HVTrack: A monolithic HV-CMOS detector for hadron therapy

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1. Hadron therapy

- An accelerator (cyclotron) generates a beam of particles with fixed energy
- The beam of particles (protons, other ions such as carbon) is focussed into the patient to destroy a tumour
- Protons (and carbon ions) deposit most of their energy at a specific distance known as the **Bragg Peak**

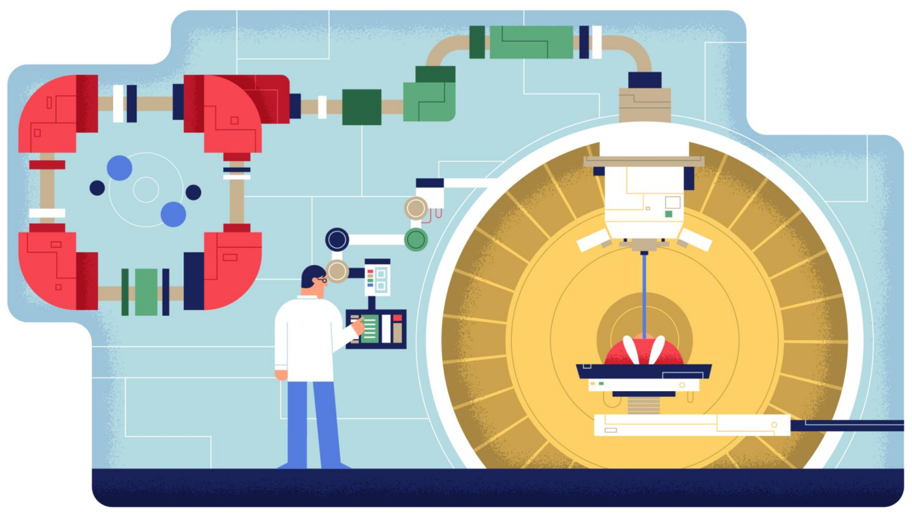


Image taken from Wired & Hitachi I animation: studioparko.com/wired-hitachi-social-innovation

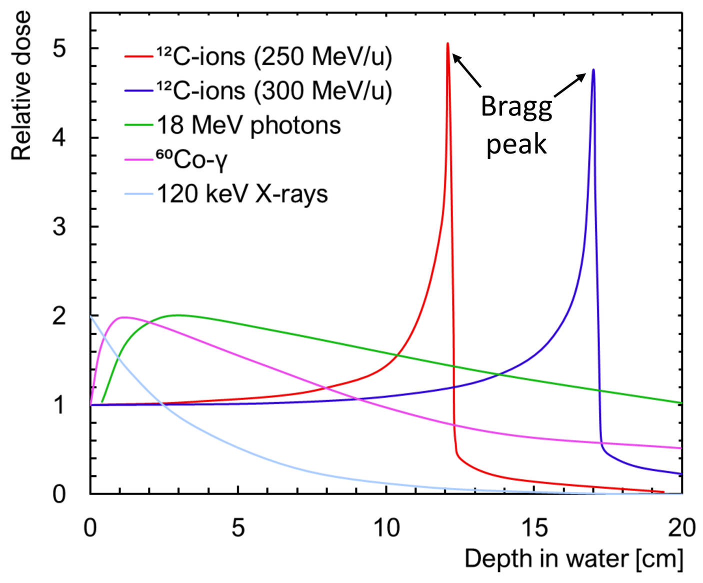
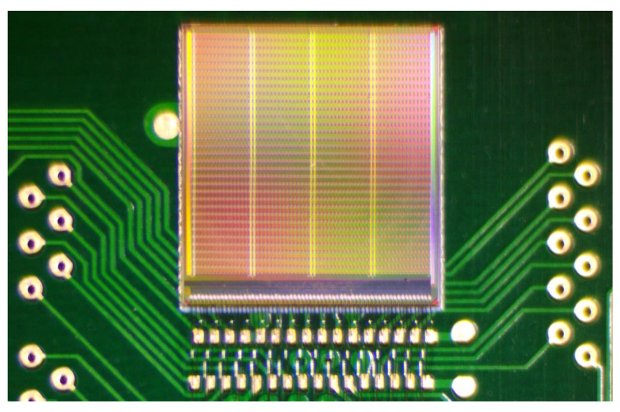


