CEBAF Operations Overview

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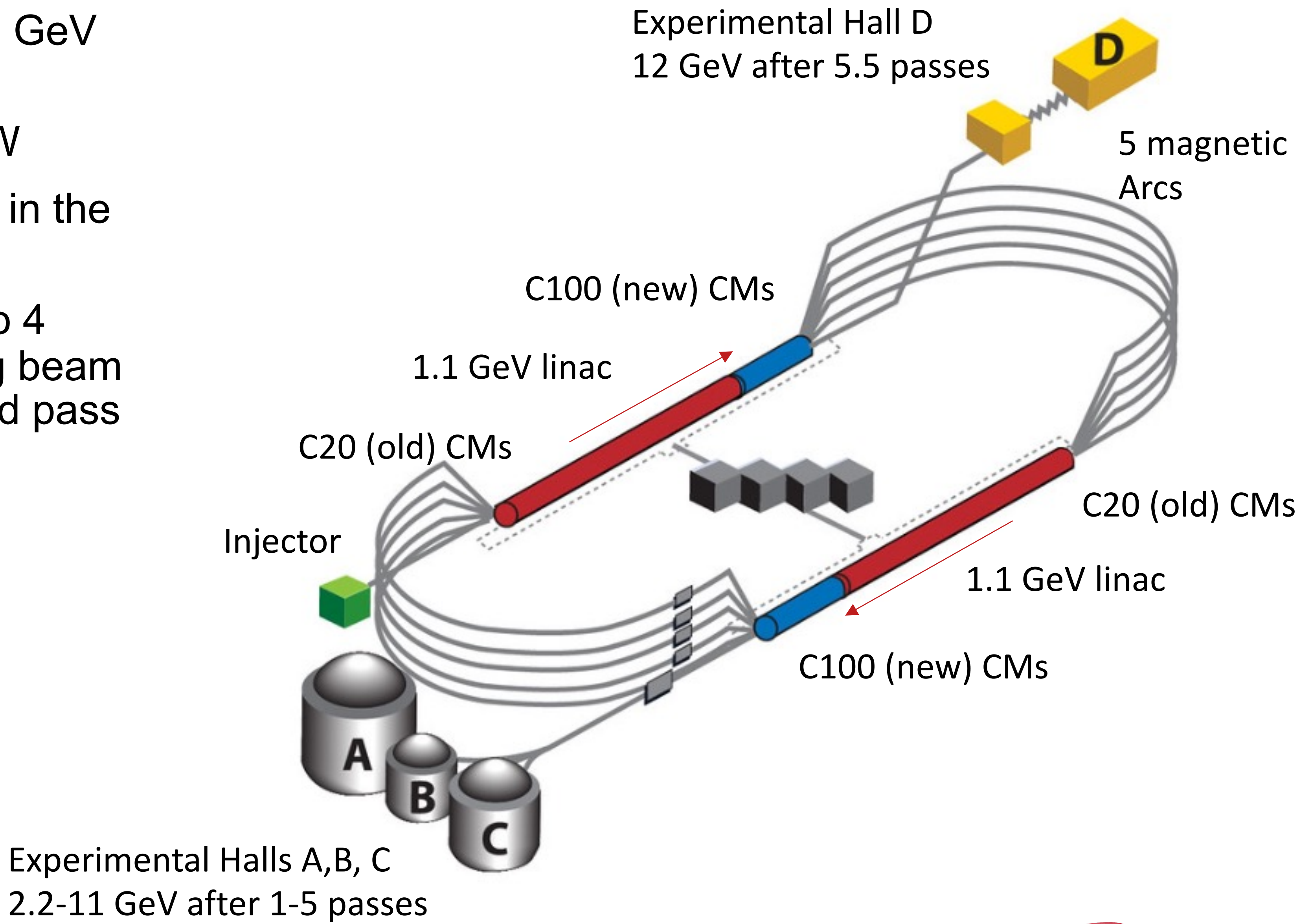
Director of Accelerator Operations

2024 Hall C Collaboration Meeting

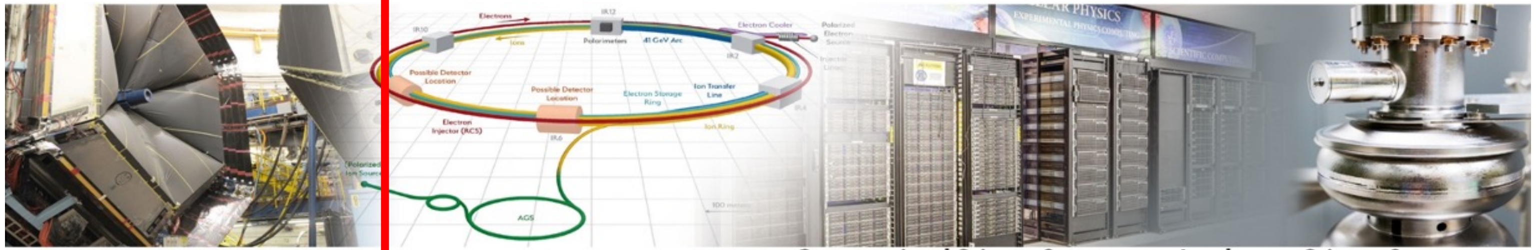
CEBAF Accelerator

- SRF, recirculating, 5.5 pass, 12 GeV Linac
- Design beam power up to 1 MW
- Total recirculated beam current in the linac up to 450 uA
- CEBAF can provide beam up to 4 Halls simultaneously, extracting beam to a specific Hall at any selected pass



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)

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%
- Beam energy:
  - CEBAF is operated at 11.5 GeV (after 5.5 pass) in FY2024. 12 GeV requested in FY2025.
  - Some experiments can trade energy for longer time and 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 always 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	

