CEBAF Pulsed Operation for JLEIC Electron Injection

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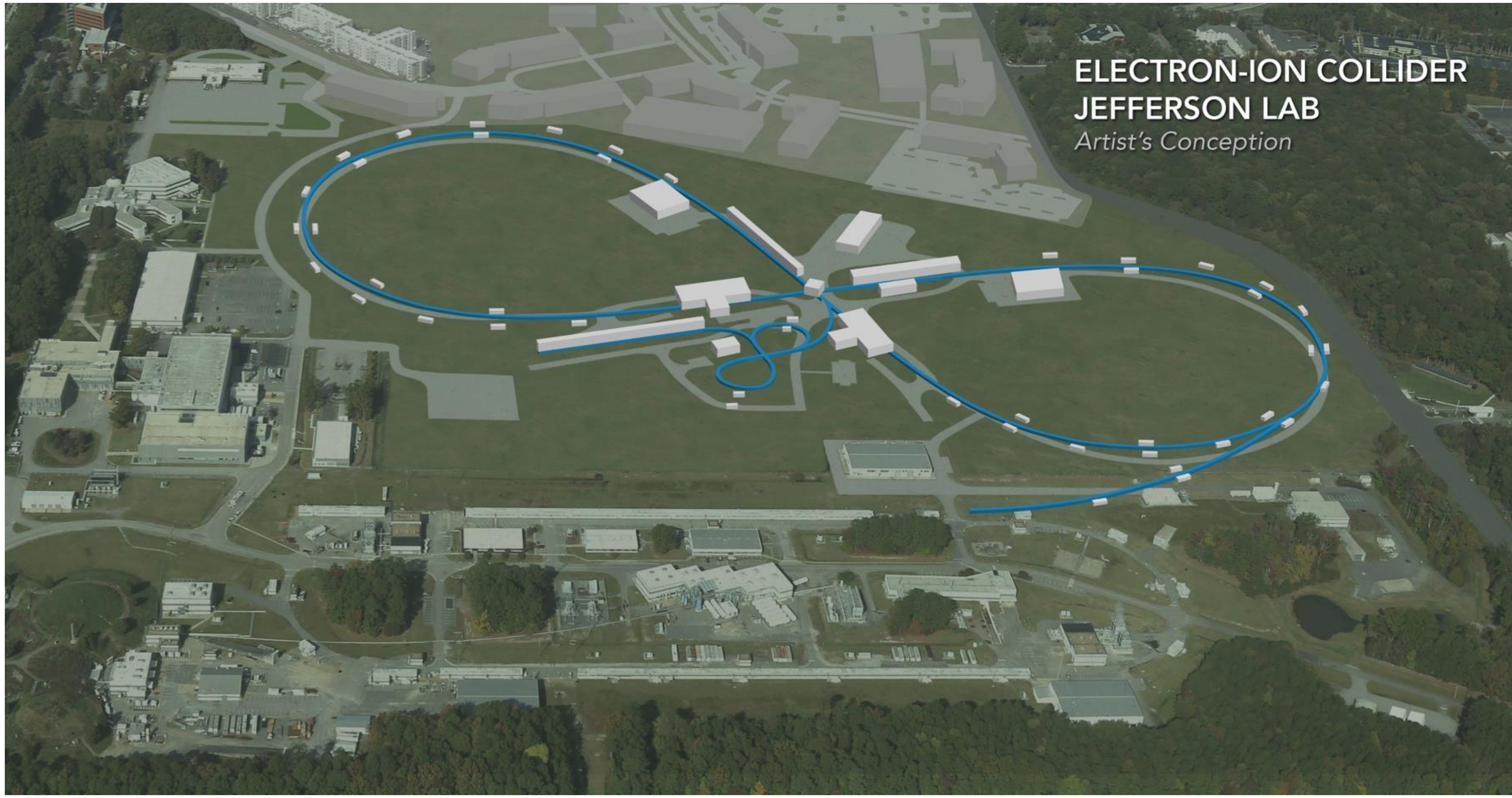


Nuclear Physics Accelerator R&D PI Meeting

November 13-14, 2018

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Project description and status

- Description:
  - JLEIC plans to use CEBAF as its electron injector, requiring high intensity (1-2mA pulsed current) bunch trains with low duty factor. CEBAF was designed as a CW linac with ~0.1mA extracted current. Pulsed operation of CEBAF needs to be investigated, with the focus on the mitigation of cavity voltage droop caused by the transient beam loading, maximizing the extracted pulsed current.
- Main goal
  - Test CEBAF in pulsed mode with JLEIC injection style bunch train. Confirm the modeling of energy droop of the bunch trains and the effectiveness of compensation schemes.
- Status
  - In progress. A few beam tests done
- Corresponding to Line 22, "Operate the JLAB Continuous Electron Beam Accelerator Facility in the JLEIC injector mode", priority High-B and Line 43, "Test of CEBAF electron injection mode", priority high-C, of the Jones' Panel report
- Supported by JLab's Additional DoE NP Accelerator R&D funding
- Funding not continued by the FY'18 NP Accelerator R&D FOA

Budget and schedule

- Budget

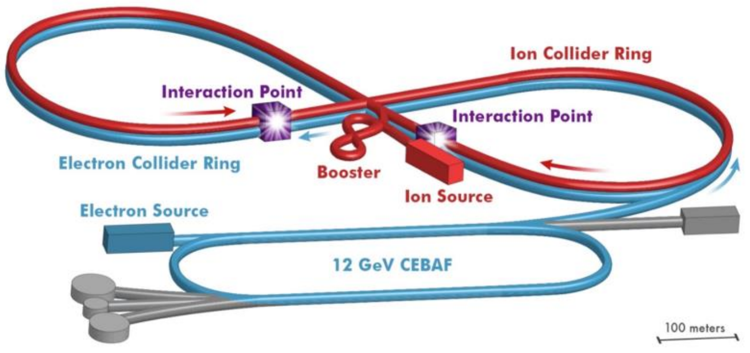
	FY'17-FY'18	Totals
a) Funds allocated	$60,720	$60,720
b) Actual costs to date	$37,367	$37,367
c) Remaining	$23,353	$23,353