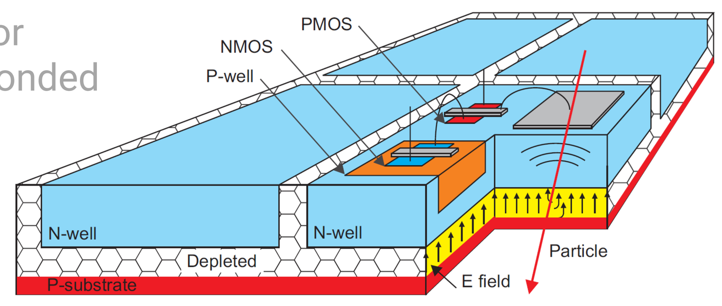
Figure adapted from G. Kraft, (2000). 10.1016/S0146-6410(00)00112-5

- Energy released by particles must be precisely controlled
- ^{12}C ions release almost all energy at Bragg peak compared to other types of particle and radiation
- Greatly improved dose targeting (tumours near critical organs)
- However, particles can scatter due to interaction with the material, affecting neighbouring healthy tissues

2. HVTrack detector



HVTrack detector glued and wirebonded to PCB



Four high-voltage pixels. (I. Perić, 2007) 10.1016/j.nima.2007.07.115

- Detectors can measure energy and trajectory of particles to evaluate scattering
- LFoundry 150 nm HV-CMOS technology used to fabricate HVTrack detector, a **High-Voltage Monolithic Active Pixel Sensor** (HV-MAPS)
- **Particle position** can be recorded by a matrix of pixels and trajectory calculated by multiple layers of detector. HV-MAPS can be thin (≈ 50 μm) to ensure scattering due to detector material is minimised,
- **Energy and time of particle** can be extracted by CMOS circuitry inside pixels. High-ρ substrate, biased to high-voltage for fast charge collection via drift.

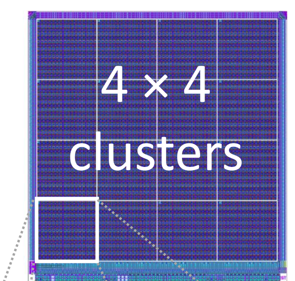
Design issues

1. Energy measurement in high particle rates. ToT technique affected by pile-up (5.)
2. Trajectory reconstruction. Detectors need to be synchronised (6.)

Solution: Gating approach (3.)

3. Gating concept

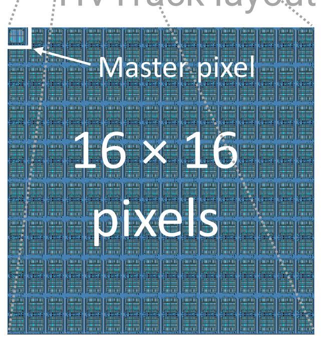
- All pixels are enabled only for a "gate", or time window t_w. Only events detected in t_w are valid
- Particle source is **synchronised** with the measurement