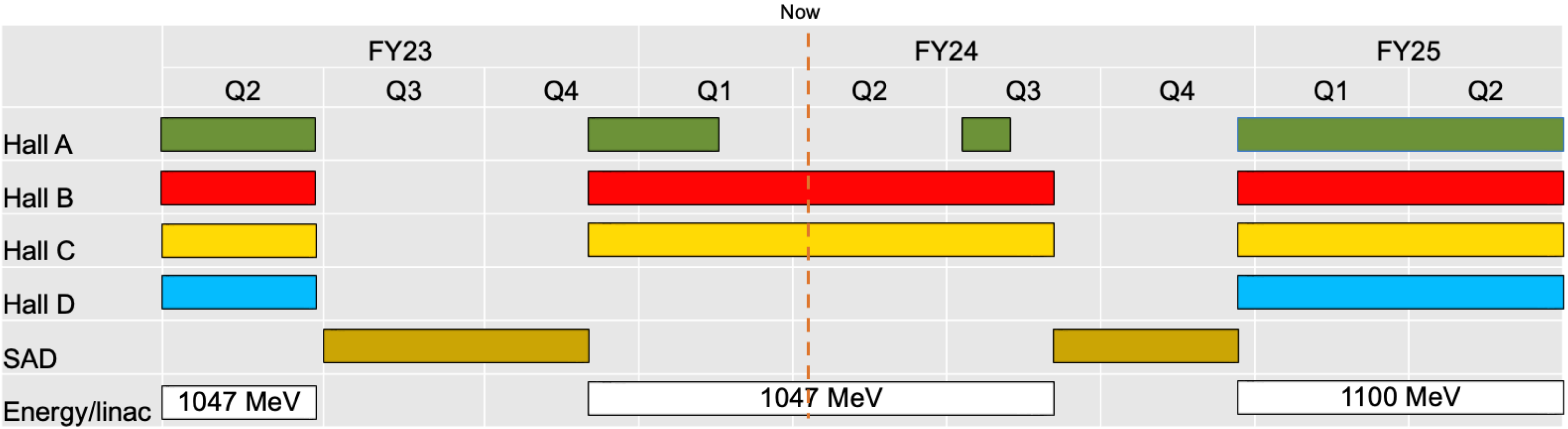
FY24 and FY25 Operations

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*



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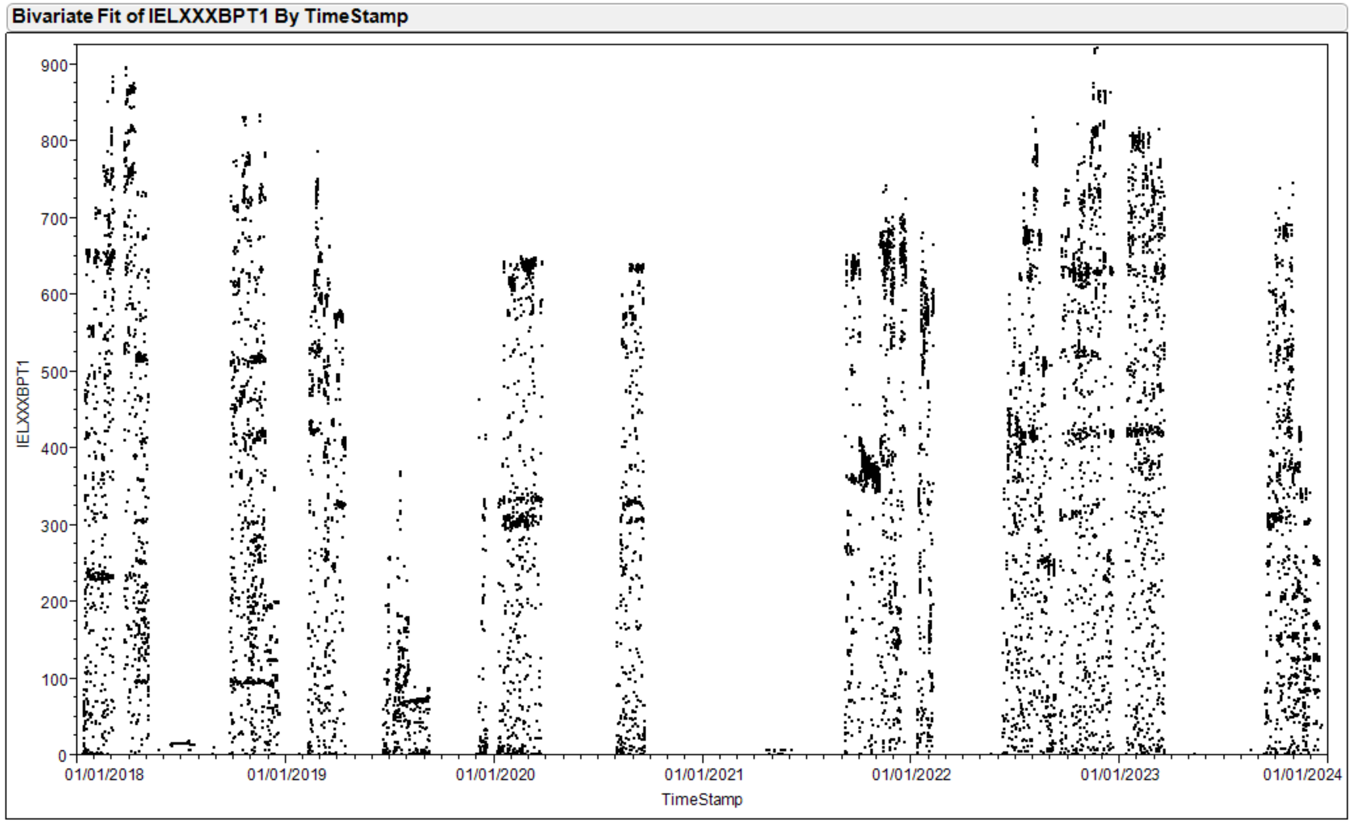
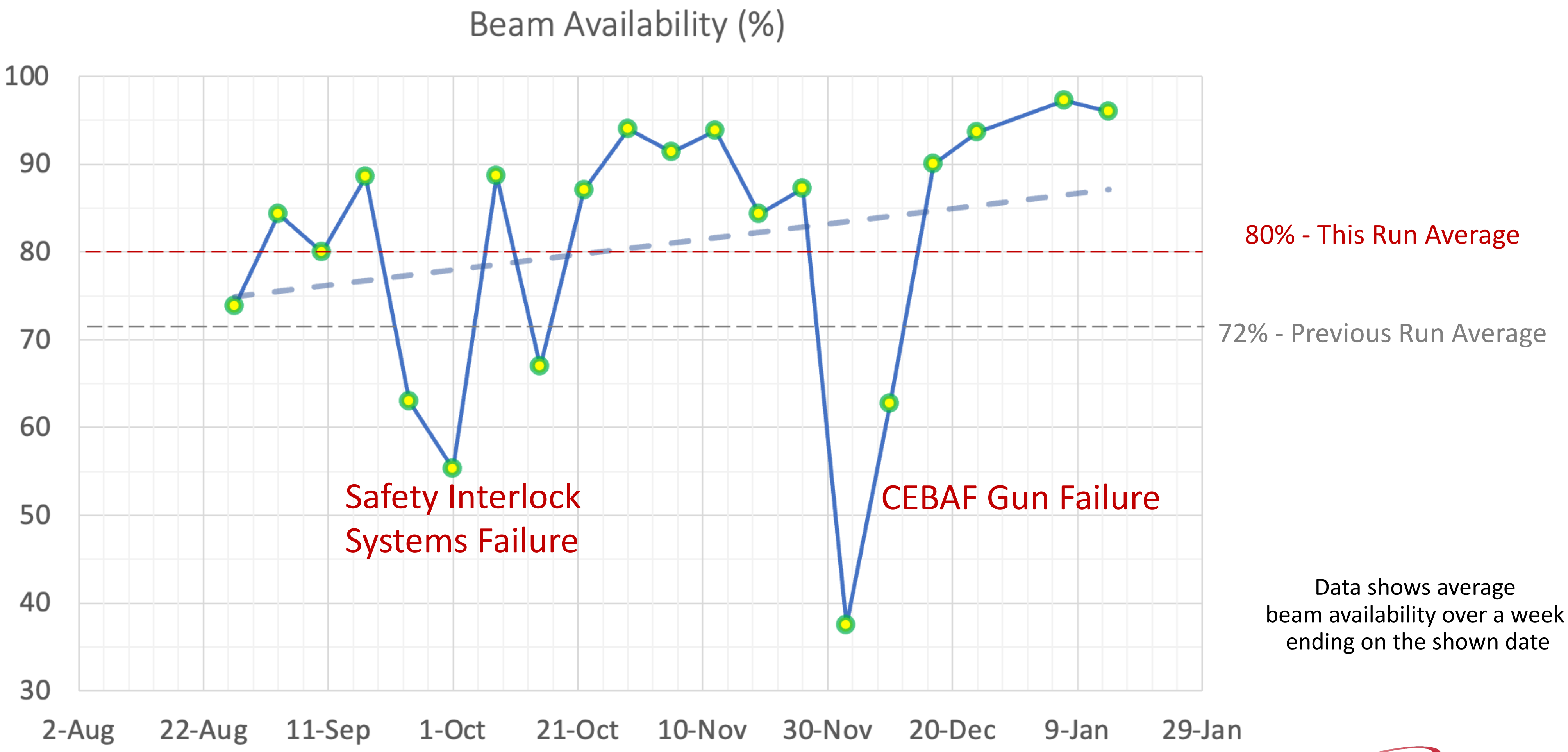
CEBAF Beam Power For 5 Last Years

