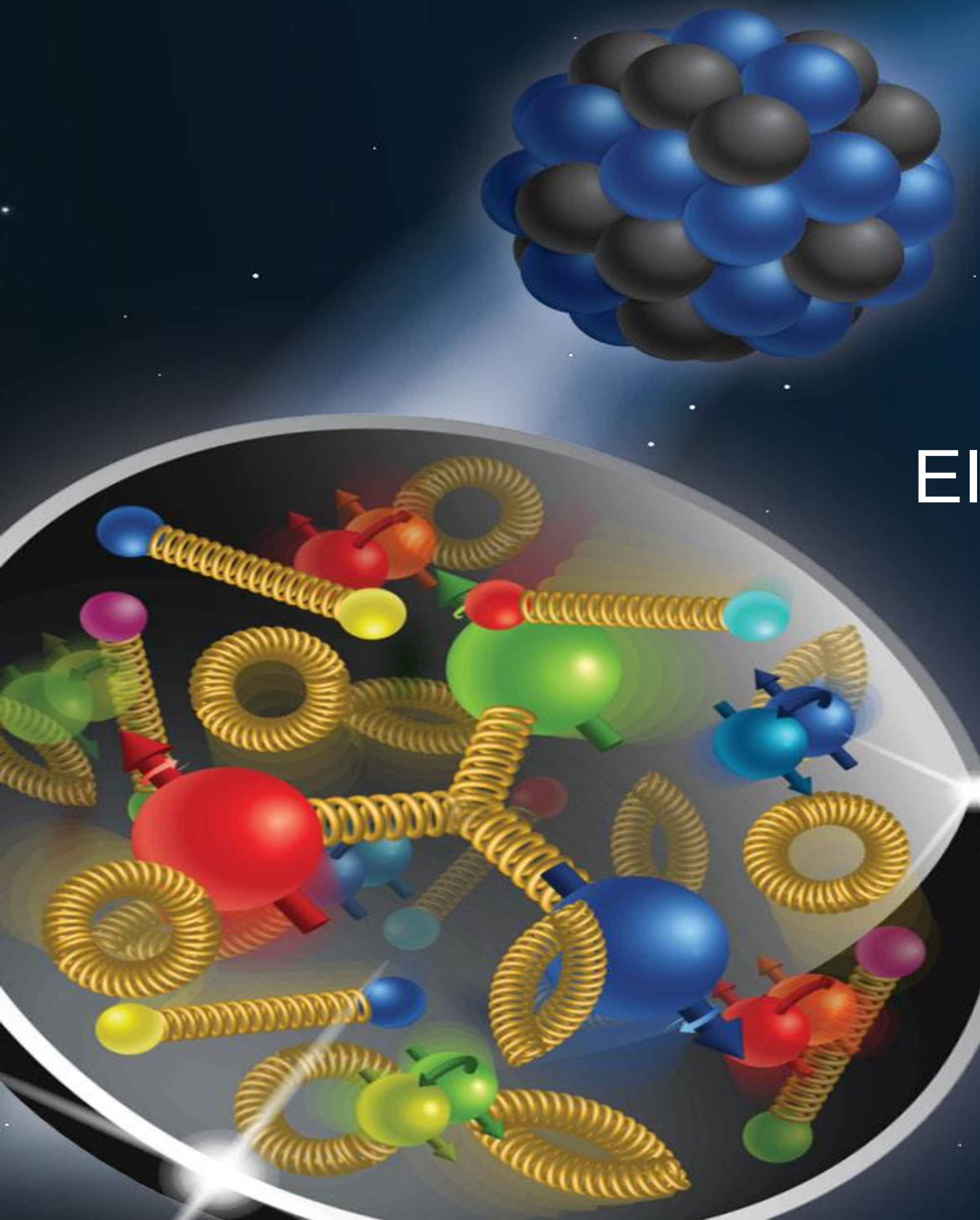


EIC IR Beam Instrumentation Considerations

FCC-EIC Joint & MDI Workshop

David Gassner

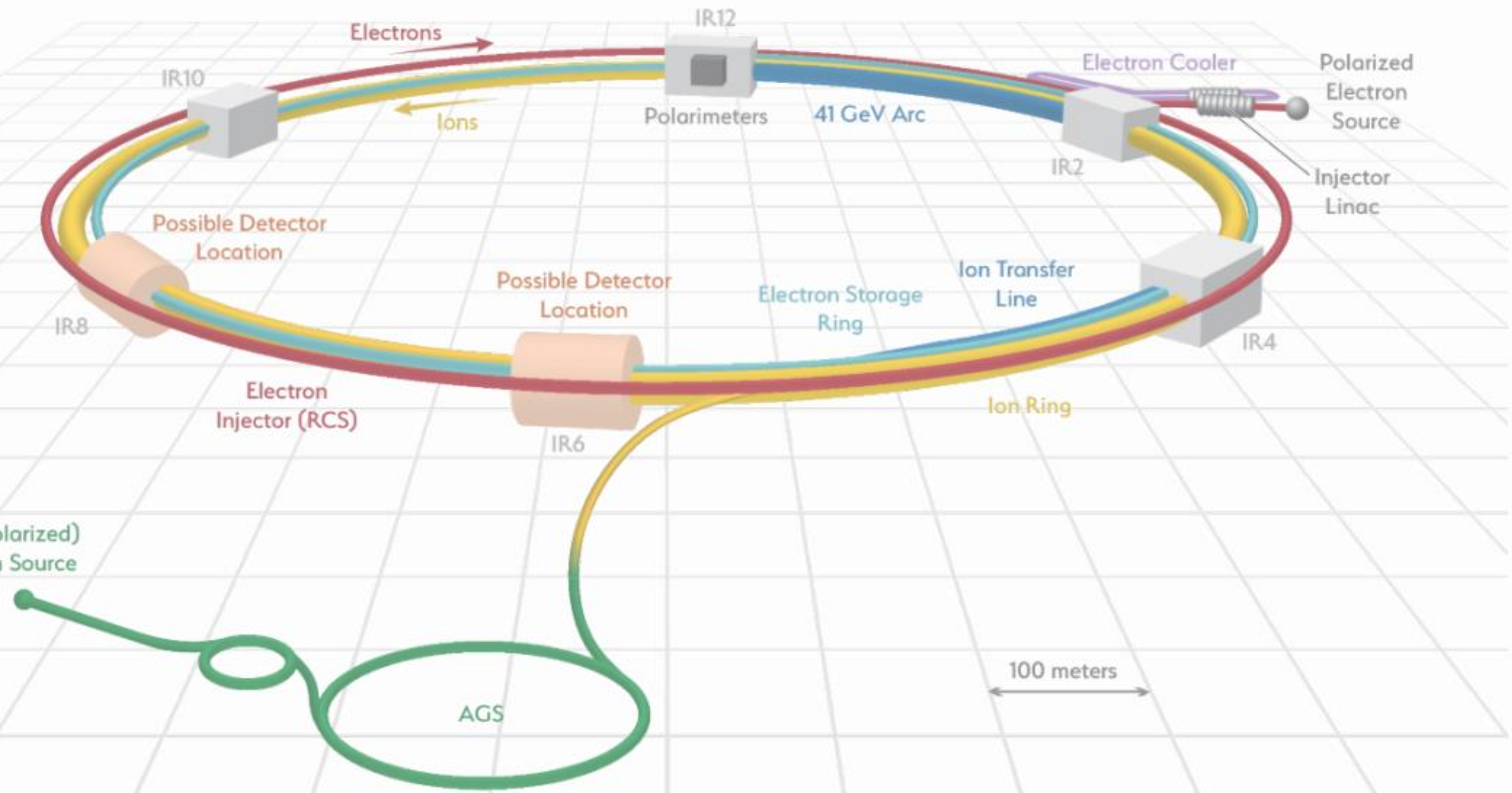
October 18, 2022

Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY | Jefferson Lab | U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- IR Introduction & status
  - Electron beam transport
  - Hadron beam transport
- IR Beam Instrumentation
  - Beam position monitors
    - Electron
    - Hadrons
  - Beam loss monitors
  - Orbit feedback at the IP
  - Crabbing angle monitors
  - Large angle beamstrahlung monitor
- Summary

