Development of an imaging system for dose monitoring in hadrontherapy

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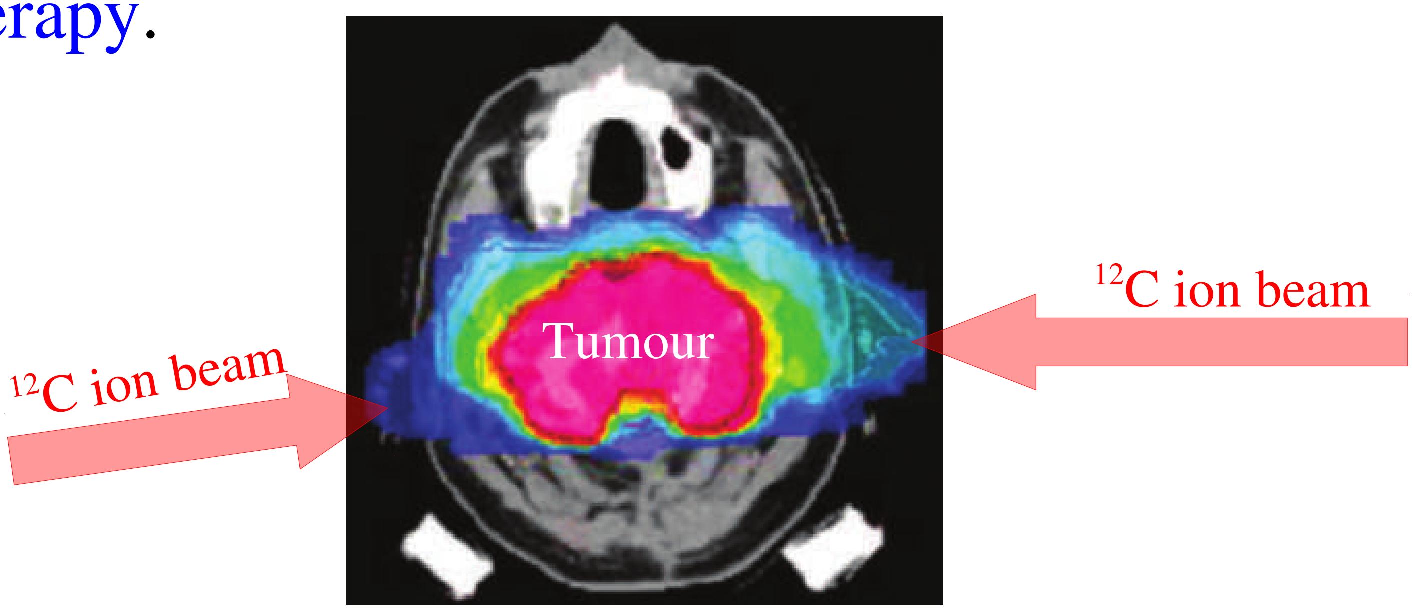
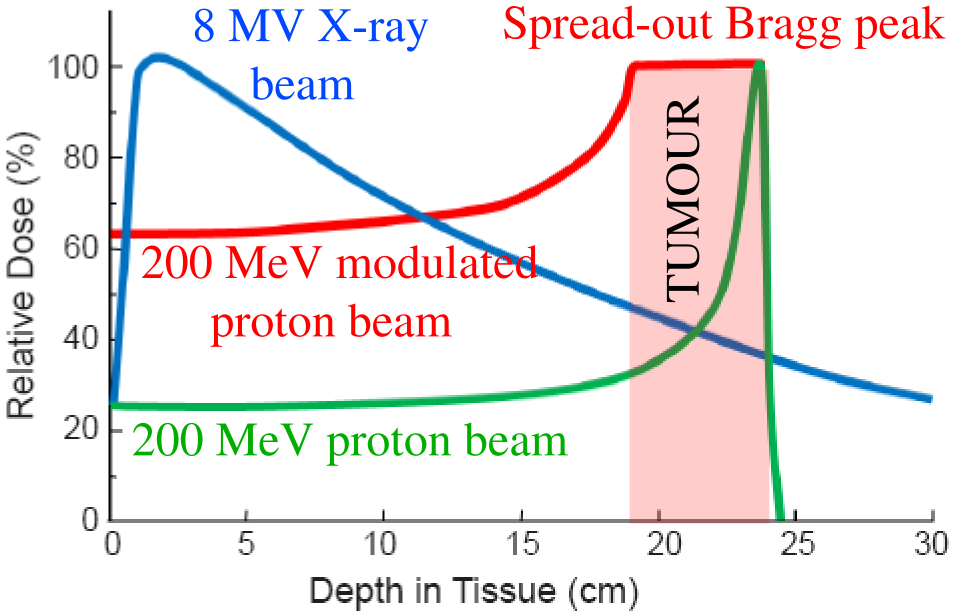
- In conventional radiation therapy, beams of X-rays are produced by accelerated electrons and then delivered to the patient to kill tumour cells.
- When the irradiating beams are made of charged hadrons (protons and other ions such as ^{12}C), radiation therapy is called hadrontherapy.



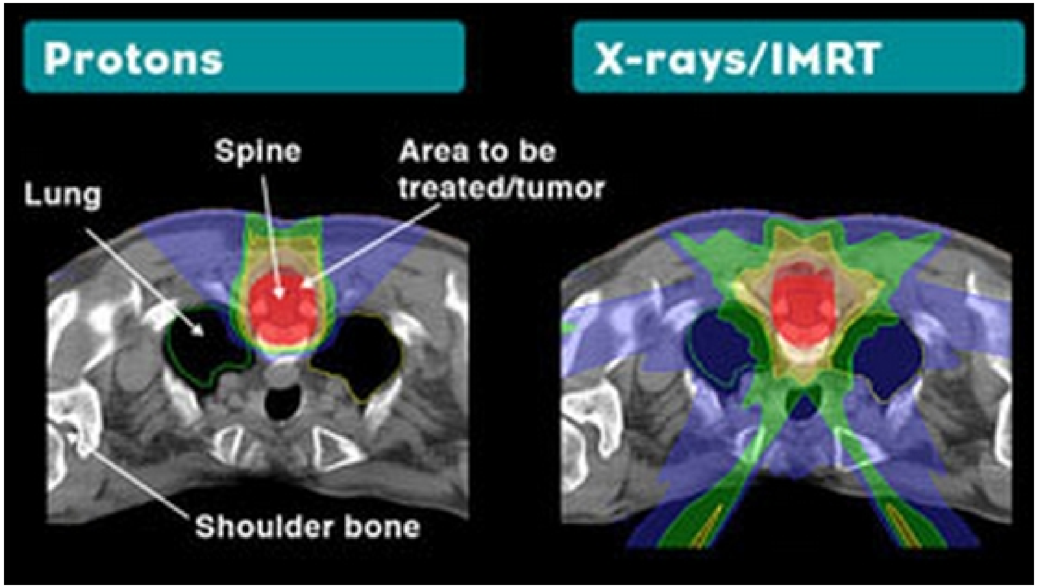
[1] Durante, M., and Loeffler J. S., Nature reviews Clinical oncology 7.1 (2009): 37-43.

