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Assessment of Low Gain Avalanche Detector Response for Ultra-High Dose Rate Proton Beam Monitoring in LhARA

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Can LGADs provide fast beam monitoring under FLASH Proton therapy conditions?

Simulation Results Demonstrate Fast Transient Response and Precise Spatiotemporal Charge Tracking Under Ultra-High Dose Rates.

1. FLASH Radiotherapy?

- Ultra-high dose rate delivery ($\geq$ 40 Gy/s) in less than 100 ms.
- Sparing of healthy tissues with equal tumor control effectiveness.
- Transient tissue hypoxia driven by rapid local oxygen depletion.

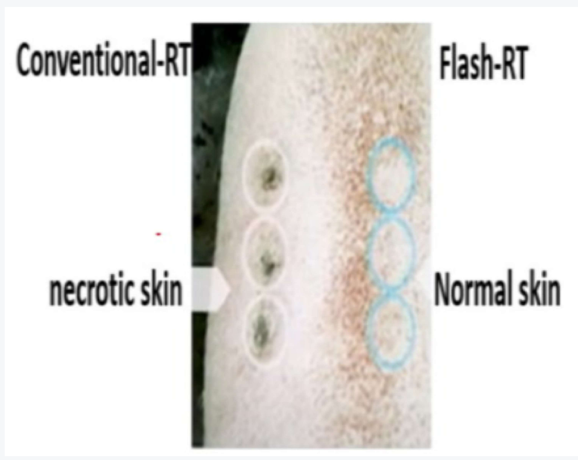

Figure 1: Comparative study on mini pigs skin (Conventional RT vs. FLASH RT).

2. Dosimetry Challenges

- **High Ion Recombination:** Ionization chambers suffer from severe volume recombination at ultra-high dose rates.
- **Detector Saturation:** Standard dosimeters exhibit rapid saturation under high-dose-rate proton pulses.
- **Ultrafast Time Resolution:** Sub-nanosecond response is required to resolve intra-pulse structure.
- **Radiation Hardness:** Detectors must withstand high particle fluxes.
- **High Spatial Resolution:** Fine Spatial Granularity for precise proton beam dosimetry.

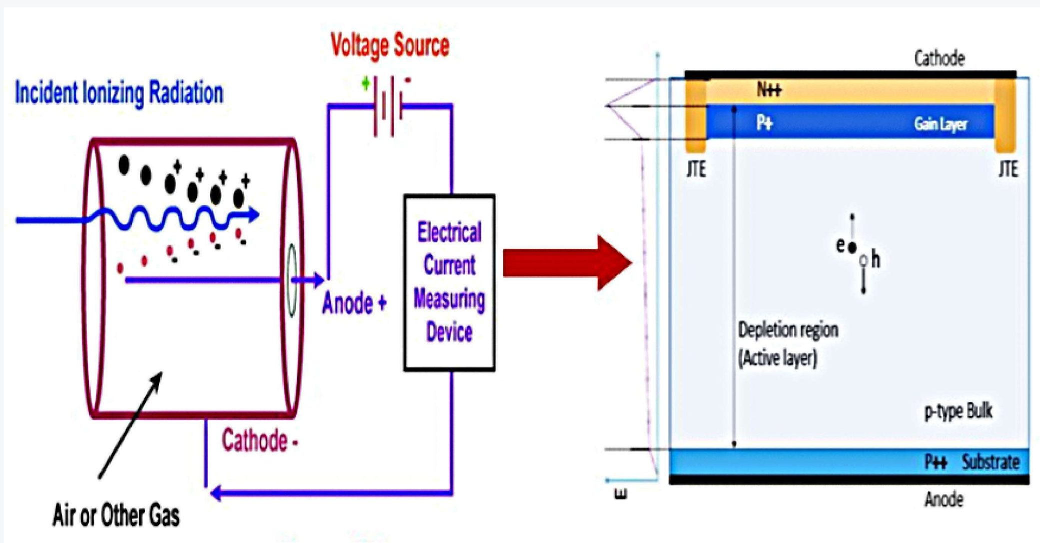

Figure 2: Dosimetry challenges under UHDR FLASH conditions.

