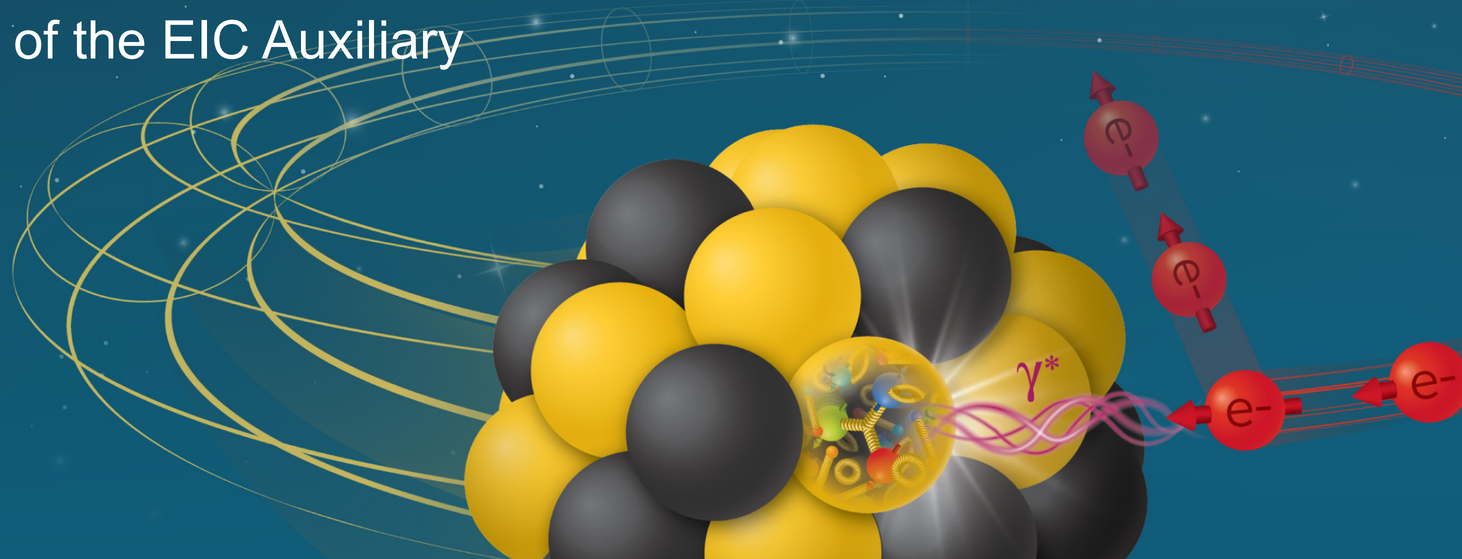
Roman Pots and Off-Momentum Detectors

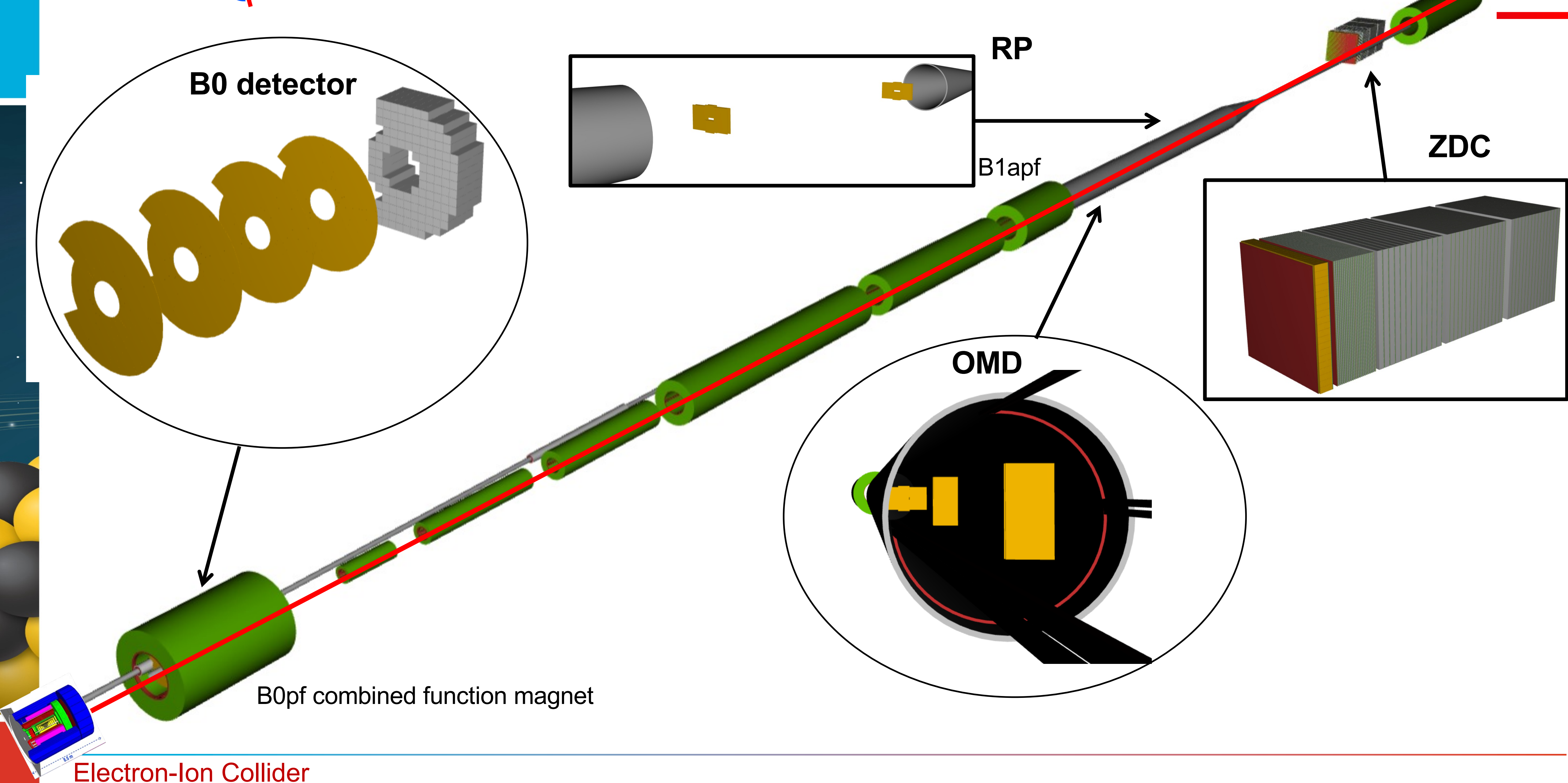
Alex Jentsch (BNL)

EIC Preliminary Design & Safety Review of the EIC Auxiliary
Far-Forward/Far-Backward Detectors
February 12th, 2024



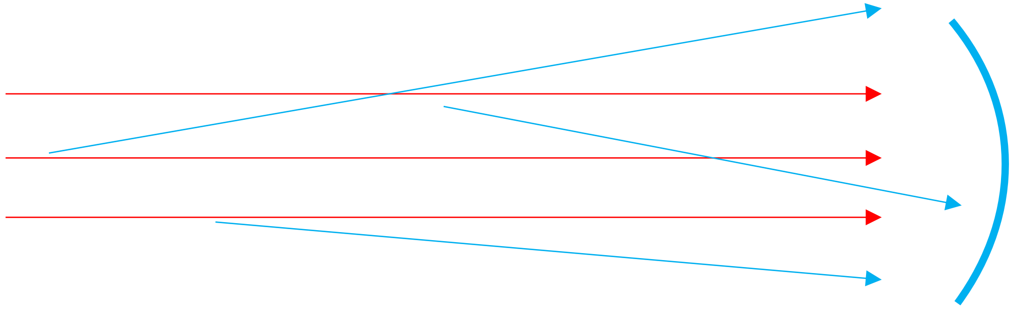
Electron-Ion Collider

The ePIC Far-Forward Detectors

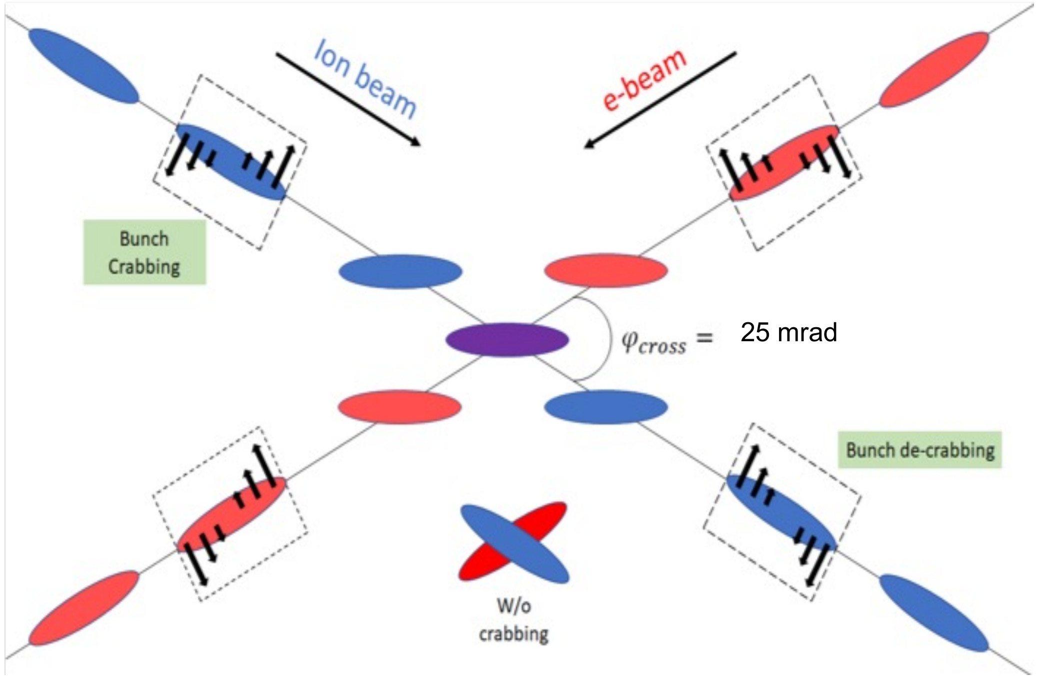


Beam Effects

- Angular divergence
  - Angular “spread” of the beam away from the central trajectory.
    - Transverse momentum kick to the beam particles.



- Crab cavity rotation
  - Rotates beam bunches in 2D.
  - Used to account for the luminosity drop due to the crossing angle – allows for head-on collisions to still take place.
  - **Induces effective vertex smearing.**



These effects introduce smearing in our transverse momentum reconstruction.

Generic Performance Requirements

Study from eRD24 effort

- The various contributions add in quadrature (this was checked empirically, measuring each effect independently).

$$\Delta p_{t,total} = \sqrt{\underbrace{(\Delta p_{t,AD})^2}_{\text{Angular divergence}} + \underbrace{(\Delta p_{t,CC})^2}_{\text{Primary vertex smearing from crab cavity rotation.}} + \underbrace{(\Delta p_{t,pxl})^2}_{\text{Smearing from finite pixel size.}}}$$

These studies based on the "ultimate" machine performance with strong hadron cooling.

	Ang Div. (HD)	Ang Div. (HA)	Vtx Smear	250μm pxl	500μm pxl	1.3mm pxl
$\Delta p_{t,total}$ [MeV/c] - 275 GeV	40	28*	20	6	11	26
$\Delta p_{t,total}$ [MeV/c] - 100 GeV	22	11	9	9	11	16
$\Delta p_{t,total}$ [MeV/c] - 41 GeV	14	-	10	9	10	12

- **Beam angular divergence**
  - Beam property, can't correct for it – sets the lower bound of smearing.
- **Vertex smearing from crab rotation**
  - Correctable with precise timing (~35ps).
- **Finite pixel size on sensor**
  - 500μm seems like the best compromise between potential cost and smearing.

These requirements can be met by the new **AC-coupled LGAD sensor technology** (eRD24 was focused on applications of this technology to the far-forward detectors).

Generic Performance Requirements

- Spatial resolution requirement → **140um or less**.
  - Angular divergence largest contributor, reduces impact of detector choice.
- Crab cavity rotation of the bunches → transverse “kick” to the particles, dependent on the location along the bunch.
  - Results in effective vertex smearing, disentangled with fast timing → **35ps to remove the full effect**.
- Timing also needed for background rejection.
- Technologies need to be radiation hard → expected radiation load on the RP and OMD ~ 100x less than at the LHC.
  - Radiation damage has impact on **timing resolution** and **spatial resolution (when charge sharing is used**.
  - Radiation studies carried out for ePIC indicate that doses delivered to AC-LGADs for RP/OMD will not lead to reduction in performance during life of experiment.

Generic Performance Requirements

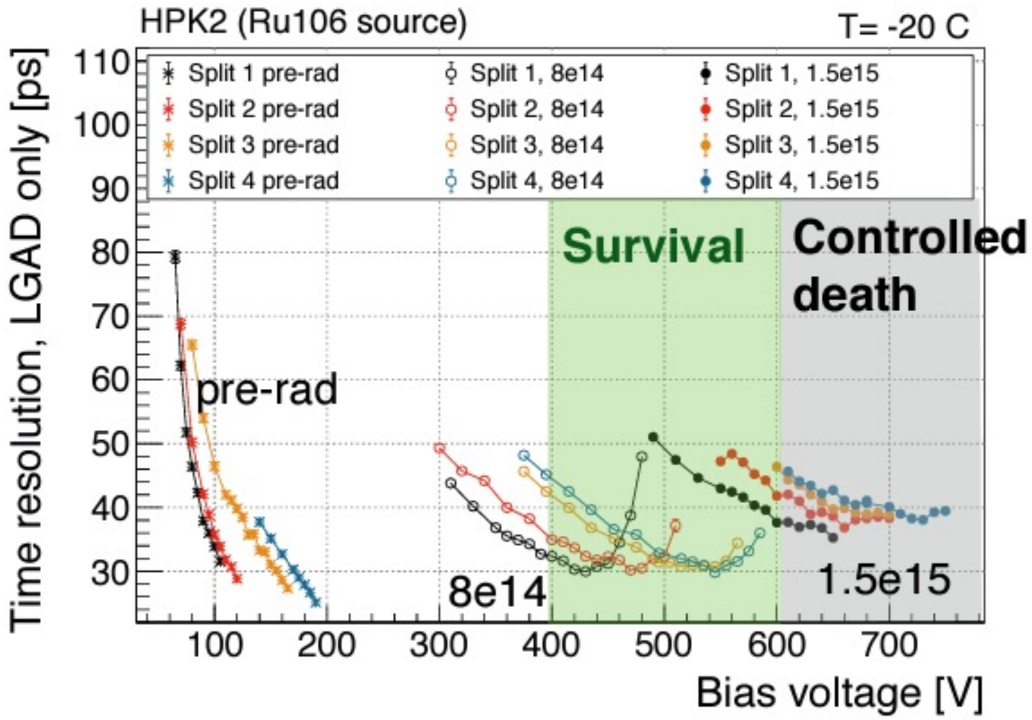
From:
https://indico.cern.ch/event/1029124/contributions/4411270/attachments/2269713/3854416/heller_LGAD_mortality_RD50.pdf

Plot shows time resolution as a function of bias voltage for various levels of irradiation of a batch HBK DC-LGADs used by ATLAS and CMS.

