Continuous Electron Beam Accelerator Facility Overview

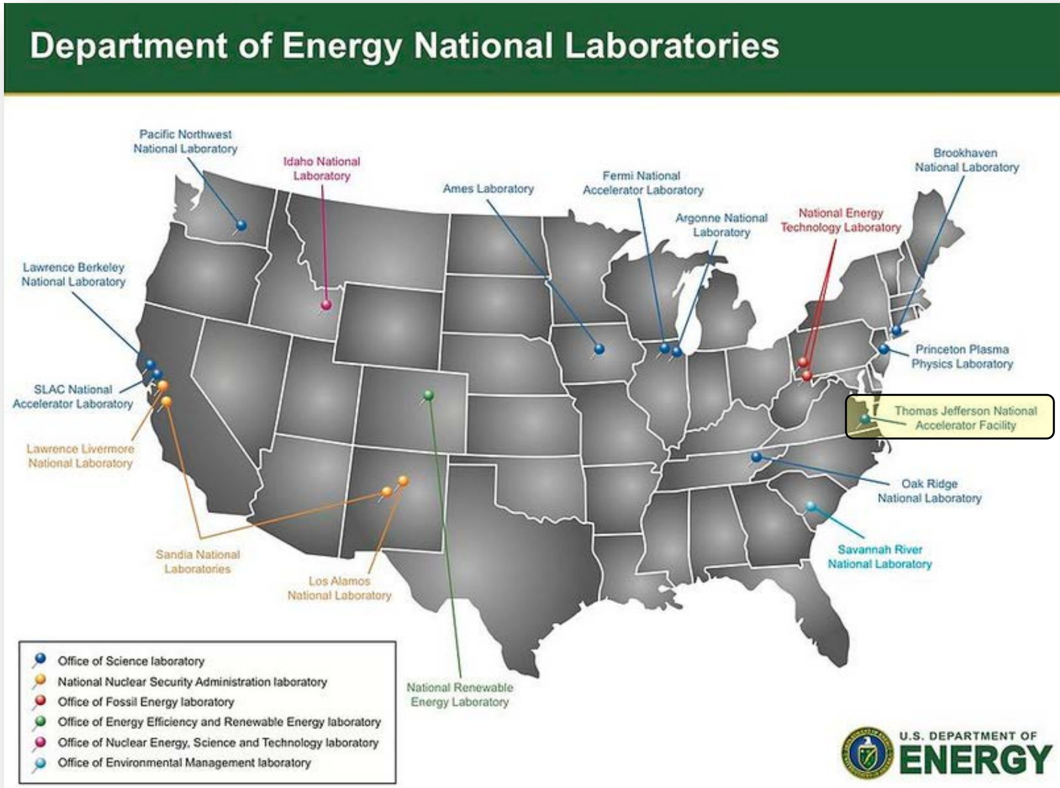
Michael Spata
Director
Center for The Advanced Studies of Accelerators

USPAS SRF 1/29/15

Outline

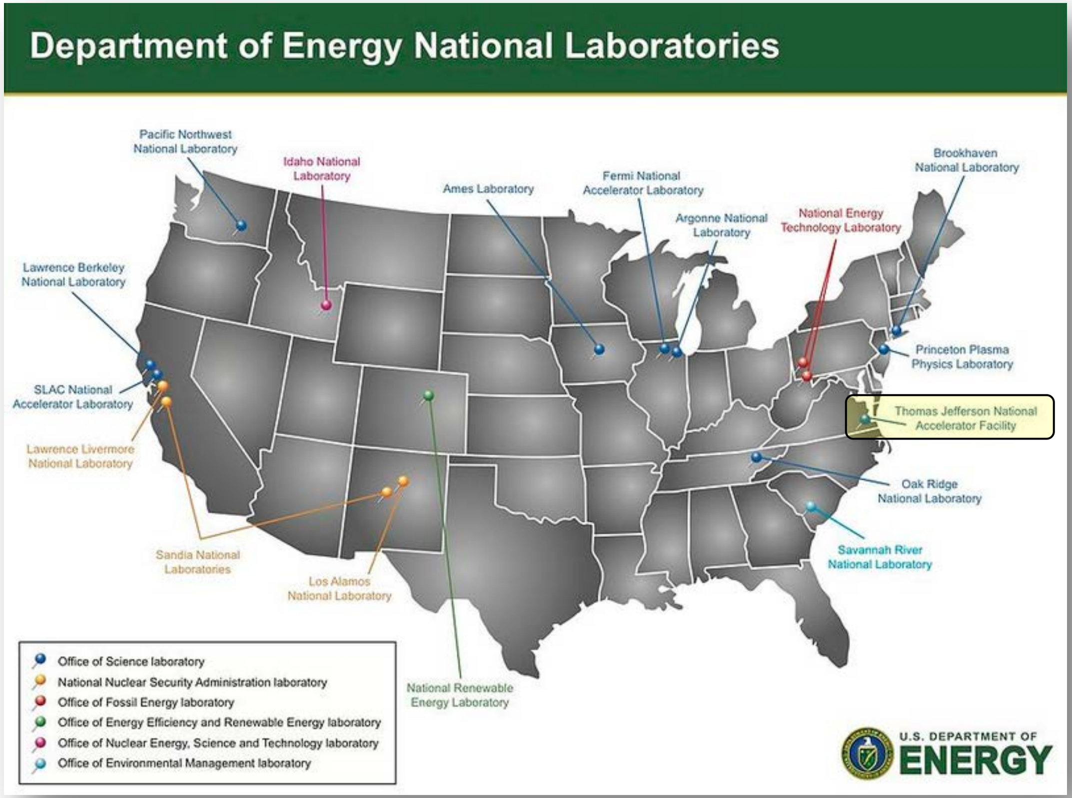
- Introduction
  - Jefferson Lab Overview
  - Scope of the 12 GeV Upgrade
- Accelerator Overview
  - Beamlines
  - Extraction System
  - Diagnostics and Tuning Techniques
- Cryomodule Operations
  - Initial Commissioning
  - Optimizing the LINAC Performance
  - Maintaining the LINAC Performance
- Beam Requirements
- Commissioning Progress and Future Plans

Jefferson Lab Overview



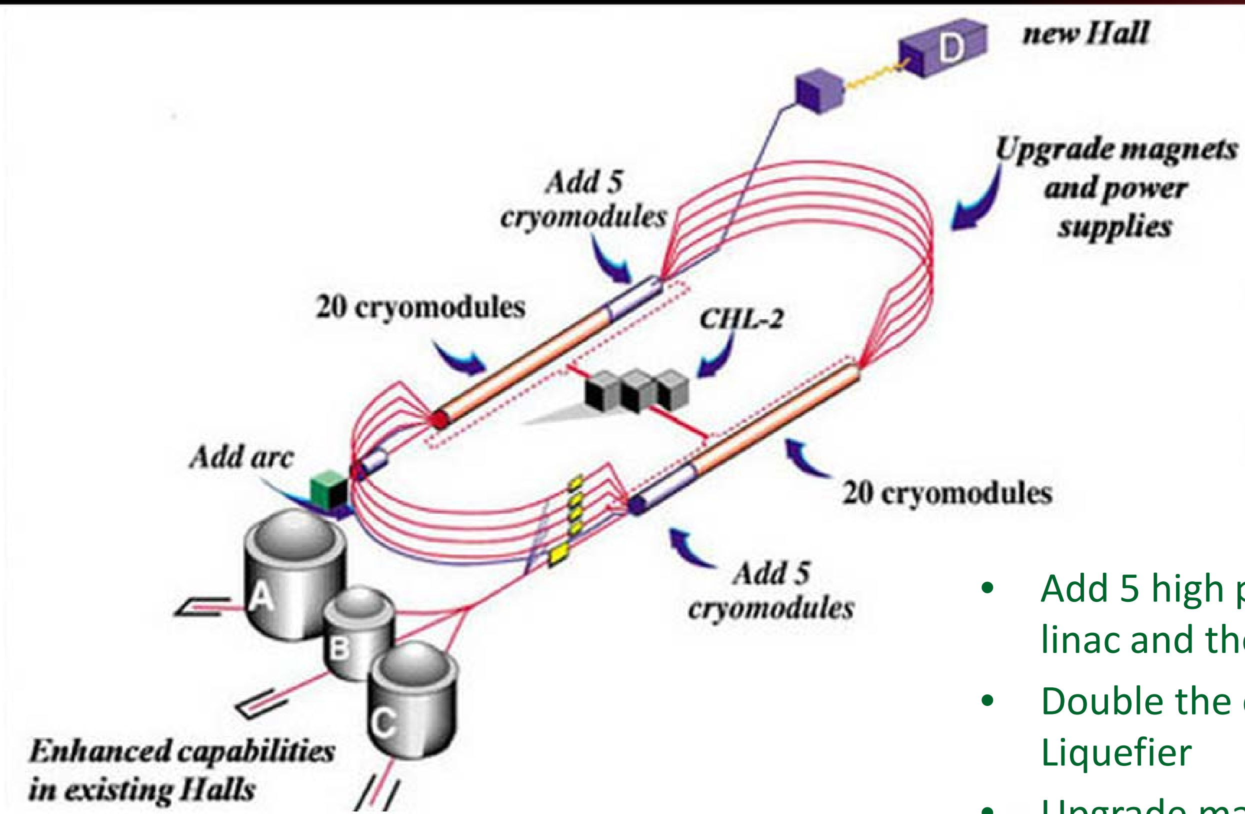
- **Core Competencies**
  - Nuclear Physics Research
  - SRF Technology Leadership
  - Polarized Electron Sources
  - Cryogenics Research and Development
  - Accelerator Physics and Diagnostics Development

Jefferson Lab Overview



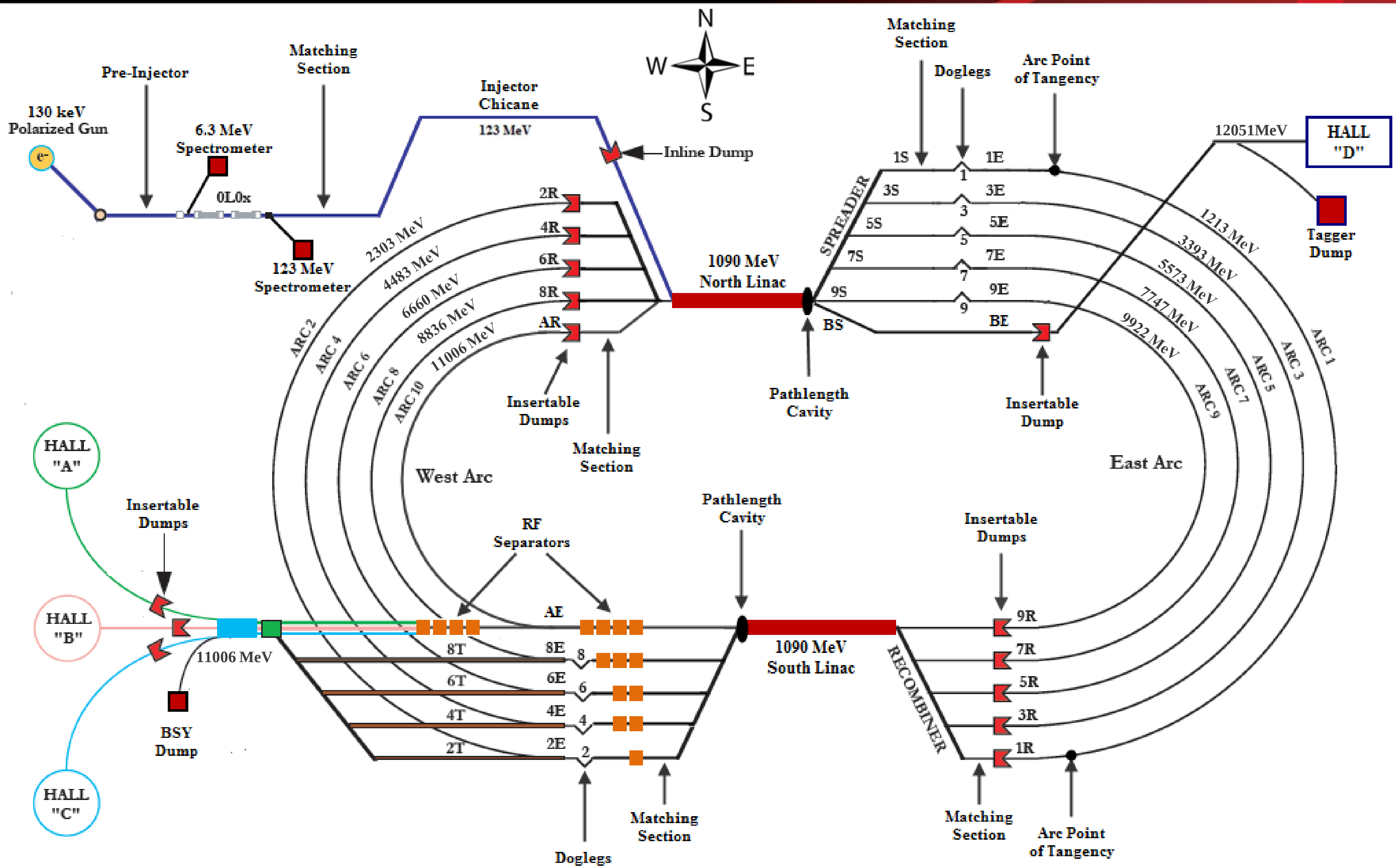
- **Quick Facts**
  - 180 M$ annual operating budget
  - 759 Full Time Employees
  - 1,385 Active Users
  - Produces ~1/3 of US PhDs in Nuclear Physics
  - 169 acres and 80 buildings and trailers

Scope of the 12 GeV Upgrade

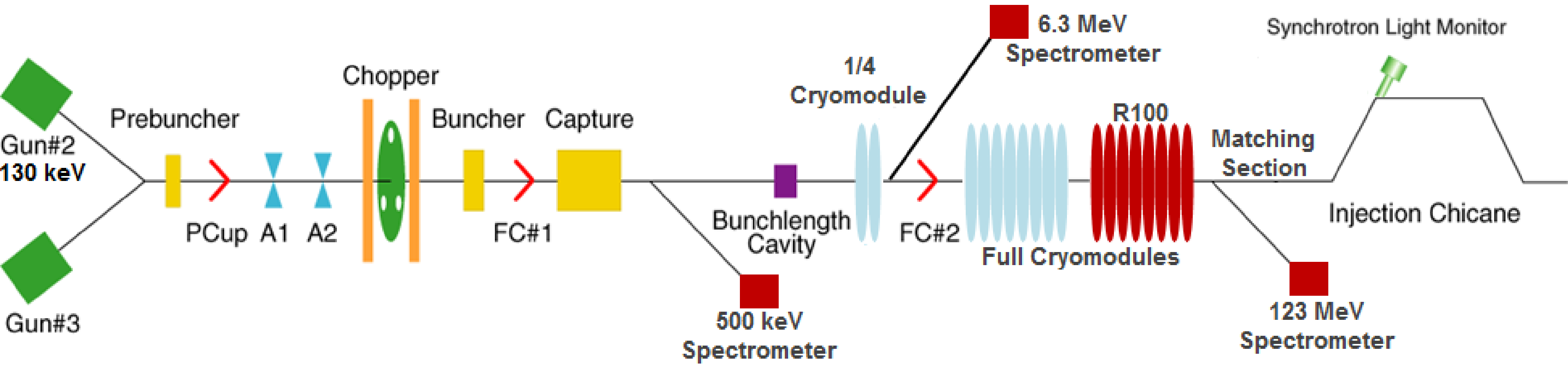


- Add 5 high performance cryomdules in each linac and their associated LLRF Systems
- Double the capacity of the Central Helium Liquefier
- Upgrade magnets and power supplies for recirculation arcs
- Upgrade Extraction, Instrumentation and Diagnostics, and Safety Systems
- Add new beamlines for Arc 10 and Hall D
- Add new experimental Hall D and upgrade existing Halls

CEBAF Overview



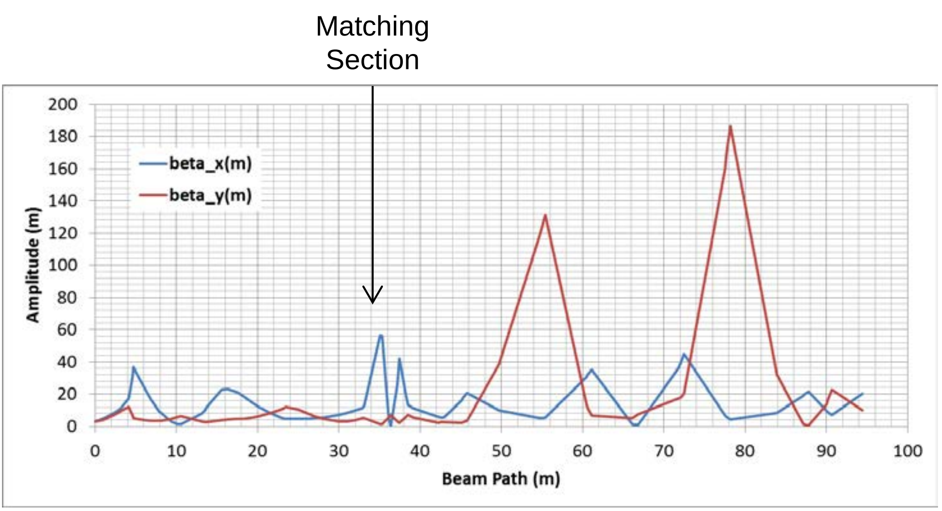
CEBAF Injector

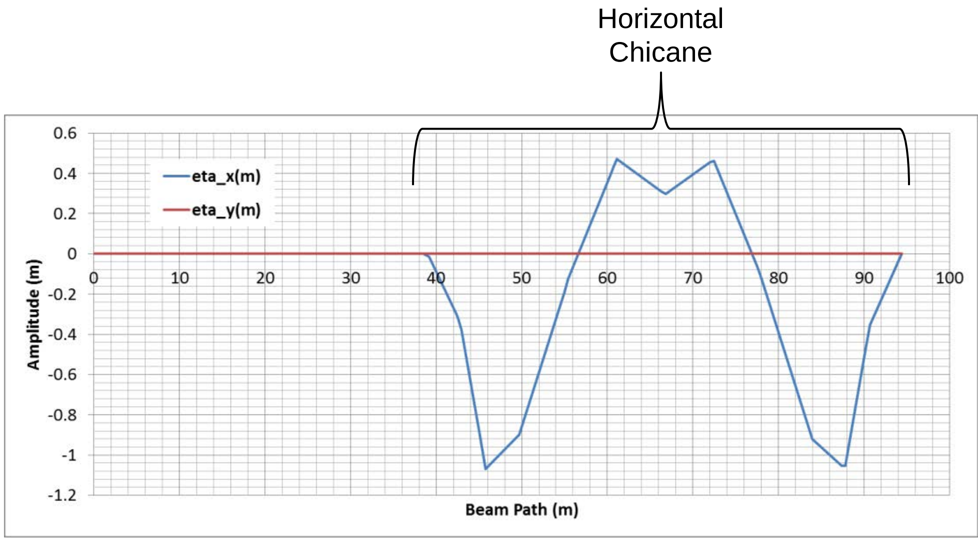


- The layout of the injector is the same as the 6 GeV accelerator up to the exit of the First Full Cryomodule.
- New components:
  - R100 Cryomodule
  - 123 MeV Spectrometer
  - Matching region shortened
  - Chicane length increased
  - Synchrotron Light Monitor
- Designed to provide 123 MeV CW beam for injection into the North Linac.

