Radiation field characterization and particle tracking with Timepix3 in ATLAS and MoEDAL

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- Data-driven readout scheme with up to 40 MPix/cm²/s (per pixel dead-time: 475 ns)
- Simultaneous measurement of energy (ToT) and time of arrival (ToA) in each pixel
- Energy resolution: ~1.4 keV (sigma) @ 60 keV (in silicon)
- **Time binning: 1.56 ns**
- Minimal detectable energy: ~ 2.5 keV
Solid-state Time-Projection Chamber: 3D reconstruction of particle tracks

Charge carrier drift motion:
e\(^-\) and h\(^+\) drift described by

\[ v_e = -\mu_e \times E(z) \]
\[ v_h = \mu_h \times E(z) \]

\(\mu_{e/h}\): Mobility of e\(^-\)/h\(^+\)

Electric field parametrization:

Si:

\[ \vec{E}(z) = \frac{U_B}{d} \vec{e}_z + \frac{2U_{dep}}{d^2} \left( \frac{d}{2} - z \right) \vec{e}_z ; \]

CdTe:

\[ \vec{E}(z) = \frac{U_B}{d} \vec{e}_z \]

\(U_B\): Bias voltage; \(U_{dep}\): Depletion voltage; \(d\): Sensor thickness

→ Look-up table: \(z(t_{\text{meas.}}, E_{\text{meas.}})\)

Test measurement: 500 µm thick silicon sensor

120 GeV/c pion tracks accompanied by δ-rays:

z-resolution:
\( \sigma_z \sim 30 \, \mu m \)
\( \Delta z_{syst} \sim 25 \, \mu m \)

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Test measurement: 2 mm thick CdTe sensor

- e+/− like event
- pair production (!?)
- cosmic µ
- fragmentation

z-resolution: $\sigma_z \sim 60 \, \mu m$
→ Improved determination of track directions
→ Improved separation of different particle classes

Timepix3 in MoEDAL

Installation of 2 Timepix3 detectors in MoEDAL in September 2018.

MoEDAL = Monopole and Exotics Detector At LHCb

Timepix3 are placed at 1.1 m distance to IP8

Timepix3 have 500 µm thick silicon sensor layers. Data are available mainly for November/December 2018 Pb ion runs.
Timepix3 in MoEDAL: November 24 – 25, 2018
Cluster rate as a function of time

Integration time: 100 s
Integration time: 1 s

Bunch train injections?
Timepix3 in Moedal:
Radiation field characterization – during collisions

Basic categorization of tracks using the ratio of energy per track and the number of pixels

Region 1:
Lowly ionizing particles ($\gamma$, $e^-$, $\pi^+$, $\mu^+$, ...)

Region 2:
Highly ionizing particles: $p +$ (E < 100 MeV), ions...
Timepix3 in Moedal: Directionality map

Primary peak:
Particles ($p^+, \mu, \pi, \ldots$) from the IP

Secondary peak(s):
Particles ($p^+, \mu, \pi, \ldots$) from collimators / beam pipe (?)
Timepix3 in MoEDAL: Directionality map

Particles from IP ($\Theta > 30$, $\phi$ in [90,180])

- $dE/dX_{MPV} \sim 1.18$ MeV cm$^{-2}$ g$^{-1}$
  - Particle with charge 1
- $dE/dX_{MPV} = 11$ MeV cm$^{-2}$ g$^{-1}$
  - Charge $\sim 3$
- $dE/dX_{MPV} \sim 42$ MeV cm$^{-2}$ g$^{-1}$
  - Charge $\sim 6$
Timepix 3 in MoEDAL: Directionality maps – During and after collision period(s)
Timepix3 in MoEDAL: Comparison of the directionality maps during pp- and PbPb-collision periods

Secondary peaks only seen during Pb-runs.

pp-collision period on September 24, 2018

Pb-run on November 25, 2018
**Timepix3 in ATLAS: Positions and goals**

**2017:** 2 Timepix3 (position TPX3-2) detectors were installed far away from the IP
- Time resolved study of radiation created in the collimators

**2018:** 2 Timepix3 detectors were installed on the extended barrel to study their capabilities
- Study the radiation fields during and after collision periods
- Measure the luminosity

**LHC Run-3 upgrade:** Installation of 13 Timepix3 two-layer stacks synchronized with LHC orbit clock
- Bunch-by-bunch absolute (?) luminosity measurement
Primary and secondary radiation created during pp-collisions (neutrons, γ-rays, electrons, charged particles)

Induced radioactivity (γ and e−)
Directionality map:

Primary and secondary radiation created during pp-collisions (neutrons, \(\gamma\)-rays, electrons, charged particles)