Split 1 — Split 4 (lowest to highest operating voltage)

Radiation: n_{eq} = 8e14 and 1.5e15 n/cm^2

***Note: the fluences shown here are ~ 2-3 orders of magnitude higher than what is expected at ePIC.



- Technologies need to be radiation hard → expected radiation load on the RP and OMD ~ 100x less than at the LHC.
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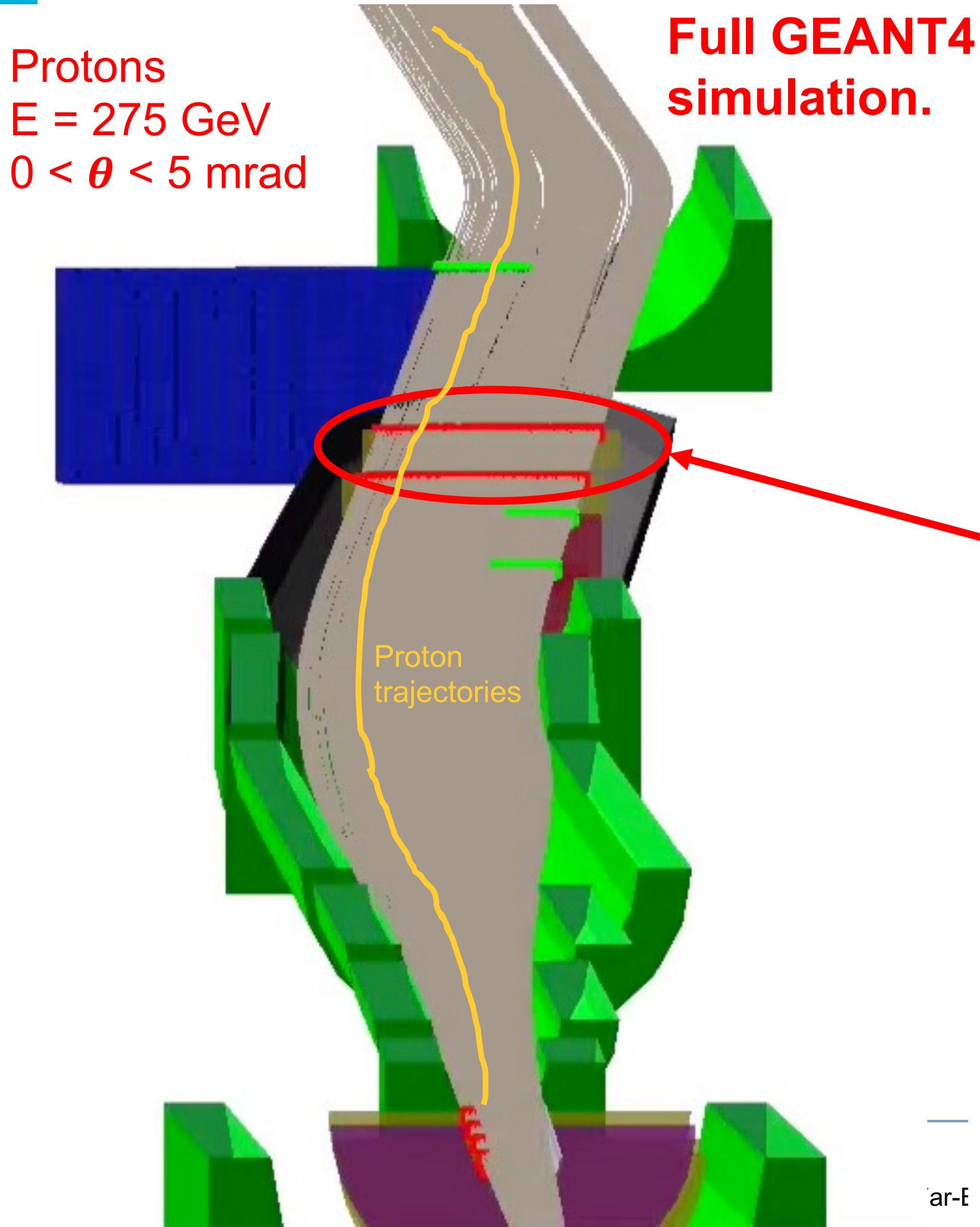
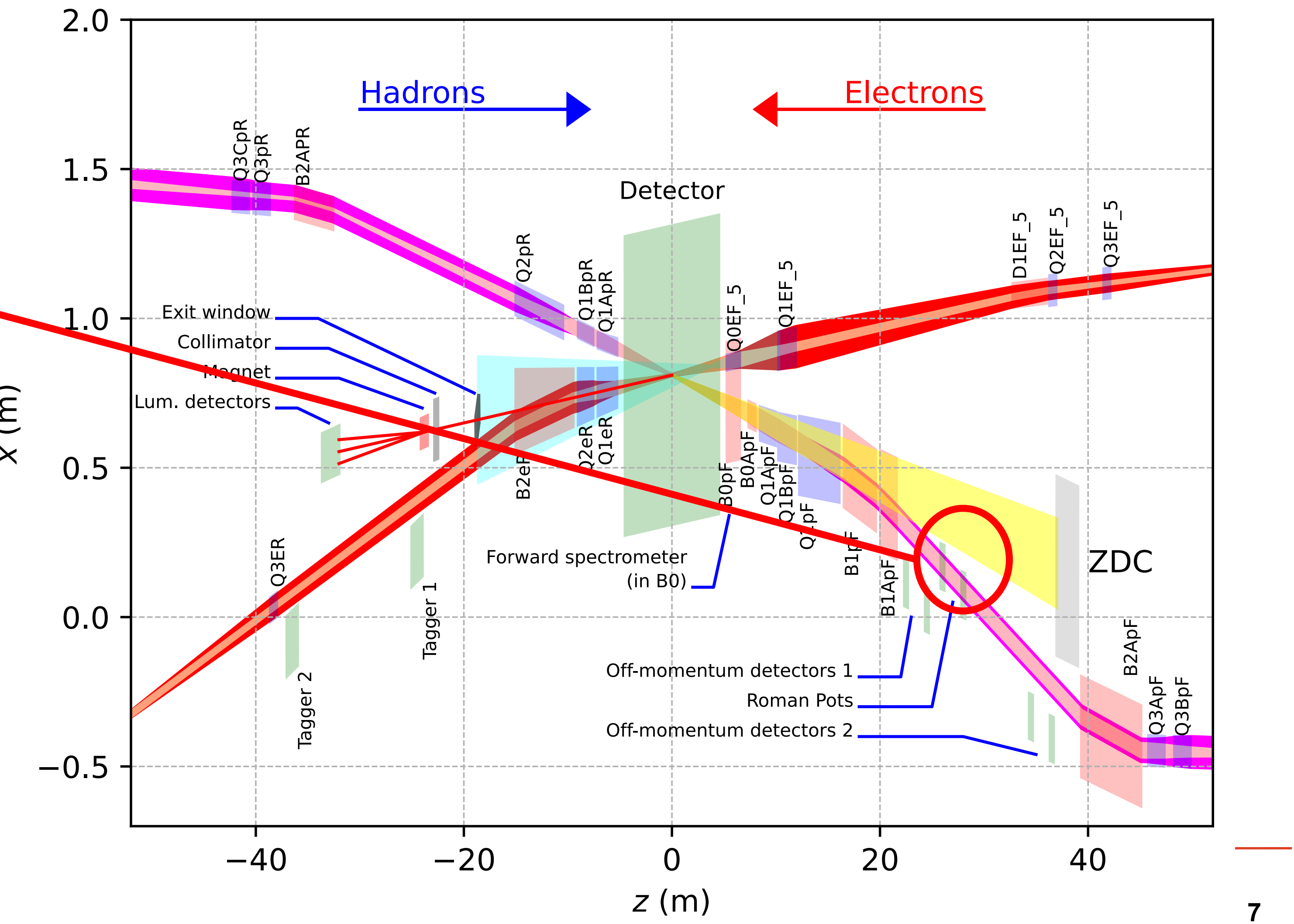
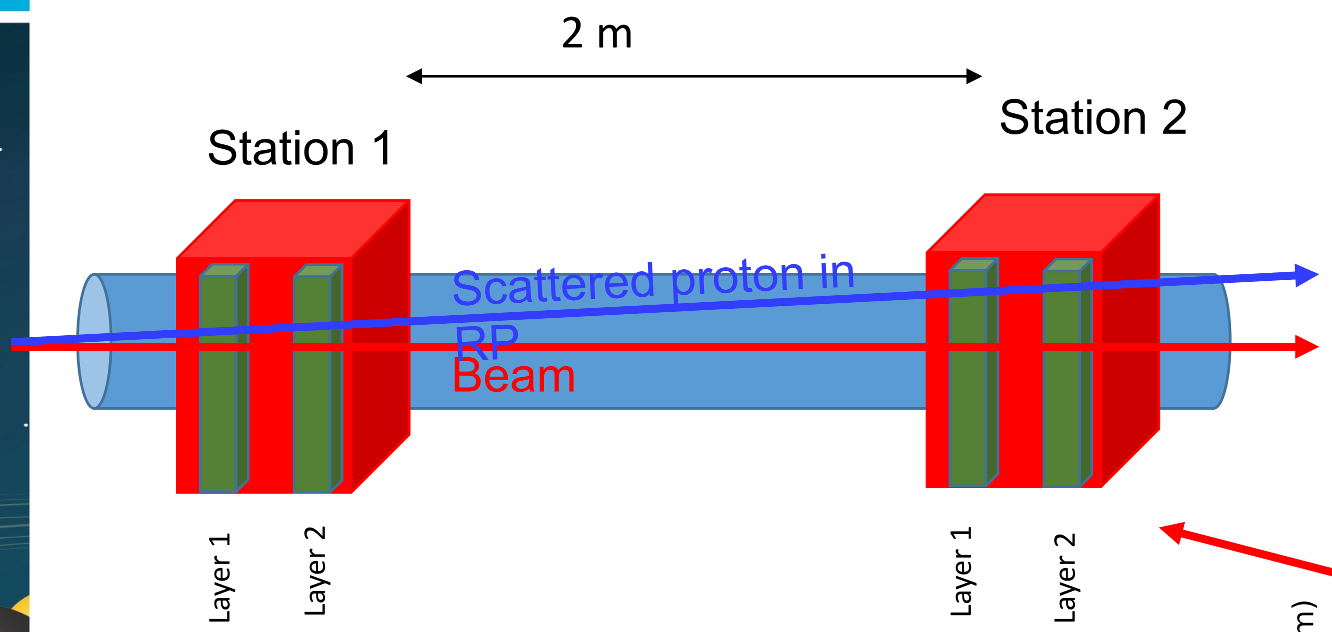
Roman Pots @ the EIC



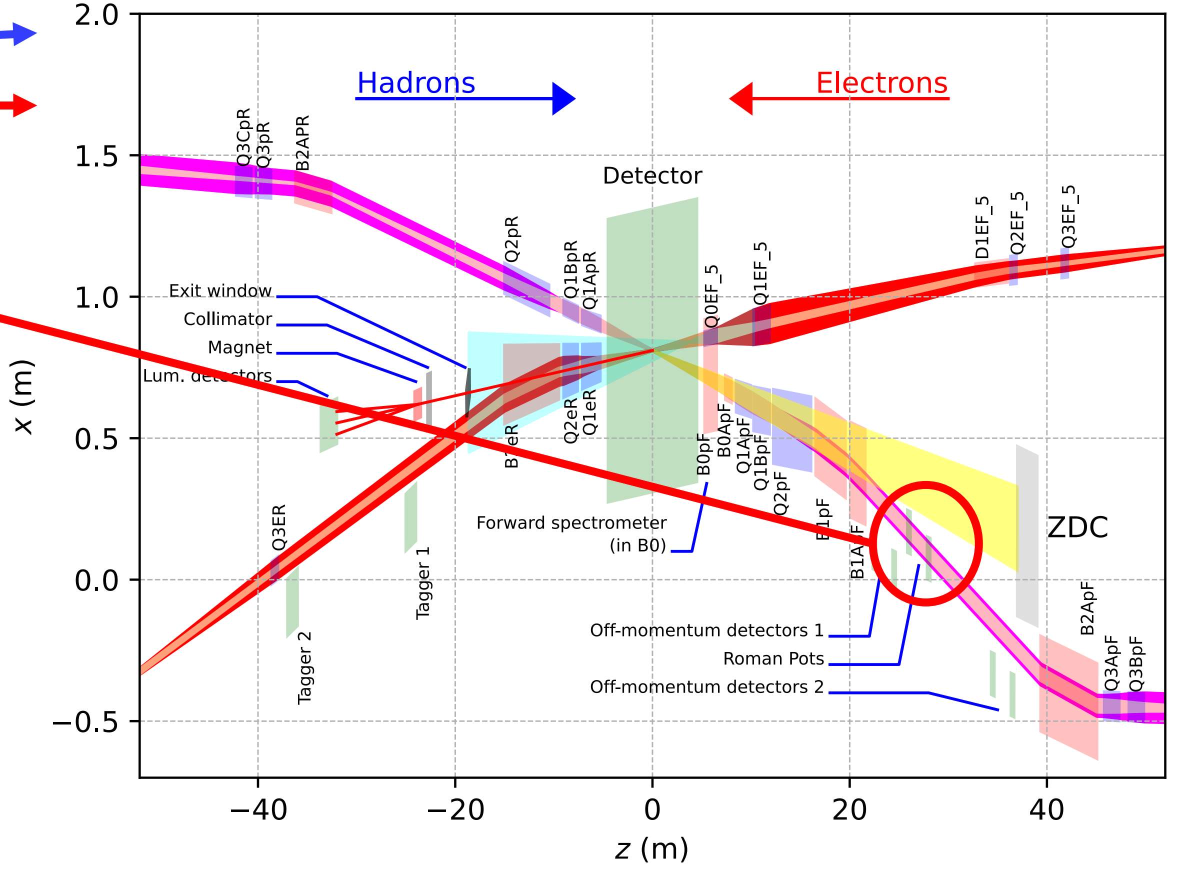
- Acceptances for the detectors driven by IR design itself (combination of apertures and optics).
  - IR was designed with the beamline detectors in-mind.



Roman Pots @ the EIC



- Two stations, separated by ~1-2 meters, each with two layers (minimum) of silicon detectors.



