Accelerator Status

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content collected from many others

Outline

- Acknowledgments and Thanks
- What has been done
- What needs doing
- What has changed
- What is still changing
- Outlook… (look out)

Most material taken from:

- Arne Freyberger's Science and Technology Review presentation at JLab on 28 Sept 2016
- Matt Poelker's Spin'16 presentation Sept. 25-30, 2016, in Champaign-Urbana, Illinois.

12 GeV CEBAF Operations

Science and
Technology Briefing
Sept. 28 2016

Arne Freyberger
Operations Department
Accelerator Division
Jefferson Lab

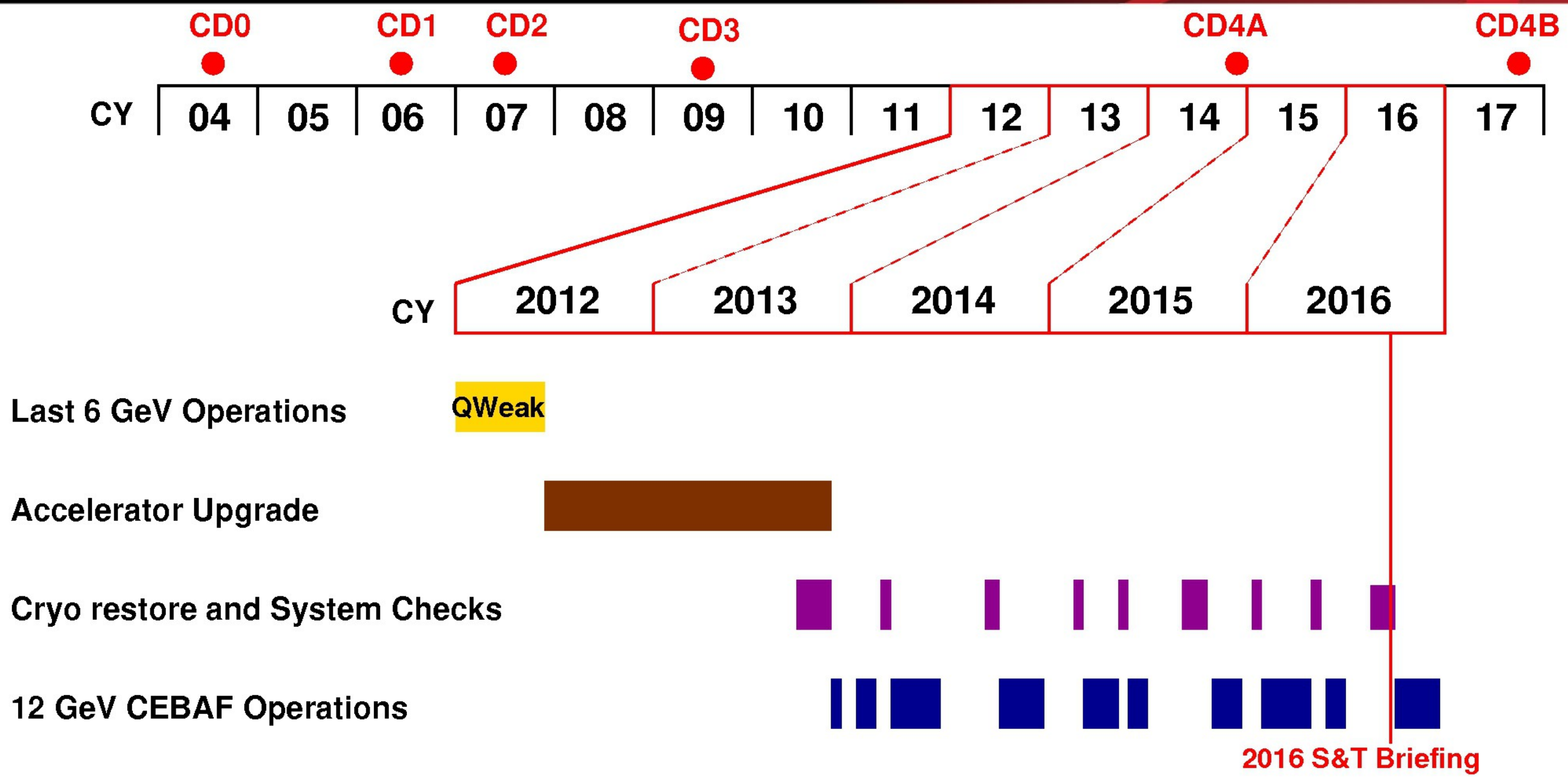
12 GeV CEBAF: Accelerator Systems and Polarized Beams

Matt Poelker

with help from A. Freyberger, C. Hovater, R. Kazimi, L. Harwood, A. Lung, J. Creel, K. Dixon, R. Geng, and many others

SPIN 2016, Champaign-Urbana, IL
Sept. 25 - 30, 2016

12 GeV CEBAF Timeline

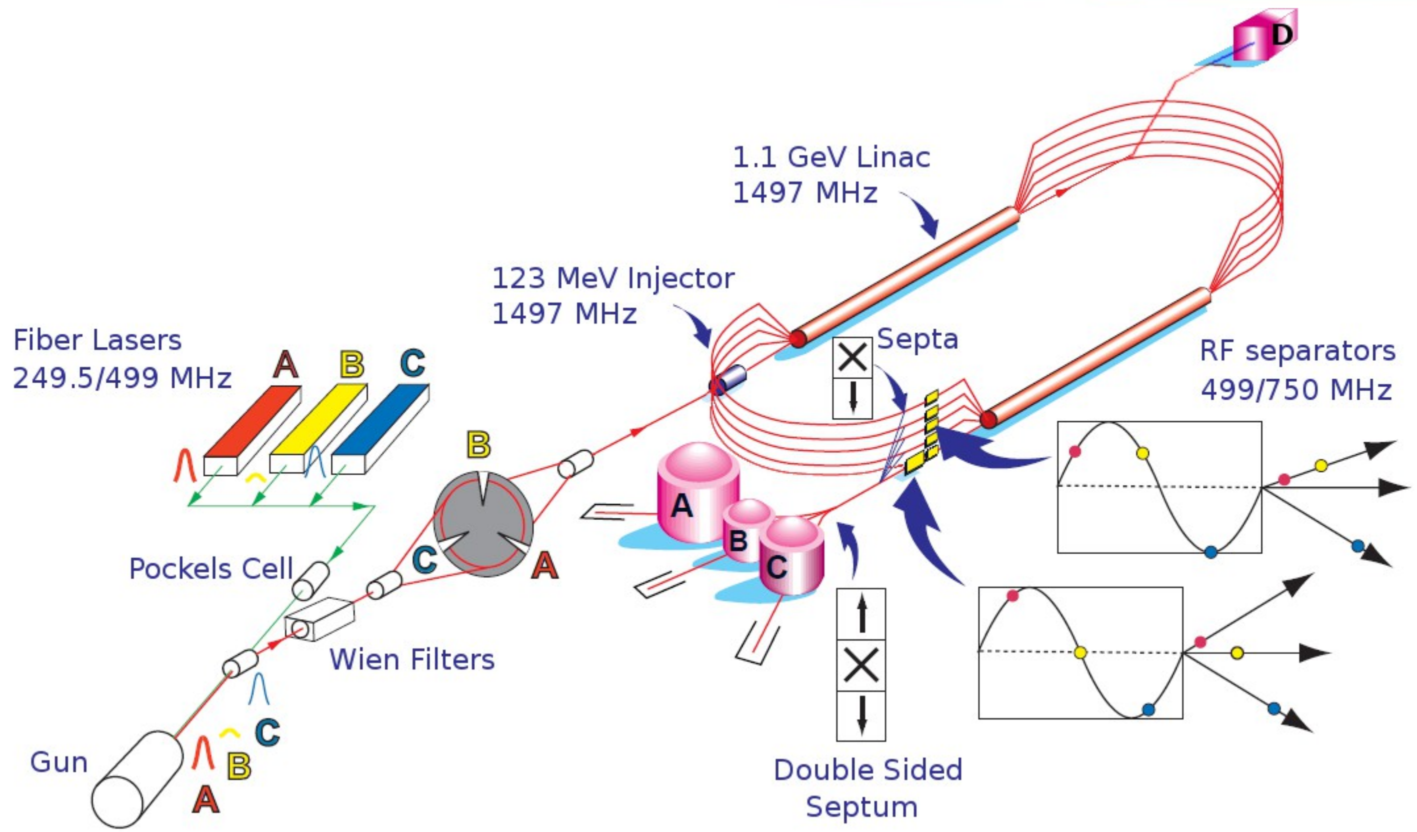


~ 50 weeks of beam operations to date (FY14,FY15,FY16)

16 weeks at design energy, 2.2 GeV/pass

6 weeks of 12GeV-preops operation (Accelerator and Hall-D KPP demonstrated)

12 GeV CEBAF Overview



- Polarized electron beam (P > 85%)
- Three 499 MHz or 249.5 MHz interleaved beams, resulting in 1497 MHz CW beam.
  - Fourth laser installed, commissioning of 4-halls schedule for Spring 2017
- CW SRF linacs, 1 MW capable
- Design energy 2.2 GeV/pass: 5.5 passes, 12 GeV (Hall-D), 5 passes, 11 GeV (ABC)
- Simultaneous delivery of ~100 μA and nA beams: 5 orders of magnitude in bunch charge
- Flexible extraction options for ABC, $1^{st}\ldots5^{th}$ pass

FY16 Beam Operations Summary

Fall 2015

- 5 weeks of beam operations at design energy: 12 GeV
  - Measured transverse emittance: **12 GeV CEBAF meets out-year spec**
  - Helium Processing in Summer 2015 helped in achieving the design energy.
  - 5^{th} pass RF separation at design energy established (new 750 MHz separation system).

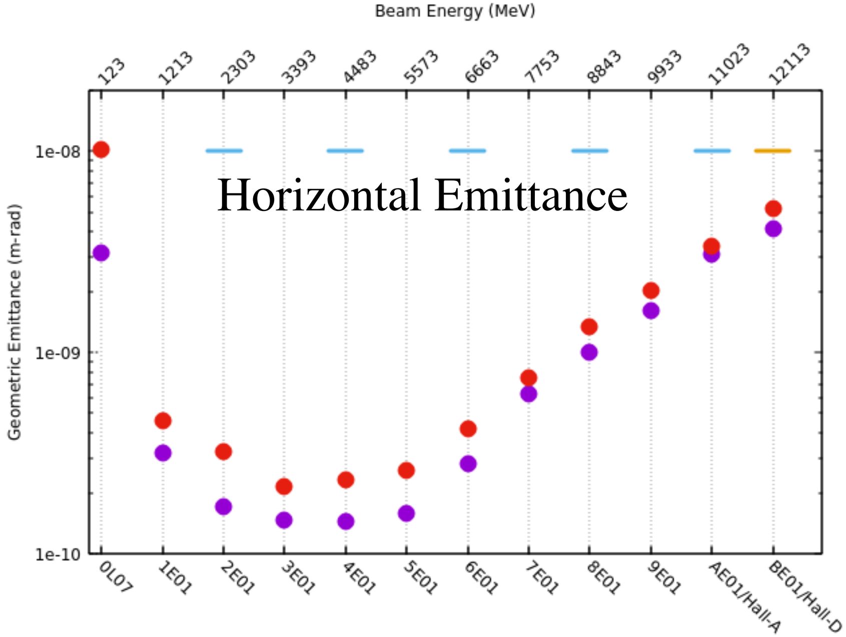
Spring 2016

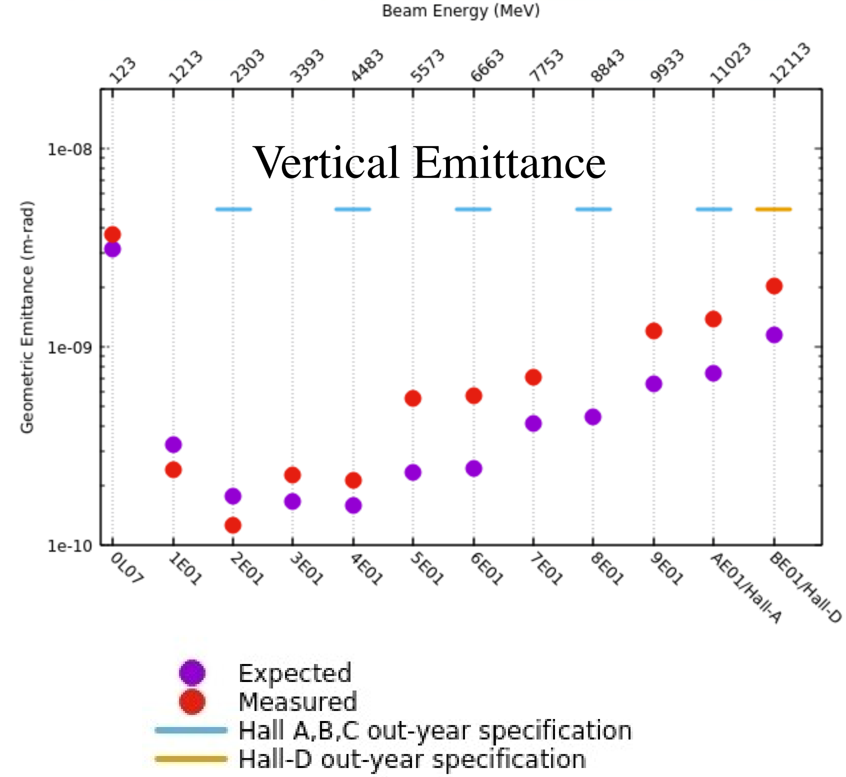
- 11 weeks planned, 10 weeks actual of beam operations at design energy: 12 GeV
  - DVCS/GMp experiment in Hall-A (passes 2,4,5)
  - HPS experiment in Hall-B (pass-1)
  - GlueX engineering run in Hall-D (pass-5.5) **COMPLETED**
- Reliability issues (RF systems, Cryo), details in Andrew's presentation

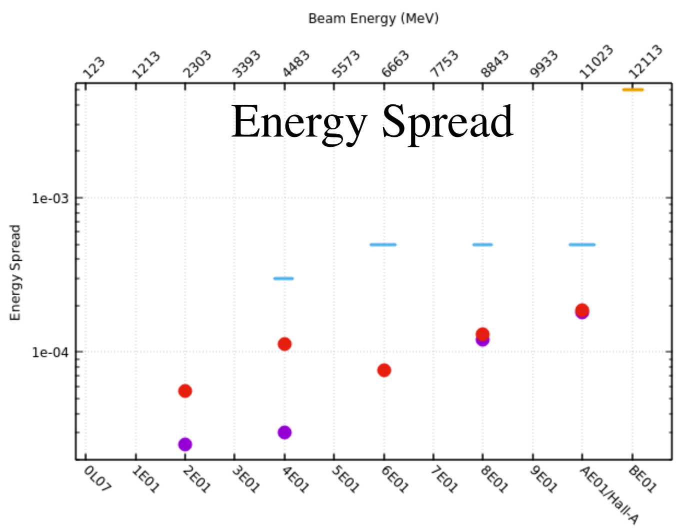
Summer 2016

- 5.5 weeks low power, one CHL configuration at ~50% of design energy
  - PRad experiment in Hall-B (passes 1 & 2) **COMPLETED**
  - Hall-C Beamline checkout (pass 2) **COMPLETED**

Beam Parameters at 12 GeV (2.2 GeV/pass)







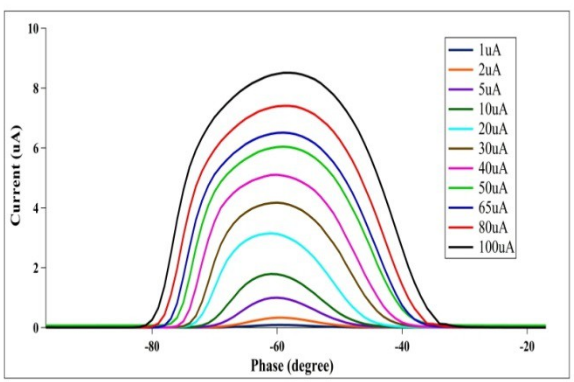
- Beam parameters at 12 GeV meet **out-year** specification.
- Growth in emittance/energy spread due to synchrotron radiation effects agrees well with expectations.

