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DEVELOPMENT OF COMPTON CAMERA PROTOTYPE FOR HADRONTHERAPY MONITORING AND MEDICAL IMAGING

J.-L. Ley¹, J.-P. Cachemiché⁴, M. Dahoumane¹, D. Dauvergne¹, N. Freud², J. Krimmer¹, J. M. Létang², X. Lojaco², V. Maxim², G. Montarou³, C. Ray¹, E. Testa¹, Y. Zoccarato¹

¹ Institut de Physique Nucléaire de Lyon; ² Laboratoire CREATIS, Lyon; ³ Laboratoire de Physique Corpusculaire de Clermont-Ferrand; ⁴ CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille

HADRONTHERAPY MONITORING

ION BEAM THERAPY INTERESTS

The two main advantages for using ion beam in cancer treatment are:

- Ballistic precision (Bragg peak) (p and ¹²C)
- Relative Biological Effectiveness (RBE) of ions is better than the one of photons (>1) (¹²C)

ION-RANGE MONITORING

Why?

- Ion range very sensitive to patient mispositioning, morphological changes...
- Risk: organ at risk could be over irradiated and/or tumor under irradiated

Goal?

- Online correction or cutting off of the treatment

How?

- Detection of the secondary particles emitted during nuclear fragmentations

RADIATION USED IN THE PRESENT WORK: PROMPT GAMMA

Correlation between prompt gamma profiles and ion ranges.

CHALLENGES

- Compton scattering detection
- Discrimination between the background (mainly neutrons and protons) and the prompt gamma
- Time of flight (hodoscope)
 - > Very high counting rates
 - > Need high temporal resolution (~ ns)
- Large energy continuous spectrum of the prompt gamma (0.1 - 20 MeV)
- Random coincidences

APPLICABILITY OF PROMPT GAMMA DETECTION TO ION RANGE MONITORING

With a collimated camera and for homogeneous targets, the ion-range monitoring can be considered at a pencil-beam basis for proton beam and at an energy-slice basis for carbon ion beam. See Table 1. A Compton camera could improve dramatically the detection efficiency.

^{*} Heidelberg Ionenstrahl-Therapiezentrum, Germany

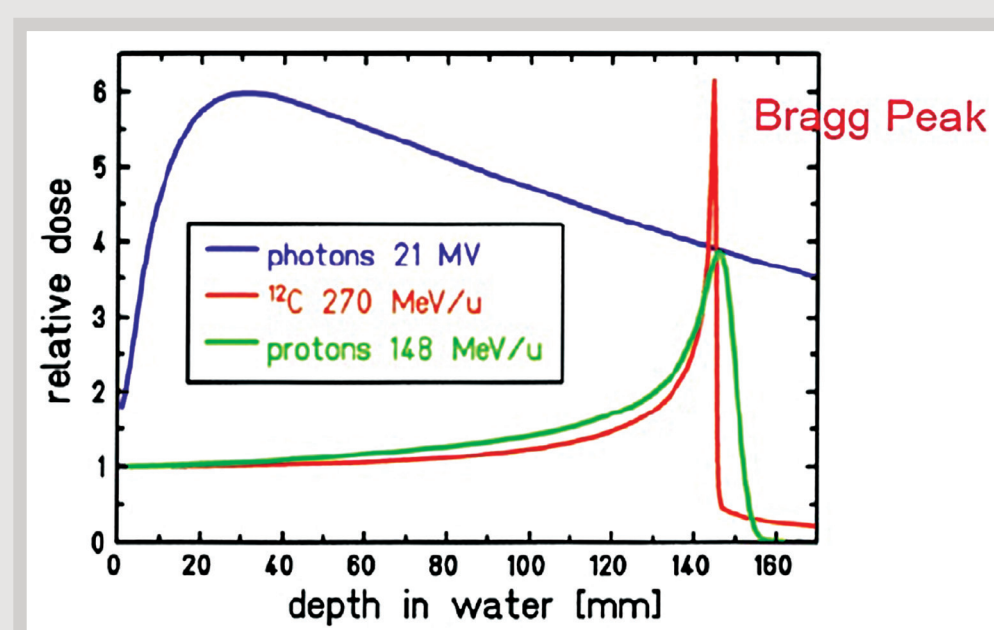


Fig. 1. Depth dose distribution for photons and monoenergetic Bragg curves for carbon ions and protons [Fokas2009].

