HIGH-INTENSITY BEAM ACCUMULATOR RING FOR ELECTRON-ION COLLIDER

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Abstract

The Beam Accumulator Ring (BAR) is part of the Electron-Ion Collider (EIC) injector complex at Brookhaven National Laboratory. It is designed to accumulate a polarized 750 MeV electron beam up to a single-bunch charge of 28 nC for injection into the Rapid Cycling Synchrotron (RCS). A compact double-bend achromat lattice is based on the NSLS VUV ring. The BAR design incorporates well-proven magnet, vacuum, RF, beam diagnostics, and control technologies. Comprehensive studies of injection and extraction schemes, error correction, and collective effects demonstrate robust beam accumulation. With the bunch shortening by RF modulation to mitigate the bunch lengthening caused by the microwave instability, all beam parameters at extraction meet the specifications. The preliminary design validates BAR performance goals and establishes readiness for integration into the EIC injector chain.

INTRODUCTION

The Beam Accumulator Ring (BAR) is a part of the Electron-Ion Collider (EIC) injector chain. It is located between the 750 MeV linac-injector and the full-energy (5-18 GeV) Rapid Cycling Synchrotron (RCS), as shown in Fig. 1

The functional role of BAR is the accumulation of charge injected from the linac to reach the high intensity of the polarized electron beam required by the specifications of the Electron Storage Ring (ESR) injection. This function will be realized via successive 30 injections of 1.1 nC bunch at a repetition rate of 30 Hz. Once 28 nC of charge in a single bunch is achieved, the former gets extracted from BAR and injected into RCS. The required beam parameters are collected in Table 1.

Table 1: Specification of Beam Parameters

	At injection	**At extraction**
Energy	750 MeV	750 MeV
Charge	1.1 nC	28 nC*
Horizontal Emittance	45 nm	$<$ 170 nm
Vertical Emittance	30 nm	$<$ 65 nm
Energy spread	4.5×10^{-3}	$0.5–5\times10^{-3}$
Bunch length	0.7 mm	20–70 mm
Repetition rates	30 Hz	1 Hz

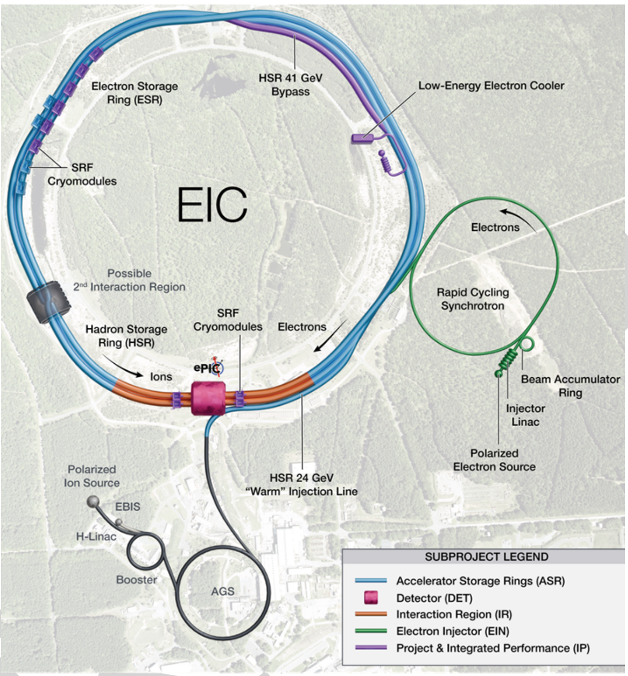

Figure 1: Schenatic layout of the EIC accelerators.

Note, a maximum charge of 32 nC is assumed in BAR in order to provide 28 nC to the RCS with a margin for particle losses along the acceleration and extraction processes.

As the repetition rate of the ESR injector is chosen as 1 Hz, the working cycle for BAR will be 1 second, with about 966 ms for accumulation and 34 ms for extraction. We also consider an option with 1.5-nC injected bunches, allowing extra time for the longitudinal phase space manipulation using RF modulation techniques to provide the bunch length and energy spread required for the injection into RCS. Two beamlines connecting the Linac to BAR and BAR to RCS are being designed to enable lossless beam transport between the accelerators.

DESIGN OPTIMIZATION FOR COST EFFICIENCY

The main goals of the BAR design are a low technical risk and a high reliability. Originally, the BAR lattice design was based on the NSLS VUV ring [1], which met all the requirements listed in Table 1. The maximum single-bunch charge accumulatied in the NSLS VUV ring was about a factor 2 higher than the BAR maximum charge of 32 nC [2]. However, the bunch length measured at NSLS VUV showed that the microwave instability threshold is much lower than

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the BAR maximum accumulated beam charge, so the bunch length and energy spread are significantly increased at 32 nC. To provide the bunch length required for the injection into RCS, we will manipulate longitudinal phase space at extraction using RF modulation techniques.

