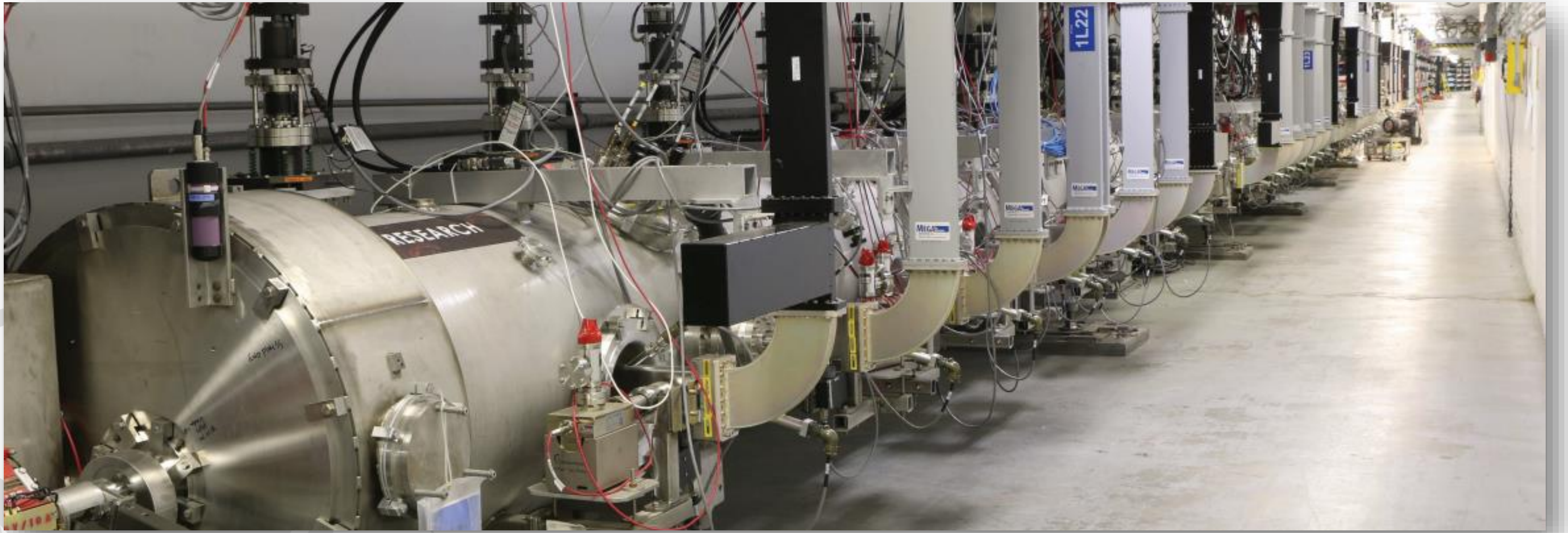
CEBAF Overview

Continuous Electron Beam Accelerator Facility



Andrei Seryi

Jefferson Lab Associate Director for Accelerator Operations and R&D

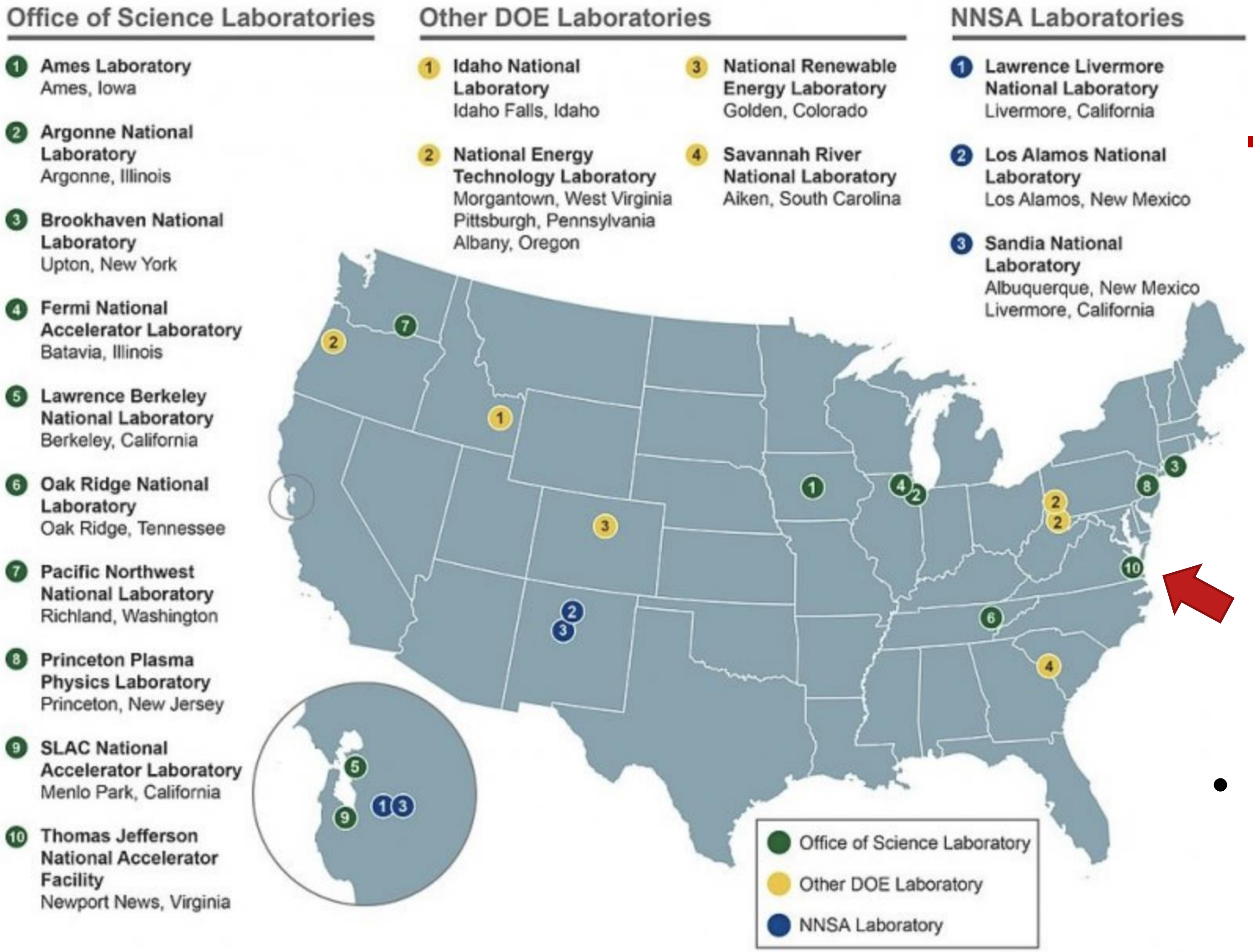
The 2023 Workshop on Fixed Field Alternating Gradient Accelerators

10 -15 September 2023

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

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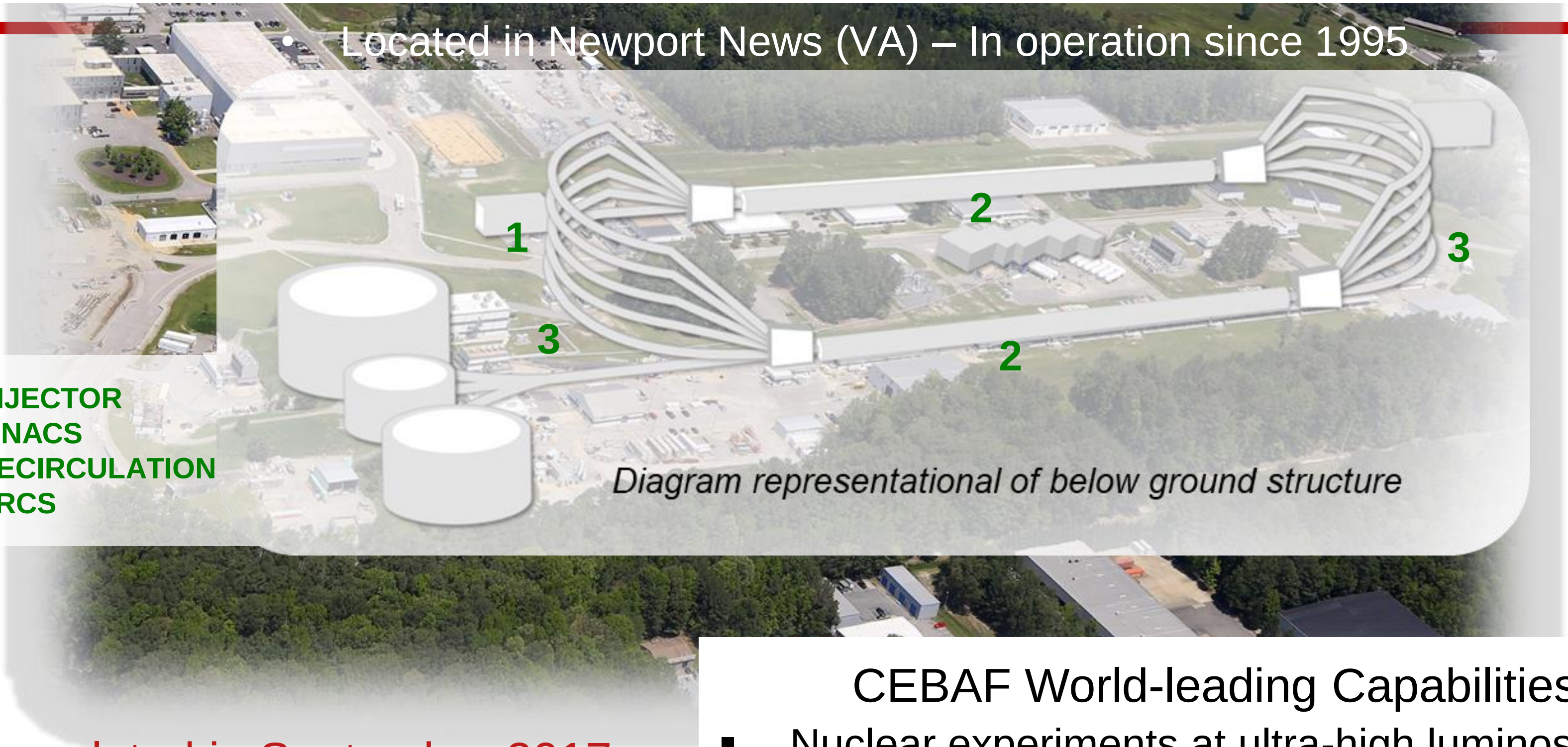
Jefferson Lab's Scientific Mission

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

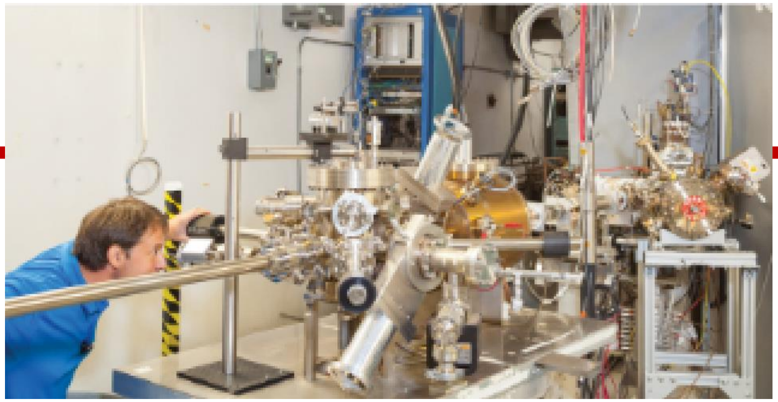


Our primary research tool is CEBAF - a superconducting high-energy electron particle accelerator

- 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

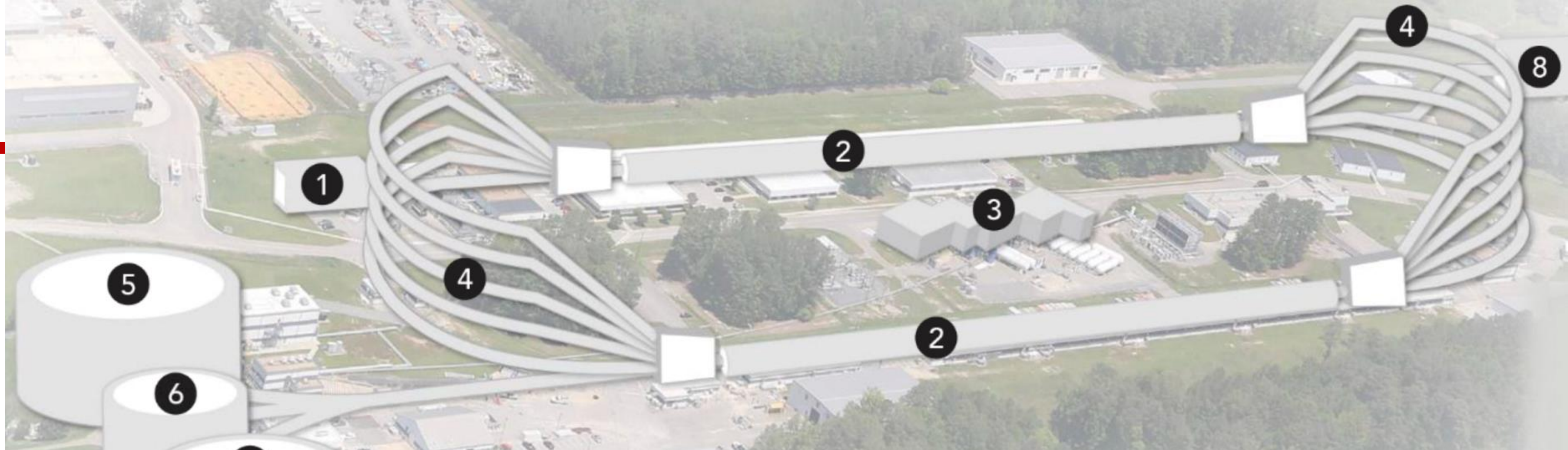
CEBAF World-leading Capabilities

- 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**

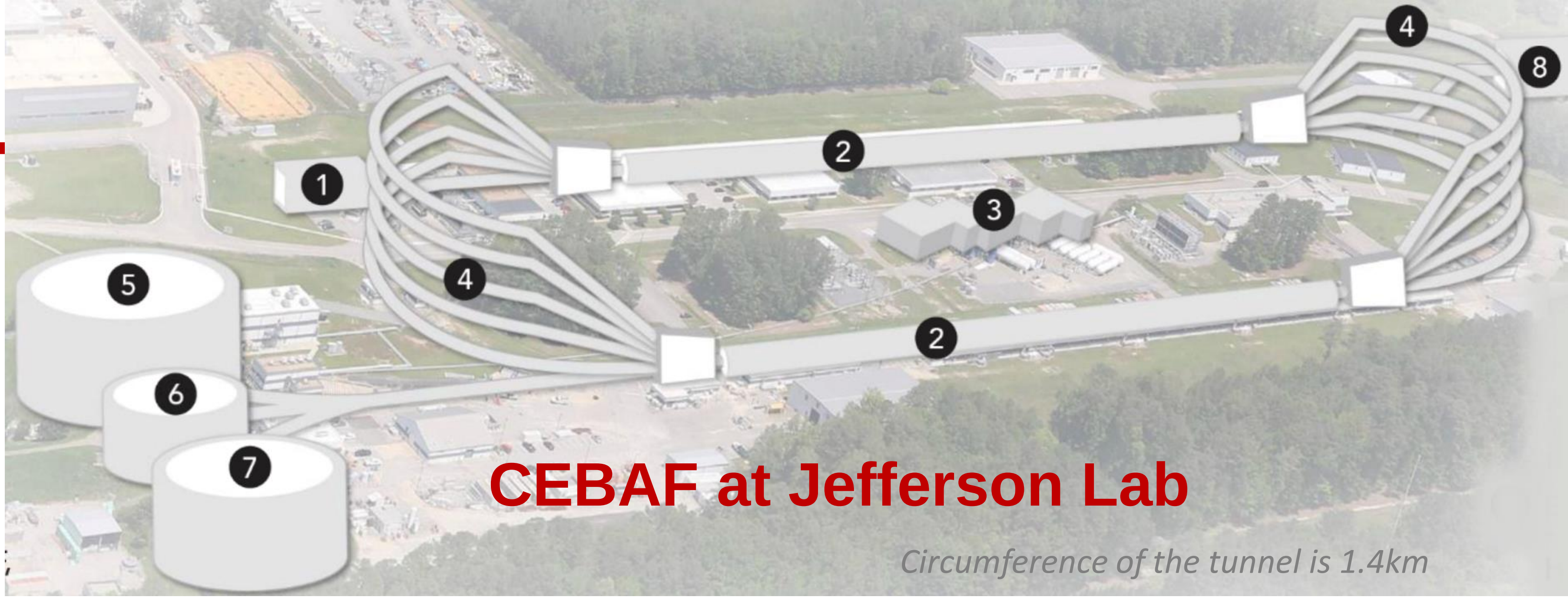
Straight sections have 25 cryomodules each. Beam travels up to 5.5 passes through linacs to get to 12 GeV

3 **Central Helium Liquefier**

CHL keeps SRF cavities at 2K temperature

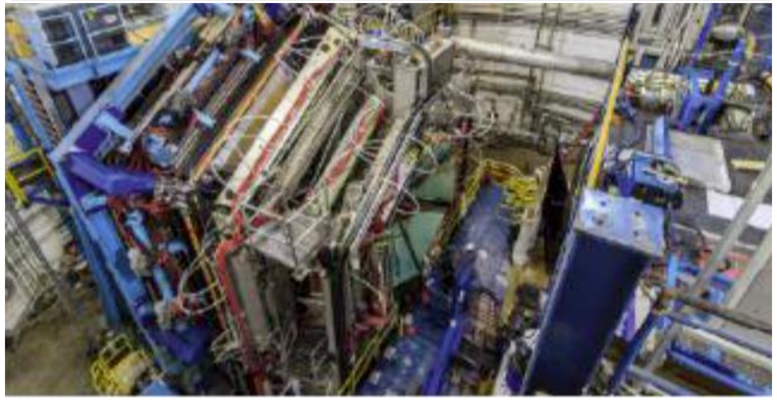
4 **Recirculation magnets**

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

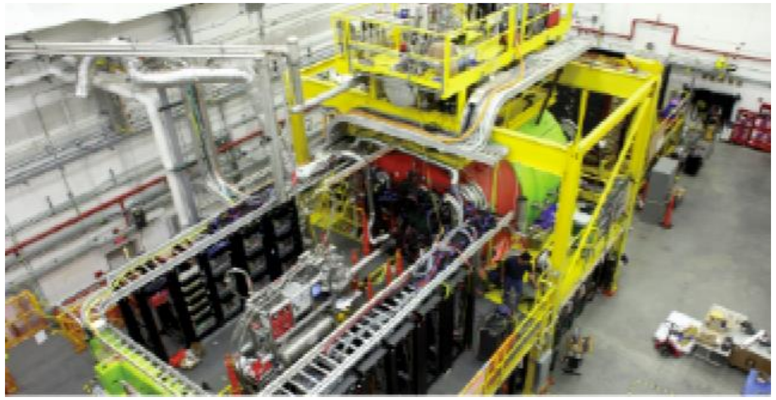


6 Experimental Hall B

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

7 Experimental Hall C

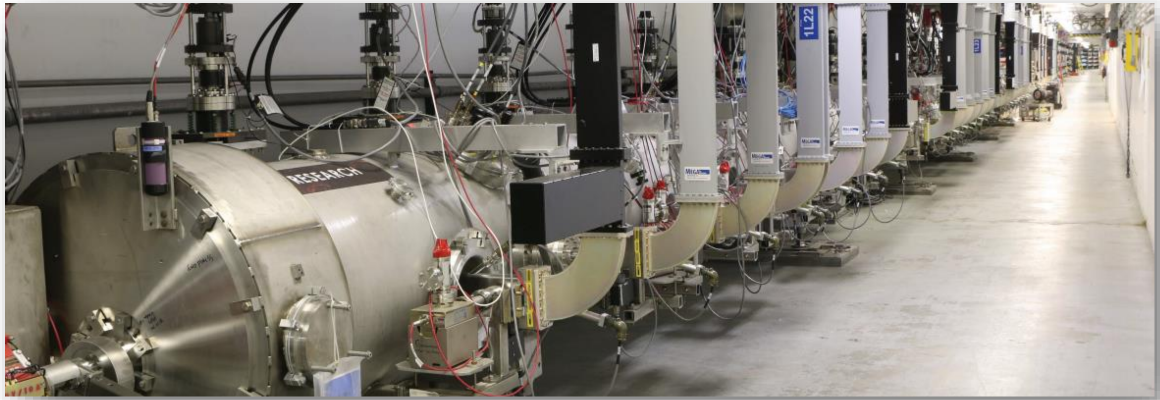
High Momentum Spectrometer measures nuclei structure at high energy and high beam current