- 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

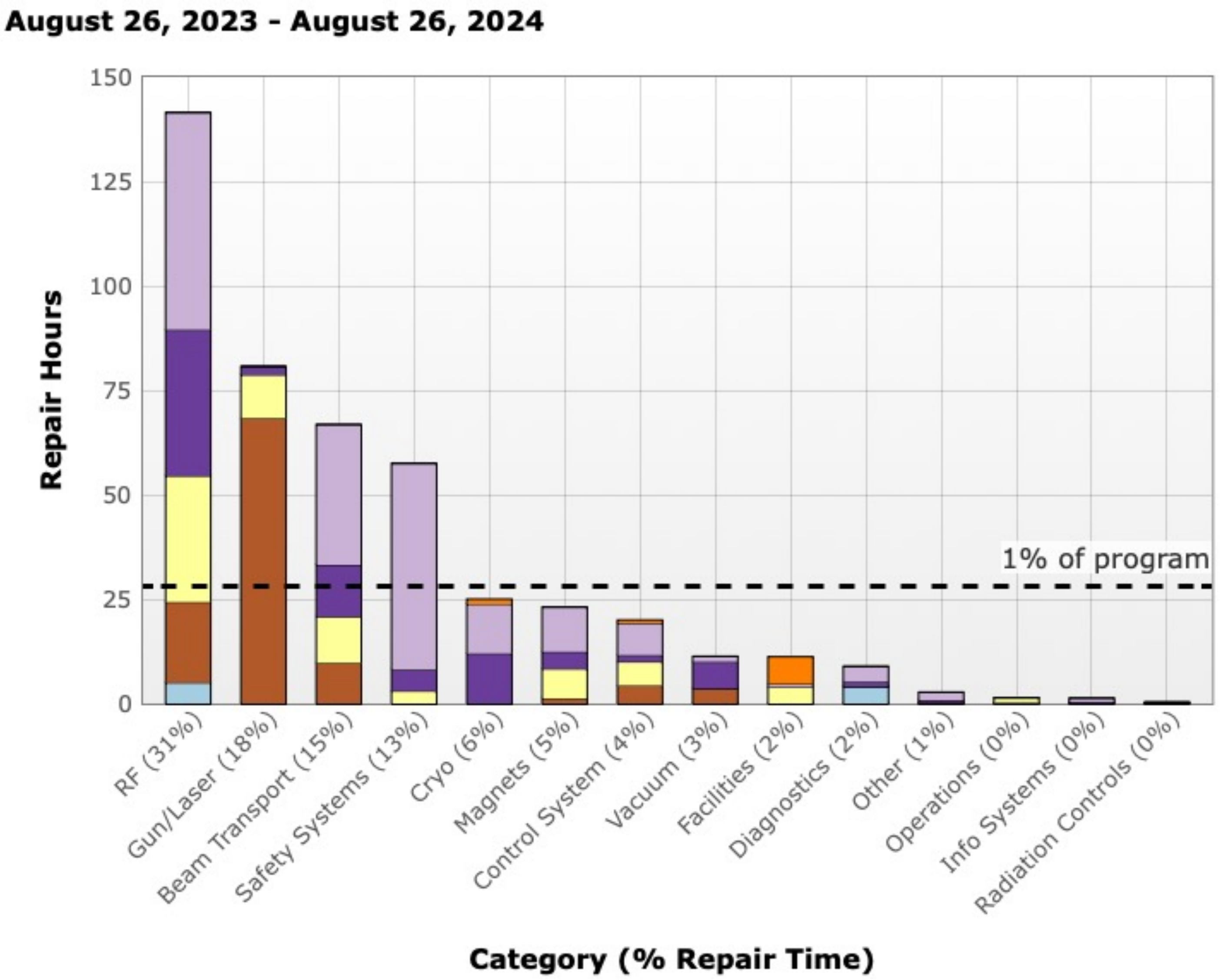


Status of CEBAF Beam Operations: Beam Availability

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



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%

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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

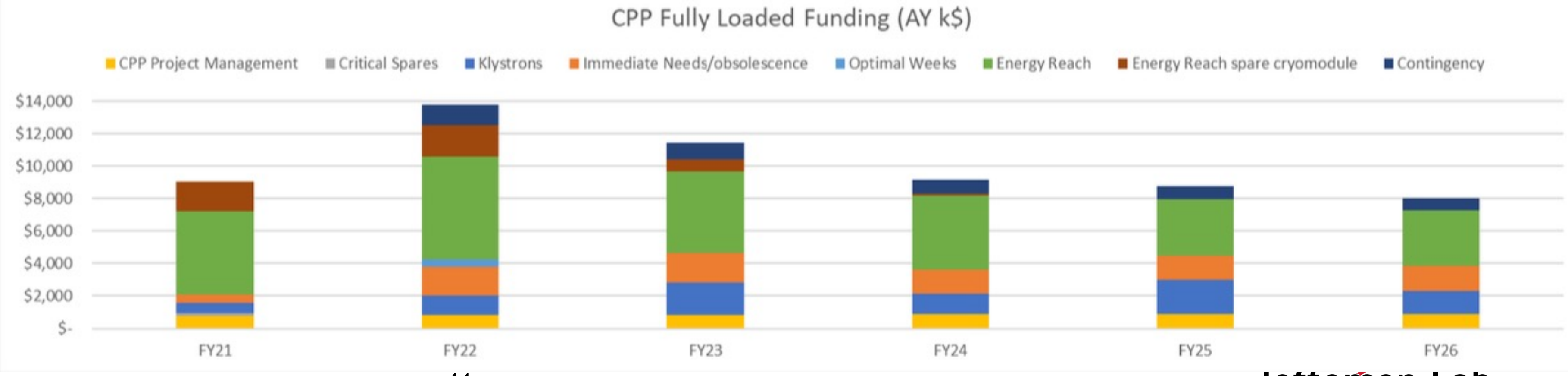
- SRF
  - C100 cavity gradient degradation.
    - Contamination due to degrading Viton seals, field emission, and high radiation
    - Possibly, dark current due to field emission
  - Loss of cryomodules and cavities to vacuum leaks and other events.
  - Cavity faults caused by microphonics and other 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

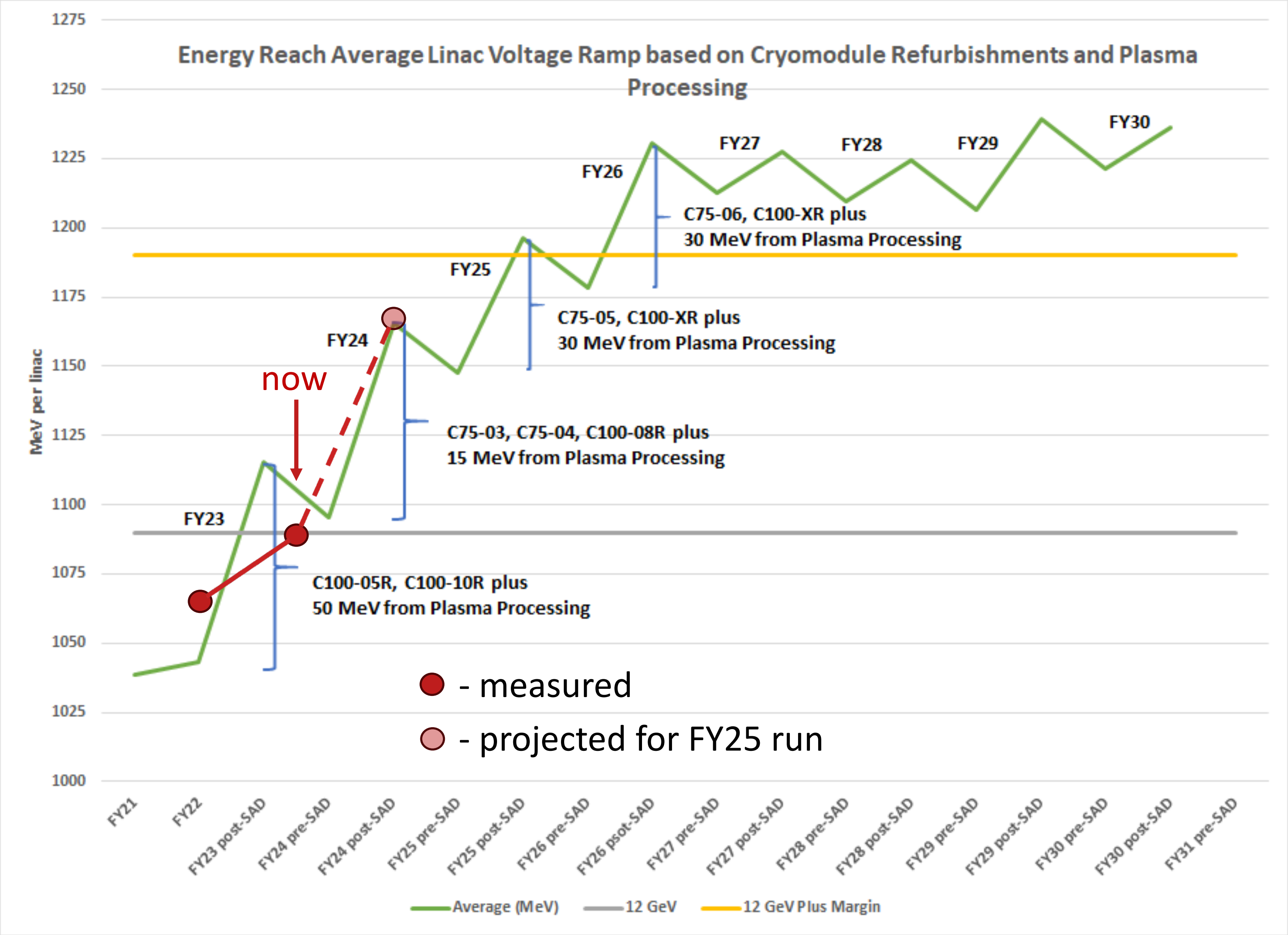
CEBAF Performance Plan (CPP)