To provide a cost-efficient solution, the ring circumference was reduced from 50 m of NSLS VUV to 36 m resulting in a twice smaller footprint providing a significant cost saving in the building construction and operation. Fig. 2 shows the evolution of BAR layout reducing the ring circumference and footprint.

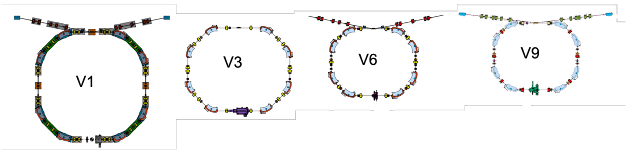

Figure 2: BAR layout evolution.

The lattice design evolved from four Double-Bend Achromat cells to two Four-Bend Achromat cells, only two straight sections remain to accomodate the injection/extraction septum magnet and the RF cavity. The use of combined-function dipole magnets allows us to reduce the number of quadruple magnets from 24 to 10, all of them are focusing. The defocusing quadrupoles are included in the 45° dipole magnets by virtue of a 3° pole face slope. Better locations of sextupole magnets in high β_x, low β_y and high β_y, low β_x locations allowed reducing the number of sextupoles from 12 to only 4.

MAGNET LATTICE AND LAYOUT

The layout of the most recent version of BAR and beam transport lines is shown in Fig. 3, the lattice functions are presented in Fig. 4, and the beam parameters are listed in Table 2.

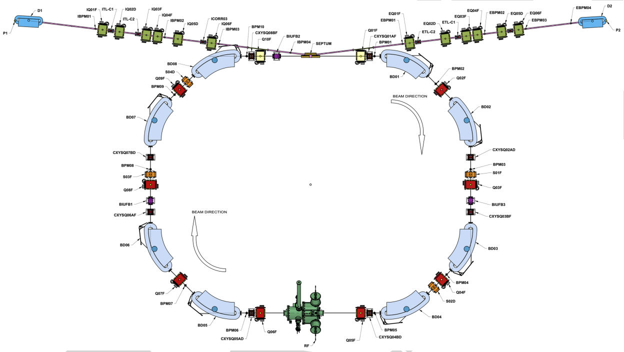

Figure 3: Layout of BAR and transport lines.

The radiation damping times were reduced by about a factr of two compared to NSLS VUV, and are comfortably lower than the time between linac pulses (33.3 ms). The betatron tunes are selected to avoid strong low-order betatron and spin resonances. The error analysis was completed using Monte-Carlo technique with all lattice errors including magnet multipole harmonics, and the magnet tolerance specifications are complete. The orbit errors and correction were analyzed resulting in the corrector strength requirement of 2 mrad. To control the betatron coupling, 8 combined-function orbit correctors will have skew quadrupole components with a quite low gradient of 0.31 mT/m. The coupling correctors are combined in two familieis.

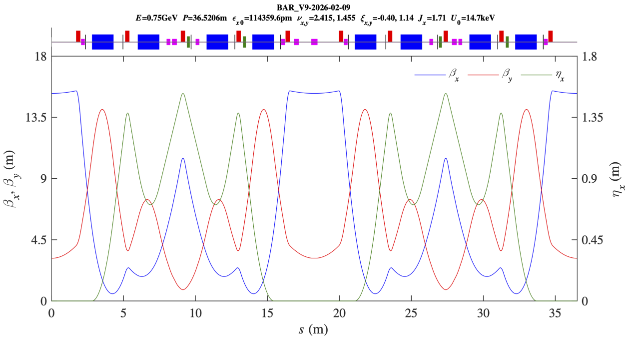

Figure 4: BAR lattice functions.

