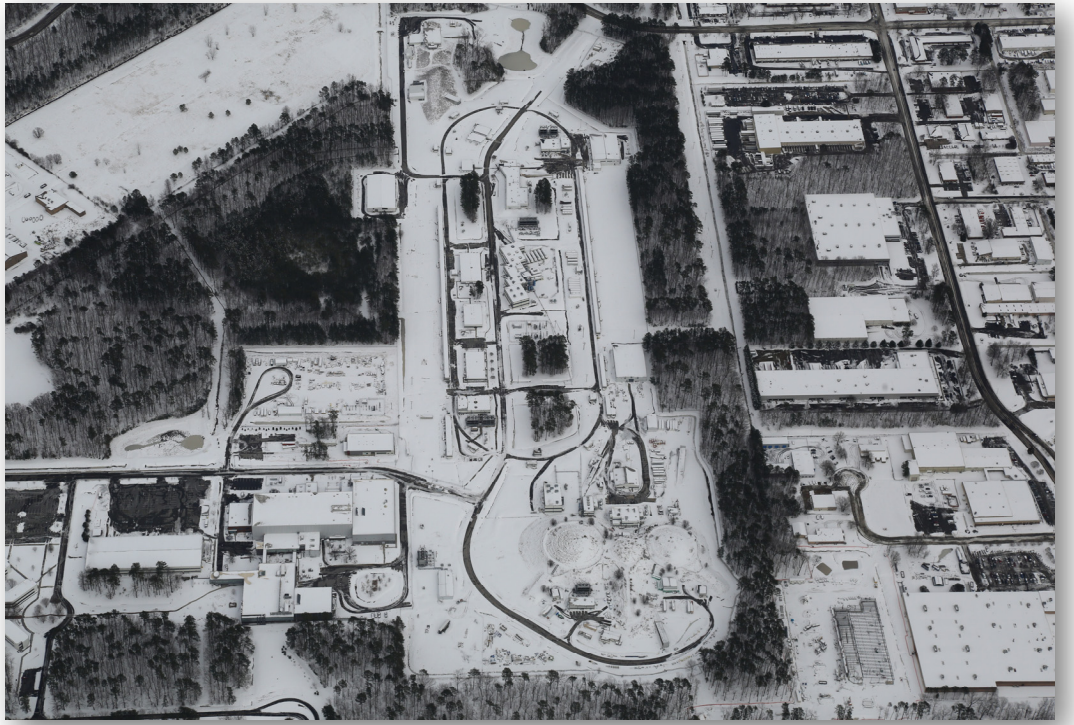
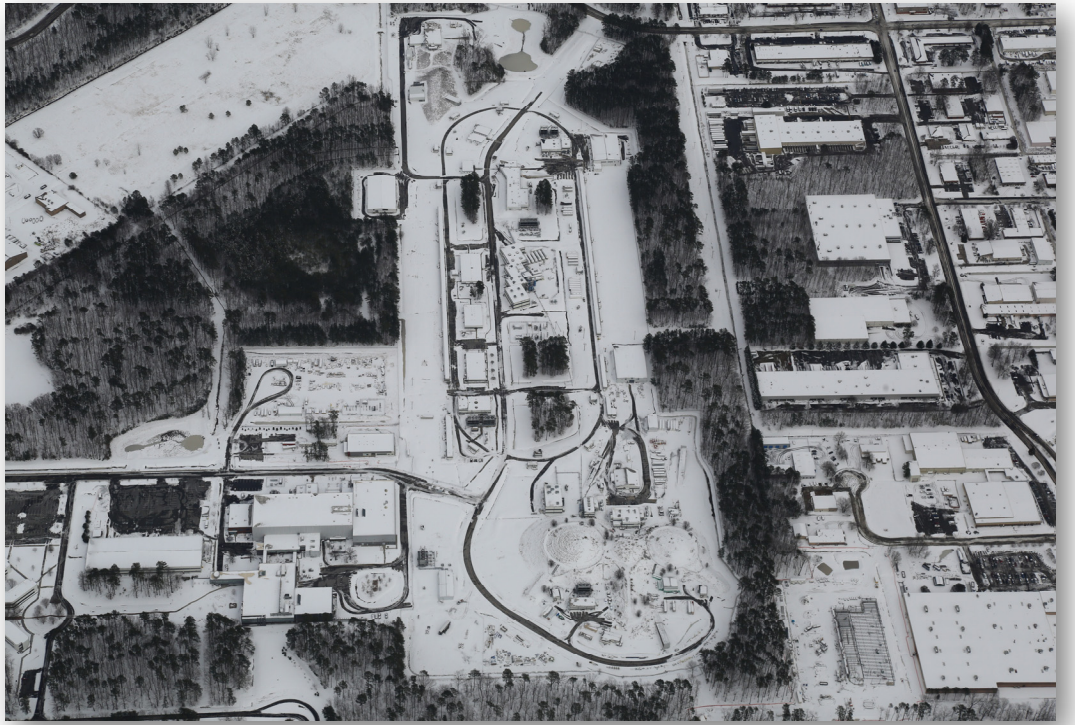
12 GeV CEBAF Initial Operational Experience and Challenges

Michael Spata
Interim Associate Director
Accelerator Division

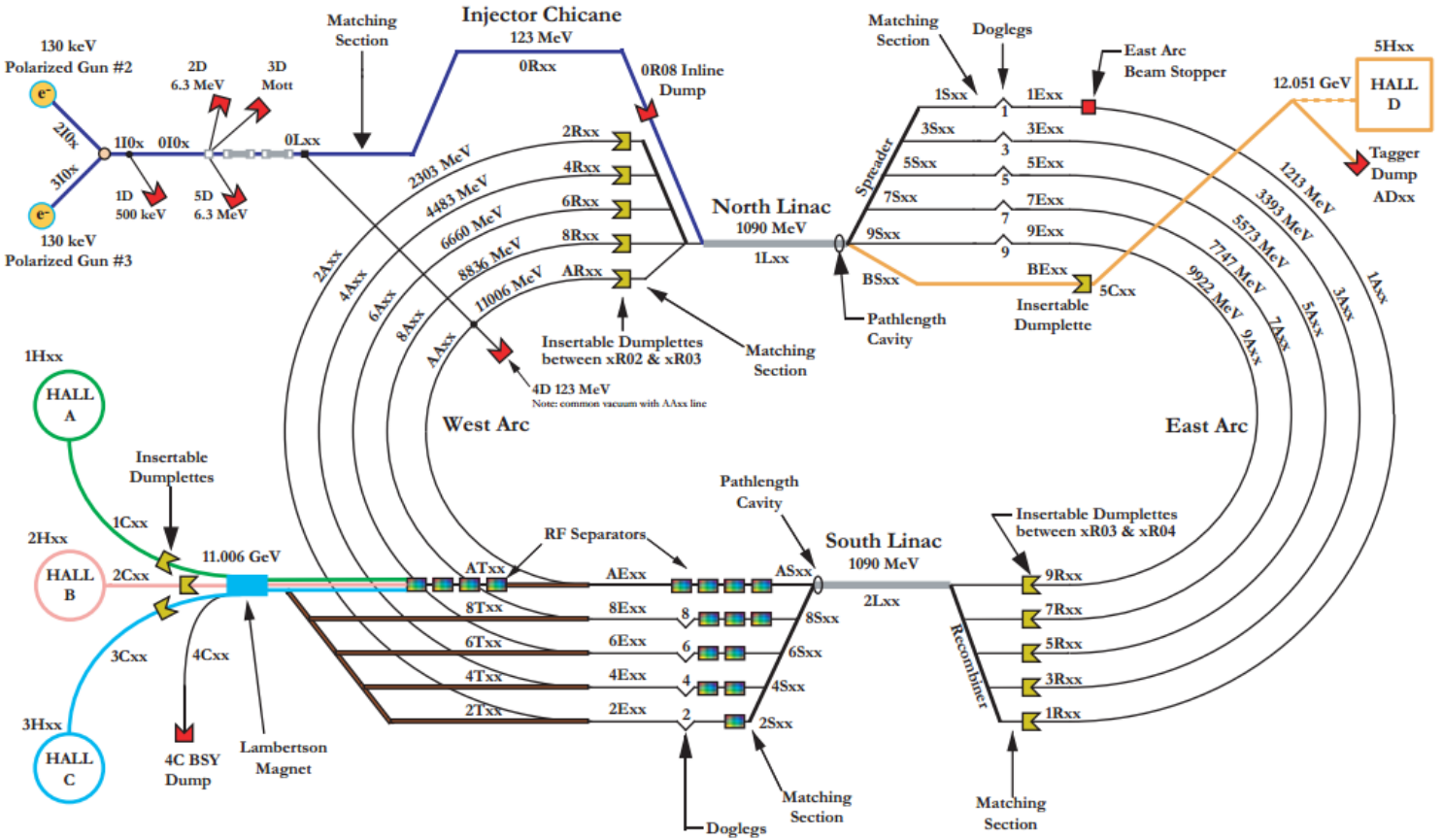


Outline

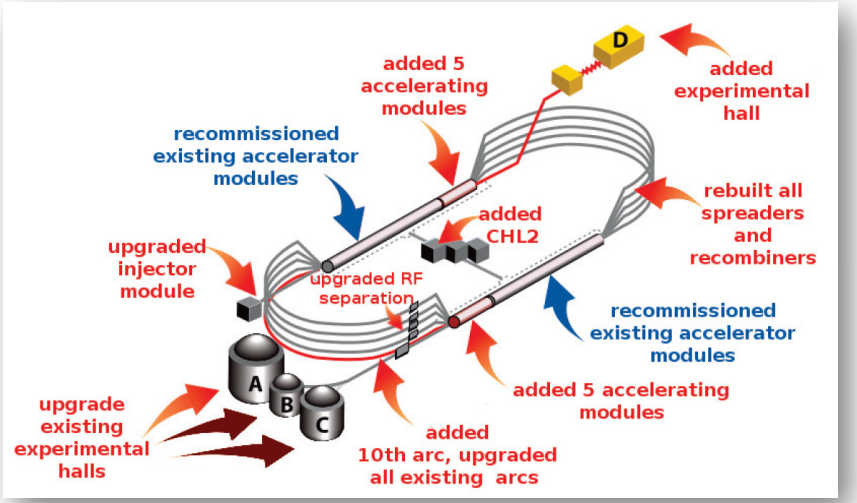
- CEBAF Overview
- 12 GeV Project Completion
- Recent CEBAF Experience
  - Beam Performance
  - 4-Hall Operations
  - Achieving Full Beam Power
- Challenges
  - System Failures
  - Energy Reach
  - Running Weeks
- Future Plans
  - CEBAF Reliability Plan
  - Cryomodule Upgrade Program
  - Injector Upgrade
- Summary



CEBAF Overview



12 GeV Project



CD-0	Mar-2004
CD-1	Feb-2006
CD-2	Nov-2007
CD-3	Sep-2008
CD-4A	Jul-2014
CD-4B	Sep-2017

Approval

Based on the information presented above and at this review, Critical Decision 4, Approve Project Completion, is approved.

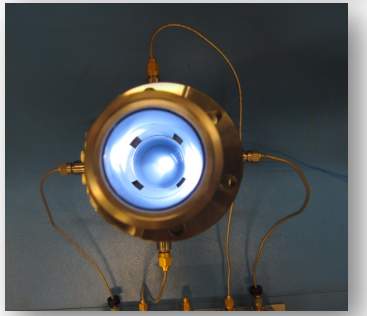
J Binkley — 9/27/17

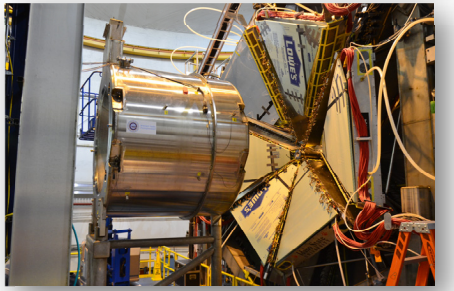
Dr. J. Stephen Binkley
Deputy Director for Science Programs
Office of Science

Date

12 GeV CEBAF Upgrade CD-4B (CD-4) ESAAB Approval — Page 8

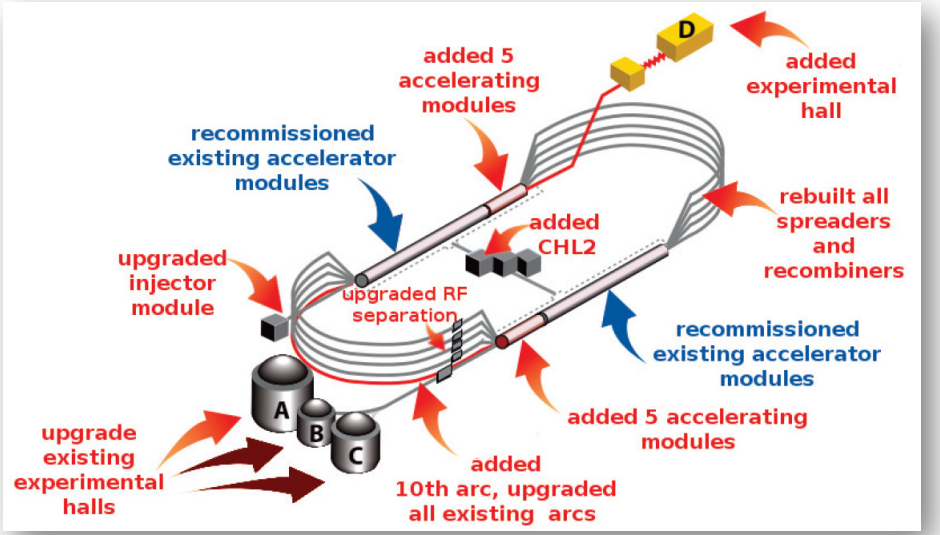
Project Completion Approved September 27, 2017!





12 GeV Project Completion

- Celebration of project completion!
- Keynote address - Honorable Paul M. Dabbar, Department of Energy - Under Secretary for Science
- Live *YouTube* stream of event happening now!



Jefferson Lab

12 GeV CEBAF Upgrade

Dedication Event

May 2, 2018

AGENDA
Arrive at 12:25 p.m.

