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CEBAF Polarized Beam for Parity Violation Experiments in the 12 GeV era

ECT* Workshop: Physics beyond the standard model and precision nucleon structure measurements with parity-violating electron scattering

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Aug. 1-5, 2016

1. CEBAF Polarized Beam
    - CEBAF Overview
    - Laser Table
    - Laser to Target Overview
    - Initial Beam Transport
2. Parity Experiments and Parity Quality Beams
3. 12 GeV CEBAF Status
4. CEBAF Injector Upgrade
5. 12 GeV Parity Experiments
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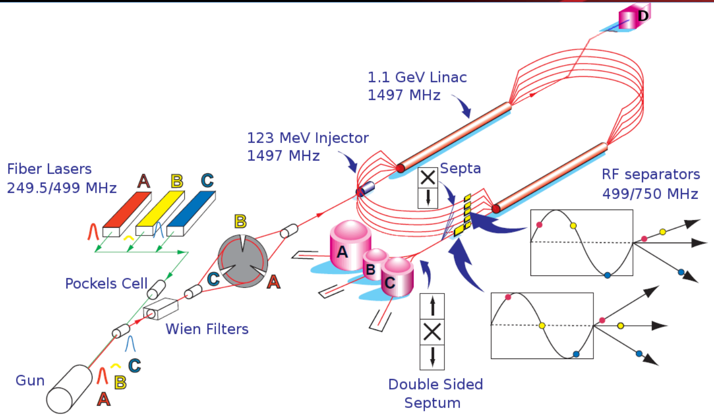
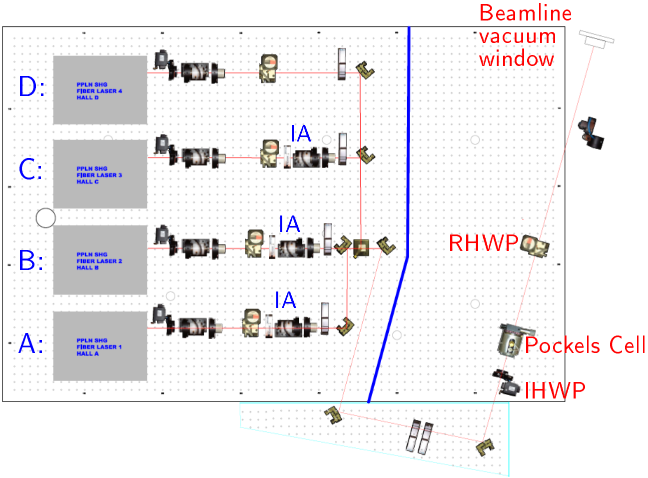
CEBAF Overview



- Maximum (design) energy 12 GeV, 5.5pass Hall-D (11 GeV 5pass for ABC).
- Simultaneous delivery of 85 μA and nA beams: 5 orders of magnitudes in bunch charge.
- Flexible extraction for ABC, 1-5 pass options.
- Polarized electron beam ($P > 85\%$).
- Three 499 MHz or 249.5 MHz beams interleaved resulting 1497MHz pulse structure.
  - Fourth laser upgrade planned for Summer 2016, commissioning Spring 2017.
- CW SRF linacs, 1MW capable.

Laser Table: Four Lasers (2016)



IA **I**ntensity **A**ttenuator, equalizes intensity across helicity states.

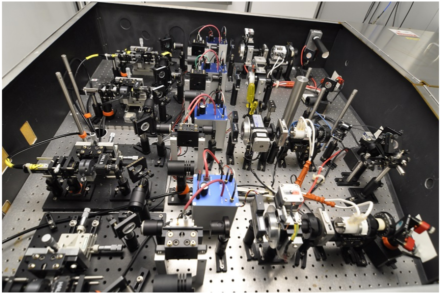
IHWP **I**nsertable **H**alf-**W**ave **P**late, flips the circular polarization.

Pockels Cell Laser light emerges with circular polarization. Reversing the voltage reverses the birefringence of the crystal and therefore the helicity.