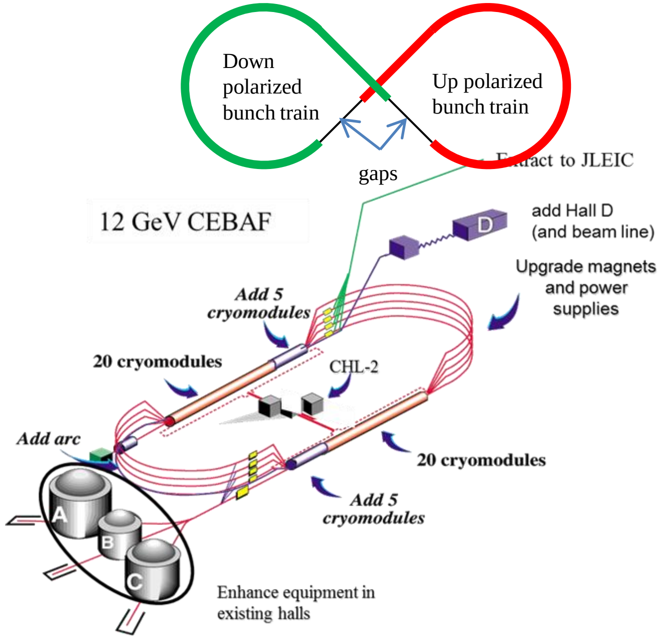
- Deliverables and schedule

Task	FY'18 Q1	FY'18 Q2	FY'18 Q3	FY'18 Q4
Test the CEBAF injector through R100 cryomodule with pulsed beam up to 2.4mA and measure the beam energy droop. Test the RF feed-forward scheme in R100				**x**
Test CEBAF with ~3.8μs bunch trains at different energy to find the upper limit of beam current in the case without compensation;				**x**

Motivation and Problem Statement

- JLEIC design uses CEBAF as electron injector
- JLEIC e-ring has the circumference of ~2256m, two 476MHz 1047m (3.49μs) long bunch trains of opposite polarization, with up to 3A average current (~7nC per bunch)
- JLEIC electron injection requires pulsed bunch trains with limited repetition rate, limited by the kicker recovery time (up to 60Hz). For each JLEIC bunch, if multiple injection is required, waiting time for each injection into the same bunch needs to be at least twice transverse damping time (up to 375 ms)
- CEBAF never ran in similar pulsed bunch train mode and needs to demonstrate such capability
  - With CW RF in CEBAF, gradient droop is the major challenge for intense bunch trains
  - Long bunch train of up to 1047m is preferred from CEBAF if we plan to fully correct the cavity gradient droop with RF feedforward using the existing CEBAF klystrons.
  - Plan to use 476MHz PEP-II RF system, bunch repetition rate 17.01-68.05 MHz to match the 1497MHz CEBAF RF frequency.
  - Experimental demonstration of such operation is recommended to eliminate the risk for JLEIC e-ring injection





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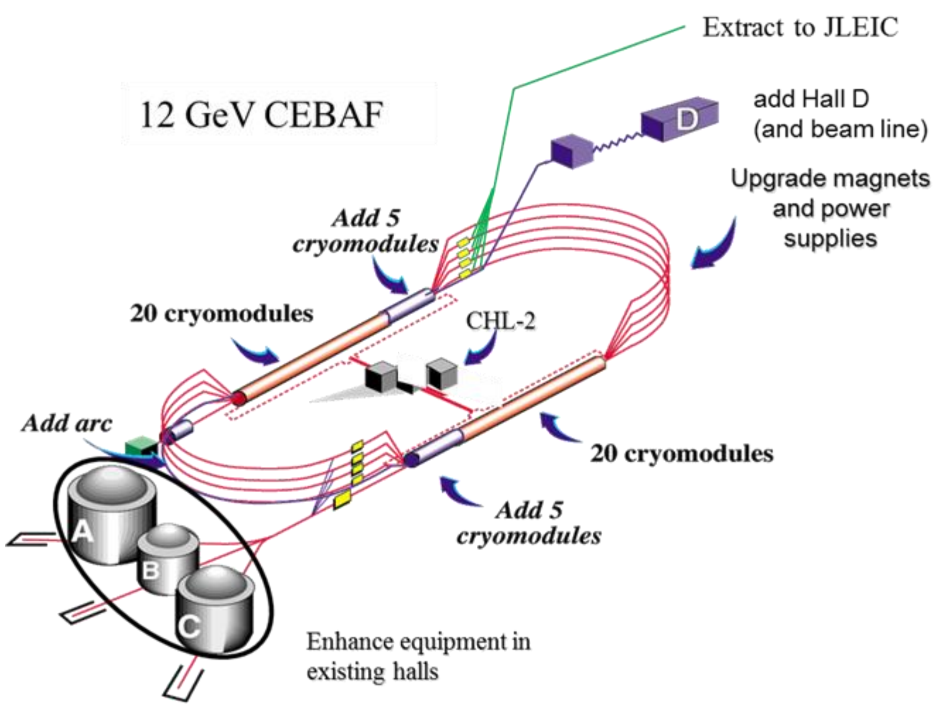
CEBAF as JLEIC Injector

