CONCEPTUAL MEIC ELECTRON RING INJECTION SCHEME USING CEBAF AS A FULL ENERGY INJECTOR*

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Abstract

The Medium-energy Electron-Ion Collider (MEIC) proposed by Jefferson Lab is planning to use the newly upgraded 12 GeV CEBAF 1497 MHz SRF CW recirculating linac as a full-energy injector for the electron collider ring. The electron collider ring is proposed to reuse the 476MHz PEP-II RF system to achieve high installed voltage and high beam power. The MEIC electron injection requires 3-10 (or 12) GeV beam in 3-4μs long bunch trains with low duty factor and high peak current, resulting in strong transient beam loading for the CEBAF. In this paper, we propose an injection scheme that can match the two systems' frequencies with acceptable injection time, and also address the transient beam loading issue in CEBAF. The scheme is compatible with future upgrade to 952.6 MHz SRF system in the electron ring.

INTRODUCTION

The MEIC proposed by JLab 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 current is also limited by synchrotron radiation power at high energy, and by RF cavity impedance induced coupled bunch instability at low energy [3]. The newly upgraded 12 GeV CEBAF linac is chosen as the full energy injector for the electron ring. It's also natural to consider reusing the high power RF system of the recently retired PEP-II in MEIC's electron ring, since PEP-II was designed for similar beam current and system RF power [4]. Although PEP-II and CEBAF have different RF frequencies, we note that 7/22 (very close to 1/π by incident) of the CEBAF linac's 1497 MHz frequency is 476.3 MHz, which is within the operational range of PEP-II's 476 MHz RF system.

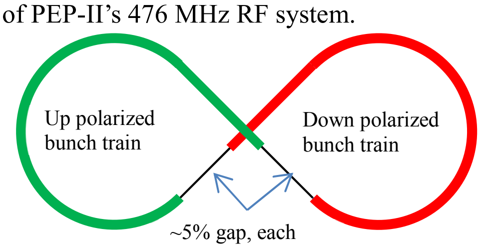

Figure 1: Bunch trains in the MEIC figure-8 ring

In the baseline design, each of the MEIC collider rings will provide two bunch trains with opposite spin polarization in the same ring, with two gaps of ~5% circumference in between, as shown in Fig. 1. The gaps result from the injection kickers' rise/fall time, and will also serve for the purposes of ion clearing etc. Under the full current operation, every bucket in the bunch train will be filled. In case the current is far below the beam-beam limit due to other limiting factors such as synchrotron radiation power, the bunch rep-rate may be reduced to a fraction of the RF frequency for higher luminosity.

Currently the harmonic number of the electron ring is set at 3416, with a circumference of around 2150 m and the revolution time of 7.17 μs.

THE ELECTRON INJECTION SCHEME

The electron ring will use transverse phase space injection. For each kicker cycle, a polarized bunch train with the length of ~45% collider ring circumference (3.23 μs) will be injected into the 1st half ring, followed by another oppositely polarized bunch train filling the 2nd half of the ring. The electron ring's transverse damping time τ_d ranges from 6 to 376 ms, depending on the beam energy and the use of damping wigglers. About $2\tau_d$ is needed to damp the injected beam before the next injection into the same half ring.

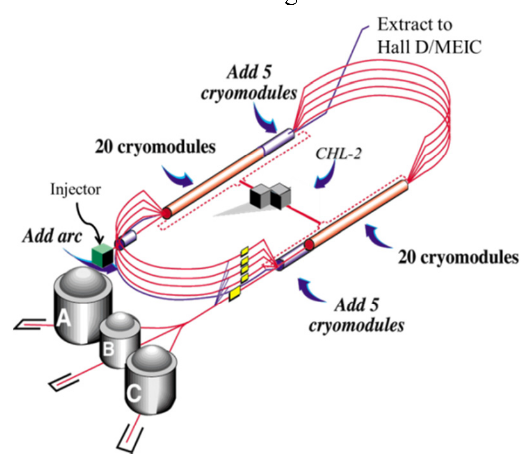

Figure 2: CEBAF after 12 GeV upgrade

Maximizing the Pulsed Bunch Train Current in CEBAF

To achieve a reasonable injection time, we need to maximize the pulsed beam current generated from CEBAF. As shown in Fig. 2, the beam in CEBAF can be accelerated during the 6 passes in the north linac and 5 passes in the south linac, before it's extracted to Hall D or MEIC. The CEBAF is capable of delivering CW extracted beam with ~1 MW beam power, nominally limited by the beam dump's CW power rating, but also limited by the system's total RF power. The beam current circulating in the linacs is usually 5-6 times of the

