

PERFORMANCE STRATEGY FOR THE FIRST YEARS OF THE EIC SCIENCE PROGRAM*

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Abstract

The Electron-Ion Collider (EIC) will begin science operations with a staged machine configuration that imposes well-defined accelerator-physics constraints on achievable luminosity and beam parameters. This paper presents the performance strategy that supports the first 3 years of the EIC Science Program. We outline the accelerator-physics activities required to deliver high-repetition-rate electron beams, heavy-ion beams, deuterium, polarized protons, and ³He, together with the performance evolution of electron and hadron polarization systems, spin rotators, bunch patterns, and longitudinal emittance control. The paper highlights the year-by-year integration of new machine capabilities, including progressive increases in beam intensity and average luminosity required to meet evolving science objectives. This framework defines the accelerator-physics roadmap for performance delivery and sustained operation of the EIC Science Program

INTRODUCTION

The Electron-Ion Collider (EIC) is a next-generation accelerator facility under construction at Brookhaven National Laboratory, designed to collide polarized electrons with polarized protons and heavy ions at high luminosity and variable center-of-mass energies [1,2]. The EIC complex (Fig. 1) consists of a DC photoelectron gun, a 750 MeV S-band LINAC, the Beam Accumulator Ring (BAR, 750 MeV), the Rapid Cycling Synchrotron (RCS, 0.750→9 GeV) and two high-energy storage rings: the Electron Storage Ring (ESR) and the Hadron Storage Ring (HSR). Electrons are accelerated in the RCS from 0.750 GeV to 5 and 9 GeV, with provision for acceleration up to 18 GeV following project completion, and subsequently injected into the ESR at the corresponding energy, with 18 GeV operation foreseen as a near-term upgrade. Hadrons are injected from the existing RHIC injector complex into the HSR at 23.8 GeV and ramped to final energies ranging from 41 to 275 GeV, depending on the species, including protons (p), ions, or He³. The 41 GeV energy bypass (Fig. 1, shown in blue) is part of the EIC baseline design. However, its construction and installation are deferred beyond the initial project scope and are planned for implementation during the early years of EIC operations.

The goal of the EIC is to deliver a design luminosity of up to 10^{33} - 10^{34} cm⁻²s⁻¹, enabled by advanced features such

as beam cooling systems, a 25 mrad crab crossing angle, high beam currents - up to $I_{av}=2.5$ A with $M=1160$ bunches of $\sigma_s\sim 7$ mm length in the ESR, and up to 0.7 A / 1 A with $M=290$ and $M=1160$ bunches of $\sigma_s\sim 60$ mm in the HSR during storage. At injection energy, the bunch length in the HSR is expected to be significantly longer, around $\sigma_s\sim 1.5$ m.

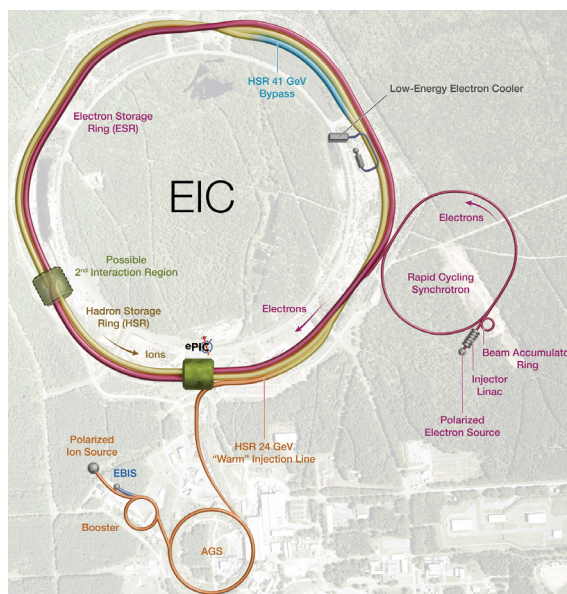


Figure 1: Top view schematic of the Electron-Ion Collider (EIC) accelerator complex, including the electron and hadron injector chains, the Beam Accumulator Ring (BAR), the Rapid Cycling Synchrotron (RCS), and the Electron and Hadron Storage Rings (ESR and HSR).

