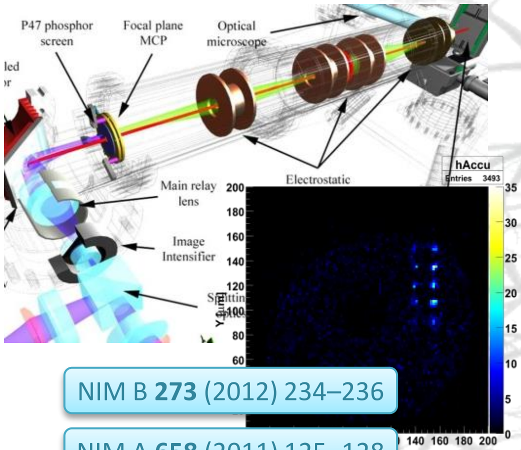
iMPACT

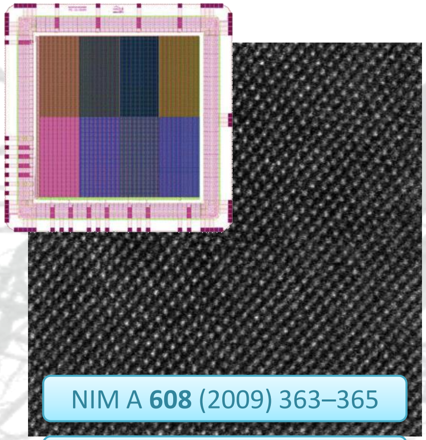
innovative Medical Proton
Achromatic Calorimeter and Tracker



NIM B **273** (2012) 234–236

NIM A **658** (2011) 125–128

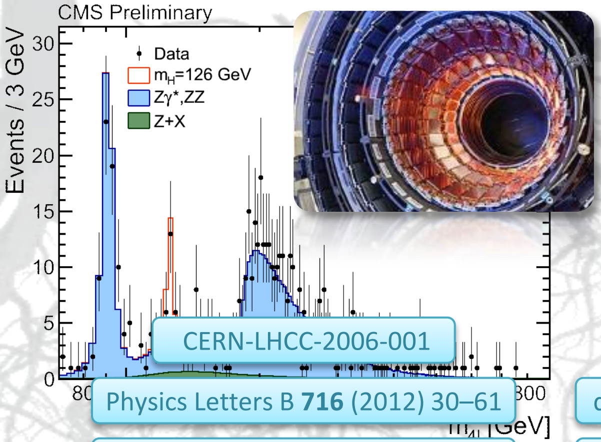
First SEU μMapping facility – INFN



NIM A **608** (2009) 363–365

NIM A **622** (2010) 669–677

0.5 Å resolution TEAM microscope – Berkeley

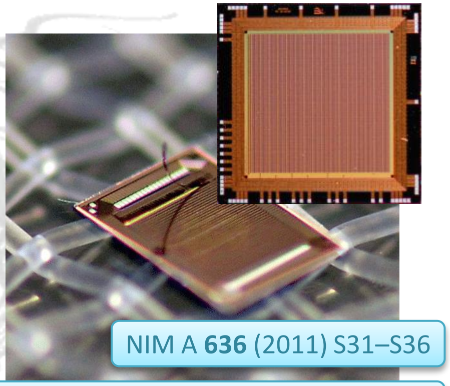


CERN-LHCC-2006-001

Physics Letters B **716** (2012) 30–61

Science **21** (2012) 1569 – 1575

Higgs boson finally found INFN @ CERN



NIM A **636** (2011) S31–S36

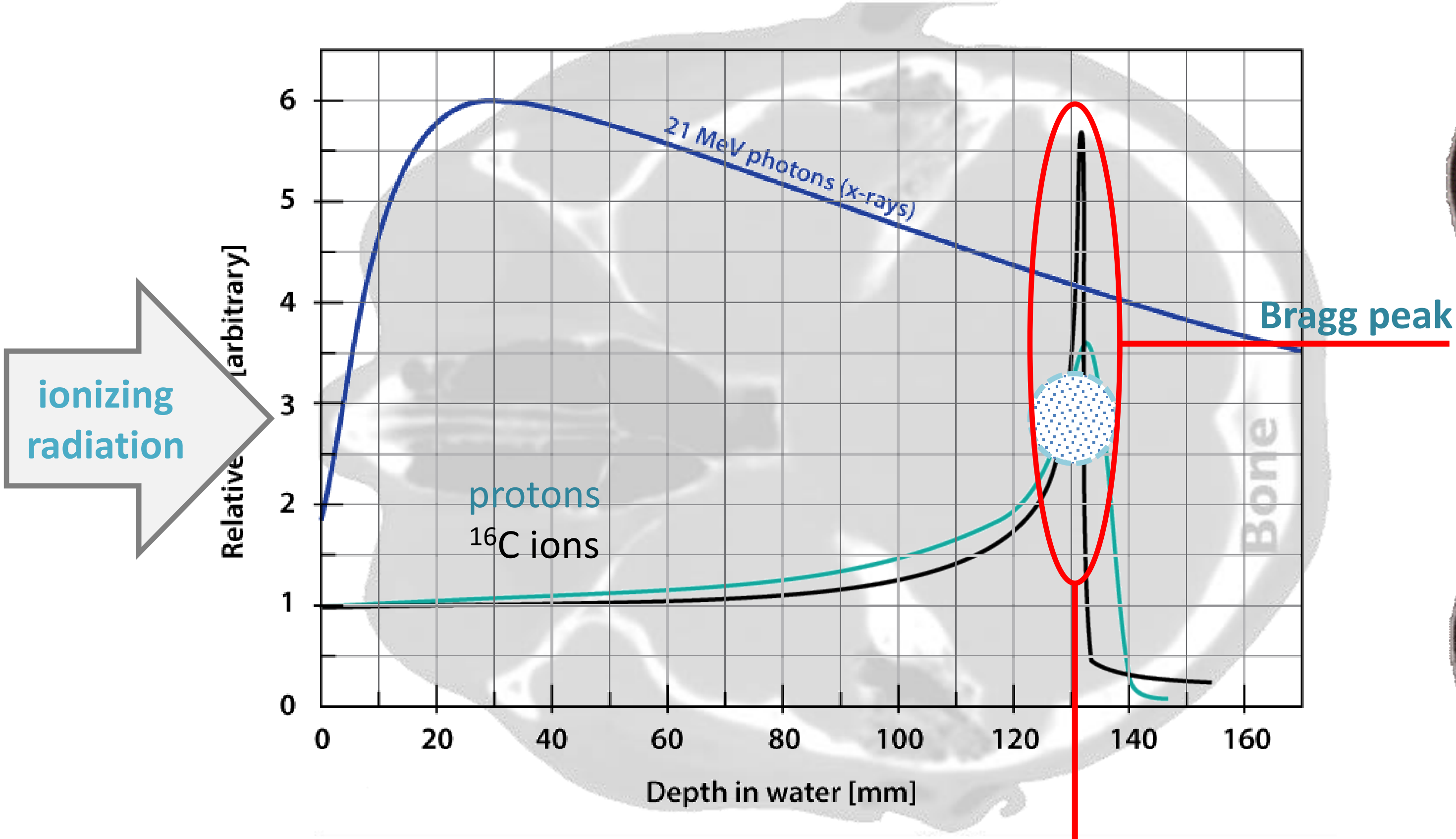
dx.doi.org/10.1016/j.nima.2012.10.098

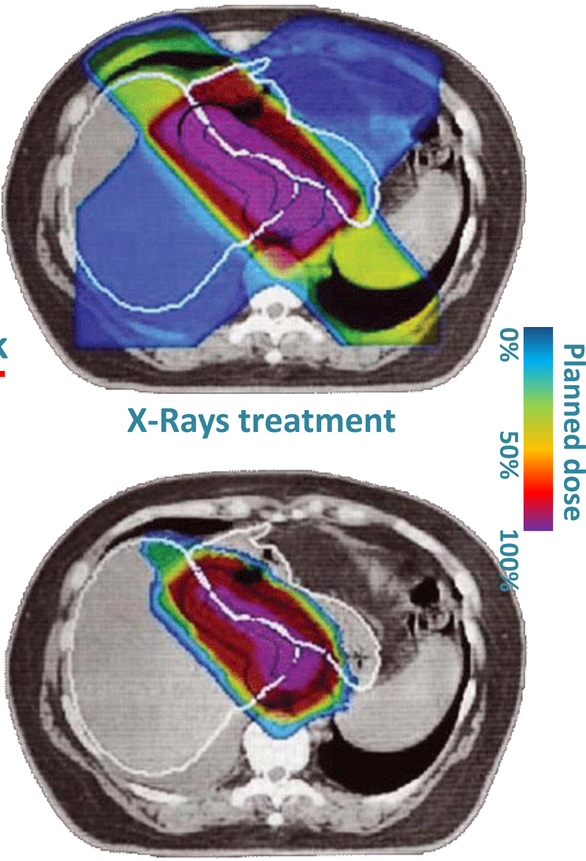
dx.doi.org/10.1016/j.nima.2013.04.042

Ongoing R&D @ INFN & CERN

Proton therapy: physics rationale

Proton (ion) energy transfer is highly localized (Bragg peak): greater effectiveness and much lower collateral damage respect to traditional x-rays therapy.