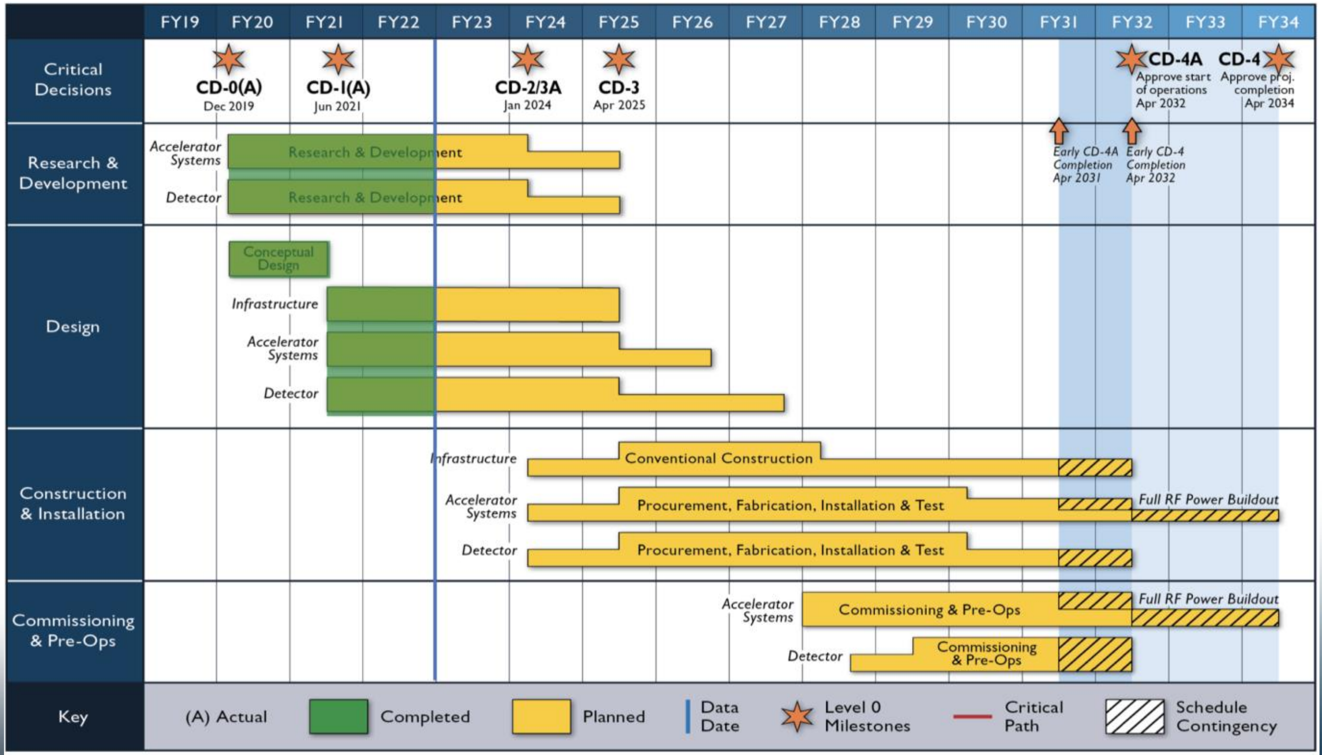


Electron-Ion Collider

IR Instrumentation Introduction

- Present status
  - Conceptual design phase
  - IR instrumentation details can be better defined after other larger system (lattice, magnet, cryostats) designs are more mature
  - Gathering IR machine parameters
  - Working on defining performance requirements
  - Improving cost estimates
  - Developing the schedule
  - Instrument simulations underway (CST, Ansys, GdfidL, etc..)

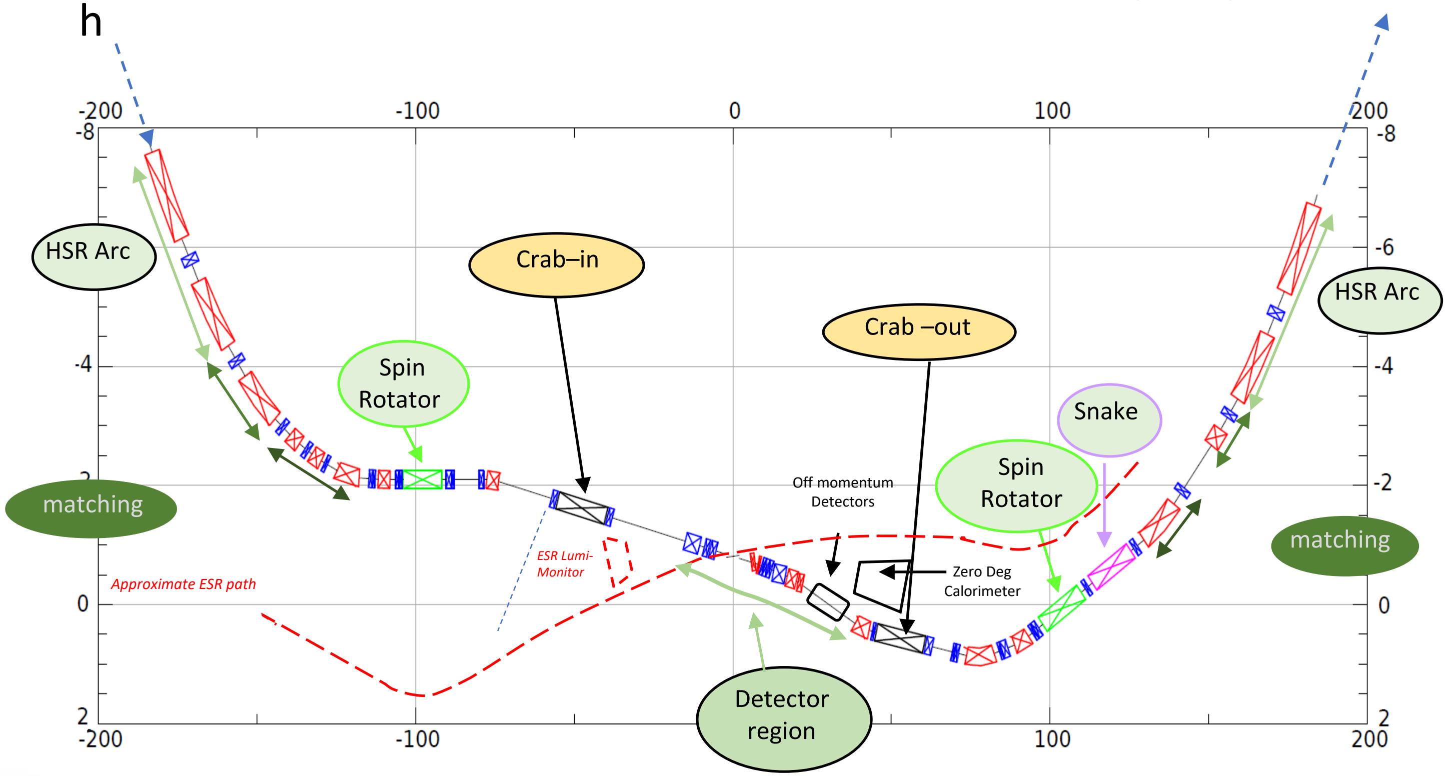
- Schedule
  - CD1 in June ‘21
  - CD2 planned Jan ’24, cost and schedule well developed
  - CD3 planned April ’25, construction start, IR designs continue
  - IR Beam instrumentation (BPMs) ready to install 2029
  - Start IR beam commissioning 2031



Hadron transport through IR6

The EIC IR is defined as +/- 130 meters from the IP
Zero-degree calorimeter not covered in this talk as this is included in the Detector Group scope.

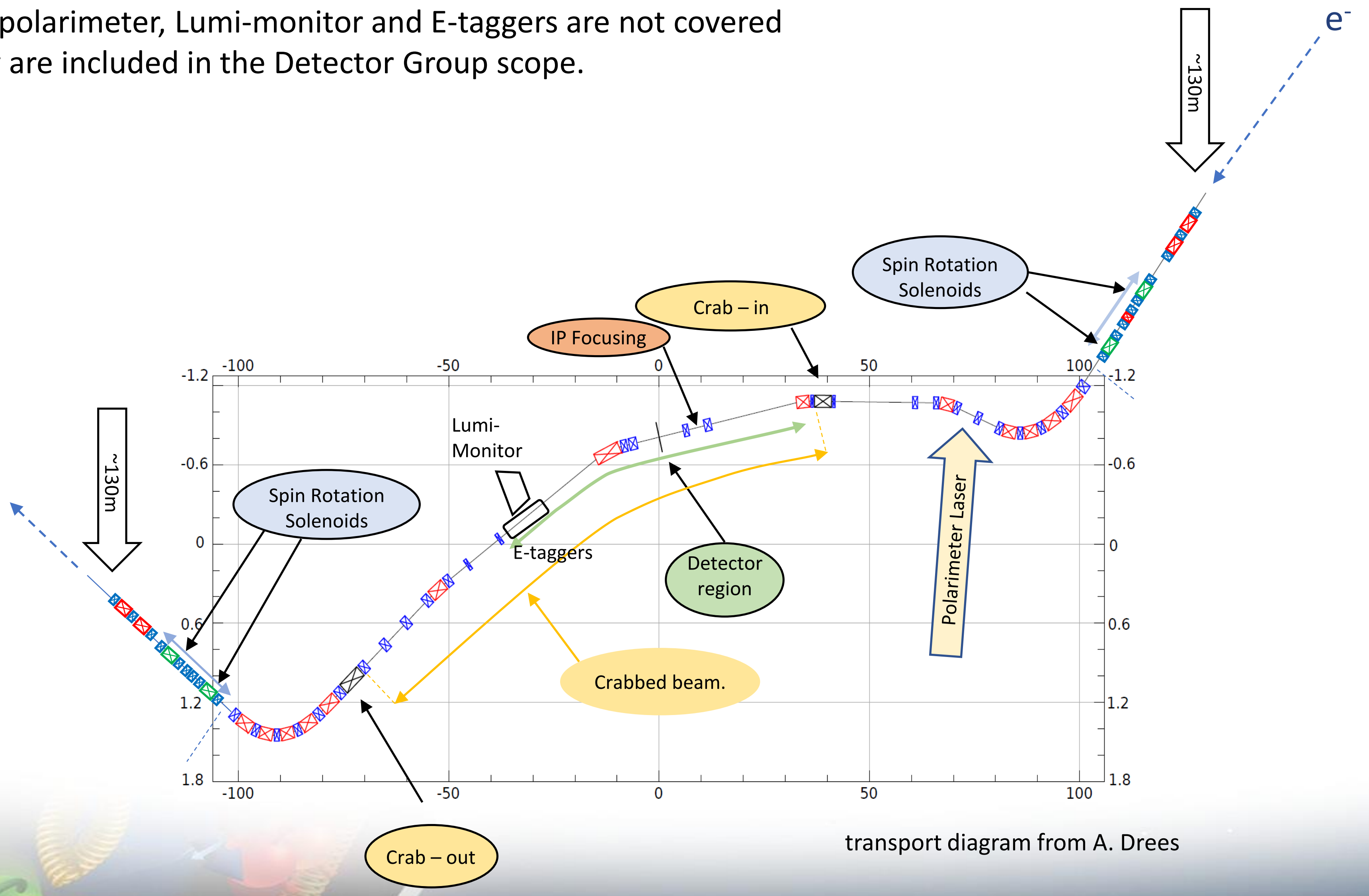
Forward and rear hadron lattice matched into Hadron Storage Ring



transport diagram from A. Drees

Electron transport layout in IR6

Details about the polarimeter, Lumi-monitor and E-taggers are not covered in this talk as they are included in the Detector Group scope.