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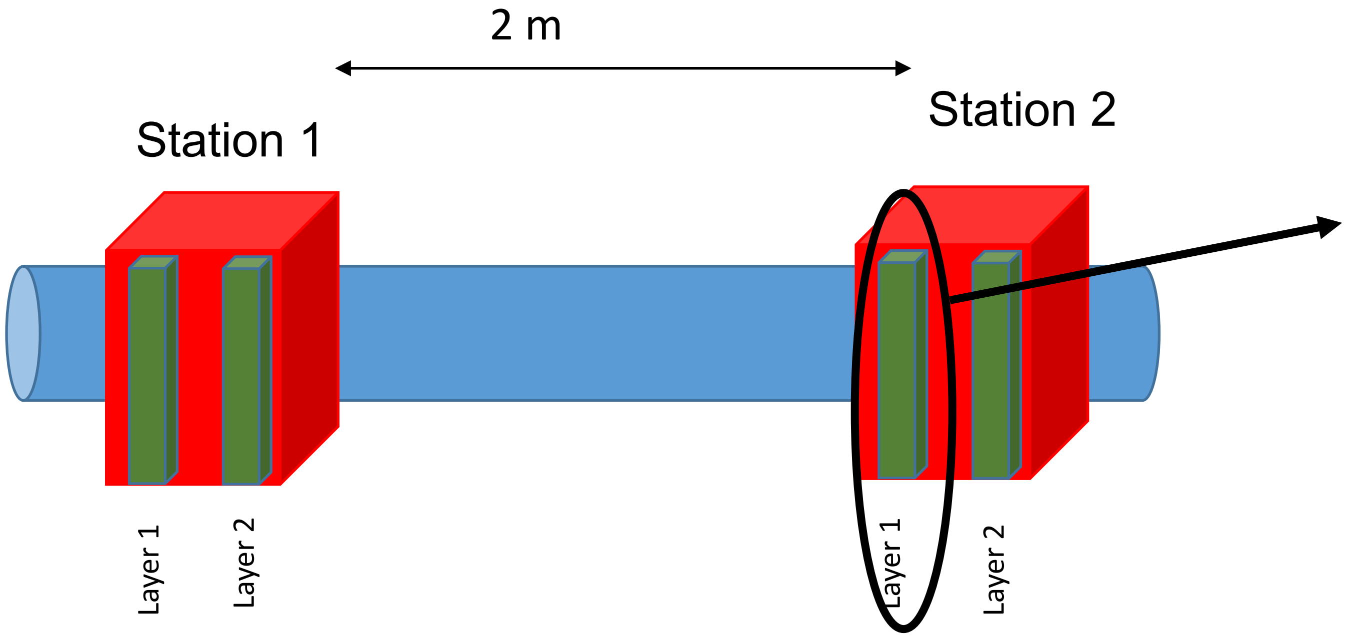
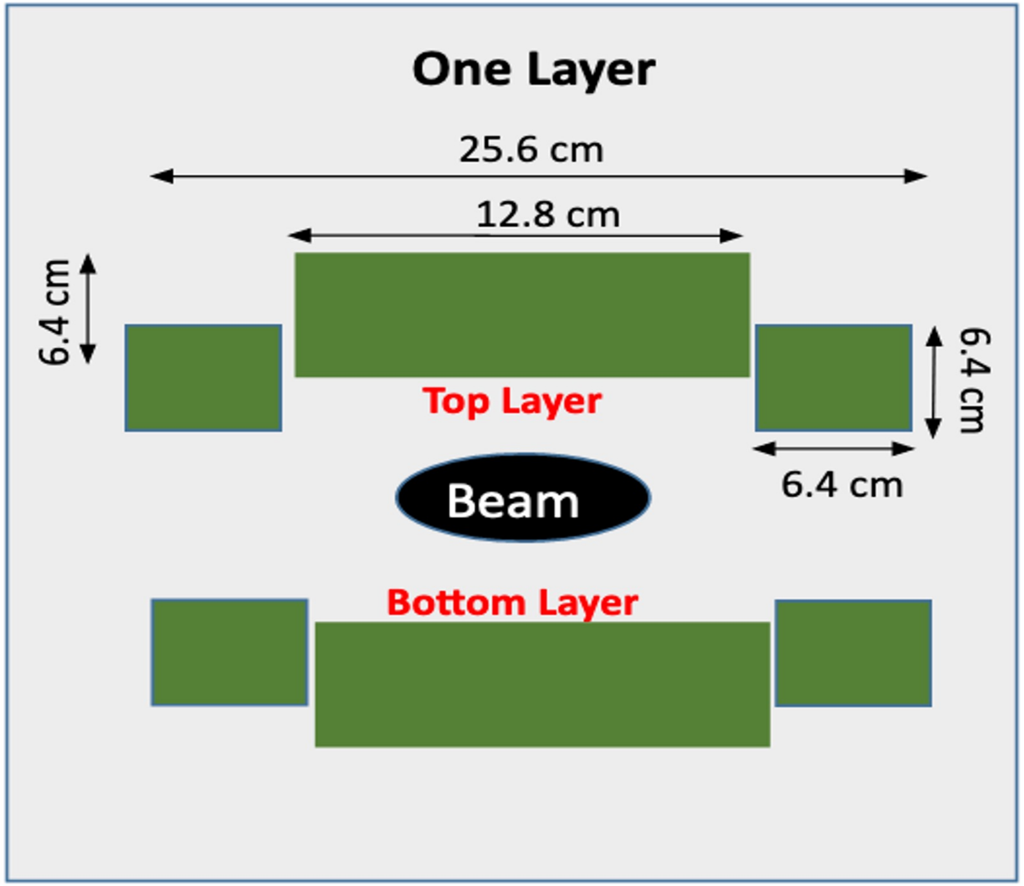
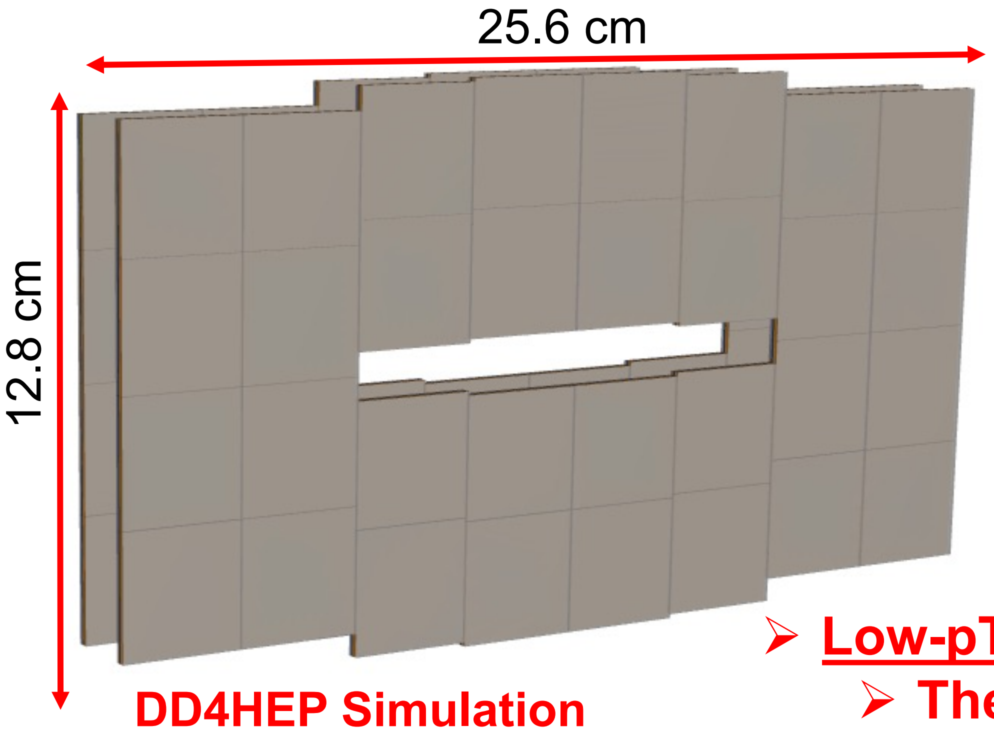




- Silicon detectors placed directly into machine vacuum.
  - Enables maximal geometric coverage, and minimizes impact on the beam.

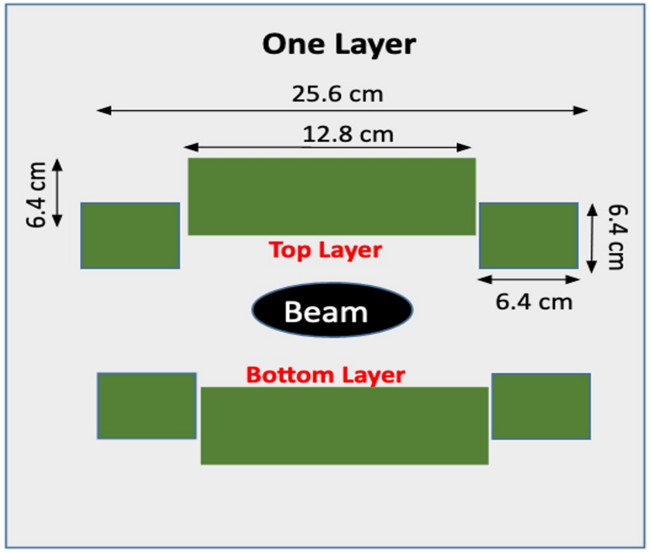
Roman Pots @ the EIC



DD4HEP Simulation

$\sigma(z)$ is the Gaussian width of the beam, $\beta(z)$ is the RMS transverse beam size. ε is the beam emittance.

$$\sigma(z) \sim \sqrt{\varepsilon \cdot \beta(z)}$$

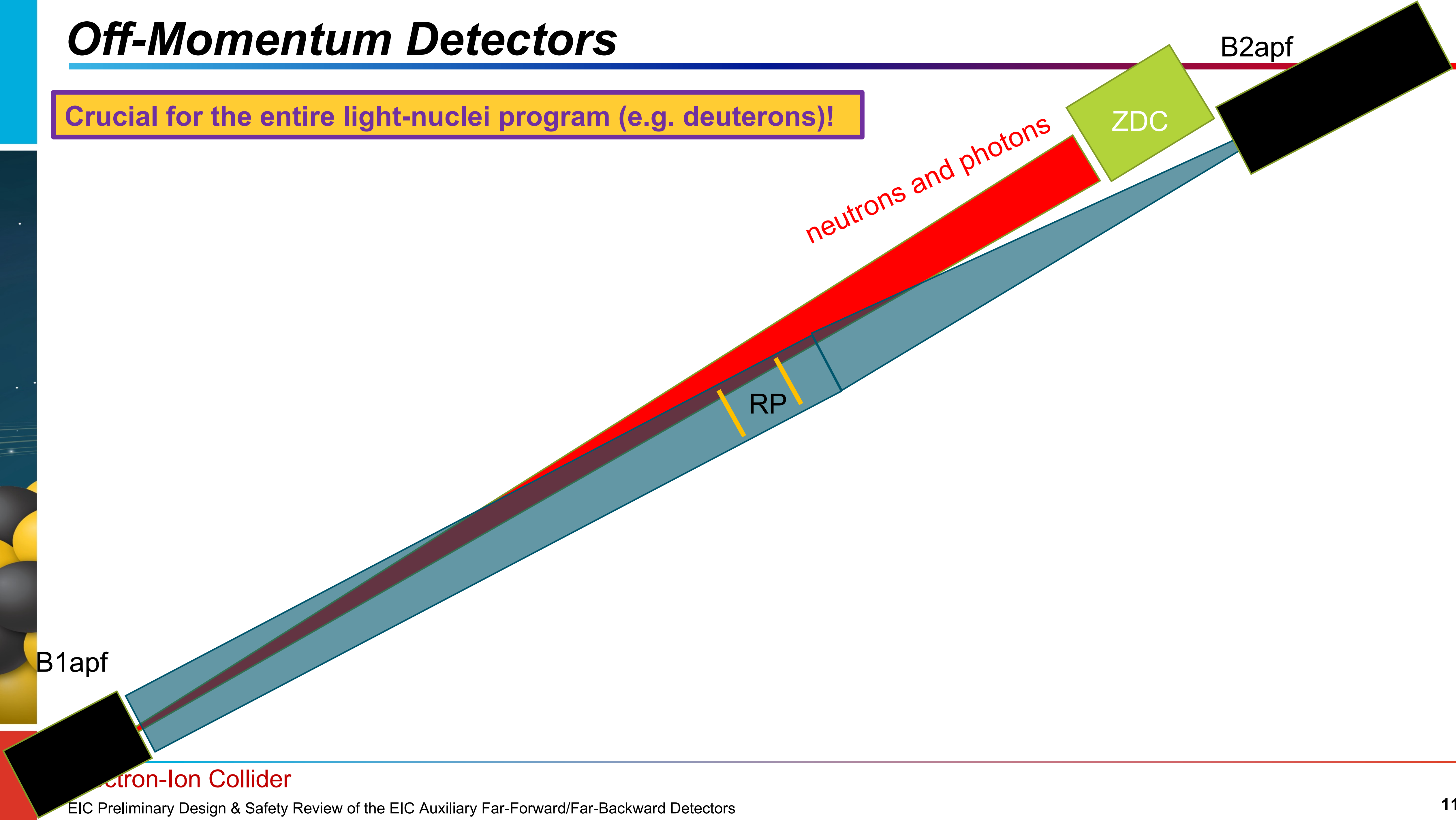


- **Low-pT cutoff determined by beam optics.**
  - **The safe distance is ~10σ from the beam center (1$\sigma \sim 1$mm).**
- **Optics change with energy**
  - **Can also be changed within a single energy to maximize *either acceptance at the RP, or the luminosity.***

- **Detectors need to be able to move to different positions for different optics configurations.**
- **Without strong hadron cooling, detectors also need to be moved *during a fill* to account for emittance growth. (IBS time is ~ 2h → doubling of emittance)**

