The GEMpix detector as real time dosimeter in external photon beam radiotherapy

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RD51 Academia-Industry Matching Event
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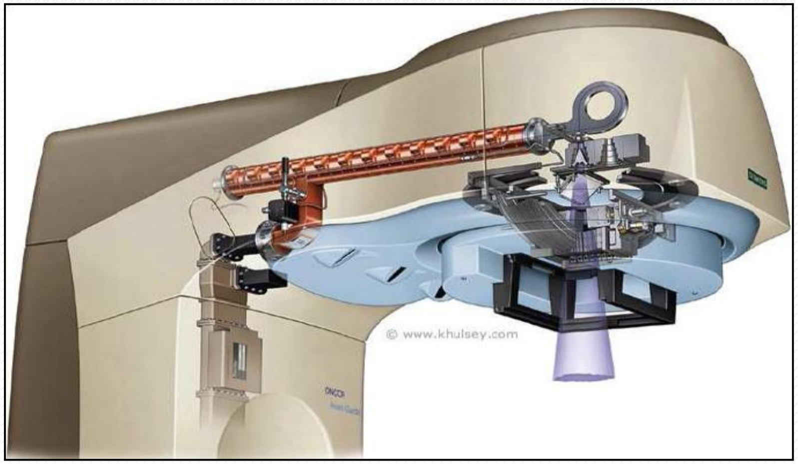
Summary

- *External Beam **Radiation therapy with photons***
- ***Intensity Modulated Radiation Therapy** (IMRT)*
- *Dosimetry and **quality assurance***
- *Dosimetry with **gafchromic films***
- *Dosimetry with **GEMpix detector***
- ***Comparison** between dosimeters*
- ***Conclusions***

External beam radiation therapy: LINear Accelerator (LINAC)



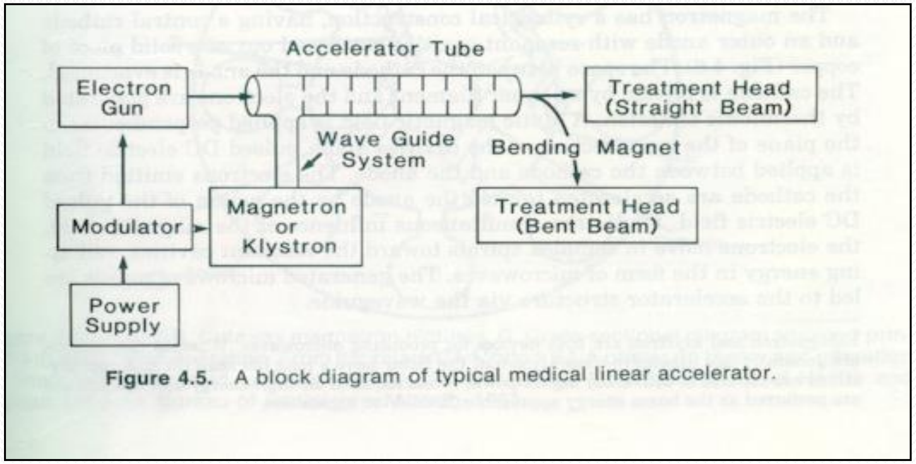
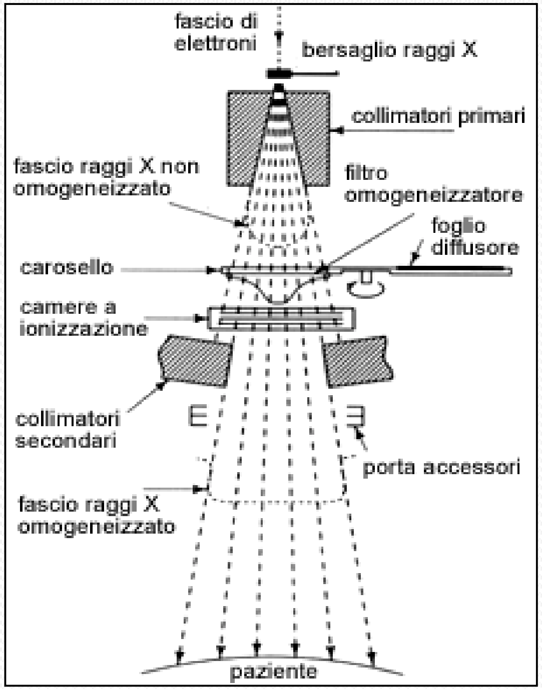


Figure 4.5. A block diagram of typical medical linear accelerator.

Beam delivery system

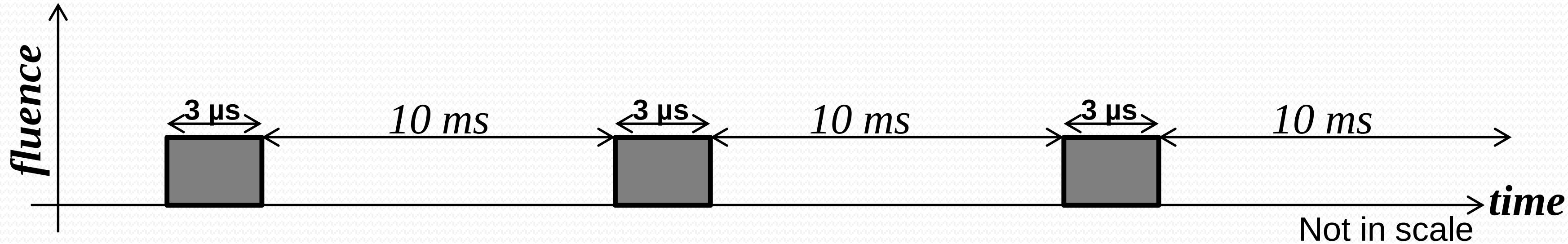


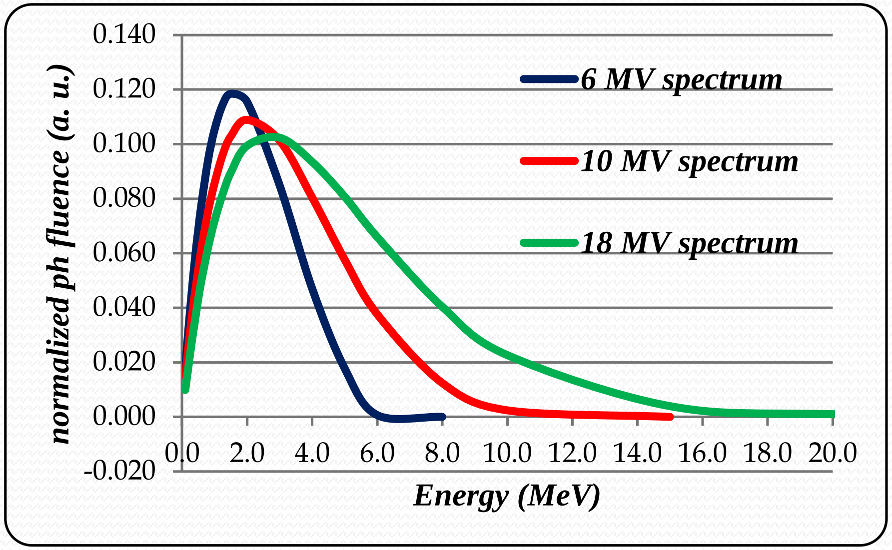
Elekta Synergy Linac @ Policlinico Tor Vergata:

- isocentric machine (ISO=100 cm)
- Energy range:
  X-rays: 4 ÷ 18 MeV
  electrons: 4 ÷ 18 MeV
- **irradiating treatment fields (@ ISO)**:
  X-rays: until 16 cm x 21 cm
  electrons: until 25 cm x 25 cm
- **pulse width 3 μs**

Time structure and energy spectrum of the beam

Pulse Repetition Frequency (***PRF***): number of pulses per second; it is equal to the number of erogated Monitor Units per min. In the present case, PRF can assume a discrete number of values: 6, 12, 25, 50, 100, 200 and 400 Hz.