- 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.



CEBAF Energy Reach Projection



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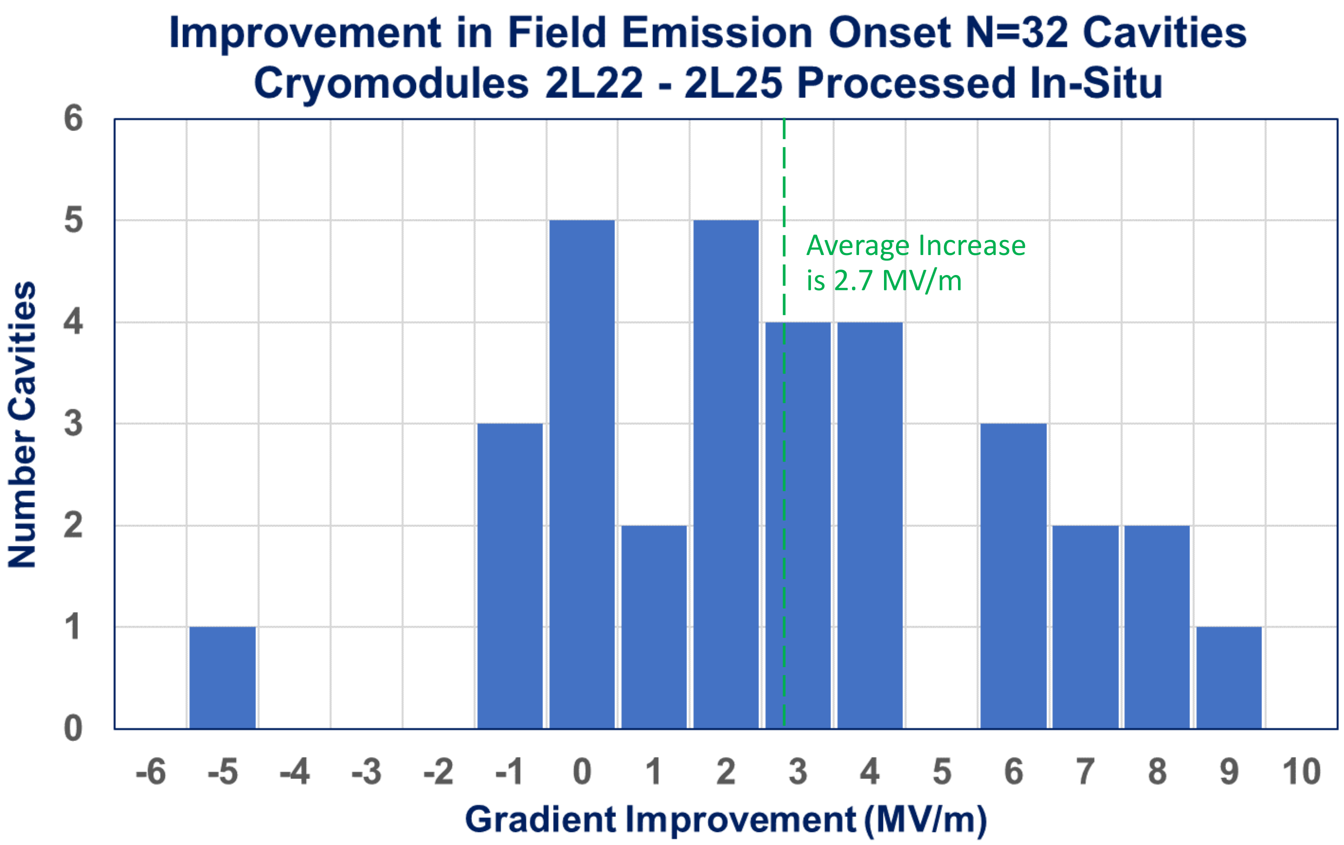
In-Situ Plasma Processing Increased Gradient by 2.7 MV/m



- Four cryomodules, 2L22 - 2L25 (all cavities), were plasma-processed in the tunnel during last SAD
- 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.

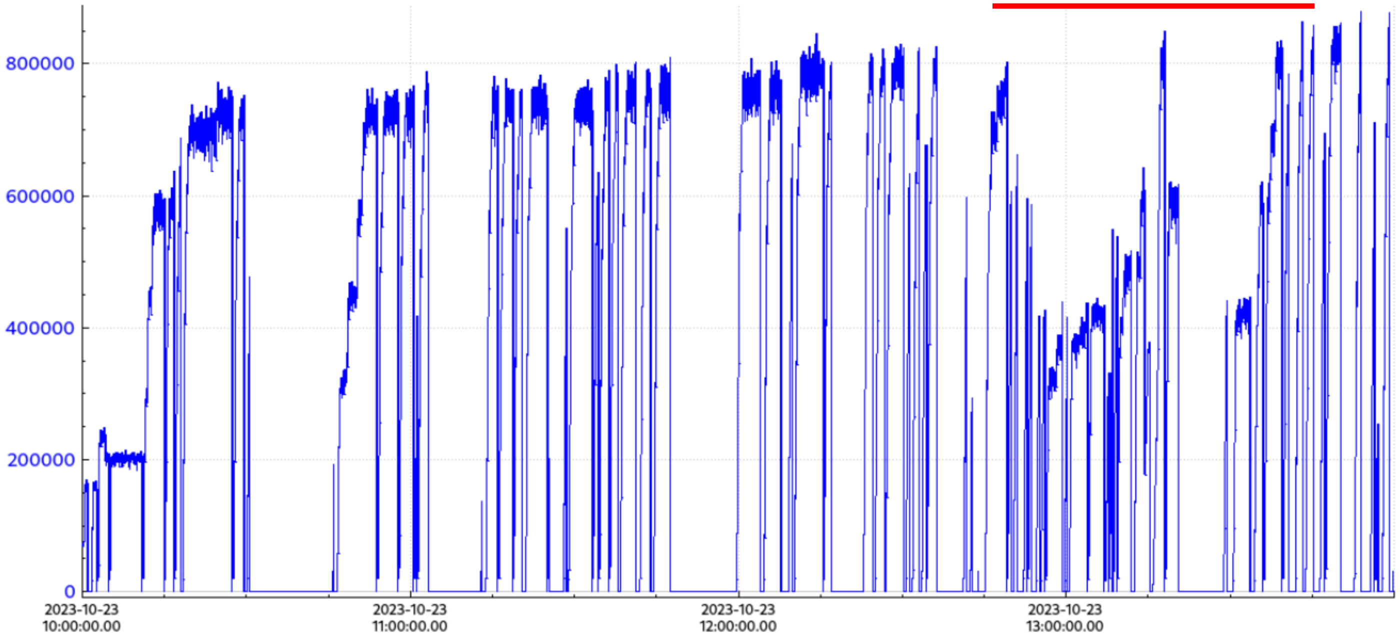
Success of plasma processing supports more aggressive curve for CEBAF energy reach