X-Rays treatment

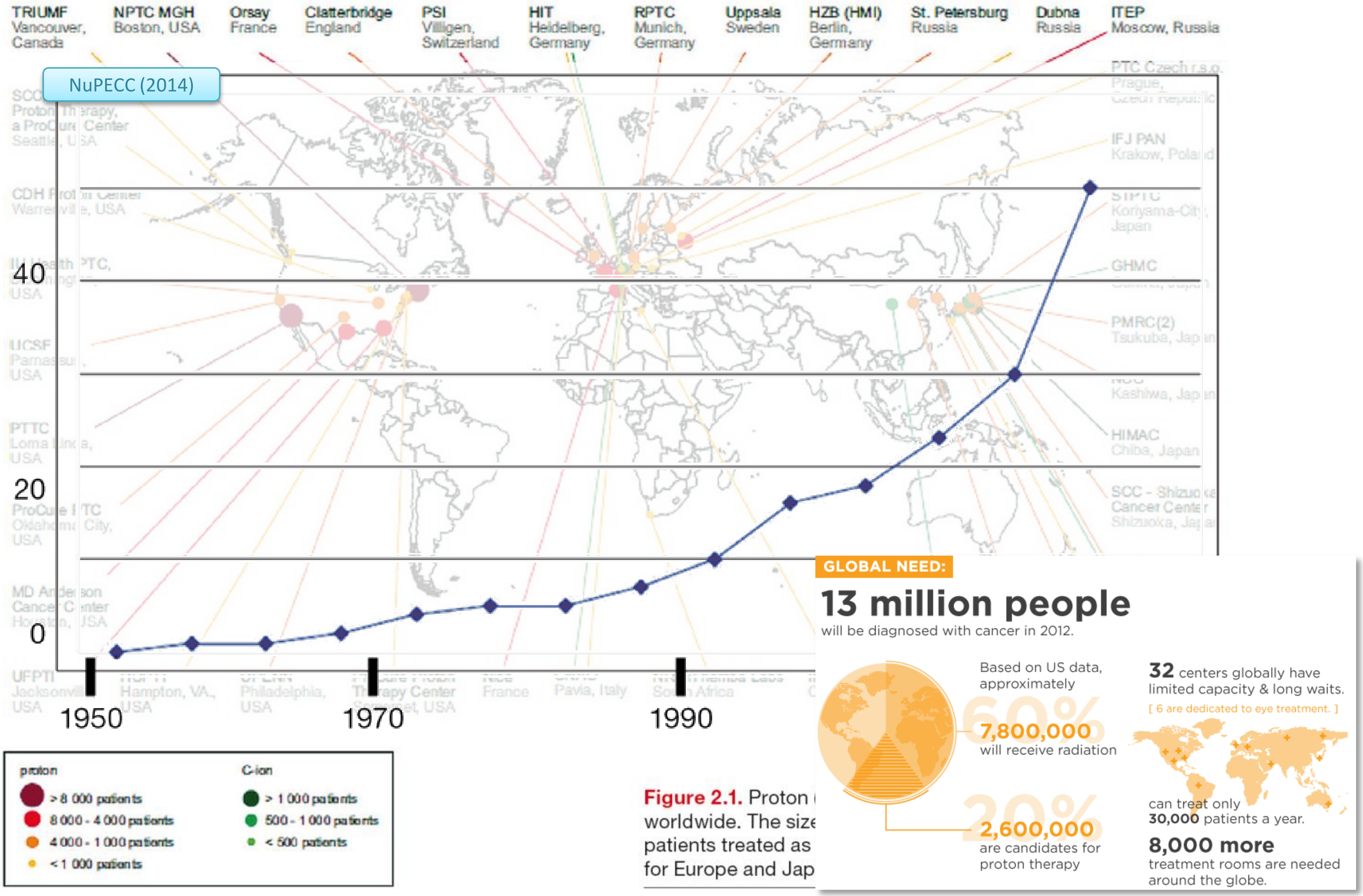
Protons treatment

The Bragg peak position (depth) in the body depends on the ion energy and the tissue density it traverses. Changing energy determines the aiming depth.

JAMA **307** (2012) 1611-20

Radiation Oncology*Biology*Physics **83** (2012) 1549–1557

Proton and C-ion therapy centers worldwide



NuPECC (2014)

Figure 2.1. Proton
worldwide. The size
patients treated as
for Europe and Jap

GLOBAL NEED:

13 million people will be diagnosed with cancer in 2012.

Based on US data, approximately 60% **7,800,000** will receive radiation

20% **2,600,000** are candidates for proton therapy

32 centers globally have limited capacity & long waits.

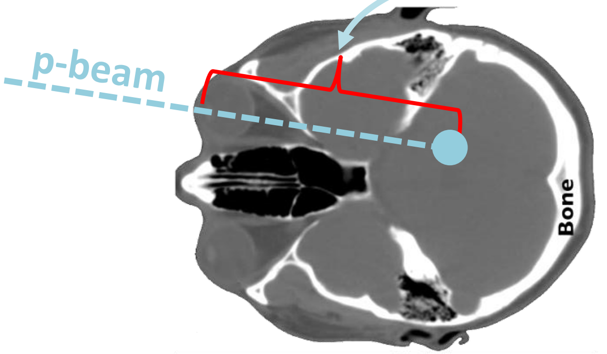
[6 are dedicated to eye treatment.]

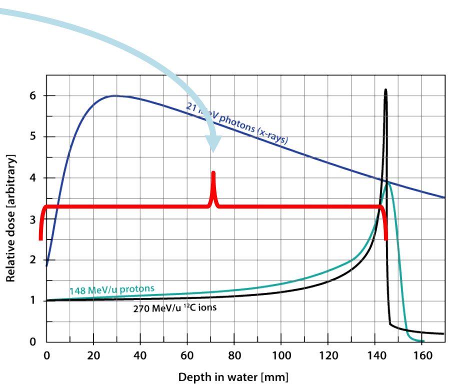
can treat only **30,000** patients a year.

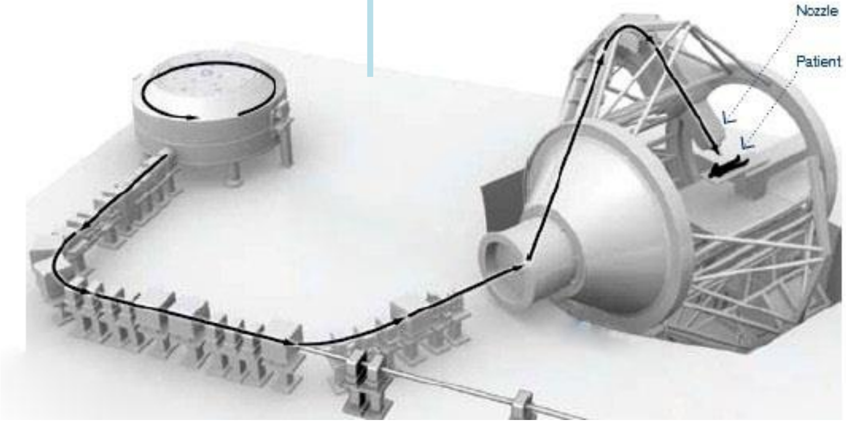
8,000 more treatment rooms are needed around the globe.

Proton therapy: the aiming limit **problem**

Aiming the Bragg peak requires fine tuning of the proton energy to account for the tissue densities they have to traverse to reach the tumor.







Poor tissue density resolution from X-Rays CT

Fine energy tuning better than 0.5%

X-ray 3D CT cannot distinguish tissue densities with the required precision: proton therapy limit today (bigger systematic error, up to 5%). But protons actually can (and with much less dose, ≈ 1.5 mGy vs. 10-100 mGy).

NIM B **268** (2010) 3295–3305

Eur. Phys. J. Plus (2011) **126**: 78

X-Rays

Protons

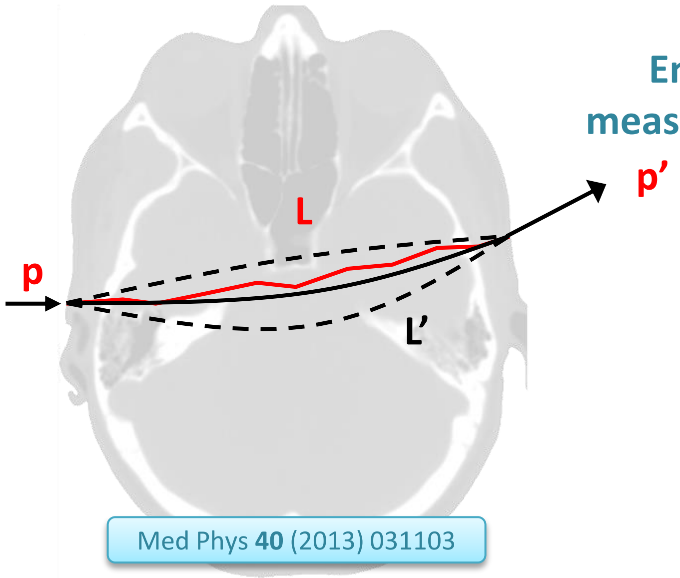
Protons – different reconstruction

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

The proton Computed Tomography (**pCT**) scanner

The pCT works on the same principle as a "standard" x-rays CT: recording particles passing through the target from different angles to reconstruct a 3D image. Main difference is that, while photons are simply absorbed, protons also scatters.

