

Experimental validation of an Allpix2-based simulation chain for Timepix3 photon detection in tokamak runaway-electron research

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Introduction

Hybrid pixel detectors such as Timepix3 simultaneously measure deposited energy, interaction position, and arrival time, making them well suited for diagnostics in intense radiation environments. Their high spatial resolution and cluster-shape analysis provide information on detected radiation, which is useful for runaway electron studies in tokamaks, where bremsstrahlung photons serve as an indirect diagnostic.

The applicability of pixel detectors in tokamak environments has been demonstrated on several devices. Timepix3 has been used as a hard X-ray diagnostic on the GOLEM [1, 2, 3] and COMPASS [3] tokamaks, while other hybrid pixel systems include the PILATUS3 detector for soft X-ray measurements on WEST [4] and CdTe-based hard X-ray camera systems on TORE SUPRA [5], TCV [6], COMPASS [7], and HL-2 [8]. To quantitatively interpret Timepix3 measurements in such environments, a simulation framework must link the incident photon field to detector observables, including photon transport, charge generation, signal formation, threshold effects, and digitization. This is important for runaway electron diagnostics, where the measured spectra depend on both the source characteristics and the detector response.

In this work, we develop and experimentally validate an Allpix Squared-based simulation framework for Timepix3 silicon detectors, benchmarked against laboratory ²⁴¹Am measurements with good agreement in detector response. The framework is then extended to tokamak-relevant conditions by incorporating bremsstrahlung sources from runaway-electron distributions, enabling studies of detector response in realistic tokamak environments.

AdvaPix Timepix3 Detector

The AdvaPix Timepix3 module (Fig. 1) consists of a silicon or CdTe sensor segmented into 256×256 pixels with a pitch of 55 μm , each acting as an independent spectroscopic channel. The detector provides a time resolution of 1.5625 ns and a maximum readout rate of approximately 40 million pixels per second [9]. The sensor is coupled to the Timepix3 readout chip [10], fabricated in 130 nm CMOS technology.

The event readout principle is illustrated in Fig. 2. In each pixel, the signal generated by an interacting particle is amplified and compared with a threshold. When the threshold is exceeded,

the event is registered and the time of arrival (ToA) and time over threshold (ToT) are recorded. The ToA provides timing information with the precision of the system clock, while the ToT is proportional to the collected charge and can therefore be used to compute the deposited energy. The recorded data are read out from the pixel matrix by the detector electronics.

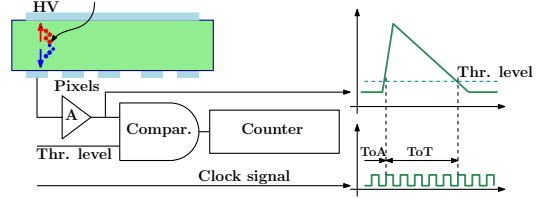


Figure 1: AdvaPix Timepix3 detection module. Figure 2: Schematic representation of sensor event readout.

Measurements

The Timepix3 detector with a 300 μm thick silicon sensor was temperature-stabilized at 20; $^{\circ}\text{C}$, which is also the temperature used during calibration. This paper presents measurements with an ^{241}Am ionizing radiation source, while additional measurements were performed with ^{22}Na , ^{55}Fe , ^{57}Co , ^{60}Co , ^{109}Cd , ^{137}Cs , ^{210}Pb , and ^{238}Pu . The ^{241}Am spectra obtained using clustering are shown in Fig. 3 (left), with the single-pixel spectra shown on the right.

The energy spectrum exhibits peaks at 59.54 keV, 33.196 keV, and 26.34 keV, originating from the decay of ^{241}Am via its daughter nuclide ^{237}Np , formed in its alpha decay. The 13.759–20.784 keV interval contains characteristic L-series X-ray lines of ^{237}Np , with reference energies from [11]. A low-energy threshold is present at ~ 3 keV, where some registered interactions may lack physical origin. The spectra also show slight geometry-dependent variations (front, back electrode side, lateral incidence), likely due to charge diffusion during collection at the readout electrodes. Overall, the measurement demonstrates the ability to resolve characteristic spectral features and confirms correct detector calibration.

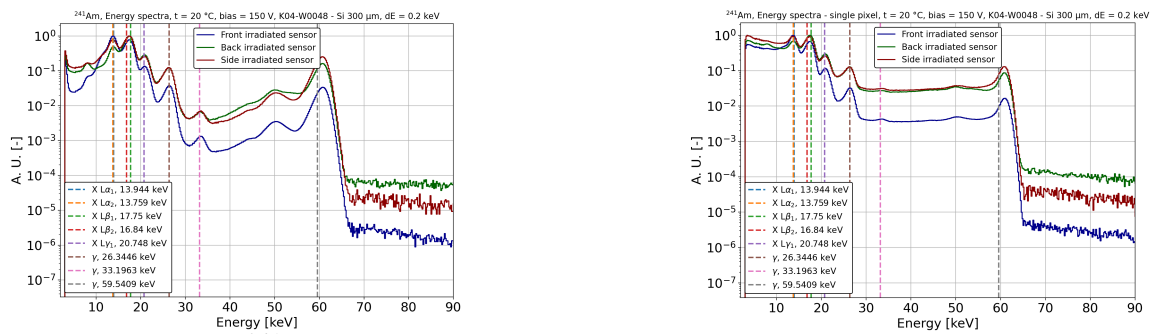


Figure 3: Spectra of ^{241}Am normalized to the $L\beta$ peak, shown for clustered events (right) and single-pixel events (left), for irradiation from top, back (readout electrode side), and side.

