Overview of the EIC Beam instrumentation and synergies with FCC-ee

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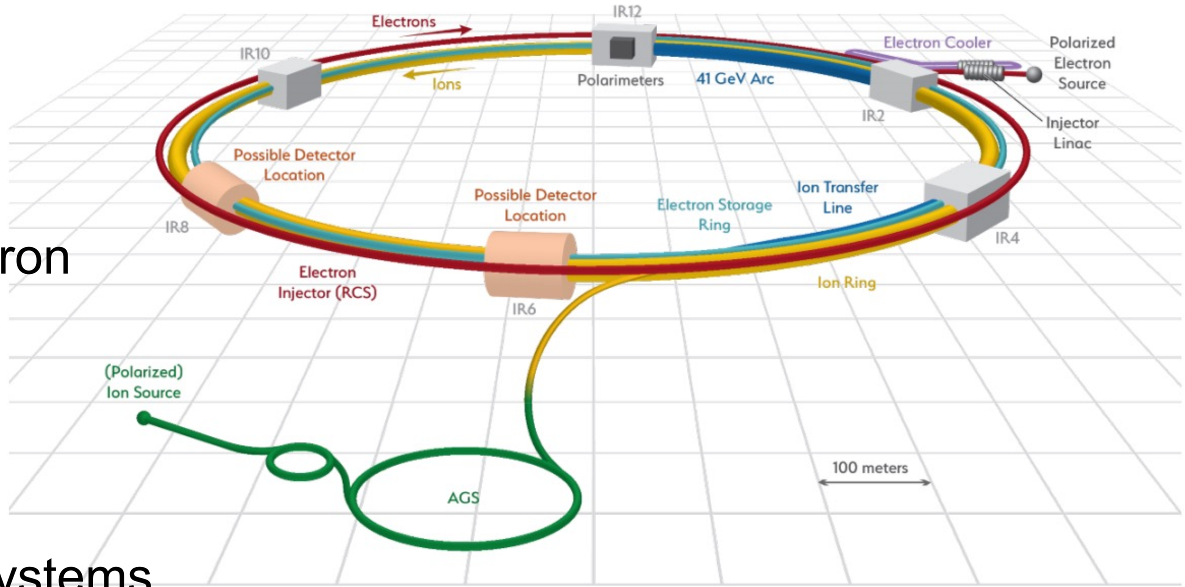
Electron-Ion Collider

Brookhaven National Laboratory Jefferson Lab U.S. Department of Energy Office of Science

Outline

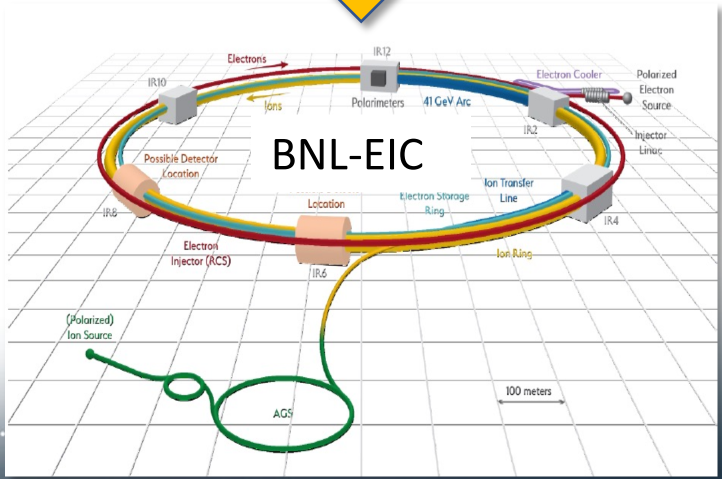
- EIC Introduction
  - Concept, layout
- Electron Diagnostics
  - Pre-Injector
  - Rapid cycling synchrotron
  - Electron storage ring
  - Interaction Region
- Hadron Diagnostics
  - Upgrades to existing systems
  - Strong Hadron Cooling Diagnostics
- Potential EIC-FCC Collaboration topics



EIC Collider Concept

Design based on **existing** RHIC

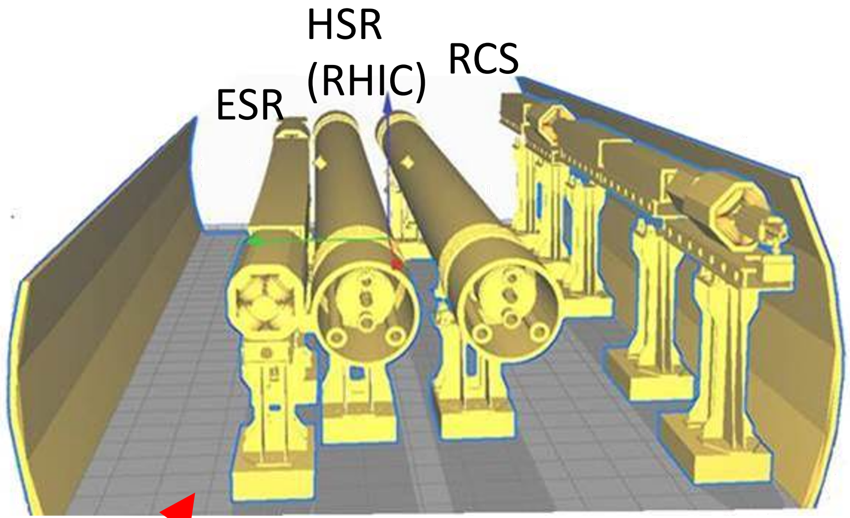
- **Hadron storage ring 40-275 GeV** **(existing)**
  - RHIC Yellow Ring
  - many bunches, 1160 @ 1A beam current
  - bright beam emittance ε_{xp}= 9 nm, flat beam
  - need strong cooling
- **Electron storage ring (5–18 GeV, new)**
  - many bunches, up to 1160
  - large beam current (2.5 A) ➔10 MW S.R. power
  - s.c. RF cavities
- **Electron rapid cycling synchrotron** (**new**)
  - 1-2 Hz
  - Spin transparent due to high periodicity
- **High luminosity interaction region(s)** (**new**)
  - L = $10^{34} cm^{-2} s^{-1}$
  - Superconducting magnets
  - 25 mrad crossing angle with crab cavities
  - Spin Rotators (longitudinal spin)