- Designed for CW operation with 1MW extracted beam power (up to 90μA at 11-12 GeV), limited by both the beam dump rating and the SRF cavities' capability to couple RF power to the beam
- Recirculating linac. Beam gets accelerated 6 passes in the north linac, 5 passes in south. ~0.5MW RF to beam power in each of the north and south linacs.
- 1.05-1.09 GeV energy gain per linac pass with 10 new C100 cryomodules, 40 original C50/C25 cryomodules
- For bunch trains <1311m, possible to achieve >=5.5MW extracted bunch train power
- Needs to provide intense bunch trains of 1047m with 2-60Hz repetition rate
  - Voltage droop ultimately limited by CEBAF arc energy spread acceptance ±0.2%
  - Gun needs have up to 30 pC/bunch. Two orders of magnitude higher than the current CEBAF gun but not beyond state-of-the art



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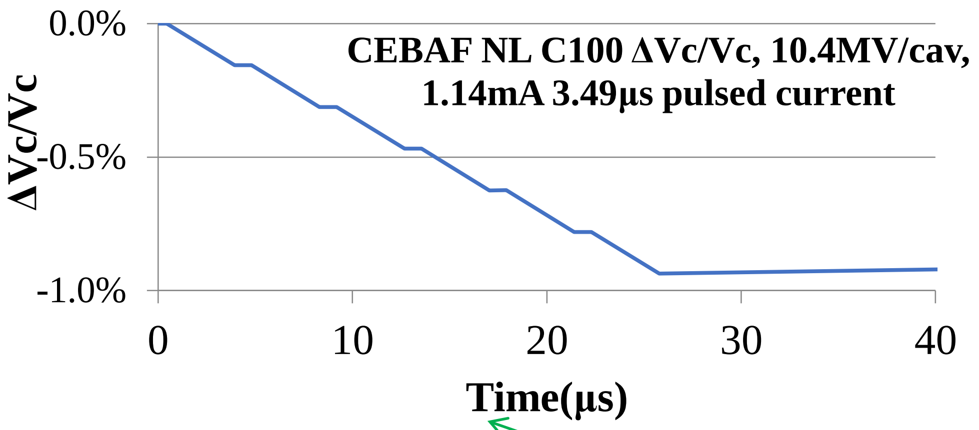
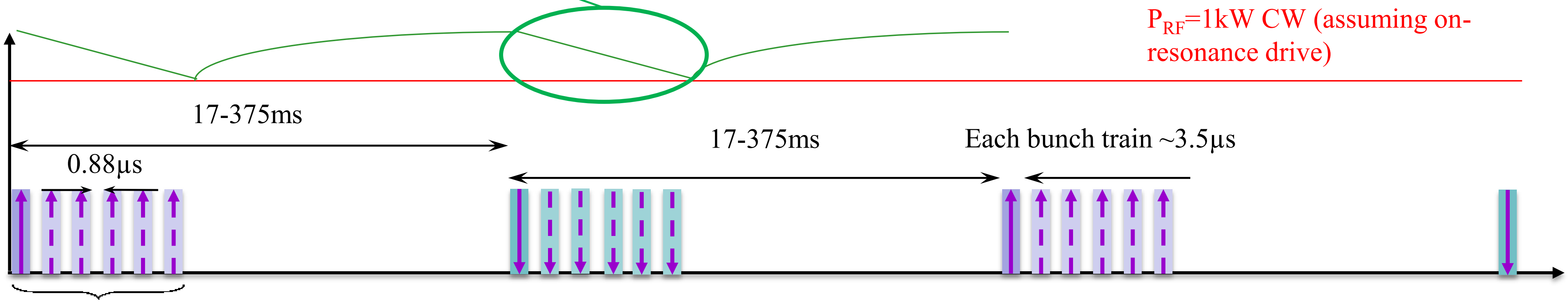
CEBAF Voltage/Energy Droop with CW RF



- When a pulse train passes an RF cavity operating on-crest on-resonance with CW RF input power and a small droop,
  - $\Delta V_c = I_b T_{train} \frac{\omega}{2} \frac{R}{Q} = Q_{train} \frac{\omega}{2} \frac{R}{Q}$
  - Absolute total droop is independent of cavity voltage and coupling.
  - Relative droop and energy spread is inversely proportional to cavity voltage
  - Reduce number of passes when energy is low helps to reduce relative droop
- CEBAF arc magnets can be adjusted to the beam energy at the center of the passing bunch train, so the relative energy droop equals the relative per pass voltage droop.

