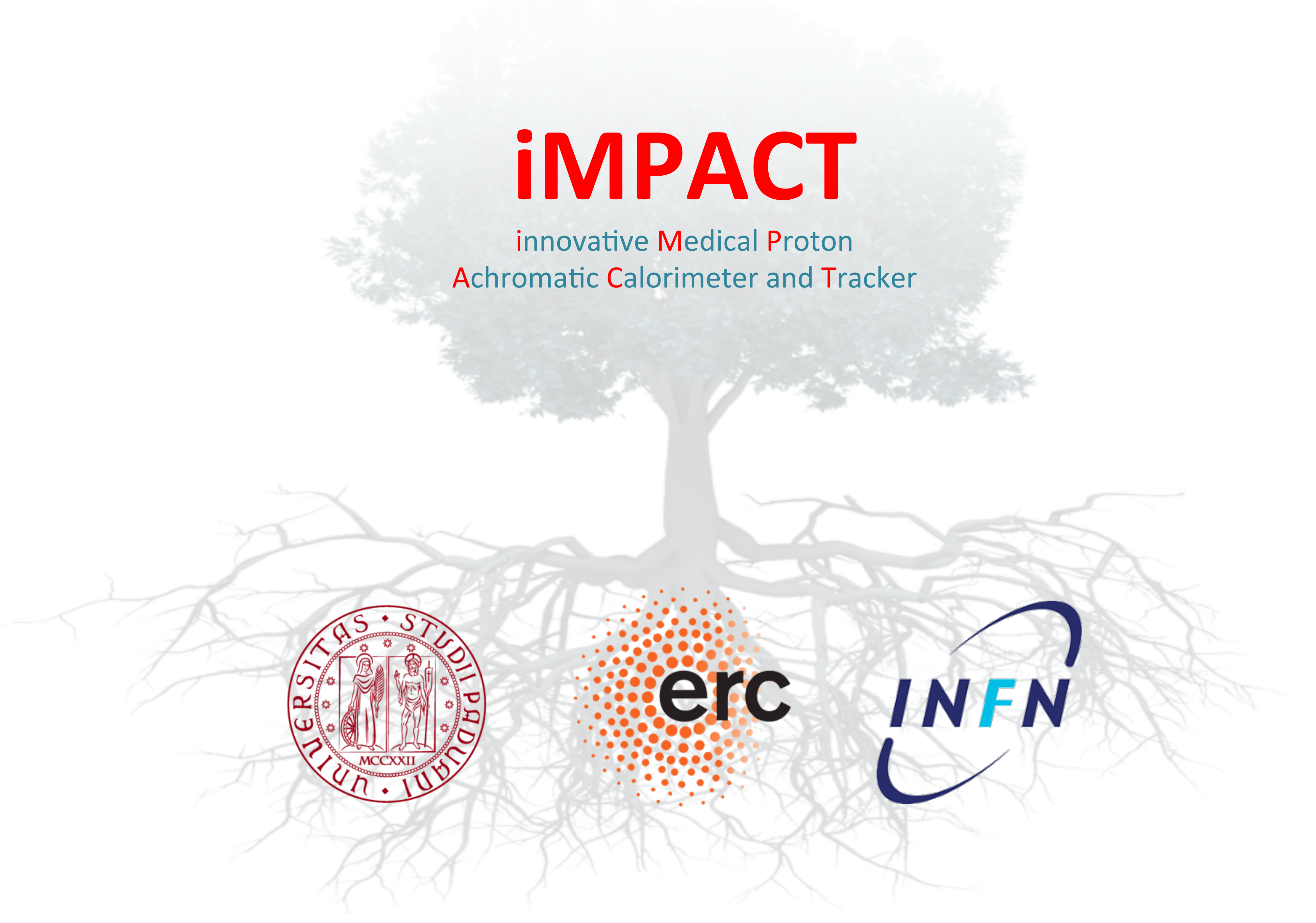
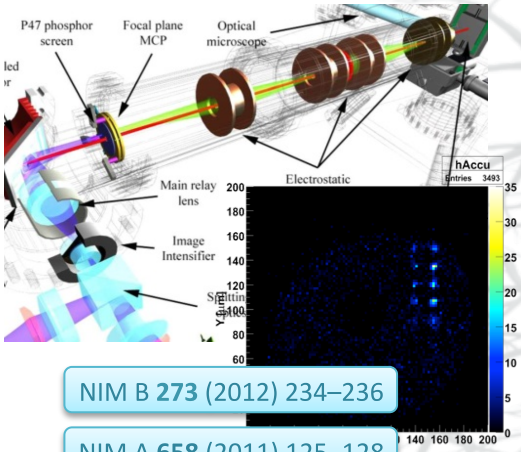


iMPACT

innovative Medical Proton
Achromatic Calorimeter and Tracker

iMPACT

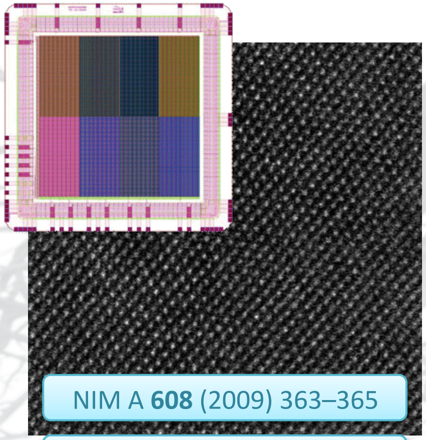
innovative Medical Proton Achromatic Calorimeter and Tracker



NIM B **273** (2012) 234–236

NIM A **658** (2011) 125–128

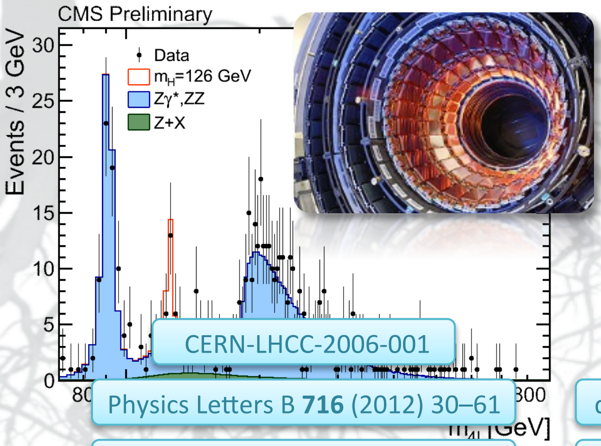
First SEU µMapping facility – INFN



NIM A **608** (2009) 363–365

NIM A **622** (2010) 669–677

0.5 Å resolution TEAM microscope – Berkeley

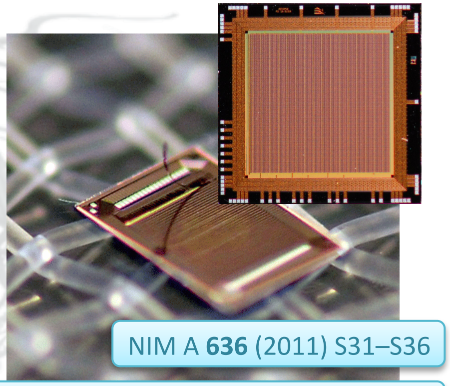


CERN-LHCC-2006-001

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

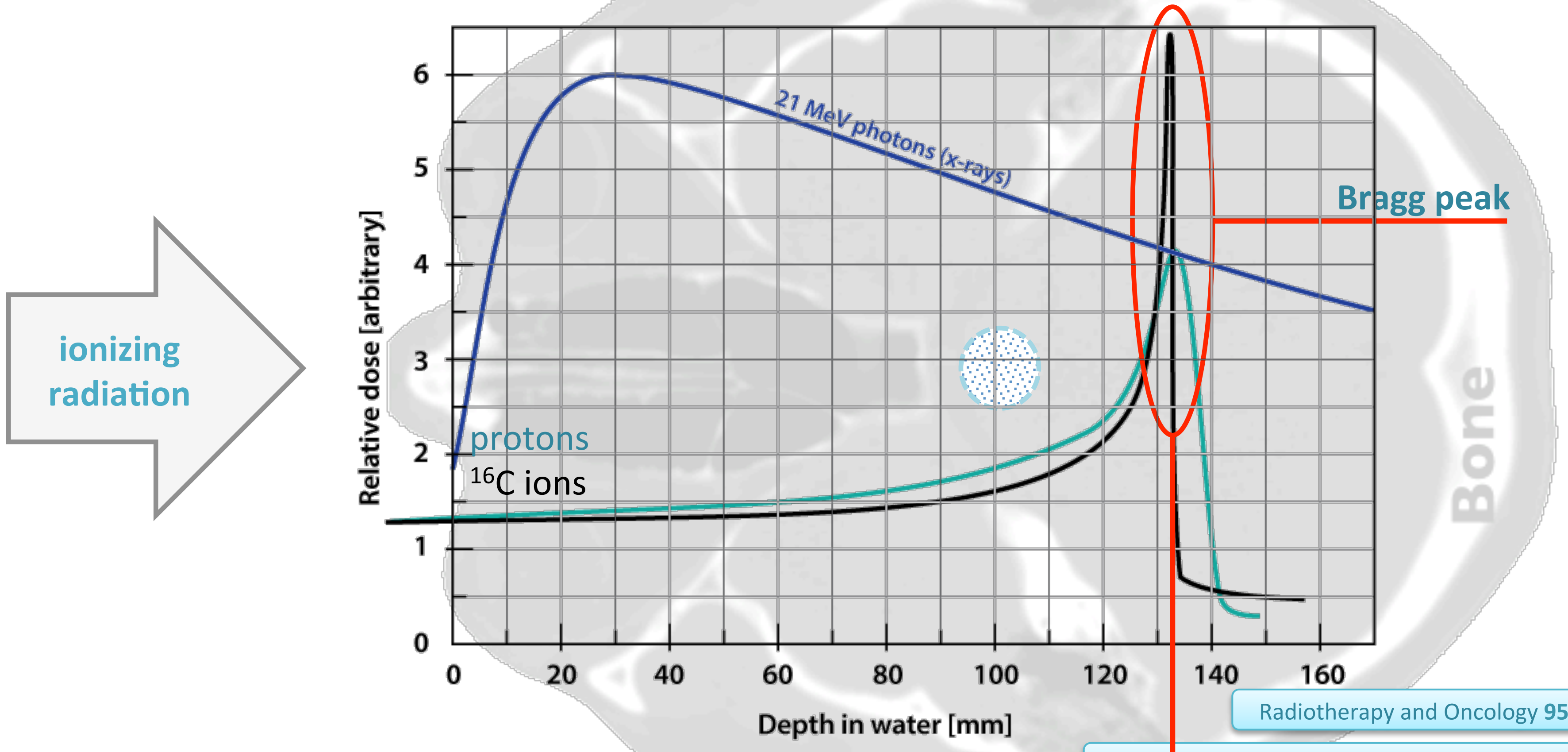
dx.doi.org/10.1016/j.nima.2013.04.042

Ongoing R&D @ INFN & CERN

Hadron therapy overview

Hadron 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.



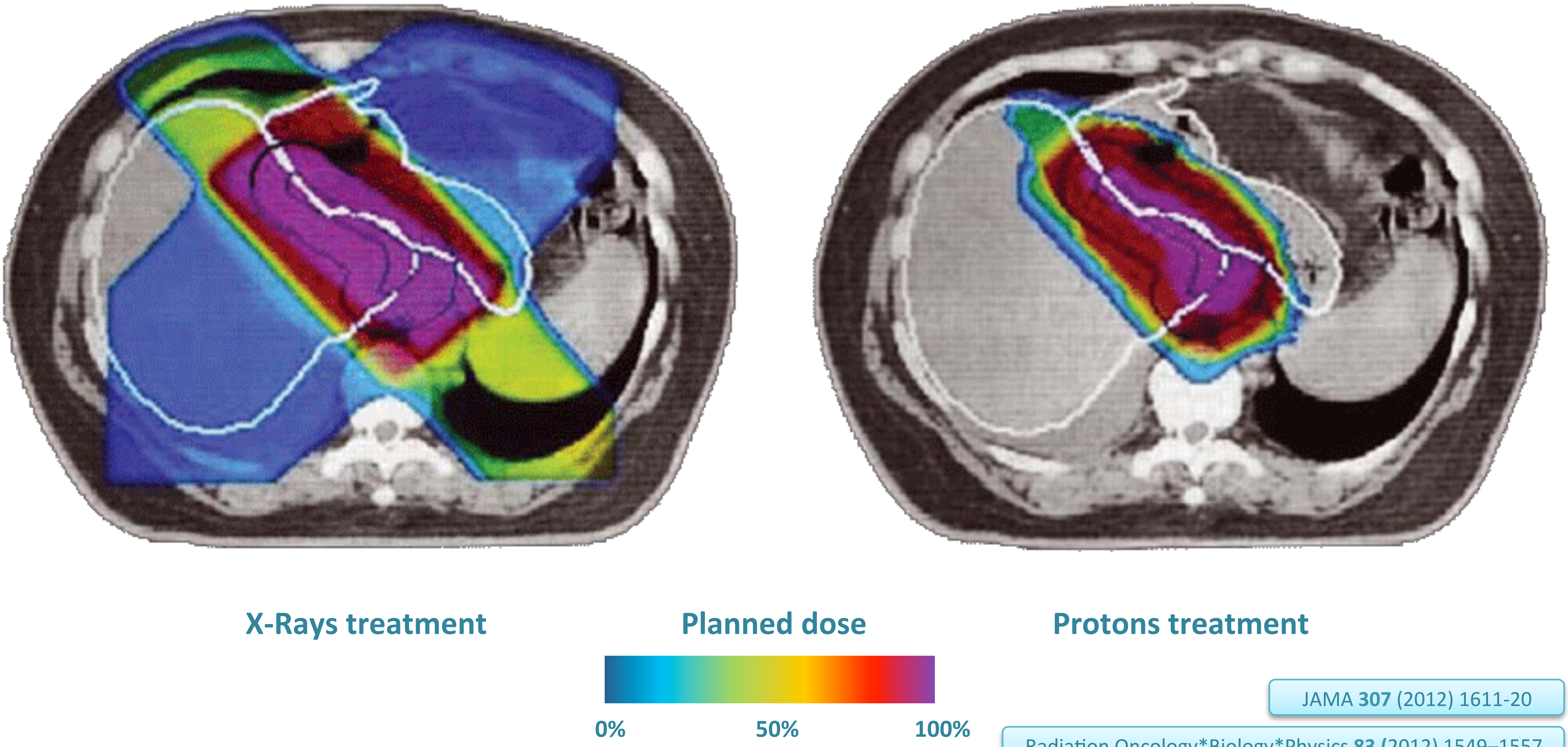
Radiotherapy and Oncology **95** (2010) 3–22

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

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.

Hadron therapy: reduced collateral damage

Much lower collateral damage respect to photons due to the focused energy deposition: less damage to surrounding tissues, less chance of secondary tumors.



