UPGRADE OF THE PROTON COMPUTED TOMOGRAPHY SYSTEM OF THE PRIMA PROJECT

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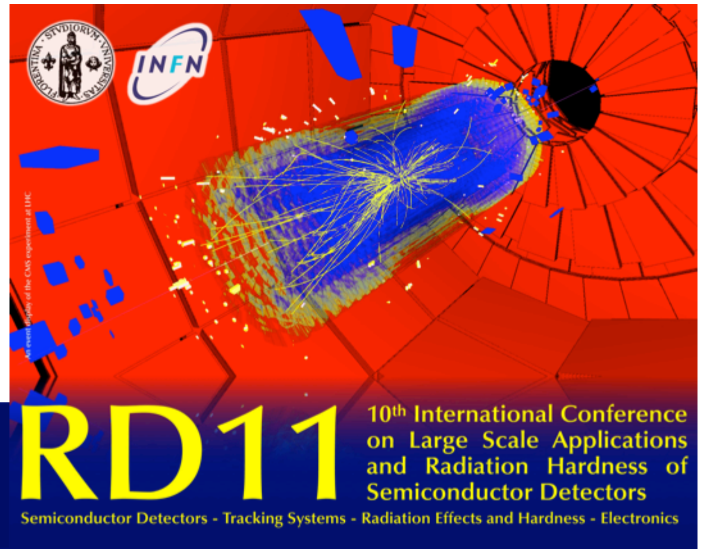


6-8 July 2011, Florence, Italy
Sala Convegni della Cassa di Risparmio di Firenze - Via Folco Portinari

Outline

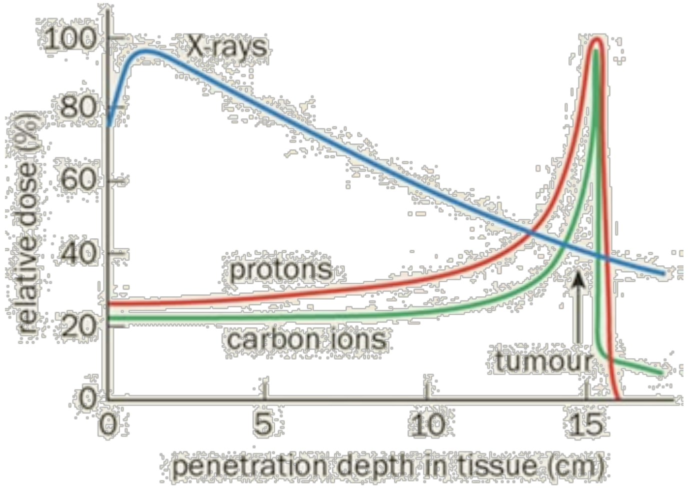
- Introduction: proton therapy and proton imaging
- Proton imaging apparatus
- Proton Radiographies at 60MeV
- Upgrade of apparatus

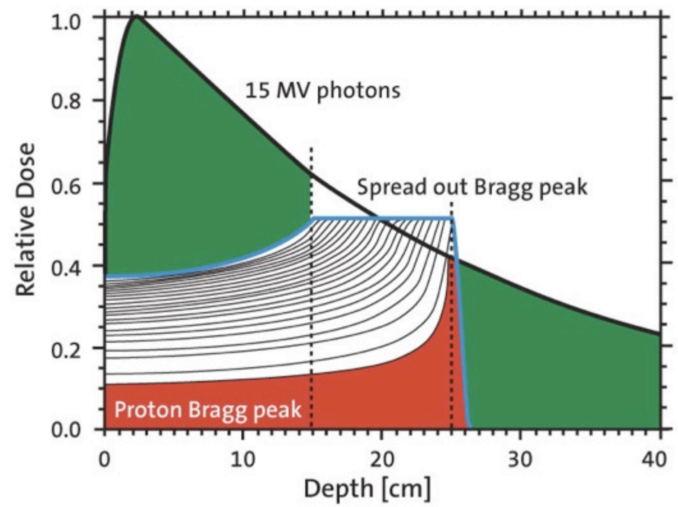
Proton therapy

The proton therapy is a good clinical treatment for cancer as it permits to obtain a dose distribution extremely conformed to the target volume.

The protons with penetration depth have a well-defined dose maximum (Bragg peak) that follows a relatively low entrance dose region. Beyond the Bragg peak the dose fall-off is very steep (from 90% to 20% of the peak dose within a few millimiters)

Through the weighted superposition of proton beams of different energies it is possible to deposit a homogenous dose in the target region using only a single proton beam direction.
(Spread Out Bragg Peak -SOBP).





proton Computed Tomography: why?

In proton therapy treatments it is important to know:

Patient positioning:

Currently performed using X-rays radiography and tomography in a previous phase

pCT → allows better accuracy and single phase positioning / treatments

Dose Calculation:

Currently performed using X-rays computed tomography

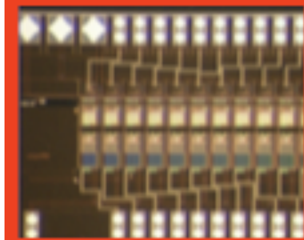
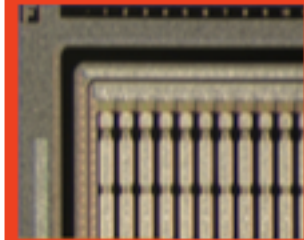
Problem: protons and photons have different interaction with matter

pCT → uses protons directly for dose calculation

The error intrinsic in this conversion (due to $\mu(\eta_e,Z)$ dependency on atomic number and electron density) is the principal cause of proton range indetermination (3%, up to 10 mm in the head)

[Schneider U. (1994), Med Phys. 22, 353]

THE "PRoton IMAging PROJECT" pCR apparatus oriented to pCT

PROGRAM

- Manufacture a high-performance prototype for proton radiography.
- Develop suitable imaging algorithms:
  - analysis of data;
  - MC simulations.
- Validate the pCR system with pre-clinical studies
- Conceive a configuration for a pCT system:
  - Hardware and data acquisition;
  - Reconstruction algorithms (ART, SART...).

Cfr *V. Sipala et al. Nuovo Cimento D (2011)*

V. Sipala et al., Nucl. Instr. and Meth. A 612 (2010) 566–570

V. Sipala et al. Nuclear Physics B, Vol. 197, Issue 1(2009) 39-42

C. Talamonti et al., Nucl. Instr. and Meth. A. 612 (2010) 571

C. Civinini et al., Nucl. Instr. and Meth. A 623 (2010) Pages 588-590

G.A.P. Cirrone et al., NIM A, vol. 576, no. 1, 11 June 2007, pp. 194-197.

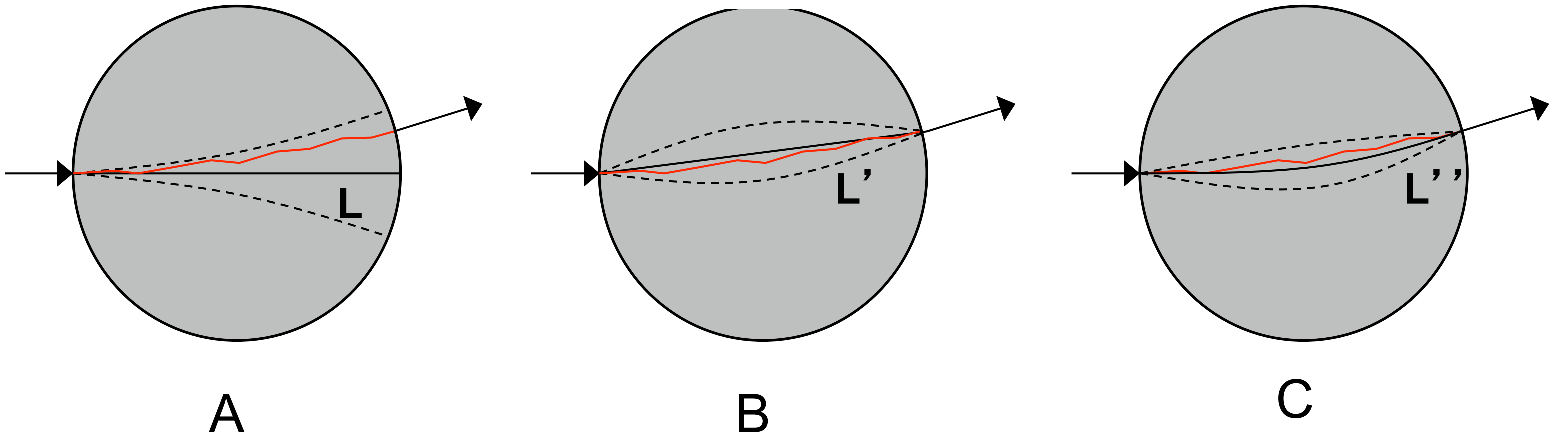
Parameters of pCT

PARAMETER	VALUE
Proton beam energy	250-270 MeV
Proton beam rate	1 MHz
Spatial resolution	< 1 mm
Electronic density resolution	< 1%
Detector radiation hardness	> 1000 Gy
Dose per scan	< 5 cGy

Problem: **protons, because the multiple Coulomb scattering, don't move in straight line.**