Voltage droop in a C100 cavity, Vc=10.4MV, ΔV/V≈0.94%



25.4µs, 6 turns-0.88µs in CEBAF NL (4.375µs per pass), 1.14mA

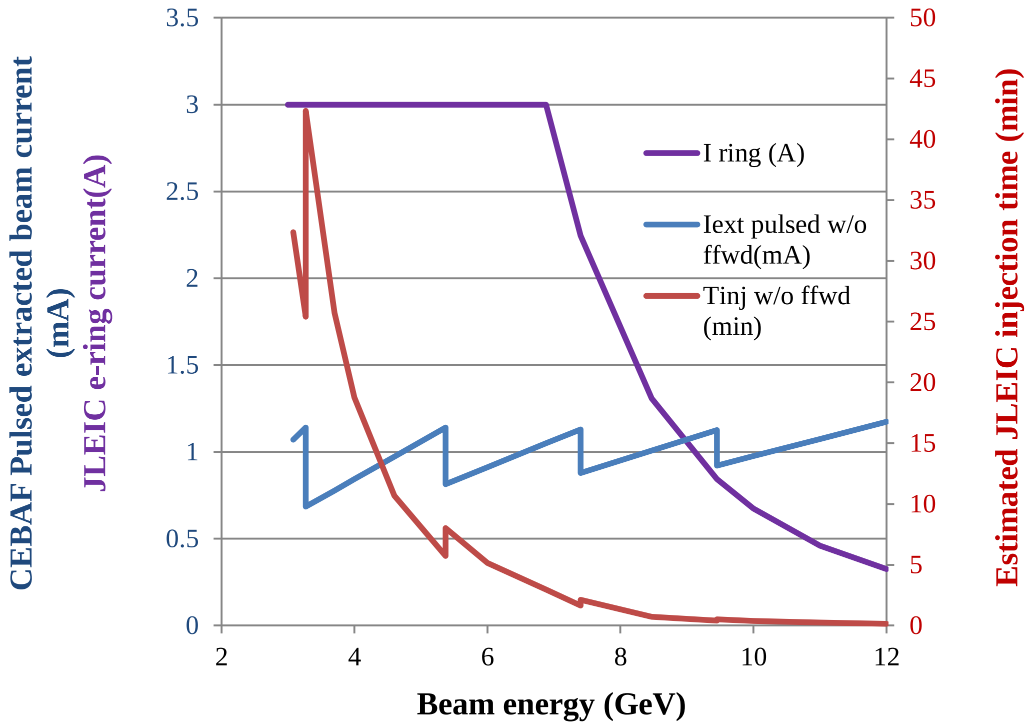
CEBAF energy droop and injection time with CW RF

Estimated voltage droop in CEBAF with CW RF (no effective feedback/feedforward)

Cavity type	Cavity # per linac	R/Q (Ω)	ΔVc with 1.14mA 3.49μs 4nC beam
C100	40	868.9	16.2 kV
C50/C25	160	482.5	9.03 kV
Per linac sum	200		2.10 MV (0.20% of 1.05GeV)

- Injection time <20 min except for energy range of 3-4 GeV
  - Could improve with RF feedforward, or higher bunch train rep-rate with damping wiggler/shorter bunch train

Estimated JLEIC pulsed injection current and injection time (limited by injector current only) with CW RF and varying number of passes



Assumes maximum kicker repetition rate 60 Hz
Assumes head-tail energy droop of 0.2% (1/2 of the ±0.2% arc acceptance), no damping wiggler

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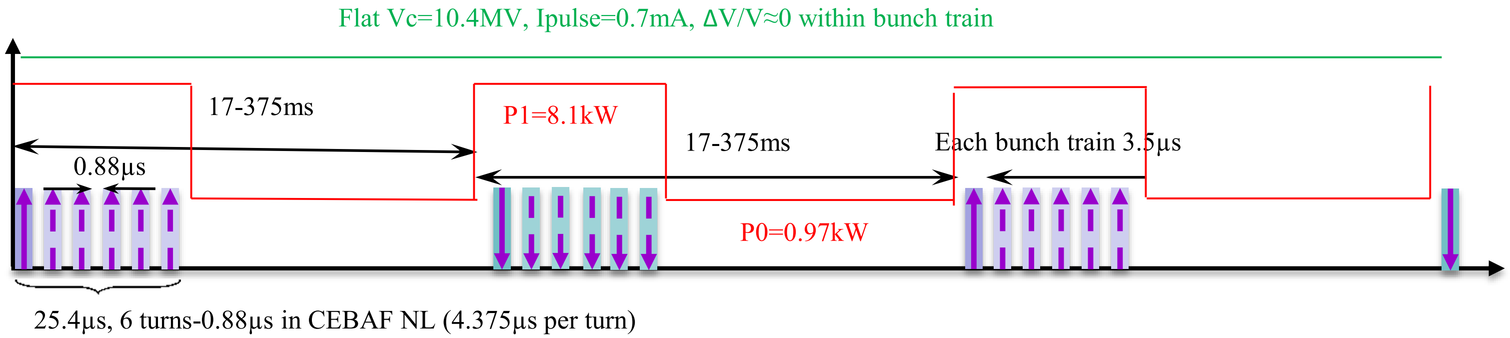
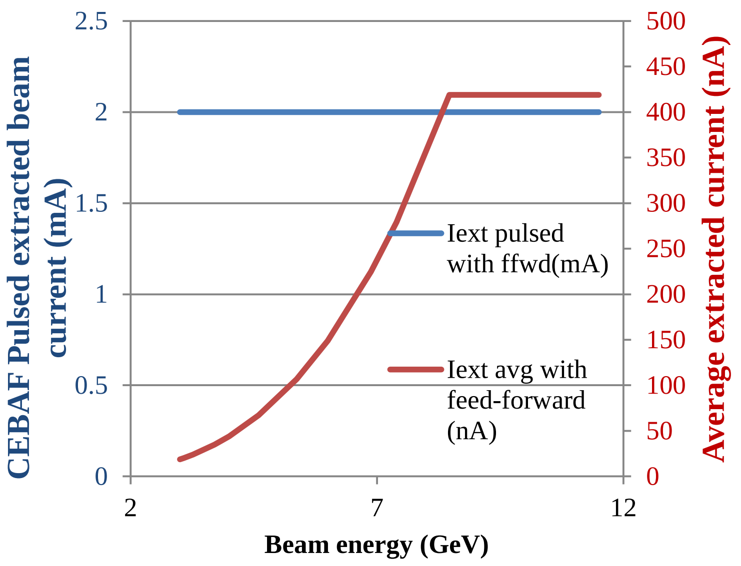
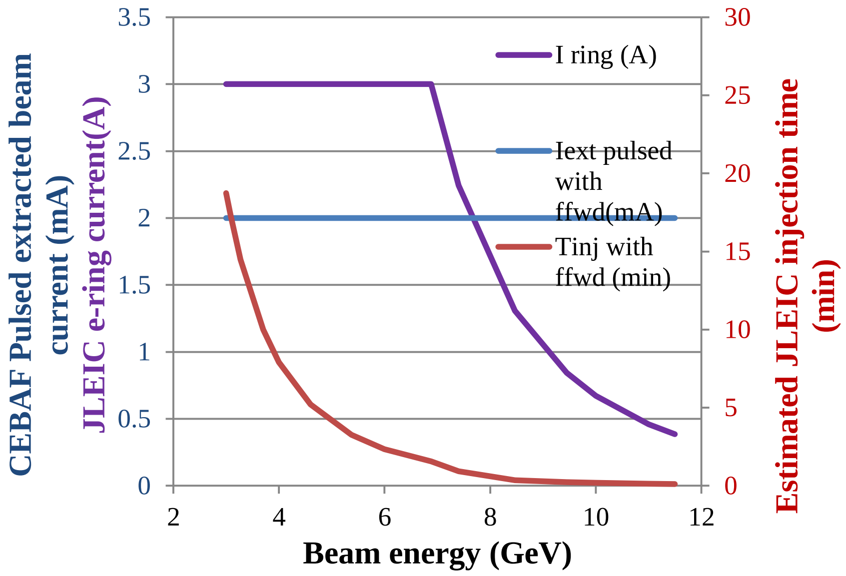
RF feed-forward to correct voltage drooping