Hadrontherapy VS **Conventional radiotherapy**

- Potential of a highly conformal dose deposition ⟶ lower dose to healthy tissues.



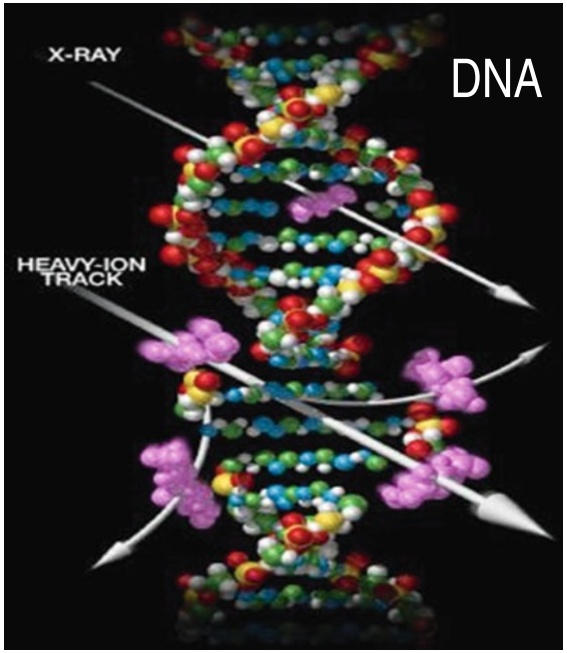
Dose deposition in human tissue[1].



A treatment planning comparison for paraspinal sarcomas [2].

[1] Jesseph, J., et al., Translational Cancer Research 1.4 (2013): 247-254.
[2] Weber D.C., et al., Int J Radiat Oncol Biol Phys. 2004;58(5):1596-1606

Hadrontherapy VS **Conventional radiotherapy**

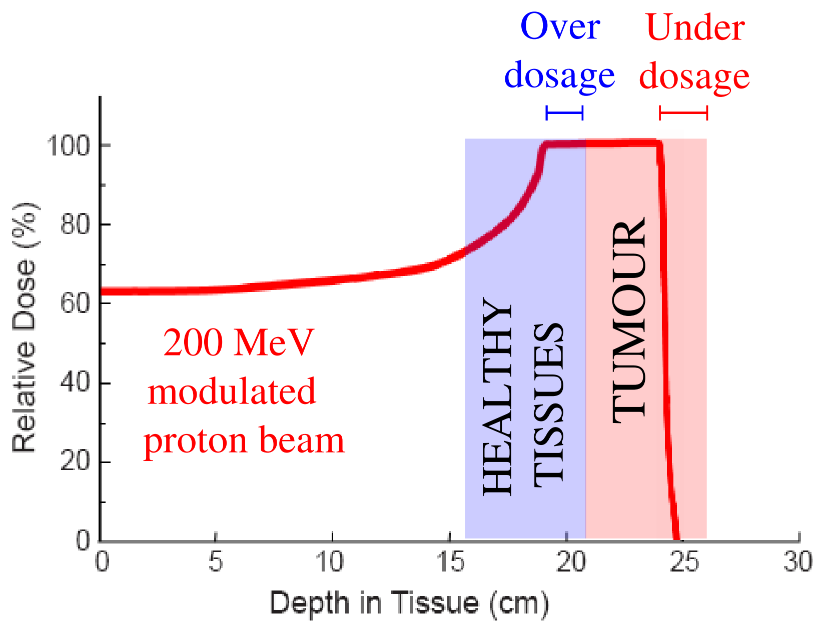


- With the use of ^{12}C ions, it is possible to obtain a high radiobiological effectiveness: the damage produced on cancer cells is more complex and difficult to repair.
- Conventional radiotherapy is cheaper: the cost of a linear accelerator for radiotherapy is lower than the one of a cyclotron or synchrotron.

LINAC for Radiotherapy	Proton therapy center	^{12}C ion therapy center
2-3 M$ [1]	15 – 80 M$	> 300 M$

[1] US data: U. Linz. *Ion Beam Therapy: Fundamentals, Technology, Clinical Applications*. Springer, 2011.

- Dose release uncertainty: the actual distribution of the released dose may be significantly different from the planned one.



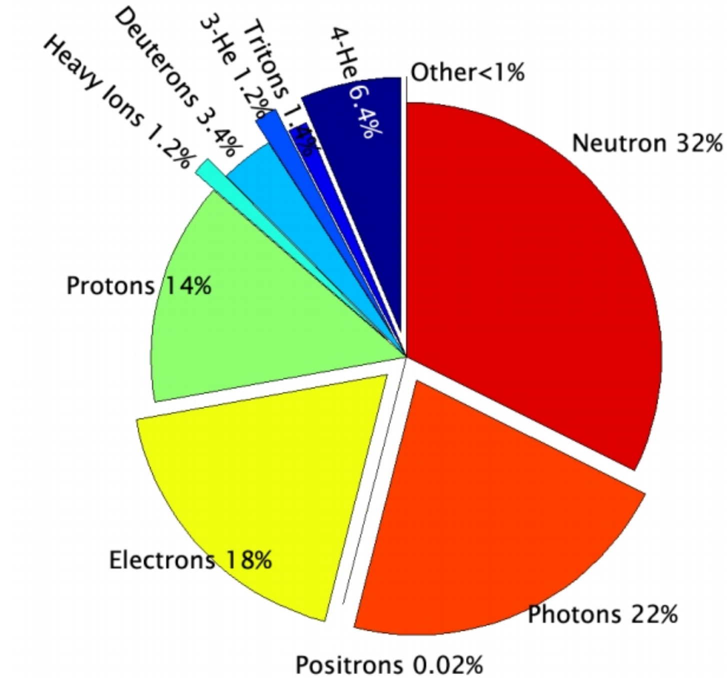
- The main causes are:
  - Patient mispositioning
  - Patient morphological changes (between the moment of the PET/CT scan and the actual treatment situation)
  - Miscalculation of tissue density and composition

