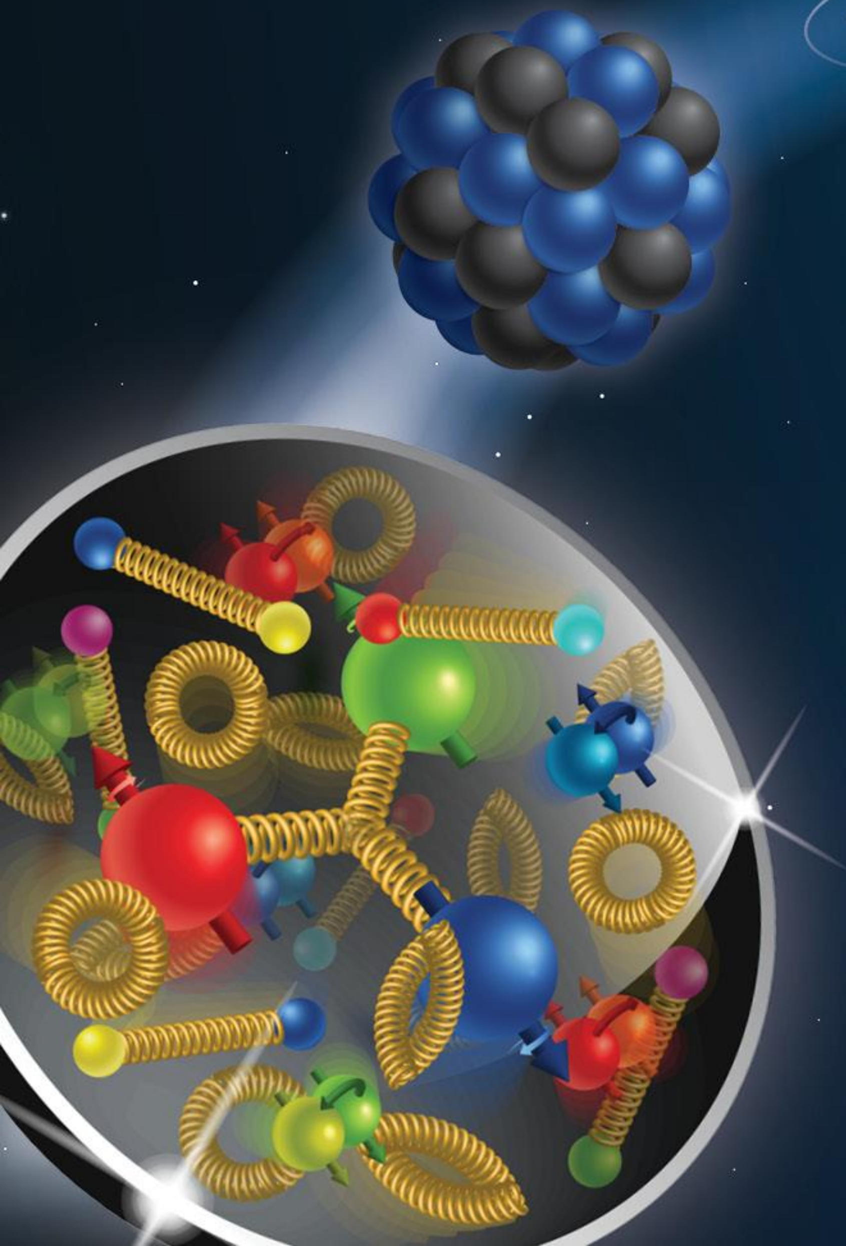


# EIC Diagnostics

David Gassner

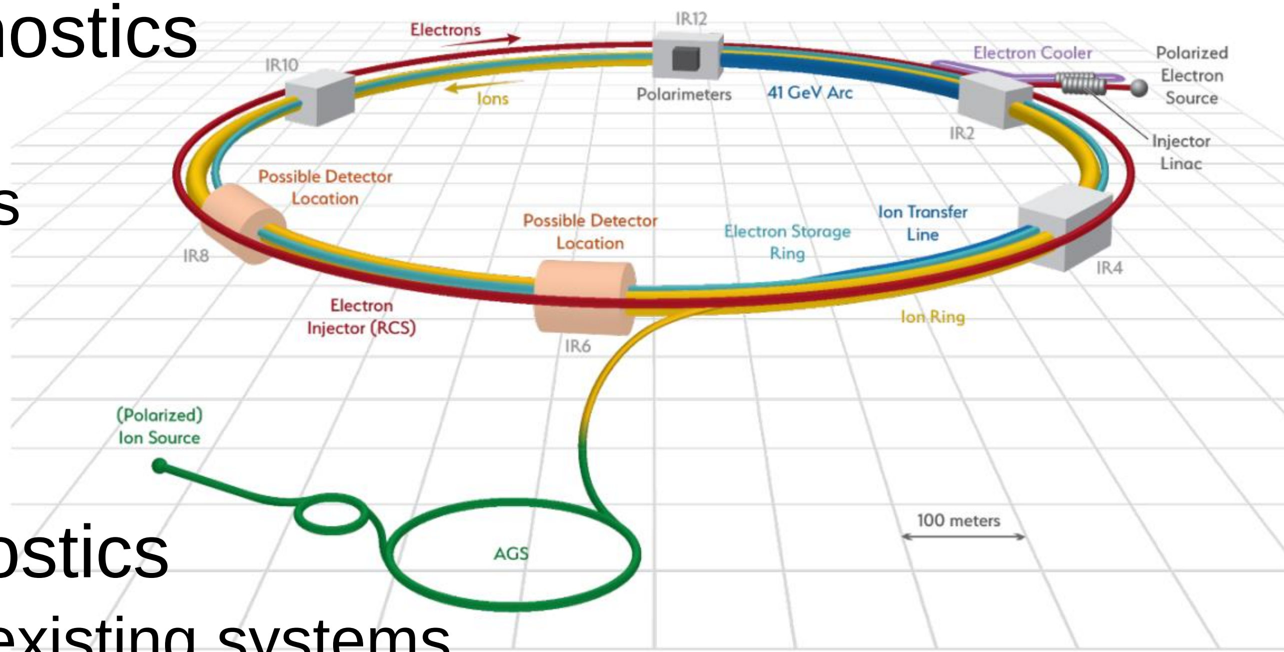
EIC Accelerator Collaboration Workshop
October 7-9, 2020

