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PULSED OPERATION OF CEBAF FOR JLEIC INJECTION*

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Abstract

The JLab Electron-Ion Collider (JLEIC) proposed by Jefferson Lab is planning to use the 12 GeV CEBAF 1497 MHz SRF CW recirculating linac as a full-energy injector for the electron collider ring, which might be the first SRF electron linac to be used as a storage ring injector. The electron collider ring is proposed to reuse the 476MHz PEP-II RF system to achieve high installed voltage and high beam power. The JLEIC electron injection requires 3-10 (or 12) GeV beam in bunch trains <4μs long with low duty factor and high peak current, resulting strong transient beam loading for the CEBAF. In this paper, we present our recent studies on JLEIC electron injection scheme and CEBAF pulsed operation.

JLEIC ELECTRON INJECTION SCHEME

The propose JLEIC, as shown in Fig. 1, is a high luminosity electron-ion collider with 3 to 10 GeV electrons and 20 to 100 GeV protons (or up to 40 GeV per nucleon for heavy ions), with the possibility to upgrade to higher energy [1, 2]. The nominal beam current in the electron ring is 3 A, but the beam current is limited by 10 MW total synchrotron radiation power at energies higher than 7 GeV. The newly upgraded 12 GeV CEBAF linac is chosen as the full energy injector for the electron ring. The preliminary JLEIC injection scheme with CEBAF was initially developed in 2014 as published in [3], and has been evolved since then.

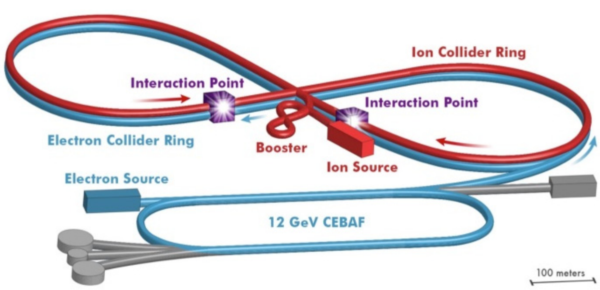

Figure 1: Conceptual layout of JLEIC.

The JLEIC electron injection uses 68.05 MHz bunch repetition rate (and possibly its sub-harmonics in circumstances) , which is 1/22 of the CEBAF RF frequency of 1497 MHz, and 1/7 of the slightly adjusted PEP-II RF system frequency 476.3 MHz. The electron ring has a harmonic number of 3584, with a circumference of around 2256 m and the revolution time of 7.52 μs.

One major capability of JLEIC is colliding polarized electrons with light ions. In this type of runs, the electron rings will provide two bunch trains with opposite spin polarization in the same ring, with two gaps of ~270 ns each in between. The gaps will match the ion ring abort gaps, and serve for the purposes of injection/abort kickers' rise/fall time as well as ion clearing.

The JLEIC electron ring uses transverse phase space injection with damping time τ_d ranges from 6 to 389 ms, depending on the beam energy and the use of damping wigglers. To maximize the total charge injected in one kicker cycle, we can inject a long polarized bunch train into half of the collider ring, with the bunch train length of ~3.5 μs, slightly shorter than the circumference of CEBAF of ~4.38 μs. The kicker cycle has a rise/fall time ~200 ns, and a flat top of 3.5 μs, comparable to the PEP-II abort kickers. At least $2\tau_d$ is needed to damp the injected portion of a bunch before the next kicker bump involving the same bucket; however we can arrange at least two kicker cycles bumping the two halves of the ring during $2\tau_d$. To arrange more than two injections during $2\tau_d$, more gaps might be needed.

