THE SCHEME OF BEAM SYNCHRONIZATION IN MEIC*

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Abstract

Synchronization of two colliding beams at single or multiple collision points is a critical issue for the design of the Medium energy Electron-Ion Collider (MEIC) at JLab. The path-length variation required to accommodate different ion energies, which varies from 20 to 100 GeV/u, could be larger than several bunch spacings. The present scheme adopted in the MEIC design is centered on varying the number of bunches stored in the ion collider ring. This could provide a set of discrete ion harmonic energies such that the beam synchronization is realized. To cover the ion energy between these harmonic energies, it is further proposed to vary simultaneously the electron ring circumference and RF frequency in both collider rings, both of them are technically feasible.

INTRODUCTION

The MEIC [1] ion collider ring accommodates a wide variation of energy from 20 to 100 GeV/u. In this medium energy range, ions are not fully relativistic yet since their $\beta=v/c$ is slightly below 1. This leads to an energy dependence of revolution time of the collider ring. On the other hand, electrons with 3 to 12 GeV energy are already ultra-relativistic, therefore, their revolution time is energy independent. The difference in speeds between colliding electrons and ions of MEIC are actually huge in terms of revolution times or path-lengths in the collider rings.

While the circumferences of the two MEIC collider rings can be designed such that the revolution times of electrons and ions are identical or matched for one particular ion energy (i.e., an electron bunch that collides with one ion bunch at an interaction point (IP) will collide with the same or another ion bunch at the same IP after one revolution), this synchronization condition cannot be maintained over the entire ion energy range. At other ion energies, the electron and ion bunches could miss each other at the IP due to different revolution times. Multiple IPs can further complicate the situation and make beam synchronization even more difficult to realize.

To provide a scale of this beam synchronization issue in MEIC, it can be shown that the difference between revolution times of electrons and 20 GeV protons is about 4.3 ns, assuming the two rings are matched at 100 GeV energy and a nominal ring circumference of 1350 m. This is equivalent to a 1.3 m path-length difference, which is large than 3 bunch spacings if the bunch repetition rate is 748.5 MHz. The situation becomes much worse for lead ions at 8 GeV/u; the path-length difference is now widened to 7.44 m, roughly 18 times the bunch spacing.

Such a challenge also exists in other colliders involving hadrons with varying medium energies. For example, in the ring-ring design scenario of eRHIC, it requires a path-length adjustment up to 0.9 m in the electron ring to cover an ion energy range from 25 to 250 GeV/u, [2].

It is very difficult to handle such a large orbital change with conventional path-length adjustment schemes not only due to the high electron and ion energies, but also because of the lack of available space in straight sections for implementing such schemes. In this paper, we present a new scheme for mitigating this issue [1].

VARIATION OF ION BUNCH NUMBERS

We start with a nominal circumference of 1350 m for the collider rings. There are 3370 bunches stored in each ring when operated at a 748.5 MHz bunch repetition rate. The ion ring circumference is about 6 cm shorter than that of the electron ring to make the revolution times of electrons and 100 GeV protons identical, such that, an electron bunch continuously collides with one particular proton bunch at an IP while both bunches are circulating in opposite directions in their own rings. This synchronization condition should still be valid when there are two or more uniformly distributed IPs in the ring.

When the proton beam varies its energy from 20 to 100 GeV, its velocity also varies, as does the revolution time in the ring. As a consequence, the beam synchronization condition is no longer valid. However, at certain proton energies, the difference of revolution times happens to equal an integer multiplier (n) of the bunch spacing; then beam synchronization is automatically restored if the ion ring stores an additional n bunches. In such cases, an electron bunch colliding with one proton bunch at an IP will collide, after one revolution, with the bunch n spacings ahead in the proton bunch train. Such proton energies are called harmonic energies. The harmonic number satisfies the following relation

$$N_0\beta_0 = N\beta \quad (1)$$

where N is number of bunches and $\beta=v/c$. The subscript 0 above denotes the values at the matched energy which is 100 GeV for the MEIC case. The number of additional ion bunches in the ring is $n=N-N_0$. Table 1 lists the first several harmonic energies in the MEIC collider ring.

Table 1: Ion Beam Harmonic Energies in the MEIC Collider Ring

Harmonic number	β	γ	Ion harmonic energy (GeV/u)
3370	0.99996	106.6	100
3371	0.99966	38.31	35.95
3372	0.99936	28.02	26.29
3373	0.99907	23.15	21.72
3374	0.99877	20.17	18.93
3375	0.99847	18.11	16.99

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It can be seen from Table 1 that the harmonic energies are distributed more densely at low energies, particularly below 20 GeV/u. Between 20 to 36 GeV/u, there are three harmonic energies. From a user point view, there should be enough choices of energies in the range of interest to physics research. Thus, one could conclude that this scheme is a viable solution to the beam synchronization issue at ion energies below 36 GeV/u. There is a particularly important implication of the above conclusion: for heavy ions like lead ions, the target energy range of MEIC is only up to 40 GeV/u; therefore, the scheme of varying number of bunches in the ion ring *alone* already provides a working solution to the beam synchronization issue if there is only one IP.

