STUDY OF BEAM SYNCHRONIZATION AT JLEIC*

V.S. Morozov#, Ya.S. Derbenev, J. Guo, A. Hutton, and Y. Zhang,
Jefferson Lab, Newport News, VA 23606, USA

Abstract

The ion collider ring of Jefferson Lab's Electron-Ion Collider (JLEIC) accommodates a wide range of ion energies, from 20 to 100 GeV for protons or from 8 to 40 GeV per nucleon for lead ions. In this medium energy range, ions are not fully relativistic, which means values of their relativistic beta are slightly below 1, leading to an energy dependence of revolution time of the collider ring. On the other hand, electrons with energy 3 GeV and above are already ultra-relativistic such that their speeds are effectively equal to the speed of light. The difference in speeds of colliding electrons and ions in JLEIC, when translated into a path-length difference necessary to maintain the same timing between electron and ion bunches, is quite large. In this paper, we explore schemes for synchronizing the electron and ion bunches at a collision point as the ion energy is varied.

SYNCHRONIZATION ISSUE

The synchronization issue at JLEIC has earlier been discussed in Refs. [1, 2]. More recently, a comprehensive study of synchronization options has been done at a series of special meetings at Jefferson Lab during July-August, 2015. We discussed schemes involving various combinations of (a) keeping or varying the numbers of bunches, (b) moving ion magnets or moving electron magnets with adjustment of RF in both rings, (c) moving electron or ion arcs, (d) electron or ion chicanes, (e) systems of path-length jumps and bypass lines, and (f) novel schemes such scanning synchronization [3]. A comprehensive report on this study including a discussion of engineering aspects has been prepared [4]. This paper briefly describes a small subset of the most promising synchronization schemes.

To ensure collisions, the arrival times of the electron and ion bunches at the interaction point (IP) of JLEIC [5] must be the same:

$$T_0 = T_{0e} = \frac{\lambda_{0e}}{c} = \frac{L_{0e}}{n_{0e}c} = T_{0i} = \frac{\lambda_{0i}}{\beta_{0i}c} = \frac{L_{0i}}{n_{0i}\beta_{0i}c}, \quad (1)$$

where the index 0 refers to a synchronized situation, T_{0e} and T_{0i} are the timings between the electron and ion bunches, respectively, λ_{0e} and λ_{0i} are the spacings between the electron and ion bunches, L_{0e} and L_{0i} are the circumferences of the electron and ion rings, n_{0e} and n_{0i} are the harmonic numbers of the electron and ion rings, β_{0i} is the relativistic beta of ions and c is the speed of light.

While the circumferences of the JLEIC collider rings (L_{0e} and L_{0i}) can be adjusted to provide the same timings ($T_{0e} = T_{0i} = T_0$) between the electron and ion bunches at one particular ion energy (determined by β_{0i}), at other energies (when $\beta_i \neq \beta_{0i}$), the colliding bunches may miss each other due to the difference in timing:

$$T_{0e} = \frac{\lambda_{0e}}{c} = \frac{L_{0e}}{n_{0e}c} \neq T_i = \frac{\lambda_{0i}}{\beta_i c} = \frac{L_{0i}}{n_{0i}\beta_i c}. \quad (2)$$

This is the beam synchronization issue. Multiple collision points may further complicate the situation.

Assuming an ion ring circumference of 2153.78 m, a nominal bunch number of 3422 (a bunch spacing of 62.94 cm and an RF frequency of 476.3 MHz) and the fact that the two collider rings are synchronized at a proton momentum of 100 GeV/c, Table 1 shows the ion path-length adjustment necessary to compensate the change of ion velocity as a function of proton momentum. Clearly, conventional path-length adjustment schemes based on a chicane type magnetic system are not feasible to handle such a large path-length difference. In this paper, we discuss possible scenarios of addressing this issue.

Table 1: Ion Path-Length Adjustment as a Function of Ion Momentum

p (GeV/c/u)	**β_i**	**ΔL_i (m)**
100	0.999956	0.000
80	0.999931	-0.053
60	0.999878	-0.169
40	0.999725	-0.498
20	0.998901	-2.272

BUNCH NUMBER VARIATION

One technique for mitigating the synchronization issue is bunch number variation. Comparing Eqs. (1) and (2), one can see that synchronization can be restored by choosing β_i and n_i such that

$$n_i\beta_i = n_{0i}\beta_{0i}. \quad (3)$$

This means that, at certain discrete energies, the difference of the revolution times happens to be exactly an integer multiple of the bunch timing. Thus, the synchronization condition can be restored by storing additional bunches in the ion collider ring.