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

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

Hadron therapy growth

NuPECC (2014)

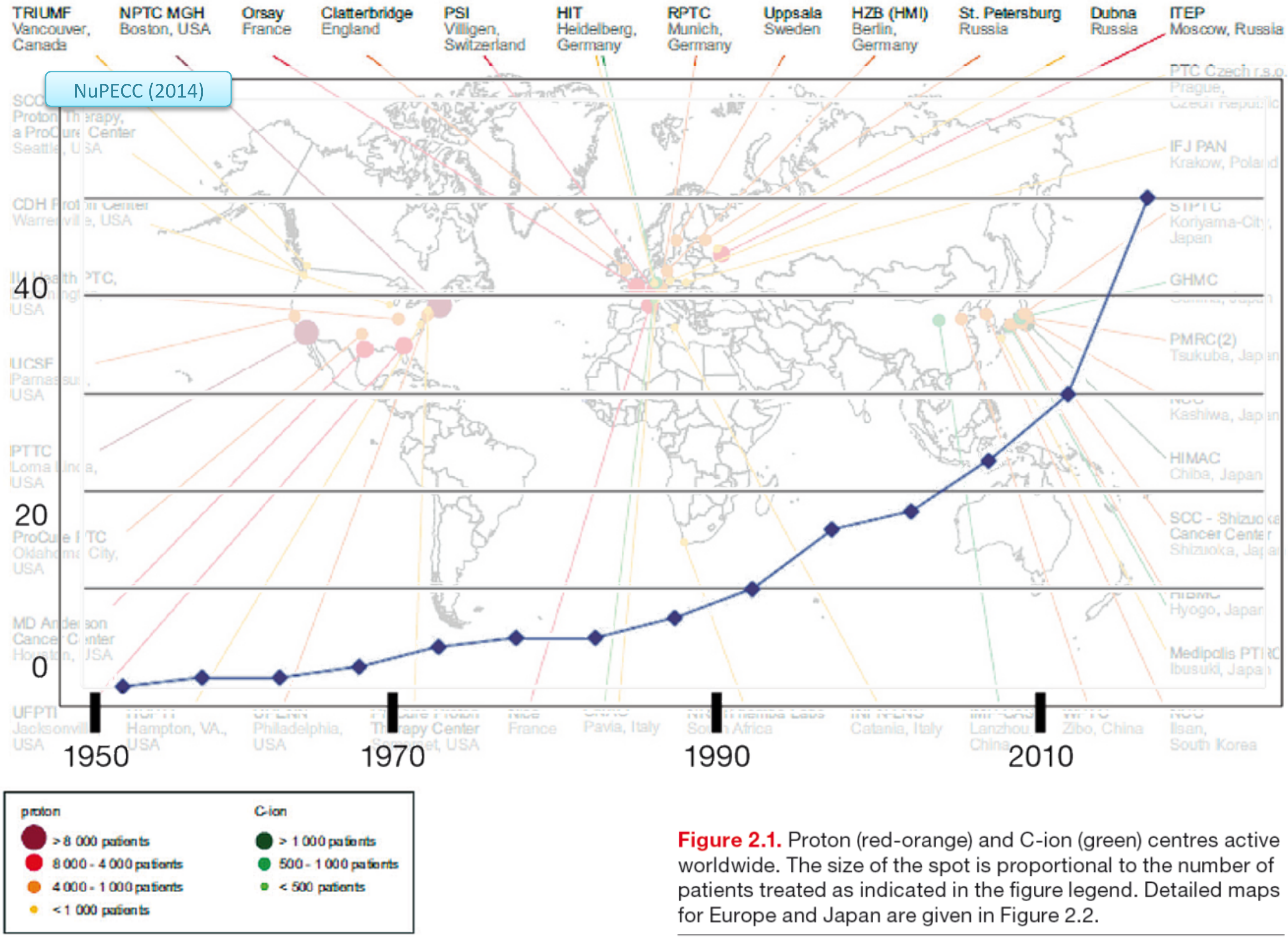
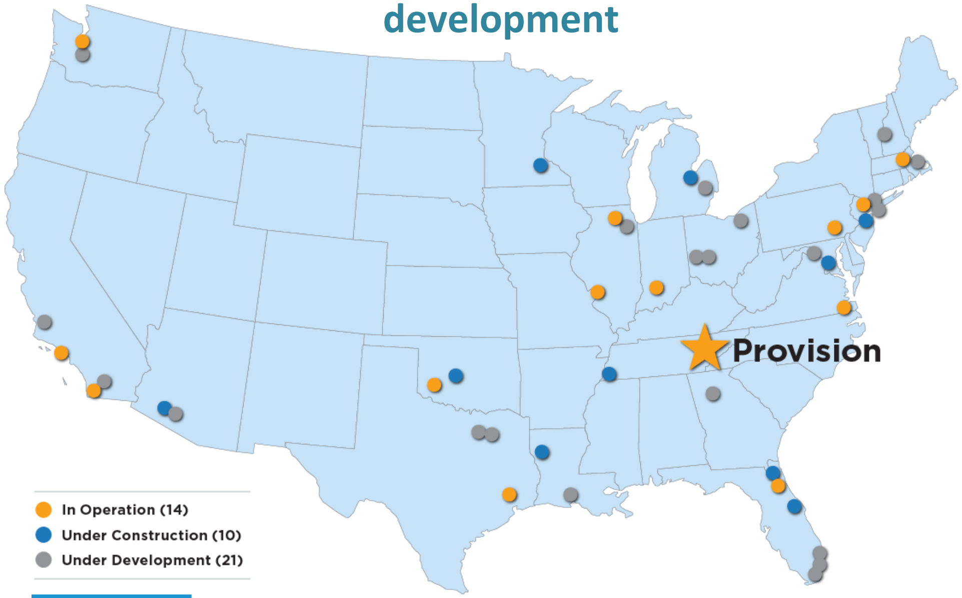


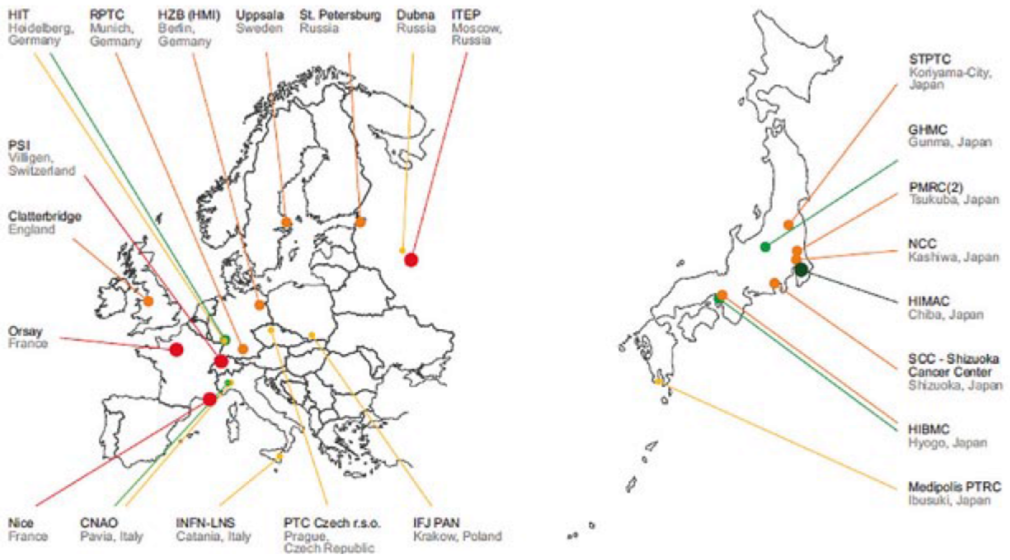
Figure 2.1. Proton (red-orange) and C-ion (green) centres active worldwide. The size of the spot is proportional to the number of patients treated as indicated in the figure legend. Detailed maps for Europe and Japan are given in Figure 2.2.

Hadron therapy facilities around the world

USA: 14 in operation, 10 under construction 21 in development



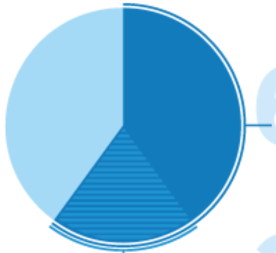
13 in Japan, 15 in Europe, 2 in Korea, 2 in Russia



US NEED:

1.6 million people

will be diagnosed with cancer in 2012.



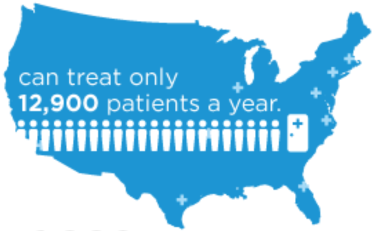
60%

960,000
will receive radiation

20%

320,000
are candidates for proton therapy

14 existing centers have limited capacity & long waits.



can treat only
12,900 patients a year.

1,000 more
treatment rooms are needed.

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.

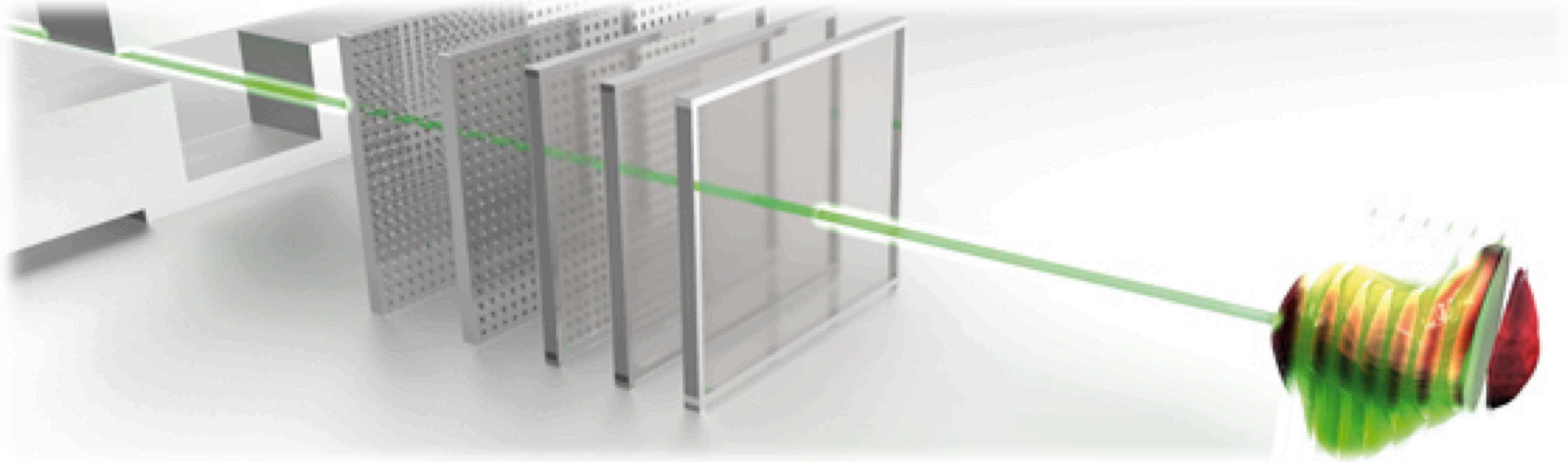
8,000 more
treatment rooms are needed around the globe.

Hadron therapy – Cyclotron based example (PSI proton therapy)

- Two fast magnets with speeds of 1 to 2 cm / msec in the left-to-right and head-to-feet axes respectively to scan through the tumour.
- In the third dimension, the depth of penetration of the protons, the design allows a change from one tumour layer to the next in about 100 msec (5 mm difference in proton range).
- Small spot size at all energies (for 100-230 MeV, the width is < 3-4 mm).
- X-ray system mounted on the gantry itself, which takes images in the direction of the proton beam.
- In-room sliding CT is for treatment planning and the daily verification of the patient position.

Hadron therapy – Synchrotron based example (Heidelberg)

- Beam energy range from 50 to 430 MeV/u.
- intensity-controlled rasterscan technique: ions pencil beam.
- 255 energy levels per ions – millimeter precision increments in beam's range.
- Penetration depth of the beam: from 20 mm to 300 mm.
- 10 selectable levels of beam intensity. Beam size from 4 mm to 10 mm.
- Online position, shape and intensity monitoring with 100 kHz refresh.
- Ultra-fast 1/2000 s beam stop.
- Facilities, ambulatories, hospital directly connected to the hospital.

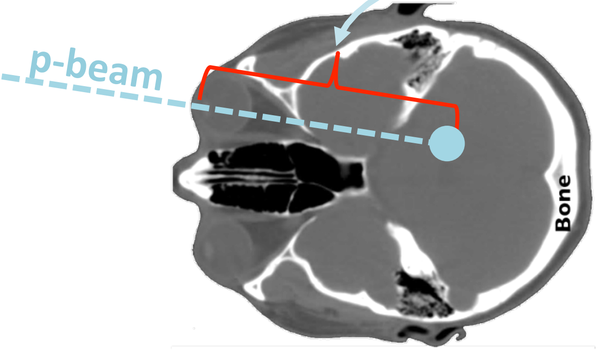


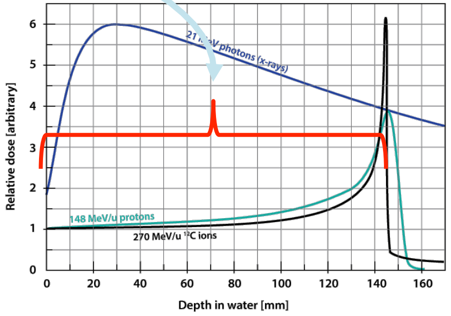
- World unique: scanning capability with heavy ions (p, He, C, O)!

So what?

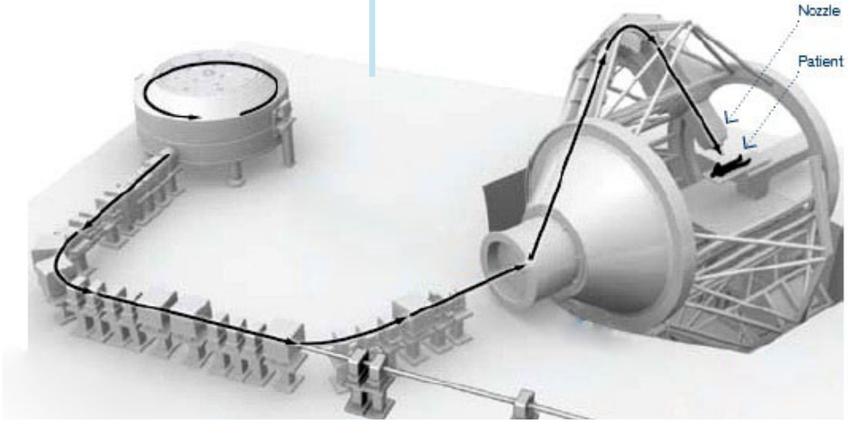
Hadron therapy: the aiming limit **problem**

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).