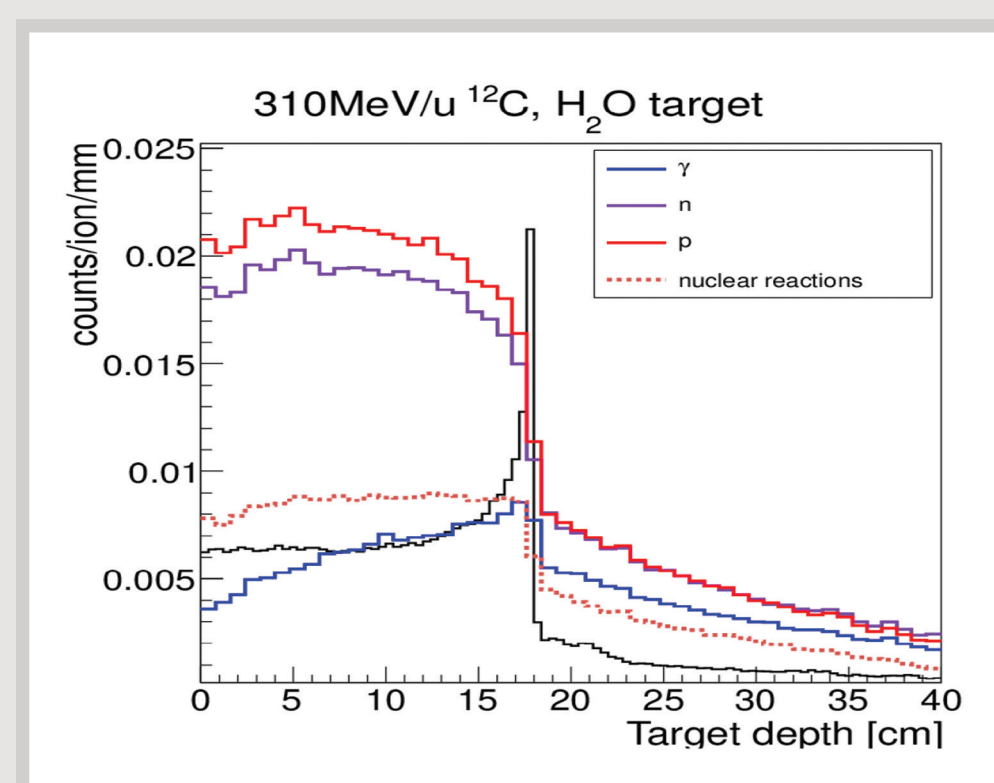


Fig. 2. Secondary particles' rate produced by nuclear fragmentation for ion beam of ¹²C at 310 MeV/u in water (simulations Geant4). [Dedes2012]

Beam	Proton	Carbon
No. of γ per ion	~ 1 - 2 x 10 ⁷	
per energy slice	~ 10 ¹⁰	~ 10 ⁸
No. of ions	per spot	~ 10 ⁸
per energy slice	2000	20
No. of γ	per spot	20
		0.2

Table 1. Orders of magnitude for applicability to ion-range monitoring with a collimated camera. The target was at 60 cm from the LYSO scintillator and the collimator in tungsten alloy had a slit of 4 mm. This experiment was made at clinical center of Heidelberg (HIT).

MEDICAL IMAGING

INTERESTS

In medical imaging, the initial photon energy is known (specific isotope). It is thus possible to select good or bad events with the total energy deposit in the camera.

The present Compton camera should:

- Have a better detection efficiency than the SPECT* in nuclear imaging (no physical collimator)
- Have a direct 3D image reconstruction
- Use radiopharmaceuticals with a higher energy photon than what is used currently (PET** maximum: 511 keV)
 - > Less attenuation in the patient

^{*} Single photon emission computed tomography.

^{**} Positron emission tomography.

STATE OF THE ART IN MEDICAL IMAGING

PROTOTYPES BUILT IN THE WORLD

The idea to use a Compton camera for the medical imaging was launched by Singh in 1987. Since, different Compton cameras were developed, but none has reached a high enough level of performance to be commercialized.