12:30 p.m.	**Light Lunch for Tour Participants** *(30 min) L102*
1 p.m.	**Tour of Jefferson Lab** *(75 min)* Machine Control Center Tour of Experimental Hall B Tour of Experimental Hall D ***Open Press***
2:15 p.m.	**Project Team and Honored Guest Photo Op** *(15 min) CEBAF Atrium*
2:30 p.m.	**12 GeV Dedication** *(60 min) Auditorium* Honored Guests Jefferson Lab Leadership, staff and scientific Users *Streamed live online via YouTube* ***Open Press***
3:30 p.m.	**Press Availability** *(30 min) L102* ***Note:*** *Formal program continues in auditorium for all other guests/staff/Users with a slide show and presentations from project leaders until the 4 p.m. reception.*
3:30 p.m.	**Physics Project Leader Presentations** *(30 min) Auditorium* *Intro by MC, H. Montgomery (2 min)* *Hall A & C Highlights, C. Keppel (8 min)* *Hall D Highlights, E. Chudakov (8 min)* *Hall B Highlights, L. Elouadrhiri (8 min)*
4 p.m.	**Reception** *(60 min) Atrium* *Light Refreshments*
5 p.m.	**End**

THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY
12000 Jefferson Avenue, Newport News, Virginia 23606
(757) 269-7100 • jlabinfo@jlab.org • www.jlab.org

Jefferson Lab is managed and operated by Jefferson Science Associates, LLC, a joint venture between Southeastern Universities Research Association, Inc., and PAE.

Jefferson Lab

Commissioning Timeline

- 13-year $338M project started in 2004 (CD-0).
- Project development phase 2004-2008 to gain approval of the Conceptual (CD1), Preliminary (CD-2) and Final (CD-3) designs.
- Start of Construction in 2008.
- 6 GeV Nuclear Physics program runs in parallel until May 2012.
- 12 GeV Commissioning starts in 2013.
- Over next four years the Key Performance Parameters for Accelerator/Hall A/Hall D (2014), Hall B/C (2017) were demonstrated.
- Simultaneous 4-Hall and full power operations achieved during the spring 2018 run period.

Milestone	Date
CD-0 Mission Need	March 2004
CD-1 Alt. Selection and Cost Range	May 2004
CD-2 Approve Performance Baseline	Nov. 2007
CD-3 Start of Construction	Sep. 2008
End of 6 GeV CEBAF Operations	May 2012
Start of 12 GeV Commissioning	Dec. 2013
Accelerator/Hall A KPP Achieved	May 2014
CD-4A Start of Initial Operations	July 2014
Hall D KPP Achieved	Dec. 2014
Hall B KPP Achieved	Feb. 2017
Hall C KPP Achieved	March 2017
CD-4B Full Ops-Project Complete	Sep. 2017
Four Hall Operations	Jan. 2018
Full Power Operations	April 2018

Physics Program in the 12 GeV Era

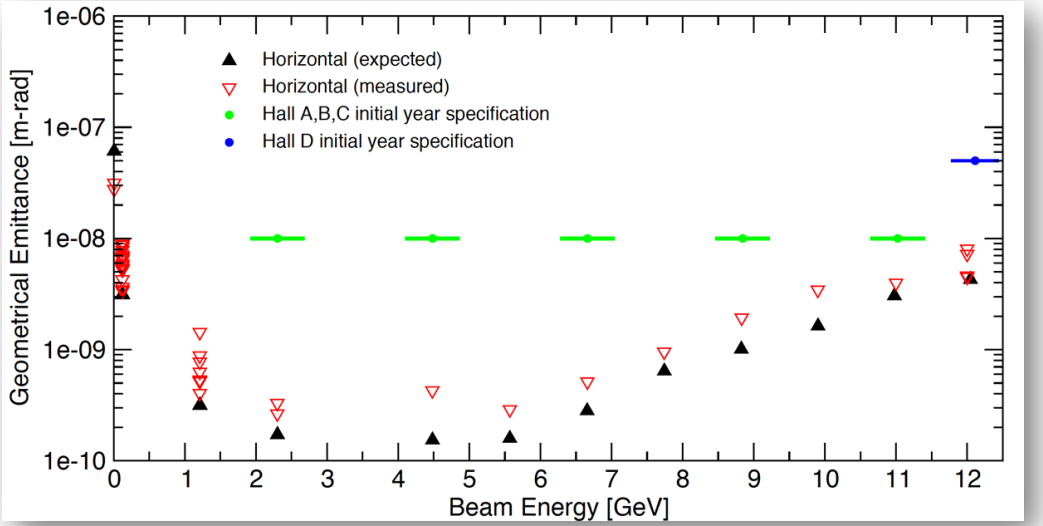
- Fall 2014 – Spring 2015: 5 GeV & 10 GeV
  - Hall A DVCS
  - Hall B HPS
  - Hall D/GlueX Commissioning
- Spring 2016: 12 GeV
  - Hall A DVCS, Form Factors
  - Hall B HPS
  - Hall D/GlueX Commissioning
- Spring 2017: 11.65 GeV
  - Hall A DVCS, GMP
  - Hall B HPS, PRAD
  - Hall B CLAS12 Project KPP
  - Hall C SHMS Project KPP
  - Hall D/GlueX Physics
- Fall 2017: 11.65 GeV
  - Hall A Short Range Correlations (tritium)
  - Hall B Engineering Run
  - Hall C Commissioning
  - Hall D/GlueX Physics
- Spring 2018: 11.65 GeV
  - Hall A Marathon
  - Hall B Engineering Run, Run Group A
  - Hall C Commissioning, Color Transparency, S2
  - Hall D D/GlueX Physics

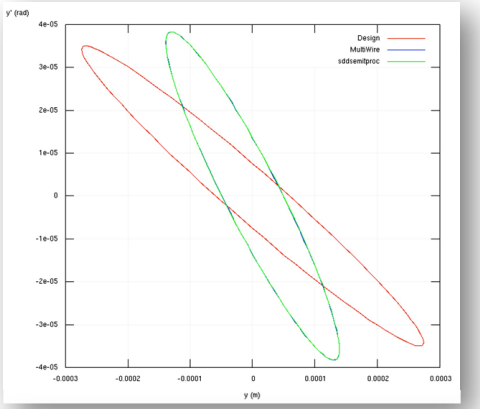
Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
Hadron spectra as probes of QCD	0	3	1	3	0	**7**
Transverse structure of the hadrons	5	4	3	1	0	**13**
Longitudinal structure of the hadrons	2	3	6	0	0	**11**
3D structure of the hadrons	5	9	7	0	0	**21**
Hadrons and cold nuclear matter	7	3	7	0	1	**18**
Low-energy tests of the Standard Model	3	1	0	1	1	**6**
Total	**22**	**23**	**24**	**5**	**2**	**76**
Total Experiments Completed	**2.5**	**1.1**	**0**	**0.4**	**0**	**4.0**
Total Experiments Remaining	**19.5**	**21.9**	**24**	**4.6**	**2**	**72.0**

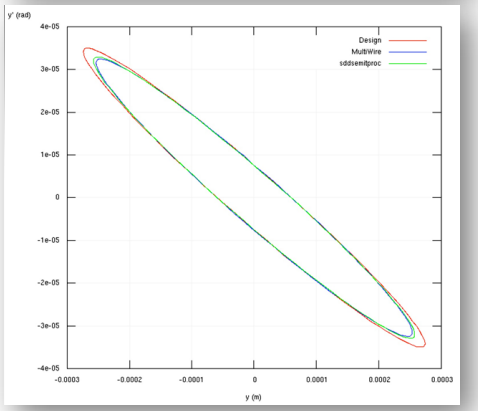
The 12 GeV Nuclear Physics Program is underway!

Beam Tuning Success

- Model vs. Machine convergence met initial and out-year specifications very early in the Commissioning Program
- Beam envelope matching application for collecting quad scan data and computing twiss functions at the entrance of each ARC back-propagated to matching section
- AutoQuad application for beam-based determination of quadrupole centers
- AutoSteer application to minimize orbit errors in arcs and across multi-pass linacs
- Automated Dispersion Correction application ready to be released
  - Please visit Dennis Turner's poster Thursday afternoon: THPML094 - New Methods for Dispersion Measurement and Correction for 12GeV CEBAF







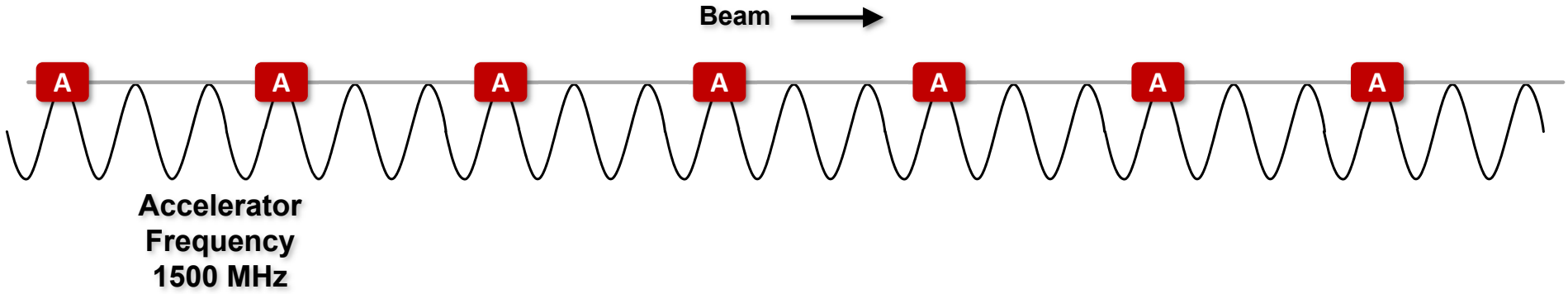
Phase Space Before and After Rematch

Jefferson Lab

Simultaneous Four-Hall Capability: 1st – 4th Pass Horizontal Separation

Hall Lasers

Hall A: 500 MHz

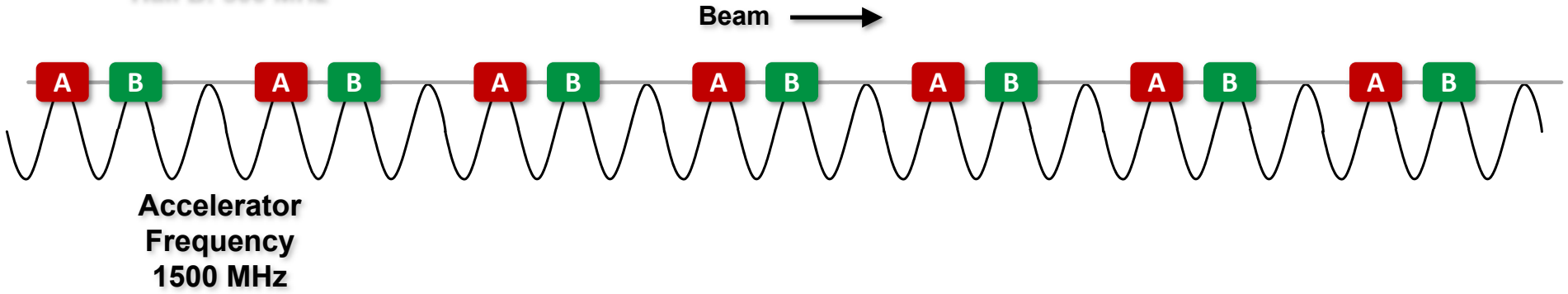


Simultaneous Four-Hall Capability: 1st – 4th Pass Horizontal Separation

Hall Lasers

Hall A: 500 MHz

Hall B: 500 MHz



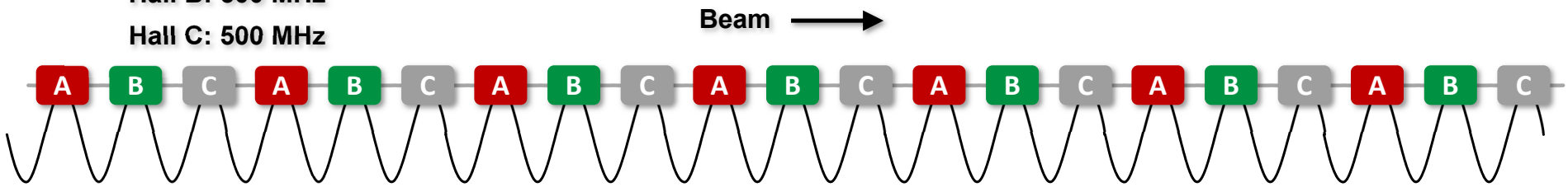
Simultaneous Four-Hall Capability: 1st – 4th Pass Horizontal Separation

