Timing detectors at the EIC

New generation 4D reconstruction and polarimetry

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The timing era
why is the physics community investing in timing?

During the last decade, the increasing demands for detectors capable of accurate time resolution have propelled the physics community to invest time and resources in the upgrade and optimization of this technology.

The tests performed on timing detectors of proton colliders have proven their performance to be compatible with the high rates and radiation levels expected in High Energy Physics experiments.

Section 01 introduces the concept of timing detectors and highlights the similarities and differences with fast detectors.
Introduction: timing and 4D reconstruction

When we talk about "Timing detectors" we usually refer to detecting devices optimized to accurately reconstruct particle events when collected from the sensor.

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

\[ L \approx |t_{\text{start}} - t_{\text{stop}}| v \]

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

The precision of the measurement can be calculated as:

\[ \sigma_{\text{tot}} = \frac{1}{N} \cdot \sqrt{\sigma_{\text{det1}}^2 + \sigma_{\text{det2}}^2 + \ldots} \approx \frac{1}{\sqrt{N}} \cdot \sigma_{\text{det}} \]

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.
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 $\sigma \sim 10$ps.
- 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...
...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 that require detectors capable of high Background rejection for exclusive events, Time of Flight, 4D tracking, SD

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 beam) precise (to identify the hadrons generated from the interaction) timing detectors.
A casual guide to Timing

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

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

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

Example of...
... The dE/dx of a particle produces a current inside the active volume. The read-out electronics sample (if needed) the signal. A fast, high-bandwidth readout system is thus required.

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

Sensor

The choice of the sensor is the first important step for designing a particle detector. The current state of the art timing detectors are based on state-of-the-art sensors.

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

- $\mu > 1000$ cm$^2$/V.s High mobility of the carriers
- $v_s > 10^7$ cm/s - High saturation velocity
- $C_{sensor} \propto \varepsilon_0 \varepsilon_r (S/d)$ 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) the energy deposited by charged particles. The most common options are represented by the use of Quartz (Cerenkov) and scintillating polymers.
The sources of uncertainty of a timing measurement can be expressed adding in quadrature the contributing factors:

\[ \sigma_t^2 \sim \sigma_{\text{jitter}}^2 + \sigma_{\text{Landau}}^2 + \sigma_{\text{TimeWalk}}^2 + \sigma_{\text{Distorsion}}^2 \]

* 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).

The choice of a performing sampler directly influence the timing precision of the instrument. The precise timing 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**.

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

* With

\[
t_{\text{rise}} = \frac{0.35}{\text{Bandwidth}}
\]

**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.
Particle ID and TOF

In preparation for future High Luminosity facilities, many HEP experiments are aiming to include fast timing sensor for and identification. The request for pile-up removal for optimal discrimination pushed the research community in the development 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 2.12 mm
- Requirement: rate 5 MHz per channel

CMS Proton Precision Spectrometer

4 Layers of sCVD Diamond detectors
- Active area - 80 mm²
- 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

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

The CMS Precision Proton Spectrometer timing system: performance in future upgrades and sensor radiation hardness studies - E. Bossini
Particle ID and TOF

The CMS MIP Timing Layer

A closer look into the chosen technologies

<table>
<thead>
<tr>
<th>Coverage</th>
<th>Barrel LYSO+SiPM</th>
<th>Endcap LGAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Area</td>
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<tr>
<td>Power Budget</td>
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<tr>
<td>Radiation Dose</td>
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<tr>
<td>Installation Date</td>
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</tbody>
</table>

- Pad size: 1.3 x 1.3 mm²
- High fill factor (>85% per layer)
- 16624 sensors of 2x4 cm²

MIP Timing

Impact on the

> improved vertex reconstruction
> lepton reconstruction
> diphoton veto
> missing transverse momentum resolution
> reduction of backgrounds
Fast detectors for high rates

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

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 = $2.9 \times 0.5 \text{ mm}^2$
- Time precision < 30 ps @ $V_{bias} = 220\text{V}$
- Tested with a 6 MeV electron beam
- Pulse repetition = 200 Hz
- Fine structure frequency is 2.858 GHz

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**Note:**
The test works as a proof of concept of high particle resolution in new generation detectors (up to tens of MHz with tens of MHz bandwidths). The loss of efficiency due to multiple-electron signals can be corrected with the post-processing procedures.