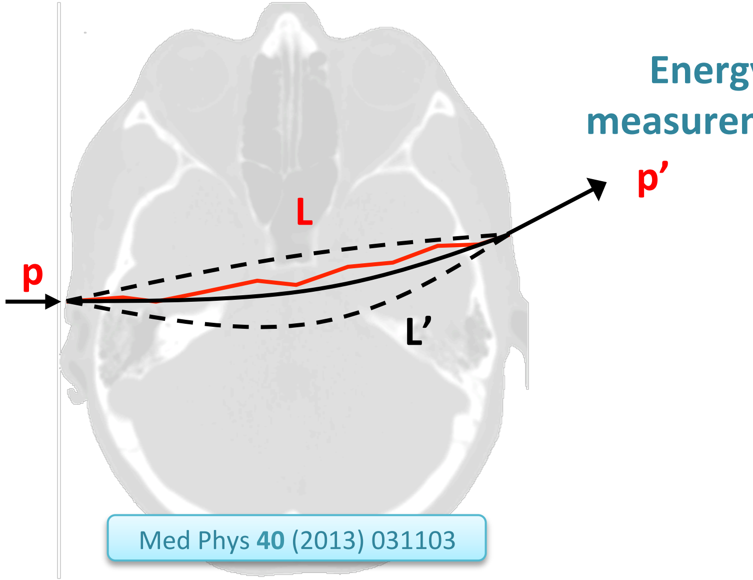
NIM B **268** (2010) 3295–3305

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

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

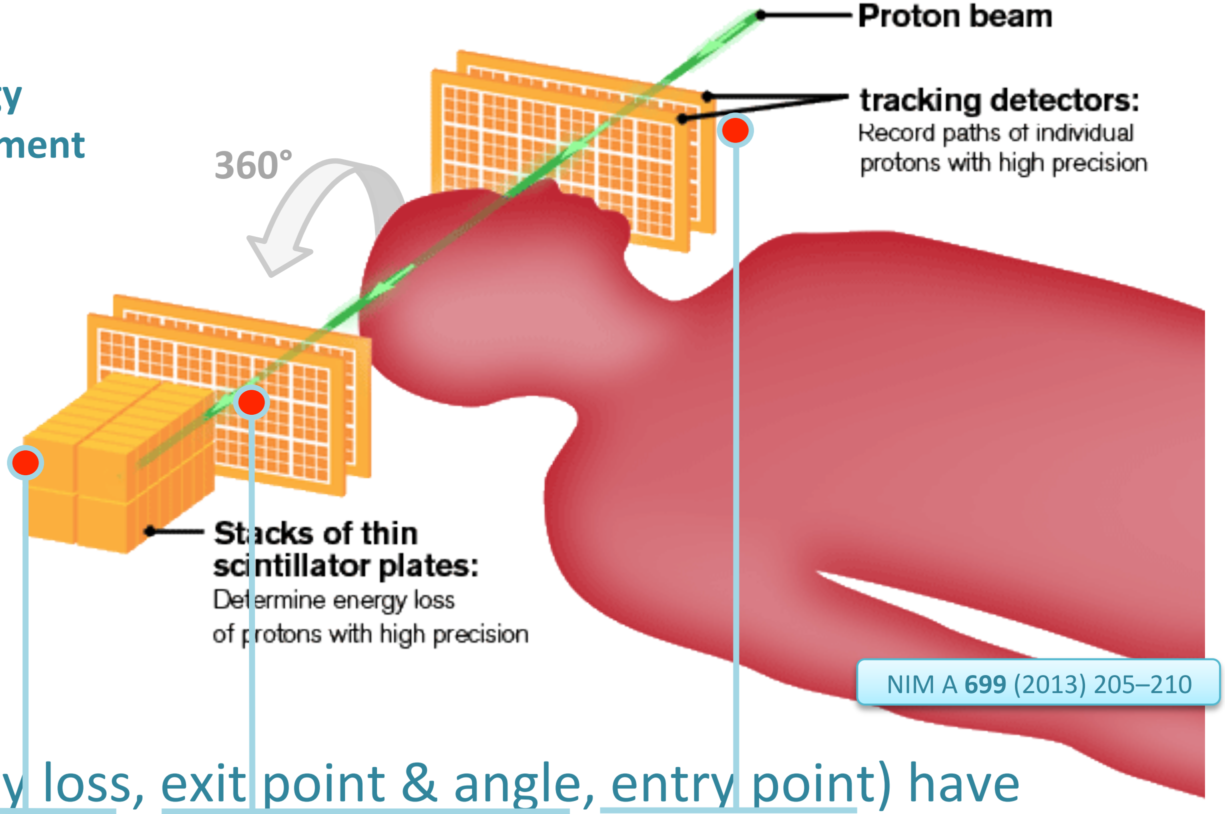
The proton Computed Tomography (**pCT**) scanner

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.



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.

State of the art: **pCT** scanners

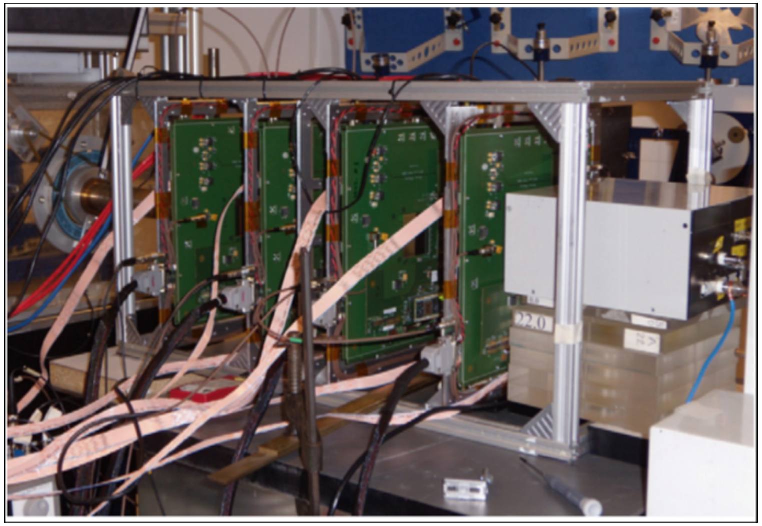
Industry

…

Technology is simply not there to record 10^9 protons fast enough to render the pCT a feasible clinical equipment.

R&D in the academics

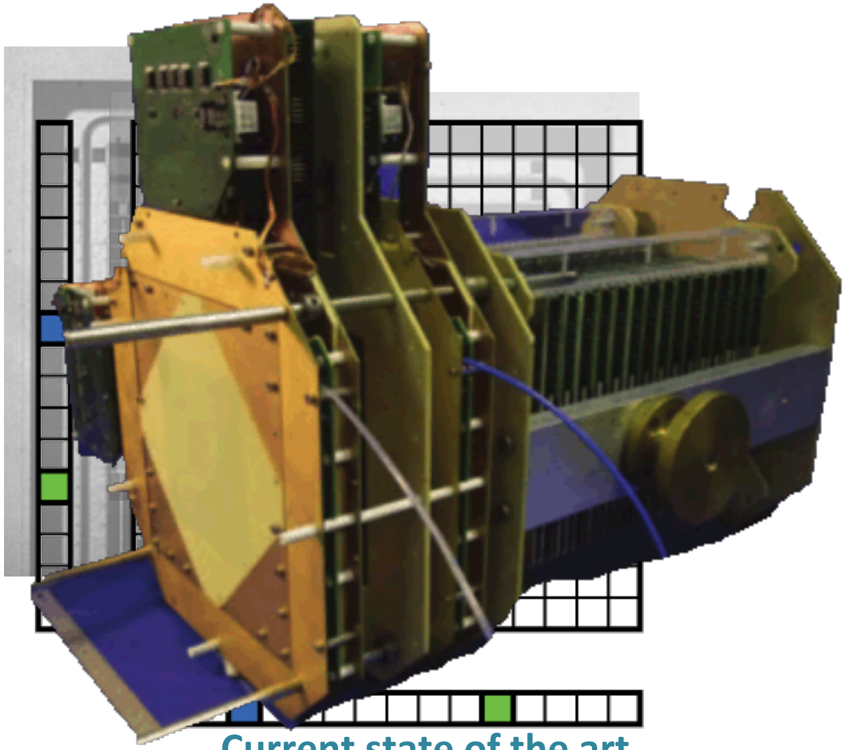
Technology comes from the effort made building HEP physics apparatus and/or space particle trackers.



The pCT approach is proven, but the speed and realization costs still limit it to the R&D real.

State of the art: **pCT** scanners in R&D world

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). **10 minutes for a full pCT**!

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).

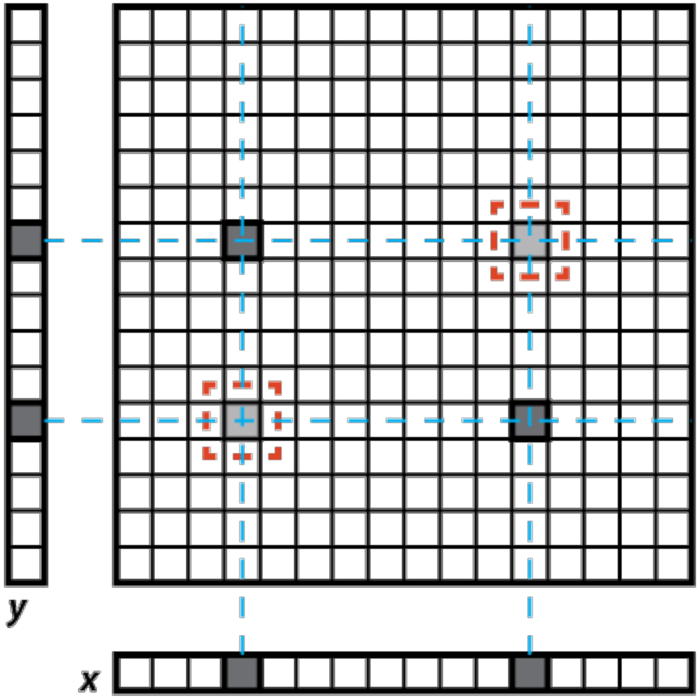
Such approach covers the large area necessary to track particles over a head-sized target (≈$10 \times 30\ \text{cm}^2$) with "affordable" complexity and bandwidth. Effective for R&D, unlikely to meet the requirements of a commercially feasible pCT system.

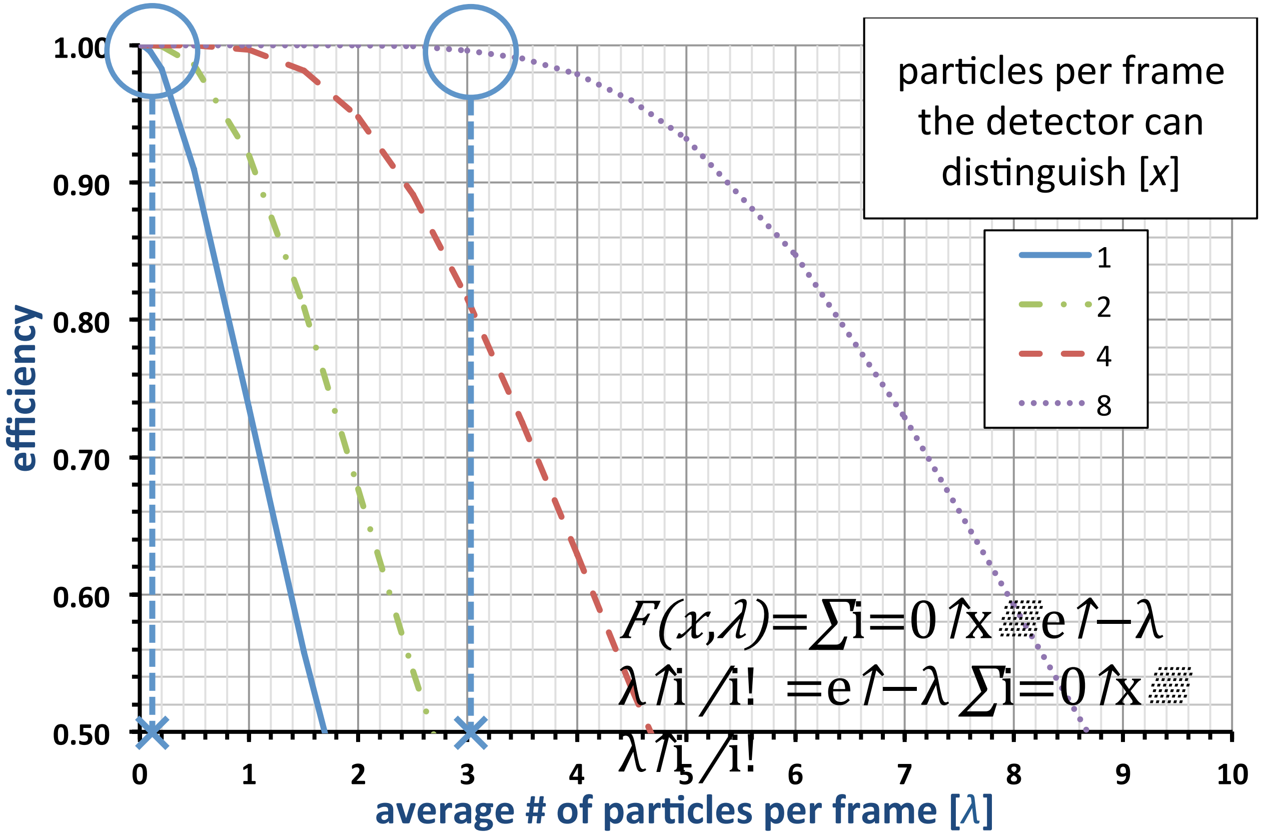
iMPACT challenge

record **10^9** tracks with μm precision and minimal material budget in **1s**

State of the art: classic tracker sensor approach

Classic ‘static’ *xy* sparsification detectors (e.g. orthogonal micro-strip) 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).



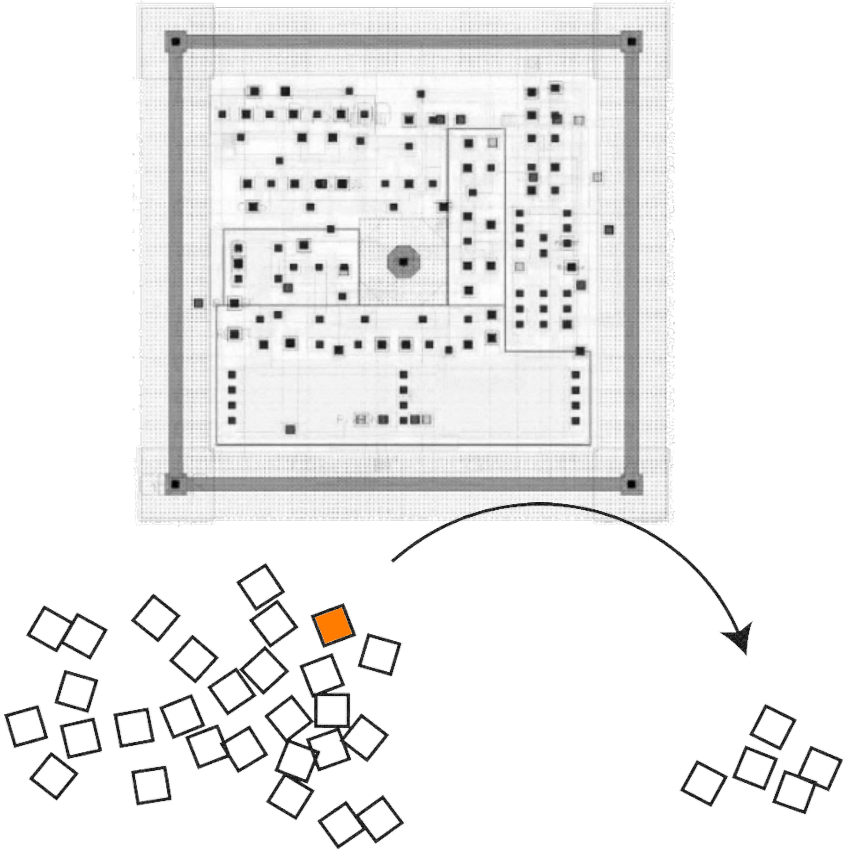


$$F(x,\lambda)=\sum_{i=0}^{x} e^{-\lambda}\lambda^{i}/i! = e^{-\lambda}\sum_{i=0}^{x}\lambda^{i}/i!$$

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

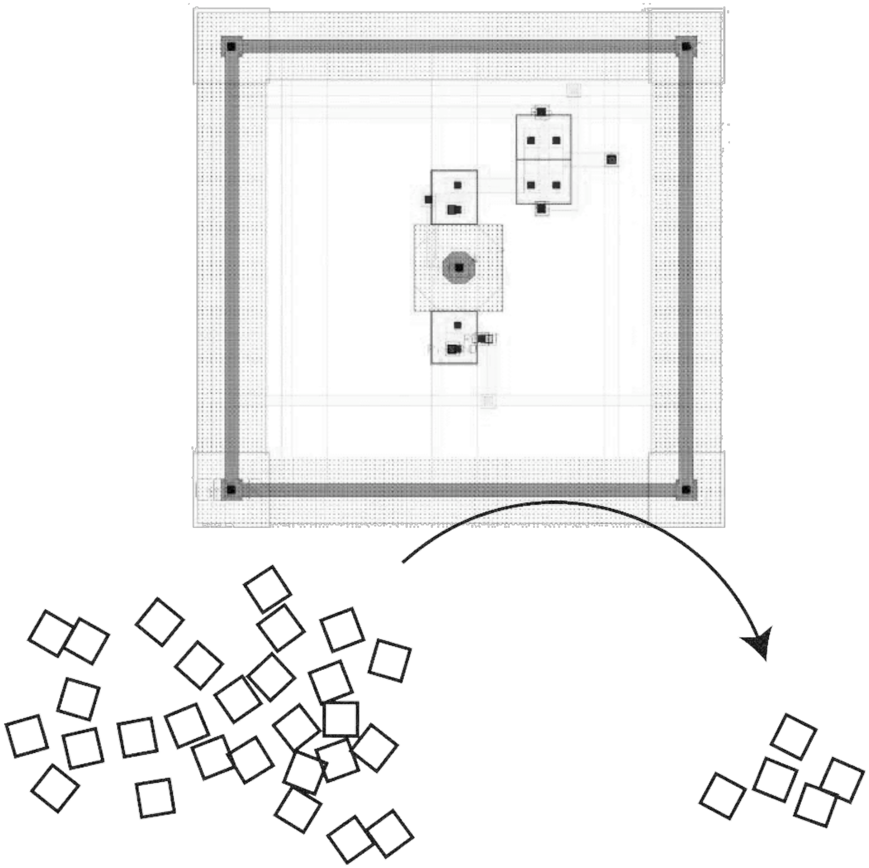
State of the art: pixel sensors architectures

Intelligent pixels (hybrid or not)



Every pixel check and store hits in case, before sending them to the periphery. Space and power required.