CEBAF Injector

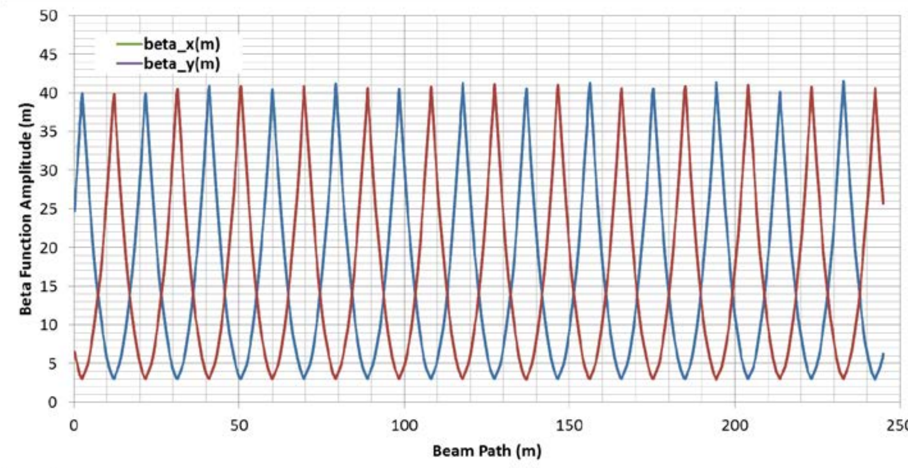
- Injector Optics:
  - Segment shown begins at exit of ¼ cryomodule and ends at exit of last chicane dipole.
  - Matching section for measuring emittance and then adjusting quad strengths to match the beam to the entrance of the North Linac.
  - Chicane provides achromatic and isochronous transport of 123 MeV beam to the North Linac.
  - Length of the back leg of the chicane increased by 21 m to accommodate the new Arc 10.
  - Chicane is horizontally dispersion suppressed.

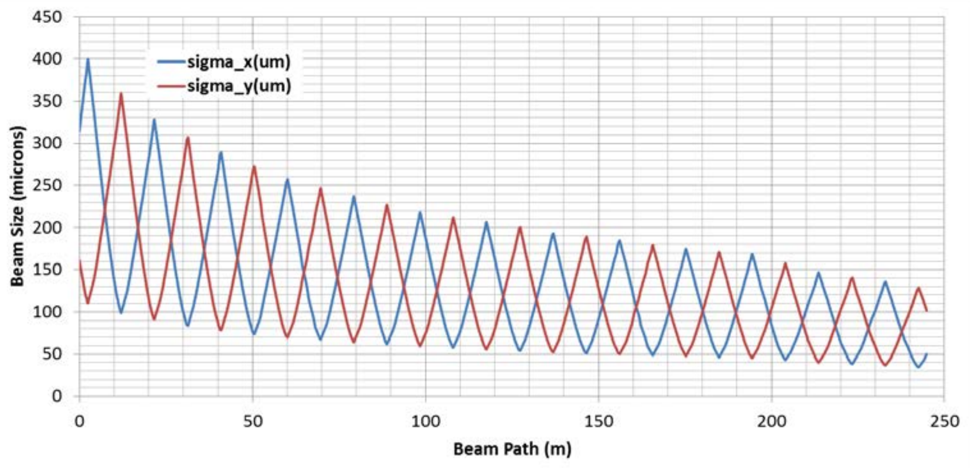




North and South Linacs

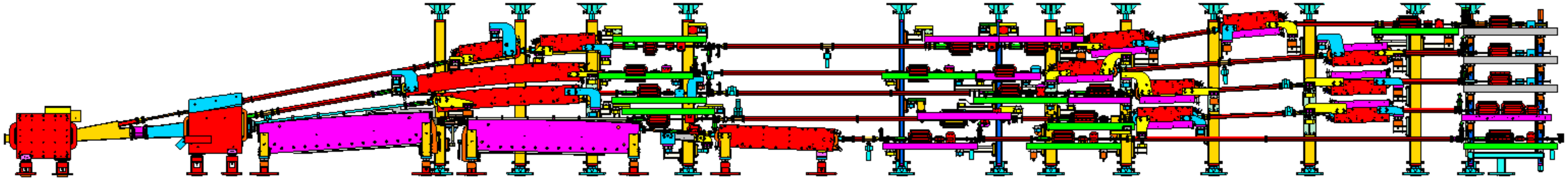
- North and South Linac Optics:
  - 9.6 m FODO channel with cryomodules between quadrupoles.
  - Beam injected with large spot size and damps as the beam is accelerated.
  - Skew quads in lattice around C20 and C50 cryomodules to correct for skew moment in cavity fields.
  - C100s have no skew moment.
  - Designed to provide 1090 MeV for a 12 GeV CEBAF



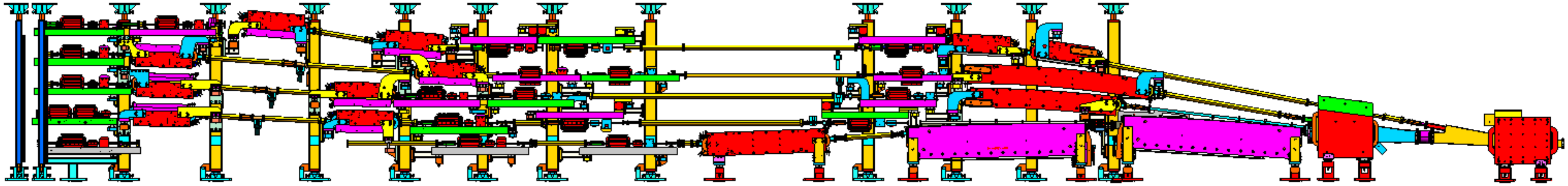


Spreaders and Recombiners

- Spreader/Recombiner layout:
  - Vertically achromatic system designed to accept broad range of multi-pass input parameters for recirculation transport.
  - Final step heights in ½ meter increments above lowest pass.
  - Quads in step control the vertical dispersion.
  - Recombiner is mirror-symmetric to the Spreader.



West Spreader

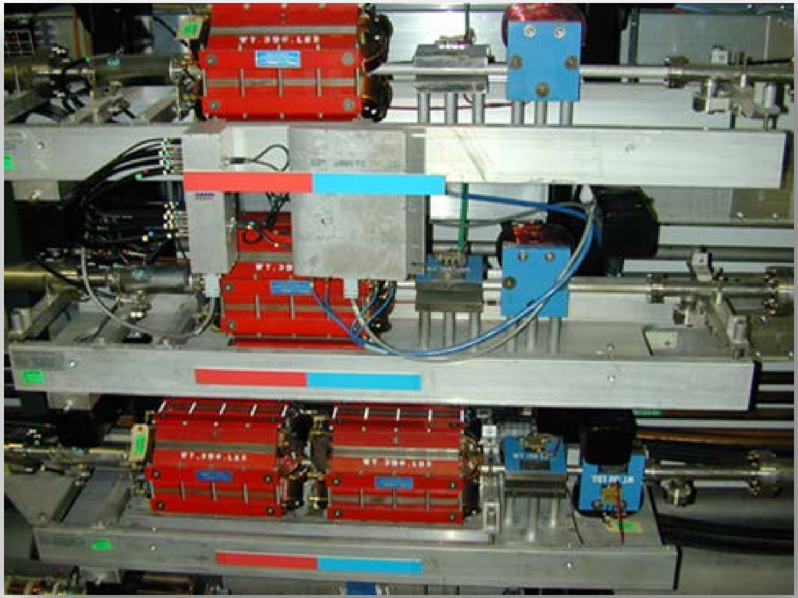


West Recombiner

CEBAF Recirculation Arcs

- Arc layout:
  - Sixteen dipoles for Arc 1 and Arc 2 and thirty-two dipoles for Arc 3-10.
  - The recirculating Pi bends are at a radius of 80 m.
  - Each Arc has 32 quadrupole girders grouped in 4 families to control achromaticity, momentum compaction and the betatron tune.
  - Beam Position Monitors at the entrance of quadrupoles.
  - Horizontal and vertical correctors throughout to control the beam orbit.

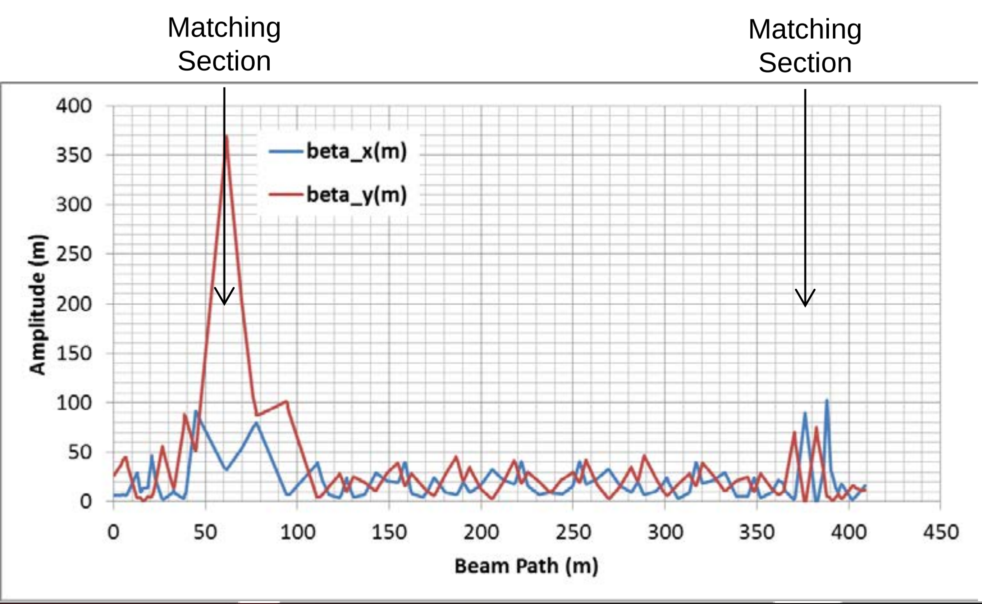
Arc Dipoles

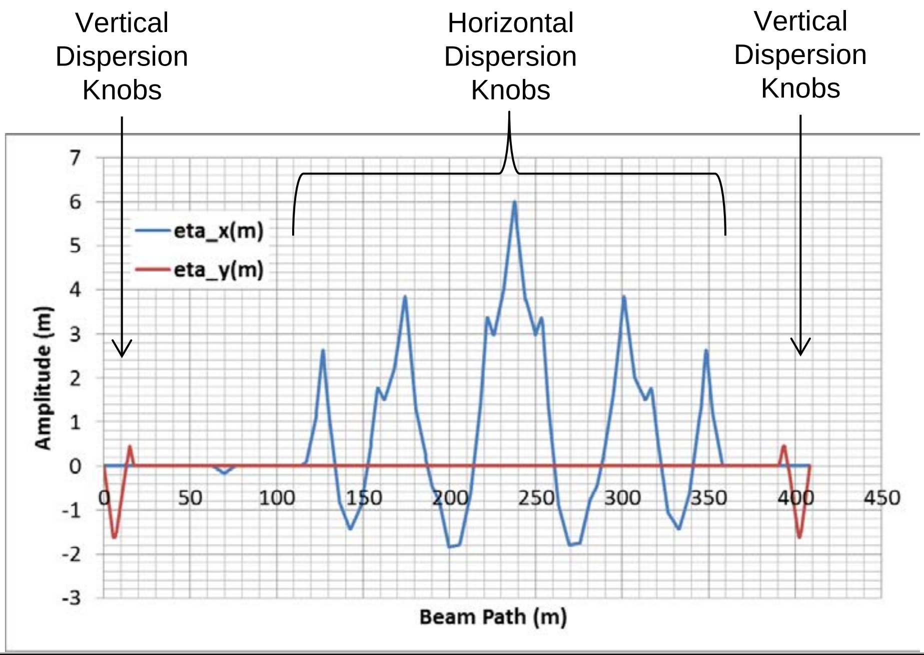


Arc Quadrupole Girders

1st and 2nd Recirculation Arcs

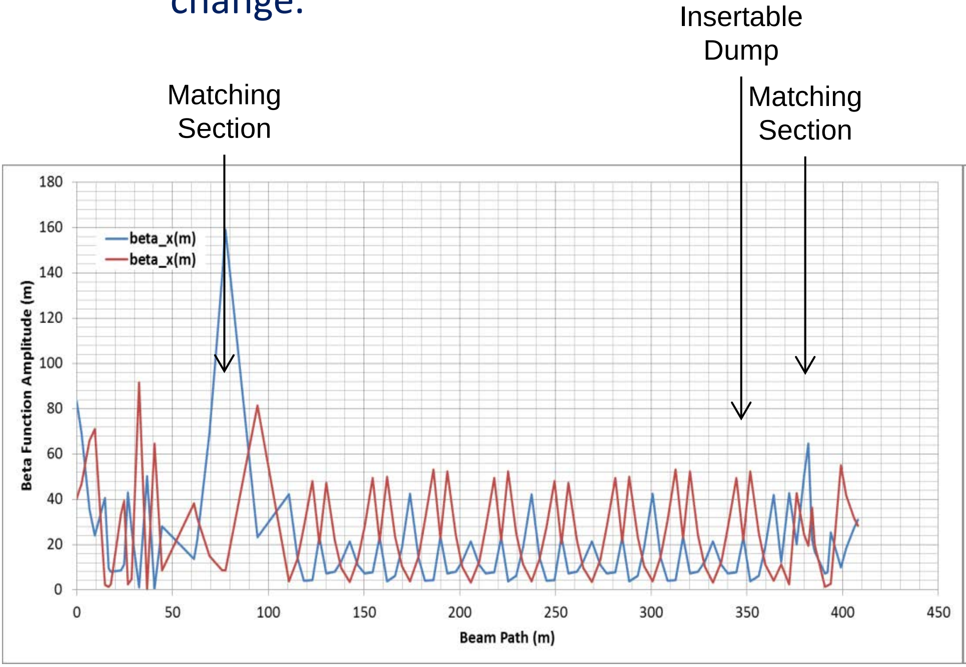
- Arc 1/2 Optics:
  - Segment begins at start of the Spreader and ends at the exit of the Recombiner.
  - Matching section in Spreader for matching the beam to the Arc.
  - Matching section in Recombiner for matching to the Linac.
  - Quads in vertical steps are used to null the vertical dispersion.
  - Quads near peaks of dispersion function within the Arc are used to null the horizontal dispersion and control M_{56}.
  - Enhanced horizontal dispersion in Arcs 1/2 provide better resolution for energy monitoring.