Probing CEBAF Performance Limits

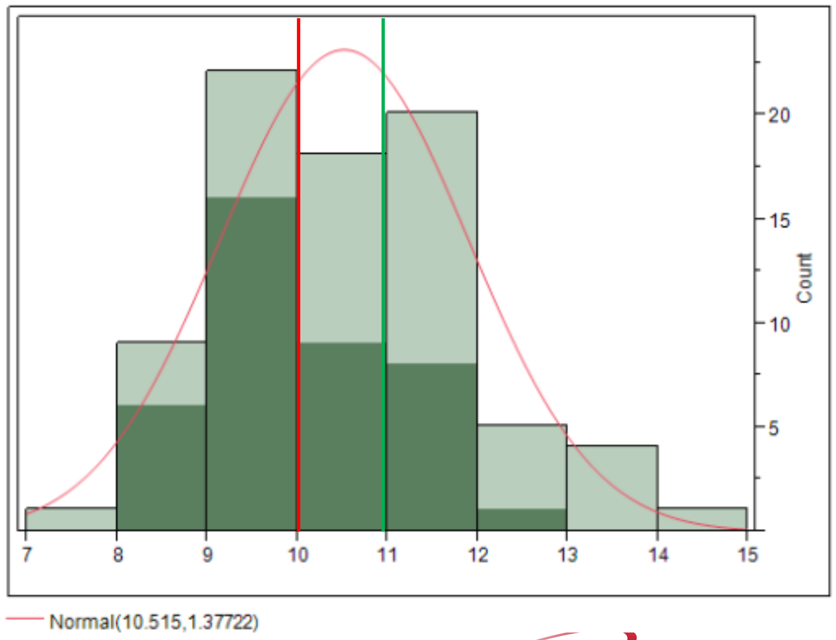
- High intensity run in 10/2023 to identify CEBAF intensity limitations.
- Performance is limited by available RF power. C100 CM klystrons are underperforming.
  - Need at least 10 kW for 1.1 MW
  - Klystrons specified at 13 kW max and 11 kW linear regime

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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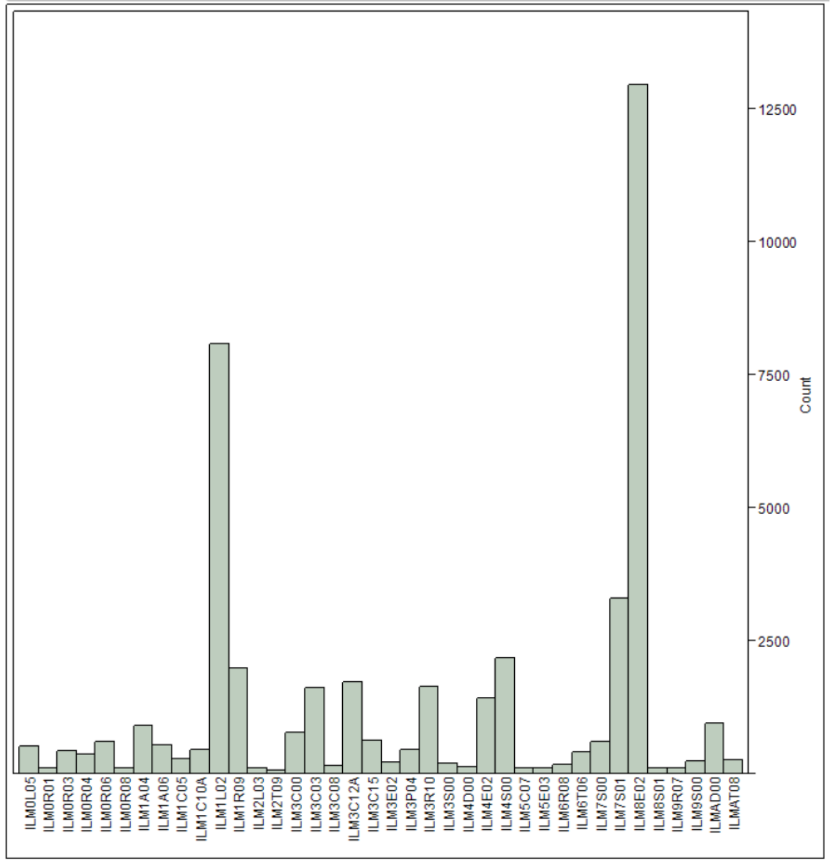
Improving Understanding of Beam Losses

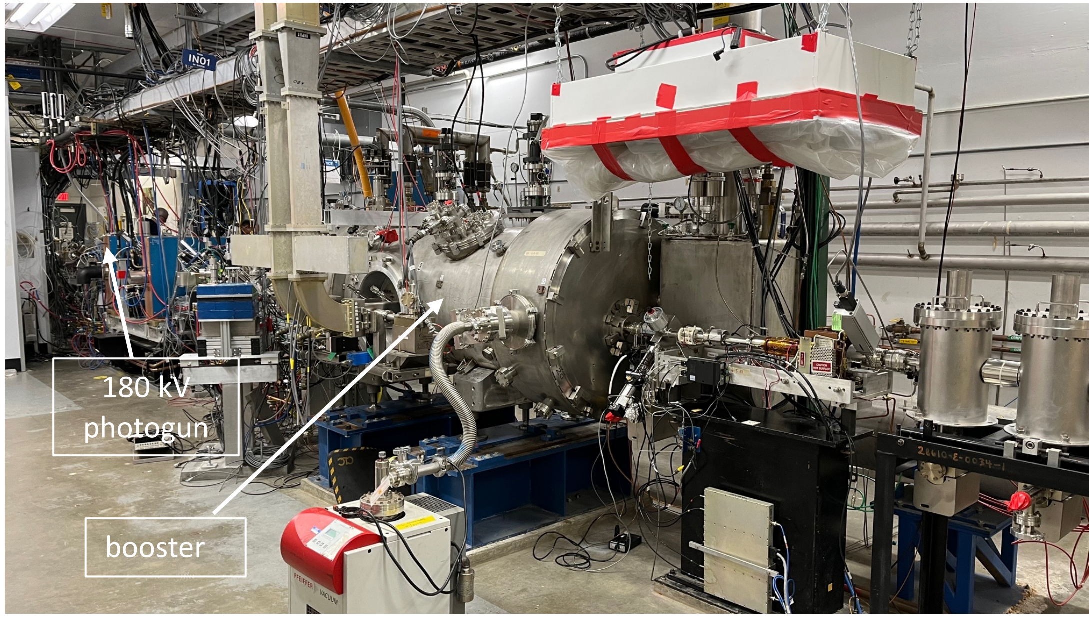
- CEBAF employs original 30-year-old analog BLM system to detect beam losses
  - System adequately protects the machine but is not well suited for understanding or optimization of beam losses
  - PMT voltage settings are likely too conservative
- Near-term approach
  - Procured 8 ion chambers with fast 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.