8 Experimental Hall D

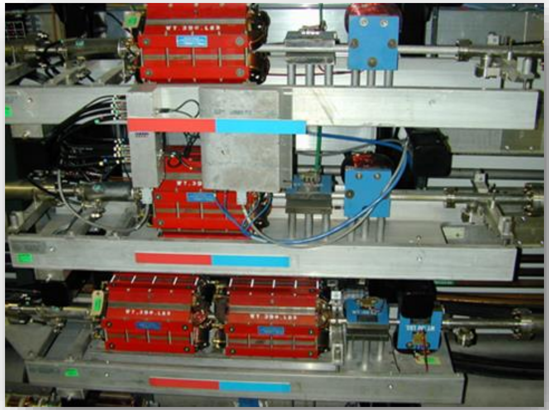
Equipped with SC magnet and detector to study strong force that binds quarks together

CEBAF Accelerator – Technical Scope

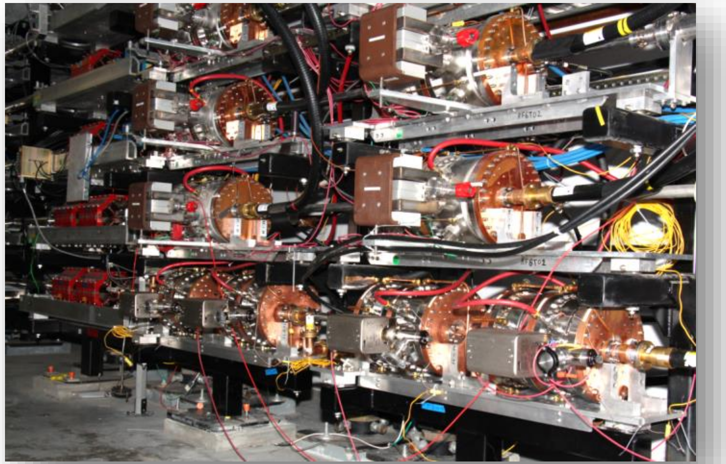


52-1/4 Cryomodules with 418 SRF Cavities to Accelerate Electrons in CEBAF

~500 Large Dipoles powered by >40 HVPS

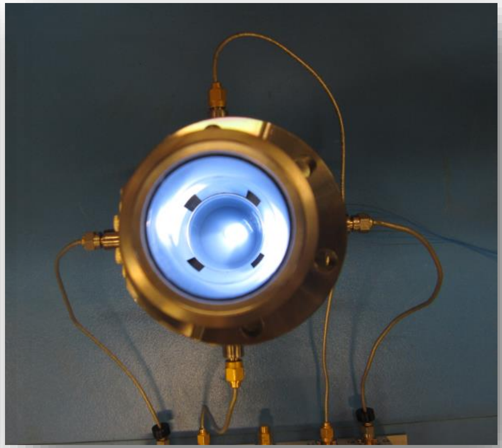


>2800 Magnets to Focus and Steer Beam



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.

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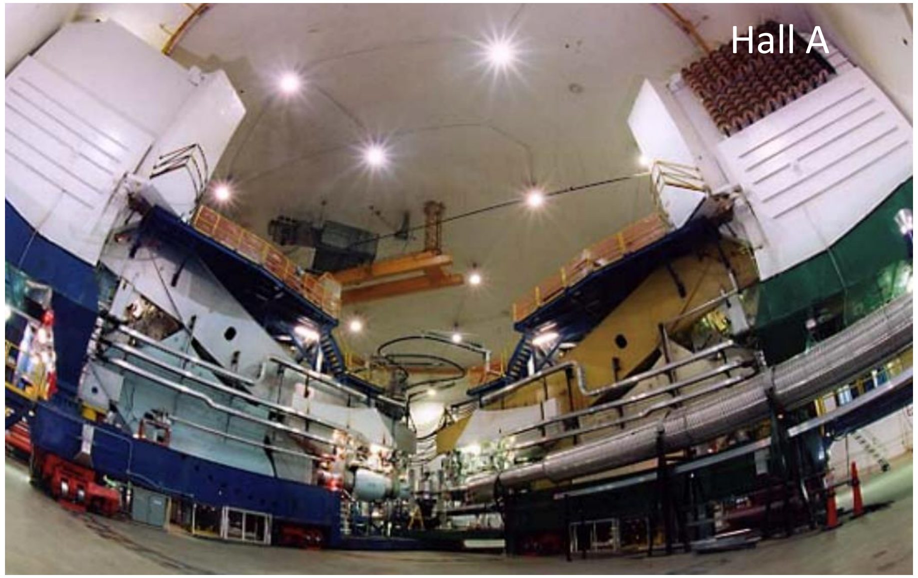
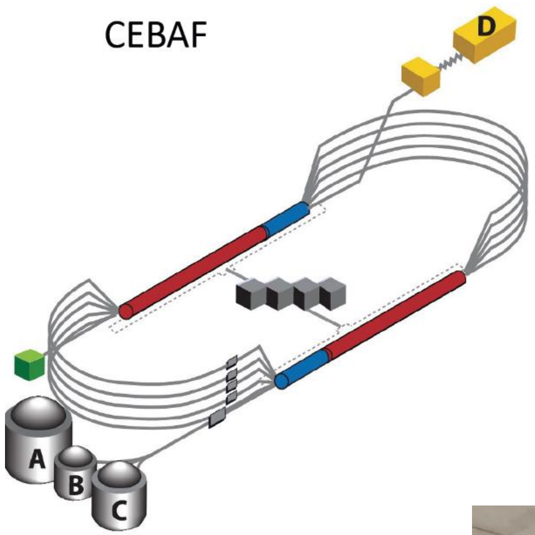
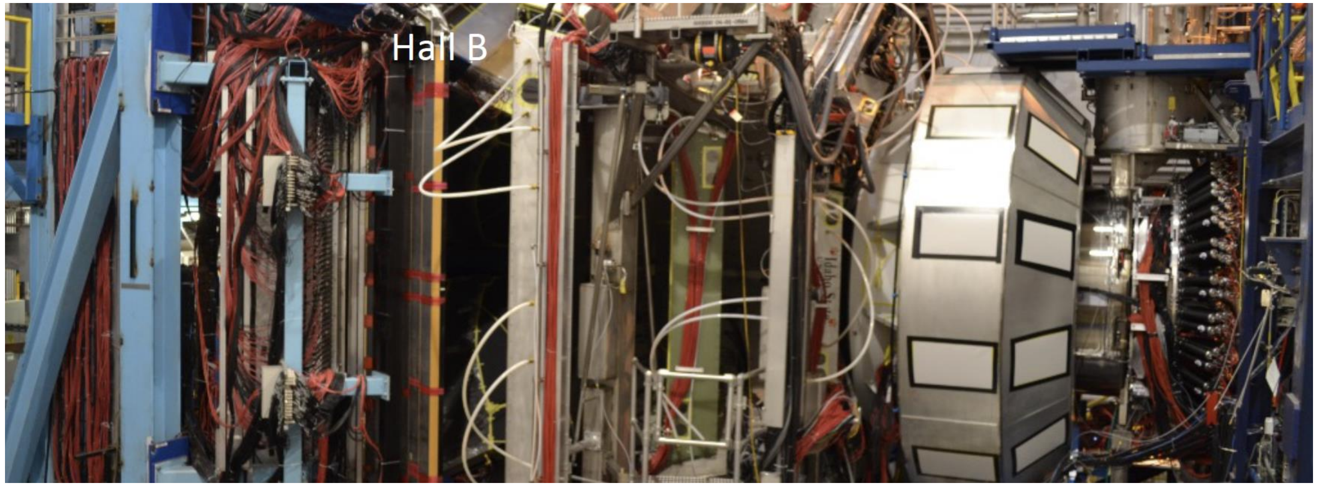
CEBAF Halls and Experiments



Hall A (HRS, SBS)



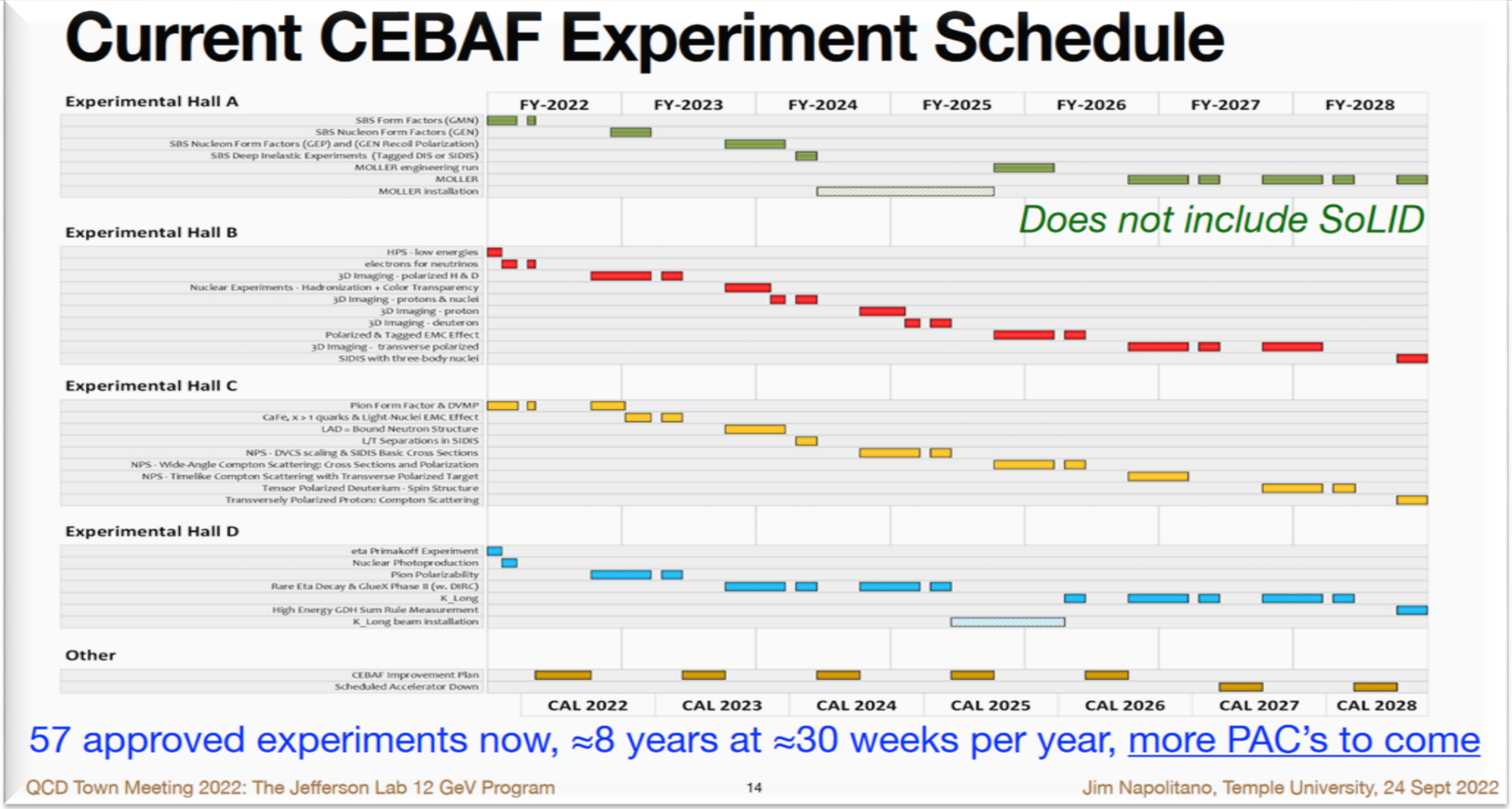
Hall D (Glue X)



Hall B (CLAS12)

Hall C (HMS and SHMS)

CEBAF 12 GeV Science is Exciting and Impactful



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

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CEBAF Construction

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

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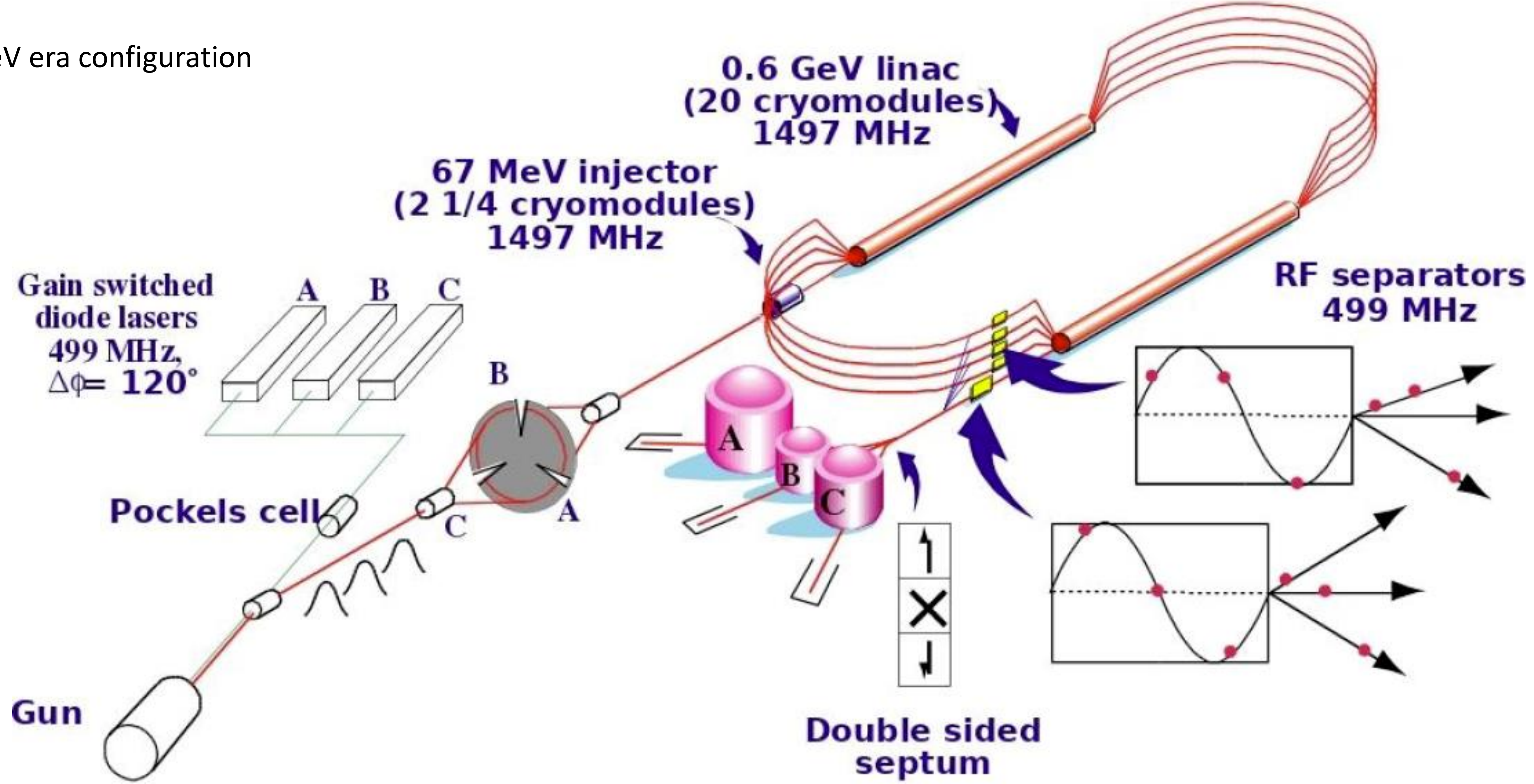
CEBAF Construction

Tunnels before hardware installations

Arcs in 6 GeV era (four beamlines)

CEBAF three halls era

6 GeV era configuration



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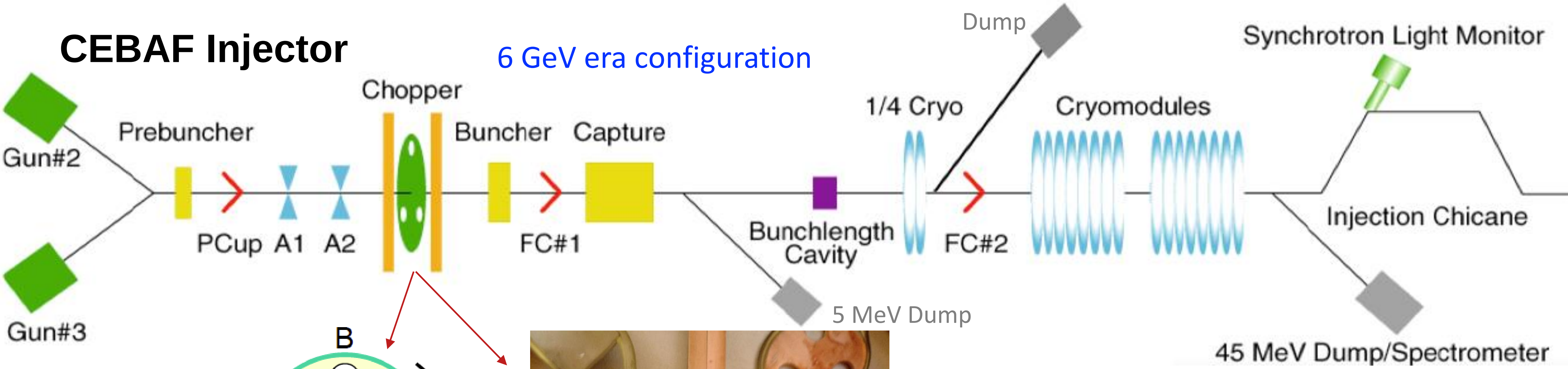
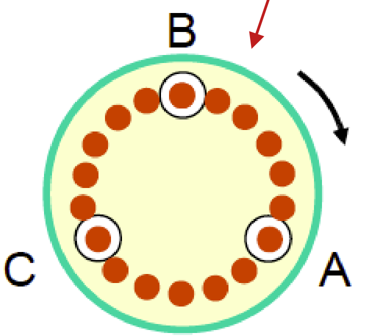
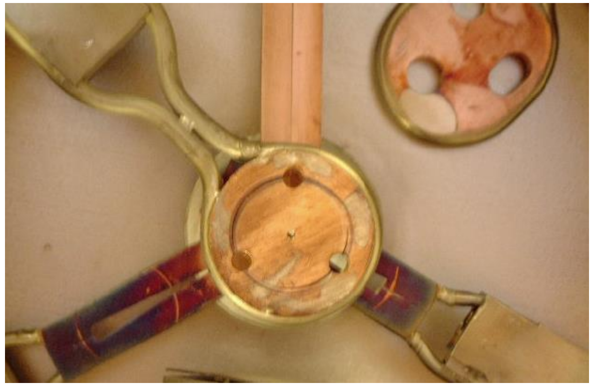
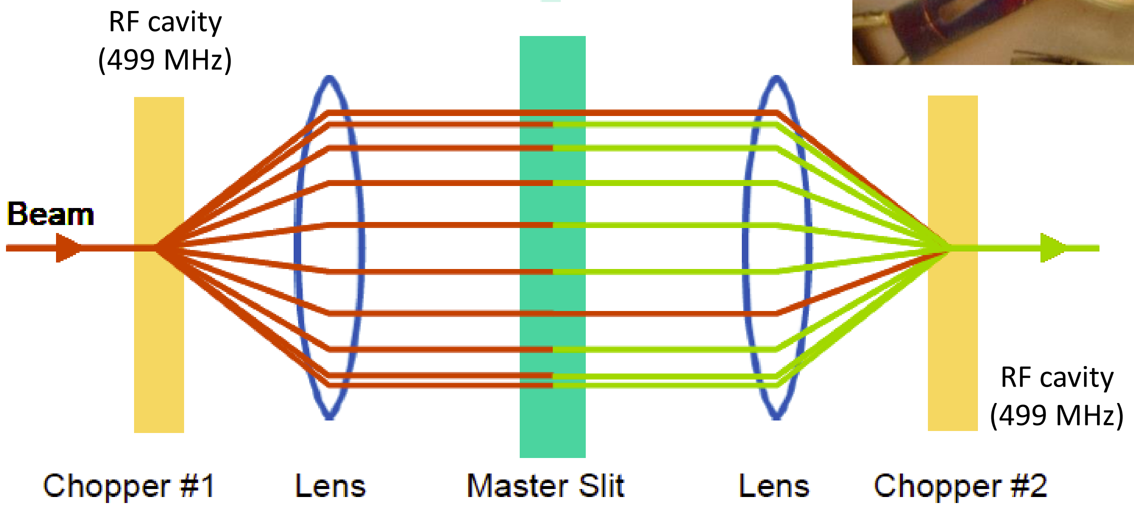
CEBAF Injector