CEBAF PULSED OPERATION

The beam in CEBAF can be accelerated during the 6 passes in the north linac (NL) and 5 passes in the south linac (SL), before it's extracted to Hall D or JLEIC. If CEBAF RF is operating in the usual CW mode, the major factor limiting the maximum charge in each bunch train is the energy droop along the bunch train caused by the transient beam loading in the SRF cavities. The maximum energy droop is limited by the ±0.2% momentum acceptance of CEBAF arc. If the bunch train is short enough compared to the cavity fill time and the RF feedback delay, and the cavity is operating on-crest on-resonance, the cavity gradient droop under CW RF is

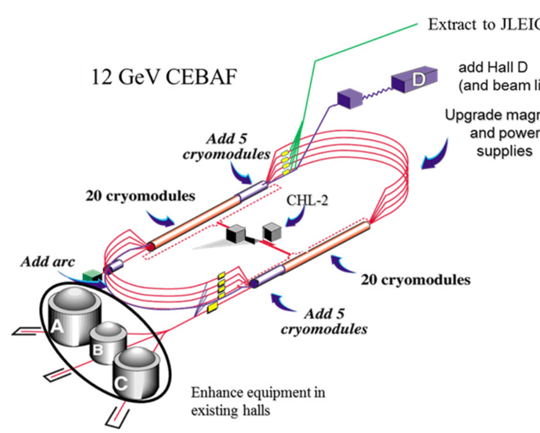

Figure 2: CEBAF after 12 GeV upgrade.

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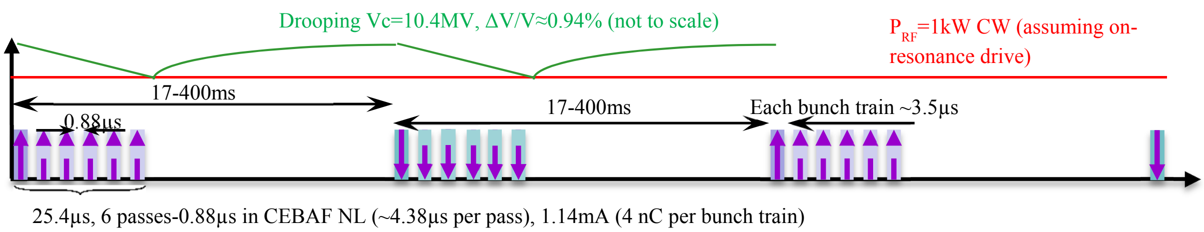
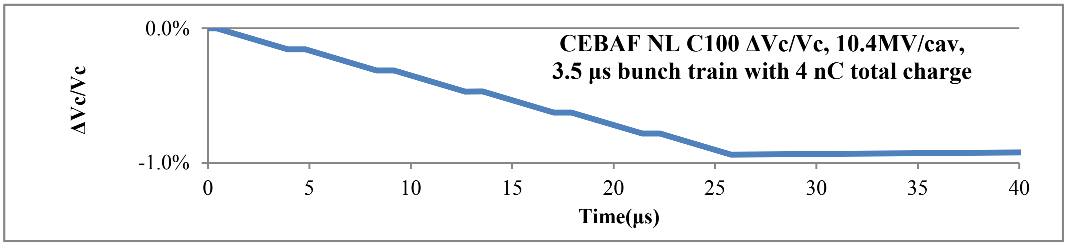
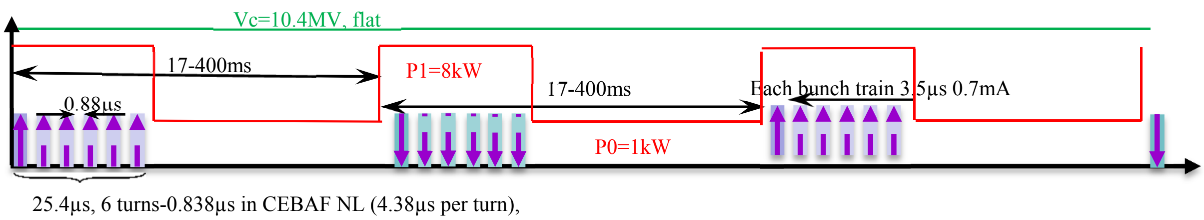


a) Gradient droop in a NL C100 cavity with typical 10.4 MV voltage and 6 passes of bunch train, CW RF



b) Detail of the transient beam loading when a bunch train passes through a C100 cavity 6 passes



c) Correcting transient beam loading in C100 cavities with RF feed-forward

Figure 3: JLEIC injection bunch train time structure in CEBAF and transient beam loading.