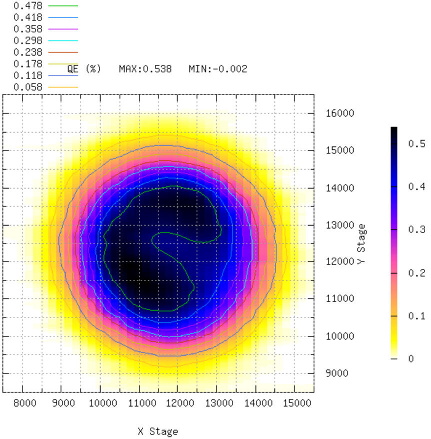
RHWP **R**otatable **H**alf **W**ave**P**late, establish a QE independent of helicity (equalize any residual linear polarization).

Laser Table: Four Lasers: Ready for Operation

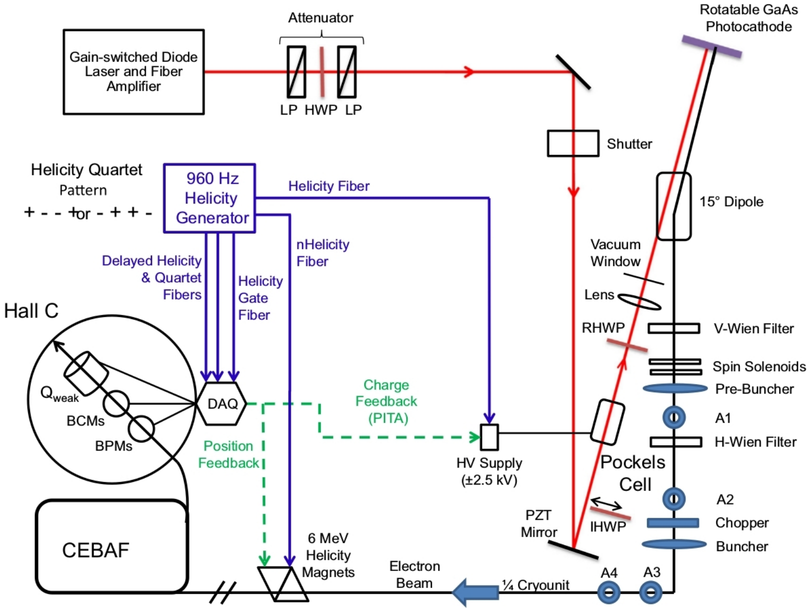
Picture of the Laser table with four lasers ready for beam!



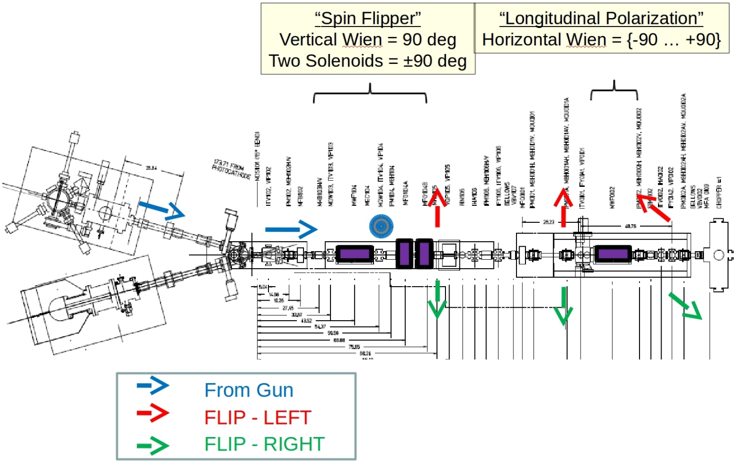
First QE measurement with the new laser table configuration.



CEBAF Polarized Electron Injector: QWeak Configuration



Electron Spin Alignment and Helicity Flip



Two Wien filters and solenoid magnets are used to set the spin alignment so that the electron spin is longitudinal at the target.
The system also provides one more means to *flip* the helicity assignment for systematic checks.

1 CEBAF Polarized Beam

2 Parity Experiments and Parity Quality Beams
- Parity Beam Parameters
- Helicity Flipping

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Parity Quality Beam: Accelerator Perspective

$\overrightarrow{D}$ Number of detected events (normalized) for positive e helicity, $\overrightarrow{e}$

$\overleftarrow{D}$ Number of detected events (normalized) for negative e helicity, $\overleftarrow{e}$

$$A_{PV} = \frac{\overrightarrow{D} - \overleftarrow{D}}{\overrightarrow{D} + \overleftarrow{D}} \approx \frac{\text{Weak}}{\text{EM}}$$

This only holds if detector acceptance (or efficiency) is independent of electron spin orientation.