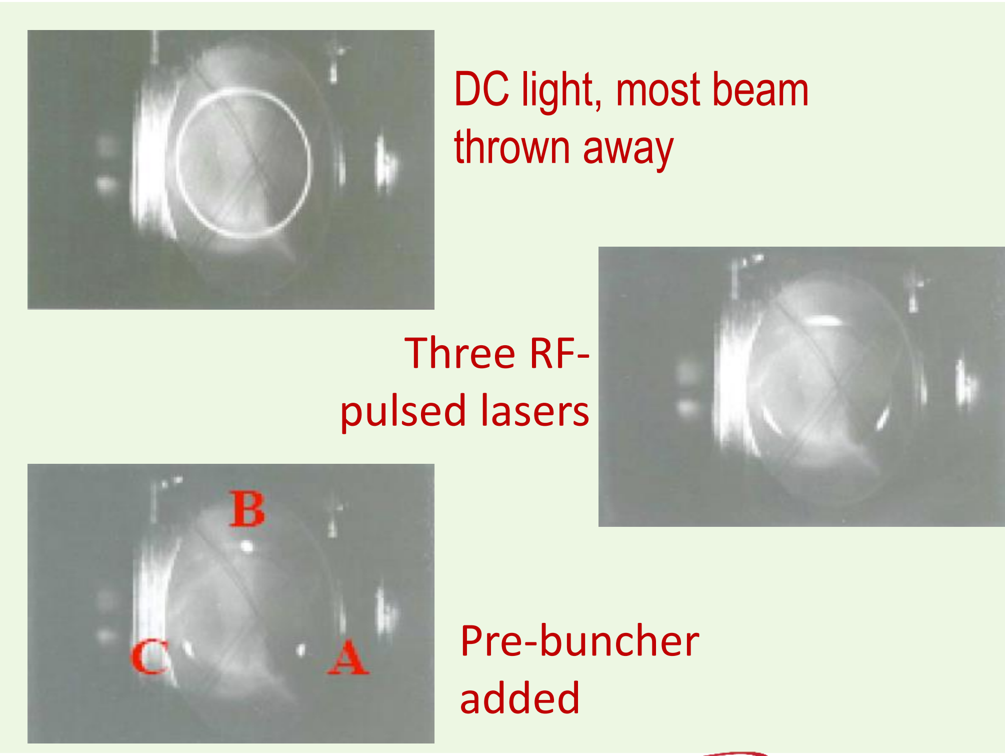
6 GeV era configuration



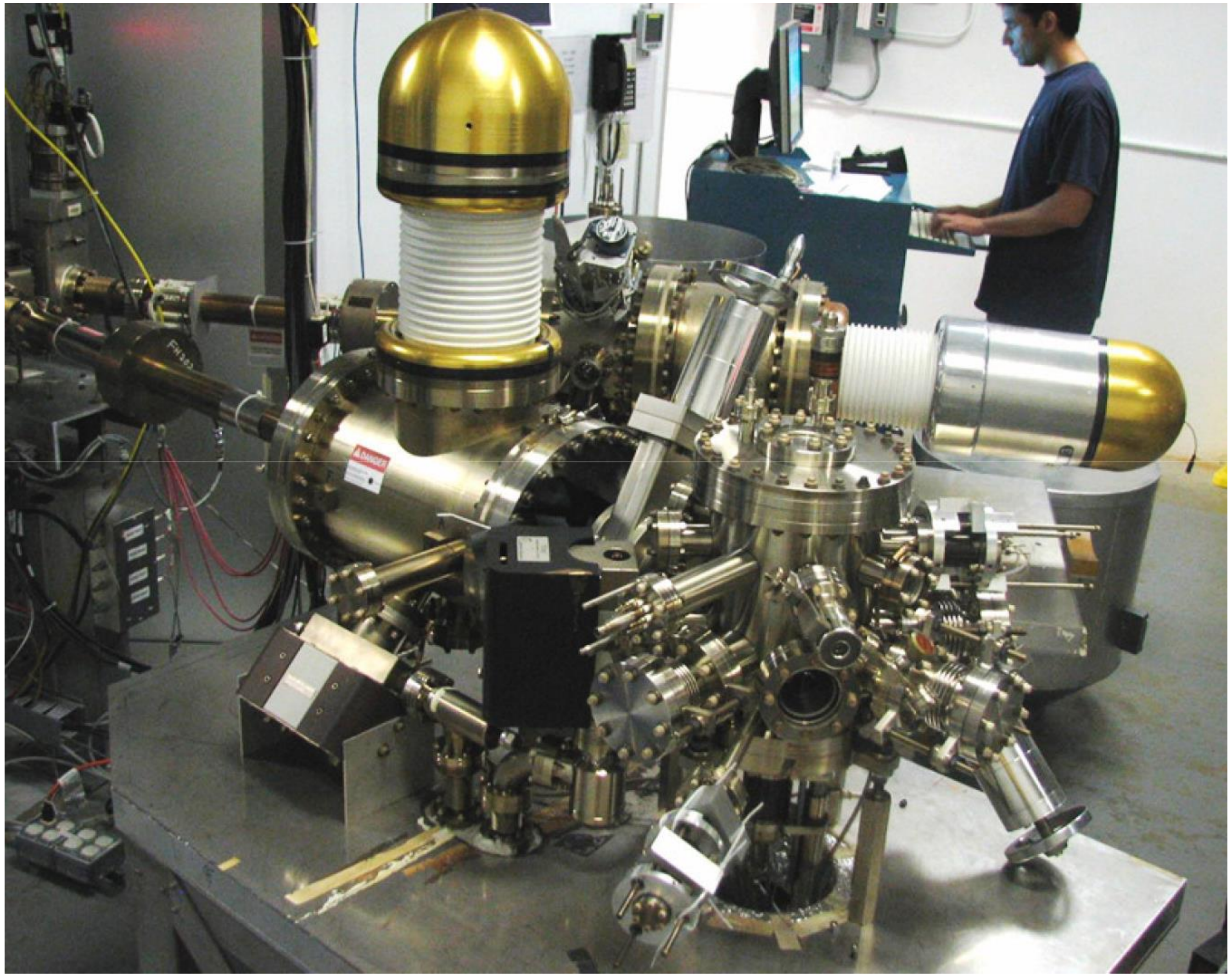








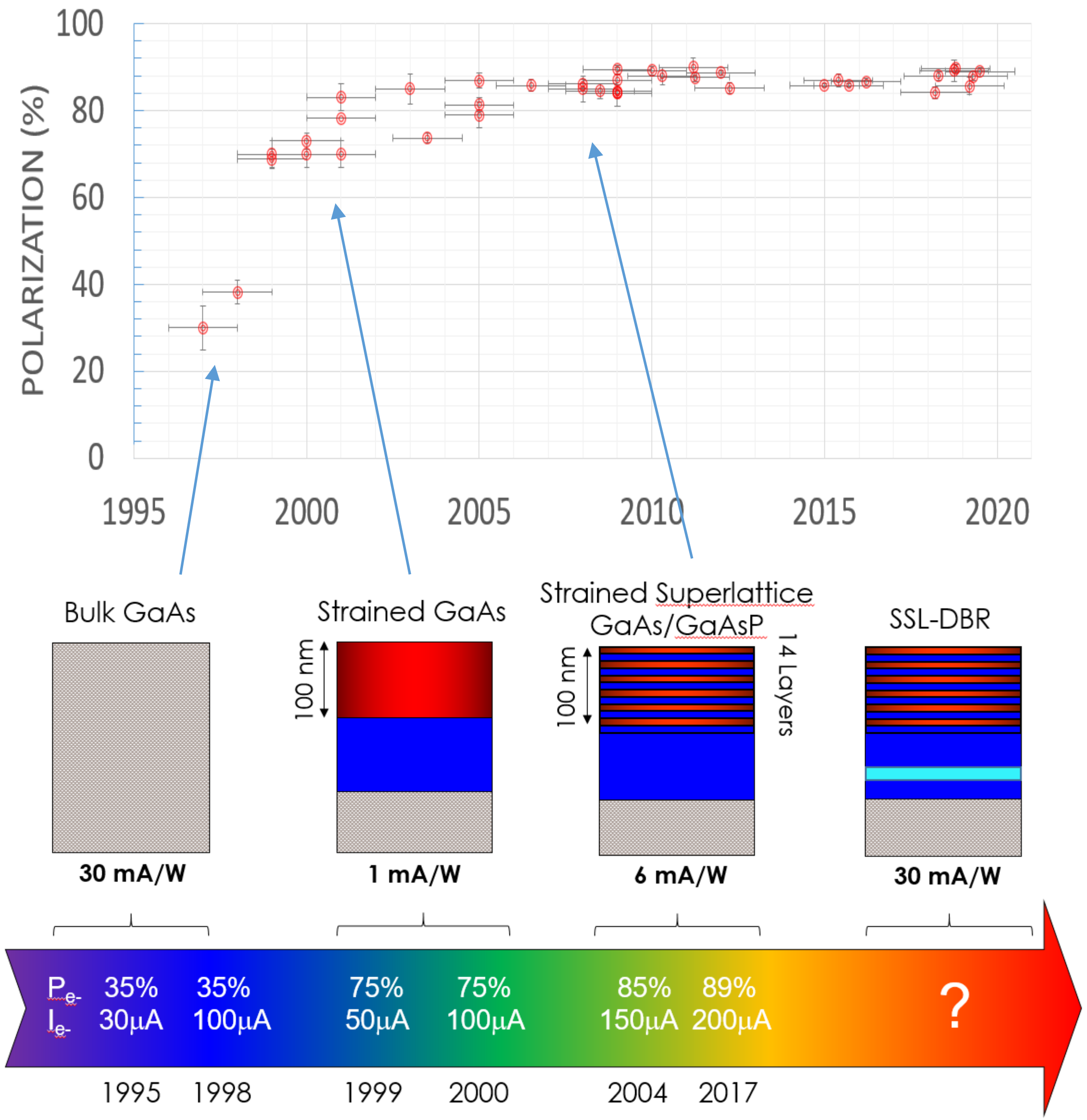
CEBAF load-lock polarized gun



- 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"

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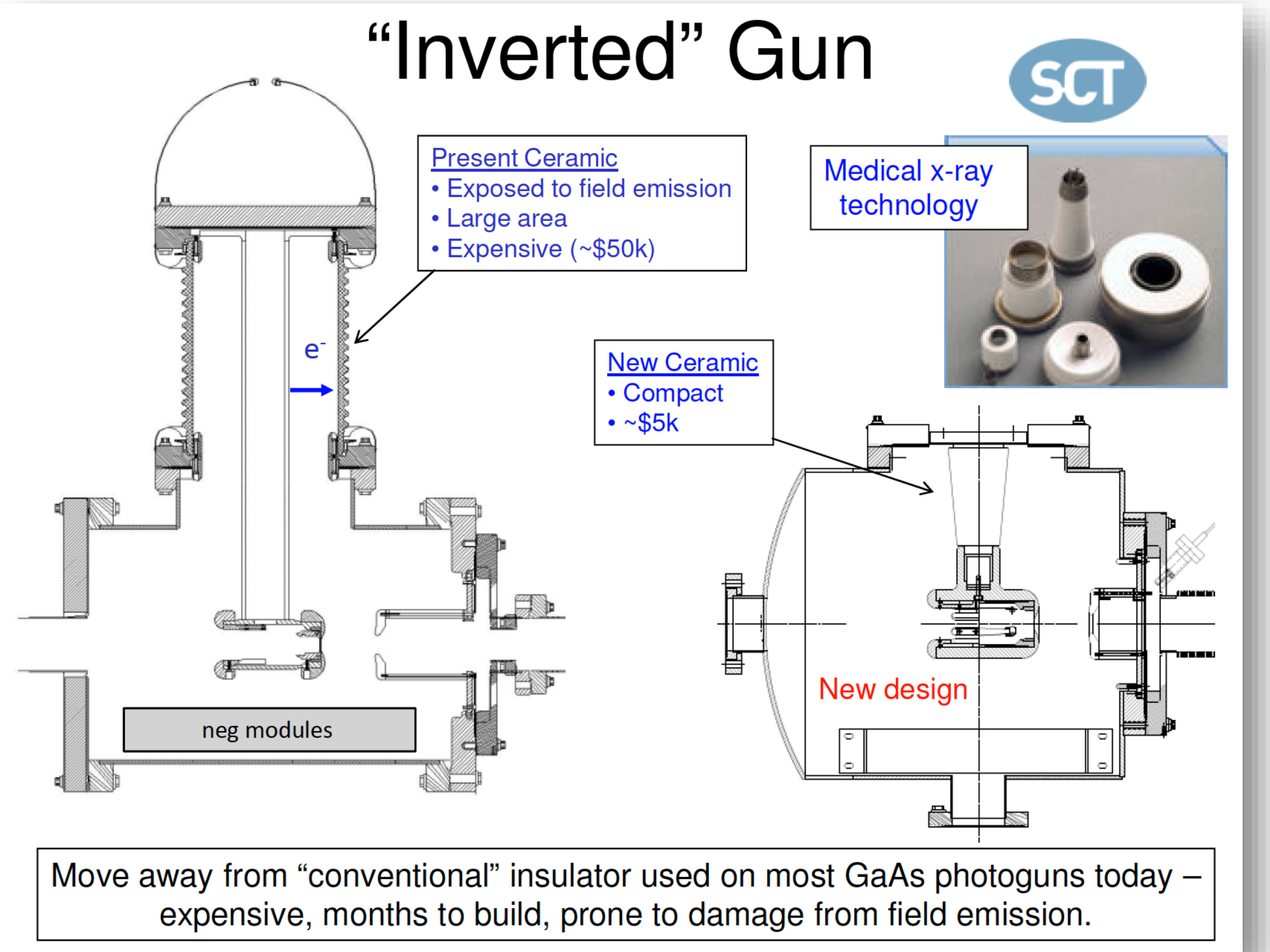
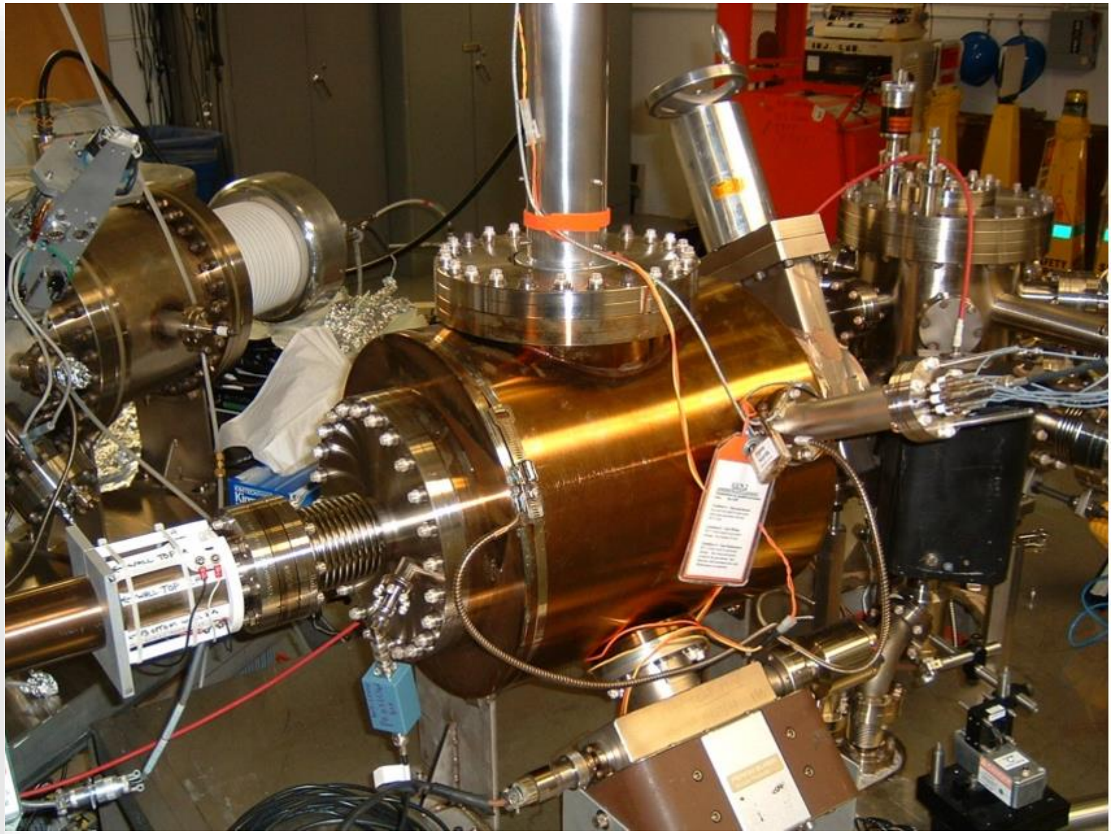
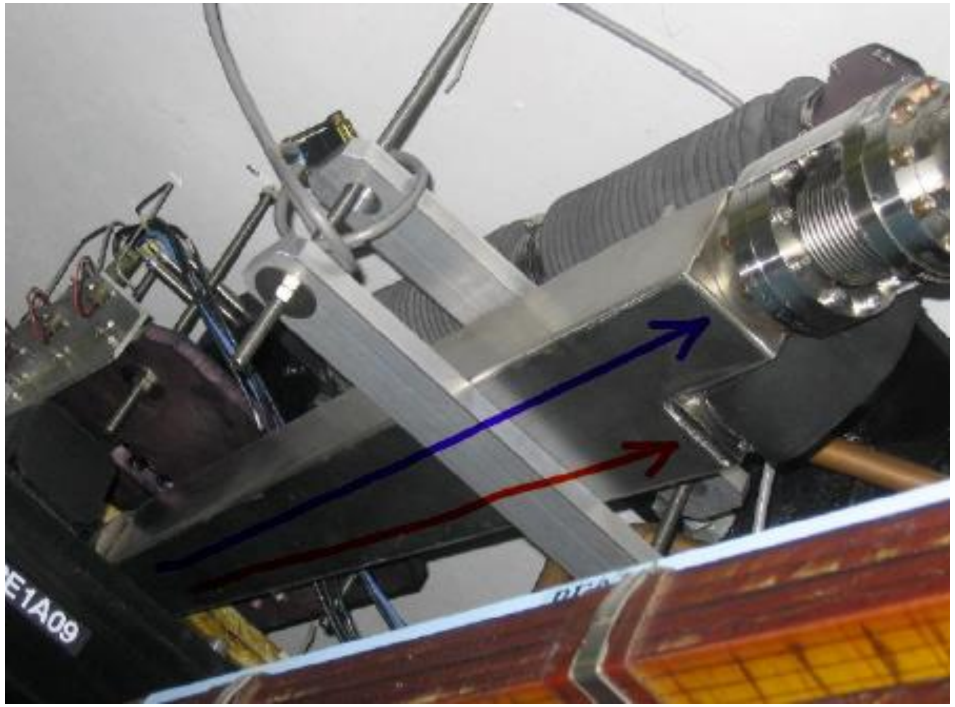
CEBAF Inverted Gun