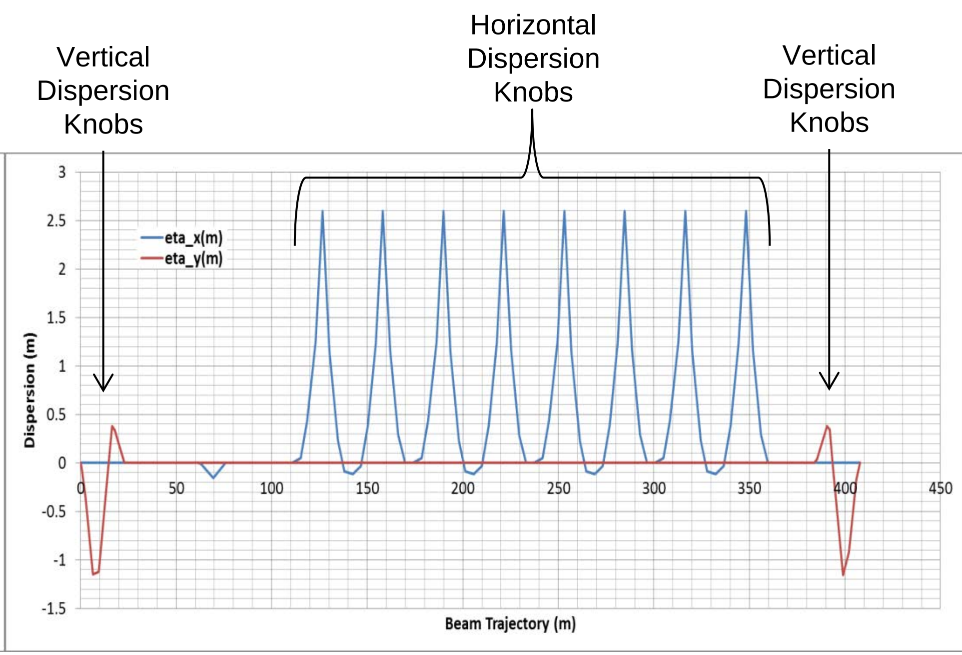




Higher Energy Arcs

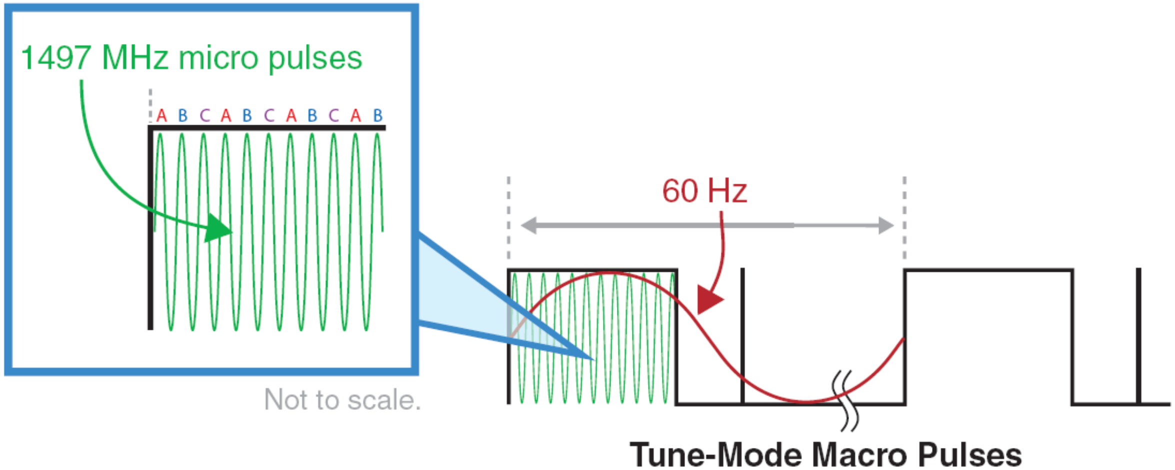
- Arc 3-10 Optics
  - The design optics for the upper Arcs is represented below.
  - Matching section in Spreader for matching the beam to the Arc.
  - Matching section in Recombiner for matching to the Linac.
  - Quads in vertical steps are used to null the vertical dispersion.
  - Quads near peaks of dispersion function within the Arc are used to null the horizontal dispersion and control M_{56}.
  - Amplitude of vertical dispersion peaks go down with pass count due to the smaller elevation change.

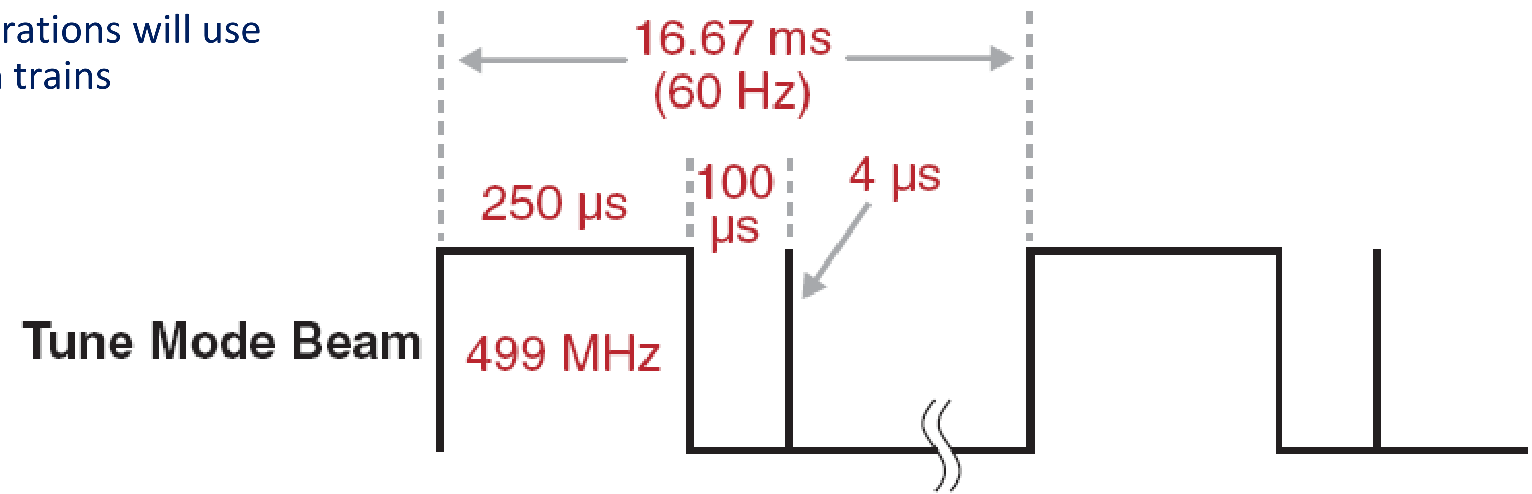




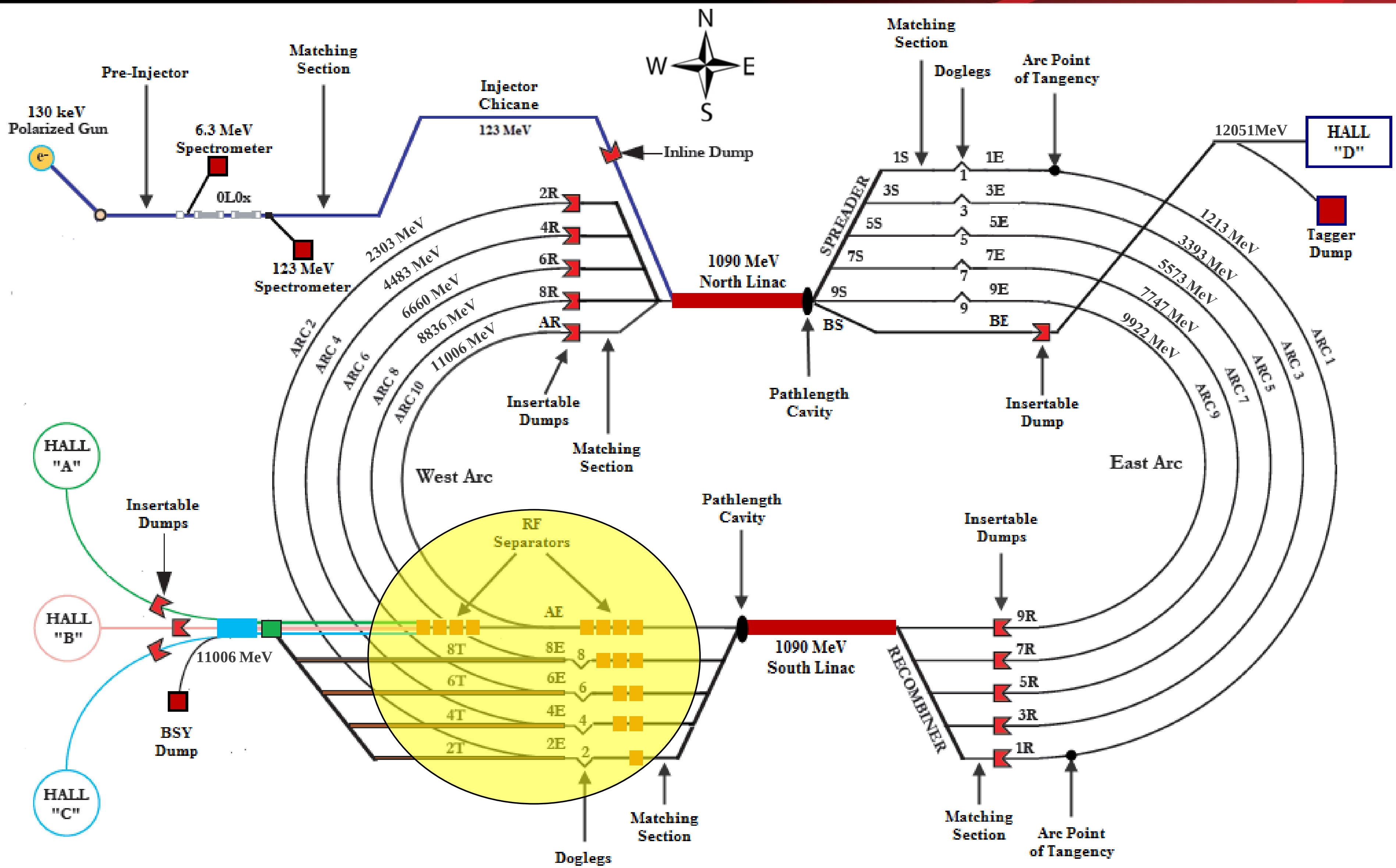
CEBAF Beam Structure

- Accelerator tuning is always done using low average power beam.
- The 250 ms pulse width at 60 Hz provides a 1.5% duty cycle.
- Nominal pulse height is 4 mA.
- Beam power is 720 W for a 12 GeV beam at this duty factor.
- The 4 ms trailing pulse is for measuring linac BPM orbits and linac arrival time.
- 3 interleaved 499 MHz bunch trains injected into 1497 MHz Linacs
- Future 4-Hall operations will use 249.5 MHz bunch trains



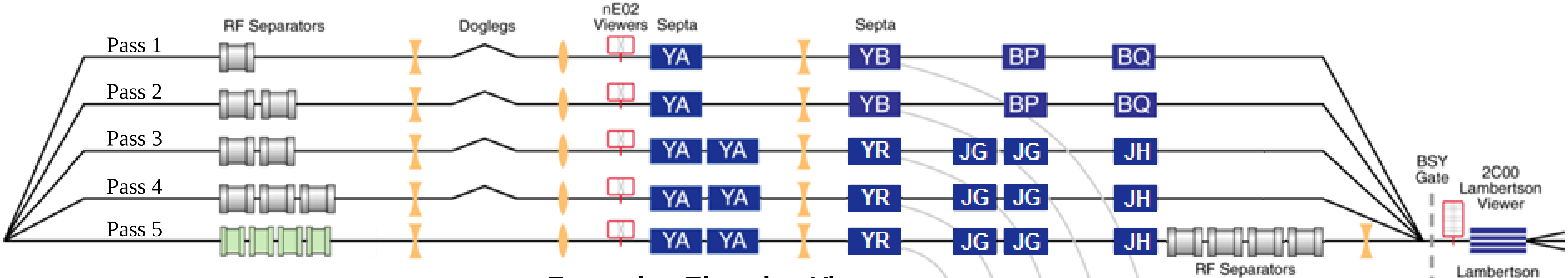


Extraction Region

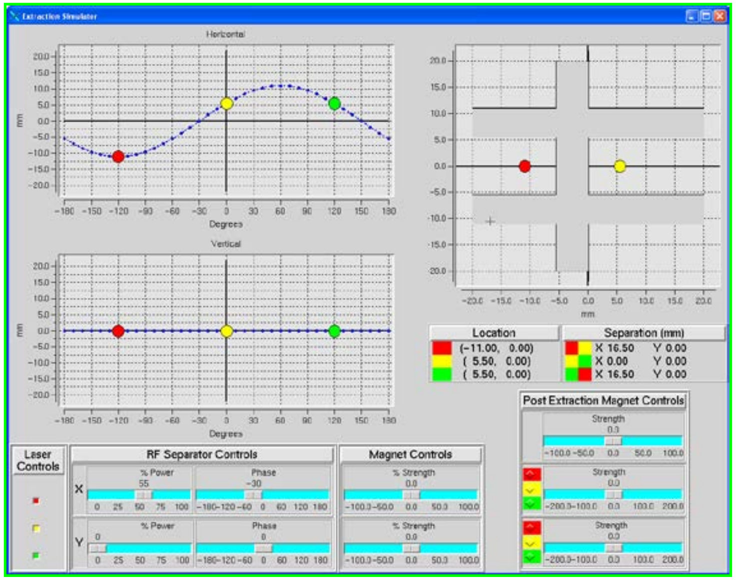


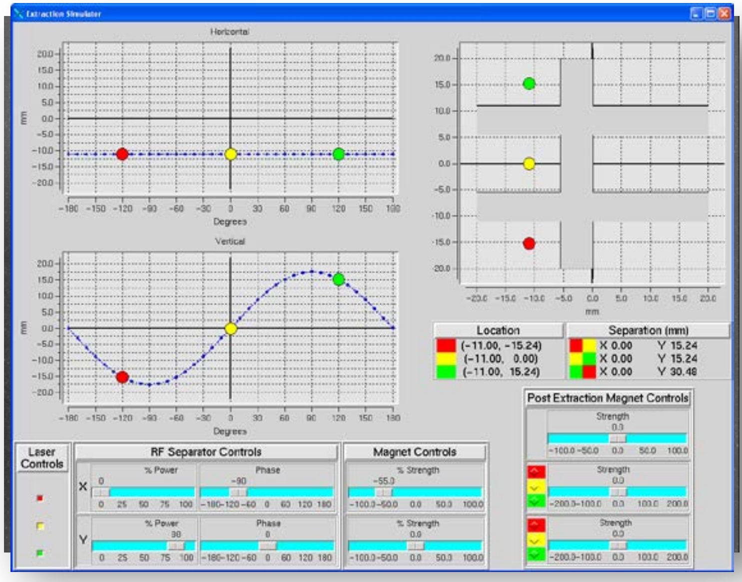
Extraction System

- Overall configuration:
  - Horizontal extraction systems at 500 MHz for 1st through 4th pass
  - Vertical extraction system at 500 MHz for 5th pass
  - New horizontal extraction system at 750 MHz for 5th pass

