CEBAF Operations Overview

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2024 JLAAC Review

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

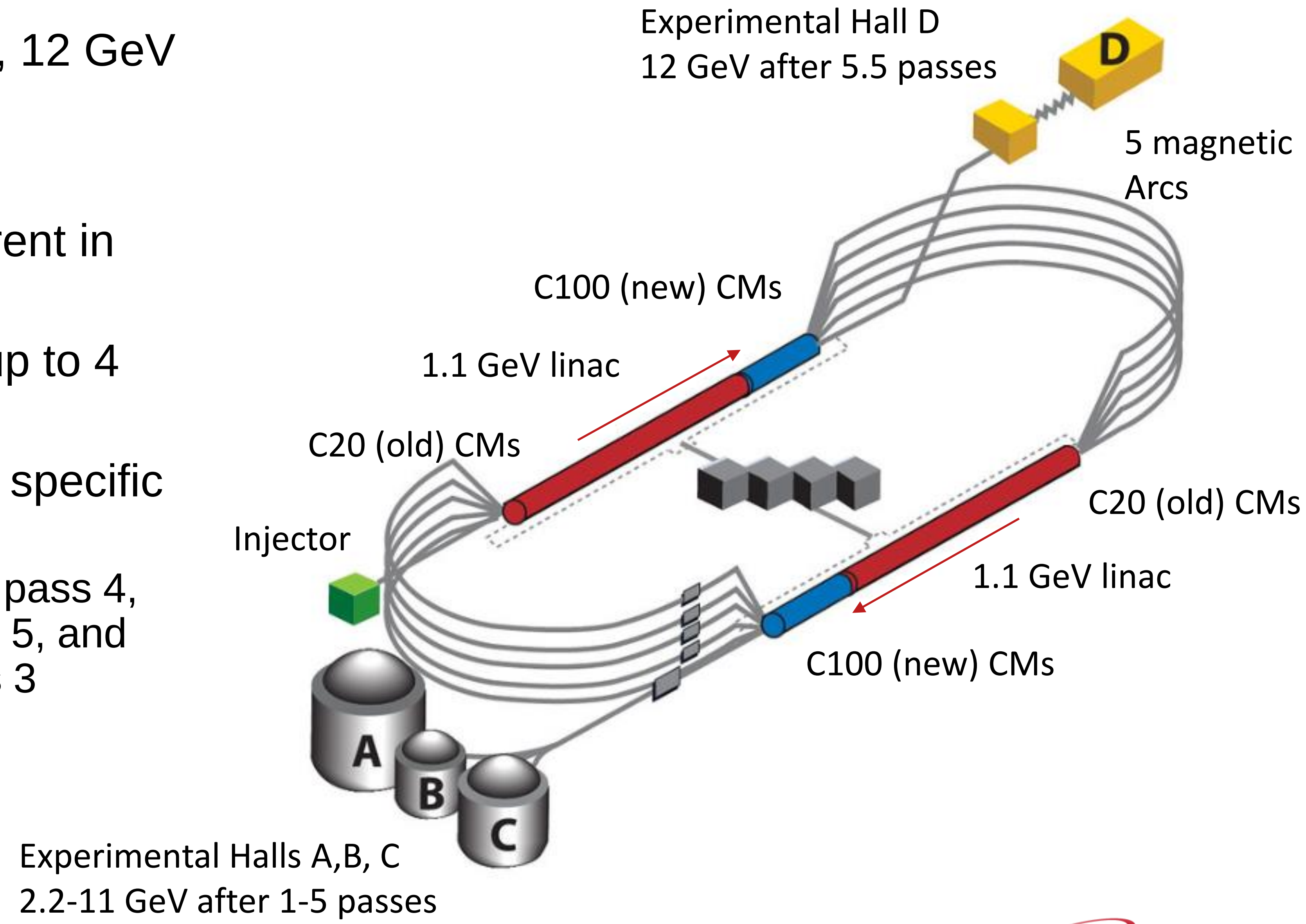
Outline

- Introduction
- Status of Accelerator Operations
- Sources of beam downtime and performance limitations
- CEBAF Performance Plan
- Accelerator Improvement Projects (AIPs) and R&D portfolio
- Operations staffing
- Accelerator Operations risks
- Summary

This presentation answers charge questions 1 and 3

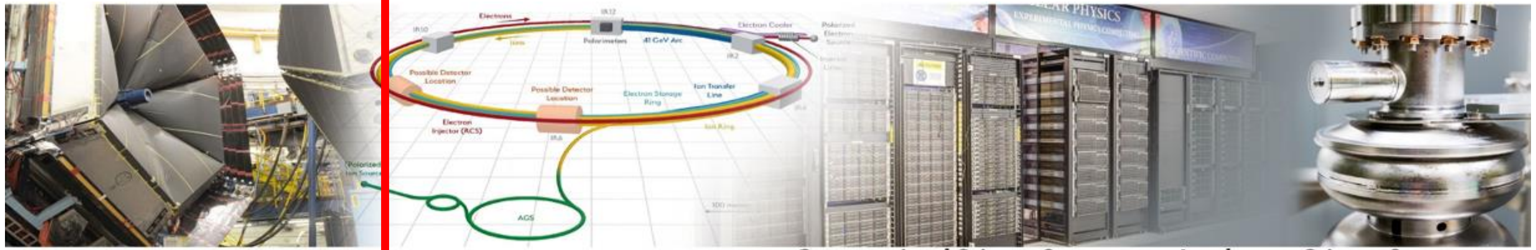
CEBAF Accelerator

- SRF, recirculating, 5.5 pass, 12 GeV Linac
- Beam power up to 900 kW
- Total recirculated beam current in the linac up to 450 uA
- CEBAF can provide beam up to 4 Halls simultaneously
- Beam can be extracted to a specific Hall at any selected pass
  - e.g., Hall A can operate at pass 4, Hall B can operate at pass 5, and Hall C can operate at pass 3



Alignment with Lab’s Mission and Long-Range Plan (LRP)

- **LRP Recommendation 1:** Capitalize on the extraordinary opportunities for scientific discovery made possible by the substantial and sustained investments. Continue effective operation of national user facilities, including CEBAF at TJNAF



Nuclear Physics at CEBAF

Vibrant 12 GeV research program, operating >30 weeks/yr, supporting > 1,800 users

MOLLER Project & SoLID proposal

Future opportunities in fixed-target, high-luminosity complementary to EIC

Theory and computation supporting NP goals

Electron-Ion Collider

Partnering with BNL in the management, design, and construction of the Electron-Ion Collider Project

Leadership in EIC scientific program

Computational Science & Technology

Vision for world-leading computational program

Developing concept of a High Performance Data Facility focused on the unique challenges and opportunities for data-intensive applications and near real-time computing needs

Computational Nuclear Physics

Accelerator Science & Technology

Accelerator component production for DOE/SC projects, including LCLS-II and LCLS-II-HE at SLAC, and SNS-PPU at ORNL

R&D in accelerators, detectors, isotopes

Adapted from S. Henderson’s all-hands presentation 07/2023

- Operate CEBAF for Nuclear Physics for >30 week/yr. for >1800 users
- Support upcoming 12 GeV experimental program (MOLLER, SoLID, K-Long)

Scope of Accelerator Operations

- Operations of CEBAF Accelerator, Real Time Support and Repair (RSR)
  - MCC (control room operator) group
  - Software/EPICS controls group
  - Labor and material required to operate and maintain CEBAF accelerator systems, e.g., RF, magnets, instrumentation. It can include some development.
    - Scope and budget are planned by system owners yearly in collaboration with Operations.
  - Does not include power and other utilities
  - FY2024 Budget $18.8M, labor 121 FTE, material $2.24M
- CEBAF Performance Plan
  - CPP Reliability, critical spares, obsolescence. FY2024 Budget is $2.76M.
  - CPP Energy Reach (cryomodule upgrade and refurbishment). Budget is in SRF-Ops.
- AIPs
  - $1.05M/year
  - Budget presently is not in Accelerator Operations

Program Requirements and Performance Limitations

- Operational time (weeks/year) is determined by DOE. Goal is 33-34 weeks/year.
- DOE metric for reliability is ≥80%
  - Scheduled program includes 100% margin (1 experiment day mapped to 2 calendar days)
- Beam energy:
  - CEBAF is operated at 11.5 GeV (after 5.5 pass) in FY2024. 12 GeV requested in FY2025.
  - Many experiments, including MOLLER, can trade energy for reduced RF fault rate
- Beam power and intensity:
  - CEBAF 12 GeV upgrade performance optimized for up to 1 MW, 450 uA recirculated current
  - CEBAF is operated at <800 kW. Beam power of 1.1 MW requested in FY2025
  - Some experiments do not require maximum energy allowing for program optimization
- Accelerator performance limitations (presently):

– Accelerator systems	~850 kW	Klystron performance below spec
– Operational Envelope	1.1 MW	Determined by the dump cooling system
– Environmental Assessment:	2 MW	

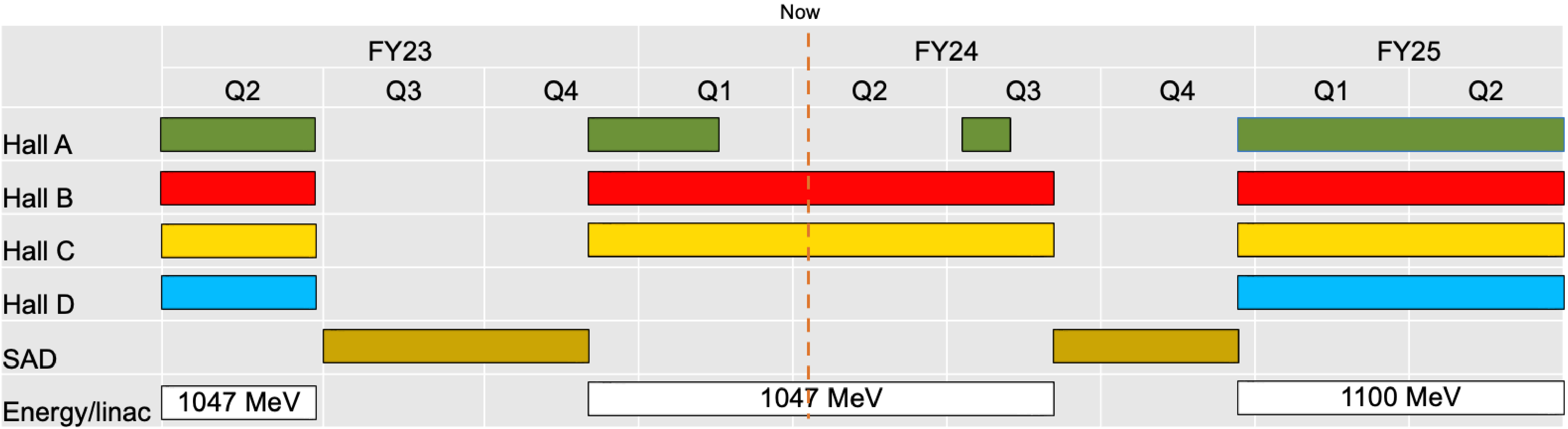
FY24 and FY25 Operations

FY24 Run

- 34 weeks of beam operations, ~31 weeks physics
- Three Halls: A (2-5), B (3-5), C (3-5)
- E = 11.5 GeV (1047 MeV/linac), P = 900 kW