Electron-Ion Collider

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

# Outline

- Electron Diagnostics
  - Pre-Injector
  - Transfer Lines
  - RCS
  - ESR
  - IR
- Hadron Diagnostics
  - Upgrades to existing systems
- Strong Hadron Cooling Diagnostics



# Pre-Injector Instrumentation Requirements

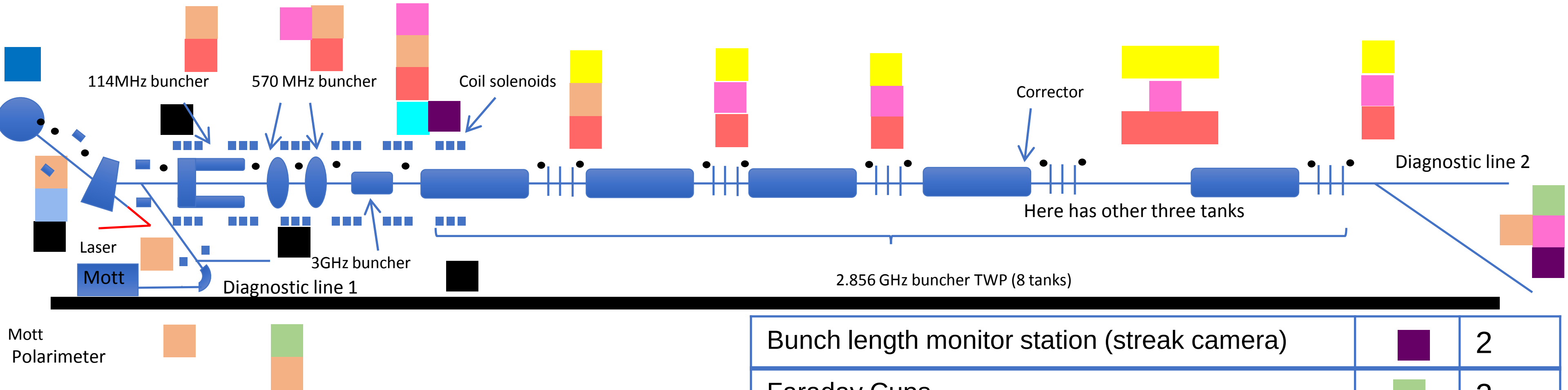
- Beam Position Monitors
  - 10 um position precision, 100pc - 7nC bunch charge range
  - Single bunch capability, 4cm round beampipe

- Current monitors (tuning)
  - ICT, FCT, Faraday Cups

- Profile Monitors: YAG/OTR
- Bunch Length: (expect 1.5ns & 4.5ps)
  - plunging radiator and streak camera,
  - considering non-destructive relative methods done by Frisch at LCLS
- Emittance: Scanning wire
- Beam Loss Monitors (tuning)
  - PMT/Scint detectors

- Polarization Measurements (use Mott Polarimeters)
  - at Cathode: 20 keV
  - Gun diagnostics beam line: 350 keV

# Pre-Injector Instrumentation

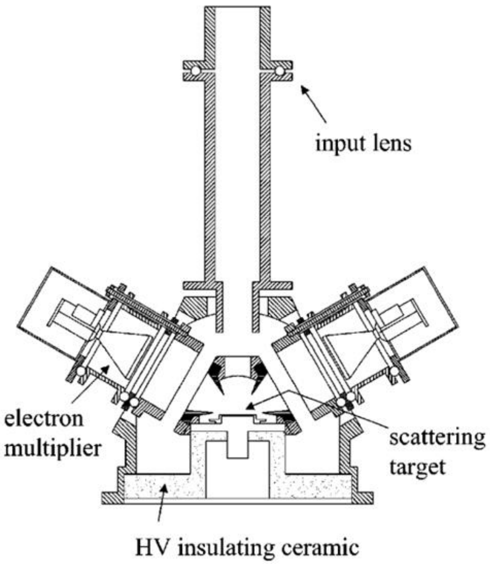



| Parameter | Value |
|---|---|
| Energy | 400 MeV |
| Charge [nC] | 100pC to 5.85nC |
| Frequency [Hz] | 1, 2 |
| $\varepsilon_n$ [mm*mrad] | 15, 60 |
| Bunch length | From 1.5 ns to 4.5 ps |
| dp/p | 0.01 |
| Polarization [%] | 85 |

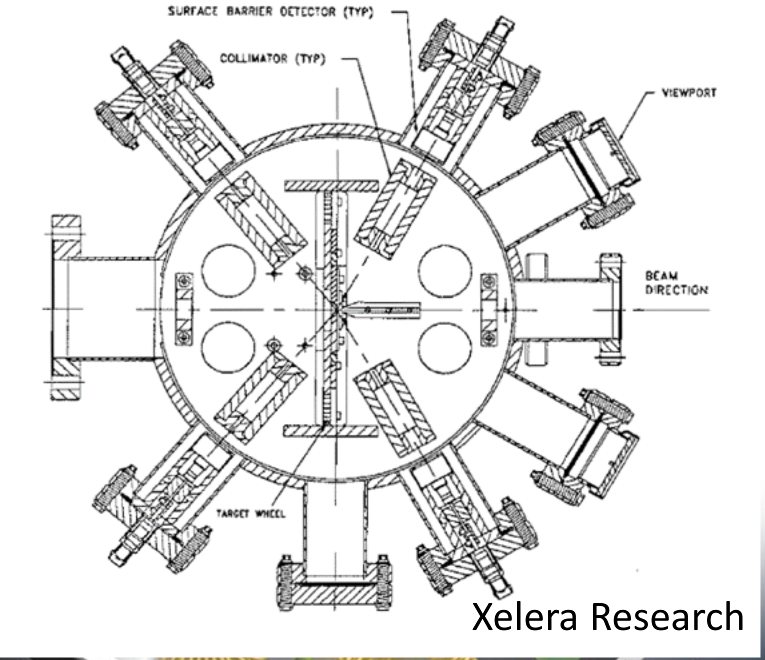
| | | |
|---|---|---|
| Bunch length monitor station (streak camera) | (dark purple) | 2 |
| Faraday Cups | (light green) | 2 |
| Wire Scanners | (yellow) | 7 |
| YAG/OTR | (tan) | 9 |
| ICT | (pink) | 7 |
| FCT | (light blue) | 1 |
| BPM | (red) | 9 |
| Ion Clearing Electrodes (BPM pick-up) | (red) | 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 |

# 2 Mott e-Polarimeters at the pre-injector

- A compact Mott polarimeter (~20 keV) at the cathode chamber will be used for checking the beam from the SL-GaAs wafer after activation. Similar to what P. Johnson from BNL built, and now offered by company SPECS.
  - Have quote for device purchase.