Bunchlength Evolution at 12 GeV

TABLE 10: Bunch length results (*rms* value) summary at all locations

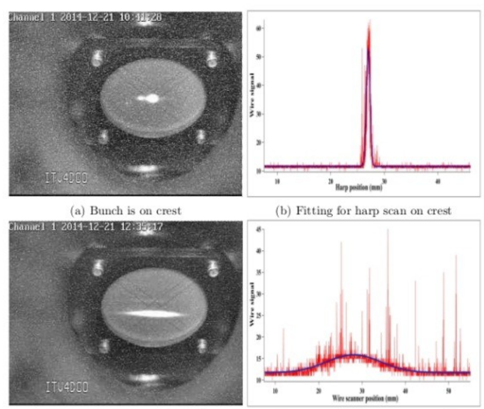
Technique	Location	Beam Energy	Measured	Expected
Brock cavity	A2	130 keV	8.31 ± 0.01 mm	6.8 mm
Slit-scan	Chopper chamber	130 keV	7.16 ± 0.04 mm	7.9 mm
Brock cavity	1D dump	130 keV	10.41 ± 0.04 mm	8.1 mm
Back-phasing	4D dump	102 MeV	80.8 ± 2.0 μm	100 μm
SLM1	Arc1	1052 MeV	91.4 ± 6.5 μm	100 μm
SLM1(compression)	Arc1	1052 MeV	46.1 ± 3.5 μm	56 μm
SLM2	Arc2	2002 MeV	112.8 ± 5.8 μm	100 μm
SLM2(compression)	Arc2	2002 MeV	42.5 ± 5.1 μm	56 μm

Slit Scan @ 130 keV



(a) Slit scan for A-laser at 249.5 MHz

RF Phase Shifts @ 102 MeV



(a) Bunch is on crest (b) Fitting for harp scan on crest

(c) Bunch is off crest by +90° (d) Fitting for harp scan at +90°

RF Phase Shifts @ 1050 MeV

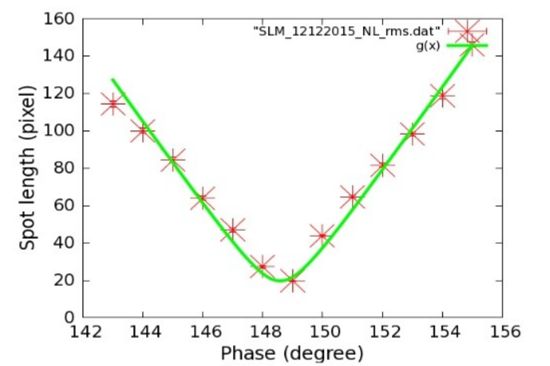
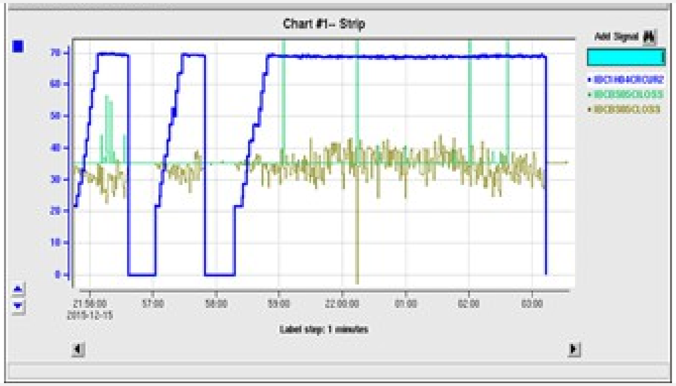


FIG. 58: Hyperbola fitting for Arc1 - *rms* calculation (CW mode).

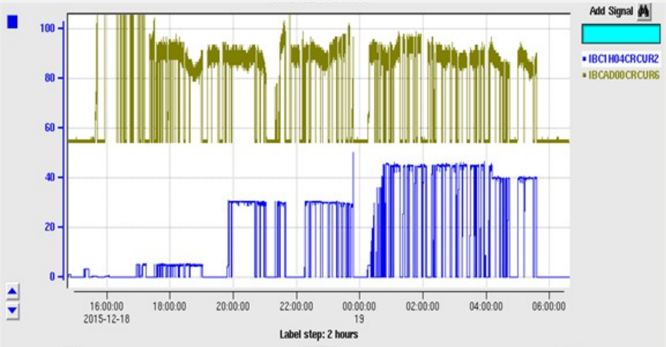
Hall-A: DVCS and GMp

- First demonstration of high current, high beam power for 12 GeV CEBAF.
- Dynamic configuration: passes 1,2,4, & 5
- 5^{th} pass operation simultaneous with Hall-D operation:
  - New 750 MHz RF separator cavities
  - New 249.5 MHz laser repetition rate.
- Beam Polarimeters (Moller & Compton) commissioned.
- Proximity of Compton detectors to beam makes this device useful as a beam diagnostic.
  - Very clean Compton signal (blue trace) achieved, high laser-on to laser-off ratio. (laser power is the green trace).
  - Halo-free beam

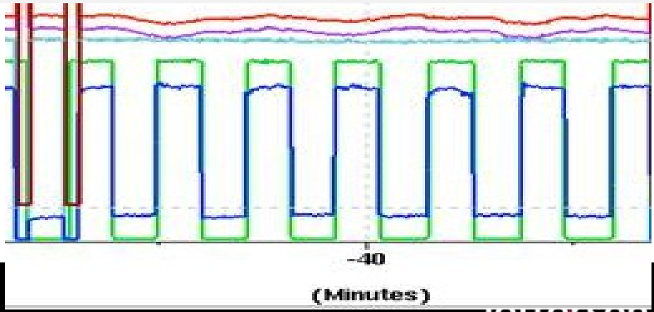
11 GeV, 70 μA, 770 kW to Hall-A



11 GeV, 50 μA to Hall-A, 12 GeV to Hall-D

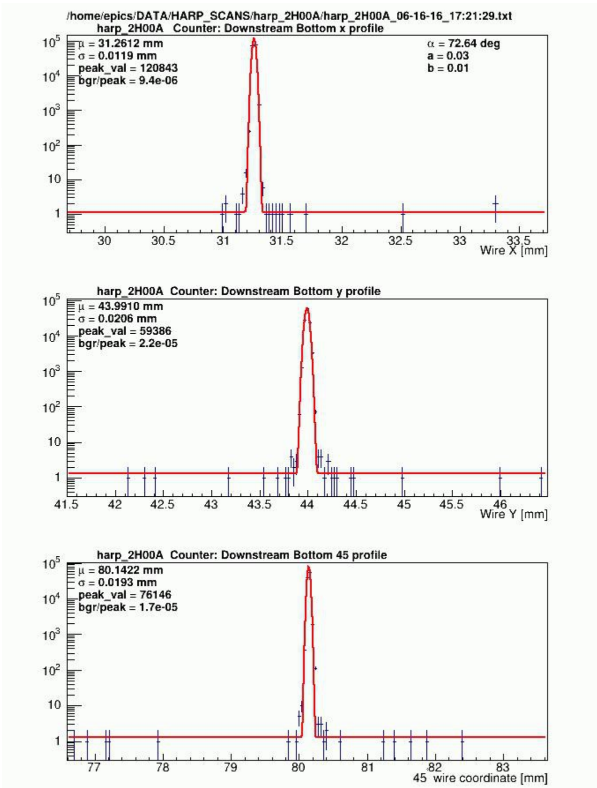


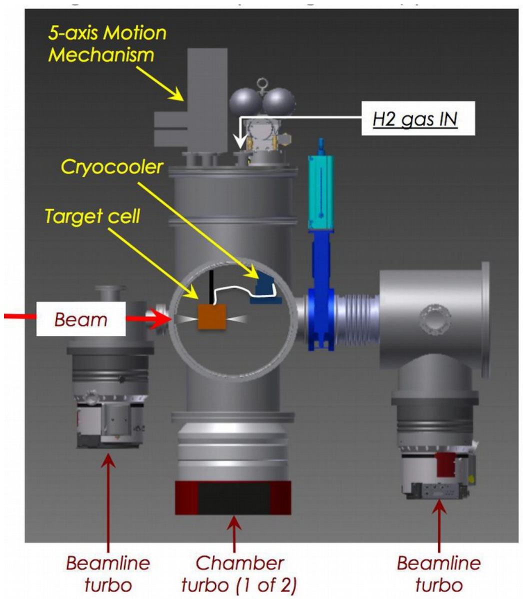
Compton Signal: Laser On/Laser Off

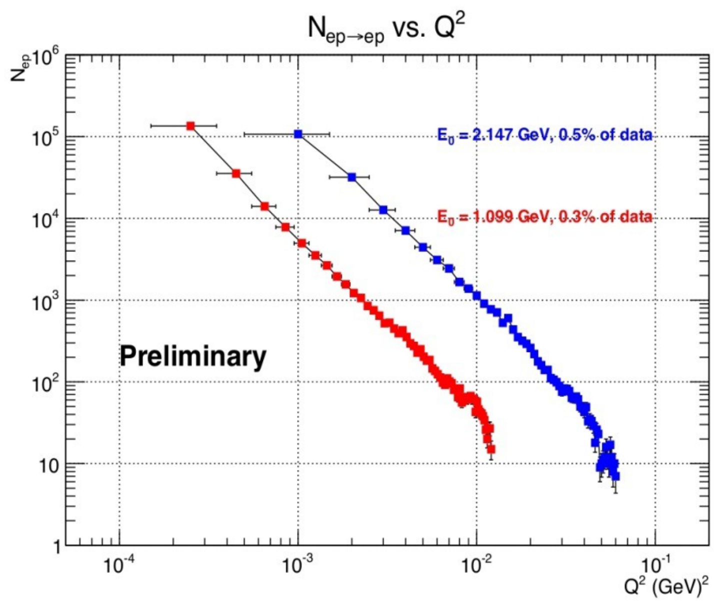


Hall-B: HPS & **PRad**

- PRad: First use of windowless gas target at JLab
  - Requires stable, halo-free, small beam on target and through the detectors
    - $\sigma_{beam} \sim 20\ \mu m$
    - Beam halo-free over 6 orders of magnitude (limit of instrumentation)
- Low Q^2 measurement, detectors placed close to the beamline.
  - Q^2 as low as $1\times10^{-4}\ GeV^2$ expected with offline analysis; $2.5\times10^{-4}\ GeV^2$ achieved on-line



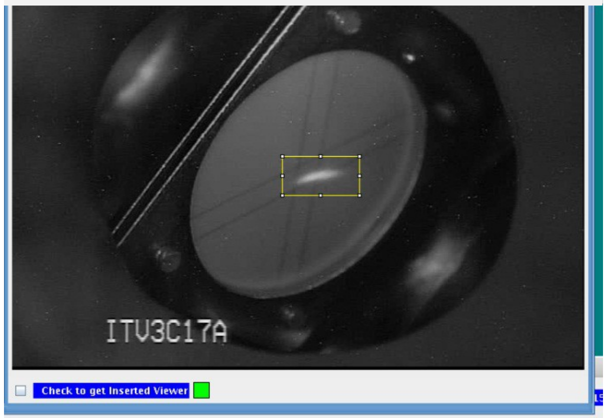




Hall-C: First Beam since 2012

- Successful beam transport checkout of the Hall-C beam, May 2016.
  - Beam switchyard to Hall-C Dump
- No major issues found:
  - Magnet polarities correct, beam diagnostics functioning.

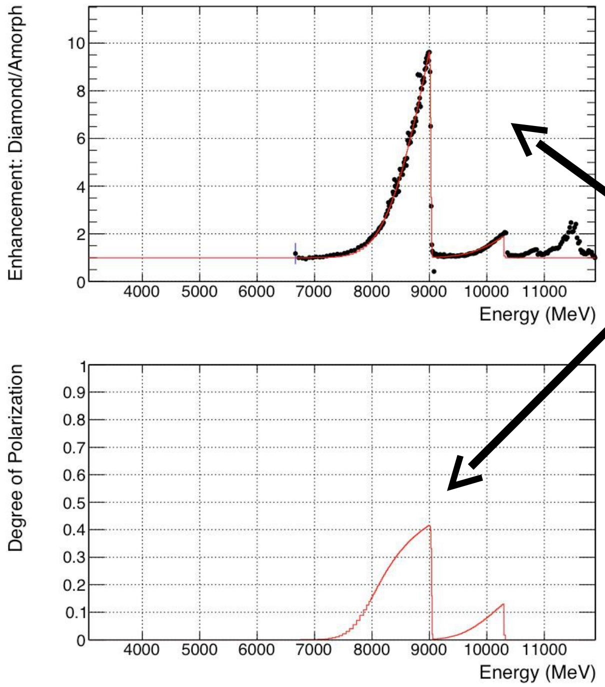
Beam on Hall-C viewer



- Completion of the Hall-C high power dump maintenance on track for beam delivery Q1 FY17
- Considerable accumulation of activated debris on the tunnel surface removed with *Decongel* prior to maintenance tasks as well as activated elements.
- Application of lessons learned from Hall A dump maintenance resulted in ALARA success.
  - Estimated worker exposure (FY15-16): 5725 person-mrem
  - Actual worker exposure (FY15-16): 3000 person-mrem

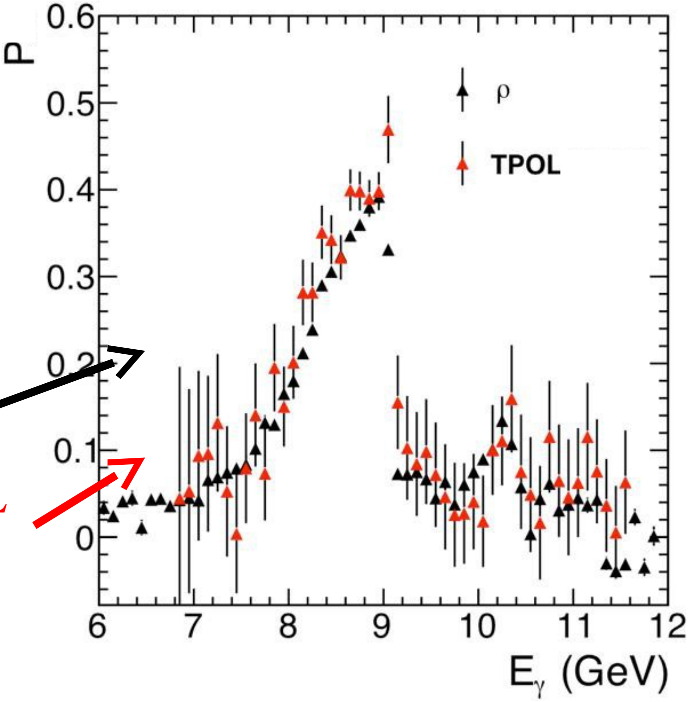
Hall-D: GlueX Engineering Run

- Linearly polarized photon beam generated via coherent bremsstrahlung in a diamond radiator.
- Photon beam traverses 75 m from radiator to collimator (3.4 mm aperture).
  - Incident electron beam position, angle, stability and transverse size impact the maximum achieved photon polarization.
- Peak photon polarization of 40% has been measured using several techniques (expectation is 40%).