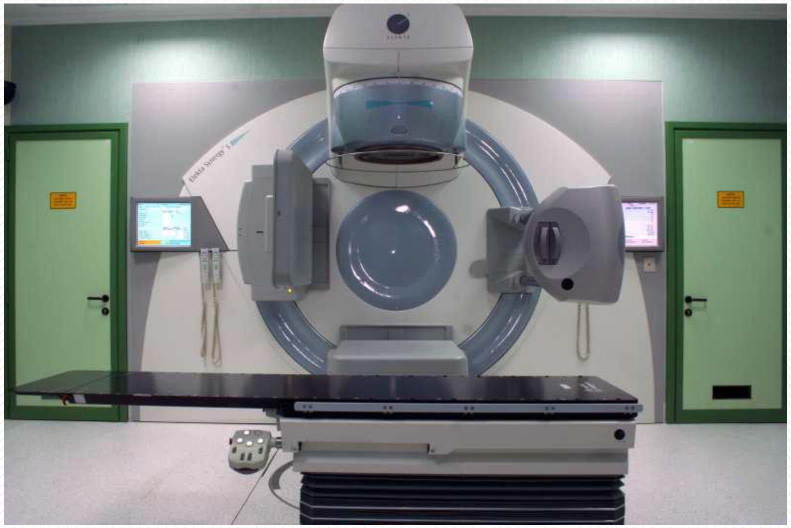
A Monitor Unit is defined respect to the monitor chamber in the accelerator head: the monitor chamber reads 100 MU when an absorbed dose of 1 Gray (or 100 rad) is delivered to a point at the depth of maximum dose in a water-equivalent phantom whose surface is at the isocenter of the machine with a field size at the surface of 10x10 cm^2.

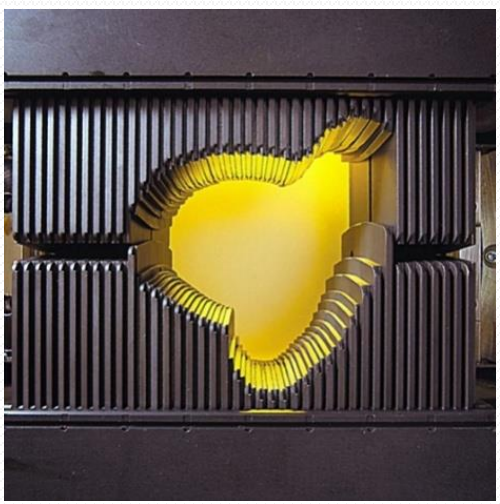
The estimated number of released photons is a medium value of **2.6×10^9 ph/(cm^2 sec)** and **8.5×10^{12} ph/(cm^2 sec)** per pulse.

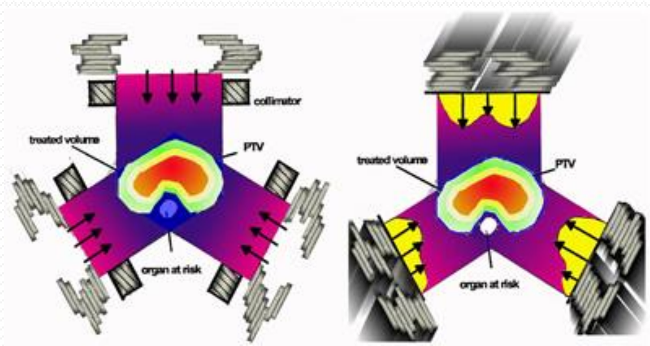
It is nececassy to work with a dosimeter able to provide a good linearity at high flux rates.

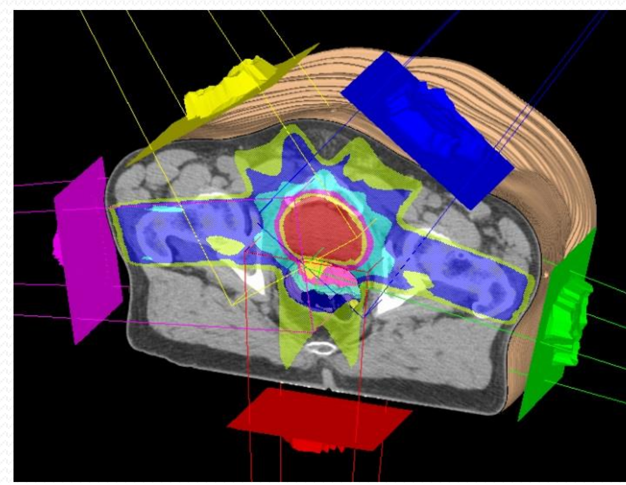
Radiotherapy: how it works

The accelerator head is equipped with a series of collimators and lamellae.







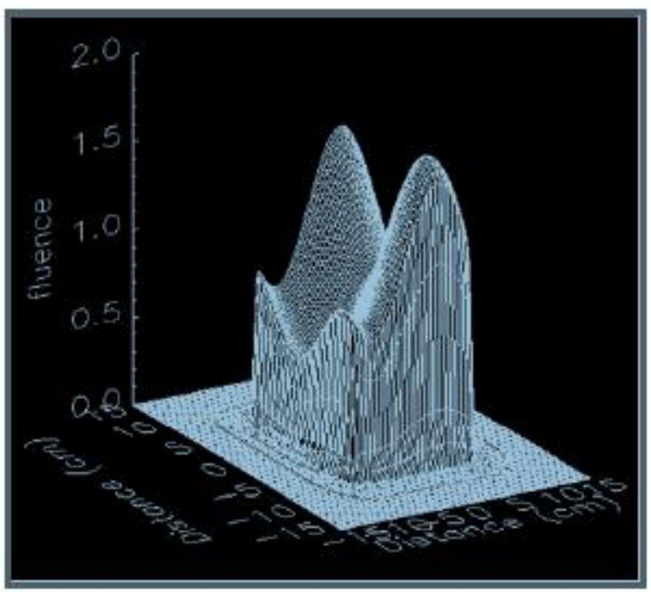


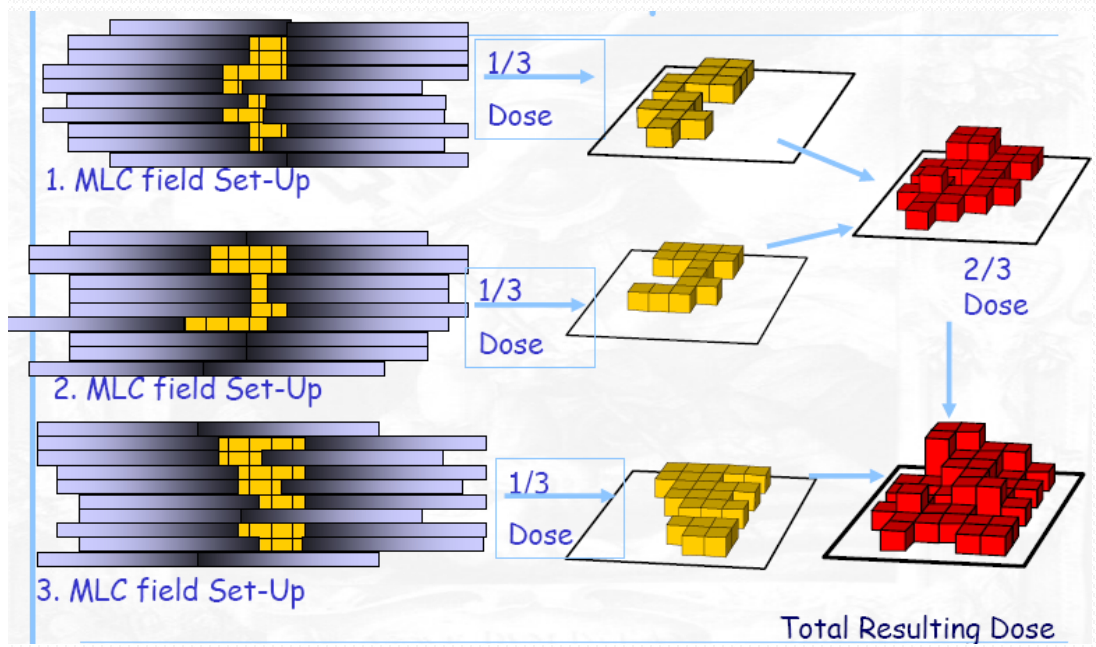
Lamellae used by the Synergy Linac have a length of 0.4 cm; the smallest irradiation beam is 8 x 8 mm^2.