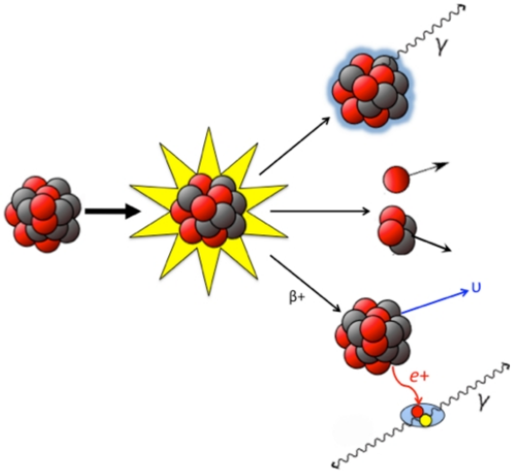
Range verification system needed

- The dose monitoring relies on the secondary radiation produced during the treatment.
- Mainly three types of emissions are currently under study for monitoring purposes:
    - Prompt photons
    - Secondary charged particles
    - Annihilation photons

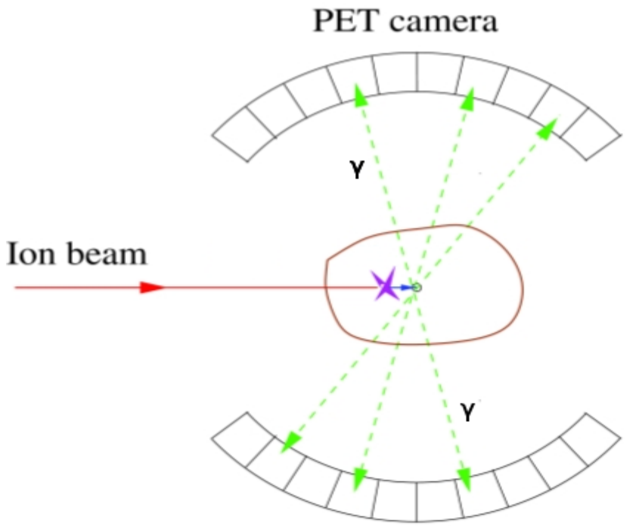
229 MeV/u ^{12}C ion beam on a real patient: outgoing radiation

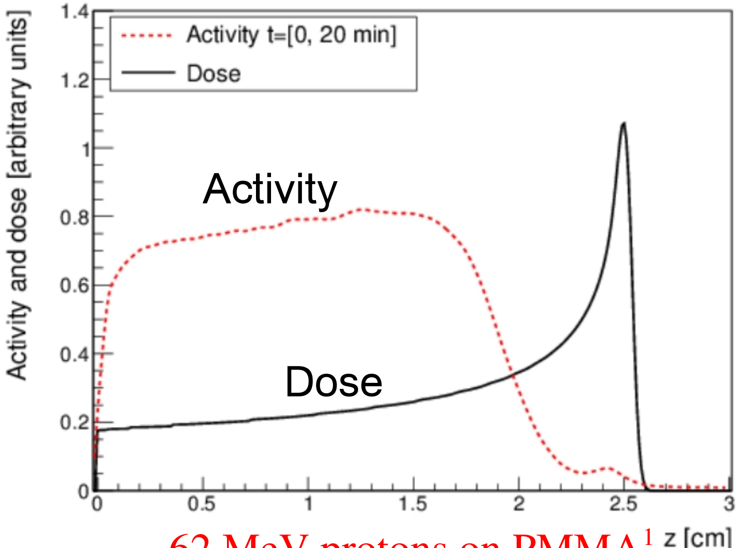
Particle name	Percentage
4-HELIUM	6 %
3-HELIUM	1 %
TRITON	1 %
DEUTERON	3 %
HEAVYION	1 %
PROTON	10 %
ELECTRON	20 %
POSITRON	0.02 %
PHOTON	20 %
NEUTRON	30 %
MUON+	0.0002 %
MUON-	0.0003 %
PION+	0.002 %
PION-	0.002 %





- The target is activated by the incident ion beam. The main β^+ emitters are: ^{11}C ($T_{1/2} \approx 20.3$ min), ^{10}C ($T_{1/2} \approx 19.3$ s), ^{15}O ($T_{1/2} \approx 2.0$ min).
- A PET (Positron Emission Tomography) system can be used to monitor the dose release by detecting the e^+e^- annihilation photons.
- No simple relation between dose and β^+ activity ⟶ *Unfolding* procedure[2].
- Metabolic washout of β^+ emitters.





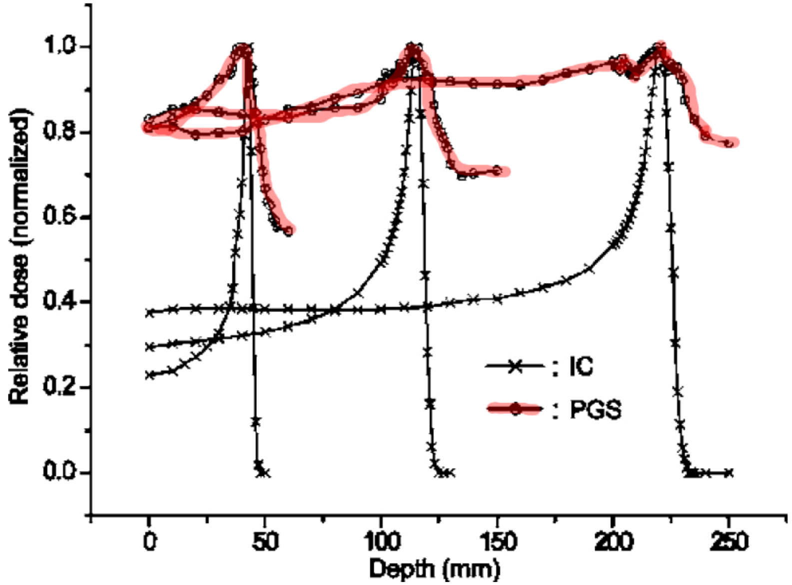
62 MeV protons on PMMA[1]

[1] Camarlinghi, N., et al., Journal of Instrumentation, 9, 04 (2014) C04005.
[2] Aiello, M., et al., Nuclear Science Symposium and Medical Imaging Conference, IEEE 2011.