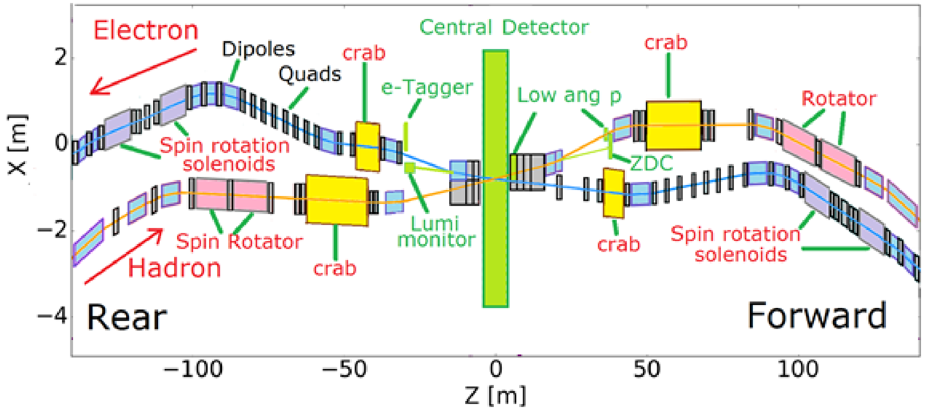


transport diagram from A. Drees

Interaction Region BPMs

- Button BPM pick-ups, designs underway
- Total = 78 in conceptual baseline
- Cover 2 beamlines (e & ions), +/- 130 m

Some IR hadron cold magnets will be reused from elsewhere in RHIC, new button BPMs



EIC IR layout for illustration only

IR Beam Position Monitors

	Type		New	Electronics	
	Warm	Cold	Pick-up	Standard	Scope
IP BPMs	2		2	2	
IP Tilt BPM	1		1		1
Forward E	12	3	14	15	
Rear E	12	3	14	15	
Forward H		12	3	12	
Rear H		9	3	9	
Crab H	4		4	4	
Crab E	4		4	4	
Roman Pots	2		2	2	
e-Spin-Rot	12		12	12	
h-Spin-Rot		2	2	2	
Sub totals	**49**	**29**	**61**	**77**	**1**
	Total e-BPMs		**47**		
	Total h-BPMs		**31**		
	Total BPMs		**78**		

Interaction region BPM Pick-ups design status

- IR BPMs far from the IP are similar to those in the electron and hadron storage rings
- Near IR BPMs are considered in the pre-conceptual phase
    - Gathering machine parameters as they become available
        - Developing performance requirements
        - Beamline layouts, mechanical constraints
    - Design challenges
        - Variety of IR BPM apertures are larger than those in the storage rings
        - Hadron operations with large radial offsets
        - BPMs inside cryostats near the IP
            - Tight space constraints
            - Challenging signal path routing
            - Very limited access for service/repairs if needed

Electron Storage Ring BPM Pick-up design

Warm ESR BPM pick-up design is underway, CST & Ansys simulations

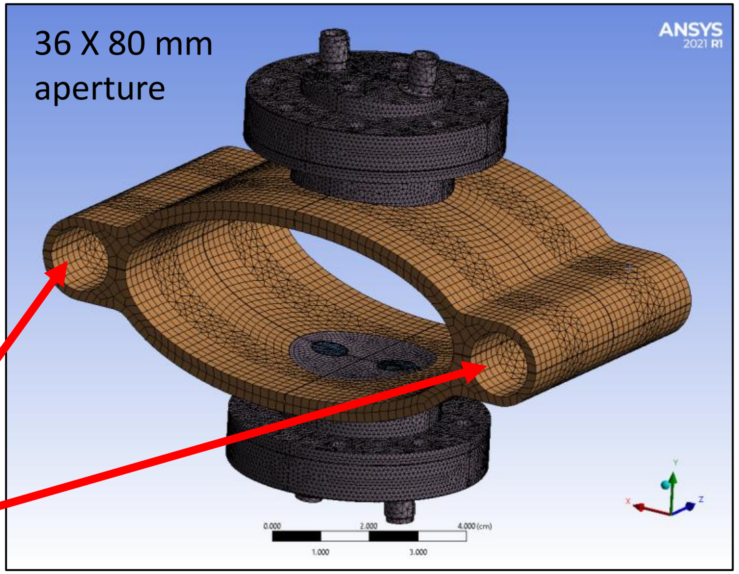
- Reviewing signal response, impedance, energy deposition, etc..

Example: electron storage ring beam parameters for 10 GeV:

- Bunch charge range = 27.5 nC
- Bunch length (RMS) = 7 mm
- Bunch spacing = 10.95 ns (1,160 bunches)
- Beam current = 2.5 Amps

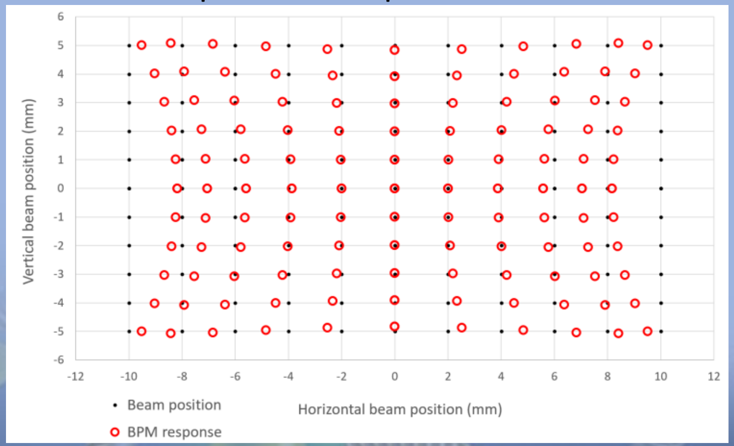
For the above parameters, preliminary results look OK

- each dual button BPM assembly heat load is ~5 W
- Max temp is button surface at 68°C (copper coated moly button)
- Impedance characteristics look good

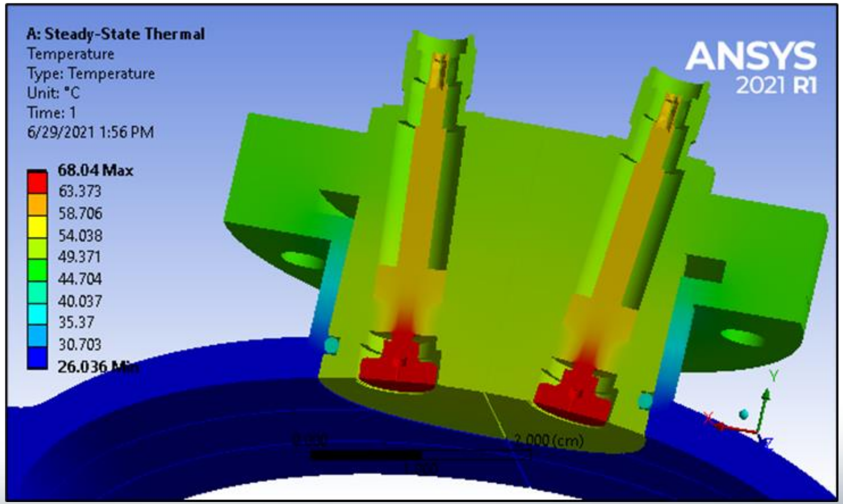


Water cooling channels

- The expected range of ESR beam positions to be measured is +/-10mm H, +/- 5mm V.
- Non-linearities will be compensated using FPGA-based lookup table interpolations.



Pin cushion distortion plot



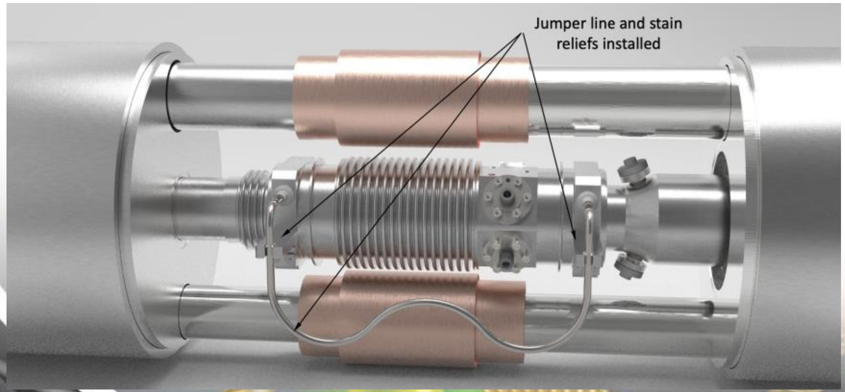
J. Bellon
S. Bellavia
A. Blednykh
C. Hetzel
P. Thieberger

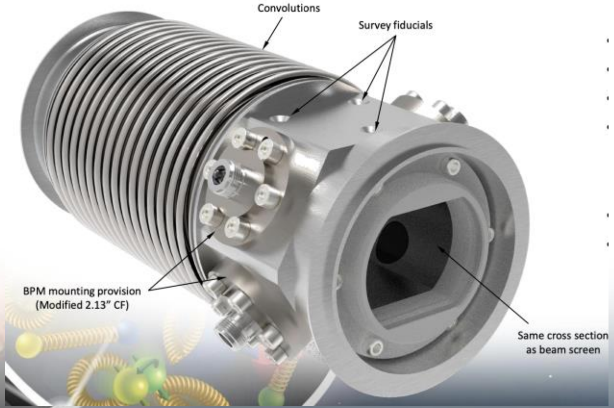
Hadron Storage Ring cryo-button BPM Pick-up

- The new cryo-BPM design considerations:
  - Aperture 50 x 64 mm (same as adjacent beam sleeve)
  - Operations with large (+/-20 mm) radial offset at store
  - Power deposition on the buttons is not excessive
  - Signal levels to meet performance requirements (20 um resolution, average over 1 second during store)
  - Dynamic range of ~ 85 dB;
    - long 125 cm RMS, 5 nC gold pilot bunches at injection
    - short 6 cm RMS, 30 nC bunches during store with large radial offset.

