LINAC OPTIONS FOR THE ION INJECTOR OF MEIC*

J. Guo#, Y. Zhang
Thomas Jefferson national Accelerator Facility, Newport News, VA 23606 USA

Abstract

In the current baseline design of the Medium-energy Electron-Ion Collider (MEIC) proposed by Jefferson Lab, a green field ion injector complex is composed of several ion sources, one linac with charge stripper, and one booster ring. The original linac design contains a short warm front end and a long SRF section with QWR/HWR cavities, capable of accelerating H^- to 285 MeV or Pb^{67+} to 100 MeV/u. Such a linac is a major cost driver of the project, despite that the required duty factor of this linac is very low. In this paper, we will compare alternative options for this ion linac, including the possibilities to lower the linac energy and choose a warm linac.

ION BEAM FORMATION AND THE CHOICE OF LINAC ENERGY

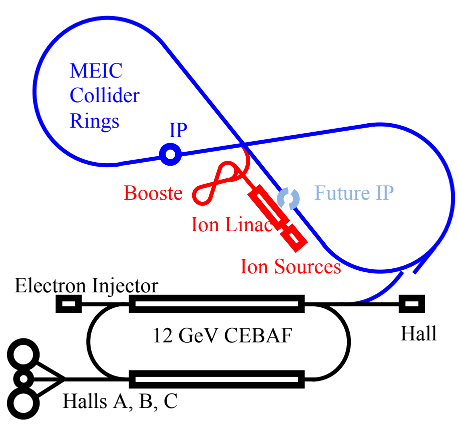

Figure 1: Layout of MEIC.

The MEIC proposed by JLab is a high luminosity electron-ion collider with 3-10 GeV electrons and 20-100 GeV protons (or ions with the same range of magnetic rigidity, i.e. lead ion with 12-40 GeV per nucleon) [1, 2]. The ion collider ring's beam current design goal is 0.5A, with the possibility for further upgrade. Figure 1 shows the layout of the collider with electron and ion injectors. The baseline ion injector complex contains the following components: 1) ion sources providing polarized H^- and other light ions, as well as un-polarized heavy ions up to lead; 2) a pulsed SRF linac; 3) a booster ring with 1/9 of the circumference of the collider ring (239.4m), kinetic energy E_k up to 7.9 GeV for proton (momentum 8.79 GeV/c/q for different ions) with DC cooling. The process to accumulate and accelerate ion beam toward collision is illustrated in Fig. 2 and outlined below [3]:

1. Eject the used beam from the collider ring, cycle the magnets
2. Accumulate strip-injected beam from the linac into the booster, perform DC electron cooling if needed
3. Capture the beam into a bucket of 0.7 circumference
4. (proton only) Ramp the booster to 2 GeV and perform DC electron cooling
5. Ramp to 7.9 GeV for proton, or to the same momentum per elementary charge for the other ion species
6. Compress the bunch length to 0.7/N of the booster circumference (N determined by booster charge)
7. Transfer the beam into the collider ring bucket to bucket, cycle the booster magnets
8. Repeat steps 2-7 by 9×N times, perform bunched beam (BB) electron cooling while stacking
9. Ramp the collider ring to the collision energy 12-100 GeV; perform bunch splitting; ready for collision.

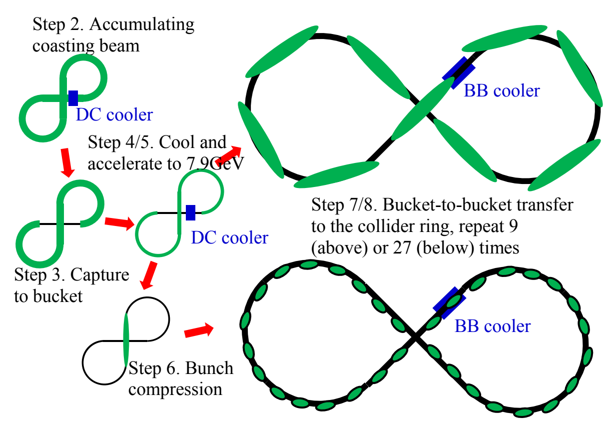

Figure 2: Illustration of the ion beam formation process, step 2-8 as listed above.

