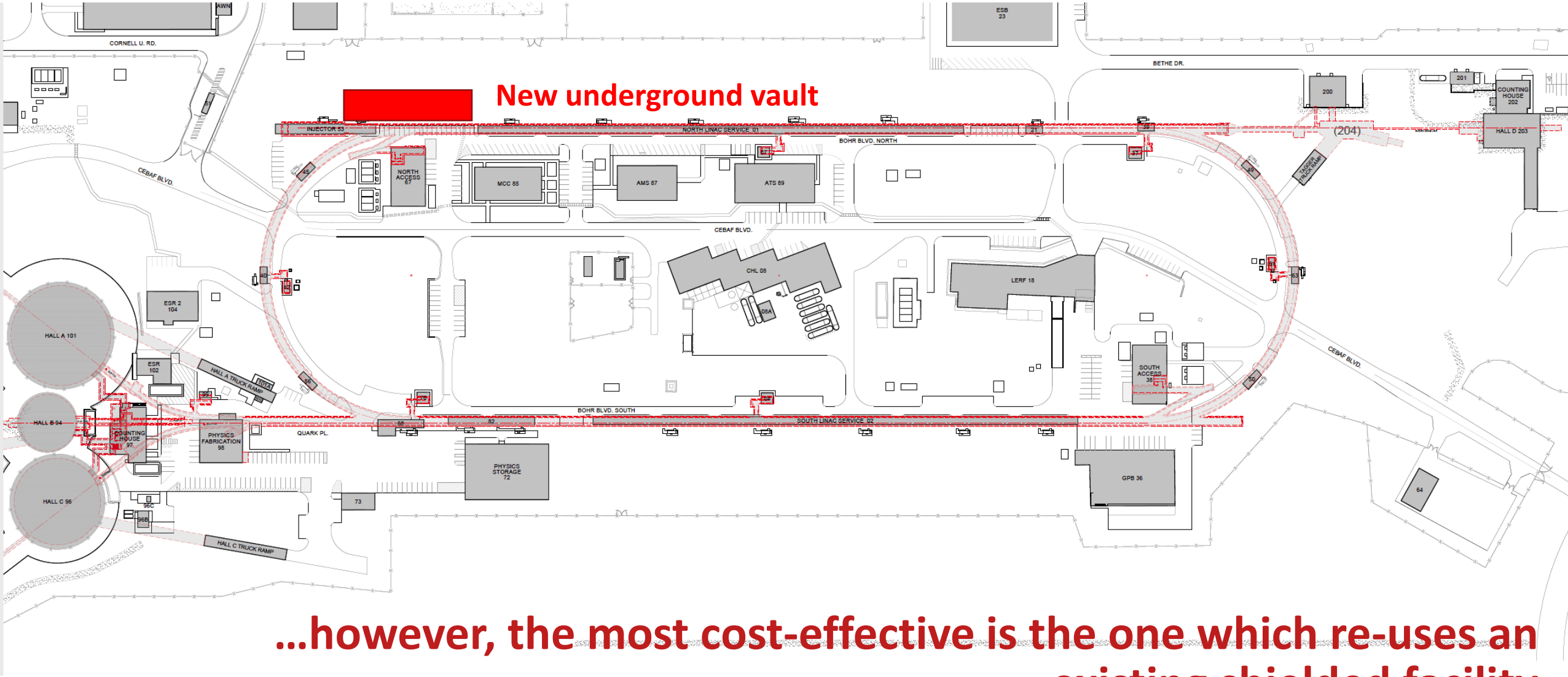




- Most of hardware from e+ stage can be re-used in the 22 GeV program – synergy with energy upgrade
- Space requirements for e+ source are similar to what is needed for ~600 MeV injector for 22 GeV program

Joe Grames et al.