Single particle tracking and Most Likely Path reconstruction

$$\int_L \eta_e(\vec{r})\,d\vec{r} = K \int_{E_{out}}^{E_{in}} \frac{dE}{S(E)}$$

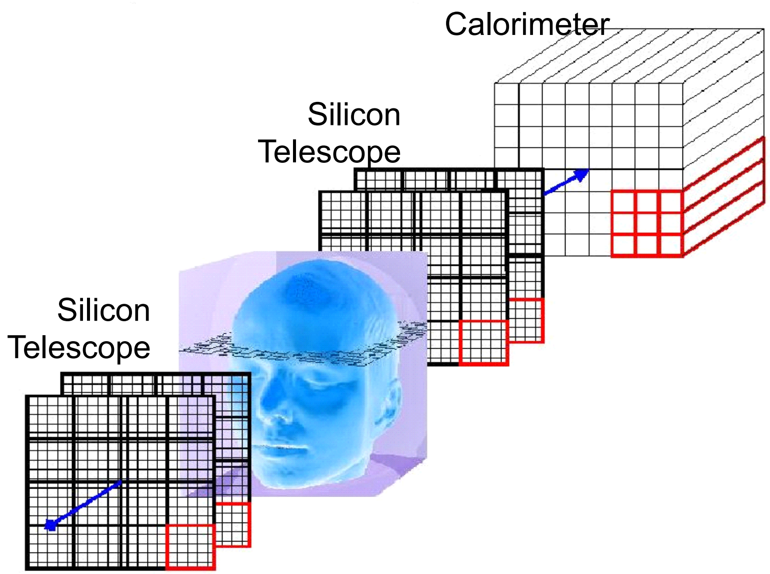


- A: Only entry position & direction known: straight line L
- B: Entry position & direction + exit position known: straight line L'
- C: Entry position & direction + exit position & direction known: curved path L", "banana-shaped", narrow confidence limits

Concept

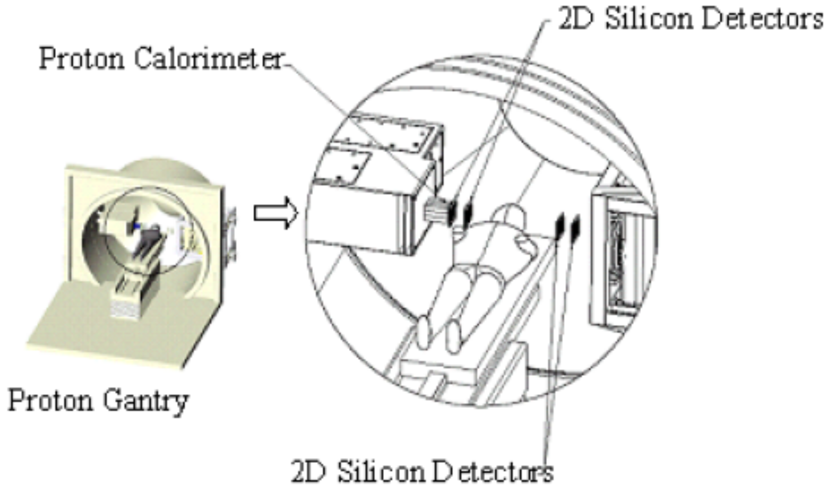
proton Computed Radiography

- Reveal the trace of the single proton using a silicon telescope
- Measure the residual energy of the proton using a calorimeter
- Reconstruct the most likely path of the single proton

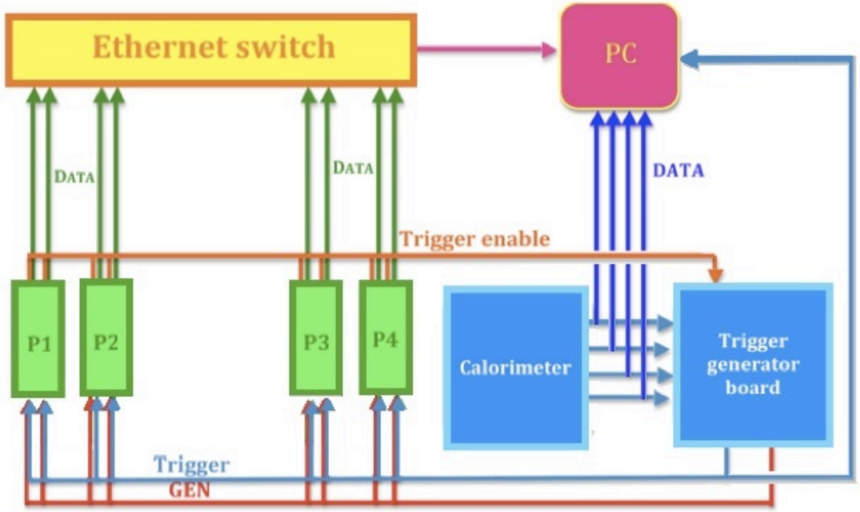


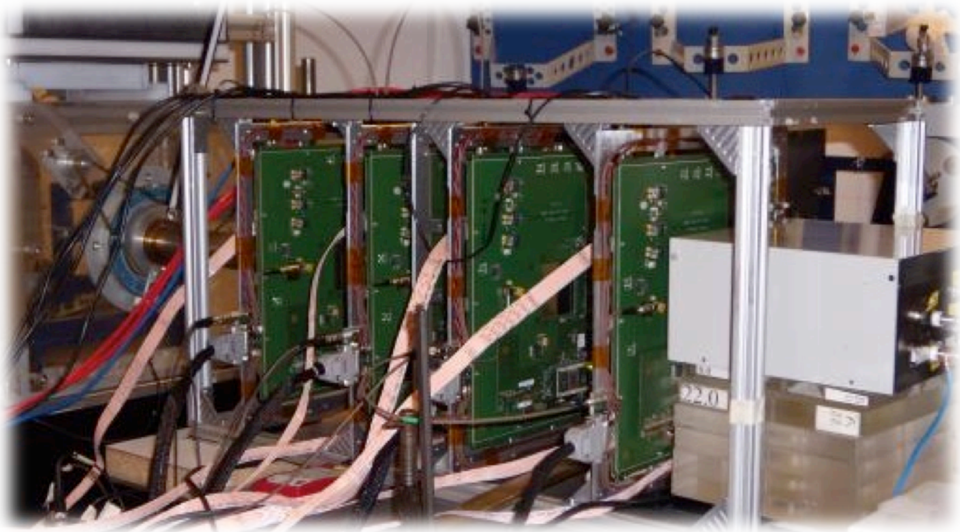
proton Computed Tomography

- pCR for different projections with a rotating gantry
- Reconstruct the image

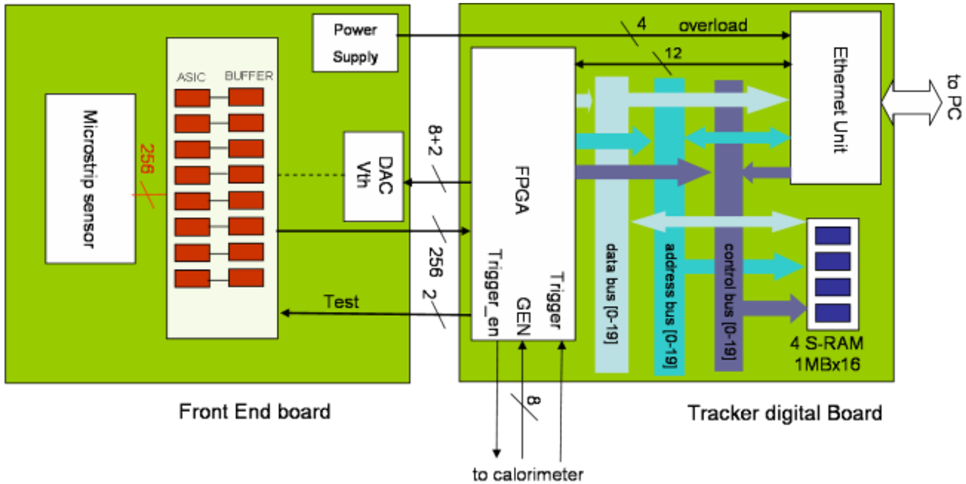


Schema of Proton Computed Radiography Device realized by the PRIMA(PRoton IMAging) collaboration



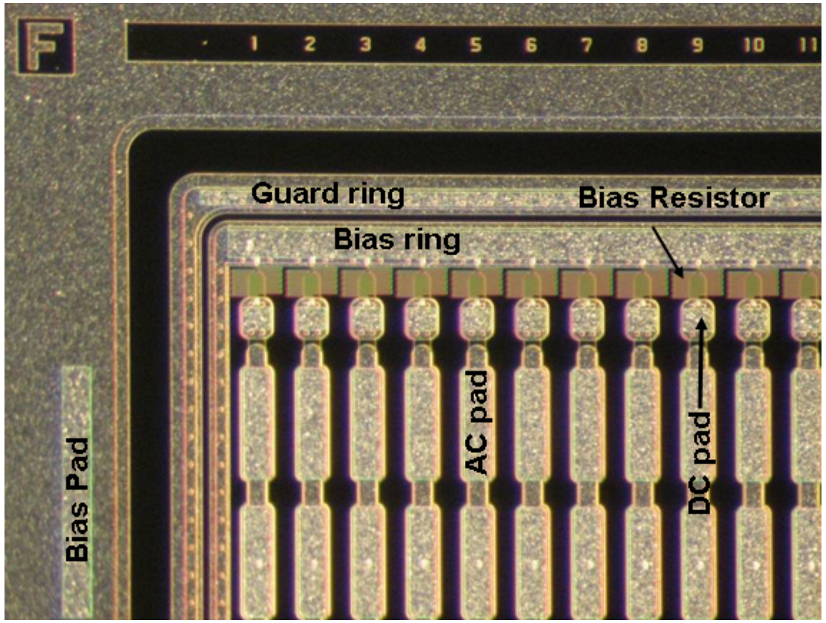


Single module architecture



- To achieve a read-out rate of 1 MHz a fully parallel digital strip readout system has been developed
- Eight 32-channel VLSI front-end chips acquire the detector signals and sends data in parallel to an FPGA (Xlinx Spartan-3AN) which performs zero suppression and moves data to a buffer memory (~$5x10^5$ events).
- An Ethernet commercial module is use both for data transfer to the central acquisition PC and to control the tracker module DAQ parameters