Different technologies are developed to detect and characterize the Compton scattering.

- Single Compton scattering: Gunma university (Japan) [Takeda2012], university college London (United Kingdom) [Alnaimi2011], Collaboration Compton Imaging for Medical Application (CIMA) [Liosa2006]
- Double Compton scattering: Hanyang university (Republic of Korea) [Seo2010]
- Electron Tracking: Kyoto university (Japan) [Kabuki2010]

DESIGN OF THE CAMERA FOR MEDICAL IMAGING (preliminary results)

SIMULATION GEANT4

- In the first stage, modification of the "hadrontherapy" prototype for medical imaging purpose
- The current parameters of this camera are gathered in Table 2

Number of particles	10 millions	Number of layers of silicon	7
Distance source - first scatterer	100 mm	Distance last scatterer - absorber	150 mm
Distance inter scatterers	60 mm	Photon energy	From 100 keV to 3 MeV
The absorber's spatial resolution	5 mm	The scatterer's spatial resolution	1 mm
Equivalent Noise Charge	200	The absorber's energy resolution	14%
Source	Point source	Emission angle	Narrow angle

Table 2. Parameters used for the simulation of the Compton camera for medical imaging.

SIMULATED PHYSICS

- Monte-Carlo simulation: Geant4.9.4
- Electromagnetic processes
- Taking into account the Doppler broadening and the photon polarization

RESULTS

- ARM* distribution is fitted by the Voigt function: convolution of Gaussian and Lorentzian functions.
- The figure of merit is the angular resolution of the camera (ARM*)
- ARM improves with energy of photon
- The ARM is 3.8 ° at 1 MeV
 - > Need for setup optimization

^{*} Angular Resolution Measure: value of the full width at half maximum (FWHM) of the distribution of differences between the real and measured angles.