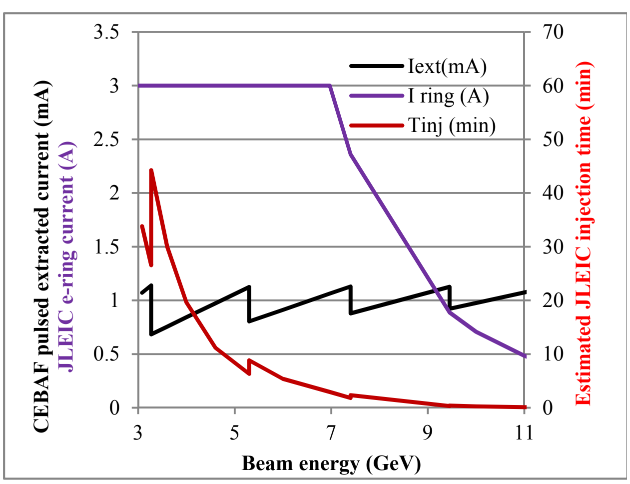


Figure 4. Beam current in the JLEIC e-ring and estimated injection time, no effective RF feed-forward/feedback.

$$\Delta V_c = Q_{train} \frac{\omega}{2} \frac{R}{Q} \quad (1)$$

where Q_{train} is the total charge of a bunch train passing through the cavity, and impedance is defined as $R=V^2/P$. The relative voltage droop is inversely proportional to the cavity voltage, so we can maximize the cavity voltage by minimizing the number of beam passes at lower extraction energies. In this case, we need to add extraction lines in the 2nd to the 6th north linac passes, also shown in Fig. 2.

We can also apply RF feed-forward to compensate the transient beam loading; however the effectiveness is limited by the available RF power and the cavity coupling. A C100 cavity with typical Qext of 3.2×10^7 and 8 kW available klystron power (not including overhead for microphonics etc) will be able to support 0.7mA pulsed extracted current with zero energy droop during the bunch train, as shown in Fig. 3c. The OC style cavities has higher coupling and will be able to support more beam current. If we allow the same 0.2% one pass voltage droop, RF feed-forward may increase the maximum extracted charge per pulse from 4 nC to ~8 nC.

Fig. 4 shows the estimated CEBAF extraction current and the JLEIC injection time at different injection energy, assuming 3.5 µs bunch train, CW RF without feed-forward or fast feedback. The waiting time between two bunch trains will be the larger of transverse radiation damping time and 16.7ms (assuming 60 Hz maximum kicker repetition rate). This estimate did not consider the time needed for the e-ring RF system to adapt to the increasing current, such as adjusting the cavity detuning for the increasing beam loading, usually in a few minutes. According to Fig. 4, the estimated electron injection time is below 30 minutes for most of the energy range, except

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for 3.3-3.6 GeV, when the energy gain per linac is as low as 0.63 GeV.

CEBAF arc magnets can be adjusted adaptively to the beam energy at the center of the bunch train in each pass. In this case the maximum allowed bunch train head to tail gradient droop for one beam pass is 0.4%. To allow some room for momentum spread caused by other factors, we limit one pass gradient droop to 0.2%.

After 12 GeV upgrade, each of CEBAF's north and south linac has 40 C100 style cavities with R/Q=868.9 Ω and 160 original Cornell (OC) style cavities with R/Q=482.5 Ω. Each linac provides a maximum 1.05-1.09 GeV energy gain per pass. If we have 4.0 nC total bunch charge in the 3.5-4 µs bunch train, the total voltage droop in one linac over one pass will be 2.1 MV, or 0.2% of 1.05 GeV, assuming on-crest on-resonance CW RF without feed-forward or feedback. Fig. 3a shows the gradient droop–recover cycle in a typical C100 cavity with 4 nC total charge in a 6 passes bunch train and under CW RF, while Fig. 3b shows the detail of the droop.

To maximize the CEBAF extracted current to the beam loading limit, the CEBAF gun and capture cavity need to be upgraded to be able to provide about 30 pC per bunch at 68.05 MHz, which is about two order of magnitude higher than CEBAF's current operation, but not beyond state of the art. The 7 sets of 476.3 MHz buckets in the collider ring can be filled in rotation.