Hall Lasers

Hall A: 500 MHz

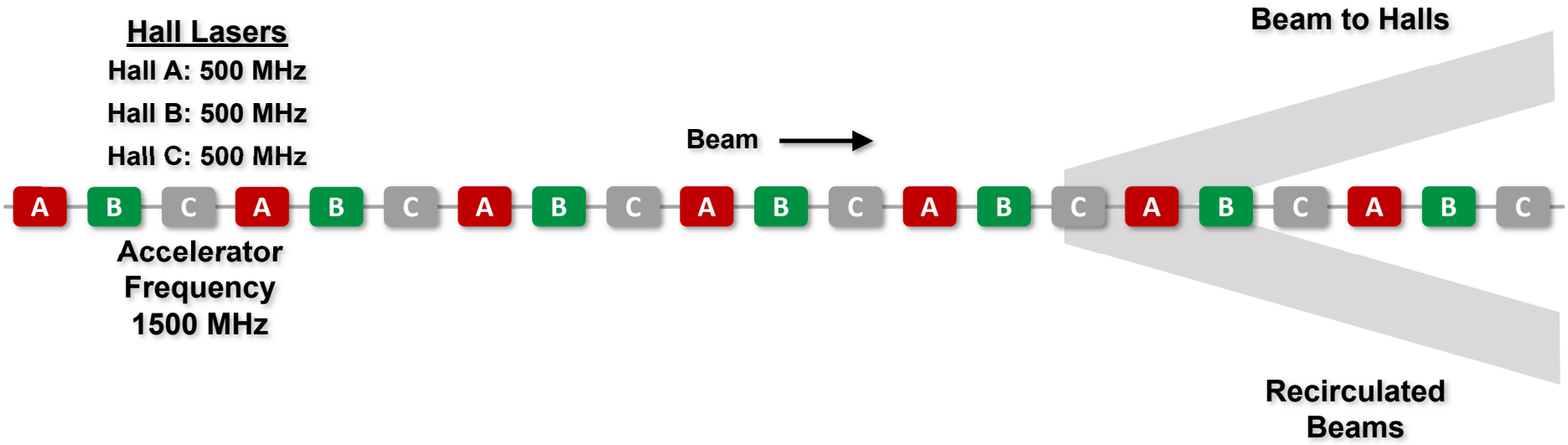
Hall B: 500 MHz

Hall C: 500 MHz

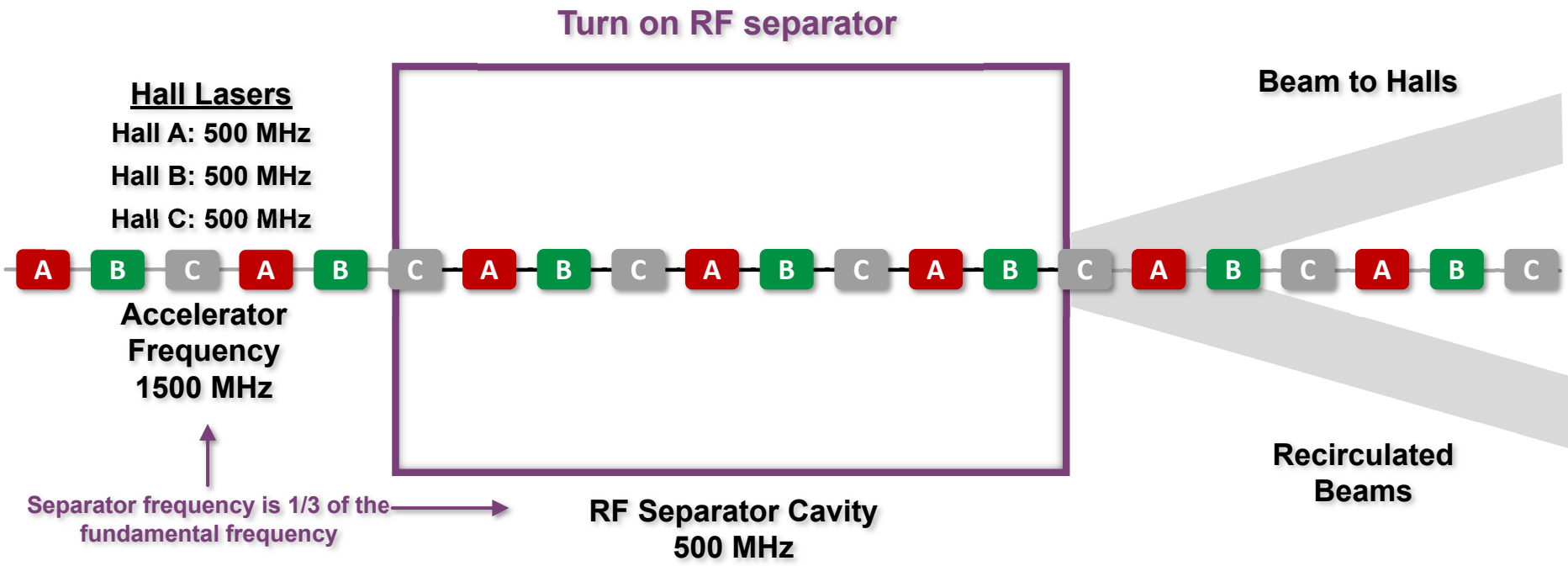


Accelerator Frequency 1500 MHz

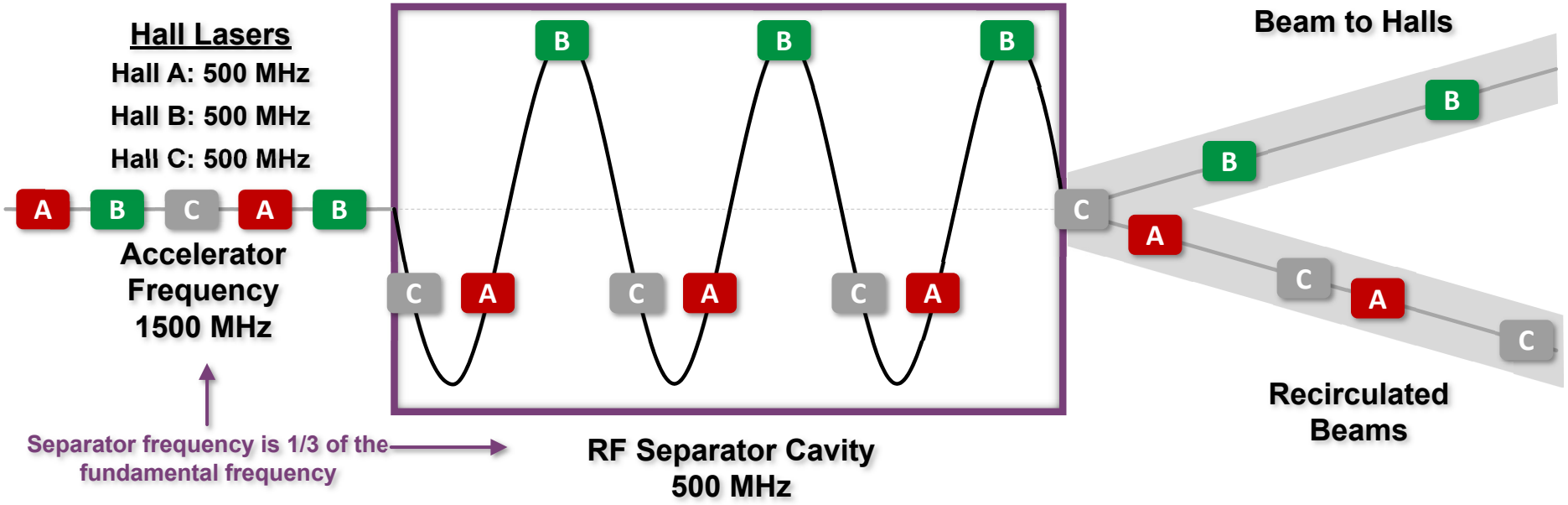
Simultaneous Four-Hall Capability: 1st – 4th Pass Horizontal Separation



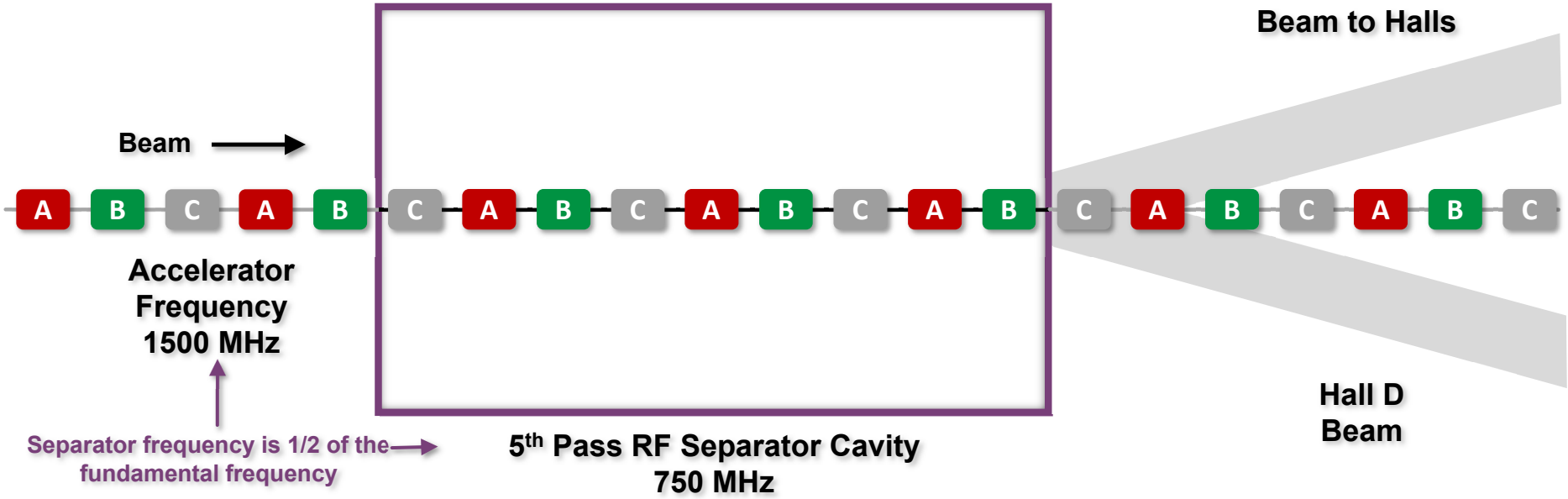
Simultaneous Four-Hall Capability: 1st – 4th Pass Horizontal Separation



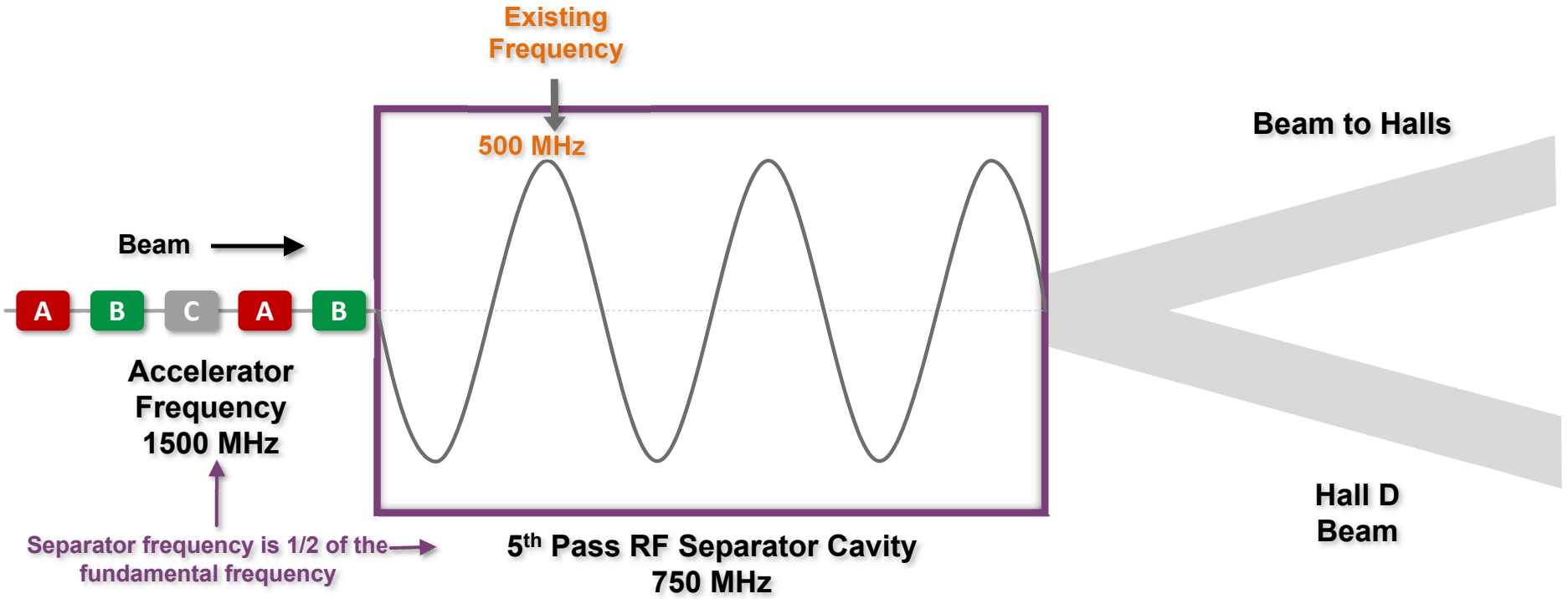
Simultaneous Four-Hall Capability: 1st – 4th Pass Horizontal Separation



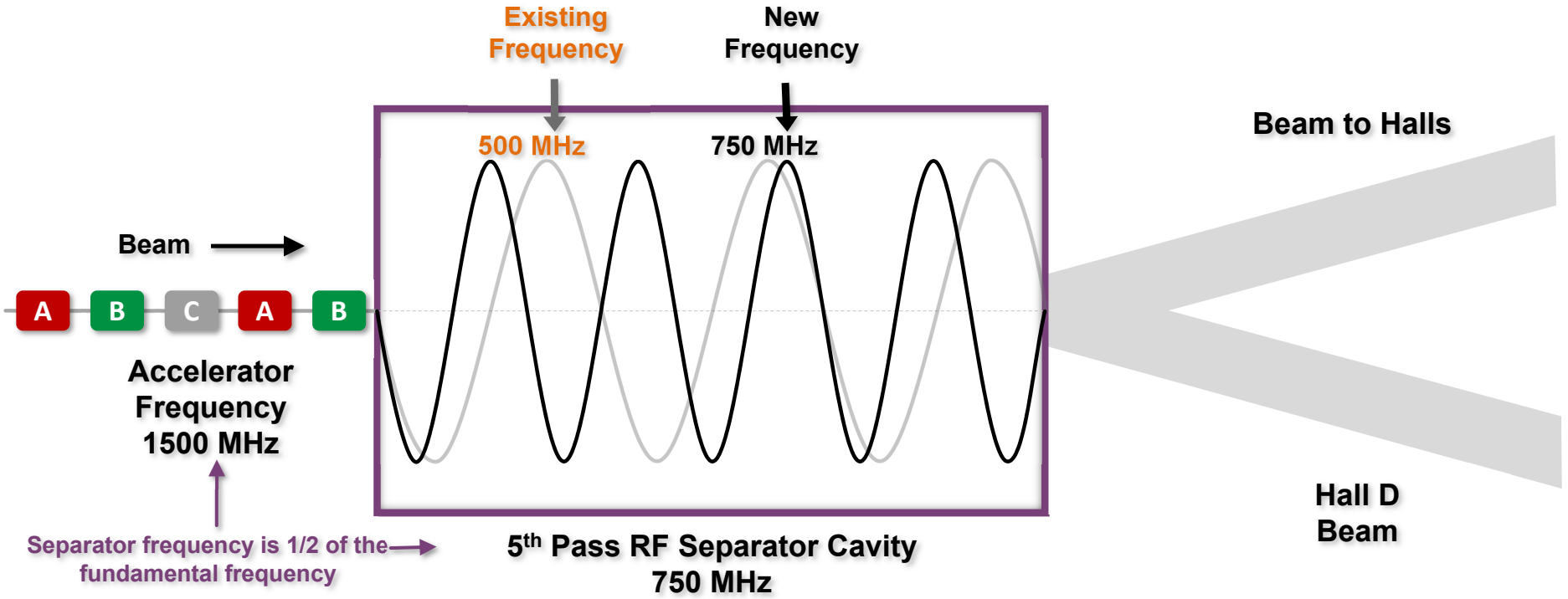
Simultaneous Four-Hall Capability: 5th Pass Horizontal Separation