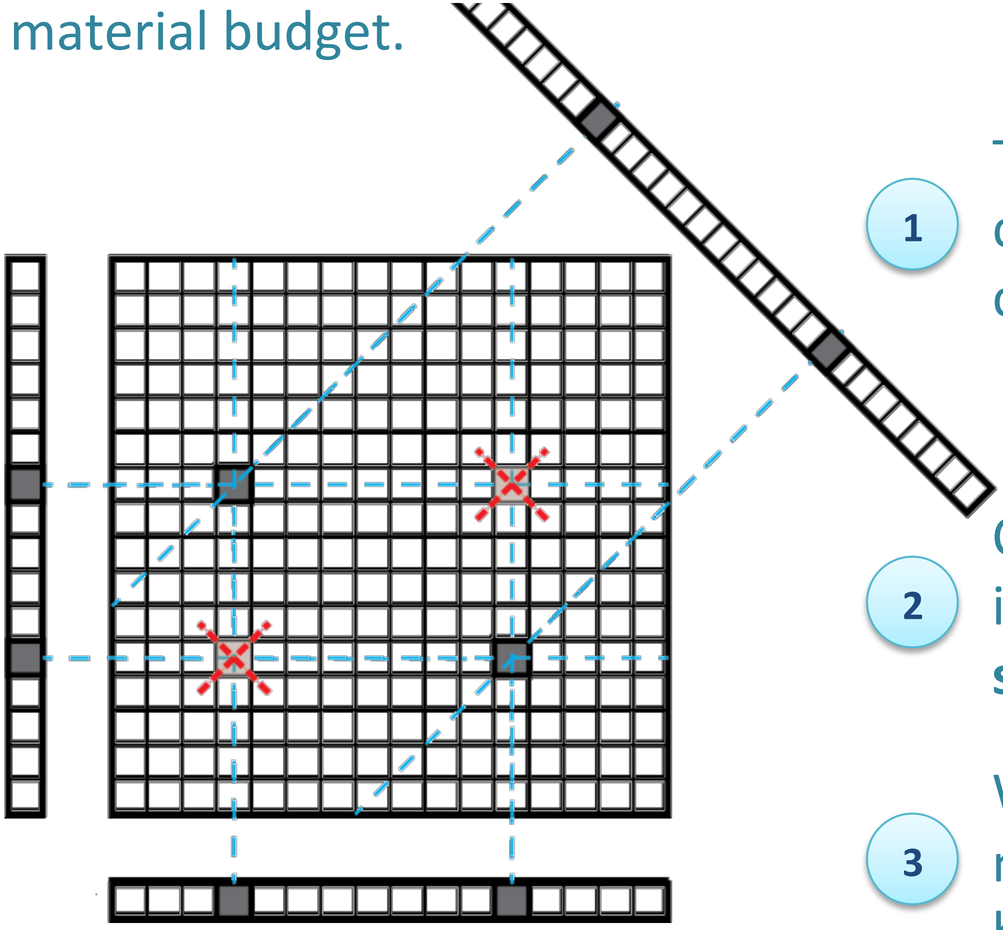
Dummy pixels



Pixel are connected to the periphery in a ‘static’ way, and they are brainless. Neither space nor power required.

iMPACT – tracker sensor architecture concept overview

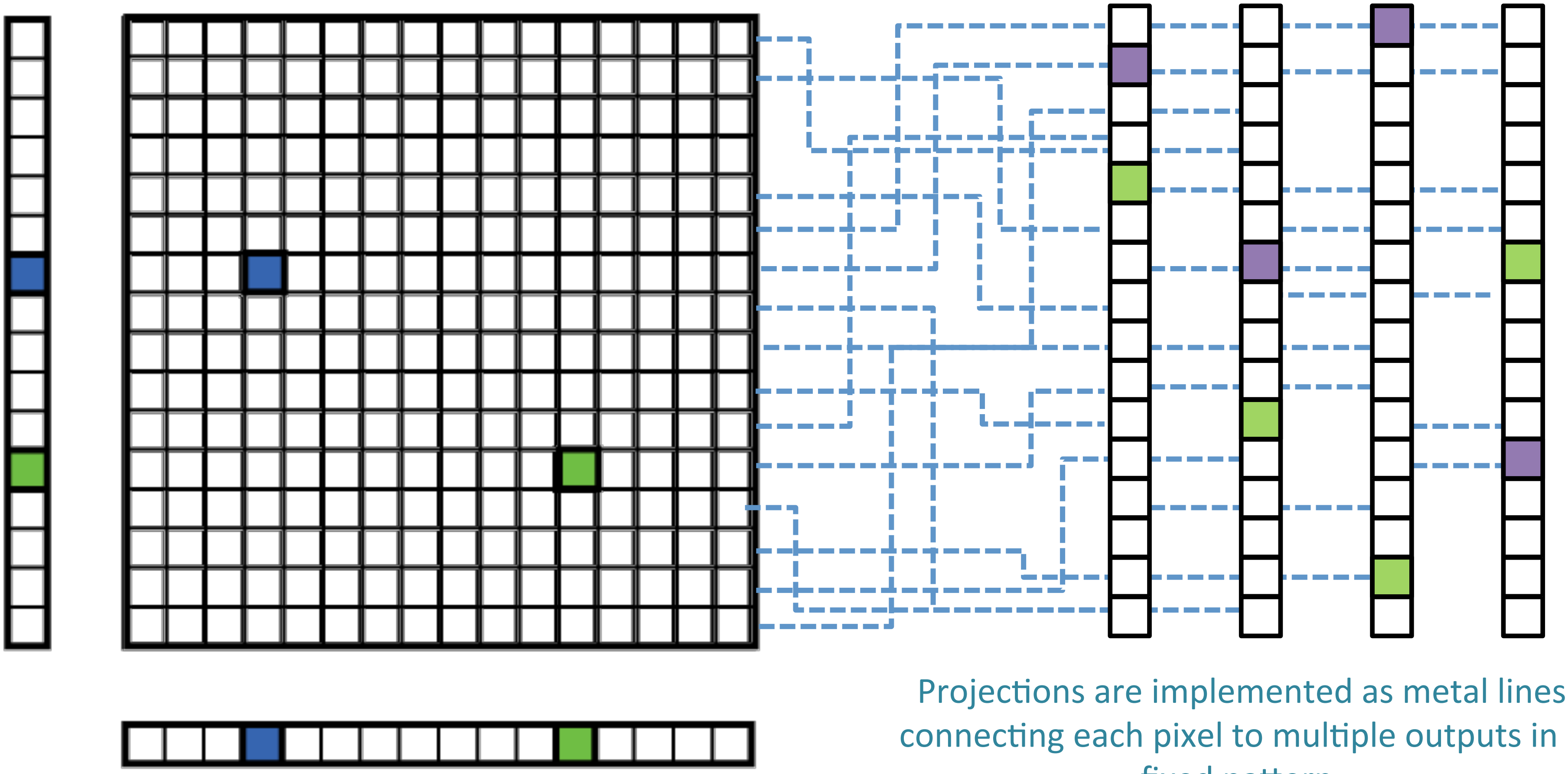
Adding additional projections to the traditional x, y strips scheme actually allows to deal with more than one particle hit per frame. Already employed in wire chambers, it cannot be adopted with strips or fibers due to complexity and material budget.



1. The naïve idea of a diagonal coordinate can be generalized to that of new set of coordinates.
2. Coordinates haven't to follow an intuitive geometry: any **orthonormal system** is actually a good one.
3. Which is the best way to add/organize more coordinates to increase multiple hits detection capability?

iMPACT – tracker sensor architecture concept

By expanding the simple diagonal projection idea to a general n projection system can improve performance, and the connections can be implemented by metal lines in modern deep sub-micron microelectronic processes.

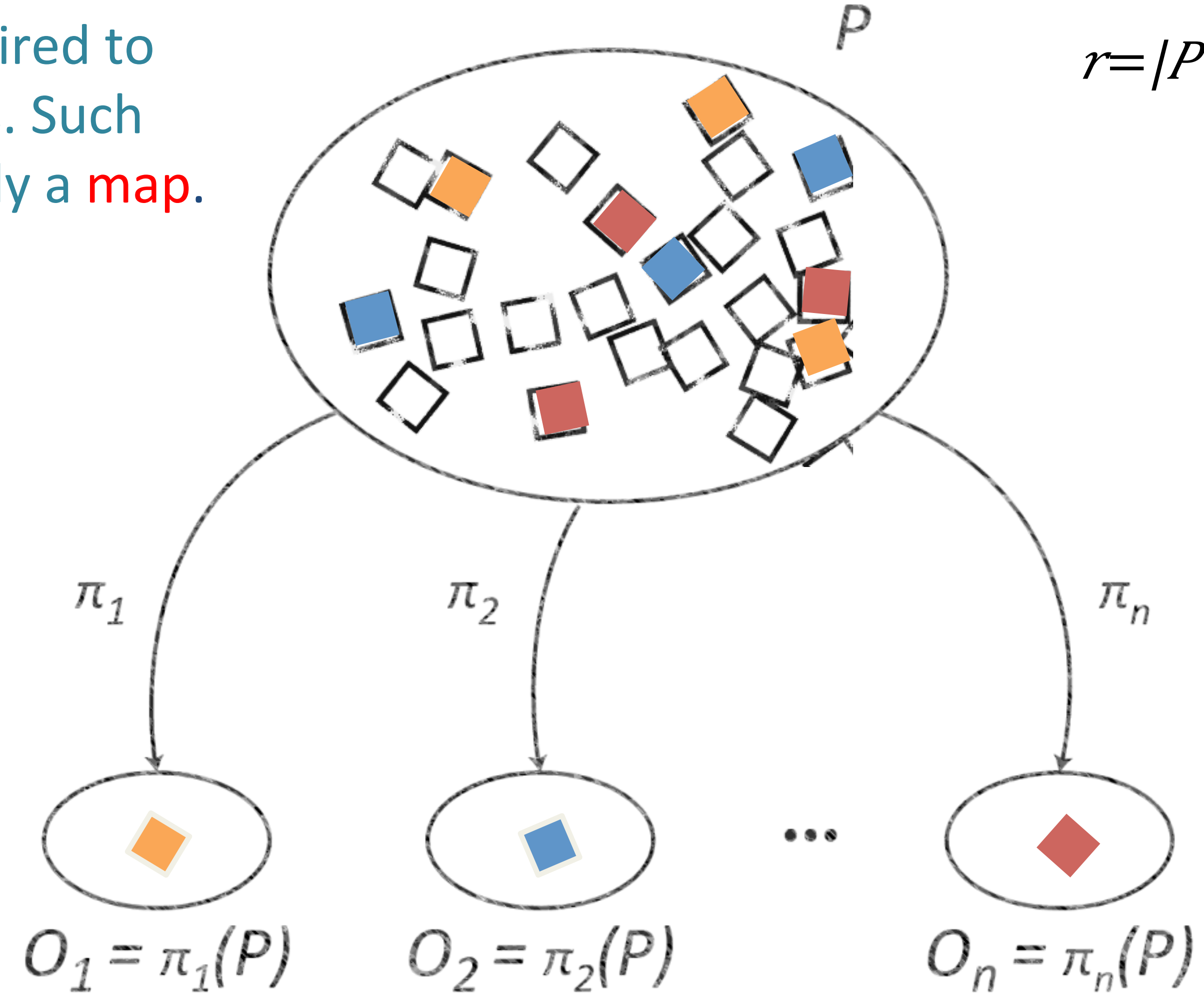


Projections are implemented as metal lines connecting each pixel to multiple outputs in a fixed pattern.

Sensor architecture: *xy* projections generalization to maps

Every pixel is hard-wired to one or more outputs. Such hard-wiring is actually a map.

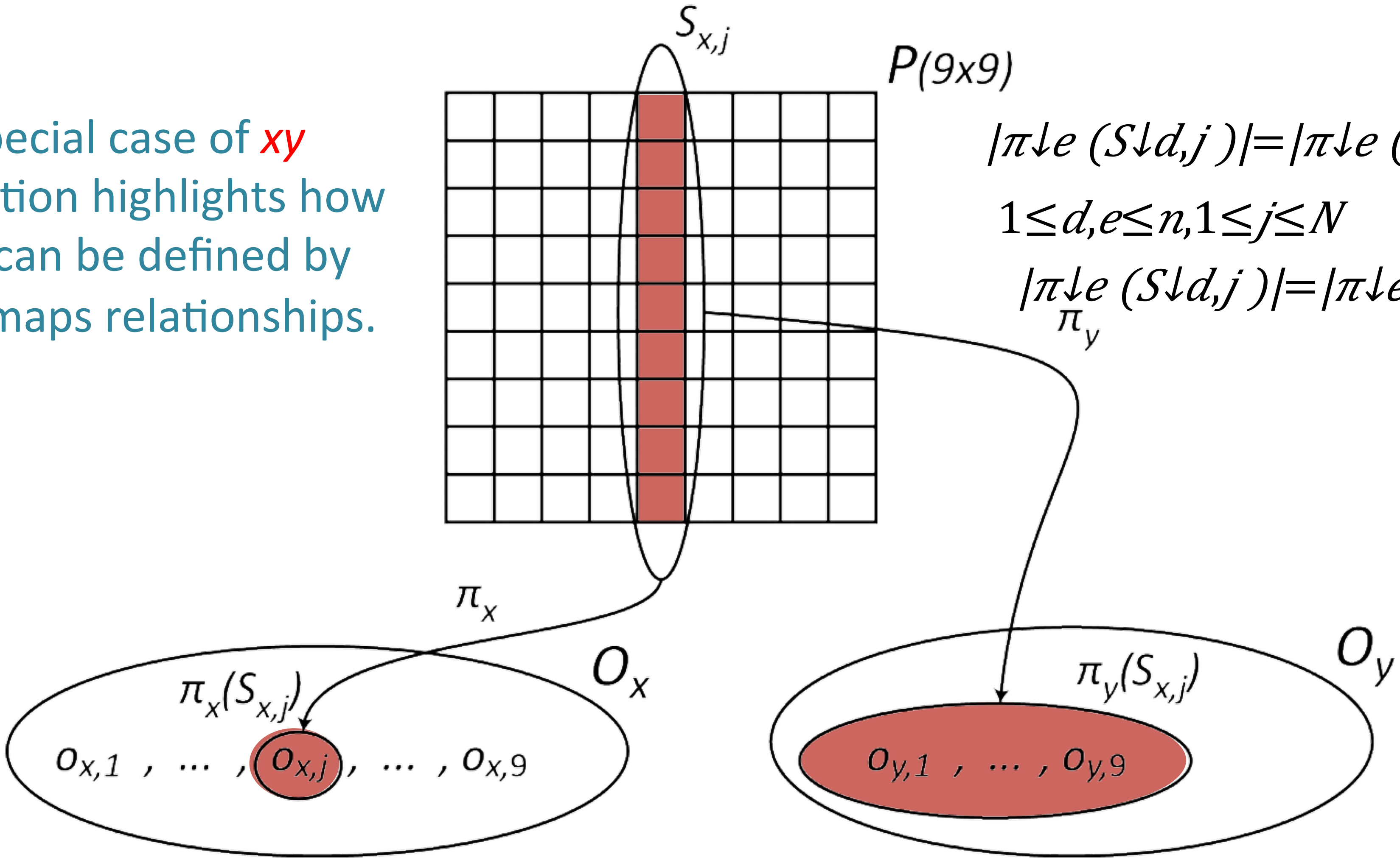
$r=|P|/\sum d=1\uparrow n$ ▒ |



Cartesian *xy* projection is just a special case of set mapping, i.e. associating set elements (pixels) to predefined, fixed groups (outputs).