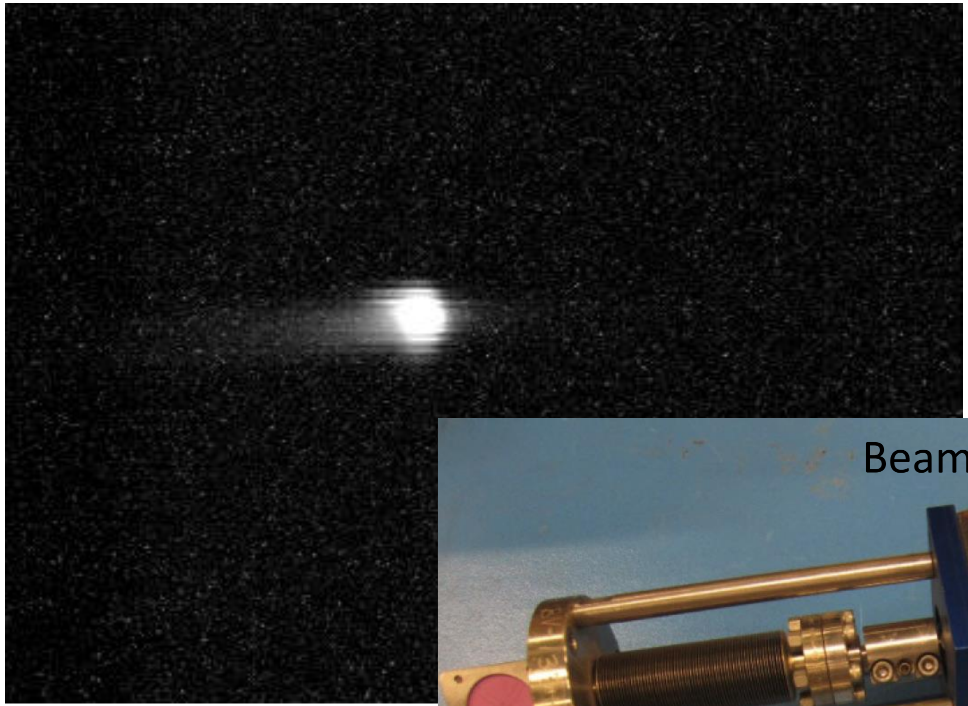


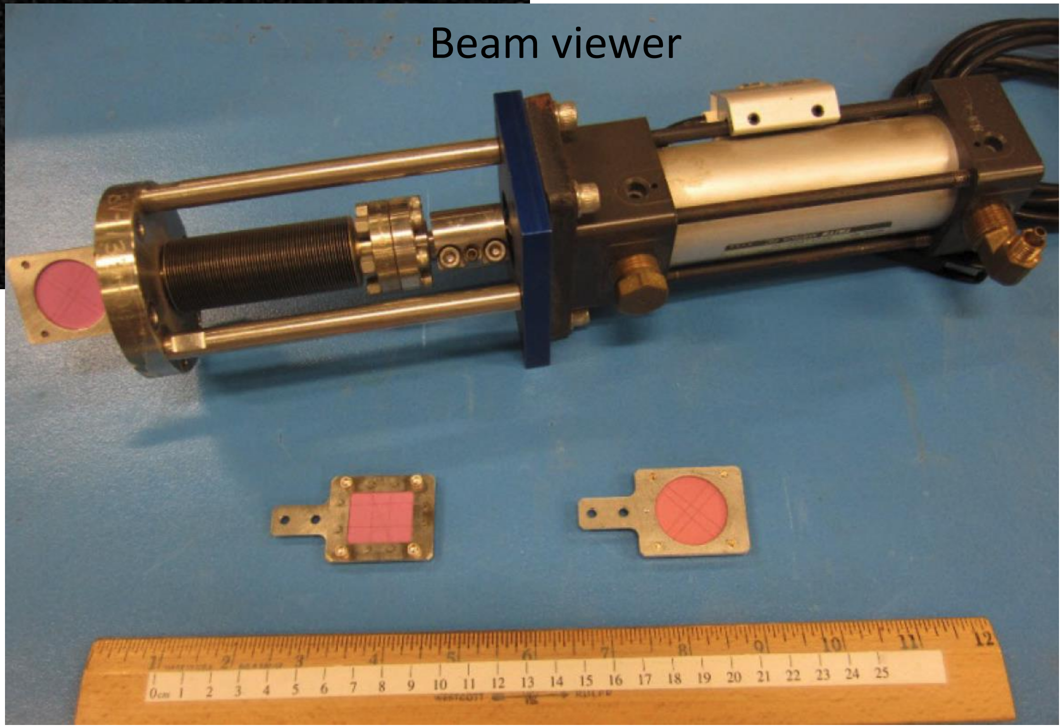


- Inverted CEBAF/ILC Gun#1 installed at CEBAF, July 2009
- Higher voltage, higher lifetime
- 200 kV for CEBAF, 350 kV for ILC

CEBAF Diagnostics







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

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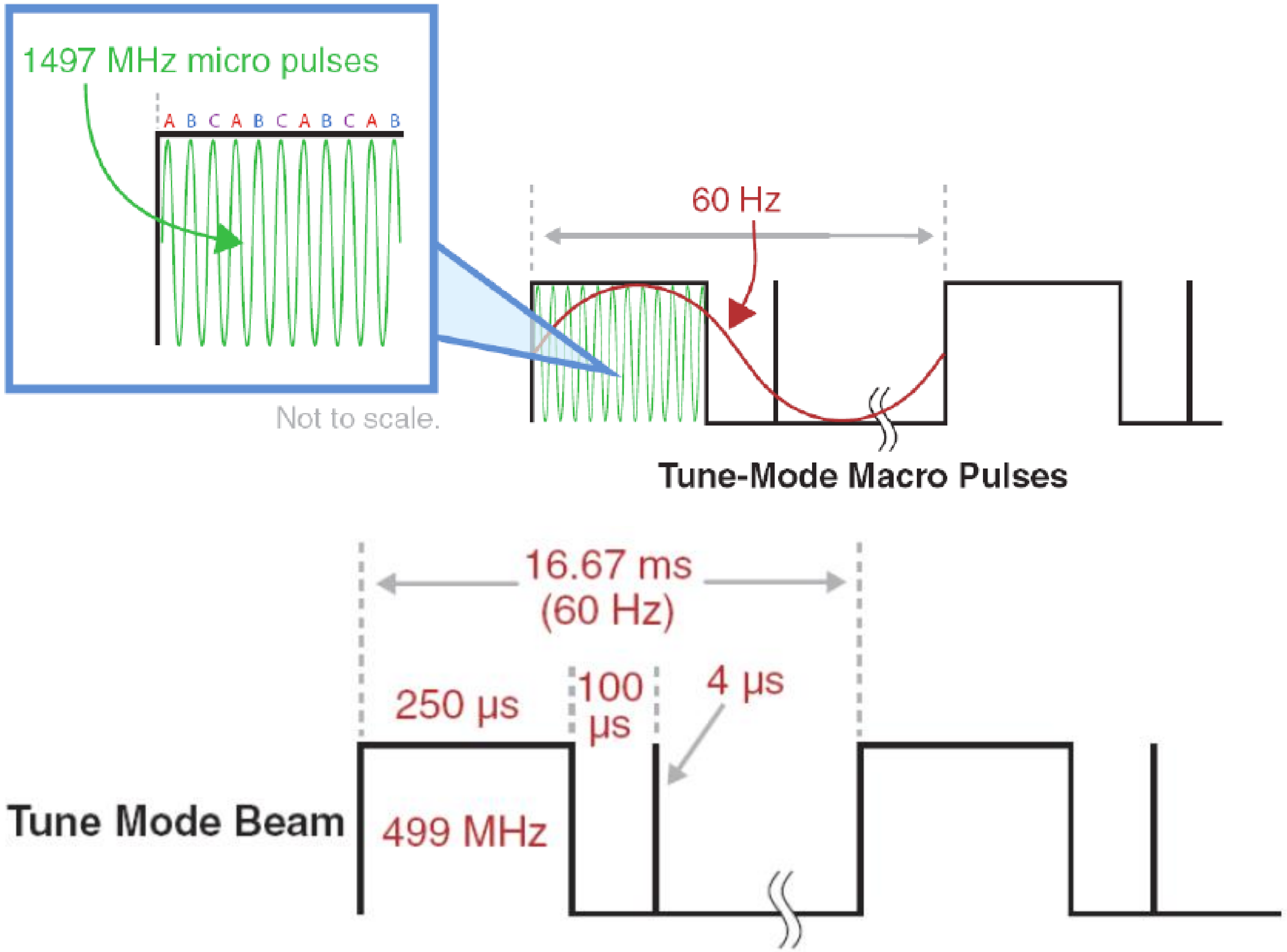
CEBAF Tune Beam

- 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



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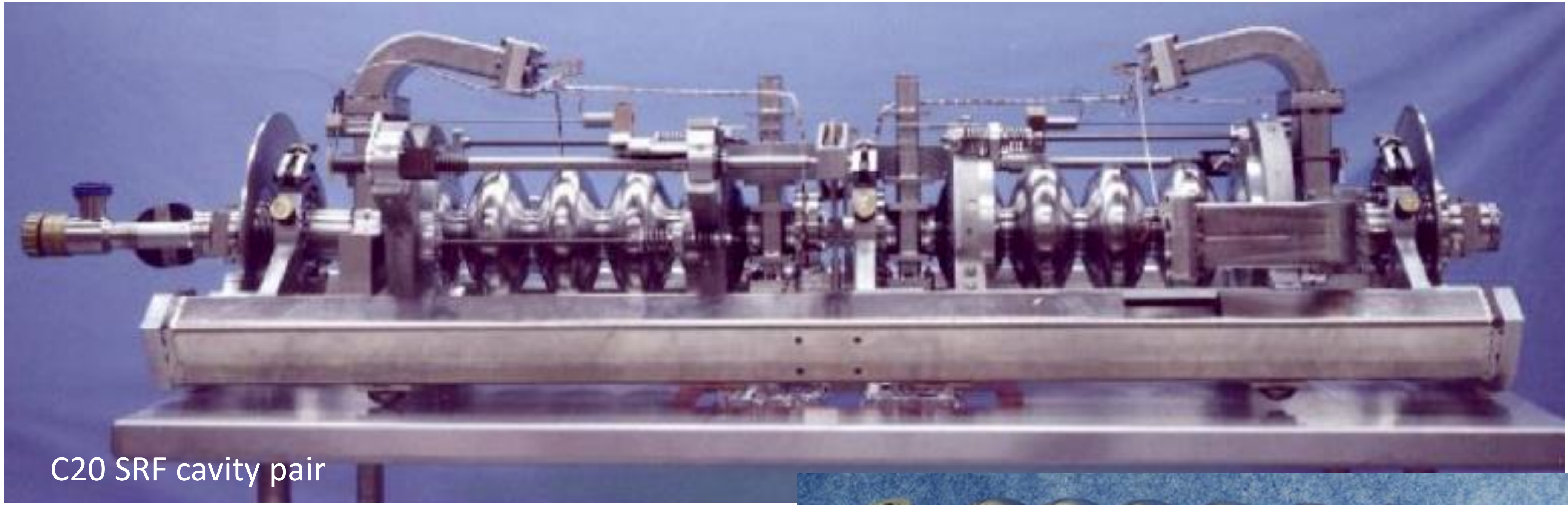
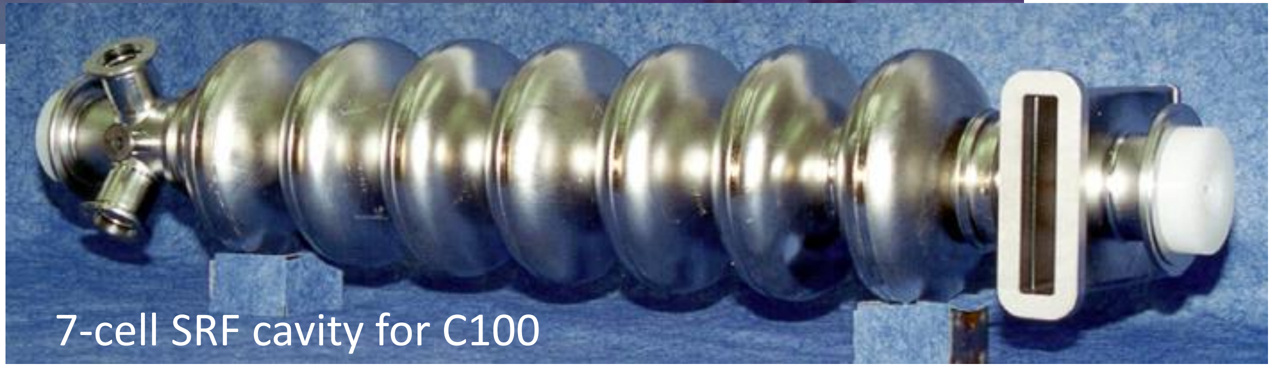
CEBAF SRF cavities and cryomodules



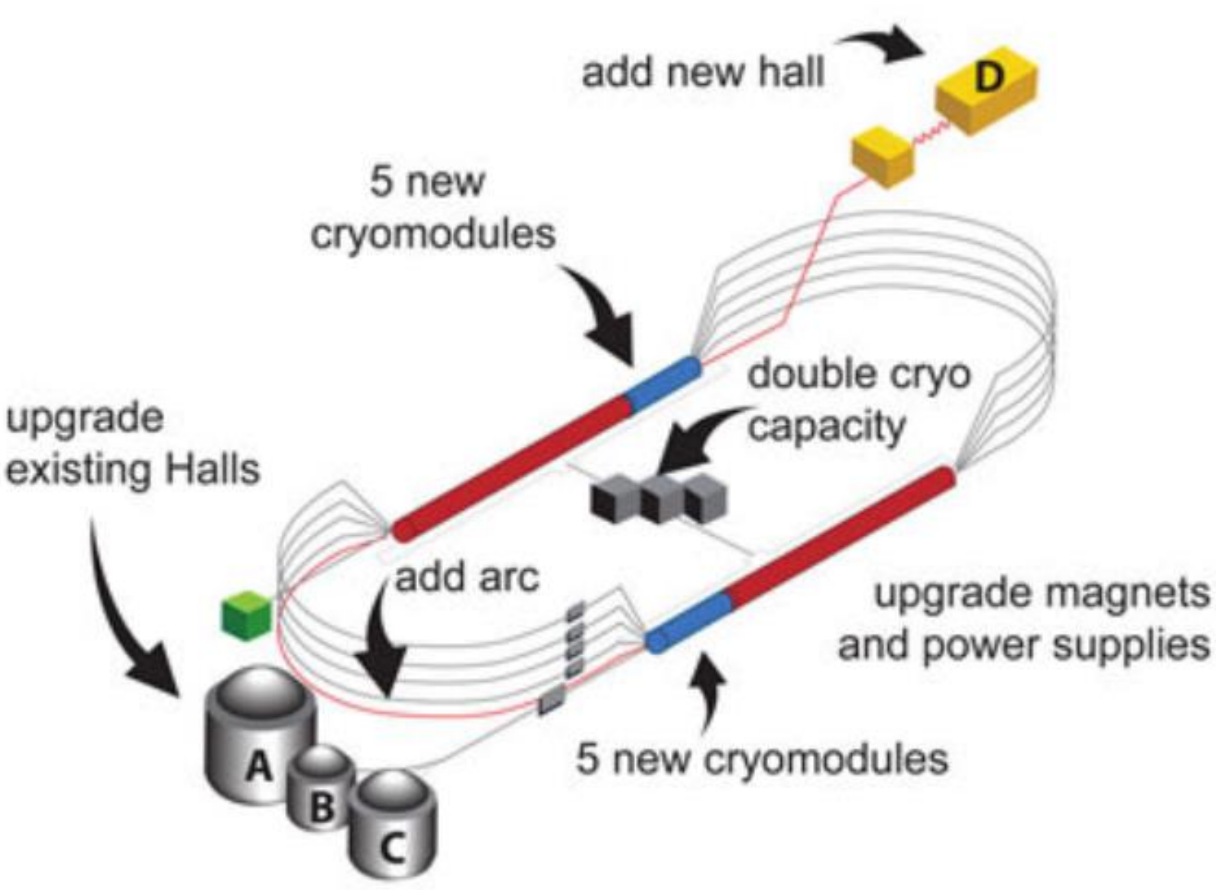
C20 SRF cavity pair



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

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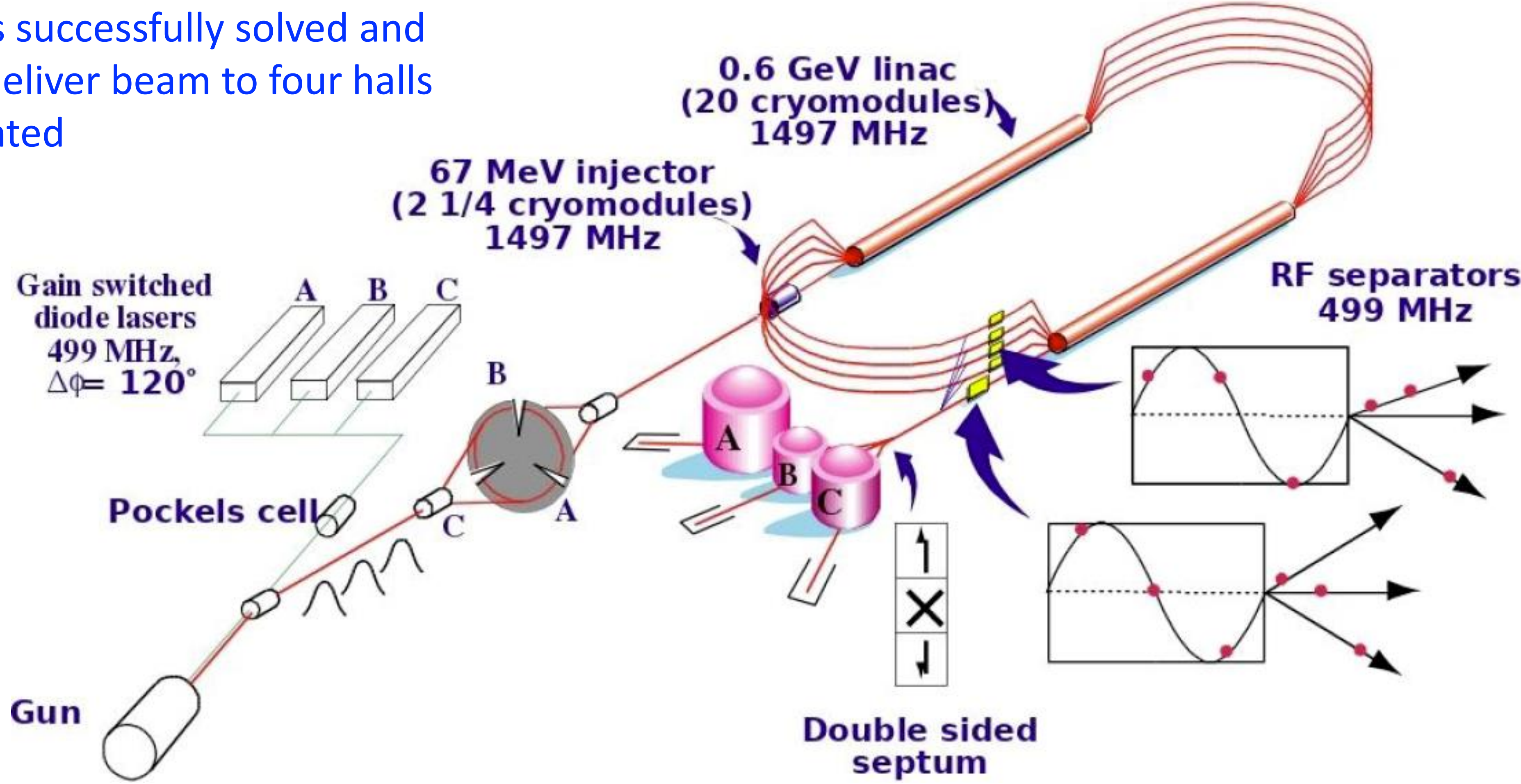
Enabling simultaneous four hall availability in 12 GeV