Off-Momentum Detectors

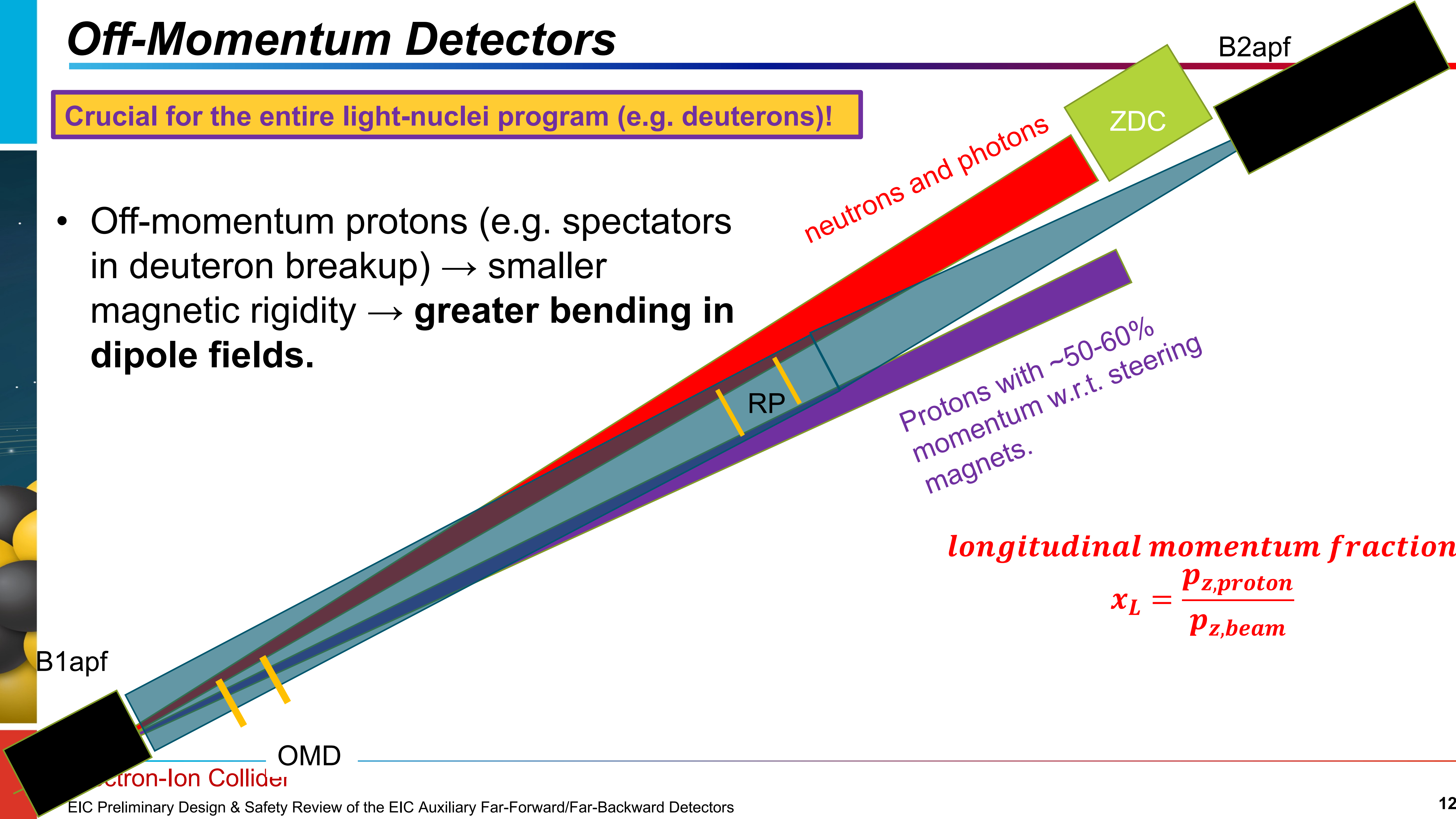
Crucial for the entire light-nuclei program (e.g. deuterons)!



Off-Momentum Detectors

Crucial for the entire light-nuclei program (e.g. deuterons)!

- Off-momentum protons (e.g. spectators in deuteron breakup) → smaller magnetic rigidity → **greater bending in dipole fields.**



longitudinal momentum fraction

$$x_L = \frac{p_{z,proton}}{p_{z,beam}}$$

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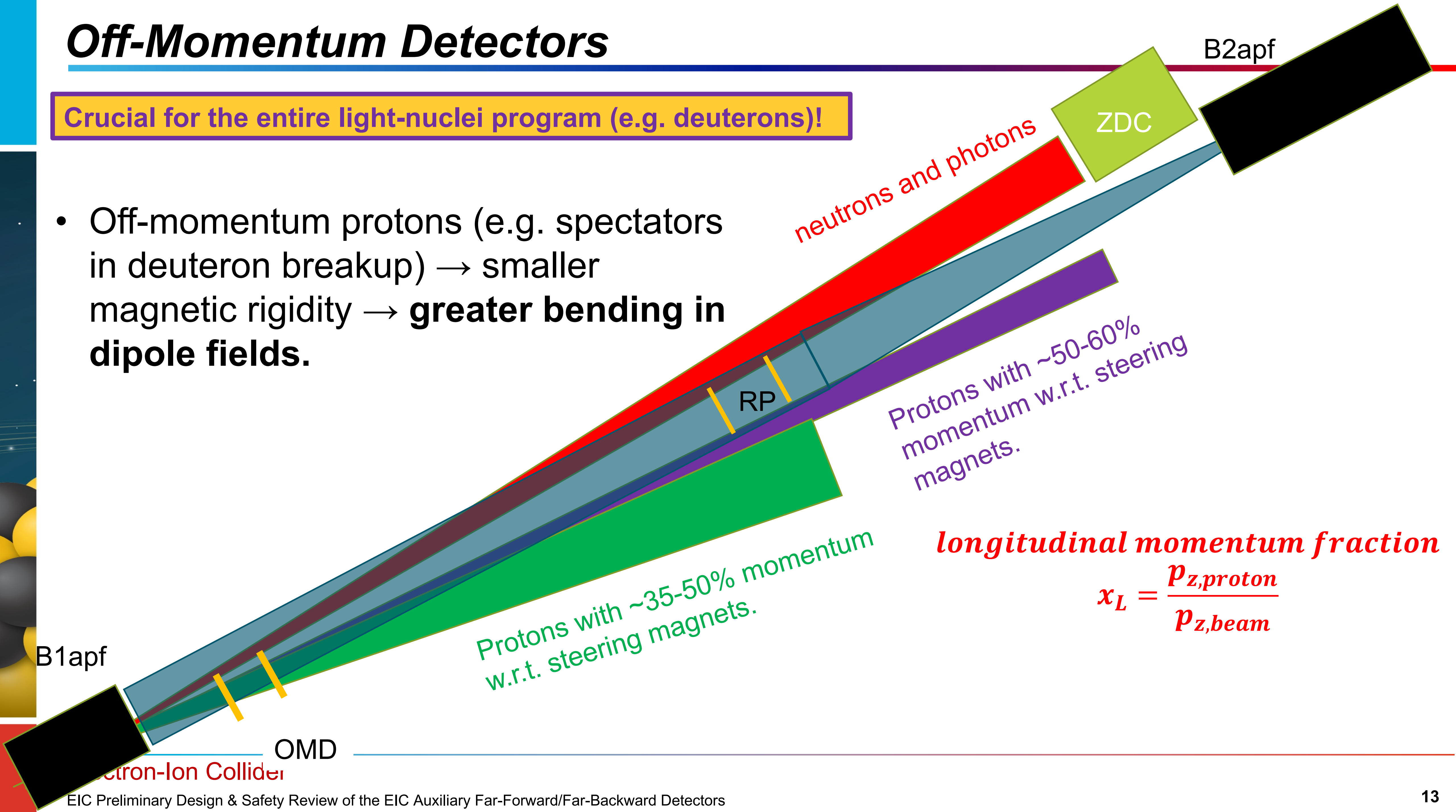

longitudinal momentum fraction

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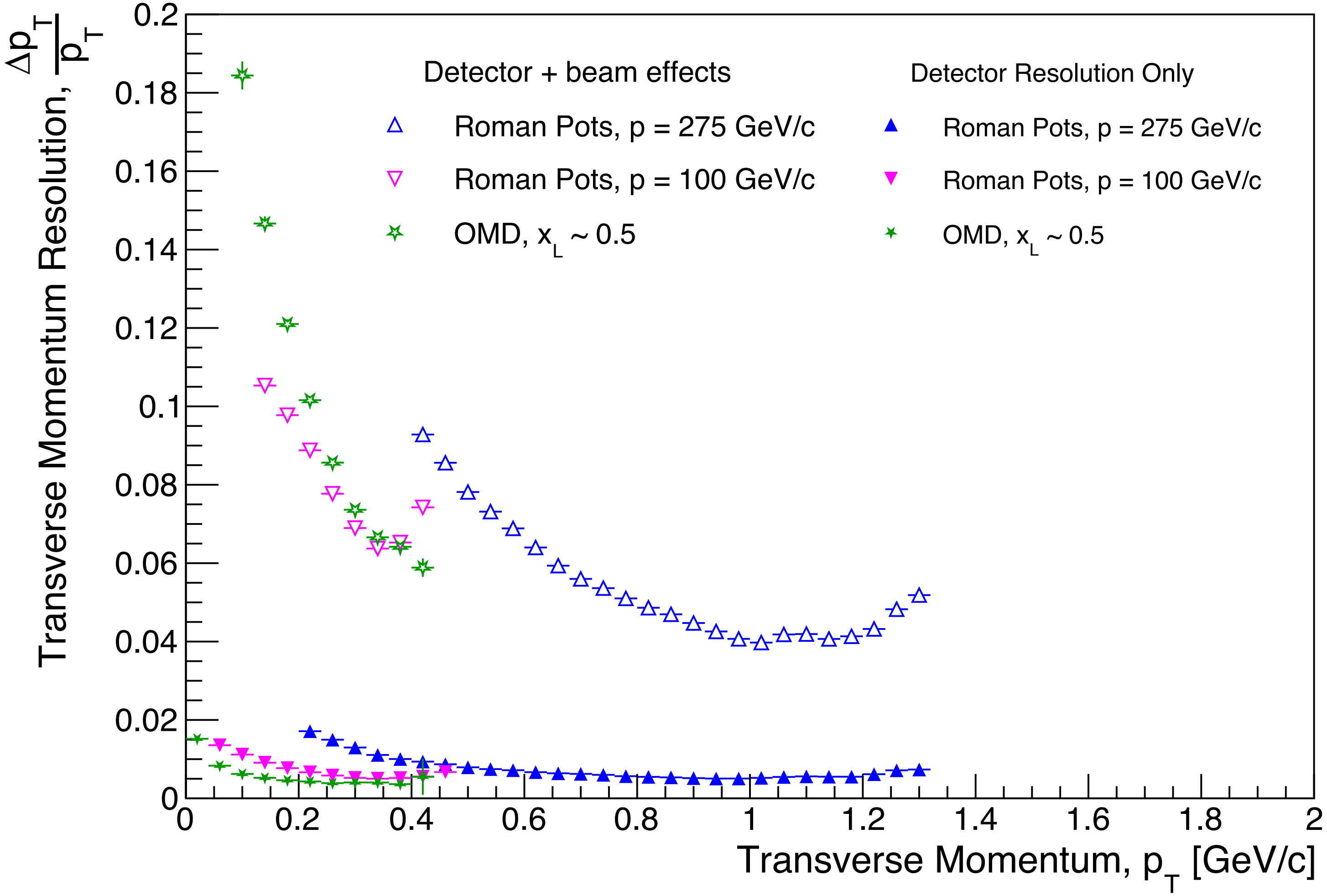
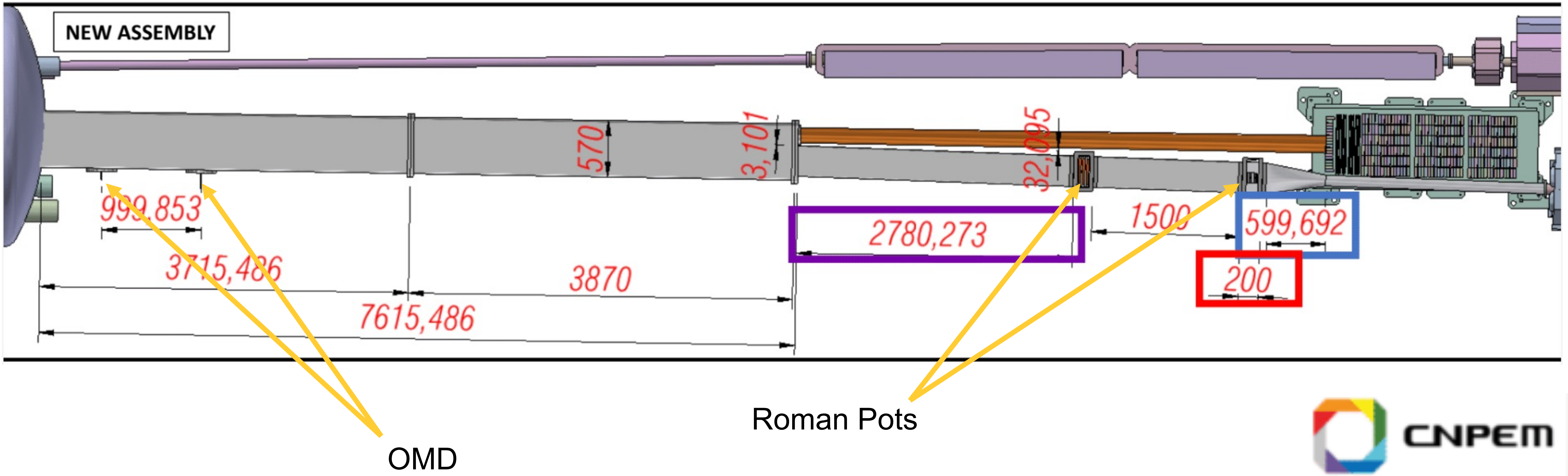
Summary of Detector Performance



- Includes realistic considerations for pixel sizes and materials.
- Roman Pots and Off-Momentum detectors suffer from additional smearing due to improper transfer matrix reconstruction (sub-dominant effect).
  - **Software issue** → A ML-based solution is almost ready for deployment.
- All beam effects included (dominant impact on smearing).
  - Angular divergence.
  - Crab rotation/vertex smearing
  - Crossing angle.

Preliminary Design of Vacuum System (not yet in global CAD)

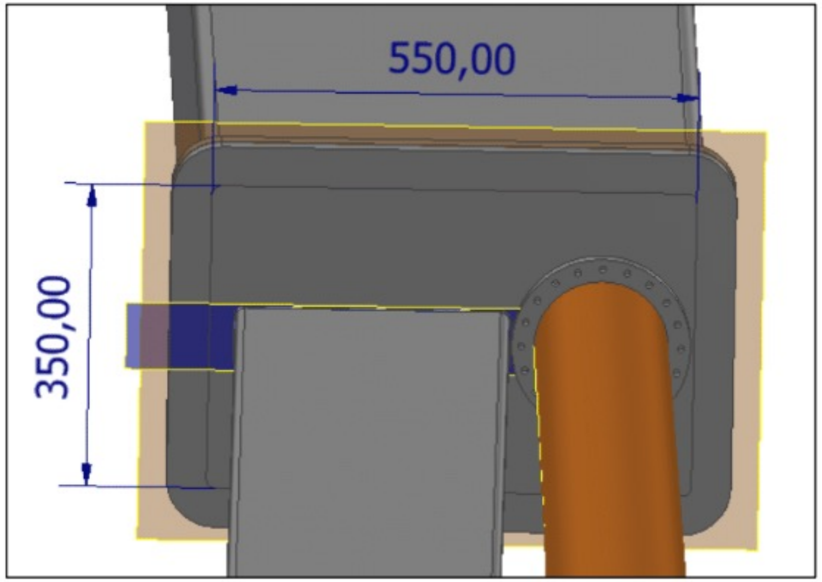


Updated preliminary setup for hadron FF region including vacuum design.