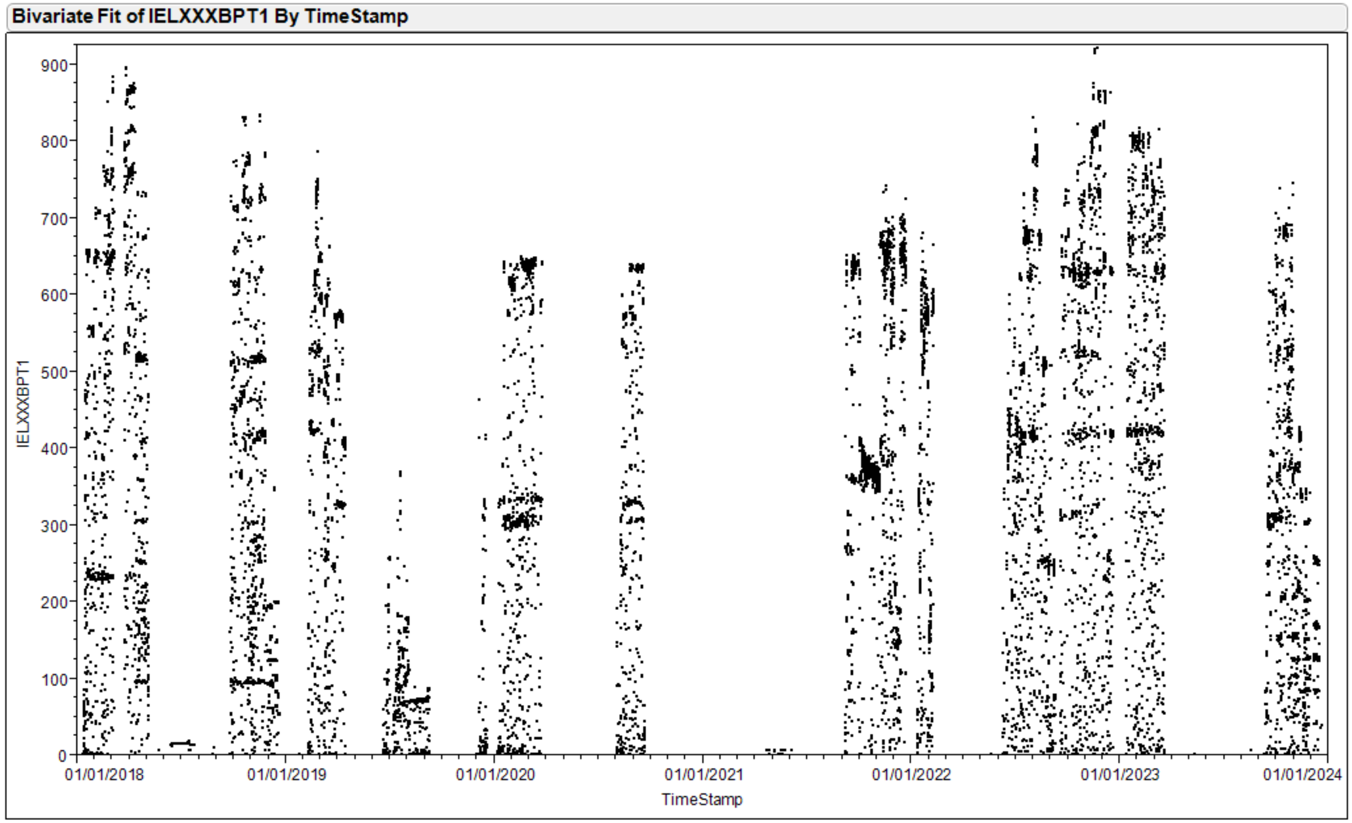
FY25 Run

- 33 weeks of beam operations, ~31 weeks physics
- Four Halls: A (3-5) , B (1-5), C (3-5), D (5.5)
- E = 12 GeV (1100 MeV/linac), P = 1.1 MW
  - *Increasing CEBAF energy reach will be critical*



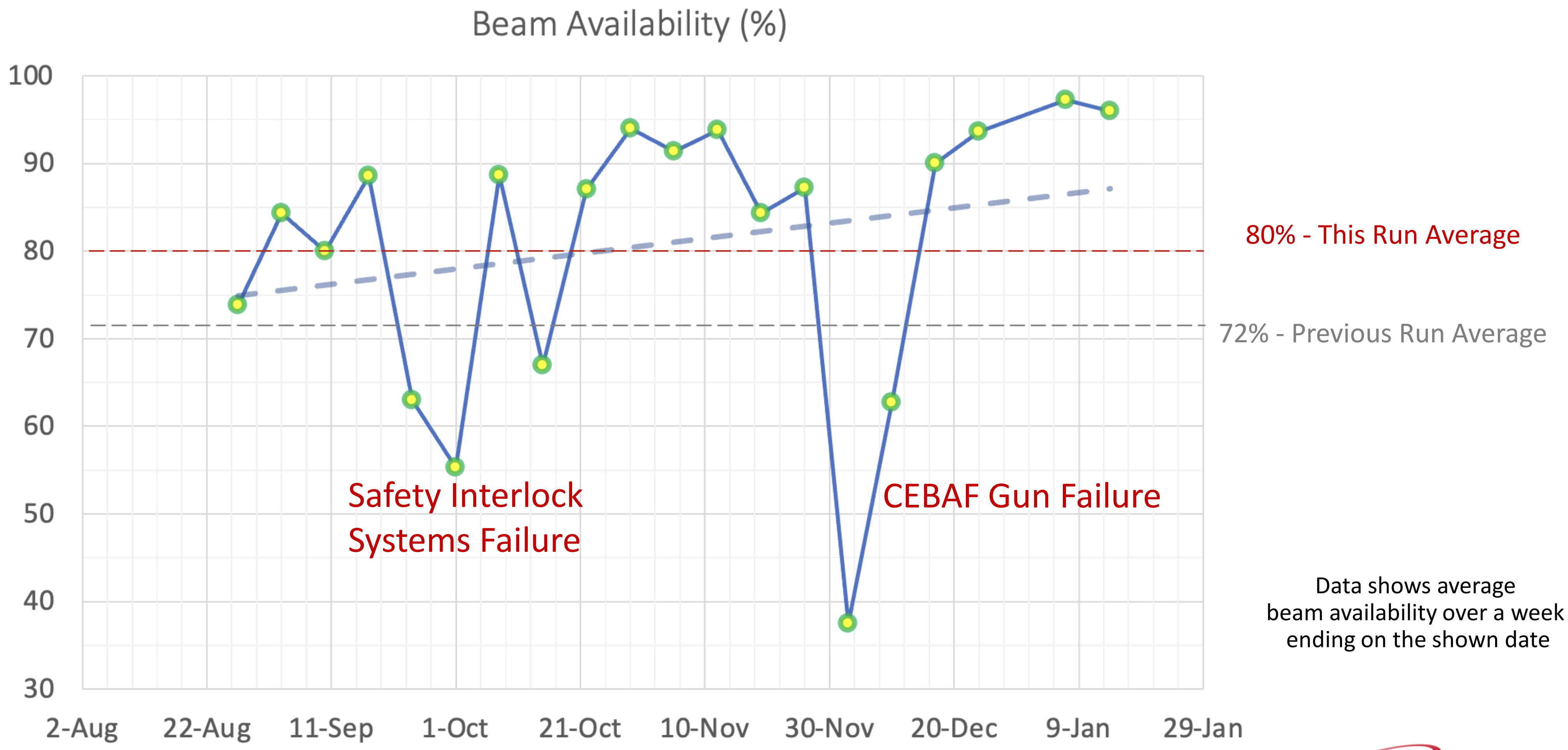
CEBAF Beam Power For 5 Last Years

- CEBAF typically operates at <800 kW
- Power is lower in FY2024 run due to
  - Hall A shutdown from Nov to Apr
  - Hall C reduced power requirements
- Runs above 800 kW (e.g., in 2022) were difficult due to frequent RF trips