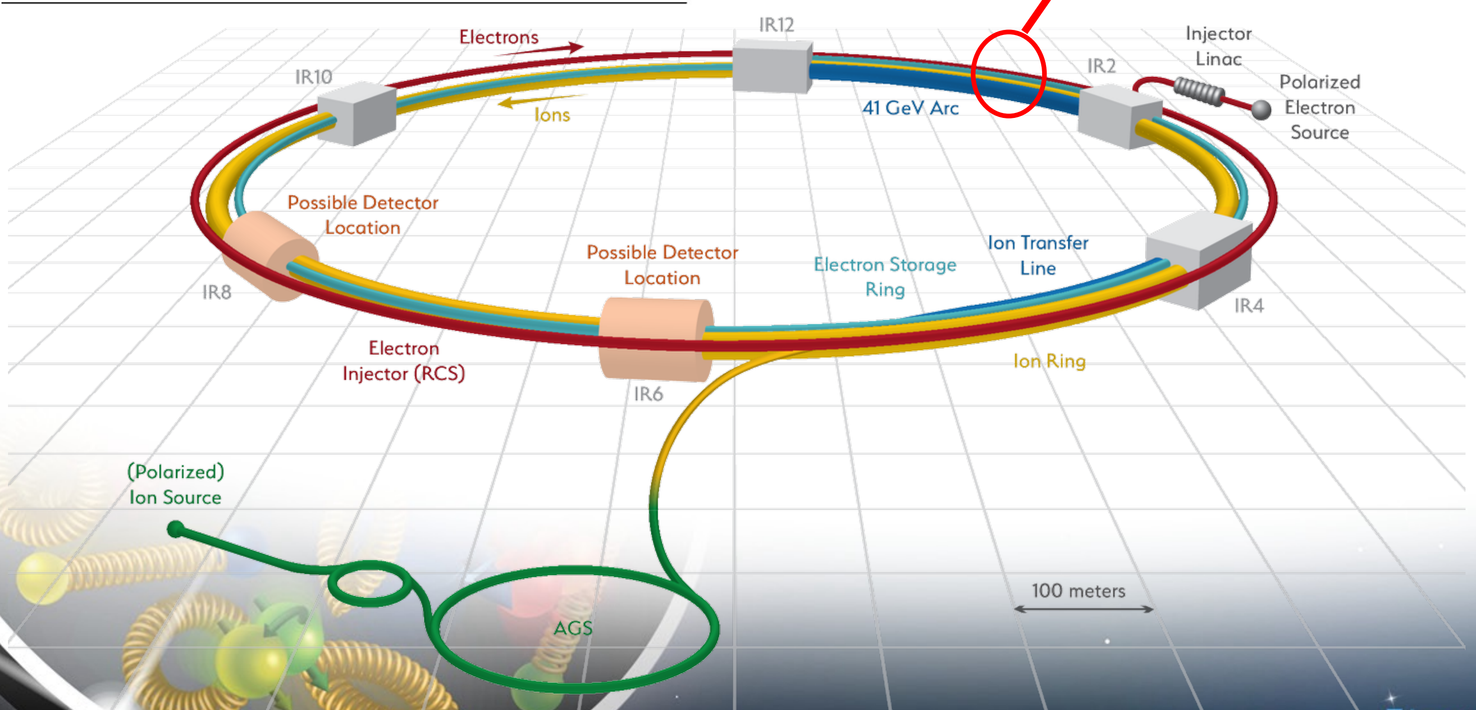


EIC Facility Layout

electron storage ring parameters

circumference [m]	3834
no. of bunches	up to 1160
energy range [GeV]	5 to 18
max. beam current [A]	2.5
max. SR power [MW]	10
$\epsilon_{x,\mathrm{RMS}}$ [nm]	20 to 24
$\beta^*_{x,y}$ at 10 GeV [cm]	43/5
RMS bunch length [cm]	1
beam-beam param. hor./vert.	0.07/0.10
polarization [%]	> 70

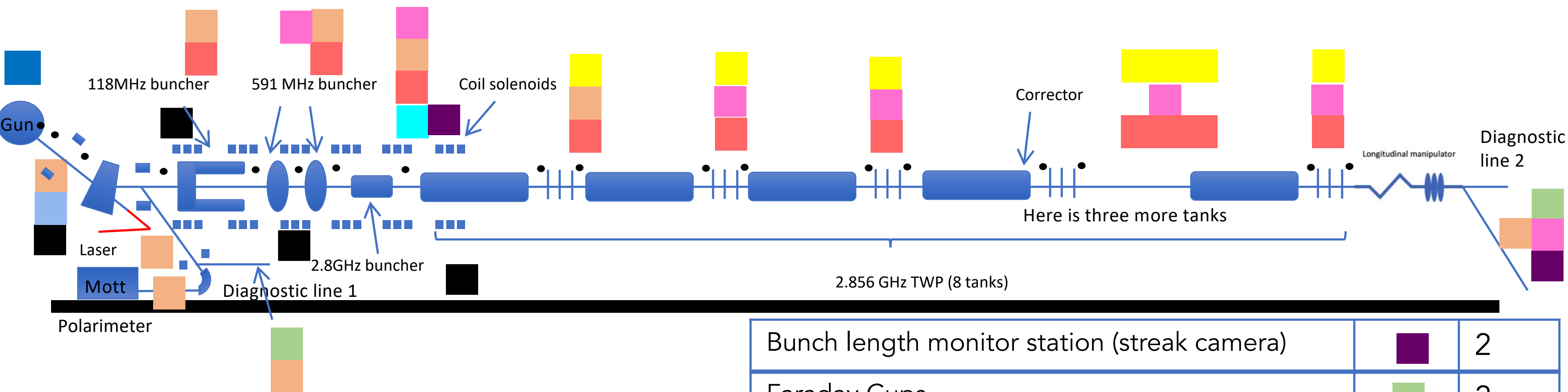




Electron Pre-Injector Instrumentation

- Beam Position Monitors
  - 100 μm position precision, 100 pC – 7 nC bunch charge range
  - Single bunch measurement capability, 4 cm round beampipe
- Charge monitors (tuning)
  - ICT, FCT, Faraday Cups
- Profile Monitors: plunging YAG/OTR screens with digital cameras
- Bunch Length: (expect 1.5 ns & 4.5 ps)
  - plunging aerogel radiator and streak camera
  - considering non-destructive relative methods using ceramic break & fast diode
- Emittance: Scanning wire
- Beam Loss Monitors
  - PMT/Scintillator detectors
- Polarization Measurements (use Mott Polarimeters)
  - at Cathode: 20 keV
  - Gun diagnostics beam line: 350 keV