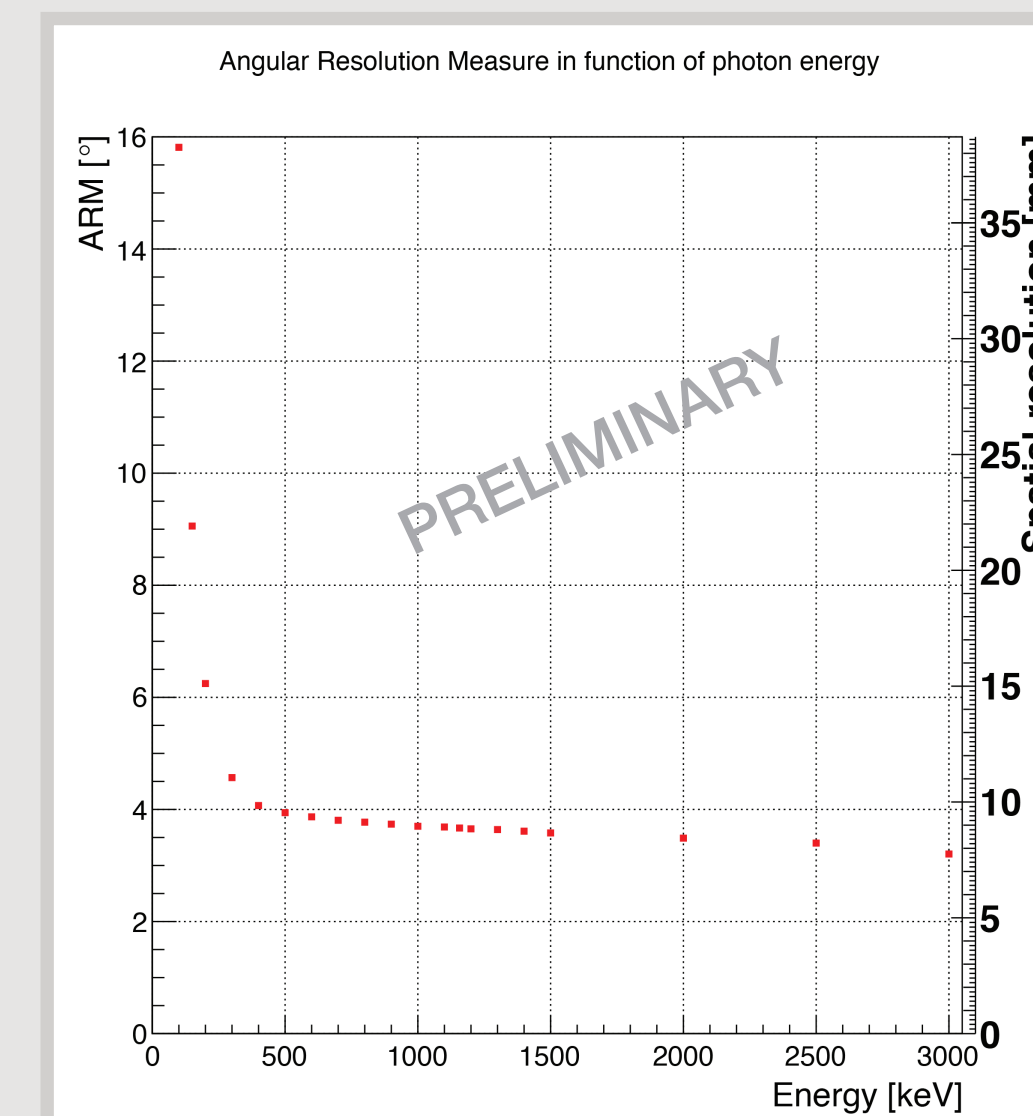


Fig. 6. Variation of the Compton camera's ARM versus the different monoenergetic photon energies. The fit of the ARM distribution is calculated by the Voigt function. The right scale is an estimation of the spatial resolution. In order to estimate this resolution, it uses a point of interaction in the scatterer located in the middle of the stack (135 mm from the source).

STATE OF THE ART IN HADRONTHERAPY MONITORING

- Different sorts of system have been developed to detect prompt gamma-ray like knife edge slit camera [Smeets2012], collimated camera with TOF [Testa2010] or without TOF [Min2012] and Compton camera [Richard2011].
- Examples of Compton camera prototypes which are in development:
 - > European project (ENVISION): university of Valencia [Liosa2012], university of Dresden [Golnik 2011], university of Lyon [Richard2011]
 - > Korean project: university of Hanyang [Seo2011]

DESIGN OF THE CAMERA FOR HADRONTHERAPY MONITORING

COMPTON CAMERA PRINCIPLES

1. Tumor irradiation

- Incident ions are tagged in position and time by a hodoscope
- Nuclear fragmentation occurs in the patient body
- Prompts gamma-rays are emitted

2. Detection with the Compton camera

- 2 interactions:
 - 1 interaction in a single layer of the scatterer stack (silicon)
 - 1 interaction in the absorber detector (BGO)
 - > Total absorption of the photon in the camera is assumed
- The 60 cm distance between the patient and the absorber are mandatory to perform TOF measurement

3. Emission point reconstruction

- 1st method
 - The intersection between the ion trajectory (provided by the hodoscope) and the reconstructed cone of the Compton camera.

- 2nd method
 - Iterative reconstruction with List Mode MLEM* [Lojaco2013]

^{*} Maximum likelihood expectation Maximization

COMPTON CAMERA PROTOTYPE DESIGN

Compromise between the spatial resolution and the detection efficiency was found. The camera optimization has been carried out by means of Geant4 simulations (Fig. 4). [Richard2011]

