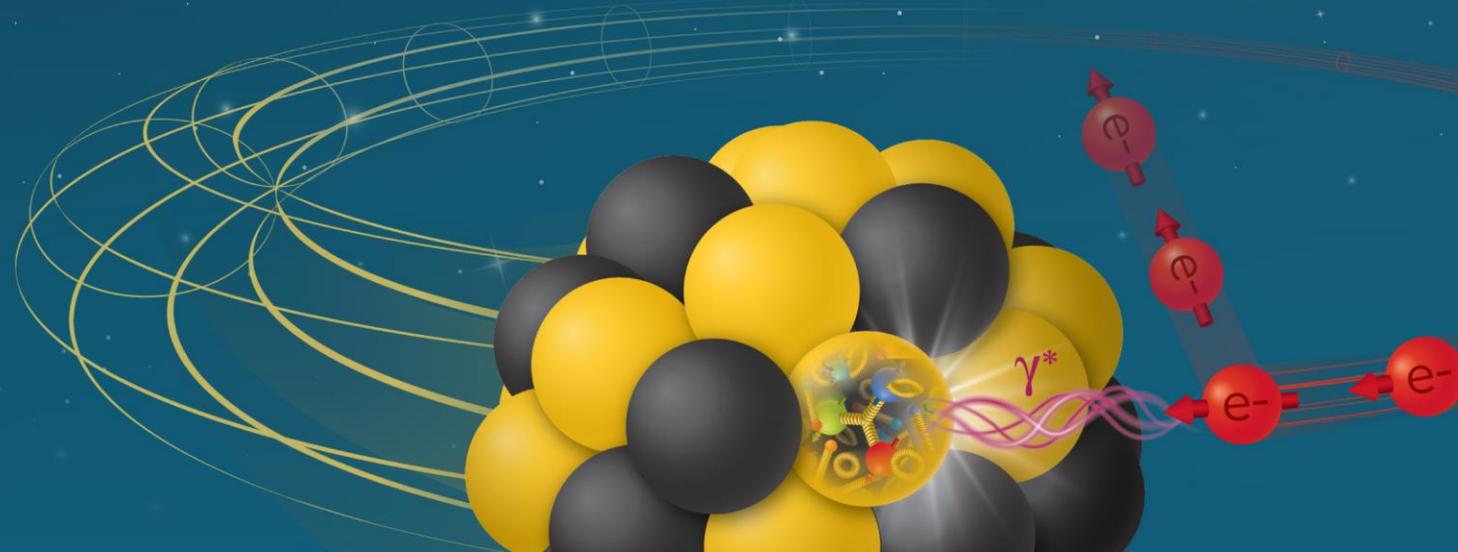# Beam Position Monitoring for Low Energy Cooling Section

