Synergies in silicon development between CERN and EIC

EP R&D Day 2021

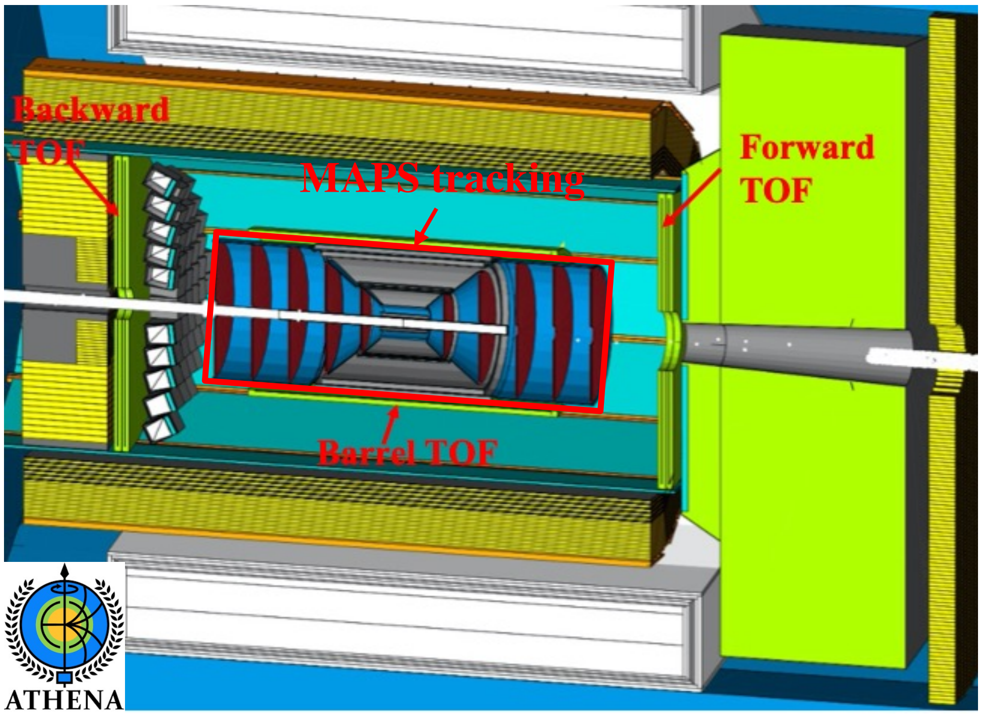
November 12, 2021

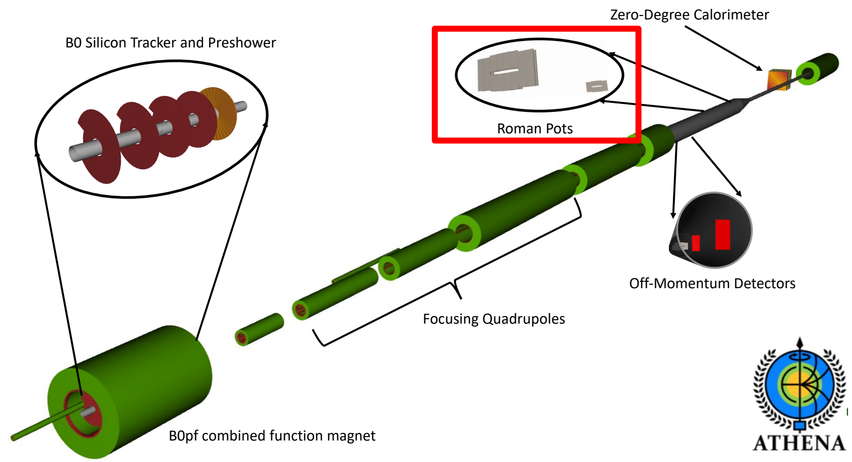
Laura Gonella

on behalf of the *EIC silicon consortium* and the *EIC LGAD consortium*

Introduction

- This presentation will focus on the synergies in the following areas:
  - MAPS for tracking
  - LGADs for timing measurements*





Figures from the ATHENA collaboration, similar detector concepts and technology choice for ECCE and CORE.

* The material presented in this talk has been provided by Alessandro Tricoli (BNL)

Motivations for MAPS at EIC

- A well integrated, large acceptance vertex and tracking detector designed with high granularity and low material budget is needed to enable high precision measurements that are key to the EIC science programme.
  - Precision measurement of the scattered electron in DIS.
  - Reconstruction of heavy-flavour decays.
  - Measurement of the charged constituents of jets.