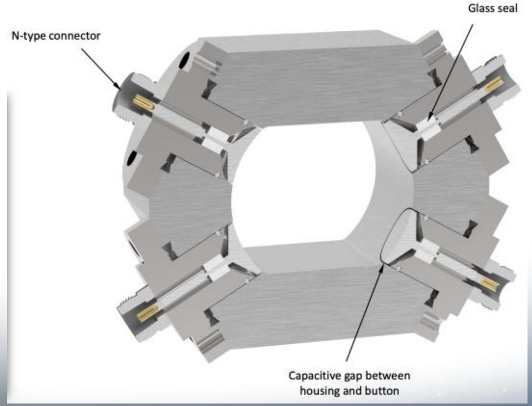
- HSR cryo-BPM pick-up design is underway, CST & Ansys simulations
- HSR beam parameters for 275 GeV (most challenging for BPM):
  - Bunch charge = 30.5 nC
  - Bunch length (RMS) = 6 cm
  - Bunch period = 40 ns, 290 bunches
  - Beam current = 0.69 Amps
  - Radial shift = 20 mm
- For the above parameters, preliminary simulation results look promising
  - Impedance characteristics look good (matched to beam sleeve)

Conceptual design of the HSR bellows/interconnect/BPM with cryo-cooled vacuum chamber sleeve bypass

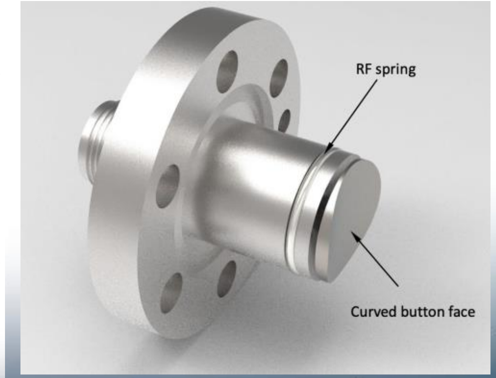




HSR BPM cross section



20 mm diameter button



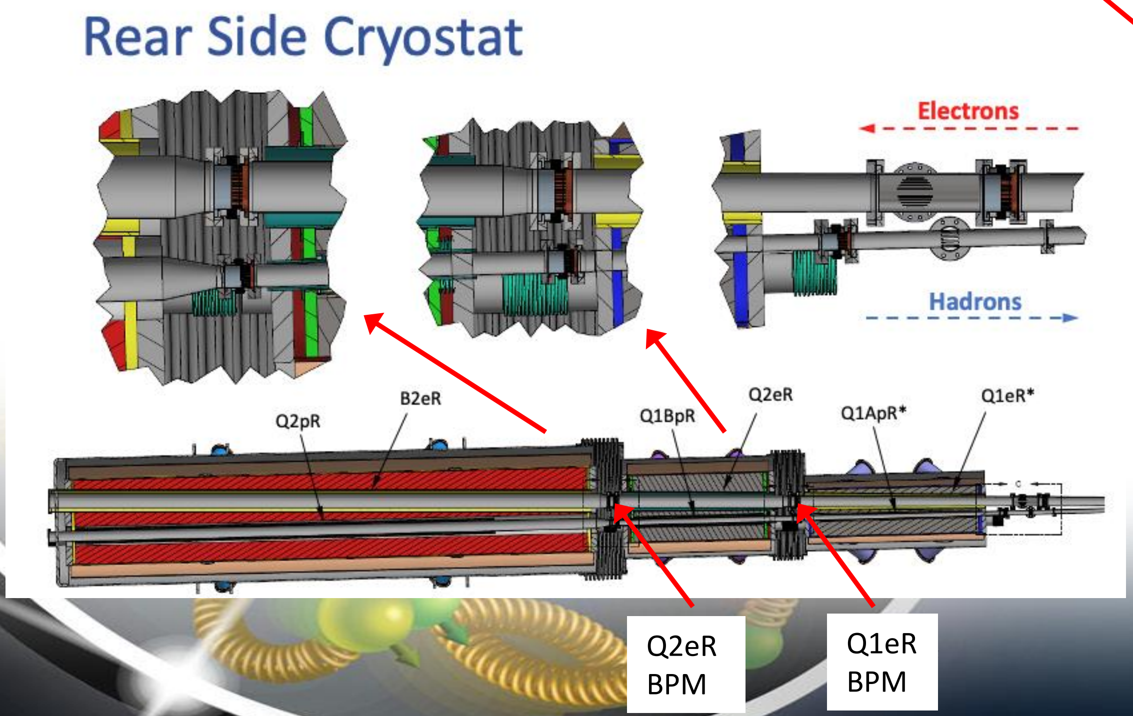
Pics courtesy of Charlie Hetzel

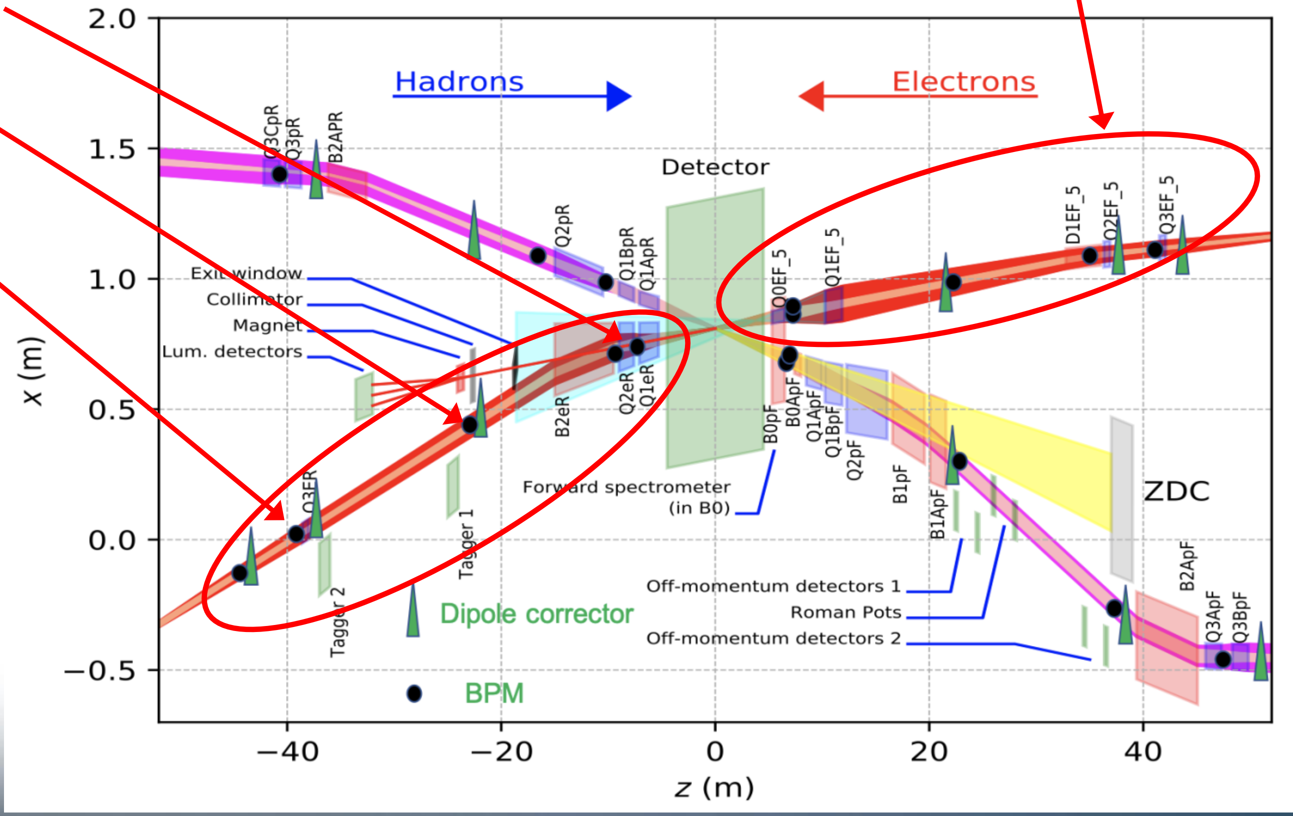
Near interaction region electron BPM Pick-ups

- Large diameter e-BPM pick-ups in the electron forward and rear region present challenge for 1 um average resolution position measurements. For comparison: ESR BPMs: 18 mm radius (1.4” diameter).

- Forward region
- Q0eF5 (~7 m from IP) 27 mm radius (2.1” diameter) in cryostat
- (~22 m from IP) 63 mm radius (5” diameter)
- Q2eF5 (35m from IP) 50 mm radius (4” diameter)
- Q3eF5 (42 m from IP) 50 mm radius (4” diameter)

- Rear region
- Q1eR (~7.3 m from IP) 56 mm radius (4.4” diameter) in cryostat
- Q2eR (~9.3 m from IP) 64 mm radius (5” diameter) in cryostat
- DS of B2eR (22m from IP) 80 mm radius (6.3” diameter)
- Q3eR (38 m from IP) 80 mm radius (6.3” diameter)





Near interaction Region hadron BPM Pick-ups

- Hadron beam transports in the IR, near the IP, are not fully designed yet
- The BPM near B1ApF will have ~13" aperture (pick-up design & measurement challenge)
- There will be an energy dependent radial offset in the IR hadron BPMs, similar to the offsets in HSR
- After IR hadron transport designs are more mature, simulations will be done to determine remaining BPM and corrector locations

- B0ApF (~7 m from IP) 27 mm radius (2.1" diameter) in cryostat
- B1ApF (~22 m from IP) 167 mm radius (13.2" diameter)

Hadron forward beamline ID's can be large. All are expected to be round; dimensions are in inches.

