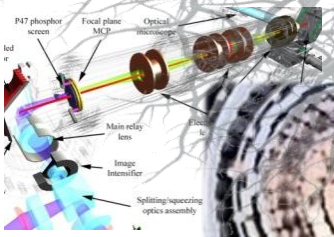
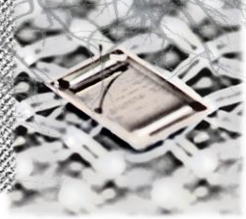
iMPACT

innovative Medical Proton Achromatic Calorimeter and Tracker

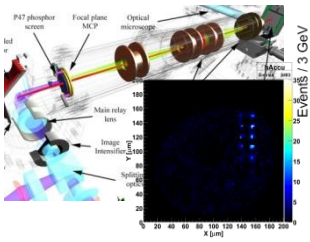




Piero Giubilato

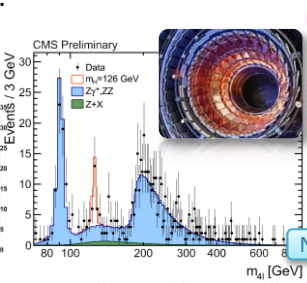
25 Nov 2014

0 The PI and the team have first hand experience and know-how on solid state detectors leading edge technologies developed in many physics research programs and experiments. Track records ranges from the first commercially available rad-hard monolithic pixel detector for Transmission Electron Microscopy, to the participation to the discovery of a Higgs boson, to the successful design and development of the first European facility for Single Event Effects micro-mapping based on Ion Electron Emission Microscopy.



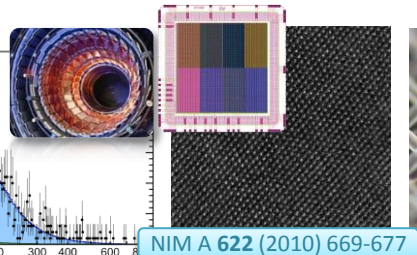
Ion Electron Emission Microscopy - INFN

NIM B **273** (2012) 234-236



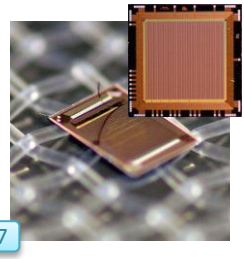
Higgs boson-like particle found INFN @ CERN

Phys. Lett. B **716** (2012) 30-61



0.5 Å microscope - Berkeley

NIM A **622** (2010) 669-677



Ongoing R&D

NIM A **636** (2011) S31-S36

NIM A **731** (2013) 146-153

WO 2013/075728 A1

The experience from all these different fields is brought together into the iMPACT project. While the iMPACT R&D goal clearly target the medical physics, the project has been conceived to also advance science in those sectors it originates from.

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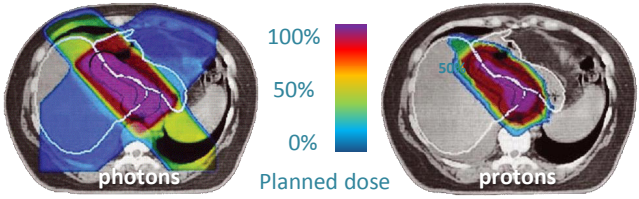
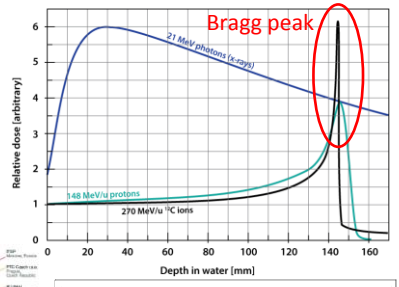
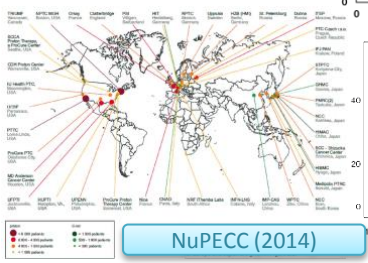
1 2 Protons / heavy ions therapy offers significant advantages over traditional x-rays therapy due to the physics mechanism which makes protons depositing their energy mostly in a narrow volume into the body (the Bragg peak), therefore reducing the collateral damage to the surrounding tissues:

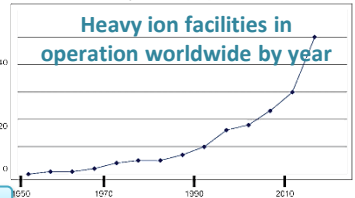




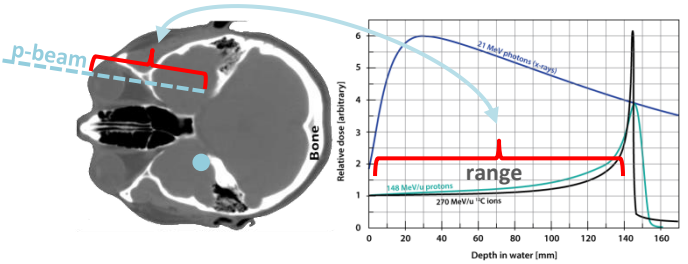
The number of protons and ^{12}C cancer treatment facilities is steadily increasing worldwide, Europe included. Smaller and more efficient accelerators and novel beam delivery systems are in development phase by many labs and companies.



NuPECC (2014)



3 To precisely aim the Bragg peak it is necessary to tune the ion energy accordingly to the tissues density it must pass through to reach the tumor. While the energy tuning can be more accurate than 1%, the knowledge of the 3D distribution of the tissue density is known with much more uncertainly, which leads to aiming (range) errors up to 5%. This is actually the main source of collateral damage in ions therapy.



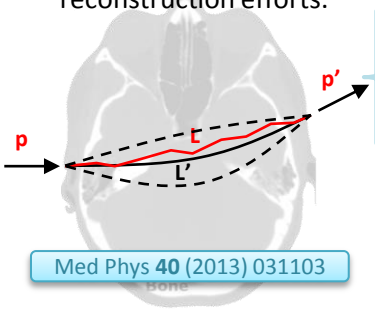
X-ray 3D CTs are nowadays used to get the 3D image representing the target tissue density distribution in space. X-rays cannot distinguish tissue densities with the required precision.

NIM B **268** (2010) 3295–3305 | Eur. Phys. J. Plus (2011) **126**: 78

Protons have much better capability to distinguish tissue densities, and deliver much less dose in doing so, ≈ 1.5 mGy vs. 10-100 mGy. Furthermore, the conversion coefficient from X-rays to protons for treatment planning is no more needed.

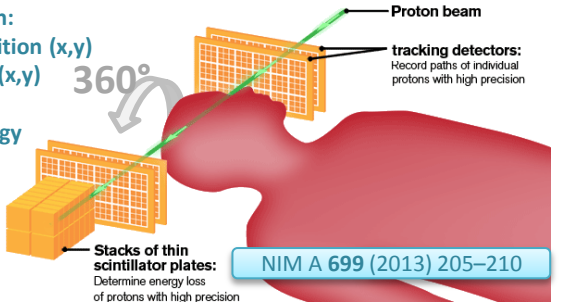
Phys. Med. Biol. **56** (2011) 2407–2421

4 To retrieve a complete 3D target image by using protons it is necessary to perform a proton Computed Tomography (pCT). The pCT works on the very same principle as a "standard" x-rays CT: recording particles passing through the target from different angles to reconstruct a 3D image. The main difference is that, while photons are simply absorbed, protons also scatters, which greatly complicates the tracking and reconstruction efforts.