Vacuum system design → in-kind contribution from Brazil.

Preliminary Design of Vacuum System (not yet in global CAD)

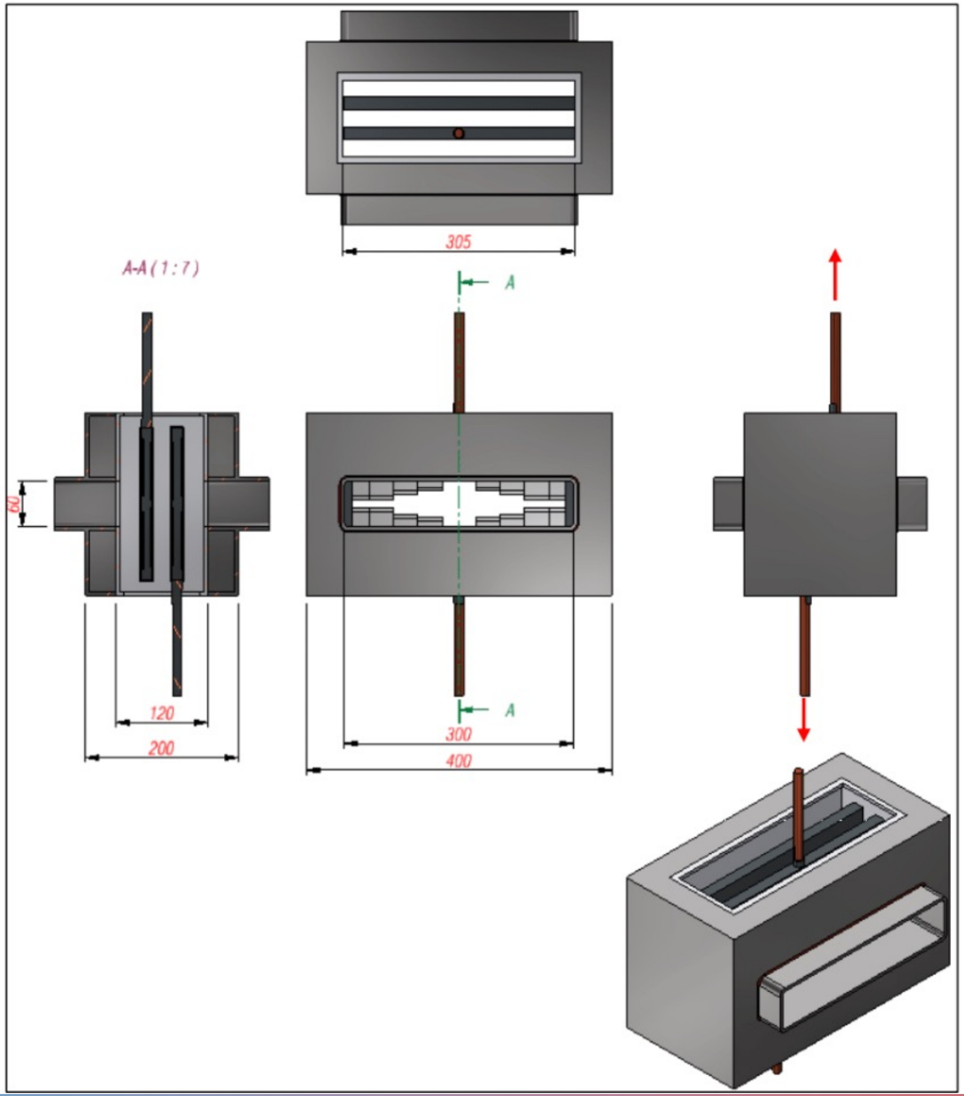
New 550x350 mm inner dimensions chamber



Transition region from larger beam pipe containing OMD to smaller pipe containing RP (left) and exit window for neutrals (right).

Vacuum system design → in-kind contribution from Brazil.

New concept for Roman pots scattering chamber



Scattering chamber design for RP sensor packages.

CNPEM

MINISTRY OF SCIENCE TECHNOLOGY AND INNOVATION

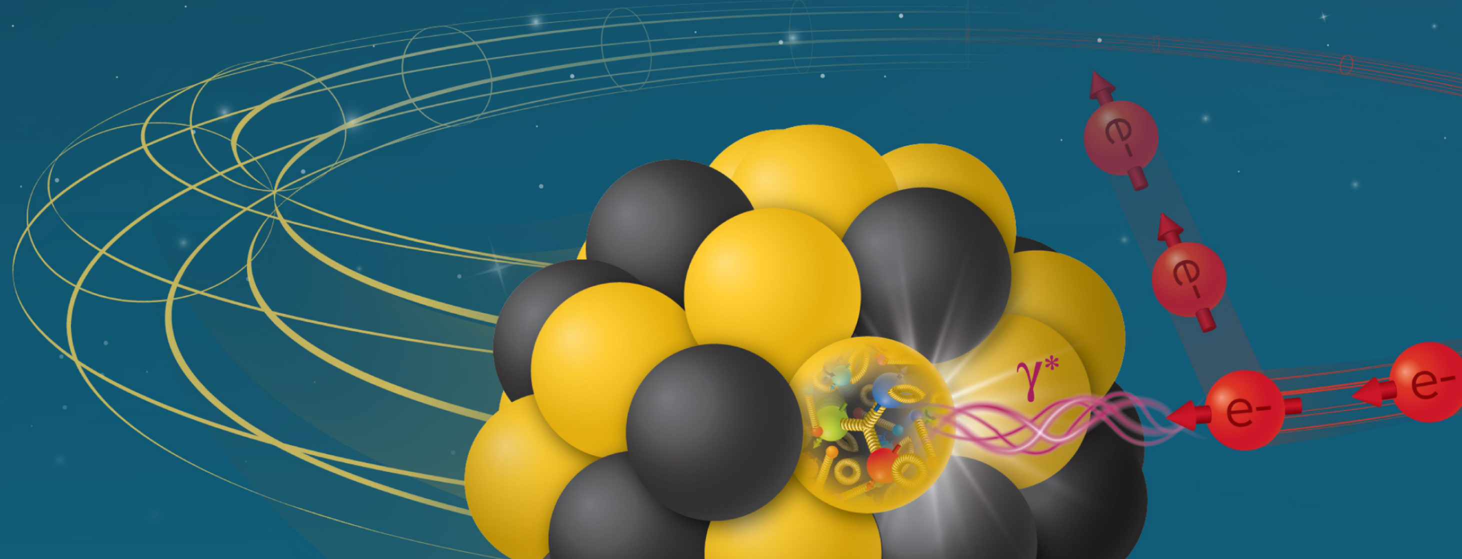
BRAZILIAN GOVERNMENT BRASIL UNITING AND REBUILDING

Effect of Vacuum Design on Beam Operation

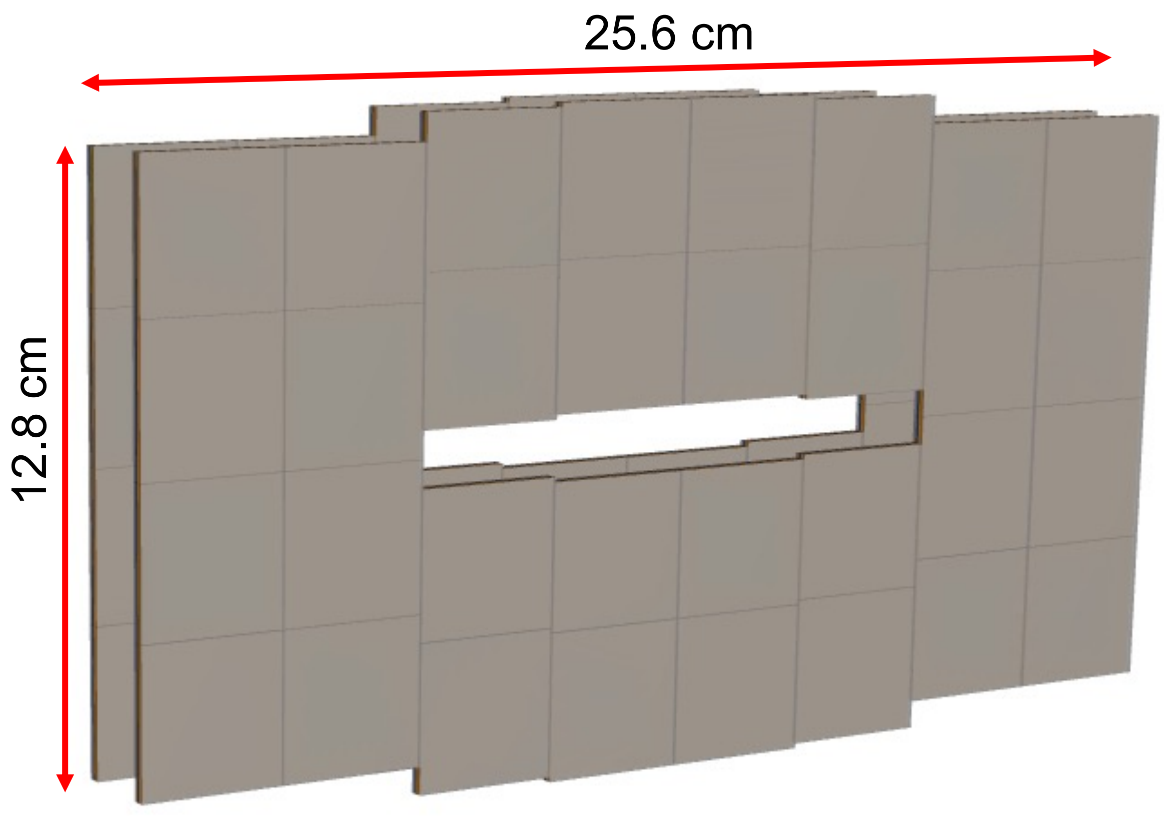
- Shape and tapering of beam pipe(s) has impact on impedance of ion beam.
- Space between detector stations (e.g. 1.5 meter separation between RP stations) creates resonating cavity.
  - Impedances under study and will require iteration.
- MolFlow calculations planned with new vacuum system design.
  - Goal is to achieve vacuum at similar level to RHIC (~1e-10 mbar).

Detector Technology

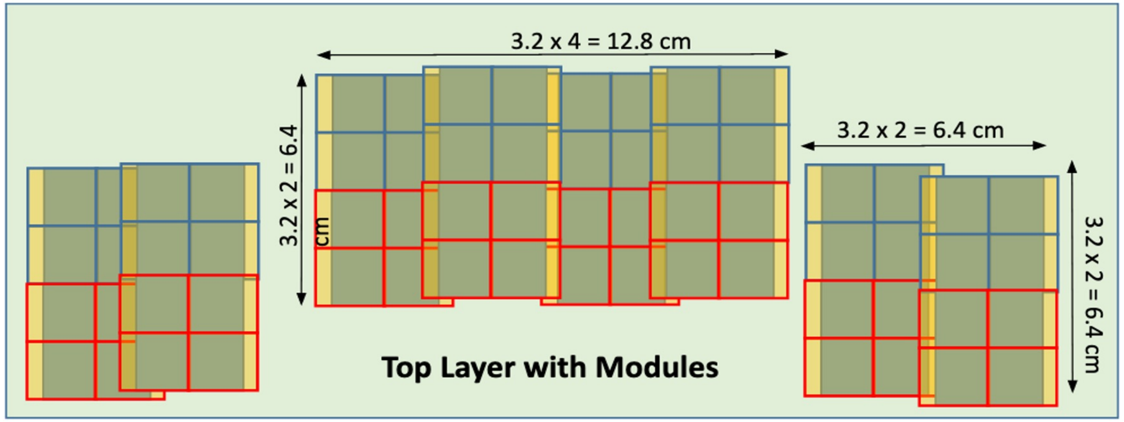
Electron-Ion Collider



Technology: AC-LGAD



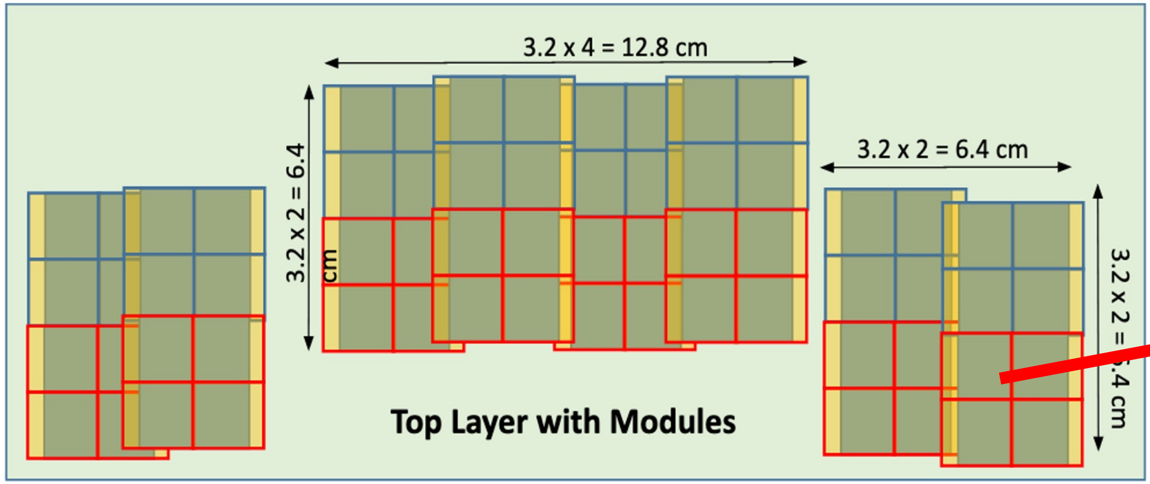
DD4HEP Simulation

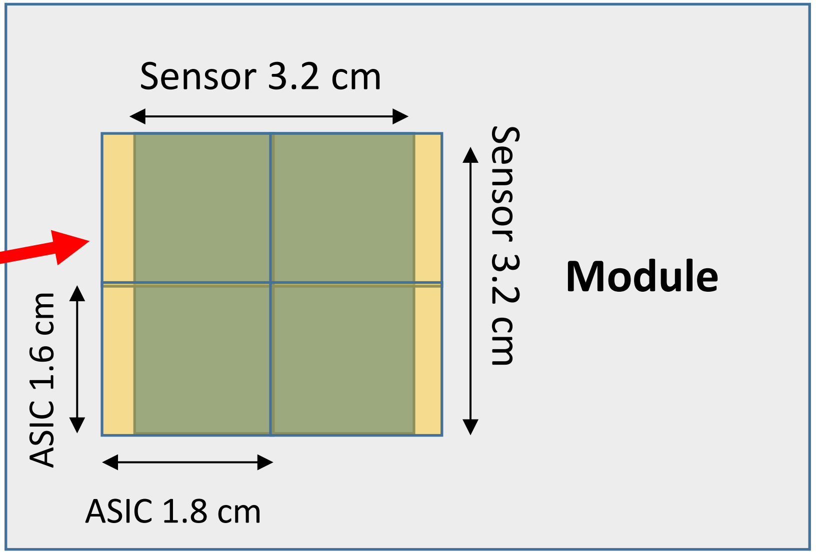


- AC-LGAD sensor provides both **fine pixilation** (500um square pixels), and **fast timing** (~30ps).
  - Based on extensive work from EIC generic R&D (eRD24) to establish needs for the Far-Forward detectors and evaluate usage of AC-LGADs.

