Timing detectors at the EIC

New generation 4D reconstruction and polarimetry

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> ...A broad spectrum of applications

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01

The timing era

why is the physics community investing in timing?

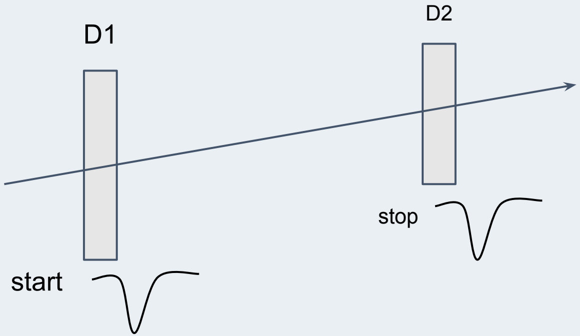
During the last decade, the increasing demand for particle detectors capable of accurate time resolution pushed the physics community to invest time and resources for the upgrade and optimization of this technology.

The test performed on timing detectors of new generation proved their performance to be compatible with the particle rates and radiation levels expected in HEP facilities.

Section 01 introduces the concept of timing resolution and highlight its similarities and differences with the concept of fast detectors.

Introduction: timing and 4D reconstruction

When we talk about “Timing detectors” we usually refer to detecting devices optimized to accurately reconstruct particles times of arrival when collected from the sensor.



In the example of two devices (D1,D2) detecting the passage of a particle...

$$L \approx |t_{start} - t_{stop}|\, v$$

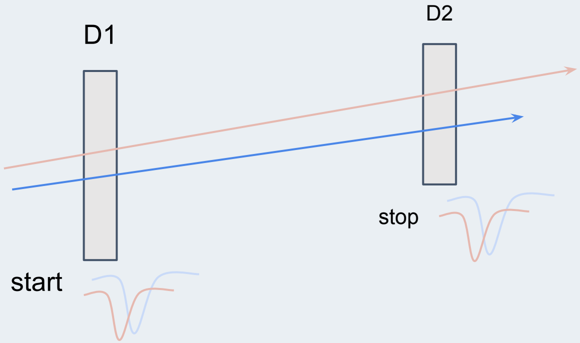
$$\sigma_z = \sqrt{\sigma_{t_1}^2 + \sigma_{t_2}^2} \cdot c$$

The precision of the measurement can be calculated as:

$$\sigma_{tot} = \frac{1}{N} \cdot \sqrt{\sigma_{det1}^2 + \sigma_{det2}^2 + ..} \approx \frac{1}{\sqrt{N}} \cdot \sigma_{det}$$

The example can be extended to include the passage of multiple particles...
In this case the Time of Flight (TOF) of different particle species can be used to perform an Identification of the detected object:

$$\Delta t = t_2 - t_1 = L\left(\frac{1}{v_1} - \frac{1}{v_2}\right) \approx \frac{Lc}{2p^2}(m_1^2 - m_2^2)$$



This class of detectors generally operates using high granularity sensors and, when paired with tracking apparatus, can provide a full **4D reconstruction** (x,y,z,t) of the event.

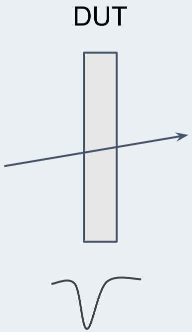
Fast or Precise?

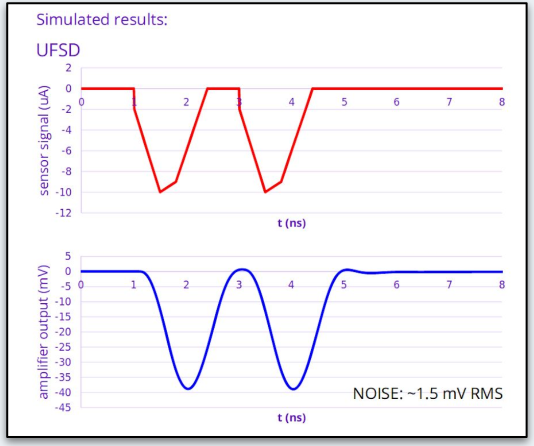
Precise Detector

- Output the timestamp of a particle's passage in the active volume with a small uncertainty.
- Suited for **TOF**, **difference of time of arrival**, **time reference for HEP detectors**...
- In new generation detectors, the time uncertainty can go as low as **σ ~ 10ps.**
- The accuracy of the timing measurement affect the spatial reconstruction accuracy $\sigma_L \propto \sigma_t$

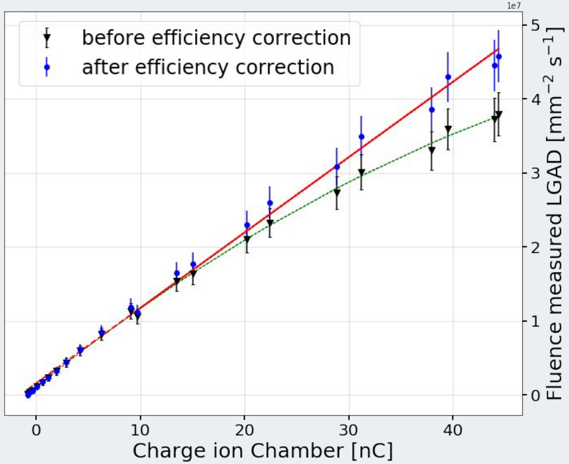
Fast detector

- Output a narrow pulse in response to the passage of a particle.
- Modern electronic components can be combined to develop circuit that outputs pulses as narrow as **~ few ns.**
- A fast integration of the signal reduces the dead time of the detector: **single particle resolution guaranteed up to high rates**





[1]



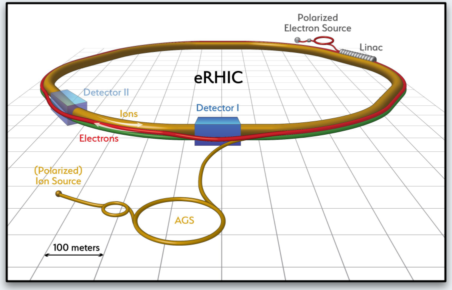
[2]