- Requirements
  - Spatial resolution: ~5 μm, ~3 μm in the vertex layers
  - Material budget: ~0.5% X/X0 per layer, ≤ 0.1% X/X0 per vertex layer
  - Integration time ~2 μs
  - Low power consumption ~20mW/cm^2

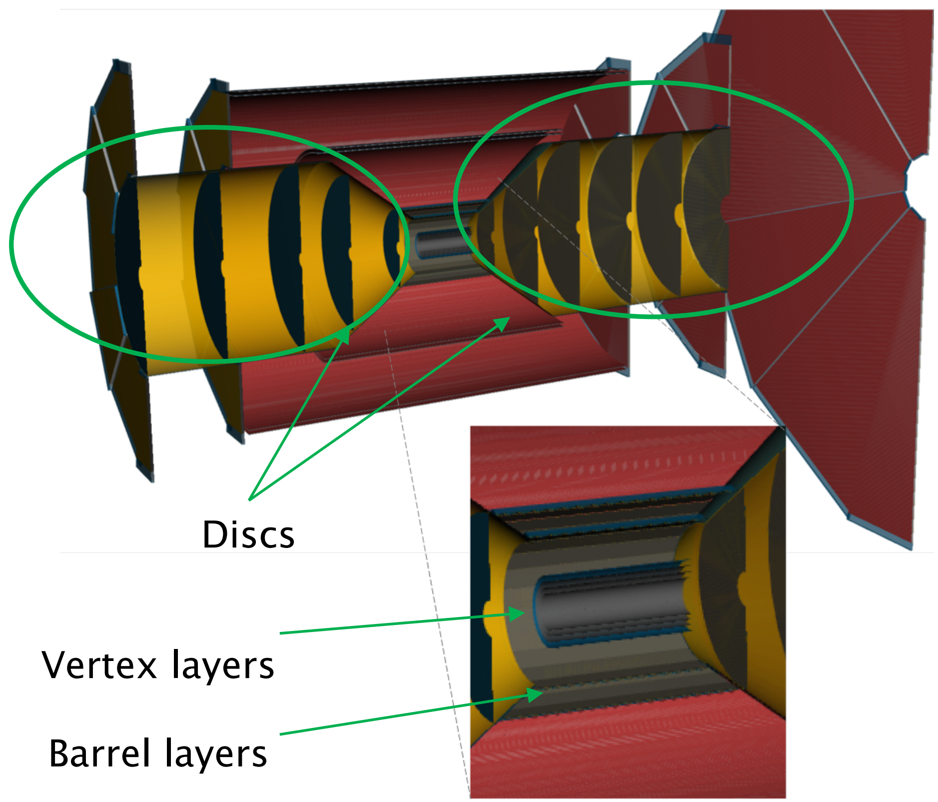
→ MAPS sensors are the only technology that can satisfy these requirements.

EIC Si-tracking detector

- Three EIC experimental proto-collaborations will submit their detector proposals on 1 December (ATHENA, CORE, ECCE).
- All proposals have a MAPS based silicon tracking detector made of vertexing, barrel and disc layers.

Example: ATHENA tracking detector (~6m^2)

- High resolution vertex tracking is proposed to be done with ITS3-like vertexing layers.
- Staves and discs are planned to be based on a sensor design optimized for cost effective, large area coverage.



EIC Si-tracking detector development

- Earlier studies of tracking and sensor needs were done with the support of the EIC Generic Detector R&D program (eRD16/18/25 projects, 2015-21).
  - Baseline performance simulations based on an ITS2-derived detector concept (i.e. same material budget but 20 um pixel pitch).
  - Survey of available MAPS options, including studies of pixel size performance with TJ investigator.

- In December 2019, the ALICE ITS3 development program using the TPSCo65 process was announced, and synergies were immediately clear…
  - ITS3 sensor design specifications have almost complete overlap with the requirements for an EIC sensor.
  - The timescales of the ITS3 and EIC projects are well-aligned.
  - The ITS3 detector concept is very attractive for the EIC vertex layers.
- … as well as differences.
  - EIC tracking detectors are expected to be 5 - 10 m^2 in size.
  - Staves and discs require a dedicated development.

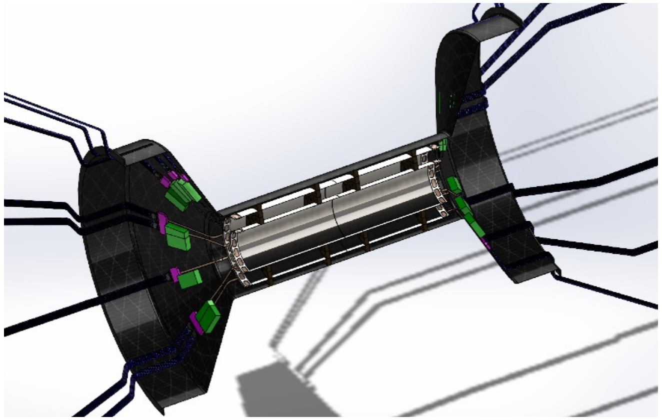
EIC Silicon Consortium

- The EIC SC formed in 2020 to develop a full silicon tracking detector solution for the EIC experiments.
- The EIC SC is open to institutes from different emerging EIC collaborations interested to work on the proposed sensor solution for their specific EIC detector implementation.
- Current members include BNL, CCNU Wuhan, INFN (Bari and Trieste), JLAB, LBNL, FNSPE CTU, NPI CSA, ORNL, STFC RAL, STFC Daresbury, Univ. of Birmingham, Univ. Brunel, Univ. of Liverpool, Univ. Lancaster.
  - BNL, LBNL, RAL: active sensor design institutes.
- The work of the EIC SC proceeds along two lines of development.
  - Work with ITS3 on wafer-scale stitched sensor and vertex layers development.
  - Develop an EIC sensor design for staves and discs with associated infrastructure building from and extending the ITS 65 nm design.