The major bottleneck for the ion injection is the space charge (SC) tune shift in the booster ring and the collider ring, especially during step 3 and 8. With given aperture (or emittance) and space charge tune shift in the collider ring at step 8, the booster's extracted beam energy determines the maximum beam current of the collider ring; the linac's extracted beam energy determines how much charge the booster ring can accumulate in each booster cycle.

Table 1 lists the space charge tune shift and the beam aperture for different linac and booster extraction energies and beam charges, with the maximum tune shift set at 0.15. With the original 285 MeV proton linac energy, it takes 9 booster cycles to form 0.5 A proton beam current in the collider ring; for 100 MeV/u lead ions from the linac, 9 booster cycles are not enough for 0.5 A colliding beam current, we need to double the number of booster cycles to 18. If we drop the linac energy to 120 MeV for proton and 40 MeV for lead, we need to increase the

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177
#jguo@jlab.org

ISBN 978-3-95450-131-1

number of booster cycles to 27 (proton) and 36 (lead). Currently we assume that each booster cycle takes 1 minute, dominated by magnet ramping and electron cooling. With the low energy linac option, the estimated time for the full beam formation cycle is acceptable.

We also considered lowering the booster ring extraction energy to 6.5 GeV to distribute the magnet ramping range in the collider ring and booster ring more evenly. The SC tune shift in the collider ring at the end of stacking (step 8) is acceptable. However, this leaves little room for future beam current upgrade, so we should keep the 7.9 GeV booster energy as long as the ramping range is reasonably achievable. The magnet rigidity ratio between 120 MeV and 7.9GeV proton is 18.

Table 1: Selected Parameters of Ion Beam Formation in the MEIC Ion Injector

Particle	Proton			Pb		
Collider ring current (A)	0.5	0.5	0.5	0.5	0.5	0.5
Linac extraction energy (MeV/u)	285	120	95	100	40	53
Booster cycles	1×9	3×9	4×9	2×9	4×9	3×9
Booster charge (μC)	0.4	0.13	0.1	0.2	0.1	0.13
Normalized emittance, step 3 (μm)	2.66	1.64	1.43	1.49	0.93	1.06
SC tune shift, step 3	0.150	0.150	0.150	0.110	0.150	0.150
6σ aperture, step 3 (mm)	40.0	39.8	39.5	39.7	39.8	39.8
Booster extraction energy (GeV/u)	7.90	6.50	6.50	2.65	2.12	2.12
Booster extraction momentum (GeV/c/q)	8.79	7.38	7.38	8.79	7.38	7.38
Normalized emittance, step 8 (μm)	0.5	0.5	0.5	1.0	1.0	1.0
SC tune shift, step 8	0.089	0.125	0.125	0.109	0.153	0.153
6σ aperture, step 8 (mm)	5.2	5.7	5.7	11.7	12.8	12.8

SRF LINAC DESIGN

The original pulsed SRF linac was designed by our collaborators at Argonne National Lab [1]. The linac starts with a warm front end including ion sources, an RFQ and an IH DTL up to 4.8 MeV/u, then an SRF section with 42 QWR cavities and 80 HWR cavities, as shown in Fig. 3. The ion source will generate Pb^{30+} beam, and a charge stripper is put in the middle of the SRF section to reduce the accelerating voltage. For 100MeV/u lead, the stripping energy is chosen at 13.2 MeV/u to minimize the total effective linac voltage to ~385 MV. The extracted Pb beam will have a charge state of 67+. The proton energy is only 285 Me V/u because the RFQ and DTL need to operate at lower voltage to keep the same velocity profile, and the SRF cavities have lower transit time factor for proton. The linac will provide 2 mA 0.5 ms pulsed light ion beams, or 0.5 mA 0.25 ms pulsed heavy ion beams. The pulse repetition rate is up to 10 Hz. The beam current is mainly limited by the ion sources and the loss during charge stripping.