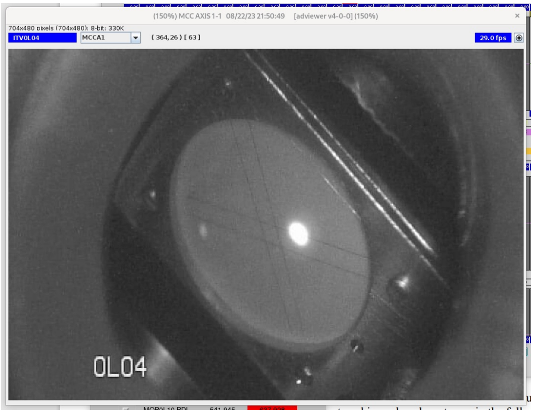


Injector Upgrade Completed

- 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

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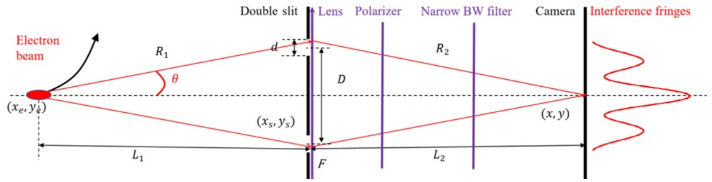
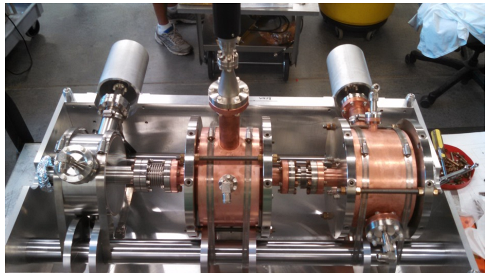
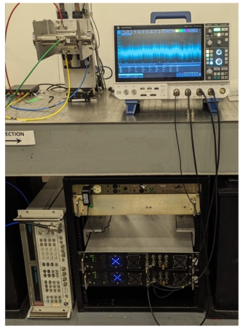
Special Instrumentation Is Developed to Support Future Experiments

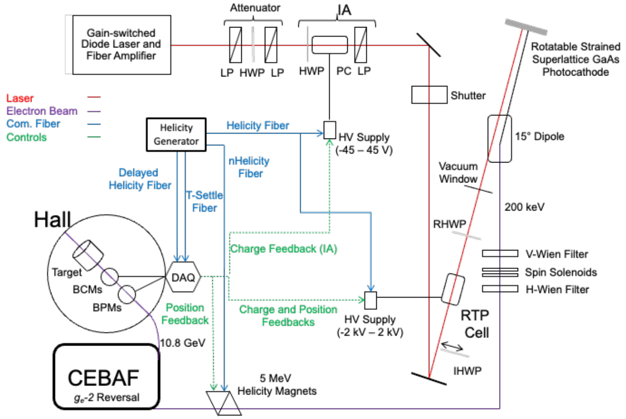
- Electron Beam Energy Spread Monitor
  - Hall C, Hypernuclear experiments
  - 3C12 location
  - Energy resolutions $\sigma E/E \sim 1*10^{-5}$ @ $\geq$ 1 Hz
  - Team is led by Kevin Jordan
- MOLLER Instrumentation
  - Helicity manipulation system
  - Feedback to maintain beam parameters
  - Hall A beam line BPMs
  - Hall A beam line BCMs
  - Instrumentation team: Nathan Rider, Riad Suleiman

Synchrotron Radiation Interferometer (SRI)









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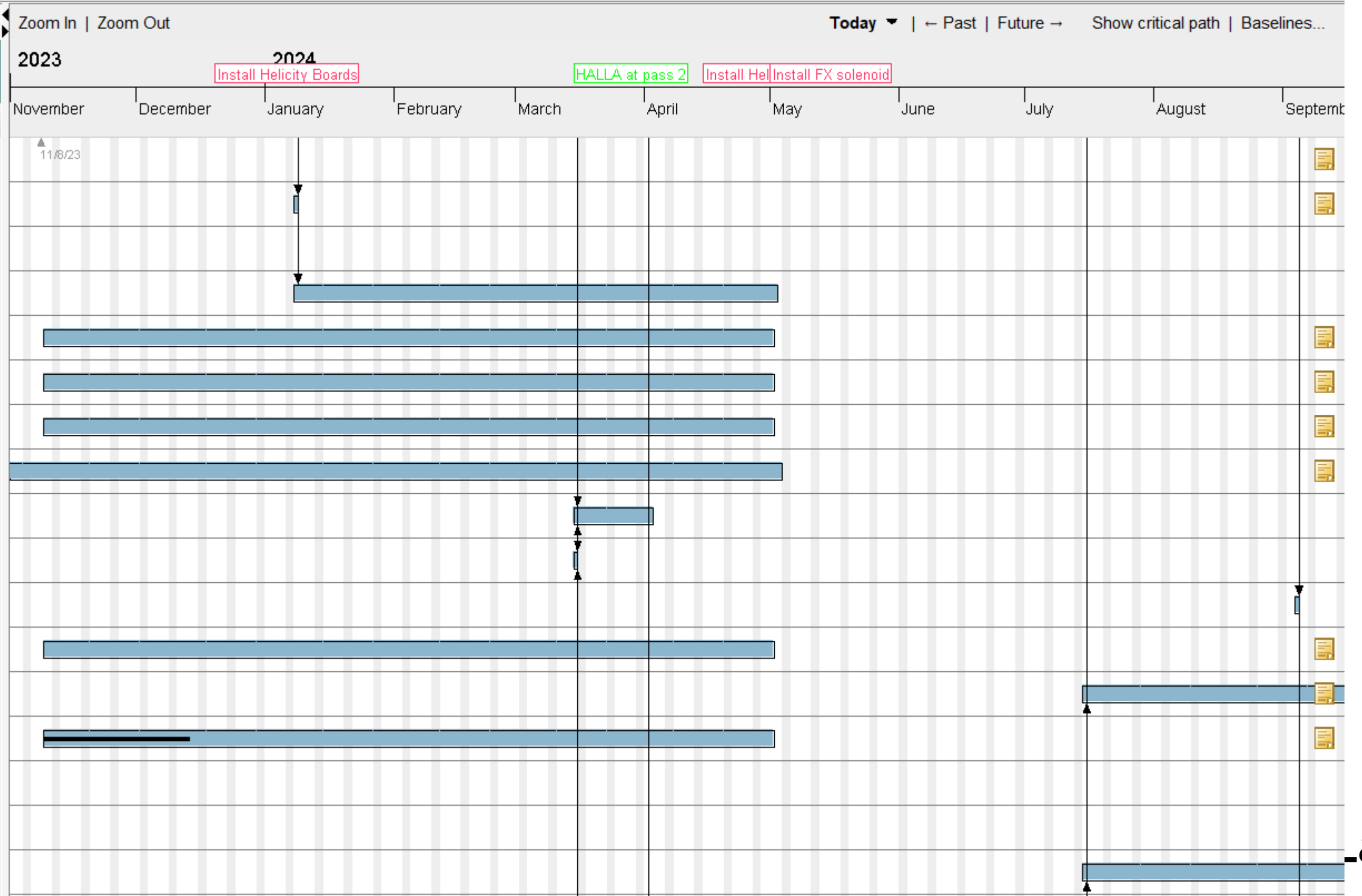
Systematic Machine Studies

- Regular machine studies are focused on but not limited to:
  - Improving understanding of the accelerator (e.g., beam-based RF calibration)
  - Future experiments: MOLLER, K-Long
  - AI/ML

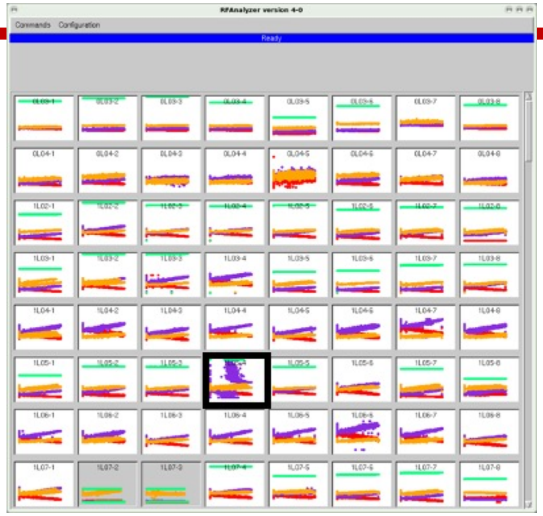
Name	Begin date	End date	Moller ...
transmission test thru FC#2	9/18/24	1/20/25	1
beam noise in injector with new helicity board	1/8/24	1/8/24	2
adiabatic damping with upgraded injector	9/18/24	9/18/24	3
beam monitor resolution assessment at 2Khz i...	1/8/24	5/2/24	4
Solenoid Wien Flip symmetry test	11/9/23	5/1/24	5
Vertical Wien Flip Symmetry test	11/9/23	5/1/24	6
Wien flip frequency study	11/9/23	5/1/24	7
wien angle changes for polarization feedback	10/30/23	5/3/24	8
beam noise in HALLA with new helicity board	3/15/24	4/2/24	9
Hall A BCM resolution study	3/15/24	3/15/24	10
sensitivity measurement of helicity magnets in ...	9/4/24	9/4/24	11
chopper scan	11/9/23	5/1/24	12
transition time measurements for different RTP...	7/15/24	10/2/24	13
RTP cell position differences	11/9/23	5/1/24	14
beam noise test in Hall A at 11 GeV at 2Khz	11/26/24	3/21/25	15
sensitivity measurement of helicity magnets in ...	11/26/24	3/21/25	16
laser properties characterization at pockel cells	7/15/24	10/2/25	17