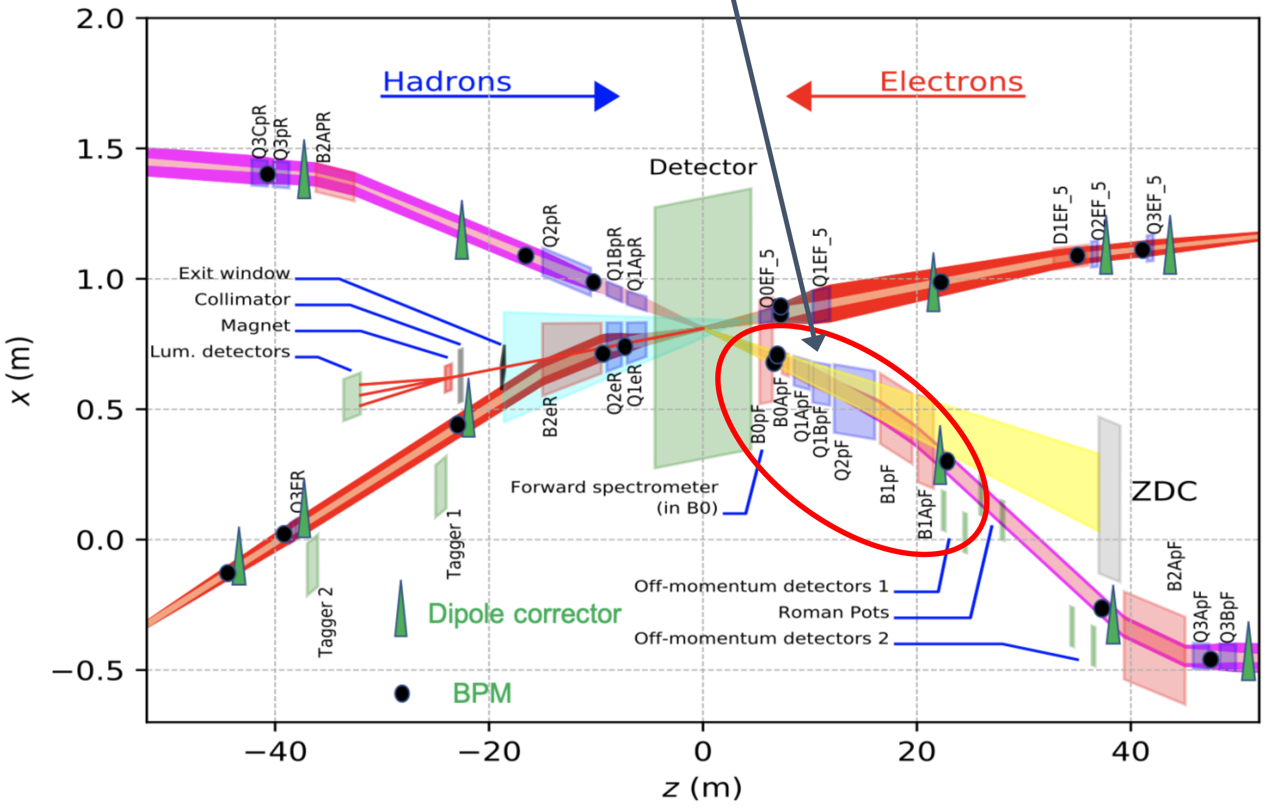
B1ApF BPM

Coil	I.D	O.D	Length	Minimum Wall
B1APF	13.23	13.79	59.06	.28
B1PF	10.63	11.17	118.11	.27
Q2PF	10.31	10.83	149.61	.26
Q1BPF	6.14	6.452	63.39	.156
Q1APF	4.41	4.64	57.41	.115
B0APF	3.39	3.556	23.66	.083
B0PF	2.04	2.24	63.75	
IP				

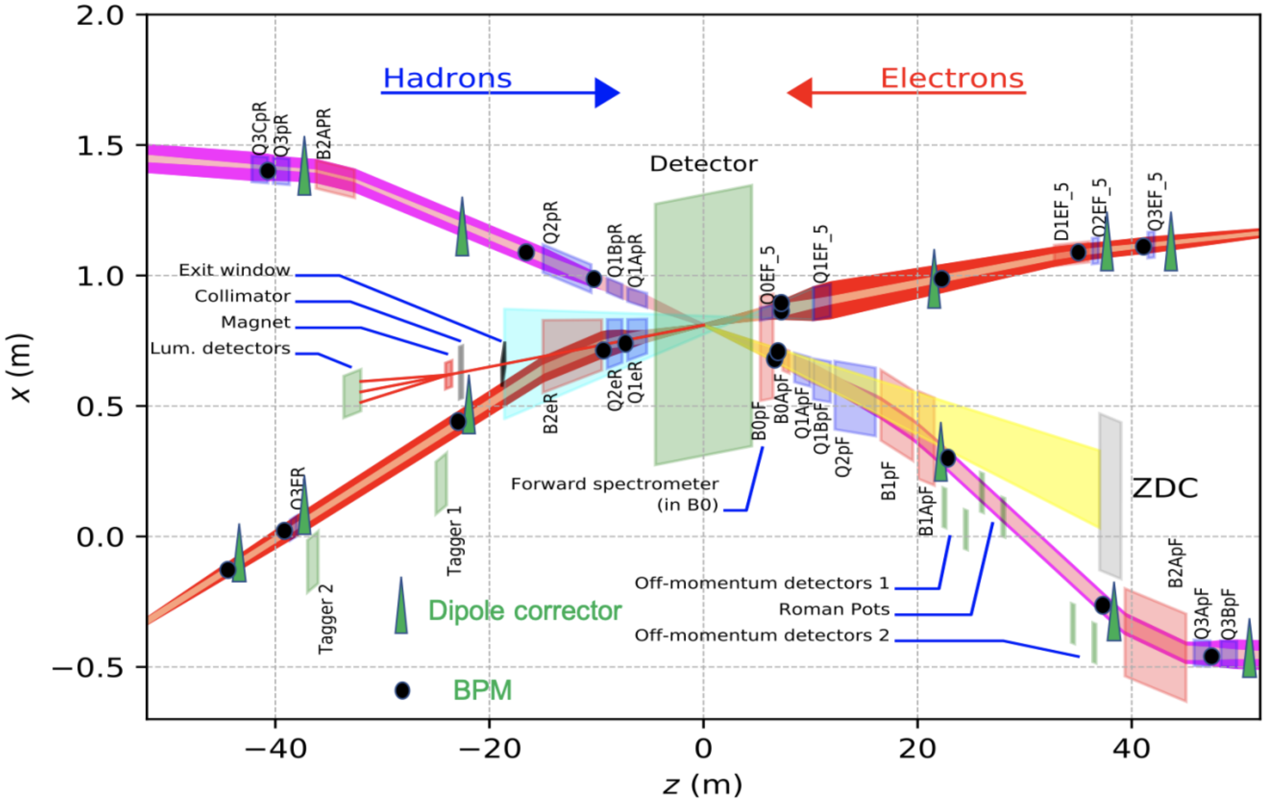
M. Anerella

Dual plane BPM

Crab tilt BPM, horiz button pair



ESR & IR Orbit correction simulations



Chuyu Liu

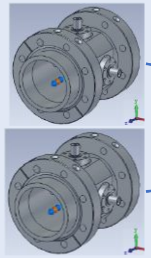
- 11 Correctors and 18 BPMs have been placed in the IR layout. Presently working on orbit correction scripts for electron beam transport through the IP.
- The preliminary electron correction results are promising, which implies the placement of electron correctors and BPMs in the IR, is reasonable.
- The next step is to run multiple correction simulations with random seeds. Check the residual orbit against the available IR aperture. Identify possible synchrotron radiation fan scraping points.
- Eventually move on to the hadron orbit correction simulations

IR Orbit feedback

- Compensation for modulated beam-beam offsets at the IP due to mechanical vibration of IR magnets at frequency range of 2 to 30 Hz.
- The baseline has 16 sets of orbit correction magnets and power supplies.
- Design based on principle demonstrated at existing RHIC 10 Hz feedback system.
  - 12 electron, dipole steering magnets (8V + 4H)
  - 4 hadron, dipole steering magnets

RHIC Example

IR BPMs



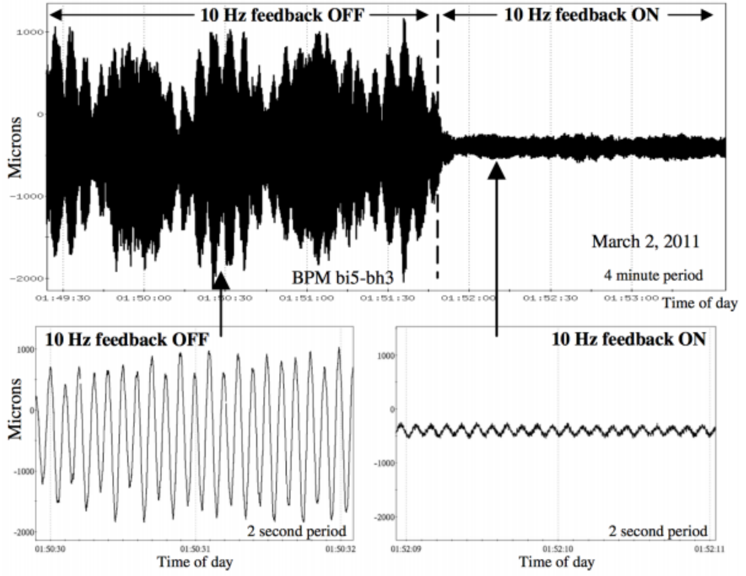
RHIC BPM IFE board with daughter card

Digital to analog converter Electronics, Xilinx ML-510

Kepco BOP-36-12M Magnet Power Supply

Steel laminated core magnet installed in RHIC

RHIC Orbit Feedback Off vs. On

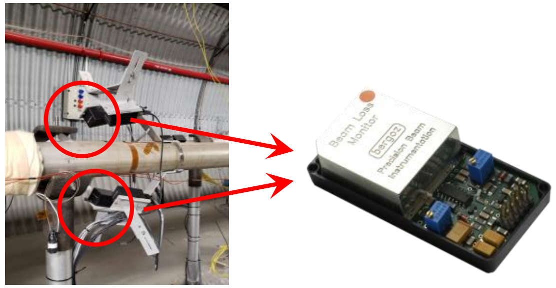


Typical BPM measurement with 10 Hz feedback OFF vs. ON (1000 data points per second).