Sensor architecture – what important is the maps orthogonality

The special case of *xy* projection highlights how maps can be defined by inter-maps relationships.



$|\pi\downarrow e\ (S\downarrow d,j\ )|=|\pi\downarrow e\ (P)|=N$

$1\leq d,e\leq n,1\leq j\leq N$

$|\pi\downarrow e\ (S\downarrow d,j\ )|=|\pi\downarrow e\ (P)|$

To be effective as a sparsification mean, projections must be mutually orthogonal: in this example, all the elements mapped to a single output value by the π_x projection must be mapped into indipendent outputs by the π_y one.

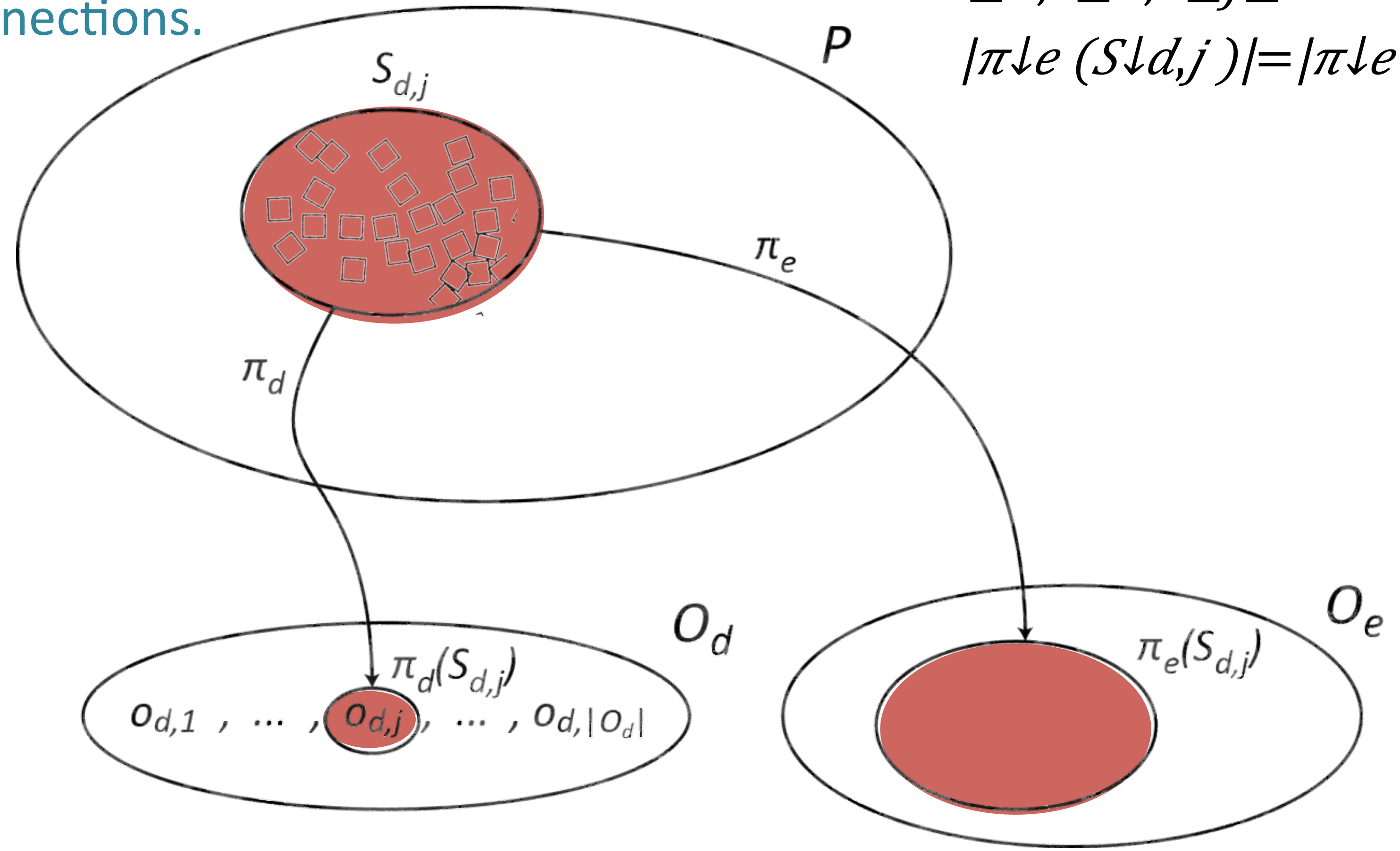
Sensor architecture – maps orthogonality is a general concept

While complex, maps can be implemented in a pixel device by metal layer connections.

$|\pi\downarrow e\ (S\downarrow d,j\ )|=|\pi\downarrow e\ (P)|=$

$1\leq d,e\leq n,1\leq j\leq N$

$|\pi\downarrow e\ (S\downarrow d,j\ )|=|\pi\downarrow e\ (P)|$



It is possible to generalizes the “special” x-y case, providing quantitative rules to build arbitrary sets of n maps defined by reciprocal <u>orthogonality condition</u>.

Sensor architecture – analythical solution to the maps problem

The simple 'wiring' seen in previous slides is a simplified artistic illustration of n abstract projections (4 in the example), i.e. mathematically defined groups not representable by simple straight lines.

$$efficency=1-[1-(1-1/H)\uparrow(H\uparrow 2-H)\uparrow n/2\ /N\uparrow 2\ ]\uparrow n$$

projections

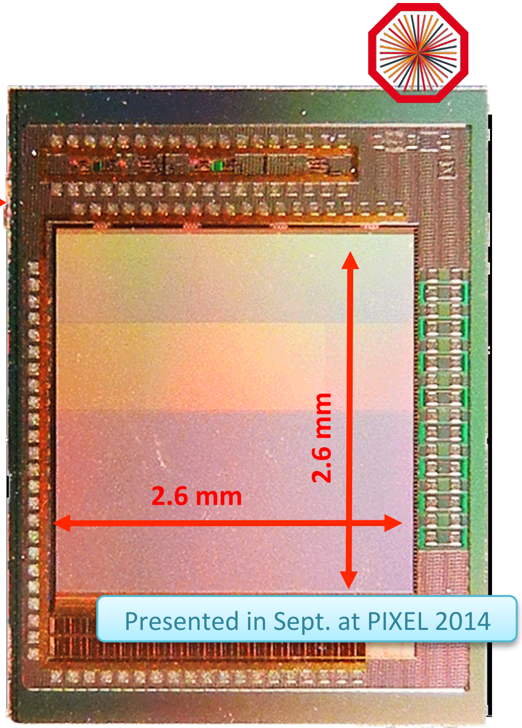
average hits per frame

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

 # side pixels

$$compression=N/n$$

 # projections



Presented in Sept. at PIXEL 2014

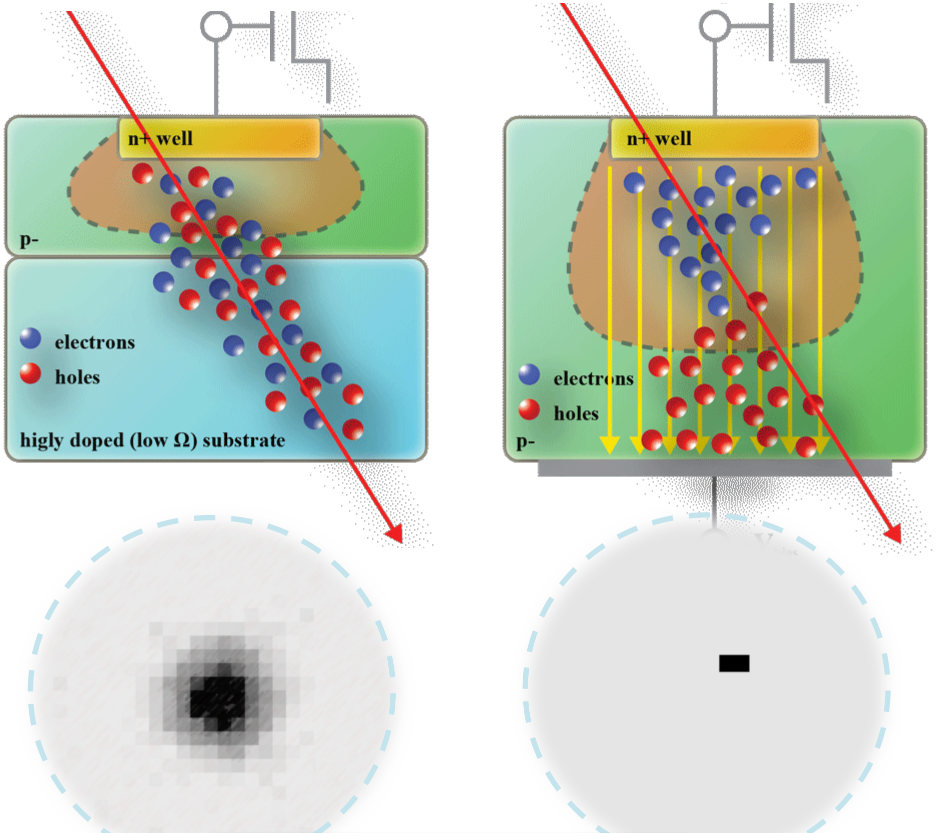
The model has been developed, demonstrated and applied by the **OrthoPix project**, a joint **Alice / CERN / Padova University** effort. A small prototype (255 × 255 pixels, 10 × 10 μm pitch) has been designed and realized embedding 4 mutually orthogonal projective maps (n = 4).

iMPACT practical details

Implementation requirements
and deisgn

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

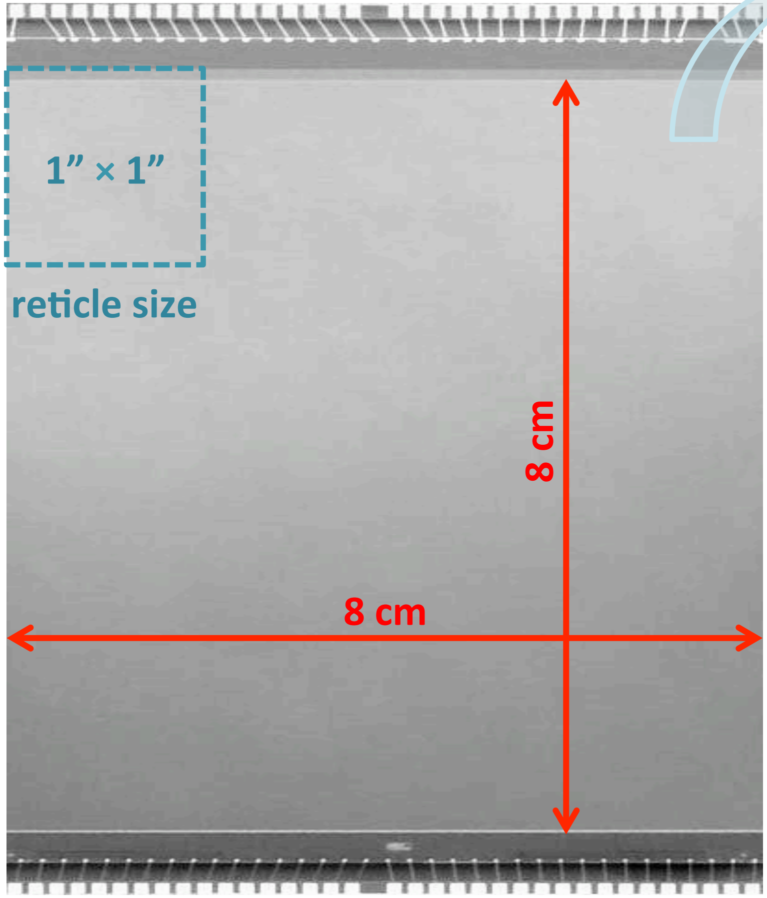
a One foundry providing such high resistivity process is 90nm IBM. A first prototype successfully built and tested (INFN/CERN LePix project).

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

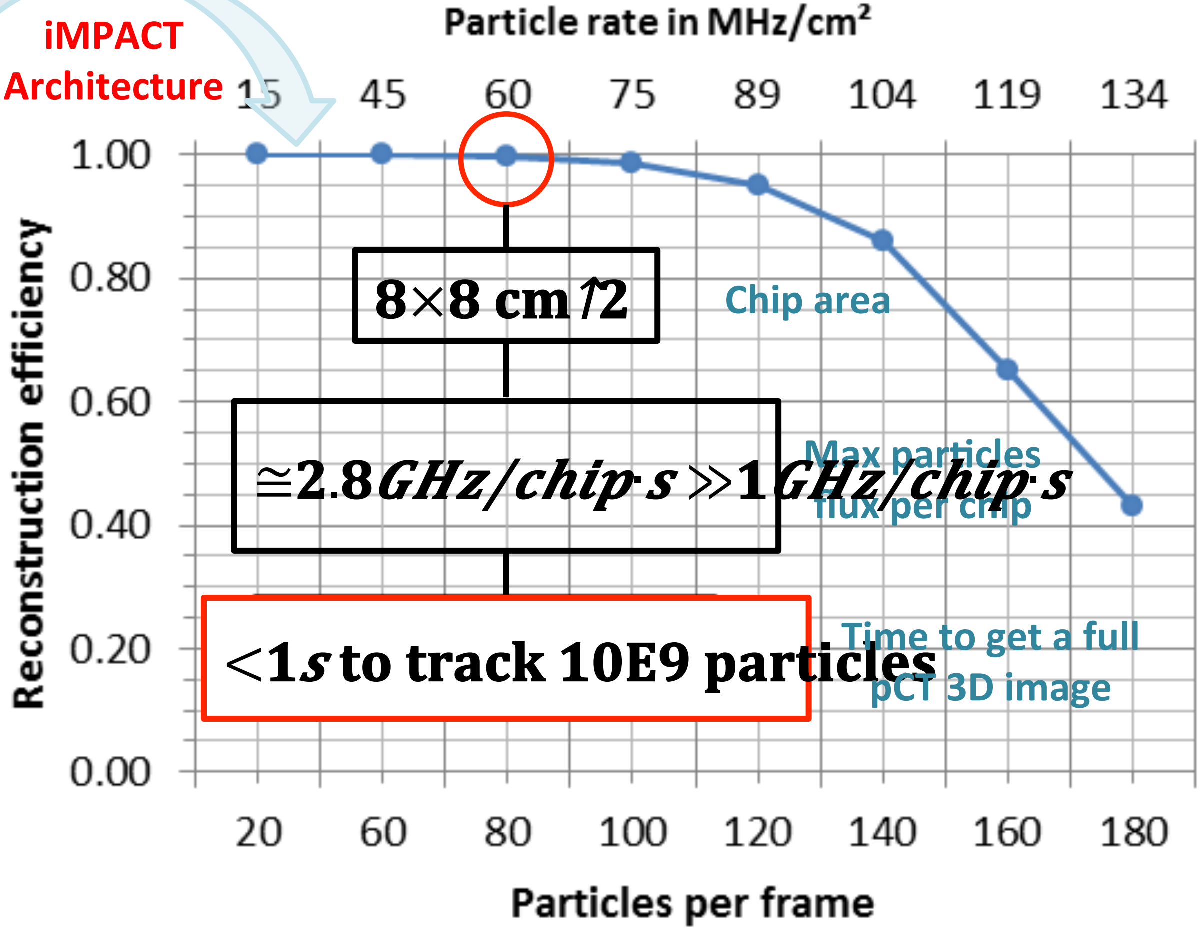
b Another foundry providing a high resistivity epitaxial layer is 0.18 µm Tower Jazz. A first prototype successfully built and tested (Explorer 0).