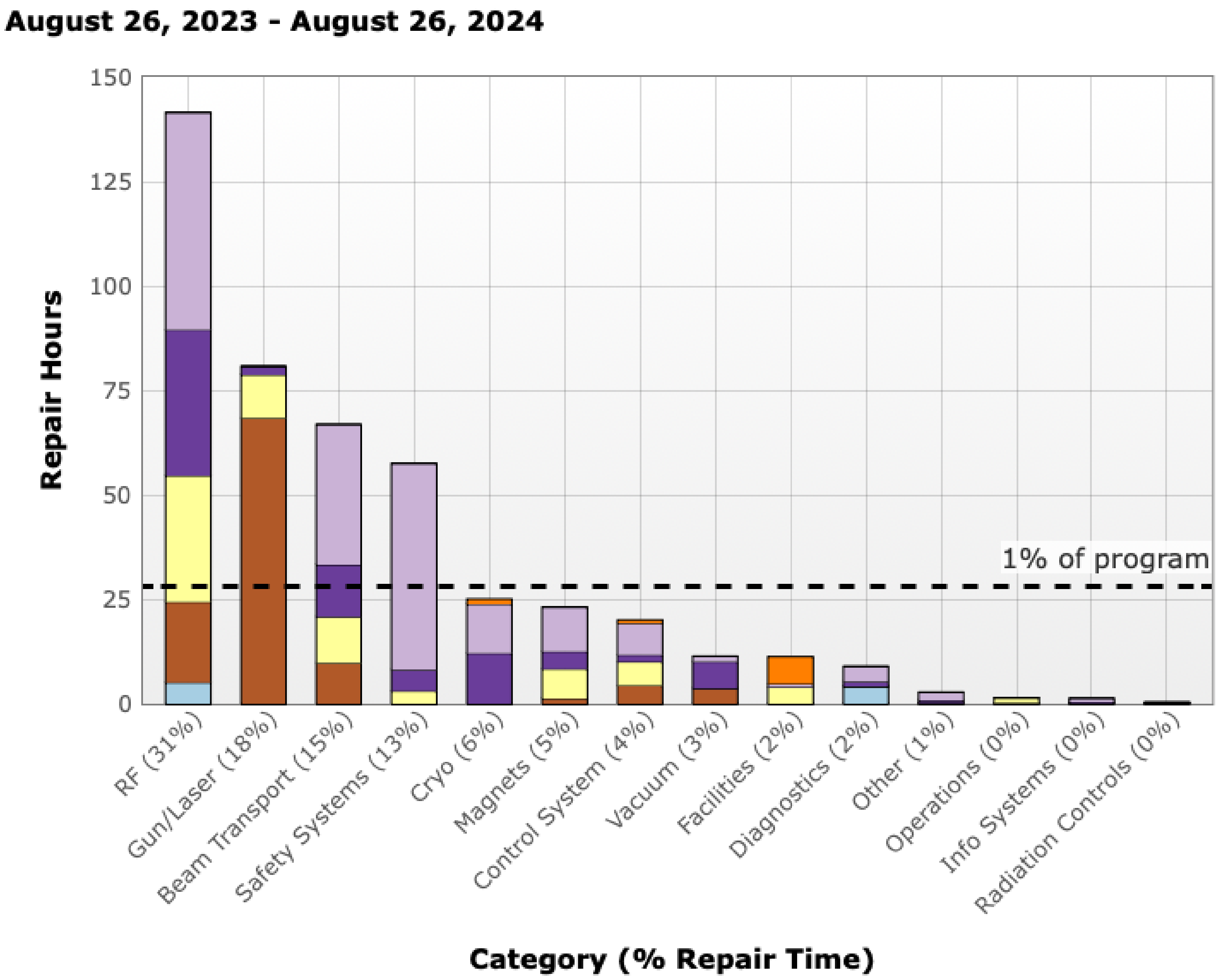
Status of CEBAF Beam Operations: Beam Availability

- Average beam availability for this run (08/26/2023 – now) is 80%
- DOE metric is ≥80%



Data shows average beam availability over a week ending on the shown date

Beam Availability and Reliability, This Run (08/26/2023 – now)



August 26, 2023 - January 14, 2024 (07:00 - 07:00)

Delivered Research (Hours)*:	1,730.8
Delivered Beam Studies (Hours)*:	83.4
Delivered Tuning & Restore (Hours)*:	375.9
Total Delivered (Hours)*:	2,190.2
Budgeted Operations (Hours)*:	2,904.0
Total Delivered / Budgeted (%)*:	75.4%
Unscheduled Failures (Hours)*:	564.2
Total Scheduled (Hours)*:	2,754.3
Research / Scheduled (%)*:	62.8%
Reliability (%)*:	79.5%

Main Sources of Downtime

- RF failures are consistently the largest contribution to downtime, >30%
  - Klystron HV PS and control boards
  - High power components (transformers, breakers, etc.)
  - Cooling
- Beam transport consistently is a high contribution, ~15%-25%
  - Beam losses due to optics and orbit drifts
  - Unscheduled tuning to reduce beam losses
- Other noticeable contributions to downtime
  - Magnet cooling channels clogging
  - Power supply failures
  - Facilities: LCW, HVAC
  - Gun is a single point failure. Although mostly reliable, it’s failure causes significant downtime.

Accelerator Performance Limitations

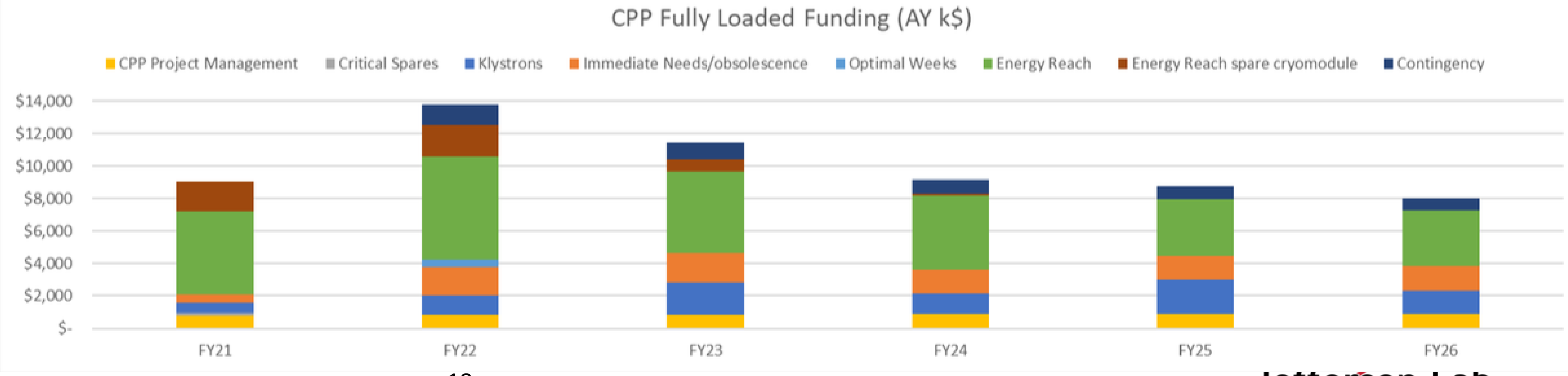
- SRF
  - C100 cavity gradient degradation.
    - Contamination due to degrading Viton seals, field emission, and high radiation
    - Possibly, dark current due to field emission
  - Loss of cryomodules and cavities to vacuum leaks and other events.
  - Cavity faults caused by microphonics and other effects.
- RF
  - RF station power lags performance requirement
- Outdated and inadequate accelerator systems, including data acquisition and post-mortem capabilities, limit understanding of the machine and application of advanced techniques such as AI/ML
  - LLRF, earlier, analog versions are still prevalent at CEBAF
  - BPMs, slow DAQ (most), no buffering for postmortem processing
  - BLMs, slow DAQ
  - (No) Global timing system, no synchronization between different systems

See slide 25

CEBAF Performance Plan (CPP)

- Established in 2017 with goal of achieving 12 GeV in 5.5 passes with good reliability.
- Reliability Project, manager: Randy Michaud
  - Critical Spares
  - Klystrons
  - Obsolescence
  - Optimal Weeks Hardware
- Energy Reach Project, manager: Tony Reilly
  - C75 program
  - C100 refurbishment program
  - Plasma processing

CPP funding vs FY. The total is $60.1M.



CPP Reliability

- Critical Spares, No scope in FY24.
- Klystrons
  - Supply chain crisis increased service cost by 60%. Supplier business has a new owner.
  - We evaluate an alternative supplier to mitigate risk
  - FY24 plan: 10 rebuilds and 10 new klystrons
- Obsolescence
  - SSG – 5 items @ $79K: ODH UPSs ordered for SAD24.
  - DC – 4 items @ $515K : New DC PM coming up to speed on CPP plans.
  - I&C – 3 items @ $360K: VME Crates awaiting PO, 15 units for SAD24
  - RF – 5 items @ $666K : Work planning for Sep SSA install SAD24.
  - ACE – 2 items @ $60K: UPS/Line Switches ordered.
- Optimal Weeks, No scope in FY24.