3. LhARA Beamline

- **Dedicated R&D Facility:** LhARA is designed for operation at and beyond UHDR FLASH conditions.
- **Unique Particle Beams:** Delivers proton and ion beams with nanosecond pulse structures.
- **In-Vitro & In-Vivo Capabilities:** Enables multi-physics and radiobiological experimentation.
- **FLASH Advancement:** Provides ideal UHDR conditions to explore and optimize FLASH proton therapy.
- **Key Challenge:** LhARA beam parameters require ultra-fast radiation detectors.

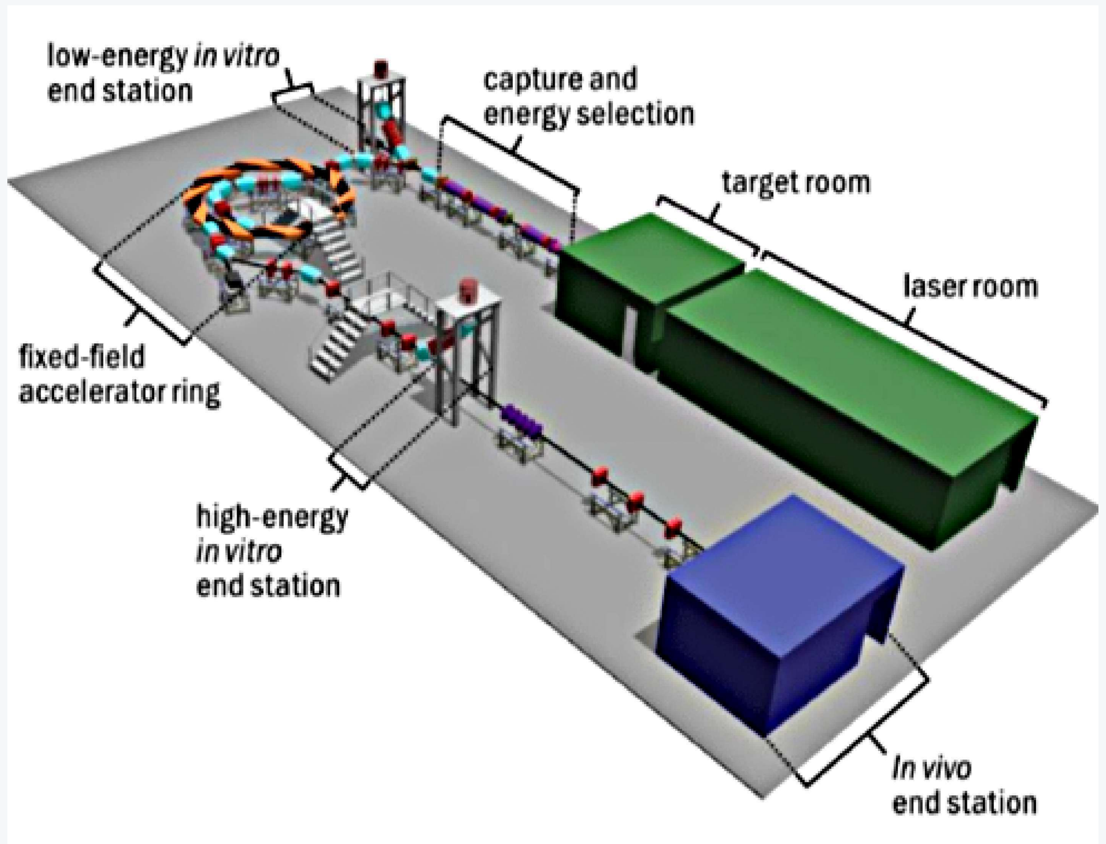

Figure 3: Schematic diagram of the LhARA beam lines.

4. Monte Carlo Dosimetric Study

Objectives & Setup:

- **Framework:** BDSIM & Geant4 Monte Carlo toolkit for high-precision particle transport simulations.