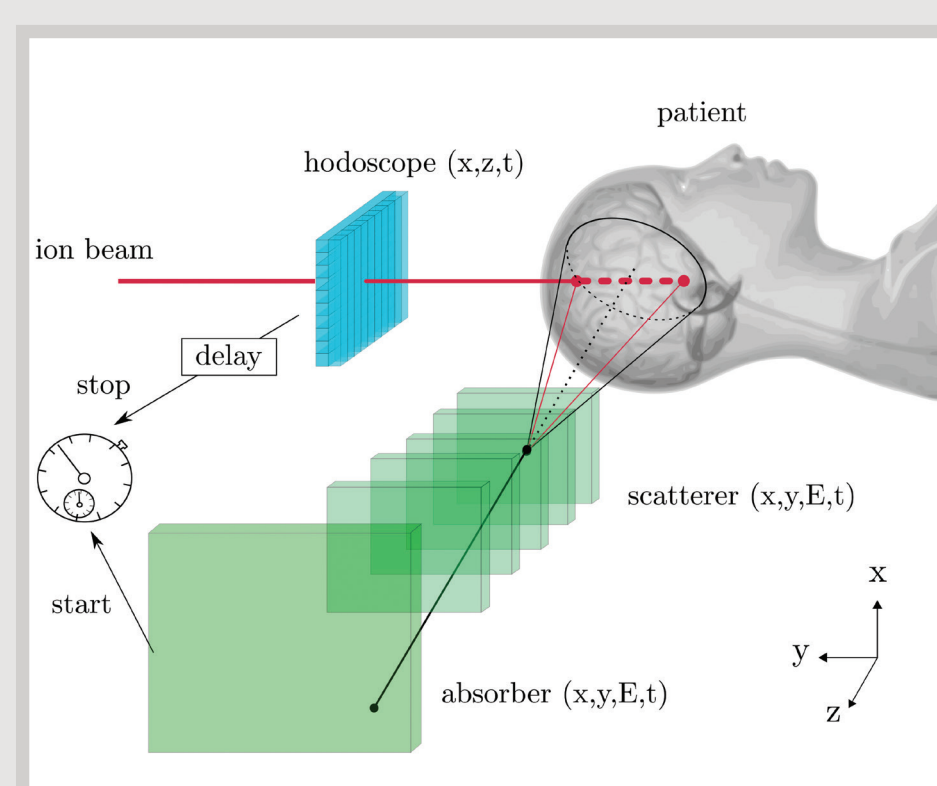


Fig. 3. Configuration of the monitoring system: the prompt gamma-ray emission points are reconstructed by intersecting the ion trajectory and the Compton cone. The ion trajectory is obtained with the hodoscope and the Compton cone is reconstructed with the camera. Time of flight (TOF) measurements between the absorber detector and the beam hodoscope (with an appropriate delay) are performed. [Richard2011]