Simulations

Photon interactions with the Timepix3 silicon sensor were simulated using the Allpix Squared framework [12], which provides detailed modeling of primary particle interactions, charge car-

rier generation and transport, and readout electronics response. Photon interactions were calculated with the Geant4 radiation transport code. A linear electric field profile was assumed, derived from a bias voltage of $V_{\text{bias}} = 150 \text{ V}$ and an estimated depletion voltage of $V_{\text{depletion}} = 70 \text{ V}$.

The deposited charge carriers were modeled using the GenericPropagation module, and the resulting propagated charge was integrated via the PulseTransfer module. No standard digitization modules were utilized within the simulation chain; instead, the raw propagated charge from each pixel was exported and post-processed using custom Python scripts to handle clustering and thresholding applications.

As a benchmark, the response of the Timepix3 sensor to photons from an ^{241}Am source was simulated. To compare the results with experimental data, the simulated response was convolved with a Gaussian kernel to approximate the intrinsic energy resolution of the detector. The comparison, shown in Fig. 4, demonstrates fairly good agreement despite the simplified detector geometry and idealized photon source used in the simulation. Minor discrepancies in the peak shapes are attributed to the absence of a proper representation of the digitization module.

To investigate the suitability of a $300 \mu\text{m}$ thick Timepix3 silicon sensor, interactions of bremsstrahlung photons generated by electron impact were simulated. Four runaway-electron energy distributions were assumed, and the corresponding bremsstrahlung spectra were calculated using the thick-target approximation. These spectra were implemented as a primary particle source in Allpix Squared using a Geant4 source macro.

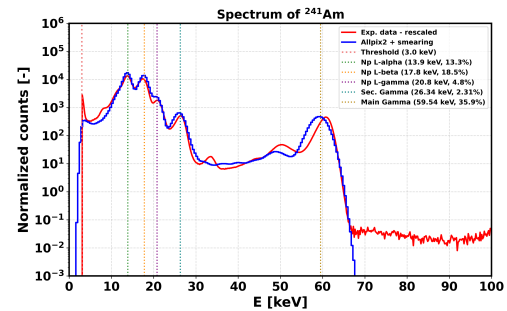


Figure 4: Comparison of simulation and experimental measurement.

The initial bremsstrahlung spectra are shown in Fig. 5, and the simulated spectra recorded by the Timepix3 sensor are presented in Fig. 6. From the recorded spectra, it can be observed that despite significant differences among the initial bremsstrahlung distributions—particularly for cases where the runaway electron energies reach up to 1 MeV —the resulting spectra recorded by the sensor exhibit remarkably similar profiles.

Such results are expected, confirming the fact that a $300 \mu\text{m}$ thick silicon sensor is nearly transparent to higher photon energies. This characteristic limits the suitability of such sensors for spectroscopic studies of runaway electrons, even on small-scale tokamaks such as GOLEM, where runaway electron energies can reach up to 1 MeV .

Despite the loss of spectroscopic capability at these energies, the detectors could still be used for photon flux measurements due to their superior performance in high-flux environments.

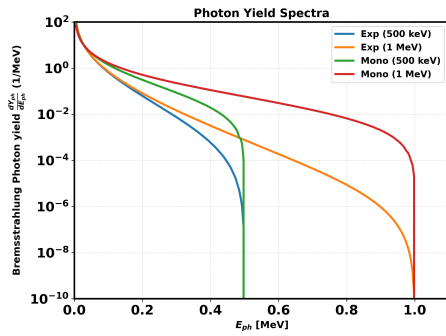


Figure 5: Calculated bremsstrahlung spectra used as the simulation input.

Conclusion

Benchmark measurements performed with the Timepix3 detector equipped with a 300 μm thick silicon sensor confirmed its reliable spectroscopic performance for laboratory gamma-ray sources. Spectroscopic measurements using a range of radioactive isotopes, with the ^{241}Am results presented here as a representative example, demonstrated the accuracy of the detector calibration and its stable spectroscopic response. These measurements validate the detector response and provide an experimental benchmark for the simulation framework used to assess detector performance in tokamak-relevant radiation fields.

Current studies indicate that a 300 μm thick Timepix3 silicon sensor is suboptimal for runaway-electron spectroscopy in tokamaks due to its limited stopping power and low detection efficiency for high-energy photons. While it remains suitable for basic photon flux measurements, detailed spectral analysis requires greater sensitivity. Future work will therefore investigate alternative sensor configurations, in particular thicker silicon sensors and high-Z materials such as CdTe, to assess their suitability for advanced runaway electron diagnostics.

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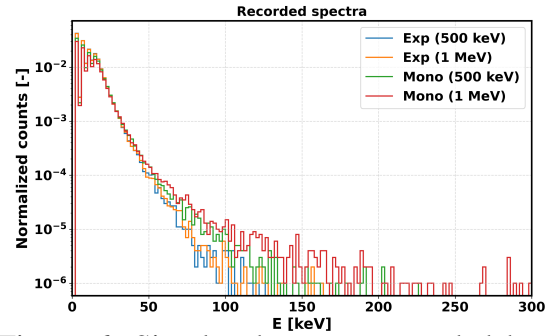


Figure 6: Simulated spectra recorded by the Timepix3 sensor.