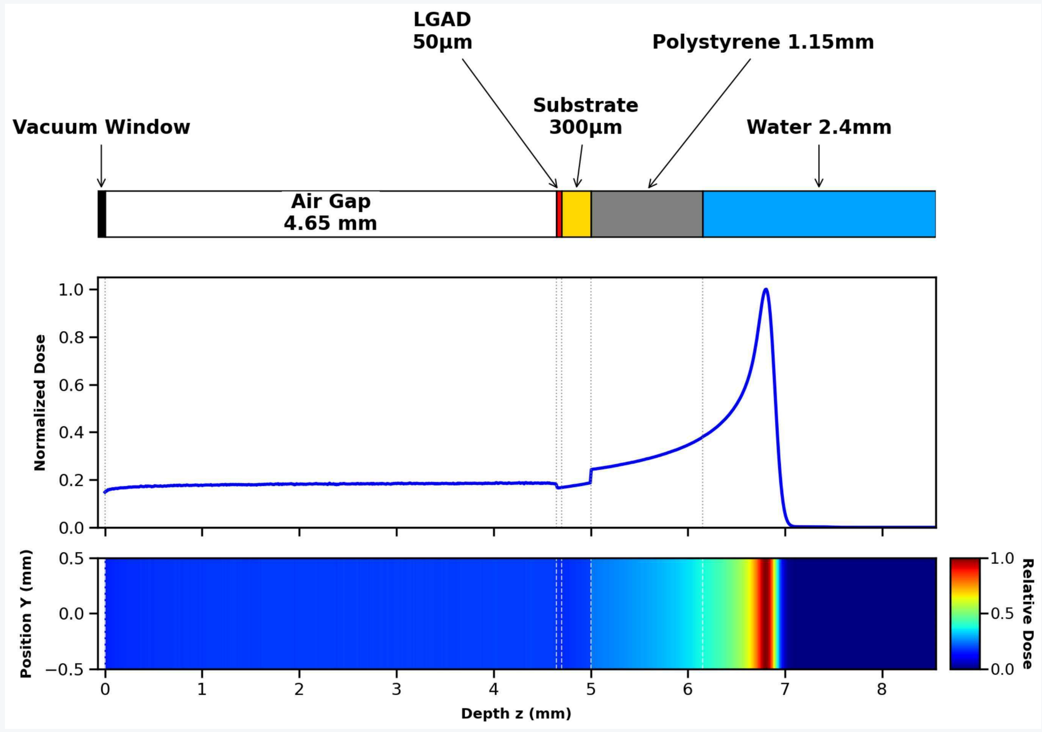

Figure 4: Simulated depth-dose profile across target beamline components.

Key Findings:

- **Minimal Beam Perturbation:** Confirms negligible beam scattering and energy attenuation induced by thin LGAD sensors.

5. TCAD Simulation

Device Structure & Modeling:

- **Doping Profiles:** High-precision Boron (P-type gain layer) and Phosphorus (N-type contact) implantation profiles.
- **Physical Models:** Includes concentration-dependent mobility, Shockley-Read-Hall (SRH) recombination, and Impact Ionization (Van Overstraeten models).

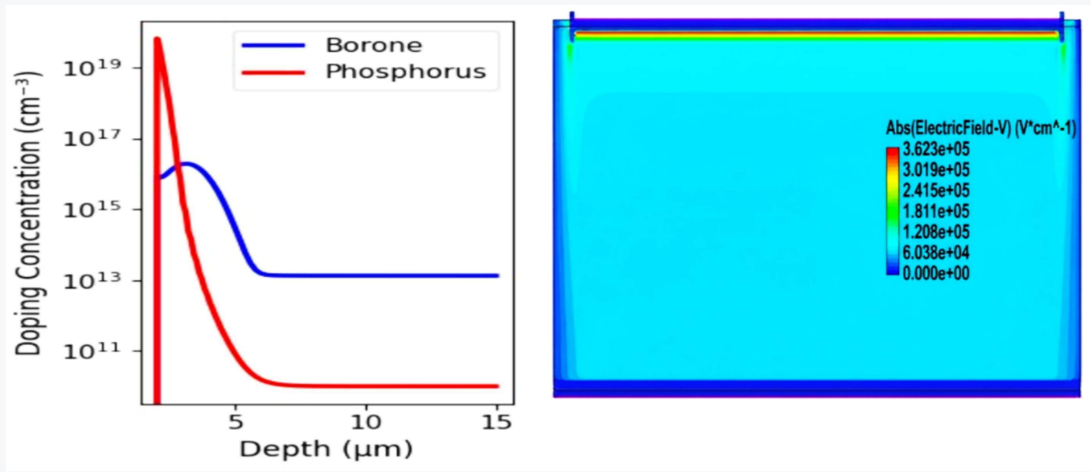

Figure 5: Doping profiles in the LGAD Gain Region (left) and 2D Electric Field Distribution (right).