Technology: AC-LGAD

- Updated layout for the **Roman Pots** with current design for AC-LGAD sensor + ASIC.





- Approach based on bump-bonding four custom ASICs to a single AC-LGAD sensor to make a "module".

ASIC size	ASIC Pixel pitch	# Ch. per ASIC	# ASICs per module	Sensor area	# Mod. per layer	Total # ASICs	Total # Ch.	Total Si Area
1.6x1.8 cm^2	500 μm	32x32	4	3.2x3.2 cm^2	32	512	524,288	1,311 cm^2

Progress on AC-LGAD development

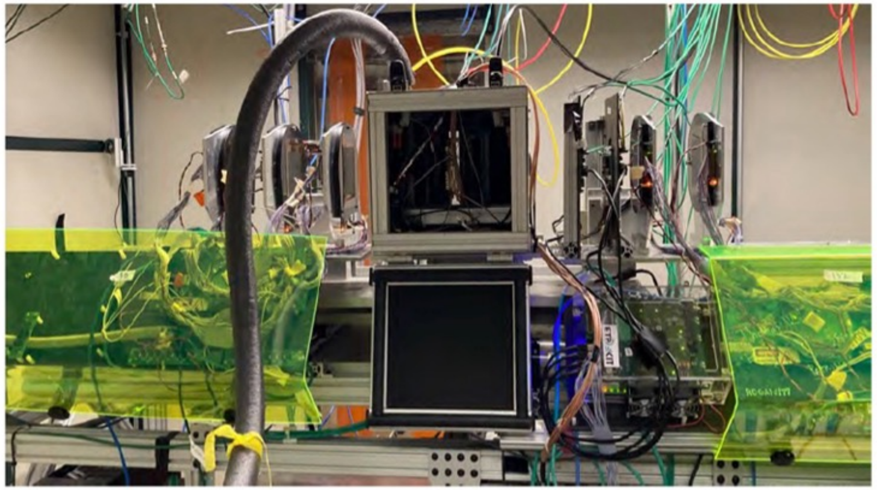
AC-LGAD Sensor

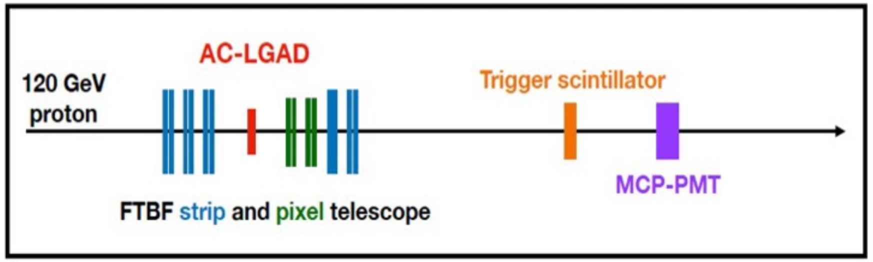
Strong synergy with ePIC forward TOF system.

- Sensors with different configurations produced by BNL-IO and HPK, and tested with 120GeV protons
- Prototype strip sensors with ~35 ps time resolution and <15 um spatial resolution (more in the next talk).
- Prototype pixel sensors with ~20 ps time resolution and ~20* um spatial resolution.

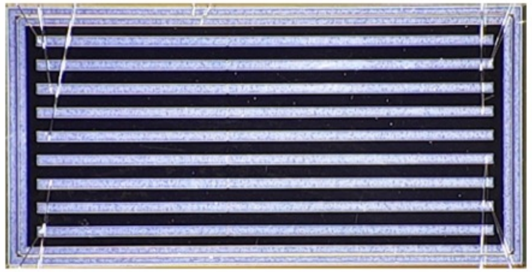
* ~50 um under metal electrodes. To be improved

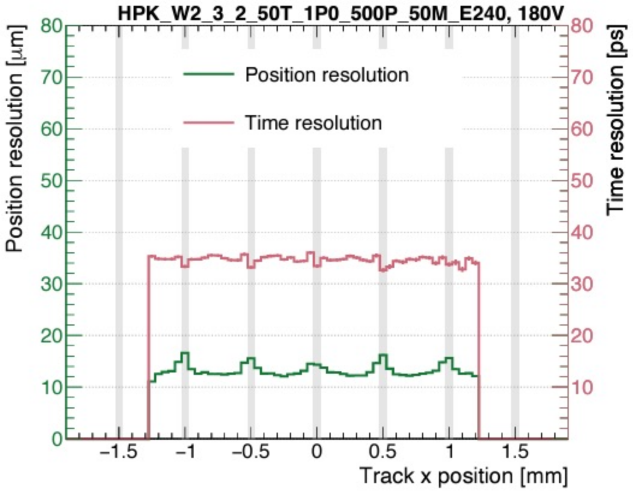
Fermilab Test Beam Setup



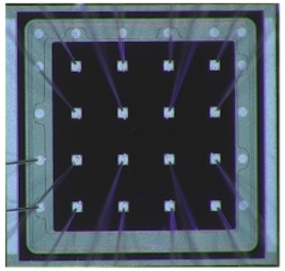


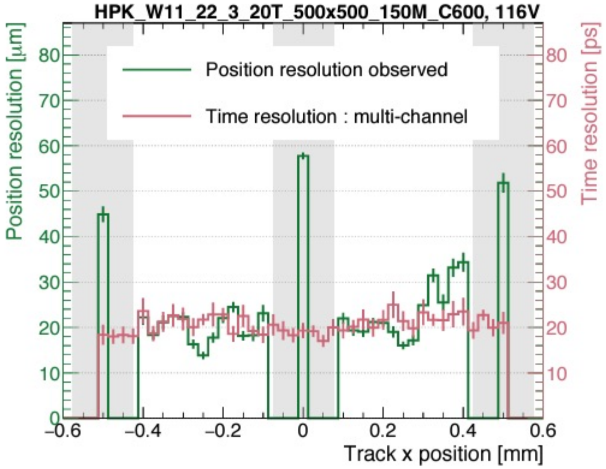
HPK Strip Sensor (4.5x10 mm²)





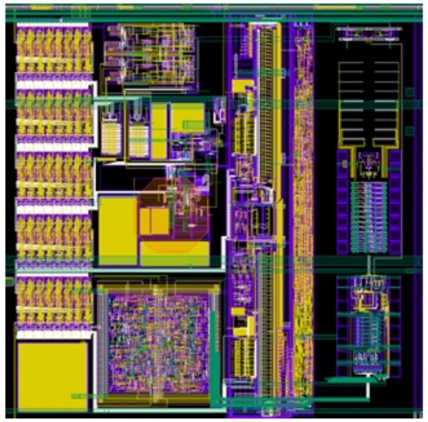
HPK Pixel Sensor (2x2 mm²)





Progress on AC-LGAD ASIC (EICROC0)

- **R&D Goals**
  - 15-20 ps jitter with minimal (1-2 mW/ch) power consumption, match AC LGAD sensors for ePIC.



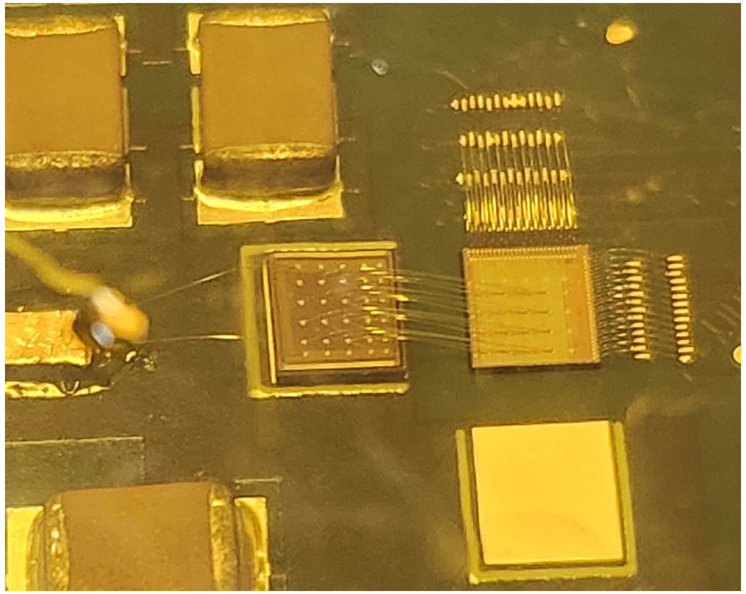
EICROC by Omega/IJCLab/Irfu/AGH

- Preamp, discri. taken from ATLAS ALTIROC
- I2C slow control taken from CMS HGCROC
- TOA TDC adapted by IRFU Saclay
- ADC adapted to 8bits by AGH Krakow
- Digital readout: FIFO depth8 (200 ns)

See talk by Christophe de la Taille (Omega): https://indico.bnl.gov/event/20473/contributions/85274/attachments/51864/88689/CdLT_EICROC_9jan24.pdf

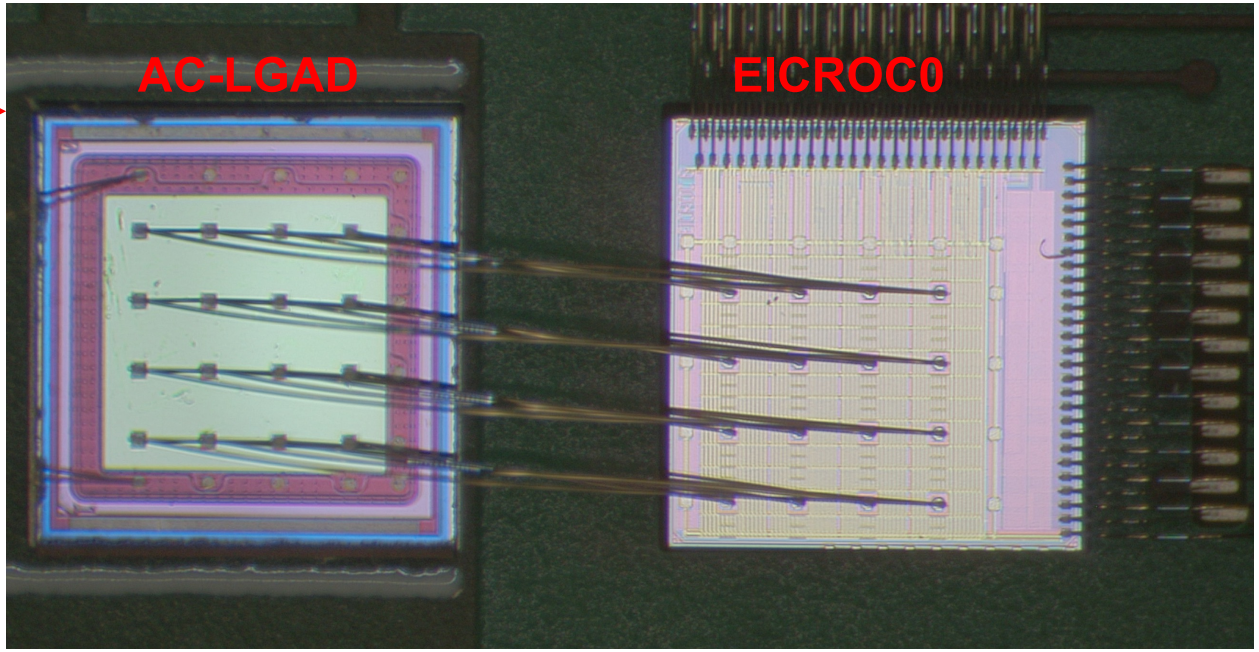
- First version of EICROC (version 0; 4x4 channels) has been tested at IJCLab, BNL, and Hiroshima U.
  - Analog response of AC-LGAD + EICROC0 observed using Sr90 source.
  - Digital signals (TDC and ADC) still under study.
  - New version of EICROC (4x4 channels, minor update to EICROC0) from IJCLab/OMEGA will be ready for testing in coming months.
    - Final version Sept. 2025 (eRD109)

AC-LGAD + EICROC0 testing



BNL AC-LGAD:

- 500x500 um^2 pixel pitch
- 100x100 um^2 metal electrode
- 30um active thickness



- AC-LGAD sensor (BNL) wire-bonded to EICROC0 (OMEGA/ICJLab) for testing on custom test board produced by OMEGA.

- Setup is presently wire-bonded (done at BNL) for initial tests.
  - First bump-bonding to be performed in the coming weeks at BNL.
- Two other similar boards with EICROC0 were produced and sent to IJCLab and Hiroshima U. for testing.

Beam test with bump-bonded AC-LGAD + EICROC0 planned for June 2024.

Summary and Takeaways

- **Major takeaway: we are on-track to meet our goals for the TDR.**
  - Next Steps:
    - Cooling of detector packages.
    - Quality assurance plan for production of AC-LGAD sensors and ASICs needs to be developed.
    - Details of movement system for both subsystems (easier for OMD).
    - Full impedance calculations with new vacuum design underway → will lead to iteration and re-evaluation.
- Basic technology considerations understood for the Roman Pots and Off-Momentum Detectors.
  - Sensor + ASIC design is progressing → performance criteria met, but beam tests with full package to be carried out.
  - Shared design criteria → Detector packages need to be movable, placed directly in vacuum, and have precise timing (35ps) and spatial resolution (< 140um).
- AC-LGAD consortium exists with and project-supported R&D (eRD112).
  - Overlap with TOF system in ePIC → allows for sharing of resources in terms of sensor/ASIC development and efficiency in very limited availability of test beams.
  - **ASIC design (EICROC) is the primary focus to complete the detector packages → final version delivered by Sept. 2025 (eRD109).**
- Simulations include beam and detector effects → impacts of engineering design (e.g. vacuum system) needs more work.
  - This pipeline exists already, and has been used for evaluation up to now → lots of dedicated expertise available here.

