CONCEPTUAL DESIGN OVERVIEW OF THE ELECTRON ION COLLIDER INSTRUMENTATION*

D. M. Gassner†, J. Bellon, M. Blaskiewicz, A. Blednykh, K. A. Drees, T. Hayes, C. Hetzel,
D. Holmes, R. Hulsart, P. Inacker, C. Liu, R. Michnoff, M. Minty, C. Montag, D. Padrazo Jr,
M. Paniccia, V. Ptitsyn, V. Ranjbar, M. Sangroula, T. Shaftan, P. Thieberger, E. Wang, F. Willeke
Brookhaven National Laboratory, Upton, NY, USA
L. Dalesio, Osprey DCS LLC, Ocean City, USA

Abstract

A new high-luminosity Electron Ion Collider (EIC) is being developed at Brookhaven National Laboratory (BNL). The conceptual design [1] has recently been completed. The EIC will be realized in the existing RHIC facility. In addition to improving the existing hadron storage ring instrumentation, new electron accelerators that include a 350 keV gun, 400 MeV Linac, a rapid-cycling synchrotron, an electron storage ring, and a strong hadron cooling facility will all have new instrumentation systems. An overview of the conceptual design of the beam instrumentation will be presented.

INTRODUCTION

The EIC [1, 2] will be realized in the existing Relativistic Heavy Ion Collider (RHIC) facility, the primary additions will be a chain of electron accelerators and systems that will reside inside the RHIC tunnel and service buildings. The well-established beam parameters of the present RHIC facility are close to what is required for the highest performance of the EIC, except for the total hadron beam current which will be increased by a factor of approximately three by increasing the number of bunches. A strong hadron cooling facility will utilize 100 mA of 150 MeV electrons to reduce the hadron beam emittance and control emittance growth due to intrabeam scattering. Polarized electrons will be generated in a new 350 keV DC gun from a strained superlattice GaAs photocathode and will be accelerated to 400 MeV in an S-band normal conducting Linac. The 3.8 km rapid cycling synchrotron (RCS) then increases the electron energy to 5, 10 or 18 GeV in 100 - 200 ms, then fills the electron storage ring (ESR). The 3.8 km ESR will provide ~70% polarized electron beams at 5, 10 or 18 GeV for collisions with the polarized protons or heavy ions in the hadron storage ring (HSR) at 41, 100 and 275 GeV. To maintain high spin polarization, each of the ESR electron bunches will be replaced every one to three minutes.

ELECTRON PRE-INJECTOR LINAC

Beam instrumentation (shown in Table 1) for the 350 keV DC gun and the 400 MeV electron LINAC [3] will be designed to measure beam properties at a repetition frequency of 1 Hz with single-bunch charge ranging from 100 pC to the design charge of 10 nC per bunch. Beam position monitors will measure the trajectory of the beam that has a bunch length range of 2 ns to 4.5 ps with better than 100 µm resolution. A pair of selected BPMs will provide time-of-flight measurements to determine the beam energy.

Table 1: Electron Pre-Injector Instrumentation

Type	Quantity
Beam Position Monitors	9
Beam Loss Monitors	5
Fast Current transformers	1
Integrating Current transformers	7
Faraday Cups	4
YAG/OTR Screen profile monitors	9
Longitudinal Profile Monitors	2
Mott Polarimeters	2
Slit scanner	1
Wire scanners	7

Transverse profile monitors using plunging YAG/OTR screens will be located throughout the beamlines. Slit scanners and wire scanners will be used to measure beam emittance. Longitudinal bunch profiles will be measured with a plunging radiator at low energy, and using synchrotron light emitted downstream of a bending magnet at 400 MeV, with a shared streak camera. Relative bunch lengths will be non-destructively measured using a ceramic gap with waveguide-coupled fast diodes downstream of the 4.5 ps bunching section. Mott polarimeters will be installed at the cathode preparation system (100 eV) and in the first diagnostic beamline upstream of the Linac (350 keV). Scintillators coupled to photo-multiplier tubes (PMTs) and/or Geiger counters, used to detect X-ray and gamma ray, will be placed after the gun, after the first dipole, in the bunching sections and between the acceleration sections to localize beam loss. Additionally, a long optical-fiber beam loss monitor will be used between the gun and the entrance of the Linac. All EIC current and charge monitors (DCCT, ICT, FCT) will be commercially provided [4].