CPP Energy Reach

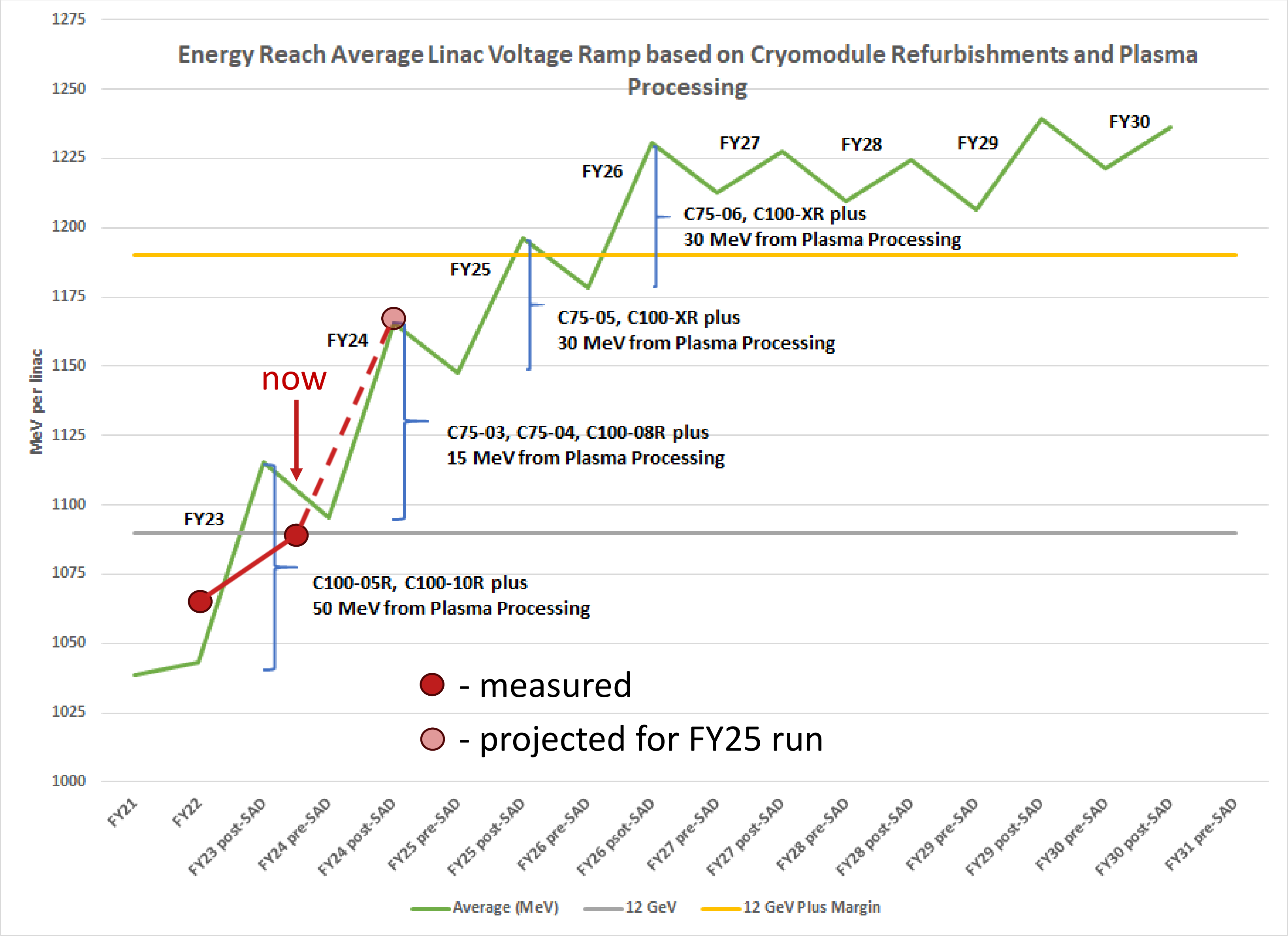
T. Reilly

- Scope
  - C75 program
  - C100 refurbishment program
  - Plasma processing
- Cryomodules refurbished and installed at CEBAF to date: C75 x 2, C100 x 4, C50 x 1, 7-cell P1 x 1
- Four cryomodules in south linac were plasma processed in situ.

Cryomodule Installation Plan

	Cryomodules Installed	Cryomodules Removed
FY23	C100, C100	C100
FY24	C100, C75, C75	F100, C20, C20
FY25	C100, C75	C100, C20
FY26	C100, C75	C100, C20
FY27	C100, C75	C100, C20
FY28	C100, C75	C100, C20
FY29	C100, C75	C100, C20
FY30	C100, C75	C100, C20

CEBAF Energy Reach Projection



T. Reilly

Jay adds: TN-24-001 has energy reach history 2016-2024

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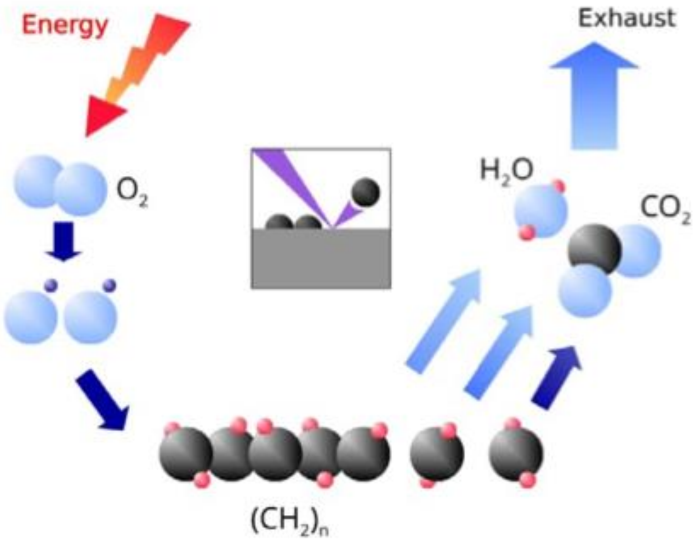
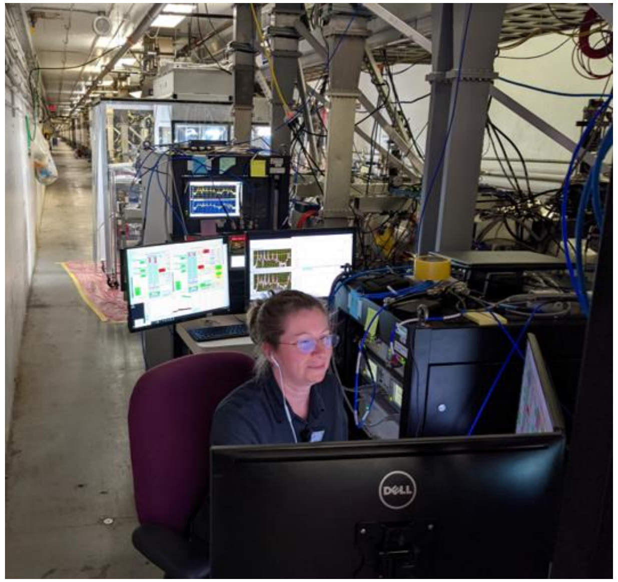
Successful In-Situ Plasma Processing Of CEBAF CMs

T. Powers

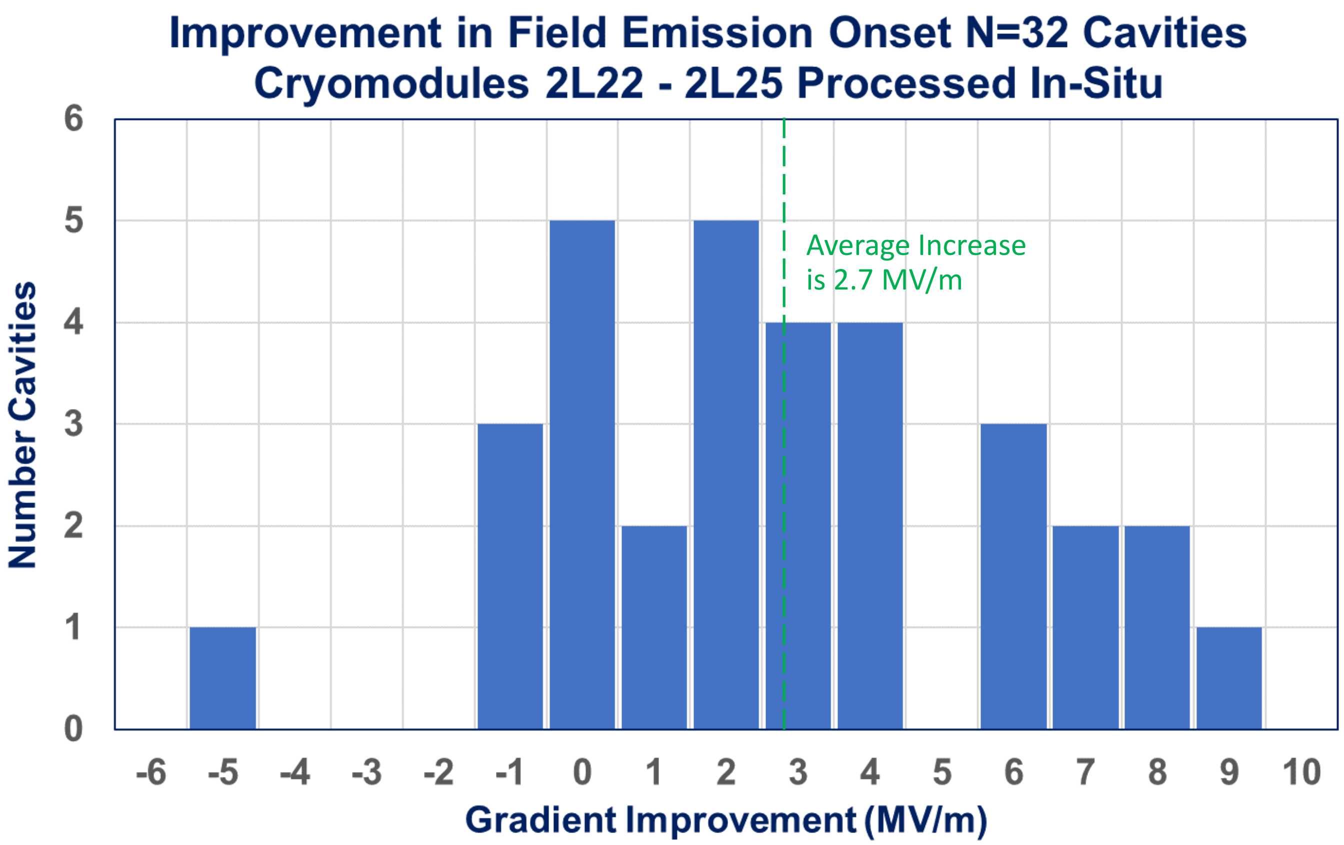




- Four cryomodules, 2L22 - 2L25 (all cavities), were plasma-processed in the tunnel during last SAD
- Path Forward
  - Process 3 to 4 C100 and C75 cryomodules during accelerator shutdowns.
  - Extend plasma processing to C75 cavities.

In-Situ Plasma Processing Increased Gradient by 2.7 MV/m

T. Powers

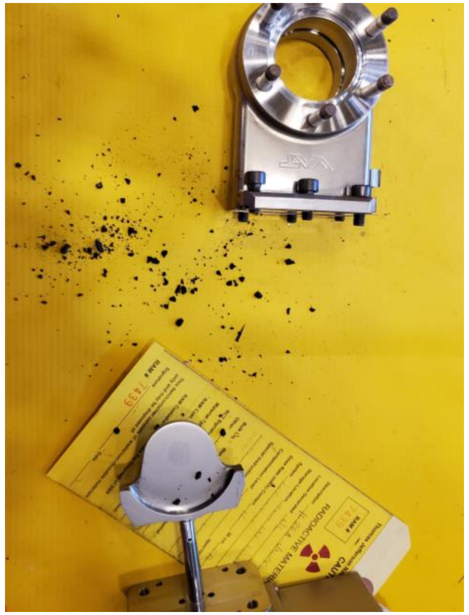


- Field emission free operation was improved by 59.1 MeV (24%).
- An average improvement of 2.7 MV/m.
- 5 cavities were field emission free after processing.