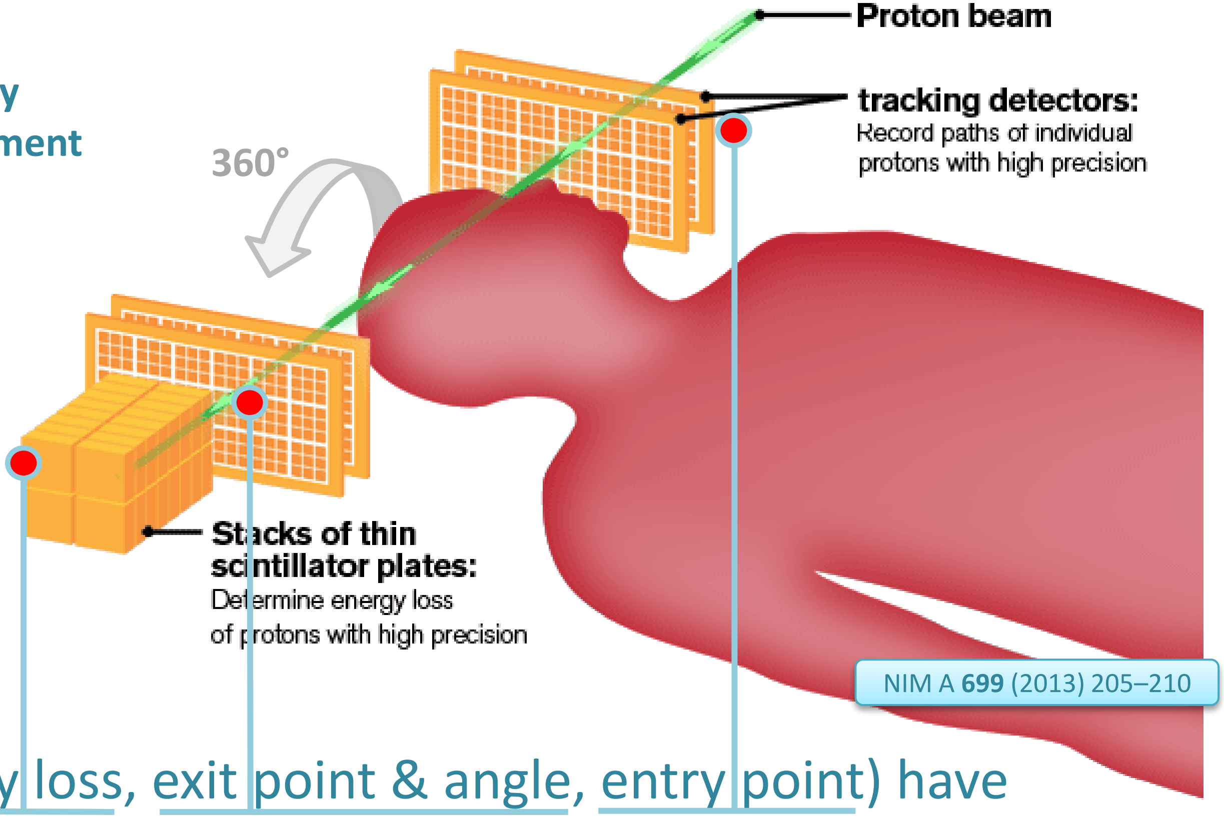
Proton true trajectory



Med Phys **40** (2013) 031103

Entry and exit points + angle

Most Likely Path calculation



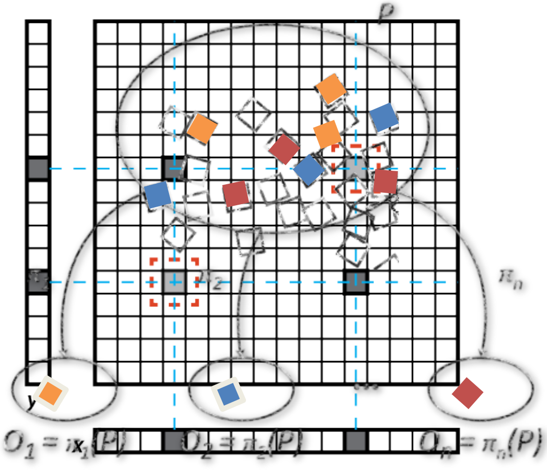
NIM A **699** (2013) 205–210

At least 10^9 proton tracks (energy loss, exit point & angle, entry point) have to be recorded to provide a detailed enough image. This leads to long exposure time (10s minutes) with current state of the art: limited to R&D only.

iMPACT challenge – record 10^9 tracks with µm precision in 1s

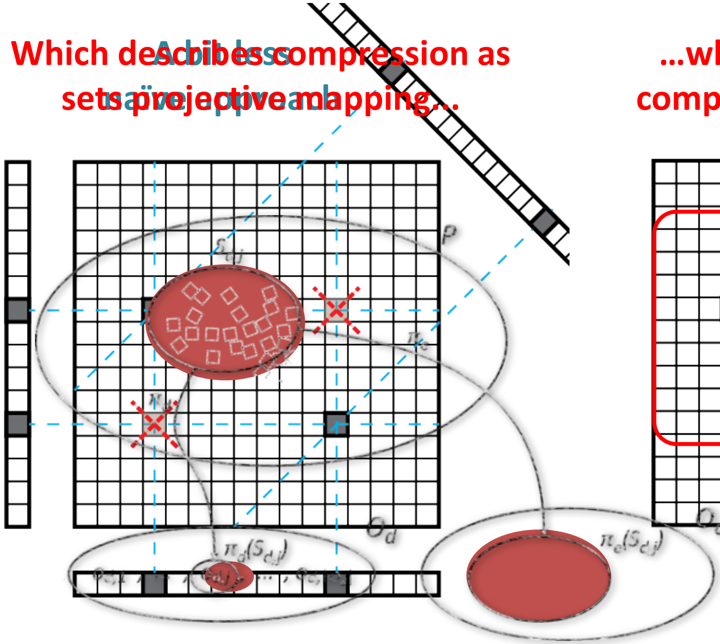
Naïve approach, current state-of-the-art

Yes, a very general, math defined one!



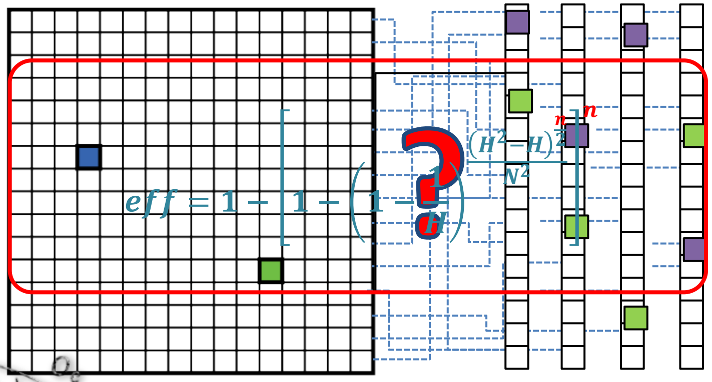
A lossless naïve approach

Which describes compression as sets projective mapping…

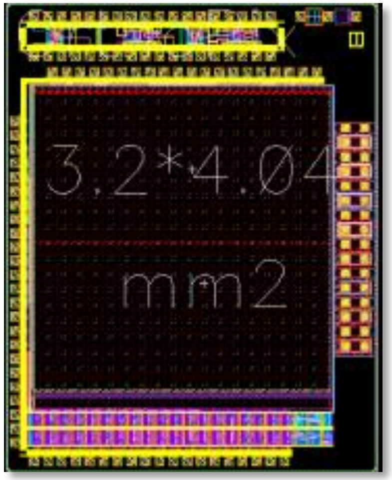


A more effective approach possible?

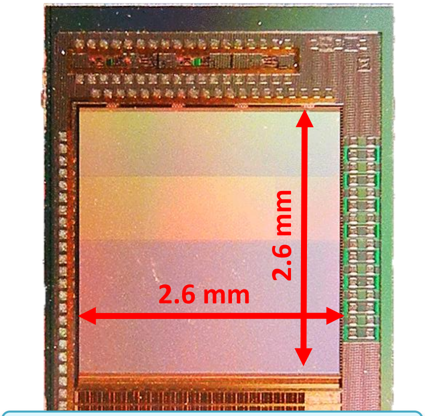
…which can be embedded into pixel fabric to compress data at the matrix level (HUGE speed)



IEEE NSSMIC **2012** 1735–1741



- 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 detector/technology meets these requirements!