**Compact Mott polarimeter (5-30 keV) for cathode preparation**




A 350 keV Mott Polarimeter will be used in the pre-injector gun diagnostics beamline. We have a quote from Xelera Research for a complete system that is based on an upgrade to a 100 keV design. (Mayes & Dunham)

# Transfer beamline Diagnostics

## Linac to RCS

| Device | Qty | Requirements |
|---|---|---|
| BPMs | 15 | 1 Hz measurement rate, ∼20 μm resolution |
| YAG/OTR | 7 | ∼50 *μm* resolution |
| ICT | 1 | position insensitive, radiation tolerant, 10 pC accuracy |
| FCT | 1 | ∼200 ps rise time, upper cutoff frequency ∼2 GHz |

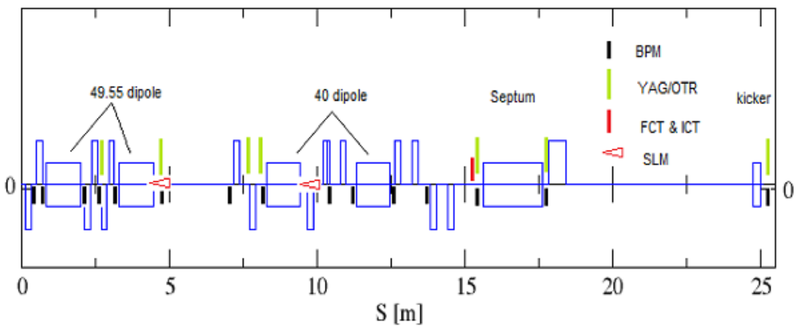
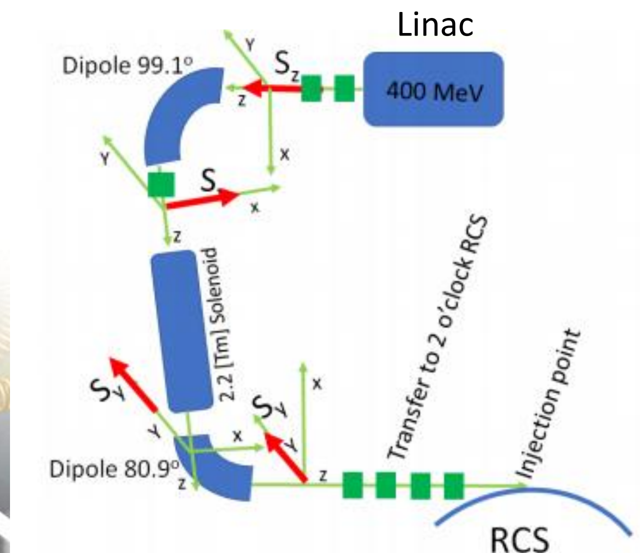
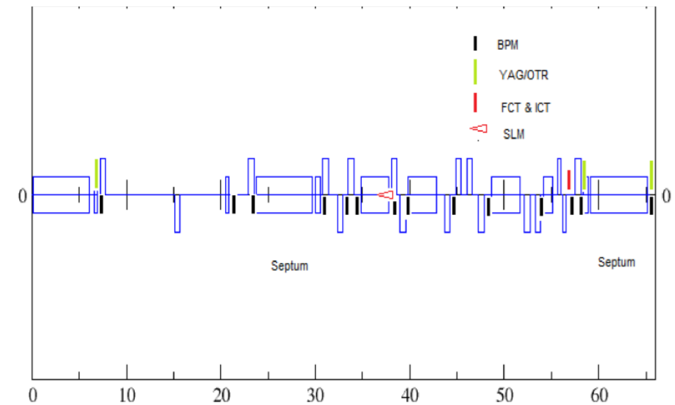



**Figure 3.132:** The spin rotator for the 400 MeV electron beam. The small green rectangles are quadrupoles on the transfer line. The arc at the bottom of the picture is part of the RCS ring.




## RCS to ESR

| Device | Qty | Requirements |
|---|---|---|
| BPMs | 14 | 1 Hz measurement rate, ∼20 μm resolution |
| YAG/OTR | 3 | ∼50 *μm* resolution |
| ICT | 1 | position insensitive, radiation tolerant, 10 pC accuracy |
| FCT | 1 | ∼200 ps rise time, upper cutoff frequency ∼2 GHz |



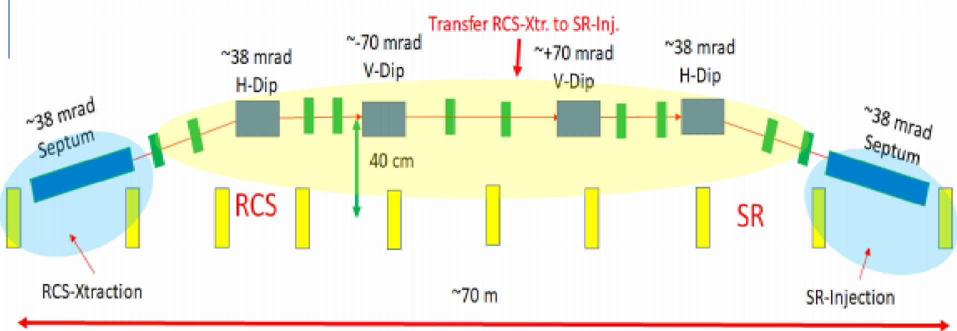




**Figure 3.145:** Schematic diagram of the layout of the RtS transfer line. The yellow rectangles represent the quadrupoles of the RCS which are placed above those of the electron storage ring. The blue highlighted areas are the extraction and injection regions. The drift space between the quadrupoles of each of the rings is about 7 m. The yellow highlighted area is the transfer line between the exit of the RCS extraction system and entrance of the electron storage ring injection system.