Electron Pre-Injector Instrumentation



Parameter	Value
Energy	400 MeV
Charge [nC]	100 pC to 7 nC
Frequency [Hz]	1, 2
ε_n [mm*mrad]	15, 60
Bunch length	From 1.5 ns to 4.5 ps
dp/p	0.25
Polarization [%]	85

Bunch length monitor station (streak camera)	(dark purple)	2
Faraday Cups	(green)	2
Wire Scanners	(yellow)	7
YAG/OTR	(orange)	9
ICT	(pink)	7
FCT	(light blue)	1
BPM	(red)	9
Ion Clearing Electrodes (BPM pick-up)	(red)	1
Single Slit Scanner, emittance, 350 keV	(cyan)	1
BLM - Optical Fiber	(black)	5
Mott Polarimeter - Cathode prep, 20 keV	(blue)	1
Mott Polarimeter - Diagnostics line 1, 350 keV	(blue)	1

Rapid Cycling Synchrotron Instrumentation

Beam Position Monitors

Synchrotron Light Monitor:

- Beam parameters:
  - 33 –180 ps bunch lengths
  - Emittance ranges: Horiz. 40 to 200 nm, Vert. 40 to 2 nm, unnormalized
- Use streak camera for bunch length, longitudinal profiles
  - Measure emittance with precision of: Horiz: 10 nm, Vert: 0.6 nm
  - Measure transverse beam size (60 µm resolution)
  - Turn-by-Turn DAQ using gated cameras for injection matching

Tune Monitors: Using fast kickers & turn-by-turn BPMs

Current & Charge monitors:

DCCT: mA level beam current

FCT: bunch charge and pattern

Beam-Based Alignment:

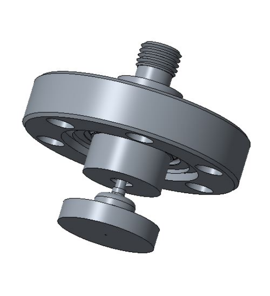
Individual quad scan method.

RCS Parameters

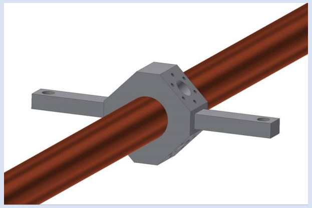
Parameter	5 GeV	10 GeV	18 GeV
Injection energy [MeV]		400	
Momentum compaction α_c		0.000372	
Max relative pol. loss		5%	
Circumference [m]		3841.35	
Ramping repetition rate [Hz]		1	
Acceleration time [ms], [turns]		100, 8000	
Total number of “spin effective” superperiods		96	
Integer horizontal tune		57	
Integer vertical tune		60	
Max vertical orbit RMS [mm]		0.5	
Number of arc Cells		192	
Number of straights		6	
Round beam pipe inner diameter [mm]		32.9	
Number of bunches injected	8	8	2
Charge per bunch at injection [nC]	7	7	5.5
Number of bunches at extraction		2	
Radio frequency [MHz]		591	
Total Cavity peak Voltage [MV]		60	
Bunching Cavity 1 [MHz]		295.5	
Bunching Cavity 2 [MHz]		147.8	
Bunch length injection [ps]		40	
Bunch length extraction [ps]	23.3	23.3	30
Hor. and Ver. emittance normalized (inj.) [mm-mrad]		26, 26	
Emittances at RCS extraction $\varepsilon_x/\varepsilon_y$ [nm]	20/2	20/1.2	24/2
RMS energy deviation at injection dp/p [10^{-3}]		2.5	
RMS energy deviation at extraction dp/p [$10^{-}3$]	0.68	0.58	1.09

RCS Instrumentation

NSLS-II Booster
11 mm button, SMA.
Place holder until
RCS BPM is designed



RCS BPM Pick-up mount

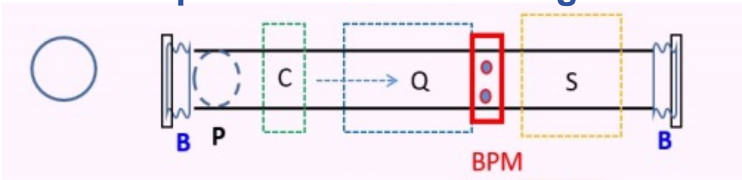


32.8 mm ID round beam pipe.

Table 4: List of RCS diagnostics types and quantities.

Types	Numbers
Beam position monitor	576
Fast current transformer	1
DCCT	1
YAG/OTR	7
Synchrotron Light Monitor	1
Tune meter	1