Several options were considered, e.g. … :



…however, the most cost-effective is the one which re-uses an existing shielded facility

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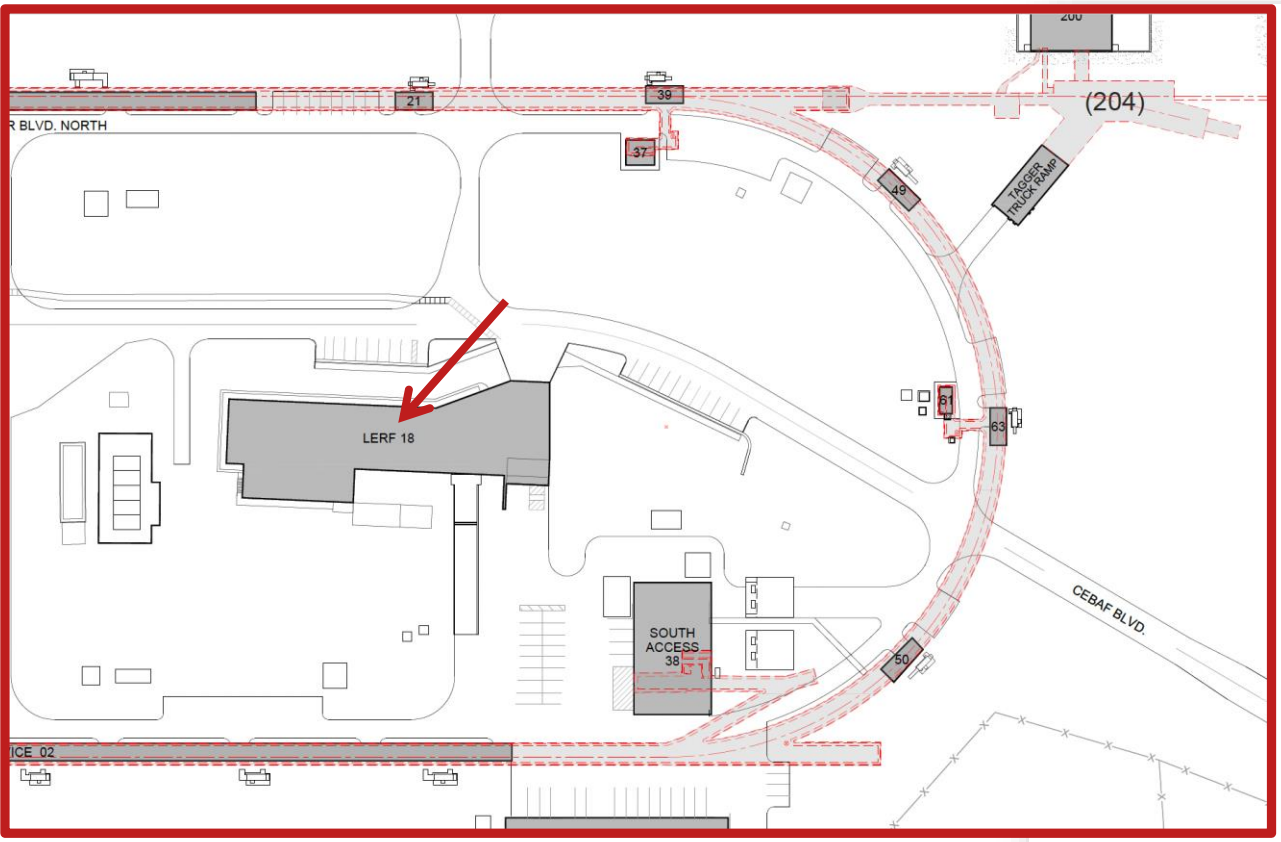
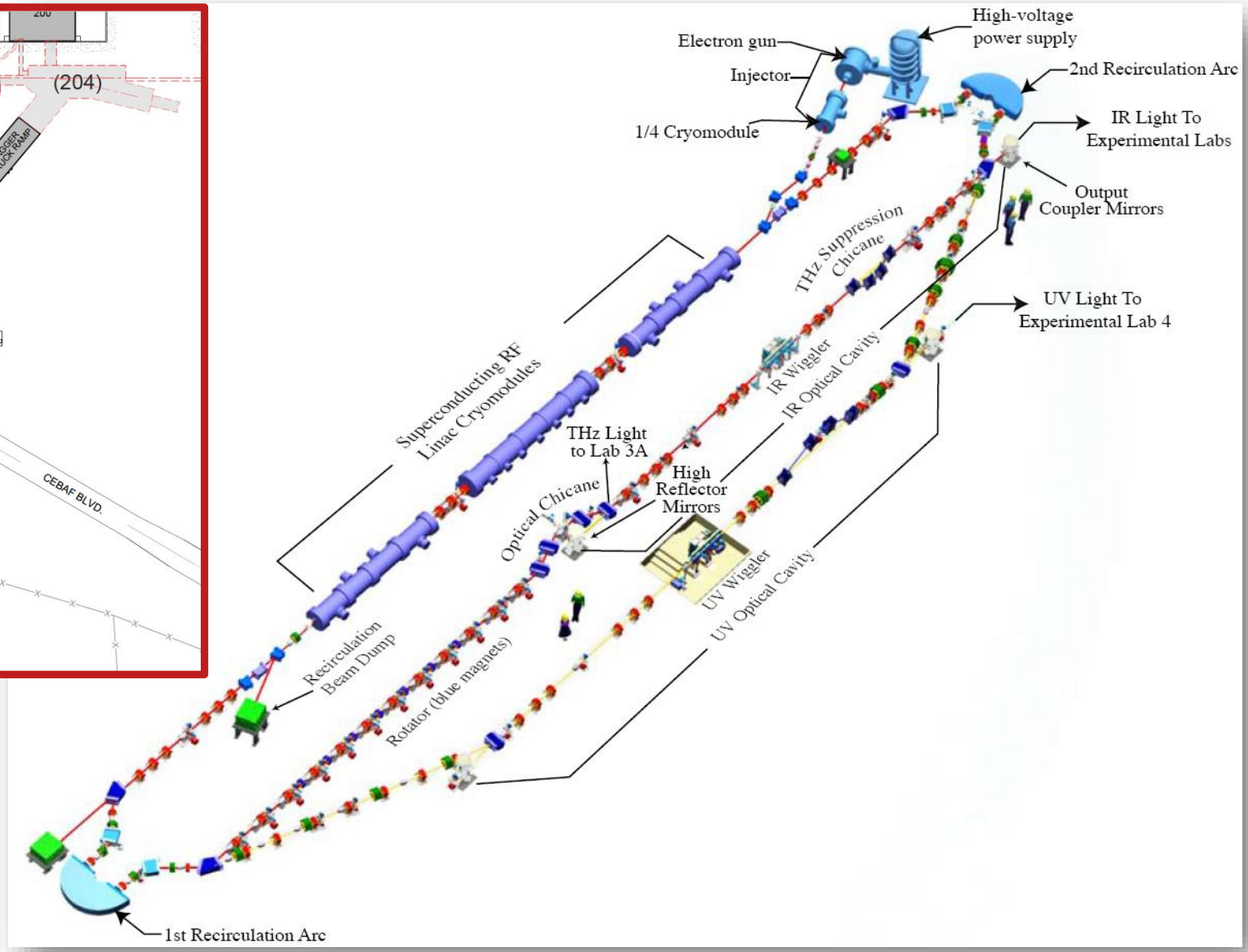
Low Energy Recirculation Facility (LERF)