- 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



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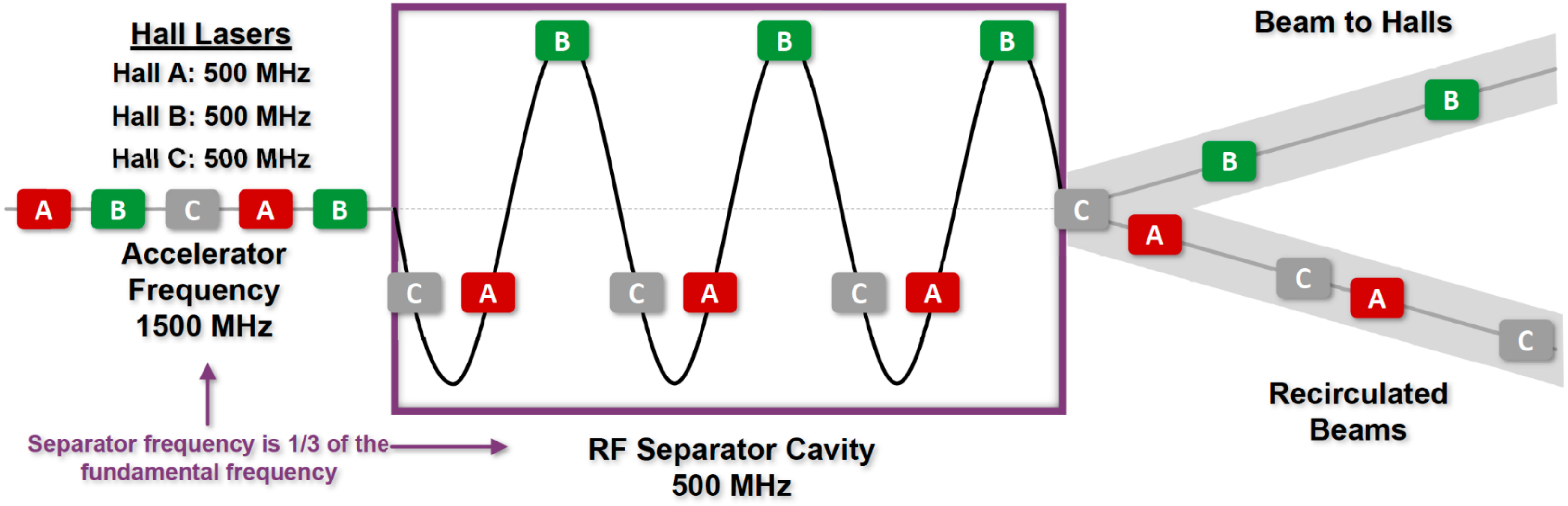
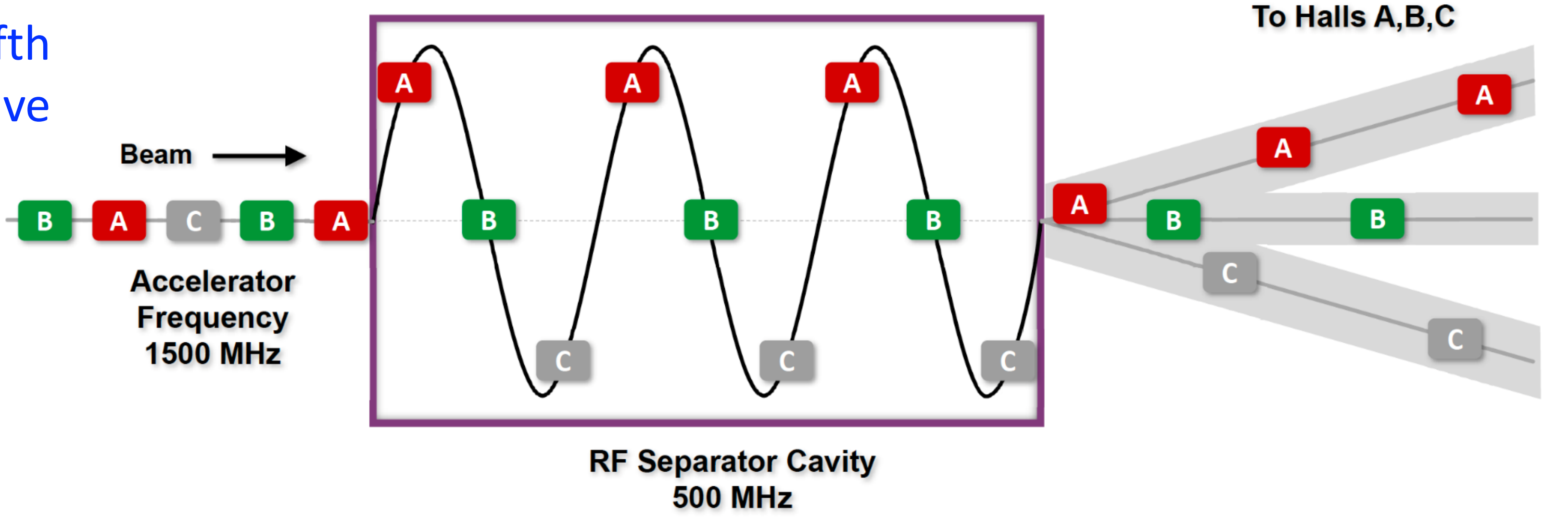
Sending beam to three halls

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



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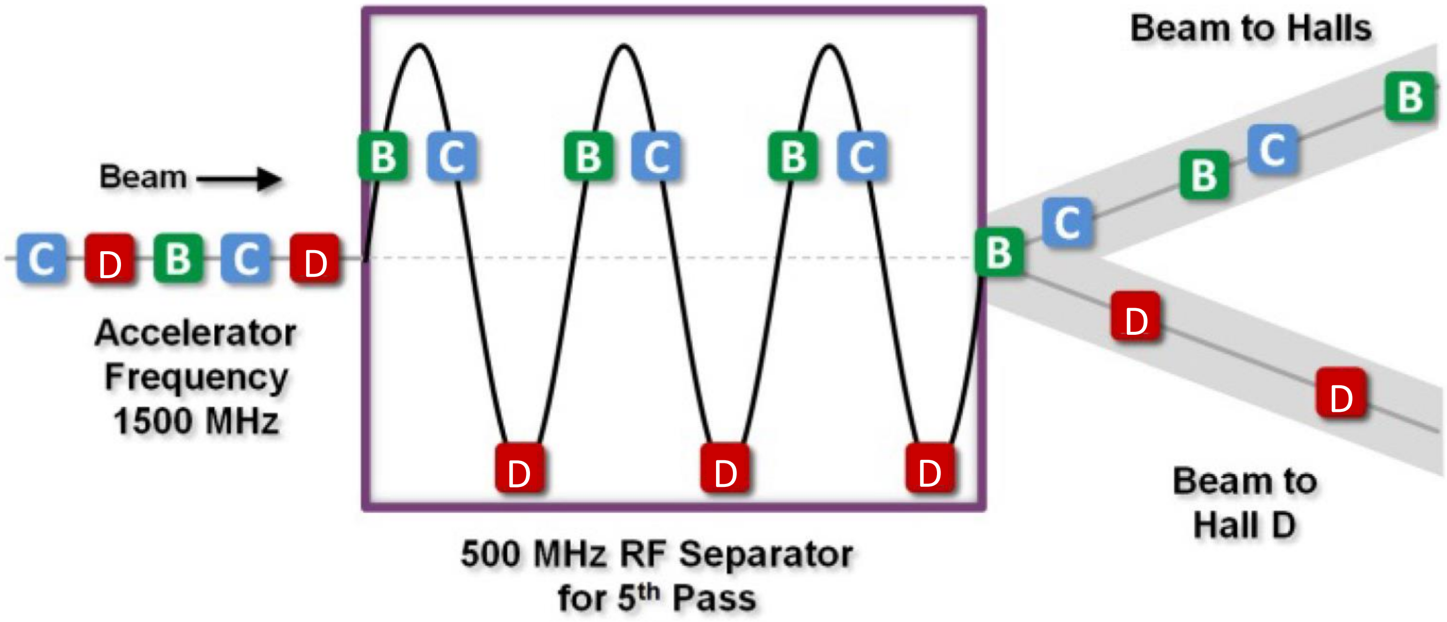
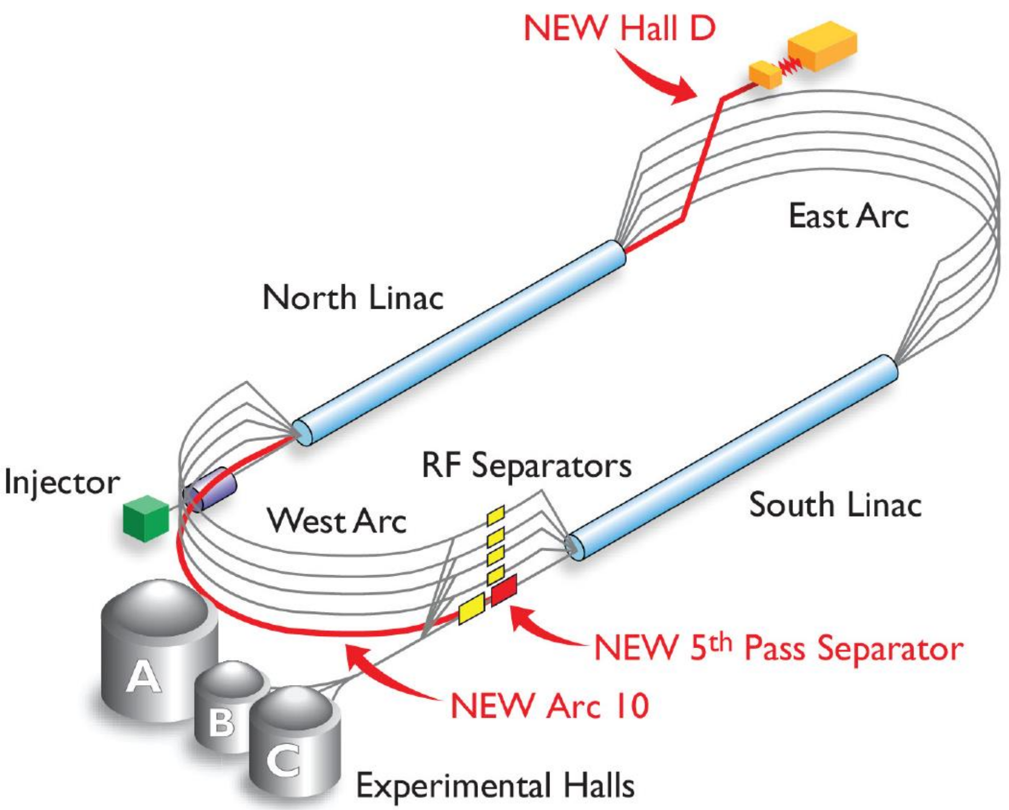
Sending beam to new hall D – the initial idea

- 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

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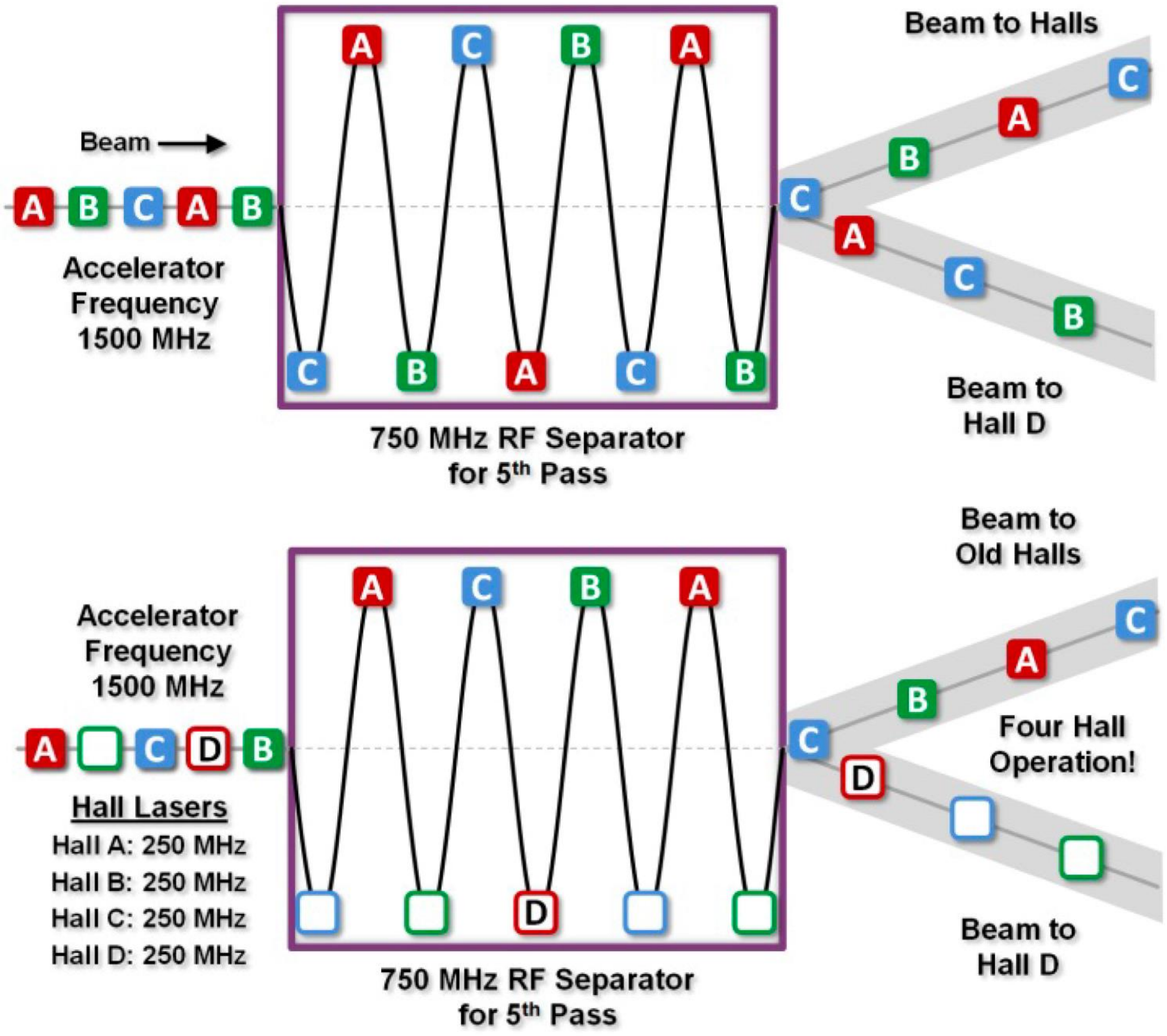
Sending beam to four halls simultaneously

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

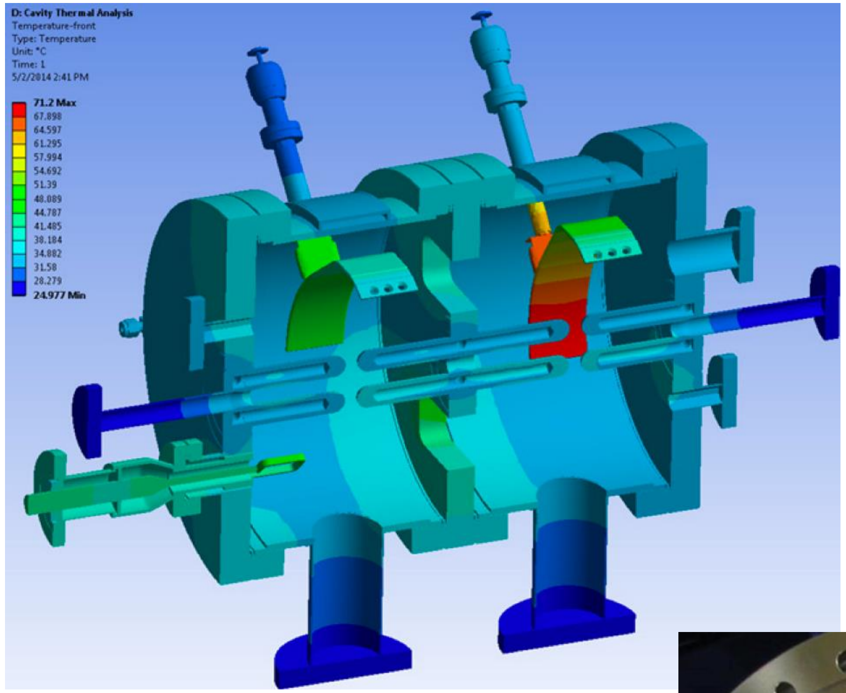
- Empty, e.g., all even buckets, but reduce the laser rate from 500MHz to 250MHz
  - (To keep same current, can double the charge per bunch)

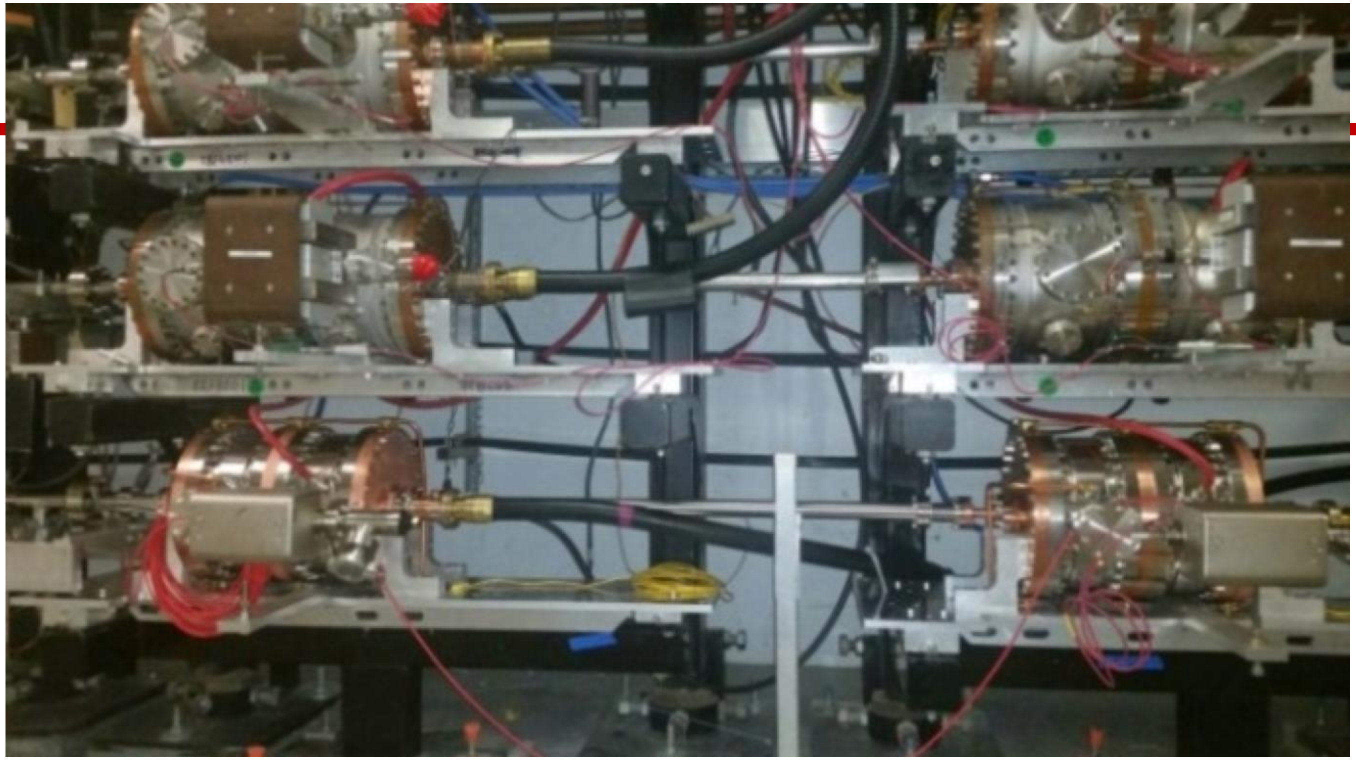
- Fill some empty buckets with bunches for the Hall D