Pulsed RF input for a typical NL C100 cavity with feed-forward
(assuming on-resonance, need more power for off resonance)
Pulse-to-pulse feed-back will help to find the correct power level with microphonics etc.



If ~0.2% droop is allowed, the estimated extraction beam current will be ~2mA at various energy, depending on cavity coupling and microphonics.





Estimated JLEIC pulsed injection current and injection time (limited by injector current only) with RF feed-forward and varying number of passes

Assumes maximum kicker repetition rate 60 Hz
Assumes head-tail energy droop of 0.2% (1/2 of the ±0.2% arc acceptance)

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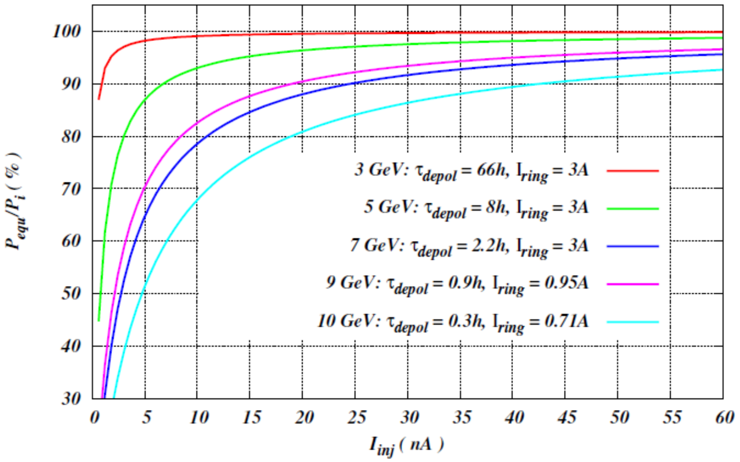
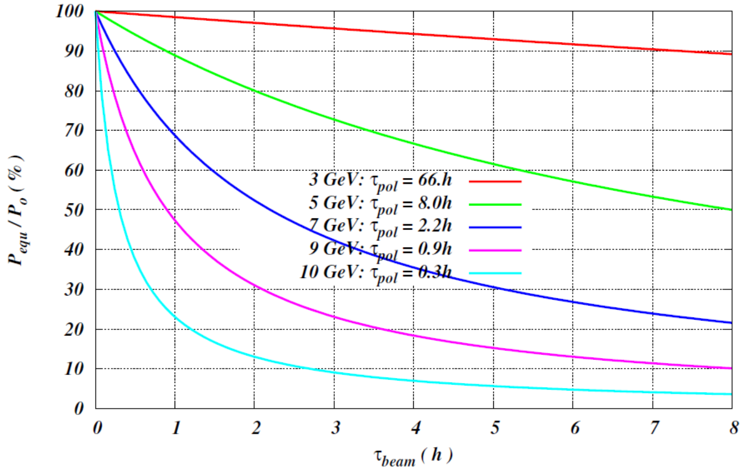
Electron polarization and top-off requirement

- Estimated polarization lifetime

Energy (GeV)	3	5	7	9	12
Lifetime (hours)	116	9	1.7	0.5	0.1

- Constant polarization is maintained by continuous injection of highly polarized electron beam from CEBAF
- Equilibrium polarization $$P_{equ} = P_0 \left(1 + \frac{T_{rev} I_{ring}}{\tau_{DK} I_{inj}}\right)^{-1}$$
- A relatively low average injected beam current of tens-of-nA level can maintain a high equilibrium polarization in the whole energy range
- Beam lifetime must be balanced with the beam injection rate and $\tau_{beam} \ll \tau_{pol}$