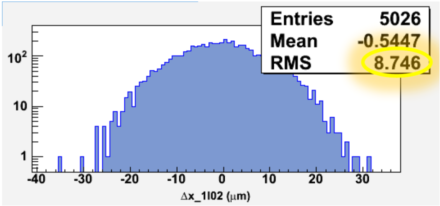
Parity Quality Beam refers to the position, angle, size and charge differences for the two helicity states averaged over the entire run.

$A_x = \overrightarrow{x} - \overleftarrow{x}$ Position difference at the target, typically in the nm range.

$A_{x'} = \overrightarrow{x'} - \overleftarrow{x'}$ Angle difference at the target, typically in the sub-nrad range.

$A_Q = \frac{\overrightarrow{Q} - \overleftarrow{Q}}{\overrightarrow{Q} + \overleftarrow{Q}}$ Charge asymmetry, 100 $\rightarrow$ 10 ppb

$A_{\sigma(x)} = \frac{\overrightarrow{\sigma_x} - \overleftarrow{\sigma_x}}{\overrightarrow{\sigma_x} + \overleftarrow{\sigma_x}}$ Beam size different at target: specification $< 10^{-4}$, how to measure?



Width of asymmetries folds contributions from:

1. **Beam stability**, $\overrightarrow{\text{helicity}}$ to $\overleftarrow{\text{helicity}}$
2. **Measurement resolution**, i.e. new BCM electronics for QWeak

The precision on determining the asymmetry centroid improves with smaller widths, enabling faster understanding of the impact of beam quality on the A_{PV} error.

The Accelerator is an Integral to PV Experimental Success

Parity Violating experiments have a strong coupling with the accelerator configuration and operation. This extends beyond the laser table and beam polarization.

Beam Stability

Minimize helicity correlated noise on beam charge, position and angle.

1. Minimize emittance at the target.
   - Well matched machine from start to end.
   - Eliminate sources X-Y coupling.
2. Establish/maintain control of beam parameters at the target (position, angular divergence)
   - Phase trombones in transport line to establish desired TWISS values at target.
3. Minimize (eliminate?) beam scraping.
   - Minimize space charge effects in the non-relativistic portion (high voltage gun).
   - Extraction setup.

Measurement resolution

1. Develop low noise electronics.
2. Develop new diagostics (helicity correlated beam size).
3. Instrument the beam line with as many monitors as possible for greater statistics.

Helicity Flipping

Helicity flipping is used to minimize systematic errors

Fast Flipping: Pockel Cell

Originally, circa late 1990s, fast meant 15 Hz, and the main concern was 60 Hz line effects.
Qweak increased the helicity flip rate to near 1 kHz to minimize systematic effects due to target density fluctuations.

- 1 kHz flip rate pushing the limits of pockel cell capabilities.
- Fast flipping rates can challenge the other experimental end-stations and beam diagnostics capabilities.

Slow Flip (Reversal): Various Methods

Global flip of the entire helicity train. Done periodically at the request of the experiment for additional control on systematic errors. Different methods probe different systematic errors.

- Insertable Half-Wave Plate on the **Laser table**. Easy
- Two Wien system in the Warm Injector section, flips the **electron beam** orientation at the start of the machine. Kind of Easy
- CEBAF energy change to change the precession amount by π. This needs to be developed in order to the minimize time required.

12 GeV CEBAF Status

1. CEBAF Polarized Beam
2. Parity Experiments and Parity Quality Beams
3. 12 GeV CEBAF Status
   - 12 GeV Emittance and Energy Spread
   - Reliability
   - Energy Reach
4. CEBAF Injector Upgrade
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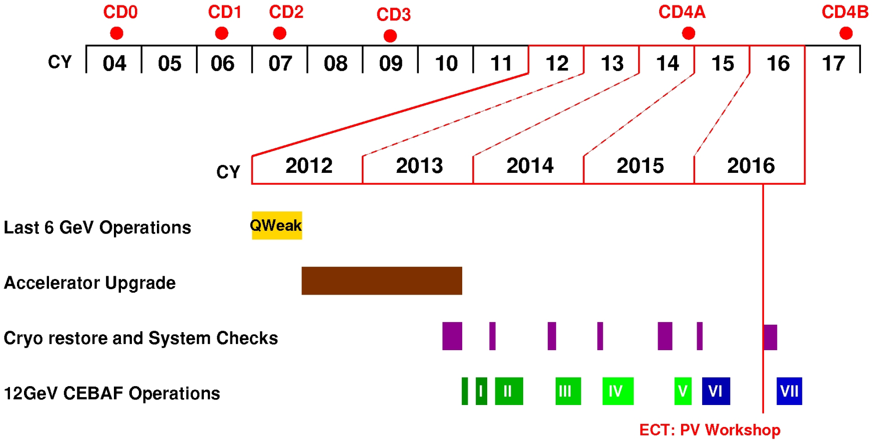
12 GeV CEBAF Upgrade Timeline