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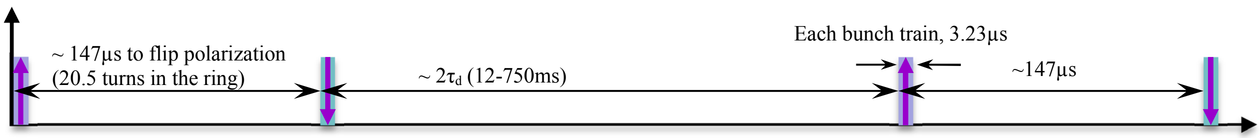
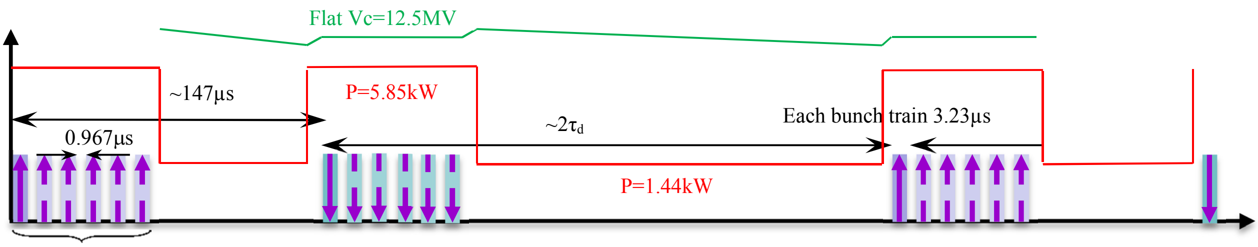


a) Bunch train from the gun with different polarization



b) RF pulses in a typical C100 cavity at 12.5 MV 0.6 mA (pulsed) synced with bunch trains in the CEBAF north linac (RF power does not include overhead for microphonics etc.)

Figure 3: Bunch train and RF pulse time structure in CEBAF (not to scale)

extracted beam current. At energies below 6 GeV, the multi-pass beam-breakup (BBU) instability may limit the CW circulating current below 1 mA.

The required bunch train length for MEIC is ~3.23 μs, which is slightly shorter than the CEBAF's revolution time of 4.2 μs. The injected/extracted beam has the same pulsed peak current as the peak current seen in the linac cavities, as shown in Fig. 3. The beam of the lowest energy pass enters the linac at least 100 μs after the last bunch train was extracted, so the multi-pass BBU shouldn't be a problem. All these factors allow us to increase the pulsed beam power to 5.5 MW, assuming each of the south and north linacs can provide approximately 0.5 MW pulsed beam power gain in each pass. Considering the 0.97 μs gap between the beam's different passes, the maximum extracted pulsed beam power can be increased further to ~7.2 MW (1MW·5.5·4.2/3.23). The maximum pulsed beam current extracted from CEBAF can be estimated as

$$I_{CEBAF} = \frac{5.5(MW)\cdot 4.2(\mu s)}{E(GeV)T_p(\mu s)}(mA). \quad (1)$$

And the total injection time limited by the capability of CEBAF is estimated as

$$T_{inj} = \frac{I_{ring}(mA)E(GeV)T_{rev}(\mu s)}{5.5(MW)\cdot 4.2(\mu s)}\tau_d. \quad (2)$$

T_p is the length of the bunch train to be injected, T_{rev} is the revolution time of the electron ring (7.17μs in the current baseline), and 4.2μs is the CEBAF revolution time. The estimated injection time without the use of damping wigglers is shown in Fig. 4. The actual injection time may also be limited by other factors, but is not likely to be significantly over 20 minutes.