I. Pinayev and S. Seletskiy

October 30, 2025
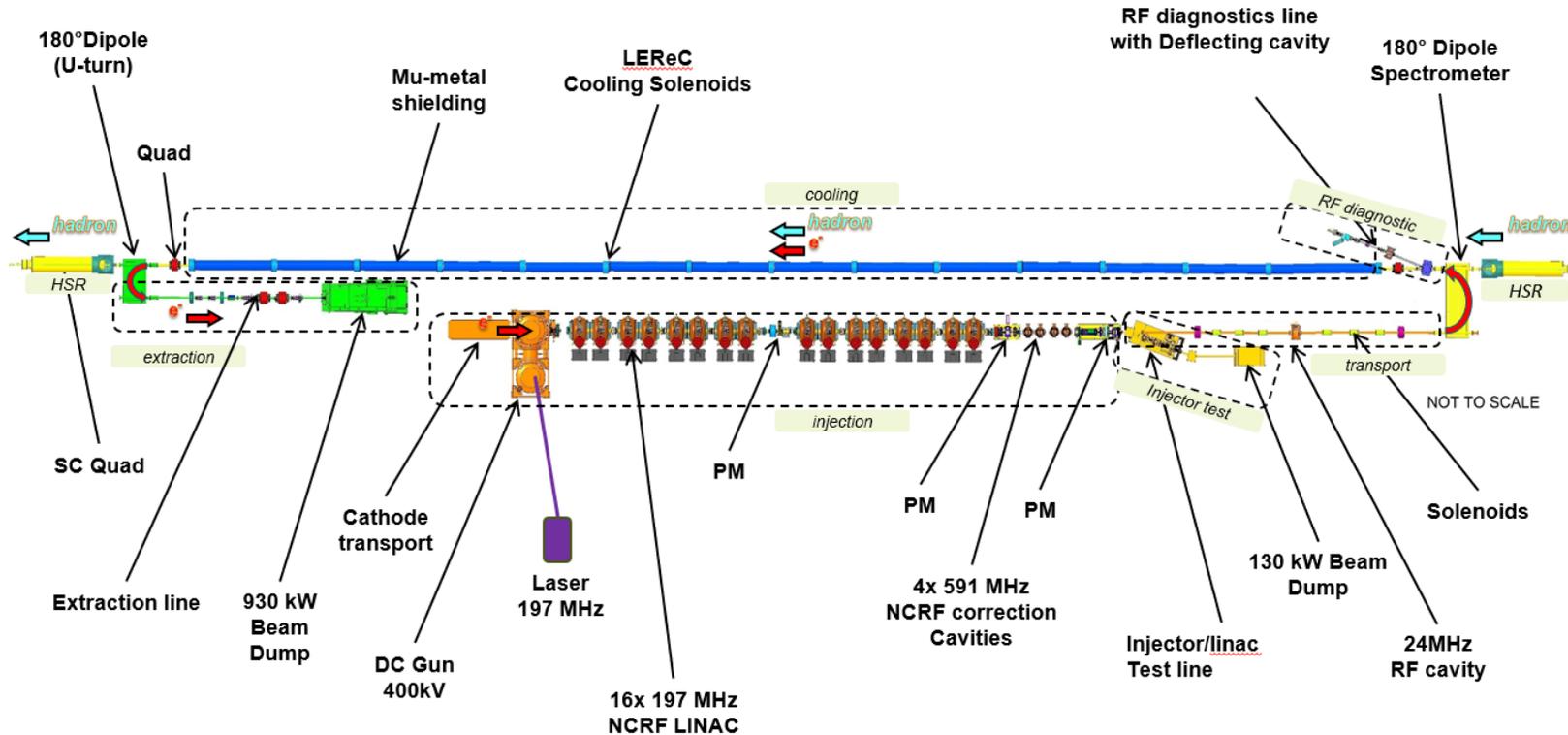
Electron-Ion Collider

Outline

- Motivation
- Beam parameters (hadron and electron)
- Signal levels and spectra analysis
- Possible design choices
- Expected performance
- Operational procedures

Cooling Section Layout

170 meters long
14 BPMs
Cooling with bunched beam
$\gamma = 25.4$
$E_p = 23.8$ GeV
$E_e = 12.5$ MeV
Proton bunch is stretched using harmonic cavity
Pipe diameter is 127 mm
Cable length can vary from 10 to 150 meters
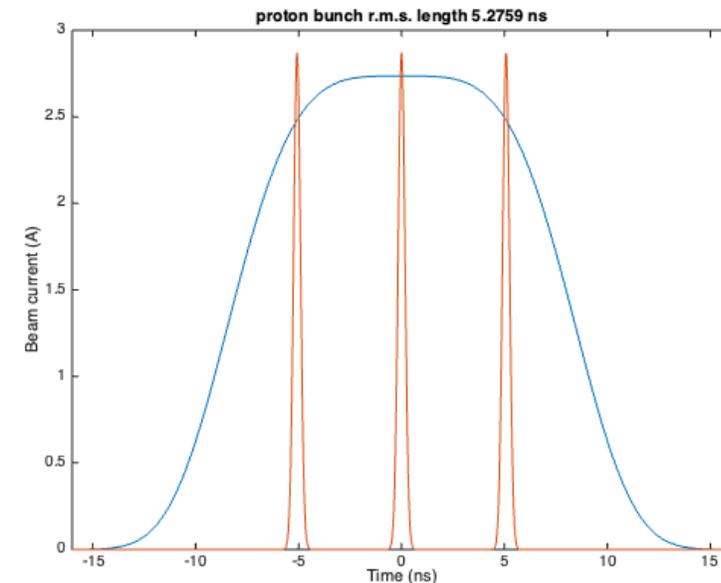
Cooling Section BPM Functionality