Intensity Modulated Radiation Therapy (IMRT)

IMRT is an advanced mode of high-precision radiotherapy that uses computer-controlled linear accelerators to deliver precise radiation doses to a malignant tumor or specific areas within the tumor.

IMRT allows for the radiation dose to conform more precisely to the three-dimensional (3-D) shape of the tumor by modulating or controlling the intensity of the radiation beam in multiple small volumes (segments).





For dose quality assurances, it is necessary to dispose of a dosimeter able to follow flunce time variations.

IMRT versus RT convenzionale

ADVANTAGES:

- An high dose conformation to the target volume;
- Minimization of doses to the surrounding normal critical structures;
- Higher and more effective radiation doses can safely be delivered to tumors with fewer side effects compared with conventional radiotherapy techniques;
- Possibility of simultaneous irradiations of multiple targets with a single treatment planning.

DISVANTAGES:

- An higher probability of exposure of healthy organs;
- A most critical positioning of the patient;
- More accurate set-up checks and more suitable immobilization systems;
- A longer time to realize the treatment planning and deliver the prescribed dose.

It is necessary to verify the delivered dose, particularly for small fields with high dose gradients.

A typical radiotherapy treatment session

- Gathering of diagnostic data and medical consultation
- Doses prescription for PTV (Planning Target Volume) and evaluation of dose tolerances to OAR (Organ At Risk)
- CT scan to collect necessary data for TPS (Treatment Planning System)
- Calculation and evaluation of the treatment planning
- ***Quality controls before treatment***
- ***In-vivo quality controls***
- Results analysis after treatment

Quality controls before and after treatment are mainly dosimetric measurements.

- **DETECTOR ARRAYS**: a matrix of detectors made of ionization chambers or diodes. In most cases ionizatin chambers use a gas mixture as sensitive medium. The pitch between two consecutive detectors is few mm (10 mm for PTW seven29, 7.07 mm for SunNuclear Mapcheck, 7.5 mm for IBA MatiXX).

- **EPID (Electronic Portal Imaging Device)**: typically these detectors are made of amorphous silicon and can be classified in direct and indirect divices. The first ones have a thin build-up layer (usually, 0,6 mm of copper) which is used as X ray converter to produce electrons before the silicon diode. The second ones have a build-up converter plus a phosphorus layer which converts electrons in visible photons.

- **FILM**: They are particular dosimeters which appear like thin foils with a thickness of few hundred microns. The inner part contains an active layer, which polymerizes under irradiation.

Film 2D dosimetry

It is possible to distinguish radiografic and radiochromic films. The latter are specific for radiotherapy.

EBT gafchromic structures

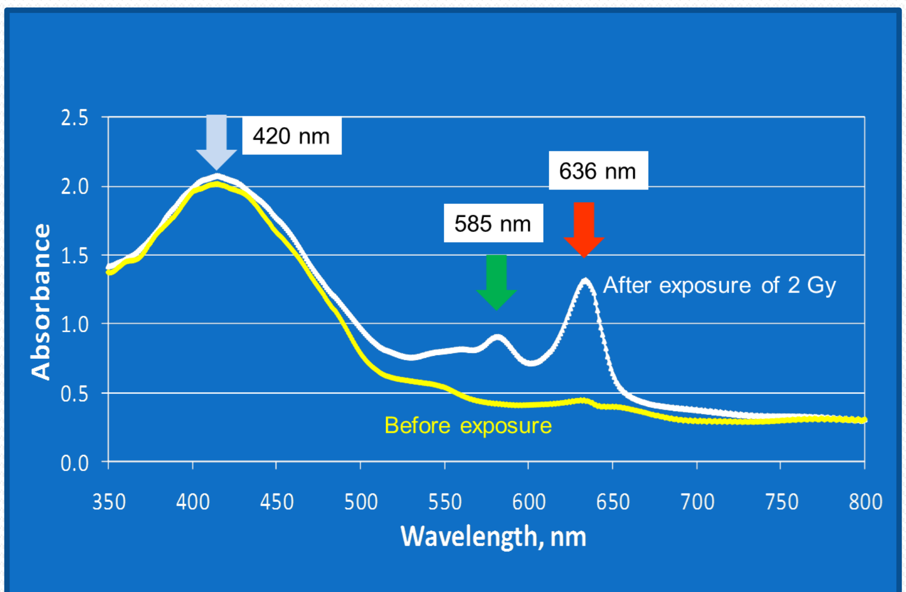
Upon irradiation, the active layer (containing a monomer) polymerizes to form a polymer colored dye.

EBT2

Clear Polyester	- 50 µm
Adhesive Layer	- 25 µm
Active Layer	- 28 µm
Clear Polyester	- 175 µm

EBT3

Matte Polyester	- 120 µm
Active Layer	- 28 µm
Matte Polyester	- 120 µm

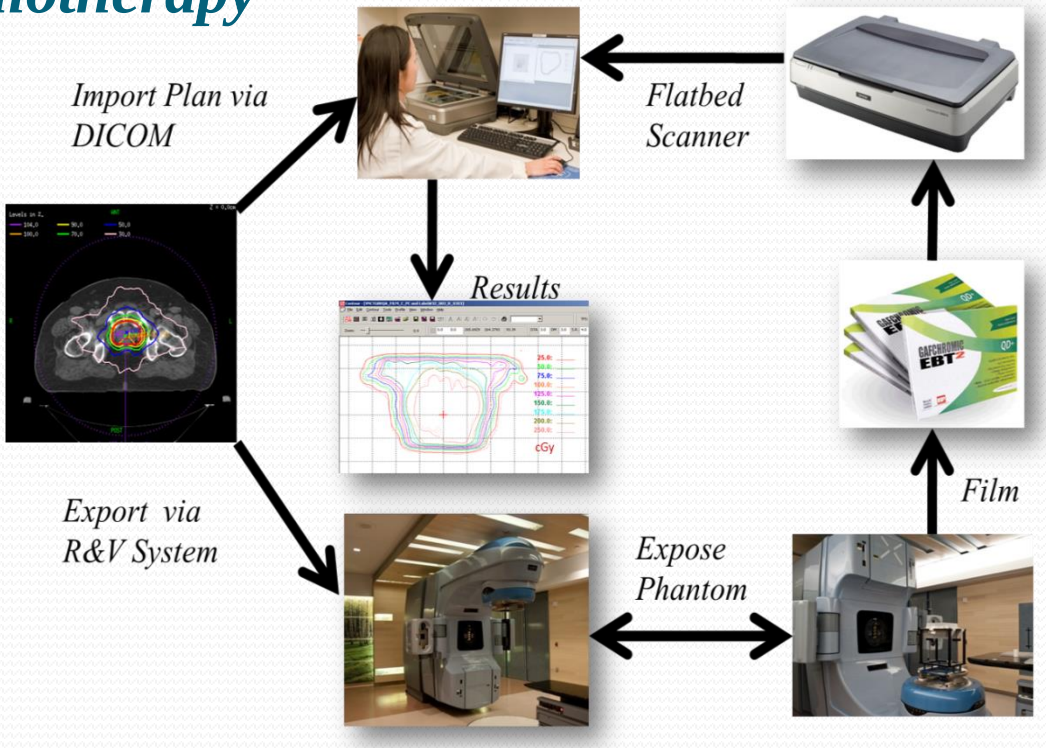


EBT gafchromic can work on three absorbance channels:

- RED: it has an high sensitivity in the dose range from 1 cGy to 8 Gy.
- GREEN: it has an high sensitivity in the dose range from 8 to 40 Gy.
- BLUE: it has a low gradient responce and is highly dependent from the active layer thickness.

Quality assurance in radiotherapy

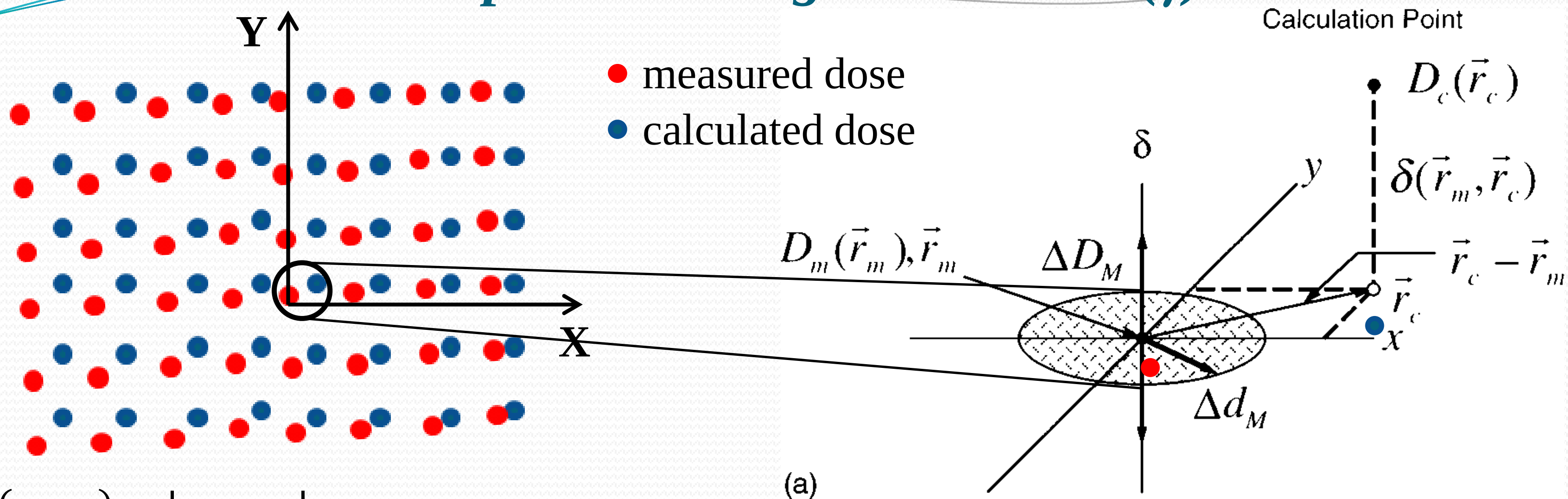
A control quality check with gafchromic requires relatively long times. It can take several hours.



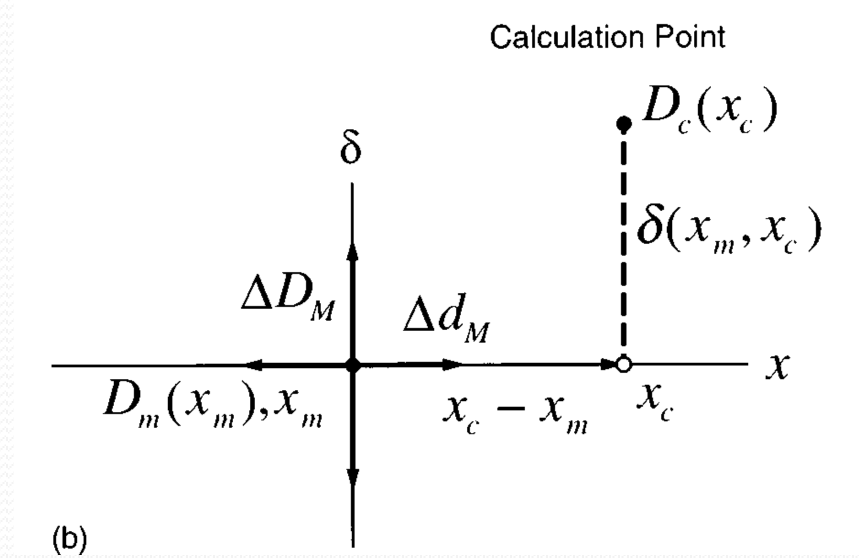
Disvantages for gafcromic film:

- *Fading*: it is highest immediately after irradiation and then slows down after some time.
- *Temperature dependence*: optical density of radiochromic films has strong temperature dependence; the temperature must be kept as uniform as possible.
- *UV sensitivity:* most of the radiochromic materials are sensitive to ultraviolet light.
- *Film orientation*: radiochromic materials are non-isotropic crystals and therefore their orientation matters.

Doses distribution comparison: the gamma index (γ)



(a)



(b)

$$r(r_m, r_c) = |r_c - r_m|$$

$$\delta(r_m, r_c) = D(r_c) - D_m(r_m)$$

$$\Gamma(r_m, r_c) = \sqrt{\frac{r^2(r_m, r_c)}{\Delta d_M^2} + \frac{\delta^2(r_m, r_c)}{\Delta D_M^2}}$$

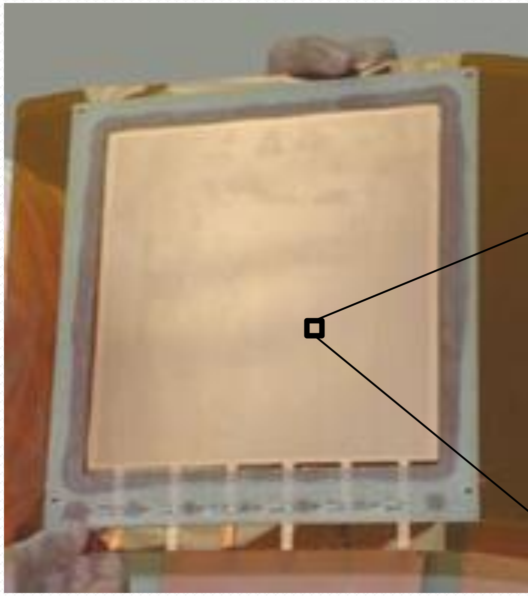
Δd = distance to agreement criterion (< 3mm)
ΔD = dose difference criterion (< 3%)

$$\gamma(\mathbf{r}_m) = \min\{\Gamma(\mathbf{r}_m, \mathbf{r}_c)\} \forall \{\mathbf{r}_c\},$$