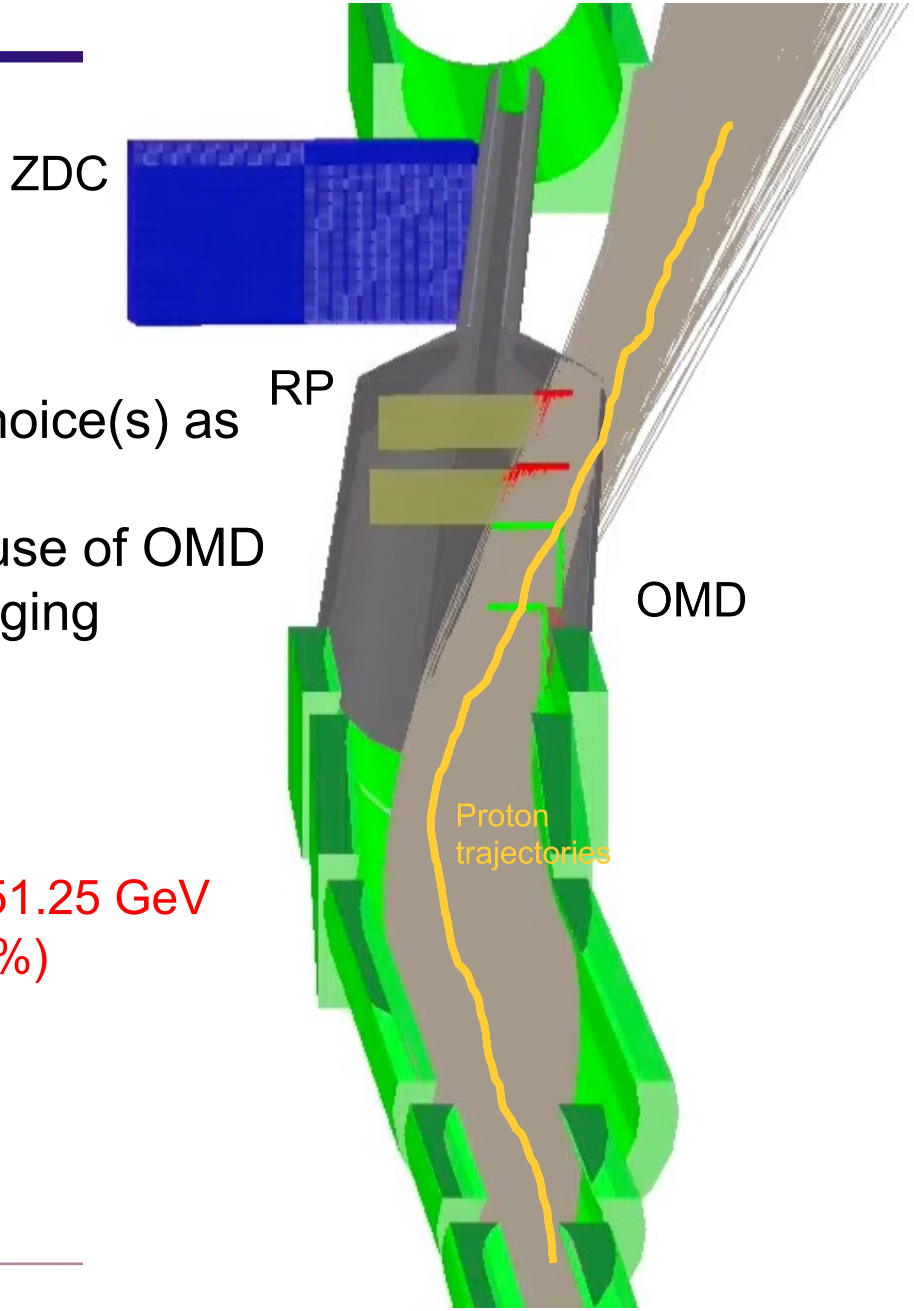
Backup

Off-Momentum Detectors

Off-momentum detectors implemented as horizontal "Roman Pots" style sensors.

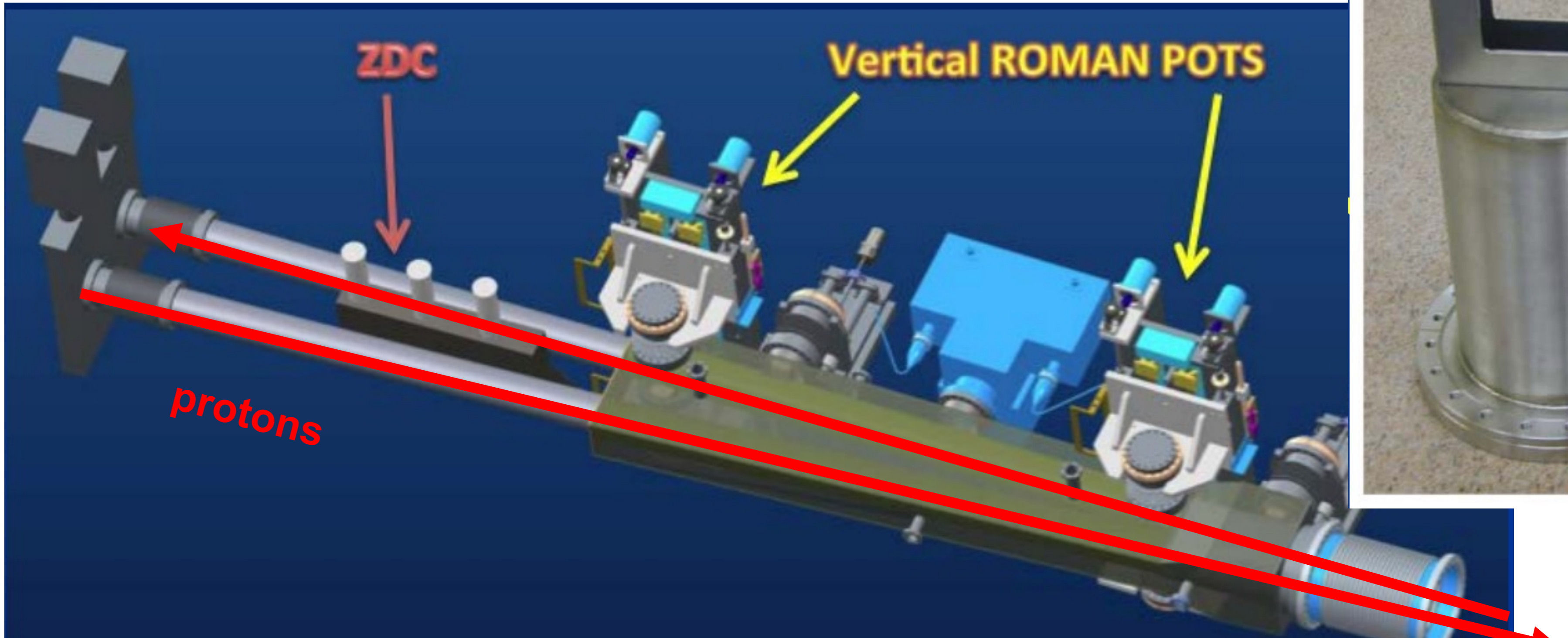
- Same technology choice(s) as for the Roman Pots.
- Need to also study use of OMD on other side for tagging negative pions.

Protons
123.75 < E < 151.25 GeV
(45% < xL < 55%)
0 < θ < 5 mrad

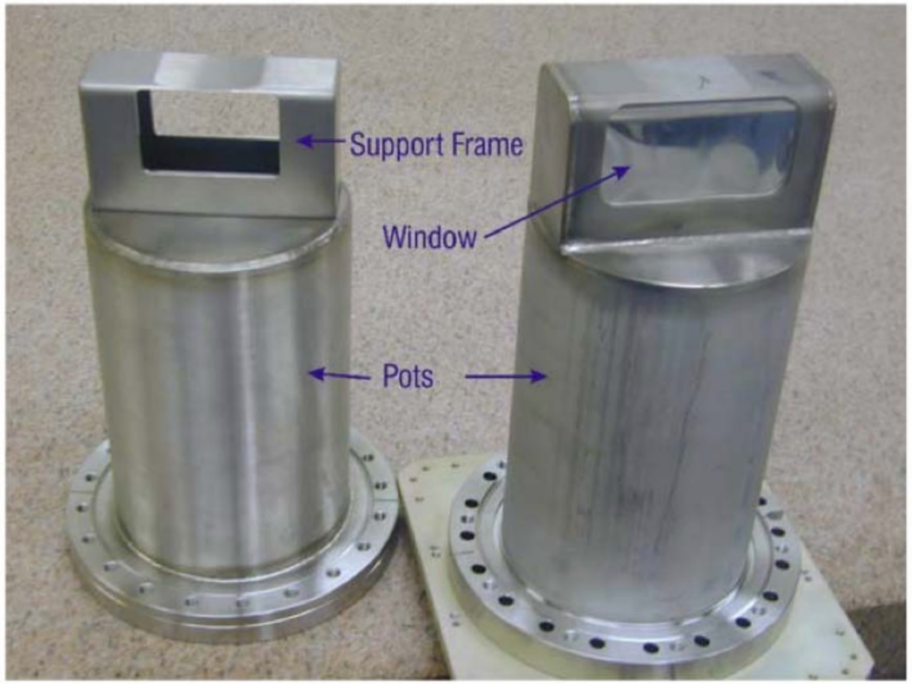


EICROOT GEANT4 simulation.

Roman Pots @ STAR



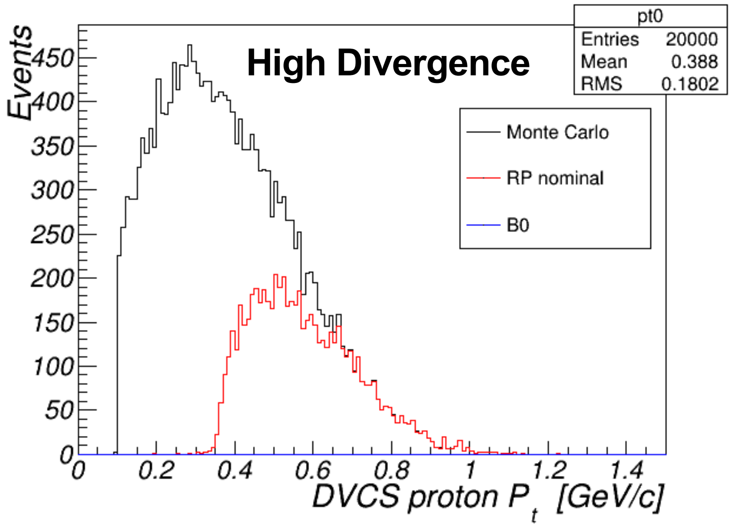
Roman Pots setup at STAR.

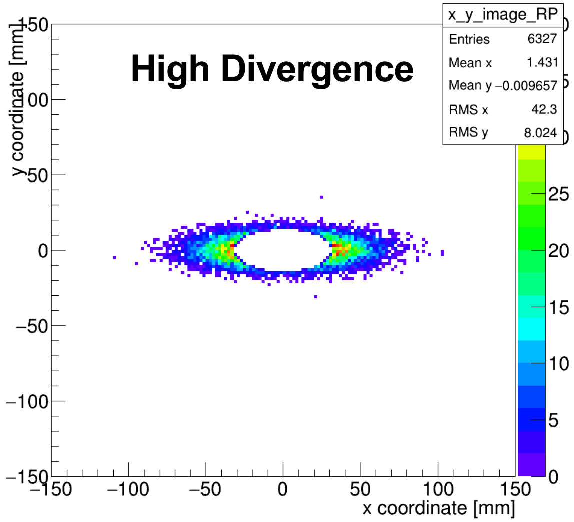


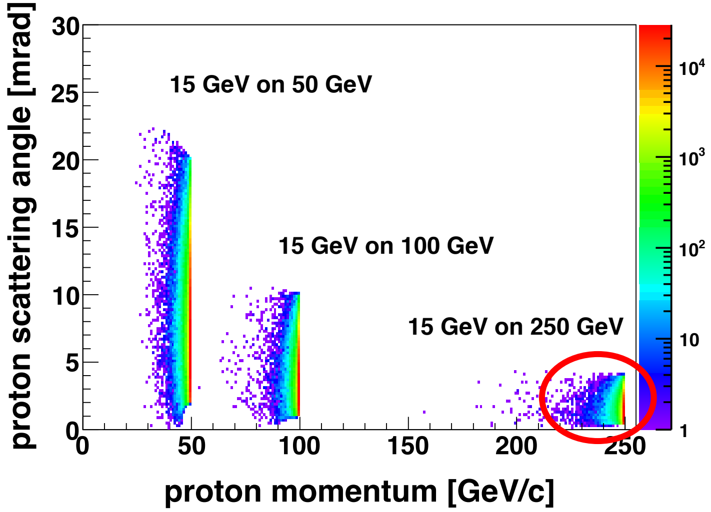
- Silicon detectors sit inside a “pot” with a thin-window to tag protons scattered at small angles (e.g. near the beam).