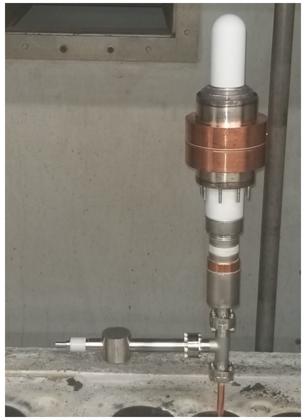
Portfolio of R&D and SBIR-Funded Projects

- 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
- He flowmeter (SBIR, Hyperboloid LLC)
  - Allows for fast and accurate measurement of cavity heat and Q_0
- 1497 MHz Magnetron RF source (SBIR, Muon Inc)
  - Demonstrate feasibility of magnetron as alternative, efficient RF source for CEBAF

Detection of anomalies in cavity field



Helium Mass Flow Monitor



First L-Band tube at Richardson Electronics

Accelerator Improvement Projects (AIPs)

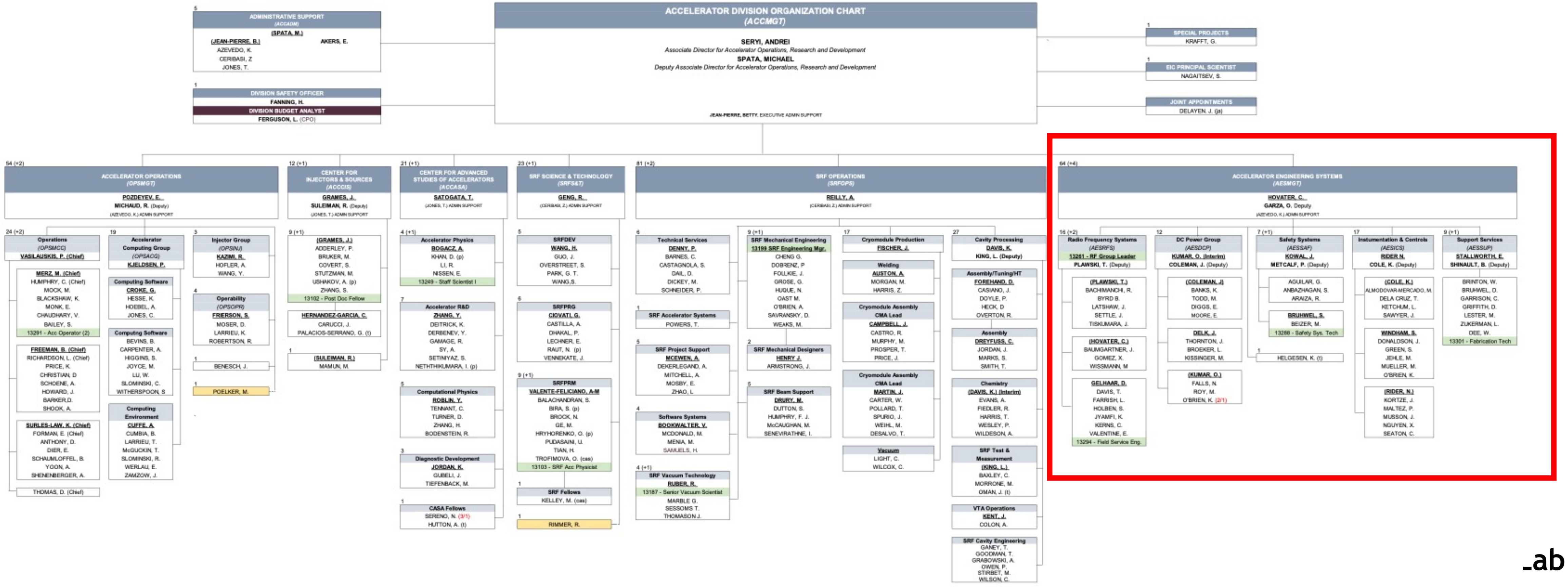
	Total cost	Past Years	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29
LLRF Digital Upgrades	3,739	1,789	660	266	905	40	40	40		
Next Gen BPM Upgrade	4,580				190	1,088	1,122	1,157	1,023	
Global Timing System	1,480								210	1,270
Beam Loss Monitoring System	TBD									
TOTAL (= Funding)	**9799+**		**1,052**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

Accelerator Division Reorganization

- Effective October 1, 2023, DC Power, RF, I&C, Safety Systems, Support Services, Vacuum Technicians, Specific Mechanical Engineering personnel moved from Engineering Division to Accelerator Division
- Goal: align resources, responsibility and accountability for CEBAF operations, maintenance and improvements within a single organization



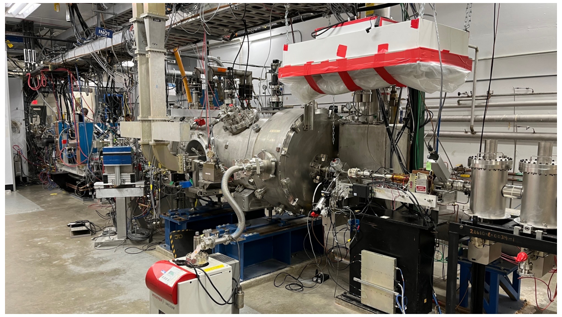
Summary

- CEBAF successfully 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.

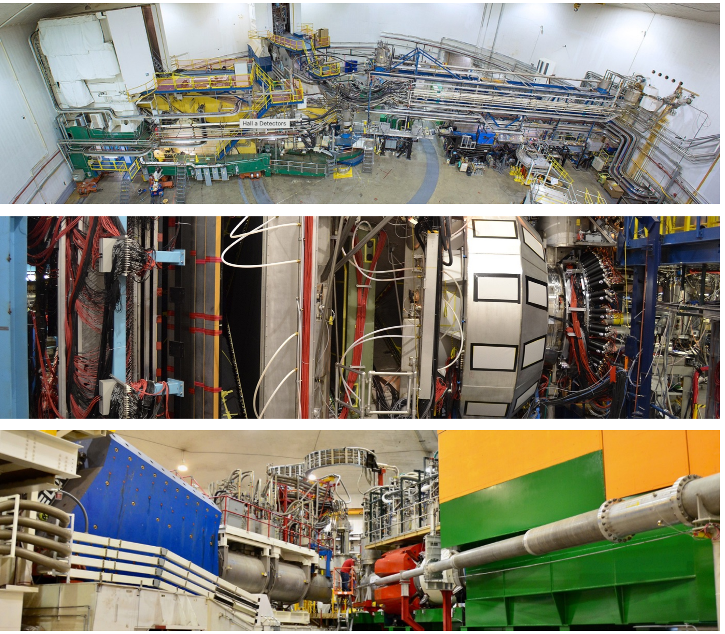
Thank You!