Current status and plans

- Vertex layers
  - Adapt ITS3 concept to EIC larger beam pipe and vertex layers radii.
  - Discussions are ongoing with ITS3 management to define areas of cooperation and co-development of the silicon sensor design and overall sensor integration, including effort and funding.

CAD drawing of EIC vertex layers

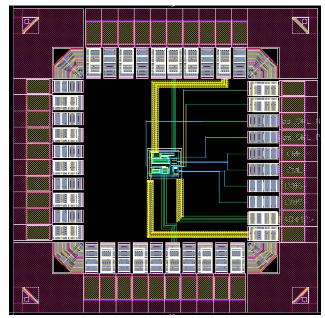


- Staves and discs
  - Large area requires low-cost, high yield sensor.
  - Discs have different size, and require good coverage close to the beam pipe for full acceptance, different sensor sizes might be needed.
  - The plan is to derive an ITS3 sensor version that can be used on a large area.
    - Keep the same functionality, stitched, but not wafer scale.
    - Start from the evaluation of the yield of the ITS3 first engineering run, to optimise sensor size/stitching versus yield and cost.
  - Possible synergies with CERN EP R&D WP1.2 (e.g. H2M project) and future LHC upgrades (e.g. ALICE3).

Participation in 65 nm developments

- RAL TD is already contributing to the 65 nm developments.
  - LVDS Receiver (1GHz) and CML Driver (10GHz) in the first 65 nm MLR.
  - Design of a PLL (dual frequency operation: 10GHz or 1.25GHz) for the first engineering run submission.

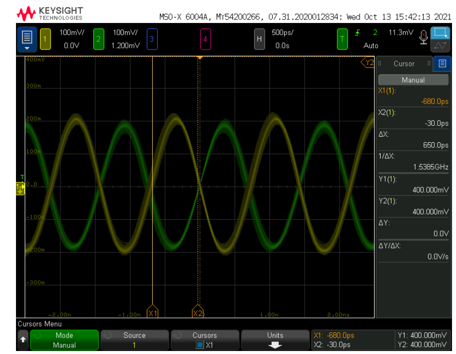
See talk by Iain Sedgwick at the CERN EP R&D WP1.2 meeting, Nov 2021
https://indico.cern.ch/event/1091910/



MLR1 Testing

Testing

- Working to at least 700MHz (1.4Gbit/s)
- 800mV differential signal at that speed
- 49.3% duty cycle
- Jitter not measurably worse than input
- Better test set up needed to fully characterise



Science and Technology Facilities Council

- BNL recently signed the NDA with CERN/TowerJazz to allow access to PDK and enable more effort. The NDA for LBNL is hoped to be signed in the next few weeks.

- Draft proposed areas of silicon design contribution: PLL block, LDO block, Digital logic test SEU chip, Readout architecture of matrix, High speed data transmission, Pixel front end circuital solutions, TCAD analysis, ADCs.
  - Initial discussions have taken place with CERN EP R&D WP1.2 and ITS3 WP2 leaders to identify common interests and needs.

EIC SC effort on modules and services

- In parallel to the sensor development, the EIC SC will be working on the development of low-mass, low-cost solutions for mechanics, cooling, RDO, etc. as needed for the EIC tracking detector design.
  - Strategies can be shared with the CERN EP R&D programme (e.g. WP1.3, WP4) and future LHC upgrades and beyond.

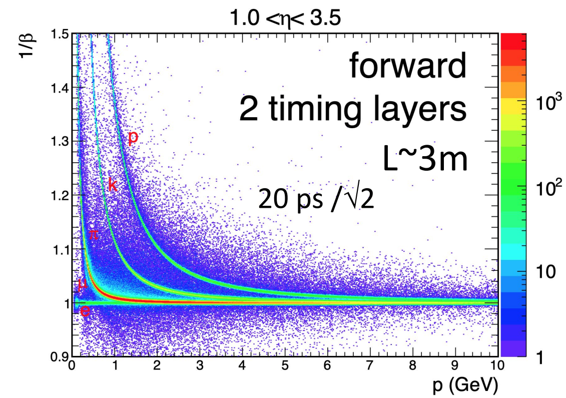
- The eRD104 and eRD111 R&D projects were created in summer 2021 supported by Project Directed R&D Funds for the developments needed for a complete EIC tracking detector design.
  - eRD104 Silicon Service Reduction.
    - DC-DC and serial powering schemes; On-detector data aggregation and high-speed optical links.
  - eRD111 Si tracker (excluding sensor).
    - Electrically and mechanically integrated module concepts designed for automated loading on staves and discs; exploration of reliable, low-cost interconnection techniques; air cooling through carbon foam between face sheets of disc plates; etc.

