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MEIC PROTON BEAM FORMATION WITH A LOW ENERGY LINAC[#]

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Abstract

The MIEC proton and ion beams are generated, accumulated, accelerated and cooled in a new green-field ion injector complex designed specifically to support its high luminosity goal. This injector consists of sources, a linac and a small booster ring. In this paper we explore feasibility of a short ion linac that injects low energy protons and ions into the booster ring.

INTRODUCTION

A polarized medium-energy electron-ion collider, MEIC, has been envisioned as a future facility at JLab beyond the 12 GeV CEBAF program [1,2]. This future collider is designed to deliver high performance including high luminosities and high polarization of both electron and light ion beams. Its luminosity concept [3] is based on a high bunch repetition rate, up to 476 MHz, which enables small emittance, short bunch length, and very strong final focusing.

The MEIC proton and ion beams are generated in a new ion injector in a green field. Recently, great efforts were made to optimize the injector design for achieving better performance and for lowering the cost. The first major change of the design is elimination of a large booster ring (3 to 20 GeV) by allowing the beams being injected directly into the collider ring from the small booster [4]. The proton extraction energy from the booster is raised to 7.9 GeV, therefore greatly easing the space charge bottleneck when the beam is injected into a full size ring (the large booster has a same circumference as the collider ring). The second major change is a proposed reduction of the linac energy by nearly 60%, leading to a large reduction of the ion linac cost. Lowering the linac energy, however, has serious impact on the process of ion beam formation, therefore, the injection scheme must be reformulated to accommodate lower injection energies and to alleviate the much stronger space charge effect. This paper reports a recent study of this topic.

MEIC ION INJECTOR

The MEIC ion injector is designed with the following major components [2]: polarized ion sources (for H^-/D^- and ^3He) and non-polarized ion sources (up to lead); a pulsed linac made of a warm front end and SRF cavities; and a single booster ring (up to 7.9 GeV). The booster ring also includes a DC electron cooler for assisting accumulation of ions and, as a part of a multi-step cooling scheme [5,6], for the initial stage of emittance reduction of all ion beams. Such DC cooling is very efficient at low energies thus it greatly improves the overall cooling rate.

Like all hadron facilities, it is a long process to form and accelerate an ion beam for collisions with an electron beam in MEIC. This process can be outlined below:

1. Eject the used beam from the collider ring, cycle the magnets;
2. Accumulate protons strip-injected from the linac to the booster ring;
3. Ramp energy to 2 GeV (the DC cooling energy);
4. Perform DC electron cooling;
5. Ramp to 7.9 GeV (the booster ejection energy);
6. Transfer the beam into the collider ring; cycle the booster ring magnets;
7. Repeat step 2 to 6 to fill the collider ring, perform electron cooling during stacking;
8. Ramp to the collision energy (20 to 100 GeV)
9. Perform bunch splitting to reach high bunch repetition rate while continuing electron cooling;
10. Resume *e-p* collisions.

Figure 1 below illustrates this beam formation process. The number of injection cycles from the booster to the collider ring depends on the linac energy. Formation of heavy ion beams in MEIC follows a similar process except it requires more injections from the booster ring.

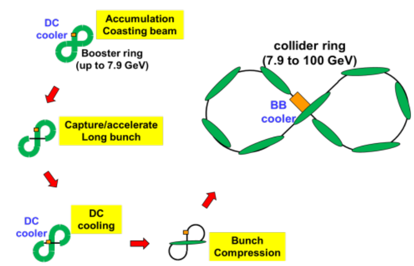

Figure 1: An illustration of the MEIC ion beam formation process. It requires multiple transfers of accumulated long bunches from the booster to the collider ring. The beam intensity is limited by the magnet apertures and the space charge effect at injection of the booster.

The MEIC ion linac is designed to accelerate protons to 285 MeV and (partially stripped) ions such as $^{208}Pb^{67+}$ to 100 MeV per nucleon [1,2,7]. Presently, we are exploring feasibility of replacing this SRF linac by a cost-effective pulsed warm RF linac (as first suggested by this author), the conceptual development is underway [8]. Alternately, lowering the linac energy could also achieve a substantial cost reduction for MEIC. One approach is installing only the warm front end and the first section of the SRF linac for the present MEIC baseline. As a result, the proton energy from the linac is 120 MeV and the lead ion energy is about 40 MeV per nucleon [7]. It is planed that extra space will be reserved for the remaining part of the SRF linac as an option of future MEIC luminosity upgrade.