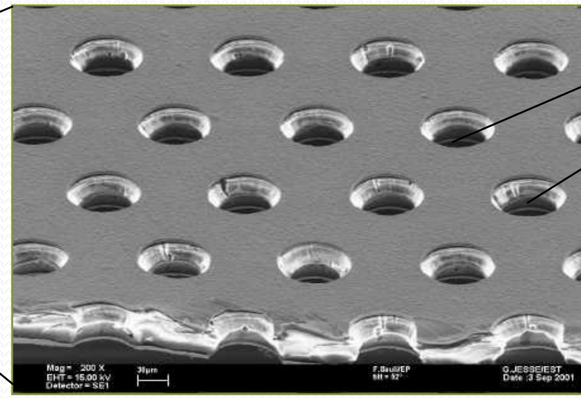
if γ < 1 → doses are comparable
if γ > 1 → doses are not comparable

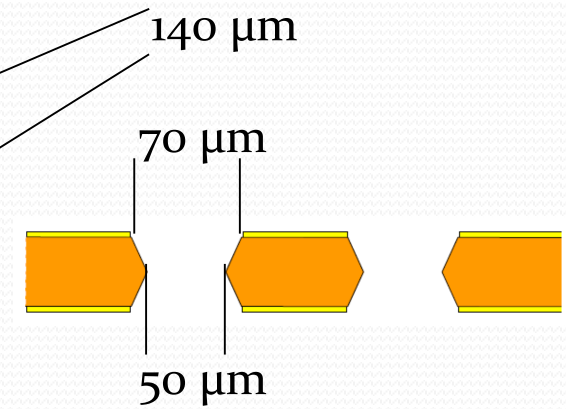
γ < 1, it must be verified on number of points > 90 %

GEM detector: Gas Electron Multiplier



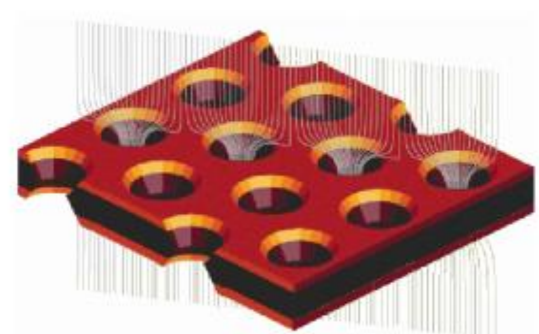
A Gas Electron Multiplier (F.Sauli, NIM A386 531) is made by a 50 μm thick kapton foil, copper clad (5 μm thick) on each side and perforated by an high surface-density of bi-conical micro-holes;

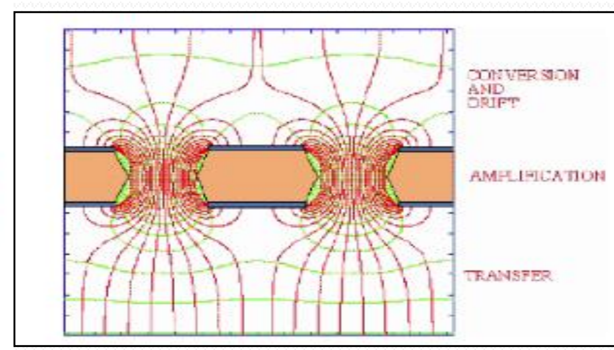




Applying a potential difference (tipycally from 300 up to 500 Volts) between the two copper cladding, an high intesity electric field is produced inside the holes (80-100 kV/cm).

GEM is used as a proportional amplifier of the ionization charge released in a gas detector.

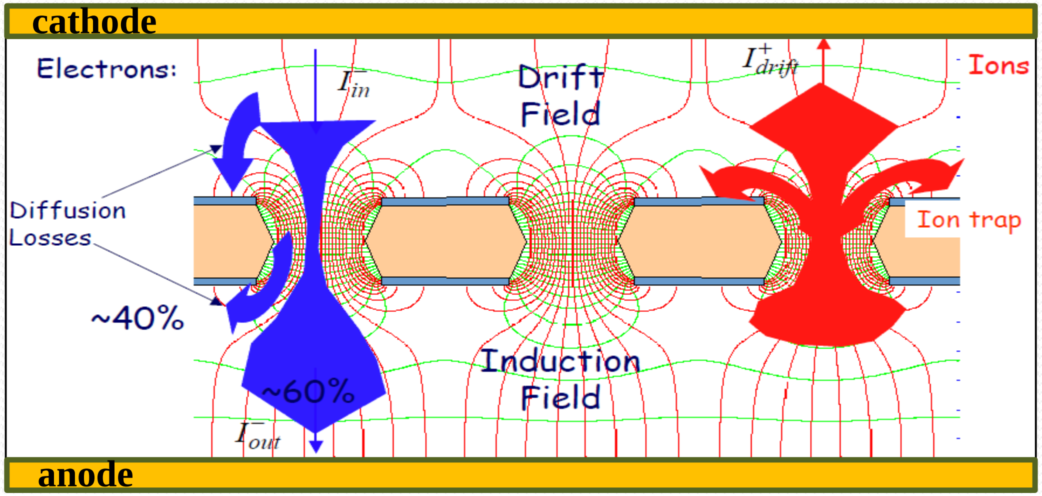




* F.Sauli - Nuclear Instruments and Methods in Physics Research A 386 (1997) 53 l-534

GEM detector: working principle

GEM electronic transparency (T)



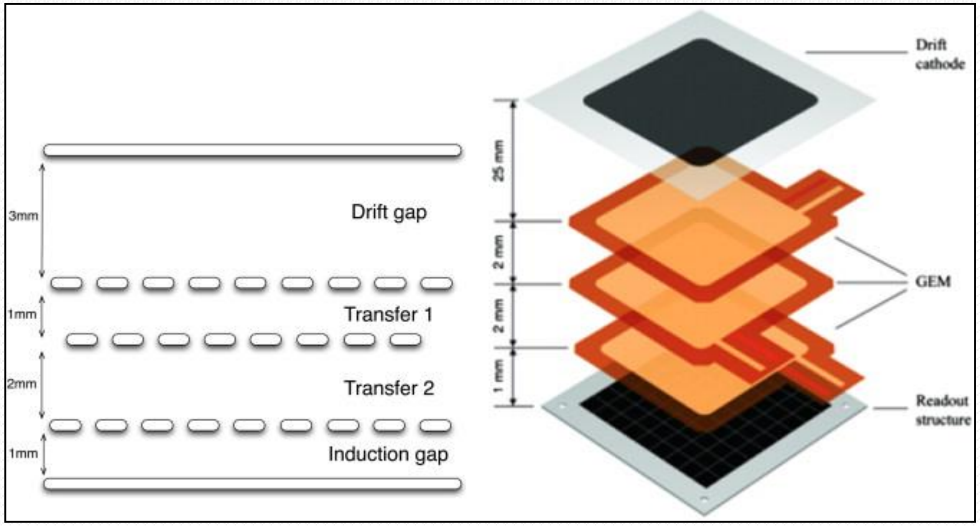
$$G_{in} = Ae^{<\alpha>V_{GEM}}$$

$$G_{eff} = T \cdot G_{in} = \varepsilon_{coll} \cdot f_{extr} \cdot G_{in}$$

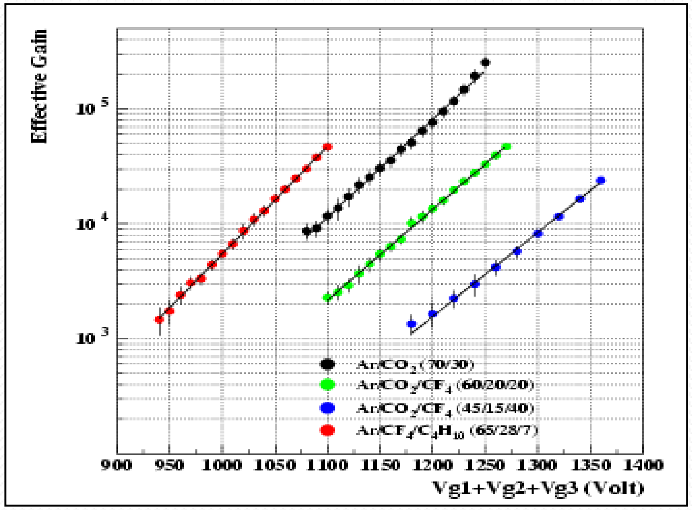
$$\varepsilon_{coll} = \frac{electrons\ collected\ in\ the\ holes}{electrons\ produced\ above\ the\ holes}$$

$$f_{extr} = \frac{electrons\ extracted\ from\ the\ holes}{electrons\ produced\ in\ the\ holes}$$

Layout of a typical Triple GEM detector constructed with standard 10 x 10 cm²



Calibration curves obtained with several gas mixtures.