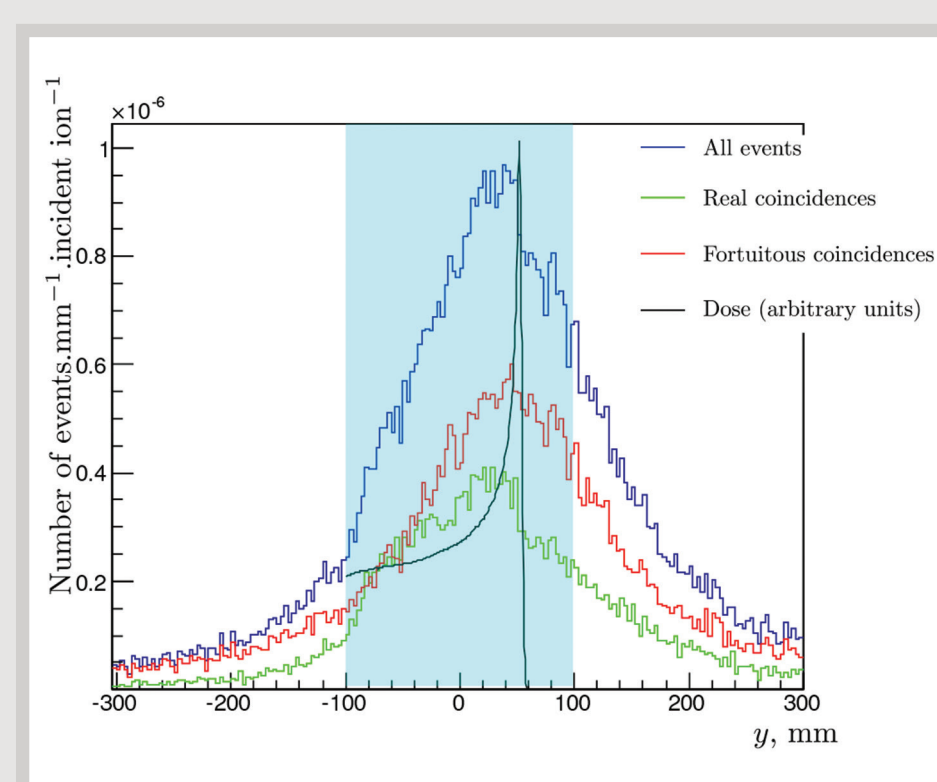


Fig. 4. Reconstructed profile in the case of a beam with the IBA time structure and of detectors with realistic energy, position and time resolution. 2.10⁹ incident protons at 160 MeV were shot. The position of the target is indicated by a light blue background. The conclusion is the limited performances of the Compton camera because of the high rate of random coincidences: fall-off retrieval precision of about 2.5 mm (standard deviation) with 2.10³ protons [Richard2011].

LEAKAGE CURRENT MEASUREMENT

GOAL

- Characterization of the leakage current for each strip of each DSSD layer as a function of the temperature
- Leakage current is an important factor because it degrades the silicon energy resolution

MATERIALS

- Climate chamber: Weiss WTL 64
- Micro Ampere meter
- Specific electronic card
- 1 DSSD (2 * 64 strips)
- High voltage: 750 V

METHODS

- Deplete all the silicon: 750 V on the 64 strips except the one which is measured
- Measure the strips for a range of temperature from +30°C to -40°C

RESULTS

- The leakage current drops down with the decreasing of temperature
- The minimum current leakage is 0.6 nA (-40°C)
- Good agreement between theoretical and measured leakage currents [Speiler1998]
 - > The DSSD will work at -20°C in a thermal chamber (under development)
- Energy resolution's estimation is 1.12 keV (FWHM) at -20°C

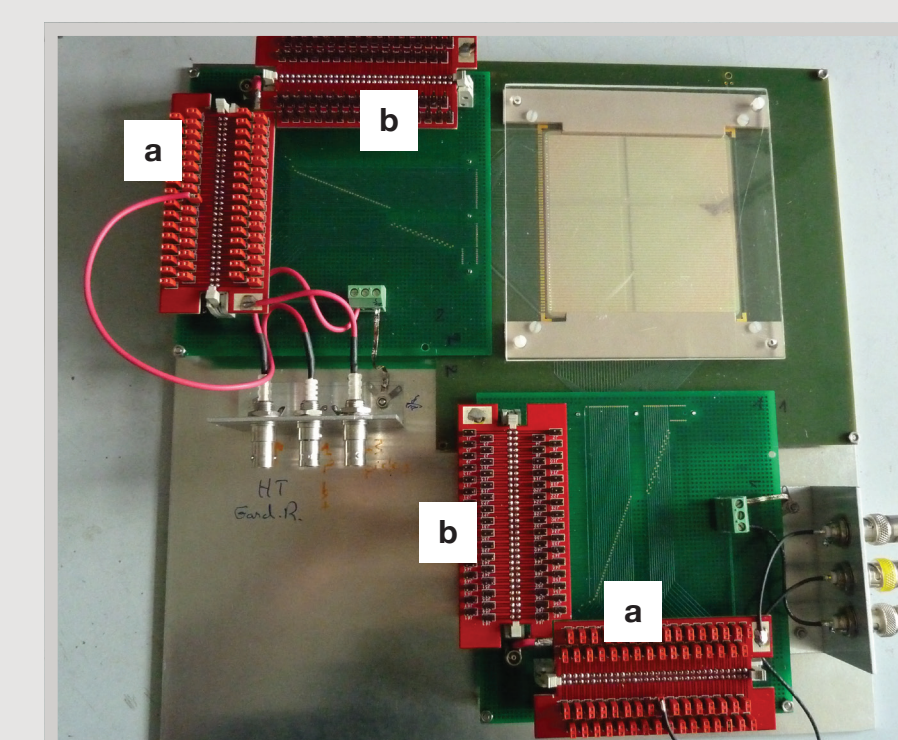


Fig. 7. Electronic card built in order to test the leakage current of the DSSD. The top card on the left is used to measure the n-side and the bottom card on the right is used to measure the p-side. The (a) pins are used to input the high voltage and the (b) pins are used to extract the signal.