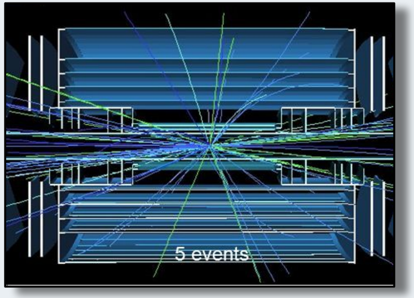
[1] Nicola Minafra - Precision Electron Polarimetry at EIC, EIC User Group Meeting, July 18-22 2017
[2] T.sidori, P. McCavana, B. McClean, R. McNulty, N. Minafra, N. Raab, L. Rock, C. Royon - arXiv:2101.07134

…A Broad spectrum of applications

HIGH RATE FACILITIES

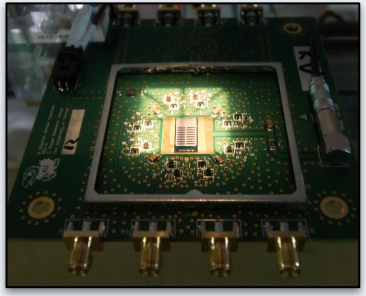
Measurements that requires detectors capable of single particle resolution such as:
Polarimetry, **Luminometry**, **Dose evaluation…**





PRECISION MEASUREMENTS

Measurements that requires detectors capable of high timing resolution:
Background rejection for exclusive events, **Time of Flight**, **4D tracking, 5D reconstruction…**



COMMERCIAL APPLICATIONS

Few other applications can be listed:
commercial sensors, **dosimetry in medical facilities**, **study of fluids interfaces…**

Note:
Part of the EIC physics program requires the use of different types of **fast(to operate with precisely polarized e-ion beams) AND precise (to identify the hadrons generated from the interaction)** timing detectors.

02

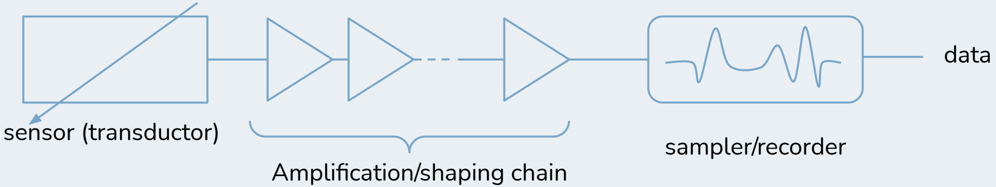
A casual guide to Timing

To optimize the timing accuracy and increase the efficiency for single particle reconstruction, the choice of a performant sensor has to be combined with the development of a fast read-out.

The output signals are later digitized and recorded with the use of high-bandwidth fast samplers.

This section will provide a rapid description of the principles of operation of timing detectors as well as an overview of some of the technologies proposed for 4D vertex reconstruction and particle ID at the EIC.

Principles of Operation



Example of a timing detector

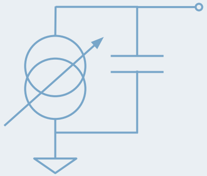
… The dE/dx of a particle produces a current in the sensor's **active volume**. The **read-out** electronics shapes and amplifies (if needed) the signal. A fast, high-bandwidth **sampler** records and store the waveforms.

Disclaimer: the detector technologies described are the ones proposed for the final design of the EIC central and forward detectors

Sensor

The choice of the sensor it's the first important step for designing a particle detector. The current state of the art timing detectors are based on **solid state** sensor.

Solid state (sCVD Diamond, LGAD, SiPM, MCP…)



- μ > **1000 (cm2/V)s** High **mobility** of the carriers
- $v_s > 10^7$ **cm/s** - High **saturation velocity**
- $C_{sensor} \propto \varepsilon_0 \varepsilon_d$ **(S/d)** the sensor capacitance is proportional to the dielectric constant (low capacitance means shorter integration time)
- The **Displacement energy** in sensors of new generation drastically improved (lifespan up to 10^{15} n_{eq})
- **Low thickness** and **material budget.** Sensor size down to ~**50μm**
- **High granularity** on the active area

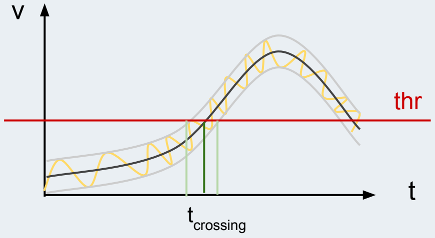
Note: some of the above mentioned detectors (**SiPM,MCP**) require an external active medium to collect (and often convert in light) the energy deposited by charged particles. The most common options are represented by the use of **Quartz** (Čerenkov effect) or **scintillating polymers.**

Read-out and Front-end

The sources of uncertainty of a timing measurement can be expressed adding in quadrature the contributing factors:

$$\sigma^2_t \sim \sigma^2_{jitter} + {}^{*}\sigma^2_{Landau} + \sigma^2_{TimeWalk} \overset{*}{+} \sigma^2_{Distorsion}$$

* contribution of the sensor



read-out

The predominant contribution introduced by the shaping and amplifying chain comes from the **noise fluctuations** that, in turn affect the Signal to Noise Ratio (SNR)

front-end

The choice of a performing sampler directly influence the timing precision of the instrument as the jitter depends on the slope of the signal's rising edge. The bottleneck of the rising time for fast detectors comes from the **sampler's bandwidth.**

$$\boxed{\sigma_{jitter} \simeq \frac{noise}{dV/dt} = 1.25\frac{\tau_{0.1} - \tau_{0.9}}{SNR} = 1.25\frac{t_{rise}}{SNR}}$$

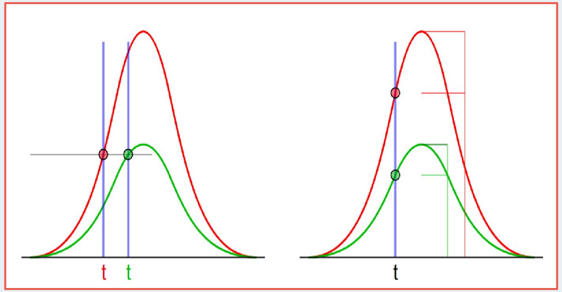
With

$$\boxed{t_{rise} = \frac{0.35}{Bandwidth}}$$

Note (post-processing data):

Some of the contributions come from effects that are intrinsic to the nature of the measurement and can only be corrected during the analysis procedure.

The **Time Walk** is the mis-reconstruction of the timestamp of simultaneous pulses with **different amplitudes**.