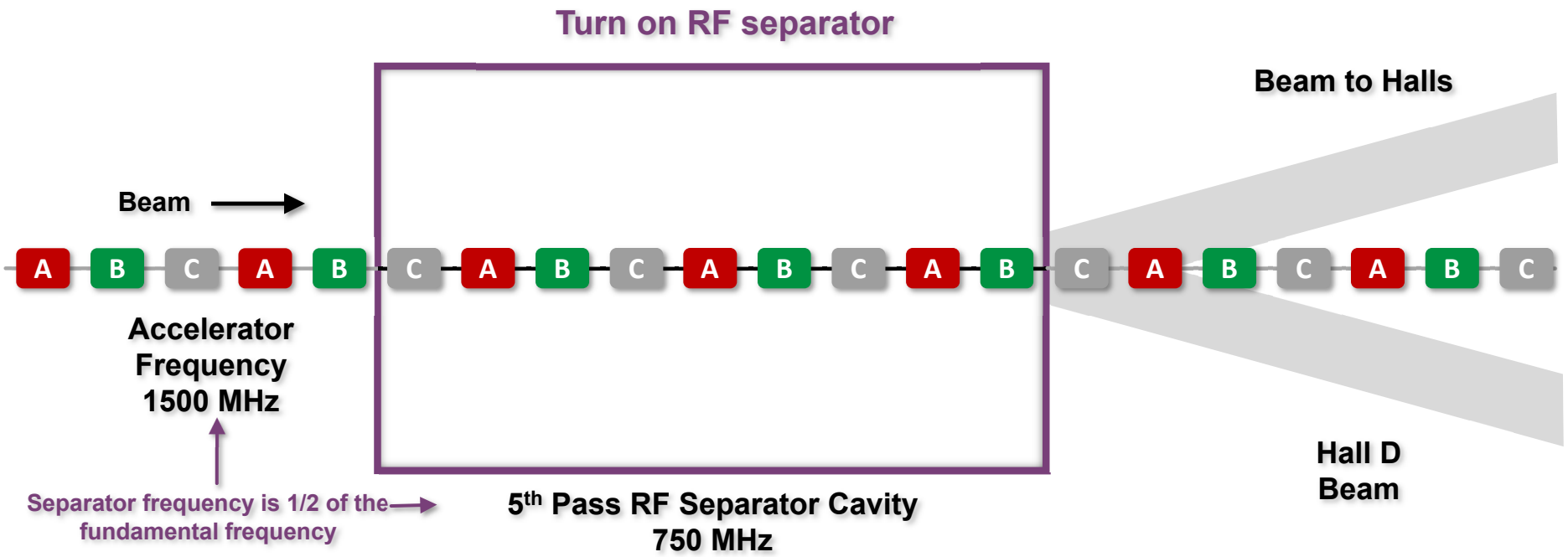
Simultaneous Four-Hall Capability: 5th Pass Horizontal Separation



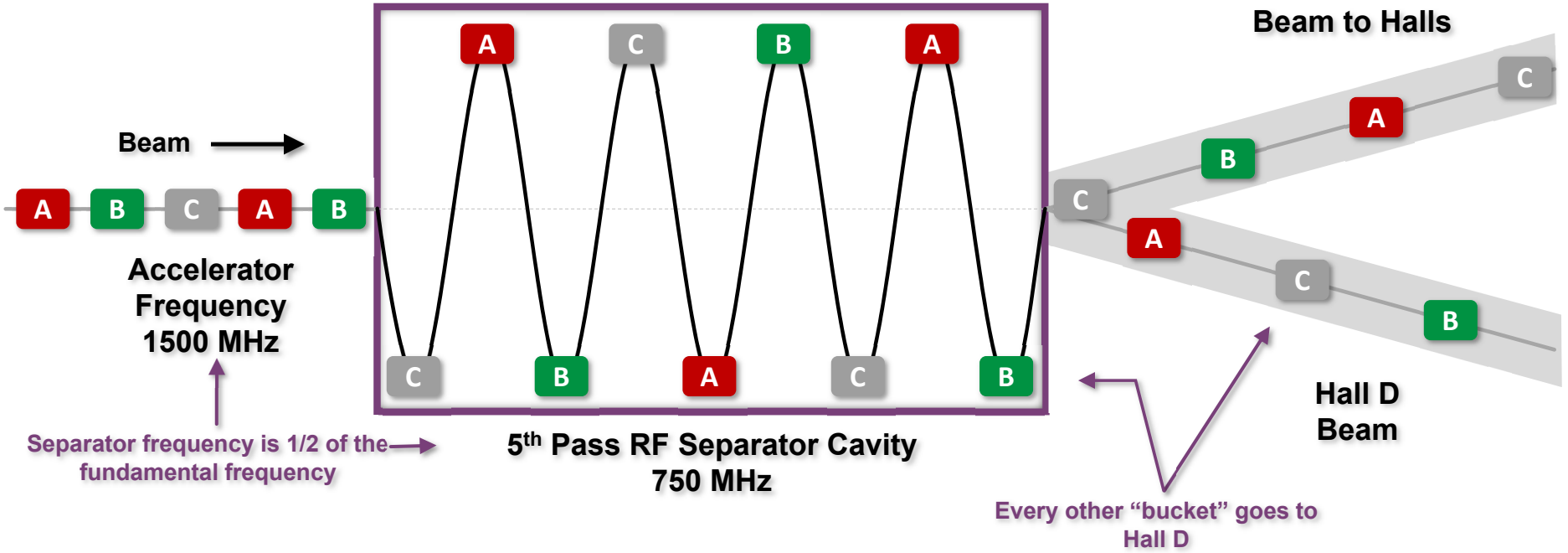
Simultaneous Four-Hall Capability: 5th Pass Horizontal Separation



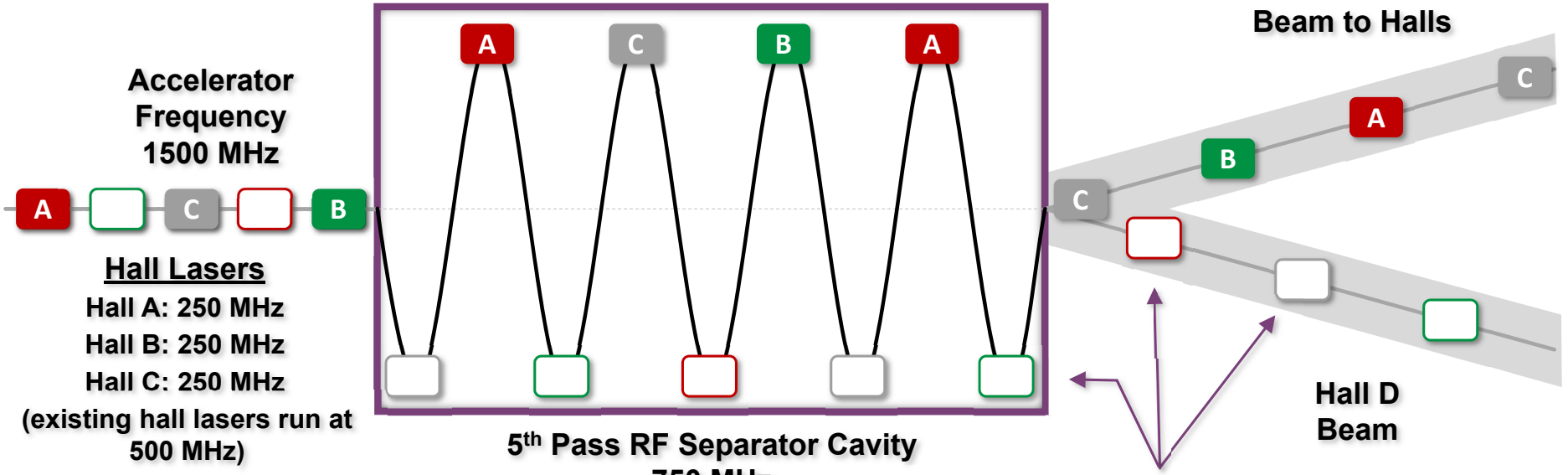
Simultaneous Four-Hall Capability: 5th Pass Horizontal Separation



Simultaneous Four-Hall Capability: 5th Pass Horizontal Separation

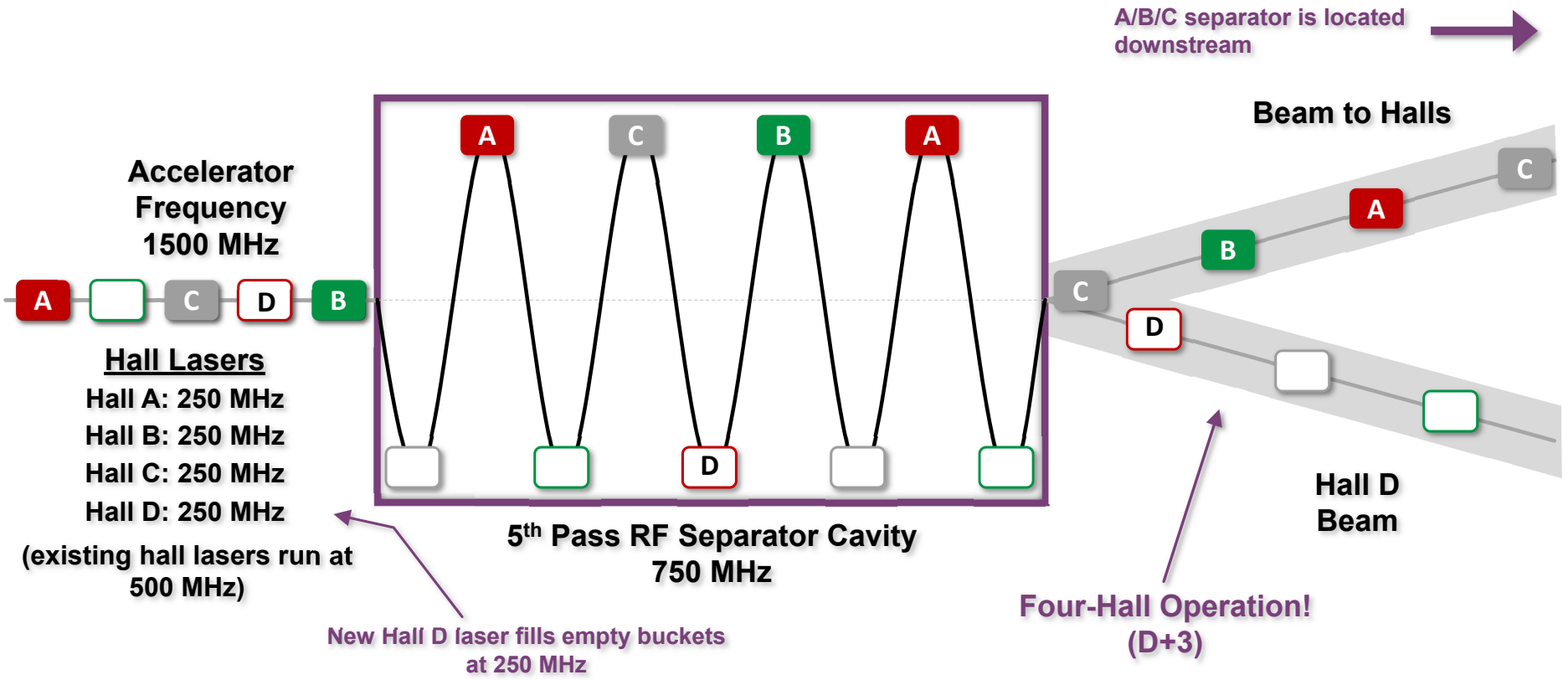


Simultaneous Four-Hall Capability: 5th Pass Horizontal Separation

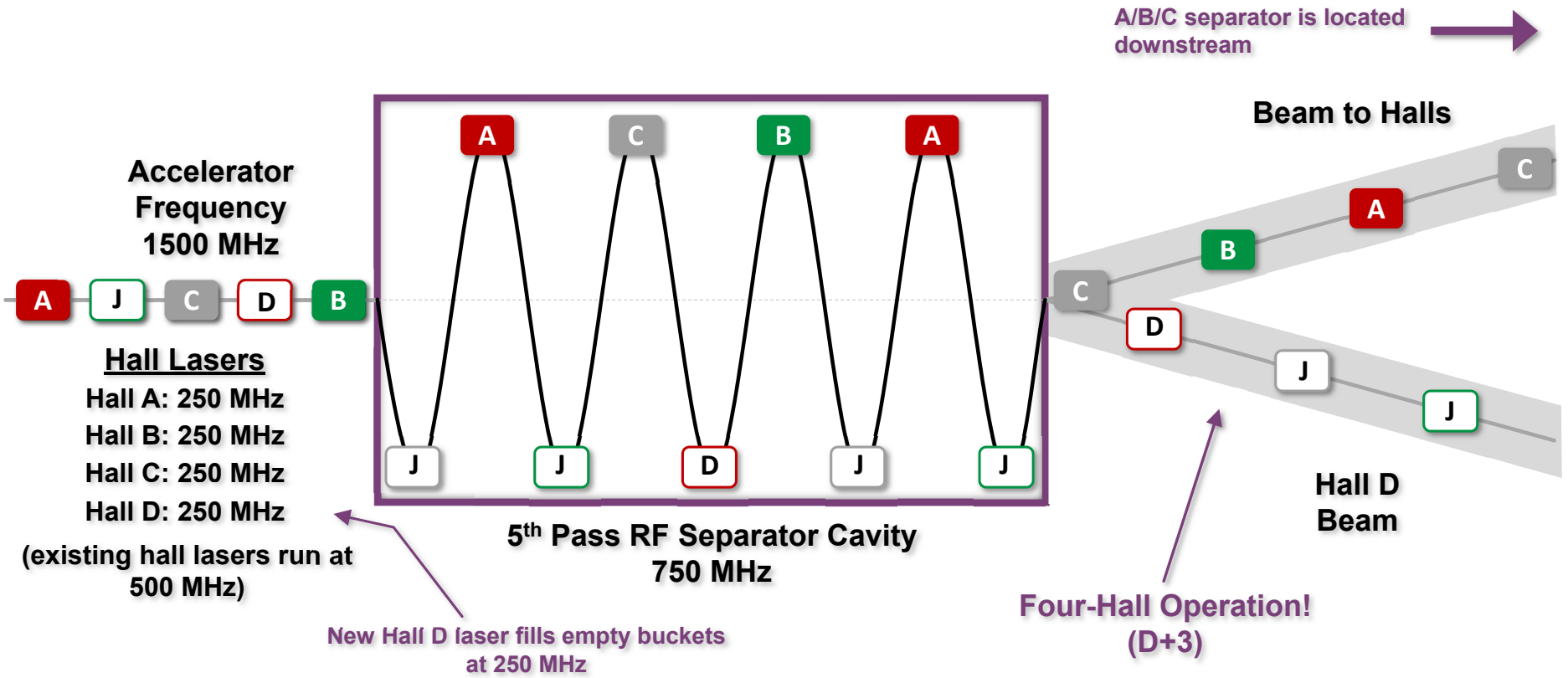


Empty Buckets – Cutting the laser pulse rate for each hall in half (from 500 MHz to 250 MHz) leaves "empty buckets", which are directed to Hall D