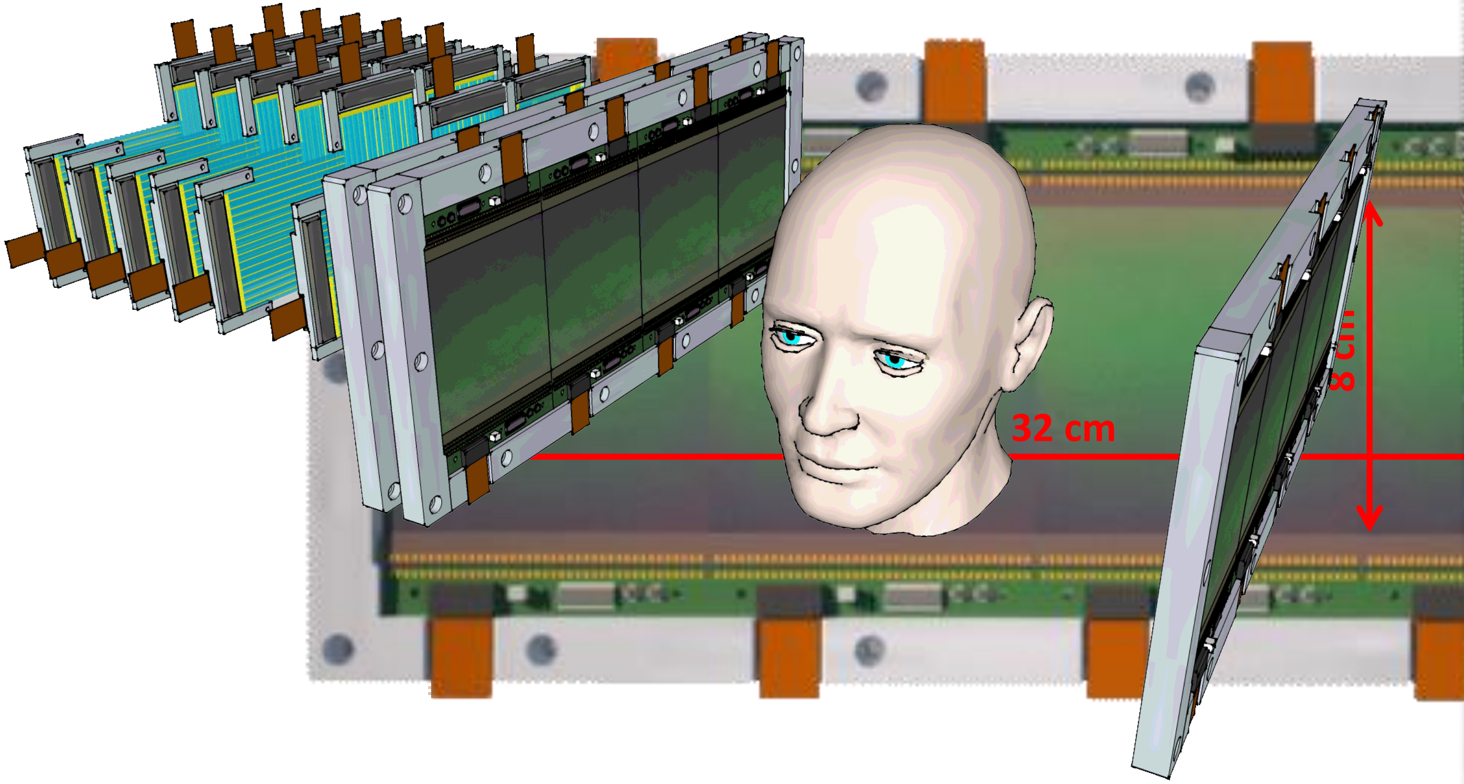


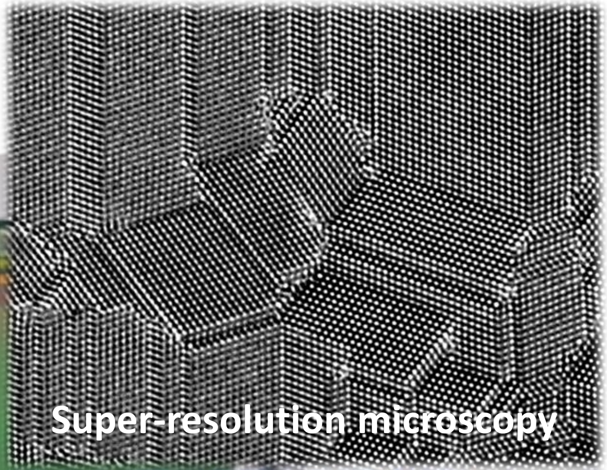
Presented in Sept. at PIXEL 2014

Tower-Jazz 0.18 µm, various substrates thickness/resistivity.

iMPACT – monolithic tracker with unparalleled performance

Based on leading pCT groups experience and the characteristics of the proposed CMOS chip, a sixteen 4 × 4 cm^2 or four 8 × 8 cm^2 tiles detector is foreseen. Such an arrangement makes it possible to group all the readout electronics and bonding pads on the two “free” sides of any chip.



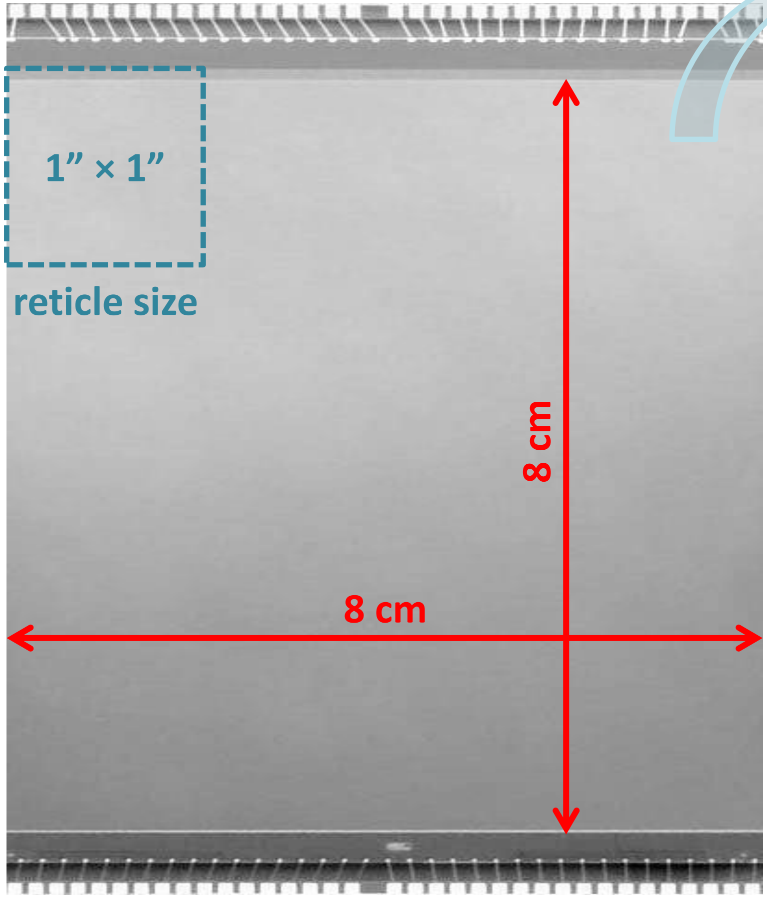

Super-resolution microscopy


HEP tracking

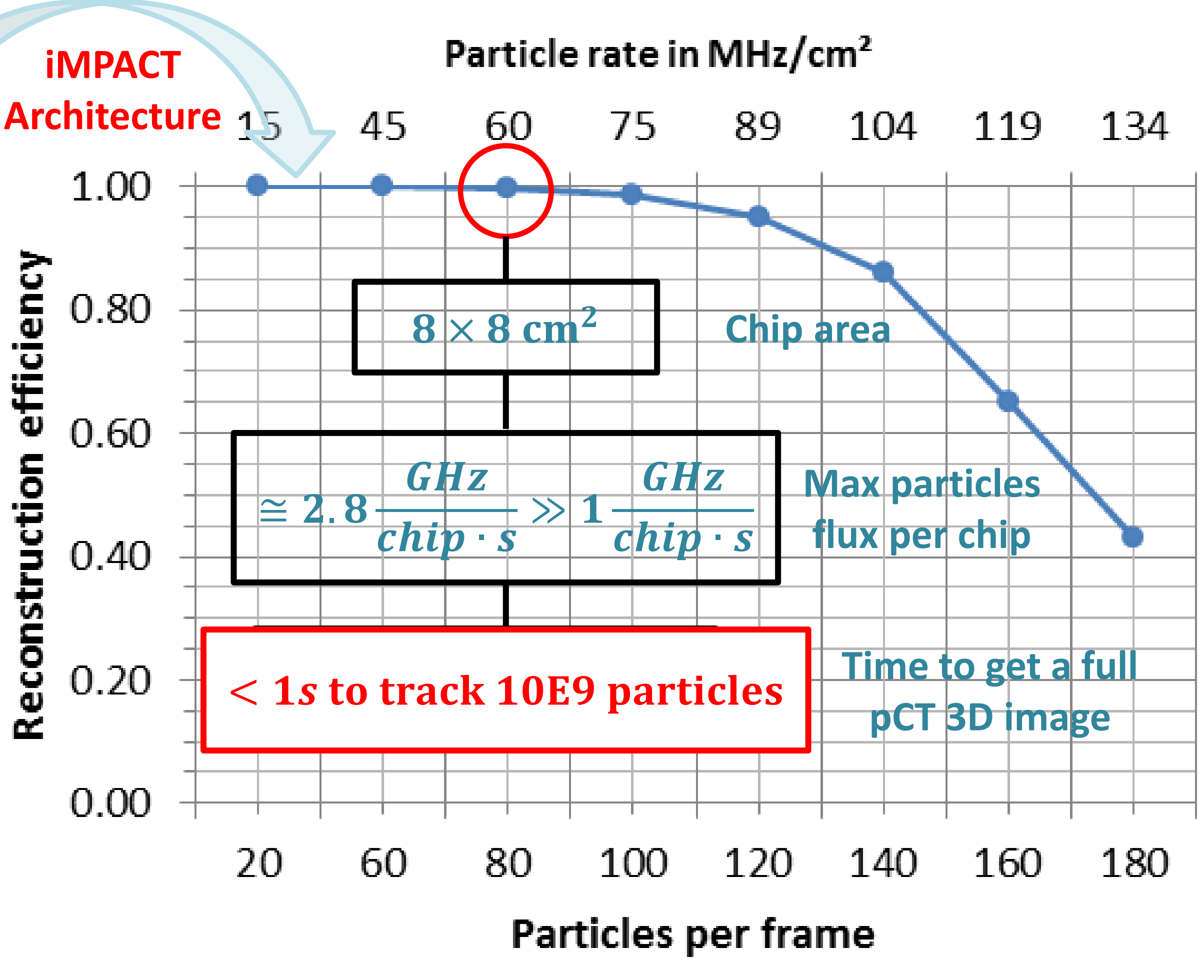
Readout is per-chip, and the whole assembly easy to integrate in a rotating head.

iMPACT – performance quantitative overview

To produce the large area detector we need for a pCT scanner in a convenient way, big size chips (some centimeters side) are necessary. Stitching allows to produce single piece detector up to 10 cm side.