- A further possibility is the detection of photons emitted by nuclear de-excitations (prompt photons), for instance:

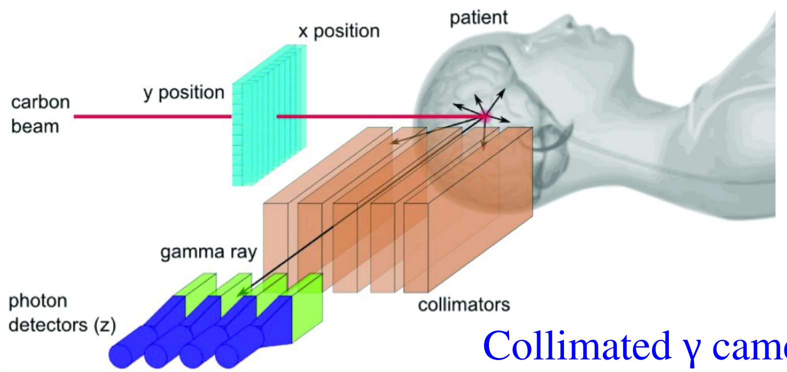
$$^{12}C^* \Rightarrow {}^{12}C + \gamma_{4.44\,\mathrm{MeV}}$$

$$^{16}O^* \Rightarrow {}^{16}O + \gamma_{6.13\,\mathrm{MeV}}$$

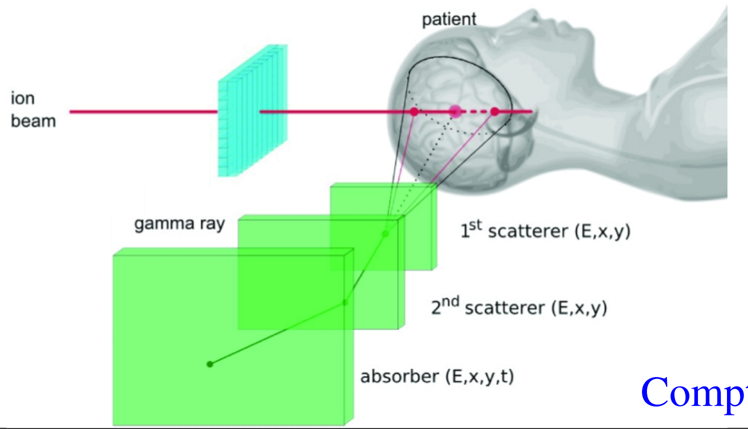


PGS = Prompt gamma scanner IC = Ionization chamber
100, 150, 200 MeV protons in water, data from:
Min, Chul-Hee, et al., Applied physics letters 89.18 (2006): 183517.

- The emission is fast, isotropic, and it is peaked near the Bragg peak.
- Detection systems:



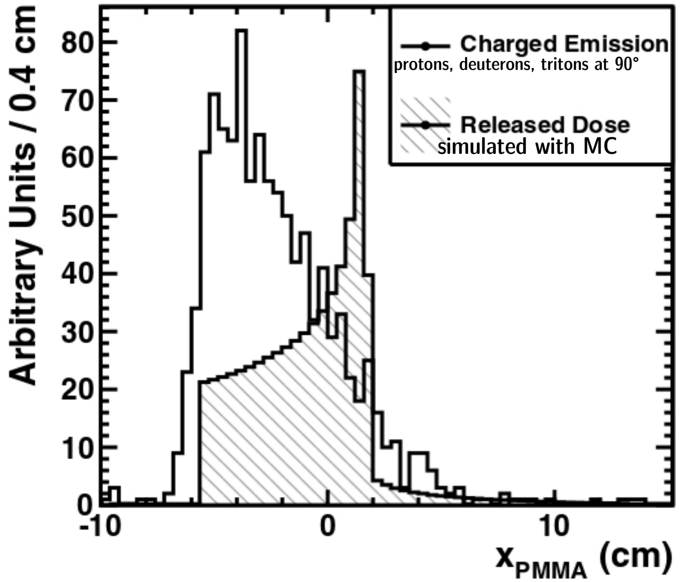
Collimated γ camera



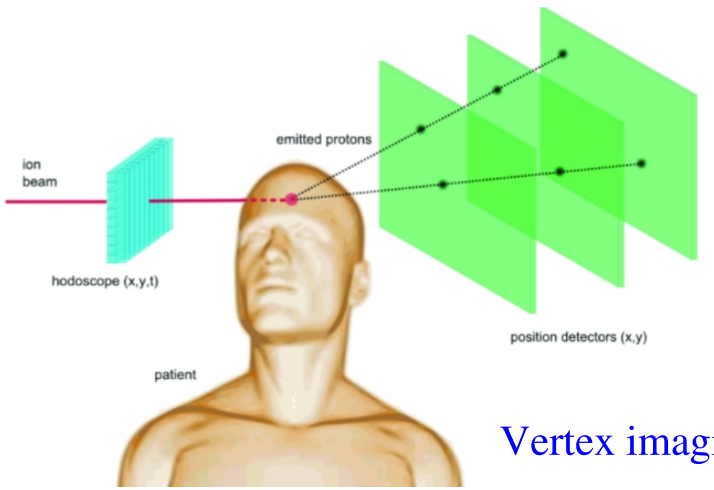
Compton γ camera

Dose monitoring with secondary charged particles

- A third dose monitoring technique[1] relies on the detection of secondary charged particles: mainly *p* and low Z nuclei from the projectile for ^{12}C beams, and *p* from the target for proton beams.
- A method to correlate the emission profile of the fragments with the Bragg peak position has been proposed by Piersanti et al. (2014) [2].
- High tracking efficiency with *vertex imaging*.