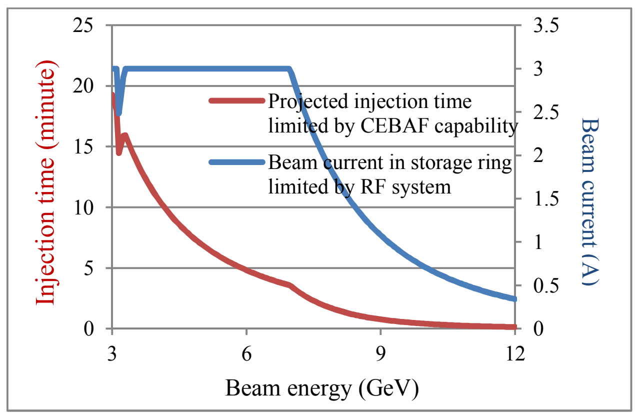


Figure 4: Beam current in the electron storage ring and estimated injection time

One potential problem for CEBAF to operate at this level of pulsed beam current is the cavity voltage drooping. A pulsed input RF power synchronized with the beam current is required to compensate the transient beam loading and keep the cavity voltage constant. The feedback in CEBAF's current LLRF system won't act fast enough to correct the gradient droop. With the current feedback, the energy deviation within the bunch train will range from ~1% for 12 GeV, 0.6 mA to ~13% for 3 GeV 2.4 mA operations, exceeding the 0.2% momentum acceptance of CEBAF's arcs. However, CEBAF's new C100 cryomodules are equipped with digital LLRF system that can provide feedforward and may have the capability to generate RF pulses as shown in Fig. 3b. The other cryomodules can be upgraded to similar LLRF system as the existing system ages.

Fig. 3b shows the pulsed beam current with a desired RF input power and the resulting cavity voltage for a typical C100 cavity located in CEBAF's north linac. 12.5 MV is the typical voltage for C100 cavities under 12 GeV operations. Assuming that our feedforward is not able to correct the 0.97 μs bunch train gap seen in the cavities,

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such gaps will generate beam energy is ~0.02% for 12 GeV 0.6 mA, and ~0.3% for 3 GeV 2.4 mA. Additional measures like gun phase change with off-crest operation may help to reduce the droop under 0.2%. The RF pulse starts slightly before the beam pulse and ends after the beam pulse, so the delay won't cause extra voltage droop during the beam pulse. Pulse to pulse voltage variation can be minimized with feedback.

Each C100 cavity is powered by a 13 kW klystron, giving plenty of overhead above the 5.85 kW RF power required to provide 0.6 mA 12 GeV (7.2 MW) beam, as shown in Fig. 3b. For lower energy and higher beam current operation, stub-tuners are available to adjust the cavity coupling and keep the reflected RF power low. The original CEBAF C50 or C25 cavities have similar ratio of reserved klystron power.

Synchronizing the CEBAF and the Electron Storage Ring

The bunch rep-rate from the gun can be set at 68.05 MHz, which is 1/7 of the ring frequency 476.3 MHz and 1/22 of the CEBAF frequency, so each bunch from the gun can be synchronized to a bucket in the storage ring. Fig. 5a shows such an injection mid-cycle that fills the 1st of every 7 buckets in the required bunch train.