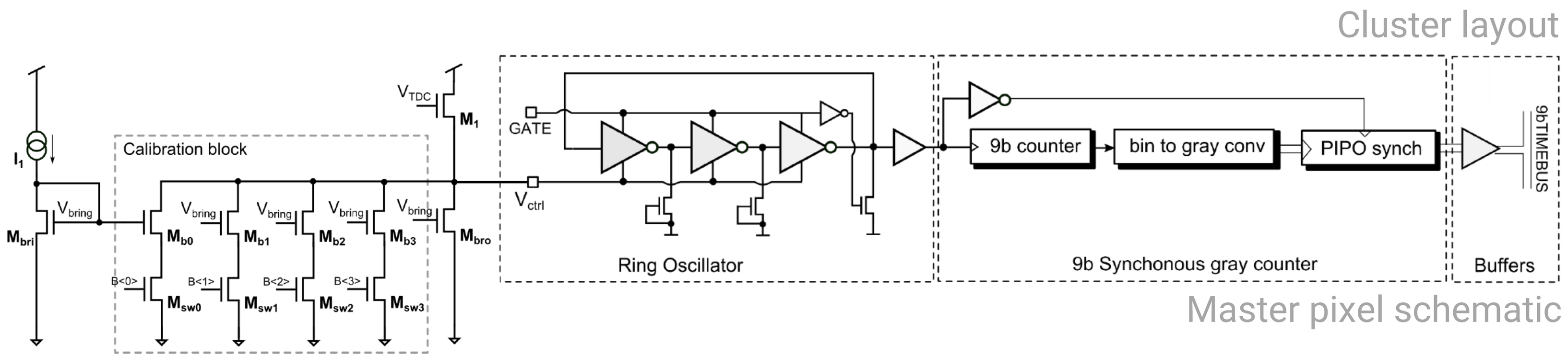
HVTrack layout

Circuit to share time information among all pixels:

- Array divided into 4 × 4 clusters with a **master pixel** to each cluster to minimise propagation time and power consumption
- Each pixel samples time information in a local memory when an event is detected (4.)
- Each master pixel consists of a ring oscillator + grey counter + buffers (for delivering time to all pixels) + calibration circuit