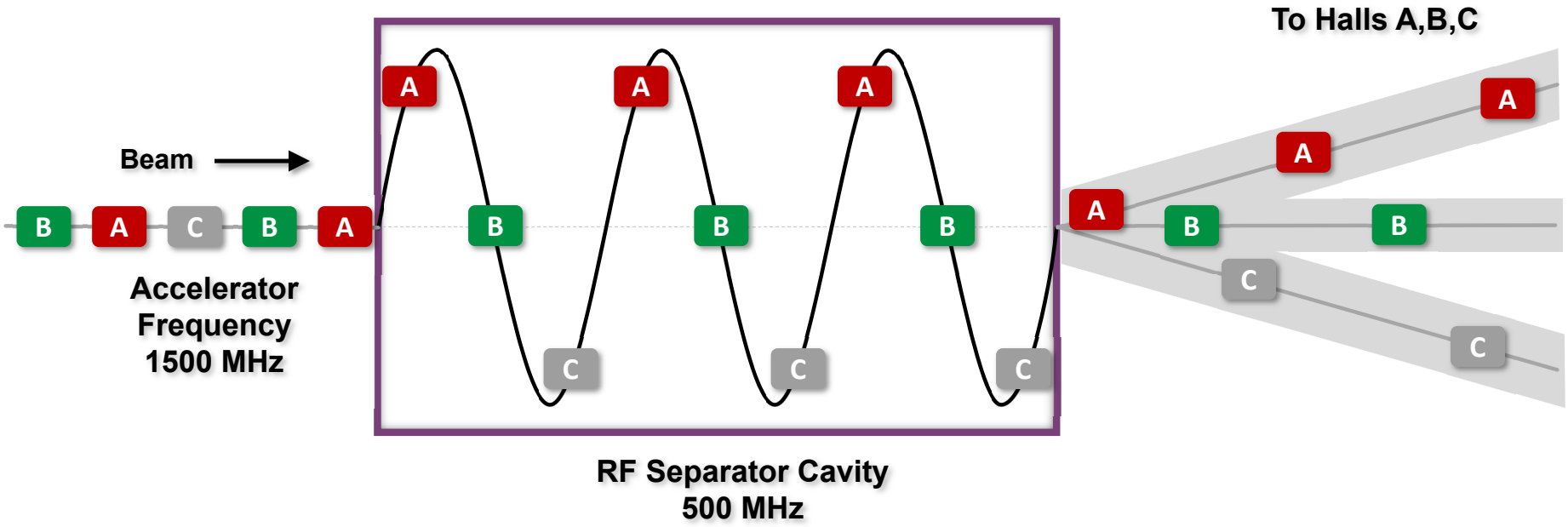
Simultaneous Four-Hall Capability: 5th Pass Horizontal Separation



Simultaneous Four-Hall Capability: 5th Pass Horizontal Separation

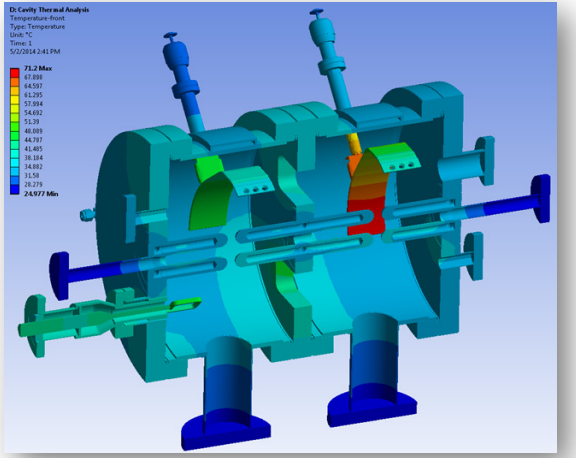


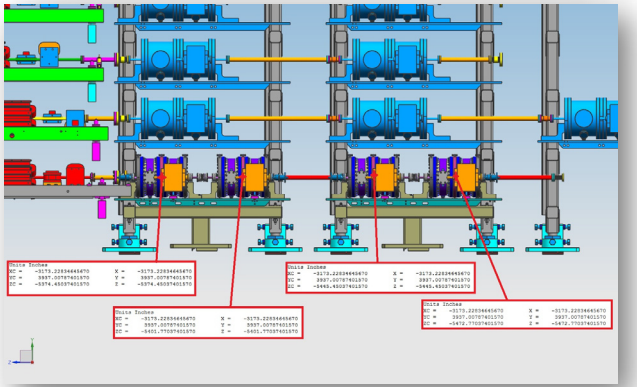
Simultaneous Four-Hall Capability: 5th Pass Vertical Separation

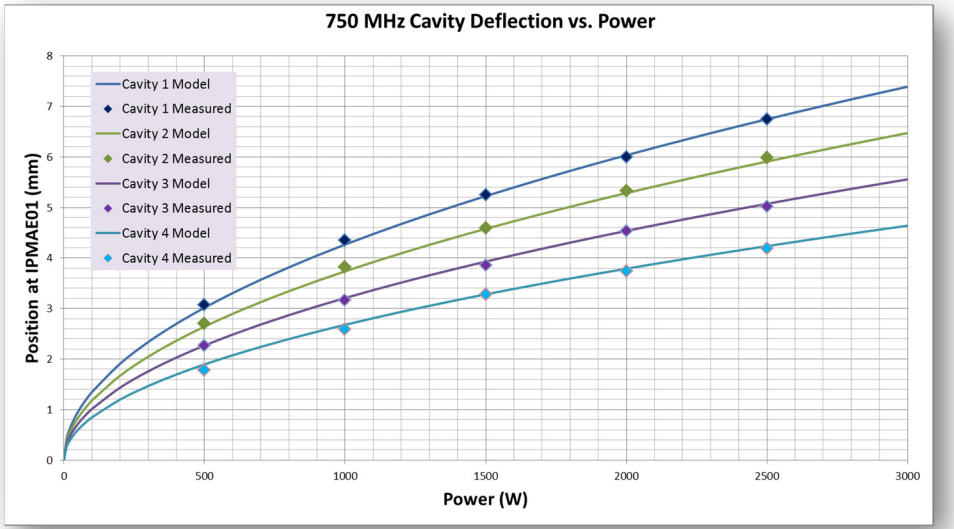


Simultaneous Four-Hall Capability: 750 MHz Separator System

- 750 MHz Separation system declared fully operational in Spring 2018 run
- Challenges along the way:
  - Managing resonance control with 750 MHz structures as compared to original 500 MHz CEBAF Separator cavities
  - Managing RF losses in transmission system (high power phase shifters, long cable runs, circulators, …)
  - Optimizing installation for maximum overhead







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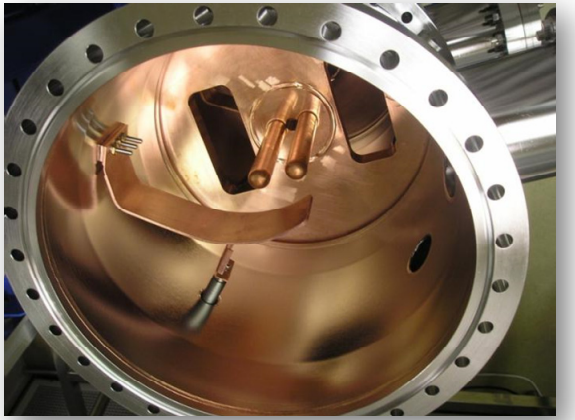
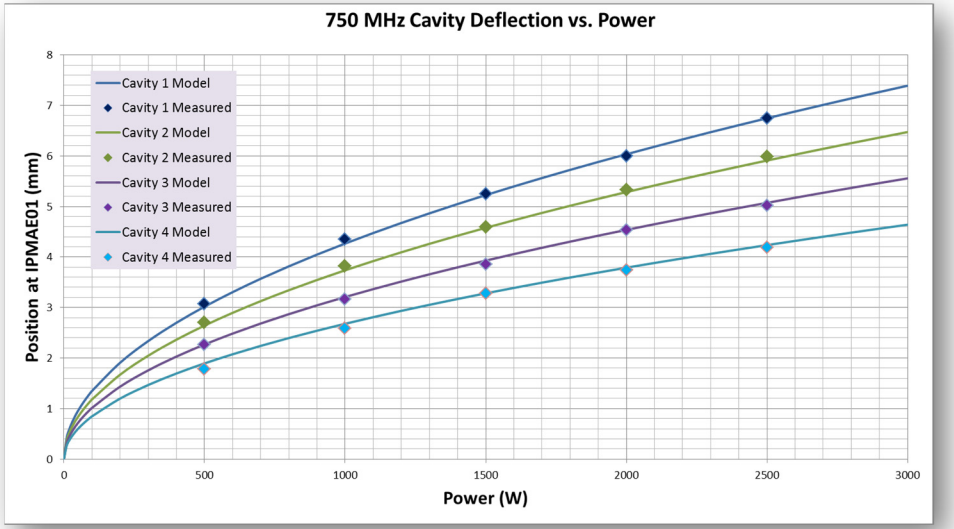
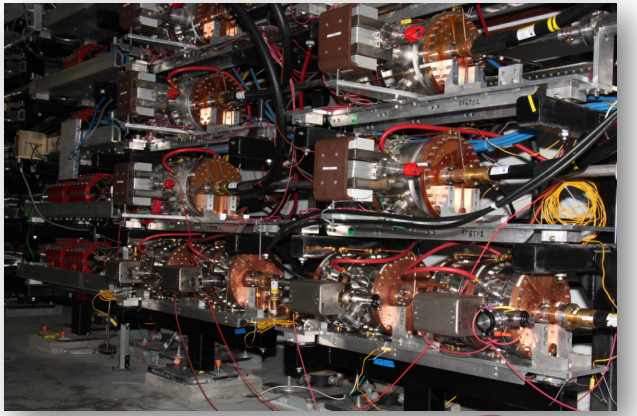
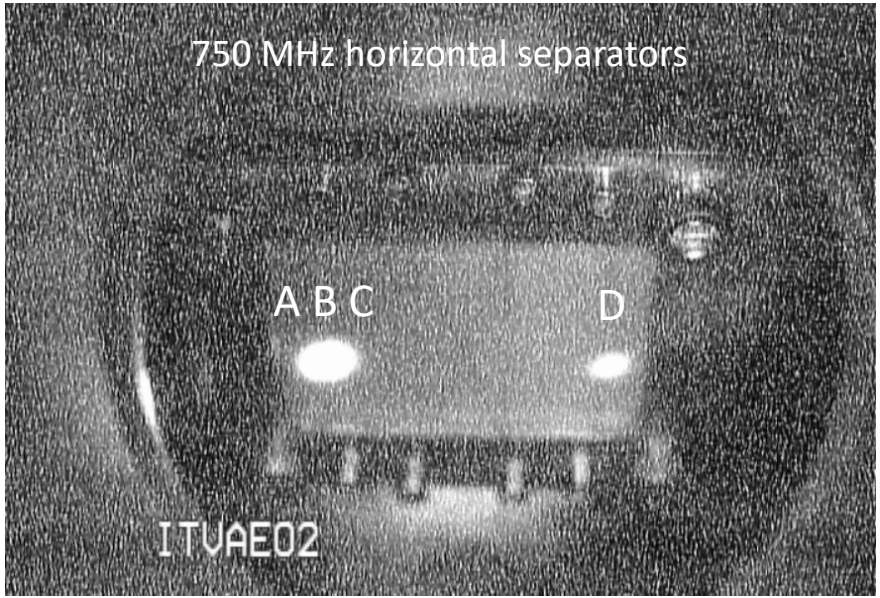