Silicon strip detector



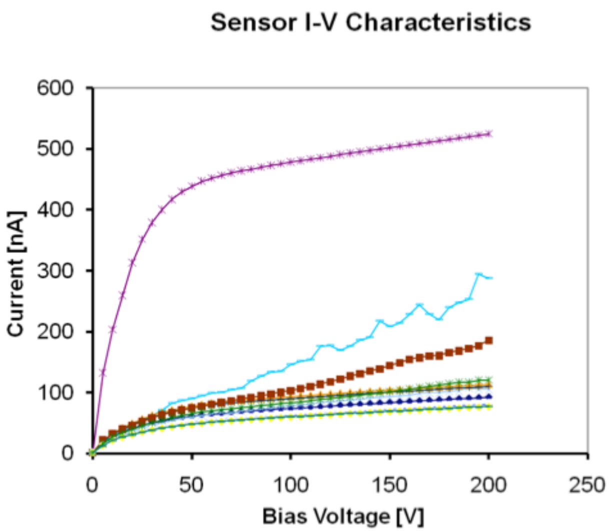
Manufactured by Hamamatsu Photonics

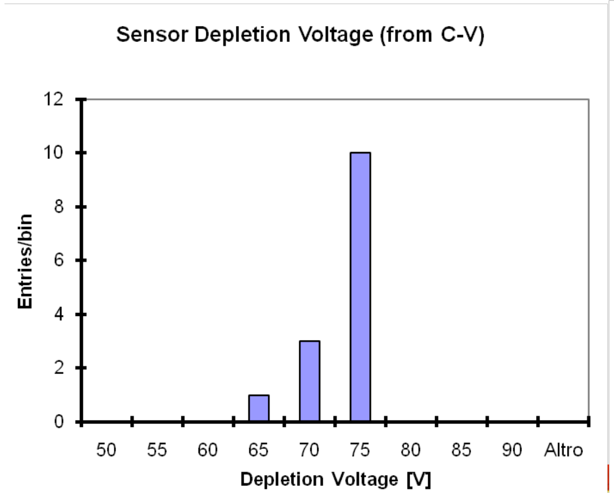
53x53 mm^2

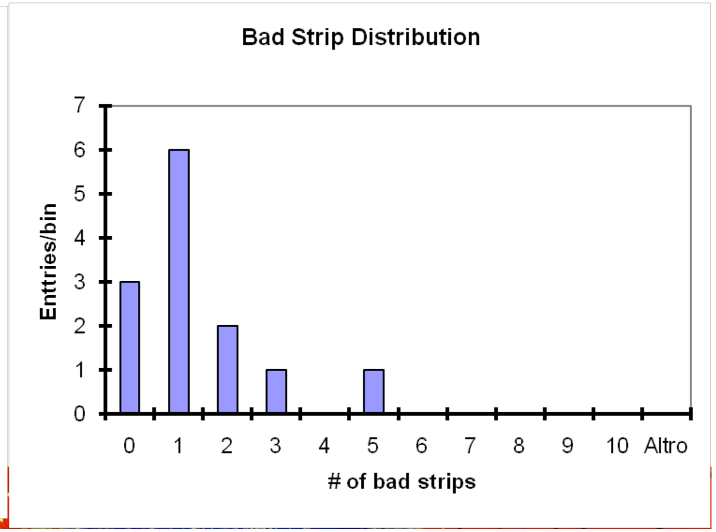
p+-on-n strips

256 ch, 200 μm pitch

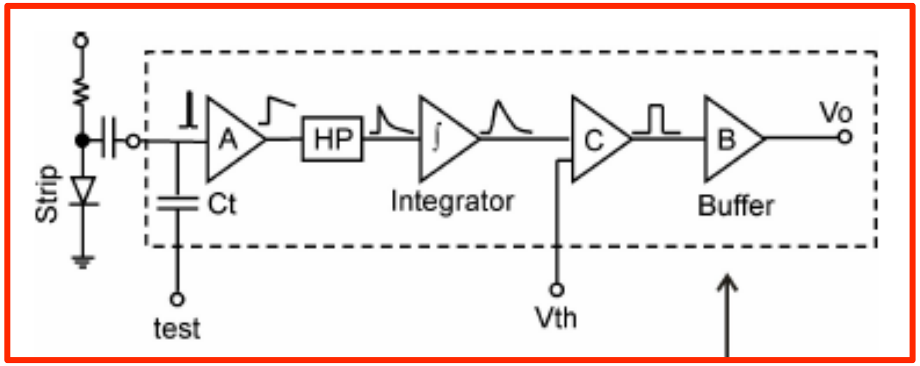
200 μm thickness
(To reduce the multiple scattering in the detector planes while keeping a good sensitivity to protons)

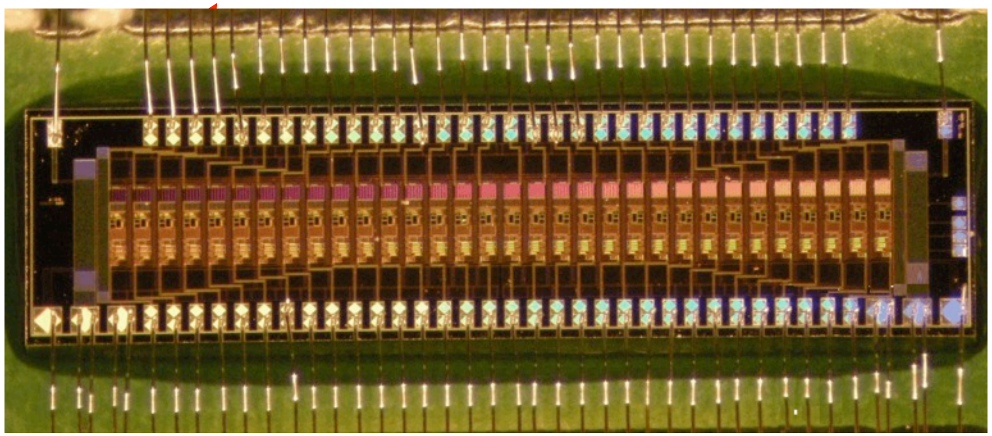






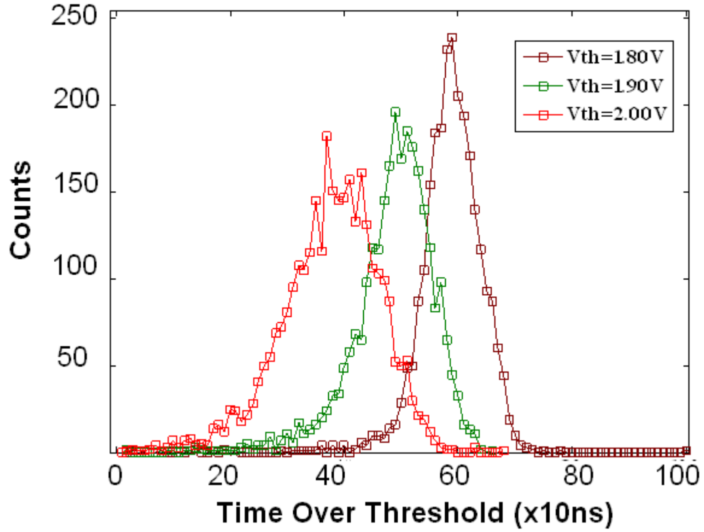
VLSI front-end description

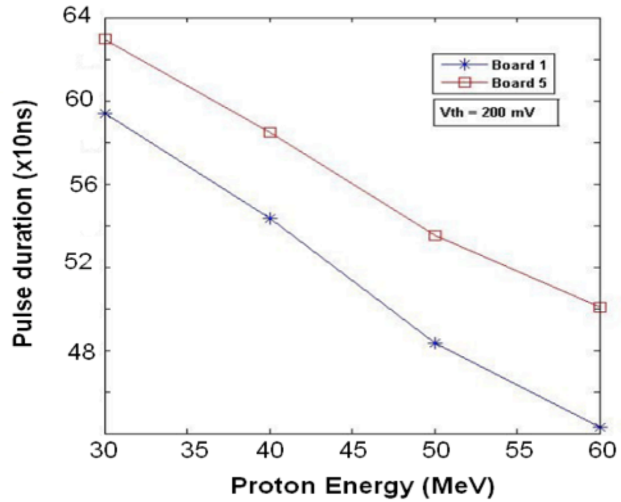




- **AMS 0.35u CMOS Technology**
- **1.6 mm x 6 mm**
- **32 channels**
- **Power dissipation = 14,5 mW @ chan**
- **Vcc = +3.3 V**