4096 × 4096 pixels **20 × 20 µm² pixels**



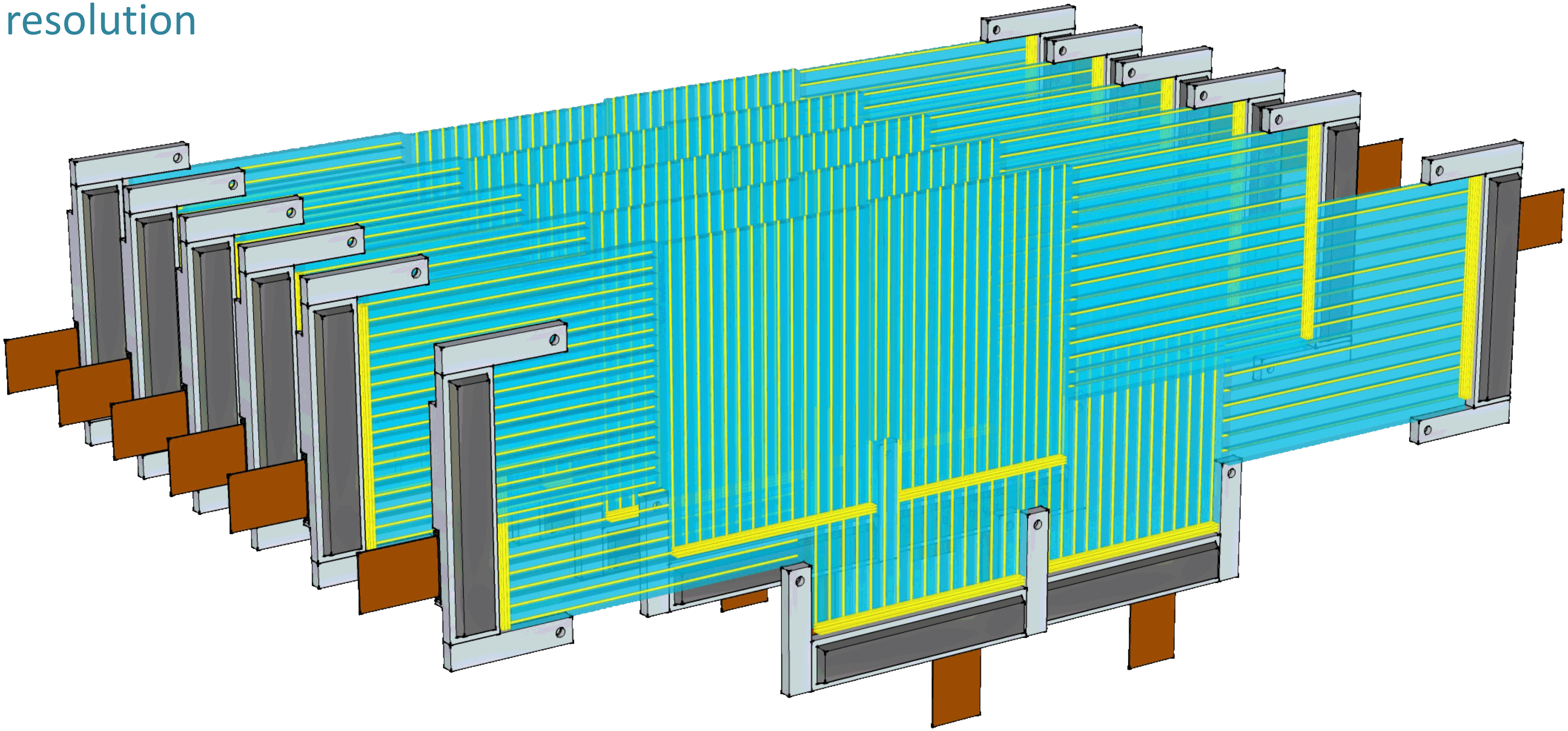
$8 \times 8\ \mathrm{cm}^2$ — **Chip area**

$\cong 2.8\,\frac{GHz}{chip \cdot s} \gg 1\,\frac{GHz}{chip \cdot s}$ — **Max particles flux per chip**

$< 1s$ **to track 10E9 particles** — **Time to get a full pCT 3D image**

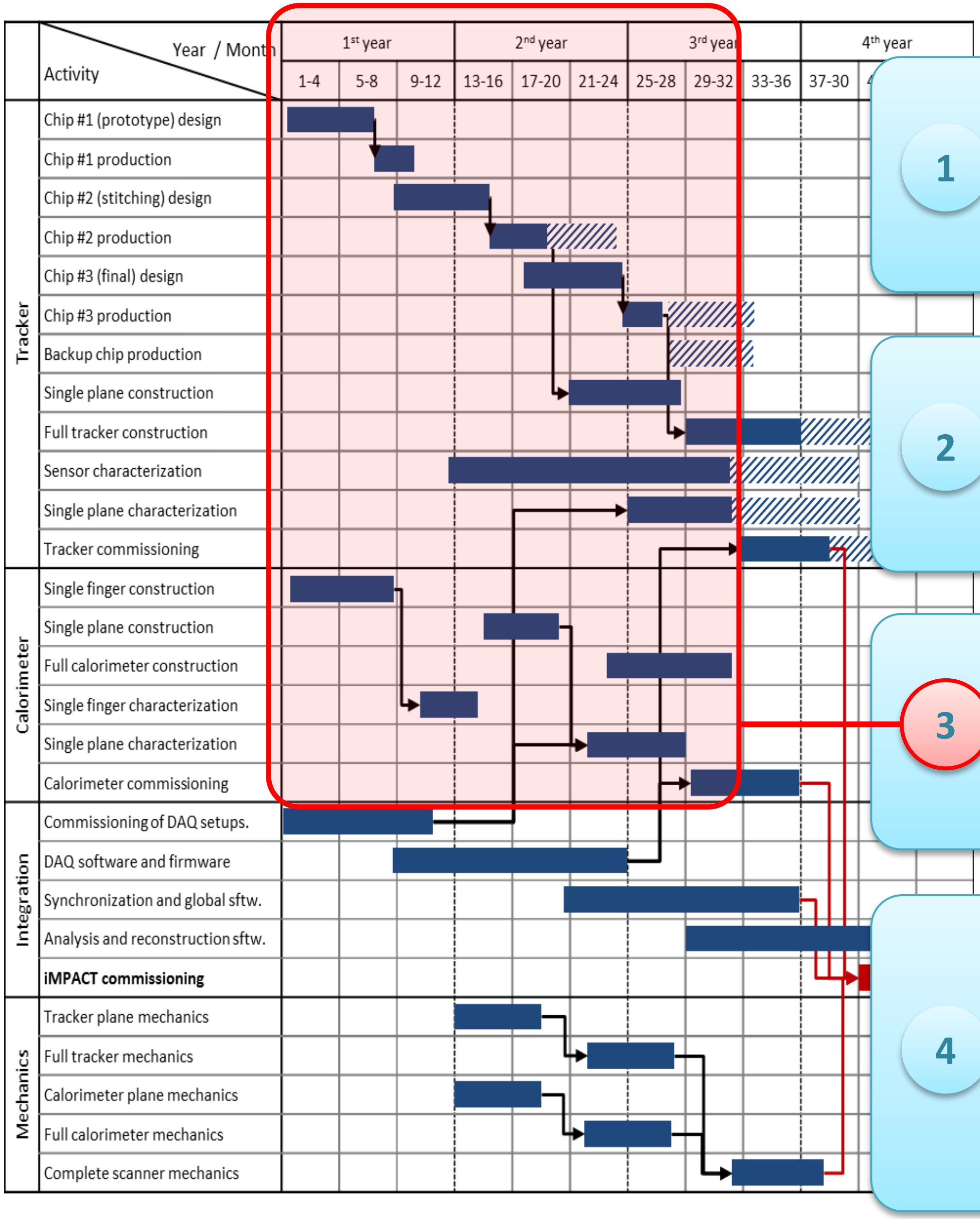
iMPACT – calorimeter

A range calorimeter (48 to 64 plates) based on segmented scintillation planes (to match the iMPACT architecture) and SiPM arrays readout, base on off the shelf components and technology. 1 GHz protons rate capable with 1% energy resolution



Each plane is 3-4 mm thick, with 16 dedicated readout fibers and SiPM array.

iMPACT – it is not a simple task…



1

First two 2 years ½ R&D on science & technology

Math to optimize the architecture, particle interaction simulations, sensors simulation and design, production techniques, ancillary systems design, etc.

2

In parallel, mandatory 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 goals 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.

4

System integration

Stitching options, system integration, single components & full assembly beam testing.

4b

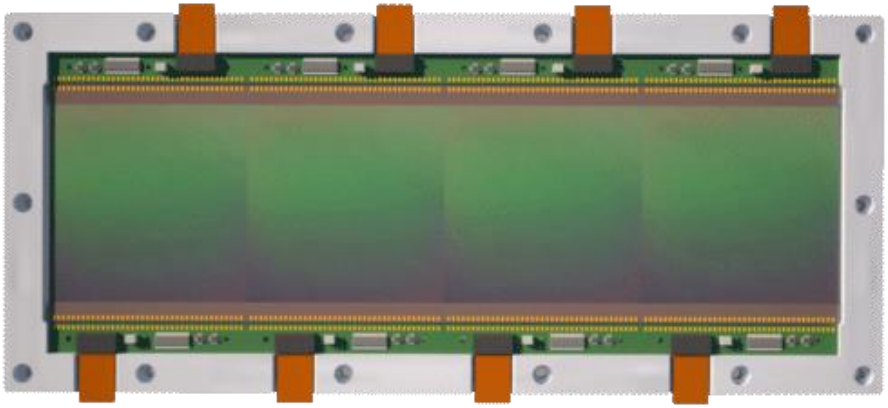
Complete science

Complete scientific goals, single parts prototypes instead than full system.

iMPACT – …but it is definitely worth it

1 Thanks to > 1GHz real tracking rate capability: full pCT with **1s exposure**

Mechanics must keep the pace; anyway exposures shorter than 30s (breathless) are achievable.

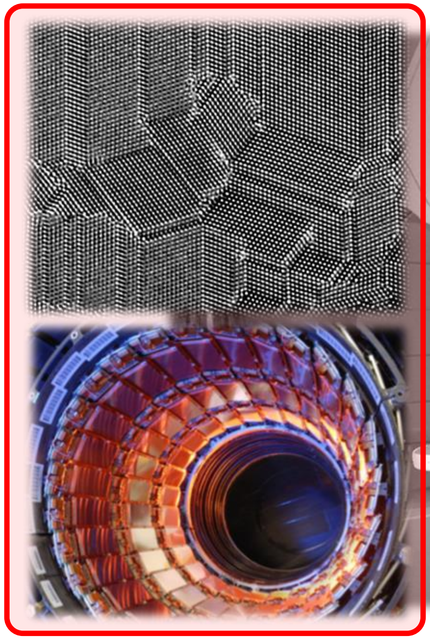


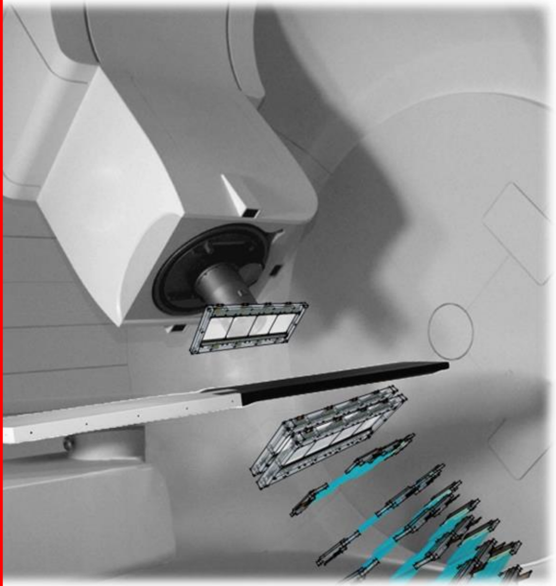
2 Ready to be integrated into real clinical environment for **real time targeting/treatment**.