For each proton:
- Entrance position (x,y)
- exit position (x,y)
- exit angle
- residual energy

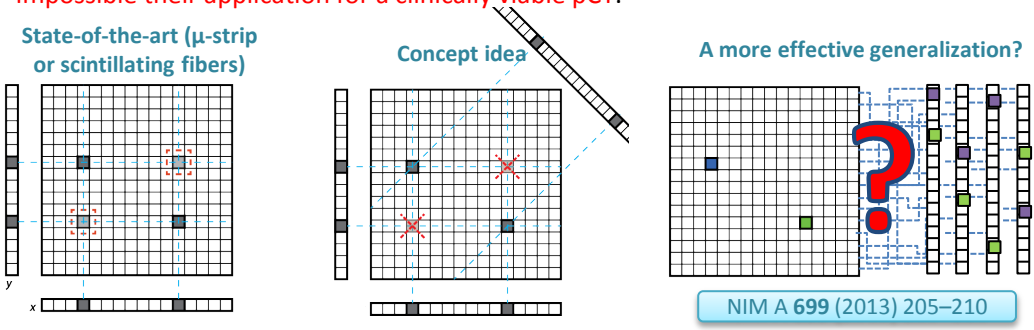
Med Phys **40** (2013) 031103



NIM A **699** (2013) 205–210

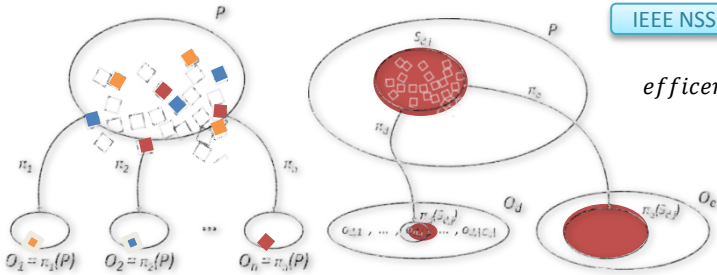
At least 10^9 complete proton tracks (energy loss, exit point & angle, entry point) have to be recorded to provide a detailed enough image. With state-of-the-art apparatus this requires long exposure time (10s minutes), making pCT impractical for real use.

5 State of the art pCT prototypes are limited in speed because of the sensor technology they use (micro-strips and/or scintillating fibres) and because they actually are 1D sensors arranged to form a projective 2D detector, which cannot distinguish more than one hit per frame. This limit implies (Poisson statistics) that the actual particle flux which is possible to track at full efficiency is about only 1/10 of the detector frame rate. Plus, the double layer arrangement increases the material the protons must transverse, increasing the scattering and adversely affecting image reconstruction. Finally, they all employ non commercial technologies, and many uses high-voltage elements, rendering impossible their application for a clinically viable pCT.



NIM A **699** (2013) 205–210

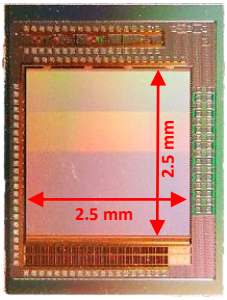
The iMPACT detector is based on an innovative architecture developed by the PI together with Dr. Walter Snoeys, which extends the intuitive idea of adding more projections (like the diagonal one in the picture) to a x-y detector to help handling more than one hit per frame. These additional (n) projections ensure the detector can actually handle more than one hit per frame, and the efficiency has been accurately modelled into a mathematical model. The mathematically described projections can be implemented into a microelectronic pixel detector.



IEEE NSSMIC **2012** 1735–1741

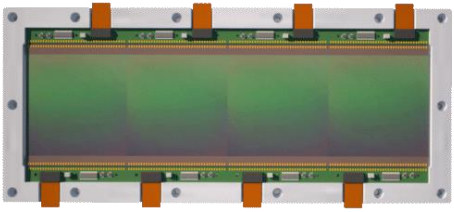
$$efficency = 1 - \left[1 - \left(1 - \frac{1}{H}\right)^{\frac{(H^2-H)^{\frac{n}{2}}}{N^2}}\right]^n$$

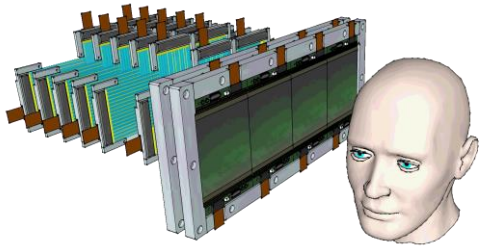
The mathematical model describes the pixel detector efficiency in tracking multiple hits per frame, and how to implement it into a real device.