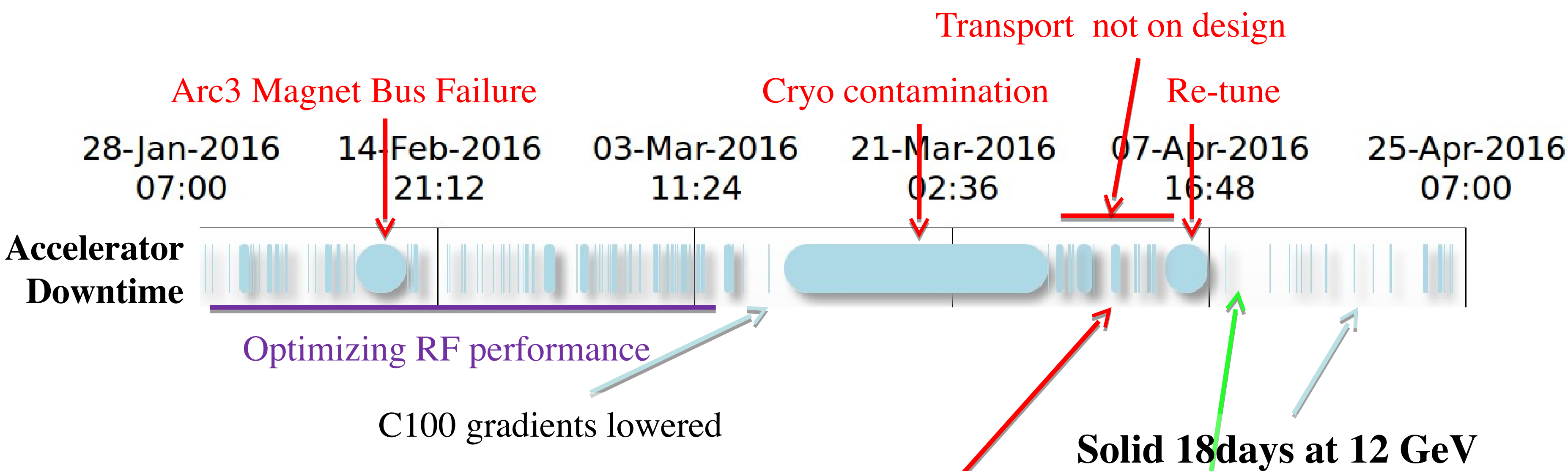


1. Fit the measured photon spectrum and extract photon polarization.
2. Analysis of a known asymmetry, ρ production
3. Triplet polarimeter:TPOL

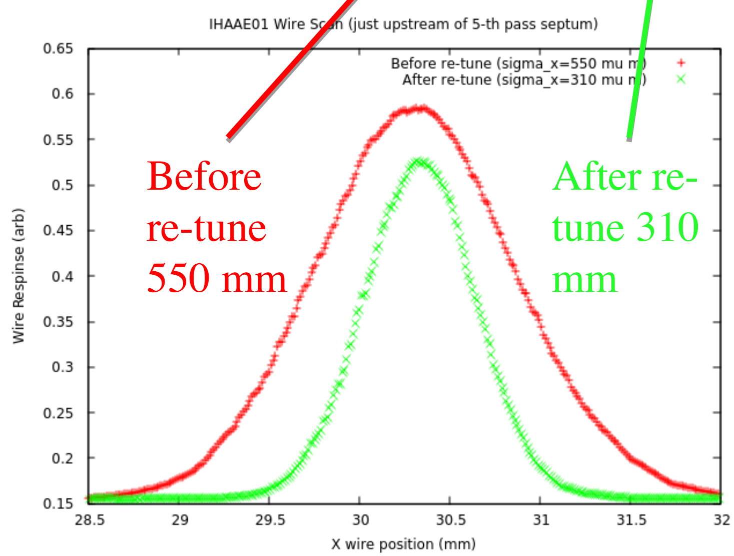
$$\gamma e^- \rightarrow e_R^- e^+ e^-$$



Spring 2016 Beam Operations



- First Physics runs with CEBAF at design energy, 12 GeV to Hall-D, 11 GeV to Hall-A (5-pass).
- 5-pass separation at design energy (11 GeV).
  - 5th pass RF separation, tight aperture, requires beam transport to be on-design for robust operation.



Horizontal beam size upstream of 5th pass septum

12 GeV Peak(best) Performance (to date)

Accelerator Incident Downtime (Hours) from April 7 - 25, 2016

Summary

Total Downtime (Hours):	**27.0**
MTTR (Hours):	0.8
Total Suspend (Hours):	22.8
Total Restore (Hours):	4.2
Period Duration (Hours):	422.0

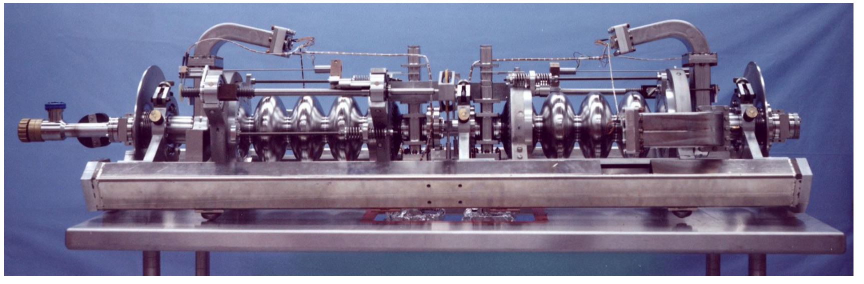
94% CEBAF System Reliability

Tight configuration control during this period; not one quadrupole magnet was manually adjusted. No tweaking, just monitoring.

Accelerating Cavities at CEBAF

We use both types for 12 GeV nuclear physics

Original CEBAF 5 cell cavity

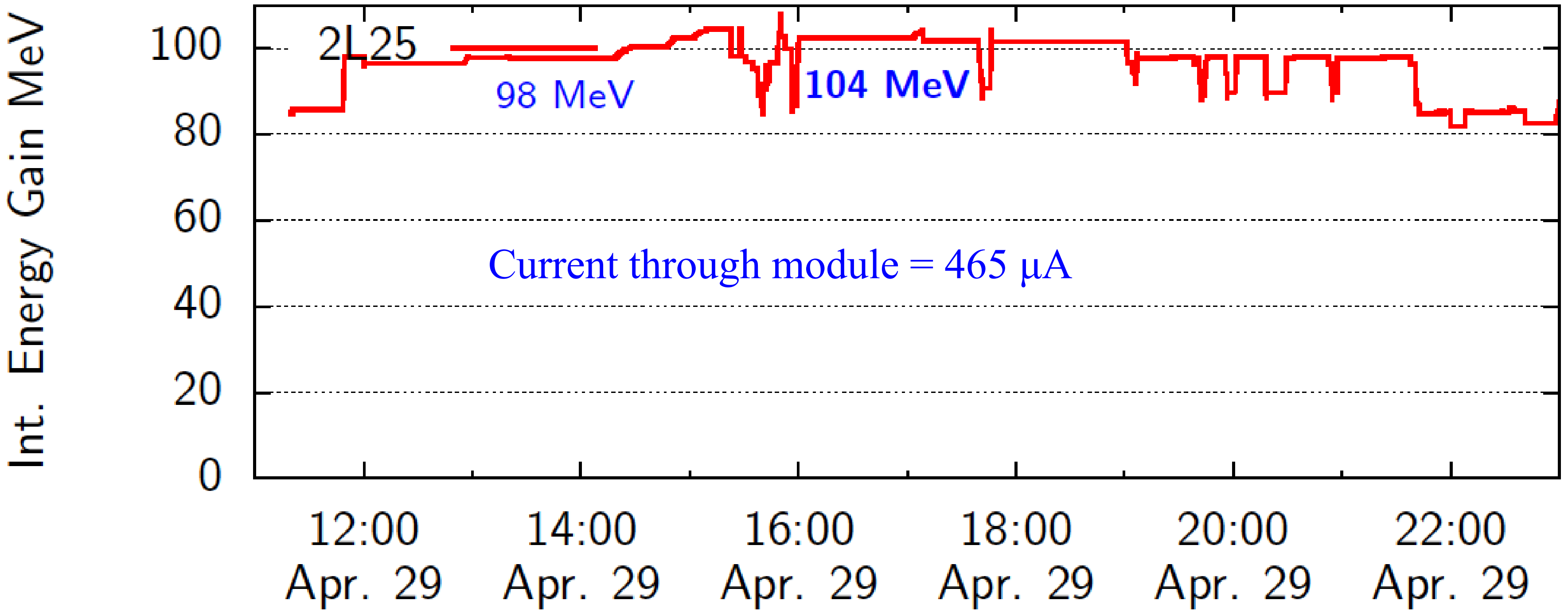


- 5-cell, Cornell-Type
- 338 cavities in 42-1/4 modules
- Design
  - Ea=5 MV/m
  - $Q_0=2.4\times10^9$ @ 5 MV/m
- Achieved after Helium Processing
  - <Ea>=7.5 MV/m, $\langle Q_0\rangle=5\times10^9$@ 5MV/m
- Achieved after Refurbishing
  - <Ea>=12.5 MV/m, $\langle Q_0\rangle=5\times10^9$ @ 5MV/m
- Total energy 2 x 600 MV
- 5 kW 2K cooling power
- 5 MW liquefier operation power

CEBAF upgrade cavity

- 7-cell, Low-Loss Shape
- 80+8 cavities in 10+1 modules
- Design
  - Ea=19.2 MV/m
  - $Q_0=7.2\times10^9$ @ 19.2 MV/m
- Achieved
  - <Ea>=22.2 MV/m
  - <Q0> @ 8.1×10^9 @ 19.2 MV/m
- Total energy 2 x 500 MV (+100 MV)
- Requires additional ~ 5 kW 2K cooling power
- Requires additional ~ 5 MW liquefier operation power

C100 Performance Demonstration

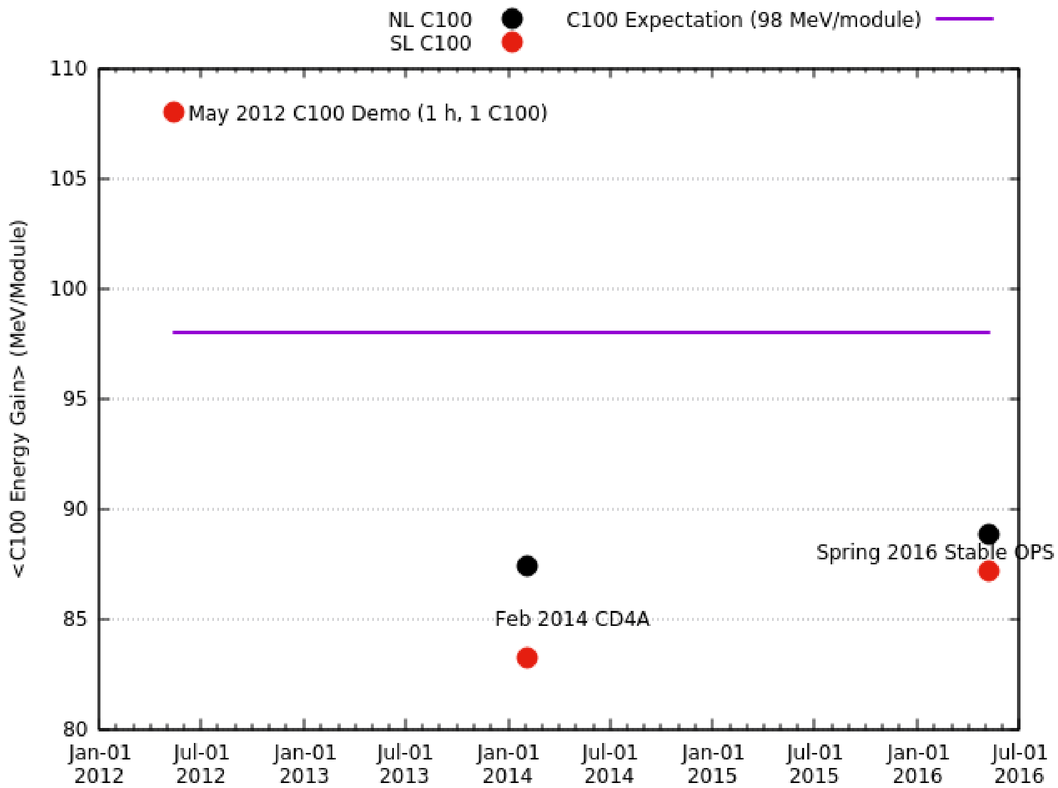


Two C100 cryomodules installed during 6-month down
Operated at nominal specifications during Qweak experiment

Energy Reach Plans

- Improve C100 performance
  - "Gradient Team" composed to address this
- Mitigate impact of gradient degradation (~34 MeV/pass/year)
  - C20 refurbishment program (C50->C75) in place until degradation is no longer occurring.
- Reduce or eliminate gradient degradation
  - Accumulation of new field emitters, particulate on the cavity surface
    - Identify field emitter particulate source (in progress).
    - Mitigate: Develop the plan, approve the plan, implement
- New issue: radiation damage of beamline elements in C100 radiation field.
  - C100 gradient large enough to accelerate field emitted electrons to energies above Neutron threshold (~10 MeV),
    - Optimize C100 gradient/field emission ratio (Gradient Team)
    - Helium process to reduce field emitter sites.
    - Improve particulate control, maintain the low FE state post HeProc (see Gradient Degradation above) .