Low voltage, no gas system. Exploits the same beam used for the treatment and could be embedded into the very same treatment gantry.

3 **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.

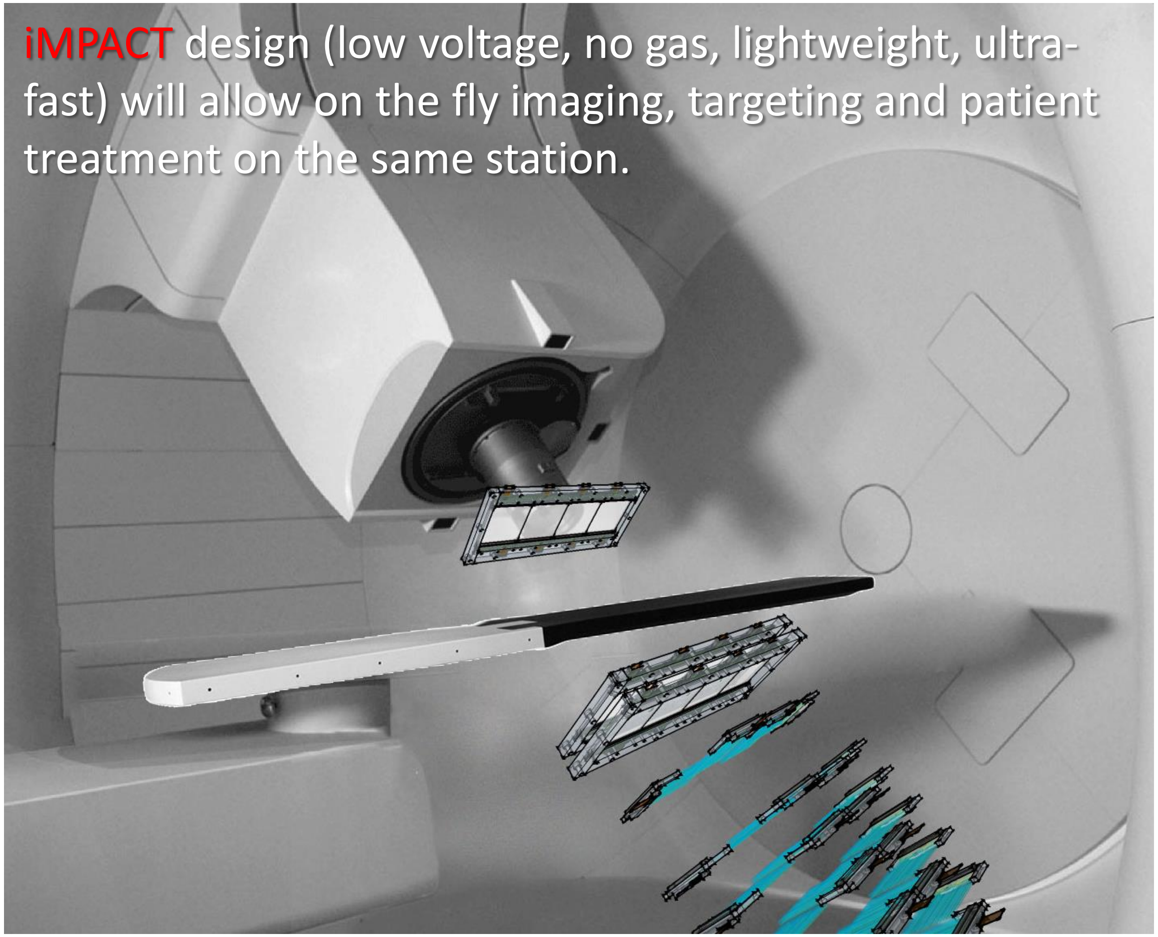




4 Monolithic & commercial system: **viable pCT + other applications**.

Reduced production, assembly and support electronics costs, mass production capability.

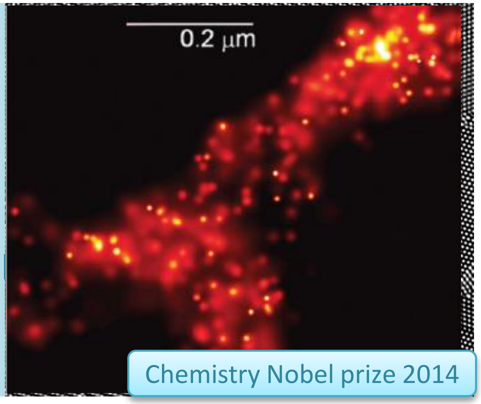
iMPACT – from physics to medical and back to physics



iMPACT design (low voltage, no gas, lightweight, ultra-fast) will allow on the fly imaging, targeting and patient treatment on the same station.

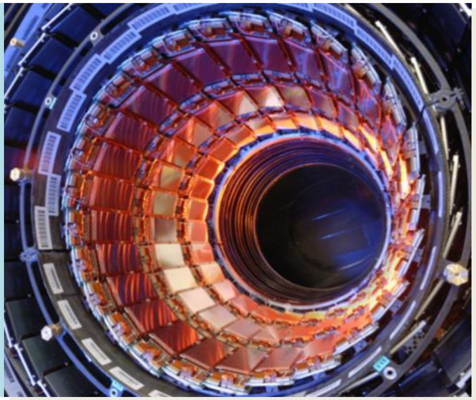
iMPACT advancements (high speed @ ultra low power & high resolution with reliable, cost-effective monolithic sensors) will be an enabling technology for the next generation physics instruments and experiments:

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

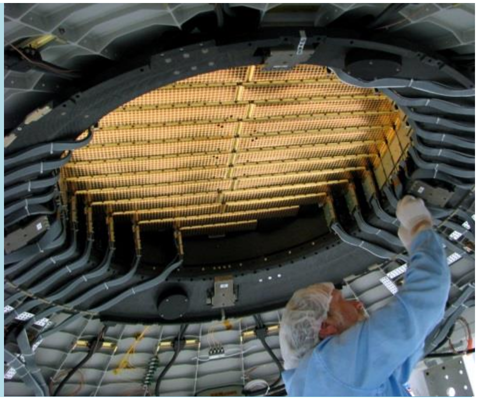


Chemistry Nobel prize 2014

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



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



iMPACT

Moving the pCT from R&D to clinical employment by redefining particle tracking

Thanks for your attention

Backup & deeper insight

iMPACT – the team

Core team

- Dr. Walter Snoeys, CERN senior engineer, will assist the PI In the design activity.
- Prof. Jeffery Wyss, an host institution member, will focus on the coordination of lab experiments and the calorimeter development.
- Dr. Serena Mattiazzo and Dr. Nicola Pozzobon, postdocs, will be in charge of the sensors characterization and the detector monte-carlo simulations.
- Dr. Tommaso Dorigo, staff senior physicist, will verify data reconstruction accuracy and coordinate of all the data analysis activities.
- Devis Pantano, Dr. Adriano Pepato and Marino Nicoletto will be the host institution technical specialists in charge for the electronics and mechanics R&D.
- Two Post-Doc and one PhD positions will be assigned in total.