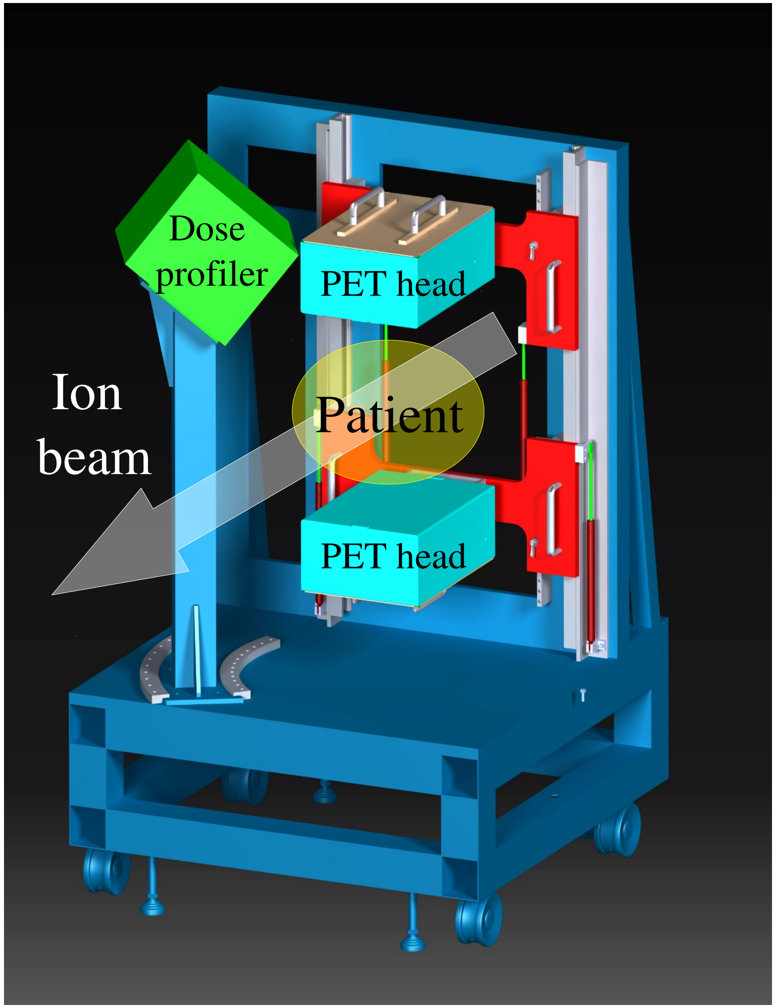
220 MeV/u ^{12}C on PMMA[2]



Vertex imaging

[1] Braunn B., et al., Nuclear Instruments and Methods in Physics Research Section B, 269.22 (2011): 2676-2684.
[2] Piersanti, L., et al., Physics in medicine and biology 59.7 (2014): 1857.

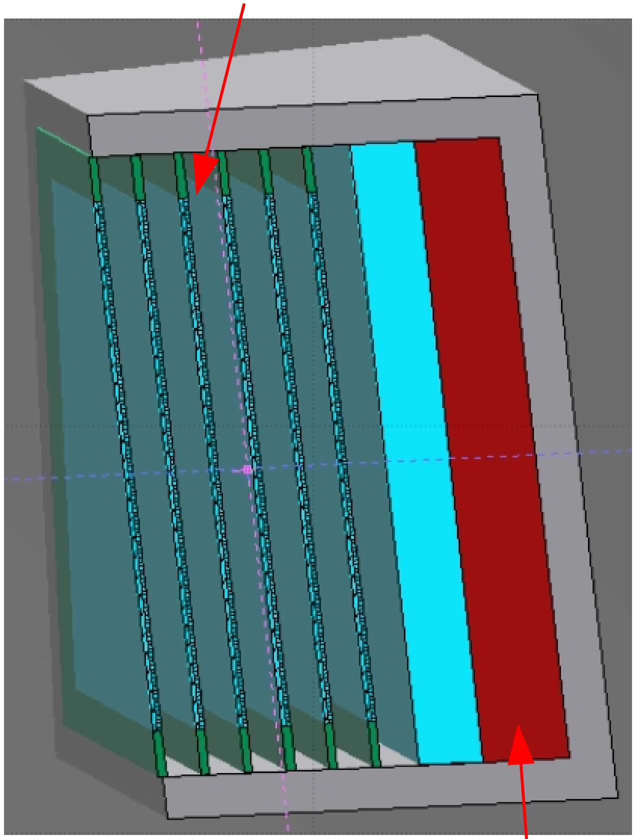
- INSIDE (INnovative Solutions for In-beam DosimEtry in hadrontherapy) is a project funded by MIUR PRIN-2010, it involves several INFN units and Italian universities (Pisa, Roma, Milano, Torino, Bari).
- INSIDE aims to build a multi-modal imaging system for dose monitoring in hadrontherapy: a **dose profiler** (for prompt photons and charged secondaries) + a **PET system**.



- The system will be tested at CNAO (Centro Nazionale di Adroterapia Oncologica), Pavia.

- The dose profiler has been designed for simultaneous detection of prompt photons and charged secondaries (Compton camera + Vertex imaging).
- The device has a detection surface of (20×20) cm^2 and 30 cm length:

  6 tracking units with 2 cm spacing and composed of two orthogonal layers of plastic scintillating fibers (500 μm × 500 μm section) + LYSO calorimeter (4×4 elements) made of 23×23 crystal pixels, each 1.6 cm long.

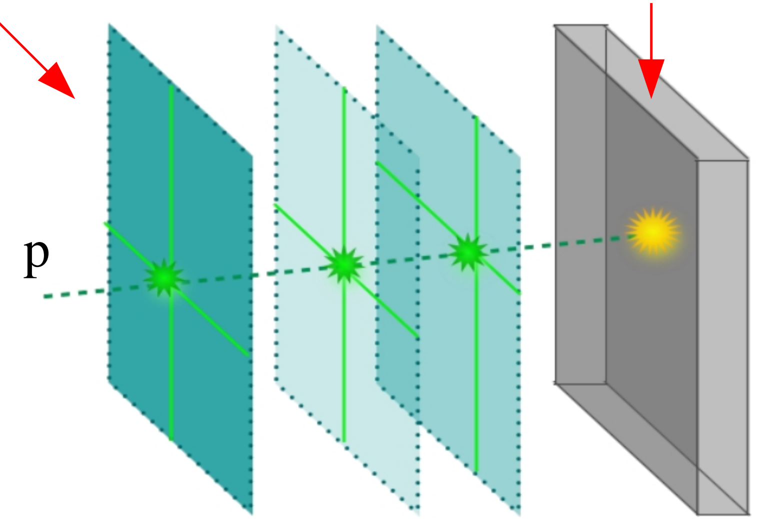


[1] Mattei, I., et al., 15th Symposium on Radiation Measurements and Applications (SORMA XV), 2014.

- **Charged event:**

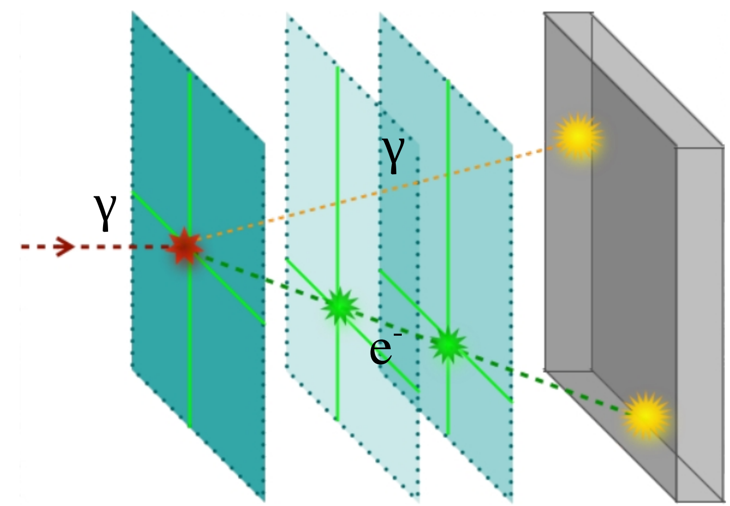
  E_{kin} ~ 30-130 MeV

  For a charged event all the tracking planes are expected to be fired along a straight line. Then, a signal along the same direction is expected in the LYSO detector.