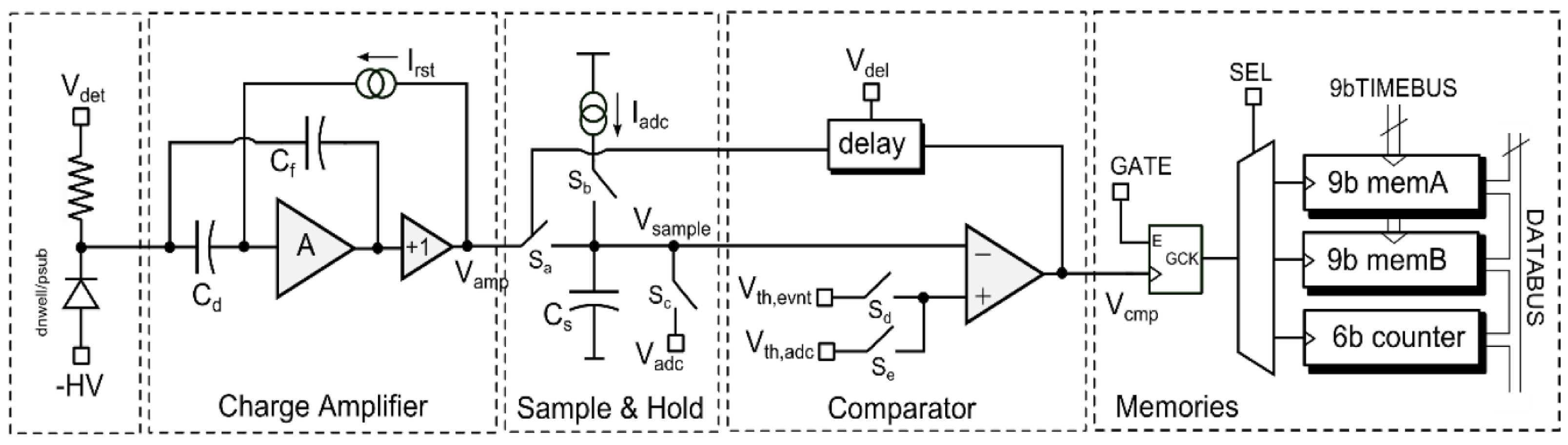


Cluster layout



Master pixel schematic

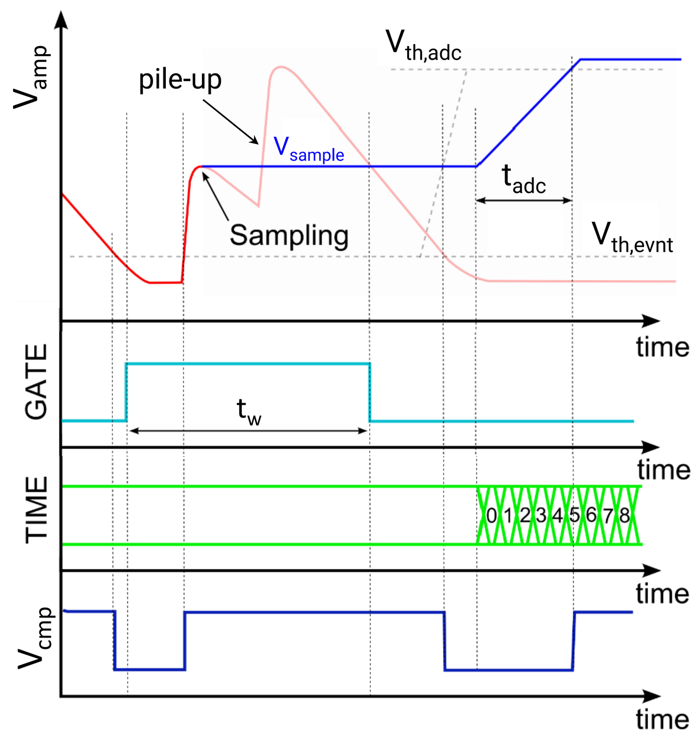
4. Pixel schematic



5. Energy measurement

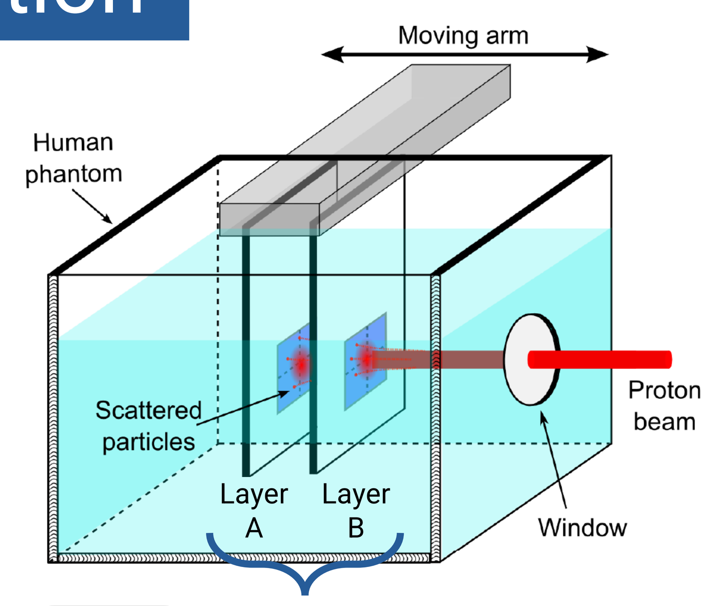
- Energy measurement is a Time-over-Threshold (ToT) technique ($V_{th,evnt}$)
- Due to high particle flux, **pile-up** is likely, which induces errors in energy measurement. How to solve this?