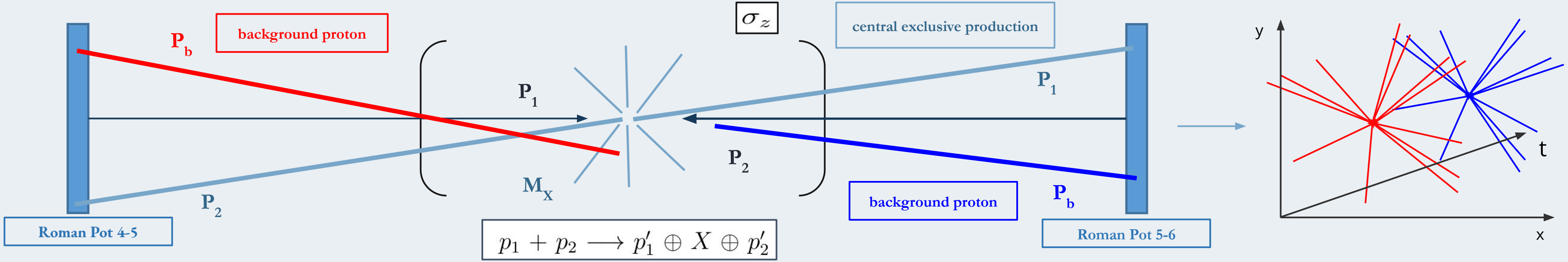


Current state and Results

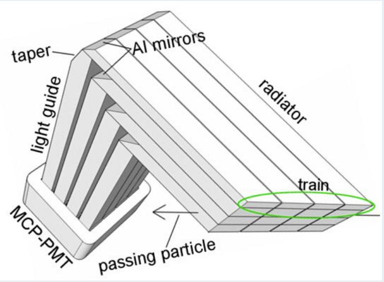
Particle ID and TOF

In preparation for future High Luminosity facilities, many HEP experiments are aiming to include fast timing sensor for particle tagging and identification. The request for pile-up removal for optimal discrimination pushed the research community in the development of top of the line solid state detectors.

ATLAS and CMS forward detectors represents a good example of TOF for pile up rejection (and not only)



The ATLAS Forward Proton Detector (AFP)



Quartic (Quartz bars + MCP readout)

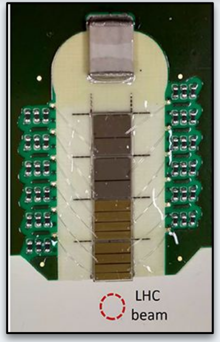
- High fill factor (>85% per layer)
- Despite the crosstalk resolution **< 25 ps**
- requirement: spatial resolution of **2.12mm**
- requirement: rate **5 MHz** per channel

ATLAS Forward Proton (AFP) time-of-flight (ToF) detector: construction & existing experience - T.Sykora

CMS Proton Precision Spectrometer

4 Layers of **sCVD Diamond detectors**

- Active area ~ **80 mm^2**
- sustainable hit rate up to **few MHz/mm2**
- double sCVD design ~ **50 ps** resolution (per plane)
- resolution degradation ~ 20-50% (full 2018 data taking)
- stable time resolution in detecting 6-7 TeV protons

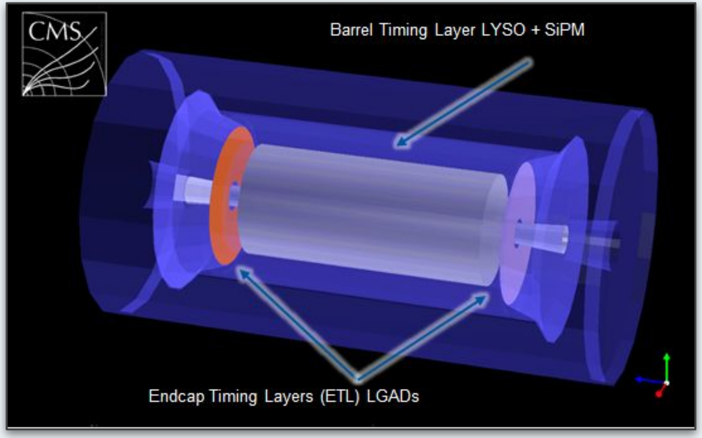


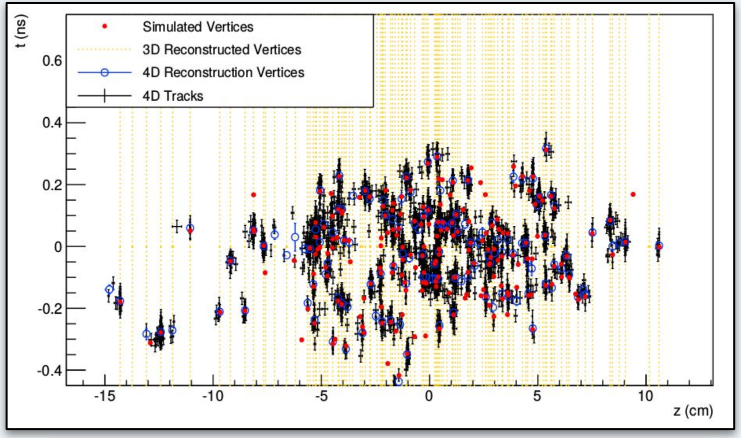
The CMS Precision Proton Spectrometer timing system: performance in Run 2, future upgrades and sensor radiation hardness studies - E.Bossini

Current state and Results

Particle ID and TOF

The CMS MIP Timing Layer





MIP Timing Layer with **40 ps** of time precision is required

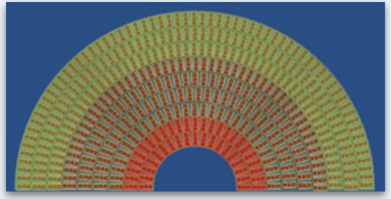
impact on the physics program:

> improved track and vertex reconstruction abilities
> lepton reconstruction efficiency
> diphoton vertex location
> missing transverse momentum resolution
> reduction of the pile up jet rate

	Barrel LYSO+SiPM	Endcap LGAD
Coverage	$\|\eta\| < 1.5$	$1.5 < \|\eta\| < 3.0$
Surface Area	$\sim$ 40 m^2	$\sim$ 12 m^2
Power Budget	$\sim$0.5 kW/m^2	$\sim$1.8 kW/m^2
Radiation Dose	$\leq$ 2e14 neq/cm^2	$\leq$ 2e15 neq/cm^2
Installation Date	2022	2024