6. Simulation Results

Charge Generation & Transport Dynamics:

- **Framework:** Allpix Squared Monte Carlo framework was used to simulate charge propagation and collection dynamics.
- **Impulse Response:** Fast charge collection driven by high internal electric fields.

Induced Current Calculation (Ramo-Shockley Theorem):

$$Q_n^{\text{ind}} = \int_{t_0}^{t_1} I_n^{\text{ind}}\, dt = q\left(\phi(x_1) - \phi(x_0)\right)$$

Where: $\phi(x)$: weighting potential at position x.

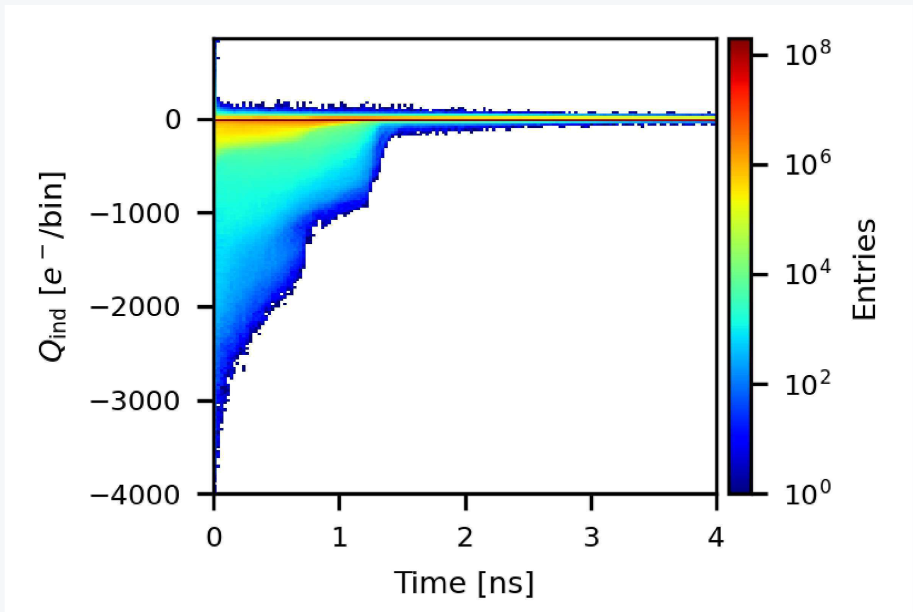

Figure 6: 2D transient induced charge distribution per pixel.

Temporal Charge Accumulation Analysis:

- Evaluation of the time-dependent response during high-flux proton pulses.