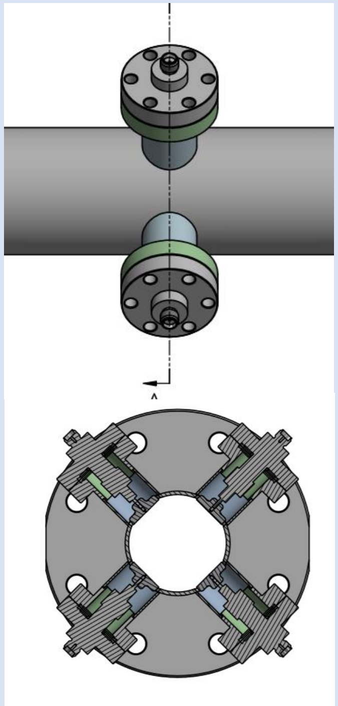
# RCS instrumentation Requirements

- Beam Position Monitors
  - Dual plane pick-ups, one per quad (576)
  - Precision 10 microns, from 1-28nC bunch charge
  - Turn-by-turn capability

- Synchrotron Light Monitors: 40-180ps bunch lengths (emittance 20nm H, 2nm V)
  - Measure transverse beam size: determine emittance, energy spread
  - Turn-by-Turn using gated cameras for injection matching
  - Streak camera for bunch length, longitudinal profiles

- Tune Monitors: fast kickers & BPMs
- Current monitor (mA beam current)

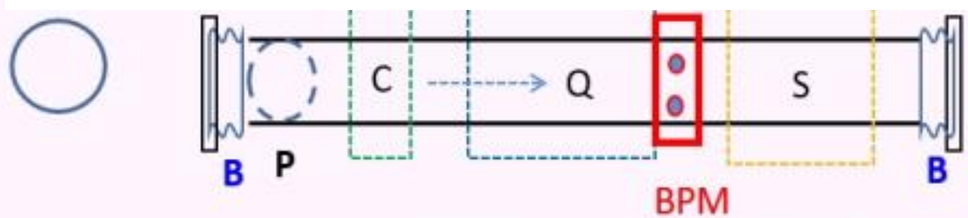
# RCS Instrumentation



Design based on NSLS-II BPM pick-up, 15mm button, 40mm 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 | 2 |
| Tune meter | 1 |




C+Q+S chamber, ~ **1.9 m**

**B** = bellows, **P** = pump ports, Φ = 40 mm

**RCS half-cell Layout showing BPM location**

**In-flange ICT**

**In-flange FCT**

**NPCT DCCT**

Purchased from GMW, Bergoz

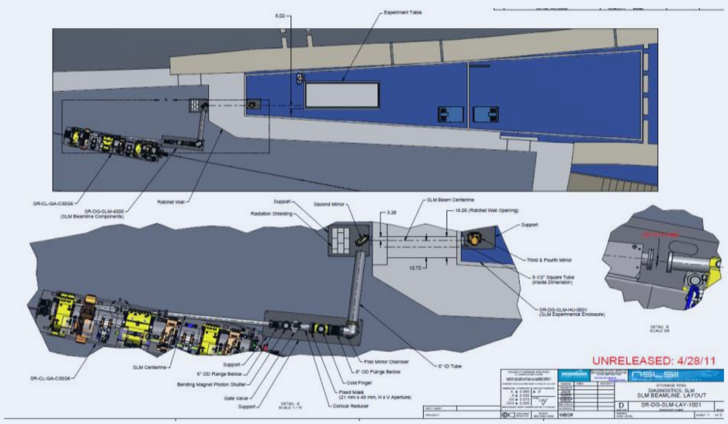
# Synchrotron Light Monitors in RCS and ESR

**Collaboration with the NSLS-II Synchrotron Light monitor experts;**

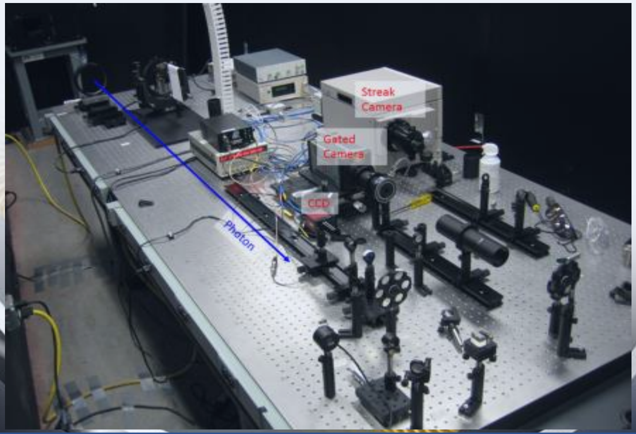
**Padrazo, Shaftan, Bacha, Kosciuk, Cheng**

- **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.**
- **Measure transverse profile, turn-by-turn profile, longitudinal profile and phase space.**
- **Streak camera with ~1ps resolution will provide longitudinal profile measurements.**

## 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

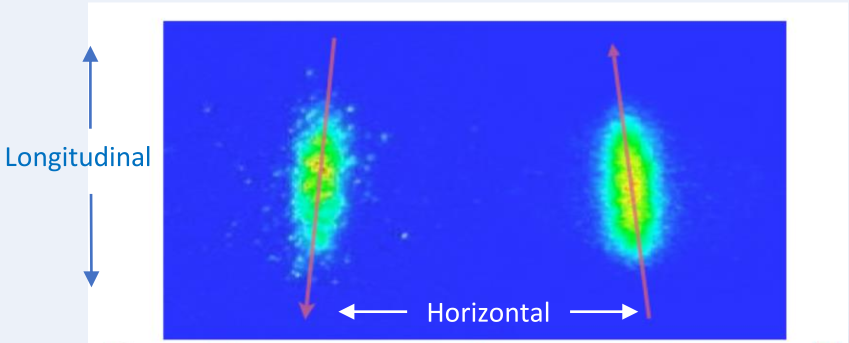



Figure 6: Images taken by streak cameras, which locate as Fig. 2, show tilt of the bunches in the LER (left) and the HER (right)[12].

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

# ESR Instrumentation Requirements

BPM System:

- Dual plane pick-up at each quad (494)
- Turn-by-turn and single bunch DAQ
- Precision 10 microns, from 1-28nC bunch charge

Synchrotron Radiation Monitors: (bunch length 60ps)

- Transverse (60um resolution), Longitudinal (Streak Camera Res), Coupling
- X-Ray Pin Hole Profile Monitor (H & V, 5um resolution)
  - emittance will be: 20nm V, 1.3nm H
- Crabbing angle (SLM) with one crab cavity off

Feedback systems:

- Slow orbit: 1Hz average positions, 5-micron accuracy
- Longitudinal: Damp beam instability, use RF Cavity kicker
- Transverse: Allows operation of the ESR at high intensity without beam in the ion ring.