This scheme can be applied to the MEIC with multiple IPs; however, the number of harmonic energies that meet the beam synchronization condition simultaneously at all IPs is reduced. As an example, if the MEIC has two IPs symmetrically distributed in the collider ring, only the even harmonic numbers in Table 1 meet the beam synchronization requirements. Such a reduction in the number of harmonic energies should not affect the low energy end, since there are still abundant harmonic energies available for experiments.

VARIATION OF ION PATH LENGTH

For those energies lying between two consecutive harmonic energies, additional mitigation is needed in order to synchronize beams at IPs. One solution is adjusting the ion collider ring circumference by up to half of the bunch spacing, which is ±20 cm for a 748.5 MHz bunch repetition rate, if there is only one IP. For a figure-8 ring with a 60° crossing angle, this represents a change of arc radius by up to ±2.4 cm. Such a scheme is technically challenging to implement since the MEIC ion collider ring is made of SC magnets whose apertures are difficult to be enlarged to accommodate a shift of the magnetic centers.

VARIATION OF ELECTRON PATH LENGTH AND RF FREQUENCY

Alternately, beam synchronization can also be achieved by varying the circumference of the electron ring instead; however, the RF frequency must be adjusted accordingly. The main advantage of this scheme is that, being a normal conducting magnet ring, change of the electron ring circumference is far easier since apertures of the magnets could be made large enough for a shift of the magnetic center. It can be shown that, for only one IP, changes of electron ring circumference and RF frequency must satisfy the following equations

$$f/f_0=(N_p/N_{p0})(\beta/\beta_0) \qquad L_e/L_{e0}=(N_e/N_{e0})(f_0/f) \qquad (2)$$

where f is the RF frequency, N_p and N_e are harmonic numbers in the ion and electron rings respectively. The subscript 0 again denotes values at the matched proton energy, which is 100 GeV for MEIC. We take the simplest case of fixed number of bunches stored in the electron ring, namely, $N_e=N_{e0}$. Table 2 shows the results for MEIC with only one IP. The last three columns of the table are changes of RF frequency, circumference and radius of the figure-8 electron ring. The later is calculated using formula $\delta R_e = \delta L_e/(8\pi/3)$ for a figure-8 ring with a 60° crossing angle, where $\delta L_e=L_e-L_{e0}$ and $\delta R_e=R_e-R_{e0}$. Figure 1 and 2 below illustrates variations of the MEIC electron collider ring circumference and frequency of the warm RF or SRF systems in the collider rings as functions of ion energy for different harmonic numbers.

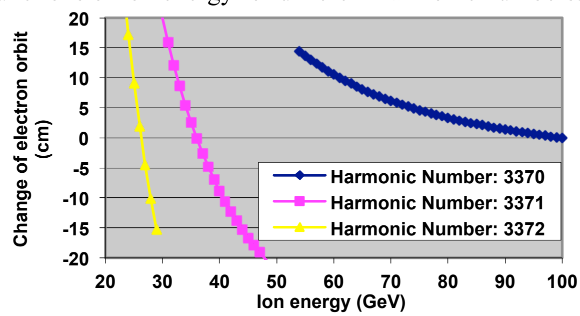

Figure 1: variation of the MEIC electron collider ring circumference for synchronizing two colliding beams at one IP for different ion energies

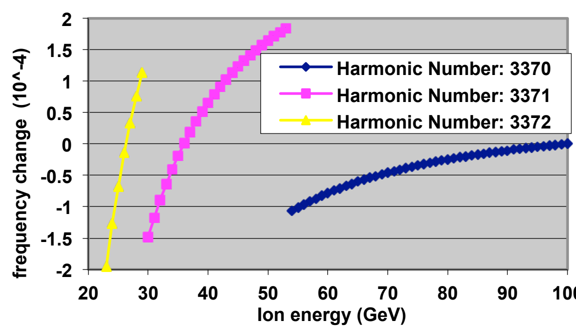

Figure 2: Variation of the MEIC collider ring RF frequency for synchronizing two colliding beams at one IP for different ion energies.

MULTIPLE IPs

We foresee up to three IPs in MEIC. For the case of only two IPs symmetrically located in two straights and even number of bunches in each ring, no additional mitigation measure compared to above described will be needed for beam synchronization. When there are three IPs (two of them are positioned in one of two straights of figure 8) and(or) odd number of bunches, synchronization for collisions can be provided by a small adjustment of the beam-beam crossing angle (that causes a required longitudinal shift of the collision point) by use of small dipole magnets installed in the IR area. Shift of the IP in a detector is limited at maximum by a quarter of bunch spacing (±10 cm), and it can be reduced by a factor of 2 being shared between two IPs. Such a shift is viewed as admissible by the detector designers. The associated change of the beam-beam crossing angle is in range of about ±1% of 50 mrad, which does not require a reconsideration of IR optics.