- Provide transverse alignment of the proton and electron beams with 35 microns accuracy

- Provide a relative angular spread between the proton and electron beams with 20 microradian accuracy

- Able to measure the hadron pilot bunches with with required precision

- Capable of handling signal levels for the stored hadron beams

- Minimal cross-talk between two BPM systems during cooling

- Desirable to measure phase shifts between the signals induced by the proton and electron beams for the matching of the relativistic factors
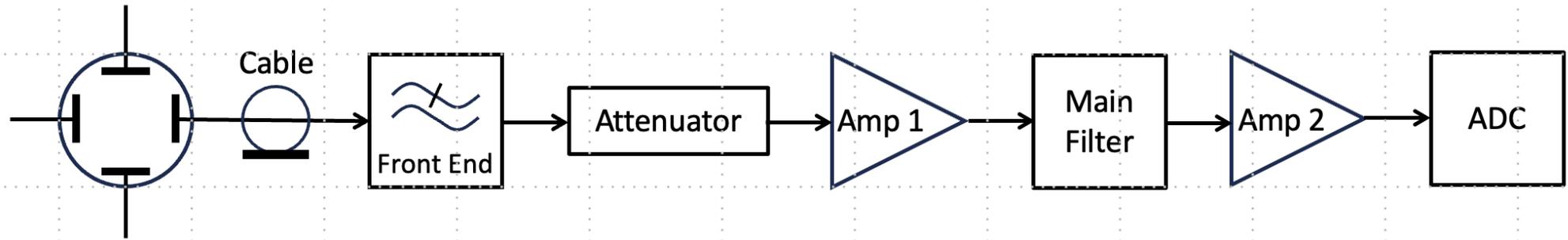
Beam Parameters

- Hadron beam
  - Proton pilot 5 nC 2 ns
  - Gold pilot 5 ns 4.2 ns
  - Proton cooled (projected) γ=25.4 44 nC 3 ns flat top
  - Ramp 44 nC 2 ns
  - Protons at store 31 nC 200 ps (24.6245 MHz)
  - Protons at store 11 nC 200 ps (98. 5 MHz)
  - Protons during ramps 45 nC 200 ps (98.5 MHz)
  - Gold at store 6.3 nC 300 ps 98.5 MHz

- Electron beam (projected)
  - Train of 3 bunches
  - Train repetition rate 24.625 MHz
  - Bunch separation 5.1 ns (197 MHz RF)
  - Bunch charge 1.2 nC
  - Bunch length 170 ps