A closer look into the chosen technologies

ETL - LGAD

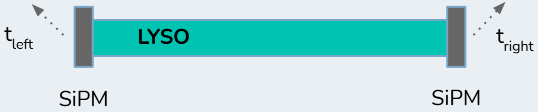


•Pad size: 1.3 x 1.3 mm^2

•High fill factor (>85% per layer)

•16624 sensors of 2x4 cm^2

BTL - LYSO + SiPM



•Lutetium-yttrium orthosilicate crystals activated with cerium
•active volume (per strip) = 3 × 3 × 57 mm^3

•SiPM active area = 9 mm^2,

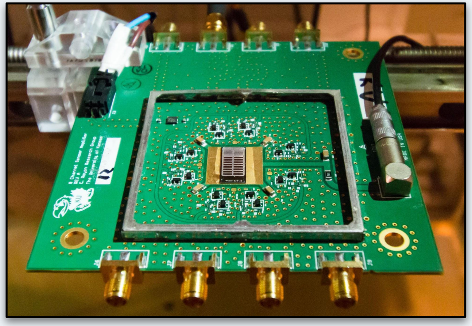
•SiPM light collection efficiency (LCE) ~ 15%

[1] Precision timing at CMS for HL-LHC - Artur Apresyan | TREDI 2017
[2] Test Platform for Automated Scan of Multiple Sensors - N.Minafra
[3] Timing detectors in the CMS experiment - T.Isidori

Current state and Results

Fast detectors for high rates

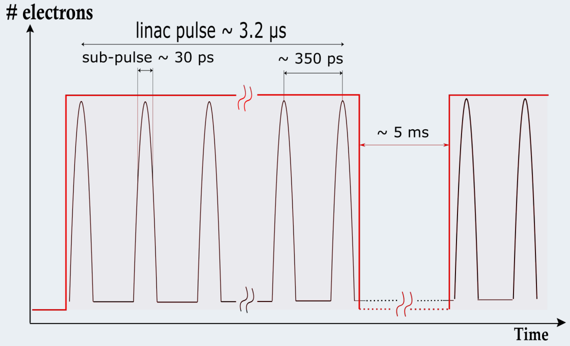
Many commercial (and research) applications require the use of fast detector for single particle resolution measurements. The ability to precisely count the number of incident particle per unit of time (without distortions due to long integration time or efficiency drop) represents an invaluable tool for evaluating **radiation doses, study beams luminosities, calculate the polarization of particle bunches**...

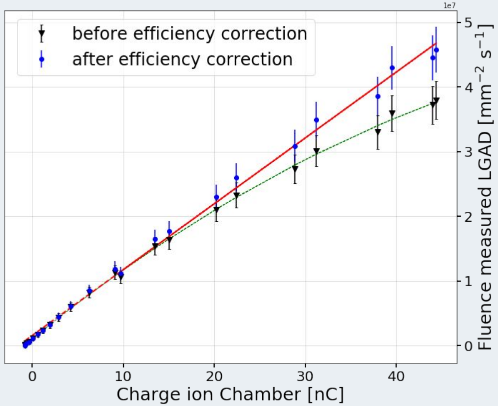


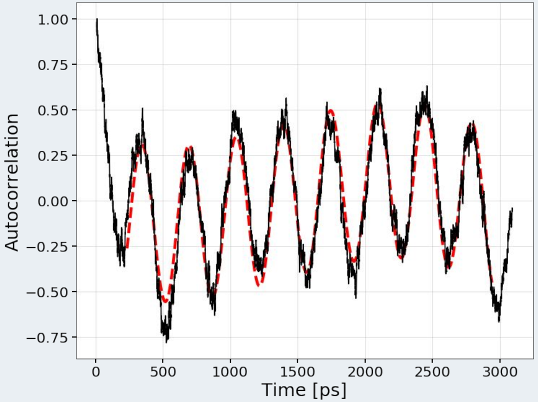
Example: monitor of a medical linac and characterization of the beam profile

Electronic board designed @ KU and characterized using a 50 μm UFSD

> Fast time integration of 5-10 ns
> Sensor's Area = 2.9 x 0.5 mm^2
> Time precision < 30 ps @ V_{bias} = 220V
> Tested with a 6 MeV electron beam
> Pulse repetition = 200 Hz
> Fine structure frequency is 2.858 GHz







Note:
The test works as a proof of concepts for single particle resolution in new generation fast timing detectors (up to **tens of MHz** with the setup displayed).
The loss of efficiency due to multiple clustered event can be corrected with the post-processing procedures.

T.sidori, P. McCavana, B. McClean, R. McNulty, N. Minafra, N. Raab, L. Rock, C. Royon - arXiv:2101.07134

03

A brave new world

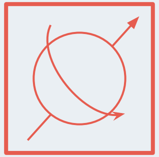
Timing detectors at the EIC

Every apparatus proposed for the final design of the EIC central detector include the use of fast and precise timing detector.

The TOF of particles produced in the central barrel can be key for an accurate discrimination between light hadrons. At the same time, the energy measurement would benefit from the use of the timestamps of the showers products in the calorimeter towers.

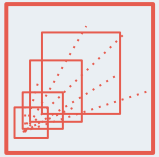
A last important subject that will be covered in the next section is the use of on-beam detectors to evaluate the polarization asymmetry of the beams.

Reminder: Timing detector Goals @ the EIC



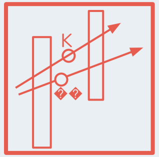
Polarimetry

The EIC facility will provide fully polarized e-ion beams [1]. The collision of polarized particles constrains the final state of the collision, which in turn helps in constraining the angular momentum of the interacting protons.



Calorimetry

The central detector designs proposed for the EIC incorporate in their apparatus fine segmented imaging calorimeters [2,4]. The design is completed by the use of timing detectors for improving the particle discrimination capabilities [3].



Particle ID with TOF

The central barrel is thought to be equipped with timing detectors for particle ID. Combined with a high-granularity tracking system, the studies of the difference in time-of-flight within the inner barrel provides a substantial aid in discriminating pions-kaons-protons[1].