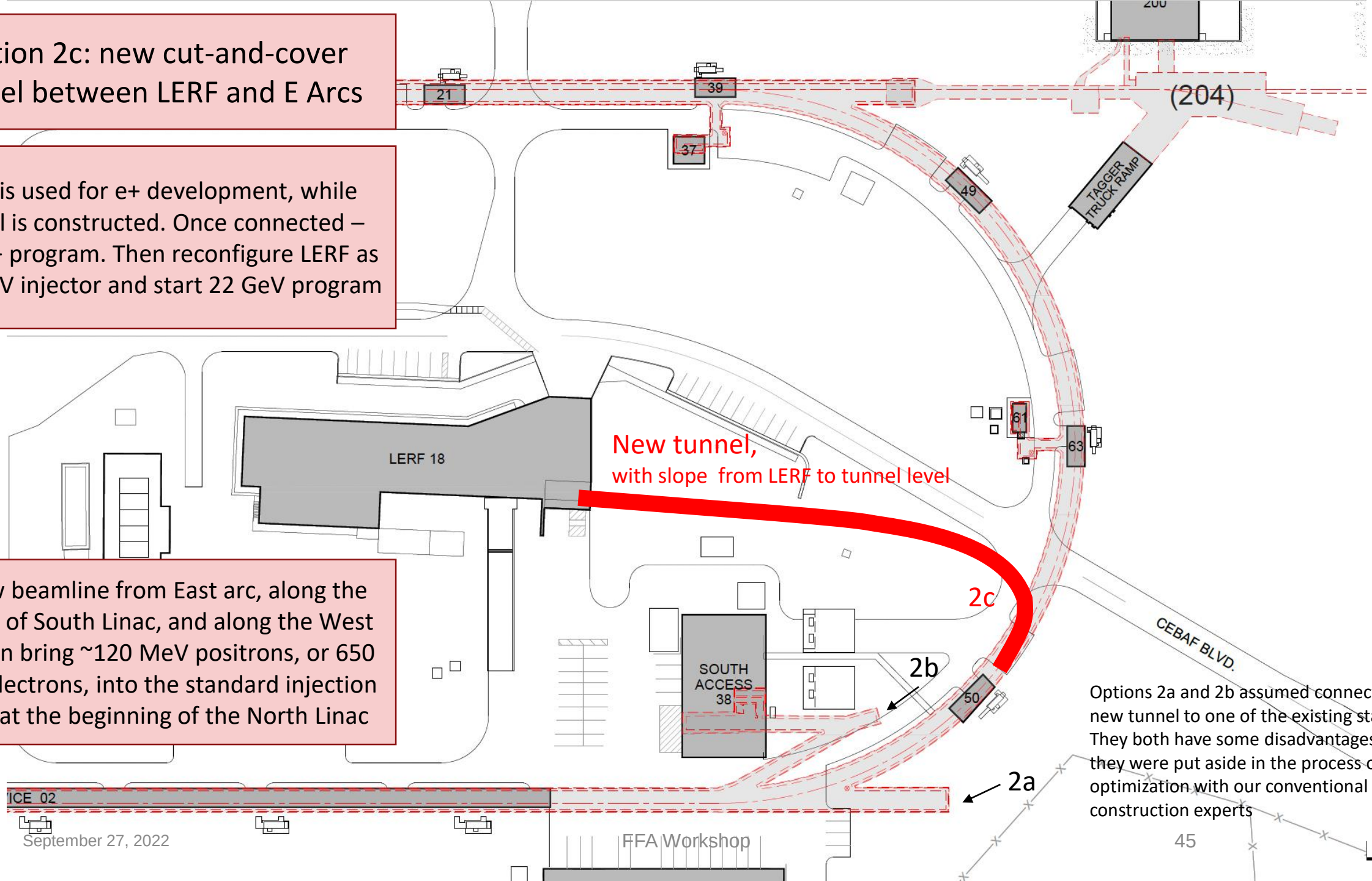


- Location of former FEL study
  - ERL based, world record performance
- **Shielded vault with size suitable for upgrades: positrons and energy upgrade 650 MeV injector**

Option 2c: new cut-and-cover tunnel between LERF and E Arcs

LERF is used for e+ development, while tunnel is constructed. Once connected – start e+ program. Then reconfigure LERF as 650 MeV injector and start 22 GeV program