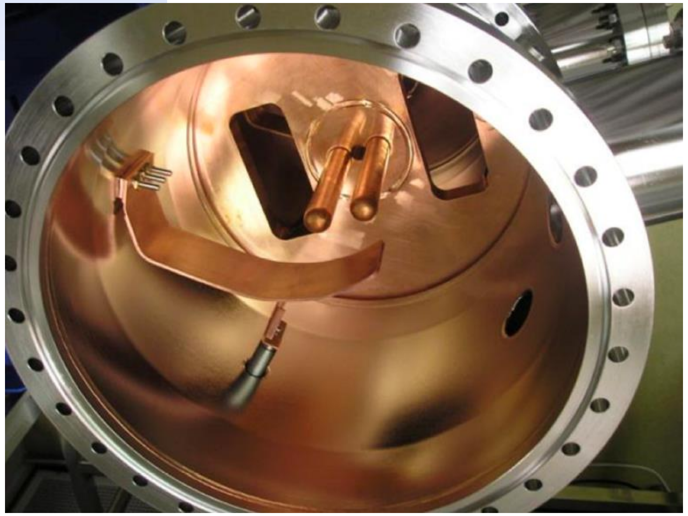


R. Kazimi, IPAC 2013, https://accelconf.web.cern.ch/IPAC2013/papers/thpfi091.pdf

750MHz separator hardware







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

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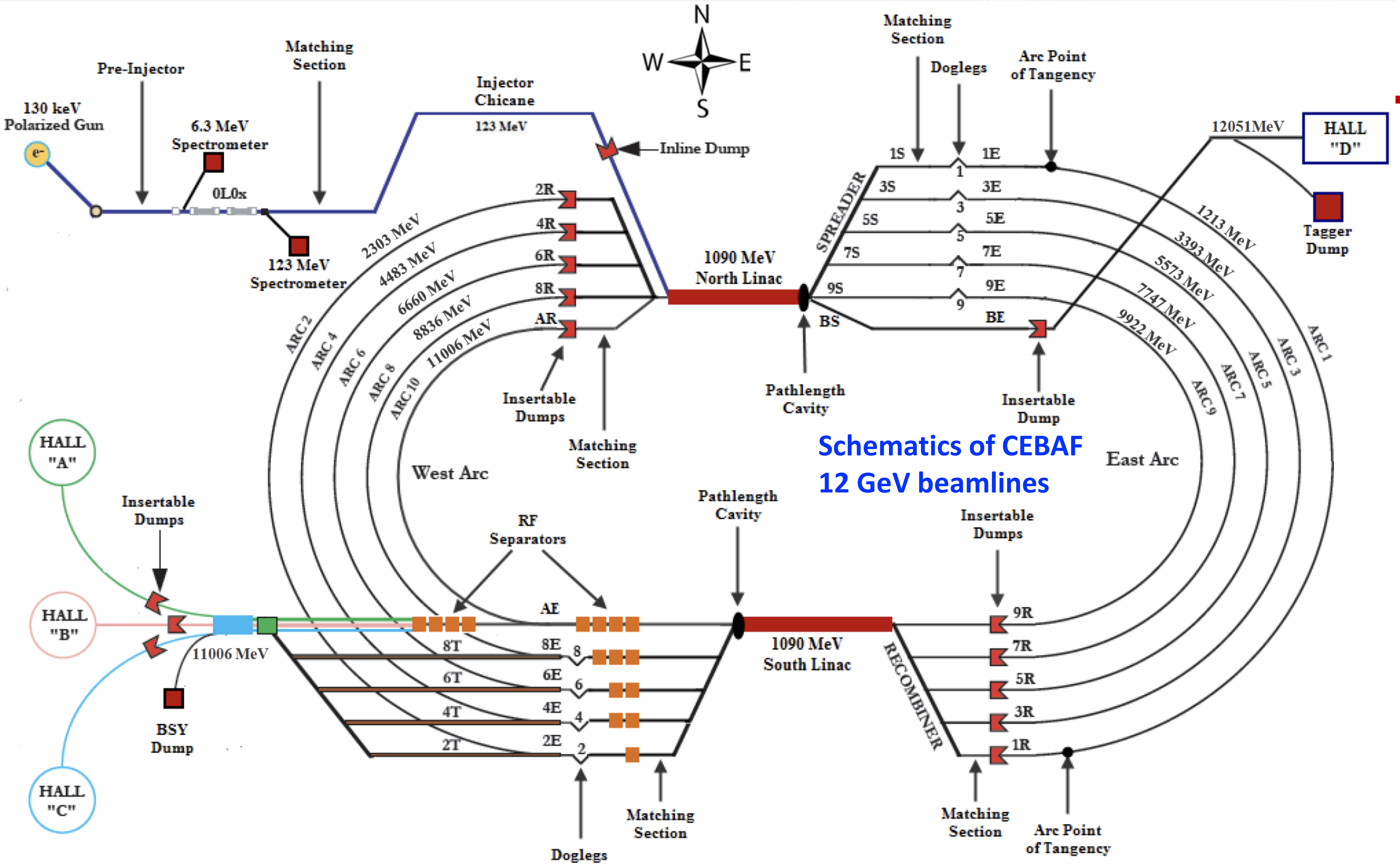
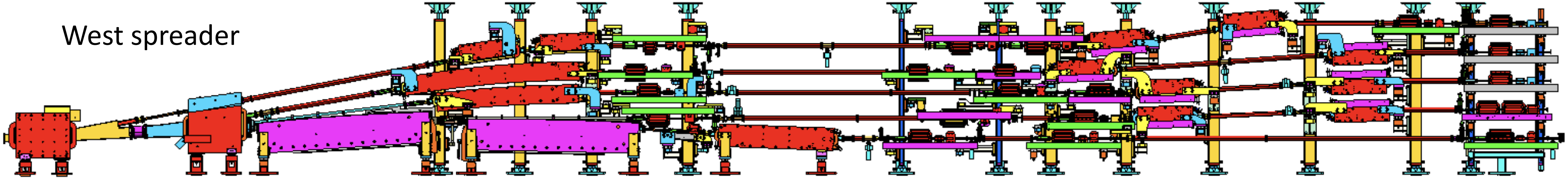
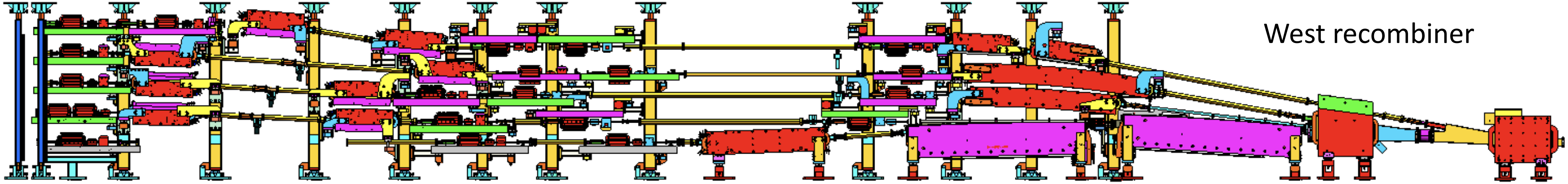


Schematics of CEBAF 12 GeV beamlines

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

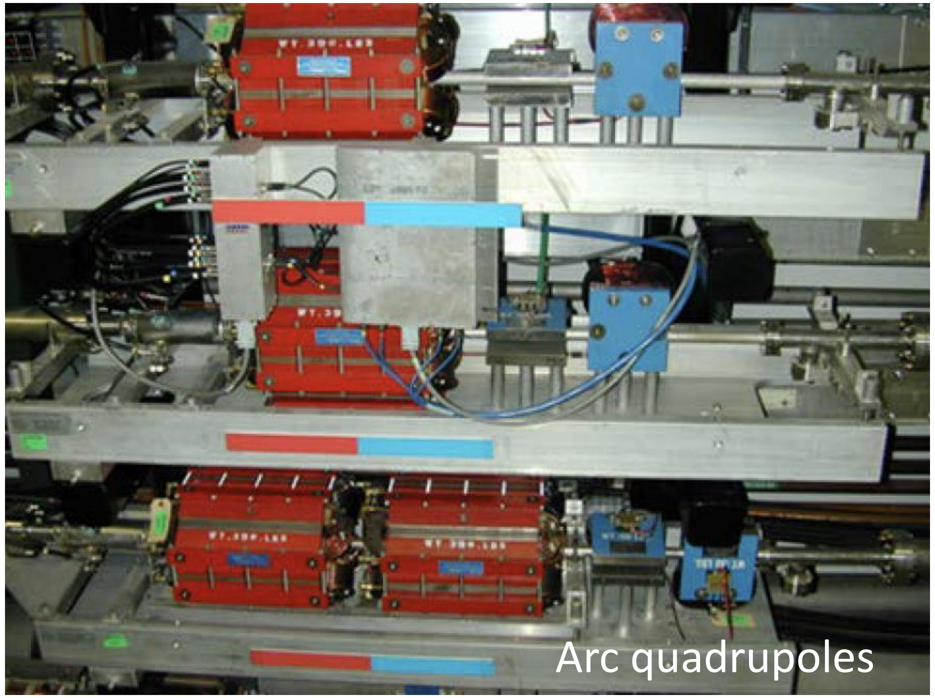




Recirculation arcs

- 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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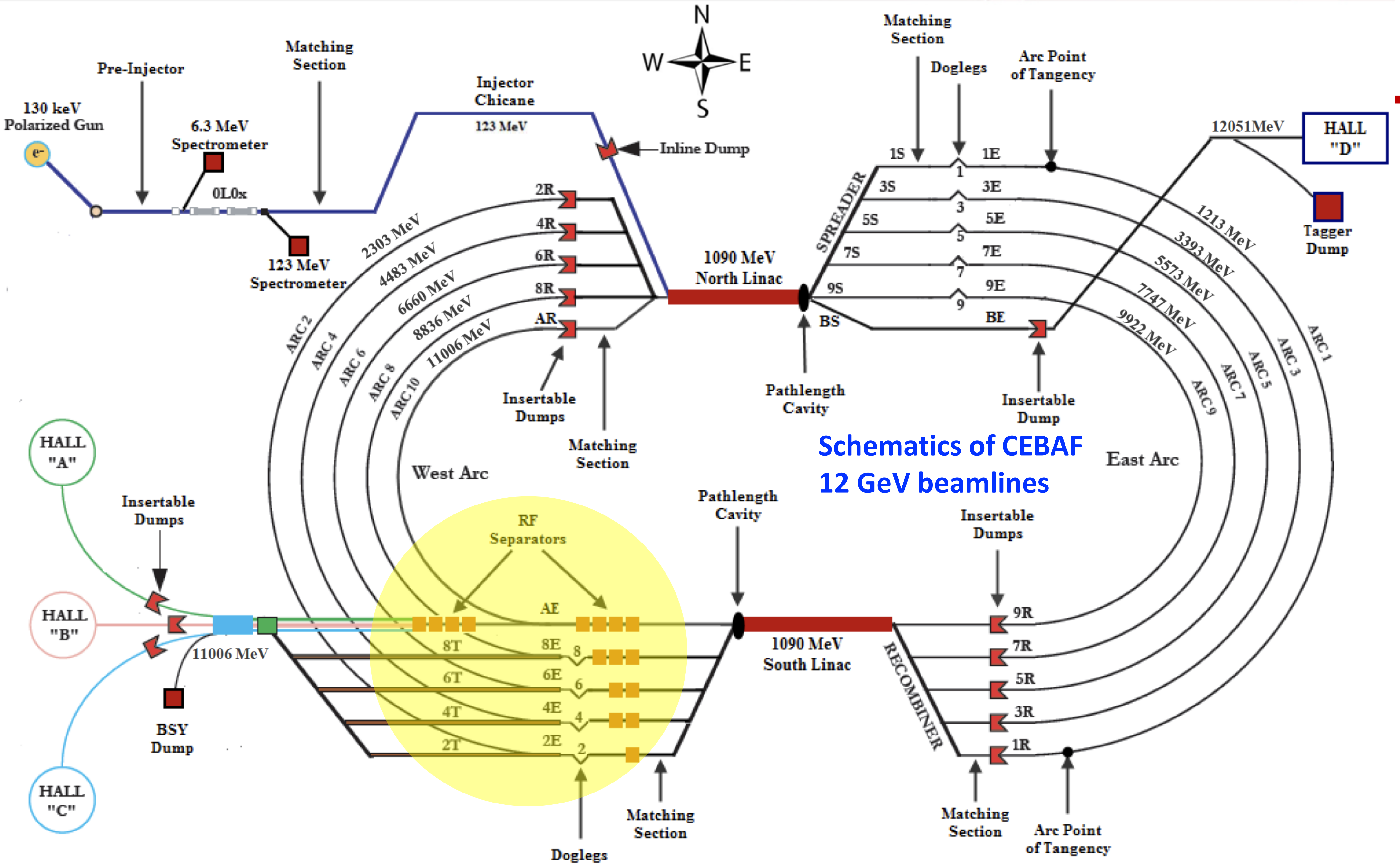

Schematics of CEBAF 12 GeV beamlines

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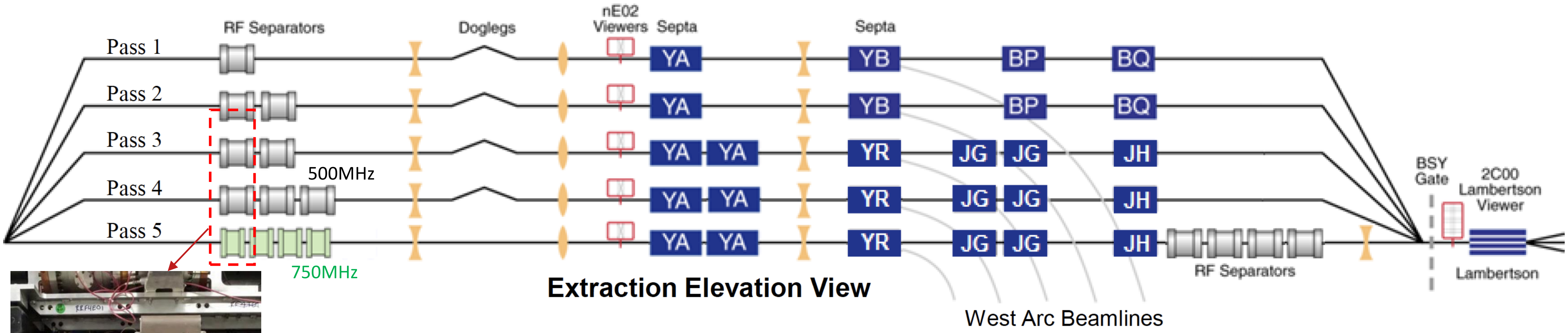
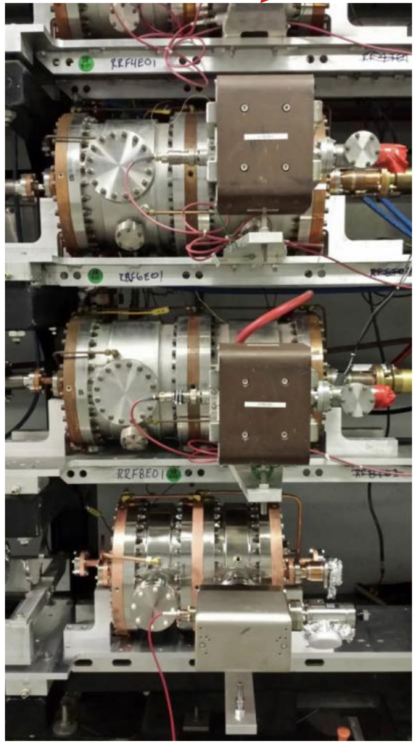
Extraction system

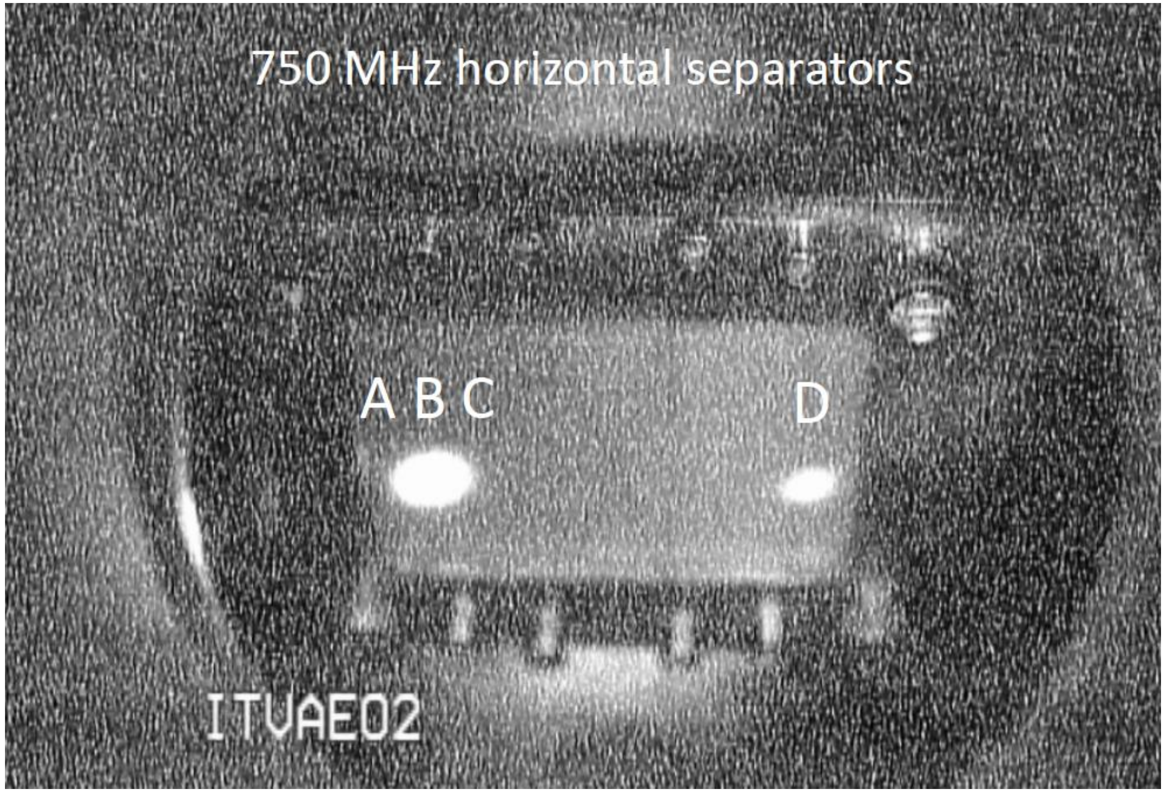




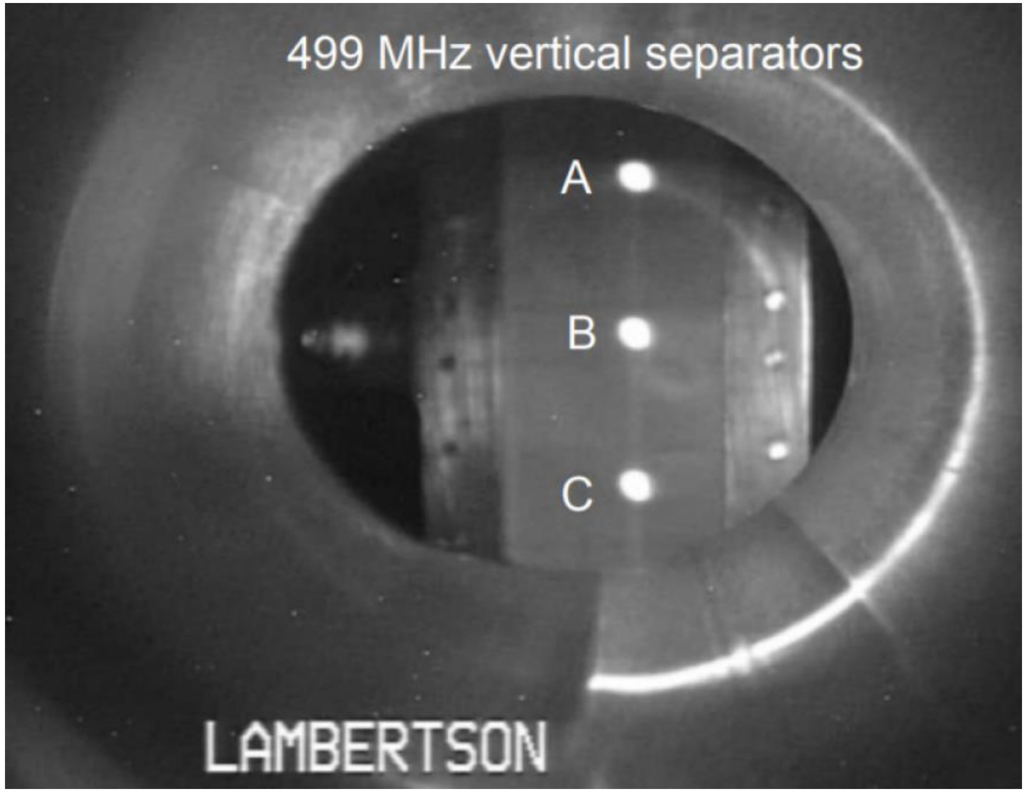
- Horizontal extraction systems at 500 MHz for 1st through 4th pass
- Vertical extraction system at 500 MHz for 5th pass
- Horizontal extraction system at 750 MHz for 5th pass to enable simultaneous four hall operation