Success of plasma processing supports more aggressive curve for CEBAF energy reach

All-Metal Gate Valves

- Contamination of CEBAF linac causes degradation of cavity performance, requires cryomodule refurbishment, plasma processing.
- One of contamination sources was attributed to radiation damage of elastomer (Viton) seals around C100 and C75 CMs
  - Viton seals can reach its lifetime in a single run
- All-metal gate valves are a viable alternative
- All-metal valves are used in SRF accelerators: X-FEL, LCLS-II, PIP-II (future)
- Risk – production of metallic particulates
  - Some gate valves cycle a dozen times a run, some not at all
- We are considering installing all-metal gate valves in CEBAF next shutdown. Exact scope of installation is under discussion (3 to 7 CMs).
- *We solicit comments on viability of this approach from JLAAC*

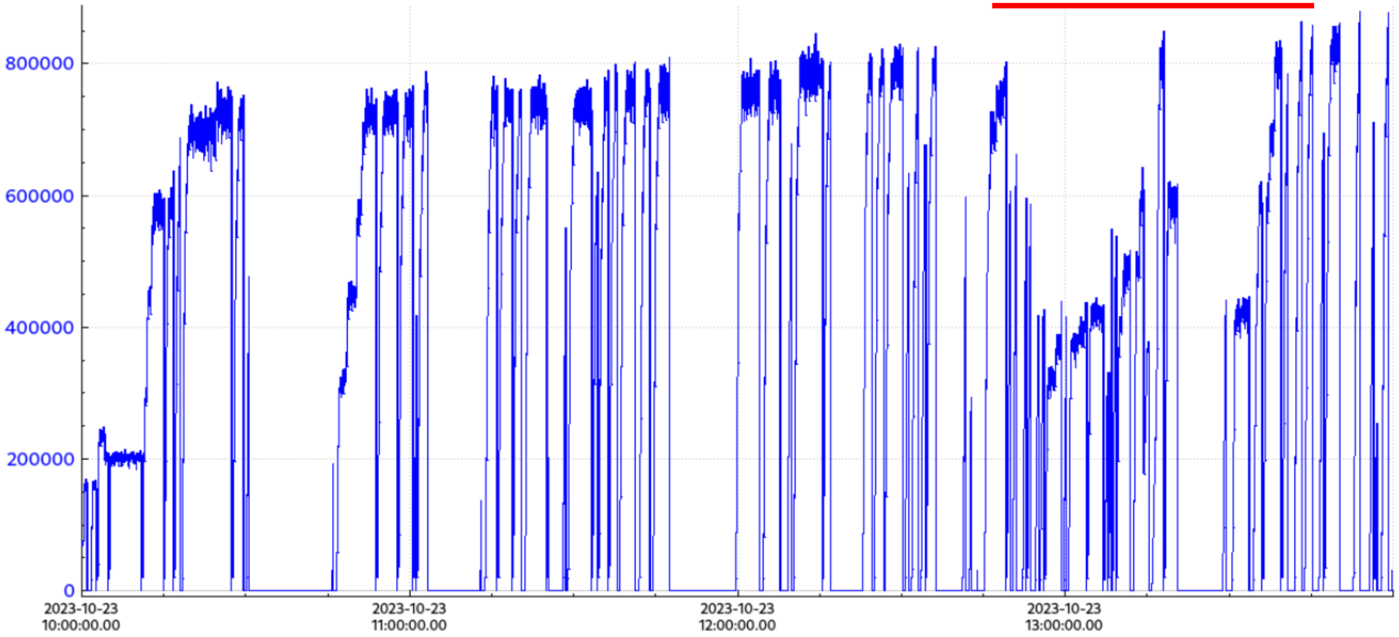


Probing CEBAF Performance Limits

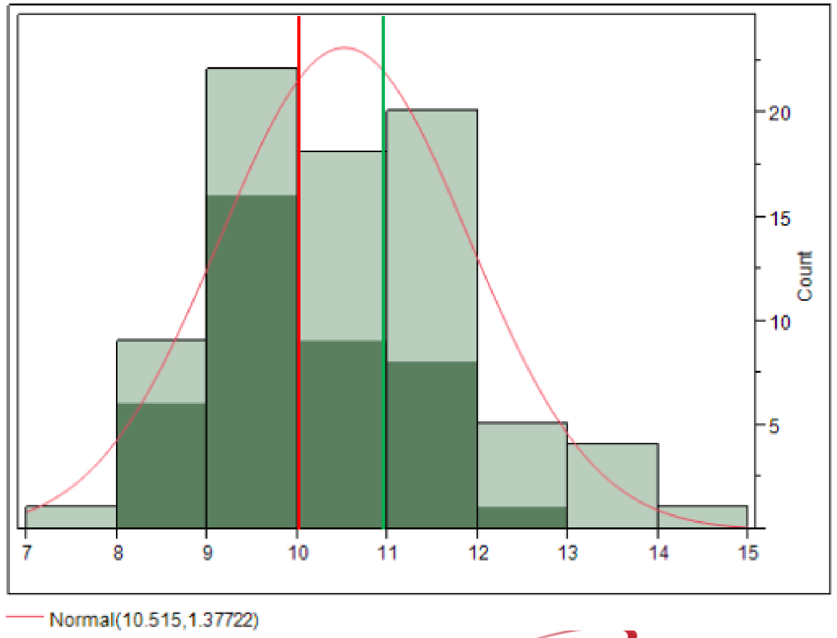
- High intensity run in 10/2023 to identify CEBAF intensity limitations.
- Performance is limited by available RF power. C100 CM klystrons are underperforming.
  - Need at least 10 kW for 1.1 MW
  - Klystrons specified at 13 kW max and 11 kW linear regime

Beam power as function of time

Maximum achieved power
850 kW (395 uA)



Measured RF Klystron Power Distribution
Need 10 kW RF for 1.1 MW beam power.
Klystrons are specified at 13 kW max and 11 kW linear.



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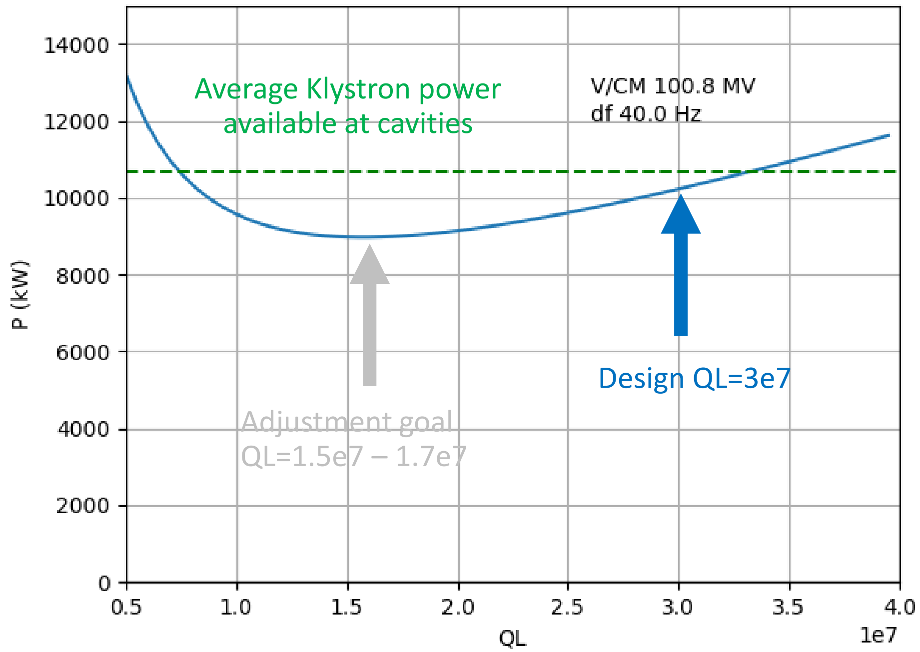
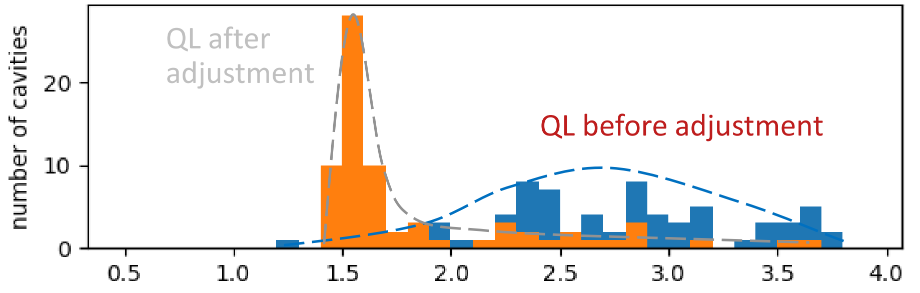
Optimization of Q_L of C100 Cryomodules

- C100 cavities were designed with Q_L of 3e7 in anticipation of high operating field and low microphonics
- Reality:
  - Microphonics is higher than specified
  - Operating field is lower than expected
- Impact:
  - C100 cavities trip due to insufficient RF power with high beam current and high microphonics
  - Difficult to control narrow-bandwidth C100 cavities
- Mitigation: Q_L of C100 cavities was reduced to optimal 1.5-1.7e7 during this SAD
- Impact to be tested during this and next runs

Required RF power as function of QL
100 MV/CM and 40 Hz detuning



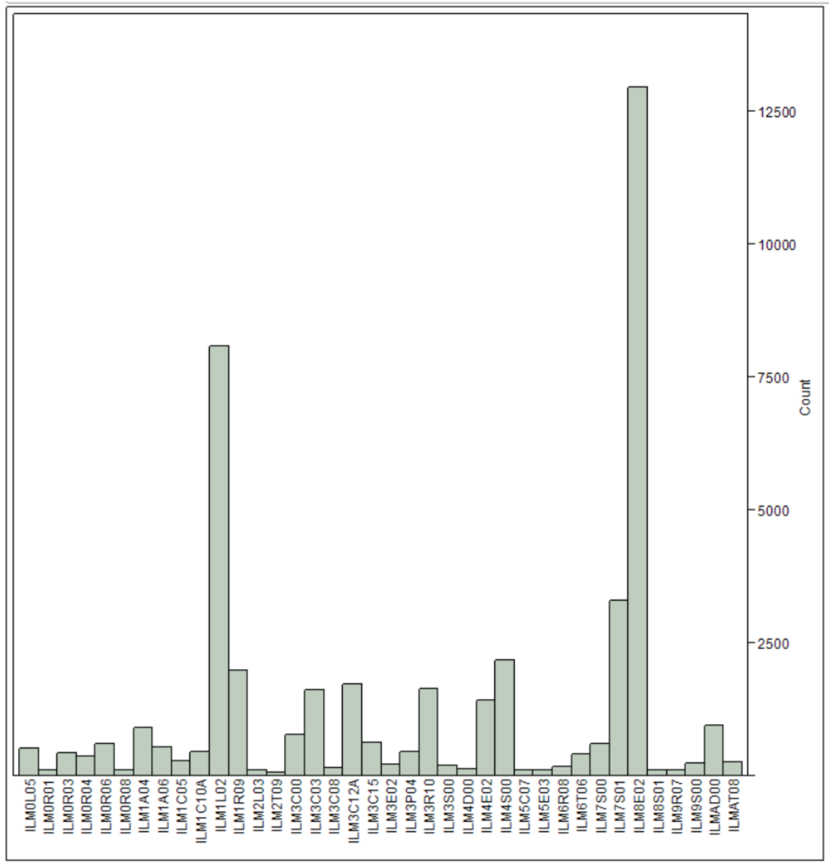


Measured QL of C100 cavities before and after adjustment

Improving Understanding of Beam Losses

- CEBAF employs original 30-year-old analog BLM system to detect beam losses
  - System adequately protects the machine but is not well suited for understanding or optimization of beam losses
  - PMT voltage settings are likely too conservative
- Near-term approach
  - Procured 8 ion chambers with fast DAQs and installed them at the location of highest losses (see figure)
  - Ion chambers are used to study beam losses and cross-calibrate existing BLMs
- Long-term approach: Conduct a mini-workshop with subject matter experts to develop path forward with the upgrade of the BLM system

Frequency of MPS fast trips pulled by BLMs
60% of all trips are caused by four BLMs
Beam losses are responsible for ~27% of all downtime.