proton bunch r.m.s. length 5.2759 ns
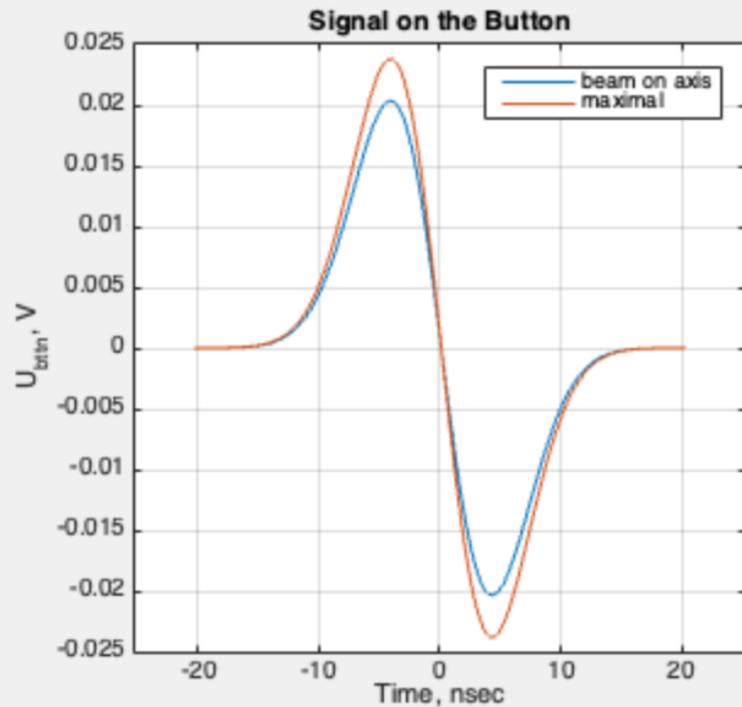
Electron-Ion Collider
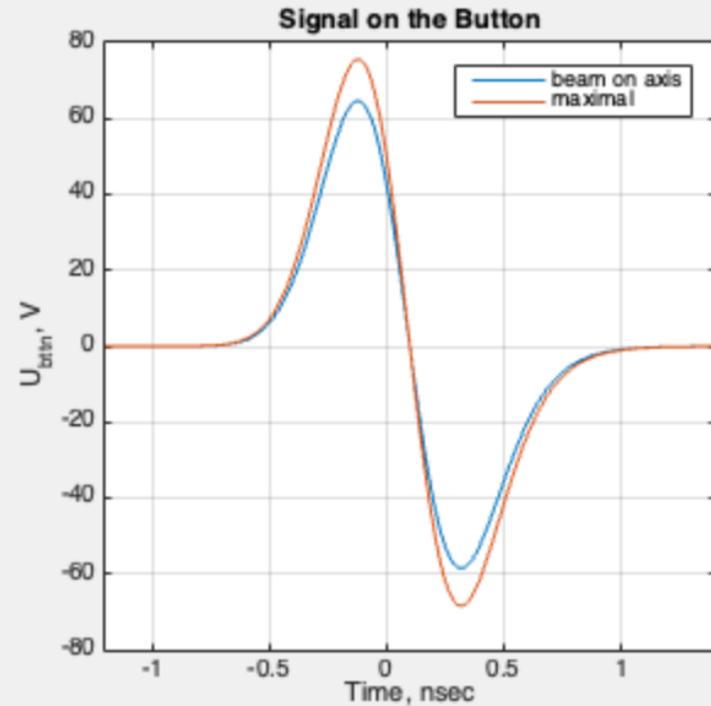
BPM Electronics Architecture

- The signal from the pick-up electrode is delivered to the RF front-end
- Front-end conditions the signal, eliminating unwanted frequencies and reducing the signal level to an acceptable level
- Attenuator normalizes the signal, preventing overload in the amplifiers and ADC
- The main filter provides the final frequency response of the analog part
- The second amplifier compensates for losses in the main filter
- ADC digitizes the signal and provides a stream of data for digital processing

Electron-Ion Collider
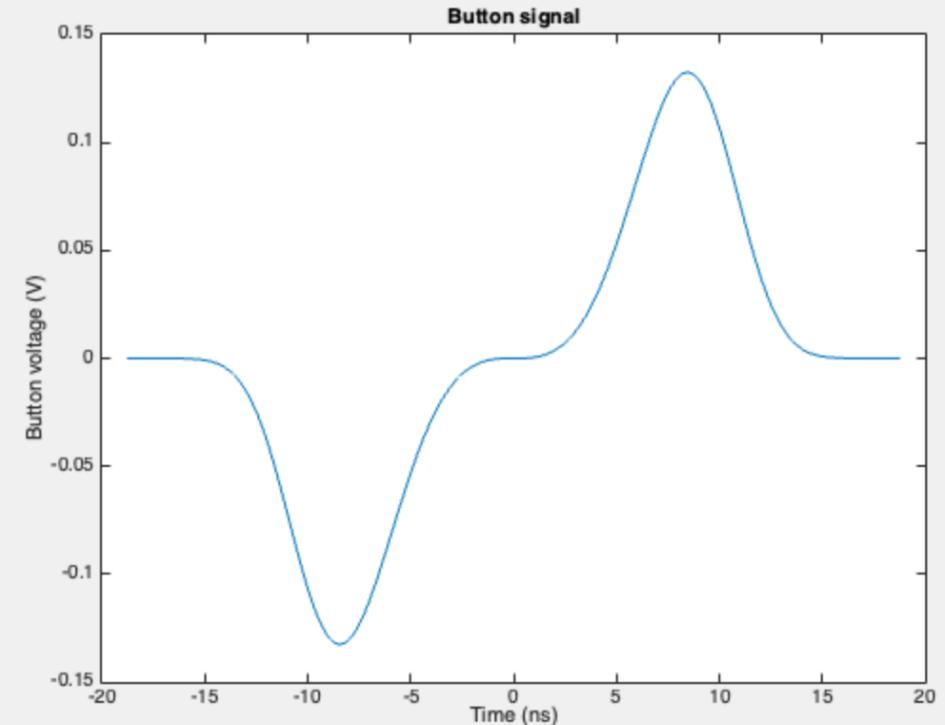
BPM Pickup Signal Levels for Protons