Table 2: Lattice and Beam Parameters

Parameter	Value
Energy (GeV)	0.75
Circumference (m)	36.52
Hor. emittance (nm)	114
Hor. tune	2.42
Ver. tune	1.46
Natural hor. chromaticity	-3.8
Natural ver. chromaticity	-1.6
Momentum compaction	0.084
Hor. damping time (s)	0.0073
Hor. damping partition	1.7
Ver. damping time (s)	0.012
Ver. damping partition	1
Long. damping time (s)	0.0096
Long. damping partition	1.3
Energy spread	5.78×10^{-4}
Energy loss per turn (keV)	14.66
Revolution frequency (MHz)	8.2089
Aver. hor. beta (m)	7.2
Aver. ver. beta (m)	4.7
Aver. hor. dispersion (m)	0.72
RF voltage (kV)	100
RF frequency (MHz)	98.5062
RF harmonic	12
Synchrotron tune	0.0046
Bunch length (mm)	61.5
RF acceptance	0.008

The injected beam centroid is 13.5 mm away from the stored beam centroid at the end of the septum magnet, the beam trajectories in the injection and extraction transport lines are to the BAR orbit bump slope (1.75 mrad). Three injection/extraction pulsed kickers are located with about 270° horizontal phase advance to provide a closed 3-kicker bump. The required strength of pulsed kickers is below 5 mrad, the kicker pulse shape is a 220 ns half-sine wave.

BEAM DYNAMICS AT HIGH INTENSITY

Beam-impedance interaction results in significant intensity-dependent bunch lengthening [3]. Although the bunch length of a 32 nC bunch is within the specifications the margin is small. Moreover, the beam injection into RCS is more efficient and reliable with shorter bunch length. So, we need the bunch shortening by RF modulation before extraction. With the optimized shapes and durations of the RF voltage and phase ramps, the bunch length meets the specifications with a decent margin, 100 kV is sufficient for the 98 MHz RF frequency, the extra RF power required for the modulation is reasonable [4].

However, if we shorten the bunch before extraction as required for the RCS injection, the transverse head-tail instability may occur, resulting in a particle loss. We plan to carry out comprehensive multi-particle simulations using a detailed impedance budget to study the beam dynamics during the RF manipulation before extraction. If the simulation shows the instability, we will consider installing a transverse damper in BAR. Another possible transverse instability may be caused by the beam interaction with higher-order modes of the RF cavities. Beam-induced heating of the kicker ceramic vacuum chambers needs to be studied too. We will also analyze the beam interaction with residual gas ions to estimate the beam lifetime and ion-driven instabilities.

TECHNICAL PROGRESS

Primary specifications for the BAR and Transport Line magnets are defined. The BAR dipole magnets will be sector shaped, solid yoke with conical pole faces. As a cost-saving solution, we are going to use MIT-Bates Quadrupole magnets, which are available for free, being magnetically measured and evaluated.

The RF voltage range required for the beam accumulation was estimated for two RF frequencies: 49 MHz and 98 MHz. Since the BAR accumulation time is only 1 second, both RF frequency options provide sufficient beam lifetime. However, the bunch is significantly longer at lower RF frequency, so the requirements to the RF modulation for bunch shortening are more challenging.

The conceptual design of vacuum chambers for dipole magnets is complete. The machined clam-shell design provides accurate dimensional control, accessible pumping location and options, simplified external cooling to eliminate separate aluminum system. The thermal analysis is good for higher peak current (266 mA with 98 MHz RF). For the straight sections, we consider extruded chambers with machined outer features for flanges, pumping, BPMs, and quadrupole pole tips.

The beam instrumentation needs to provide reliable measurements with the required accuracy over the rather modest dynamic range of 0.1nC (one tenth of a typical injected bunch charge) to 32 nC – the maximum expected accumulated current. Two options of the vacuum chamber cross-section for button-type Beam Position Monitors (BPMs) are considered: 1) NSLS VUV BPM with a rectangular cross-section 80 mm×40 mm; 2) Octagonal cross-section designed for a vacuum chamber modified to accommodate the MIT Bates quadrupoles considered to be reused in BAR for cost savings. Although the rectangular BPM is more linear at larger beam offsets than the octagonal one, a 2D 5th-order polynomial fit is efficient for both cross-sections. The beam-induced button voltages and spatial resolution are similar for both rectangular and octagonal option [5]. The suite of diagnostics and instrumentation also includes integrating current transformers (ICTs) to measure the bunch charge in BAR and transport lines for control of the injection/extraction efficiency, a wall-current monitor (WCM), and a few insertable fluorescent screens to measure a single-pass beam size and position.

SUMMARY

Our approach is to provide a cost-efficient design with low technical risk and high reliability. The NSLS VUV ring met all the EIC requirements and was our starting point. We have evolved to a 36 m ring with gradient dipoles and significantly reduced numbers of quadrupoles, sextupoles, correctors, and beam position monitors. The 45° BAR dipoles will include a 3° pole face slope to provide vertical focusing (this allowed us to remove 14 quadrupoles). We are going to use MIT Bates quadrupoles available for free, as a cost-saving option. With the bunch shortening by RF modulation, all parameters of the extracted beam meet the specifications for injection into RCS.

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