Summary of MAPS synergies

- The work of the EIC SC to develop a complete silicon tracking solution for the EIC offers many possibilities for synergies with the CERN EP R&D programme and LHC upgrades (timescales well aligned).
- Clear synergies identified with ITS3 on sensor design and vertex layers concept.
  - The ITS3 design goals are an exact match for the vertexing layers needed at EIC.
- Plans are in place to extend the ITS3 sensor architecture to a large area variant for the EIC staves and discs.
  - Synergies with CERN EP R&D WP1.2 developments and ALICE3 plans.
- The requirements for the large area EIC detector infrastructure (high yield, low-cost, low-mass) are aligned with the needs of LHC upgrades and future experiments and ongoing R&D towards those.
  - Synergies with CERN EP R&D WP1.3, WP4 developments and ALICE3 plans.

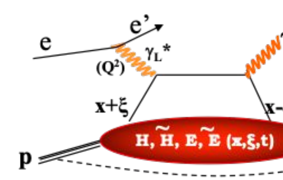
Motivations for Timing Detectors at EIC

- Particle Identification via TOF in barrel and endcap.
  - ≤20 ps timing resolution per track is needed for p/K/pion separation at low/medium momentum.
  - Segmentation in pixels or strips needed to extrapolate tracks from inner tracker and improve momentum resolution at high momentum.
  - Low material budget is a requirement.

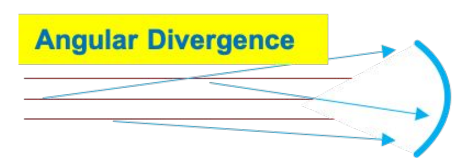


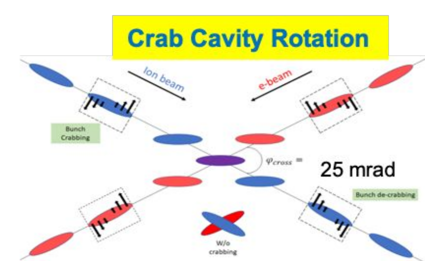
π/k separation: 0.1~4-5 GeV;
k/p separation: 0.1~7-8 GeV

- Forward proton tagging at EIC (e-hadron collisions), integral part of EIC physics programme
  - EIC Roman Pots: physics impacted by smearing of proton momentum reconstruction.
    - 35 ps timing removes crab cavity rotation effect.
    - Fine space resolution (≤500/√12 μm) mitigates angular divergence effect.

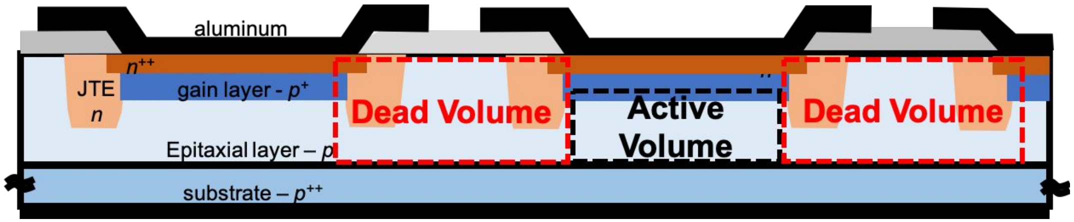


Deeply Virtual Compton Scattering at EIC

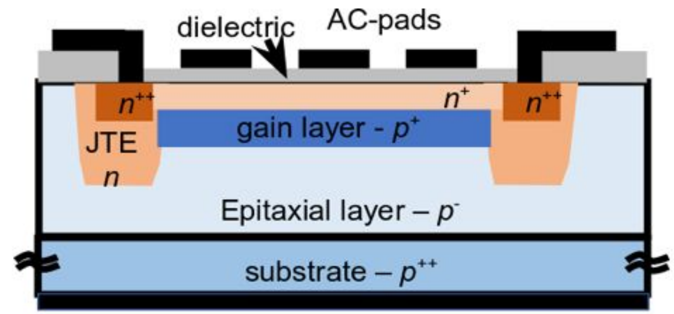




AC-LGAD



- LGAD limited by coarse segmentation, ~ 1x1 mm^2 pads.
  - Lateral dimensions of Gain layer must be much larger than thickness of substrate, for uniform multiplication.
  - Dead volume (gain~1) between the implanted region of the gain layer.
  - Excellent timing performance demonstrated up to ~10^{15} n/cm^2 but 4D detector not possible.