Test performed at LNS with 60MeV proton beam

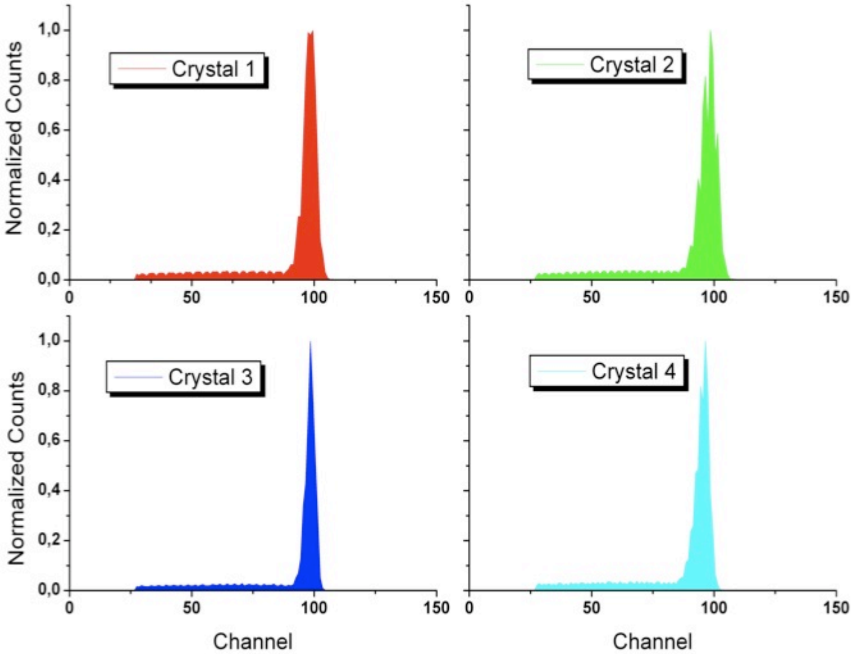




Calorimeter

- 4 YAG:Ce scintillating crystals
  Each crystal 30 x 30 mm^2 x 100mm
- 4 Photodiode 18 mm x 18 mm
- 4 commercial front-end
  (Charge Sensitive Amplifier & shaper)

YAG:Ce properties	
PHYSICAL PROPERTIES	
Density [g/cm^3]	4.57
Hygroscopic	No
Chemical formula	$Y_3Al_5O_{12}$
LUMINESCENCE PROPERTIES	
Wavelength of max. emission [nm]	550
Decay constant [ns]	70
Photon yield at 300k [10^3 Ph/MeV]	40-50



Charge spectrum @100MeV

Complete pCR apparatus

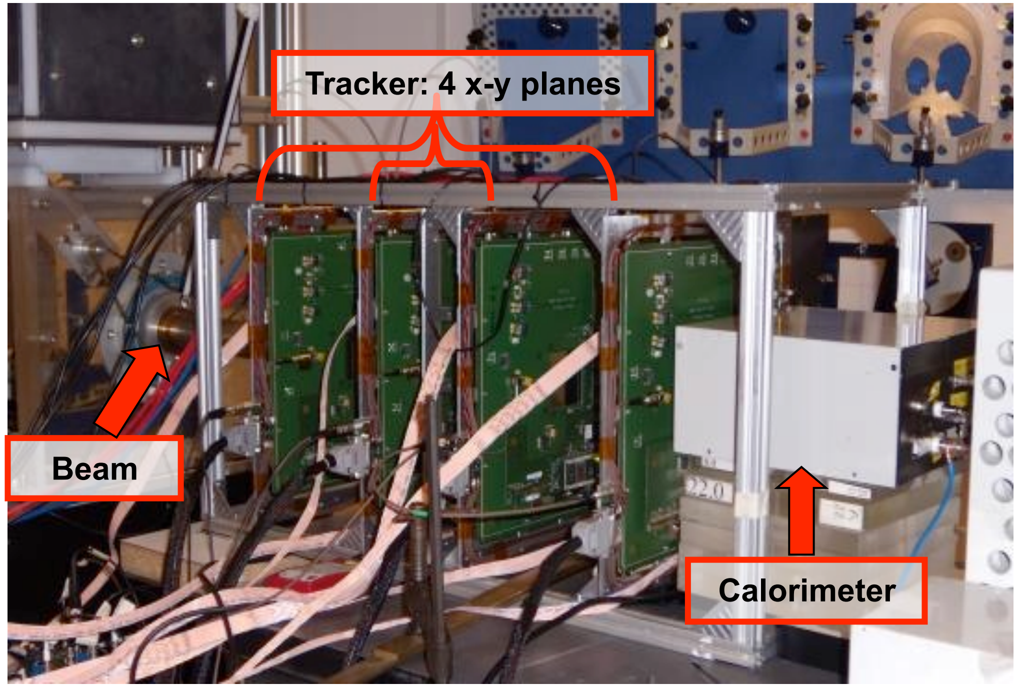
Test at LNS

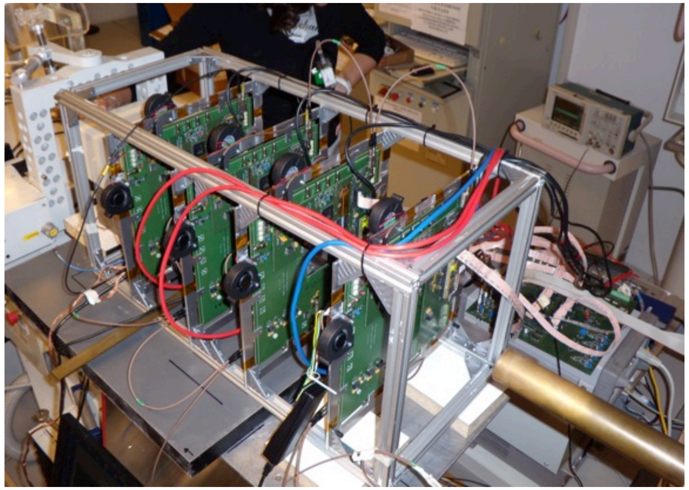
(May 2010-May 2011)