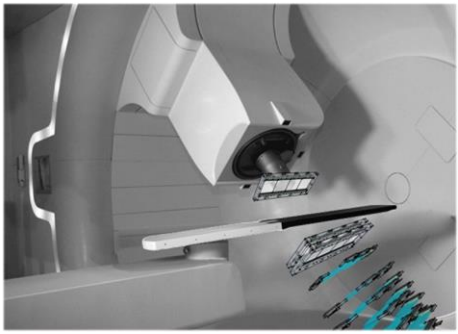


- Breakthrough architecture to achieve ultra-fast (**> 10 MHz cm^{-2}**) tracking and low power (**10 mW cm^{-2}**) thanks to in-fabric data compression.
- Monolithic, thinned (**≤ 50 μm**) device to minimize material budget, hence proton scattering.
- **Cost effective**, reliable, simplified commissioning & operations, commercial process (for large production).
- No present detector/technology meets these requirements!

6 A working iMPACT detector will allow building a tracker and a calorimeter of unprecedented characteristics. From leading pCT R&D groups experience and the characteristics of the proposed sensor, a sixteen 4 × 4 cm^2 or four 8 × 8 cm^2 tiles detector is foreseen for the tracker. Such an arrangement makes it possible to group all the readout electronics and bonding pads on the "free" side of any chip.

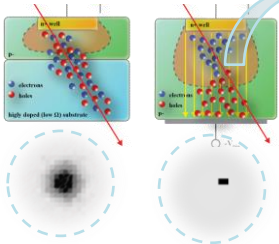






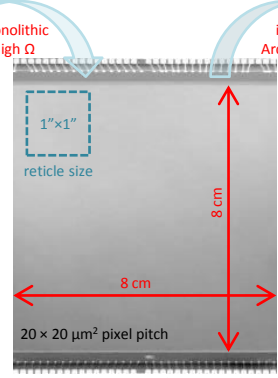
The tracker is the most challenging goal of the design, but will be worthless without a calorimeter of matching speed. The proposed solution exploits the same **architectural** concept developed for the tracker, applying it to a multi-segmented range calorimeter (hence achromatic) which will be capable of registering the residual energy of more than one particle in its sensitive volume.

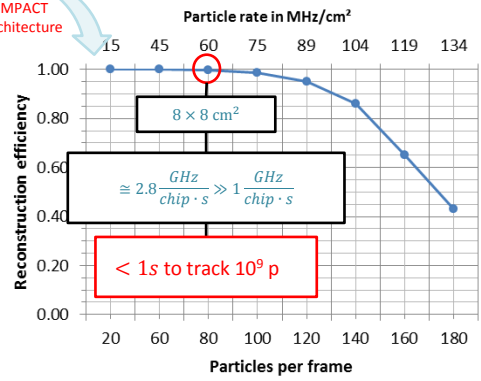
7 iMPACT architecture will be embedded into a commercial high resistivity substrate or epitaxial layer CMOS process. The high resistivity ensures higher charge collection speed (hence higher frame rate) and better control over the protons cluster size, a key parameter to optimize the readout bandwidth. With such characteristics and the possibility to produce large area detector via the stitching process (also commercially available), we aim to build large (up to a 8 × 8 cm^2 in the best hypothesis) detector of up to 4096 × 4096 pixels able to track protons at more than 1 GHz.