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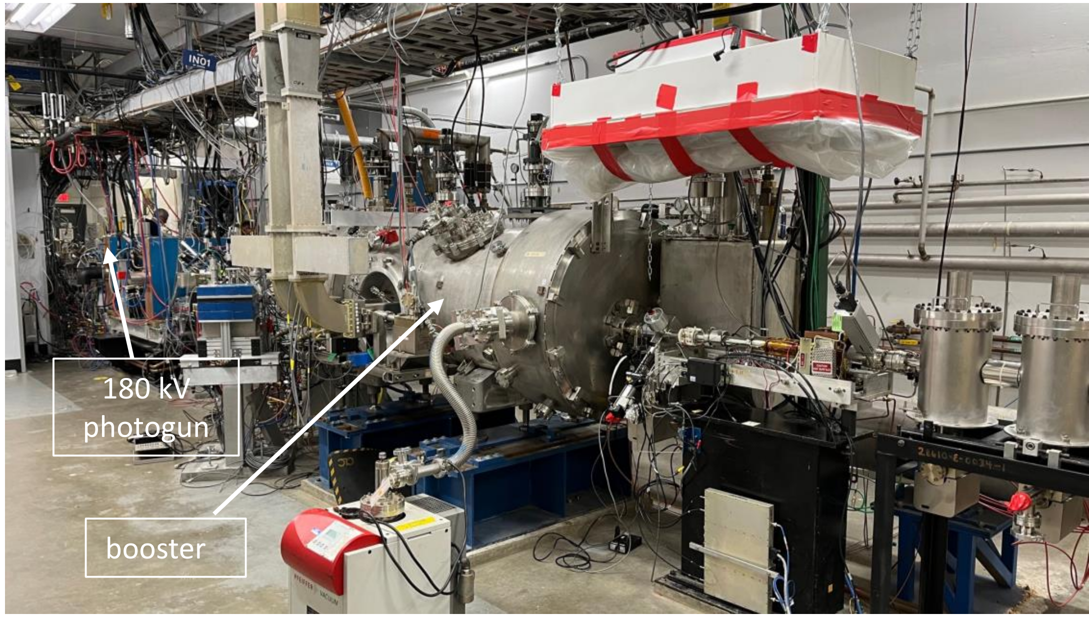
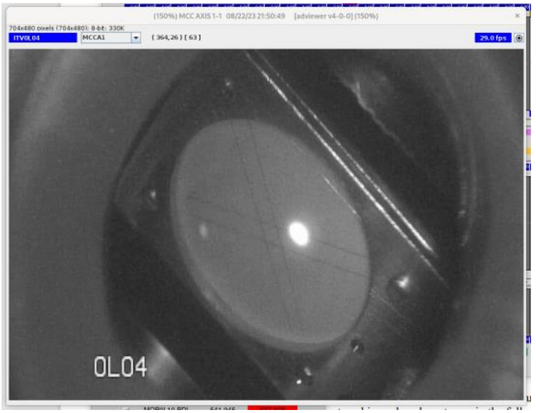
Injector Upgrade Completed

- The injector upgrade reduces helicity correlated asymmetry for the Parity Quality program (MOLLER) and improves beam quality for high charge/bunch beam (K-Long).
- Scope
  - Increased gun voltage from 130 to 180 keV.
  - Upgraded Wien filters.
  - Solenoids with a larger aperture.
  - New SRF Booster cryomodule with reduced deflection and coupling.
- Injector is used successfully for this beam run.
- Increased beam energy improved beam stability significantly.
- Beam tests to quantify beam Parity Quality and fully evaluate the injector are on-going



New injector and Booster CM
In the CEBAF tunnel



Beam in the injector

Accelerator Improvement Projects (AIPs)

	Total cost	Past Years	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29
LLRF Digital Upgrades	3,739	1,789	660	266	905	40	40	40		
Next Gen BPM Upgrade	4,580				190	1,088	1,122	1,157	1,023	
Global Timing System	1,480								210	1,270
Beam Loss Monitoring System	TBD									
TOTAL (= Funding)	**9799+**		**1,052**	**1,063**	**1,095**	**1,128**	**1,162**	**1,197**	**1,233**	**1,270**

- Challenges
  - Cost-Of-Living funding does not allow acquisition of critical systems before FY30.
  - Incremental production and installation spread over multiple years is costly and inefficient.
- LLRF, BPMs, BLMs, and Timing together provide complementary, synchronized data.
- Focused funding and construction of these systems will provide maximum benefit for CEBAF Operations.

See next slide

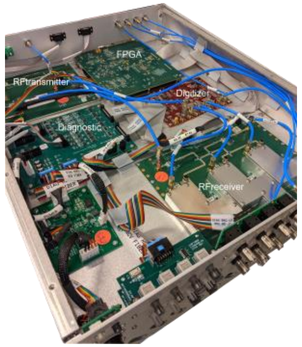
Benefits Of Advancing LLRF, BPM, BLM, and Timing System

- LLRF Upgrade
  - Provides advanced functionality for field control and diagnostics capabilities.
  - Upgrade in progress. Installation to proceed until 2027.
- Next Generation BPMs
  - Addresses obsolescence. Provides new functionality: high bandwidth DAQ, buffering, interface to global timing system, suitable for capturing fast transients.
  - Porotype construction in progress. Plan to install by 2028.
- BLM System Upgrade
  - Provides new functionality (faster DAQ, buffering, interface to timing system). Total loss monitors can extend area coverage.
- Global Timing System
  - Synchronizes instrumentation and allows correlating their response to beam events

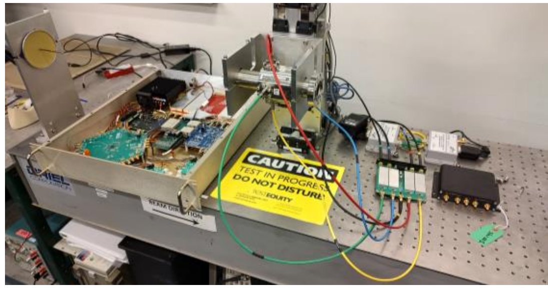
- These systems will benefit CEBAF the most if they are treated as parts of an integrated system, complementing each other.
- Advanced functionality and global timing will provide insight into machine behavior and allow us to use modern tools such as ML/AI.
- *We ask JLAAC to comment on this concept and usefulness of advancing procurement of these systems.*