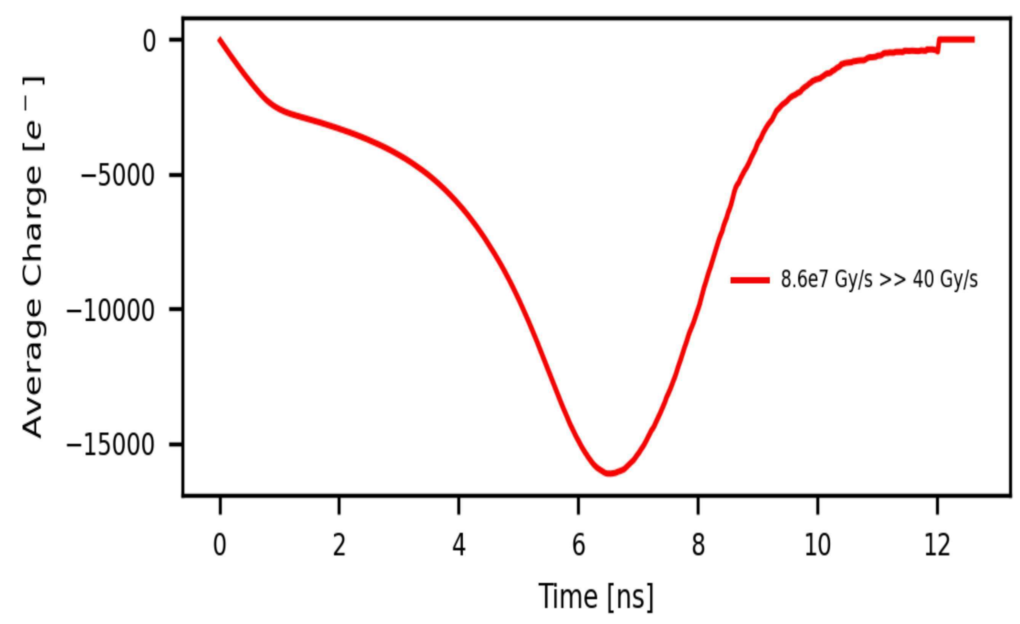

Figure 7: Time evolution of the average accumulated charge.

Key Performance Metrics:

- **Sub-nanosecond Collection:** Ultrafast rise time enables clear pulse separation under nanosecond beam structures.

7. Spatial Resolution Performance

Residual Analysis & Spatial Resolution:

- **Hit Reconstruction:** Position residuals evaluate the deviation between reconstructed hit positions x_{reco} and true Monte Carlo primary particle impact points x_{true}:

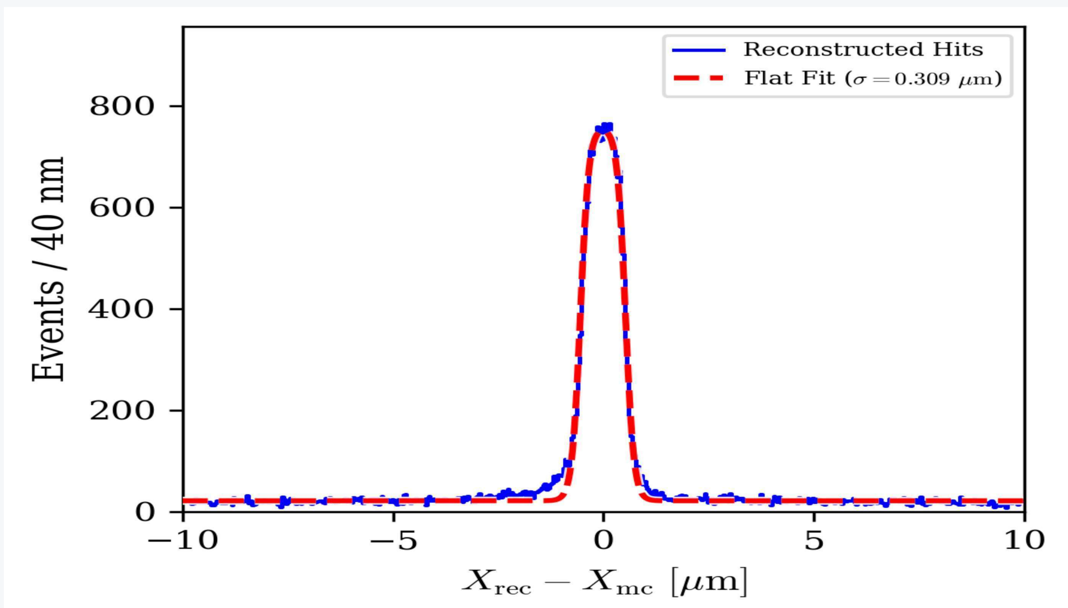

Figure 8: Position residual distribution ($\Delta x = x_{\text{reco}} - x_{\text{true}}$).

- **Theoretical Limits vs. Simulation:** For a pixel pitch p:

$$\sigma_{\text{theo}} = \frac{p}{\sqrt{12}} \approx 0.288\,\mu\text{m} \quad \text{vs.} \quad \sigma_{\text{sim}} = 0.309\,\mu\text{m}$$

- **Agreement:** Aligns with theoretical bounds, ensuring the high spatial accuracy needed for proton beam monitoring.

8. Conclusion & Outlook

Main Findings:

- **Ultra-fast timing:** Fast signal formation allows pulse-by-pulse beam monitoring.
- **Spatial accuracy:** Fine granularity supports precise beam dosimetry.

Next Steps:

- Beam-test validation
- Experimental dosimetry
- Multi-pad LGAD array
- Real-time beam monitoring

References

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