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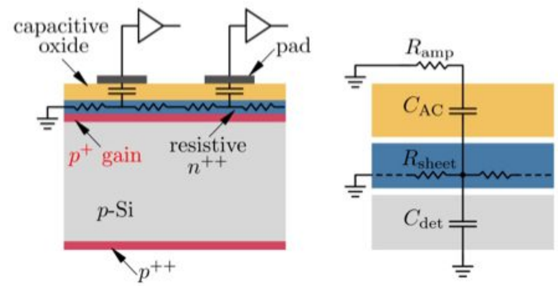
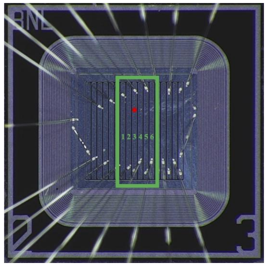
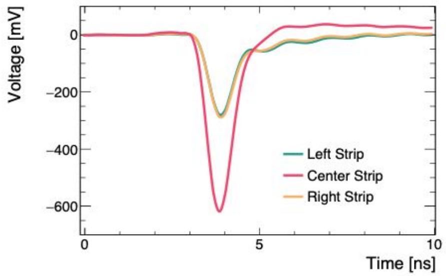


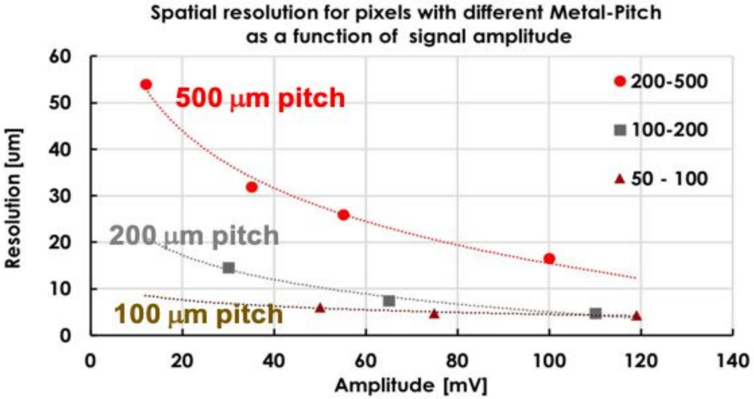
⇒ 100% fill factor and fast timing information at a per-pixel level both achieved!

AC-LGAD

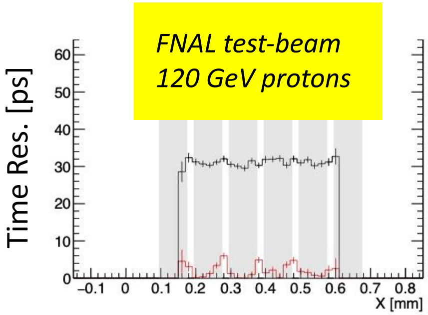
- Signal sharing through AC-coupling can be exploited to improve space resolution beyond $1/\sqrt{12}$ by combining signal from multiple electrodes.
    - e.g. 100μm metal pixel, 200 μm pitch gives ~5μm resolution.
- Sparse metallization results in lower noise, and lower power in electronics by limiting channel count.
    - Pitch and gap size can be adjusted to minimize number of channel and detector capacitance.
- Good time resolution of LGADs is preserved
    - ~30 ps is demonstrated in test-beams, expected ≤20 ps with 20 μm active thickness.
- Expected similar radiation tolerance as LGADs (up to ~10^{15} n/cm^2).