- **Compton event:** E_γ ~ 1-10 MeV

  If a Compton event occurs, the scattered electron will traverse the tracker planes (with a trajectory far from a straight line because of MS). Moreover, the LYSO detector will provide Compton gamma position information.



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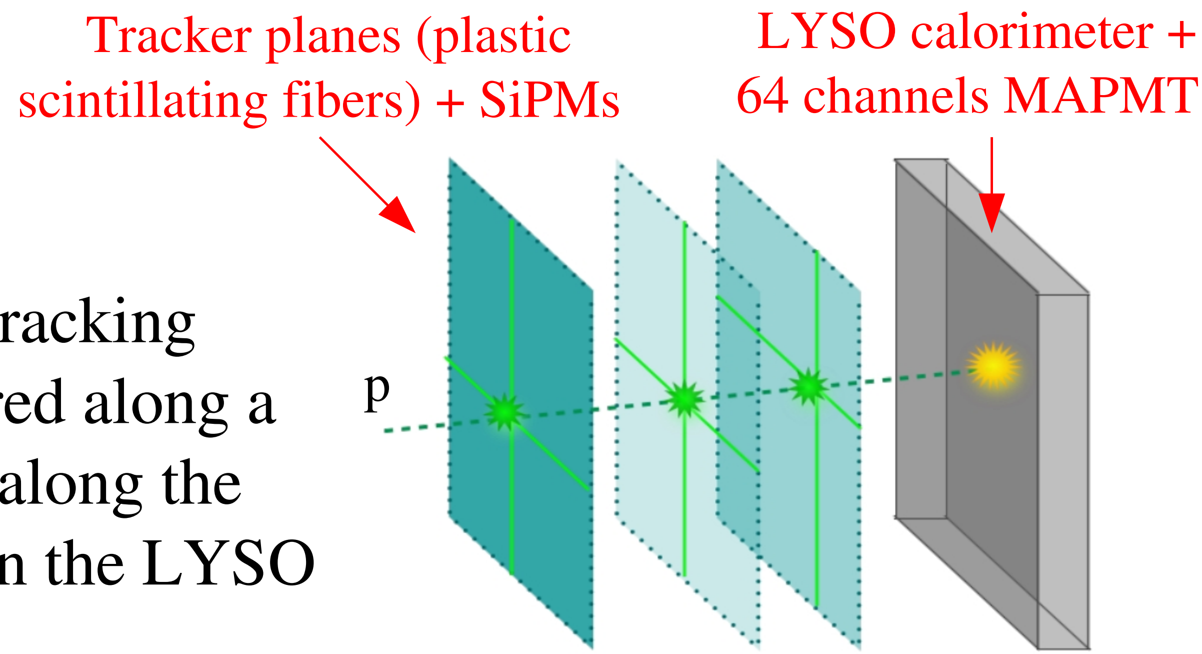


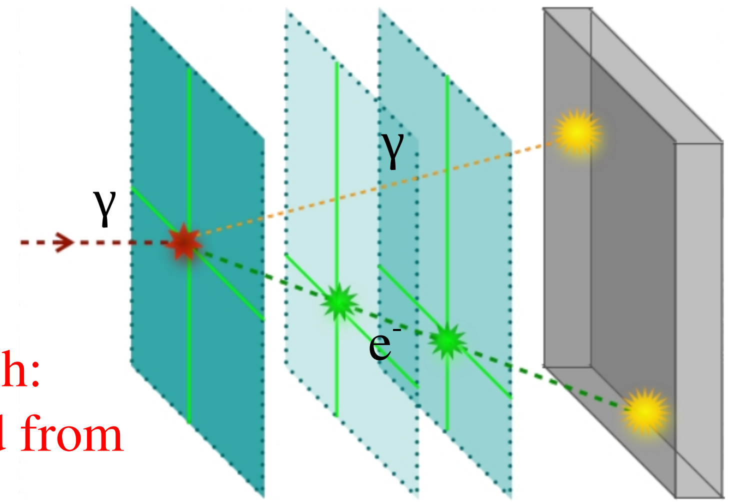
- **Compton event:** E_{γ} ~ 1-10 MeV

$$\hat{p}_{\gamma} = C_1 \hat{p}_{\gamma'} + C_2 \hat{p}_{e'}$$

$$1 = C_1^2 + C_2^2 - 2C_1C_2\cos\theta$$

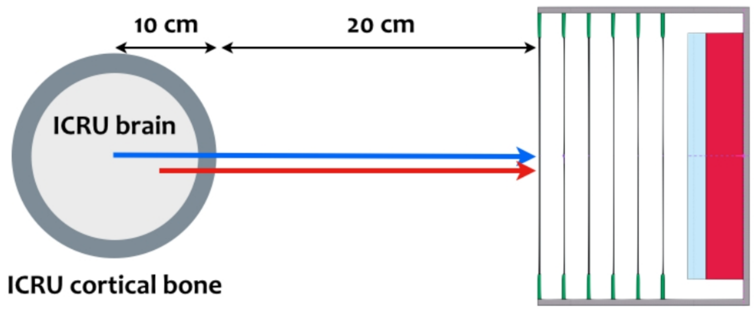
$$C_1 = \frac{|\vec{p}_{\gamma'}|}{|\vec{p}_{\gamma}|};\; C_2 = \frac{|\vec{p}_{e'}|}{|\vec{p}_{\gamma}|}$$