Energy Delivery: C100 Performance



- FY14-FY16 is the first large scale use of high gradient SRF cavities (C100) for sustained beam operations.
- Identification of why the C100s are collectively not achieving the individual commissioning values is on-going.

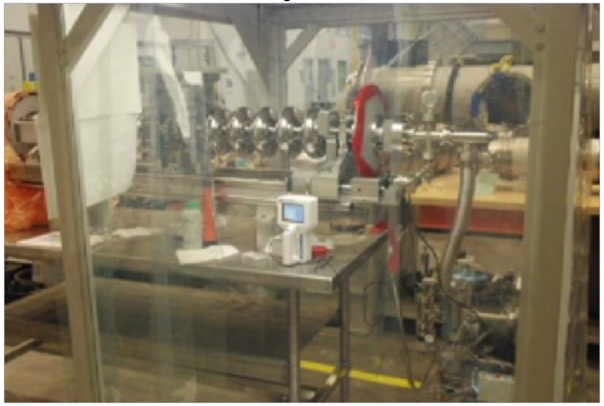
Energy Delivery: Field Emission

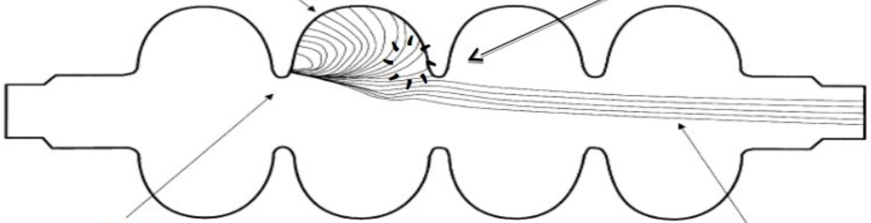
- Original C20 modules have ceramic windows that charge/discharge(trip) in the presence of field emission
  - As field emitters accumulate->trip rate increases->gradient lowered.
- C100 modules accelerate field emitted electrons above Neutron threshold

  Short Term: Impingement of energetic electrons on warm region surface causes vacuum degradation, resulting in valve closure and beam termination.

  Long Term: Material activation and radiation damage of beam-line components.

Images of particulates found on cavity surface

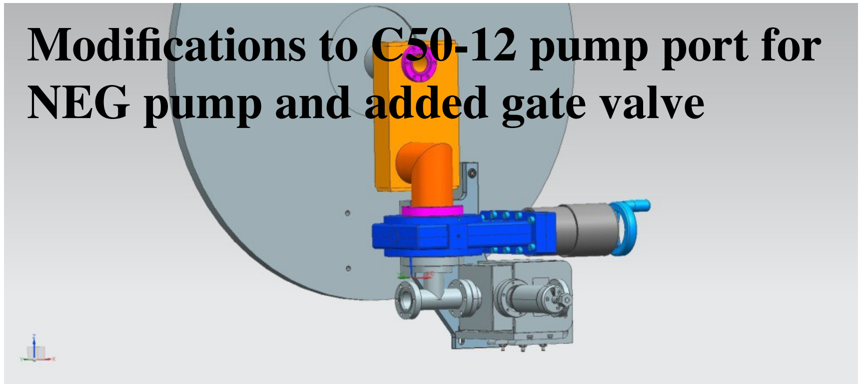




Field Emission: Recent Activity

- Successfully tested new Helium Processing (HeProc) procedure on one C100 module this past Summer.
  - HeProc on high FE cavities during Shutdown periods.
- Removed, particulate sampled and thoroughly cleaned the two warm girders associated with C50-12 installation zone
  - Significant particulate found on inner surface of beam-line vacuum space
- Developed and used a new in-tunnel clean room for cryomodule C50-12 installation vacuum work. Strive to achieve low particulate condition during cryomodule and warm girder vacuum work.
- Install new NEG-Ion pump systems associated with C50-12 installation.
  - Calculations show that modern NEG-ion pump systems have pumping rates competitive with the cryo-pumping of the module.
  - Original ion-pumps **ineffective as pumps**, very **effective as particulate generators**.

Field Emission: Recent Activity


Modifications to C50-12 pump port for NEG pump and added gate valve

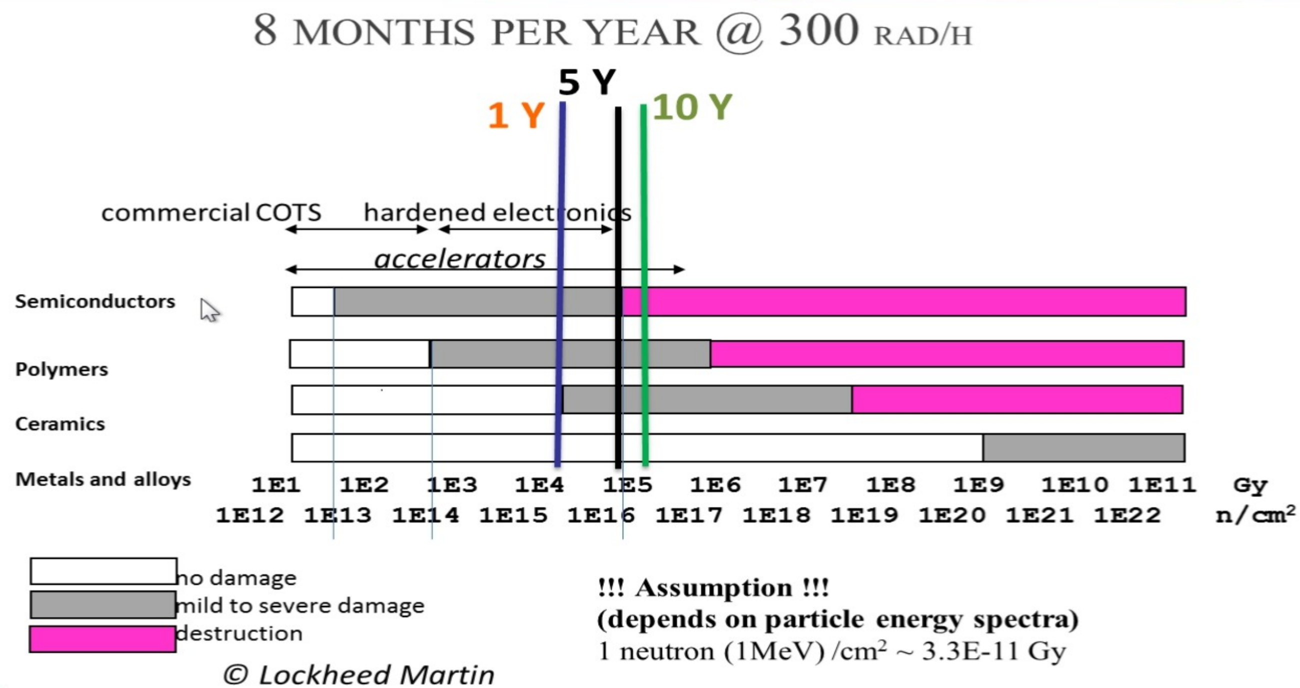

Particles found on beamline gate valve viton seal.

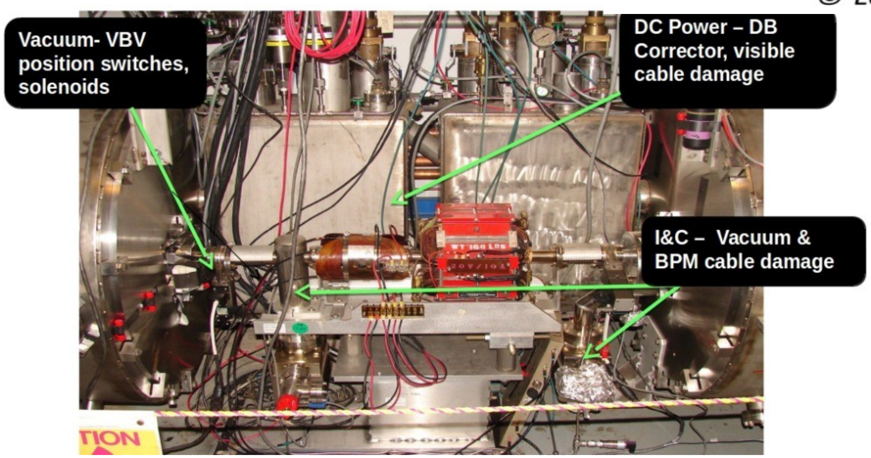
C20 Gate valve failure due to particulate accumulation not radiation damage


New tunnel clean room

C100 Radiation Damage

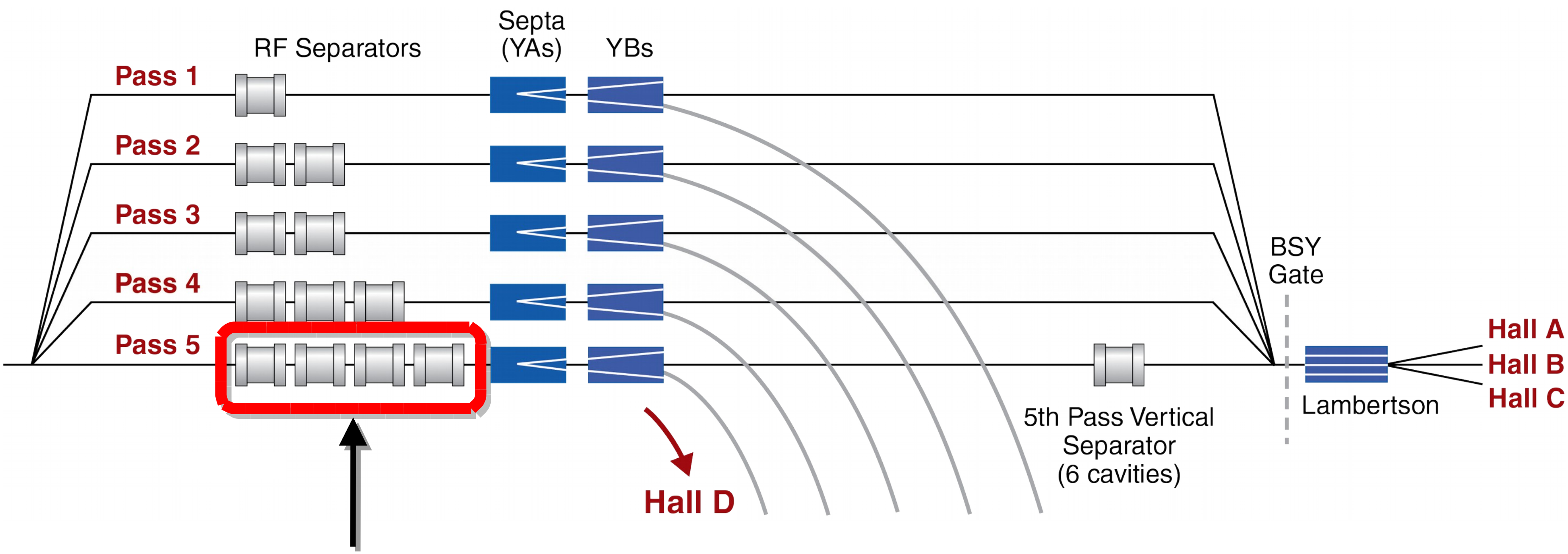
- Estimated activation assuming 30 wks/year operation at ~12 GeV energy.
- Radiation damage to cables and plastics observed Spring 2016





- Plan to harden the C100 region elements in place; partially completed Summer 2016.
- Long term impact on C100 module worrisome (ceramic feedthroughs).

5th Pass RF Separation Hardware

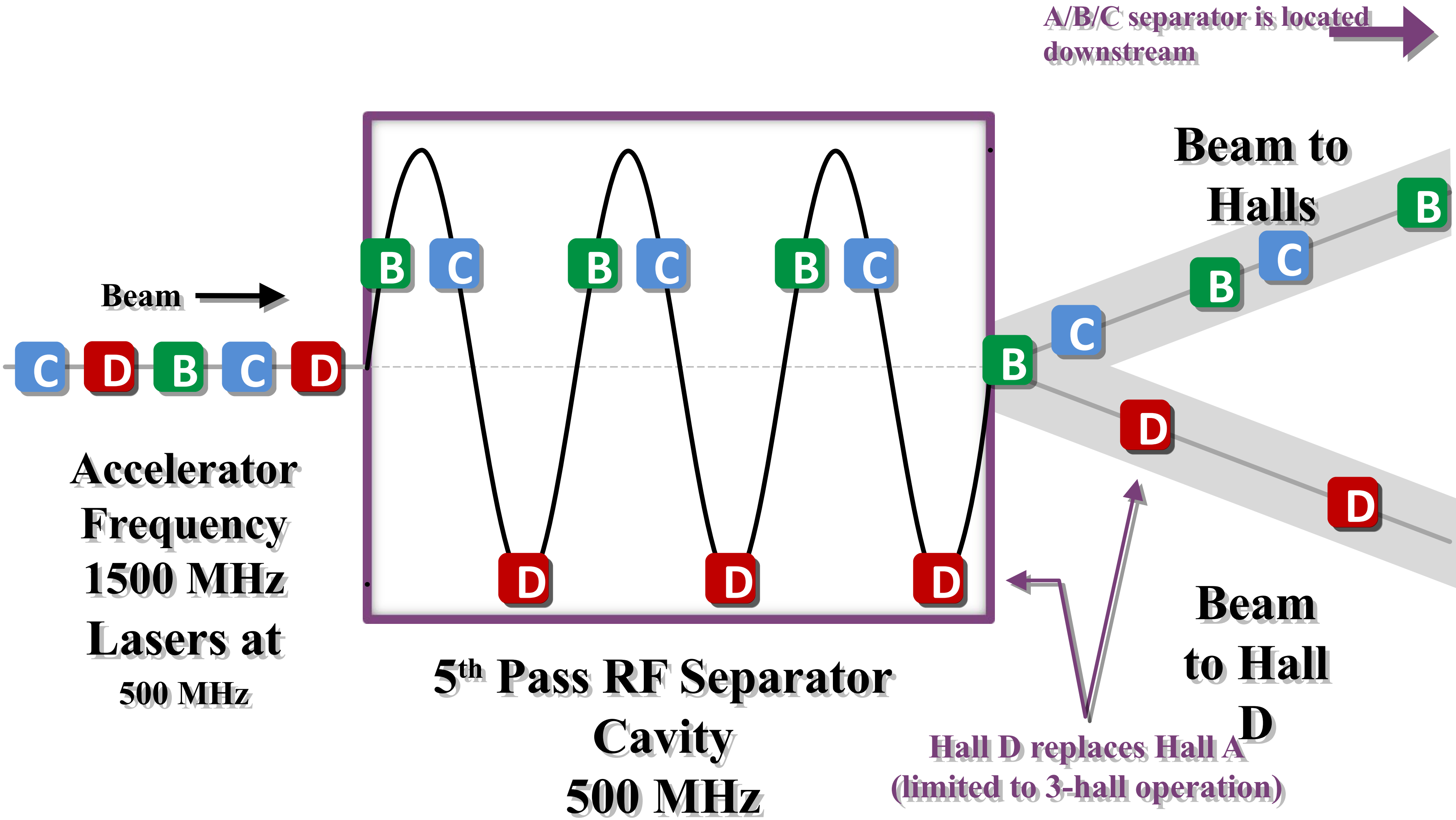


Horizontal 5th Pass Separator (kicks out Hall D for 5.5 pass)