Induced radioactivity (\(\gamma\) and e\(^{-}\))
**Timepix3 in ATLAS:**

Equation to describe the growth and decay of induced radioactivity

\[
M_{\text{act}}^i = \sum_{k=1}^{n} M_{\text{act}}^{i-1,k} \times e^{-\lambda_k t} + (M_{\text{tot}}^i - M_{\text{act}}^{i-1}) \times \theta (M_{\text{tot}}^i - M_{\text{act}}^{i-1}) \times \sum_{k=1}^{n} Y_k \times (1 - e^{-\lambda_k t})
\]

Decay of atoms activated before i-th time bin

Activation during i-th time bin (valid only during collisions)

- \(M_{\text{tot}}\): total count rate measured in the given TPX frame (normalized to unit time)
- \(M_{\text{act}}\): count rate caused by all activation products
- \(\lambda\): decay constant, \(\lambda = \ln(2)/T_{1/2}\); \(T_{1/2}\) is the half-life
- \(t\): time period between the end of \((i-1)\)-th bin and the end of \(i\)-th bin
- \(Y_k\): normalization constant, used to fit the growth/decay curve to the measured data
Timepix3 in ATLAS: Measurement of the induced radioactivity in the ATLAS cavern

- Measured
- Total activation
- Components

Count rate (s⁻¹)

Day in 2018

17.05 18.05 19.05 20.05 21.05
Conclusion

- Timepix3 detectors were installed in ATLAS and MoEDAL and used to characterize the charged particle fields.
- Their particle tracking capability and the possibility to separate different particle species was used to study particle directions and trace them back to the interaction points.
- The creation and decay of radioisotopes was described by a model and applied to the data allowing the identification of few created radioisotopes.

Thank you very much for your attention!
Timepix3 in ATLAS: Identification of radioisotopes

Determined half-lifes are not sufficient to really indicate which isotope was present. What about the energy spectrum?

Compton edge at 338 keV ($E_\gamma \sim 511$ keV) with $T_{1/2} \sim 47305$ s → From $\beta^+$ decay of $^{64}$Cu*

Peak at 24 keV with $T_{1/2} \sim 16548$ s → From $^{115m}$In **

*) $^{64}$Cu can be created by: $^{63}$Cu(n, $\gamma$)$^{64}$Cu

**) $^{115m}$In can be created by: $^{115}$In (n, n')$^{115m}$In
Using filtering on track properties events of interest can be filtered out of the data set.

Minimum Ionizing Particles (MIPs) were selected using linearity criterion.

Timepix3 in ATLAS: Measurement of MIP fluence and particle directions

Unfiltered data set: 10 s integration time

Selected straight tracks: 10 s integration time

Directionality map of MIPs:

Pb-run on November 25 (line with indicates intensity):
- The primary peak points back to IP8.

pp-collision period on September 24
(backprojection of the bin with the highest number of events).
**Methodology verification and precision**

**Experiments:**
- Pion test beams (120 GeV/c, 40 GeV/c) at the Super-Proton-Synchrotron at CERN
- Cosmic muons

"Raw data": Detector response in the form of 2D projections. 500 µm thick silicon
Test beam measurement (40 GeV/c pion beam):
2 mm thick CdTe sensor

Charge collection efficiency correction:
Energy correction: \( E_{\text{corr},i} = \frac{E_{\text{meas},i}}{\varepsilon_{\text{cc}}(z)} \)
\( \varepsilon_{\text{cc}}(z) \) was determined in the measurement

\[
\frac{dE}{dX} = 2.71 \text{ MeVcm}^2/\text{g}
\]

Achieved z-resolution \( \sim 60 \mu \text{m} \)

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Test beam measurement (40 GeV/c pion beam):
2 mm thick CdTe sensor – e⁻/⁺ like events

$E_{\text{dep}} = 5.66$ MeV

$E_{\text{dep}} = 1.56$ MeV

$E_{\text{dep}} = 3.96$ MeV

Pair-production (!?):

$E_{\text{dep}}$: Total energy deposition in the CdTe sensor layer.
Test beam measurement (40 GeV/c pion beam):

2 mm thick CdTe sensor – Fragmentation

\[ E_{\text{dep}} = 37.06 \text{ MeV} \]
Impact and applications

- **Life-sciences:**
  - Single layer Compton camera (→ Search for γ radiation sources) [1]
  - Secondary particle tracking in hadron therapy

- **Space weather:**
  - Measurement and separation of e⁻/p⁺ (and their directions) in the Van-Allen Radiation belts [2]
  - Measurement of particles in Solar Particle Events

- **Applications in nuclear and particle physics**
  - Particle tracking and radiation field characterization (ATLAS, MoEDAL)
  - Vertex reconstruction and angular correlation measurements
  - Double beta decay experiments (?!?!) [3]

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