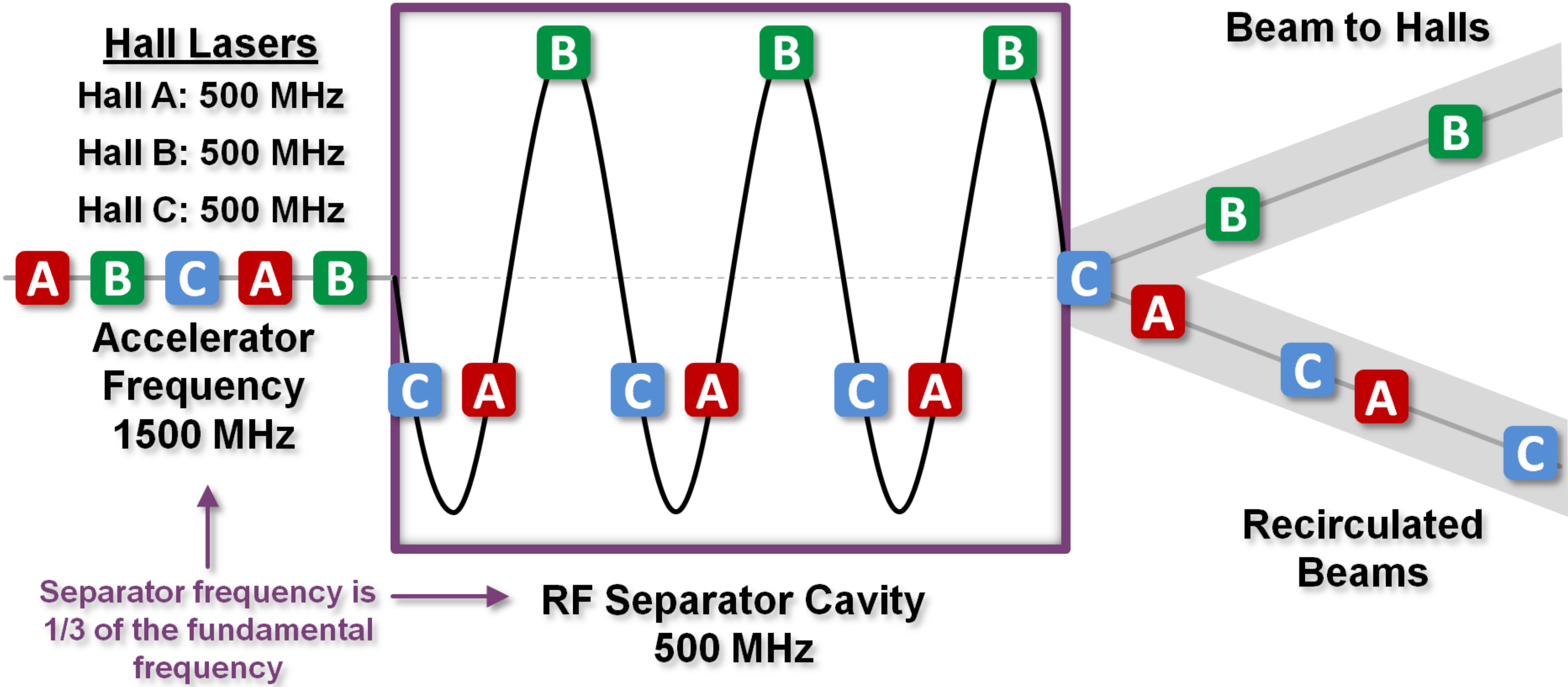


Extraction Elevation View

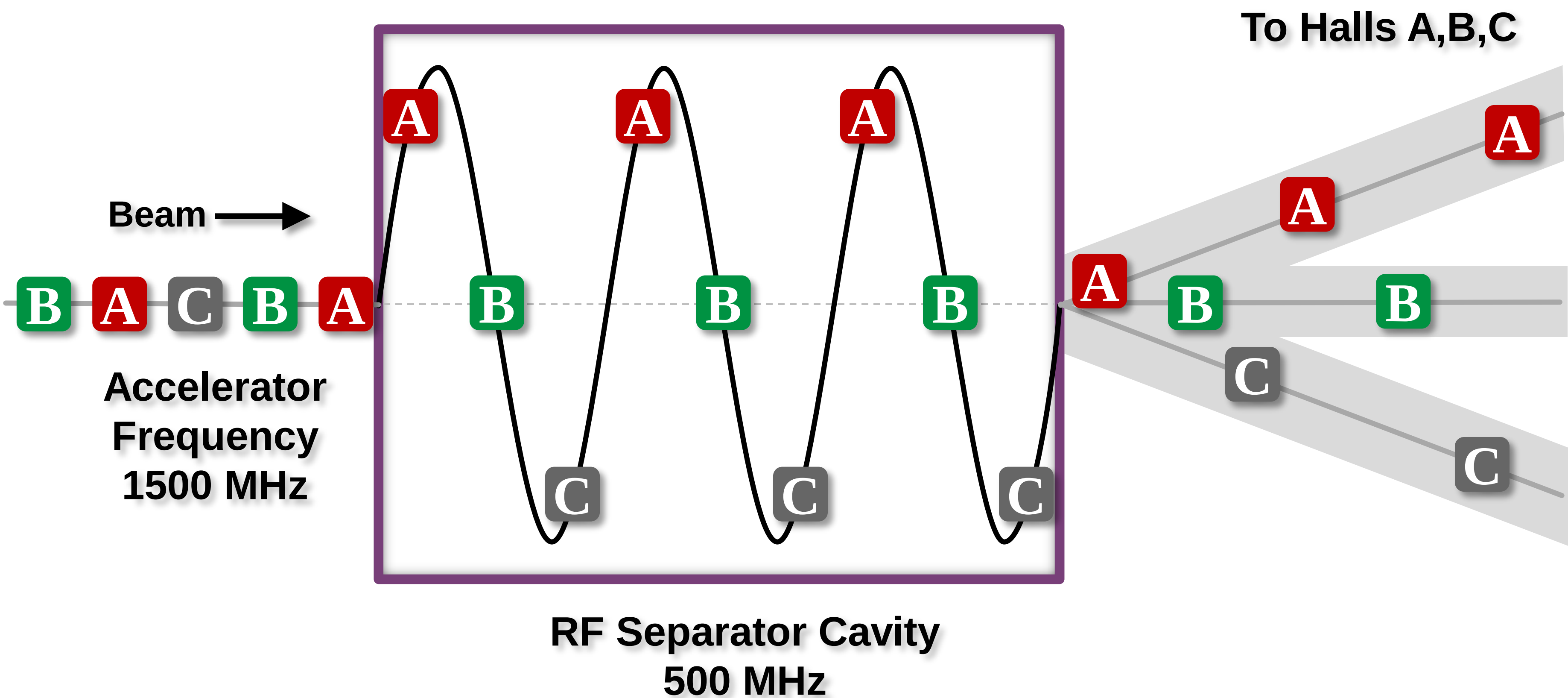




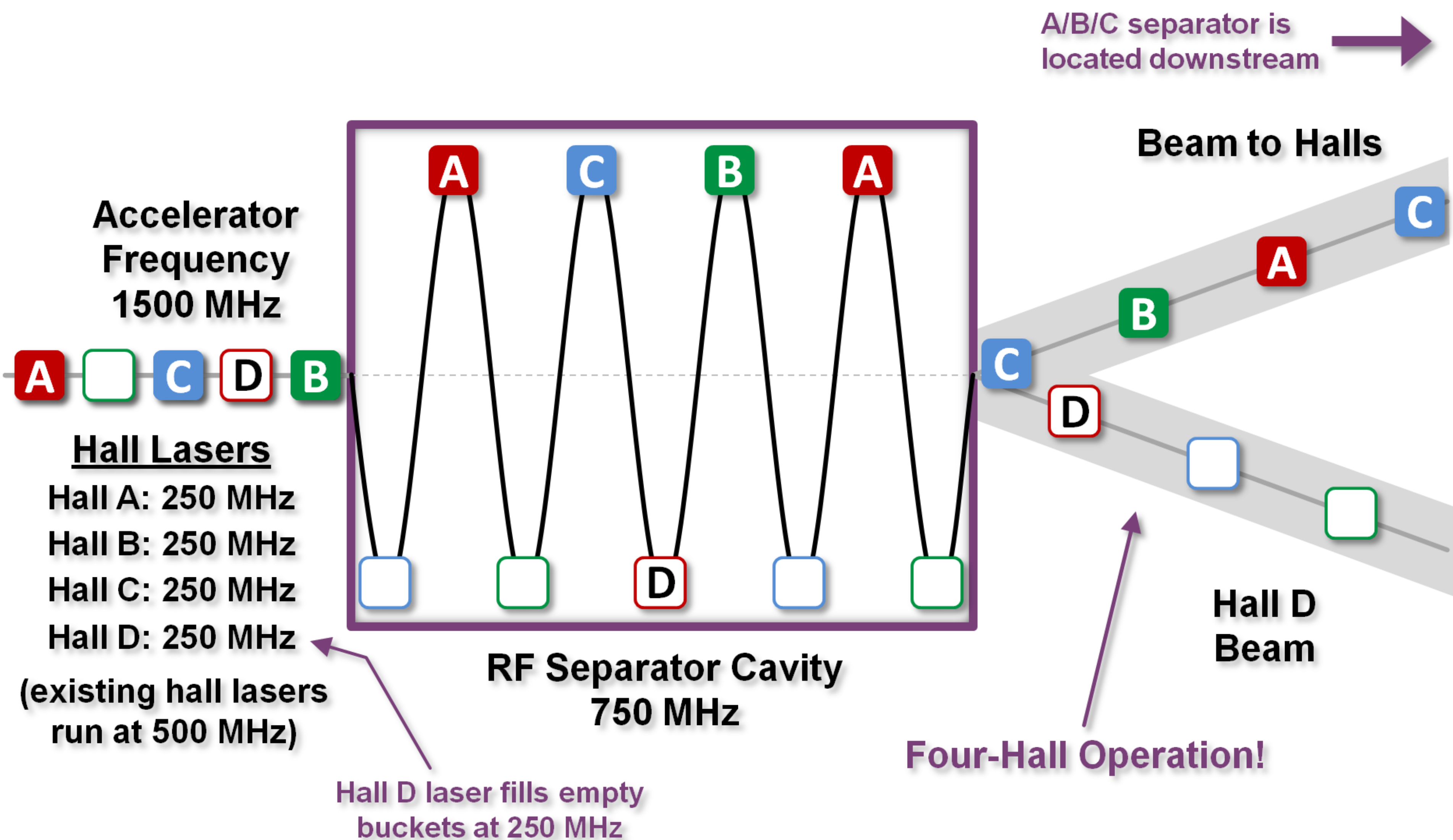
Existing Horizontal RF Separation



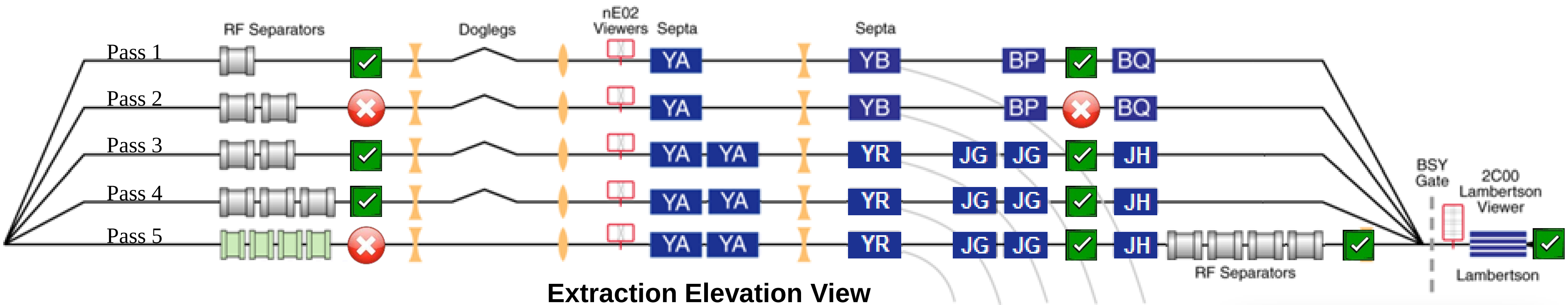
Halls A,B,C 5th Pass Vertical Separation



5th Pass Horizontal RF Separation

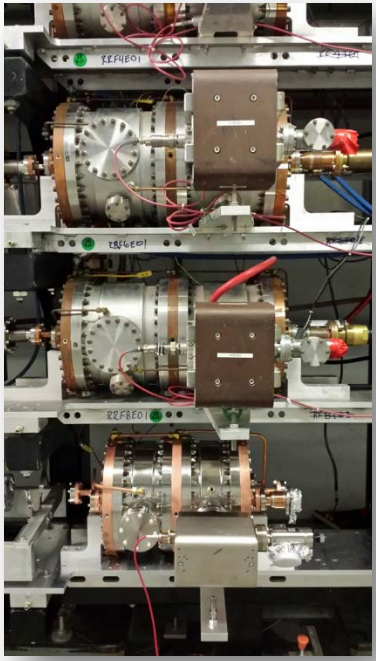


Extraction System Status



Extraction Elevation View

- What remains to be done
  - Fix Dogleg vacuum chamber in 2nd pass
  - Commission second pass horizontal RF and Magnet systems
  - Recheck setup of high power phase shifters for 4th pass horizontal system
  - Install 5th pass horizontal 750 MHz cavities
  - Commission 5th pass horizontal RF and Magnet systems

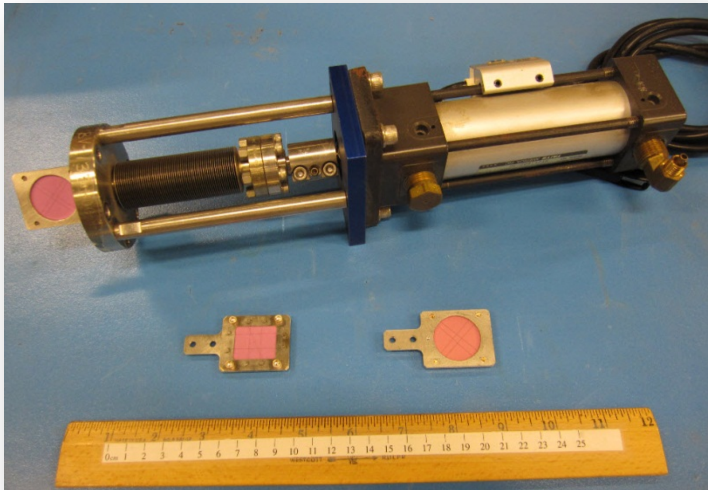


1st 750 MHz RF Separator Installed under 500 MHz Cavities

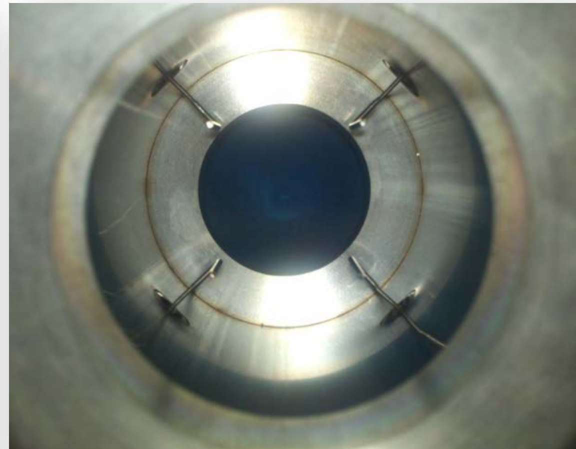
Diagnostics

- Bunch Length Monitors
  - 6 GHz pill box cavities for optimizing longitudinal beam profile in the Injector.
  - Commissioning an interferometer as an online diagnostic
- Beam Viewers
  - Insertable flag for monitoring general beam quality. Located in all beamlines for measuring spot evolution. Also used in dispersive locations to phase cavities.
- Beam Position Monitors
  - 4-wire M15 and M20 style in all existing beamlines and the new ARC 10. Additional BPMs added to new Spreaders and Recombiners.
  - Stripline style BPMs newly developed for the Hall D beamline.
- Pathlength Monitors
  - 499 MHz pill box cavities located at the end of the linacs to measure arrival time of the beam for each pass.
- Beam profile monitors
  - Wire Scanners used for matching in the injector, at the entrance of each Arc and in front of the 2 kW beam dumps for Halls A, B, C and D.
  - Synchrotron Light Monitors in Injector, Arc 1, Arc 2, Arc 10, and Hall beamlines.