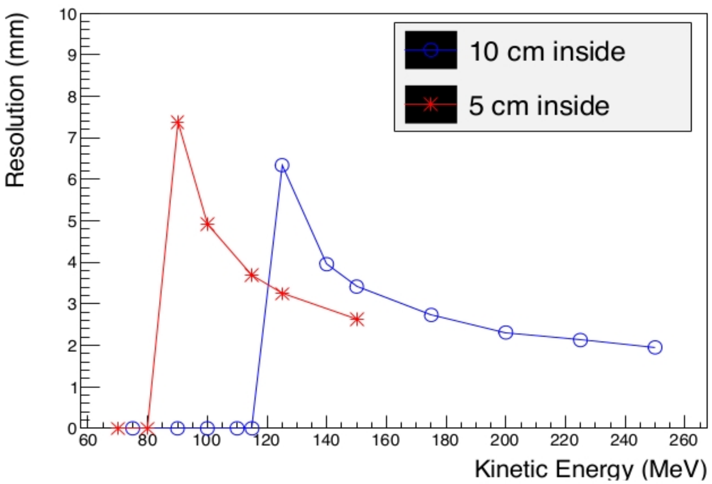
Statistical approach: C_1 and C_2 are obtained from MC simulations



Expected performances

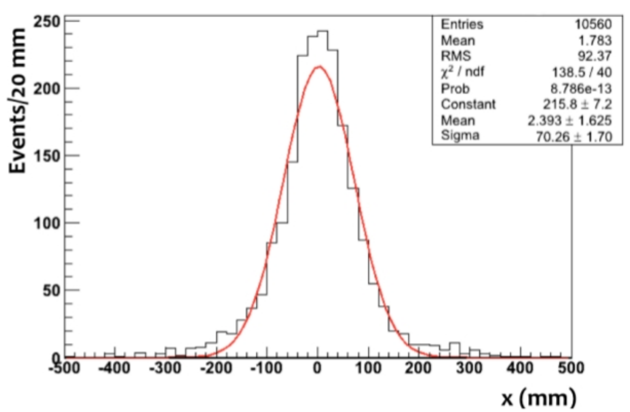
- Charged track reconstruction: < 1 mm overall resolution





- Compton reconstruction:

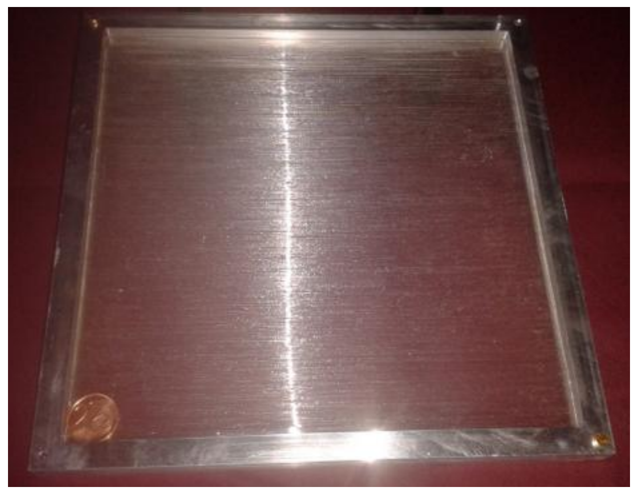
  < 5 mm overall resolution



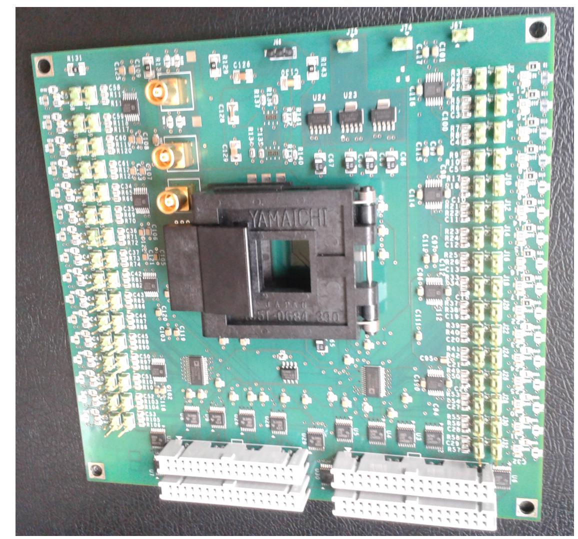
[1] Mattei, I., et al., 15th Symposium on Radiation Measurements and Applications (SORMA XV), 2014.

- **Status of the work**: the dose profiler is under development mainly in Rome (calorimeter mechanics and electronics, tracker mechanics) and in Milan (tracker electronics).