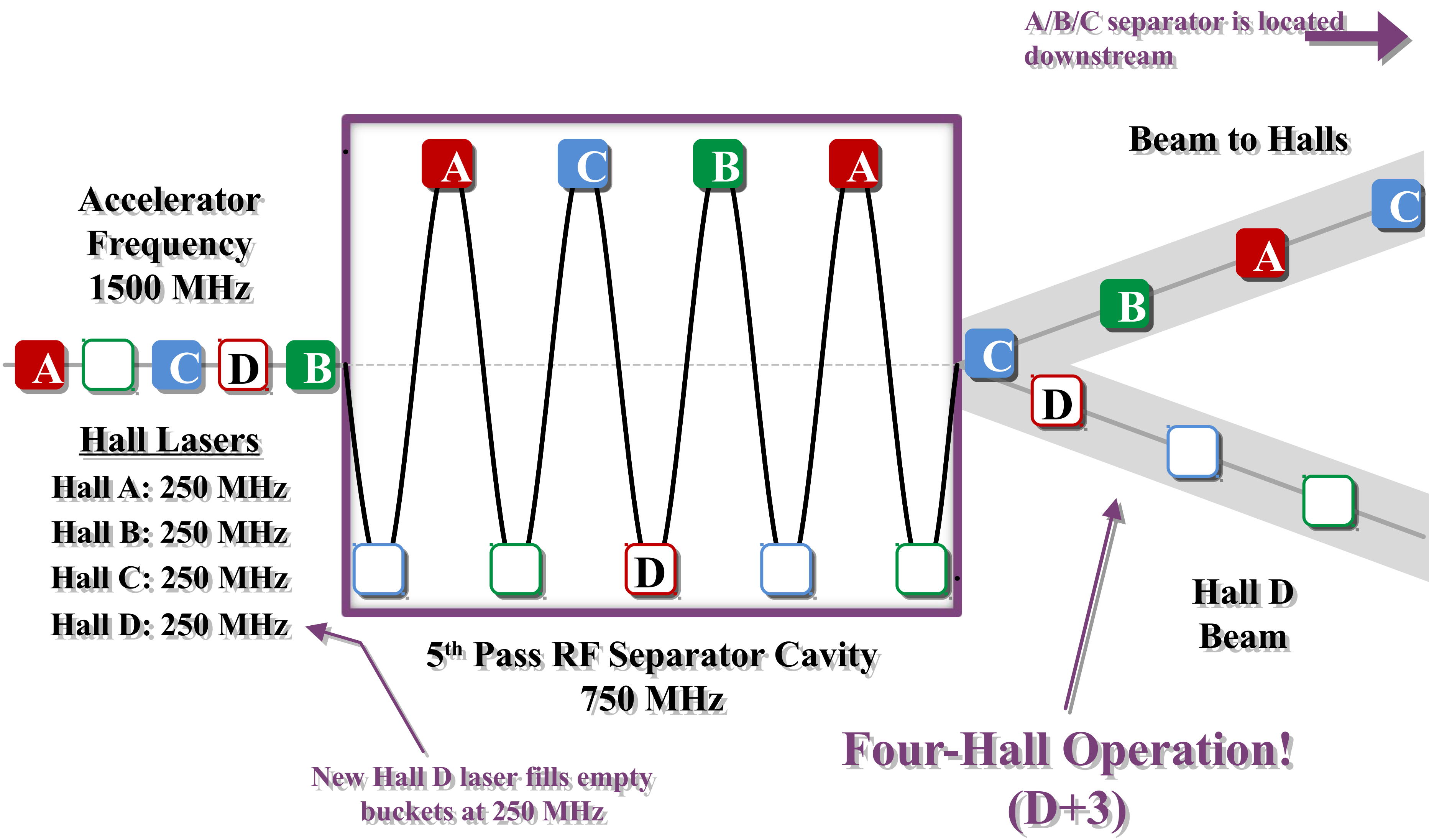
D+2: 500 MHz

D+3: 750 MHz

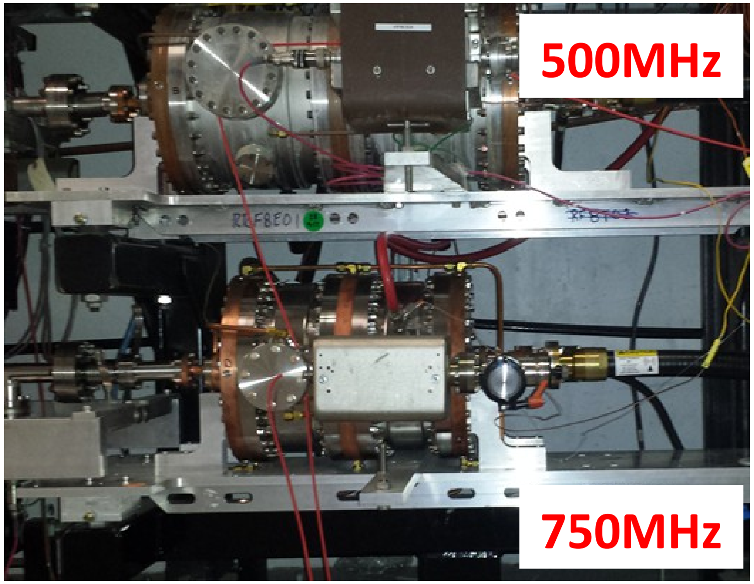
RF Separation – "D + 2"

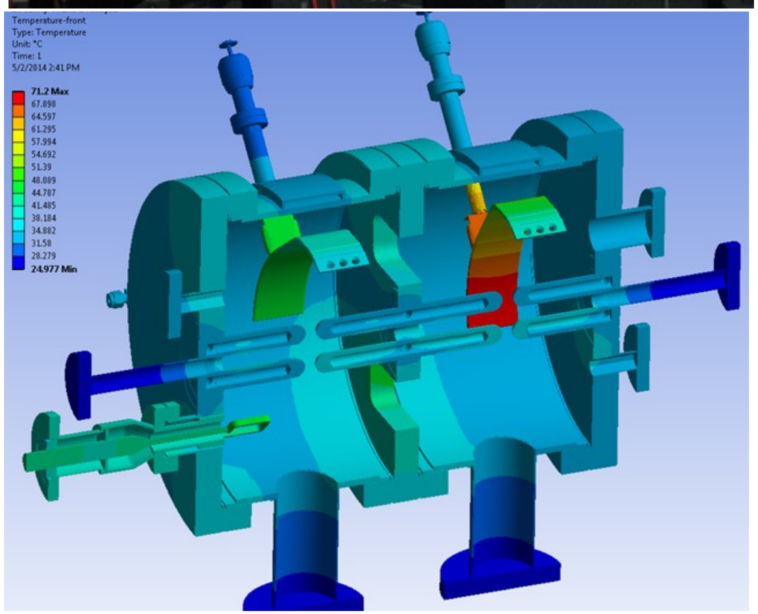


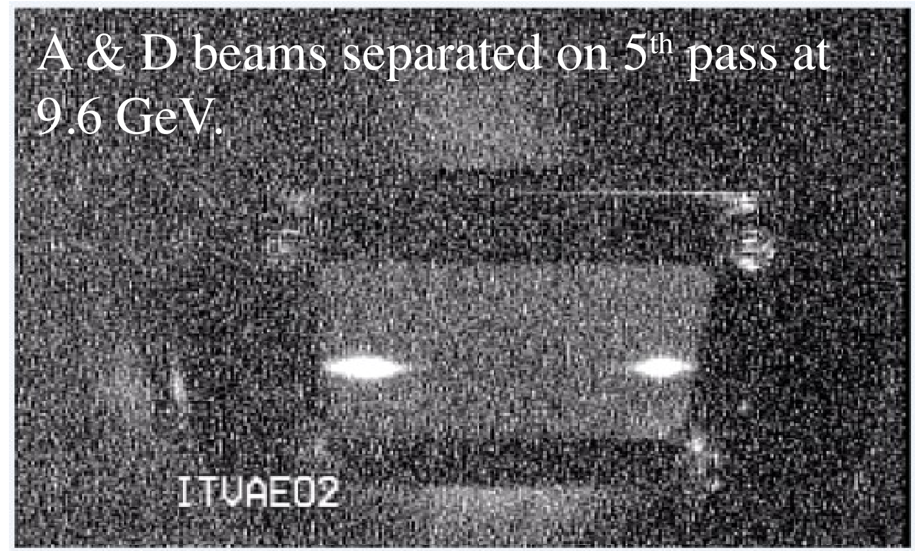
RF Separation – "D + 3"



750MHz Separation







11 GeV maximum beam energy

Improvements were implemented Summer 2016 to increase beam separation:

•Proper cavity placement relative to Lambertson magnets (9% gain in separation)

•Increase IOT power and cooling controls (10% gain)

Four Laser Upgrade for CEBAF

Fall 2015 – Spring 2016

- Simultaneous 3-beam operation with either 250/499 MHz rep rate
- Clever firmware solution allowed this with standard 499 MHz laser-RF system

Summer 2016

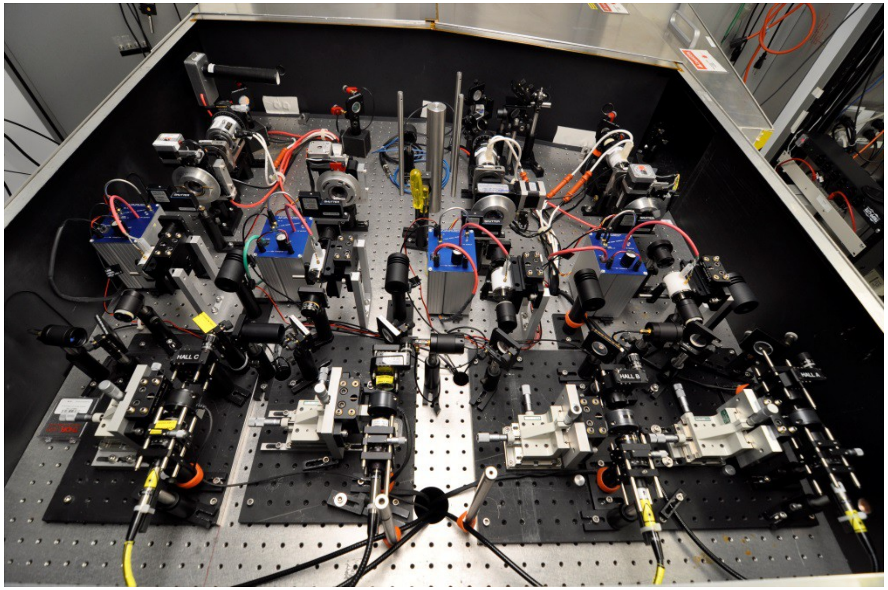
- Rebuilt laser system, added 4th laser
- Four beams from polarized electron source (chopper photo, right)

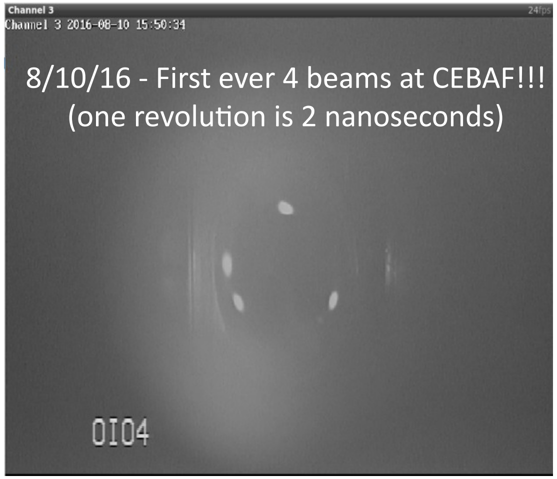
Winter 2016

- Planned installation of final 4-laser RF system
- Quick switch between rep rates from MCC, full 360 degree phase adjust

Spring 2017

- Planned 4-beam delivery to 4 Halls



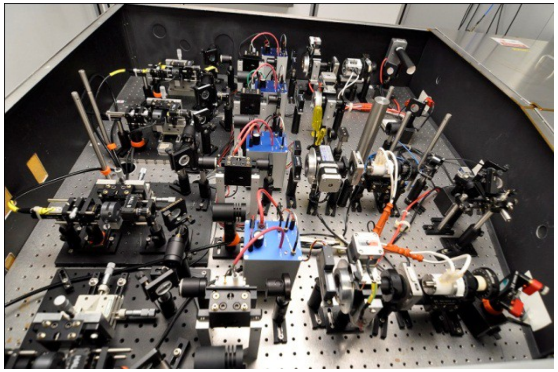


Four Hall Operations

- Laser table upgrade complete, four laser installed
- RF controls for fourth laser to be completed Q1 FY17

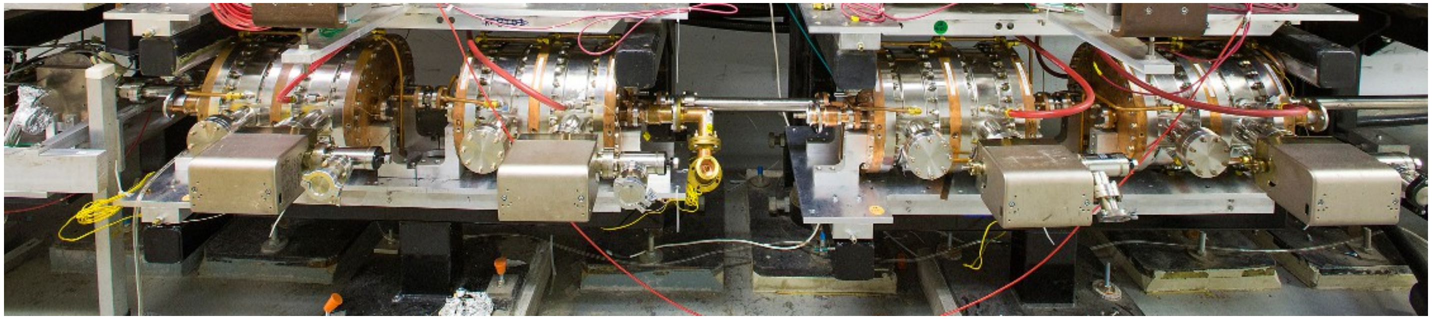
- 750 MHz separator cavities improved during Summer 2016
  - Compact placement (9% gain in separation)
  - Increase IOT power and cooling controls (10% gain)