CEBAF PULSED BEAM STUDY

A series of CEBAF beam study have been proposed to demonstrate CEBAF's capability to provide the pulsed beam for JLEIC injection. The studies include the measurement of the cavity voltage droop and energy droop due to transient beam loading, sending the long bunch train through CEBAF for multi-passes, and demonstrate the RF feed-forward principle. The demonstration is focused on the transient beam loading and won't involve increasing the charge per bunch for 68.05 MHz operation.

In the beam tests, we run CEBAF hall A/C lasers at 499 MHz in the "viewer limit" mode with 4-10 µs bunch trains and up to 0.4 pC per bunch. These two beams occupy 4 of the 6 CEBAF 249.5 MHz bucket groups. We also use another low current (~1 µA) 249.5 MHz bucket to hold hall B beam in "tune mode", which has a 250 µs bunch train followed by a 4 µs train, and serves as a probe beam for certain BPMs that could not see the 4 µs bunch train.

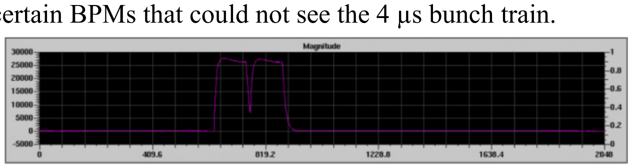

Figure 5. CEBAF NL M56 cavity signal for 100 µA 4µs bunch train accelerated through CEBAF for 1.5 passes.

In one beam study, a 4 µs bunch train with up to 200 µA was sent through CEBAF for 1.5 passes, and the turn by turn beam current was monitored by the NL M56 cavity. There was no beam loss with 100 µA beam current, as Fig. 5 shows. However the M56 cavity probe saturated at 150 µA. A future beam test should have the proper M56 cavity attenuation and 5.5 CEBAF passes, with up to 400 µA pulsed beam current.

We were able to measure the cavity voltage droop in the CEBAF injector cavities. Fig. 6 shows one measurement in the CEBAF cryomodule 0L04 cavity 1, which is a C100 style cavity. The measurement shows a common 60 Hz mode background, but that mode is stable and can be deducted with a measurement without beam. The measured voltage droop for a cavity operating at 7.7 MV/cavity (11 MV/m) was only ~0.05% with 10µs 300µA bunch train, which is about factor of three less than the calculation. Currently we don't yet have a good explanation to this discrepancy; however the experimental results are in favor of faster injection.

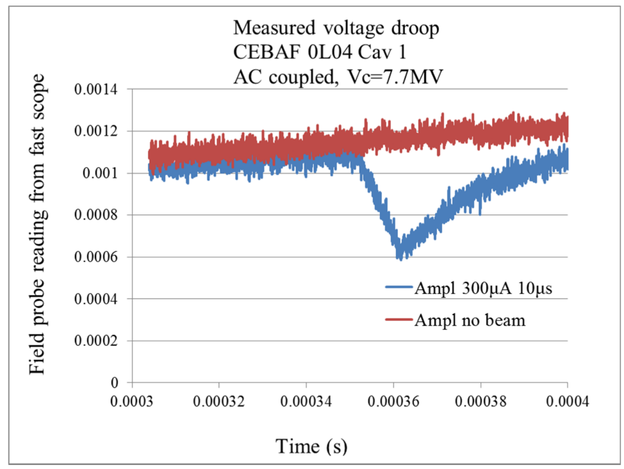

Figure 6. Measured voltage droop in CEBAF 0L04 Cav 1.

SUMMARY

We proposed the JLEIC electron injection scheme using pulsed long bunch trains provided by CEBAF. The main issue of transient beam loading has been studied in CEBAF. Analytical calculation shows that the injection time can be less than 30 minutes for most of the energy range, except for a very small range of beam energy 3.3-3.6 GeV, when we start to use 2.5 passes extraction with the lowest linac energy gain per pass. The injection time can be reduced further with RF feed-forward and/or damping wigglers. The preliminary beam experiments show lower voltage droop than estimated and further study is needed. Energy spread measurements also need to be improved.

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