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

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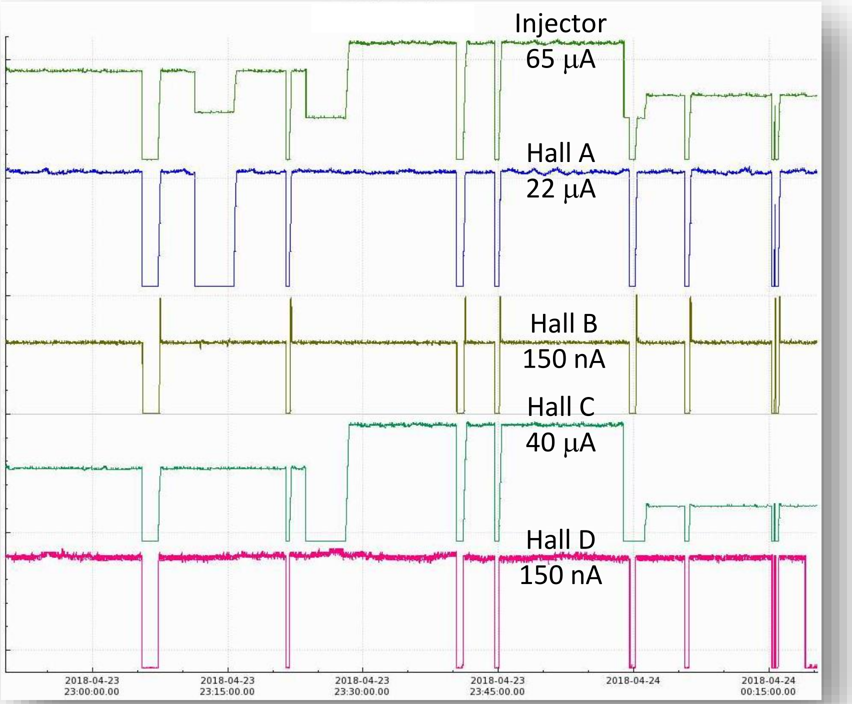
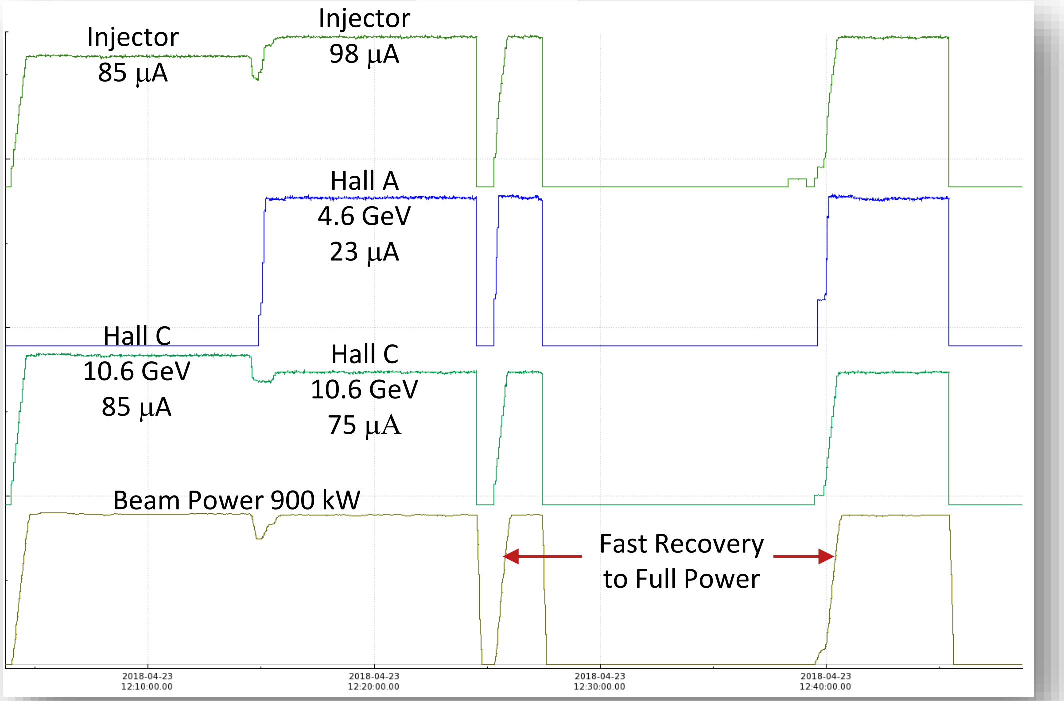
CEBAF four hall operations

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)

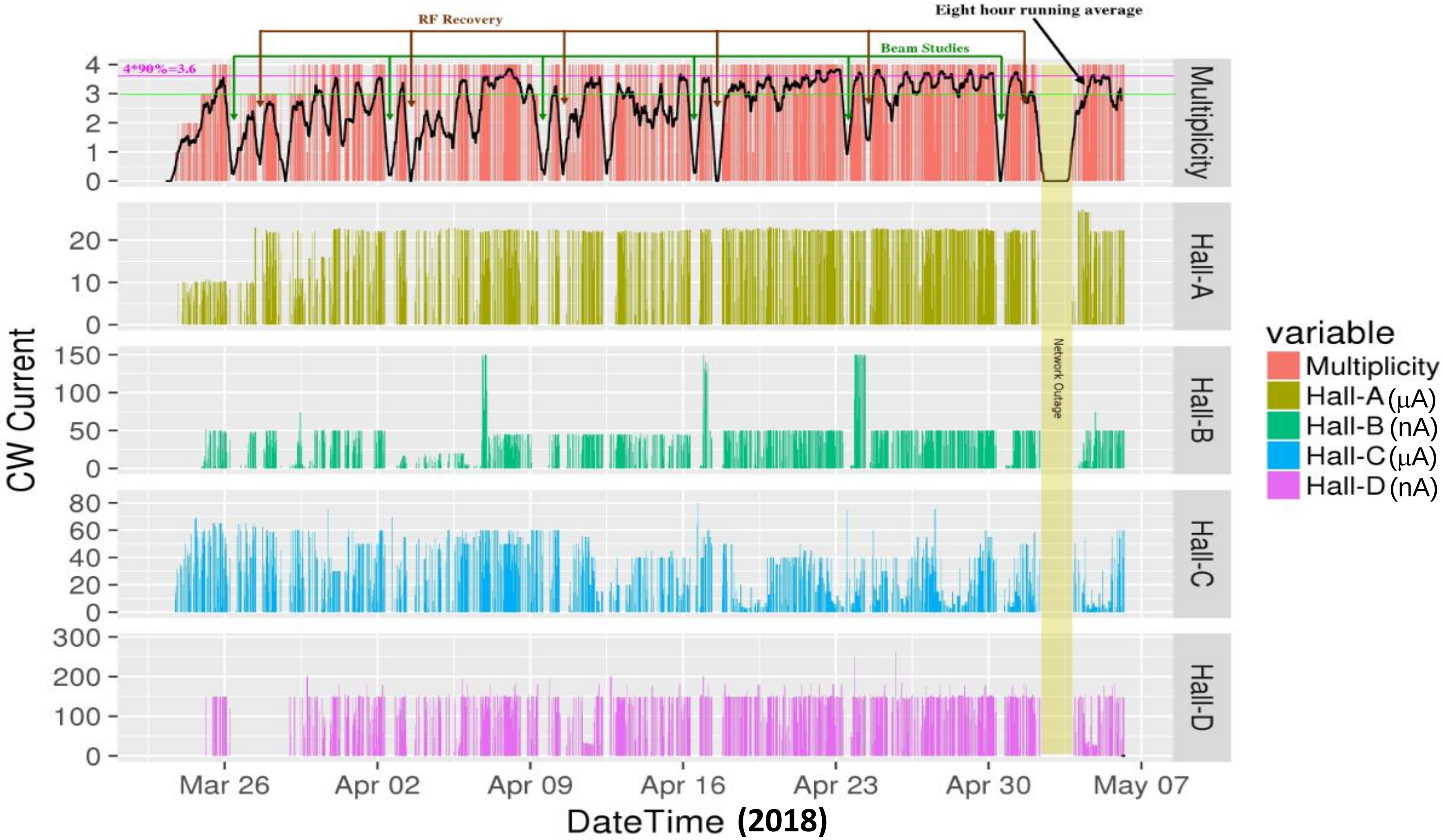


Full Power Beam Delivery (~45 minute time slice)

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



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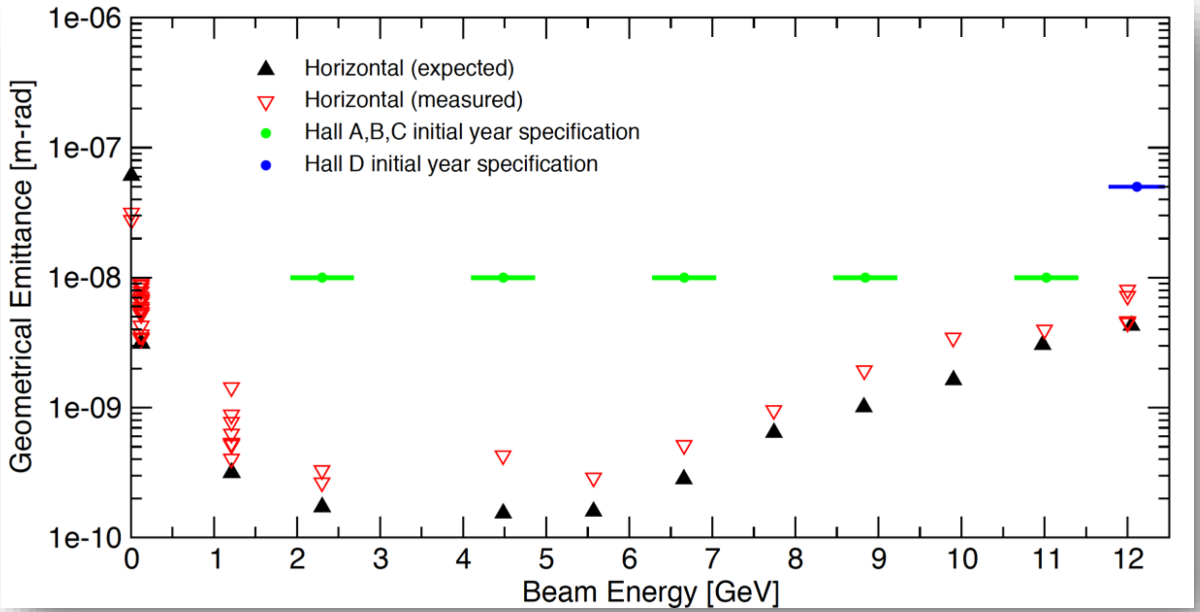
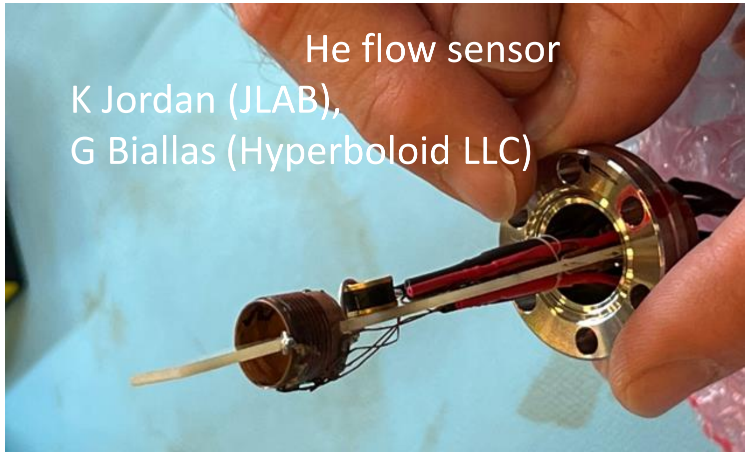
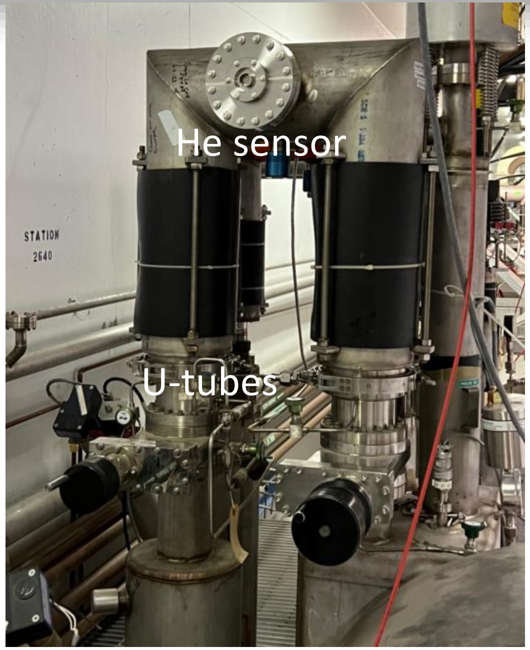
CEBAF beam quality and NP program demands

- Beam performance is meeting specifications for the Nuclear Physics Program
- Increased demands for parity beam quality for future runs and Moller
- Upgraded QCM installed in CEBAF this year
- New diagnostics being developed and tested (BNNT screens, cameras, Liquid He flow meters, NDX neutron monitors)
- 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 Rep. Rate ABC	499 MHz
Nominal Hall Rep. Rate D	249.5 MHz
Geometric Emittance at Full Energy	3nm-rad(X) 1 nm-rad(Y)
Energy Spread at Full E	0.018%
Polarization	>85%

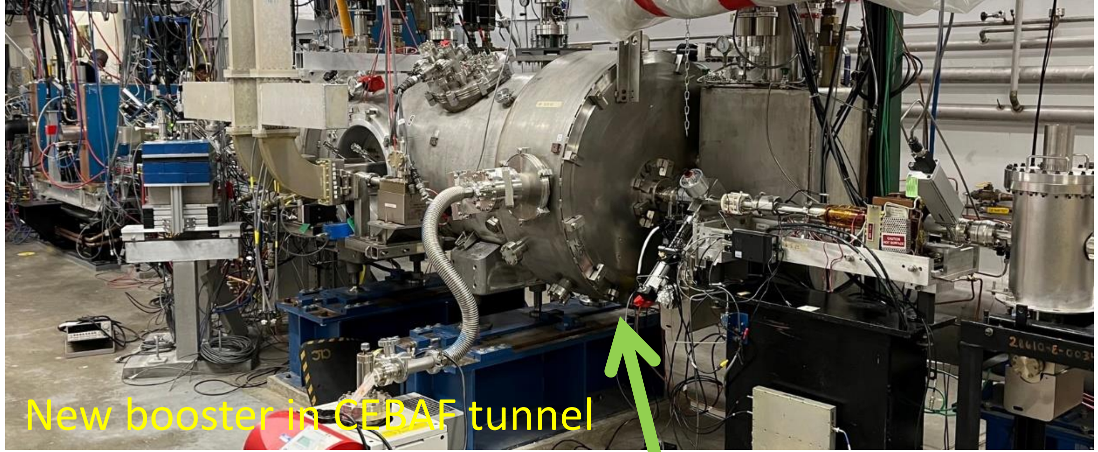


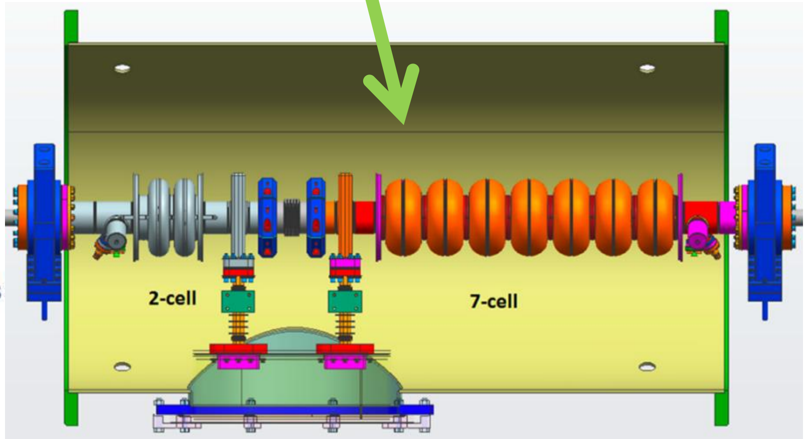


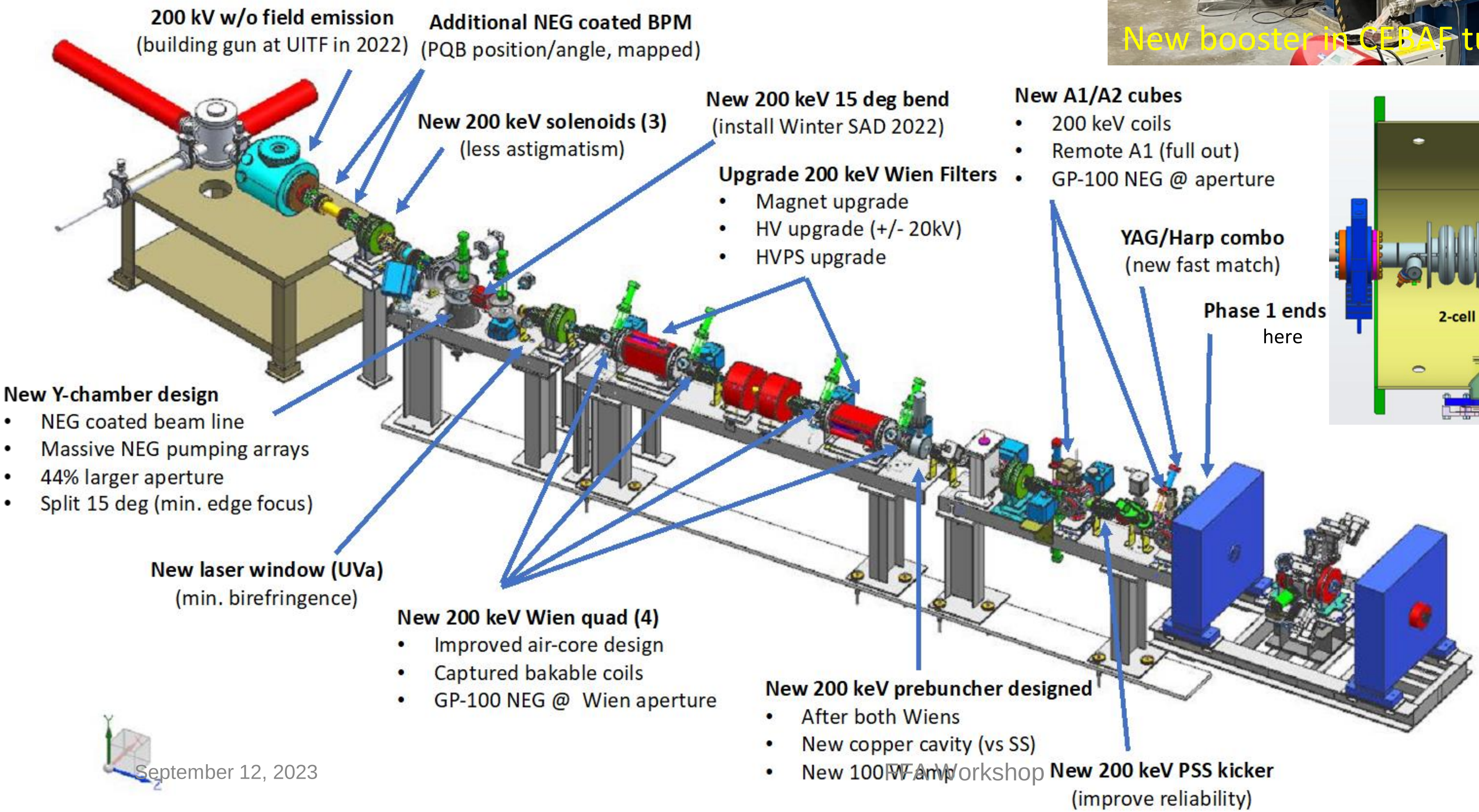


BNNT – Boron Nitride NanoTube

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







CEBAF operations and CPP

- CEBAF operations:
  - Typical run: 32 weeks per year
  - Scheduled downtime ~3 months
- CPP project – CEBAF Performance Plan
  - Efforts on improving reliability and increase of the energy margin
- CPP energy reach:
  - 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
  - Developed plasma processing of CMs for their in-situ cleaning