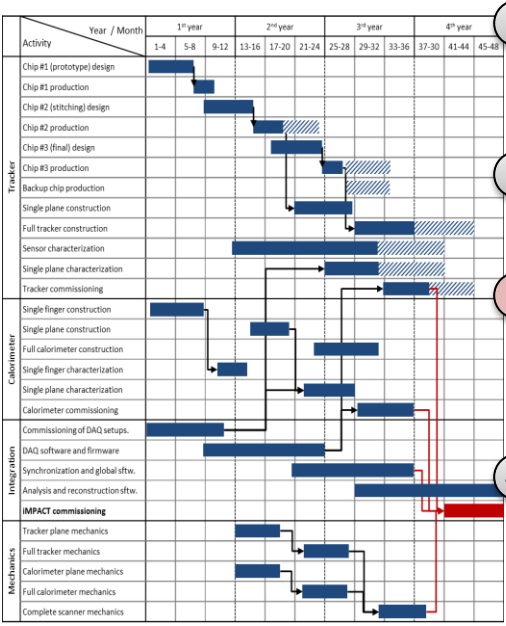
Clusters size of a 300 MeV proton (50 µm pixel pitch) with standard (left) and high Ω depleted substrate (right).

NIM A **731** (2013) 146-143





8 iMPACT R&D goal is to demonstrate the validity of the idea, ideally realizing a prototype to demonstrate all developed solutions. To better deal with the many challenges the project will face, a major status review is planned at 2 to 2.5 years into the project, to steer the resources accordingly to the achieved results so far.



1 **First two 2 years ½ R&D on science**
Architecture math, interaction simulations, sensors simulation and design, post-processing technique development, medical requirements adaptation, etc.

2 **In parallel, support systems R&D**
Fast mechanics, DAQ systems, software. All activities managed by specific, field expert people on the project.

3 **After 2 & ½ years (science demonstrated)**
At this point all the single key challenges should have been addressed at R&D level, i.e. 70% of the scientific potential of the project realized, move to prototype realization (4a). Otherwise complete science (4b).

4a **System integration**
Stitching options, system integration, single components & full assembly beam testing.

4b **Complete science**
Complete scientific goals, build single elements prototypes instead than a full system demonstrator.

9 iMPACT wants to completely redefine pCT performance, rendering it an extremely effective diagnostic tool. In parallel, the advancements proposed by the iMPACT design will lead to a pCT compatible with a real medical/patient environment.

Full pCT with 1s exposure
Mechanics must keep the pace; anyway exposures shorter than 30s (breathless) will be considered a success.

Higher resolution @ lower power due to reduced thickness & monolithic, in-matrix compression. 20 µm pixel pitch, single layer (thinned down 50-100 µm thickness) for each tracking station.

Ready to be integrated into real clinical environment for real time targeting and/or treatment. Low voltage, no gas system. Exploits the same beam used for the treatment and could be embedded into the very same treatment gantry.

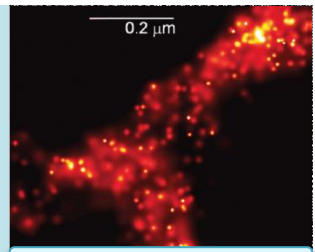
Based on monolithic commercial technology: viable pCT + other applications. Reduced production, assembly and support electronics costs, mass production capability for large instrumented areas.

10

Demonstrating the feasibility of a breakthrough pCT system is iMPACT main goal. But since its inception, many other fields of application which would benefits of such performance improvement has been carefully considered. The iMPACT project has in fact born from the PI and others team members direct experience in High Energy Physics, Electronic Microscopy, Space Telescopes and similar fields. The idea to improve the scientific reach of these research realms is integral part of the project.

iMPACT advancements (high speed @ ultra low power & high resolution with reliable, cost-effective monolithic sensors) will be an enabling technology for the next generation physics instruments and experiments:

e^- and visible light super-resolution microscopy requires maximum speed (in-matrix data compression) and small pixel pitch (< 10 μm).



Chemistry Nobel prize 2014

Next generation HEP trackers and calorimeters needs large surface, thin, ultra-fast, low power sensors, low cost commercial technology.

Science **21** (2012) 1569-1575

Space-born trackers and telescopes needs ultra low power, ultra high resolution (weak magnets in space), extremely reliable.