HSR

Different hadron species are foreseen to collide with the electron beam. Depending on the species, the beam is accelerated to the required operational energy. As an example, the sequence for proton beam injection into the HSR is outlined below; this sequence may be further refined during commissioning.

Since the EIC utilizes RF systems inherited from RHIC, the following steps are performed. The proton beam is injected into HSR at 23.8 GeV in a single-bunch mode, with injection cycle of ~ 3 s per bunch, accumulating up to 290 bunches using the 24.6 MHz RF system ($h=315$). The beam is then accelerated to the operational energy (e.g., 275 GeV), after which the spin rotators and snakes are ramped to their operating currents (~ 10 min). The bunch structure is subsequently formed through a sequence of bunch splitting and longitudinal RF gymnastics, from 290

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to 580 bunches using the 49.2 MHz normal-conducting (NC) RF system ($h=630$) and further to 1160 bunches using the 98.5 MHz RF system ($h=1260$). The 197 MHz NC RF cavities are then used for bunch compression, followed by activation of 591 MHz superconducting RF (SRF) cavities (4 cavities in 2 cryomodules) for final bunch shortening and preparation for collisions. A radial orbit shift is applied to synchronize the revolution frequencies of the hadron and electron beams. Finally, the crab cavities are activated and tuned in phase and amplitude. The total time required to prepare the HSR beam under these conditions is expected to be on the order of 50 minutes.

From the commissioning standpoint, operation with a reduced number of bunches (e.g., $M=290$) and selection of hadron species and energies that keep the beam close to the nominal orbit are preferable. In this configuration, the need for a horizontal radial orbit shift - potentially reaching up to ~ 20 mm near the focusing quadrupoles in the arcs at high energies - is minimized. This reduces sensitivity to aperture limitations, nonlinear fields, optics distortions, lattice optimization constraints, and the required corrector strengths during early operation.

PERFORMANCE EVOLUTION

During commissioning and the first years of the EIC science program, the collider will operate in a staged configuration, in which key accelerator systems are installed and commissioned progressively. As a result, several performance-enhancing subsystems will not be fully available at the start of operations, leading to conservative beam intensity and luminosity conditions.

The following systems will not be fully deployed or operational during early commissioning and initial science: **591 MHz SRF system (ESR)**: Initially, only two cryomodules (four cavities out of the final twelve) will be installed in the ESR. This configuration limits the maximum achievable electron beam current at 9 GeV to ~ 0.9 A within $M=1160$ bunches (~ 10 nC/bunch) and ~ 0.63 A within

$M=290$ bunches (~ 28 nC/bunch). Full installation of all six cryomodules will enable operation at design currents (~ 2.5 A and $M=1160$).

394 MHz crab cavity systems: Initial operation will rely on the available 197 MHz crab cavities in the interaction region [3]. The full 394 MHz crab cavity systems in the ESR and HSR, required for optimal crossing-angle compensation and peak luminosity, will be commissioned in later stages.

Beam cooling systems: Advanced cooling systems, including the Low-Energy Cooler (LEC) at injection energy and stochastic cooling in the HSR, will not be available during early operation. Their absence will result in larger emittances and reduced beam luminosities. These limitations constrain the maximum achievable beam intensities, beam quality, and luminosity during the initial phase. However, even within the constraints described above, the beam currents listed in Table 1 should be interpreted as target operational values rather than immediately achievable conditions. Achieving these intensities will require a progressive commissioning period.