RCS multipole chamber showing BPM location



C+Q+S chamber, ~ **1.9 m**
B = bellows, **P** = pump ports, Φ = 32.8 mm

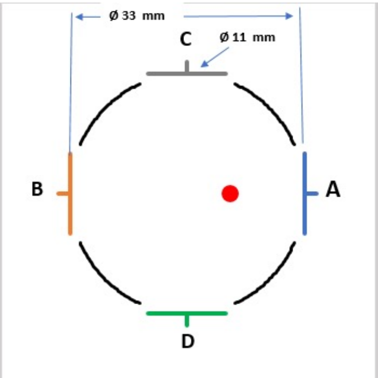
In-flange ICT

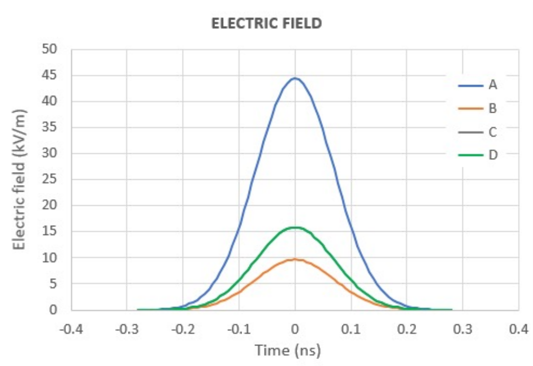
In-flange FCT

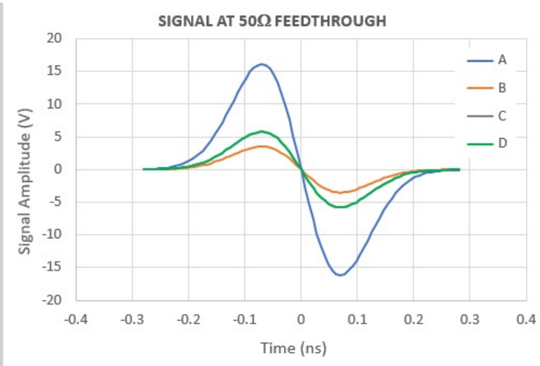
NPCT DCCT

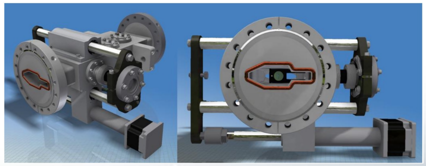
ALL COTS from GMW, Bergoz

BPM simulation of 1nC (min expected), 70 ps bunch offset by 6mm H, 11mm button









NSLS-II Storage Ring plunging YAG/OTR screens. Plan to modify design for RCS

Electron Storage Ring Instrumentation

Beam Position Monitors
Synchrotron Light Monitors: 21-27 ps bunches, RMS beam size at IP: 100 μm H, 10 μm V

- Measure transverse beam size (60 μm resolution)
- X-Ray Pin Hole Profile Monitor (H & V, 5 μm resolution)
- Longitudinal beam size (Streak Camera resolution of a few ps)
- Measure coupling
- Crabbing tilt angle

Feedback systems:

- Slow orbit: 1 Hz average position measurement, ensure an RMS orbit stability of less than 10% of the RMS beam size everywhere in the ESR.
- Transverse damper: Allows operation of the ESR at high intensity without beam in the ion ring
- Longitudinal damper: Damp coupled bunch instabilities, using RF cavity kicker

Tune Monitor: Strip-line kicker & turn-by-turn BPMs
DC Current transformer: Bergoz NPCT DCCT provides few μA resolution (2.5 Amps beam current)
Fast Current Transformer: fill pattern
Beam Loss Monitors: At strategic locations; injection, extraction, collimators, absorbers, etc…
Beam-Based Alignment: Individual quad scan method.

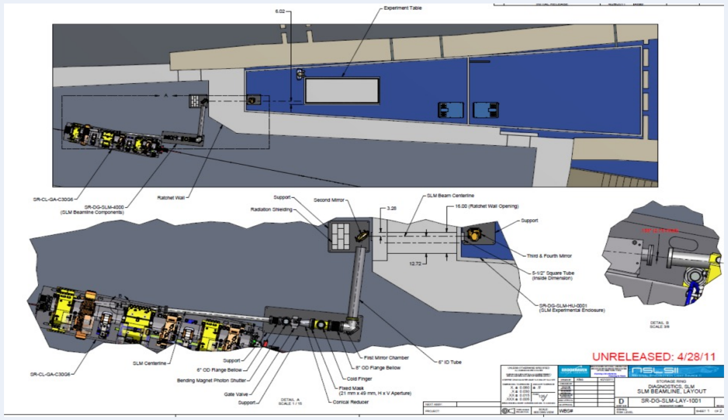
Synchrotron Light Monitors in RCS and ESR

Collaboration with the NSLS-II Synchrotron Light monitor experts;

Padrazo, Shaftan, Bacha, Kosciuk

- **A cooled mirror in the ESR will direct the visible portion of synchrotron radiation to an enclosed light transport, then to an optical table in a service building.**
- **Streak camera will provide longitudinal profile measurements.**
- **Measure turn-by-turn and average transverse profiles and phase space.**

NSLS-II Synchrotron Light Monitor layout



NSLS-II Optical table with Streak camera

Electron Crabbing angle can be directly measured using a synchrotron light monitor with streak camera at a location TBD in the electron Storage Ring.

Crab cavity bunch tilt angles measured at KEKB

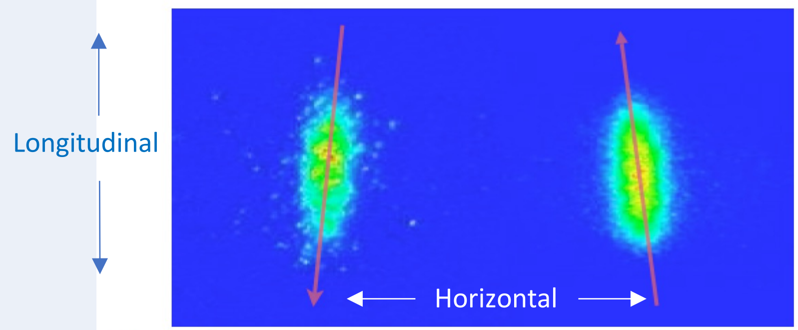


Figure 6: Images taken by streak cameras, which locate as Fig. 2, show tilt of the bunches in the LER (left) and the HER (right)[12].

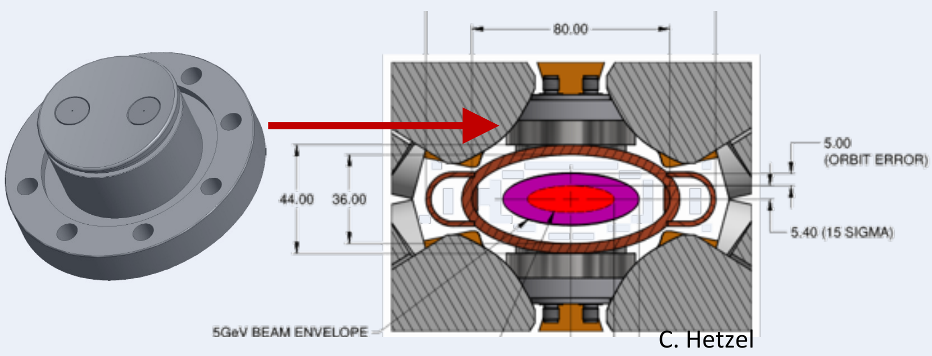
Compensation of the Crossing Angle with Crab Cavities at KEKB, Abe et al, 2007