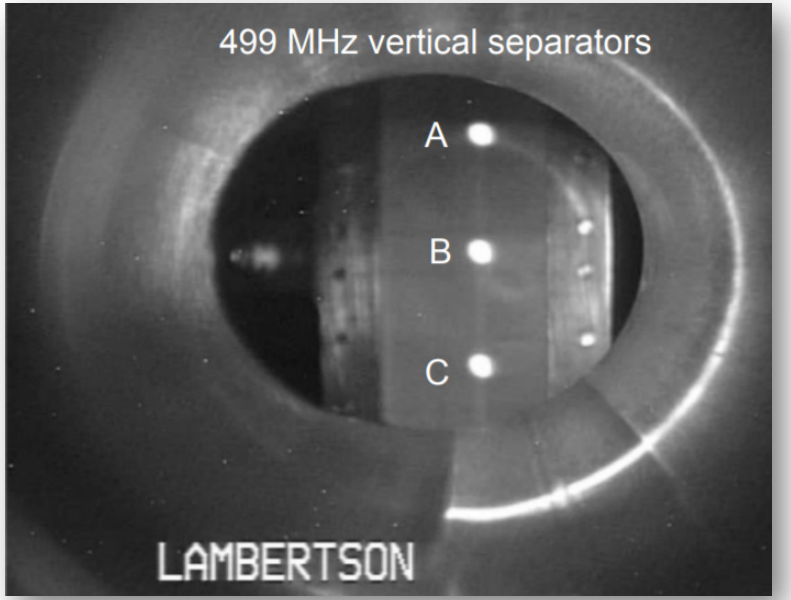


Simultaneous Four-Hall Capability

- 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



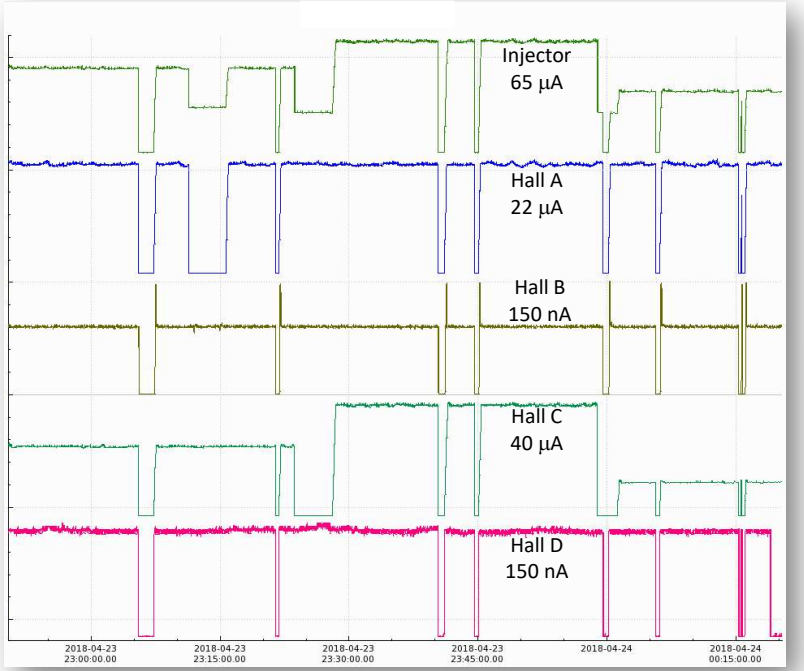
Viewer at Entrance of Extraction Septum

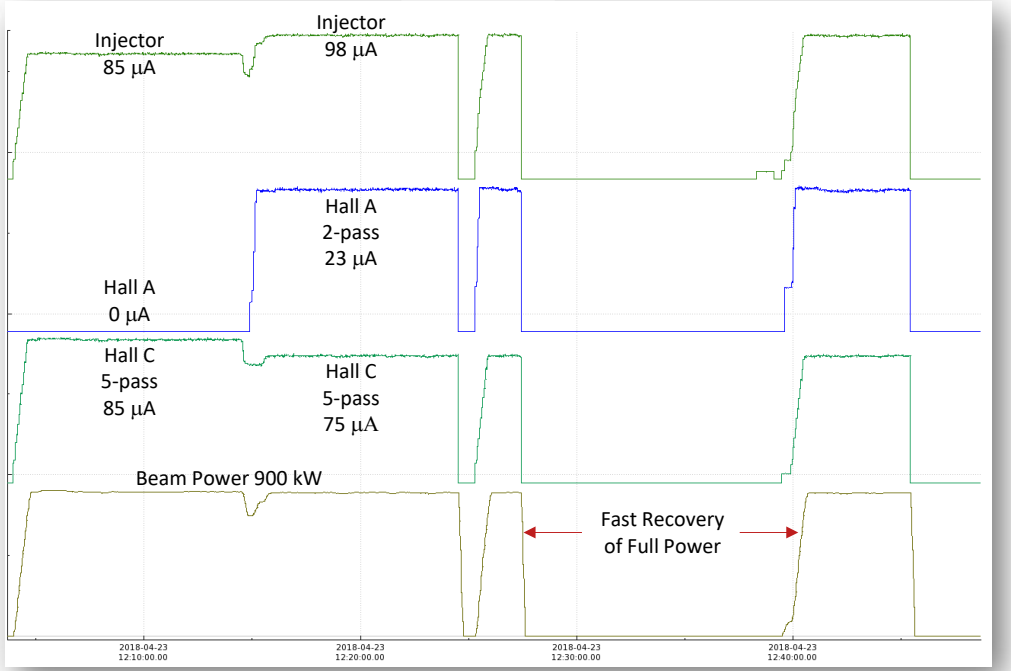


Viewer at Entrance of Beam Switchyard

4-Hall and Full Power Operations

- Routine 4-Hall Operations throughout the Spring 2018 Run
- Stable Full Power Operation demonstrated on April 23

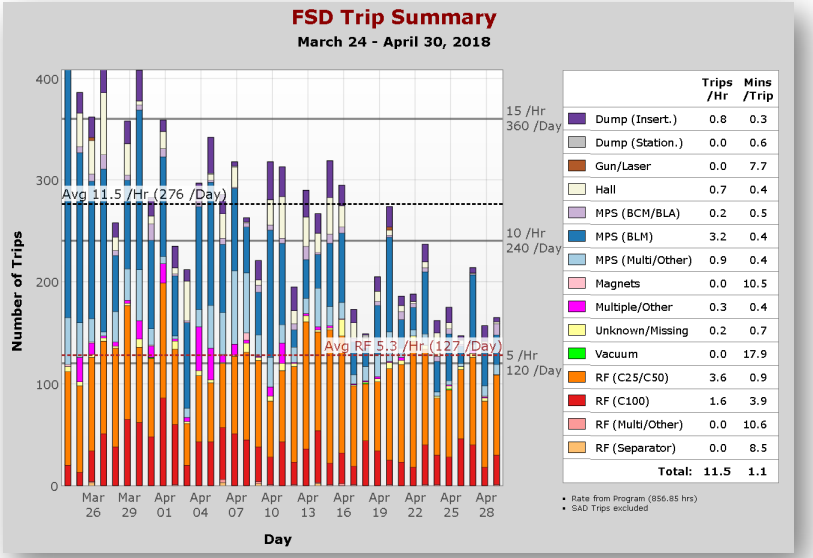


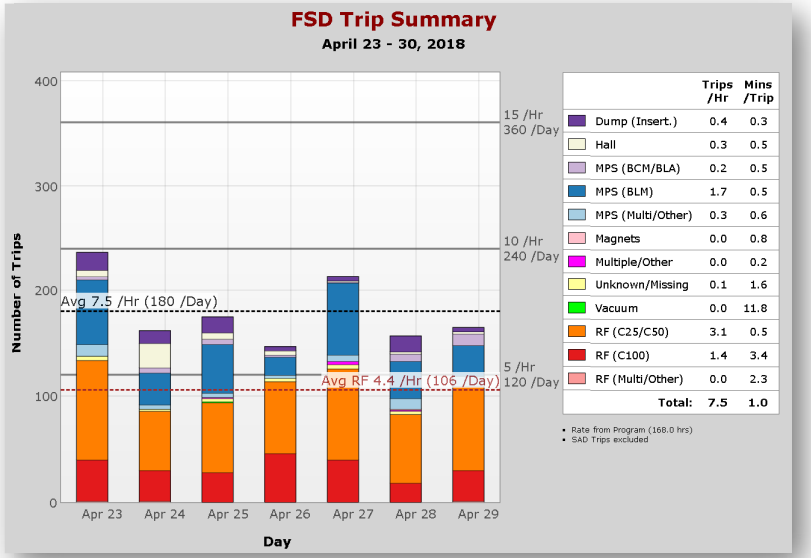


Evolution of Recent Availability

- Fast Shutdown Trips (FSD) – less than 5 minutes to recover the beam
- C100 - average trip recovery time 3.30 minutes/trip
- C20/C50 and loss faults - average trip recovery time 0.47 minutes/trip
- Data in table includes lost time from FSD and system failures

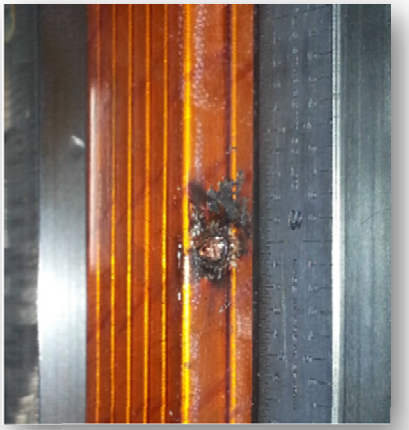
Period	Availability
Last 30 Days	73.9%
Last 7 Days	84.6%
Last 3 Days	86.0%
Last 24 Hours	87.9%

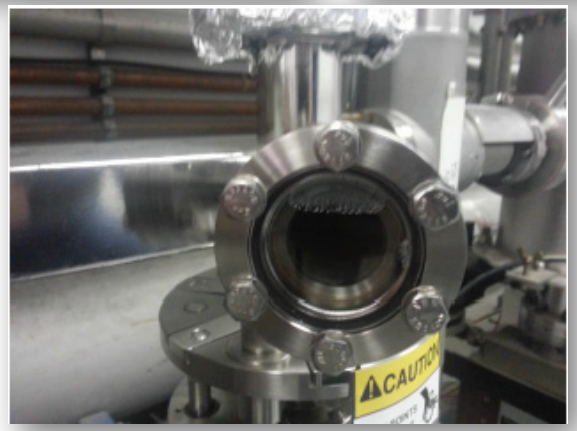




12 GeV Challenges

- **Spring 2014**: Coil and vacuum failure for 3m Septum magnet; **3 week interruption** to replace damaged coil and repair the vacuum chamber. This failure consumed the existing spare coil.
- **Spring 2015**: Cold compressor failure in 2 K cold-box; No spare at JLab, consumed the SNS cold compressor spare. **Program change required:** Ran at half design energy after 5 week down.
- **Fall 2015:** YR coil on 3-pass extraction generated a spontaneous leak. No 3-pass program for FY16, repaired Summer 2016, consumed a YR coil spare. **Required Hall-A DVCS experiment to rearrange its run plan.**
- **Fall 2016**: Arc7 box supply choke failure, no spare. **Program change required** to single hall operation until supply repaired.
- **Fall 2016**: 5th pass separator vacuum leak**. Program change required**: could not support 5th pass beam to Hall-A simultaneously with 5.5 pass beam to Hall-D.
- **Spring 2017**: Broken wire on 2 K cold-box connector; **Scheduled program terminated.**
- **Spring 2018:** 5MVA CHL Compressor Transformer failed; **2 week interruption** to replace matched pair.





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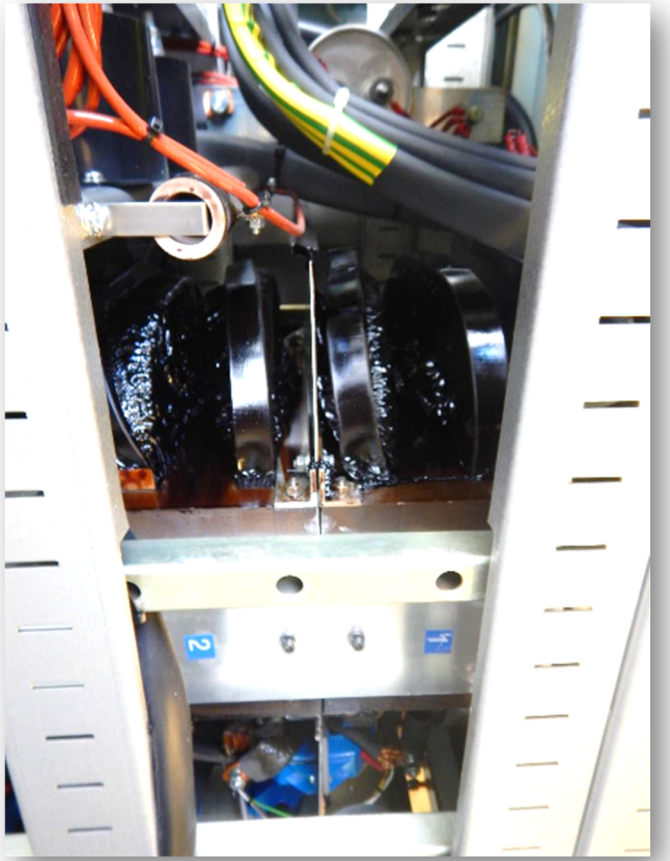

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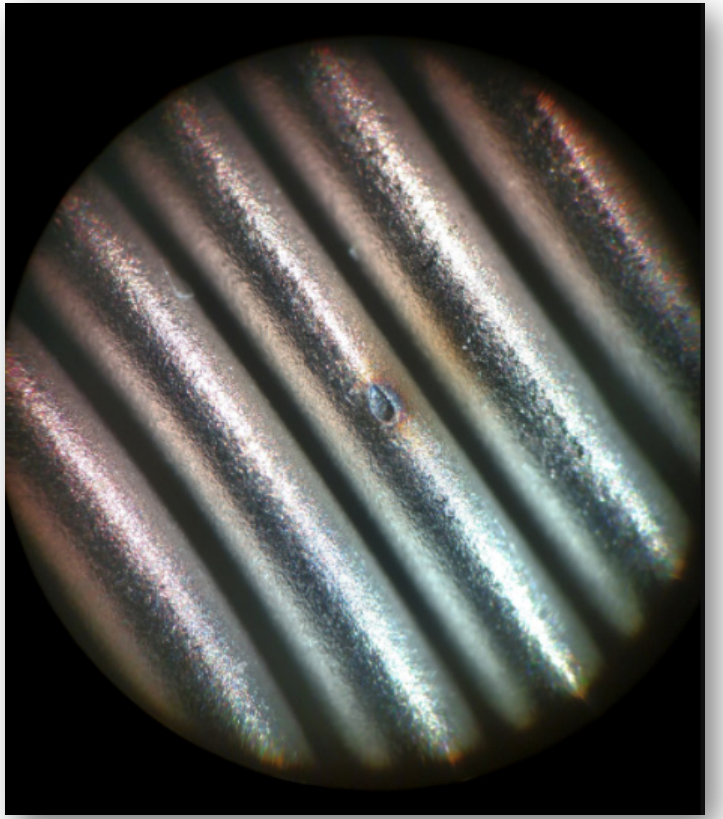