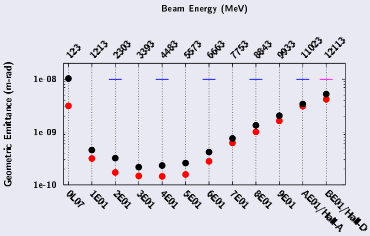


≈ 47 weeks of beam operation to date.

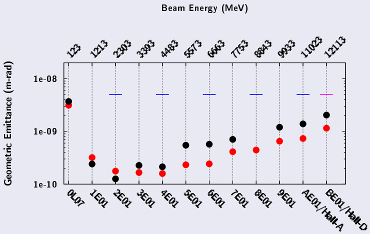
16 weeks at design energy, 2.2 GeV/pass

CEBAF Beam Parameters at Design Energy (2.2 GeV/pass)

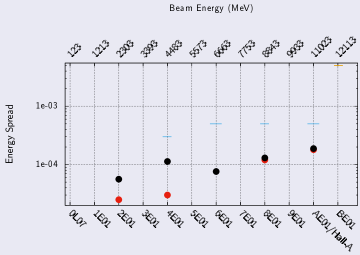
Horizontal emittance: ε_x

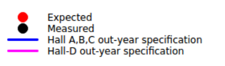


Vertical emittance: ε_y



Energy spread: $\frac{\delta E}{E}$



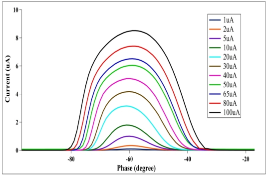


Bunchlength Evolution

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

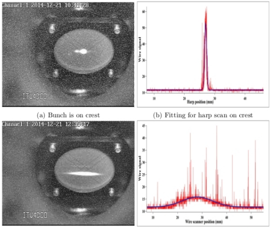
Technique	Location	Beam Energy	Measured	Expected
Brock cavity	A2	130 keV	8.31 ± 0.01 mm	6.8 mm
Slit-scan	Chopper chamber	130 keV	7.16 ± 0.04 mm	7.9 mm
Brock cavity	1D dump	130 keV	10.41 ± 0.04 mm	8.1 mm
Back-phasing	4D dump	102 MeV	80.8 ± 2.0 μm	100 μm
SLM1	Arc1	1052 MeV	91.4 ± 6.5 μm	100 μm
SLM1(compression)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

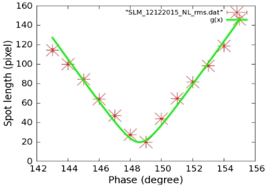


FIG. 58: Hyperbola fitting for Arc1 - *rms* calculation (CW mode).