[1] Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all
[2] M. Chadeeva -CALICE highly granular calorimeters: imaging properties for hadronic shower analysis
[3] José Repond -TOPSiDE: Concept of an EIC Detector
[4] SiD concept: http://www.linearcollider.org/P-D/ILC-detector-concepts/SiD

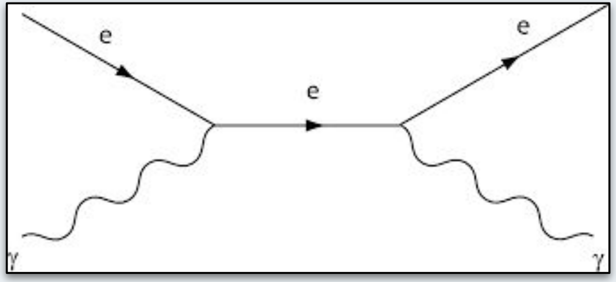
Polarimetry

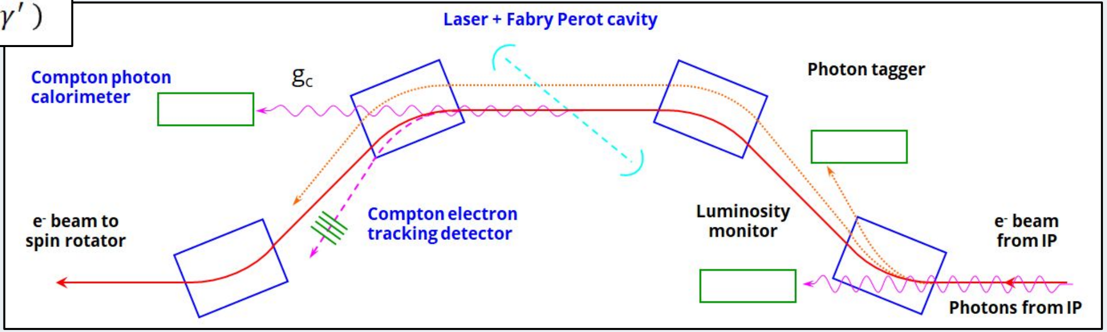
Compton polarimeters represent the best option for measuring the polarization asymmetry of high energy particle beams.

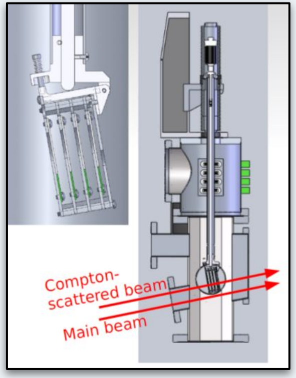
After every interaction @ the EIC, the level of polarization is verified using on-beam detectors. Starting from the photons polarization coming from the laser+Fabry Perot cavity (measurable) and estimating the predicted QED asymmetry, the apparatus constraints the electrons polarization:

$$\sigma(\vec{e} + \gamma \rightarrow e' + \gamma') \neq \sigma(\overleftarrow{e} + \gamma \rightarrow e' + \gamma')$$

[1]



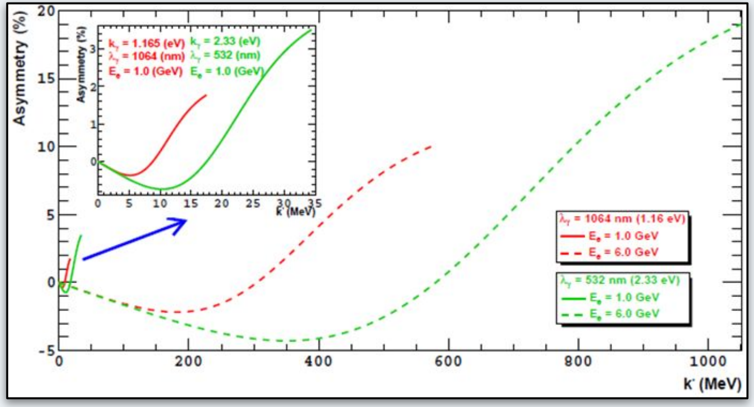




$$A_{EXP} \equiv \frac{N^+ - N^-}{N^+ + N^-} = \boldsymbol{P_e} * P_\gamma * A_{QED}(E_e, k_\gamma, k_{\gamma'})$$

Roman pots: solid state detectors (in the primary vacuum) approaching the beam using a movable support

Resolves the shape of the expected asymmetry by measuring the strip-by-strip asymmetry.
> Compton edge and zero needed to fit $\mathbf{P_e}$ to
$A_{measured} = P_e A_{theory}$



[1] N. Minafra- Precision Electron Polarimetry at EIC, July 18-22 2017

Polarizing the beams

Polarimetry

Let's take a look at some of the worst case scenario: High-Lumi @ EIC

High luminosity
560 MHz RF
1320 bunches
10 ns between bunches
Electron current up to 2.4 A
Ion current up to 0.92 A

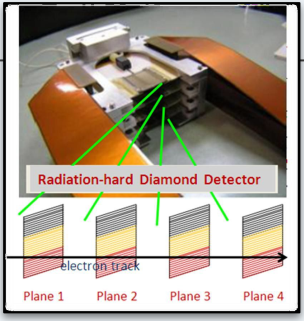
Note: Aiming for 1% or better electron polarization accuracy (and 0.5 % for parity violation program)

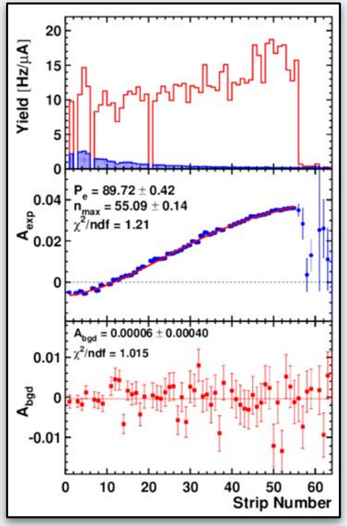
!! Need a fast, efficient and precise detector capable of single particle resolution for 10 ns spaced bunches (uniquely associate a detected particle with the correct bunch crossing) **!!**

Current technology [2]

The electron detector

> set of four diamond planes each with 96 "microstrips" of metal alloy etched on the Surface.
> Each strip is 0.180 mm wide separated by 0.02 mm.