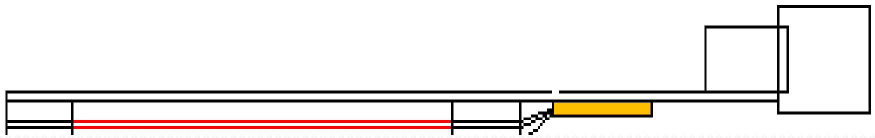


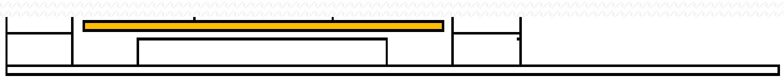
GEMpix detector

The detector, developed within the ARDENT Collaboration, as two main components:

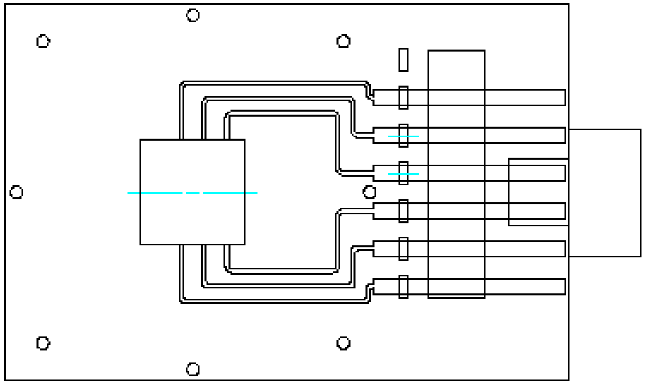
- A quad medipix without silicon layer
- A triple-GEM with filter and HV connectors

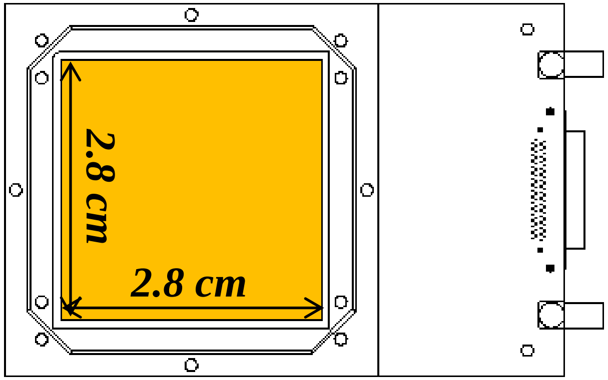
New HV GEM board

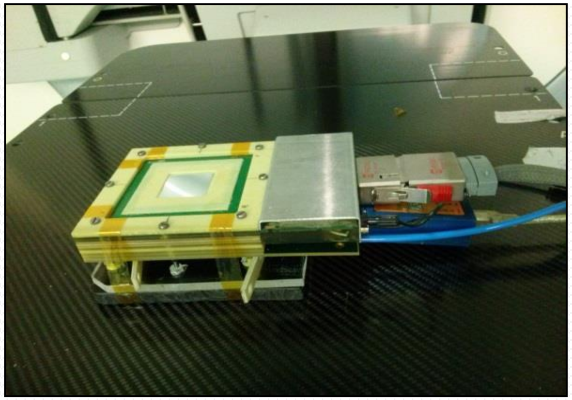




Quad medipix board (M.Campbell, J.Alzoy)

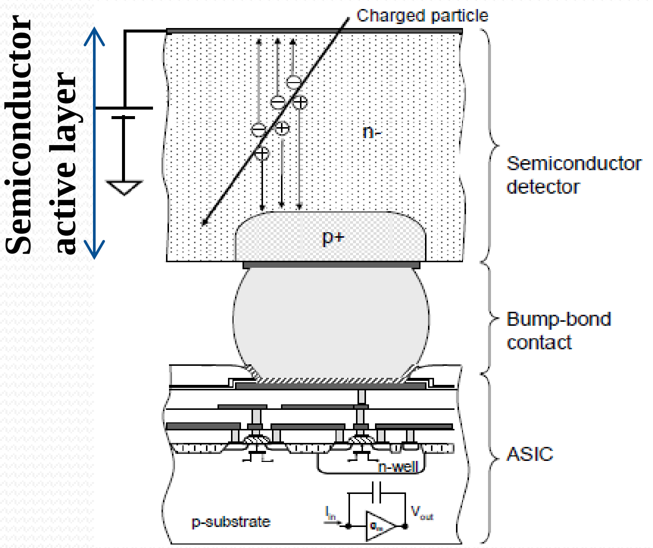




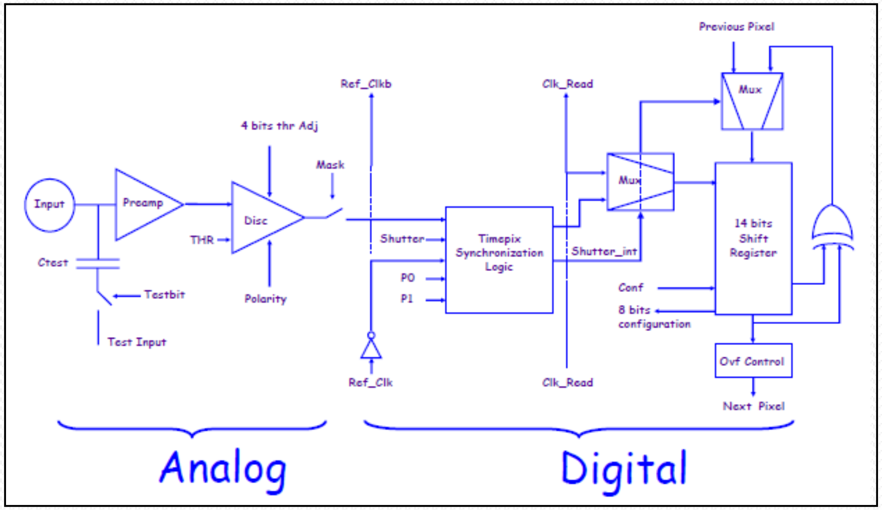


A Medipix chip has 256 x 256 pixles, each having an area of 55 x 55 μm^2. Quad Medipix is made of 4 medipix chip hold together (512 x 512 pixles).