Table 2: Change of Ion Harmonic Number, Electron Ring Circumference and Arc Radius, and RF Frequency in MEIC

Energy (GeV/u)					Collider Ring				
Proton	Deuteron	Lead	Γ	β	HN	f (MHz)	$\delta f/f_0$ (10^{-4})	δL_e (cm)	δR_e (cm)
100			106.6	0.99996	3370	748.5	0	0	0
90			95.92	0.99995	3370	748.49	-0.10	1.39	0.17
80			85.26	0.99993	3370	748.48	-0.25	3.34	0.40
70			74.61	0.99991	3370	748.47	-0.46	6.18	0.74
60			63.95	0.99988	3370	748.44	-0.78	10.6	1.27
50	50		53.29	0.99982	3370	748.40	-1.25	16.9	2.03
45	45		47.96	0.99981	3371	748.59	1.23	-16.6	-1.98
40	40	40	42.63	0.99972	3371	748.53	0.66	-8.84	-0.83
38	38	38	40.5	0.99970	3371	748.53	0.36	-4.83	-0.58
35.9	**35.9**	**35.9**	38.32	0.99966	3371	748.5	0	0	0
34	34	34	29.84	0.99962	3371	748.47	-0.40	5.43	0.65
32	32	32	27.71	0.99957	3371	748.43	-0.89	12.1	1.43
30	30	30	26.65	0.99951	3372	748.61	1.48	-20.0	-2.39
28	28	28	25.58	0.99944	3372	748.56	0.76	-10.2	-12.2
26.3	**26.3**	**26.3**	28.02	0.99936	3372	748.5	0	0	0
26	26	26	27.71	0.99935	3372	748.49	-0.14	0.05	0.01
24	24	24	25.58	0.99924	3372	748.41	-1.27	17.2	2.05
22	22	22	23.45	0.99909	3373	748.52	0.24	-0.08	-0.01
21.7	**21.7**	**21.7**	23.15	0.99907	3373	748.5	0	0	0
20	20	20	21.32	0.99890	3374	748.60	1.29	-17.4	-2.08
	19	19	20.25	0.99878	3374	748.51	0.09	-1.28	-0.15
	18.9	**18.9**	20.17	0.99877	3374	748.5	0	0	0
	17.0	**17.0**	18.11	0.99818	3375	748.5	0	0	0

Note HN is the harmonic number in the ion collider ring, $\delta f/f_0$ is the relative change of RF frequency, δL_e and δR_e are change of the electron ring circumference and arc radius. Numbers in red font corresponds to harmonic energies.

DISCUSSION

It is considered that a change of the MEIC electron ring circumference of up to ±20 cm is technically feasible. The corresponding arc radius change is ±2.4 cm which can be realized through shift of the magnetic centers of the magnets. With two IPs, the arc radius change is doubled, thus it may require additional mitigations to absorb a fraction of the required path length change.

The key to the present scheme is a tuneability of the SRF frequency up to a few 0.01%. While it has never been attempted before, changing the frequency of an SRF system by such a small amount is conceivable [3]. An R&D effort is underway in support of the design effort.

To support the present scheme, the MEIC full energy electron injector (the CEBAF SRF linac) also needs a capability of frequency tuning. A recent 6 GeV CEBAF machine test indicated the required tuning range is likely achievable [4]. Other solutions are also under study.

Further, the ERL-circulator ring based electron cooler of MEIC [1] must be adjusted accordingly to synchronize the cooling electron beam with the colliding ion beams. This must involve varying both the ERL recirculating path and the circulator ring circumference, in addition to tuning of the SRF linac frequency. Since both the ERL and the circulator ring are compact (about 100 m in ring circumferences), the required path-length adjustment is very small (about 1.5 cm) which can be handled in a conventional method.

It should be noted that higher bunch repetition rates always have an advantage in achieving synchronization of colliding beams. As an example, if the bunch repetition rate of MEIC is increased to 1497 MHz (the base RF frequency of CEBAF), the required path-length adjustment will be reduced by a factor of two.

To summarize this paper, we conclude that a scheme has been found for ensuring beam synchronization in the MEIC collider rings. At low proton energies and over the whole energy range of heavy ions, varying the number of ion bunches in the collider ring provides a simple working solution. This should also solve the problem for a low energy electron-ion collider (LEIC) at JLab with proton energy ranged from 10 to 25 GeV [5]. For proton energies of 40 to 100 GeV, variation of the electron ring's circumference has an advantage; however, tests are needed to verify that varying the frequency of SRF modules by up to 0.013% is achievable.

A note from the authors: The main results presented in this paper are partially included in the MEIC design report [1], however, the work was completed by the authors of this paper.

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