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 μm^2 pixels



8×8 cm↑2

Chip area

≅2.8 $GHz/chip\cdot s \gg 1\, GHz/chip\cdot s$

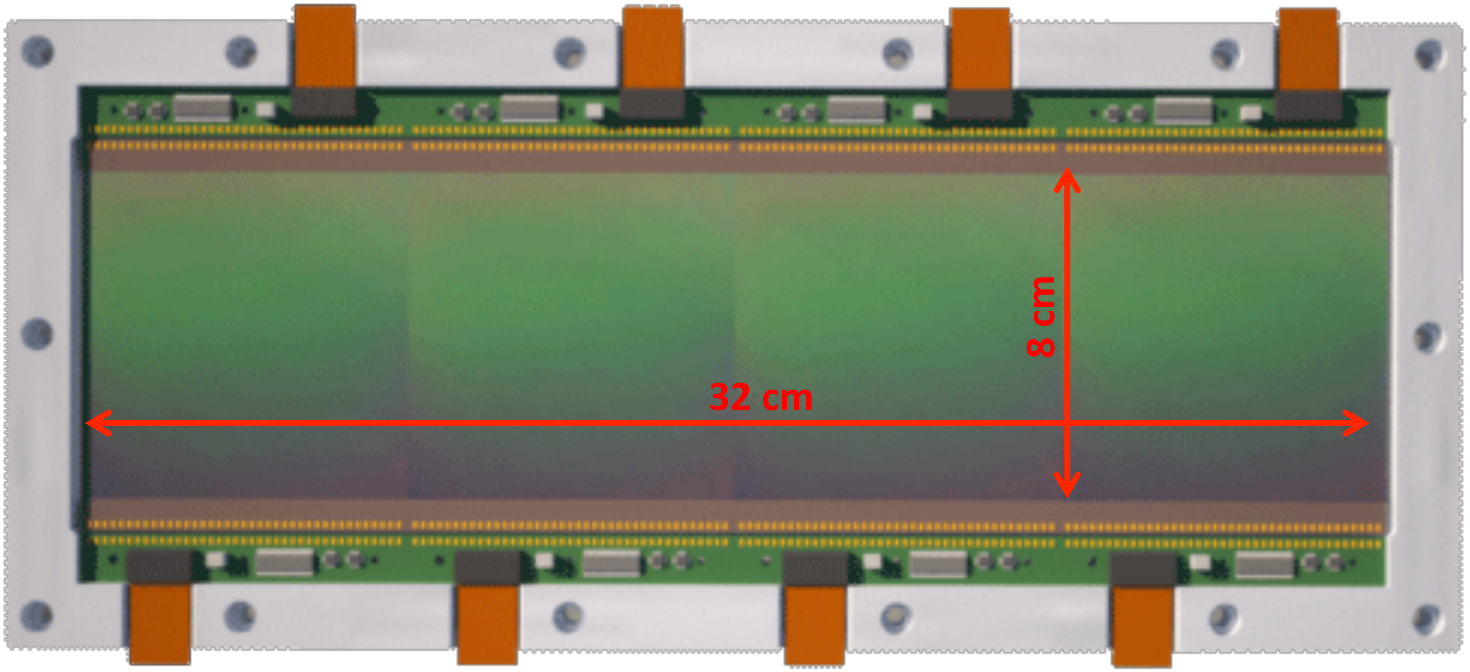
Max particles flux per chip

$<1s$ to track 10E9 particles

Time to get a full pCT 3D image

iMPACT – GHz tracker and calorimeter

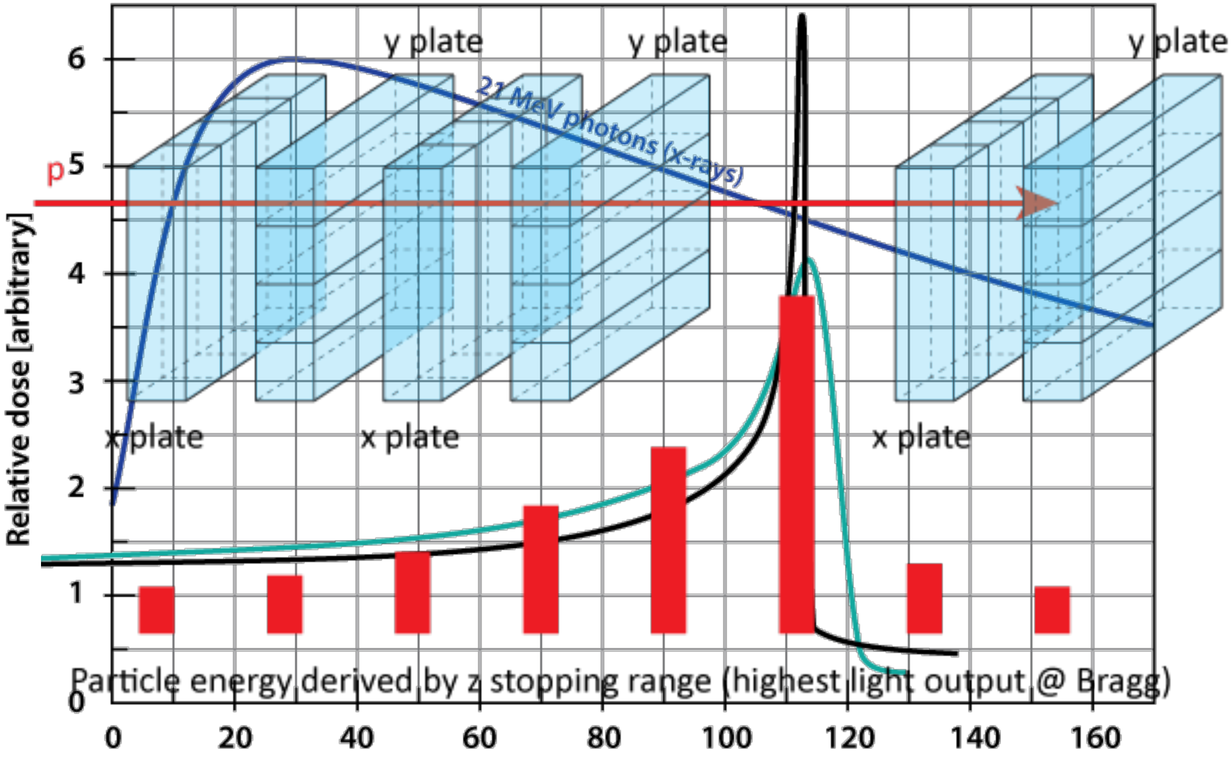
Based on leading pCT groups experience and the characteristics of the proposed CMOS chip, a sixteen 4 × 4 cm^2 or four 8 × 8 cm^2 tiles detector is foreseen. Such an arrangement makes it possible to group all the readout electronics and bonding pads on the two “free” sides of any chip.



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

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.

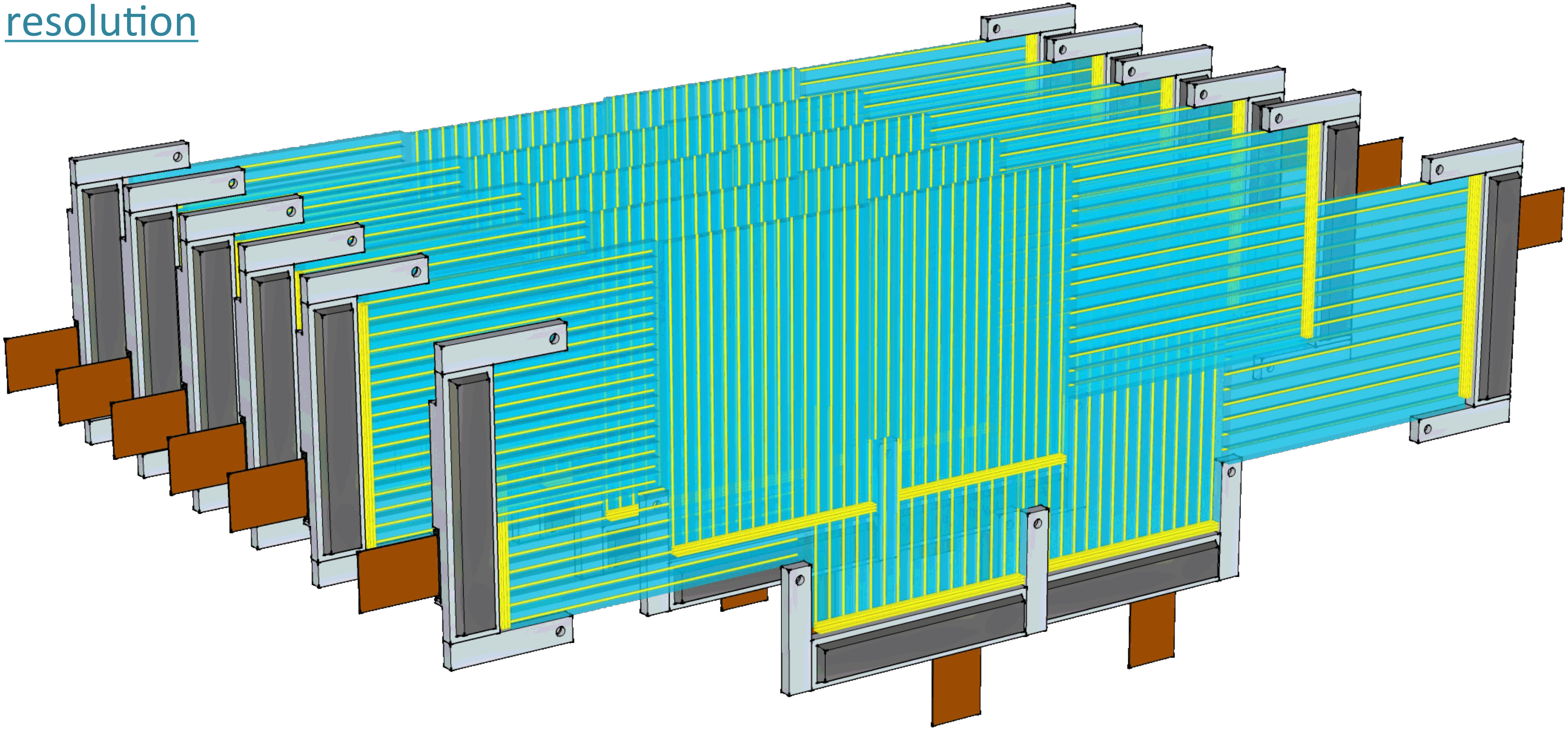


Particle energy derived by z stopping range (highest light output @ Bragg)

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.

iMPACT – calorimeter

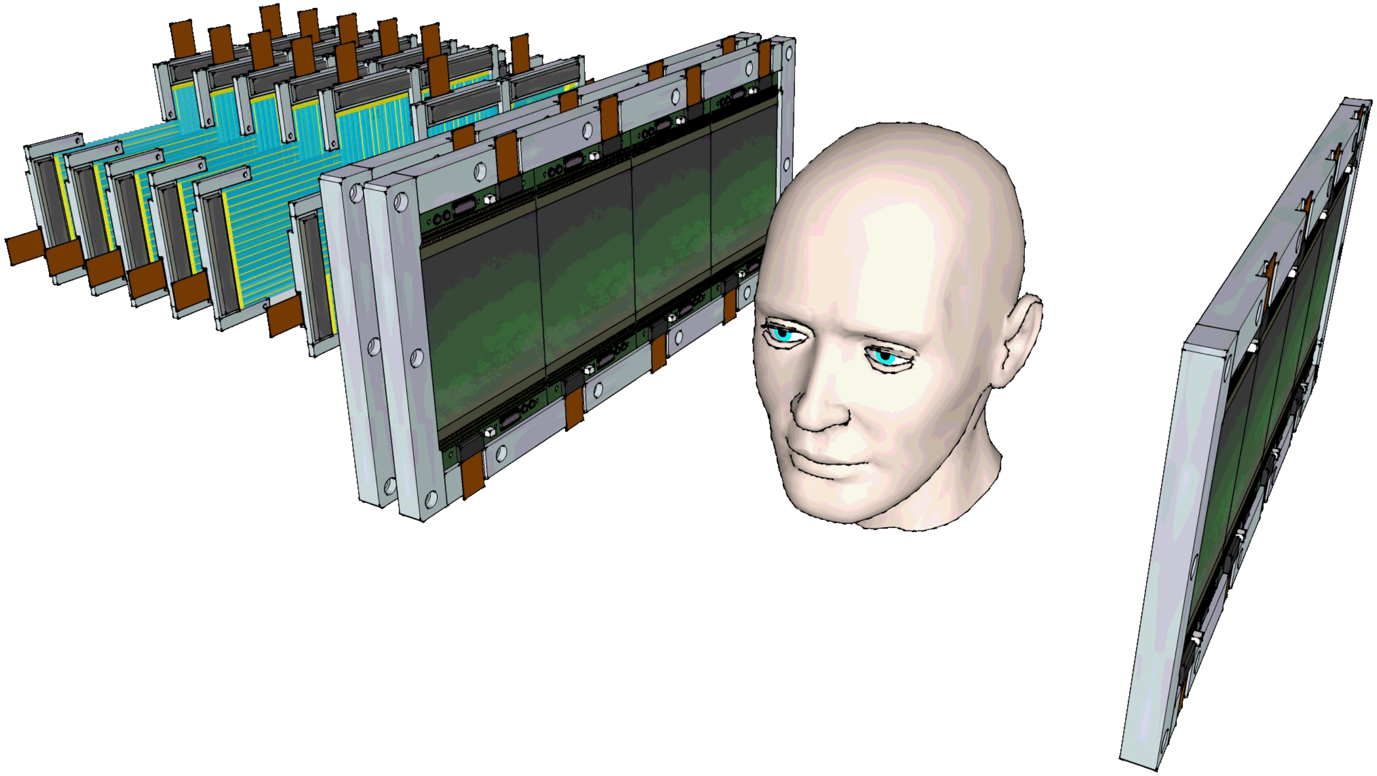
A range calorimeter (48 to 64 plates) based on segmented scintillation planes (to match the iMPACT architecture) and SiPM arrays readout, base on off the shelf components and technology. 1 GHz protons rate capable with 1% energy resolution



Each plane is 3-4 mm thick, with dedicated interconnected SiPM cluster array.

iMPACT – how to get approved (10^3 rule by A. Marchioro)

- Breakthrough solutions to achieve ultra-fast (**> 10 MHz cm^{-2}**) tracking and calorimetry at low power in silicon (**20 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), low voltage calorimeter for real clinical usage.