Existing Diagnostics

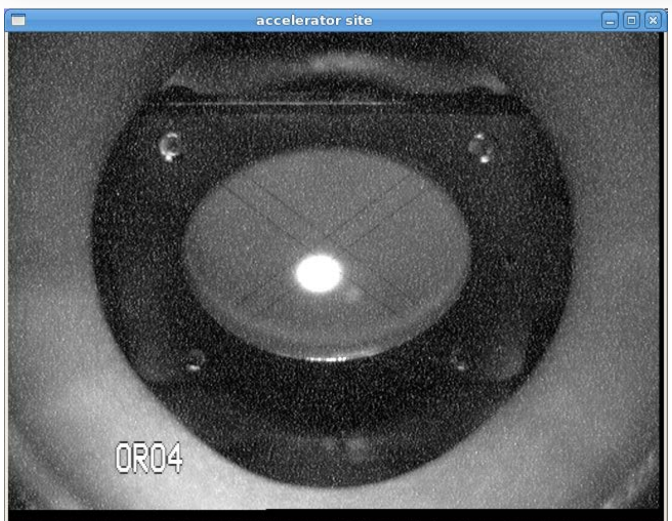


Beam Viewers

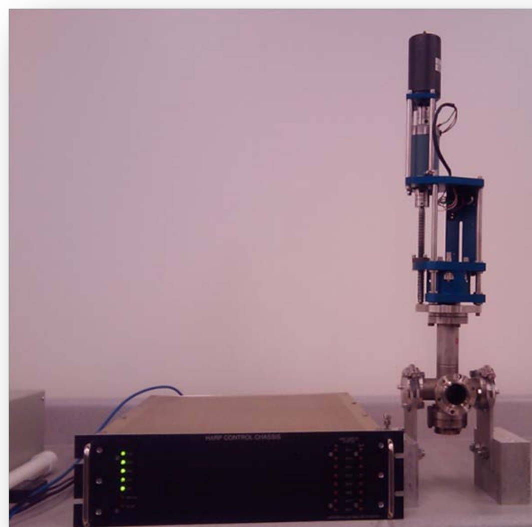


Antenna-Style Beam Position Monitor

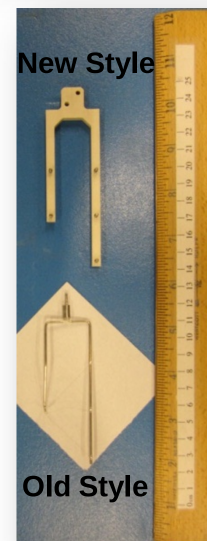
Pathlength Cavity



Beam on Viewer in Chicane

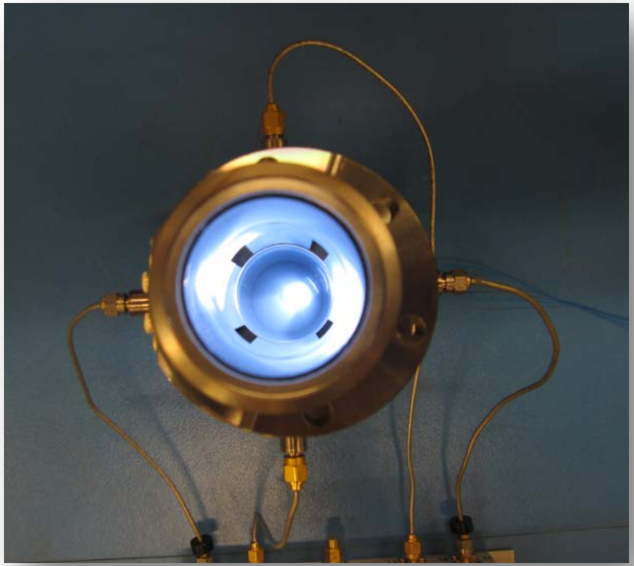


Wire Scanner and Electronics

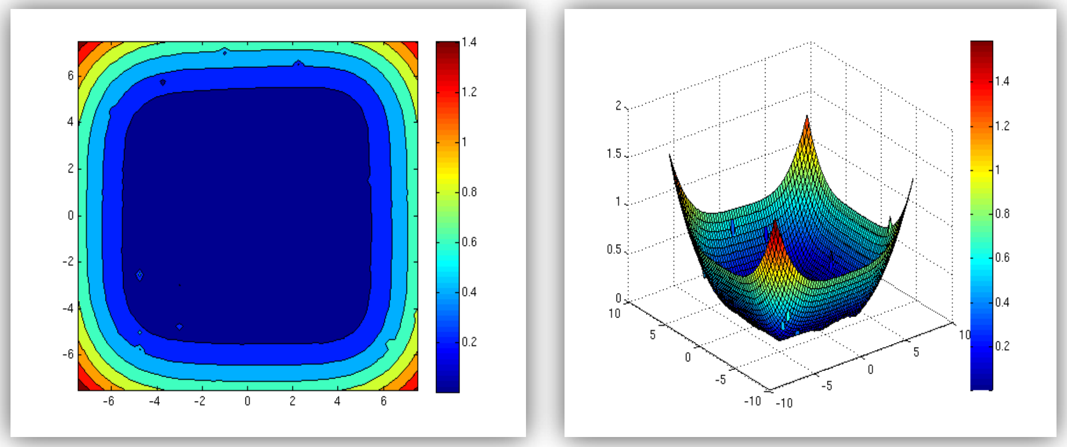


Wire Scanner Forks

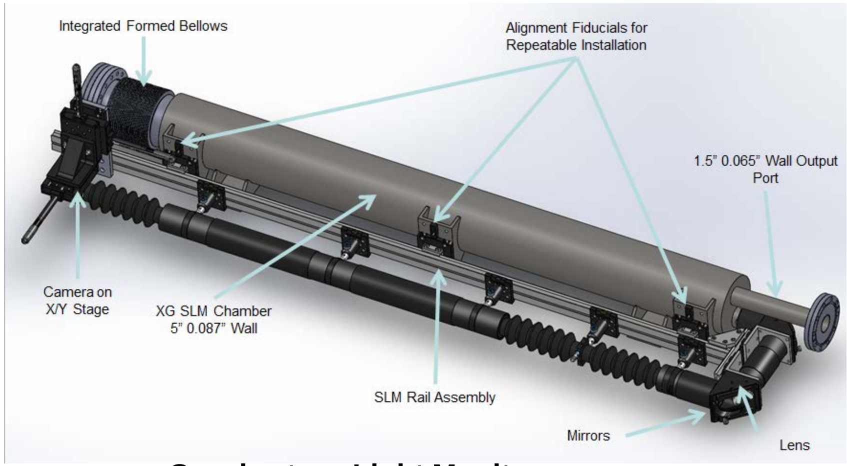
Diagnostics for New Beamlines



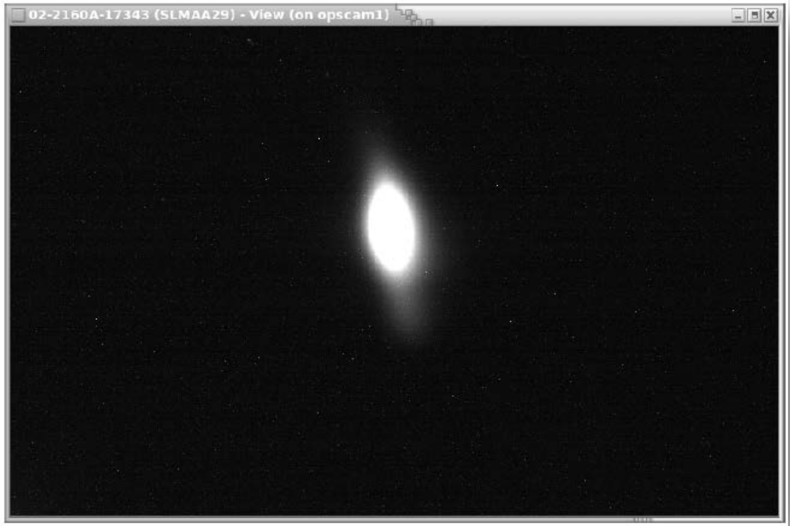
Stripline Beam Position Monitor



Map of BPM Response from Stretched-Wire Test Stand



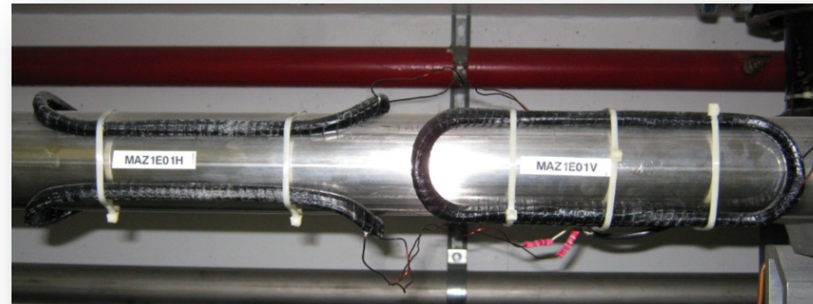
Synchrotron Light Monitor



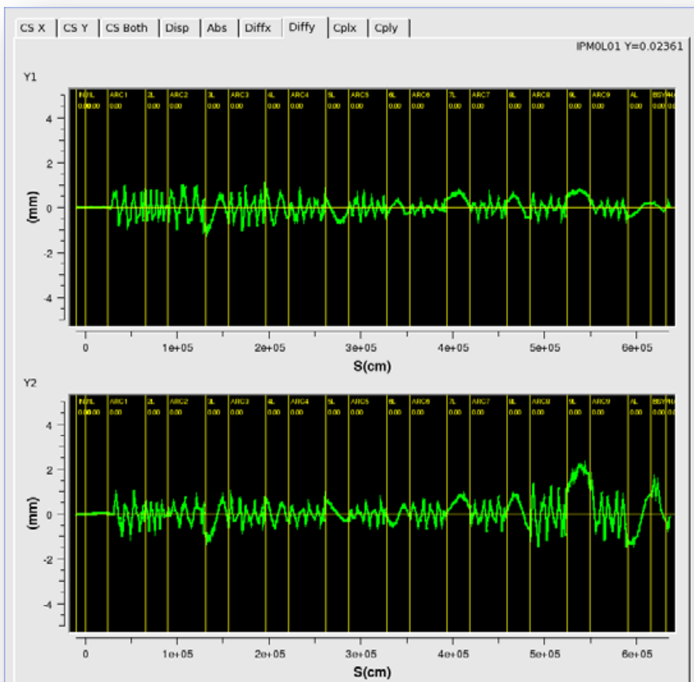
Synchrotron Light from 9 GeV Beam in Arc10

30 Hz Differential Orbit Tuning

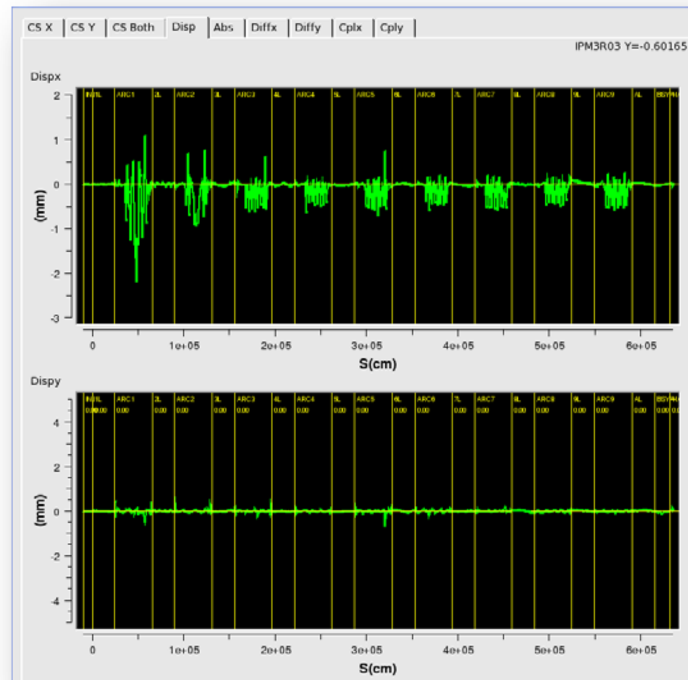
- Air-core kicker magnets in Arc 1 are used to provide differential orbit data at 30 Hz.
- System uses two kickers in each plane separated by a phase advance of 90 degrees.
- The left figure shows the differential orbits for the y-plane.
- System also used to modulate the energy in the North Linac at 30 Hz to measure/minimize dispersion leakage.



A pair of 30 Hz. Kicker magnets in Arc 1



Differential orbits in the Vertical Plane



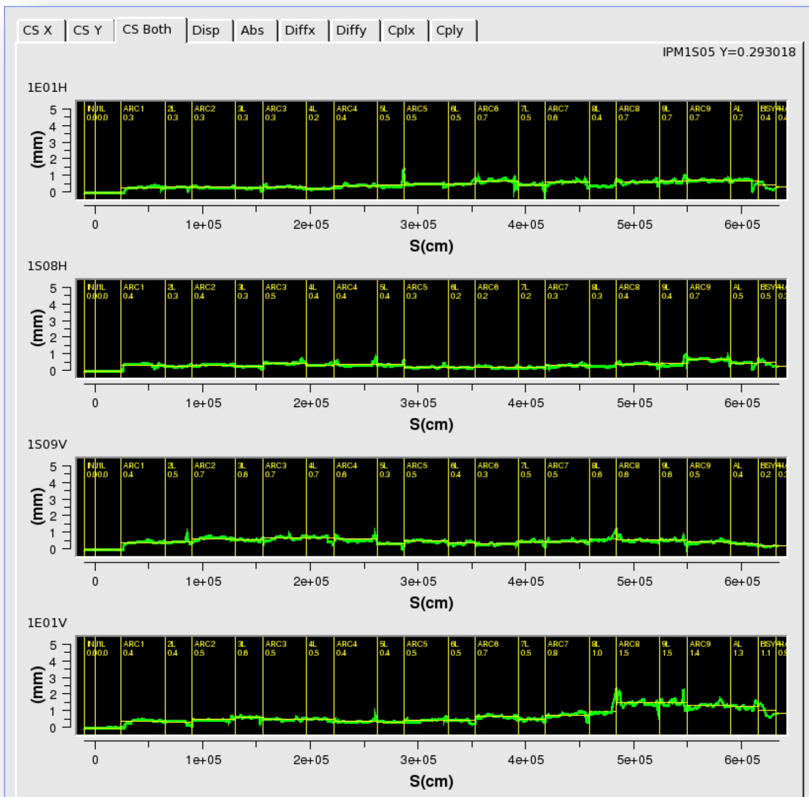
Horizontal and Vertical Dispersion Pattern

Courant-Snyder Tuning

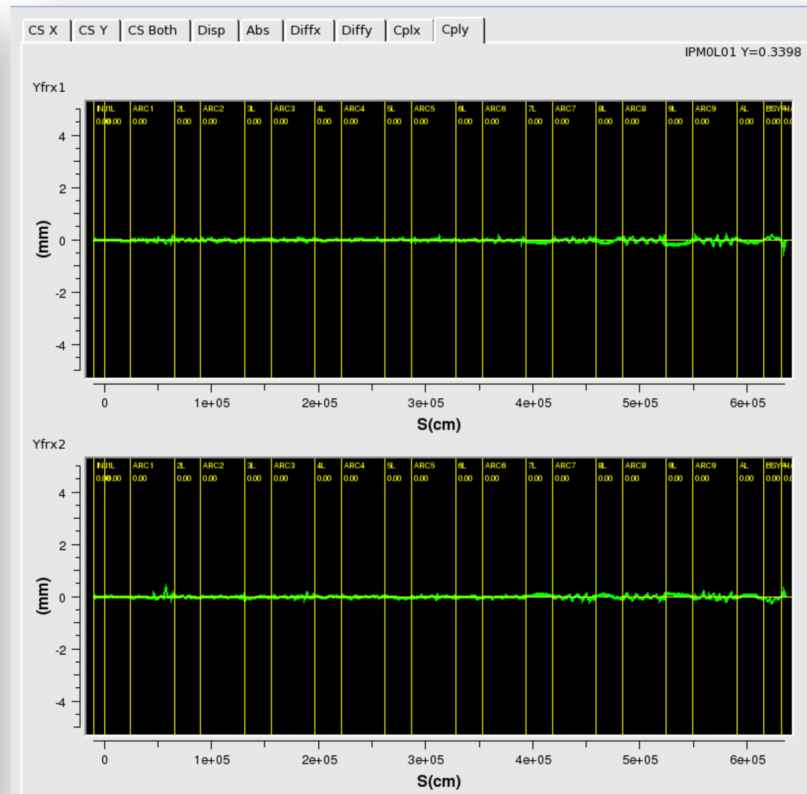
- The Courant-Snyder Invariant refers to the invariance of the phase-space beam ellipse as it traverses the accelerator

$$\epsilon = \beta x'^2 + 2\,\alpha x x' + \gamma x x^2.$$

- The 30 Hz beam position data is analyzed to calculate the normalized invariant and compare to model.
- Lower left figure shows a reasonably well-tuned result for each of the four kickers.
- The same system is used to report the extent of the X-Y coupling errors in the system.



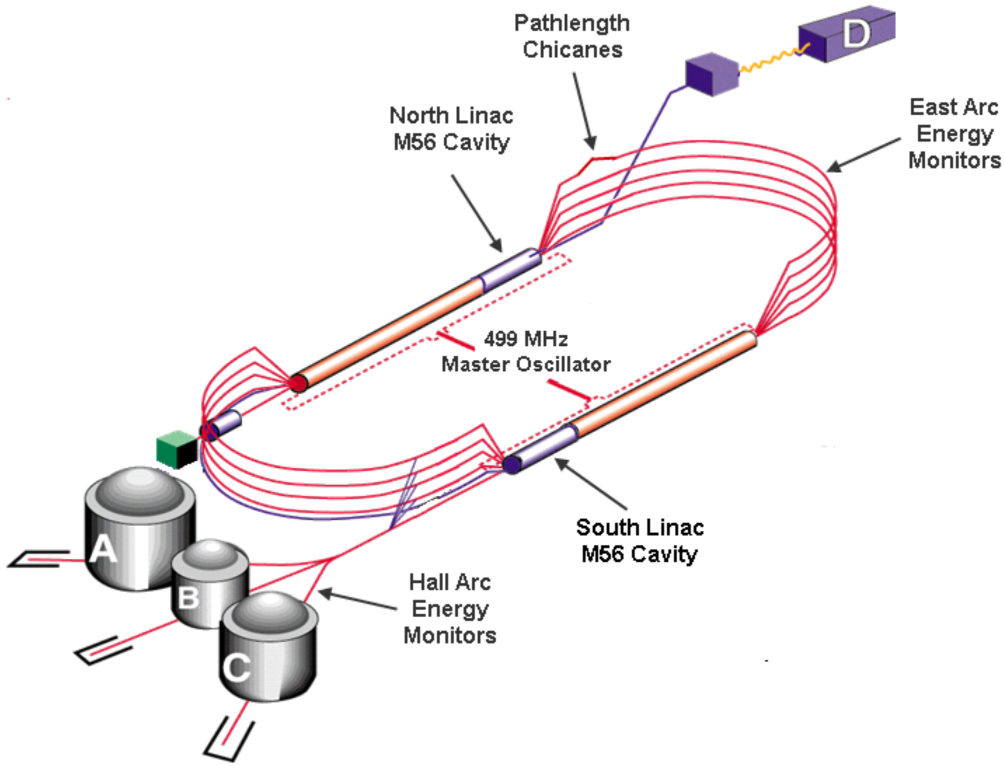
Courant-Snyder Invariant for Four Differential Orbits

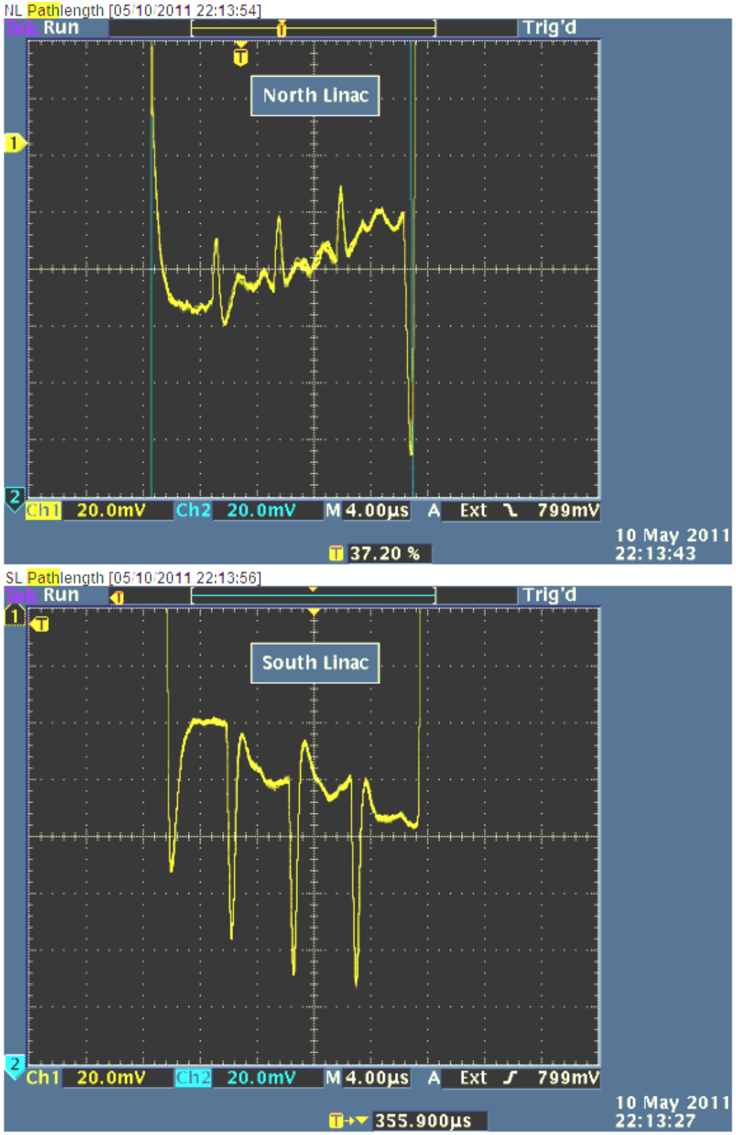


Coupling to Y-plane from X Differential Orbits

Pathlength Compensation

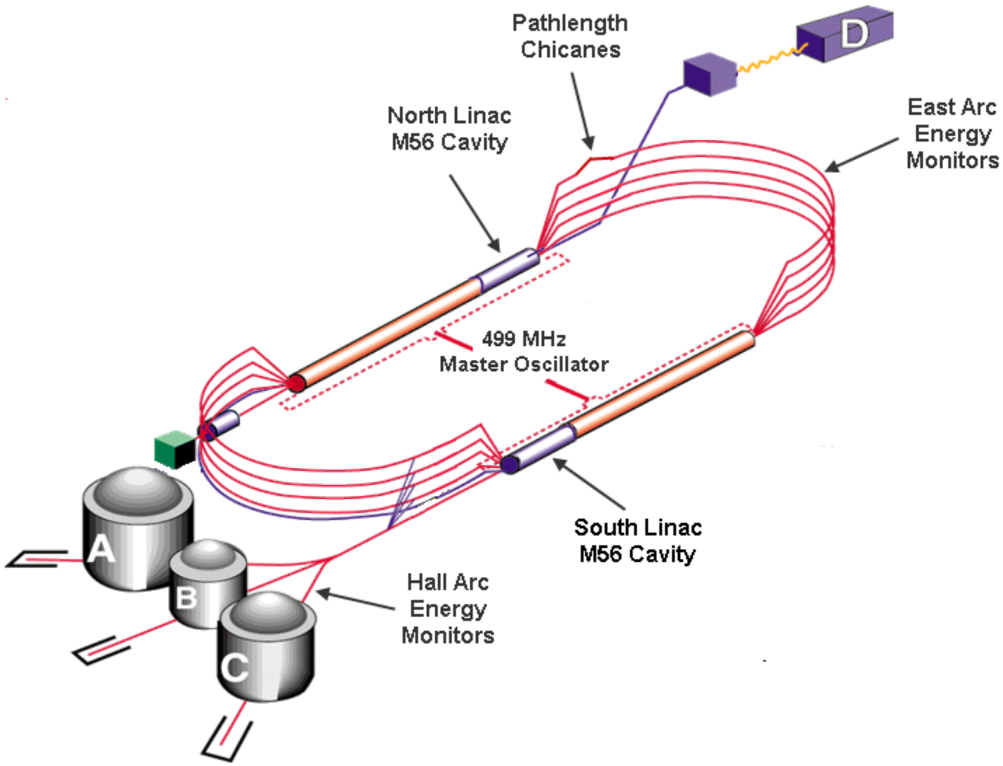
- Arrival time in linacs depends on distance travelled.
- The pass-pass length of the machine needs to be an integral number of RF wavelengths for peak acceleration.
- Changes in pathlength due to uniform expansion of the tunnel are compensated with changes to the RF frequency of the Master Oscillator.