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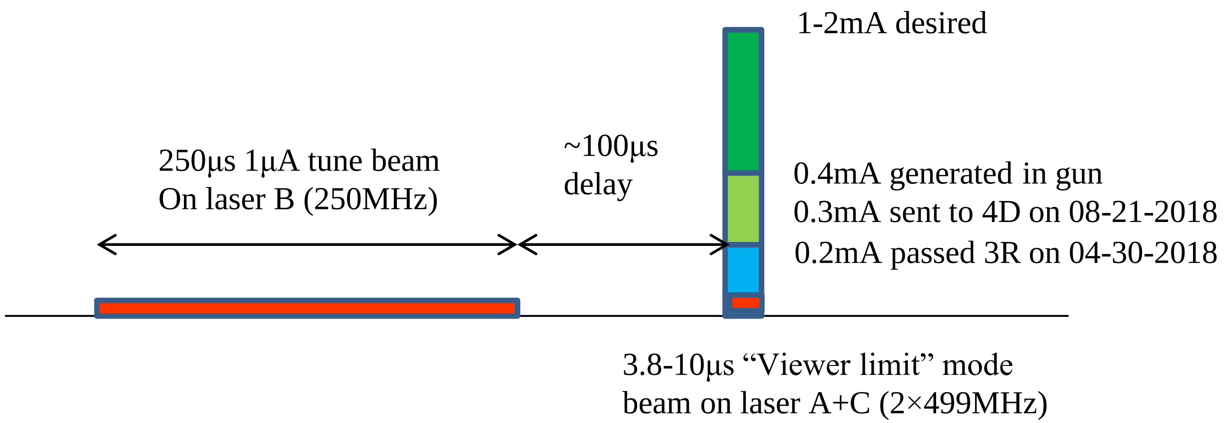
Beam tests summary

- Before March 16, 2018
  - Two tests at CEBAF injector gun to generate the 4 μs bunch trains of up to 0.4mA
- April 30, 2018
  - Sent up to 0.2mA 10μs bunch trains through CEBAF for 1.5 passes. Measured the beam current turn by turn. The gradient droop measurement was not successful
- August 20-21, 2018
  - Beam test in the CEBAF injector with up to 0.3mA 10μs beam. Measured the cavity gradient droop in CEBAF injector. Tried to measure energy spread in 4D spectrometer but failed to fit the results.

CEBAF pulsed operation test: beam set-up

- A 250μs 1-2μA "probe" bunch train for the BPMs in CEBAF injector and arcs (can't see 4 μs beam), generated with laser B at 250MHz using CEBAF "tune beam" mode; tested to be sufficient for BPMs
- 4μs JLEIC beam generated with laser A+C in "viewer limit" mode, 100μs after the tune beam
  - Might increase to 10μs to accommodate linac BPMs to differentiate beams of different passes
  - 2×499MHz to increase beam current with moderate charge per bunch
- 60 Hz bunch train rep-rate

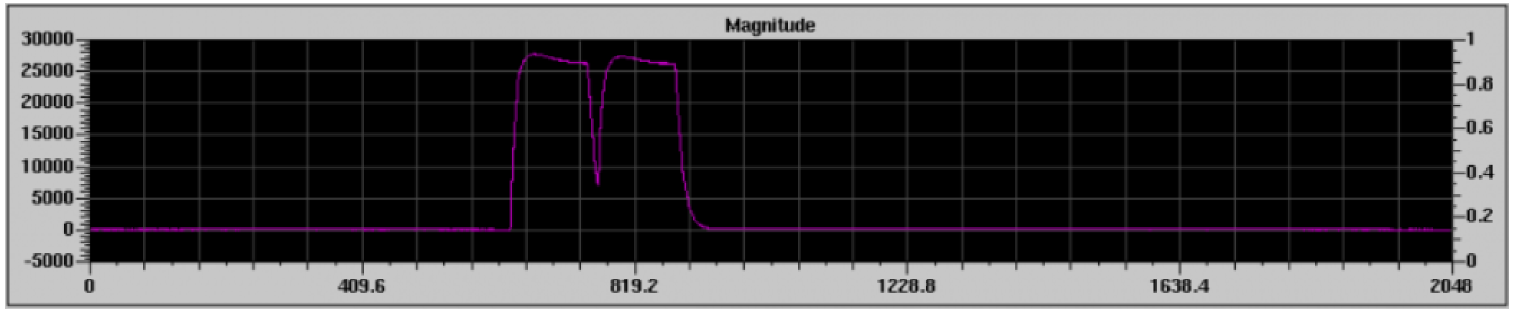


Bunch train structure for current CEBAF tests

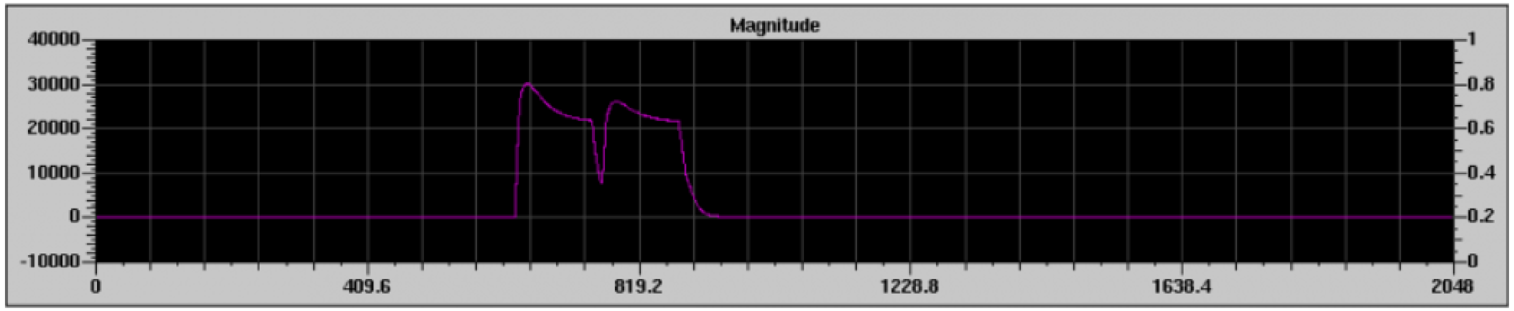
1.5 pass CEBAF test (04/30/2018)