Gold pilot bunch. 5 nC, 4.2 ns long   Proton bunch. 44 nC, 0.2 ns long   Cooled Proton bunch. 44 nC

Signal Conditioning with RF Front-End of the Hadron BPM

Before front-end   After front-end

The low-pass front-end filter stretches the pulse and reduces the peak voltage

Electron-Ion Collider

Spectra for the Proton BPM Signals

Proton signal spectrum during cooling. Maximum at 25 MHz. Dip at 50 MHz

Proton signal spectrum at the store. Due to the shorter bunch, the maximum is at 800 MHz.

BPM Pick-up Signal Levels for the Electrons

Selection of Signal Processing

- Proton beam

  - Sampling at the peak of the pulse (currently employed at RHIC) will require changing the clock phase, which is hard to implement

  - Narrowband processing does not work due to the different spectral content at cooling and the store

  - We will use the sum of the squares of the ADC readings to calculate pulse energy. To equalize the signal levels the low-pass filter will be used in the RF front end

- Electron beam

  - Narrowband processing at 600 MHz is suitable because the proton signal is weak at cooling

  - The signal from the protons at the store is strong at 600 MHz and can be used for the BPM offset cross calibration

Noise Estimation for the Electron BPM

- For the electron beam with a current of I_e = 88 mA (3.6 nC, 24.6 MHz), the signal level after 130 meters of LMR-240 cable is 5 mV r.m.s. (10 MHz BW filter centered at 591 MHz)

- An amplifier with a noise figure of 2.6 dB has a thermal noise level of 4 μV. The corresponding SNR is 61.9 dB

- For the ADC clock jitter of 70 fs, the SNR is 71.7 dB

- 11.4 ENOB corresponds to 68.4 dB SNR

- The scaling factor is 32 mm, and the noise jitter for the single bunch is 30 microns

- Averaging over 260 bunches (1 turn) reduces the noise position to 2 microns

- For a 10 kHz BW required for orbit feedback, we have an extra gain of 3, bringing the noise below 1 micron

Noise Estimation for Proton BPM

Qbunch, nC	Tbunch, ps	Nbunch	Frep, MHz	Dpipe, mm	Scale, mm	Dbttn, mm	Cbttn, pF	Cable		Lcable, m	Fcable, MHz	Nseeds
45	9075	1	24.6250	127	31.7500	30	5.5000	LMR-240	⇕	130	66.5277	16

Noise, uV	Ffe, MHz	FE Type		FE Order	FE loss, dB	Attenuator, dB	Ffilter, MHz	Filter Type		Filter Order	Loss, dB	Fsample, MHz	ENOB	Jitter, ps
10	135	Bessel	⇕	3	0.7500	0	135	Bessel	⇕	3	0.7500	492.5000	11.4000	0.7000