N. Rider

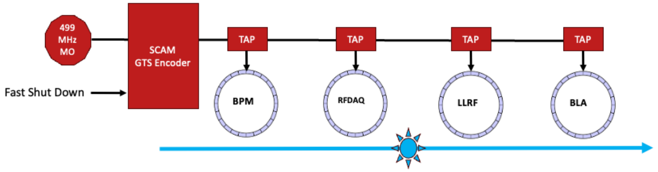
LLRF v3



New gen. BPM prototype

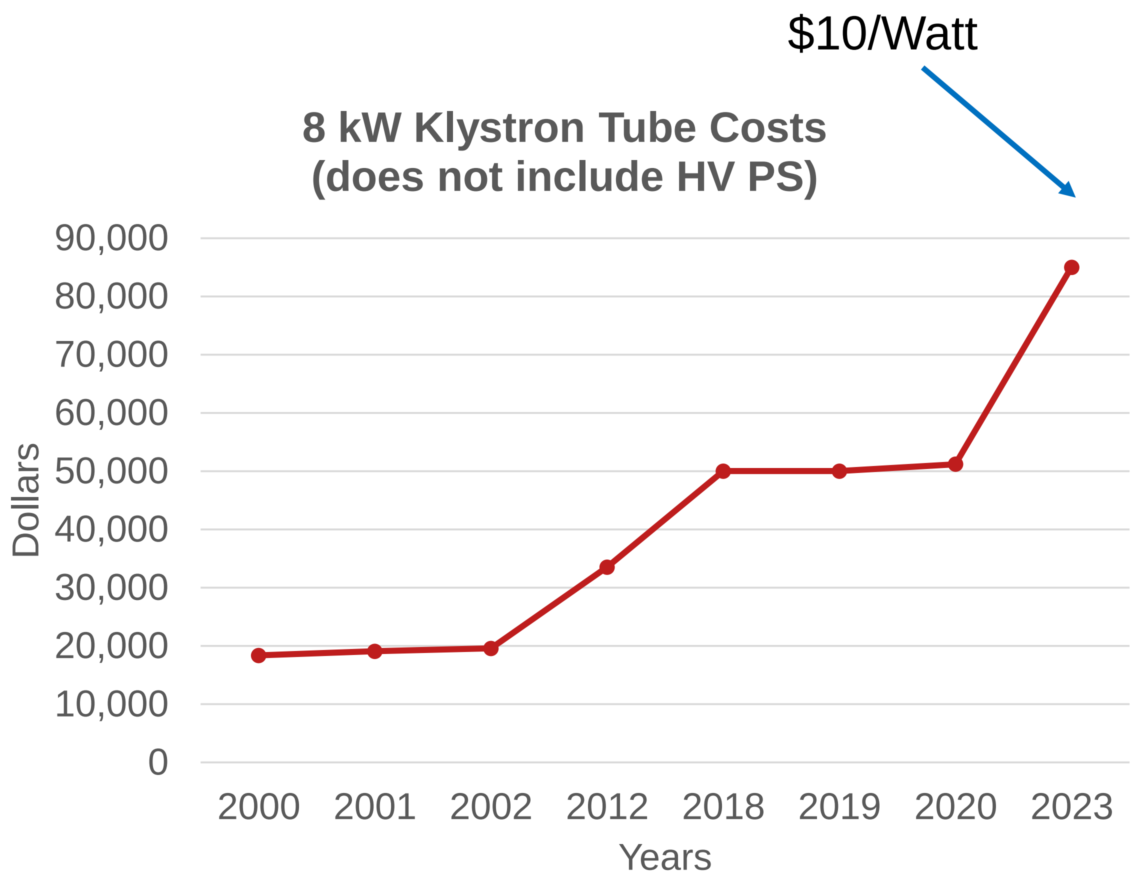


Global timing system concept



Next Generation CEBAF High Power RF

- Klystron has been a reliable RF source at CEBAF for almost 30 years
- Industry is changing
  - Design experience is aging out.
  - Solid State became much more prevalent in the last 10 years.
- Cost of Klystrons surpassed cost of Solid-State Amplifiers.
- It becomes difficult to find klystron vendors.
- Aging CEBAF HP RF system is the main source of downtime: HV PS, Transformers, Klystron control electronics.
- *We need to think about next generation RF solution for CEBAF*



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Next Generation CEBAF High Power RF: Alternatives

H. Wang

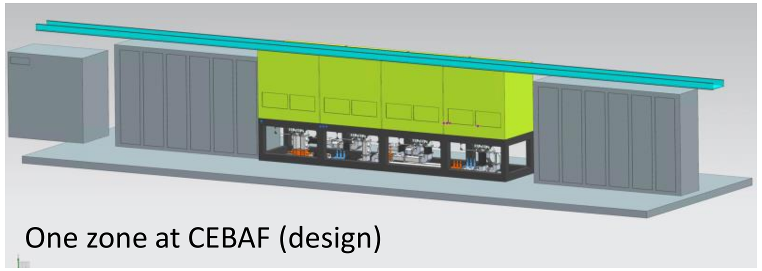
Solid State Amplifiers (SSA)

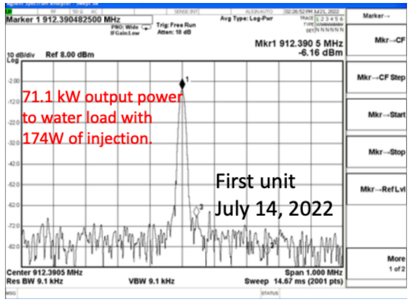
- Solid State Amplifiers are widely accepted technology that matured over last 20 years.
- Viable alternative to tubes between 100 MHz – 2 GHz.
- SSA efficiency > 40% for class A/B…more for class F.
- SSA is technology of choice for LCLS-II, FRIB, PIP-II.
- **Status:** requirements for CEBAF 8 kW SSA developed. Ready to contact vendors to get proposals for one CEBAF cryomodule. Project will be funded as AIP.

Magnetrons

- Promise of high-efficiency, high power, and, possibly, lower cost.
- Widely used technology for industrial applications but not accelerators.
- R&D is conducted to demonstrate required phase and amplitude stability and address short lifetime.
  - 75 kW, 915 MHz AMTek magnetron funded by DOE Accelerator Stewardship award
  - SBIR with Muons, Inc. for 1497 MHz magnetron


LERF SSAs


One zone at CEBAF (design)



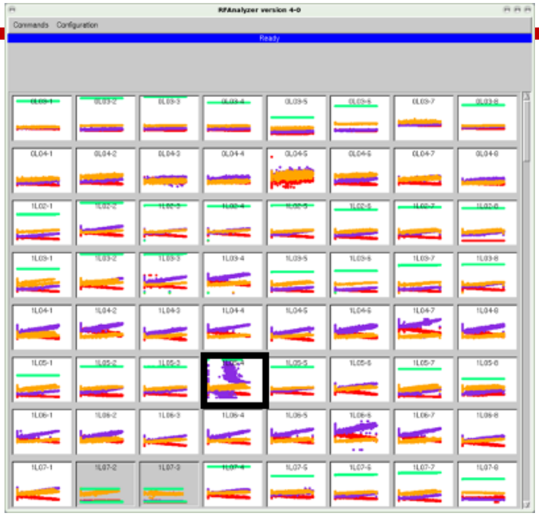
We request and will appreciate comments from JLAAC

Portfolio of R&D and SBIR-Funded Projects

- Three AI/ML DOE funded projects (FOA-LAB-20-2261)
  - Automate identification of unstable SRF cavities.
  - C100 Cavity Fault Prediction.
  - CEBAF cavity field emission management using neutron detectors and surrogate models (ML)
    - Reduce field emission, increase lifetime of components

C. Tennant
D. Turner

Detection of anomalies in cavity field



- He flowmeter (SBIR, Hyperboloid LLC)
  - Allows for fast and accurate measurement of cavity heat and Q_0

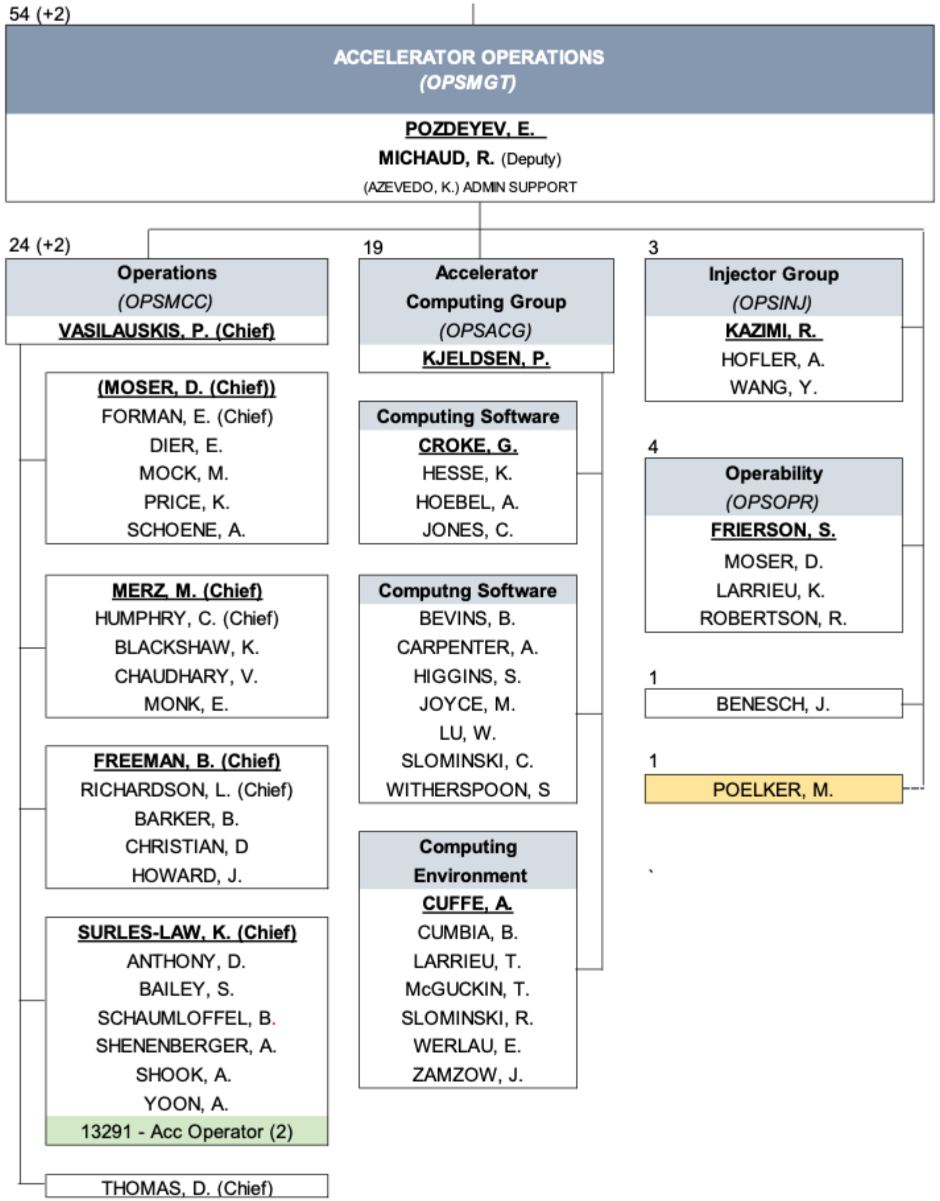
M. Spata

Helium Mass Flow Monitor

- 1497 MHz Magnetron RF source (SBIR, Muon Inc)
  - Demonstrate feasibility of magnetron as alternative, efficient RF source for CEBAF

First L-Band tube at Richardson Electronics

Accelerator Operations Staffing



- Personnel of operator group increased to 25, bringing Ops staffing to adequate level.
  - 7 new operators hired with a loss of 2 operators over the last year.
- Operability deputy hired to focus on improving reliability and failure analysis
- Competition for technical expertise with EIC and other projects is a concern
  - Projects will compete for expert knowledge (e.g., SRF/RF/LLRF) required to support CEBAF

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CEBAF Operations Risks And Their Mitigation

- Top risks
  - Loss of experienced personnel supporting CEBAF Operations
  - Aging linac systems and infrastructure affect CEBAF performance and increase rate of component failures to unacceptable level (e.g., loss of CMs, RF failures, CF failures)
  - Changing market conditions and industry can cause obsolescence of accelerator components and/or increase cost of maintenance
  - Energy reach fails to meet goals
  - Funding after CPP ends is insufficient to maintain CEBAF performance and reliability
- CPP and AIPs are examples of Risk Mitigation
  - We will benefit from pulling AIPs ahead and combining them to take full advantage of provided capabilities
- Formal risk registry exists for CPP. No formal risk registry for Operations exists yet. We plan to develop it.