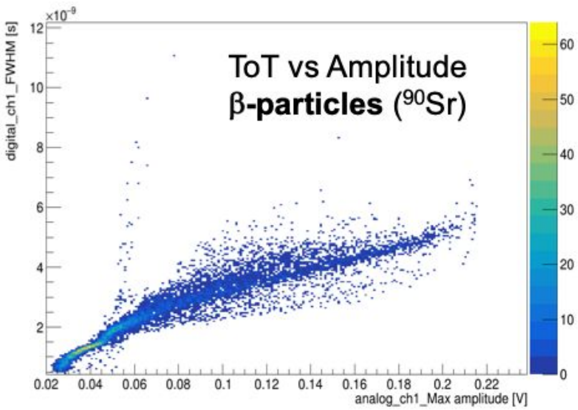
Torino group

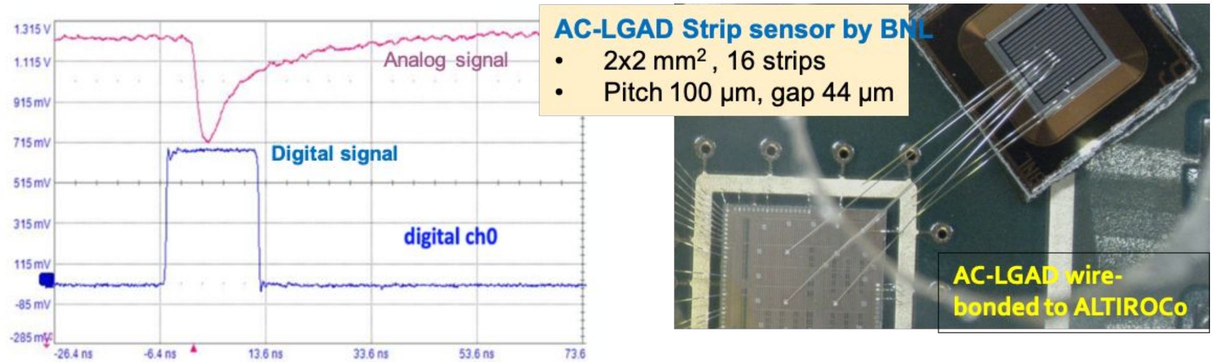


BNL sensor: 100μm pitch and 20μm inter-strip gap

AC-LGAD

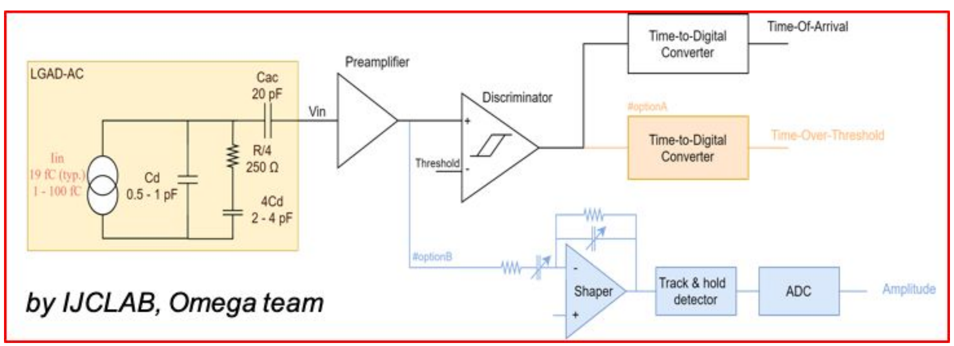
- AC-LGAD strip sensor was successfully readout by ALTIROC0 (ATLAS HGTD ASIC prototype).





ToT can be used as proxy for Amplitude when combining signals from neighbouring electrodes in position and time measurements.

- Ongoing design of ASIC for EIC RPs (500µm pitch pixels, 30 ps timing) based on ALTIROC architecture.



The LGAD Consortium Goals

- Submission of Expression of Interest (EOI) for EIC detectors based on LGADs on Oc. 30th, 2020 by 14 Institutes, 33 people.
  - Interests in different detector concepts (Generic 4D Tracker, TOF, Roman Pots, preshower) and expertise in several area (sensors, electronics, system design, engineering and construction).
- Create a collaborative effort to develop EIC detector technologies based on the LGAD technology.
  - Bring together people with common interest in LGAD-based detectors in HEP, NP and other communities.
  - Share expertise on the common aspects of the underlying technology that transcend any specific detector realisation.
  - NB: the consortium does not intend to replace the collaborative effort of a detector project, but supplement it, in order to study common challenges and possibly develop common solutions across different detector projects.
- On a longer term this consortium will be a stepping stone for other, longer-term applications of LGADs.
  - Collaborators have joined with interests in other applications, e.g. FCC, LHCb, NA62, PIENUX etc.

R&D Effort for LGADs at EIC

- EIC community has recognised that a coherent effort is needed in the R&D to develop LGAD technologies for EIC applications.

- eRD112 was created in summer 2021 as an R&D project to support LGAD developments for EIC TOF and Roman Pots (2021 to 2026 time span of R&D).
  - This effort is embedded in the wider-scope LGAD consortium.
  - Participating Institutes are a subset of the LGAD consortium (BNL, Rice, UIC, UCSC, IJCLAB/Omega, LANL).
  - Tight schedule of deliverables to meet the stringent EIC deadlines.
    - Definition of detector specifications and layouts.
    - Sensor prototyping and testing (several submissions to BNL and HPK foundries).
    - Electronics development (ASICs and flexes).
    - Prototyping of mechanical supports and cooling system.

Summary of LGAD synergies

- eRD112 and LGAD Consortium aim at developing a common (or similar) detector layout(s) that can work for TOF and Roman Pots (similar sensor and electronics) to minimise costs and effort.
- Several developments can be common with other applications beyond EIC, e.g. ALICE.
  - Sensor R&D, e.g. sharing of design, wafer submissions to foundries and testing.
    - LGADs development has been driven by ATLAS and CMS timing detector and is now well established; AC-LGAD development is advanced, supported by a strong community of LGAD experts.
  - Electronics development: ATLAS HGTD and CMS ETL used as stepping stones.
    - On-going ASIC design for EIC RPs by IJCLAB/Omega, other institutes are expected/welcome to join to expand scope to include electronics for the TOF detector.
    - Different conditions between EIC and LHC (e.g. radiation levels, hit occupancy and triggers) entail implementation of different technical solutions, but sharing of information, expertise and designs can be beneficial to both communities.
  - Strategies for Cooling and Mechanical supports can be shared.
- Good match between EIC schedule and schedules for LHC upgrades that can be exploited.