RAPID CYCLING SYNCHROTRON

The EIC RCS [5] will accelerate two batches of four 7 nC bunches in adjacent buckets that are 1.69 ns apart that will subsequently be merged into two 28 nC electron bunches that are 2.43 µs apart by means of two steps of pairwise merging on a 1 GeV porch using the 591 MHz,

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† gassner@bnl.gov

295 MHz and 148 MHz RF systems. Once per second, new electron bunches are injected and accelerated (in 100 ms or 200 ms) to a beam energy of up to 18 GeV and injected into the fixed-energy ESR and brought into collisions with the hadron beam. The RCS BPM pickups will be in a rotated button arrangement. There will be one dual plane BPM at each of the 576 quadrupoles, located in a 32.8 mm diameter round beam pipe. The bunch intensity range is 1 to 28 nC, with a bunch length range between 16 – 91 ps. The required BPM resolution is on the order of 100 µm for the injected bunch and 10 µm for average orbits over many turns.

To facilitate commissioning and for re-establishing beam in the RCS, 7 plunging fluorescent screen transverse profile monitors will be installed, one after the injection septum and one in each of the 6 sectors. The screen profile monitor design will have similarities to the ones used in the NSLS-II storage ring with careful attention given to the impedance characteristics. See Table 2.

Table 2: RCS Instrumentation

Type	**Quantity**
Beam Position Monitors	576
Synchrotron Light Monitor	1
DCCT	1
Fast Current Transformer	1
Tune Monitor	1
Fluorescent Screens	7

The betatron tunes will be monitored at injection using BPMs to measure injection oscillations and during acceleration using turn-by-turn BPMs with beam excitation applied using fast strip-line kickers. A synchrotron light monitor (SLM) will be used for transverse profile measurements in the RCS using synchrotron radiation emitted from a bending magnet. The synchrotron radiation will be extracted through a dedicated optical beamline to a remotely located experimental room. The measured profiles will be used, together with modelled or measured beam optics, to infer the beam emittances and energy spread. Turn-by-turn measurements using gated cameras will provide measurements of injection matching, evaluate beam size evolution and beam position stability during acceleration. A streak camera will provide measurements of the bunch length and longitudinal profiles. A wide-band longitudinal bunch length monitor will be used to provide data for a mountain range display to show the bunch merging evolution.

TRANSFER LINE INSTRUMENTATION

Instrumentation in the two electron transfer beam lines (as shown in Table 3) will provide measurements for beam commissioning, regular monitoring, and optimization of routine beam operations. The BPMs will measure the single-bunch trajectories at a 1 Hz rate and will be used as input for trajectory correction and/or feedback to optimize beam transmission efficiency. In addition, the BPMs will be used to measure the beam energy and characterize the accelerator lattice. BPMs located in high dispersion regions will monitor relative changes in the beam energy. The orbit response matrix will be measured and monitored using the BPMs, to localize lattice errors. The electron transfer lines will also include multiple plunging YAG/OTR screens. These will provide position and profile measurements for beams with low (YAG) and high (OTR) bunch charge. A YAG/OTR station at a dispersive location will be used to determine the beam energy spread. Multiple, strategically located YAG/OTR stations will be used in combination for beam emittance measurements. The ion injection to the HSR will be changed from sector 6 for RHIC, to sector 4 for the EIC. The instrumentation in the new single pass beam line in the tunnel from sector 6 to sector 4 will be similar to the existing devices in the much longer AGS to RHIC transport.

Table 3: Transfer beamline Instrumentation

Type	**Quantity**
Linac to RCS transfer	
Beam Position Monitors	15
YAG/OTR Screens	7
Integrating Current Transformer	1
Fast Current Transformer	1
RCS to ESR transfer	
Beam Position Monitors	14
YAG/OTR Screens	3
Integrating Current Transformer	1
Fast Current Transformer	1
Sector 6 to HSR ion transfer	
Beam Position Monitors	6
Screen Profile Monitors	6
Integrating Current Transformers	2
Beam Loss Monitors	10

ELECTRON STORAGE RING

The ESR BPM button pickups will be in a planar arrangement, similar to those found in many light source storage rings. There will be one dual plane BPM pick-up at each of the 494 quadrupoles, located in a 36 x 80 mm multipole chamber beam pipe. The bunch intensity range is 2 to 28 nC, with bunch lengths between 7 – 9 mm, and bunch numbers between 290 – 1160 with respective bunch spacing of 40.7 – 10.2 ns, with a maximum current of 2.5 Amps. The most challenging position measurement will be made using the first 20 BPMs after the injection septum to ensure an acceptable injection orbit trajectory. The required resolution of 10 µm horizontal and 5 µm vertical is needed for the single newly injected replacement bunch during operations with 1160 circulating stored bunches in the ring. The average position resolution requirement of the stored beam is on the order of 1 um over many turns.