Digression: Machine Optics Impact

275 GeV DVCS Proton Acceptance







<u>High Divergence:</u> smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

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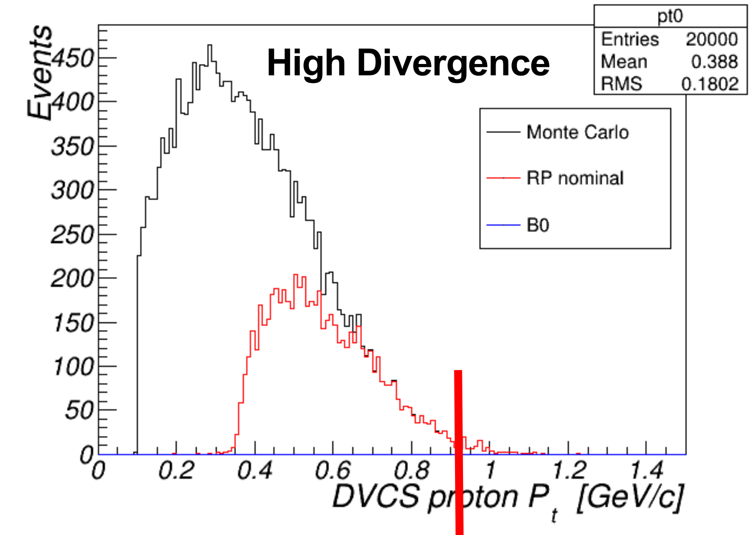
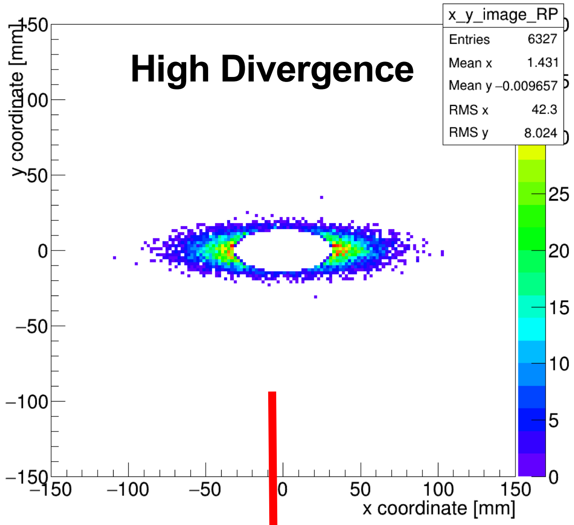
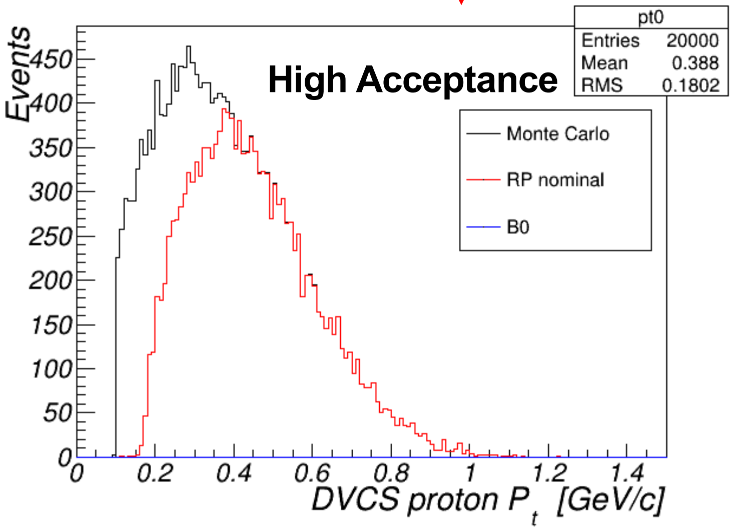
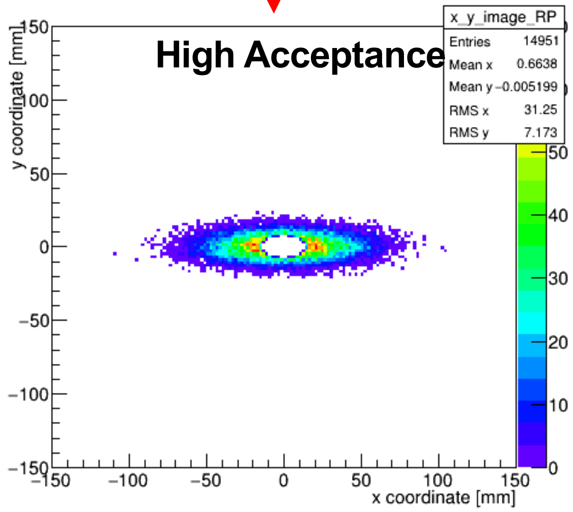
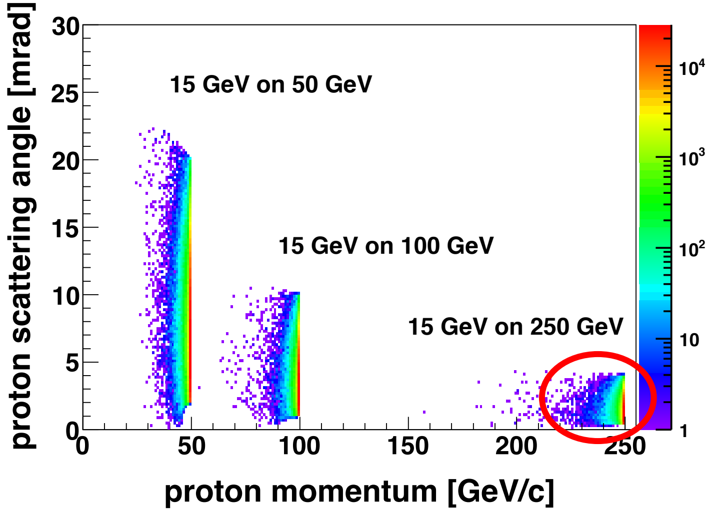








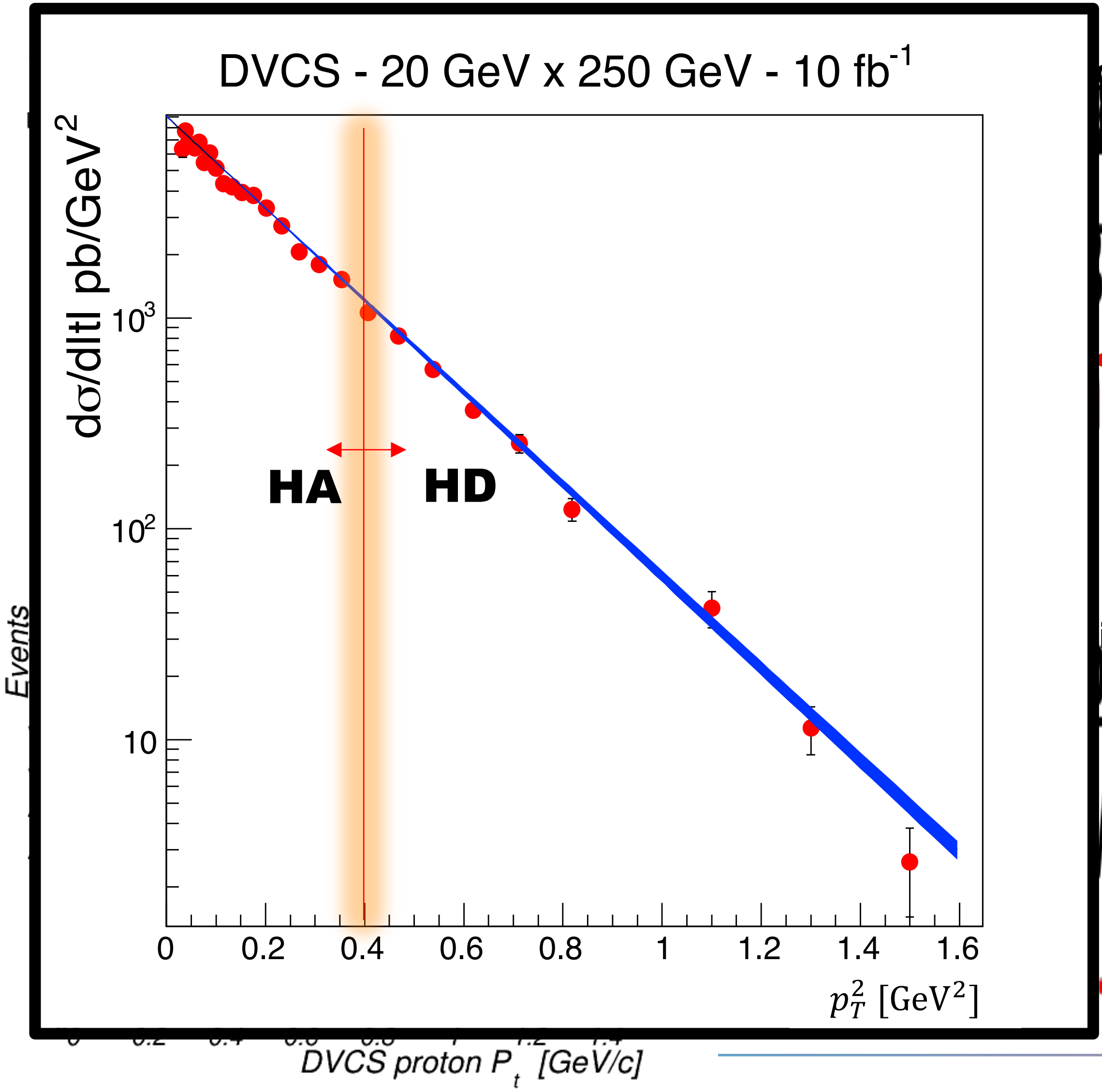


High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

High Acceptance: larger β^* at IP, smaller $\beta(z = 30m)$ -> lower lumi., smaller beam at RP

Digression: Machine Optics Impact

275 GeV DVCS Proton Acceptance



Using the two configurations, we are able to measure the low-p_T region (with better acceptance) and high-t tail (with higher luminosity).

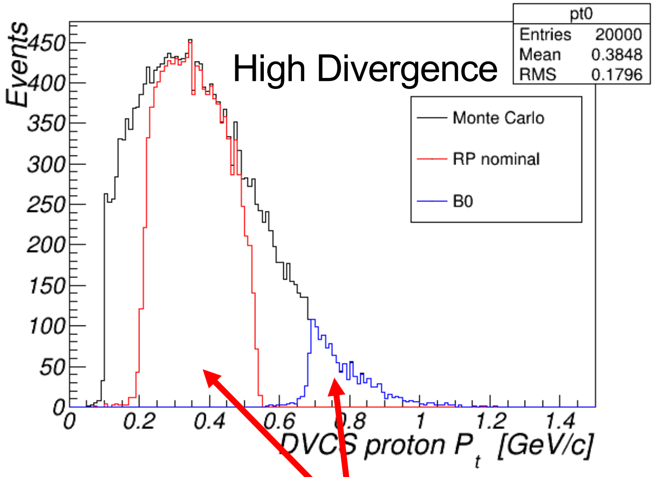
Detectors need to be able to move to different positions for different optics configurations.

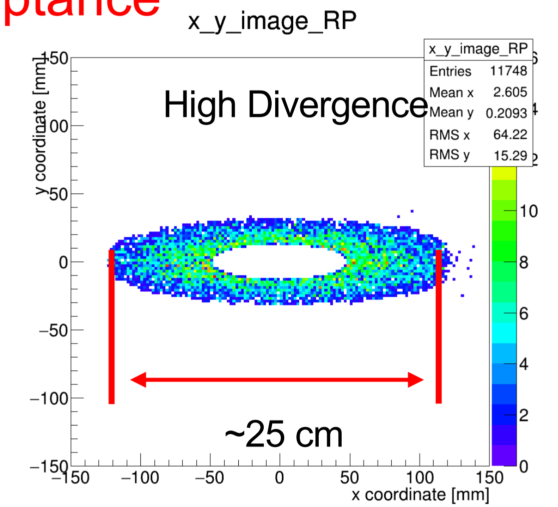
lower lumi., smaller beam at RP

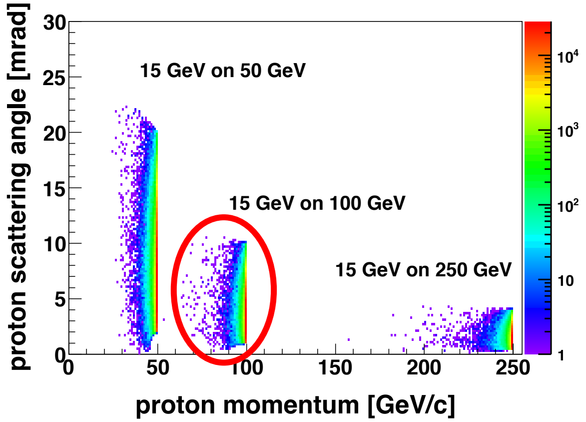
, smaller beam at RP

Machine Optics: Roman Pots

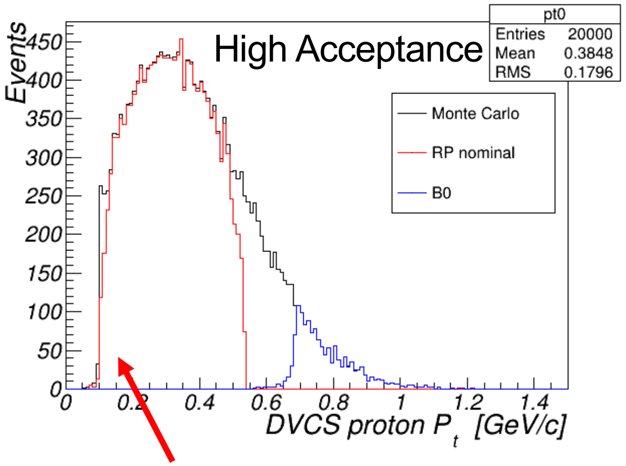
100 GeV DVCS Proton Acceptance

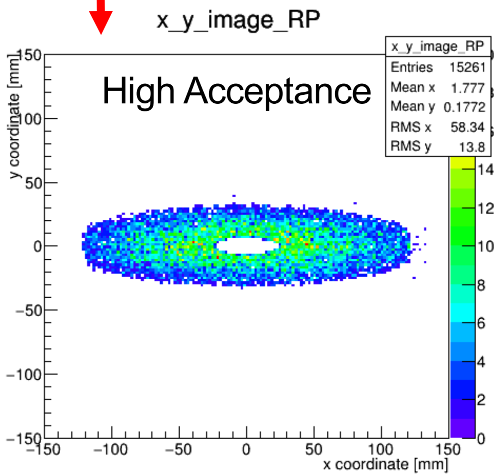






Need both detector systems together here!

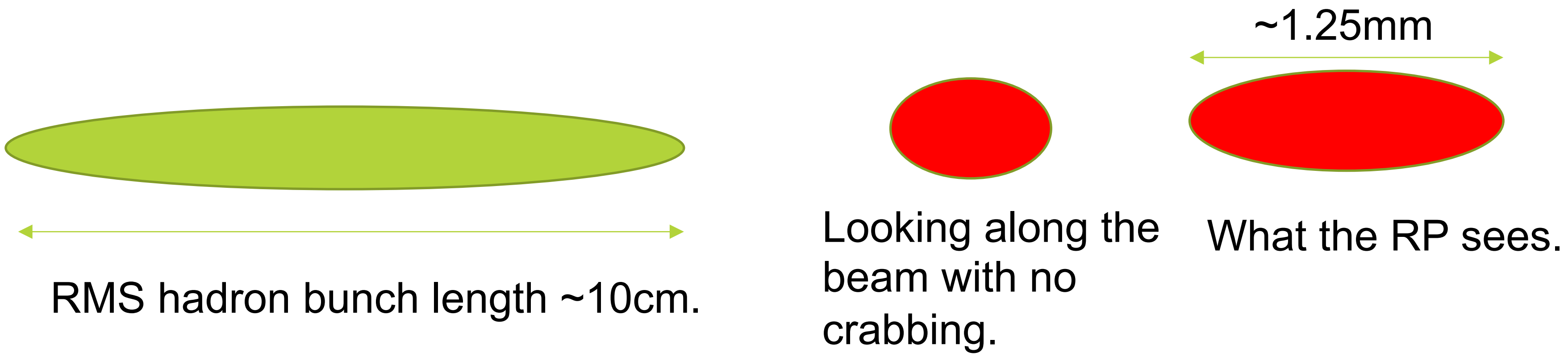




Improves low p_t acceptance.

Momentum Resolution – Timing

For exclusive reactions measured with the Roman Pots we need good timing to resolve the position of the interaction within the proton bunch. But what should the timing be?



- Because of the rotation, the Roman Pots see the bunch crossing smeared in x.
- Vertex smearing = 12.5mrad (half the crossing angle) * 10cm = **1.25 mm**
- If the effective vertex smearing was **for a 1cm bunch**, we would have **.125mm** vertex smearing.
- The simulations were done with these two extrema and the results compared.

> - **From these comparisons, reducing the effective vertex smearing to that of the 1cm bunch length reduces the momentum smearing to negligible from this contribution.**
> - **This can be achieved with timing of ~ 35ps (1cm/speed of light).**