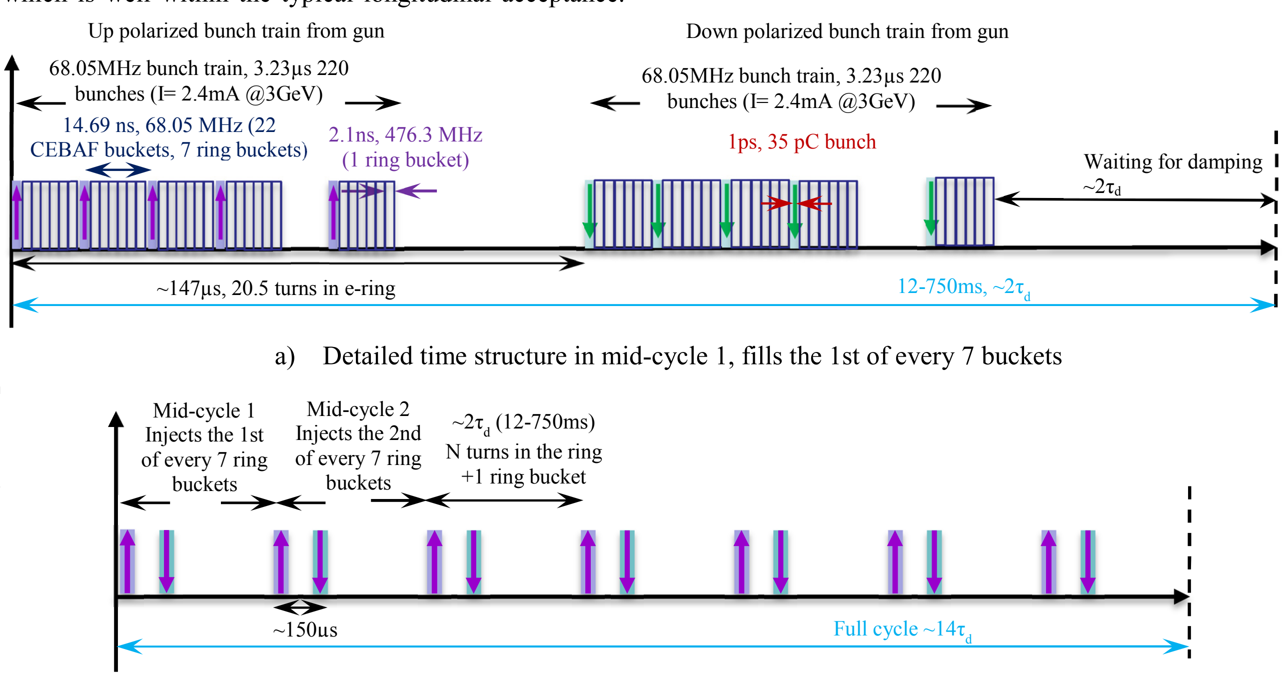
A full injection cycle needs 7 mid-cycles to fill every bucket in the ring's bunch trains, as shown in Fig. 5b. The ring phase needs to shift 1 bucket after every mid-cycle. This shift can be achieved by a slight change in ring RF frequency, in the range of 1-100 Hz depending on damping time. This may give a phase change of up to ±2° during the 150 µs period when the injection is active, which is well within the typical longitudinal acceptance. At the end of the full cycle, we also need to jump the gun trigger by one 68.05 MHz bucket ahead; otherwise the next full cycle will start with the 8th bucket in the ring.

To maximize the CEBAF current to the power limit, the charge per bunch needs to be raised to up to 35 pC (for 3 GeV operation), which is about 100 times of current operation, but not beyond state of the art.

For reduced rep-rate collider operation, we only need to fill a fraction of the buckets in the ring. The gun rep-rate will be reduced further (unless the collider rep-rate is reduced to 1/7). The harmonic number of the electron ring needs to have as many integer divisors as possible. The reduced rep-rate operation is only needed at higher energy when the ring's beam current is low, and we don't have to maximize the CEBAF beam current to the RF power limit to get a reasonable injection time, so it won't increase the burden of the gun further.

SUMMARY

We show a conceptual injection scheme for the MEIC electron collider ring that reuses PEP-II RF system in the ring and uses CEBAF as the injector. The scheme can match the different frequencies in RF systems of the PEP-II and CEBAF. CEBAF is capable to provide the pulsed beam with the quality and intensity required for MEIC injection. The pulsed operation of the CEBAF requires RF feedforward capability in the LLRF system, which is already available in CEBAF's C100 12 GeV upgrade cryomodules. We can upgrade the original CEBAF RF stations gradually as their existing LLRF system ages. The gun also needs to be upgraded with higher charge per bunch capability.



a) Detailed time structure in mid-cycle 1, fills the 1st of every 7 buckets

b) Time structure of a full injection cycle, fills every bucket of the two bunch trains in the ring one time

Figure 5: Injection cycles (not to scale)

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