Summary of CEBAF Beam Physics at 12 GeV

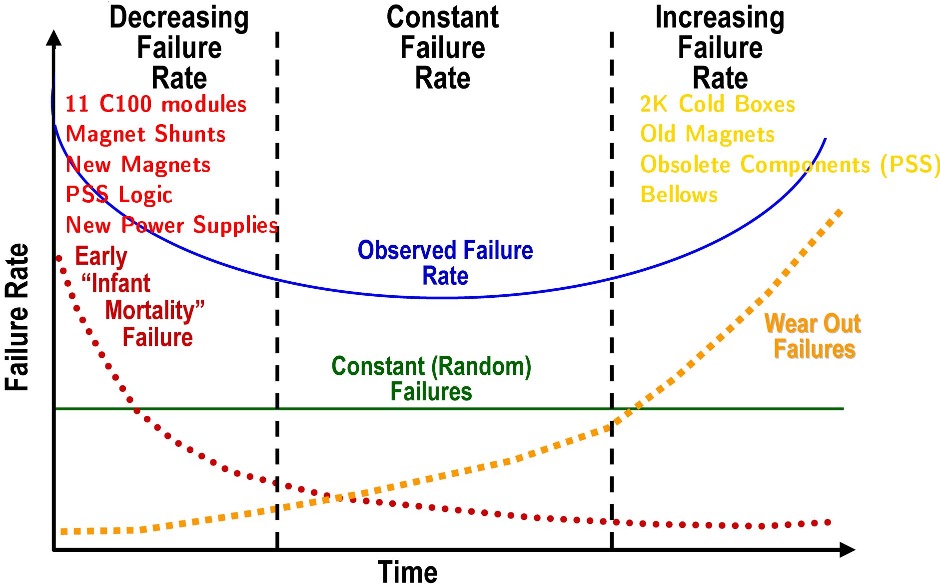
- Horizontal transverse emittance is in reasonable agreement with the design expectations and meets the out-years requirements.
- Vertical transverse emittance meets the out-year requirements but is greater than the expected value. Possibly due to off nominal orbits in the spreader and recombiner sections.
- Upper pass (passes 4 and 5) energy spread is in very good agreement with design expectations and meets out-year specification for all passes except pass-1.
  - Energy spread on the lower passes requires very careful setup and control of RF phasing and bunch length. Not required during these run periods. This is nothing new, careful attention to CEBAF setup was required for experiments requiring very low energy spread. The limit on energy spread is determined by the best one can set and control the RF phase on each cavity.

CEBAF design has been validated; the measured beam properties meet the Physics requirements. Emittance and energy spread growth due to synchrotron radiation agrees with the measurements and is well within the CEBAF operation parameters.

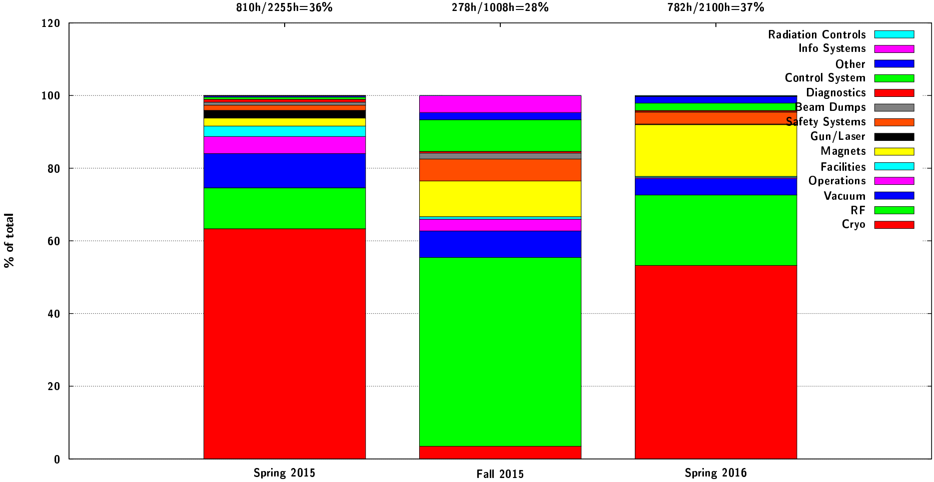
Would like to see the transverse measurements extend to the 5 MeV and the 500 (200) keV regions to establish complete control of emittance evolution.

Fighting Both Sides of the Bathtub Curve

losing some battles but preparing the win the war.

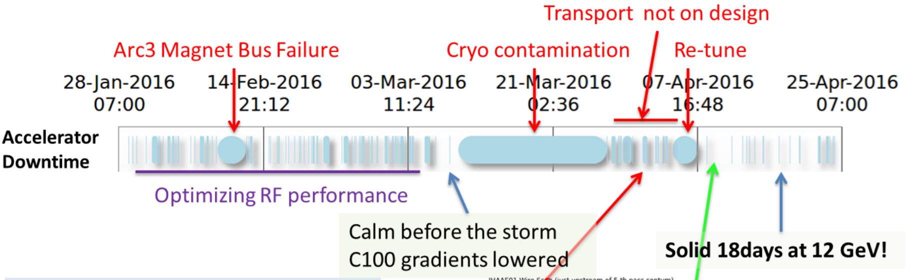


Hardware downtimes for last three run periods

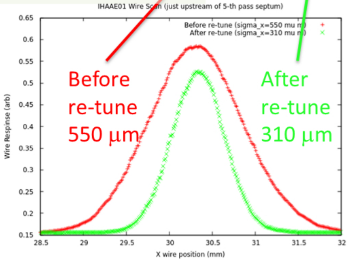


This does not include the **trips** which account for about 6min out of each hour, or 10% additional downtime. And does not include tune-time.