ESR Beam Position Monitor Requirements

ESR BPM Measurement Mode	Resolution H/V	Drift	Bunch Intensity
Pilot bunches, machine setup:			
Pilot bunch, single turn	100um/100um	50um/50um	2nC
Pilot bunch, 10^3 turns, avg.	30um/30um	30um/30um	2nC
Newly injected refill bunch, in presence of stored beam:			
New bunch, low charge	50um/10um	10um/10um	2nC
New bunch, high charge	10um/5um	5um/5um	7-28nC
Stored beam:			
Turn-by-turn, low charge	30um/30um	30um/30um	2nC
Turn-by-turn, high charge	10um/10um	10um/10um	7-28nC
10^3 turns, avg.	5um/5um	5um/5um	7-28nC
1 sec average	1um/1um	1um/1um	7-28nC

ESR Beam Position Monitor Pick-ups

- 494 ESR BPM pick-ups, one per quad, 36 x 80 mm chamber
- Initial design based on NSLS-II Large-Aperture button BPM pick-up.

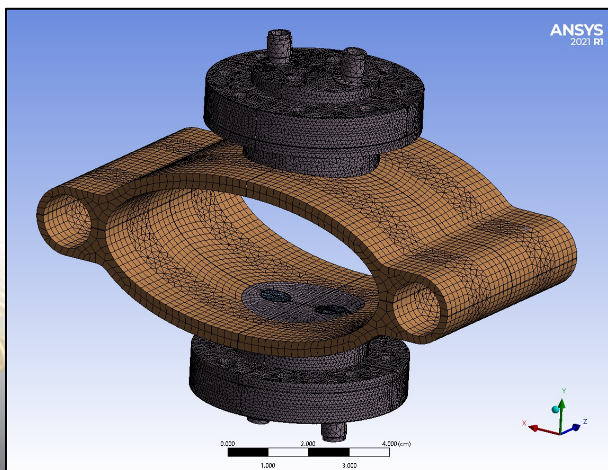


EIC ESR multipole vacuum chamber cross section

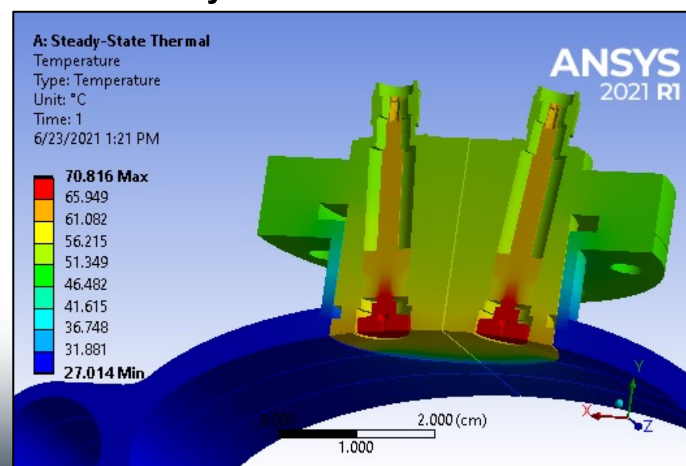
Work is underway evaluating:

- BPM signal level calculations
- Particle Studio simulations of BPM assembly
- Optimize for ESR
- Electronics locations in service buildings and alcoves around ~3.8 km ring
- Cable types & lengths (range 80 to 240 m)

Ansys model



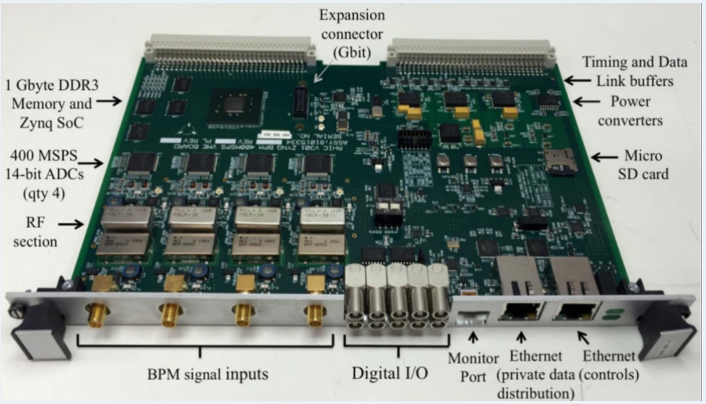
Ansys thermal simulation

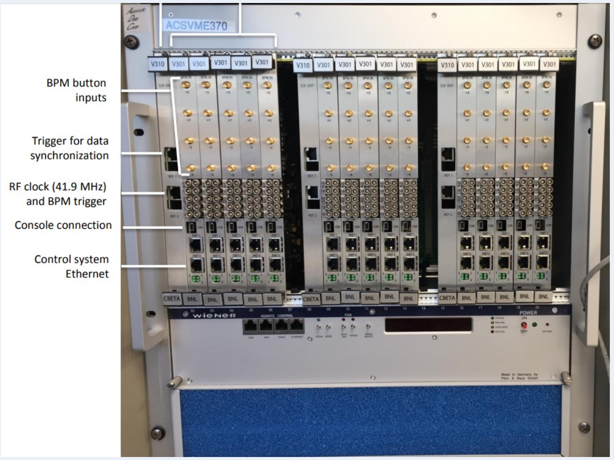


C. Hetzel
J. Bellon
S. Bellavia

EIC Beam Position Monitor Electronics

All EIC BPM electronics will be based on a revised version of the BNL designed V301 VME modules to meet EIC spec's. Successfully used at CBETA at Cornell, LEReC and locations at RHIC.

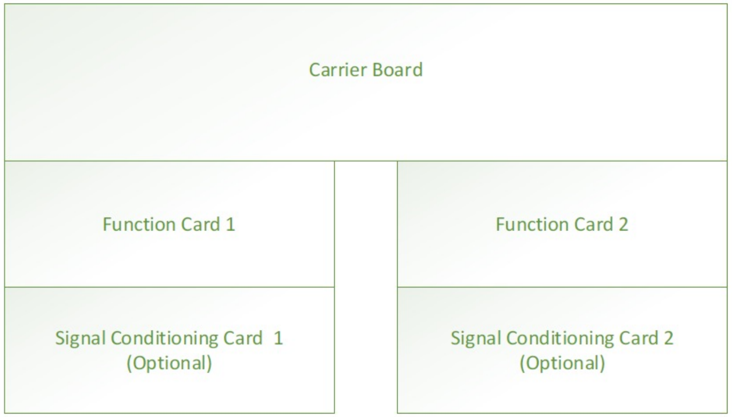




BPM electronics in VME chassis, up to 16 per

Working on integrating V301 BPM electronics functionality into an EIC Common Platform.