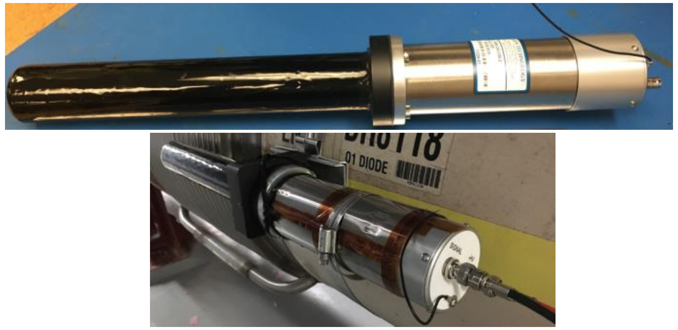
IR Beam Loss Monitors

- Provide protection against unexpected sudden beam loss, input to MPS & beam abort system
- Plan to do beam loss simulations to determine IR loss locations, detector locations
- Several types of detectors in the baseline:
    - 10 RHIC style BLM ion chambers on each side of IR (20)
    - 10 Pin Diode style Bergoz BLMs on each side of IR (20)
    - 2 Paddle Scint/PMTs on each side of the detector (4) measure background level

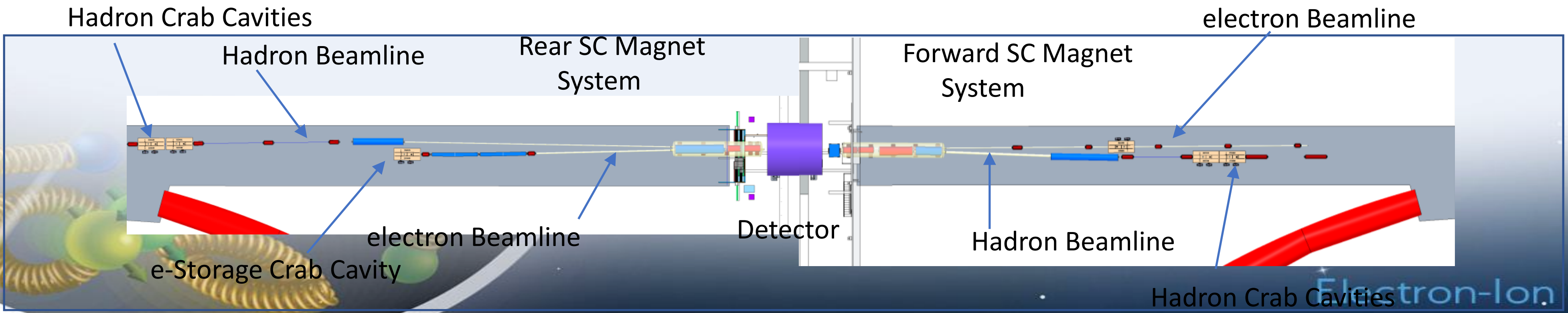
RHIC style BLM Ion Chamber



Bergoz Pin Diode BLMs



Scint/PMT BLMs



Hadron Crabbing Angle Measurements

Crabbing angle near IP determined by different degrees of BPM signal distortion depending on the tilt angle, the zero-crossing time difference is approximately proportional to the tilt angle.

Concept by P. Thieberger
IPAC2018-WEPAF018

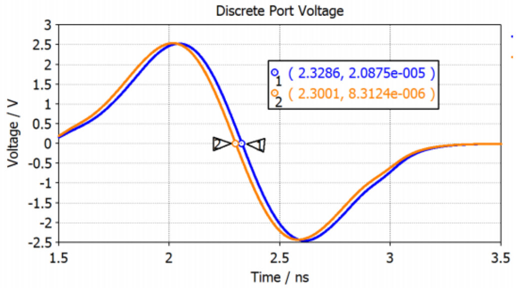


Figure 4: Particle Studio output for the two, opposite, horizontal PUEs when using a 60 mm diameter BPM with 10 mm diameter PUEs with a simulated crabbed bunch input described in Fig. 3.

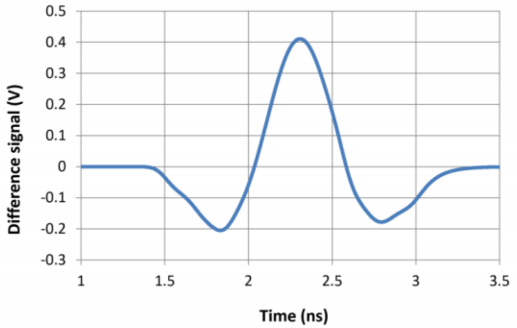
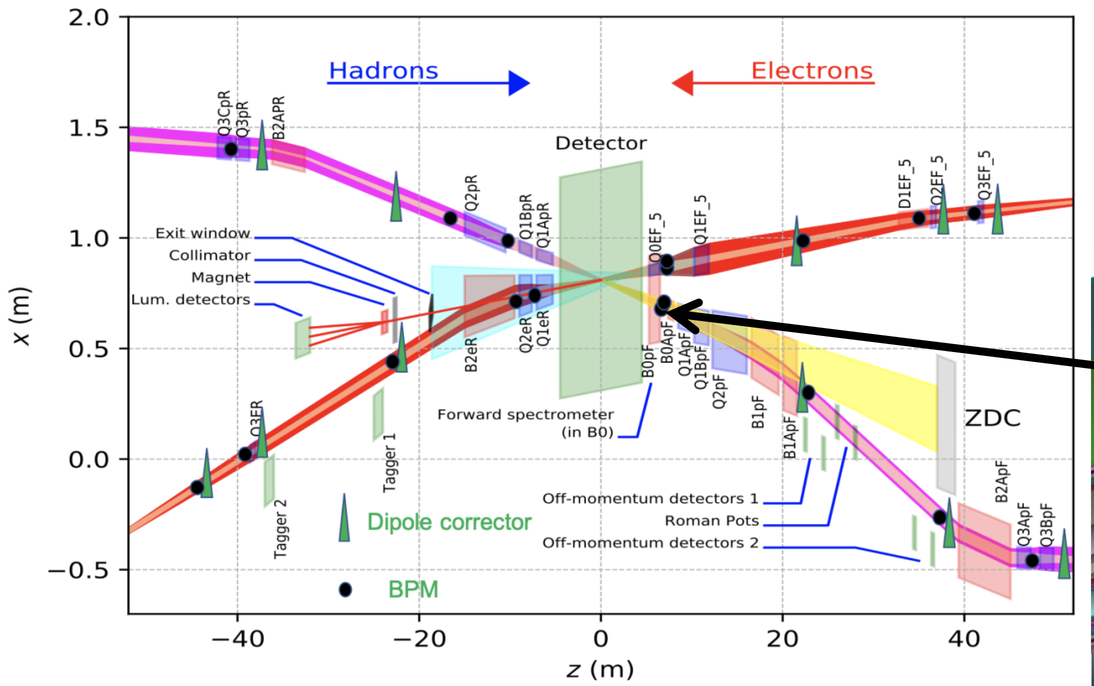


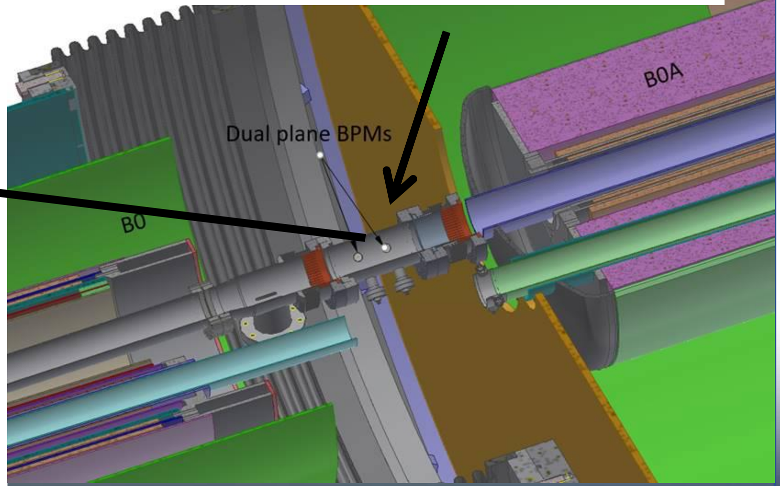
Figure 5: Difference signal obtained by using the simulation output shown in Fig. 4.

Concept has not demonstrated yet. Due to sensitivity to long cable thermal effects, considering using a fast differential signal splitter in reverse, as combiner, close to the BPM

In the space between B0pF and B0ApF the horizontal BPM buttons should see the maximum tilting of the bunch, (crabbing angle 12.5 mrad.) Bending magnets and drifts behave alike with respect to crab rotations.



Proposed location between B0pF & B0ApF



A Head-tail monitor (stripline pick-up) will be installed in the HSR somewhere outside of the IR that can measure hadron crabbing angle with the de-crabbing cavity turned off.

Successful test at the SPS:

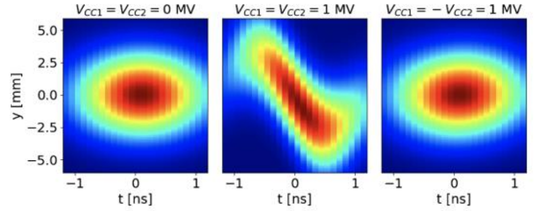
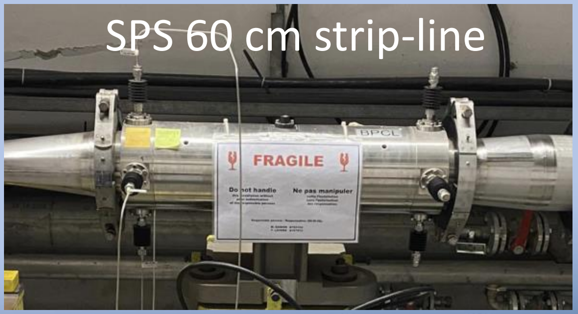


FIG. 3. Intra-bunch motion from three different cases measured with the HT monitor. Left: crab cavities switched off (voltage = 0). Center: synchronous crabbing with both cavities in phase corresponding to $V_{CC} \approx 2$ MV total voltage ($V_{CC1} = V_{CC2} = 1$ MV). Right: cavities in counterphase, corresponding to residual $V_{CC} \approx 60$ kV total voltage.