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 separation has no margin and requires beam transport to be on-design for robust operation.



Horizontal beam size upstream of 5th pass septum

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

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

Energy Reach versus CEBAF Uptime

Retreat!

In order to provide some gradient margin, lower CEBAF energy to 1050 MeV/linac (based on the requirement to have at least 50 MeV/linac of margin at the end of the year, Spring 2017).

Pass	Beam Energy (MeV)
1	2217
2	4317
3	6417
4	8517
5	10617
5.5	11667

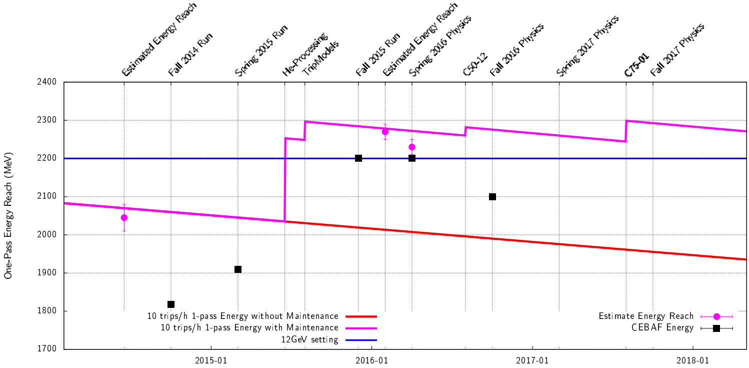
Energies in the upper passes will be slightly lower due to synchrotron radiation losses which are not included in the above table.

50 MeV/linac of gradient margin will permit:

- Problematic (high field emitting) cavities to be turned down (or off).
- Ability to by-pass problematic cavities.
- Ability to absorb a C20/C50 catastrophe (by-pass entire zone) without major impact to the run.

Gradient Improvement and Energy Reach

- Refurbish weakest cryomodules, C50(C75) program.
  - C75 (proposed new refurbishment plan) is a cell replacement for a C20 module with a goal of delivering 75 MeV of energy per module.
- Gradient Team: Operations, SRF and RFpower staff working to develop plans for optimizing gradient system performance, maximum gradient and reliability.



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- Overview
- New $\frac{1}{4}$ cryomodule

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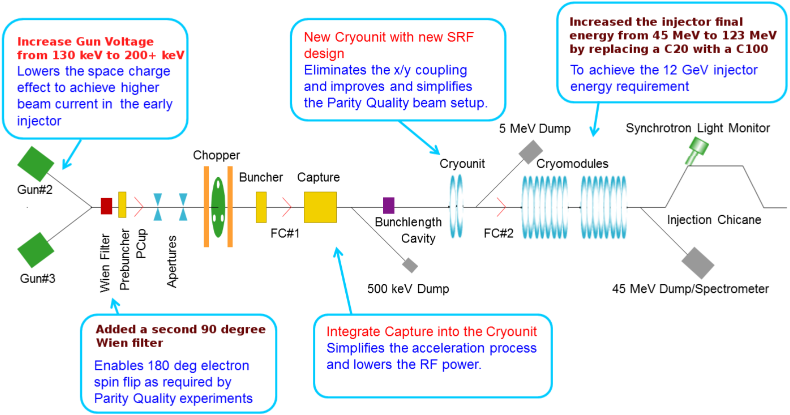
CEBAF Injector Upgrade

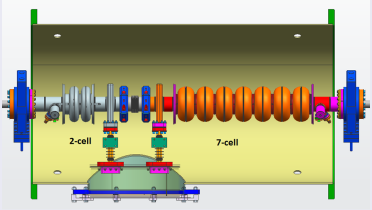
Project Start: 2009

- Upgrade total energy to 123 MeV to retain $\frac{E_{Inj}}{E_{pass1}}$ ratio.
- 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 new $\frac{1}{4}$ cryomodule for 200+ keV beam energy.