- **1U chassis for 19" rack, each can service 2 BPMs**
- **Need new electronics for approximately 1400 BPMs**
- **Will also be used by LLRF and a variety of other systems**



Hadron Ring Diagnostics

Upgrade most of the existing diagnostics systems

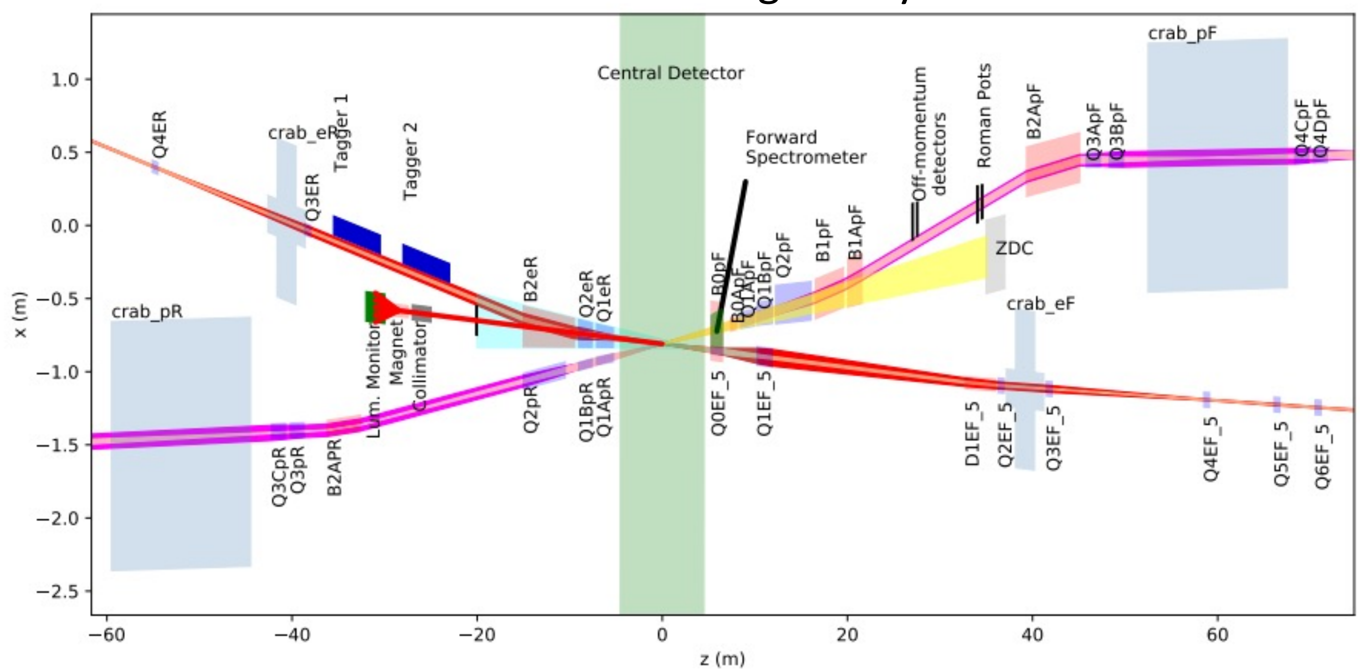
- Instrumentation in the new hadron injection transfer line (IR6 to IR4)
  - 2 CT's, 6 Profile Monitors, 6 BPMs, 10 BLMs
- New button BPM pick-ups and electronics
- Ionization Profile Monitors Upgrade
  - Includes higher voltage bias, and higher density MCP to improve performance
- Wall Current Monitor Upgrade:
  - Replace existing resistive WCM with a wider band electro-optical detector that can resolve the 6 cm (180 ps) proton bunch length.
- Multi-use strip-line kicker upgrades:
  - H & V Tune meter kicker, Longitudinal damper, Injection damper, Gap cleaner
- Base-band Tune System (BBQ) Upgrade: new kicker, pick-up, electronics
- HF & LF Schottky Upgrade: new pick-ups, electronics
- Head-Tail Pick-up Upgrade: new pick-up
- DCCT: upgrade detector and electronics (1 Amp beam current)
- Collimators: Primary, secondary and momentum
- Beam Loss Monitor system upgrade

All hadron ring beamline component upgrades include improved impedance characteristics.

Interaction Region Instrumentation

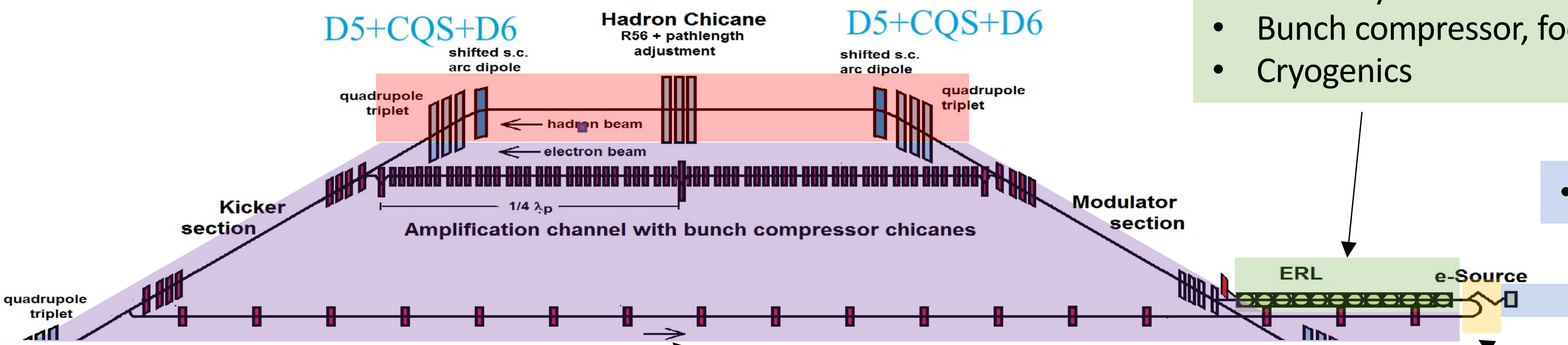
- Beam Position Monitors:
  - Dual plane button pick-ups (78)
  - Position precision TBD, 2 - 28 nC bunch charge range
  - Special BPM pick-up near IP with wide band electronics to measure hadron crab tilt
  - No pick-ups are common to both beams (25 mrad crossing angle)
- Beam Loss Monitors:
  - Ion Chambers, PMT/Scintillator, Pin Diodes distributed a critical locations
  - Beam pipe temperature
- Orbit Correction near the IP:
  - BPMs and corrector magnets