Two SLMs imaging visible radiation will be located near bending magnets. Water-cooled, in-vacuum mirrors will be used to transport the light out of the vacuum chamber. Several mirrors with good surface quality (< lambda/10) will guide the light to a remotely located experimental room

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containing a CCD/CMOS camera, a gated camera, and a streak camera. An X-ray pin hole monitor will provide a higher resolution (~5 µm) beam profile measurement, compared with the visible SLMs (~60 µm) which are limited by diffraction. This beamline will also allow independent measurements of the energy spread and horizontal and vertical emittance. See Table 4.

Table 4: Electron Storage Ring Instrumentation

Type	Quantity
Beam Position Monitors	494
Beam Loss Monitors	30
Synchrotron Light Monitors	2
X-ray Pin-Hole Monitor	1
DCCT	1
Fast Current Transformer	1
Compton Polarimeter	1
Longitudinal BbB feedback	1
Transverse BbB feedback	1
Slow orbit feedback	1
Tune Monitor	1

BLMs will be located only at strategic locations that include injection and at collimators. A Compton polarimeter will be installed to make a 1% (statistics) measurement of the beam polarization for an individual electron bunch. Both transverse and longitudinal bunch-by-bunch feedback systems are required to damp coupled-bunch instabilities. A tune monitor will utilize a transverse strip-line kicker and BPMs to measure the fractional betatron tunes.

HADRON STORAGE RING

The majority of existing RHIC instrumentation [6] devices in the superconducting HSR will be replaced with improved versions that have better impedance characteristics for operations with the EIC beams. See Table 5.

Table 5: Hadron Ring Instrumentation

Type	Quantity
Beam Position Monitors	276
Beam Loss Monitors	200
Ionization Profile Monitors	2
DCCT	1
Longitudinal Profile Monitor	1
HF Schottky	1
LF Schottky	1
Polarimeters	2
Tune Meter kicker	1
Base-Band Tune Meter	1
Longitudinal Damper	1
Injection Damper	1
Gap Cleaner	1
Head-Tail Pick-up	1

The HSR bunch intensity range is 1 to 30 nC, with bunch lengths between 6 - 7.5 cm, and bunch numbers between 290–1160 with respective bunch spacing of 40.7–10.2 ns, with a maximum current of 1 Amp. The existing 279 RHIC cold BPM striplines will be covered with a screen/sleeve and not used, new cold button pick-ups will be installed nearby each one. The BPM resolution requirement is on the order of 100 µm for the injected bunches and 10 µm for average orbit over many turns. Absolute polarization measurements will be made using a polarized atomic hydrogen jet, similar to the method used in RHIC. For relative polarization measurements, materials analysis of the carbon ribbon targets used in the existing RHIC proton-carbon (pC) polarimeter indicates that the higher proton beam currents at the EIC will induce heating to temperatures causing the targets to break after only a few seconds in the beam. A search for alternative target materials or methods has been initiated. The existing RHIC resistive wall current monitor will be replaced with a wider bandwidth electro-optical detector that can better resolve the longitudinal characteristics of the 6 cm (180 ps) ion bunches [7].

ELECTRON COOLING

To achieve a luminosity of 10^{34} $cm^{-2}s^{-1}$ in the EIC during long collision runs, it is desirable to cool the hadron beams to balance emittance growth rates due to intrabeam scattering thereby allowing the same hadron beam to be kept for long collision runs (~24 hours). A dedicated strong hadron cooling facility [8] with ~ 400 meters of beam transport will provide the 150 MeV, 100 mA electron beam that will co-propagate with the ions in the modulator and kicker regions, then return to an Energy Recovery Linac so the beam can be dumped at low energy. The button BPMs will measure average positions of the 100 pC – 1 nC bunches with 10-100 µm resolution in the transport beamlines. The co-propagating e-ion transverse alignment needs to be <5% of the ~0.7mm RMS beam size in the modulator and kicker.

Table 6: Strong Hadron Cooling Instrumentation

Type	Quantity
Beam Position Monitors	110
Beam Loss Monitors	88
Synchrotron Light Monitors	4
DCCT	2
Integrating Current Transformers	8
Fast Current Transformers	8
Faraday Cup/Dump Monitors	12
Screen Profile Monitors	35
Emittance Slit Monitors	7
Wire Scanners	9
Collimators	4
Relative Bunch Alignment	1
Beam Pipe Temperature Monitors	70

Transverse profiles of the few mm sized beam will be measured with plunging YAG/OTR screens in the beam transports. A streak camera will image synchrotron light emitted from dipoles to measure the expected ~40 ps longitudinal profiles. The synchrotron light will also be used to measure and ensure the slice energy spread stays $<10^{-4}$ which is necessary for cooling. Slit and wire scanners will be used to measure the 1.9 - 2.8 µm RMS normalized emittance. Beam losses will be measured using fiber-optic cables coupled with photomultiplier tubes and pin-diode BLMs. The beam pipe temperature will be monitored at critical locations to sense beam scraping. See Table 6.