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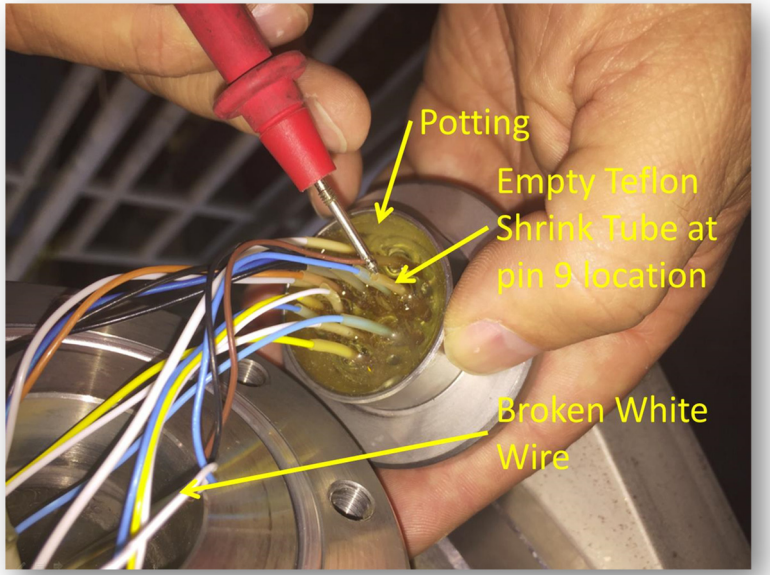

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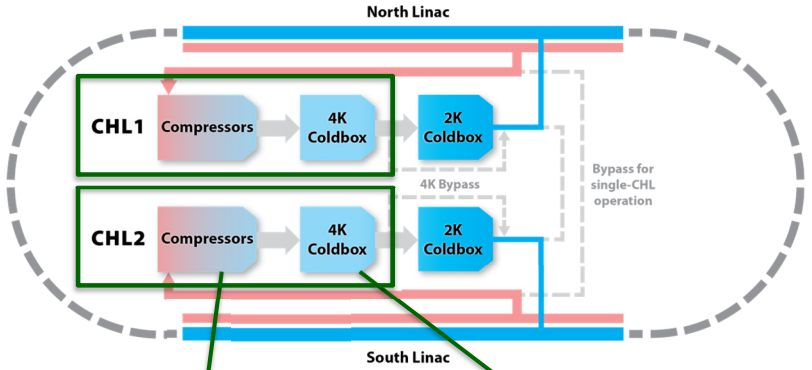
12 GeV Challenges - Central Helium Liquefier

System	Years of Operation
CHL1	1991 – Present
CHL2	2013 – Present
2K Coldbox #1	1994 – 2000, 2013 – Present
2K Coldbox #2	2000 - Present

CHL1	CHL2
4.6 kW @ 2.1 K	4. 8 kW @ 2.1 K
250 g/s	250 g/s
5.5 MW	3.8 MW

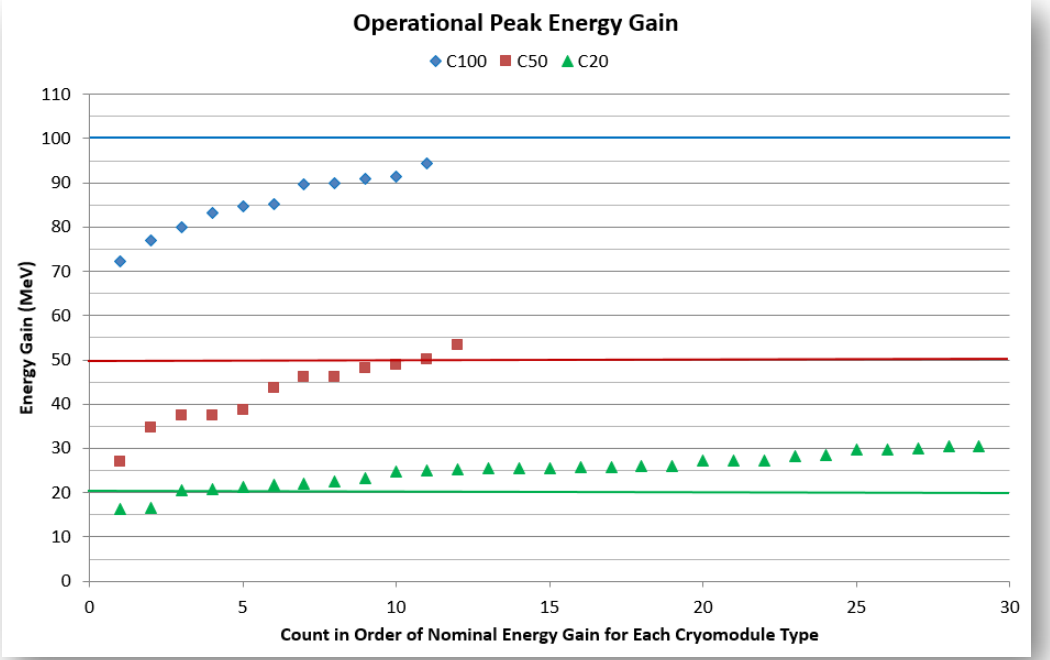


12 GeV Upgrade

- High availability throughout 6 GeV era (99%)
- However:
  - System failures during 12 GeV commissioning
  - Contamination events have caused lost time in Spring 2014, Spring 2015 beam runs and 2017 Summer Shutdown

12 GeV Challenges - Energy Reach

- Total energy gain for each linac set to 1050 MeV/linac in Spring 2017 (3.6% below nominal 1090 MeV/linac)
- C100 cryomodules - operating below design to minimize field emission
- C50 cryomodules - optimized for Q_0
- C20 cryomodules – original CEBAF cryomodules optimized for minimal trip rate



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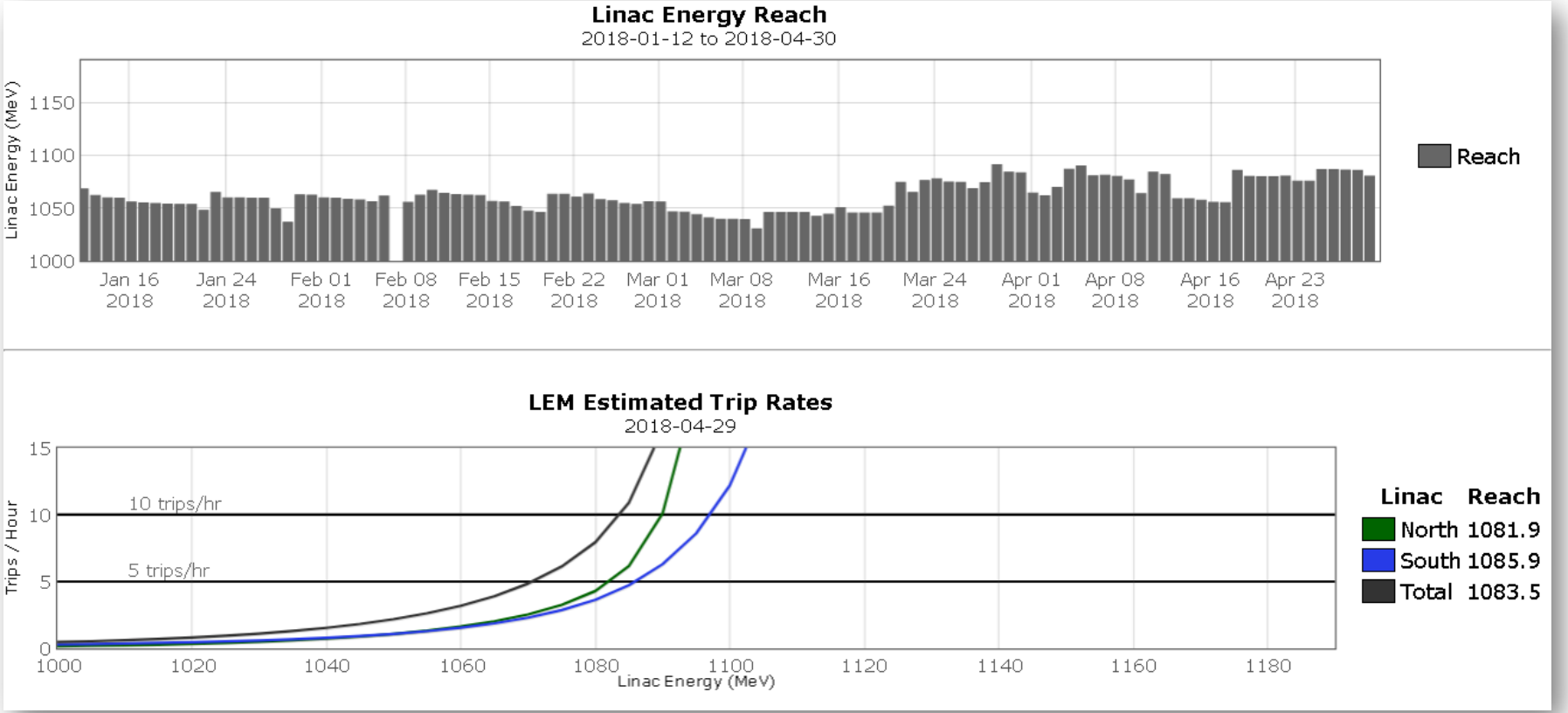
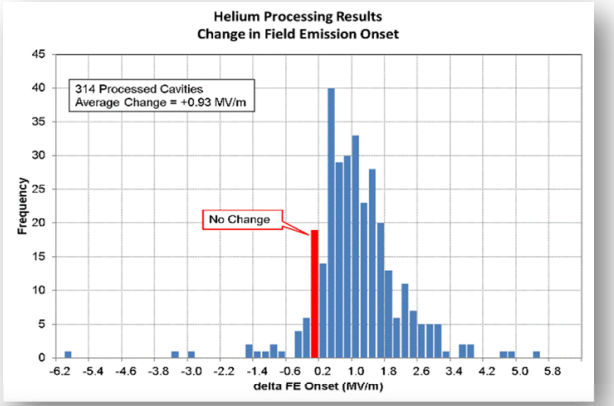
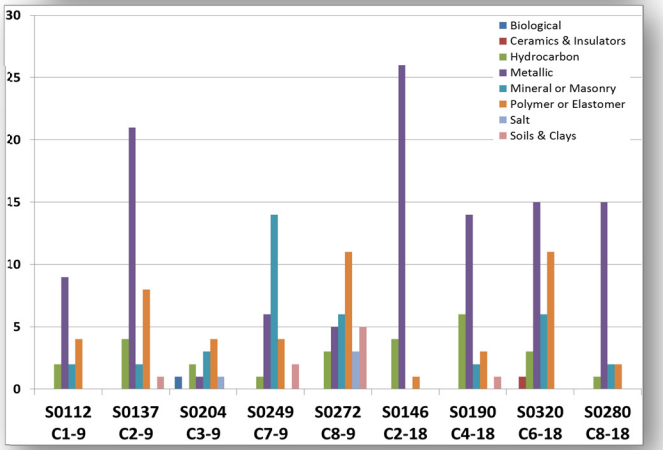
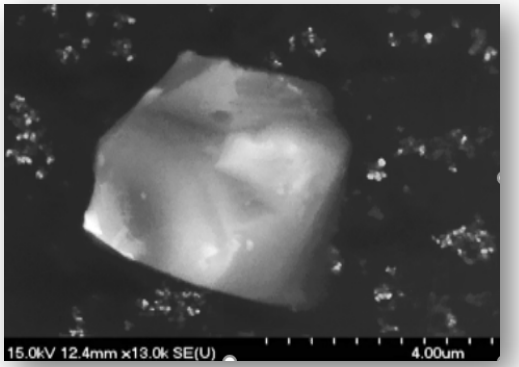


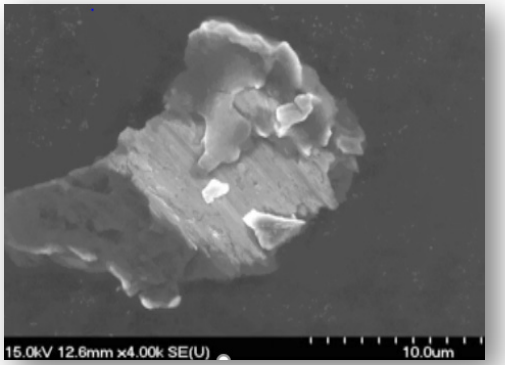
12 GeV Challenges – Field Emission

- Field emitters in SRF cavities erode operational gradients
- Historical loss is ~17 MeV/linac/year (~1.5%)
- Detailed particulate capture and analysis on refurbished cryomodules has been conducted:
  - Mostly metallic (Steel, Copper)
  - Particulates found on cavities and warm region girders
  - Particles as large as 1 mm
- Helium processing can improve performance



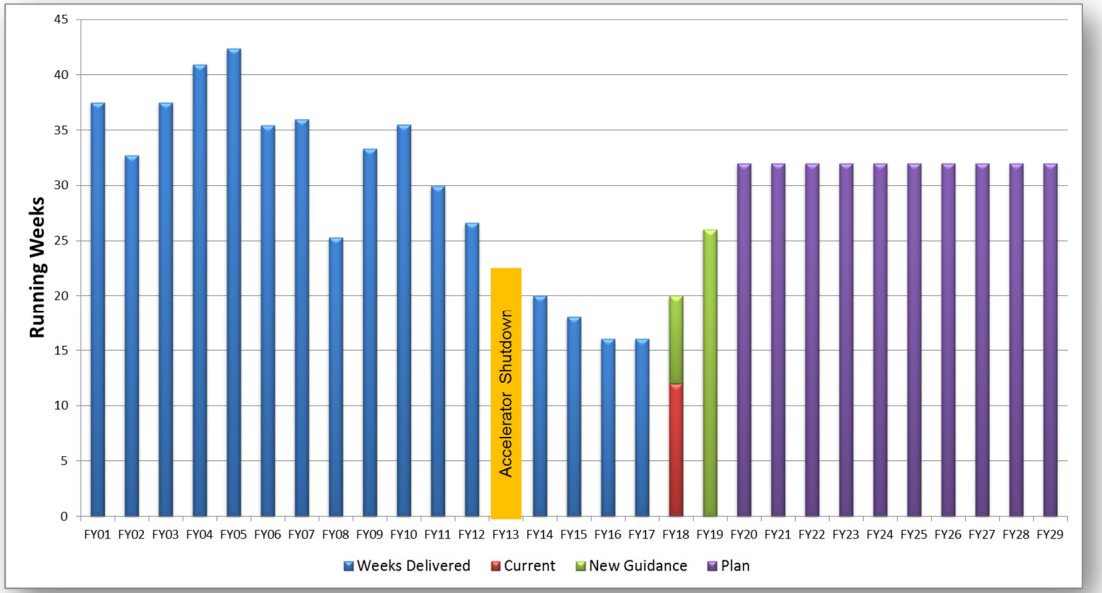






12 GeV Challenges - Running Weeks

- Running weeks limited over the last few years
- Recent budget guidance has us turning a corner on post-construction running weeks
- FY18 run extended from 12-20 weeks
- FY19 guidance is to plan for 26 weeks
- Out-years goal set at 32 weeks which is our adopted reference plan



Future Plans: CEBAF Performance Plan (CPP)

Each run in the 12 GeV era included an event that resulted in a change to the program.