EIC Interaction Region Layout



EIC Strong Hadron Cooling Parameters & Layout

	Value
Proton energy [GeV]	275
e-beam energy [MeV]	150 ★
e-beam normalized emittance [mm-mrad]	2.8
e-beam rms beam size [mm[	0.7
e-beam energy spread	1 x 10^{-4} ★
Rep. Freq. [MHz]	98.5
Average electron beam current [mA]	120 ★
Electron beam charge [nC]	1
Cooling time [min]	50



- ERL RF system
- Bunch compressor, focusing
- Cryogenics

- Electron source

- ERL High Energy beam transport(HEBT)

- ERL merger (Zigzag)

E. Wang

Strong Hadron Cooling Instrumentation

Utilize experience gained at LEReC and CeC PoP, reuse some devices

- Beam Position Monitors
  - 10 – 100 μm precision, 100 pC – 1 nC bunch charge range
    - Average position measurement of CW beams
  - Co-propagation e-ion transverse alignment <5% of ~0.7 mm RMS beam size in modulator and kicker
    - Achieved at LEReC: <5% RMS beam size alignment using BPM switching method
- Current monitors (for tuning & MPS) (120 mA beam, 1 nC/bunch)
  - DCCT, FCT, ICT, Faraday Cups
- Profile Monitors (throughout 400 m beam line) (e-beam size – few mm's)
  - YAG/OTR – plunging transverse profiles
  - SLM (streak camera – longitudinal profile – expect 40 ps bunch length)
  - Emittance Slits, Wire scanners (expect electron rms normalized emittance range 1.9 - 2.8 μm)
  - Halo scrapers
- Beam Loss Monitors (for tuning & MPS)
  - PMT/Scintillators & Pin Diodes
  - Beam pipe temperature
- Sliced energy spread measurement at 150 MeV (ensure $<10^{-4}$), use transverse deflecting cavity
- Electron & Ion bunch longitudinal relative alignment
  - 1 micron stability of the longitudinal alignment (e.g. path length changes due to magnet field ripple)
- Energy Recovery Linac related diagnostics.

Strong Hadron Cooling Diagnostics Table

EIC Strong Hadron Cooling Instrumentation Table

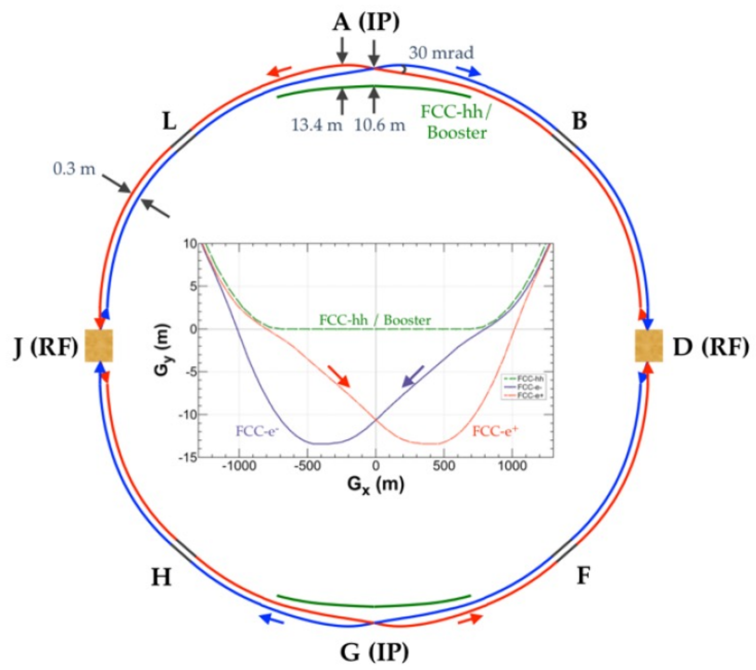
Gassner, Paniccia 21Oct20

System	400 MeV LEReC Gun to Linac transport (2 bunchers) with zig-zag merge	SCRF Linac 150 MeV 591 MHz (9 cavities) 60m	Linac to Modulator transport 10m	Linac HE Diagnostics Beamline 10m?	SHC Modulator Common Region 50m	SHC Amplifier Chicane electrons 100m	SHC Hadron Chicane 100m	SHC Kicker Common Region 50m	electron return to merge 230m	HP Dump transport & HP Dump 5m	LP Dump transport & LP Dump 5m	LE electron Diagnostics Beamline 5m	Quantity Totals
Beam Position Monitors													
BPMs	8	12	5	5	8	20	10	8	25	3	3	3	110
Current and Charge Monitors													
DCCT	1									1			2
ICT	1		1	1		1			1	1	1	1	8
FCT	1		1	1		1			1	1	1	1	8
Dump/Faraday Cups	2	1	1	1	1	1		1	1	1	1	1	12
Profile and Emittance Monitors													
Screen Profile Monitors	4	4	2	2	4	4		4	6	2	1	2	35
Wire Scanners	1	3	1		1	1		1	1				9
Emittance Slit Scanners	1	3				1		1	1				7
Halo Scrapers/Collimators	1		1						1			1	4
Transverse Deflecting Cavity				1									1
Synchrotron Light Monitors													
Longitudinal, H & V profiles				1	1	1		1					4
Relative bunch alignment								1					1
Beam Loss Monitors													
PMT/Scintillator BLMs	5	10	4	4	4	10	10	4	25	4	4	4	88
Thermal monitors													
Beam pipe temperature	6	5	5	5	5	5	5	5	10	8	8	3	70
Totals	31	38	21	21	24	45	25	26	72	21	19	16	359