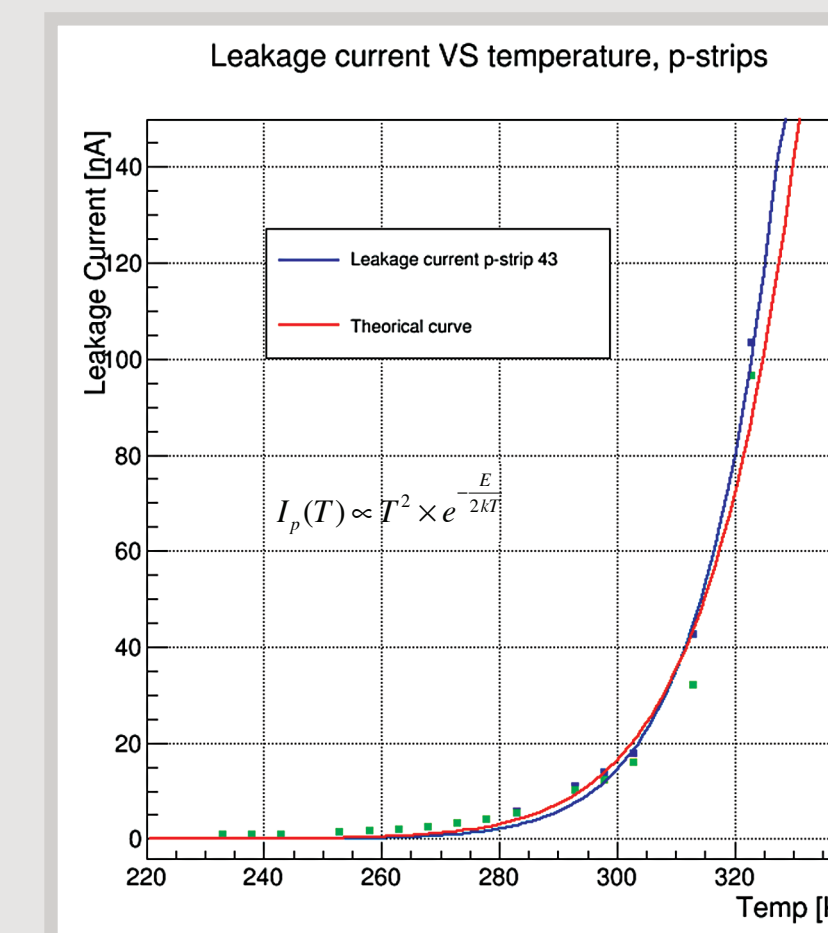


Fig. 8. Current leakage measured in function of temperature. The blue points are measures of strip 43 and the green ones are measures of strip 35 (strips 35 and 43 are normal strips). The measures of strip 43 are represented by the blue curve and the red curve represents the theoretical values of the leakage current (as defined by the formula on the graph).

PROTOTYPE DEVELOPMENT

THERE ARE THREE PARTS: THE HODOSCOPE, THE SCATTERER AND THE ABSORBER

1. Hodoscope

- Scintillating square fibers: 140 * 1 * 1 mm³
- Number of fibers: 2 * 128
- 8 PMs* Hamamatsu multianodes H8500
- Number of channels / PM: 64

2. Scatterer (DSSD** from SinteF)

- Number of layers: 7
- Dimensions: 90 * 90 * 2 mm³
- Number of strips: 2 * 64
- Pitch: 1.4 mm

3. Absorber (fluted BGO)

- Dimensions: 380 * 380 * 30 mm³
- Number of blocks: 100
- Dimensions per block: 38 * 38 * 30 mm³
- 4 PMs per block

All electronics (Front End and DAQ) for this hardware are in development.

