Investigation of LGAD sensors for applications in charged particle therapy

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4DInSiDe PRIN meeting
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LGAD/UFSD sensors investigated for applications in charged particle therapy since 2014.

Current studies (proof-of-concept):

- particle counter for beam monitoring in hadrontherapy (INFN MOVE_IT project, CSN5)
- beam energy measurement from time-of-flight of single protons (INFN MOVE_IT project, CSN5)
- Reference time for range monitoring with prompt gamma timing (INFN I3PET experiment, CSN5)
- Fine (ns) beam structure for in-beam PET with fast decay isotopes (INFN I3PET experiment, CSN5)

Future:

- Higher segmentation
- Optimize the sensors and the electronics (speed, radiation resistance, material budget)
- Integration of the above devices in a 4D tracker for beam monitoring/characterization and imaging applications in proton therapy
Charged Particle Therapy @ CNAO

CNAO – Pavia IT

<table>
<thead>
<tr>
<th>Particles</th>
<th>Energy Range</th>
<th>Flux</th>
<th>Range in Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>60 - 250 MeV</td>
<td>(\sim 10^9) p/(cm(^2)s)</td>
<td>3 - 27 cm</td>
</tr>
<tr>
<td>(C^{6+})</td>
<td>120 - 400 MeV/u</td>
<td>(\sim 10^8) cm(^{-2})s(^{-1})</td>
<td></td>
</tr>
</tbody>
</table>

Clinical precision on measurement of number of protons \(\sim 1\%\)

One year operation \(\sim 10^{15}\) p/cm\(^2\)
IC vs silicon detectors for beam monitoring

** Ionization chambers**

- Charge collection time: \(~ 100 \mu s\)
- Sensitivity: \(~ 10^4 \) protons
- Spatial resolution: \(~ 100 \mu m\)
- Time resolution: Poor
- # of particles: Indirect

** Silicon detectors**

- Fast response time, single particle detection
- Charge collection time: \(~ 1 \) ns
- Sensitivity: Single particle
- Spatial resolution: \(~ 10 \mu m\) (depending on the segmentation)
- Time resolution: \(~ 100 \) ps (30 ps with UFSD)
- # of particles: Direct counting

Advantages of solid state detectors for fast scanning modalities, monitoring of small dose spots, beam structure detection, timing applications, ....
IC vs silicon detectors for beam monitoring

Ionization Chambers ✅

- Saturation effects at very high currents
- Radiation resistant
- Simple, reliable, stable

Solid State Detectors ❌

- Signal pile-up (depending on the segmentation)
- Prone to radiation damage
- More complex architecture, readout and operation
Modeling and Verification for Ion beam Treatment planning

Implementation of advanced radiobiological models in ion TPS, experimental verification in-vitro and in-vivo.

Two prototypes of UFSD for radiobiological applications @ three irradiation facilities:

1. to **directly count** individual protons:
   - area 3x3 cm²;
   - up to fluence rate of $10^8$ p/s cm² (with error < 1% - clinical requirement);
   - segmented in strips $\rightarrow$ beam projections in two orthogonal directions;

2. to **measure the beam energy** with time-of-flight techniques, using a telescope of two UFSD sensors:
   - error < 1 mm range in water.

For additional details [http://www.tifpa.infn.it/projects/move-it/](http://www.tifpa.infn.it/projects/move-it/)
Test of 50 μm UFSD2 prototypes @ CNAO (protons)

**UFSD2 production (2017)**

- 50 um thickness

**Readout**
- Passive FE boards aligned to the beam
- CIVIDEC broadband 40 dB amplifiers
- CAEN digitizer (5 Gs/s)

**Clinical Proton Beam**
- Beam FWHM ~ 10mm
- Max flux ~ $10^9$ p/s delivered in spills
- Beam flux range: 20% - 100% of max flux.
- Beam energy range: 62 – 227 MeV (5 – 2 MIPs)
Signal distribution

- Increasing threshold

- Good S/N separation needed for all the energies;
- Larger S/N at lower beam energies;
- Peaks corresponding to **individual protons** can be easily distinguished;
- large amplitude fluctuations;
- short peak duration;

**Signal waveform acquired on a clinical proton beam**

<table>
<thead>
<tr>
<th>Channel 1</th>
<th>227 MeV protons</th>
</tr>
</thead>
</table>

**Threshold**

**Number of protons**

2 ns
**Concern: pile-up inefficiency**

**Measured vs. estimated rate**, CNAO proton beam, using a PTW pinpoint I.C., 3 energies (62-105-227 MeV), varied beam flux (20 – 50 – 100% of max).

![Graph showing measured vs. estimated rate](image)

\[ R = \frac{Q}{C} e^{-\frac{Q}{C}\tau} \]

\( Q = \text{total charge in I.C.}/\Delta T_{\text{tot}} \)
\( \tau = \text{deadtime} \)
\( C = \text{charge/proton in the I.C.} \)

V.Monoaco (UNITO) - 4DInSiDe medical applications
Results from tests at CNAO (Sept. 2018)

**Average rate estimated with the pin-hole ionization chamber [MHz]**

<table>
<thead>
<tr>
<th>Average beam flux (GHz/cm²)</th>
<th>Measured</th>
<th>Corrected AND</th>
<th>Corrected OR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25</td>
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<td></td>
<td></td>
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<tr>
<td>0.5</td>
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<td></td>
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<tr>
<td>0.75</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:** saturation effects depend on the instantaneous particle rate (higher than average due to the bunched beam structure).