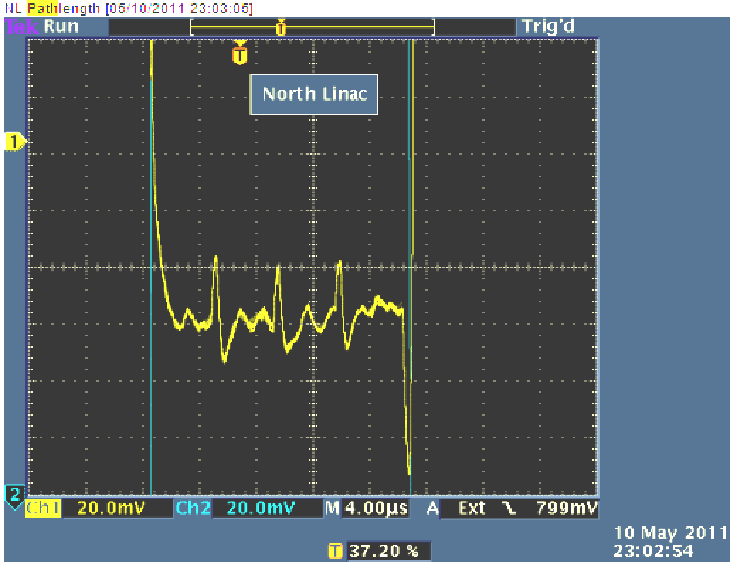


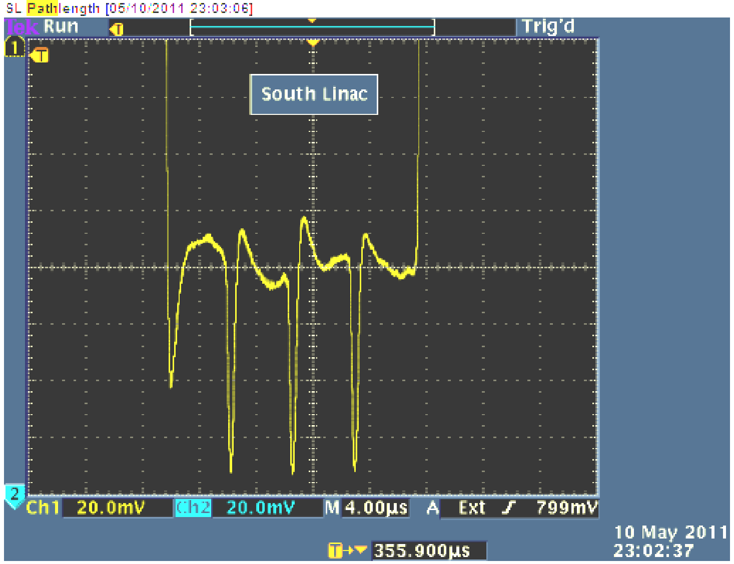


Pathlength Compensation

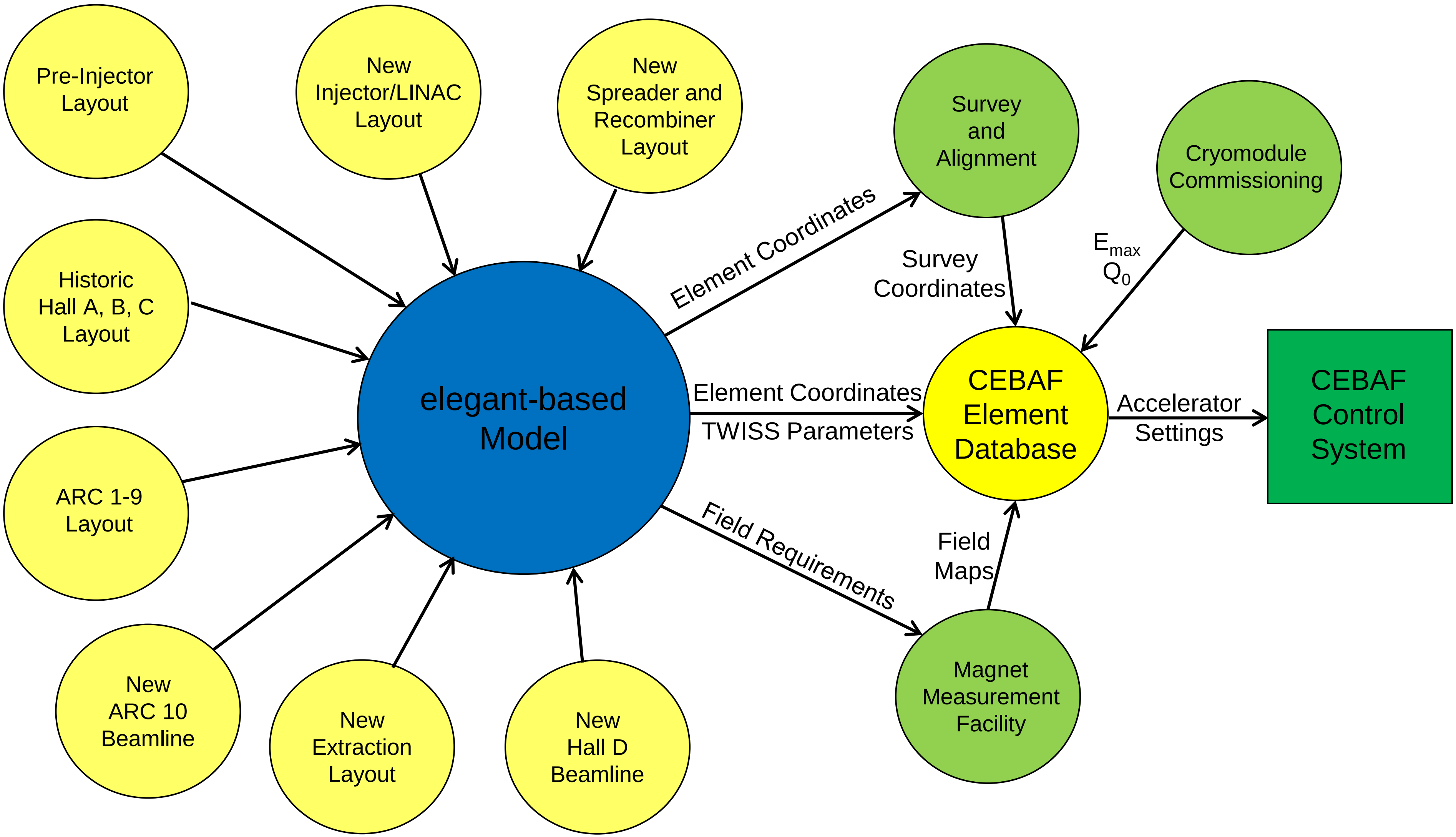
- Pathlength optimized after 100 Hz shift in the 1497 MHz Master Oscillator.
- Pathlength chicanes compensate for residual non-uniform changes to the overall machine length.





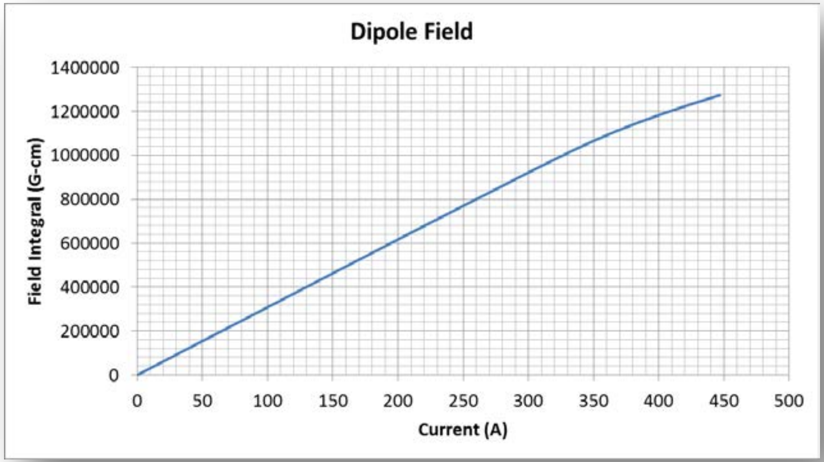


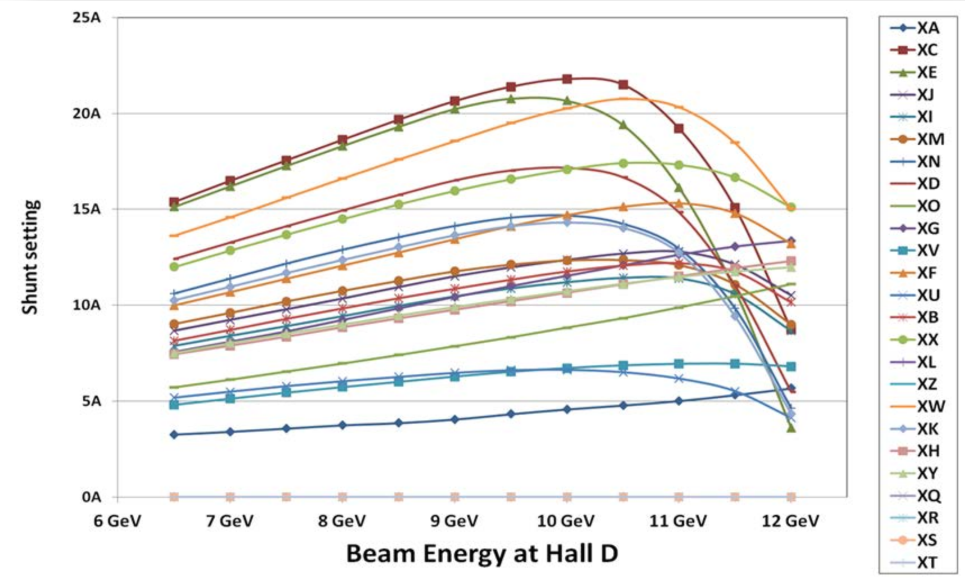
Model-Based Operations

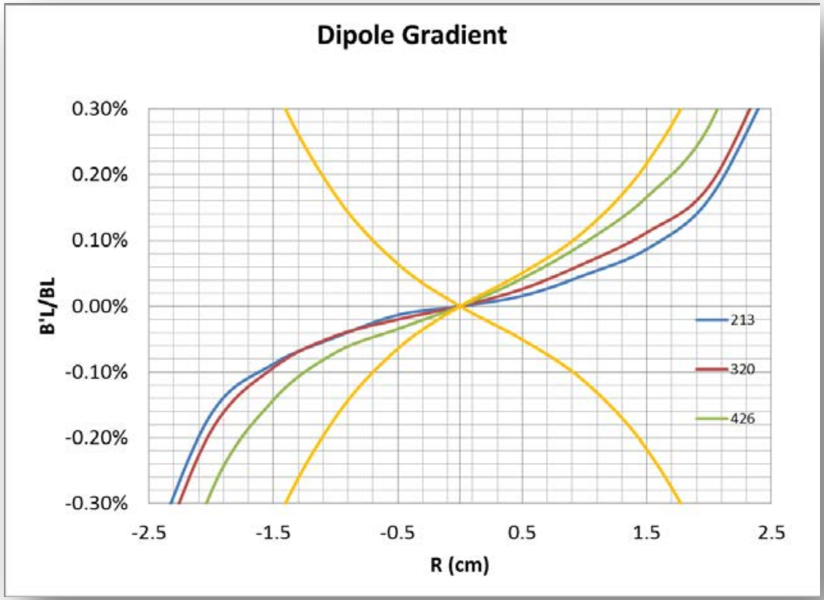


Magnet Field Quality

- Magnet Measurement Facility Data
  - All dipole and septa magnets measured for field quality.
  - All quad families measured for field quality.
  - Integrated field and dipole gradient data entered into the CEBAF Element Database.
  - Control system gets information from the CEBAF Element Database.





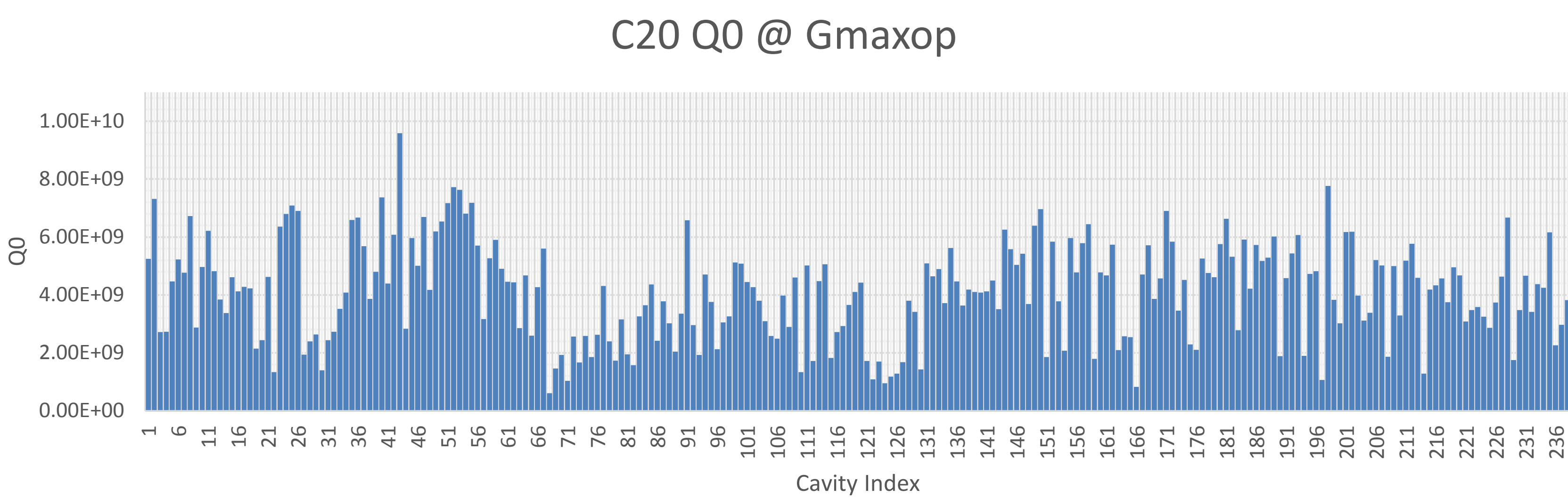


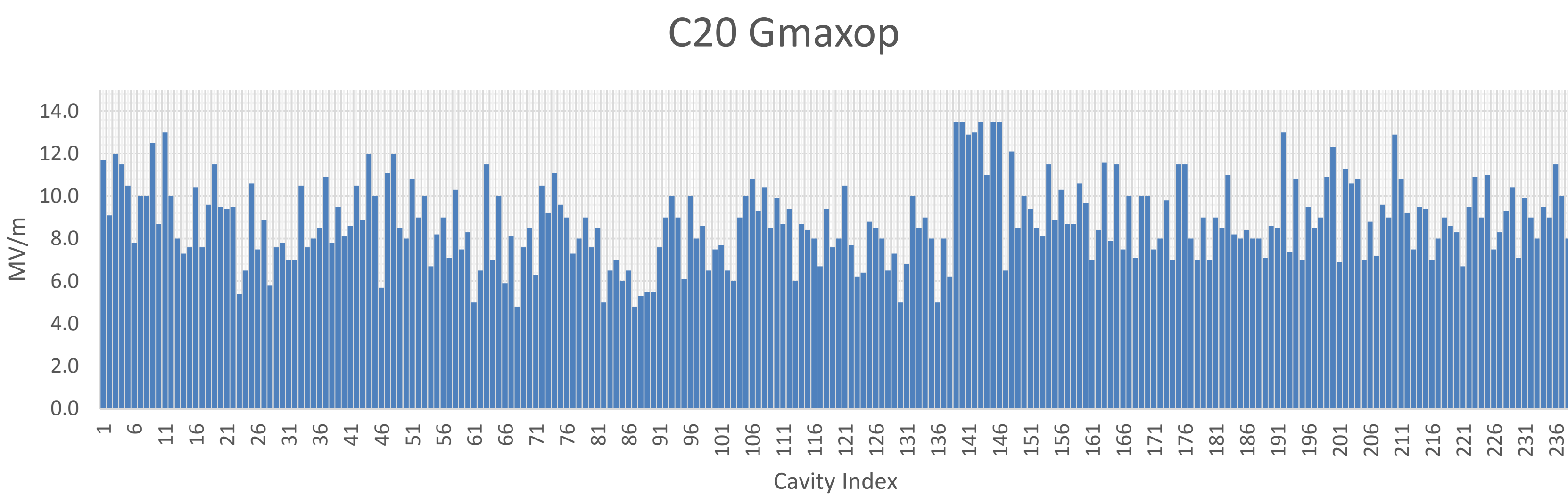
Cryomodule Commissioning

- All 418 SRF cavities were commissioned in advance of beam operations.
  - Measured:
    - ✓ Maximum accelerating gradient
    - ✓ Cavity Q_0s
    - ✓ Field emission survey