Beam Loss Monitors:

- At strategic locations; injection, extraction, collimators, absorbers, etc…

Tune Monitor: Strip-line kicker & TbT BPM

DC Current transformer: (1kHz BW, few uA resolution) 2.5 Amps beam current

Fast Current Transformer: (fill pattern)

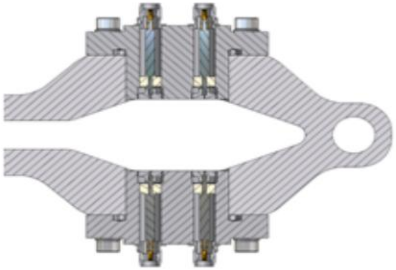
# ESR Instrumentation

| Types | Quantity |
|---|---|
| Beam position monitor | 494 |
| Fast current transformer | 1 |
| DCCT | 1 |
| Synchrotron Light Monitor | 2 |
| X-ray Pin-hole | 1 |
| Polarimeter | 1 |
| Tune meter | 1 |
| Scrapers | 4 |
| Longitudinal bunch-by-bunch feedback | 1 |
| Transverse bunch-by-bunch feedback | 1 |
| Slow orbit feedback | 1 |

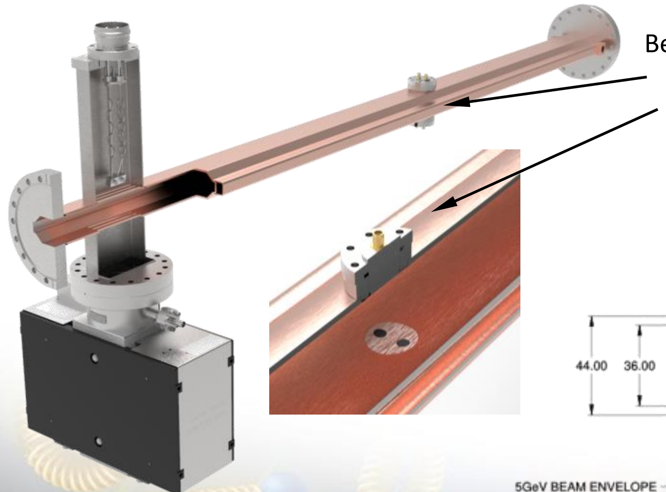
# ESR Beam Position Monitors

- 494 ESR BPMs, one per quad, 36 x 80 mm chamber
- Design and estimate based on NSLS-II Large-Aperture button BPM pick-up.

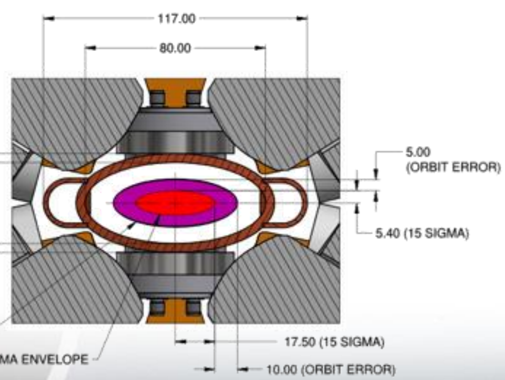
**NSLS-II Large Aperture BPM pick-up, dual 7mm buttons**



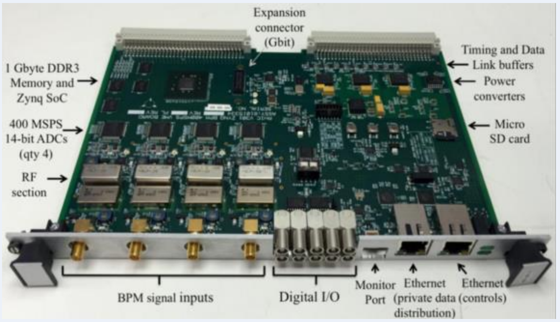
**NSLS-II SR LA BPM Assembly cross section**



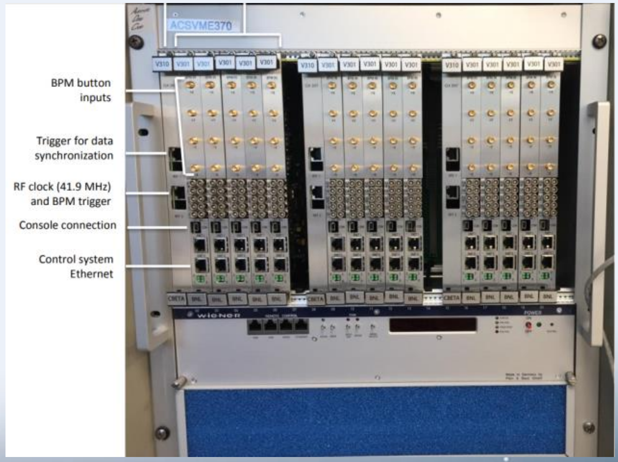

**ESR vacuum chamber model**




**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 LEReC, CeC and CBETA at Cornell**



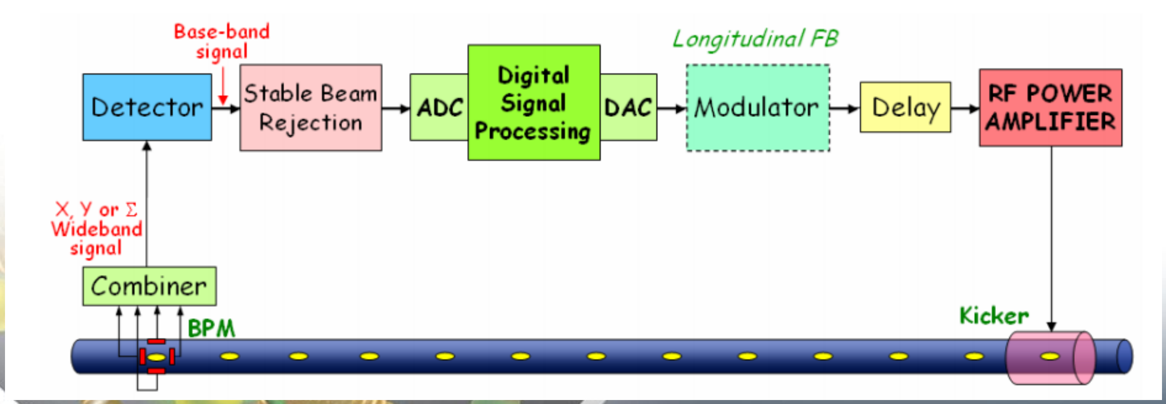

**BPM electronics in VME chassis, 15 per**

# ESR Transverse BbB Feedback

- Detector: A beam position monitor (BPM) with good sensitivity, at a location with large beta, zero dispersion
- Signal processing unit: both commercial products (I-Tech, DimTel) and and in-house design possible
- Kicker: A strip-line kicker (~1m) with high shunt impedance, good matching to avoid reflected power back to the RF PA.