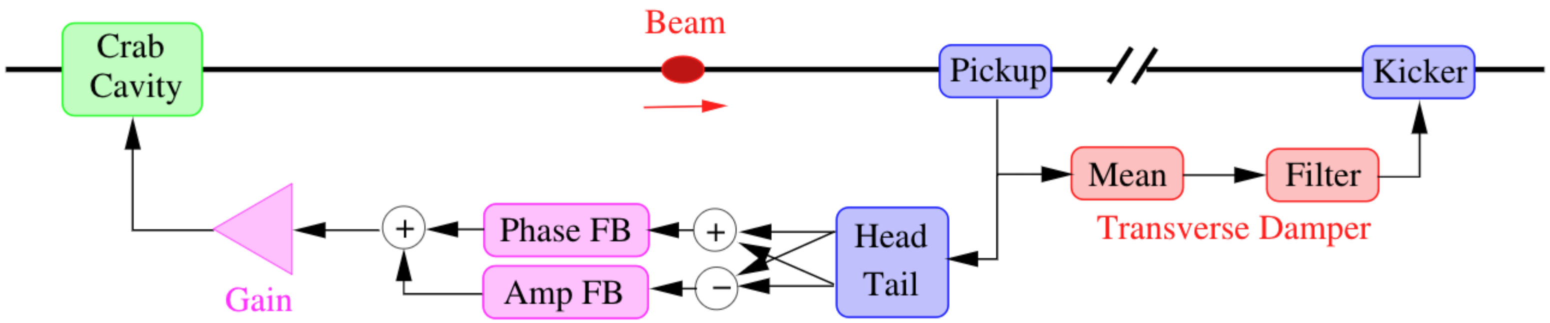


R. Calaga et al. PRAB 24 062001, June 2021

Hadron Crabbing Angle - Residual Measurement

Need crabbing angle residual (noise) measurement, located someplace away from the IR

- Purpose is to reduce emittance growth
- A dedicated feedback system could mitigate crab cavity noise effects. A similar system is planned for the HL-LHC.



- The bunch head and tail position would be extracted from the pickup signal. The head/tail Δ and Σ estimate the bunch tilt and offset (amplitude and phase noise respectively).
- Themis Mastoridis has conducted simulations of such a system for the EIC HSR to study its potential performance and limitations.
- The performance of the system will greatly depend on the pickup precision, location, and additional technical specifications (signal processing/equalization, longitudinal motion effect, etc).
- The pick-up resolution needed for EIC HSR: TBD
- Type of pick-up under discussion (electro-optical?), considering multiple pickups.

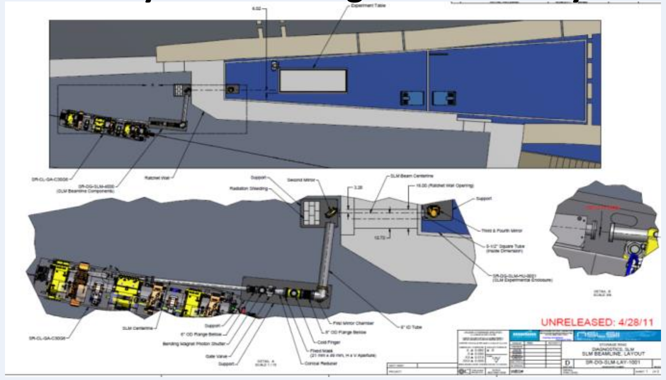
T. Mastoridis, K. Smith, et al.

Electron Crabbing Angle Measurements

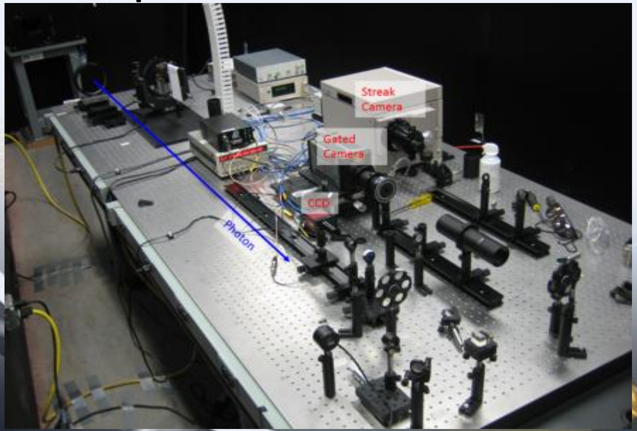
- Electron Crabbing angle can be directly measured using a synchrotron light monitor with streak camera at a location TBD in the electron Storage Ring. Principle was demonstrated KEKB. Challenge is that this has not been done at BNL, different parameters at EIC.
- A cooled mirror will direct the visible portion of synchrotron radiation to an enclosed light transport, then to an optical table in a service building.

ESR synchrotron light monitor design generally based on NSLS-II SLM

NSLS-II Synchrotron Light Monitor layout



NSLS-II Optical table with Streak camera



- Operational strategy for the measurement:
- Since there is no room for an SLM in the IR, the electron crabbing angle cannot be directly measured in the IR during operations. It can be measured elsewhere in the ESR during a studies mode.
- With the crabbing cavity turned on, and the decrabbing cavity turned off, the crab tilted beam will precess around the ring. A SLM will be located in the ESR lattice (away from the IR) at a location chosen with a large angle to optimize the measurement.
- When the decrabbing cavity is turned on (during normal operations), there should be no residual electron crabbing angle outside of the IR.
- Working with NSLS-II colleagues to determine electron bunch crabbing angle measurement capability using ESR lattice and beam parameters.

Crab cavity bunch tilt angles measured at KEKB

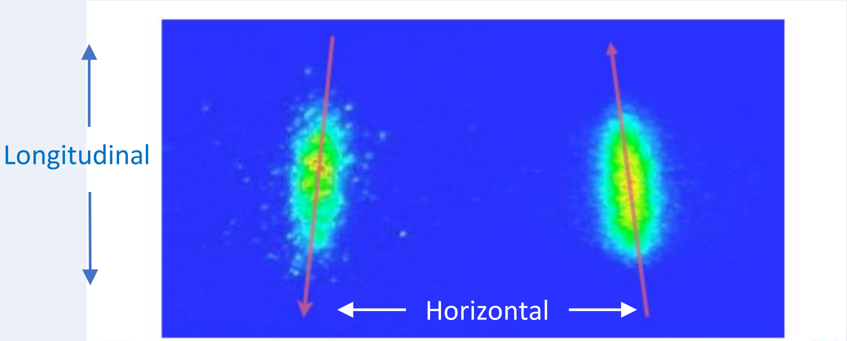
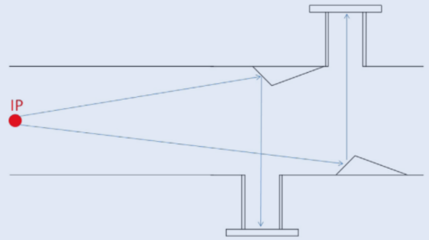


Figure 6: Images taken by streak cameras, which locate as Fig. 2, show tilt of the bunches in the LER (left) and the HER (right)[12].

Compensation of the Crossing Angle with Crab Cavities at KEKB, Abe et al, 2007

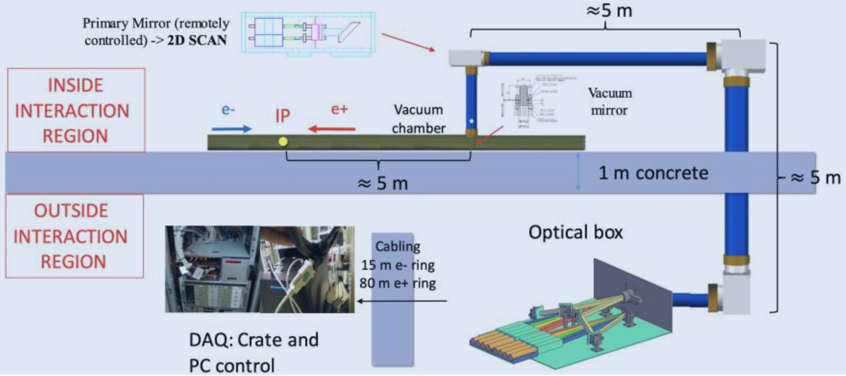
Large Angle Beamstrahlung Monitor (under consideration)

Demonstrated at CESR and SuperKEKB:

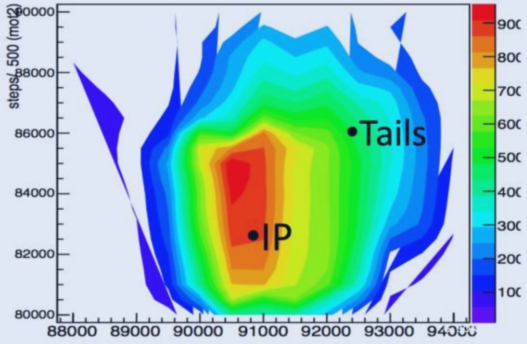


LABM light extraction principle

SuperKEKB LABM schematic



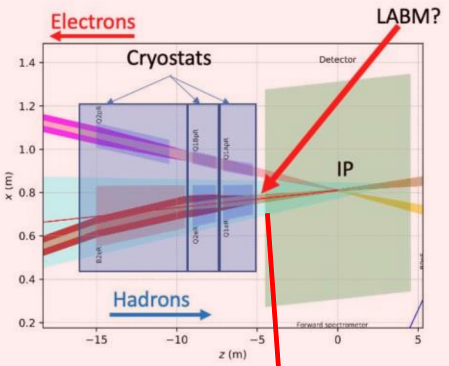
G. BONVICINI, S. DI CARLO



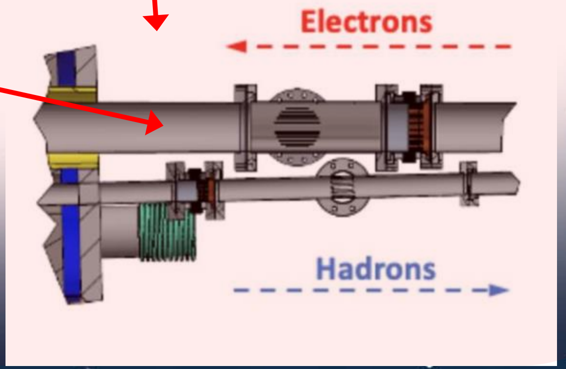
LABM heat map image

- A single-sided LABM is proposed to be installed near (~ 5 m) the EIC IP to measure rates produced by the electron beam.
  - (A large angle beamstrahlung monitor for EIC, 2020 NIMA 164656)
- Visible light collected at "large angles" (~ 6 mrad for EIC) by small mirrors integrated into the top and bottom of the beampipe, reflect the light through view ports to processing electronics.
- A variety of beam parameter measurements using radiation emitted by the collisions at the IP.
  - beam size, aspect ratios, offsets, bunch length
- The plan looking forward is to create 3D models of the mirror/viewport chamber and do CST simulations to check impedance, and other logistical installation considerations.