Reliability Team convened to perform a gap analysis of historical systems performance relative to specific metrics shown in table.

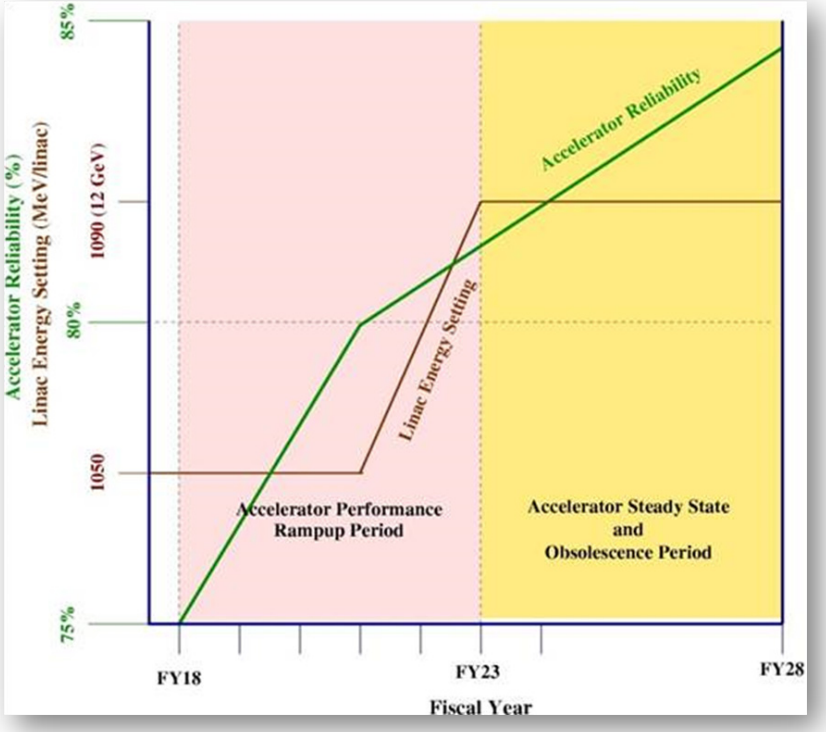
CPP captures a multi-year strategy to:

- Establish an energy of 1090 MeV/linac with sufficient overhead to absorb short-term loss of RF cavities taken offline for maintenance.
- Confront obsolescence issues for the older systems in CEBAF that have been online for nearly 30 years.
- Minimize downtime due to a lack of critical system spares.
- Transition into a program of sustained four hall operations for over 32 weeks/year.

Category	Goal	Unit/Metric
Reliability	> 80	%
Optimal Running Weeks	≥ 32	weeks/year
Beam Tuning Hours	< 8	hours/week
Beam Studies Hours	8	hours/week
Peak Hall Multiplicity	4	number of halls
Linac Design Energy	1090	MeV
Linac Energy Margin	> 100	MeV
Overall FSD Trip Rate	< 15	trips/hour
Overall FSD Trip Downtime	< 5	minutes/hour
RF Trip Rate	< 10	trips/hour
Beam Loss Trip Rate	< 10	trips/hour

Future Plans: CEBAF Performance Plan

- 10-year plan with two major periods
  - Performance Ramp-up (FY18-23)
  - Steady State and Obsolescence (FY23-28)
- Linac energy 1050 MeV/linac through FY21
- Gain energy margin while at 1050 MeV/linac
  - Helium Processing
  - Effort to arrest gradient degradation
  - C75/C100 Cryomodule Refurbishment Program
- Ramp linac energy to 1090 MeV/linac by 2023
- Steadily improve availability over the out-years



Future Plans: CEBAF Performance Plan

- Availability/Reliability Plan:
  - Purchase CEBAF and Cryogenics critical spares
  - Purchase 6.5 kW and 13 kW klystrons
  - Arrest gradient degradation
    - Upgrade warm linac girders with modern pump technology
    - Implement clean room protocol for all in-field linac girder assembly work
  - Address immediate obsolescence issues
  - Build and commission a new 2K cold-box

Component	System	Objective
ARC Magnet Power Supply	DC Power	Critical Spares
3m Septum Power Supply	DC Power	Critical Spares
Hall Magnet Power Supply	DC Power	Critical Spares
3m Septum Magnet Coil	DC Power	Critical Spares
S/R Common Magnet Coil	DC Power	Critical Spares
800 HP CHL Compressor Motor	Cryogenics	Critical Spares
CHL Warm Compressor Bodies (2)	Cryogenics	Critical Spares
CHL Diffusion Pumps	Cryogenics	Critical Spares
ESR Warm Compressor Bodies (2)	Cryogenics	Critical Spares
ESR Diffusion Pump	Cryogenics	Critical Spares
Linac U/L-tube Transfer Lines (5)	Cryogenics	Critical Spares
CHL Relief Valves (11)	Cryogenics	Critical Spares
8 kW C20/C50 Klystrons (20)	RF	Energy Reach
13 kW C100 Klystrons (2)	RF	Energy Reach
C20 Warm Beamline Girders	Linac Vacuum	Energy Reach
C100 Warm Beamline Girders	Linac Vacuum	Energy Reach
Particulate-Free Vacuum Hoods	Linac Vacuum	Energy Reach
C75 SRF Cavities	SRF Cryomodules	Energy Reach
Safety PLC Upgrade	Personnel Safety	Obsolescence
25 L/S Ion Pumps	Beamline Vacuum	Obsolescence
Uninterruptible Power Supplies	Controls	Obsolescence
Network Switches	Controls	Obsolescence
Network Console Servers	Controls	Obsolescence

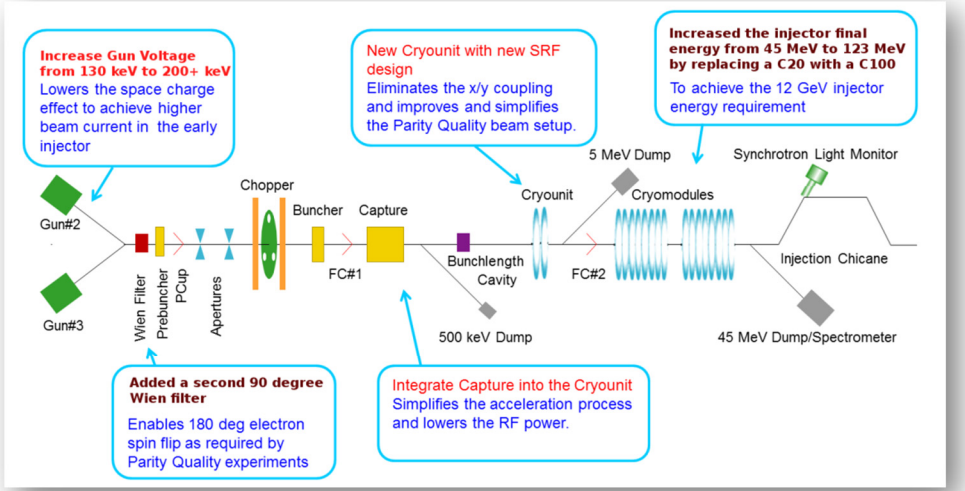
Future Plans: Cryomodule Refurbishment Program

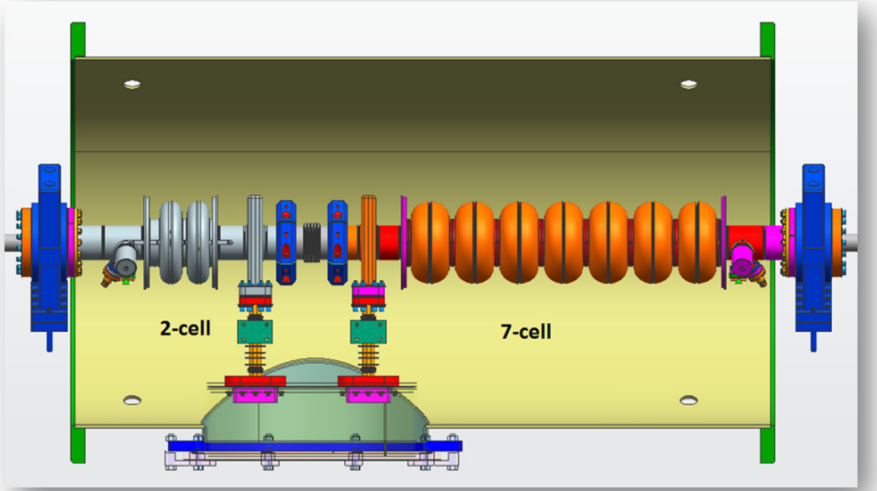
- Summer 2018:
  - Helium process five zones (10-15 MeV/pass)
  - Install F50 and F100 in North Linac (30-40 MeV/pass)
- C75 Refurbishment:
  - Best cost in terms of MV/$
  - Replace C20 cavities with high current 5-cell cavities
  - Upgrade LLRF analog controls to digital
  - Specs: 18.5 MV/m and $Q_0 > 8e9$
- C100 Refurbishment
  - Reprocess cavities to eliminate field emission and thereby minimize dynamic heat load and radiation (LCLSII standard)
  - Apply best practices for “clean” installation and maintenance

Fiscal Year	Cryomodule
FY18	F50, F100
FY19	C75-01
FY20	C75-02, C100-R1
FY21	C75-03, C75-04, C100-R2
FY22	C75-05, C75-06, C100-R2
FY23	C75-07, C75-08, C100-R3
FY24	C100-R4
FY25	C75-09
FY26	C100-R5
FY27	C75-10

Future Plans: Full Injector Upgrade

- Upgrade for Gun HV 130 kV - 200 kV, reduced space charge to support reliable, low-loss high bunch charge operations.
  Status: Installing summer 2018.
- New ¼ cryomodule – to replace first and oldest SRF element in CEBAF
  Status: Cooled to 2K last month. Will install in CEBAF after tested with beam. Planned for summer 2020.





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- Many challenges as well
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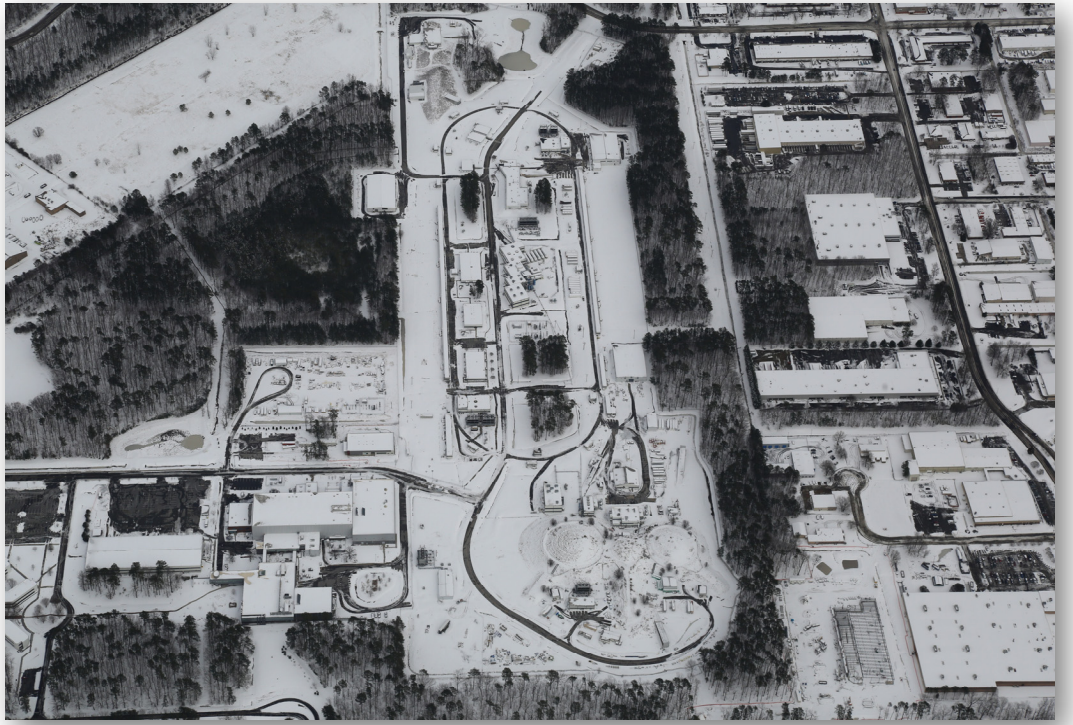

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Thank you!

Acknowledgements

- Thanks to Arne Freyberger, Randy Michaud, Matt Bickley, Steve Suhring, Ken Baggett and the Accelerator Reliability Team for their analysis and development of the CPP.
- Thanks to Tony Reilly, Charlie Reece, Rongli Geng, Bob Legg and Mike Drury for providing information related to SRF cryomodule performance and plans going forward.
- Thanks to Javier Gomez for Nuclear Physics program information.
- Thanks to Matt Poelker for Full Energy Injector upgrade information.
- Thanks to Reza Kazimi for developing the 4-Hall concept and Tom Oren for the graphics