Injector Upgrade Status

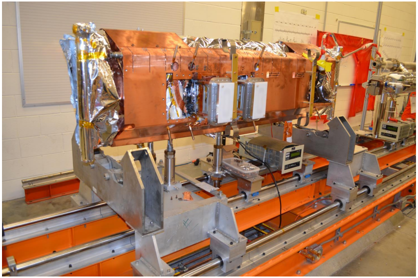
New $\frac{1}{4}$ Cryomodule Design

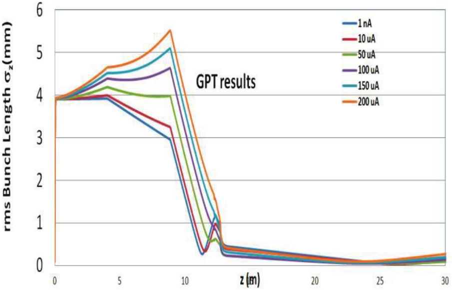


Done	200kV capable gun installed, need 200+ kV power supply
Done	Vertical Wien filter installed
Done	C100-0 installed in 0L04 slot, injector 123 MeV capable
Done	New $\frac{1}{4}$ cryomodule design
Oct 2016	New $\frac{1}{4}$ cryomodule fabrication complete
FY17	New $\frac{1}{4}$ cryomodule commissioning in UITF
FY18+	Upgrade and commissioning the elements between gun and $\frac{1}{4}$ cryomodule to support 200keV transport.

New $\frac{1}{4}$ cryomodule

- Cold mass ready for assembly into the $\frac{1}{4}$ cryomodule.
- New stub tuner and RF coupler design that reduce transverse kicks, compared to the existing $\frac{1}{4}$ cryomodule.
- New HOM couplers that effectively damp HOM modes without introducing X-Y coupling.





- Injector Upgrade design has been optimized via particle tracking simulations.
- Simulations favored 2-cell/7-cell option with 200 keV Gun operation.
- Design supports a simultaneous delivery of a wide range of bunch charge.

Injector Upgrade Schedule: Strawman

Driving Terms

- Need to complete the upgrade 2+ years before MOLLER experiment.
- Test all new components ($\frac{1}{4}$ cryomodule,...) in the Upgraded Injector Test Facility (UITF).

2017 Test/Commission new $\frac{1}{4}$ cryomodule at UITF.

2017 Complete design and engineering of elements between gun and $\frac{1}{4}$ cryomodule.

- Do not have the pre-buncher sandwiched between the two Wien filters. Simplifies injector setup and helicity flip via Wiens.
- Utilize UITF for tests to validate design decisions, minimize risk.

Summer 2018 Install new $\frac{1}{4}$ cryomodule in CEBAF, upgrade Gun HV to 200 kV, upgrade pre-buncher, Wien filter, chopper, magnet power supplies to support 200 keV beam energy.

Fall 2018 Commission new injector in CEBAF.

Spring 2019 New injector ready for parity experiments.

Beyond 2019 Push to higher Gun voltages.

- New 350 kV capable gun ($)
- New chopper design to better support simultaneous 4-hall operation ($$$)
- New warm pre-buncher cavity($$$)

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- Schedule
- Parity Beam Issues

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Parity Quality Beams (PQB) at CEBAF

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/CREx (To Be Scheduled, FY18+?)	1	90	70	^{208}Pb (0.5mm)	500±15	<100±10	<1±1	<0.3±0.1	$<10^{-4}$
MOLLER (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. 12 GeV CEBAF can support these experiments without modification.

MOLLER PQB requirements more stringent than previous parity experiments. Upgraded CEBAF Injector is designed to make achieving these stringent requirements more *routine*.

FY18: Oct-01-2017 $\to$ Sep-30-2018 (Tentative)

Fall 2017: $E = 2.1\mathrm{GeV/pass}$, 13 weeks

Hall-A	More Tritium Experiments: E12-11-112, (passes 1&2). This is very firm.
Hall-B	CLAS12 Eng. Run, Run Group A. (pass 5)
Hall-C	E12-09-017,002,011 (passes 3,4,5)
Hall-D	Only if four-hall capable

Spring 2018: $E = 2.1\mathrm{GeV/pass}$, 13.6 weeks

All Halls	Tentative schedule to be set in Nov. 2016, made firm in May 2017.

You can only request scheduling when construction of all major components of the experiment are completed, as at this stage the experiment layout and components are considered frozen, and any design modifications will require a change control, approved by the Division Management.