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morozov@jlab.org

While the bunch number variation technique does not provide a complete solution, it greatly improves the situation by limiting the maximum necessary path length adjustment to plus or minus a half of the bunch spacing, which is not very large due to JLEIC's high repetition rate. Table 2 shows the ion path-length adjustment as a function of ion momentum in case of bunch number variation. Compared to Table 1, the issue is significantly reduced. The energies satisfying Eq. (3) below 40 GeV are sufficiently dense that no path length adjustment is needed.

In case of different bunch numbers in the electron and ion collider ring, an electron bunch colliding with one proton bunch at the IP, after one complete revolution, will collide with a different bunch down the proton bunch train. On one hand, this offers a unique advantage in suppressing bunch-charge- and bunch-polarization-related systematic effects in the detector. On the other hand, there is a potential for dynamic instability [6, 7]. We believe the instability will be suppressed to the large numbers of colliding bunches and the Landau and synchrotron radiation damping effects. This problem is currently being studied in simulations [8].

Table 2: Ion Path-Length Adjustment as a Function of Ion Momentum in Case of Bunch Number Variation

p (GeV/c/u)	**β_i**	**n_i**	**ΔL_i (m)**
100	0.999956	3422	0.000
80	0.999931	3422	-0.053
60	0.999878	3422	-0.169
40	0.999725	3423	0.132

MOVING ELECTRON MAGNETS AND TUNING RF IN BOTH RINGS

Moving warm electron magnets is technically easier than moving super-conducting ion ones. For this reason, we focus on this option below. However, the bunch timing and therefore the bunch frequency are no longer equal to the nominal ones:

$$T_i = T_e \neq T_{0i,e}\ ,\ \ f_i = f_e = \frac{1}{T_e} = \frac{n_{0e}c}{L_{0e}+\Delta L_e} \approx \frac{n_{0e}c}{L_{0e}}\left(1-\frac{\Delta L_e}{L_{0e}}\right) = f_{0e}\left(1-\frac{\Delta L_e}{L_{0e}}\right) \neq f_{0i,e}\ . \quad (4)$$

Thus, the RF frequency has to be adjusted in both the electron and ion rings along with the electron path length. Employing ion harmonic jumps again limits the necessary electron path length adjustment to plus or minus a half of the bunch spacing (±31.47 cm) and hence, according to Eq. (4), the necessary frequency adjustment. Table 5 lists the required electron path-length change and RF frequency adjustment as functions of the ion momentum.

Table 3: Electron path-length change and adjustment of RF frequency in both collider rings as functions of the ion momentum in the case of variable ion bunch number

p (GeV/c/u)	**β_i**	**n_i**	**ΔL_e (m)**	**Δf (kHz)**
100	0.999956	3422	0.000	0
80	0.999931	3422	-0.053	-11.8
60	0.999878	3422	-0.169	-37.3
40	0.999725	3423	0.132	29.1

Moving Electron Arcs

Moving magnets in the electron arcs reduces the range of magnet motion in comparison to moving magnets in a chicane but one then has to deal with a large number of magnets. The total bending angle θ of the electron collider ring is 523.4°. Assuming uniform radial movement of the arcs, the total range of radial shift of all arc elements is

$$\Delta R = \lambda / \theta \approx 69 \text{ mm} \quad (5)$$

Clearly, this cannot be done by simply moving the beam in the magnet apertures. With about 336 gaps between the regular arc dipoles and quadrupoles, the maximum required gap change is about 1.9 mm. Note that the assumption of uniform arc expansion or contraction requires a dogleg at each end of the arc with a transverse shift range of 69 mm.

Movable Electron Chicane

Adjusting the path length by moving magnets in a chicane requires movement of a relatively small number of magnets but the range of movement in comparison to moving the whole arcs is larger. The chicane option described here does not require the chicane dipoles to exceed the nominal bending angles of the arc dipoles. Since there are no sagitta issues, regular arc dipoles can be used for such a chicane.

Consider an arc section consisting of a number of regular arc FODO cells with the exception that the two edge and two middle dipoles bend by angles different than regular FODO dipoles. The bending angles of the edge and middle dipoles are varied but the sum of the bending angles of one edge dipole and one middle dipole is always equal to the bending angle of a single regular FODO dipole. This way the total bending angle of the whole section remains fixed. We also require that the cord of this arc section stays fixed. Then the geometry of the rest of the ring does not change. The path length change in such a chicane comes from redistributing bending between the edge and middle dipoles. When the bend of these four special dipoles is concentrated in the edge dipoles, the chicane is in its shortest configuration. When the bend is concentrated in the middle dipoles, the path length is the longest. The geometry of a chicane consisting of five FODO cells is shown in Fig. 1.