Laser Table with 4 lasers



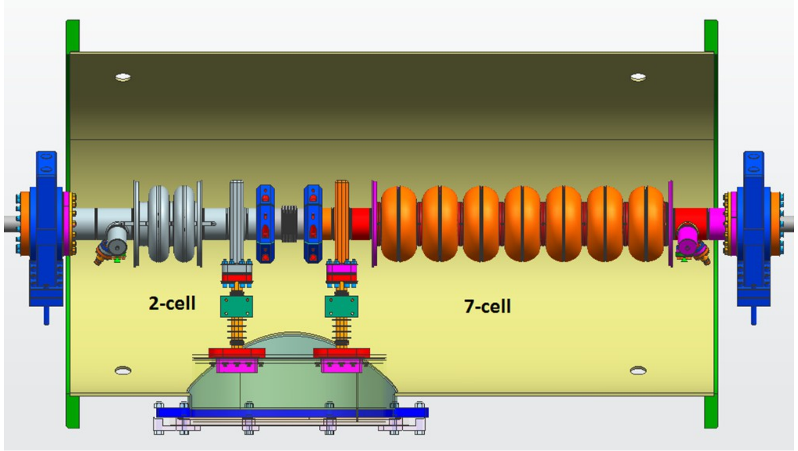
CEBAF simultaneous four-beams commissioning scheduled for Spring 2017

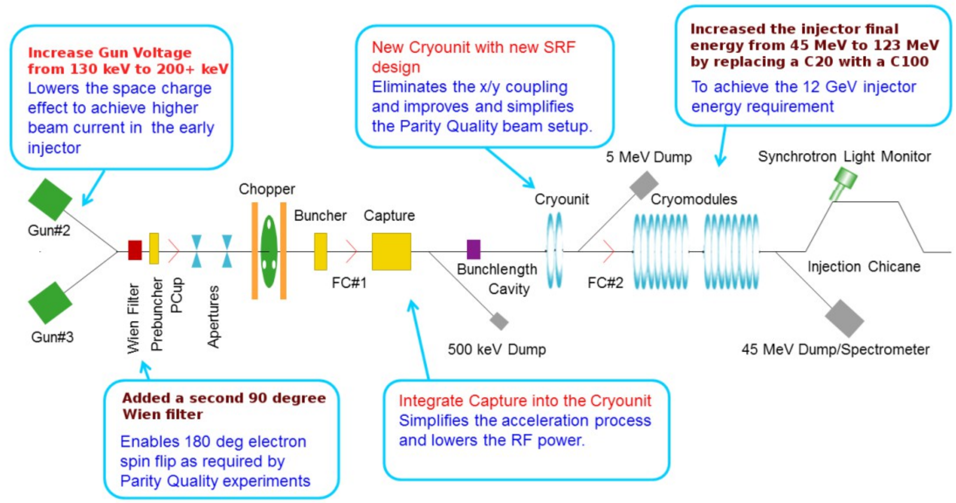
750 MHz Separators



Injector Upgrade

- 200 kV gun, reduced space charge effects to support reliable, low-loss high bunch charge operations.
  - Reliable support of 12 GeV Parity Violating experiments due to clean transport.
  - Reliable support of 5-pass operation which requires 249.5 MHz beam structure (twice the nominal bunch charge).
- New ¼ cryomodule (first and oldest SRF element in CEBAF)
  - More straight forward Injector transport-> less beam tuning
    - New stub tuner and RF coupler design do not introduce transverse kicks.
    - New C100 style HOM couplers do not introduce X-Y coupling.





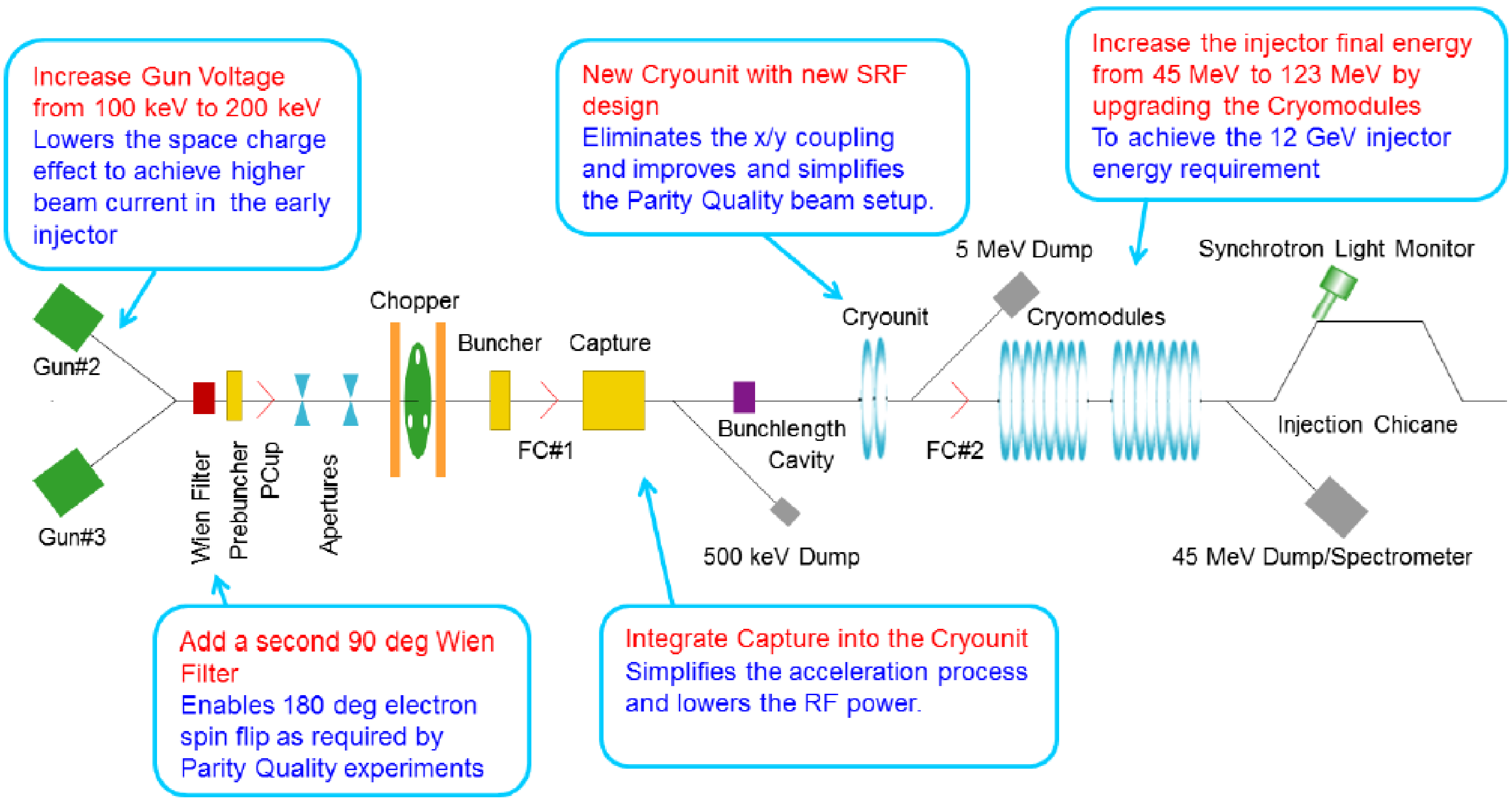
CEBAF Parity Violation Experiments

Experiment	Energy (GeV)	Pol (%)	I (μA)	Target	A_{PV} Expected (ppb)	Charge Asym (ppb)	Position Diff (nm)	Angle Diff (nrad)	Size Diff ($\delta\sigma/\sigma$)
HAPPEx-I (Achieved)	3.3	38.8 68.8	100 40	^{1}H (15 cm)	15,050	200	12	3	
G0-Forward (Achieved)	3	73.7	40	^{1}H (20 cm)	3,000-40,000	300±300	7±4	3±1	
HAPPEx-II (Achieved)	3	87.1	55	^{1}H (20 cm)	1,580	400	2	0.2	
HAPPEx-III (Achieved)	3.484	89.4	100	^{1}H (25 cm)	23,800	200±10	3	0.5±0.1	
PREx-I (Achieved)	1.056	89.2	70	^{208}Pb (0.5 mm)	657±60	85±1	4	1	
QWeak-I (Achieved)	1.155	89	180	^{1}H (35 cm)	281±46	8±15	5±1	0.1±0.02	
QWeak (Analysis In Progress)	1.162	90	180	^{1}H (35 cm)	234±5	<100±10	<2±1	<30±3	$<10^{-4}$
PREx-II (To Be Scheduled, FY18?)	1	90	70	^{208}Pb (0.5mm)	500±15	<100±10	<1±1	<0.3±0.1	$<10^{-4}$
MØLLER (To Be Scheduled, FY21+?)	11	90	85	^{1}H (150 cm)	35.6±0.74	<10±10	<0.5±0.5	<0.05±0.05	$<10^{-4}$

- PREx-II and its cousin, CREx, have requirements similar to QWeak-I. CEBAF can support these experiments without modification.
- Møller PQB requirements order of magnitude more stringent than previous parity experiments.

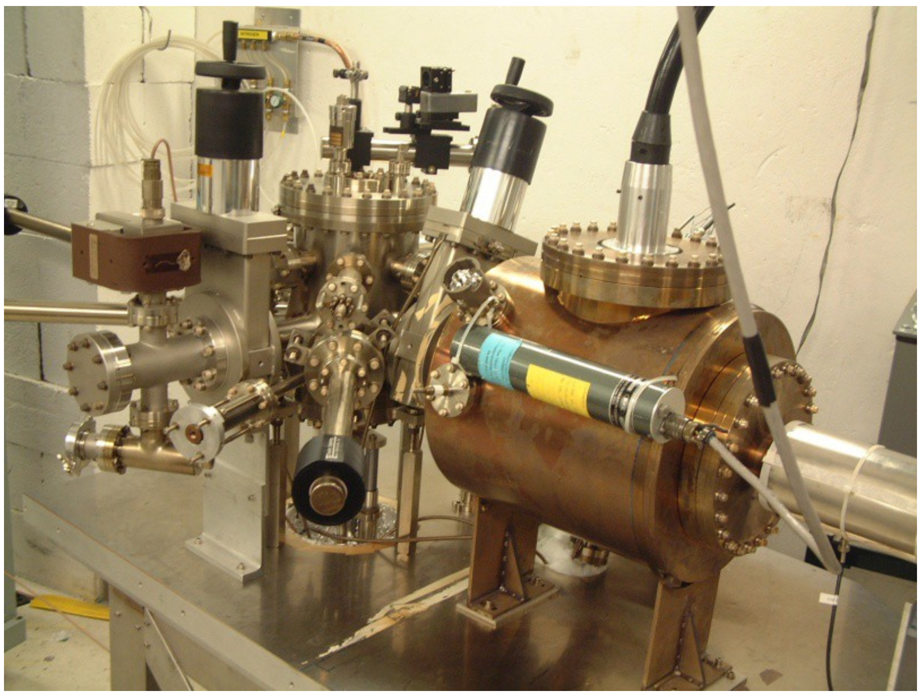
CEBAF Injector Upgrade

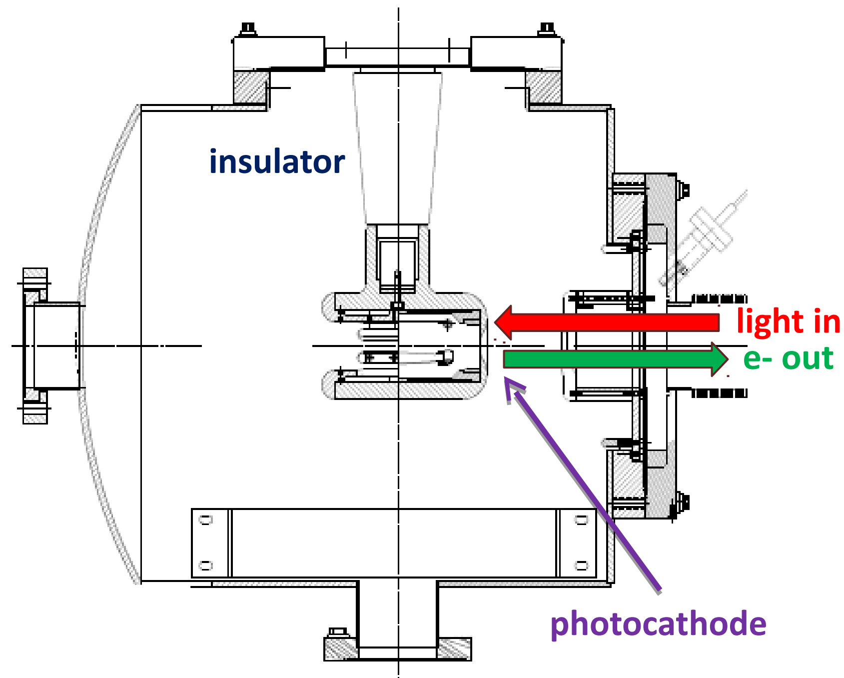
- Upgrade Gun HV to reduce space charge effects, minimize losses, improve A_Q stability.
- Upgrade $\frac{1}{4}$ cryomodule to reduce/eliminate x/y coupling.
- Upgrade all the elements between Gun and $\frac{1}{4}$ for 200 keV beam energy.



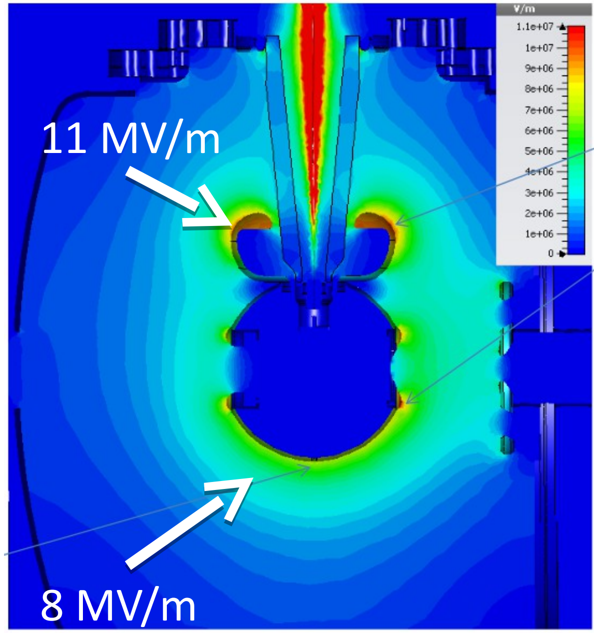
CEBAF – ILC 200 kV Inverted Gun

Developed and ready for installation
-Commissioned at Test Cave to 225 kV w/o field emission
-Large Grain Niobium electrode
-But prefer a bit more voltage headroom….