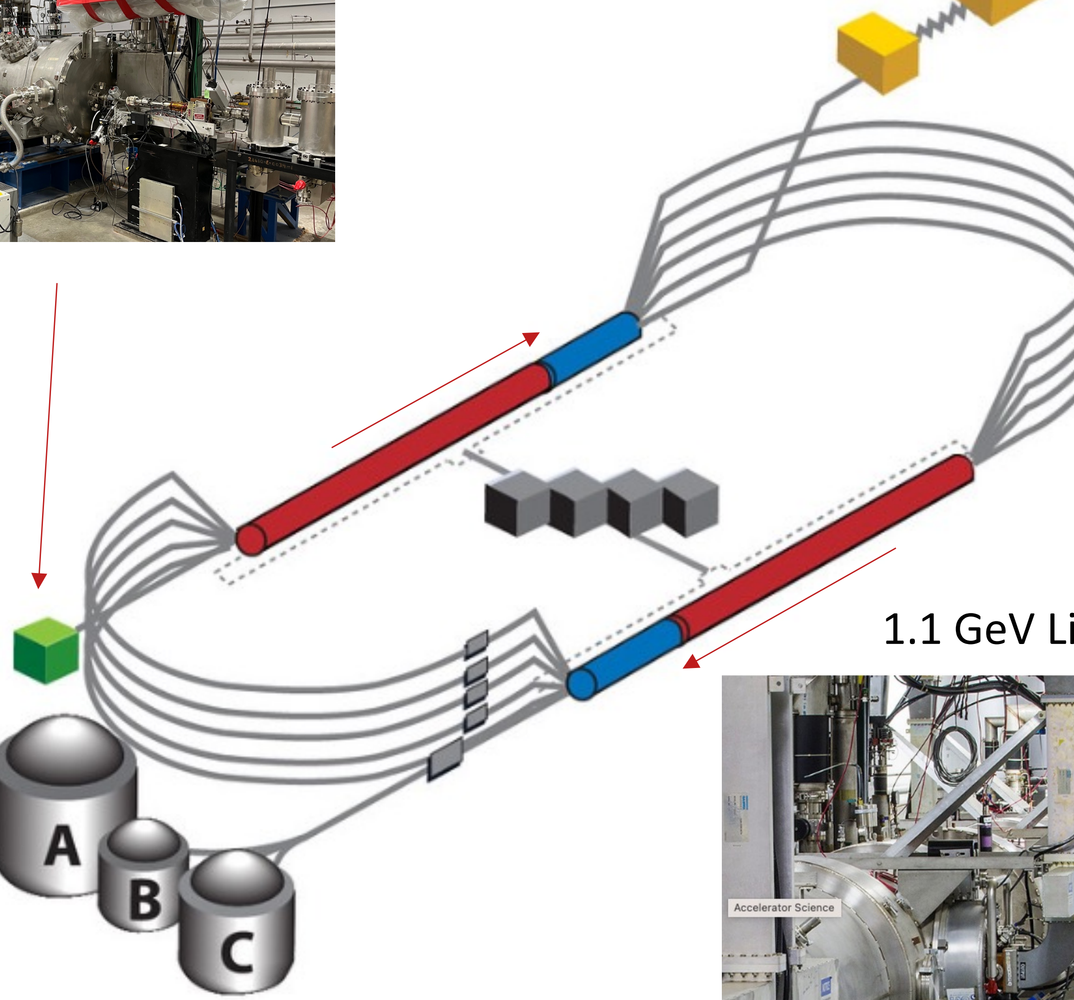
CEBAF Accelerator

Injector



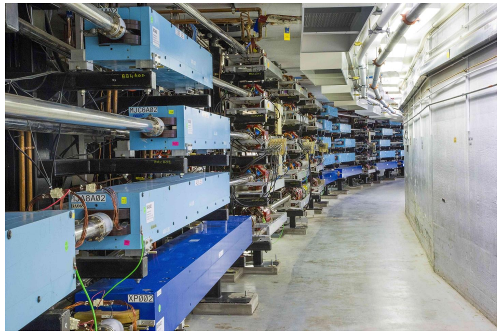
Halls A, B, C





Hall D

5 Magnetic Arcs



1.1 GeV Linac

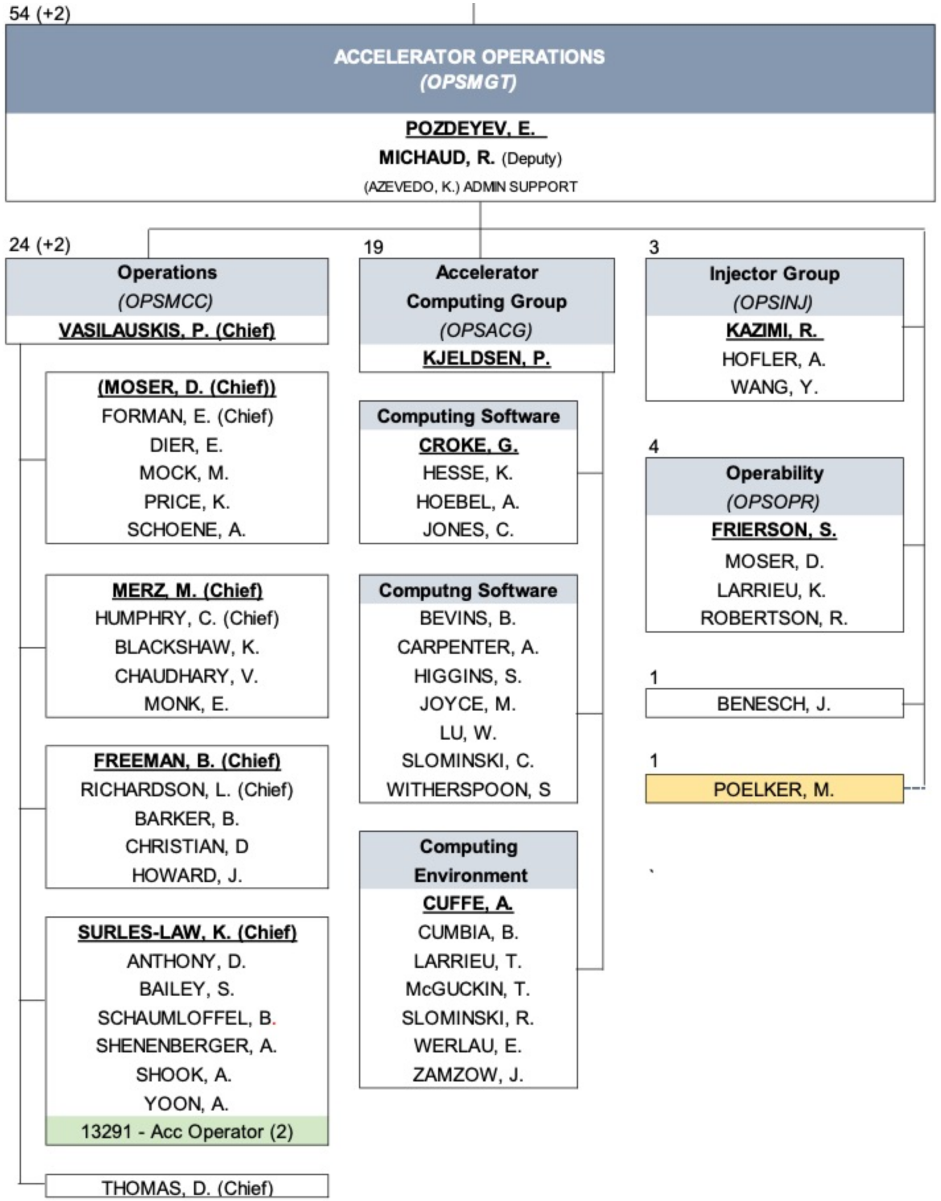
Current Priorities of CEBAF Operations

- 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

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
- Accelerator Operations plan, including updated CPP, is under development

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

How Do CEBAF Operations Compare To Other Facilities

- The Good
  - Close interaction with experimental halls
  - Strong CEBAF operator group and training
  - Work release system (ATLis)
- The Bad
  - Culture of reactive approach to hardware maintenance results in low reliability
  - Inconsistent use of best engineering practices and processes and lack of ownership
- And we really need to think about it…
  - How are we going to upgrade aging infrastructure under present funding and schedule boundary conditions
  - Succession planning