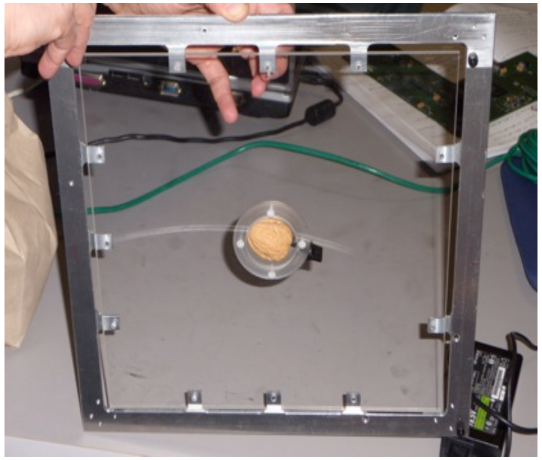
-Alignment test

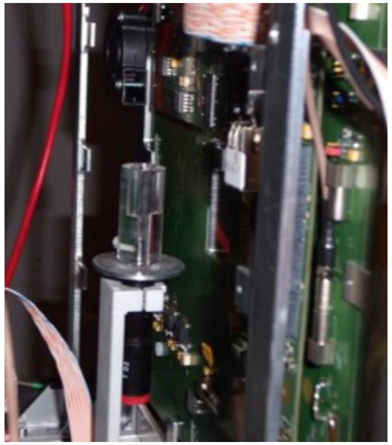
-Radiography test

-Tomography test

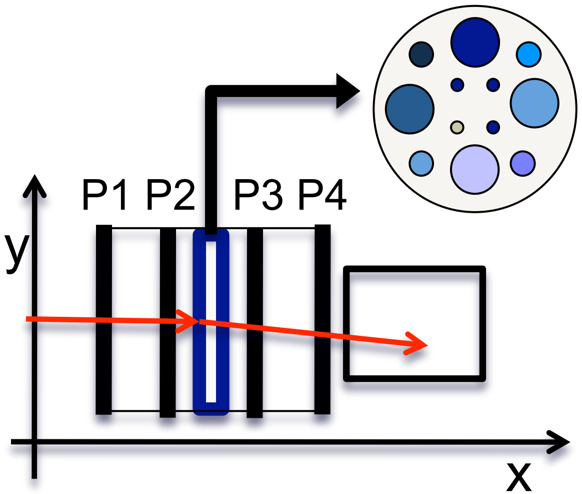






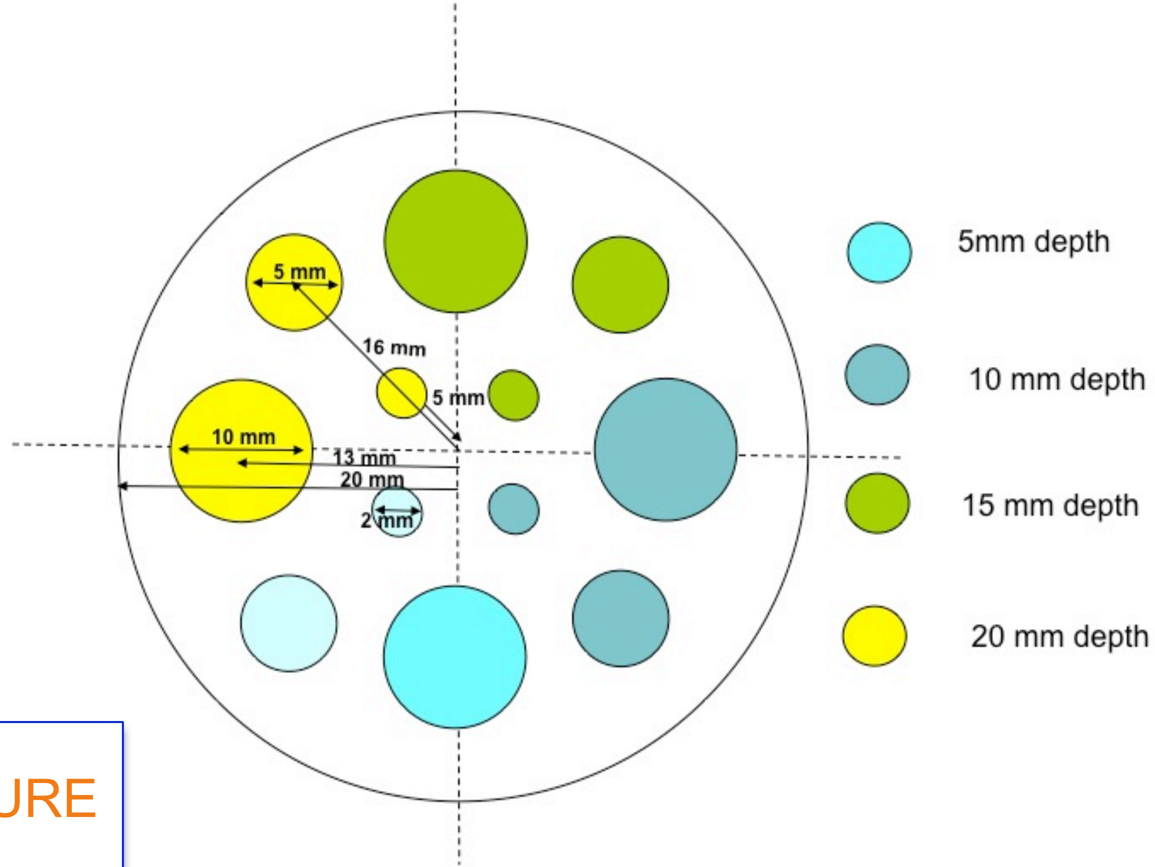


Complete pCR apparatus - *Test at LNS (13May 2010)*



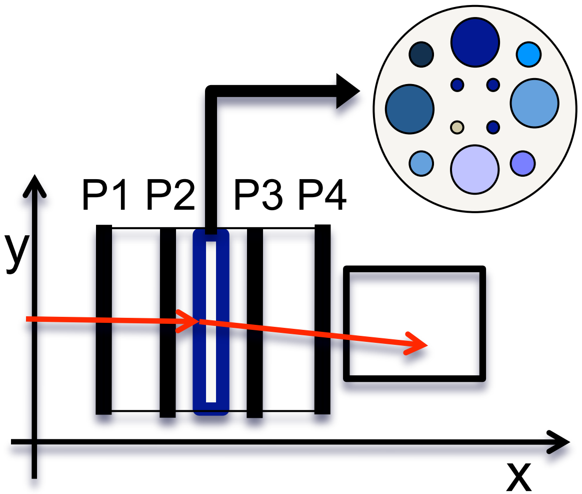
Experimental setup

DATA ANALYSIS PROCEDURE
- •MLP reconstrution
- •Back-projection of the data
- •Phantom image

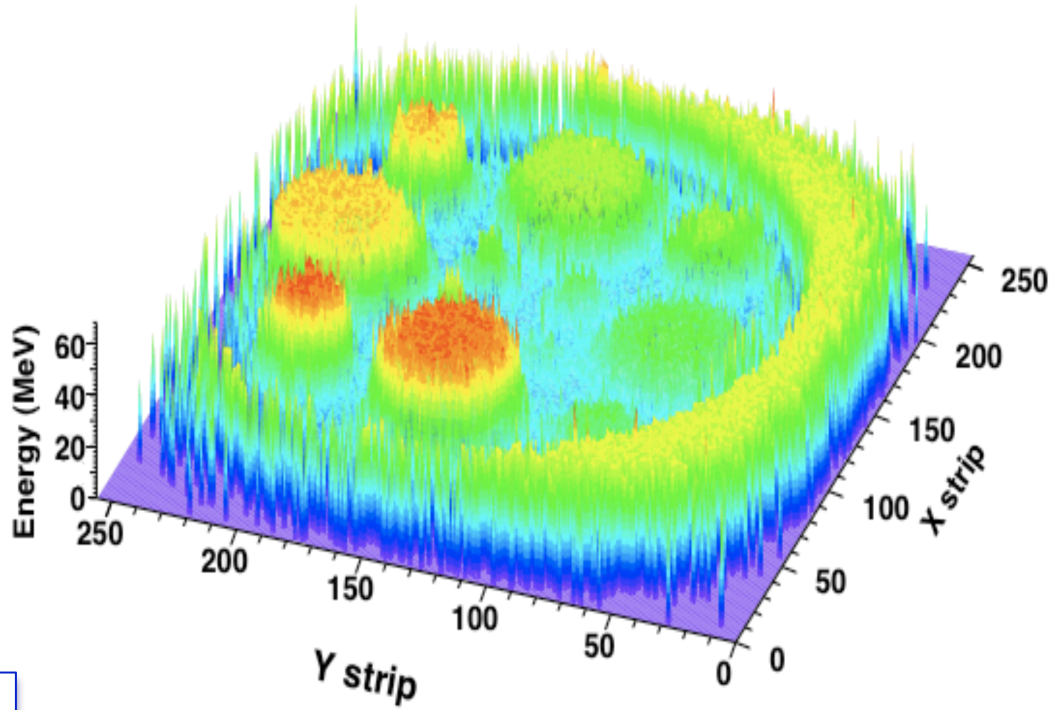


Phantom design

Complete pCR apparatus - *Test at LNS*



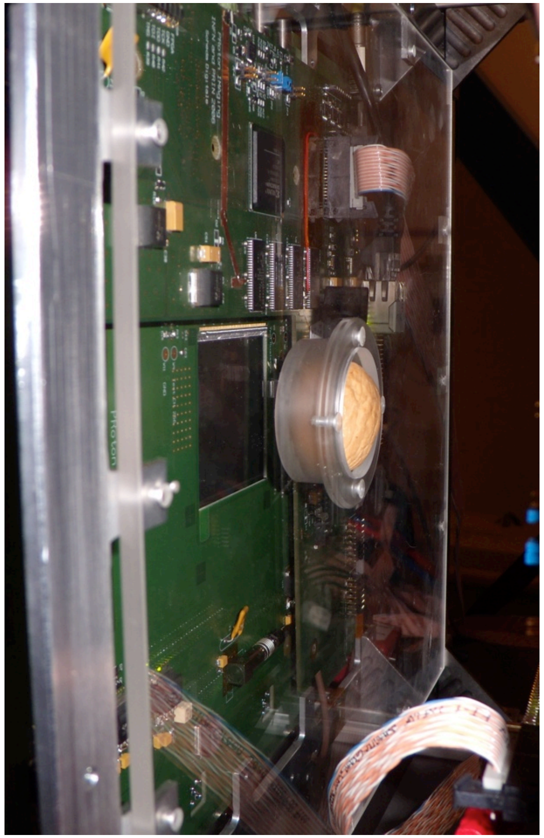
Experimental setup

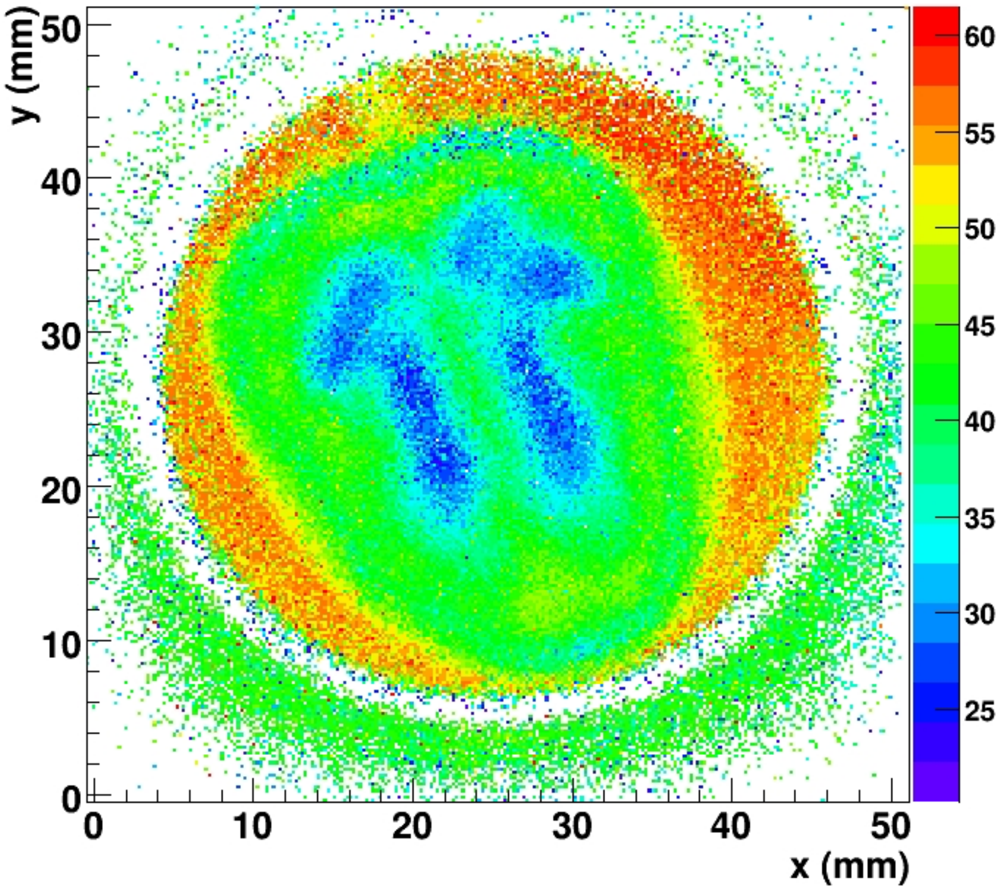


DATA ANALYSIS PROCEDURE
- MLP reconstrution
- Back-projection of the data
- Phantom image