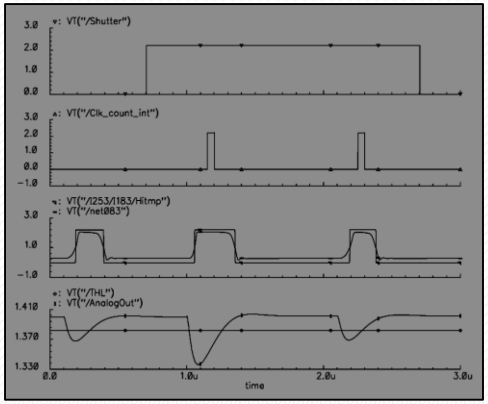
The GEMpix detector: detector layout and front-end-electronics



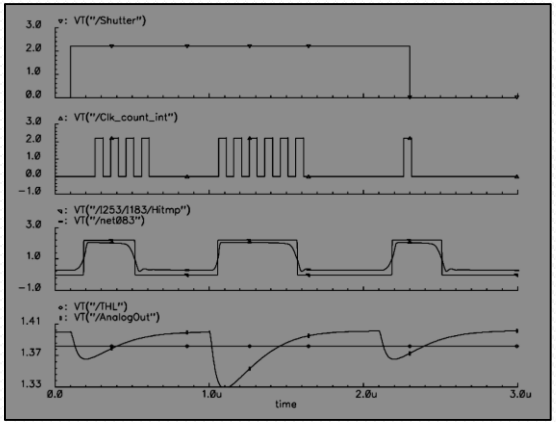
ASIC block scheme of a single pixel



Counting Mode



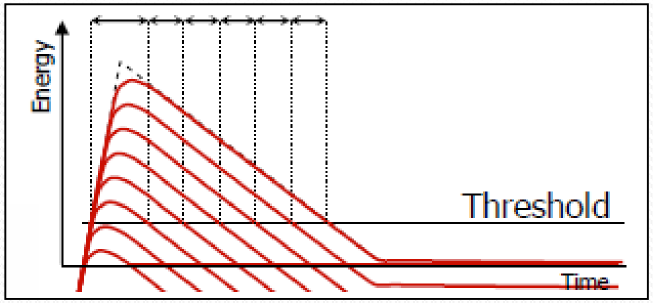
Time over Threshold Mode

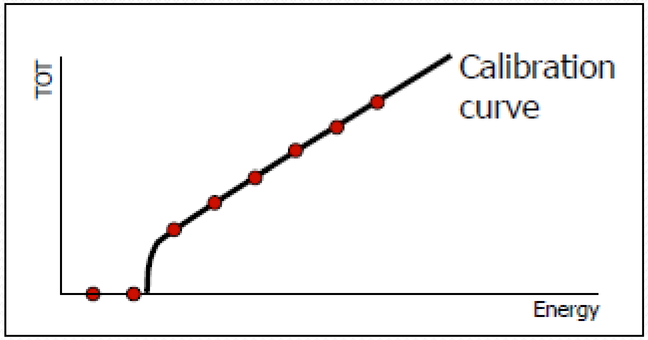


Physical dimensions	*14.08 x 14.08 mm^2*
PADs	*55 x 55 µm^2*
Charge collection	*e^-, h^+*
Pixel functionality	*Counting, ToT, Timepix*
Amplifier gain	*~ 18 mV/ke$^-$*
Noise	*~ 75 e$^-$*
Linearity	*Up to 50 ke$^-$*
Minimum threshold	*~ 500 e$^-$ (expected)*
Counter depth/overflow	*14-bit/yes*
Max Analog Power	*6.5 µW/pix; 190 mA/Chip*
Static digital power	*200 mA @ 100 MHz*
Read out	*Serial/Parallel*

The GEMpix detector: Timepix and Time over Threshold mode

medipix





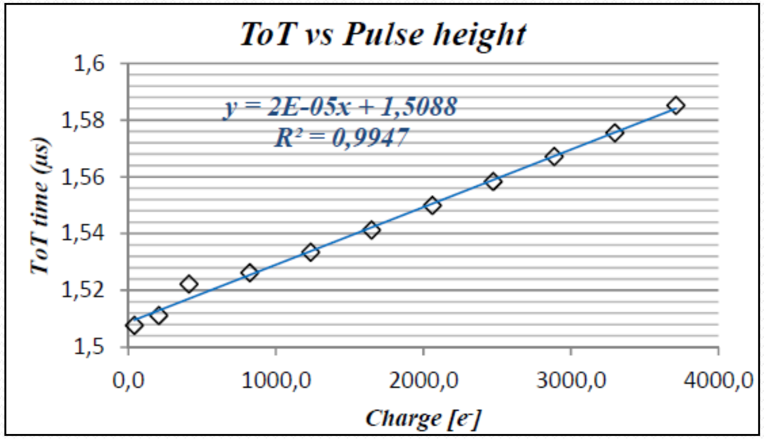
Counter in each pixel can be used as Wilkinson type **ADC** to measure energy of each particle detected.

If the pulse shape is triangular then Time over Threshold is proportional to collected charge i.e. to energy.

Due to limited bandwidth the pulse can be NEVER perfectly triangular.

Non linear TOT to energy dependence

GEMpix quad



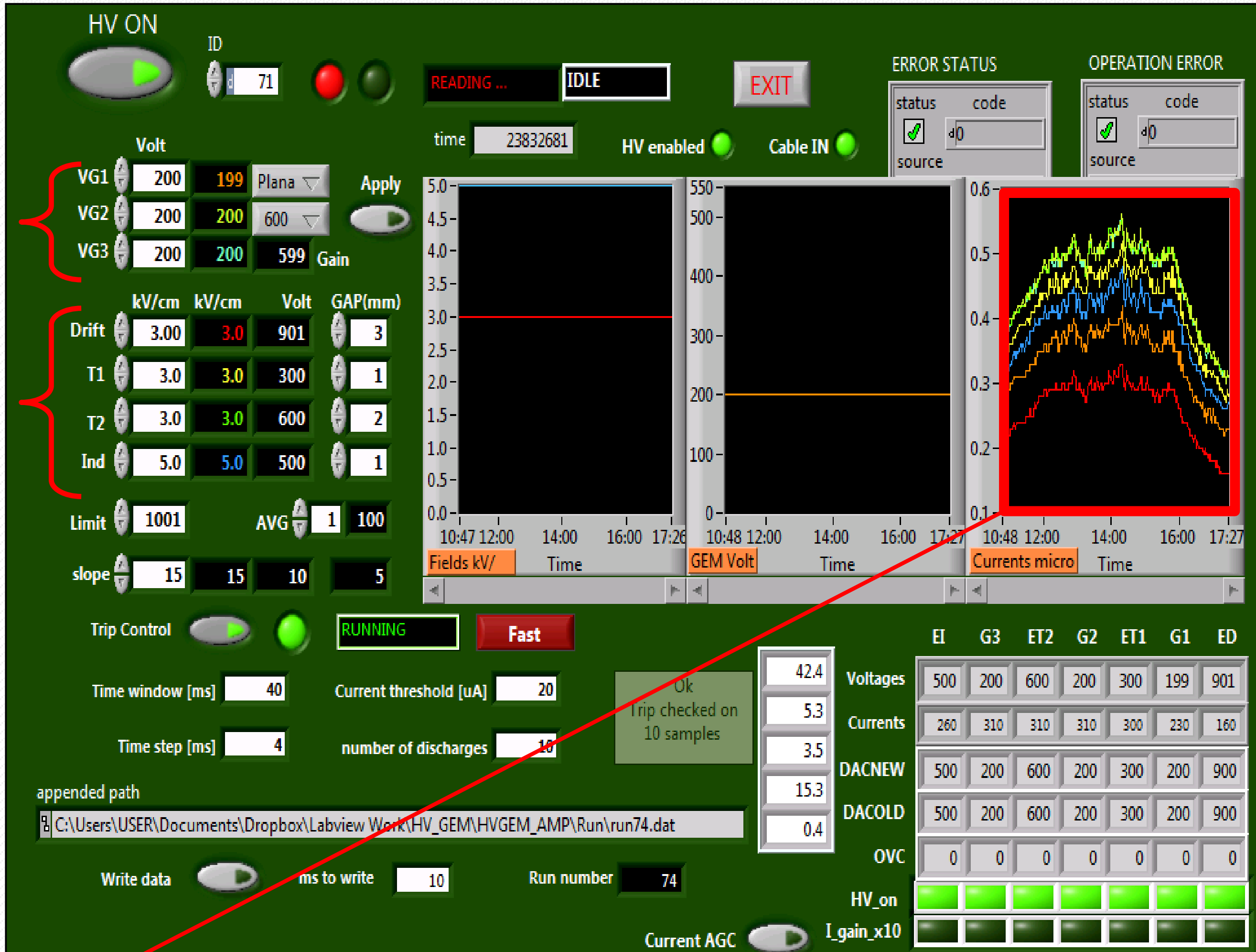
For the GEMpix used for these measurements ToT linearity with charge has been verified with an internal test capacitor. A potential applied to this capacitor corresponds to a given charge induced on the pixel.