- Beam setup
  - Hall B tune beam 1μA + Hall A/C 499MHz VL beam, 13-200μA, 60Hz
  - Terminated at 3R with 3.8-10μs VL beam

- After reducing M56 gain to 0 (avoiding saturation), NL beam current (terminated at 3R) showed no pass-to-pass beam loss at 100 μA set up (measured at Faraday cup)
- When beam current increased to 150μA, M56 saturated and could not provide a proof of no pass-to-pass beam loss.
- Will install attenuator on M56 pickup for next beam study
- Gradient droop and energy spread measurement not successful in this beam study



M56 measured beam current with laser C set to 100μA 4μs



M56 measured beam current with laser A/C set to 150μA (saturated)

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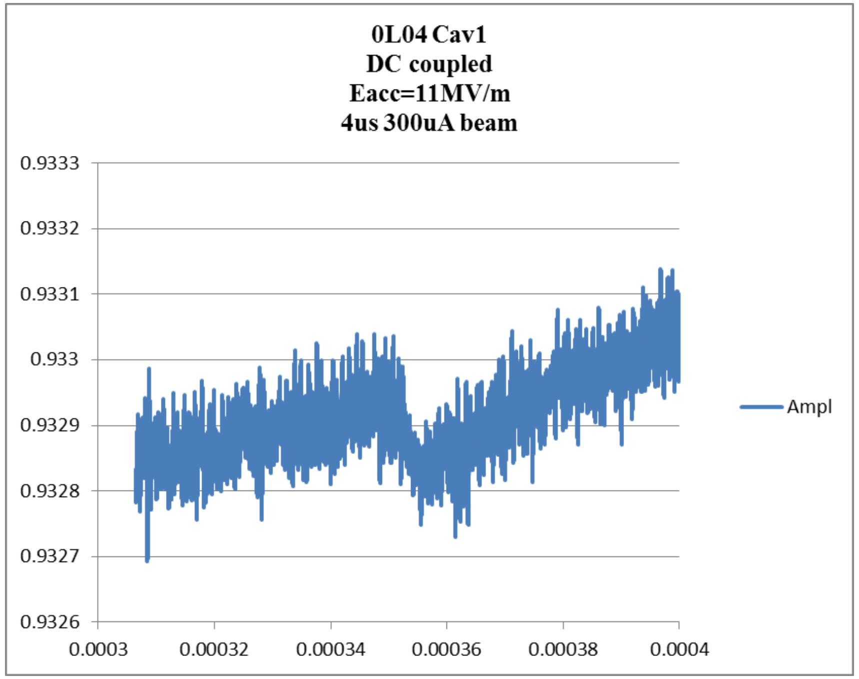
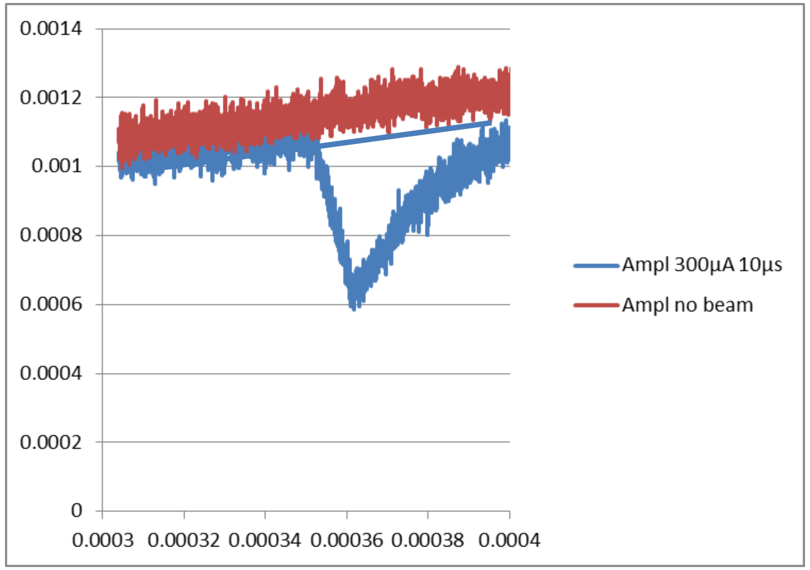
Injector gradient droop measurement (08/20/2018-08/21/2018)



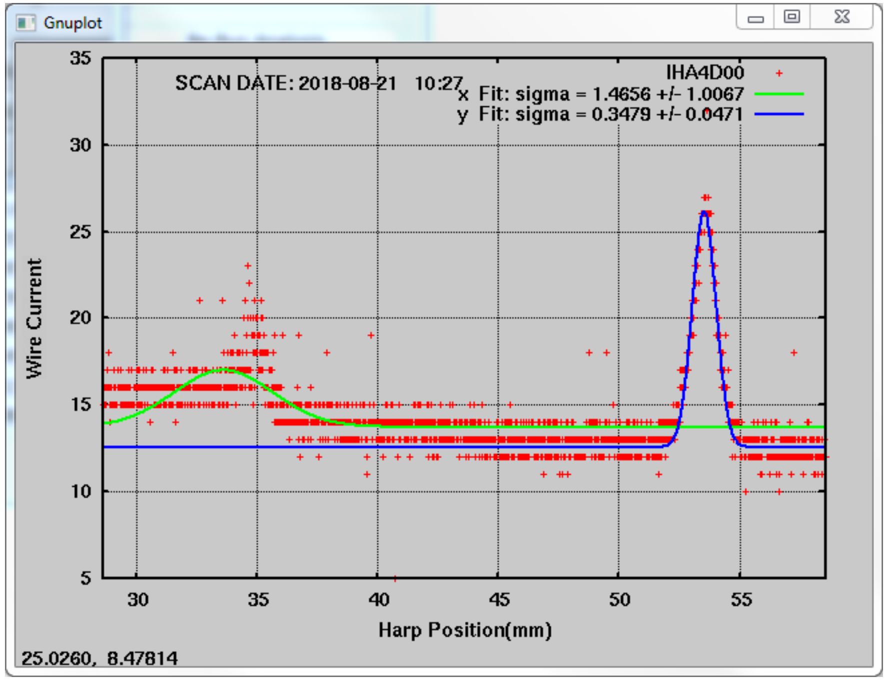
0L04 cav1 (R100)
AC 1MΩ coupled
Eacc=11MV/m, Vc=7.7MV