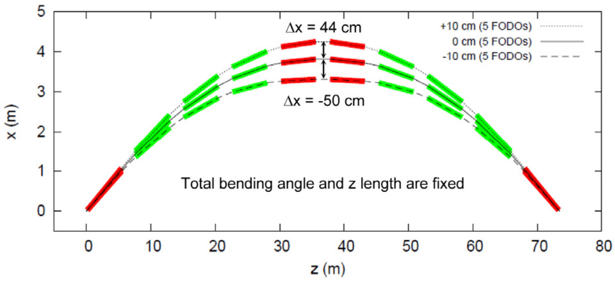

Figure 1: Five-FODO-cell movable electron chicane.

The transverse magnet shift needed for a 20 cm path length adjustment is about 94 cm with the change of inter-magnet spacing of about 11 mm. A number of such chicanes or a larger transverse shift is needed to provide the total needed path-length change. The chicane optics has to be tuned to account for the change in the bending angles and, for this reason, is not convenient for chromaticity compensation.

SYNCHRONIZATION WITH EQUAL NUMBERS OF BUNCHES

Synchronization with pair-wise bunch collisions requires much greater beam path-length adjustment and/or frequency tuning range than the case of non-pair-wise bunch collisions. The main reason for considering this option is the possibility of a dynamic instability caused by non-pair-wise collisions. This instability does not appear to be critical in the JLEIC case but is still being studied.

To minimize the required RF frequency change, the ion bunch number changes with energy as shown in Table 4. Then, to keep the collisions pair-wise, the electron bunch number is also changed to match the ion harmonic number. The electron path length is changed to accommodate the additional bunches. Energy ranges between the bunch number changes are covered by one of the schemes described above. Covering the ion energy range from 18 to 100 GeV requires addition of 4 electron bunches and therefore a total path length change of 4λ = 252 cm.

Table 4: Change of the ion bunch number with energy

Ion energy (GeV/u)	**Bunch number**
47.25	3423
29.28	3424
22.91	3425
19.38	3426

The large necessary electron path length adjustment can be obtained using a system of electron bypass beam lines shown in Fig. 2. The edge dipoles shown in red send the electron beam down one of the 5 paths. The parameters of each path line are given in Table 5.

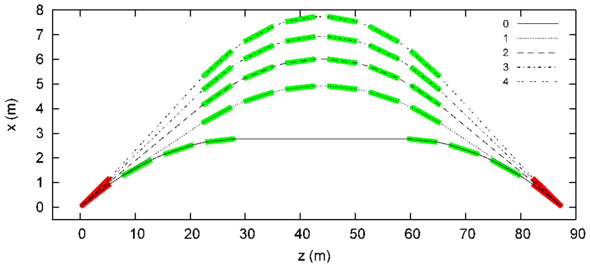

Figure 2: System of electron bypass beam lines.

Table 5: Parameters of the Individual Beam Lines in Fig. 2

Line #	**B1 angle (°)**	**B2-4 angle (°)**	**Δx_{max} (m)**	**ΔL (m)**
0	2.8	2.8	0	0
1	2.8	2.8	2.14	0.315
2	0.74	3.49	3.23	0.74
3	-0.97	4.06	4.15	0.97
4	-2.47	4.56	4.96	2.47

CONCLUSIONS

There are solutions for synchronizing bunch collisions in JLEIC when ion energy changes. Since change in the ion beam energy is expected to happen on a half a year to a year time scale, the necessary adjustments can be made in a few days during a shutdown. There are options for both equal and different numbers of bunches in the electron and ion rings. Most of the proton program can be completed with equal numbers of bunches. Bunch variation may only be needed for heavy ions.

The movable electron chicane scheme (involving bunch number variation, modest RF frequency adjustment, and two or three chicanes similar to that illustrated in Fig. 1) seems preferable because (a) moving warm electron magnets is technically easier than moving super-conducting ion magnets, (b) since the required movement is large enough that it requires special design even when all arc magnets are shifted, it is preferable to deal with a small number of specially designed magnets and movers, and (c) the available RF tuning range is consistent with the frequency adjustment requirements (CEBAF frequency mismatch is within the momentum acceptance of the electron collider ring).

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