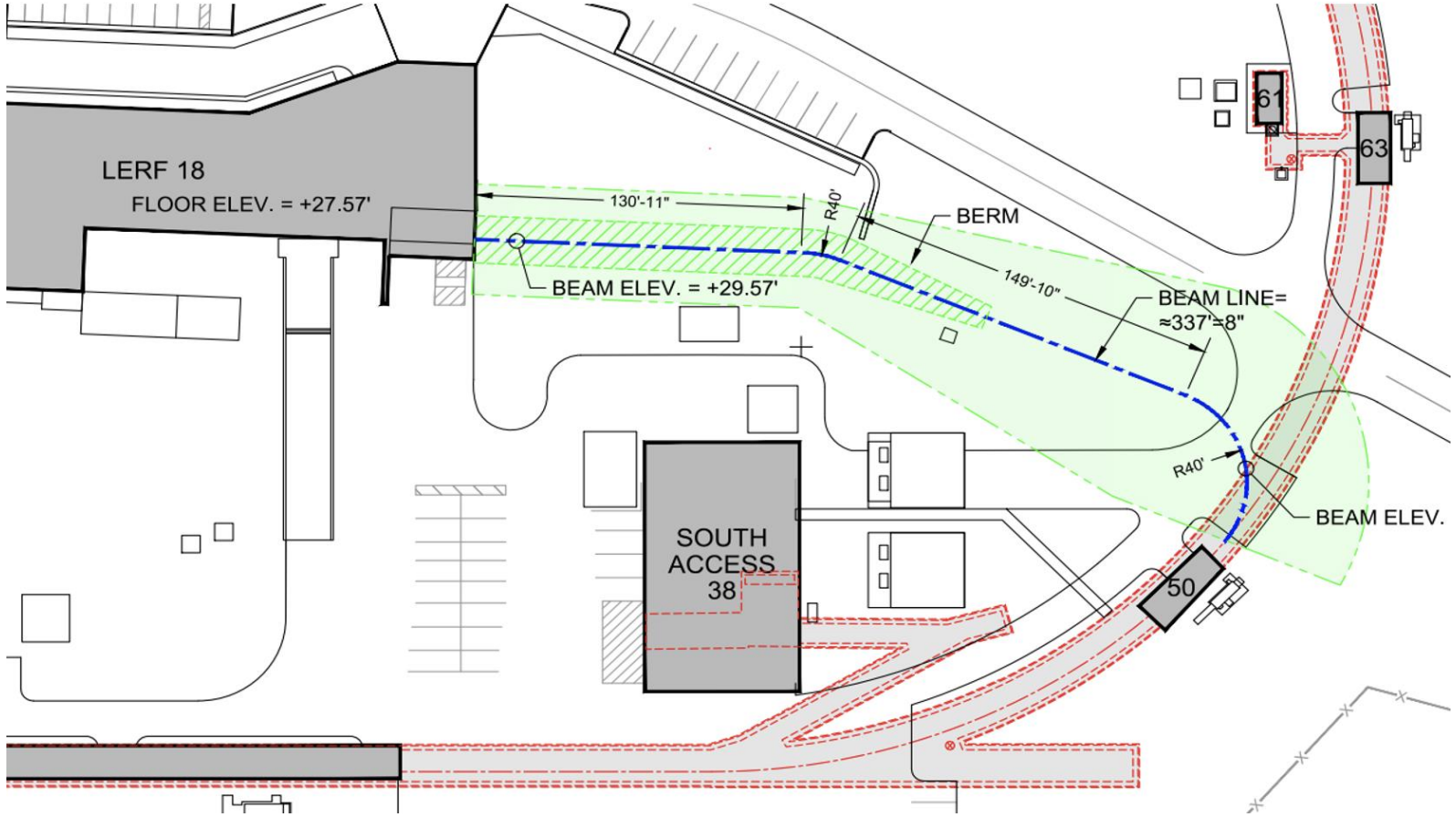
A new beamline from East arc, along the ceiling of South Linac, and along the West arc, can bring ~120 MeV positrons, or 650 MeV electrons, into the standard injection point at the beginning of the North Linac

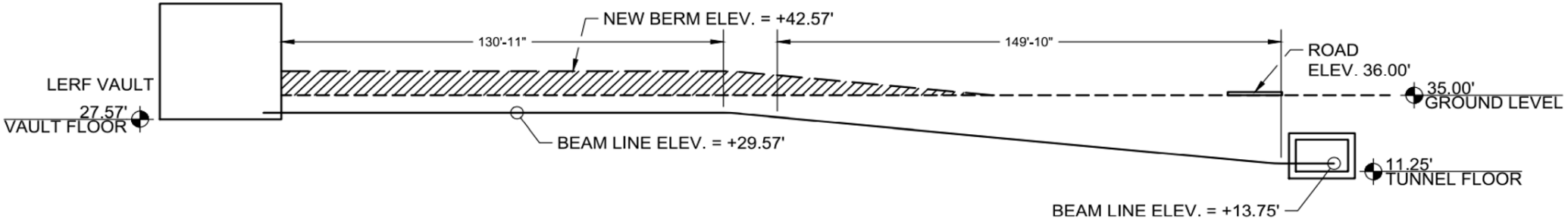


Options 2a and 2b assumed connecting the new tunnel to one of the existing stabs. They both have some disadvantages and they were put aside in the process of design optimization with our conventional construction experts

Tunnel to East Arc

- Conventional Facilities construction experts assessment and design optimization
  - Options 2a and 2b assessed
  - Option 2c suggested and evaluated
  - Feasibility confirmed
- Rough cost estimates for hardware are in the process





Summary

- CEBAF provides unique opportunities for nuclear physics studies
  - 12 GeV upgrade completed in 2017
  - Four halls running simultaneously since January 2018
- CEBAF 22 GeV staged approach via e+ : modern, energy efficient and affordable, complementary to EIC
  - See presentation by Alex Bogacz tomorrow

Thank you!