To ensure the amplified imprint of the ion beam on the cooling electrons interacts with the same part of the ion bunch in the kicker region that the electrons encountered in the modulator, a 1 micron stability for the longitudinal alignment is required in the kicker region. The primary source of instability will be from particle path length changes due to beam line transport magnetic field ripple. Determining a method to make this challenging longitudinal relative alignment is being studied.

INTERACTION REGION

The instrumentation in the IR regions [9] will assist in establishing and maintaining optimum collision configuration, protecting critical devices, and monitoring beam parameters. The electron and hadron beams collide at the interaction point with a 25 mrad crossing angle. To maintain luminosity, a global and local IR orbit feedback system controlling both beams will be implemented to compensate for ~10 Hz variations in the hadron ring arising from triplet magnet oscillations, and excitations in the range from 2 to 30 Hz in the ESR. Four dual-plane beam position monitors (BPMs), two for each beam, will be installed near the interaction points. For fast correction, 12 air-core steering magnets (8 for the vertical plane and 4 for the horizontal plane) will be used in the ESR. Of the 8 magnets, 4 provide position and angle trajectory control and the remaining 4 magnets cancel the dispersion introduced by the trajectory correction. Four vertical steering magnets, of the same type as the magnets used in the existing RHIC 10 Hz feedback system, will be designed for the IR of the hadron ring.

Table 7: Interaction Region Instrumentation

Type	Quantity
Beam Position Monitors	78
Beam Loss Monitors	30
Crab Tilt Monitor	1
IP Orbit Correction	2
Beam Pipe Temperature Monitors	40

Beam loss detectors will be installed near radiation-sensitive devices and at potential high loss regions in the IR to monitor both the hadron and electron beams. See Table 7.

Crabbing Angle Measurements

The electron and hadron bunches will be rotated horizontally by superconducting crab cavities to compensate the loss of luminosity due to the crossing angle inherent in the geometry of the IR. The crabbing angle of the bunches will be measured to setup and monitor these crab cavities. Even though the crabbing angle is confined between the cavities on either side of the IR during normal operations, the measurement can be carried out at a place with proper phase advance in other regions of the ring. Crab cavities placed on one side of the IP will perform the rotation of bunches, and crab cavities on the other side will restore the nominal orientation. To setup the crab cavities, the crabbing angle will be measured for the following cases: with cavities off as a baseline, with cavities at only one side of the IP turned on, and with cavities on both sides of the IP turned on.

An ion bunch tilted by the crab cavities will traverse a horizontal button BPM near the IP and produce signals on opposite pickup electrodes that will have different degrees of distortion depending on the tilt angle. This distortion can be viewed on a fast oscilloscope. In particular, the zero-crossing time difference between the two signals will be approximately proportional to the tilt angle. Simulations were performed to study this effect as a possible diagnostic tool for measuring the crabbing angles of hadron beam for the EIC. A dedicated ion crab tilt BPM will be installed close enough to the IP so that it can see the 12.5 mrad design ion tilt angle [10]. The electro-optic longitudinal profile monitor in the ESR can also be used to monitor the crabbing angle outside of the IR.

The electron beam crabbing angle will be monitored using a streak camera imaging synchrotron light generated at a location outside of the IR with minimal horizontal dispersion and optimal crabbing angle phase advance. The streak camera detects a horizontal beam profile which is tilted from vertical by an amount proportional to the crabbing angle when only the crab cavities on one side of IP are turned on. The tilt angle will be tuned to zero using the streak camera measurement as the phase of the crab cavities on the other side of the IP is optimized. The optimal phase advance from IP to the SLM will be a multiple of pi for maximum sensitivity to the tilt angle in the x-z profile.

COMMON ELECTRONICS PLATFORM

An FPGA based common platform for EIC electronics is planned for use in many systems that include instrumentation, power supply and low-level RF. The conceptual design is envisioned to have a carrier board with the capability for 2 customizable daughter/function cards and be packaged in a 1U chassis. Also under consideration is the use of a multi-slot chassis for high quantity systems, primarily the BPMs. The basic hardware architecture will be common for all systems, the packaging may include a few different versions. The carrier board will be available in both standard and high-performance configurations and have capabilities that include Gigabit ethernet, RS-232, and timing/clock generation. Each daughter card will have ~8” width and provide digital I/O, ADC, DAC and multi-Gigabit serial links to the Carrier FPGA. Electronics for one BPM can be serviced by one daughter card.

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