Particle rate measured in one strip

Pile-up effects mitigated using correlation between two neighbouring strips (2 correction methods)

MOVEIT goal (< 1% error)
Results from tests at TIFPA (Feb. 2019)

Data collected at 70, 125 and 228 MeV and different beam currents.

Average rate estimated with the pin-hole ionization chamber [MHz]

Move-It Goal
(< 1 % error)
Fast electronics for particle counting

2 different ASICs developed

**ABACUS_CSA (F. Fausti)**
Charge Sensitive Amplifier
Capacitive feedback

**ABACUS_TIA (G. Mazza)**
Trans-Impedance Amplifier
Resistive feedback

- 24 readout channels
- Technology node: 110 nm
- Area: 2x5 mm² - 140 pads
- Vdd: 1.2 V
- Discriminators with independent thresholds (internal DACs)
- Differential output to FPGA for counting

ABACUS_CSA tested up to > 100 MHz/channel
Beam energy from Time-of-Flight

Beam telescope
UFSD sensors

Beam
Δt  v  E

Maximum error on ToF per unit distance L corresponding to an uncertainty < 1 mm range in water.

For 1m distance, 228 MeV:
Max error on TOF = 4 ps
Energy measurement - coincidences

Channel 1
HPK pad (80 um, 9 mm$^2$)
227 MeV protons

Channel 2
HPK pad (80 um, 9 mm$^2$)
227 MeV protons

Constant fraction algorithms applied
$\Delta t$ measured for different beam energies and distances
Some sensors sent to APTEK (California) and thinned down to 120 µm or 70 µm thickness (the original total thickness is 600 µm)
\[ \langle \Delta T \rangle = 5.823 \text{ ns} \]
Stat error on \( \langle \Delta T \rangle \) = 0.001 ns

Time resolution for single crossing
\[ \sigma(t) = \frac{82 \text{ ps}}{\sqrt{2}} \approx 58 \text{ ps} \]

Protonterapia (Trento)
E = 184 MeV
d = 97 cm

Protonterapia (Trento)
time resolution range = 40-75 ps
(UFSD3 sensors 50 \( \mu \text{m} \) thickness)

CNAO (Pavia)
time resolution range = 75-115 ps
(HPK sensors 80 \( \mu \text{m} \) thickness)
Results @ CNAO (Pavia, synchrotron, proton beam)

Residual [MeV] (Measured – Nominal Energy)

Nominal Energy [MeV]

Root mean square deviation
280 keV (@97 cm)
270 keV (@67 cm)

1 mm range

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Results @ Protonterapia (Trento, cyclotron, proton beam)

- Residual Energy (Measured - Nominal Energy)
- Nominal Energy [MeV]
- 97 cm
- 67 cm

Root mean square deviation:
- 341 keV (@97 cm)
- 701 keV (@67 cm)

1 mm range
Future perspectives

The current R&D is intended to demonstrate the capabilities of a single particle counting silicon detectors for beam monitoring purposes.

**MOVE_IT goal:** radiobiological experiments with scattered proton beams
- max particle rate $10^8$ p cm$^{-2}$ s$^{-1}$
- 3x3 cm$^2$ sensor area
- two detector planes with orthogonal strips for beam shape profiling

For beam monitoring in clinical applications:
- pixelated detector (pixel size $\sim 100 \times 100$ $\mu$m$^2$ for $10^{10}$ p/(cm$^2$·s))
- embedded readout electronics
- radiation resistance $> 10^{15}$ p/cm$^2$
- larger area ($\sim 20 \times 20$ cm$^2$)
- material budget ($< 1$ mm H$_2$O)

**4DInSiDE PRIN 2017 (INFN-TO, UNITO, UNIPG, UNIPO, CNR)**
Development of LGAD devices with:
- very low thickness ($\sim 20$ $\mu$m active thickness)
- $\sim 100$ % active area
- unchanged time resolution up to $5 \cdot 10^{15}$ n$_{eq}$/cm$^2$
Other applications (in-beam PET for range monitoring)

- Hadron beam
- $\beta^+$ decay
  - 511 keV photon
- $\beta^+$-decay isotopes produced by nuclear interactions of the beam particle with the tissues.
  - Reconstruction of activity distribution to assert the proton range during treatment.
Fast decay isotopes for PET range monitoring

LGAD sensors for on-line detection of the beam structure (PET acquisition enabled in periods with no beam, to minimize background from prompt-\(\gamma\) decays)

(0-80) s integral activity

(80-81) s in-spill activity

CNAO 228 MeV

\(\sim 0.2 \mu s\)

~ 10 ms

TIFPA, Trento

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Prompt-gamma timing

I3PET (INFN, CSN5)

\[ \Delta t = t_2 - t_1 \]

decay position range

LGAD sensors to provide the reference time \( t_1 \)

Hadron beam

\( \gamma \) decay

Prompt photon

\( t_1 \)

\( t_2 \)