^{*} Photo-multiplier
^{**} Double-sided Silicon Strip Detector

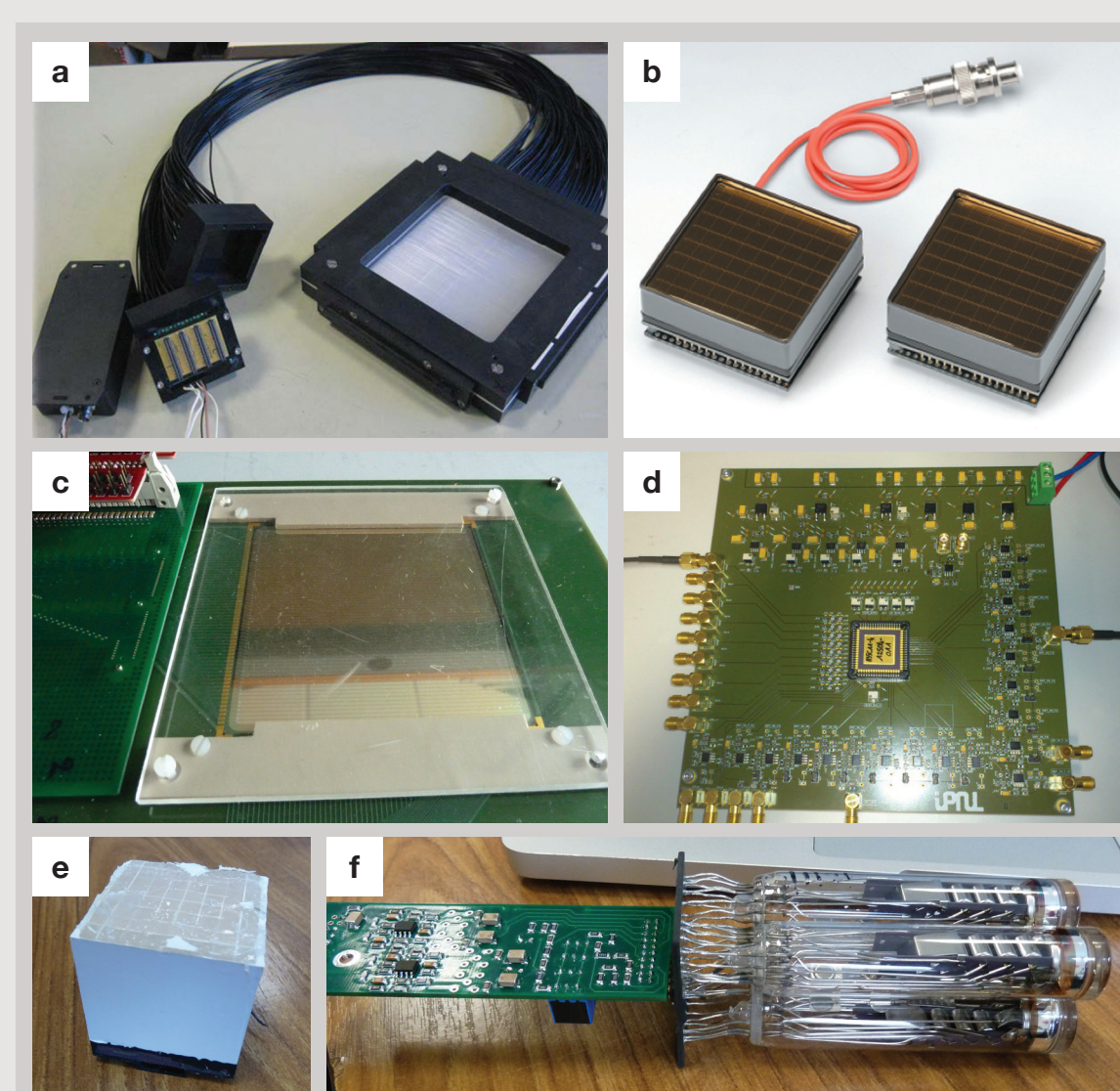


Fig. 5. a. The hodoscope; b. 2 PMs Hamamatsu H8500 connected via optic fibers (on each side); c. DSSD mounted on an electronic card; d. First prototype of an ASIC of the DSSD's front end; e. Block BGO (100 blocks compose the absorber); f. Each block is connected to 4 PMs

ONGOING

INSTRUMENTATION

- Development of various electronic cards (Front End, DAQ, acquisition devices),
- Development of the thermal chamber for the DSSDs
- Development of the acquisition program
- The first measurements with the prototype are expected for the beginning of 2014.

SIMULATION (MEDICAL IMAGING)

- Deepen the state of art
- Study of the parameters which could impact the camera's spatial resolution and detection efficiency
- Optimization of a Compton camera for high energy gamma (more than 511 keV)

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