Electron Ion Collider



warm beamline space available for LABM mirrors and windows



Summary

Have IR instrumentation systems functional requirements

Working on detailing individual system performance requirements

Beam position monitors:

Many of IR BPMs (far from the IP) will be similar to those used in the ESR & HSR, designs are underway

Final IR BPM quantity and locations TBD

BPM pick-ups near the IP will need special design attention, different from the ring BPMs

Radial offsets and large beam pipe apertures present measurement challenges

BPMs inside cryostats present mechanical engineering challenges

Beam loss monitors:

Variety of loss detector types are in the baseline

Plan to do IR loss simulations to determine detector types at specific locations

IR orbit correction method planned is similar what was proven at RHIC

Use BPM measurements and corrector magnets

Crab tilt angles measured by:

Hadrons: Dedicated BPM pick-up near IP, and head-tail monitor in Hadron Storage Ring away from the IR

Electrons: Synchrotron light monitor in ESR, away from the IR

Large angle beamstrahlung monitor – under consideration for EIC

Acknowledgements

EIC instrumentation team at BNL

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Charlie Hetzel
Doug Holmes
Rob Hulsart
Chuyu Liu
Frederic Micolon
Michiko Minty
Rob Michnoff
Christoph Montag
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Thank you for your attention!

ESR BPM Resolution Requirements

Gassner/Montag 21Mar22

Can expect similar requirements for most of the IR electron BPMs

The BPMs close to the IP may need special requirements

ESR BPM Measurement Mode	Required Resolution (σ) Horiz	Required Resolution (σ) Vert	Allowable drift Horiz	Allowable drift Vert	Bunch Intensity
Pilot bunch, single turn	100 μm	100 μm	50 μm	50 μm	(2 nC) 1.25×10^{10} e^-
Pilot bunch, 10^3 turns, averaged	30 μm	30 μm	30 μm	30 μm	(2 nC) 1.25×10^{10} e^-
Newly injected refill bunch * (with 289 or 1159 existing bunches)					
New bunch position measurement for first 20 BPMs (low charge)	50 μm	10 μm	10 μm	10 μm	(2 nC) 1.25×10^{10} e^-
New bunch position measurement for first 20 BPMs (high charge)	10 μm	5 μm	5 μm	5 μm	(10 - 28 nC) 6.25×10^{10} e^- to 1.75×10^{11} e^-
Stored 290 or 1160 bunches					
Bunch-by-bunch position measurement not required					
Turn-by-turn, (low charge)	30 μm	30 μm	30 μm	30 μm	(2 nC) 1.25×10^{10} e^-
Turn-by-turn, (high charge)	10 μm	10 μm	10 μm	10 μm	(10 - 28 nC) 6.25×10^{10} e^- to 1.75×10^{11} e^-
10^3 turns, averaged	5 μm	5 μm	5 μm	5 μm	(10 - 28 nC) 6.25×10^{10} e^- to 1.75×10^{11} e^-
1 second average (78k turns)	1 μm	1 μm	1 μm	1 μm	(10 - 28 nC) 6.25×10^{10} e^- to 1.75×10^{11} e^-
Feedback systems					
Transverse bunch-by-bunch (one special BPM), 1 mm meas. range	3 μm	TBD	TBD	TBD	(10 - 28 nC) 6.25×10^{10} e^- to 1.75×10^{11} e^-
Longi bunch-by-bunch (one special BPM), phase measurement	TBD	TBD	TBD	TBD	(10 - 28 nC) 6.25×10^{10} e^- to 1.75×10^{11} e^-

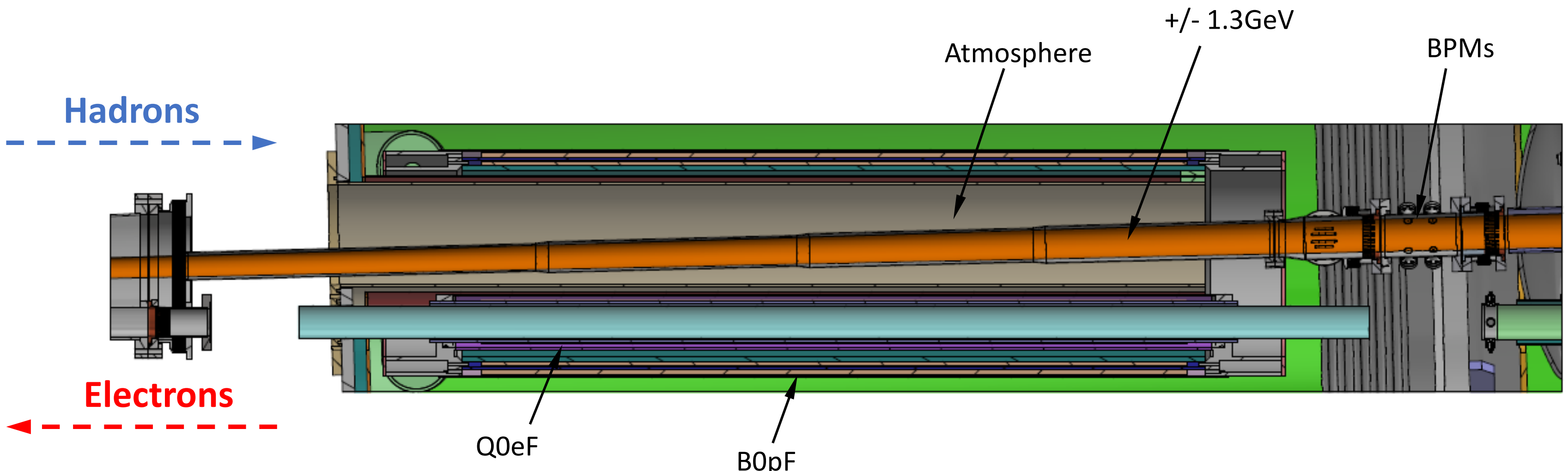
*__Note__: EIC CDR p 758, ch 6.9.3: To monitor and fine tune injection matching**, four BPMs** (two each at dispersive and non-dispersive locations) will be used to monitor betatron and synchrotron oscillations of the first injected bunch.

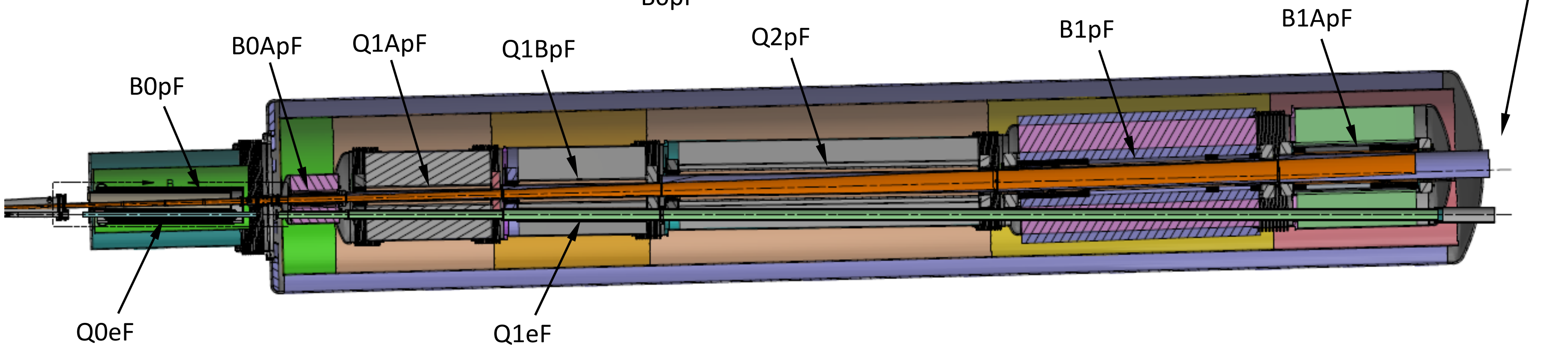
*"I would think a single turn would be sufficient, and if this capability is a substantial cost driver we could restrict it to **the first 20 BPMs** downstream of the injection point." CM 9Nov20 email*

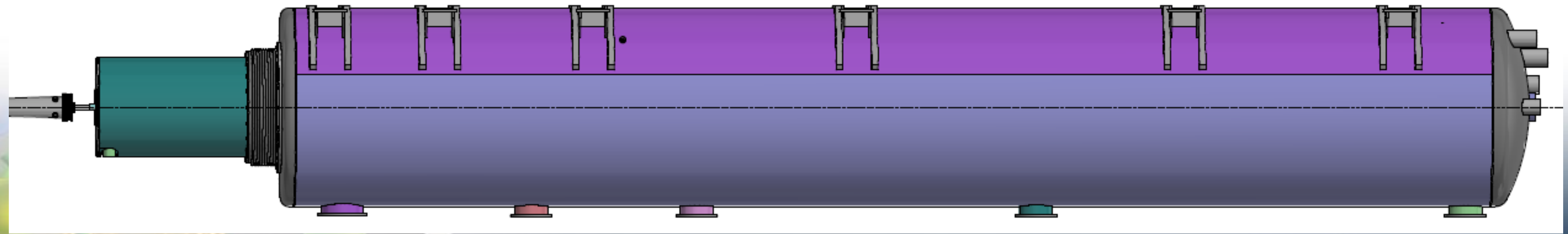
Allowable Drift: this is related to how much the position measurement can change due to outside influences (cable and rack temperature, etc…) , assuming the beam does not drift

Forward Side Cryostat (~17 m length)

Relatively large radial offsets in the hadron BPMs near the IP also present challenge for quality measurements, performance requirements TBD.







Rear Side Cryostat (~12 m length)