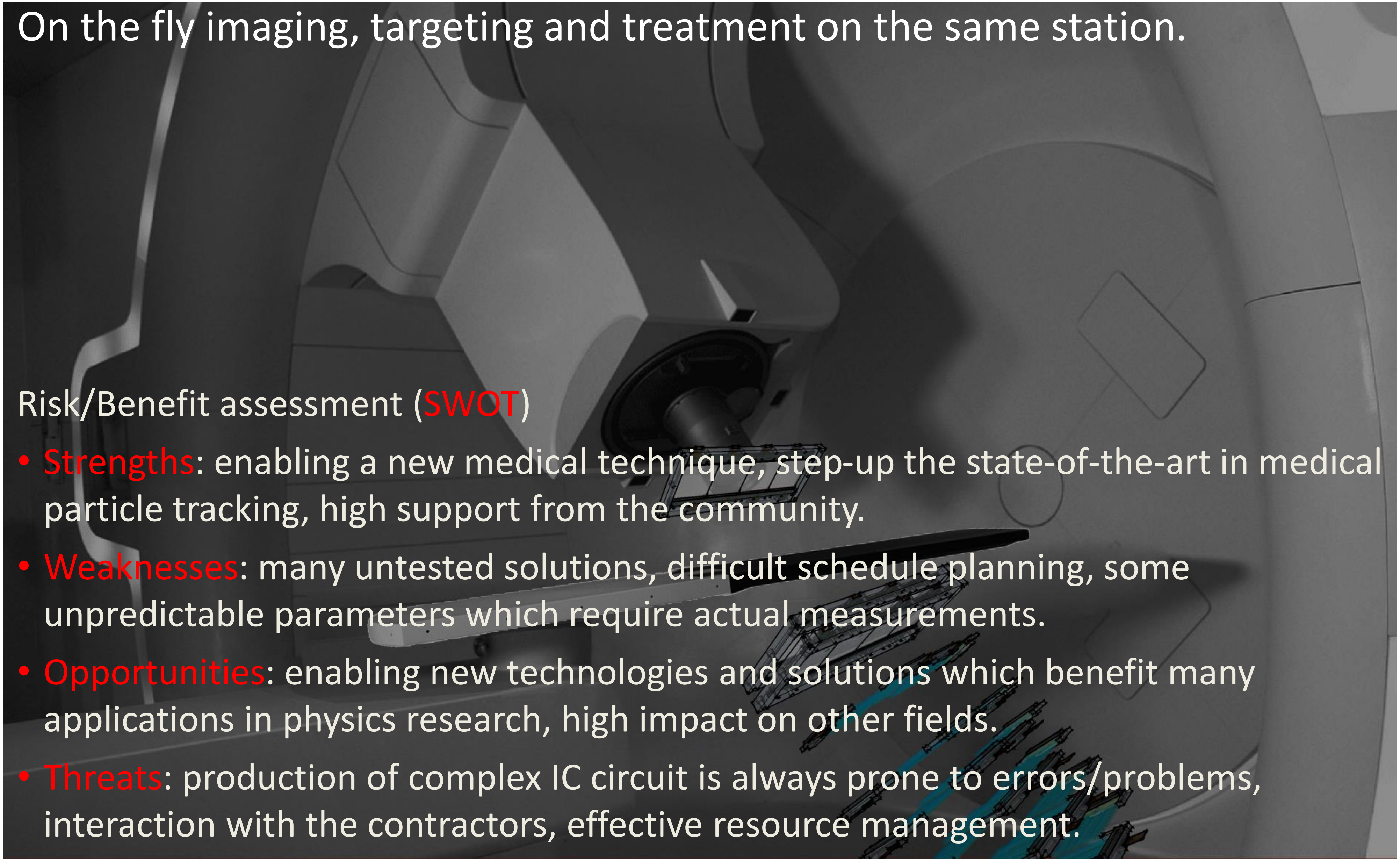
External support

- Prof. Massimo Carpinelli, professor of Medical Physics at University of Sassari, will act as permanent reviewer of the project development.
- Dr. Renzo Leonardi, Dr. Marco Schwarz, Dr. Carlo Algranati, all from Trento proton treatment center will advise on real-word treatment delivery issues.

iMPACT – budget

Group	Item	Cost
Personnel	Two post-doc over 4 years	408,000 €
	All others supported by the host or theyr own institution	-
Sensors development	Submission (average ≈250.000€ each)	700,000 €
	Stitching option (only last submission)	50,000 €
	Wafer post processing	10,000 €
IT	Control computers and backup systems	20,000 €
Consumables	DAQ electronics (2 PXI systems)	100,000 €
	Calorimeter SiPMs	80,000 €
	Mechanics and electronics consumables	40,000 €
Travels	Testing at teast-beam facilities	20,000 €
	Travel and conference participation	20,000 €
Total direct		1,408,000 €
Total	(+25% overhead)	**1,810,100 €**

iMPACT – SWOT



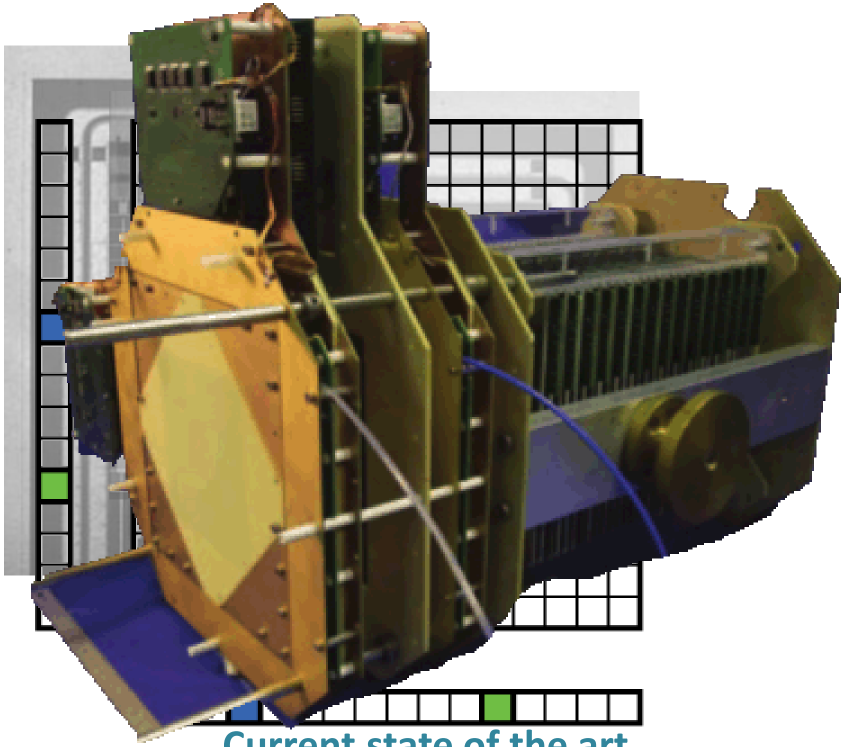
On the fly imaging, targeting and treatment on the same station.

Risk/Benefit assessment (SWOT)

- Strengths: enabling a new medical technique, step-up the state-of-the-art in medical particle tracking, high support from the community.
- Weaknesses: many untested solutions, difficult schedule planning, some unpredictable parameters which require actual measurements.
- Opportunities: enabling new technologies and solutions which benefit many applications in physics research, high impact on other fields.
- Threats: production of complex IC circuit is always prone to errors/problems, interaction with the contractors, effective resource management.

State of the art in pCT scanners

State of the art prototypes pCT trackers employ silicon micro-strips or scintillating fibers to get high speed readout over large area at reasonable bandwidth.



Current state of the art,
in-house built gaseous detector

1. "Slow", as readout speed of 10s MHz (and actual particles rate much less due to Poisson). NIM A **699** (2013) 205–210
2. Requires two layers (x and y) for every station, material budget affects protons scattering + high voltage or gas.
3. Non commercial technology, built in house (scintillating fibers) or derived from HEP experiments (micro-strips).

Such approach covers the large area necessary to track particles over a head-sized target ($\approx 10 \times 30\ \text{cm}^2$) with "affordable" complexity and bandwidth. Effective for R&D, unlikely to meet the requirements of a commercially feasible pCT system.

iMPACT detector – the OrthoPix architecture

The simple “additional diagonal projection” approach can be actually extended to implement a system employing n abstract projections, i.e. mathematically defined groups not representable by simple straight lines.

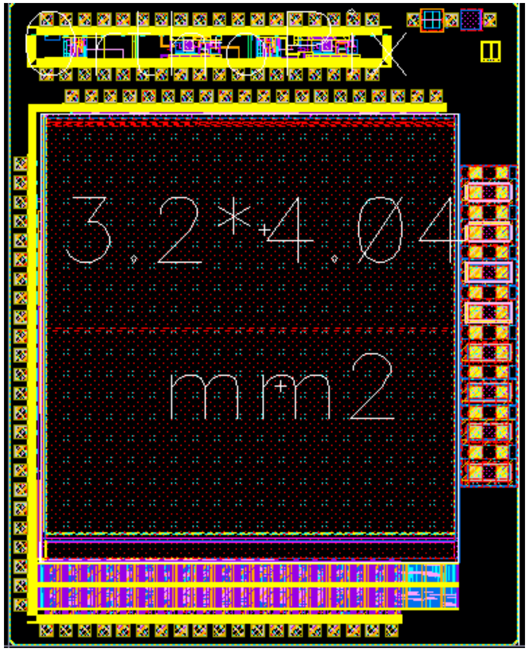
Method and system for compressing a data array
P. Giubilato and W. Snoeys – Patent – C31652PCT

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

 # hits per frame

For practical values of n (n >3) this stays ≈ 1 even with more than one hit per frame ($H > 1$).

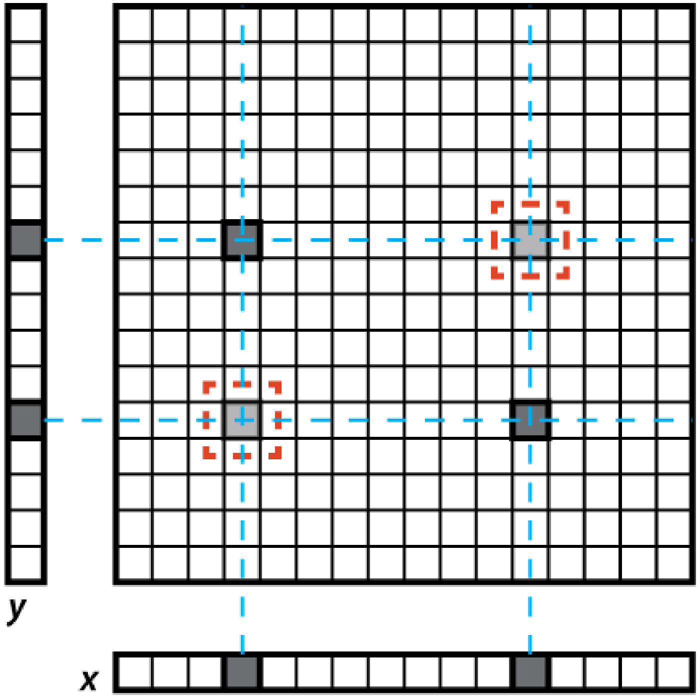
$$compression = \frac{\overset{\text{\# side pixels}}{N}}{\underset{\text{\# projections}}{n}}$$