A brave new world

Timing detectors at the EIC

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

The TOF of particles produced in the central detector is crucial for an accurate discrimination between like particles. Simultaneously, the energy measurement would benefit from the use of the timestamps of the showers produced by the particles in the calorimeter towers.

A last important subject that will be covered in this section is the use of on-beam detectors to measure 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...
The central barrel is thought equipped with timing detectors for particle ID. Combined high-granularity tracking studies and timing of the difference in time for charged particles within the inner barrel provide substantial aid in discriminating particles-kaons-protons.

[1] Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all
[3] José Repond -TOPside: Concept of an EIC Detector
Polarimeters represent the best option for measuring the polarization asymmetry of high energy particle beams. After every interaction at the EIC, the level of polarization is verified using on-beam detectors. Starting from the photons polarization laser + Fabry Perot cavity (measurable) and estimating the predicted QED asymmetry, the apparatus constraints the electrons polarization.

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

**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 $P_e$ to $A_{\text{measured}} = P_e A_{\text{theory}}$

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

!! 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) !!

...Fast
> Single particle every bunch crossing per channel
> expected rate for 10 kW laser power >3 GHz per 5 cm²
> Sensor, amplifier, digitizer, DAQ to be designed

...And Precise
> Increased segmentation
> Less challenging detector requirements, but more channels
> Digitizer, DAQ to be designed

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

** 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^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

** TOPSiDE **

- Tracker + calorimeter equipped with timing
  - Silicon sensors with time resolution of about 10 ps


13th International Workshop on high-pT Physics in the RHIC/LHC Era University of Tennessee, Knoxville, TN March 19 - 23, 2019
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.

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**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 $\sigma_t \approx 10\, \text{ps}$ !

**TOPSiDE design**

**barrel** (-3 < $\eta$ < 3)
- The electromagnetic section utilizes LGAD as active medium for the calorimeter (treated in the next section)

**Forward region** (3 < $\eta$ < 5)
- RICH counter provides particle ID for $p_{\text{hadrons}}$ 10 - 50 GeV/c
- TOF with LGAD for $p_{\text{hadrons}}$ < 10 GeV/c

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[1] Particle identification for a future EIC detector - Ilieva, Y.; Allison, L.; Barber, C.; Cao, T.; Del Dotto, A.; Glebe, M.; McKisson, J.; Nadel-Turonski, P.; Park, K.; Rapport, J.; Schwarz, C.; Schwiening, J.; Wong, C. P.; Zhao, Z.; Zor; PRL 2018

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...

...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 cm^2 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](image)

**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 cm²
- 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 sampling)
- Software compensation
- Leakage corrections
- Gain monitoring
- Identification of underlying events
- Application of Particle Flow Algorithms

TOPSiDE combines imaging calorimetry with precision 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 and hence 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 at 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
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

**Silicon PhotoMultiplier (SiPM)**
- Photo detection efficiency (PDE) ranges from 20 to 50%
- Gain $\sim 10^6$
- Low timing jitter
- not sensitive to external magnetic fields
- Small dimensions and low voltages required for bias

**Multi Channel Plate (MCP)**
- avalanche transit time $\sim$100 ps range
- Gain $\sim 10^4 - 10^8$
- fast rise time
- exceptionally low dark current $<0.5\text{pA/cm}^2$
- 0.4-3.0 mm thick plates
- up to $\sim 1\text{M channels/cm}^2$ of 5-15 mm diameter

Used in DIRC, RICH...
Timing in Calorimetry

When used together with the Energy reconstructed by a calorimeter tower, the time information provides a fundamental tool to distinguish events 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 information.

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