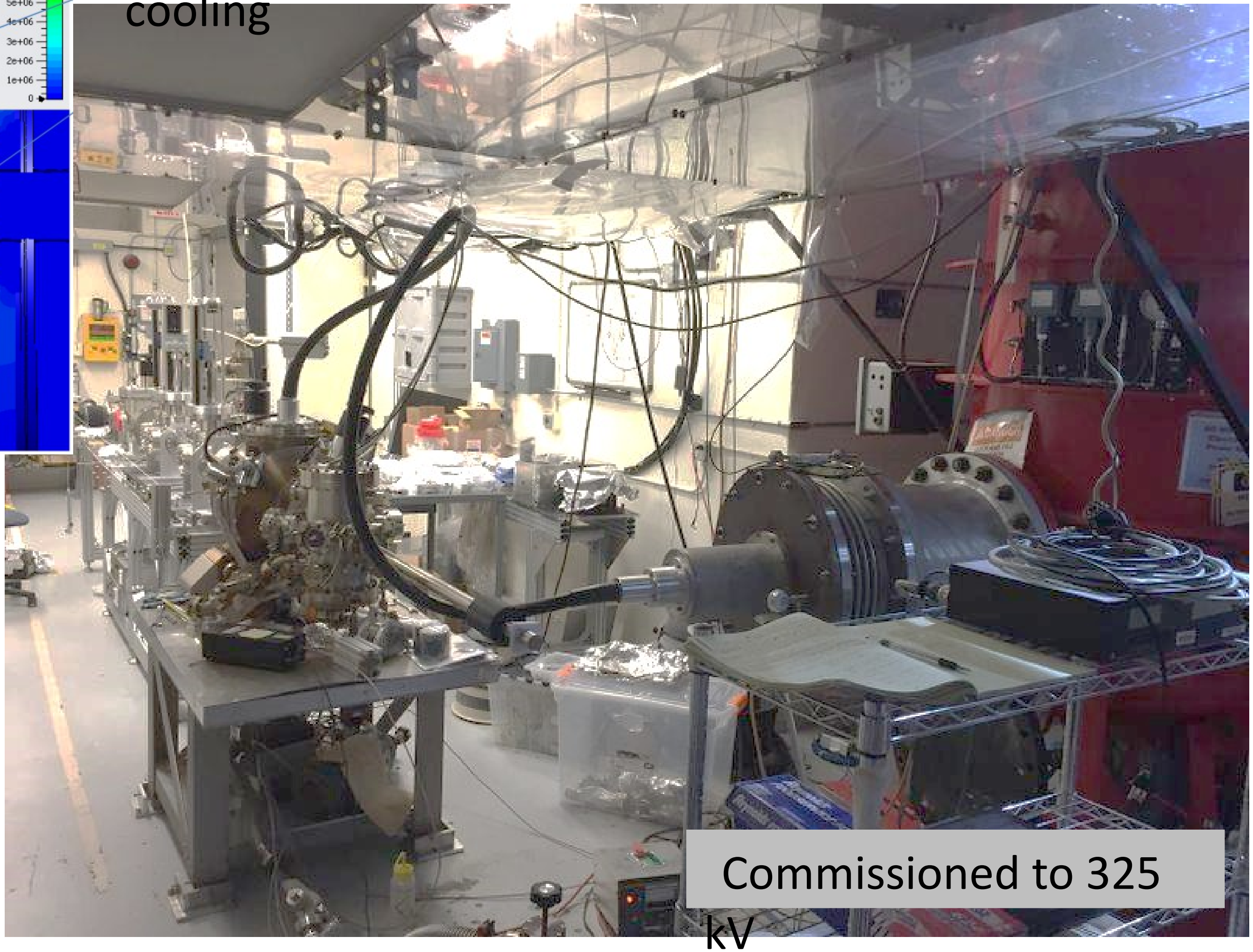




Testing > 300 kV Inverted Guns



Magnetized beam generation – for electron cooling

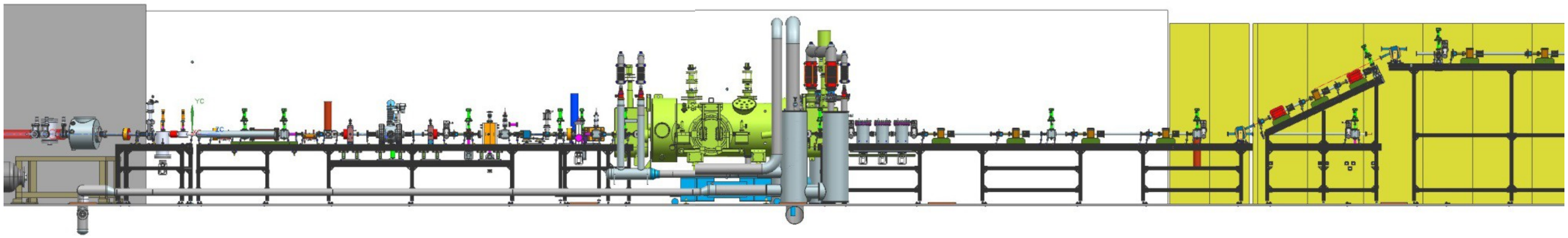


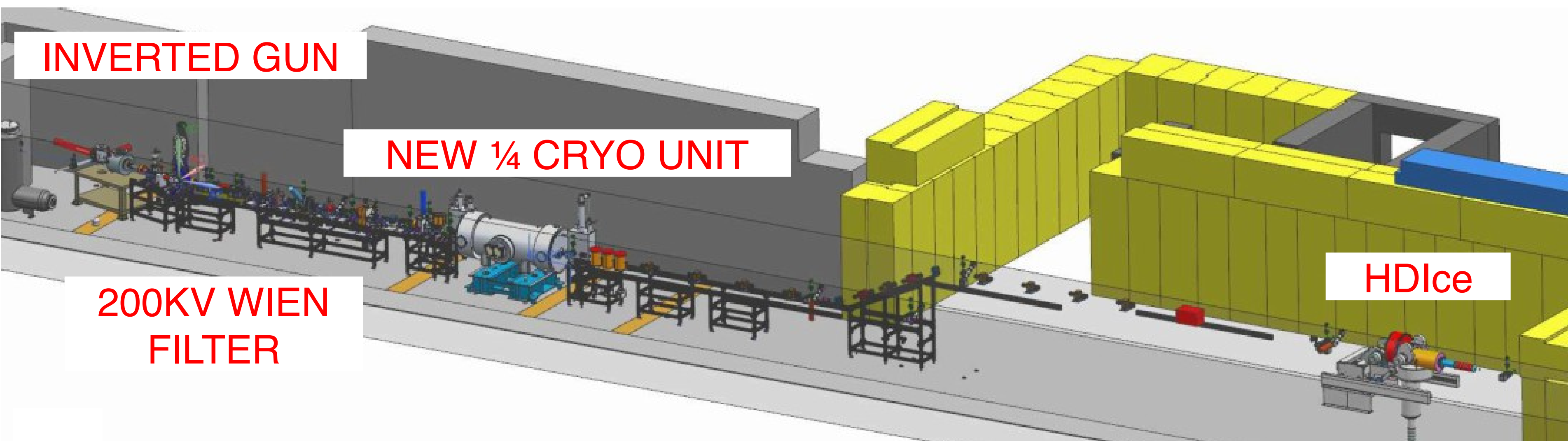
Commissioned to 325 kV

CEBAF Injector Upgrade Status

Done	200kV capable gun installed, need 200+ kV power supply
Done	Vertical Wien filter installed
Done	C100-0 installed in 0L04 slot, injector 123 MeV capable
Done	New $\frac{1}{4}$ cryomodule design
June 2016	New $\frac{1}{4}$ cryomodule fabrication complete
FY16/FY17	New $\frac{1}{4}$ cryomodule commissioning
FY17+	Upgrade and commissioning the elements between gun and $\frac{1}{4}$ cryomodule to support 200keV transport.

Injector Test Facility





10 MeV accelerator

- Commission HDIce and the new CEBAF injector
- Expect keV operations soon
- New gun and 200 kV Wien Filters at CEBAF during Summer 2017

Summary

12 GeV CEBAF beam transport design validated and meets the users out-years requirements.

- Completed the first 12 GeV experiment: PRad.
- Completed commissioning of the GlueX experiment, ready for physics.
- Beam has been successfully transported through every CEBAF 12 GeV element.

Operations, SRF, Source, Beam Physics and Engineering groups effectively addressing issues (reactive mode) and developing future plans (proactive mode).

- Search for the cause of gradient loss is narrowing in on the warm regions between cryomodules as the source of new particulates.
  - Development of mitigation plan is the next step.
- C75 refurbishment plan developed and is ready for testing with 2 cavities in C50-07B.
- Identification of activation and radiation damage of C100s and nearby regions.
  - Reduce activation/damage by optimizing C100 gradients based on FE.
  - Radiation hardening of the warm region components adjacent to the C100 modules.

FY17 Beam Operations

Fall 2016

- 11 weeks of beam operations at 11.6 GeV
  - DVCS/GMp experiment in Hall-A (passes 1,3,4,5)
  - GlueX experiment in Hall-D (pass-5.5), first production run for GlueX
  - Hall-C test beam, tentative
- Continue to probe RF systems for more gradient (especially C100s)

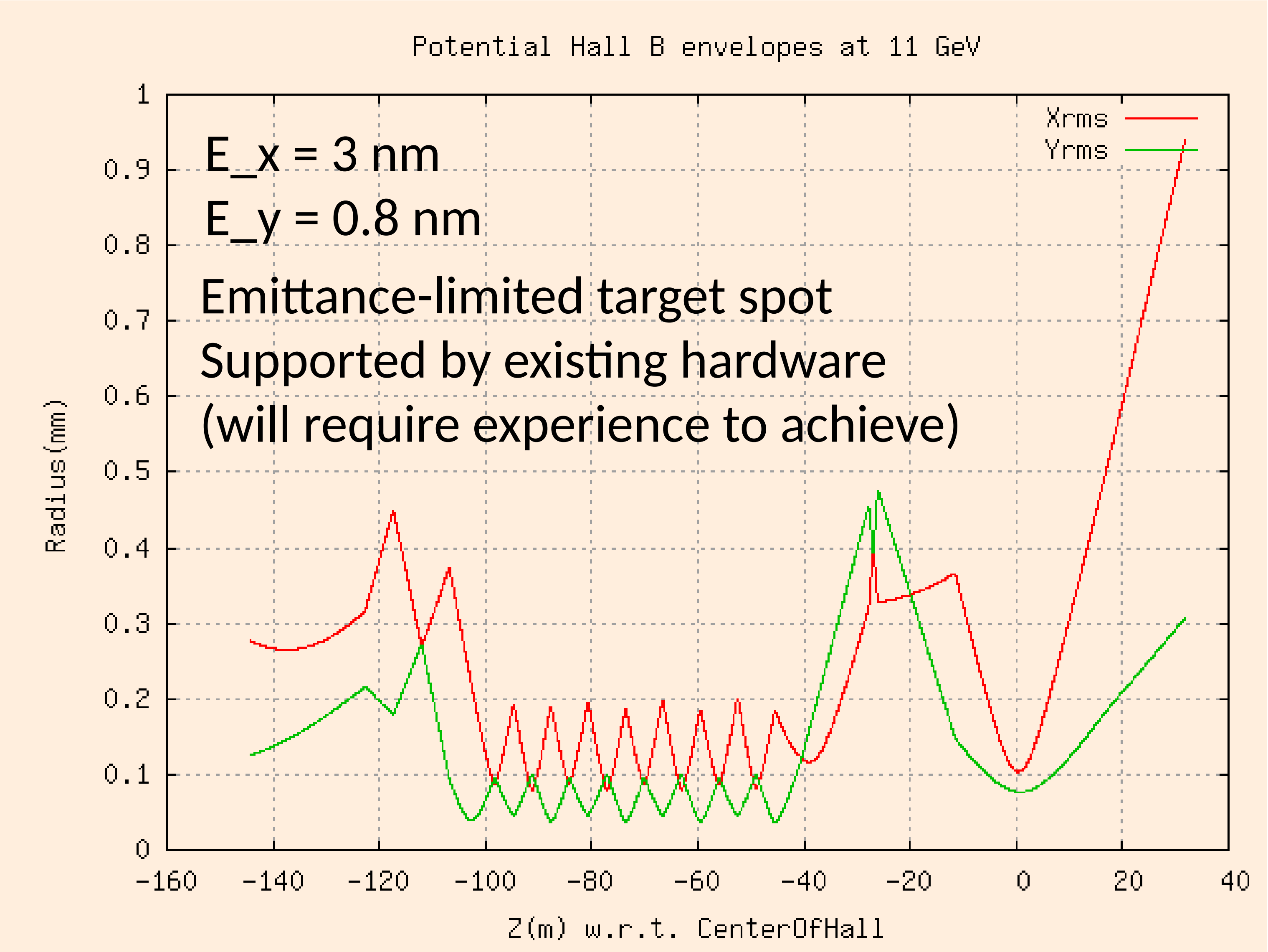
Spring 2017

- 15 weeks of beam operations at 11.6 GeV
  - Hall-A E12-10-103 (passes 2,3,4,5)
  - Hall-D GlueX (pass 5.5)
  - Hall B&C when available for beam [PRESENTLY APRIL for HALL B]
- Four beam commissioning/demonstration

Summer 2017

- 4 weeks low power, one CHL configuration at ~50% of design energy
  - Hall-A E12-14-009 (pass 1)
  - Hall-B&C when available for beam
- Install and commissioning C50-07B, HeProc FE C100s