Potential EIC-FCC Collaboration topics

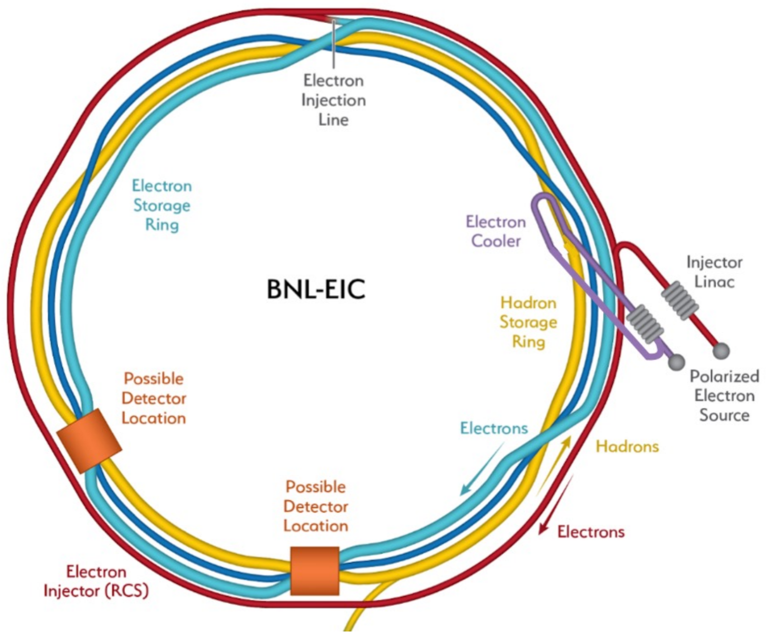
- Many common electron storage ring parameters include bunch intensity, length, spacing, and beam current.
- Similar operational modes.

FCC-ee



97.75 km double ring, full-energy $e\pm$injection, injection every ~2 min into same bucket

EIC

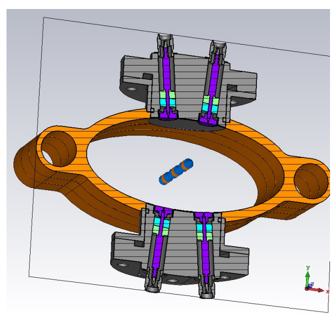


3.83 km double ring, full-energy $e-$injection, injection rate 1 Hz, every 2 min into same bucket

Potential EIC-FCC Collaboration topics

BPM button pick-ups

- Electromagnetic design and optimization for low wake, beam coupling impedance, heat load
- Vacuum chamber details: cross-section profile, materials, cooling channels, etc.
- Arrangement & integration with the quadrupoles, mechanical mounting considerations
- Prototyping with industry, manufacturing in quantity and eventual beam tests



EIC ESR BPM

FCC BPM

BPM electronics

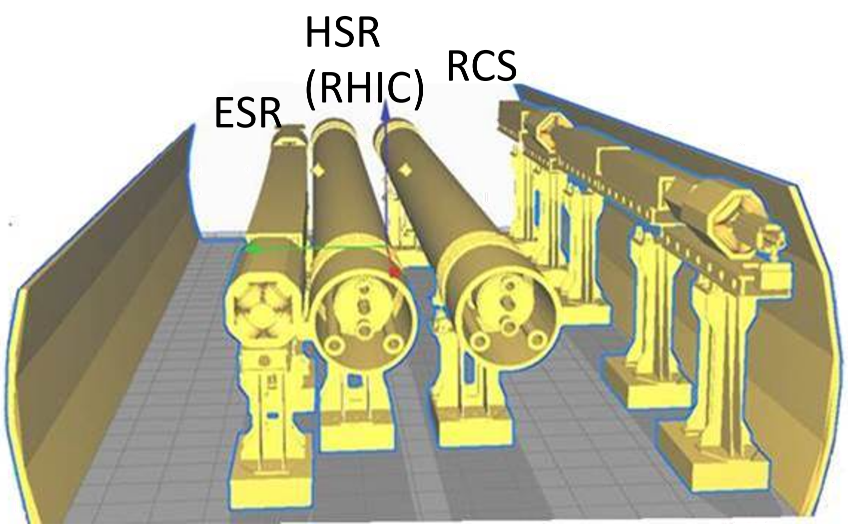
- Study radiation tolerant FE electronics in the tunnel.
- Back-end data collection electronics in a non-radiation area.
- Data acquisition methods and decimation concepts.
- Signal transmission strategies, and bandwidth requirements

Contributions from M. Wendt

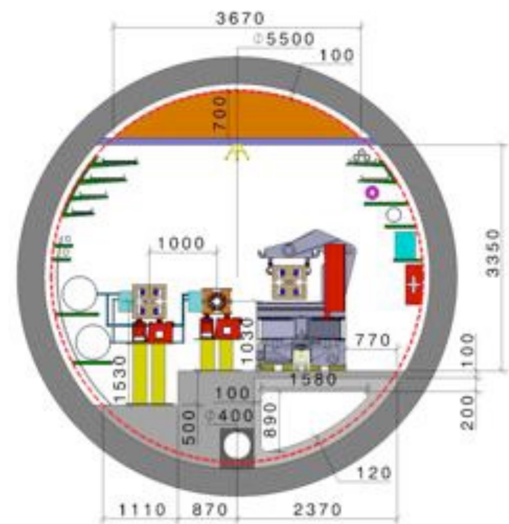
Potential EIC-FCC Collaboration topics

Beam Loss Monitoring

- **EIC and FCC will both have 3 active rings in the same tunnel, there are cross-talk challenges with the different species and loss mechanisms. Consider machine protection strategies.**
- Define specifications – Resolution, dynamic range and time response – Fluka simulations
- Design study for identifying losses from different beams (electron/ion, main ring/booster)
- Design study on BLM detector types
- Design, prototyping hardware and validation testing



EIC Tunnel



FCC Tunnel

Polarimetry

- EIC plans for a Compton polarimeter for measurements in the ESR
- EIC-FCC collaboration discussions already underway

Contributions from T. Lefevre

Thank you for your attention!

Electron-Ion Collider

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