[1] **...Fast**

> Single particle every bunch crossing per channel

> expected rate for 10 kW laser power >3 GHz per 5 cm^2

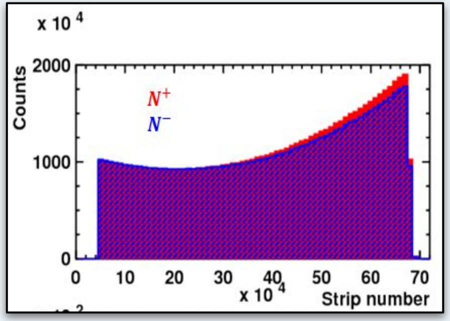
> Sensor, amplifier, digitizer, DAQ to be designed

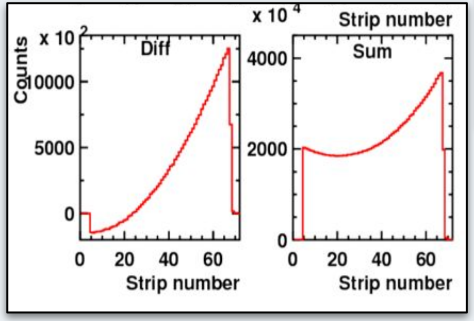
... And Precise

> Increased segmentation

> Less challenging detector requirements, but more channels

> Digitizer, DAQ to be designed

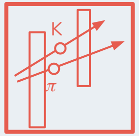




[1] N. Minafra- Precision Electron Polarimetry at EIC, July 18-22 2017

[2] A. Narayan et al. - Precision Electron-Beam Polarimetry at 1 GeV Using Diamond Microstrip Detectors

Particle ID with TOF



Multiple detector designs were proposed (BEAST,ePHENIX,TOPSIDE).
The scheme below, gathered from **[1]**, summarized layer by layer the technologies under study.

Design request

Pion/kaon/proton separation

Central barrel **$p_{hadrons}$ < 7 Gev/c**
Forward zone **$p_{hadrons}$ < 100 Gev/c**

Popular choices for the Major Subsystems

Vertex detector ⟶ Identify event vertex, secondary vertices, track impact parameters
Silicon pixels, e.g. MAPS

Central tracker ⟶ Measure charged track momenta
~~Drift chamber~~, TPC + outer tracker or Silicon strips

Forward tracker ⟶ Measure charged track momenta
GEMs, Micromegas, or Silicon strips

Particle Identification ⟶ pion, kaon, proton separation
Time-of-Flight or RICH + dE/dx in tracker

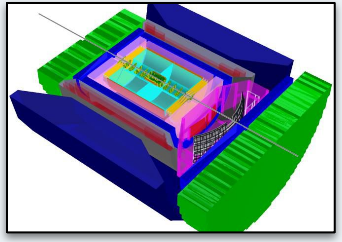
Electromagnetic calorimeter ⟶ Measure photons (E, angle), identify electrons
Crystals (backward), Shashlik or Scintillator/Silicon-Tungsten

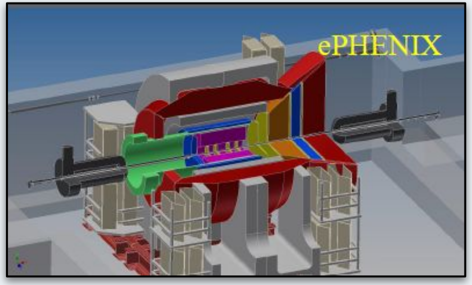
Hadron calorimeter ⟶ Measure charged hadrons , neutrons and K_L^0
Plastic scintillator or RPC + steel

Muon system ⟶ Identify muons as punch-throughs
Plastic scintillator or RPCs + yoke or none

+ Beam pipe, Solenoid, very forward and backward detectors

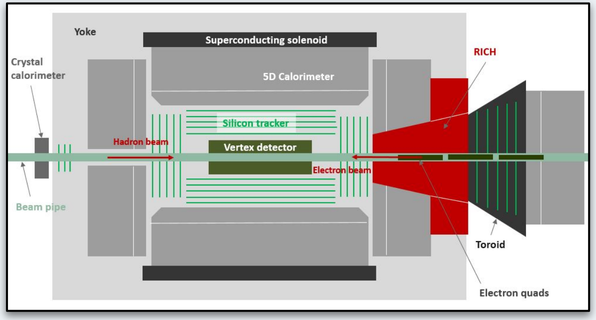
BEAST (Brookhaven eA Solenoidal Tracker)
Low momenta (p < 1 GeV/c)
>dE/dx in tracker or time-of-flight with **moderate resolution**
Intermediate momenta (1 < p < 3 – 4 GeV/c)
>Ring Imaging Čerenkov with Aerogel (n~ 1.05)





ePHENIX
RICH + DIRCs for particle ID
DIRC performances studied by eRD14 PID EIC

TOPSiDE
tracker + calorimeter equipped with timing
>Silicon sensors with time resolution of about 10 ps

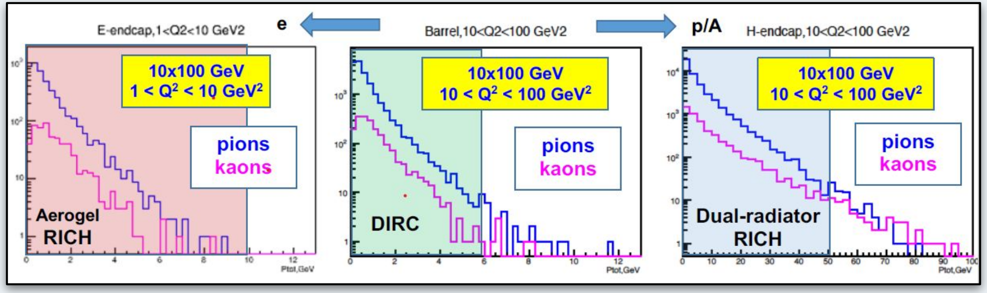


[1] José Repond- EIC Detectors: An Overview
13th International Workshop on high-pT Physics in the RHIC/LHC Era University of Tennessee, Knoxville, TN March 19 – 23, 2019

Particle ID with TOF

[1] Particle identification for a future EIC detector - Ilieva, Y.; Allison, L.; Barber, C.; Cao, T.; Del Dotto, A.; Gleason, C.; He, X.; Kalicy, G.; McKisson, J.; Nadel-Turonski, P.; Park, K.; Rapoport, J.; Schwarz, C.; Schwiening, J.; Wong, C. P.; Zhao, Zh.; Zorn, C.