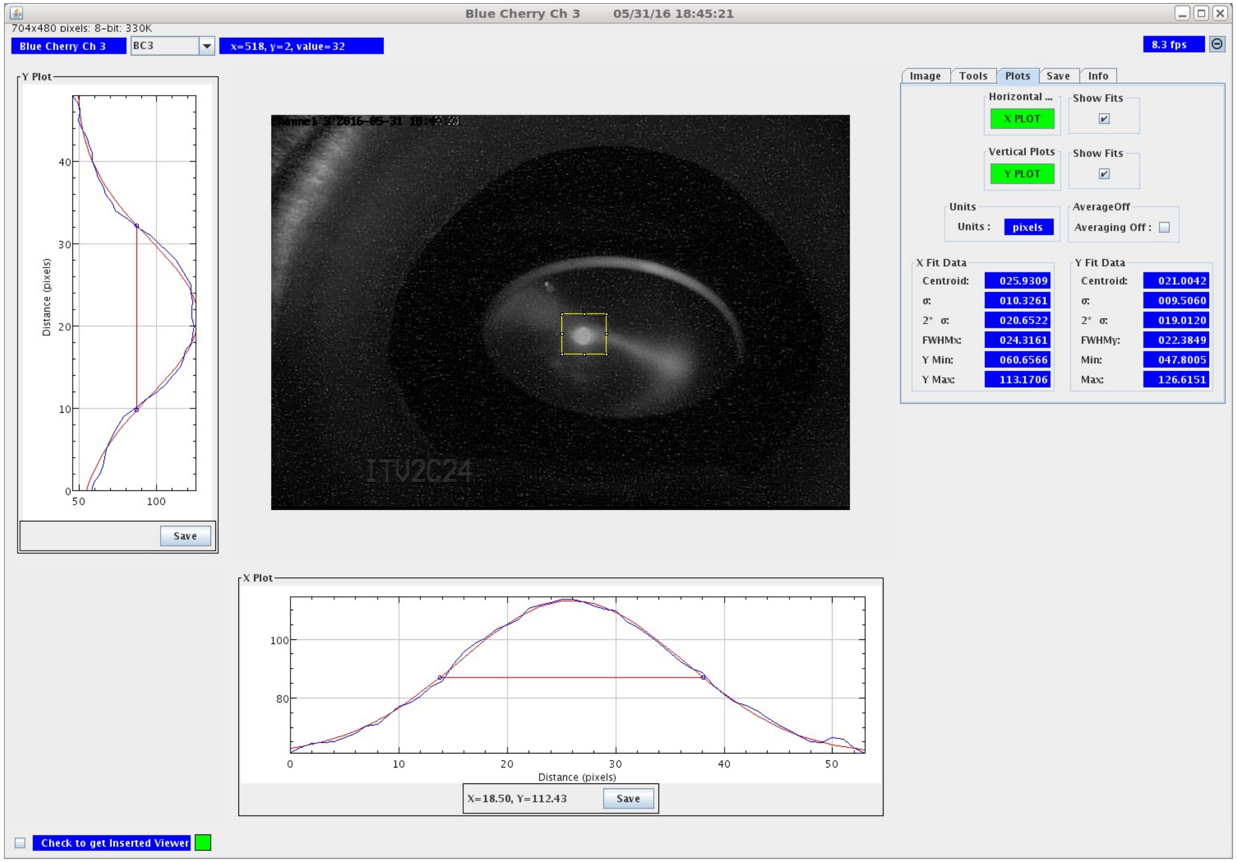
Potential Hall B 11 GeV Beam Envelope



Tagger dump cannot go to 11 GeV

- Solution taken: bury the beam into the tagger yoke.
- RadCon is involved and believes this is feasible
  - Personnel issues not in contention
  - Experimental background can be controlled
- Standard "tune mode" beam I_avg ~ 100 nA, much greater than typical Hall B current
- Alternate tune-up mechanisms must be devised
- ITV2C24 is the nearest surrogate for tagger viewer
- Controls allow for testing prior to fiducialization
- Coordination with nanoAmp BPMs may be helpful

ITV2C24 (YAG) viewer CW capable



Bits Still Under Development

- Accelerator-wide
  - MOMod to provide linac phase lock to beam
  - Online (non-invasive) CW path length monitor
  - Viewer-based profiles for emittance/matching
- Hall B
  - Improve nanoAmp BPM behavior
  - Better utilize Digital Receiver BPMs
  - Restore 2C20 Synchrotron Light Monitor
  - Beam dump procedure development for tagger yoke
  - Possible skew quad correction near Lambertson

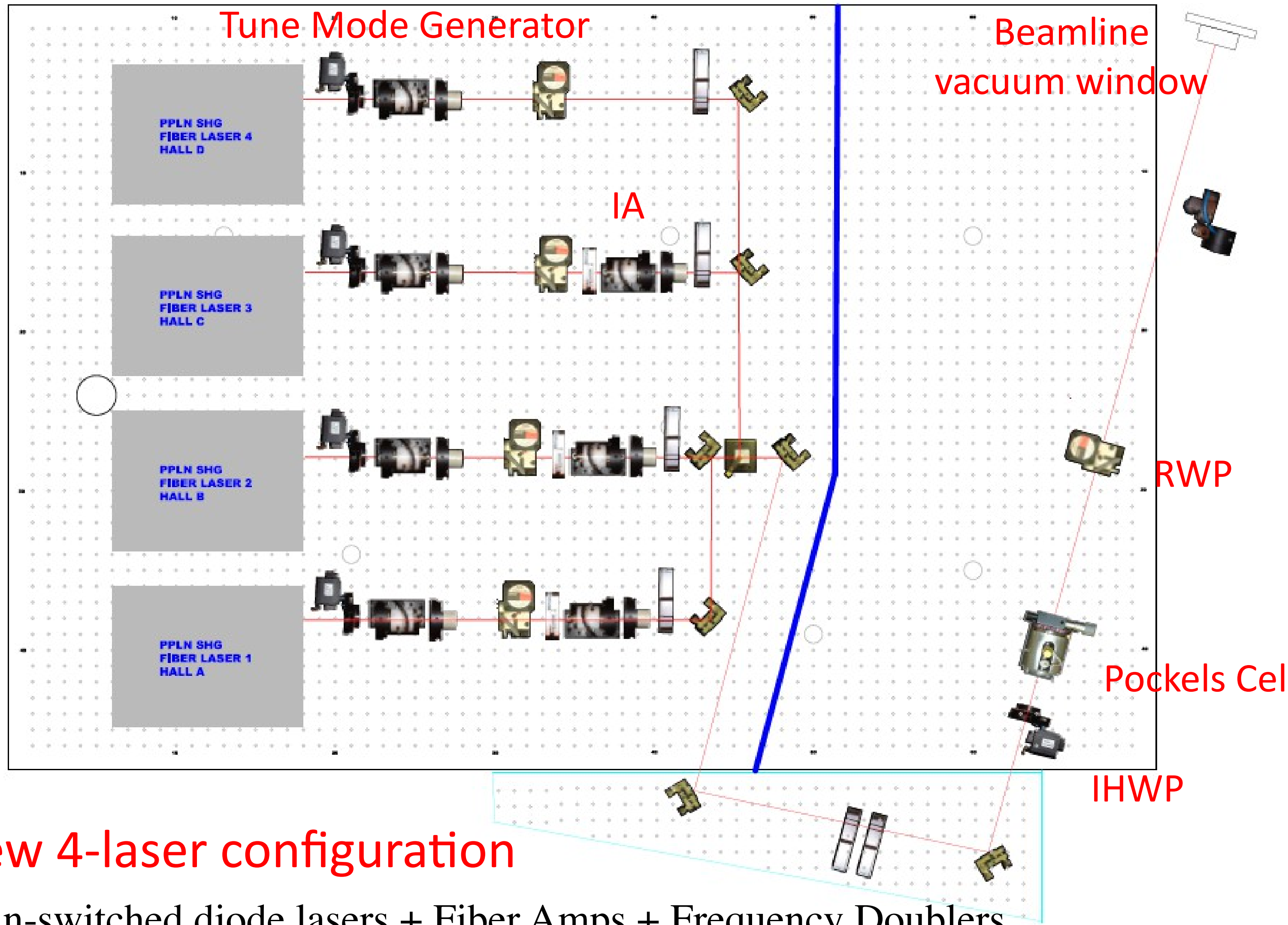
Overview

- The accelerator can work at 12 GeV
- Unexpected (rad) damage near C100s calls for attention
- Improving reliability analysis within a mix of old and new
  - Procedures, tools, and diagnostics
  - Fault analysis and root cause corrections
  - Information tracking and data handling improving
- Fiscally tight this year
  - More operating hours scheduled than last year
  - Less money available than last year
- Challenging….

End

- Backup slides follow

12 GeV Laser Table: Summer 2016

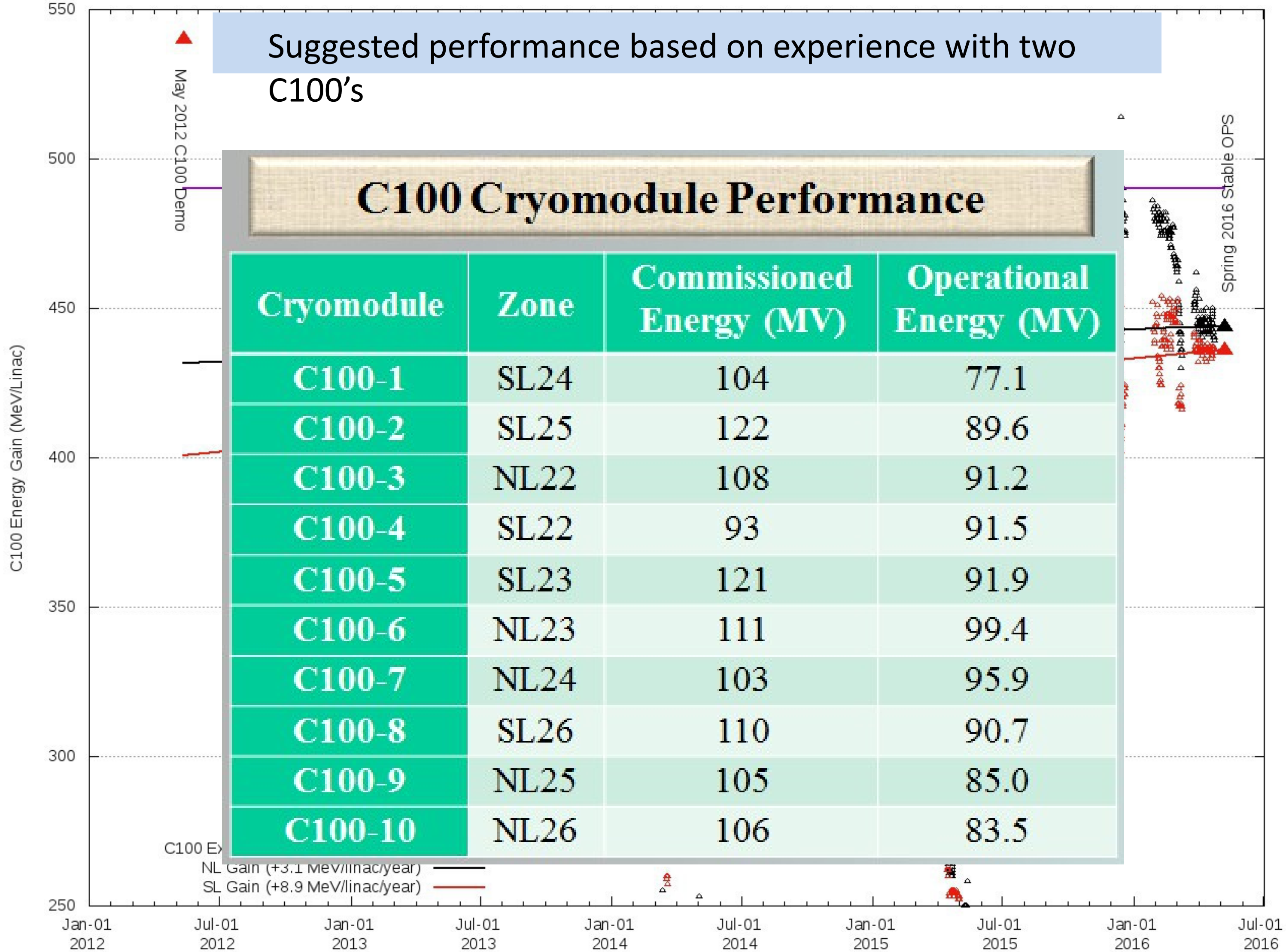


New 4-laser configuration

Gain-switched diode lasers + Fiber Amps + Frequency Doublers

C100 Operational Performance with Beam

Suggested performance based on experience with two C100's



C100 Cryomodule Performance

Cryomodule	Zone	Commissioned Energy (MV)	Operational Energy (MV)
C100-1	SL24	104	77.1
C100-2	SL25	122	89.6
C100-3	NL22	108	91.2
C100-4	SL22	93	91.5
C100-5	SL23	121	91.9
C100-6	NL23	111	99.4
C100-7	NL24	103	95.9
C100-8	SL26	110	90.7
C100-9	NL25	105	85.0
C100-10	NL26	106	83.5

CEBAF Operations StayTreats

Local workshops held near the start of the Summer shutdowns to discuss CEBAF performance and future plans.

- 2014 1-day local workshop on SRF/RF/Cryo systems.
  - Presentations and Summary available via the links.
  - ~40 participants, 17 presentations
  - Crucial in developing the plans to reach the design energy.
- 2015 3-day local workshop on all aspects of CEBAF Operations
  - Presentations and Summary available via the links.
  - ~ 50 participants, 58 presentations
  - Further preparation for operating at design energy, planned for Fall 2015.
  - C75 conceptual design
  - Reliability and CEBAF performance raised in importance
- 2016 3-day local workshop: Emphasis on CEBAF Reliability.
  - Presentations available, Summary in preparation.
  - Peak participant count of ~80, 38 presentations.
  - Remote presentations from SNS and RHIC Operations.
  - Maximizing CEBAF Reliability within constraints

12 GeV Initial Beam Requirements

Hall	Emittance (nm-rad)	Energy Spread σ (%)	Spot Size σ (μm)	Halo
A	$\varepsilon_x < 10$ $\varepsilon_y < 5$	<0.05 (12 GeV) <0.003 (2-4 GeV)	$\sigma_x < 400$ $\sigma_y < 200$ $(\sigma_y < 100)$ (2-4 GeV)	$< 1 \times 10^{-4\dagger}$
B	$\varepsilon_x < 10$ $\varepsilon_y < 10$	<0.1	$\sigma_x < 400$ $\sigma_y < 400$	$< 2 \times 10^{-4\dagger}$
C	$\varepsilon_x < 10$ $\varepsilon_y < 10$	<0.05	$\sigma_x < 500$ $\sigma_y < 500$	$< 2 \times 10^{-4\dagger}$
D	$\varepsilon_x < 50$ $\varepsilon_y < 10$	<0.5	At Radiator: $\sigma_x < 1550$, $\sigma_y < 550$ At Collimator $\sigma_x < 540$, $\sigma_y < 520$	$< 1\%^{\ddagger}$

† Ratio of the integrated non-Gaussian tail to Gaussian core.

‡ Ratio of Halo background event rate to physics event rate.

12 GeV Out-year Beam Requirements

Hall	Emittance (nm-rad)	Energy Spread σ (%)	Spot Size σ (μm)	Halo
A	$\varepsilon_x < 10$ $\varepsilon_y < 5$	<0.05 (12 GeV) <0.003 (2-4 GeV)	$\sigma_x < 400$ $\sigma_y < 200$ $(\sigma_y < 100)$ (2-4 GeV)	$< 1 \times 10^{-4\dagger}$
B	$\varepsilon_x < 10$ $\varepsilon_y < 10$	<0.1	$\sigma_x < 400$ $\sigma_y < 400$	$< 2 \times 10^{-4\dagger}$
C	$\varepsilon_x < 10$ $\varepsilon_y < 10$	<0.05	$\sigma_x < 500$ $\sigma_y < 500$	$< 2 \times 10^{-4\dagger}$
D	$\varepsilon_x < 50$ $\varepsilon_y < 10$	<0.5	At Radiator: $\sigma_x < 1550$, $\sigma_y < 550$ At Collimator $\sigma_x < 540$, $\sigma_y < 520$	$< 1\%^{\ddagger}$

† Ratio of the integrated non-Gaussian tail to Gaussian core.

‡ Ratio of Halo background event rate to physics event rate.