# ESR Longitudinal BbB Feedback

- Detector: BPM sum signal, horizontal position measured by BPM at dispersive location or phase measurement
- Signal processing unit: FPGA-based unit, DimTel provides transverse and longitudinal in the same box
- Kicker: Considering using a similar cavity kicker design that was developed at DAΦNE



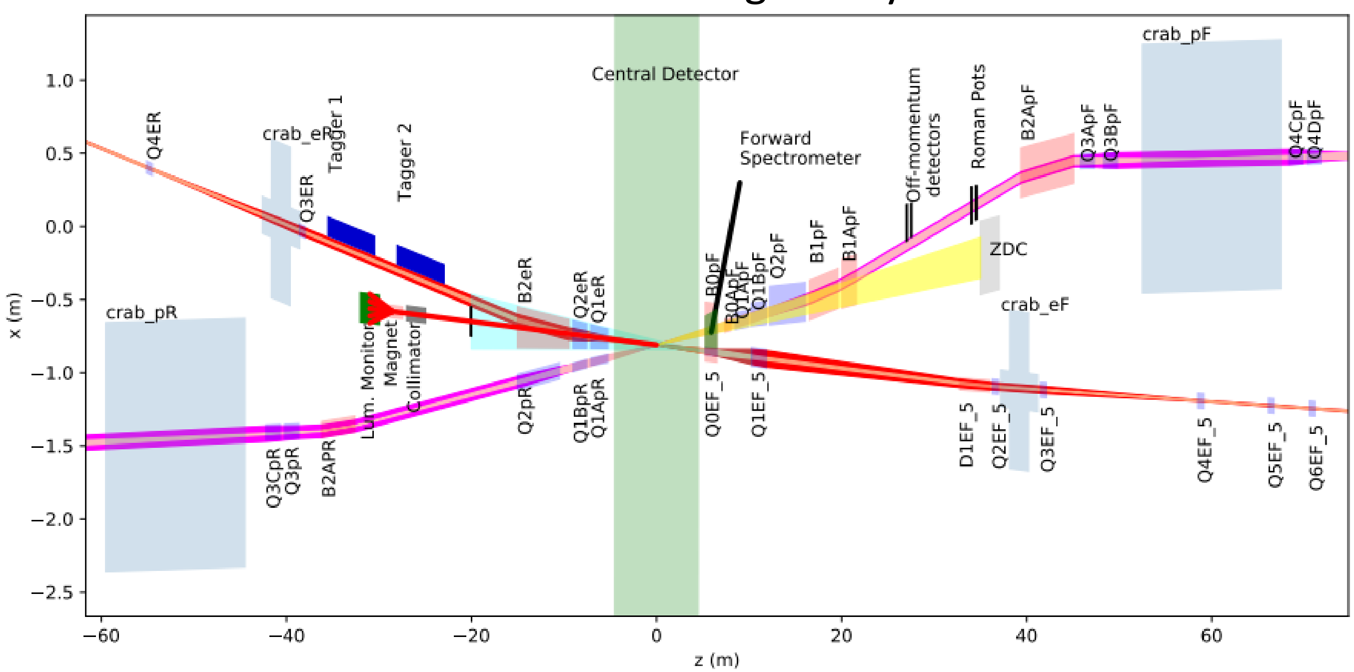

'iGp', by Dimtel

'Libera Bunch-by-Bunch', by Instrumentation Technologies

# IR Instrumentation Requirements

- Beam Position Monitors:
  - Dual plane button pick-ups
  - Position precision TBD, 1-28nC bunch charge range
  - Some BPMs near IP might not have symmetrical chambers
  - Special BPM pick-up near IP with wide band electronics to measure hadron crab tilt
- 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



# IR BPMs

- Total = 78
- Cover 2 beamlines (e & h), +/- 125m

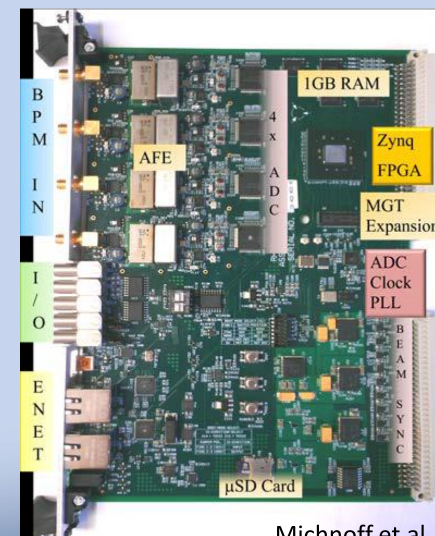
15 IR hadron cold magnets with BPMs will be reused from elsewhere in RHIC

## IR Beam Position Monitors

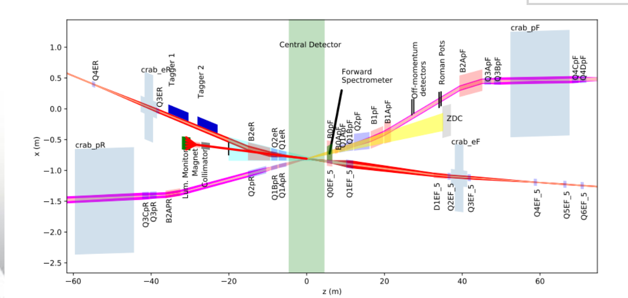
| | Type | | New | Electronics | |
|---|---|---|---|---|---|
| | Warm | Cold | Pick-up | Standard | Scope |
| IP BPMs | 4 | | 4 | 4 | |
| IP Tilt BPM | 1 | | 1 | | 1 |
| | | | | | |
| Forward E | | 14 | 14 | 14 | |
| Rear E | | 14 | 14 | 14 | |
| | | | | | |
| Forward H | | 12 | 3 | 12 | |
| Rear H | | 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** | **27** | **51** | **63** | **77** | **1** |
| | | | | | |
| Total e-BPMs | | | 46 | | |
| Total h-BPMs | | | 32 | | |
| | | | | | |
| **Total BPMs** | | | **78** | | |

BPM Electronics based on next generation BNL designed V301 VME modules.