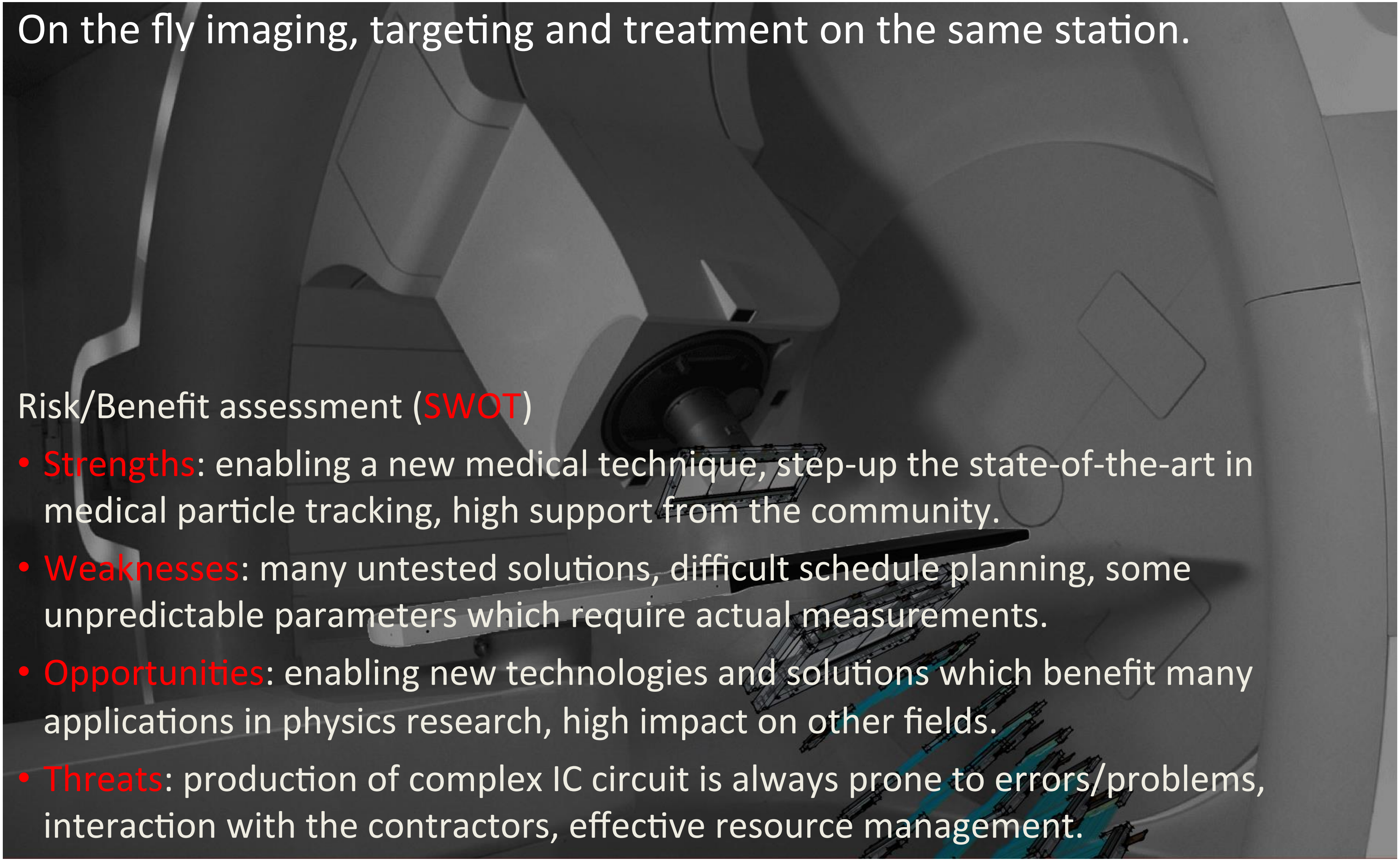


10 times faster × 10 times better × 10 times cheaper = 10^3 gain

Planning & outreach

what the ERC panel is actually interested in and looking for!

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.

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 methodology of data analysis.
- 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.

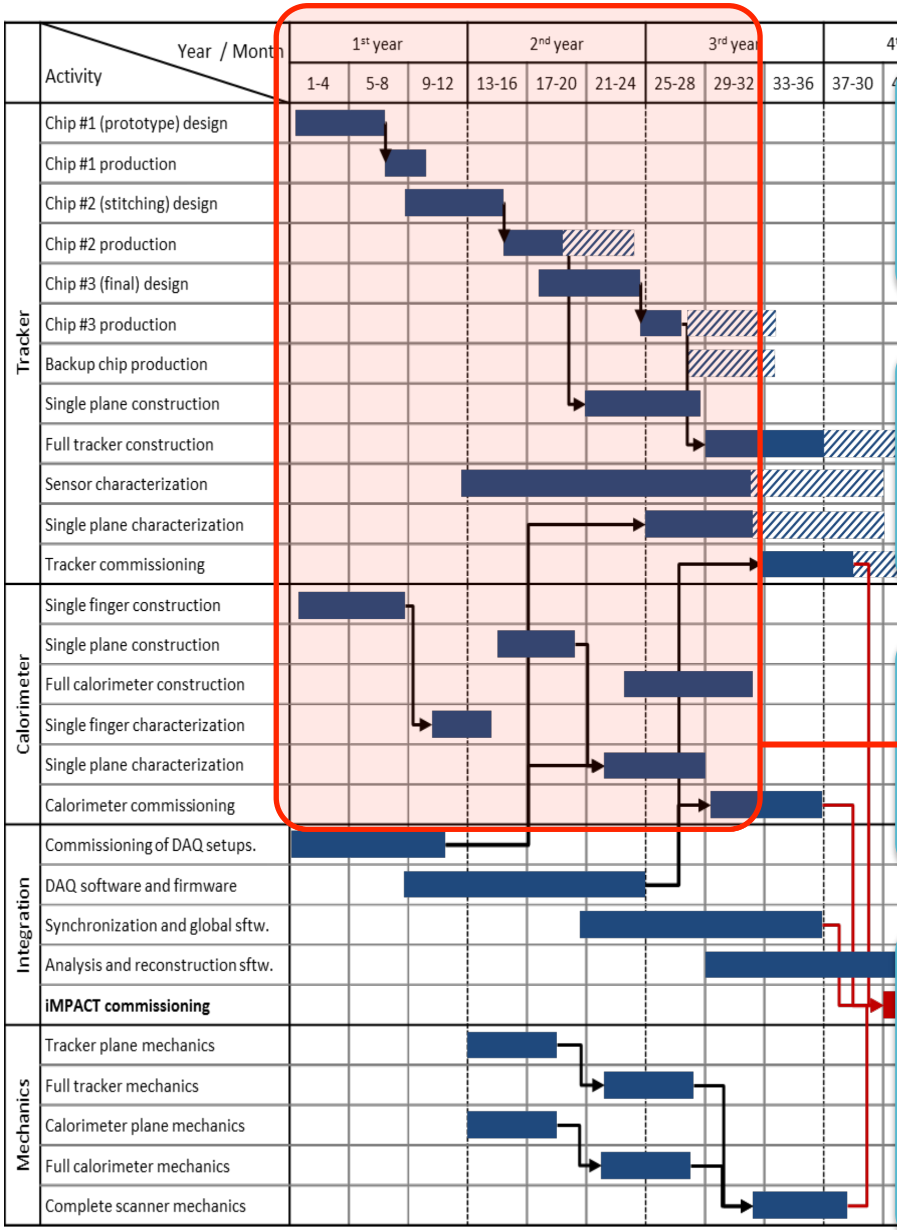
External support

- 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 – 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.

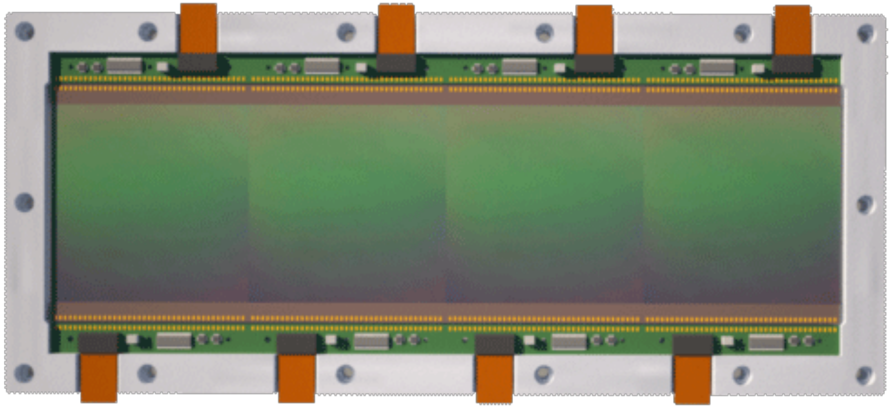
iMPACT – …but it is definitely worth it

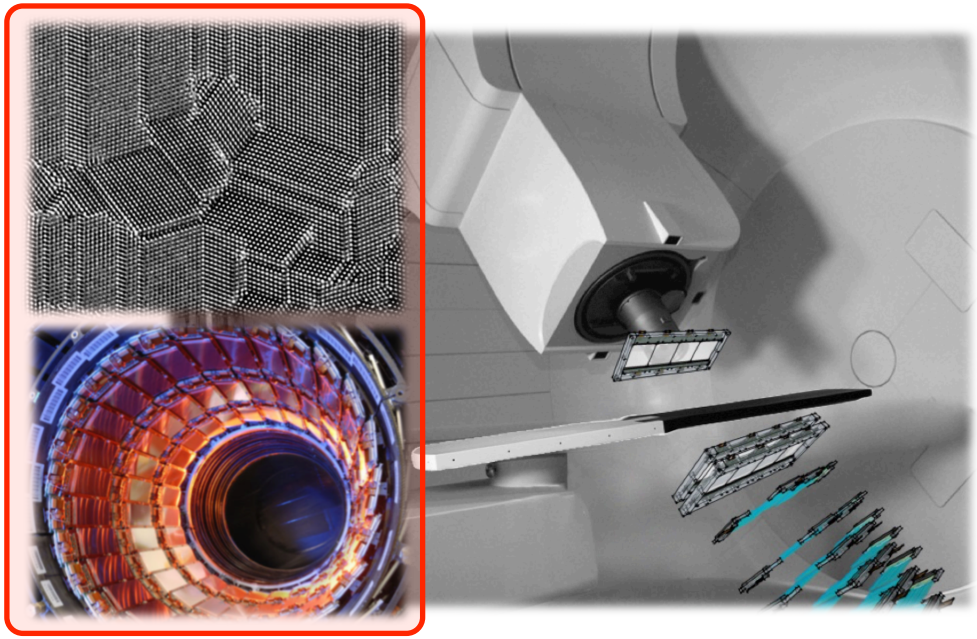
1 Thanks to > 1GHz real tracking rate capability: full pCT with **1s exposure**

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

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.





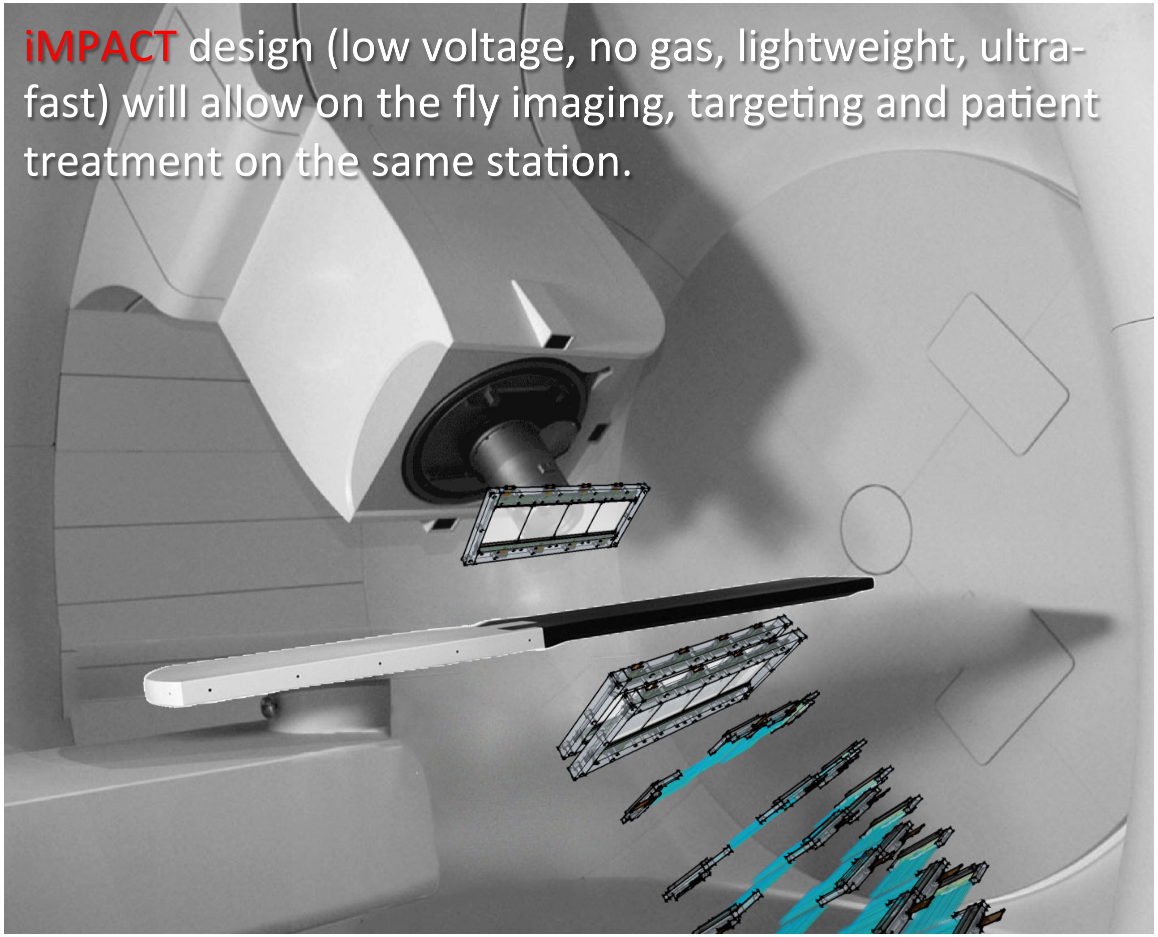
2 Ready to be integrated into real clinical environment for **real time targeting/treatment**.