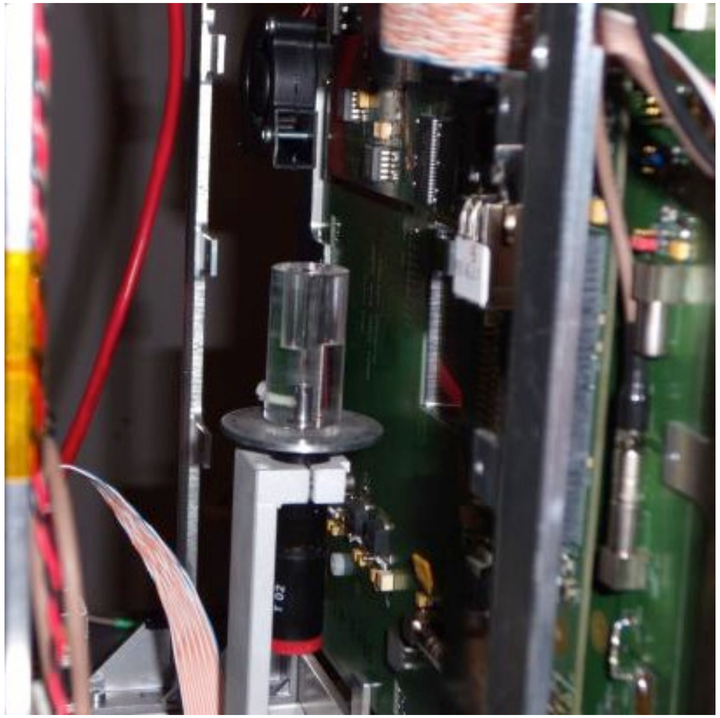
Phantom image

Test at LNS: Walnut radiography

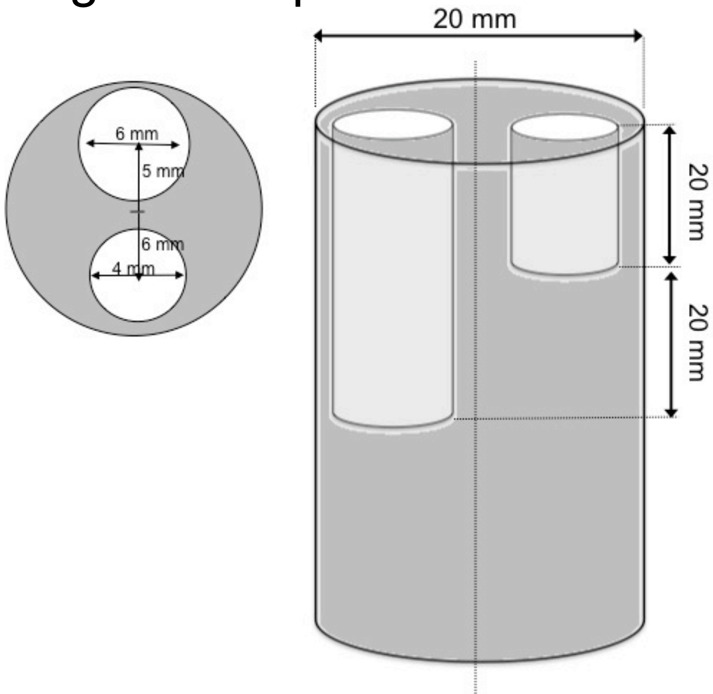




First tomography setup

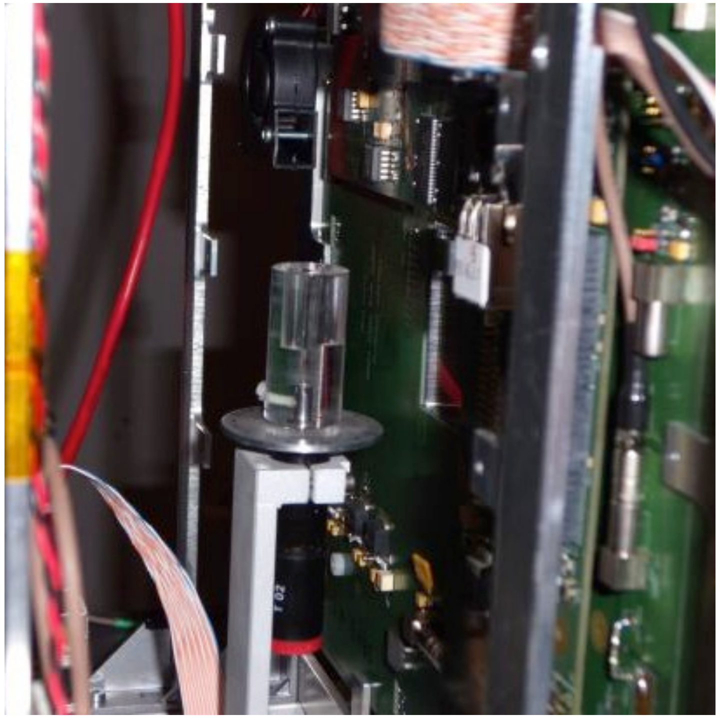


Design of the phantom

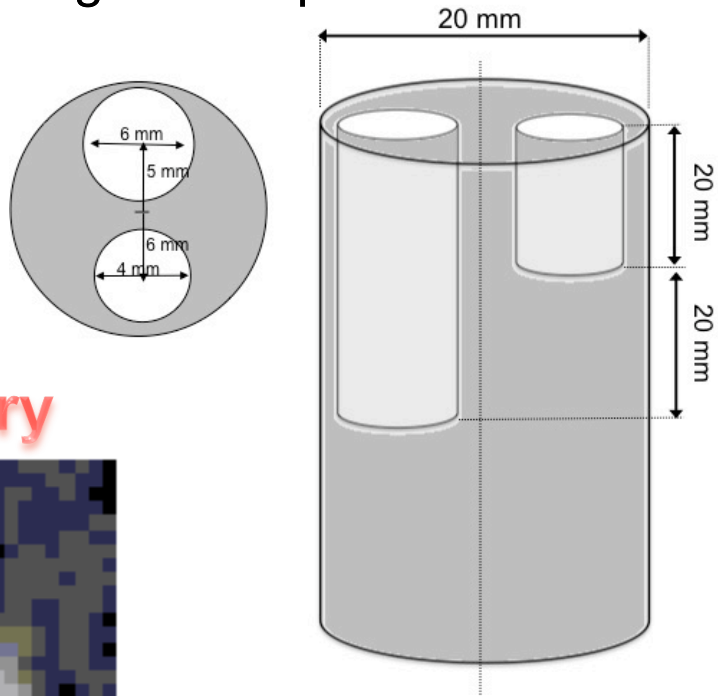


Data analysis is in progress

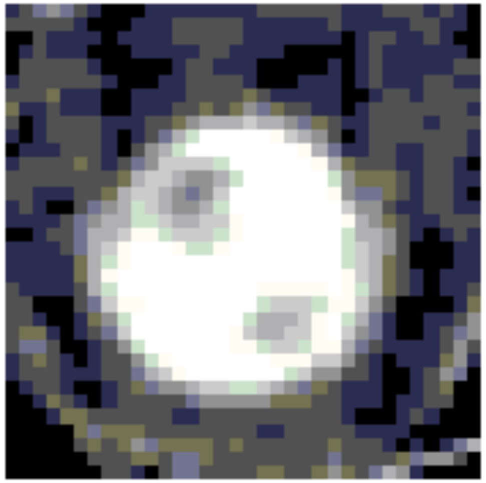
First tomography setup



Design of the phantom



Very preliminary



Data analysis is in progress

Status @ July 2011

A system for proton radiography has been realized:

- Field of view of about $5x5cm^2$
- Acquisition time of the order of 10sec (10kHz, 10^5 events)

The complete apparatus has been tested with 60MeV proton beam at LNS

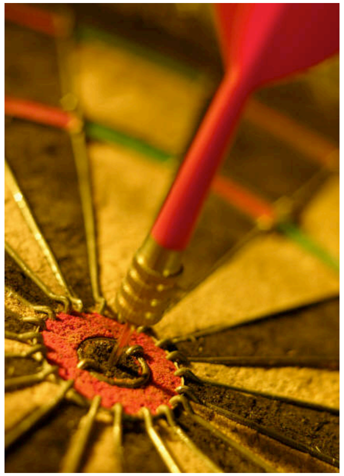
Semi analytical reconstruction methods of the proton radiography has been developed and tested with data

The tomographic data analysis is in progress

The PRIMA upgrade is defined

Future planes

- Analysis of the tomography data and development of reconstruction algorithm
- New test of the apparatus at higher energy
- **Construction of pCT apparatus for clinical application**



PRIMA Upgrade

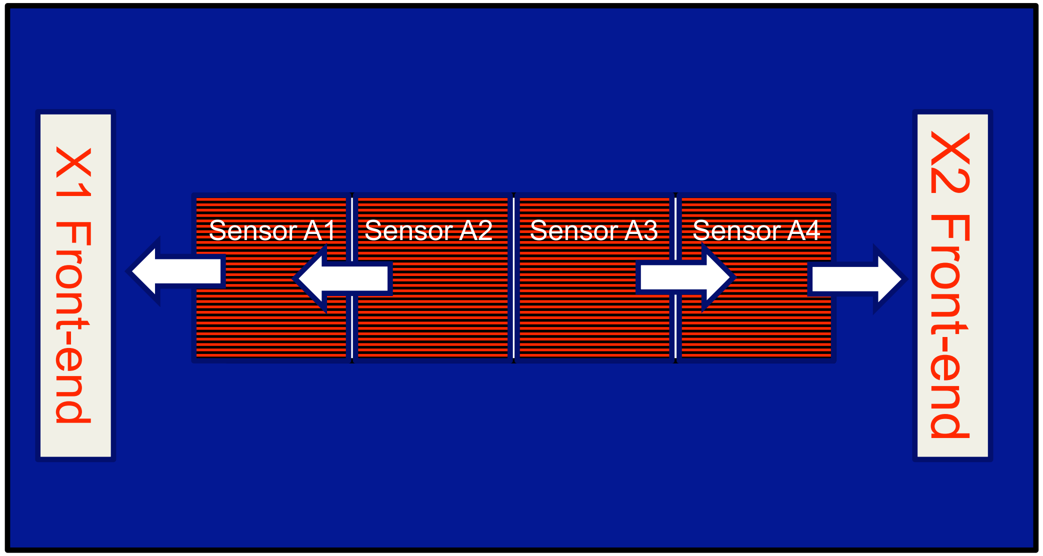
GOAL: pCT system for clinical applications.