Used at LEReC, CeC and CBETA




Michnoff et al

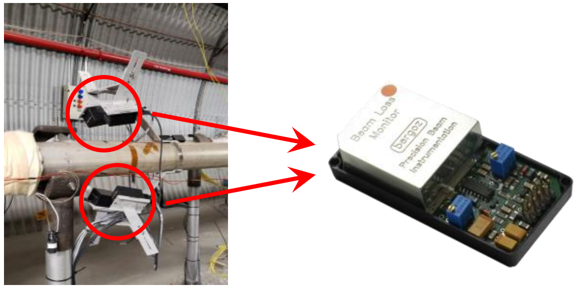



EIC IR layout

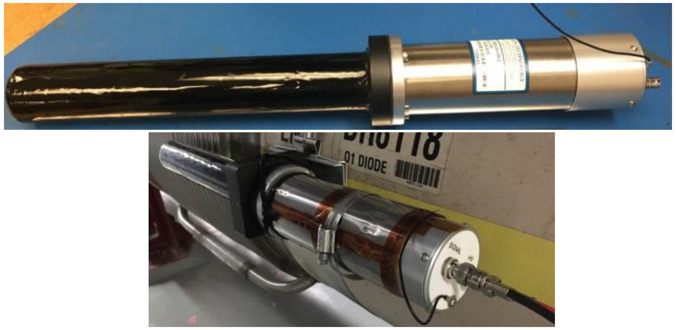
# IR Beam Loss Monitors

- Proven technology used for many years at C-AD.
  - 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 levels

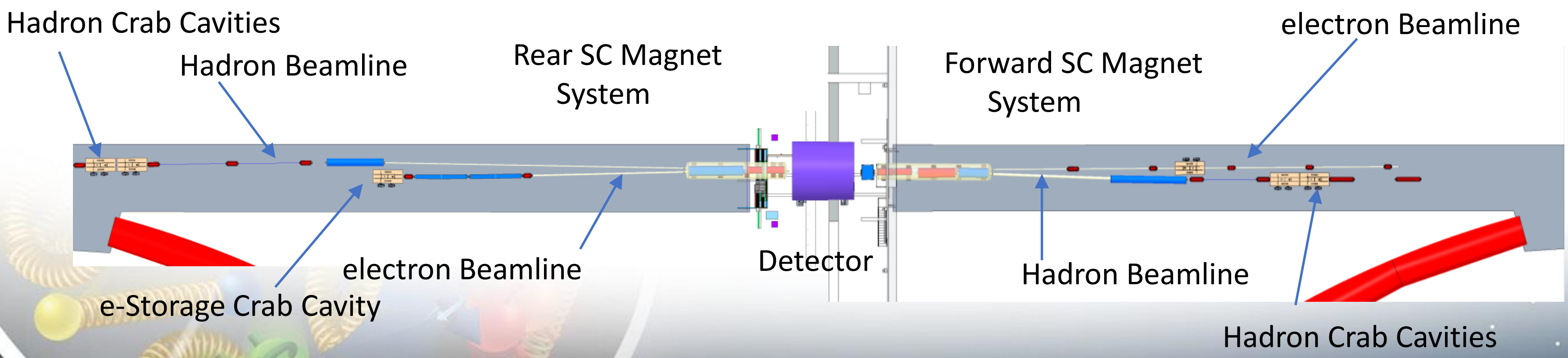
RHIC style BLM Ion Chamber




Bergoz Pin Diode BLMs

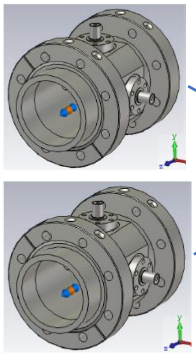


Scint/PMT BLMs



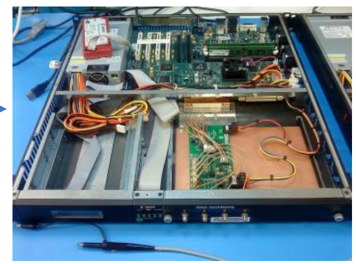
# IR Orbit feedback

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



IR BPMs

RHIC BPM IFE board with daughter card

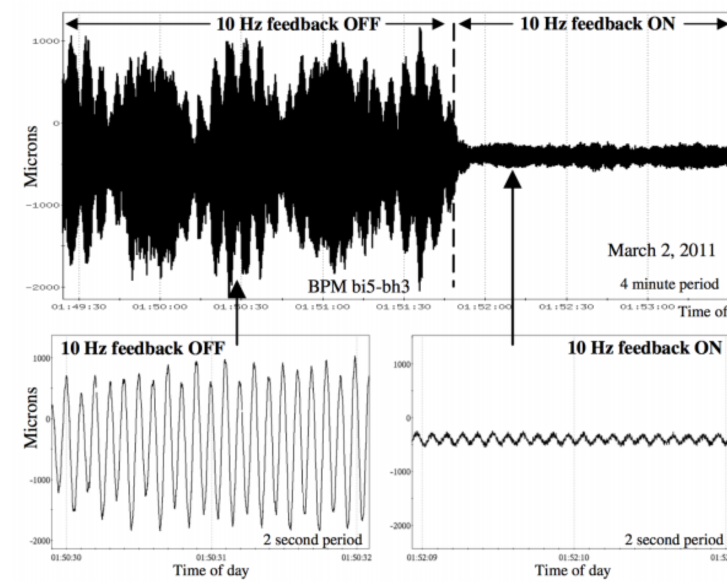


Digital to analog converter Electronics, Xilinx ML-510

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).

# Hadron Ring Diagnostics

## Upgrade most of the existing diagnostics systems

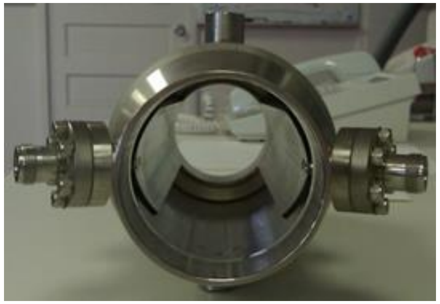
- Instrumentation in the new hadron injection transfer line (IR6 to IR4)
  - 2 CT's, 6 Profile Monitors, 6 BPMs, 10 BLMs
- New button BPM pick-ups and electronics
- Ionization Profile Monitors Upgrade
  - Includes higher voltage bias and higher density MCP to improve performance
- Wall Current Monitor Upgrade:
  - Replace existing resistive WCM with a wider band electro-optical detector that can resolve the 6cm (180ps) 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
- Beam Loss Monitors: use existing IC detectors, new electronics, pin-diodes
- 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)

All upgraded hadron ring beamline component upgrades include improved impedance characteristics.