Calorimeter electronic module

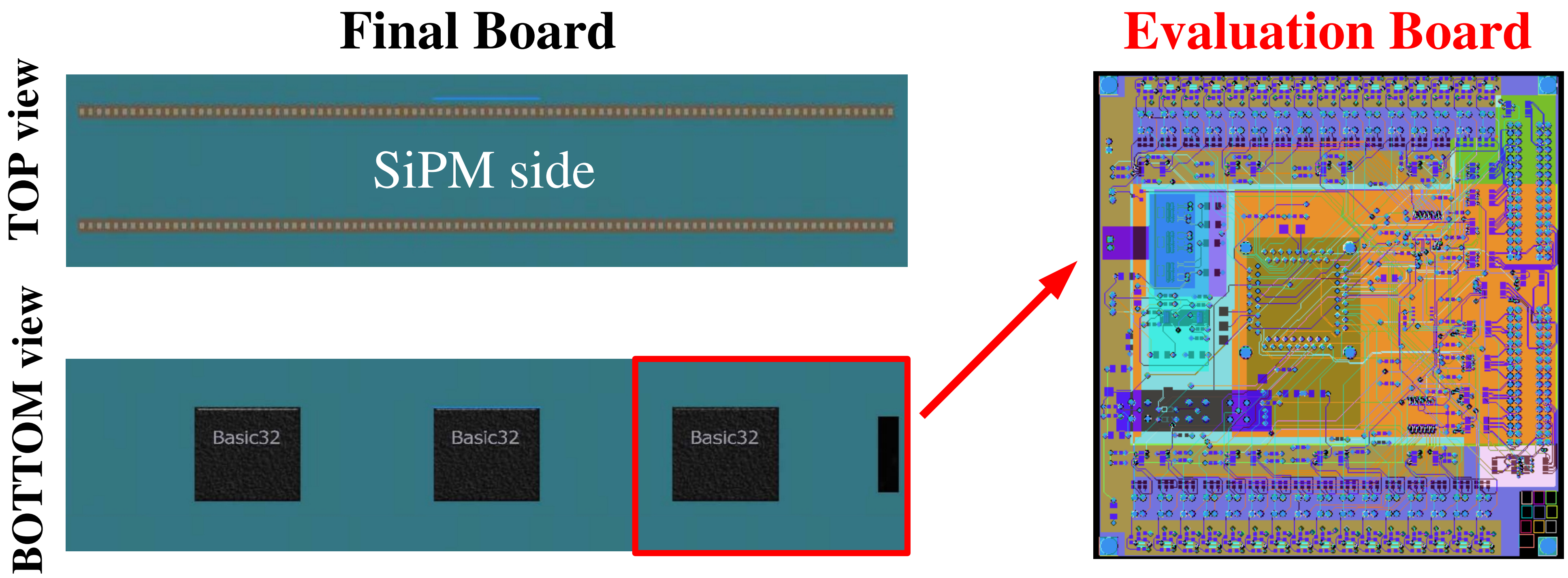


Tracker plane made of scintillating fibers

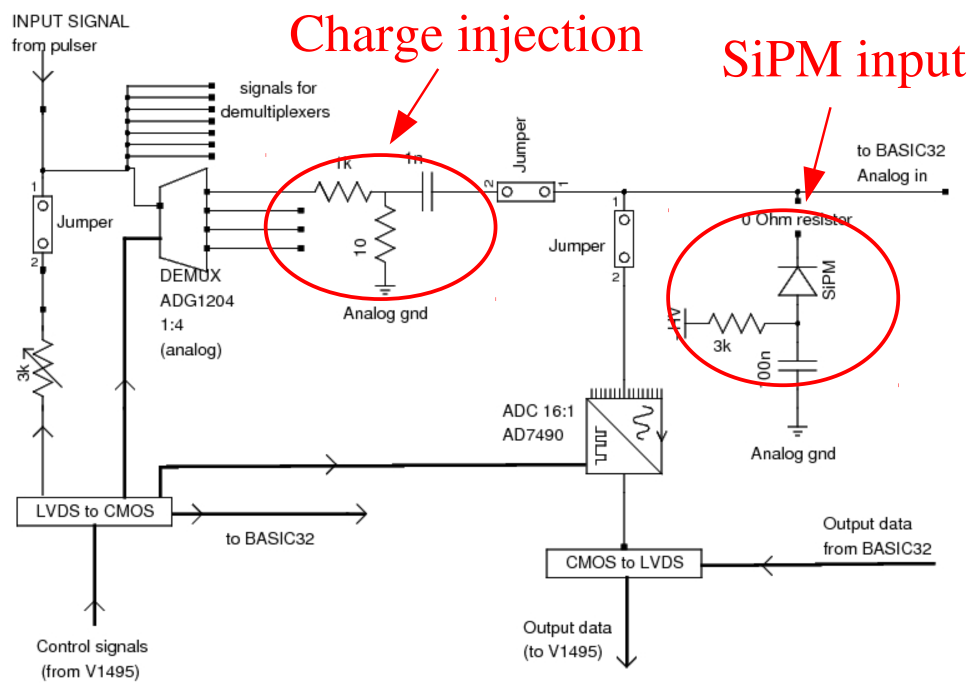


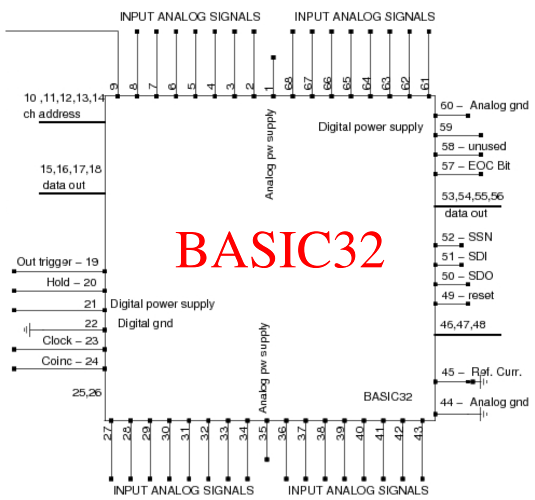
Prototype of the tracker readout electronics

- The evaluation board, a prototype of the tracker readout electronics, has been designed as a subset of the final board.
- It aims to read the signals produced by the SiPMs which are employed as photodetectors for the scintillating fibers.

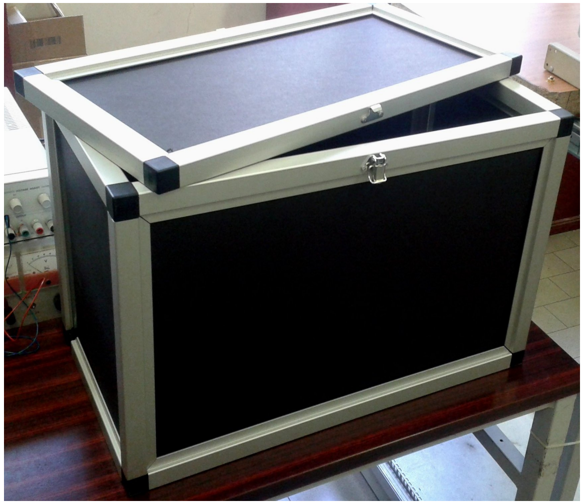


- The SiPM output is read by the BASIC32_ADC (developed by Politecnico di Bari).
- BASIC32_ADC is able to provide a digital signal proportional to the amount of charge contained in the SiPM pulse (*energy signal*).

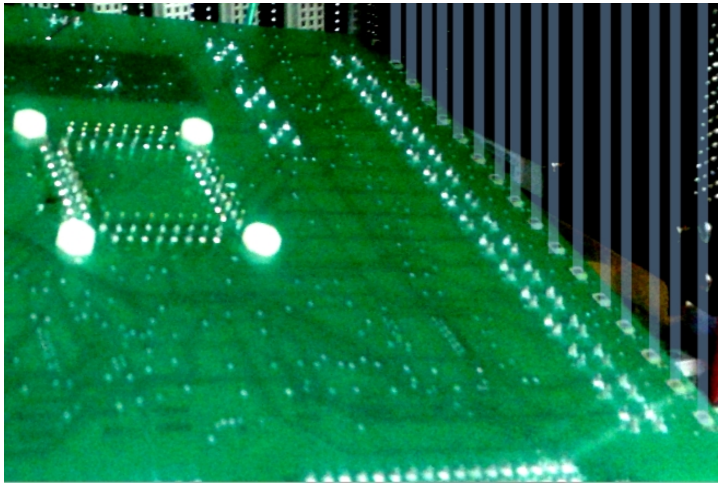




- Charge injection test using the CAEN board (v1495)
- SiPM input test within the Light Tight Enclosure (Newport LTE-12) and light pulse produced by a LED.
- Characterization of a sub-system of the tracker composed by several scintillating fibers connected to the evaluation board.



Newport LTE-12



Evaluation board + scintillating fibers

Thanks for your attention!