In the 2018 publication [1], a combination of RICH, DIRC and a dual radiator RICH is simulated to evaluate the particle ID capabilities
> **e-endcap:** aerogel RICH with **TOF** (or dE/dx) for lower momenta
> **h-endcap:** combined gas and aerogel RICH to cover the full range with **TOF**
> **barrel:** a DIRC is the most compact and cheapest way to cover the full momentum range for the barrel area.



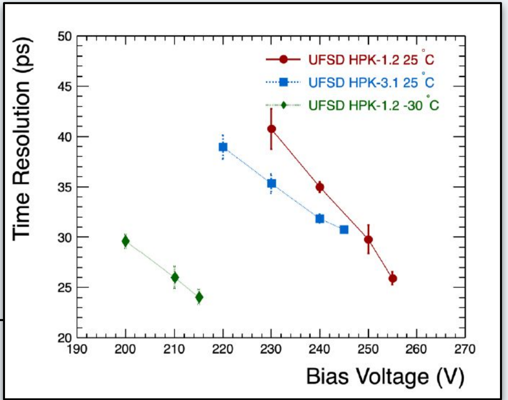
TOPSiDE LGAD

> Easier designed, inspired by the SiD collaboration
> Avoid the use of RICH, DIRC in the barrel (bulky and delicate)

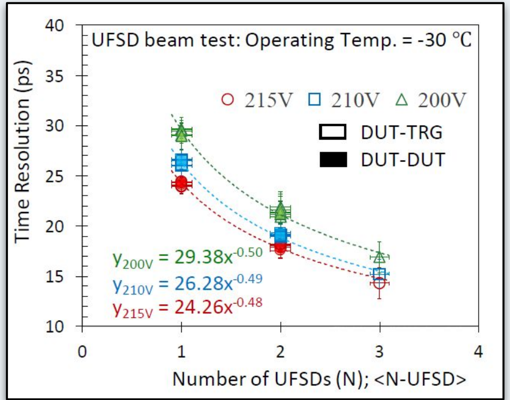
But…

energy resolution of single particles, timing resolution requirement for time-of-flight identification of hadrons, reconstruction of kinematical variables, and reconstruction of the F2 structure function…. Are achievable with **σ_t~ 10 ps !!**

TOPSiDE design
barrel (-3 < η < 3)
The electromagnetic section utilizes LGAD as active medium for the calorimeter (treated in the next section)
Forward region (3 < η < 5)
RICH counter provides particle ID for $\mathbf{p_{hadrons}}$ **10 - 50 GeV/c**
TOF with LGAD for $\mathbf{p_{hadrons}}$ **< 10 Gev/c**



[2]



Number of DUTs	UFSD Timing Resolution (ps)		
	V_{bias} = 240 V (T = 25 °C)	V_{bias} = 255 V (T = 25 °C)	V_{bias} = 215 V (T = -30 °C)
N = 1	35.1 ± 1.0	25.6 ± 0.5	24.2 ± 0.7
N = 2	25.0 ± 0.7	18.7 ± 1.1	18.0 ± 0.9
N = 3	-	14.7 ± 1.2	14.3 ± 1.5

[2] M. Jadhav, W. Armstrong, I. Cloet, S. Joosten, S. M. Mazza, J. Metcalfe, Z.-E.,Meziani, H.F.-W. Sadrozinski, B. Schumm, and A. Seiden - arXiv:2010.02499v3

Calorimetry

Each one of the detector designs encloses the entire solid inside the EM and Hadronic Calorimeters

While ePHENIX and BEAST employ most common technologies….

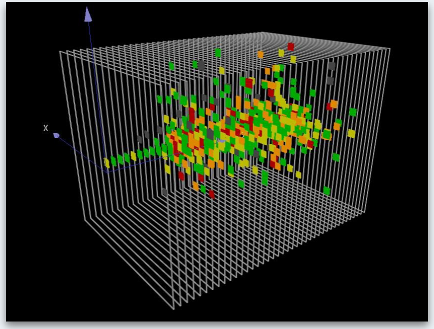
Electromagnetic calorimeter
($\eta < -2$) → $PbWO_4$ crystals with ~2%/√E energy resolution
($-2 < \eta < 3.5$) → Tungsten powder + scintillating fiber with 7 – 10%/√E
Hadron calorimeter
Scintillator plate + lead absorber with ~50%/√E (Not present in the barrel)

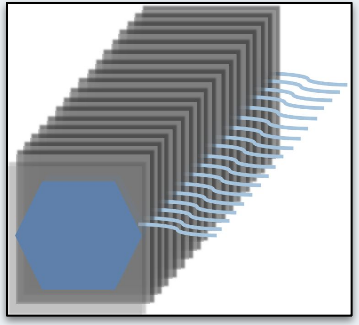
…TOPSiDE most innovative feature is the employment of:

5D Calorimetry

Very fine lateral and longitudinal granularity
10^7 channels

ElectroMagnetic Calorimeter
> Ultra fast silicon sensors (0.16 cm2 to 1.00 cm^2) + scintillator (4.5 x 0.5 cm^2)
Hadronic Calorimeter
> Scintillator pads (3 x 3 cm^2) + Resistive Plate Chambers (RPCs) with readout pads of 1 x 1 cm^2





Structure
20
layers
1 wafer/layer
Interleaved with tungsten (smallest Molière radius) plates
Data: position (x,y,z), precision time

Assumptions
8" wafers
Area ~ 324 cm 2
1 x 1 mm
2 pixels → 32,400 pixels/wafer
Total number of readout channels ~ 650,000

Advantages:
> The particle ID becomes trivial (from the precise shower reco shape)
> Software compensation
> Leakage corrections
> Gain monitoring
> Identification of underlying events
> Application of Particle Flow Algorithms

TOPSiDE combines imaging calorimetry with precision timing measurement to provide pion-kaon-proton separation.

Conclusions

>The effort of the physics community brought to the development of **increasingly more accurate timing detectors**.

> In order to explore new physics or study rare events, HEP facilities are forced to increase the delivered luminosities: need for **fast and radiation hard devices** to comply with the expected rates.