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

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

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

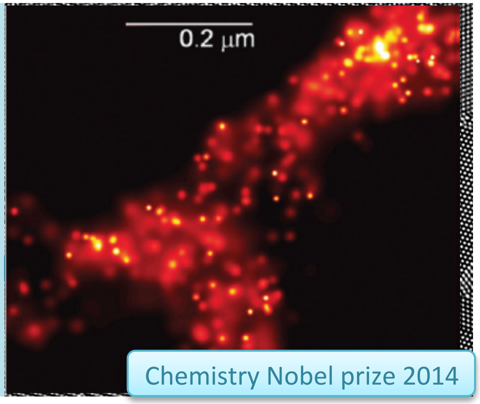
Outreach – from physics to medical and back to physics



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

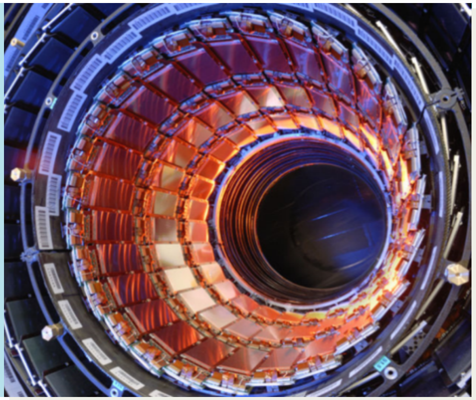
iMPACT advancements (high speed @ ultra low power & high resolution with reliable, cost-effective monolithic sensors) will be an enabling technology for the next generation physics instruments and experiments:

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

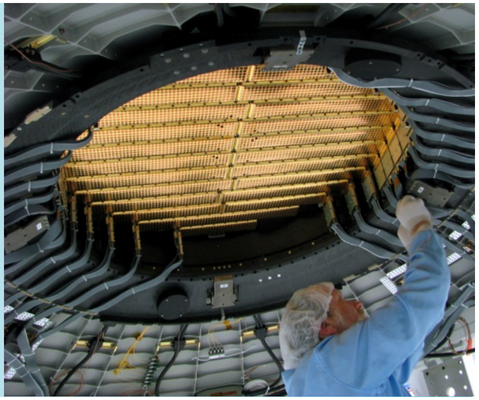


Chemistry Nobel prize 2014

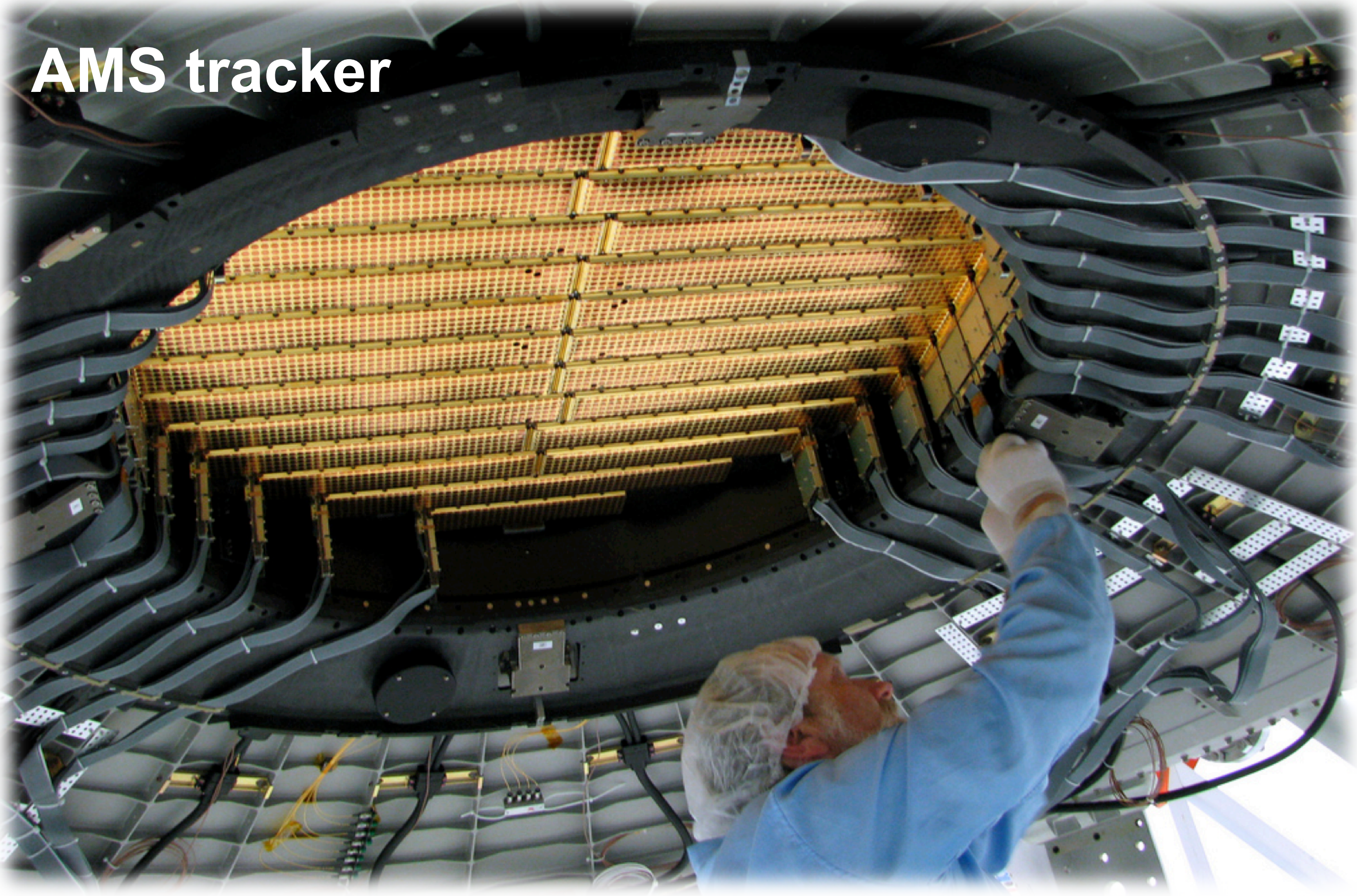
Next generation HEP trackers and calorimeters needs large surface, thin, ultra-fast, low power sensors, commercial technology to keep costs down.



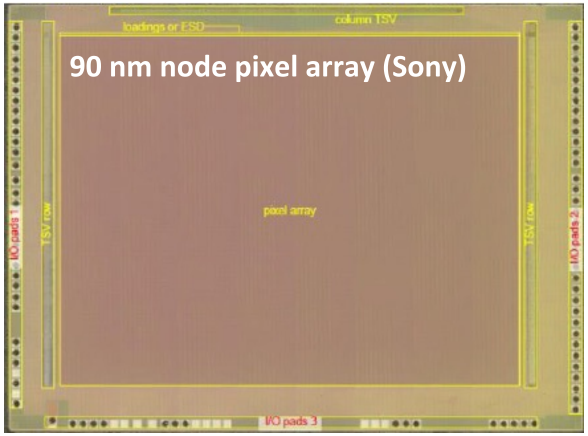
Space-born trackers and telescopes needs ultra low power, ultra high resolution (weak magnets there), extremely reliable (space spec) detectors.



Outreach – very small pixels & ultra low power for space

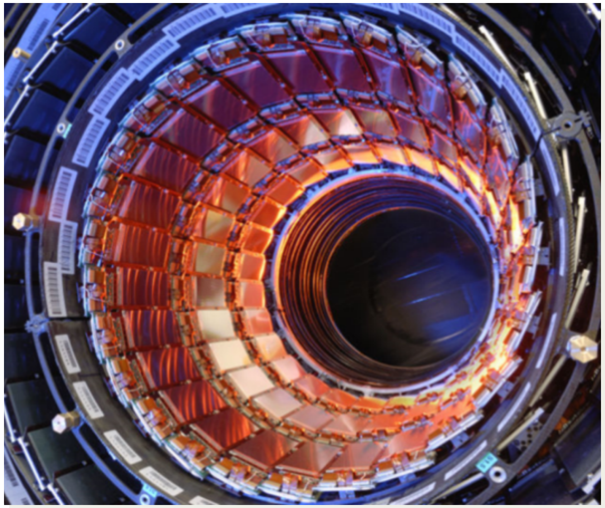


- No much room for heavy magnets in space experiments!
- Extra-small pixels to achieve the target tracks resolution.
- No much room for power supplles also:
- ultra low power definitely a must!



- Monolithic a clear choice to meet all this goals.
- Extreme reliability in rush operational conditions
- Cheap to produce for large-area detectors.

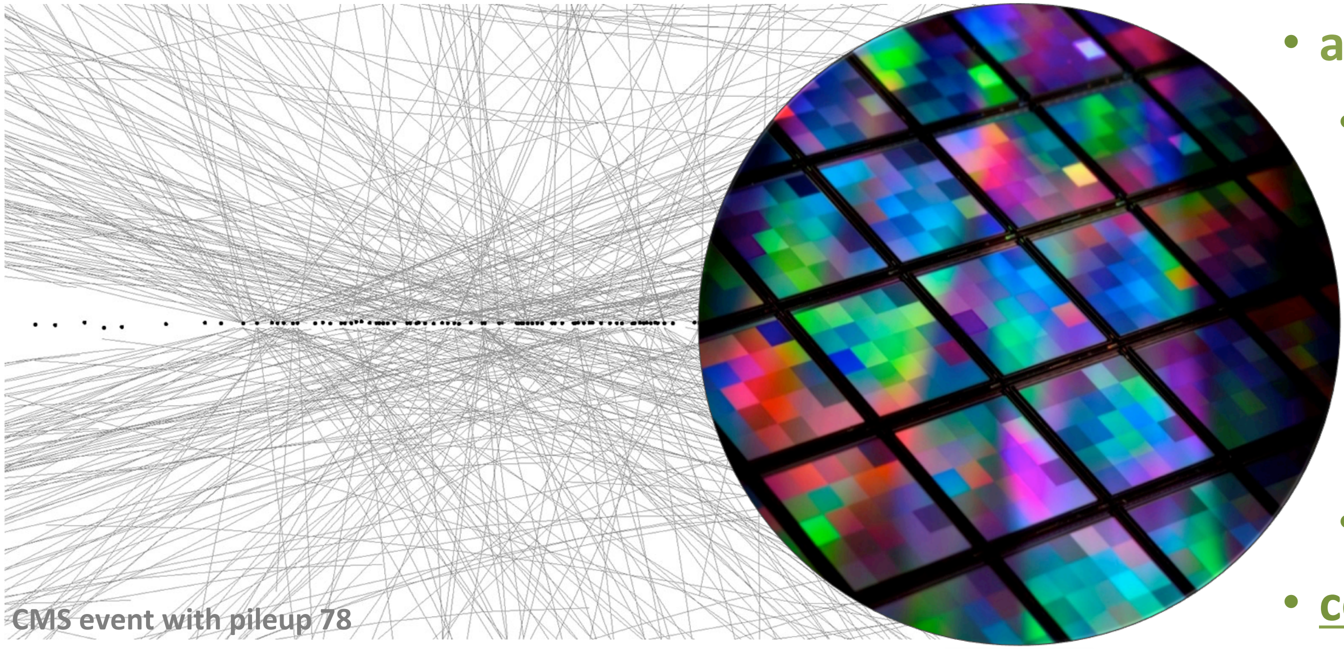
Outreach – cost, power and performance for HEP



From R&D53 findings (ChiPix65)

P. Giubilato - IFD 2015 Torino

- Investigating and proving the effectiveness/reliability of advanced technological solutions is becoming more and more difficult…
- Using 65nm tech node in a 1 Grad environment (**R&D 53**):
  - Consider changing the innermost layers at interval(s), i.e. design the whole system from scratch to support this possibility.
  - …



CMS event with pileup 78

- availability
  - pixel cell size
  - **radiation tolerance**
  - power budget
  - material budget
  - technology node
  - ease of assembly
- costs

iMPACT

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

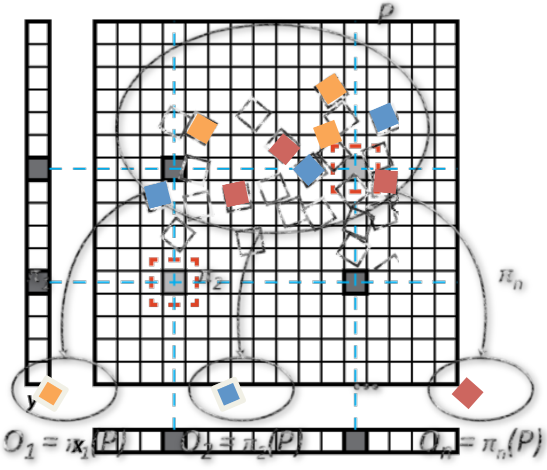
Thanks for your attention

Backup & deeper insight

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

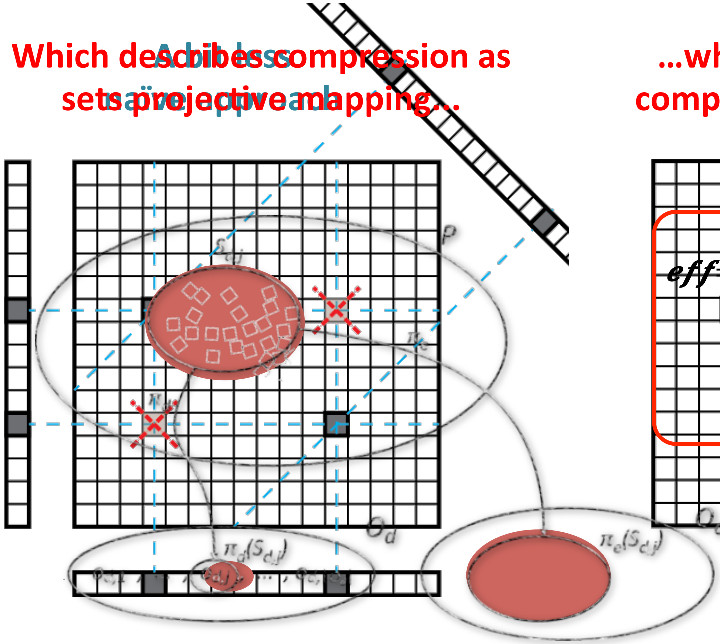
Naïve approach, current state-of-the-art

Yes, very general, math defined one!



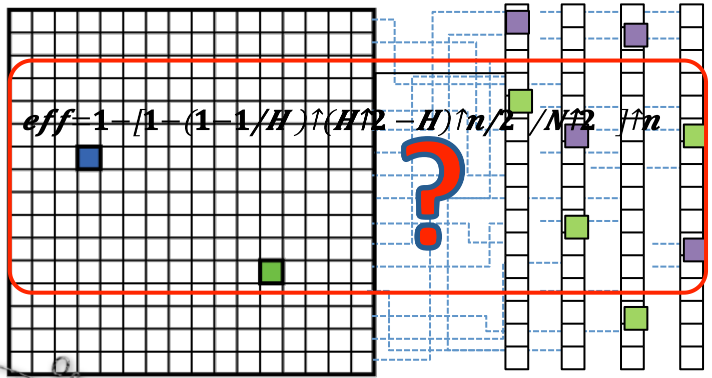
A bit less naïve approach

Which describes compression as sets projective mapping…

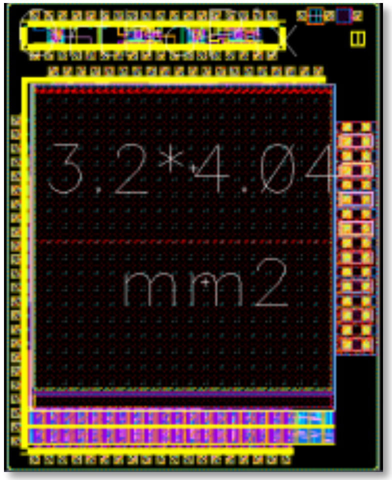


A more effective Approach possible?

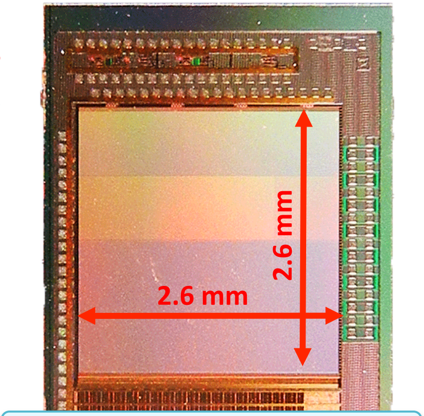
…which can be embedded into pixel fabric to compress data at the matrix level (HUGE speed)



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.