- Larger active area
- On line data acquisition

→Active area 5 x 20 cm^2 using the 5x5cm^2 detectors

→New data acquisition system

Tracker module



Front

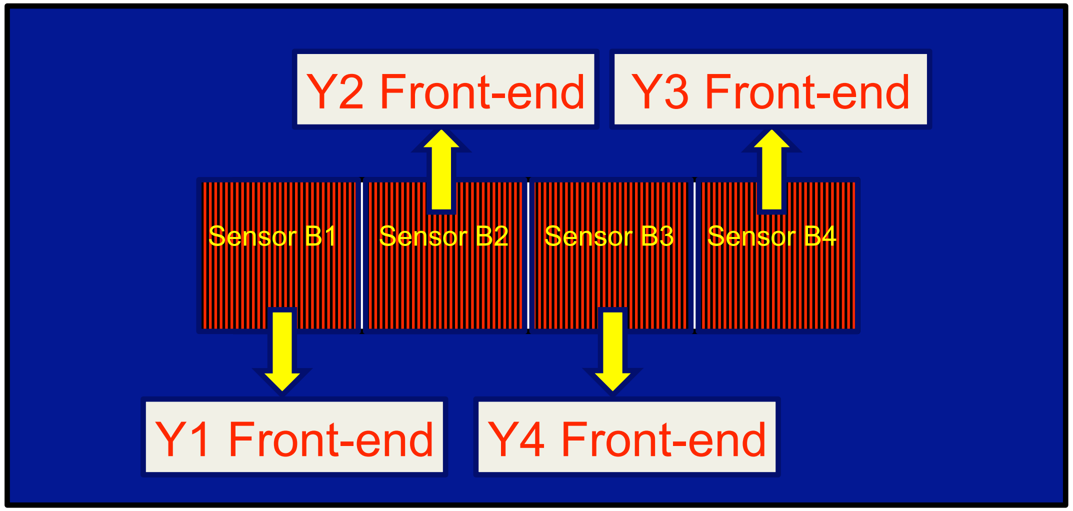
X-Plane

- *4 detectors*
- *2 Front-end data blocks*

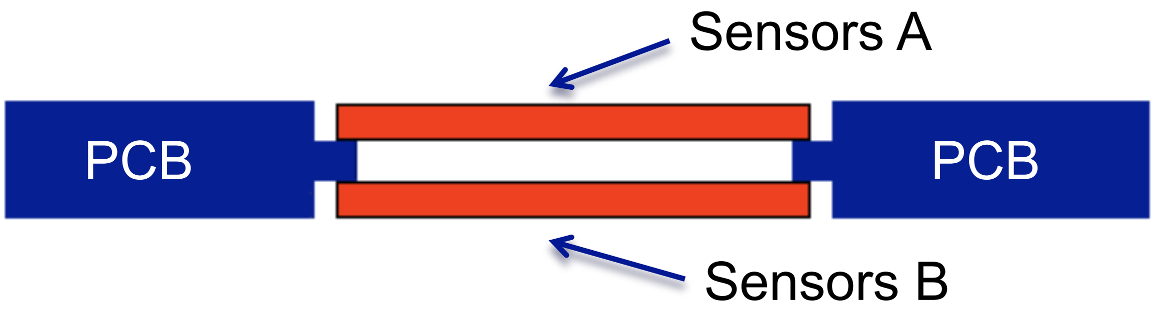
Back

Y-Plane

- *4 detectors*
- *4 Front-end data blocks*



Tracker module cross-section



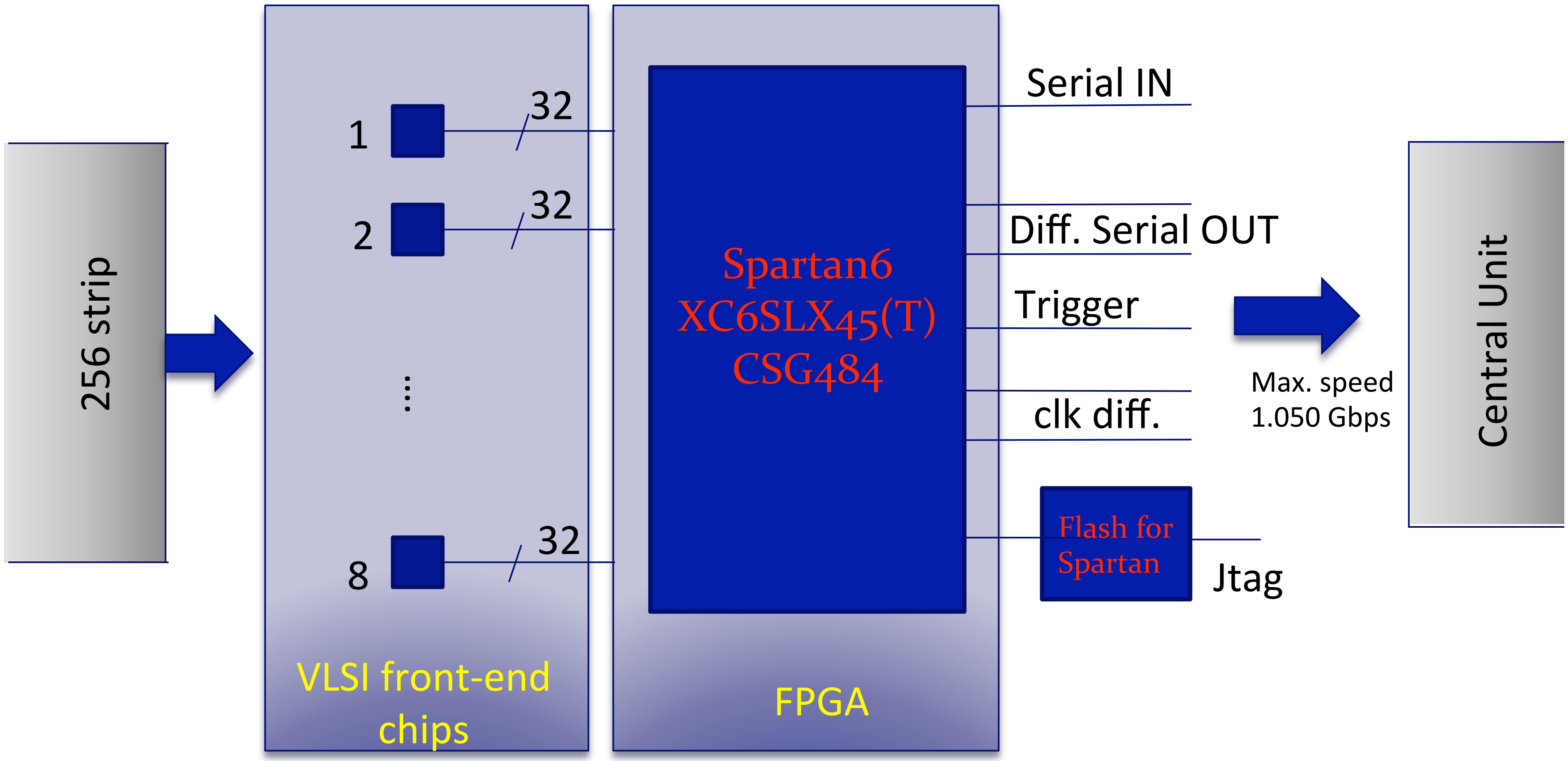
- Detectors directly mounted on printed circuit board (PCB)

Glued on the central hole, on both sides, using a small support precisely machined

- The sensor bias contact connected to the front face

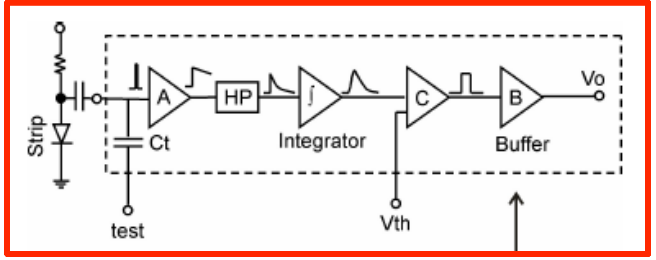
- Electronics components mounted in both sides of PCB

Tracker module:front-end block



Front-end chip

- Starting of old chip:



and of test results:

- Threshold value dispersion
- Non-linearity response

New front-end chip charactristics

- 32 channels
- Each channel: Preamplifier + shaper CR-RC^3 + Comparator + DAC (8bit)
- New digital part for serial-parallel conversion and for chip and channel selection