Backup

MAPS: useful links

- EIC SC mailing list: subscribe at https://lists.bnl.gov/mailman/listinfo/eic-rd-silicon-l

- EIC SC Indico pages: https://indico.bnl.gov/category/386/

- Expression of interest: https://indico.bnl.gov/event/8552/contributions/43219/

- eRD25 project proposal: https://wiki.bnl.gov/conferences/images/6/6d/ERD25-Report-FY21Proposal-Jun20.pdf

LGAD: Useful links

- LGAD Consortium mailing list: lgads-eic@mailman.rice.edu
  - To subscribe, send an email to A. Tricoli (alessandro.tricoli@cern.ch) , W. Li (wl33@rice.edu) or do it yourself through web interface https://mailman.rice.edu/mailman/listinfo/lgads-eic

- EIC LGAD Consortium Indico pages: https://indico.bnl.gov/category/323/
  - General interest meetings:
    - Electronics - https://indico.bnl.gov/event/11717/
  - Expressions of Interests - https://indico.bnl.gov/event/10704/
  - Kick-off - https://indico.bnl.gov/event/9693/

Motivations for Timing Detectors at EIC

- **Particle Identification via TOF in barrel and endcap**
  - ≤20 ps timing resolution per track is needed for p/K/pion separation at low/medium momentum
  - Segmentation in pixels or strips needed to extrapolate tracks from inner tracker and improve momentum resolution at high momentum
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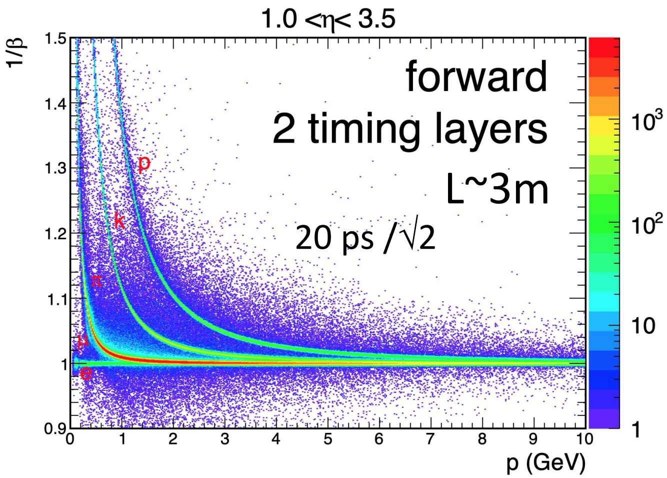

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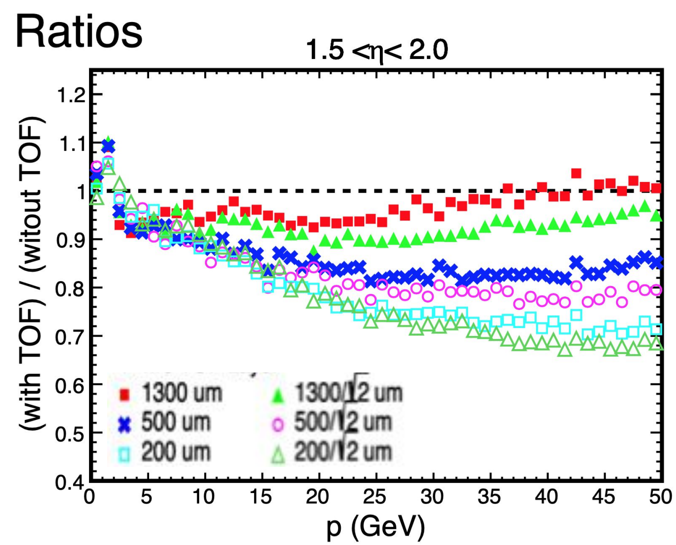
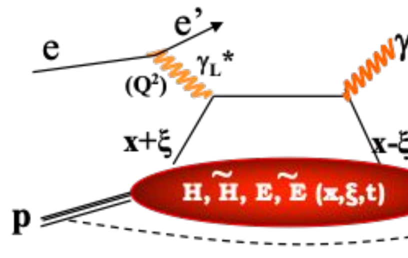


***Track p_T resolution** improvement with fine ToF det. segmentation*

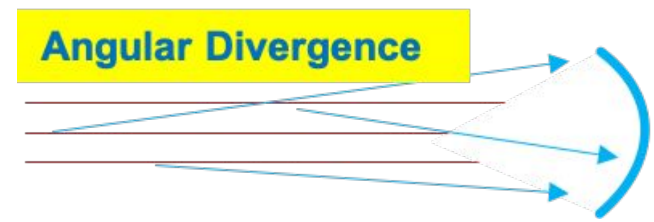
	Time resolution / hit	Position resolution / hit	Material budget / layer
Barrel ToF (Tracker)	<30 ps	(3-30 μm for Tracker)	$< 0.01\ X_0$
Endcap ToF (Tracker)	<25 ps	(30-50 μm for Tracker)	e-direction $< 0.05 X_0$ h-direction $< 0.15 X_0$