Simulate

	Gain, dB	Fcut, MHz	Noise, dB
Ampl 1	20	1440	2.3000
Ampl 2	6	1440	2.3000

Uavg, V	sigmaU, mV	Position Noise, um
0.9427	0.4920	23.4339

ADC input ⇕

ADC Signal (2nd Amplifier Output)
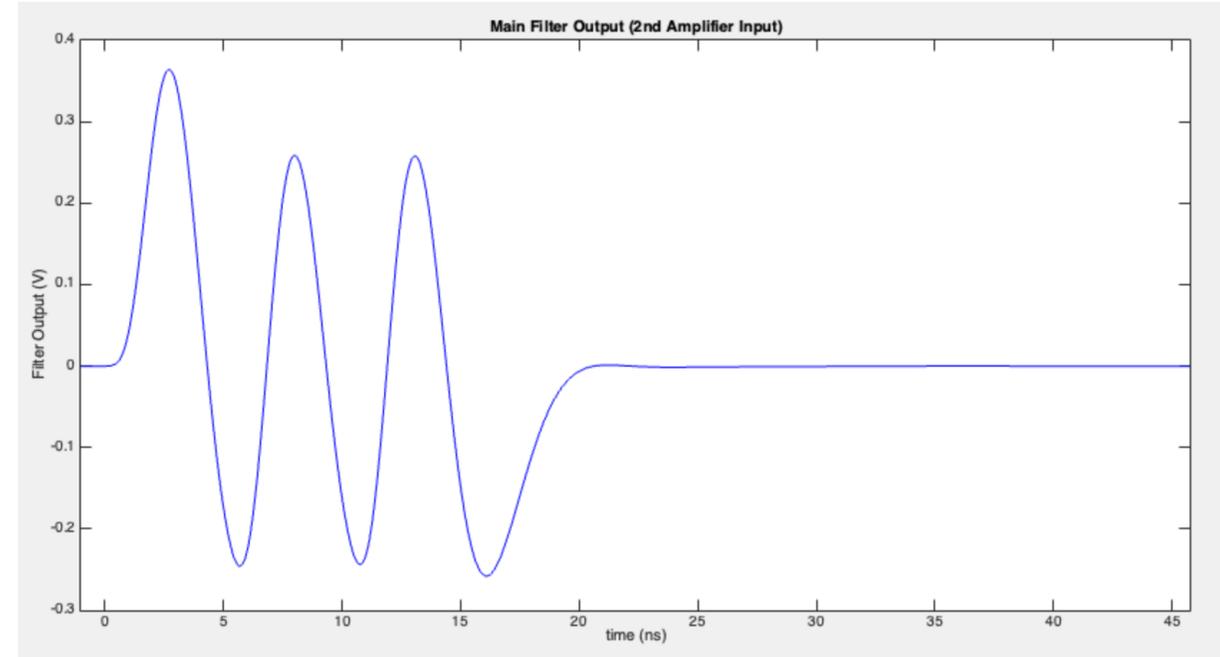
— ADC Input
× ADC Readings

Voltage (V)

time (ns)

Single-bunch measurement has a precision of 20 microns

For a single turn (260 bunches), resolution improves to 1.25 microns

For the orbit feedback, the precision is better than 0.5 microns

Offset Calibration for Two BPM Systems

- Hadron and electron BPMs can have different electrical offsets due to the unequal losses in the cables and signal processing
- The cross-calibration of the BPMs will be done when only one beam is present: either the proton beam at the store or the electron beam
- The proton beam generates a factor 10 stronger signal and can be used continuously during operation
- The electron beam can also produce a usable signal for hadron BPMs

Matching of the Relativistic Factors

- The difference in the relativistic factors results in the phase shift between BPMs separated by drift *L* at the observation frequency *F*

- We measure the phase offset with only one beam present. Then the second beam is injected, and we measure the phase change

$$\Delta\varphi = 2\pi F \frac{L}{c}\Delta\beta \approx 2\pi F \frac{L}{c}\frac{1}{\gamma^2}\frac{\Delta\gamma}{\gamma} \approx 2\pi 25 \times 10^6 \frac{150}{3 \times 10^8}\frac{1}{25^2}\frac{\Delta\gamma}{\gamma} \approx 0.12\frac{\Delta\gamma}{\gamma}$$

- For the $\Delta\gamma/\gamma = 10^{-4}$, the phase shift will be around 10^{-5} radians ($0.0007°$). While modern BPM systems can provide a sufficient signal-to-noise ratio, achieving such low drift in the cable might be challenging. Nevertheless, the system can complement the energy measurement with a dipole.

Conclusion

- The beam position monitors are expected to provide the required alignment of the electron and proton beams
- The signals will be separated in the frequency domain
- The cross-calibration of the electrical offsets is possible with either beam
- Utilizing the phase measurement of the signals from two BPMs can help to match the relativistic factors

Electron-Ion Collider