July 1	Call for Scheduling (Beam Time) Request		
July 30	Deadline for Scheduling Request Submissions		
October 1	Draft 18-Month Schedule Released		
October 15	Deadline for Input of User Community on Draft Schedule		
November 1	18-Month Schedule Released		
	Year 1	January - June	Schedule Reaffirmed
	Year 1	July - December	Firm Schedule
	Year 2	January - June	Tentative Schedule
April 1	Draft 18-Month Schedule Released		
April 15	Deadline for Input of User Community on Draft Schedule		
May 1	18-Month Schedule Released		
	Year 1	July - December	Schedule Reaffirmed
	Year 2	January - June	Firm Schedule
	Year 2	July - December	Tentative Schedule

2016 Scheduling Cycle (on-going)

July 30 2016	Call for Beam Time Request just ended on July 30th.
Nov 1 2016	Firm schedule defined for July $\to$Dec 2017, Tentative schedule defined for Jan $\to$ June 2018
May 1 2017	Firm schedule defined for Jan $\to$ June 2018, Tentative schedule for defined July $\to$ Dec. 2018

2017 Scheduling Cycle

July 30 2017	Next Beam Time request deadline.
Nov 1 2017	Firm schedule defined July $\to$ Dec 2018 (**First opportunity for PREx-II/CREx**), Tentative schedule defined for Jan $\to$ June 2019 (**Most probable PREx-II/CREx run-period**).
May 1 2018	Firm schedule defined Jan $\to$ June 2019, Tentative schedule defined for July $\to$ Dec. 2019

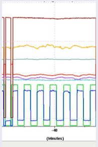
Parity Beam Issues

- Caryn Palatchi (parity beam) and Bob Micheal (polarimetry) presentation tomorrow.

Hall-A Compton real-time signals

laser on/off— photon signal

Great! (11 GeV):



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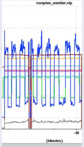
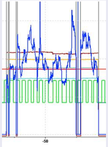


Bad:



- 12 GeV commissioning complete, transition to operations for NP.
- Ramp-up support for parity quality beam measurements during beam studies.
- Need to optimize Injector Upgrade with Experimental schedule.
- 5-pass separation implies 249.5 MHz structure, so bunch charge is double the 499 MHz equivalent CW beam current
  - 85 μA @ 249.5MHz has the same bunch charge as 170 μA @ 499 MHz (MOLLER space charge effects same as QWeak).
- 5-pass separation not fully commissioned, need to establish reliable, routine, operation through this tight aperture.

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Acknowledgements

Thanks to Matt Poelker, Joe Grames, Riad Suleiman, John Hansknecht, Ciprian Gal, Dave Gaskell for providing graphics used in this presentation.

The Breakfast Analogy

A Pig and a Chicken are walking down the road.
The Chicken says: "Hey Pig, I was thinking we should open a restaurant!"
Pig replies: "Hm, maybe, what would we call it?"
The Chicken responds: "How about 'ham-n-eggs'?"
The Pig thinks for a moment and says: "No thanks. I'd be committed, but you'd only be involved."

CEBAF Operations and Source group are **committed** to extending the Parity Violating experimental success into the 12 GeV era.

Summary

- CEBAF beam parameters at the design energy, 12 GeV, meet the out-year Physics requirements.
  - Measured parameters are near the expected values.
  - **Polarized beam ($P \approx 89\%$) has been delivered to Hall-A on Pass-1,2,4,& 5 (11 GeV)**.
- CEBAF reliability at design energy is lower than the 6 GeV reliability, which is as expected. For $x < 1 \Rightarrow x^2 < x$
  - CEBAF Energy margin is insufficient for sustained, robust 2.2 GeV/pass operations.
  - Cryogenics remains a single point of failure.
  - Brief periods of robust operations have been achieved. Requires proper machine setup, optimized RF setup and vigilance.
- Major pieces of the 4-hall laser/RF-separation systems have been tested and plans are to complete the project in FY17.
  - **New laser table configuration in-place, ready for parity users to evaluate and improve**.
- **Injector Upgrade on-going, take delivery of the $\frac{1}{4}$ cryomodule by end of 2016**.
- Beam operations Fall 2016 and beyond for scheduled NP experiments with beam studies to support future experiments.
  - **Parity quality beam team already active, with the majority of the 12 GeV Commissioning issues in the rear view mirror, beam study time for more measurements should be easier to schedule**.

The first 12 GeV CEBAF Physics run has just ended. There were successes and failures. Through the hard work of all involved the most was made out of a non-ideal situation.

END HERE!!!

Thank You for your time and attention.