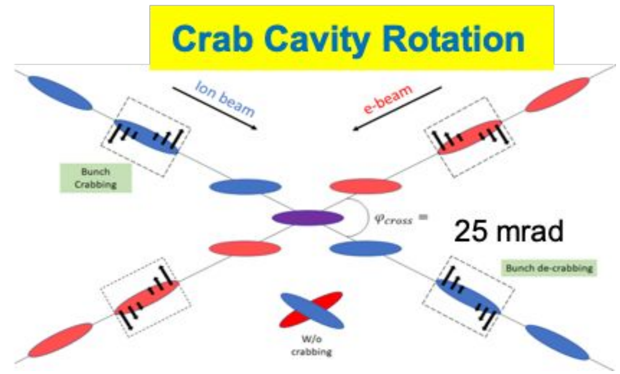
Motivations for Timing Detectors at EIC

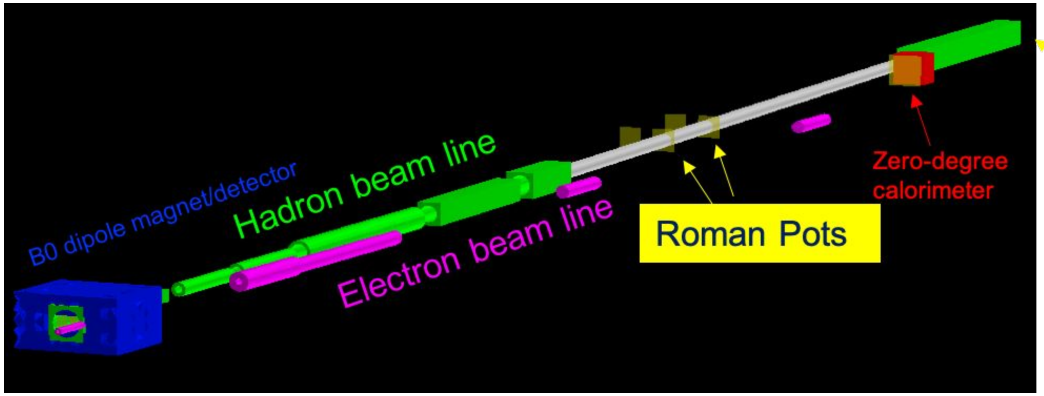
- Forward proton tagging at EIC (e-hadron collisions)
  - Integral part of EIC physics programs
- **EIC Roman Pots**: physics impacted by smearing of proton momentum reconstruction
  - 35 ps timing removes crab cavity rotation effect
  - Fine space resolution (≤500/√12 μm) mitigates angular divergence effect



Deeply Virtual Compton Scattering at EIC







Participating Institutes and People

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  - 14 Institutes, 33 people
- Interests in different detector concepts
  - TOPSiDE, 4pi Hybrid LGAD/SOI Tracker, Generic 4D Tracker, TOF, Roman Pots, Preshower
- Interests and expertise in several different areas
  - Sensors, Electronics, System Design, Engineering and Construction
- More participants have joined since the EOI

Expression of Interest (EOI):
Fast timing silicon detectors for EIC detectors

Artur Apresyan[d], Whitney Armstrong[a], Elke-Caroline Aschenauer[b], Mathieu Benoit[b], Carlos Munoz Camacho[f], Janusz J. Chwastowski[e], Olga Evdokimov[m], Salvatore Fazio[b], Frank Geurts[j], Gabriele Giacomini[b], Sylvester Joosten[a], Alexander Kiselev[b], Wei Li (contact)[j], Xuan Li[g], Constantin Loizides[i], Jessica Metcalfe[a], Zein-Eddine Meziani[a], Rachid Nouicer[b], Christophe Royon[n], Hartmut Sadrozinski[l], Bruce Schumm[l], Abe Seiden[l], Laurent Serin[f], Rafał Staszewski[e], Stefania Stucci[b], Jacek Świerblewski[e], Christophe de la Taille[c], Daniel Tapia Takaki[n], Alessandro Tricoli (contact)[b], Maciej Trzebiński[e], Cinzia Da Via[k], Bolesław Wysłouch[h], and Zhenyu Ye[m]

- Argonne National Lab (ANL)
- Brookhaven National Lab (BNL)
- Organisation de Micro-Électronique Générale Avancée (OMEGA), Ecole Polytechnique
- Fermi National Lab (FNAL)
- Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN)
- Laboratoire de Physique des 2 Infinis Irène Joliot Curie (IJCLAB)
- Los Alamos National Lab (LANL)
- Massachusetts Institute of Technology (MIT)
- Oak Ridge National Lab (ORNL)
- Rice University (Rice)
- Stonybrook University (Stonybrook)
- University of California, Santa Cruz (UCSC)
- University of Illinois, Chicago (UIC)
- University of Kansas (KU)