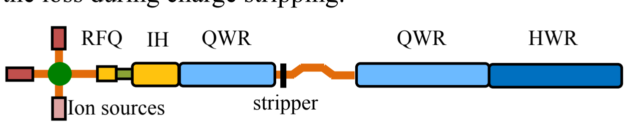

Figure 3: Layout of the SRF linac.

Recently, our Argonne collaborators updated the design to a short linac [4], capable to deliver 130 MeV proton and 42 MeV Pb^{61+} beam with only 45 cavities and enhanced accelerating gradient. The energies are slightly higher than the energies listed in table 1, providing a little more margin. The Pb charge stripping energy is 8.2 MeV/u, with ~175 MV total effective linac voltage.

WARM LINAC CONCEPTUAL DESIGN

The duty factor required for the MEIC linac is extremely low. For each booster cycle shown in table 1, the injected charge is less than 1 μC. With the significant beam loss during strip-injection, the booster accumulation can be done in one or several linac pulses for light ions and 10s of pulses for heavy ions, taking just a few seconds. For each full ion beam formation cycle (which occur once in several hours), the beam in the linac will be turned on for only 10s or 100s of milliseconds. Even during the several seconds of booster accumulation, the duty factor is only up to 0.5%. Considering that the static heat load in the cryomodules will consume cryogenic power 24 by 7 even when the SRF linac is idling, it's natural to consider warm linac as an alternative. Adding to the warm linac's advantage is the lower particle energy and velocity required. When $\beta<=0.3$, warm DTL structures, especially the IH (Interdigital H-mode) and CH (Cross-bar H-mode) types [5], have very high R/Q for low beta ions and can generate competitive shunt impedance per unit structure length. The SRF linac design also includes a warm IH DTL up to 4.8 MeV/u.

Multi-gap structures like DTL have very narrow velocity range for peak transit time factor (TTF), due to the invariable phase between gaps. So DTL must operate at fixed β profile. The structure will be optimized for the heaviest ions (lowest q/a), and need to lower the

ISBN 978-3-95450-131-1

accelerating voltage for lighter ions, so that all the particles will have the same exit E_k/u. Single/double gap structures in the SRF linac can operate at close to full voltage for different ion species and give about the same E_k/q.

We conceptually designed a DTL linac with 95 MeV proton (increases the booster cycles to 36) and 53 MeV/u Pb^{61+} (decreases the booster cycles to 27), as shown in Fig. 4. The choice of energy makes the performance comparable to the SRF linac with 120 MeV proton and 40 MeV/u Pb.

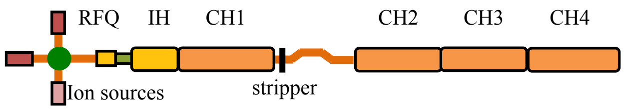

Figure 4: Layout of the DTL linac.

Table 2: CH DTL Conceptual Design Parameters

DTL Section	CH1	CH2	CH3	CH4
Lowest q/a particle	Pb^{32+}	Pb^{61+}	D^-	H^-
Exit energy (MeV/u)	8.1	53.0	67.7	95.2
Exit β	0.130	0.322	0.361	0.417
Number of structures	1	9	2	2
Average V_{eff} per structure (MV)	21.3	17.0	14.7	13.2
Average Z_{eff}/L (MΩ/m)	91	58	43	38

The warm linac has an identical warm front end up to the IH as in the SRF linac. The rest are 4 sections of totally 14 CH DTLs. Every two CH structures share the split power from a 325 MHz (or 352 MHz) 2.5 MW (or 2.8 MW) pulsed klystrons, which are the most cost effective commercially available pulsed RF sources in this frequency range. Each structure is ~5m long and takes ~1MW cavity power when accelerating the lowest q/a particles. The pulsed beam power in each structure ranges from several to 30 kW, depending on the structure and ion species. The power from each klystron will be split into two structures. CH1 is one structure optimized for Pb^{32+}, delivering 8.1 MeV/u for charge stripping. This is slightly closer to the optimal stripping energy than putting two structures in CH1 before the stripper. CH2 has nine structures optimized for Pb^{61+}, with exit energy at 53 MeV/u. CH3 has two structures optimized for D^- and will be turned off during Pb operation, with exit energy 68 MeV/u. CH4 has the last two structures that accelerate H^- to 95 MeV. The effective voltage of each CH structure is estimated from the effective shunt impedance per unit length parameter of the FAIR proton linac structures (up to 70 MeV) with the closest β [6]. The total effective linac voltage is 261 MV. Table 2 lists some parameters of the CH DTL linac. The total length of the CH structures is about 70 m, which is longer than the SRF linac.