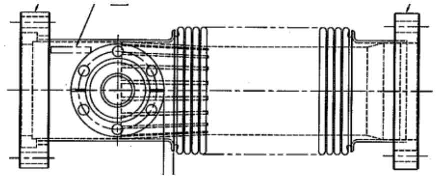
# Hadron Ring BPM Upgrade

## New BPM pick-ups, cryo-cables, electronics

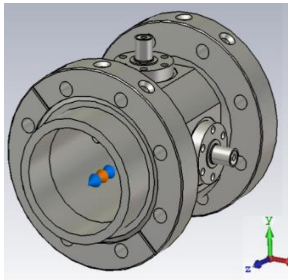
- To avoid heating of the cryogenic signal cables, the existing RHIC stripline BPMs will be shielded to minimize impedance; all Yellow Ring and one Blue sextant.
- 290 new button type BPMs will be installed in the hadron ring along the side shielded strip-line BPMs.
- Replace existing Tefzel insulated rigid coax cryogenic cables with improved $SiO_2$ version, similar to what is used at LHC, quantity = 710.



Existing strip line BPM will be shielded



Existing 12" bellow adjacent to strip line BPM that will be replaced with new button BPM and shorter bellows



New BPM design, 69 mm ID, 11mm diameter buttons

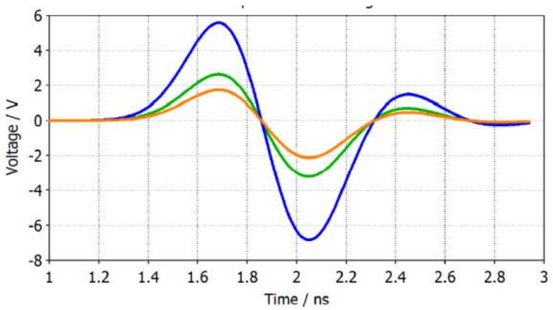
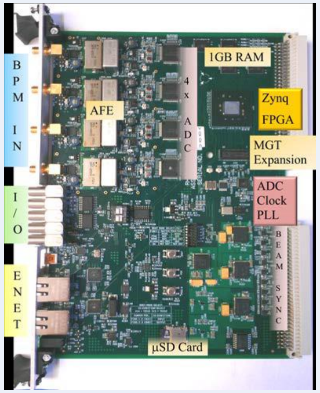



**Figure 6.202:** Simulated signals from the BPM shown in Figure 6.201 for a 5 cm RMS bunch containing $3 \times 10^{11}$ protons and offset in the x-direction by 10 mm.

Simulated BPM signals from a 5cm bunch, $3 \times 10^{11}$ protons, offset +/- 10mm



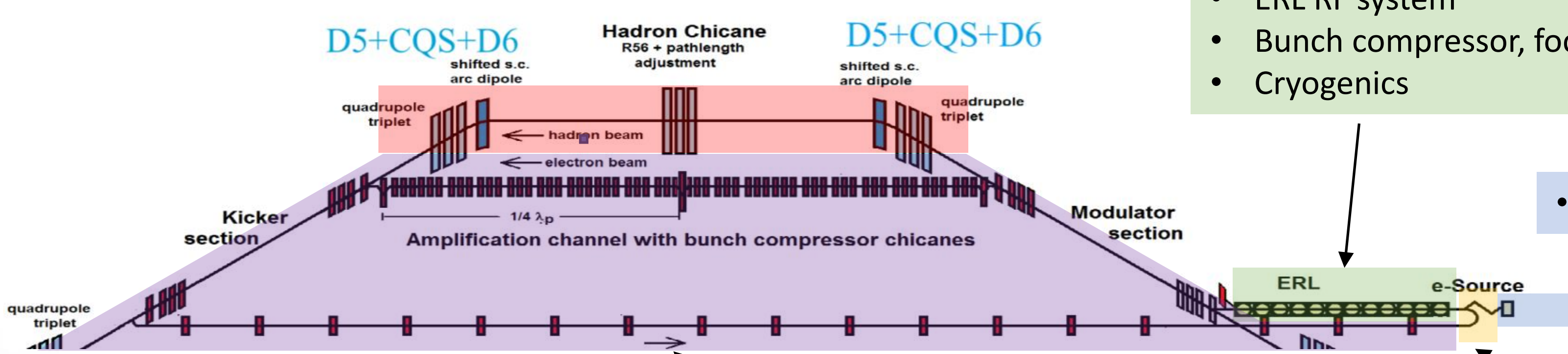

**BPM Electronics based on next generation BNL designed V301 VME modules**

# 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 Diagnostics Requirements

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

- Beam Position Monitors
  - 10 um precision, 100pc - 1nC bunch charge range
  - Average position measurement
  - Co-propagation transverse alignment (10u) of electron and ions in modulator and kicker
- Current monitors (for tuning & MPS) (120mA beam, 1nC/bunch)
  - DCCT, FCT, ICT, Faraday Cups
- Profile Monitors (throughout 400m beam line) (e-beam size – few mm's)
  - YAG/OTR – plunging transverse profiles
  - SLM (streak camera – longitudinal profile – expect 40ps bunch length)
  - Emittance Slits, Wire scanners (expect electron rms normalized emittance 2.8um)
  - Halo scrapers
- Beam Loss Monitors (for tuning & MPS)
  - PMT/Scintillators & Pin Diodes
  - Beam pipe temperature
- Sliced energy spread measurement at 150 MeV (ensure $<10^{-4}$)
- 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.

# Summary

Most of the beam diagnostics are conventional and the methods have been employed here and at other facilities.

The following are diagnostics that we don't presently have direct experience with at C-AD:

- Synchrotron Light Monitors (RCS & ESR) NSLS-II support
  - Longitudinal bunch parameters
  - Horizontal & Vertical beam size (Double-slit Interferometer)
  - X-ray Pin Hole Monitor
- Crab angle monitoring and feedback:
  - Hadron Storage Ring (E-O detector, fast BPM)
    - E-O detector prototype testing planned at CeC PoP next year
  - Electron Storage Ring (SLM)
- ESR Transverse & Longitudinal BbB feedback
- Strong Hadron Cooling
  - Sliced energy spread measurement at 150 MeV ($10^{-4}$)
  - Electron & Ion bunch longitudinal relative alignment stability of 1 micron