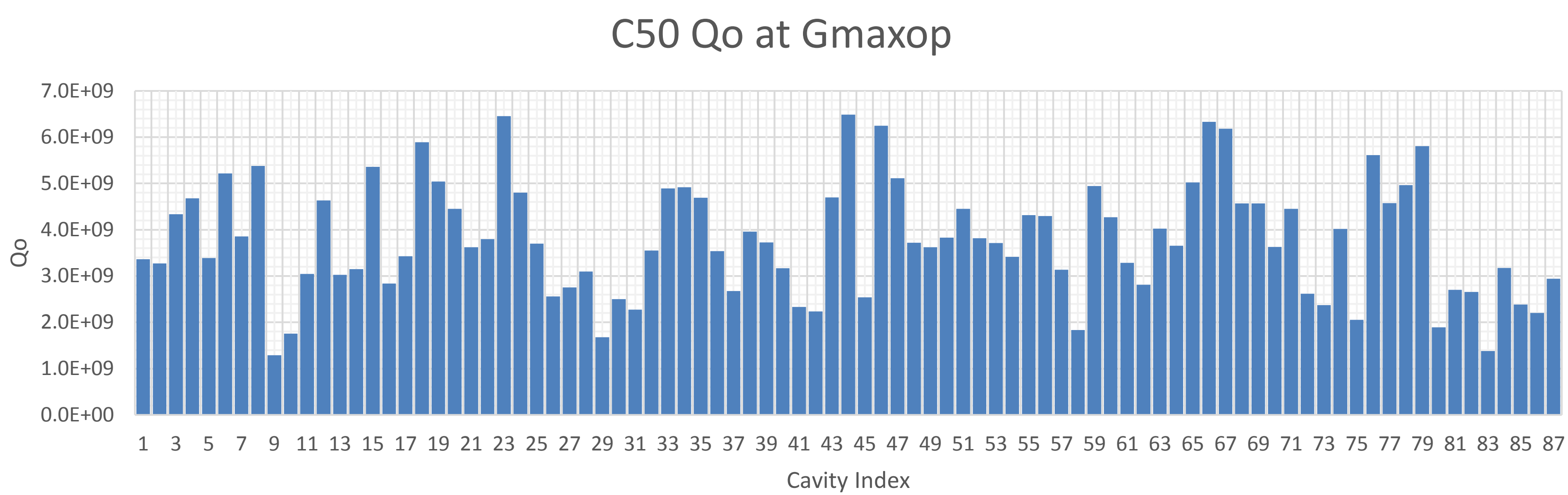
Linac	Type	Ncav	<GMES> (MV)	GMES_{RMS} (MV)	Min-Max (MV)	Egain (MeV)
Inj	C20	10	6.72	0.81	5.86-8.63	33.6
NL	C20	119	7.19	1.64	2.97-11.71	427.6
NL	C50	40	11.03	1.49	6.34-13.45	220.7
NL	C100	38	17.59	2.40	9.80-20.77	467.9
SL	C20	108	7.05	1.40	4.78-10.56	380.7
SL	C50	47	10.06	1.90	6.41-12.36	236.4
SL	C100	40	16.66	2.75	9.70-20.00	466.4

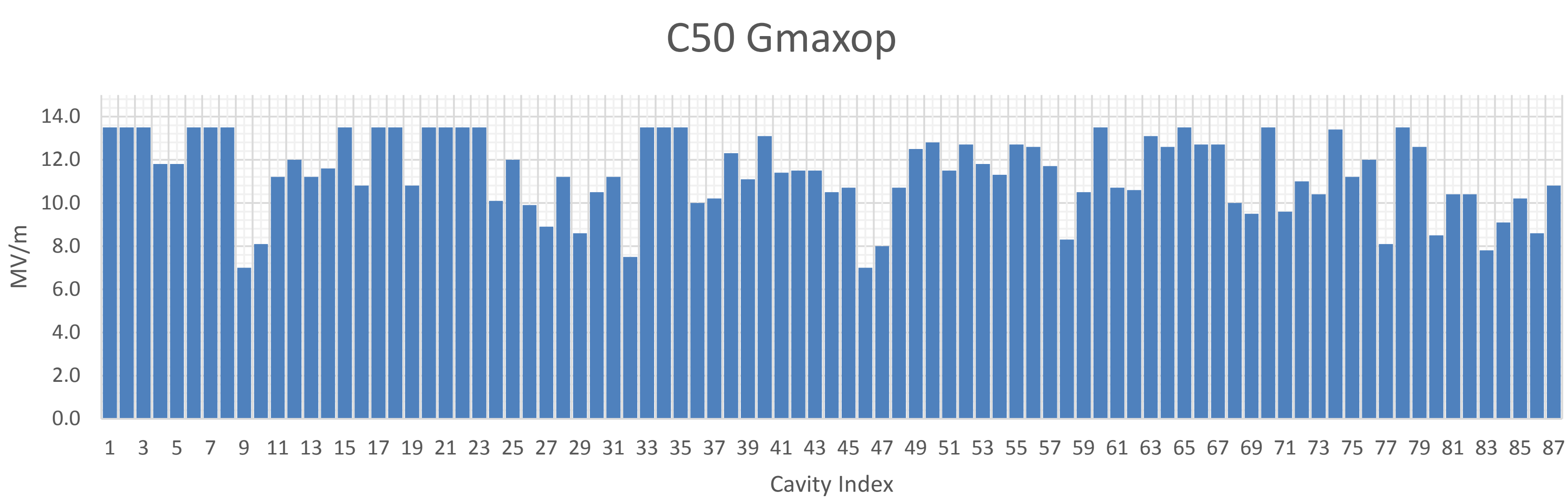
C20 Cavity Performance



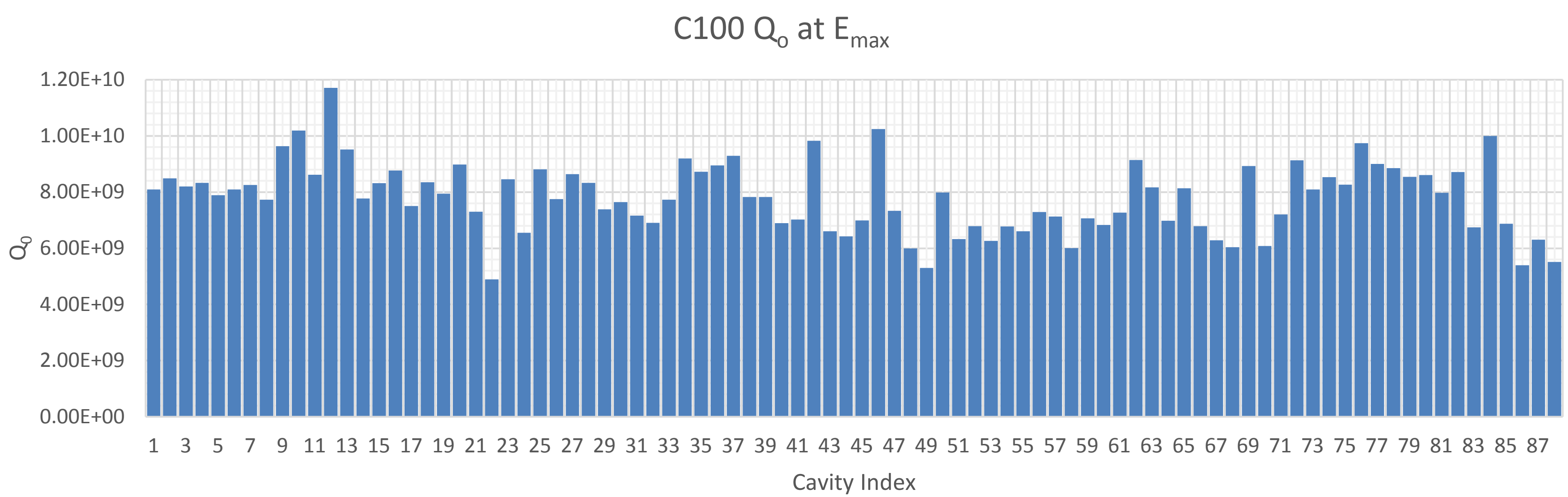


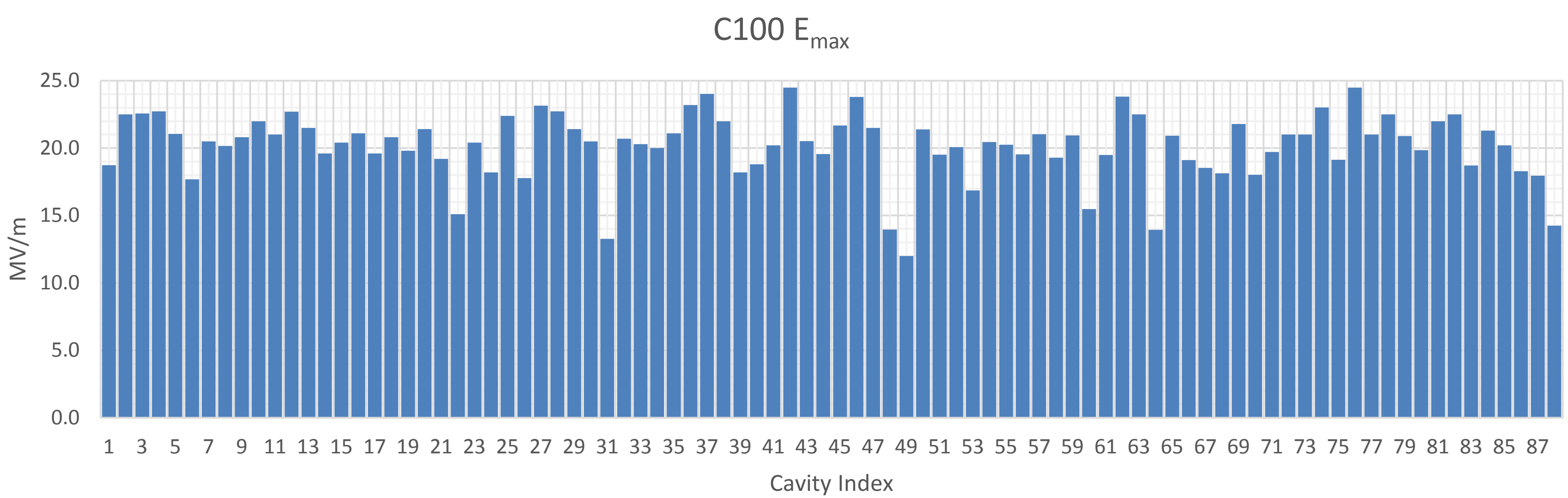
C50 Cavity Performance





C100 Cavity Performance





Cryomodule Operations

- Optimizing Cavity Phases
  - New software package under development - “Phaser”
    - Dither each cavity phase ±10 degrees
    - Measures the energy response in the Arc Beam Position Monitors
    - Determine phase error from asymmetry of response
    - Should be able to get to less than 0.25 degrees
- Optimizing Cavity Gradients
  - Automated routine to calibrate all cavities relative to one reference cavity
    - Calibrate one high gradient reference cavity relative to the Arc Beam Position Monitors
    - Turn off one cavity and use reference cavity to recover energy in Arc
    - Repeat for all cavities
    - Expect residual errors of a few percent

Optimizing the SRF Performance

Run Period	Dates	Max. 5.5pass Energy	Trip Downtime Goal (% - min/hr)
ACC-III	Fall2014	11 GeV	<20% <12
ACC-IV	Spring2015	11 GeV	<17% <10
Phy-I	Fall2015	12 GeV	<20% <12
Phy-II	Spring2016	12 GeV	<17% <10
Phy-III	Fall2016	12 GeV	<13% <8
Phy-IV	Spring2017	12 GeV	<12% <7
Phy-V	Fall2017	12 GeV	<10% <6
Phy-VI	Spring2018	12 GeV	<10% <6
Ultimate		12 GeV	<5% <3

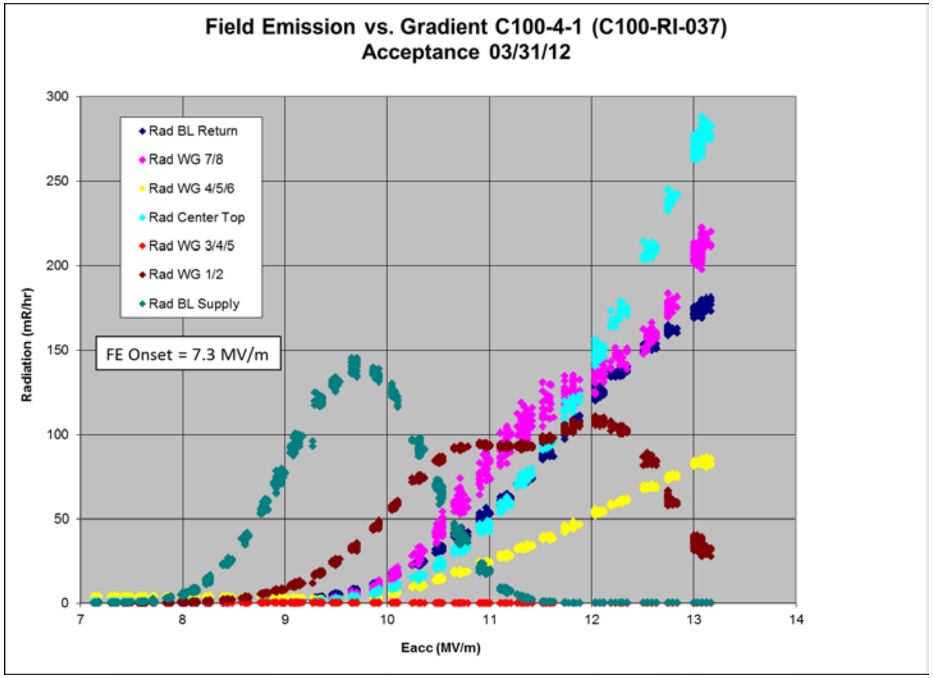
Multiple options for reaching the availability goals over time:

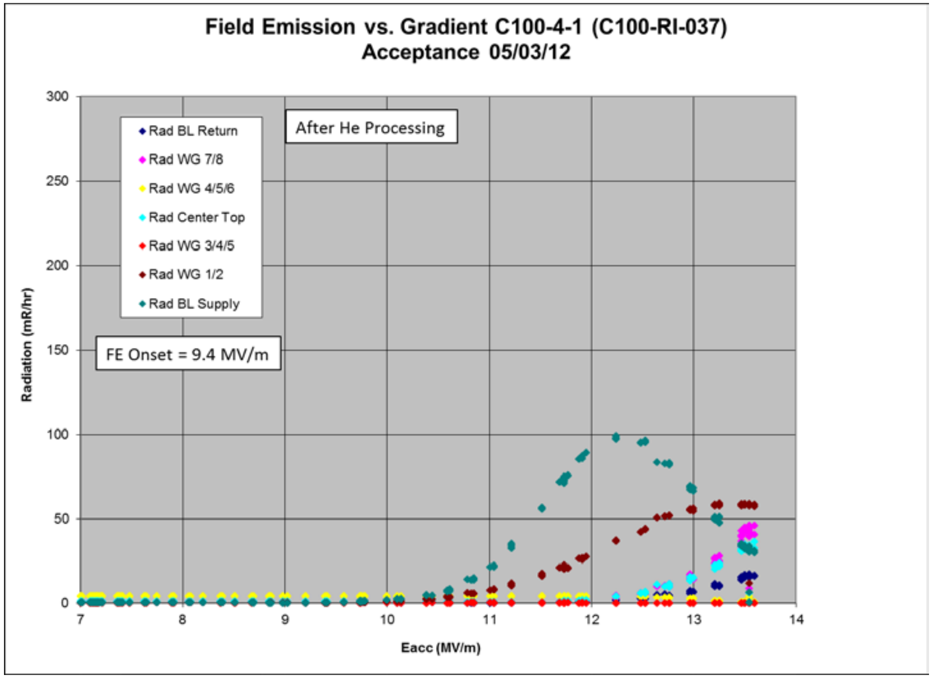
- Improve C20 trip models, maximize gradient/minimize trip rate.
- C50 program, one C50 refurbishment is in progress.
- Build more C100s.
- In-situ Helium Processing to reduce field emission.