Summary

- CEBAF usefully delivers beam to experimental halls in support of DOE NP mission.
- Beam run is in progress. Average reliability for the current run is 80%.
- We are actively addressing sources of downtime and performance limitations and managing future risks.
- CEBAF Performance Plan and AIPs are used to improve performance of the machine, improve reliability, and address risks.
- Looking forward to another successful year of delivering beam to NP users.

Thank You!

Current Priorities of CEBAF Operations

- Deliver beam (up) to four halls for nuclear physics program safely and reliably, meeting program's requirements
- Execute CEBAF Performance Plan to extend CEBAF energy reach up to 12 GeV after 5.5 passes with margin.
- Increase beam availability, reduce unscheduled downtime and frequency of trips
- Improve hardware reliability through acquisition of critical components and spares. Address hardware obsolescence
- Enhance CEBAF capabilities through AIPs, upgrades, and R&D
- Prepare for upcoming experiments
- Maintain strong operations team capable of meeting operational challenges

Machine Studies And Operator Training

Y. Roblin
D. Turner

Machine Studies

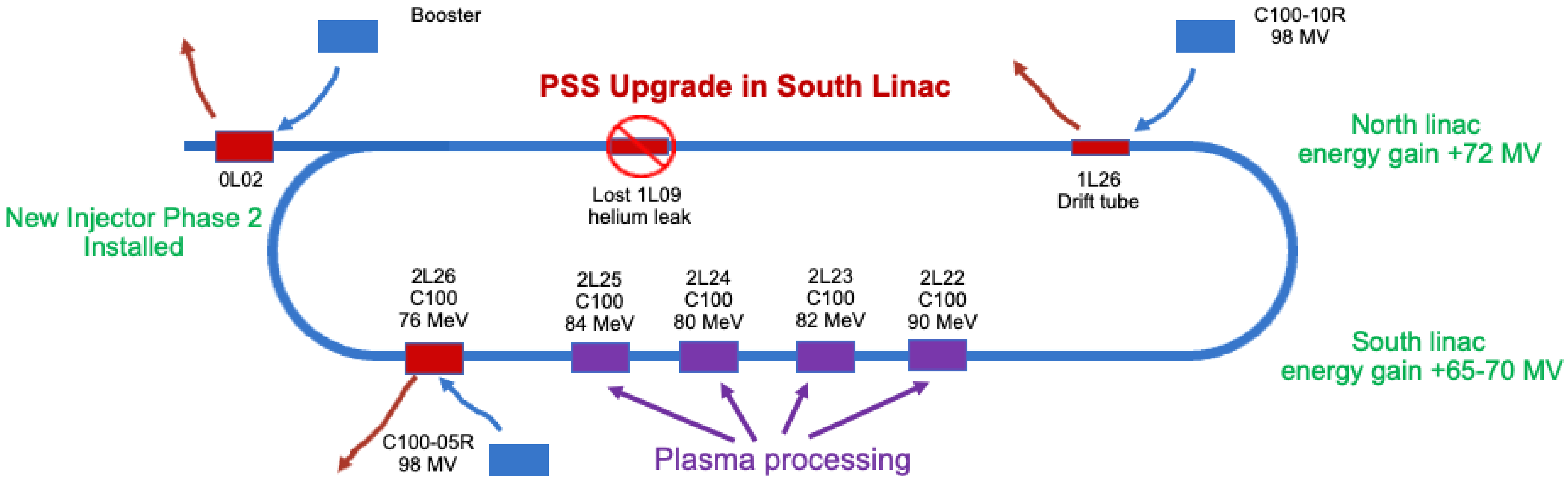
- Systematic beam studies to improve performance of the machine, understand performance limitations, and conduct R&D for future experiments are conducted bi-weekly (1 shift) and when opportunity presents itself
- Beam studies are managed by CASA in coordination with Ops and other departments
- Study plans are approved, prioritized, and scheduled at a weekly BTEAM meeting

Operator Training

- Senior crew chiefs conduct hands-on operator training of junior operators on a live machine when either opportunity presents or during machine studies
- These sessions provide unique opportunity to train young operators
- Junior operators execute beam tuning procedures and operate hardware

FY23 Scheduled Accelerator Downtime (SAD) Completed

- New injector will reduce helicity correlated asymmetries for MOLLER.
- Installed cryomodules and plasma processing increased the energy reach.
- Upgrade of Personnel Safety System in South Linac. Certification once per year is considered.



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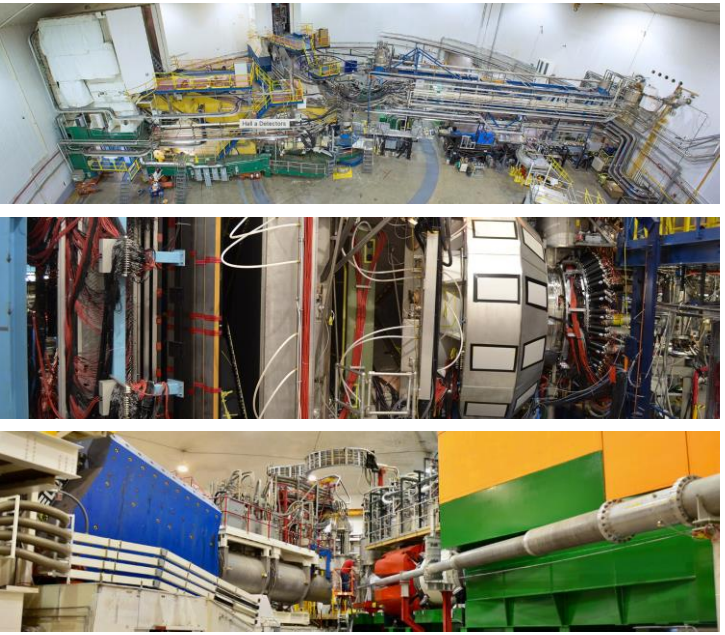
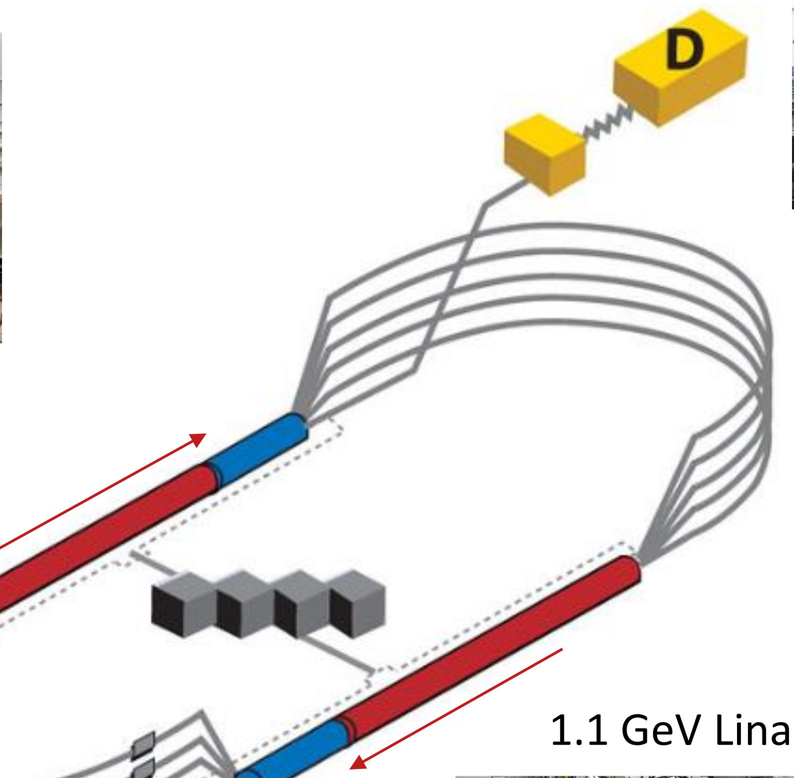
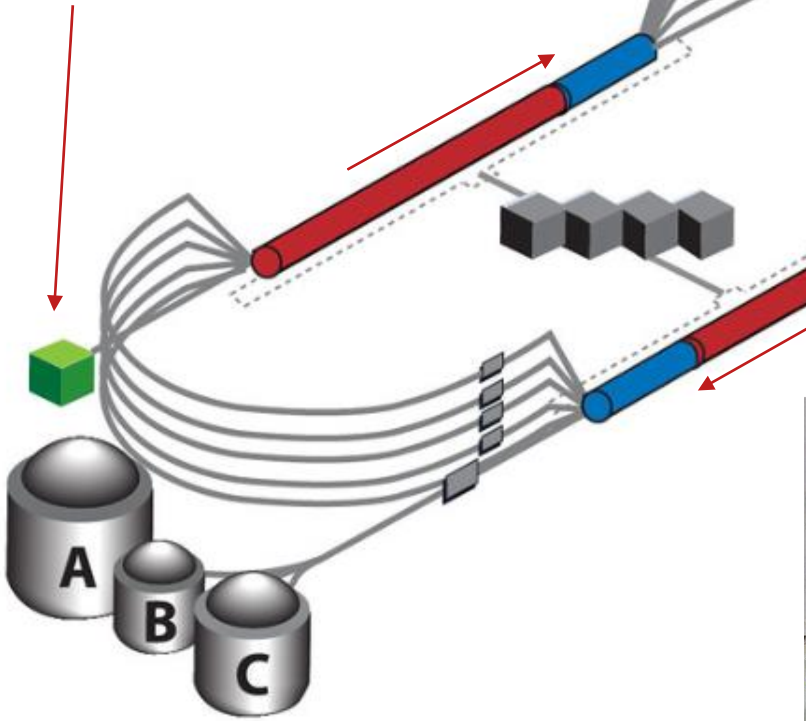
CEBAF Accelerator

Injector

Halls A, B, C



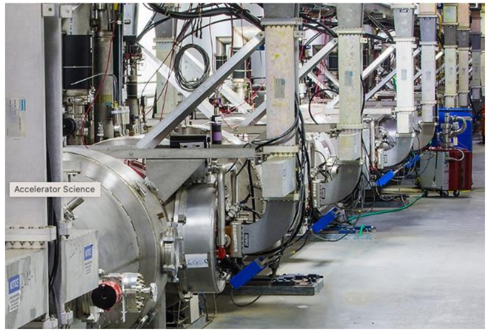




Hall D

5 Magnetic Arcs

1.1 GeV Linac



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