> **Precise timing detectors** are often an important tool to employ when the pile-up doesn't allow a simple simple 3D reconstruction.

> The timing precision requested for particle ID @ the EIC is **stringent (~10ps) but achievable**: new results on solid state detectors are promising.

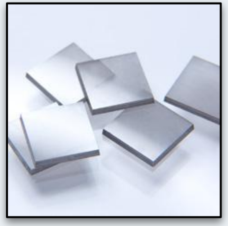
> The **sub-1% accuracy in the electron polarimetry** needed for the EIC operation at high lumi can be achieved improving the time integration and response of current detectors. The results presented (KU board) can work as a benchmark for detectors with single particle resolution in high rate environments.

Thank you for your attention!

Backup

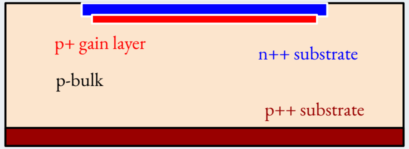
Principles of Operation

A bit of jargon and technicalities..



Chemical Vapor Deposition (sCVD) diamond

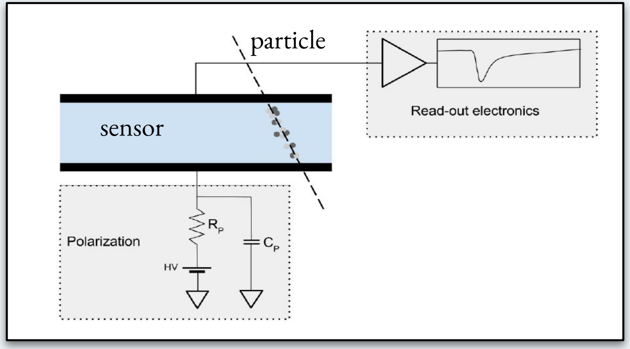
> low dielectric constant (low capacitance)
> high carriers mobility
> incredibly low dark currents
> The complicated production process limits the size to few mm^3
> intrinsically radiation hard

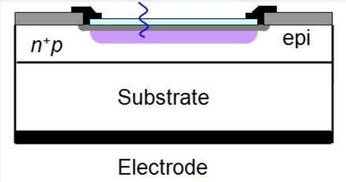


Low Gain Avalanche Diode (LGAD)

> low gain(compared to APDs) → necessity to add an additional gain layer
> fast rise time (dark currents' electron don't cause avalanche processes)
> low dark currents
> the thickness is substantially reduced (> 50 μm)
> Can be produced with Carbon insertion to reduce the radiation damages

Standard operation

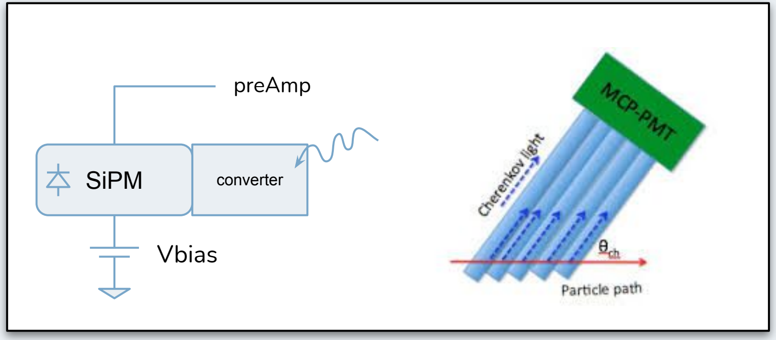


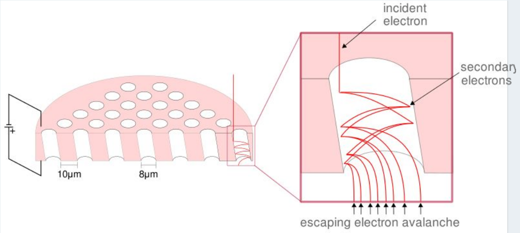


Silicon PhotoMultiplier (SiPM)

> Photo detection efficiency (PDE) ranges from 20 to 50%
> Gain ~ 10^6
> Low timing jitter
> not sensitive to external magnetic fields
> Small dimensions and low voltages required for bias

Standard operation





Multi Channel Plate (MCP)

> avalanche transit time ~100 ps range
> Gain ~ $10^4 - 10^8$
> fast rise time
> exceptionally low dark current < 0.5pA/cm2
> 0.4-3.0 mm thick plates
> up to ~1M channels/cm^2 of 5-15 m m diameter

Used in DIRC, RICH...

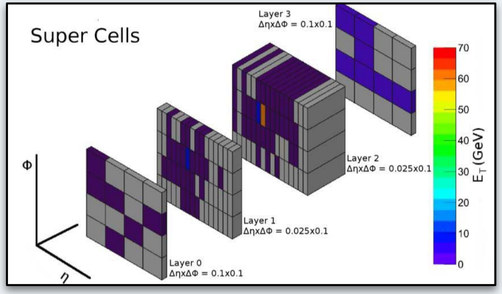
Current state and Results

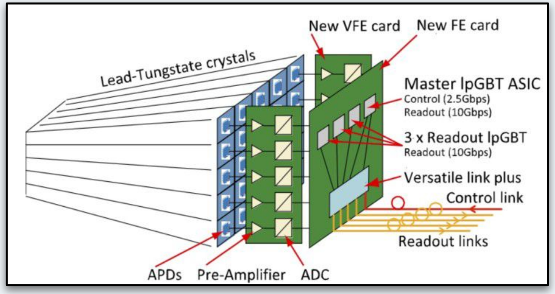
Timing in Calorimetry

When used together with the Energy reconstructed by a calorimeter tower, the time information provides a fundamental tool to **discriminate particles** in high rate environment.

Note: Whenever the granularity of the read-out allows a fine segmentation of the signal, the measurement takes the name of **5D reconstruction.**

The need for pileup mitigation in high-Luminosity facilities affects the design of experiments EM and Hadronic calorimeters.





Liquid Argon
Faster shaping
Reduced out-of-time pile-up
Better discrimination scintillation vs spikes
Faster rise time
timing resolution ~ 0.5 ns (high-energy tail)
bunch-crossing ID resolution << 25 ns

Lead-Tungstate crystal read by APD

Faster shaping
Reduced out-of-time pile-up
Better discrimination scintillation vs spikes
Faster rise time
30 ps timing resolution