The expected performance during the first years of the EIC science program is summarized in Table 1. The beam currents and bunch configurations listed reflect the operational conditions achievable in the initial staged configuration. The corresponding luminosities are derived from these parameters and represent performance targets for early physics running. Heavy-ion collisions with electrons during Science Year 1 will immediately enable exploration of unique physics opportunities, even at the initial luminosity available during early collider operation. Heavy-ion operation during early commissioning is also favorable from the synchronization perspective, since the required HSR radial orbit shift remains relatively small for the initial ion species and beam energies. For example, at 118 GeV/u, the required average shift is ~ 5 mm.

Table 1: First Years of the EIC Science Program

	Science Year 1	Science Year 2	Science Year 3
Species	Silver (Ag)	Deuterium (d)	Proton (p)
Energy, ESR \times HSR	9 GeV $e^- \times$ 118 GeV/u Ag	9 GeV $e^- \times$ 130 GeV/u d	9 GeV $e^- \times$ 130 GeV p
Integrated Luminosity	$\sim 0.9 \text{ fb}^{-1}$	$\sim 3.9 \text{ fb}^{-1}$	$\sim 1 \text{ fb}^{-1}$
Average Luminosity	$\sim 6.2 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$	$\sim 2.7 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$	$\sim 6.8 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$
Polarization, e^-/h	Commissioning only / No	Yes / No	Yes / Yes
Average Current, $I_e \times I_h$	0.63 A \times 0.07 A	0.9 A \times 0.3 A	0.9 A \times 0.3 A
Number of Bunches	290 \times 290	1160 \times 1160	1160 \times 1160
Roman Pot	No	No	Yes

Science Year 2 introduces higher-luminosity electron-deuterium collisions with polarized electron beams, enabling the start of the polarized physics program while maintaining reduced complexity on the hadron side through unpolarized deuteron operation. The increased

number of bunches and higher average beam currents provide a luminosity increase relative to Science Year 1.

Science Year 3 expands the physics reach to fully polarized electron-proton collisions and includes the commissioning of the Roman Pot system for forward physics

measurements. At this stage, simultaneous polarization of both beams becomes essential for the spin physics program. The achievable HSR beam intensity during the first science years remains limited by beam-beam interaction constraints associated with the absence of the 394 MHz crab-cavity system. These limitations will be progressively relaxed in subsequent operation stages through staged installation of additional RF systems, crab cavities, and beam-cooling capabilities.

LUMINOSITY PERFORMANCE

Figure 2 shows the projected luminosity evolution for the first three EIC Science Years under staged commissioning assumptions using a Python-based luminosity model

developed by W. Bergan [4]. Science Year 1 operation is based on electron-heavy-ion (silver) e-Ag collisions with partial RF installation in the ESR, without 394 MHz crab cavities in the ESR and HSR, and without low-energy cooling (LEC) at injection energy or stochastic cooling, resulting in reduced luminosity performance (black trace). Adding stochastic cooling increases the average luminosity (red trace).

Science Year 2 introduces higher-luminosity e-d collisions with increased bunch number and beam currents. Since deuterium and proton operation use similar beam parameters, the luminosity performance is primarily determined by beam-dynamics limitations and staged accelerator configuration.