Helium Processing

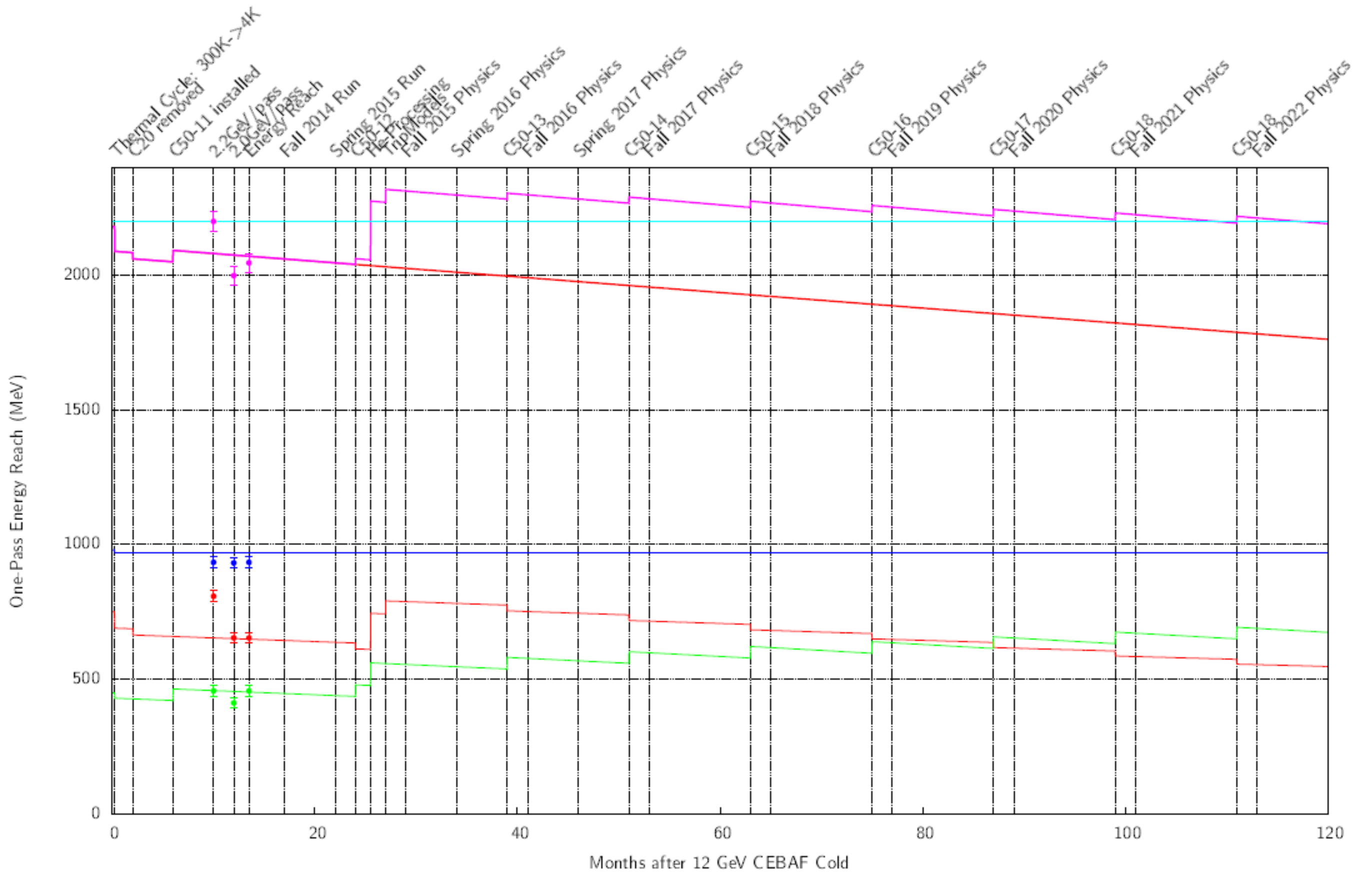
Helium Processing of a CEBAF Cryomodule:

- Introduce helium gas into cavity vacuum space.
- Run RF to clean cavity surfaces.
- Warm up and pump down to remove residual gas.
- Improves high-field Q, reduces x-ray production and greatly reduces incidence of arcing at the cold ceramic window.





Maintaining Gradient



- Coordinated effort to reach 2.2 GeV per pass with acceptable performance for Physics
  - Helium processing
  - C-50 Refurbishment Program

Beam Physics Requirements

Beam/beamline requirements @ 11-12 GeV: Initial requirements

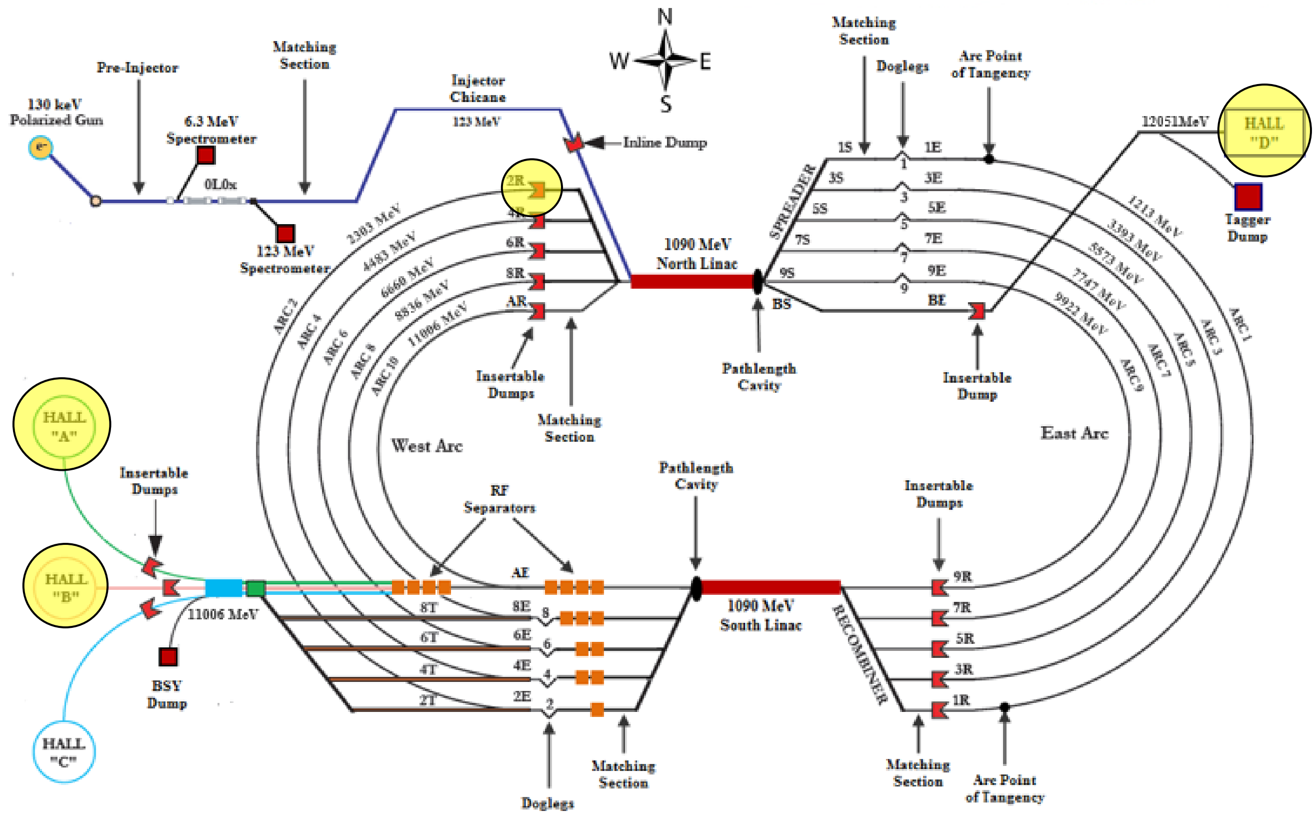
Hall	Emittance	Energy spread (σ)	Spot size (σ)	Halo	Other
A	$\varepsilon_x < 10$ nm-rad, $\varepsilon_y < 5$ nm-rad	0.05% (12 GeV) 0.003% (2-4 GeV)	$\sigma_x < 400$ μm $\sigma_y < 200$ μm ($\sigma_y < 100$ μm, (2-4 GeV))	1×10^{-4} Gaussian integral/pedestal integral	
B	$\varepsilon_x < 10$ nm-rad, $\varepsilon_y < 10$ nm-rad	0.1%	$\sigma_x < 400$ μm $\sigma_y < 400$ μm	2×10^{-4} Gaussian integral/pedestal integral	Beam Position Stability < 200 μm Beam Current Stability $\Delta I/I < 5\%$
C	$\varepsilon_x < 10$ nm-rad, $\varepsilon_y < 10$ nm-rad	0.05%	$\sigma_x < 500$ μm $\sigma_y < 500$ μm	2×10^{-4} Gaussian integral/pedestal integral	Beam Position Stability < 500 μm
D	$\varepsilon_x < 50$ nm-rad, $\varepsilon_y < 10$ nm-rad	<0.5%	At radiator: $\sigma_x < 1550$ μm $\sigma_y < 550$ μm At collimator: $\sigma_x < 540$ μm $\sigma_y < 520$ μm	1×10^{-4} Gaussian integral/pedestal integral	Beam Position Stability < 200 μm 1 nA < Beam Current < 3 μA

Beam Physics Requirements

Beam/beamline requirements @ 11-12 GeV: Requirements after 2+ years

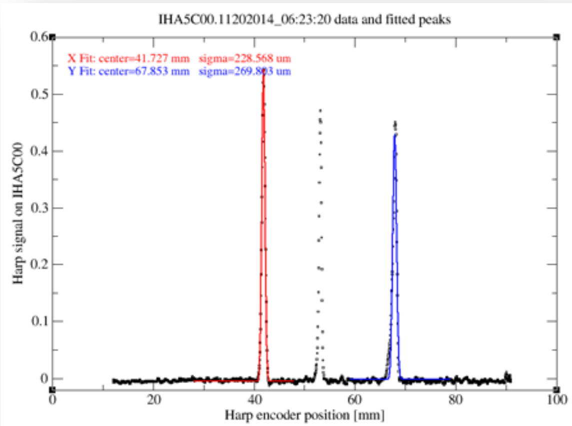
Hall	Emittance	Energy spread (σ)	Spot size (σ)	Halo	Other
A	$\varepsilon_x < 10$ nm-rad, $\varepsilon_y < 5$ nm-rad	0.05% (12 GeV) 0.003% (2-4 GeV)	$\sigma_x < 400$ μm $\sigma_y < 200$ μm ($\sigma_y < 100$ μm, (2-4 GeV))	$1\mathrm{x}10^{-4}$ Gaussian integral/pedestal integral	Parity-Violating Experiments: Charge asymmetry < 0.1 ppm Position difference < 1 nm Angle difference < 10 nrad RMS size difference < 1μm Compton Polarimeter: $\sigma_x \sim 50$ μm, $\sigma_y \sim 50$ μm
B	$\varepsilon_x < 10$ nm-rad, $\varepsilon_y < 10$ nm-rad	0.1%	$\sigma_x < 400$ μm $\sigma_y < 400$ μm	$1\mathrm{x}10^{-4}$ Gaussian integral/pedestal integral	Charge asymmetry < 10^{-4} 60 Hz structure < 15% Microscopic duty cycle > 80%
C	$\varepsilon_x < 10$ nm-rad, $\varepsilon_y < 5$ nm-rad	0.05% 6 GeV:0.03%	$\sigma_x < 400$ μm $\sigma_y < 200$ μm	$1\mathrm{x}10^{-4}$ Gaussian integral/pedestal integral	Beam Position Stability < 200 μm Parity-Violating Experiments: Charge asymmetry < 0.1 ppm Position difference < 1 nm Angle difference < 10 nrad RMS size difference < 1μm
D	$\varepsilon_x = 10$ nm-rad, $\varepsilon_y < 5$ nm-rad	<0.5%	At radiator: $\sigma_x < 1550$ μm $\sigma_y < 550$ μm At collimator: $\sigma_x < 540$ μm $\sigma_y < 520$ μm	$1\mathrm{x}10^{-5}$ Gaussian integral/pedestal integral	Beam Position Stability < 200 μm Electron Polarization < 1% 1 nA < Beam Current < 3 μA

Commissioning Milestones

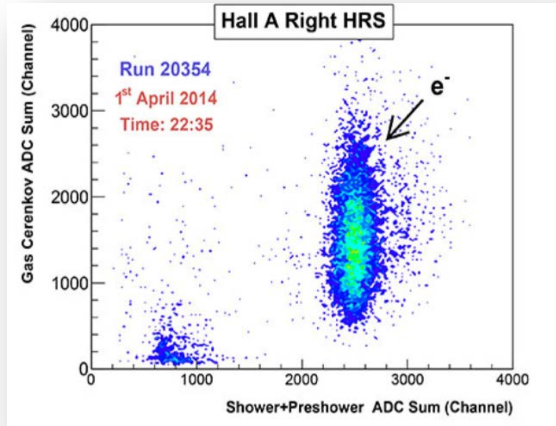


- Achievements to date
  - Deliver 2.2 GeV Beam to the 2R dump.
  - Commissioned all beamlines except Hall C and the 4T beamline
  - Deliver greater than 10 GeV in 5.5 passes to Hall D.
  - Delivered beam for Physics to three halls simultaneously

Commissioning Milestones

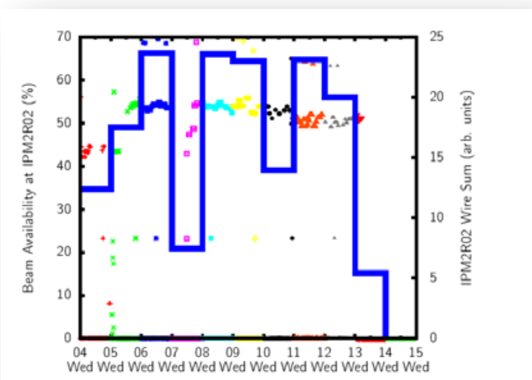


Meeting Beam Size Requirements

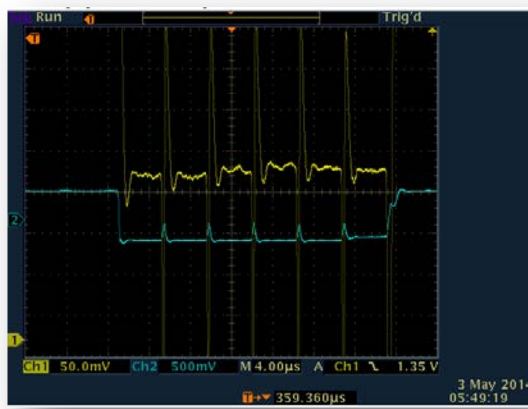


First data from Scattered Electrons in Hall A

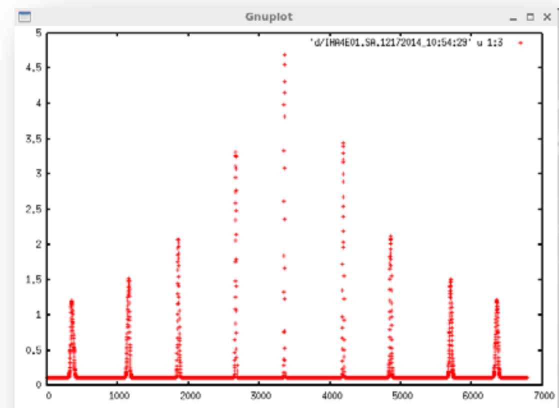
10.5 GeV Beam to Hall D Ramp



8 Hour Availability for 2.2 GeV Run



Six Beams in the NL for the First Time



Emittance Scan During the Last Run

Next Phase of Beam Operations

- Some of the challenges to refine CEBAF Operations:
  - Optimizing the performance of the SRF Systems.
  - Understanding Synchrotron Radiation Effects.
    - ✓ Synchrotron Radiation Compensation Coils.
    - ✓ Minimizing emittance growth due to synchrotron radiation losses.
  - Model Development - Reduce amplitude of tuning quads.
    - ✓ Emittance measurements at the entrance of each arc.
    - ✓ Linear Optics from Closed Orbit (LOCO) – measure body gradients of Spreader, Arc and Recombiner dipoles.
    - ✓ RayTrace – measure phase-space pseudo-ellipse using coordinated corrector kicks in x-plane and y-plane. Compare to model of phase-space evolution to look for point sources of model errors.
  - Ramp energy to 12 GeV to Hall D.
    - ✓ Dogleg Upgrade.
    - ✓ Tunnel Air Conditioning.

Future Run Plans

Winter 2015 Shutdown

- Install the 5th pass 750 MHz RF Separator system.
- Install the 250 MHz drive lasers for the polarized source.

The last two bullets allow for simultaneous operation of Hall A and Hall D at the highest pass and for simultaneous 4-Hall operations.

Spring 2015 Run

- Commission the 750 MHz RF Separators.
- Commission the 250 MHz Drive Laser system.
- Deliver beam for Physics contingent on funding.

Future Run Plans

Summer 2015 Shutdown

Major installation work is planned for this shutdown that will enable us to make the push to 12 GeV for the first time. The highlights for the shutdown are:

- Installation of a C50 cryomodule.
- Installation of the tunnel air conditioning.
- Completion of a lab wide upgrade of the power distribution, cooling towers and network.
- Helium processing of SRF cryomodules to reduce field emission and increase the energy reach of the linacs.

Future Run Plans

Fall 2015 Run

- Demonstrate 12 GeV capability for the first time.
- Finalize optics setup, energy scaling and procedures.

Spring 2016 Run

- Establish beam to Halls B and C in preparation for CLAS12 and SHMS detector checkout.
- Deliver beam in support of Hall B and C detector checkout.
- Support Engineering run in Hall D and Physics in Hall A.
- Deliver beam for Physics contingent on funding.

Last C100 Arriving in Tunnel

Thanks!