Given the extremely low duty factor, the RF power consumption in the structures can be negligible in both cases of the warm and SRF linac. The SRF linac's power consumption is dominated by the static cryogenic heat load. With 5 cryomodule and 45 cavities operating at 4K, the wall plug power in the cryo-plant would be close to 30 kW, which might be higher than the equipment idle power for the warm linac, but still insignificant.

The cost comparison between the SRF and warm DTL options is very primitive at this stage. So far the difference between the two options is smaller than the error bar of our estimation; the SRF option may cost less with some cost savings achieved in the updated design, such as higher gradient in the cavities. The main reason for higher cost in the warm linac is the extra accelerating voltage needed in CH3/4, as CH1/2 have to lower the voltage when accelerating light ions. If an upgrade to higher linac energy is needed in the future, the SRF advantage will be more obvious, as the DTL efficiency deteriorates at higher β.

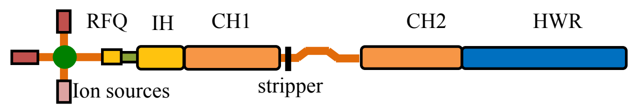

Figure 5: Alternative SRF linac design with extended warm section.

Another option is to extend the warm DTL section of the SRF linac to a higher energy of ~25 MeV/u with four CH structures and two 2.5 MW klystrons, and then use 3 SRF HWR cryomodules (7-9 cavities each) to accelerate Pb^{61+} to 55 MeV and H^- to 130 MeV, as shown in Fig. 5. This design will fully utilize the high efficiency of pulsed CH structures at low β, but avoid building sections of warm structures that can only accelerate light ions, so the total linac voltage is about 205 MV. The QWRs in the SRF design replaced by the CH structures also have degraded TTF in part of the β range for the light ions. For this option, the extraction energy for most ion species will meet the requirement of 27 booster cycles injection into the MEIC collider ring, and the cost-effectiveness might be improved further.

SUMMARY

We updated the MEIC ion formation scheme with the low energy linac option. With 40 MeV/u Pb and 120 MeV proton, the ion injection of 0.5 A beam current can be done within 27-36 booster cycles. We compared the SRF and DTL options for such a linac. With the beam current and duty factor required for MEIC, the two options are close in operation and construction cost, as well as the performance. However, SRF will have obvious advantage if we plan to increase the energy or find a side program in the future. A third option is to extend the warm section in the SRF linac to 25 MeV/u, which may optimize the design further.

REFERENCES

[1] S. Abeyratne et al., Science Requirements and Conceptual Design for a Polarized Medium Energy

ISBN 978-3-95450-131-1

Electron-Ion Collider at Jefferson Lab, edited by Y. Zhang and J. Bisognano, (2012).

[2] S. Abeyratne et al., MEIC Design Summary for NSAC EIC Cost Estimate Sub-Committee, edited by G. A. Krafft, (2015).

[3] Y. Zhang, "MEIC Proton Beam Formation with a Low Energy Linac", TUPWI035, Proc. of IPAC'2015.

[4] P. N. Ostroumov et al., "Pulsed SC Ion Linac as an Injector to Booster of Electron Ion Collider", MOPB068, Proc. of SRF'2015.

[5] U. Ratzinger, "H-type Linac Structures," CERN-2005-003, p351.

[6] W. Barth et al., Technical Design Report, FAIR Proton Linac, 2008.

ISBN 978-3-95450-131-1