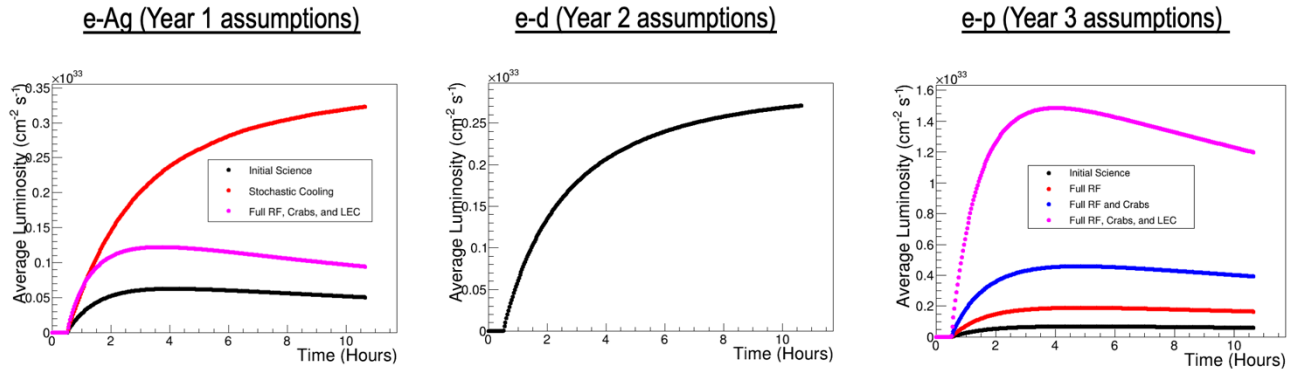


Figure 1: Evolution of the average luminosity for e-Ag, e-d, and e-p collisions during the first years of the EIC science program under staged RF, crab-cavity, and beam-cooling configurations.

Science Year 3 extends operation to polarized e-p collisions and demonstrates the strong luminosity gains achievable through the progressive installation of full RF systems, crab cavities, and low-energy cooling (LEC) at injection energy. During early operation, in the absence of the 394 MHz crab-cavity system, the achievable HSR beam intensity remains limited by beam-beam interaction constraints (black trace). These limitations are progressively relaxed as additional RF cavities, crab cavities, and cooling systems become available, resulting in substantially improved luminosity performance (magenta trace).

COMMISSIONING CONSIDERATIONS FOR EARLY OPERATION

Early EIC commissioning will proceed under staged accelerator configurations in which beam intensity, luminosity, and operational complexity increase progressively as additional accelerator systems become available. During this phase, several accelerator-physics and machine-protection considerations play an important role in defining the achievable operational envelope.

Commissioning considerations for early EIC operation include collective effects associated with the collimation system, vacuum chamber impedance, and interaction-region components, which must remain compatible with stable operation and acceptable beam-induced heating during beam-current ramp-up. Particular attention is required for

impedance control in the HSR, including space charge, geometric and resistive-wall wakefield effects, as well as higher-order-mode (HOM) power deposition and damping in the SRF systems at increasing bunch intensity. Cross-checks of collective effects during early low-intensity commissioning are important for establishing the operational path toward the ultimate EIC design beam parameters and luminosity goals.

An additional commissioning challenge for Science Year 1 is the delivery of high-charge electron bunches (~ 28 nC) from the injector complex into the ESR with a reduced bunch pattern ($M=290$). Operation at such high bunch charge requires careful control of collective effects in the injector chain, including those associated with the Beam Accumulator Ring (BAR) and Rapid Cycling Synchrotron (RCS), as well as single-bunch stability, longitudinal beam dynamics, and preservation of beam quality during accumulation in the BAR and acceleration in the RCS [5,6].

In the HSR, the absence of low-energy cooling (LEC) and stochastic cooling during early operation results in larger and round hadron beams with transverse emittances of order ~ 3 μm , compared with the ultimate design emittance regime of ~ 0.3 μm targeted in later operation stages [7,8]. Under these conditions, the space-charge impedance contribution is reduced; however, studies of space-charge effects at injection energy, together with geometric and resistive-wall wakefields, are continuing and remain important considerations during injection, accumulation, and

acceleration. The larger emittances also require more conservative beam-beam parameters and optics configurations during initial operation.

Additional commissioning activities include staged commissioning of the crab-cavity systems, synchronization of electron and hadron revolution frequencies through controlled radial orbit shifts in the HSR, commissioning of spin rotators and polarization systems, and integration of interaction-region components such as Roman Pots, detector chambers, and polarimeters. As operation progresses toward polarized electron-proton collisions, beam-beam stability, polarization preservation, and interaction-region optimization become increasingly important for sustained high-luminosity collider performance.

Overall, the staged commissioning strategy provides a controlled operational path from first beam and initial collisions toward full collider performance, with luminosity progressively increasing as RF systems, crab cavities, beam cooling, and optics optimization are implemented.

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