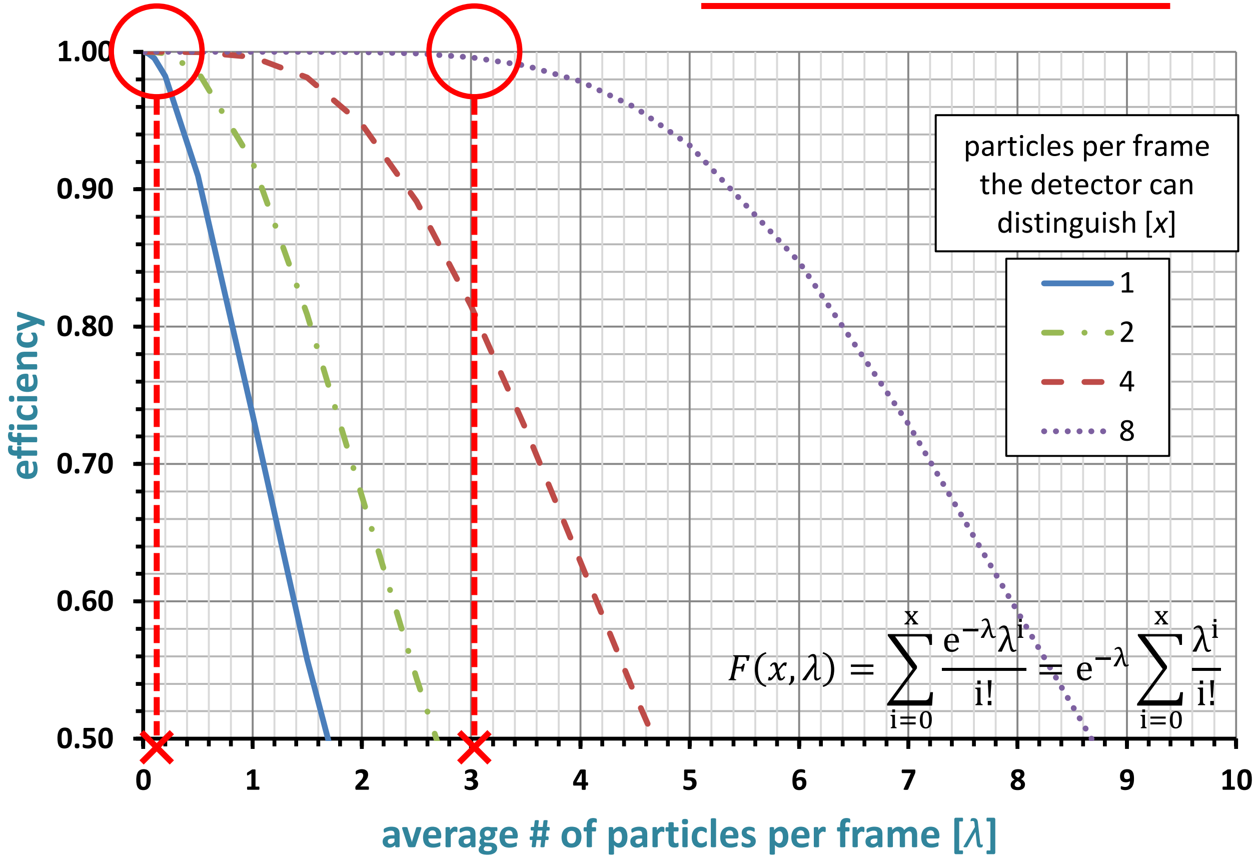


The math has been developed, demonstrated and applied by the OrthoPix project, which led to a joint CERN / Padova University patent. This architecture has been specifically developed to be embedded into solid state pixel detectors, and first prototypes has been already submitted.

iMPACT tracker – the importance of Poisson statistics

Present x, y detectors employed in prototype pCTs are limited in speed due to the fact they cannot distinguish multiple hits per frame. Poisson statistics therefore severely limits the average particle rate per unit of surface (≈1/10 of frame rate).



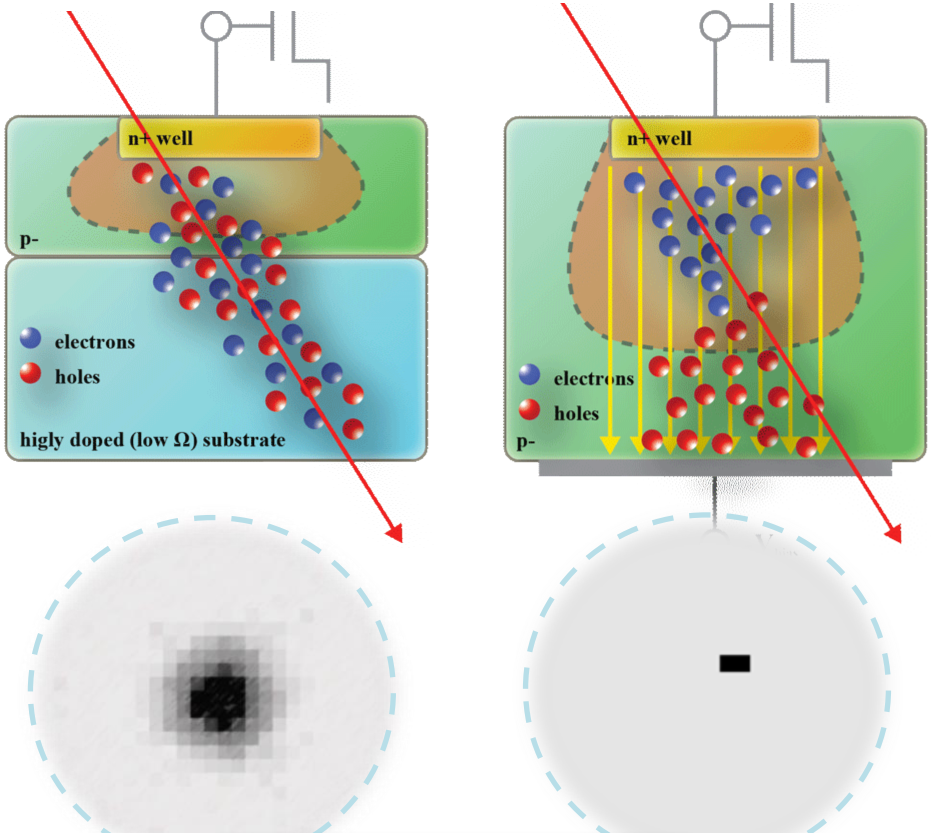


$$F(x,\lambda) = \sum_{i=0}^{x} \frac{e^{-\lambda}\lambda^{i}}{i!} = e^{-\lambda}\sum_{i=0}^{x}\frac{\lambda^{i}}{i!}$$

The ability to distinguish more than one particle per frame drastically improves the average particle rate the detector can handle -> speed improvement.

iMPACT detector – high resistivity CMOS technology

To exploit the fast OrthoPix architecture, charge collection has to happen in just few nanosecond, which requires charge collection by the drift mechanism (instead by diffusion as standard CMOS pixel detectors, which takes tens of ns).



dx.doi.org/10.1016/j.nima.2013.04.042

PSI test beam 2012 – 300 MeV protons

Clusters focusing improves data compression

a

One foundry providing such high resistivity process is 90nm IBM. A first prototype successfully built and tested (INFN/CERN LePix project).

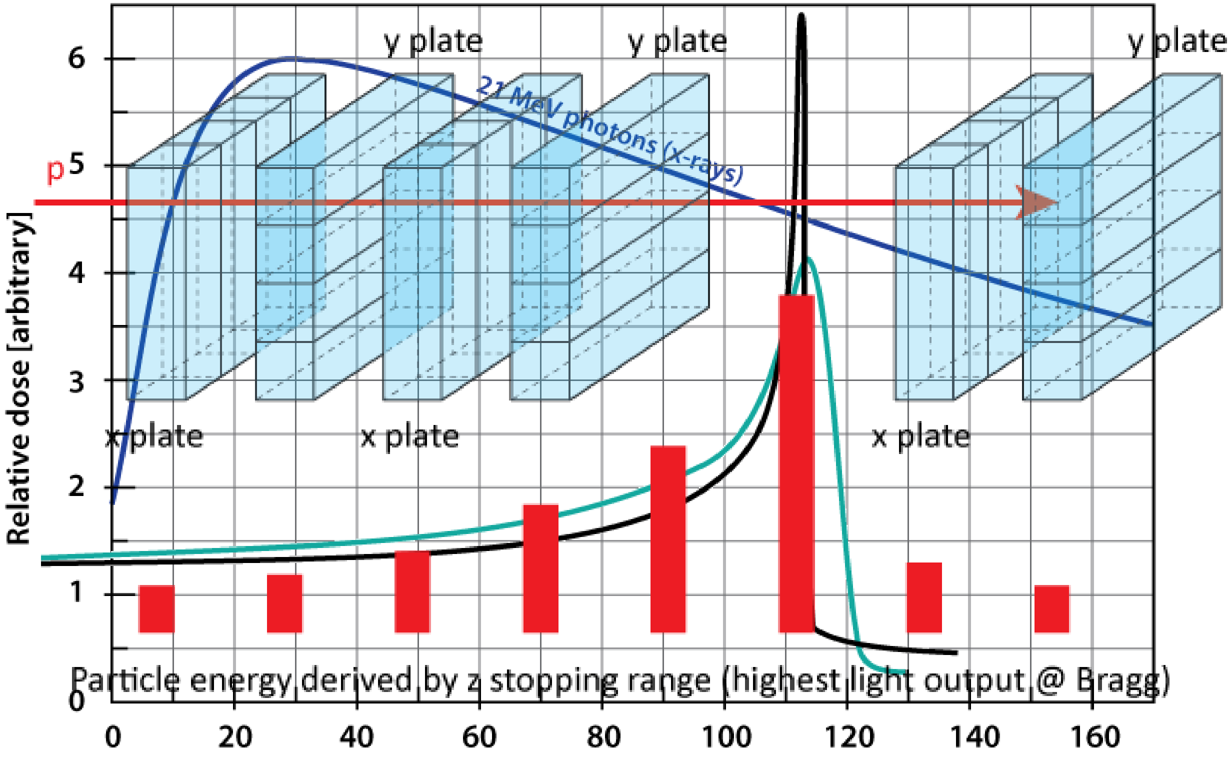
dx.doi.org/10.1016/j.nima.2012.10.098

b

Another foundry providing a high resistivity epitaxial layer is 0.18 μm Tower Jazz. A first prototype successfully built and tested (Explorer 0), another submitted, to be tested in June/July.

iMPACT calorimeter – highlights

Together with the position, the energy of the proton after it exits the target must be measured. No present solution can achieve the 1 GHz particle rate necessary to keep-up with the iMPACT tracker.



We propose a novel proton calorimeter which exploits the very same Bragg peak characteristic of protons to measure their residual energy. It is based on orthogonal layers of segmented scintillating fingers read out by SiPM and dedicated FPGAs electronic.