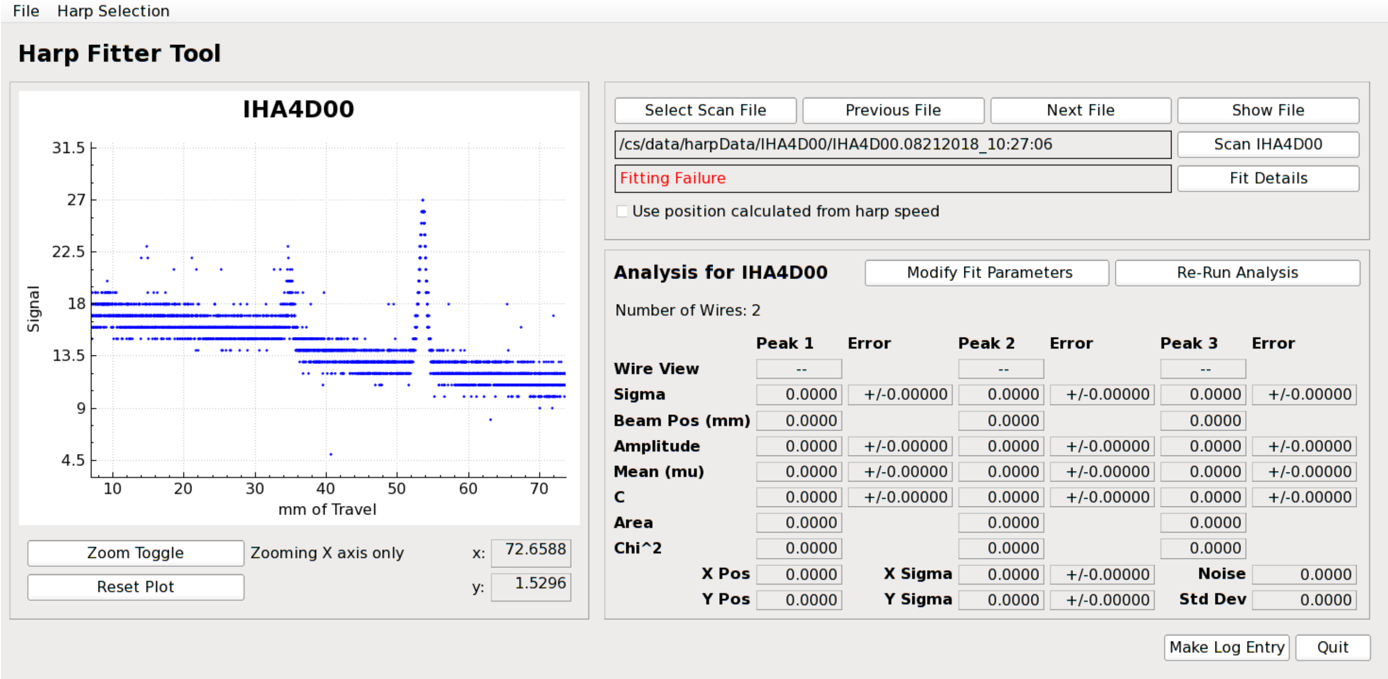


- Measured gradient droop in the CEBAF injector R100 cryomodule with ANALOG DEVICES AD8361 RF power detector
  - Detector calibration confirmed good linear response to CW RF voltage
- Δamp≈0.45mV (0.05%) for 10µs 300µA bunch train AC coupled measurement, ≈0.15mV (0.016%) for 4µs 300µA DC coupled measurement
- Analytical model (on crest, no detuning, without any feedback/feed forward) shows 0.064% voltage droop for 4 µs 300µA, 0.16% for 10 µs, a factor of 3-4 difference for both DC and AC coupling.
- No solid explanation for the discrepancy yet, although the experimental results are in favor of faster injection.
  - Proposing next beam study with R&S®FSWP8 Phase Noise Analyzer and VCO Tester

Energy spread measurement in CEBAF injector (08/20/2018-08/21/2018)

- Tried to do HARP scan in the 4D spectrometer to measure the energy spread, but the horizontal signal is too noisy for fitting
- Investigating how to improve the fit





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Summary and future works

- The scheme for JLEIC electron injection using CEBAF is developed with reasonable injection time and top off rate
- Gradient droop is the main concern of CEBAF pulsed operation, but can be limited to an acceptable level according to analytical model
- Preliminary CEBAF multi-pass beam test saw 100μA pulsed beam passing through without noticeable beam loss. Future experiment will improve instrumentation for higher beam current.
- Preliminary gradient droop measurement does not agree with the analytical estimate, but in favor of fast injection. Will have improved instrumentation in the next test.
- Expect to complete the above two baseline CW RF beam test tasks before the end of FY19 CEBAF physics run.
- RF feed-forward test in R-100 is deemed as risky for CEBAF operation. May need to find another facility such as LERF or UITF to test, with uncertain schedule.

Thank You