INJECTION SCHEME WITH A LOW ION LINAC ENERGY

It is understood that intensity of an accumulated hadron beam in a booster ring is primarily limited by the magnet

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aperture and the space charge tune-shift at injection. When the injection energy (i.e., the linac energy) is decreased, the beam geometric emittance is increased, so is the transverse beam size. As a consequence, it demands a larger magnet aperture for providing adequate beam-stay-clear under the same ring optics. Similarly, the space charge tune-shift is inverse proportional to the relativistic factor $\beta\gamma^2$. Decreasing the linac (injection) energy would reduce maximum number of particles that can be accumulated in the booster ring. Therefore, more transfers from the booster are needed to fill the collider ring to attain the beam current target (and number of stored particles). Table 1 shows three sets of design parameters of the proton beam formation in the MEIC ion injector. In Table 1, the third and fourth columns correspond to the design cases with a 285 MeV ion linac but two different beam currents in the collider ring. The booster ring circumference is assumed roughly one-ninth of that of the collider ring. For a nominal design current of 0.5 A needed for MEIC, only nine injections from the booster are required to fill the collider ring. Each injection has 2.5×10^{12} protons. To support a 1.5 A beam current in the MEIC collider ring, three times more transfers from the booster ring are required, as illustrated in the fourth

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

Linac energy (proton)	**MeV**	**285**	**285**	**120**
Nominal current in the collider ring	A	0.5	1.5	0.5
Booster circum. (*1/9 of collider ring*)	m	239.4	239.4	239.4
Accumulated protons in booster	10^{12}	2.5	2.5	1.25
Normalized emittance	mm	2.66	2.66	2.35
RMS spot size	mm	6.7	6.7	8.1
Beam-stay-clear (6 × RMS spot size)	mm	40.1	40.1	48.6
Space charge tune-shift at coasting		**0.11**	**0.11**	**0.11**
Capture (for acceleration)	MeV	285	285	120
Harmonic number		1	1	1
RF frequency	MHz	0.80	0.80	0.58
Synchronous phase φ_s		36.9°	36.9°	52°
Protons in each bucket	10^{12}	2.5	2.5	0.83
Bucket size (as fraction of circumference)	m	171 (71%)	171 (71%)	167 (70%)
Space charge tune-shift after capture		**0.154**	**0.154**	**0.158**
After 1st stage acceleration	GeV	2	2	2
RF frequency	MHz	1.19	1.19	1.19
Synchronous phase φ_s		36.9°	36.9°	52.0°
Bucket size (as fraction of circumference)	m	115.8 (48%)	115.8 (48%)	81.3 (34%)
Spot size and beam-stay-clear	mm	3.5 / 21.2	3.5 / 21.2	3.1 / 18.9
Space charge tune-shift		**0.027**	**0.027**	**0.021**
After DC cooling	GeV	2	2	2
Normalized emittance	µm	0.5	0.75	0.5
RMS spot size & beam-stay-clear	mm	1.5 / 9.2	1.9 / 11.3	1.5 / 9.2
Space charge tune-shift		**0.135**	**0.09**	**0.096**
After 2nd stage acceleration	GeV	7.9	7.9	7.9
RF frequency	MHz	1.25	1.25	1.25
Synchronous phase φ_s		36.9°	36.9°	52°
Bucket size (as fraction of circumference)	m /	110.3 (46%)	110.3 (46%)	77.8 (32%)
RMS spot size and beam-stay-clear	mm	0.86 / 5.2	0.86 / 5.2	0.86 / 5.2
Space charge tune-shift		0.015	0.01	0.011
Bunch compression	GeV	7.9	7.9	7.9
RF frequency	MHz	1.25	1.25	1.25
Synchronous phase φ_s		23.6°	55.6°	58.2°
Bucket size (as fraction of circumference)	m	141.8 (59%)	67.1 (28%)	64.5 (27%)
Space charge tune-shift		**0.012**	**0.016**	**0.013**
Injection into collider ring	GeV	7.9	7.9	7.9
Injections from the booster		9	9×3	9×3
Harmonic number		9	9×3	9×3
Protons in the collider ring	10^{12}	2.5×9=22.4	2.5×9×3=67.3	1.25×9×2=22.4
Space charge tune-shift		**0.105**	**0.148**	**0.115**

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column of Table 1 and in Figure 2, in order to mitigate the intensity bottleneck due to the space charge effect during injection to the booster ring. The normalized emittance after DC electron cooling cannot be lower than 0.75 µm, due to the space charge tune-shift limit at injection of the collider ring. This trick of increasing number of injections from a booster ring is used in other hadron facilities to overcome intensity challenges without hardware upgrade [9]. Thus, it can be concluded that the higher energy (285 MeV) linac design is sufficient for forming a proton beam that has three times higher current than what is needed in MEIC. This also suggests that the MEIC linac energy can be reduced for cost reduction without compromising the injector performance.