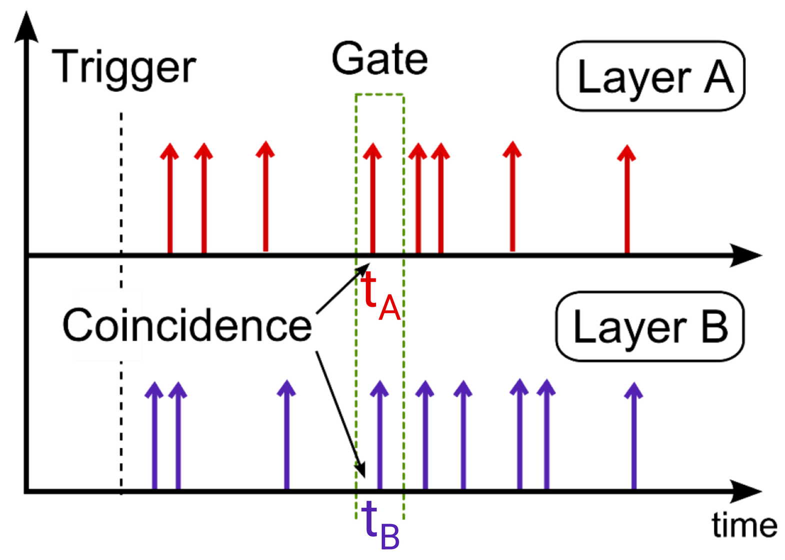
1. **Tracking phase:** GATE is high, S_a is on, and S_d is on to set comparator to $V_{th,evnt}$
2. **Sampling phase:** Detection of first event, S_a is off, sampling output of CSA in C_s, subsequent (pile-up) events are discarded.
3. **Post-sampling phase:** S_e is on, sets comparator threshold to $V_{th,adc}$
4. **Conversion phase:** S_b is on, enabling I_{adc} and the ramp. TIME is started. When signal reaches $V_{th,adc}$, the value of t_{adc} is sampled

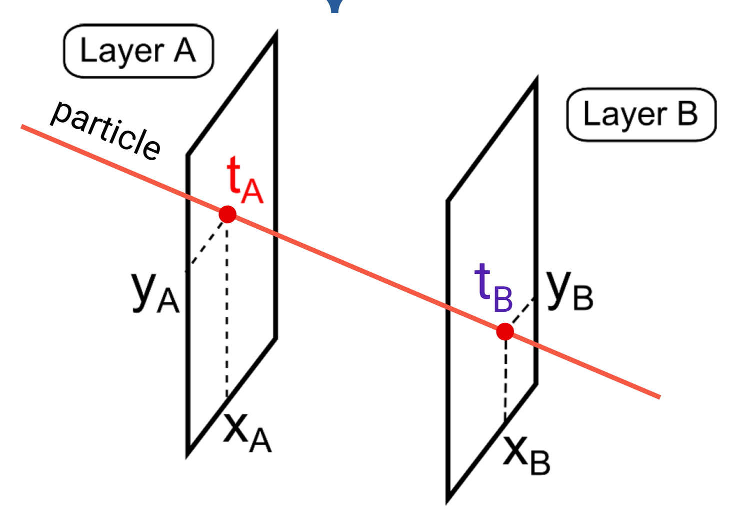


6. Trajectory reconstruction

- Water equivalent "Human phantom"
- Two detectors are used to measure the tracking trajectory with hit positions (x_A, y_A) and (x_B, y_B) to evaluate scattering due to interaction with the sample
- A gate is used to allow coincidence measurement with synchronised source.



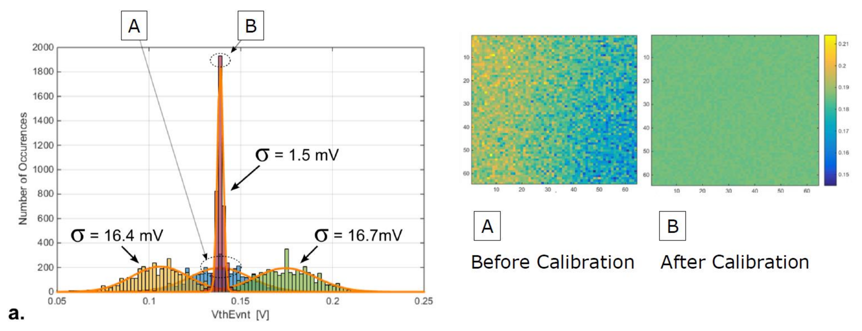




7. Experimental results

Energy measurement

Detector was exposed to a ^{90}Sr source (37 MBq)



Time measurement

Synchronous pulsed laser triggered by the gate