DAQ of tracker: architecture

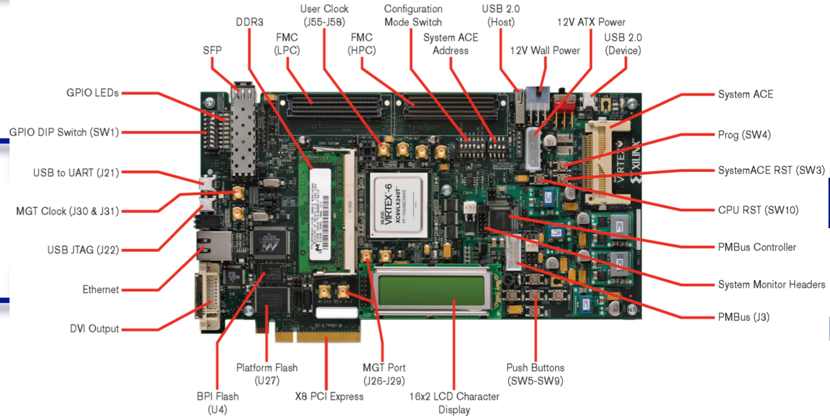
Tracker module

Tracker module

Tracker module

Tracker module

Serial links
6 x board

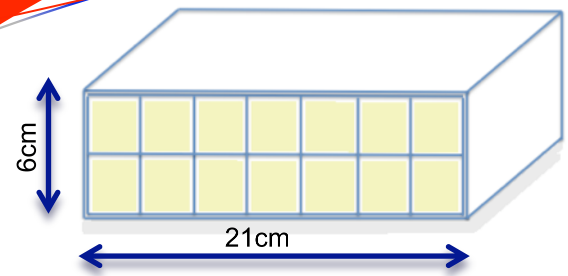


PC

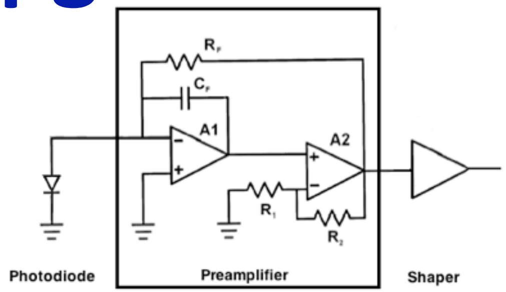
net links

Status: Evaluation board → acquired
Test of serial links → in progress

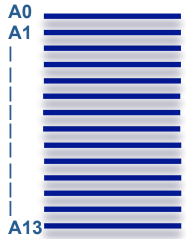
Calorimeter Upgrade



Calorimeter Layout



Single channel front-end



Sampling, data storage and transfer

NI 5751
32-Channel Digitizer Adapter Module for NDT Applications

- 16 simultaneous 50 MS/s, 14-bit channels
- 8 digital inputs
- 8 digital outputs
- Ability to synchronize multiple devices for high-channel-count applications

NI PXIe-7962R
NI FlexRIO FPGA Module for PXI Express

- DSP-focused Virtex-5 SX50T FPGA programmable with the LabVIEW FPGA Module
- 512 MB onboard DDR2 DRAM
- Access to 132 single-ended I/O lines, configurable as 66 differential pairs
- Customizable I/O with the NI FlexRIO Adapter Module Development Kit (MDK)
- 16 DMA channels for high-speed data streaming at more than 800 MB/s

NI PXIe-8102 RT
1.9 GHz Intel Celeron T3100 Dual Core With LabVIEW Real-Time

- Deployment platform for LabVIEW Real-Time and LabWindows™/CVI Real-Time applications
- Execution target for NI LabVIEW Real-Time Version 8.6.1 or later applications
- 1 GB (1 x 1 GB DIMM) 800 MHz DDR2 RAM standard, 2 GB maximum
- 1 GB/s maximum system and 250 MB/s maximum slot bandwidth
- Integrated hard-drive, USB, serial, Gigabit Ethernet, and other peripheral I/O

Calorimeter Upgrade

NI 5751
16-Channel Digitizer Adapter Module for NDT Applications

- 16 simultaneous 50 MS/s, 14-bit channels
- 8 digital inputs
- 8 digital outputs
- Ability to synchronize multiple devices for high-channel-count applications

NI PXIe-7962R
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- 1 GB (1 x 1 GB DIMM) 800 MHz DDR2 RAM standard, 2 GB maximum
- 1 GB/s maximum system and 250 MB/s maximum slot bandwidth
- Integrated hard-drive, USB, serial, Gigabit Ethernet, and other peripheral I/O

- Sampling of 14 analog signals
- Output of trigger signal
- "Global Event Number"(GEN output

- Pre – elaboration data
- Trigger generator
- GEN generetor

- Data storage
- Data transfer

Thanks!!!

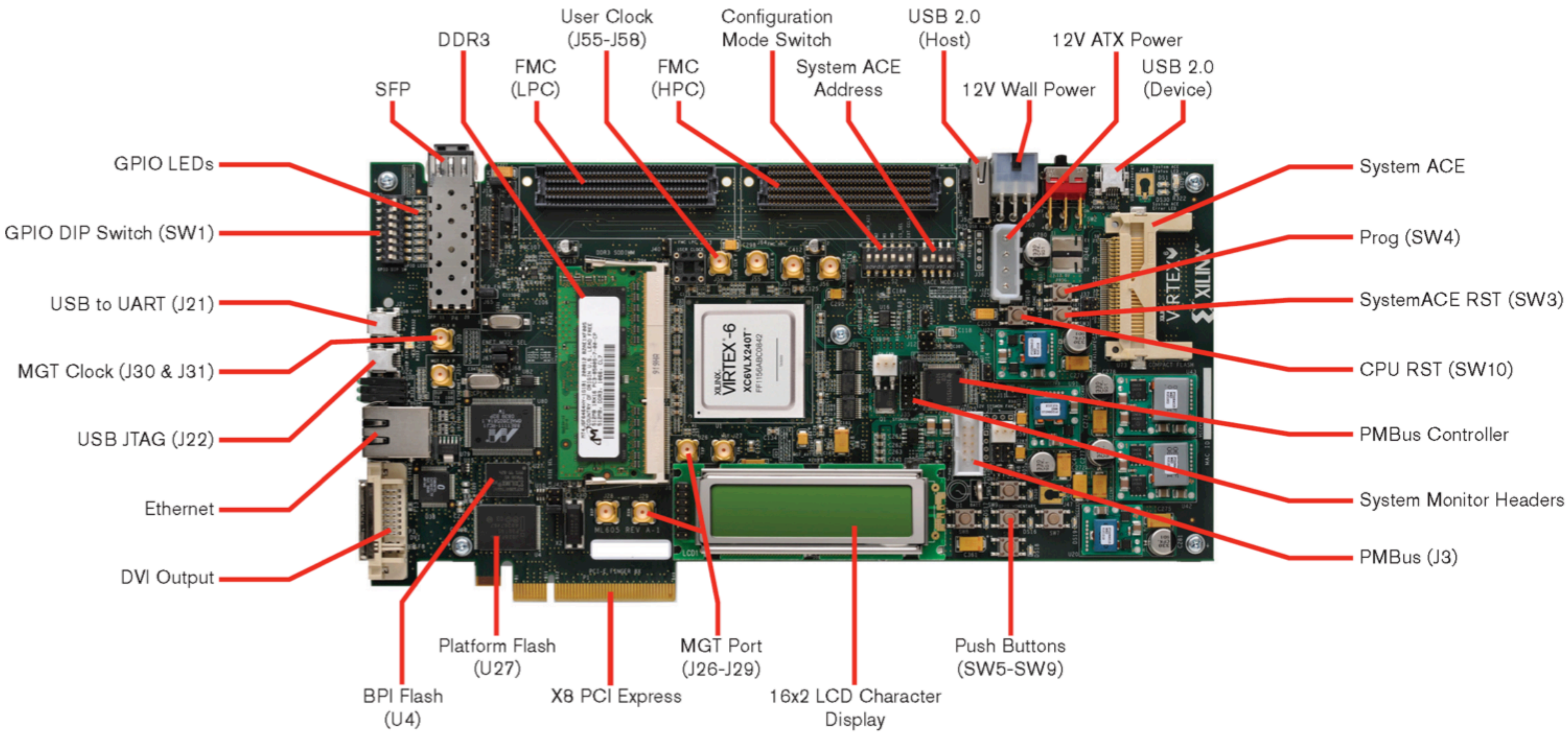
Spare slides

Stima del data rate

- Per ogni blocco di lettura (in parallelo con tutti gli altri)
  - Massimo numero di strip da trasferire: 16
  - Numero medio di strip da trasferire: 1.5
- Per ogni strip
  - 8 bit per address (0…255)
  - 6 bit per inizio segnale wrt trigger (-1.0…+0.2μs @ 50MHz sampling)
  - 6 bit per durata del segnale (0…1.2μs @ 50MHz sampling)
- Per ogni evento
  - Massimo (8+6+6) x 16 = 320 bit
  - Tipico (1/10 Massimo) = 32 bit
- Durata trasferimento su seriale @100Mbps
  - Massimo: 3.2μs
  - Tipico: 320 ns

Data building tracciatore

- Event size
  - Massimo: 320 bit x 6 blocchi x 4 schede → 1kByte
  - Tipico: 32 bit x 6 blocchi x 4 schede → ≈ 800 bit
- Data rate (1 MHz trigger)
  - Massimo: 1GByte/s
  - Tipico: 800 Mbps
- Image size (tipico)
  - 180 proiezioni @ $1x10^5$ ev → 1.5 Gbyte + overhead



•PCI Express
•Gb Ethernet
•USB
•160 + 68 User I/O (modulo espansione su FMC)

•DDR3 → 512 MB (fino a 2GB) @ 800Mbps
•Flash → 2GB