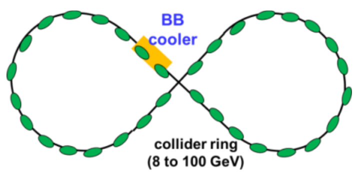

Figure 2: The MEIC ion collider ring receives 3×9 injections of long bunches from the booster ring.

When the linac energy is lowered from 286 MeV to 120 MeV, the energy dependence term ($1/\beta\gamma^2$) of the space charge tune-shift of the booster ring is increased roughly by a factor of two. To compensate it, the accumulated protons in the booster ring must be reduced by half in order to attain the same value of the space charge tune-shift. As shown in the last column of Table 1, we now need 18 injections from the booster ring. It can be seen the space charge tune-shift is below the design limit (~0.16) at each step of the beam formation process.

BOOSTER RING MAGNET APERTURE

With a 120 MeV ion linac, we assume the space charge limited normalized emittance of the accumulated proton beam is 2.35 µm-rad and the energy spread is 1×10^{-3}, both numbers are in the ranges that have already been achieved in the existing hadron facilities. They results in 8.1 mm beam horizontal spot size at injection of the booster ring, assuming the booster ring optics design has a 14 m maximum betatron function and 2 m maximum horizontal dispersion. Including the magnet sagitta and a beam orbital steering allowance (±5 mm), the required magnet apertures are 12.5 cm and 10.5 cm in the horizontal and vertical direction respectively. Such aperture requirements are considered technically reachable [10].

TOWARDS 476 MHz REPETITION RATE BY MULTIPLE SPLITTING SCHEME

The MEIC design utilizes a high bunch repetition rate up to 476 MHz for both colliding beams for achieving high luminosities. The corresponding bunch spacing is 2.1 ns (i.e., 0.63 m). Therefore, there are total 3500 buckets in the collider ring when its circumference is approximately 2200 m. If including gaps in the bunch train whose length is 10% of the ring circumference, number of the stored bunches is 3150 if all buckets except those in the gaps are filled. Each short bunch has 6.56×10^9 protons according to the MEIC baseline design [2].

As discussed in the previous section, with a low (120 MeV) ion linac design, 18 long bunches are transferred from the booster to the collider ring. If the RF frequency in the ion collider ring is chosen 2.72 MHz at the injection energy, there are 20 large RF buckets in the collider ring; 18 of them are filled by long bunches from the booster ring through a bucket-to-bucket transfer. The two empty buckets (220 m in length) are reserved for gaps in the bunch train. The number of protons in each long bunch is now reduced to 1.15×10^{12} due to the gap in the ring. This reduces the space charge tune-shift by 10% in every step in the last column of Table 1.

We propose a scheme of three consecutive rounds of bunch splitting, namely, 1→7, 1→5 and 1→5, to convert one injected long bunch to 175 (=7×5×5) short bunches in 476 MHz repetition rate. Bunch splitting is achieved by adiabatically switching off a low frequency RF system and simultaneously adiabatically switching on a high frequency RF system. Table 2 lists the design parameters for this bunch splitting process. Additional RF systems with frequencies in between of those listed in Table 2 may also be needed to stretch these bunches and then split them.

Table 2: Bunch Splitting Parameters (for One Long Bunch)

Splitting	Bunches	RF Freq.	Bunch Spacing	Protons /bunch
		MHz	ns	10^{10}
	1	2.72	367.65	114.8
1→7	7	19.04	52.52	16.4
1→5	35	95.2	10.5	3.28
1→5	175	476	2.1	0.656

One advantage of the bunch splitting scheme over an alternate scheme of de-bunching to a coasting beam then re-bunching with high repetition rate is avoiding a potential instability which could cause longitudinal beam emittance blow-up when the beam becomes a coasting one. It also provides an easy way to introduce gaps in the bunch train. A successful example of the multiple bunch splitting scheme can be found in the LHC injector where a single long bunch in the proton booster synchrotron (PSB) is split 1→3, 1→2 and 1→2 consecutively to 12 short bunches (thus acquiring a 25 ns bunch spacing). The beam emittance is well preserved during the process [9].

CONCLUSION

In this paper, we present an injection scheme for the MEIC proton beam with a reduced linac energy. It requires 18 injections from the booster to the collider ring. We also discuss a bunch splitting scheme to convert a beam from a low bunch repetition rate to a high one.

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