Original CEBAF (OC)
C75 Cavity (HC- High Current) made from Ingot Niobium


C100 CM being refurbished


C100 cavity with argon-oxygen plasma in each of 7 cells

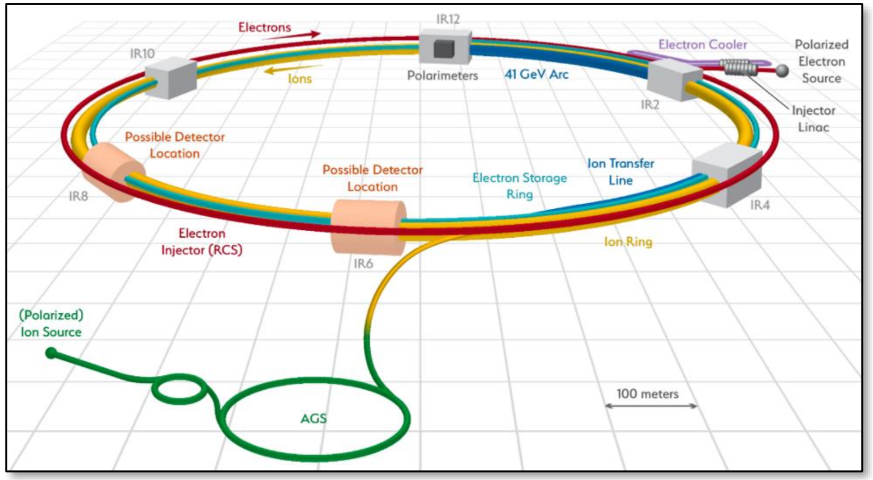
Recent ISO9001 Certification
Variety of cryomodules types in JLAB SRF Institute

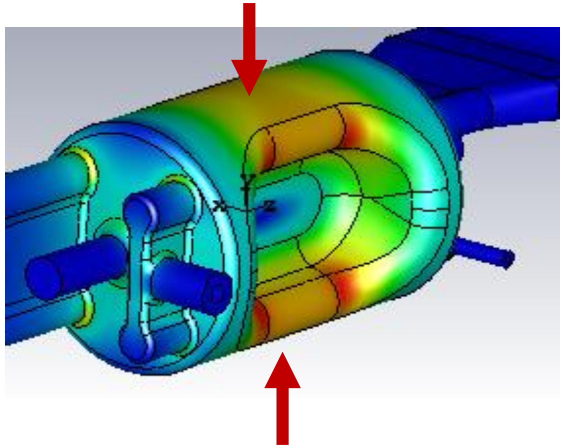

C100 in-situ plasma processing


C100 in-situ plasma processing

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 & operation
  - SRF – based on our world leading expertise
  - ERL – based on world-record ERL-based FEL
  - Cryo and magnets – based on our ops. & design expertise
  - 2nd IR design, etc. – based on our collider design expertise
- CEBAF upgrade will create complementary to EIC experimental program, boosting NP science portfolio



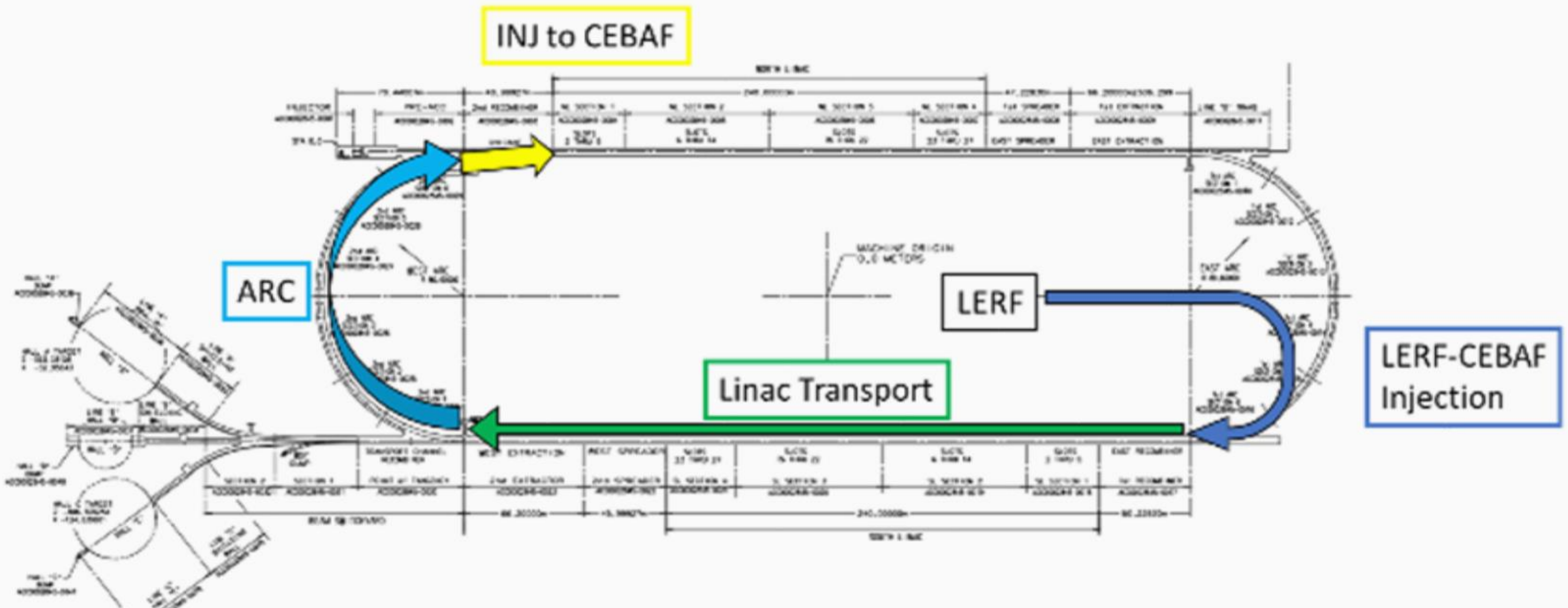


Crab cavity tuning mechanical analysis

Jefferson Lab Accelerator Upgrades, the 'Big Picture'

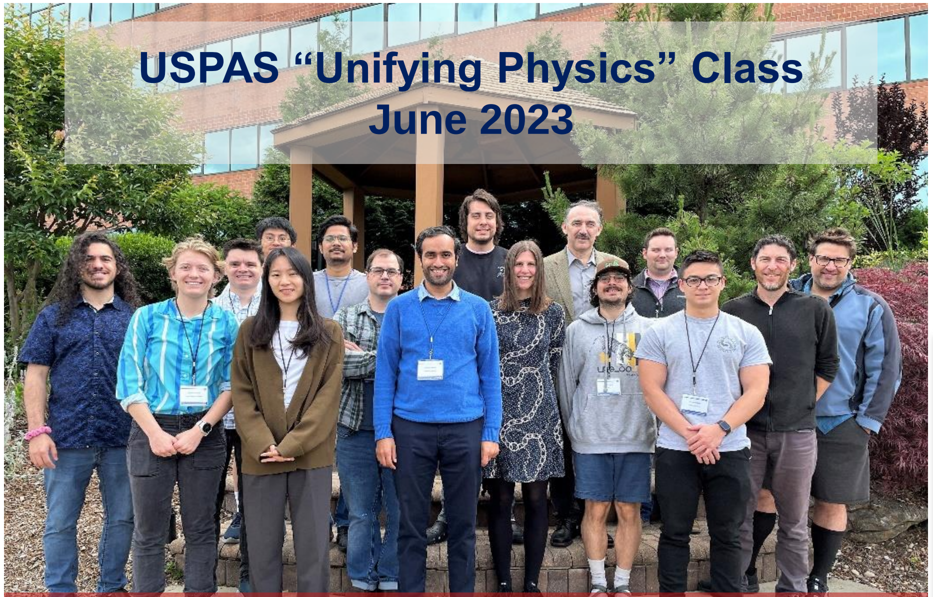
Capitalizing on recent science insights and US-led accelerator science and technology innovations, develop a staged program at the luminosity frontier

- 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



Thia Keppel "JLab upgrade perspectives", at Town Hall Meeting on Hot & Cold QCD, Sep, 2022, https://indico.mit.edu/event/538/

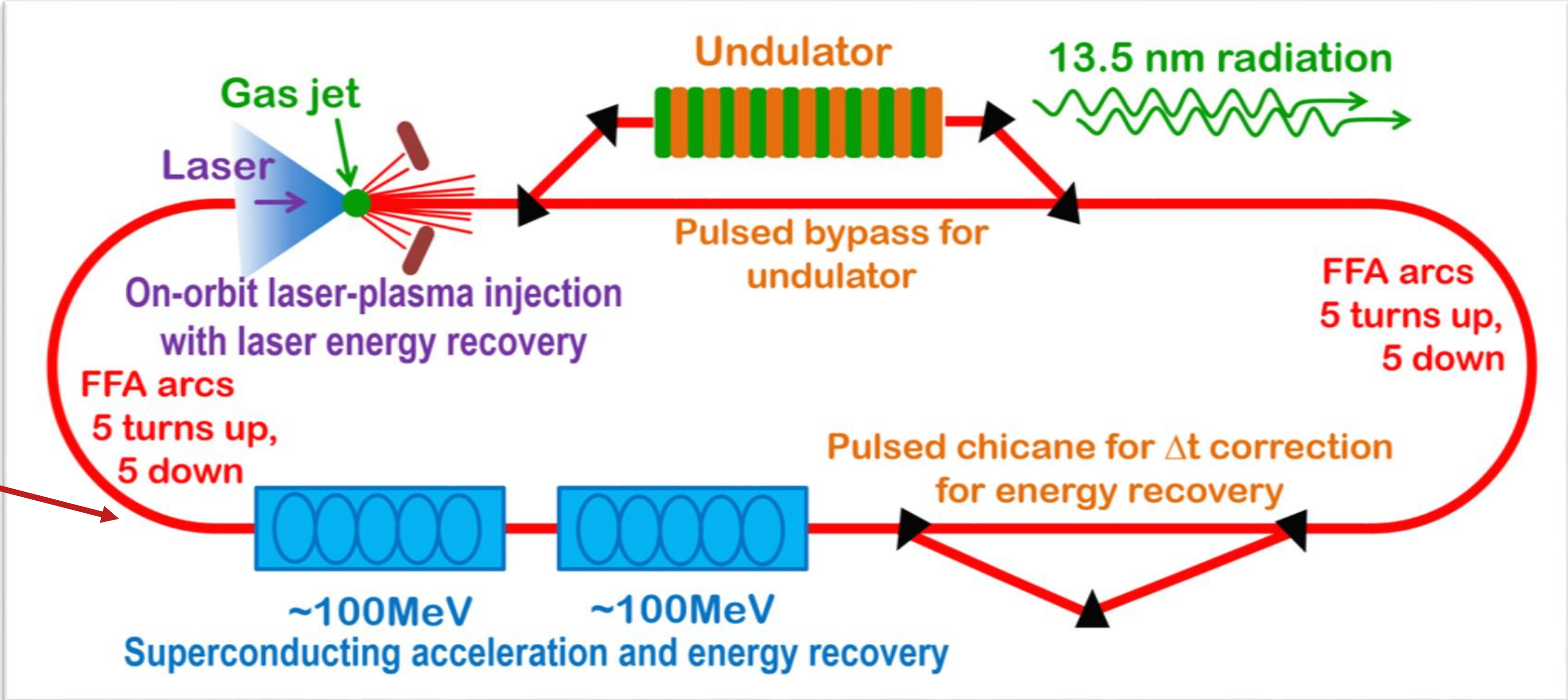
CEBAF and CEBAF 22GeV are inspiring new ideas



Left to right: 1st row: Parker Landon, Hyojeong Lee, Ganesh Tiwari, Bryan Belcher
2nd row: Eiad Hamwi, Jared De Chant, Charles Rohde, Marlene Turner, David Garcia, Erel Milshtein
3rd row: William Fung, Sridhar Tripathy, James Maslow, Andrei Seryi, Spencer Kelham, Matthew Meengs

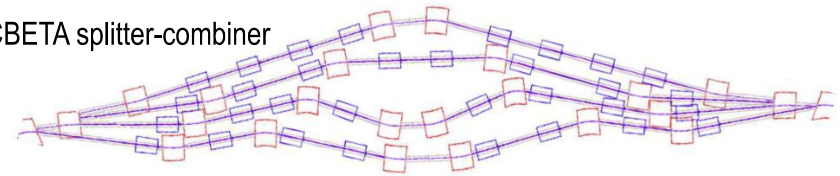
Mini-Project 3 - Compact recirculation-FFA-ERL-based 13.5 nm FEL with on-orbit laser-plasma injection with energy recovery

In a week, students were able to define main parameters of this conceptual design, making several improvements and inventions on the way



Note that there are no splitters-combiners. Student were tasked to avoid them, via making turn-to-turn phase shift small, or to make it equal to RF wavelength

CBETA splitter-combiner



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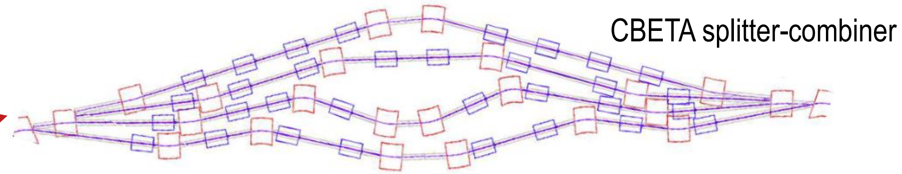
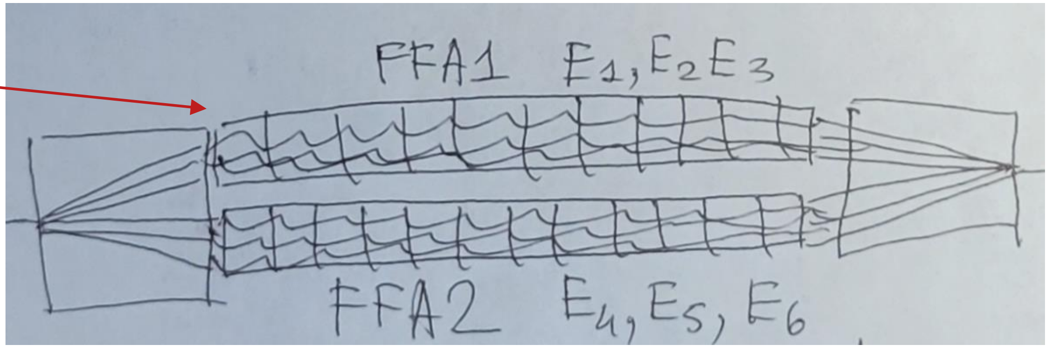
CEBAF and CEBAF 22GeV are inspiring new ideas

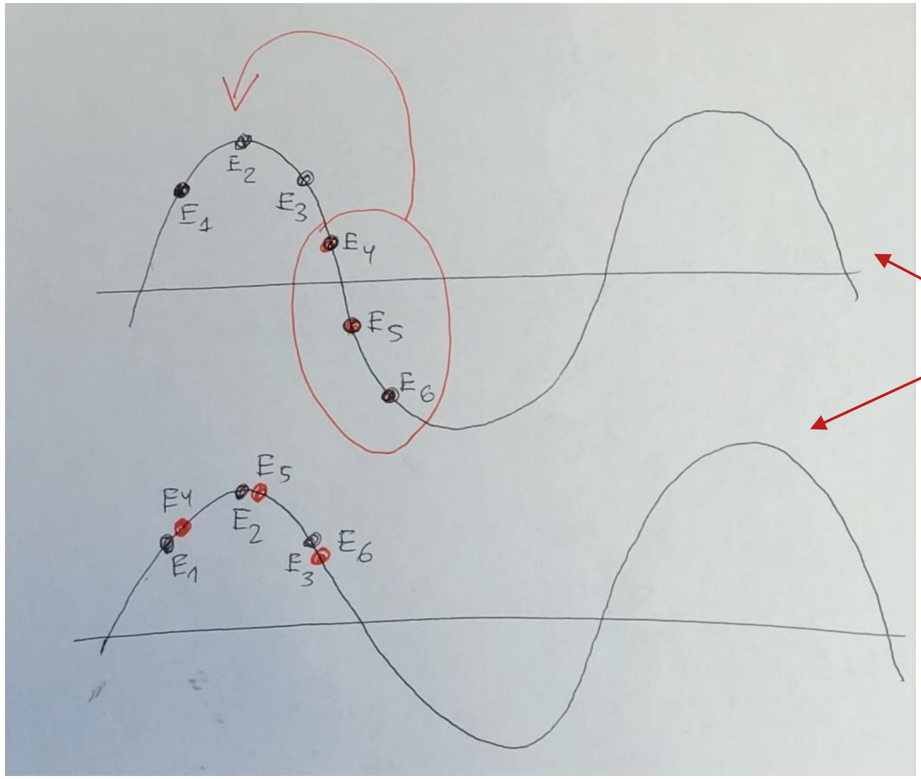
USPAS-2023 and CEBAF 22 GeV inspired the following question:
Is it possible to change the approach to splitters-combiners?



Instead of classical splitter-combiner with individual orbits,
use splitter-combiner with two FFA groups of orbits of different energy



Examples for 6 turns FFA arcs



The two-FFA-groups splitter-combiner would allow to shift the phases of the orbits 4, 5, 6 back to the accelerating phase of RF

Since FFA optics inside of such splitter-combiner is strong, this approach may offer the following benefits:

- more compact design in comparison with standard approach
- lower curly H and lower SR emittance growth
- easier Twiss matching into strong focusing FFA arcs

This is a concept. Question to experts – is it feasible? Can it be designed? Disadvantages vs benefits?

Summary

- CEBAF provides unique opportunities for nuclear physics studies
  - 12 GeV upgrade completed in 2017
  - Four halls running simultaneously since January 2018
- We welcome everyone to FFA 2023 Workshop, and looking forward to further develop the design for CEBAF 22 GeV FFA upgrade
- Looking forward for fruitful discussions!

Thank you!