GEM detector: High voltages

Labview Control Pannel for the High Voltage

GEM voltage (gain)

Electric fields

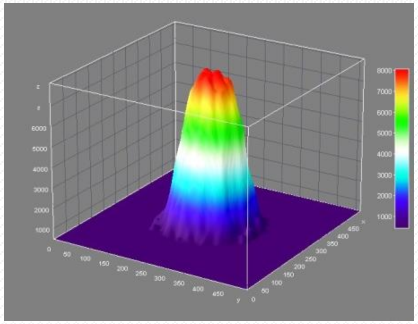


High Voltage Module for triple-GEM detector

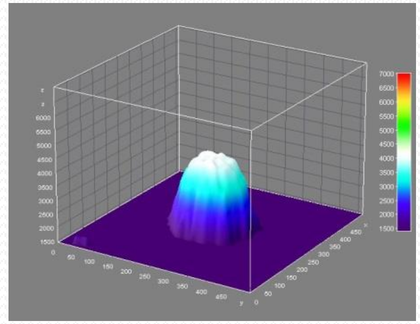
Real-time electrodes current measurements: each channel has a nano-Ammeter which measures the current with a sensitivity of 10 nA.

The GEMpix detector: energy and dose rate dependence

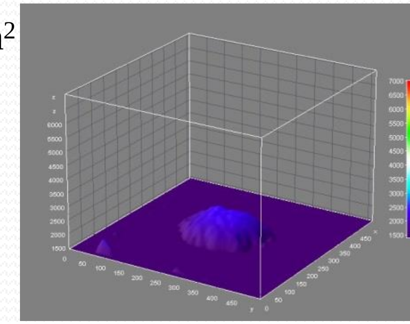
8x8 mm^2
6 MV



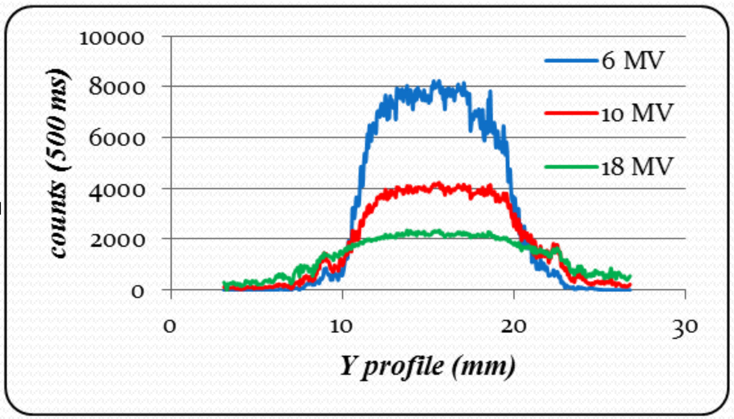
8x8 mm^2
10 MV

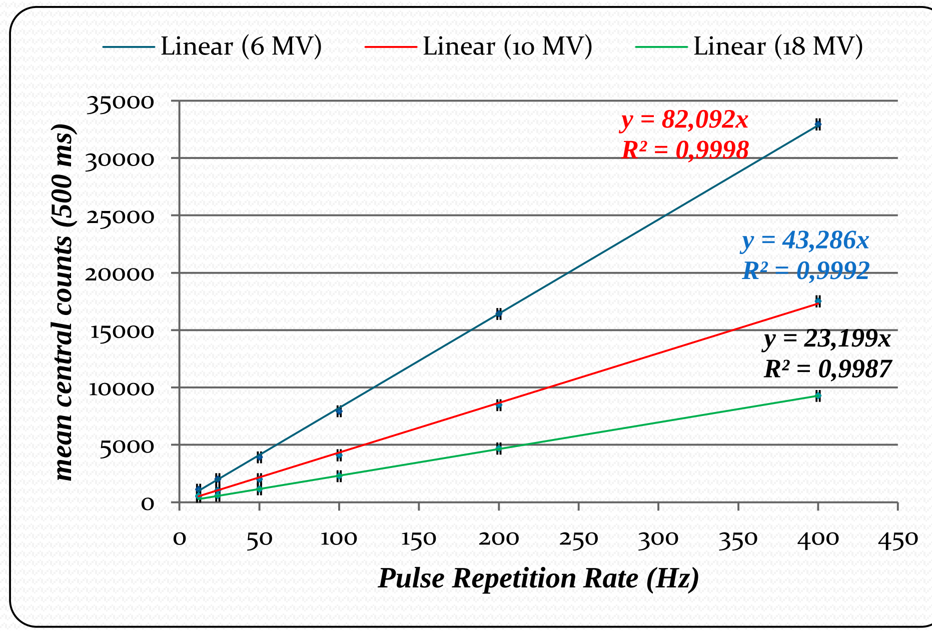


8x8 mm^2
18 MV

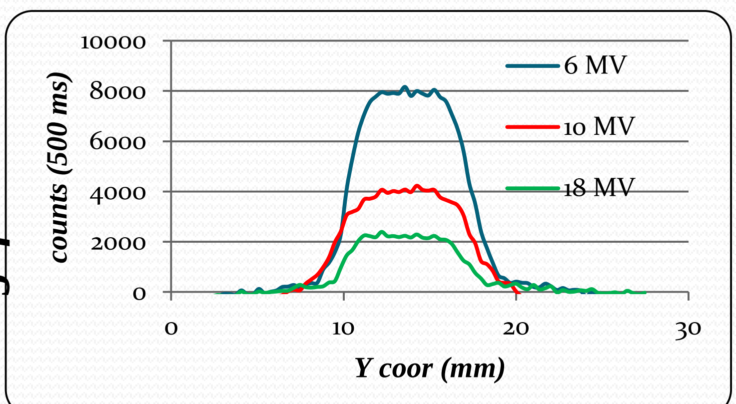


GEMpix



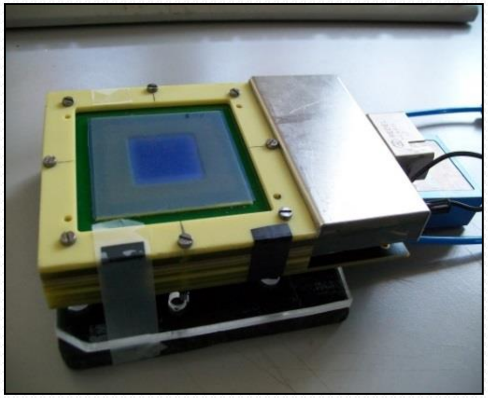


gafchromic



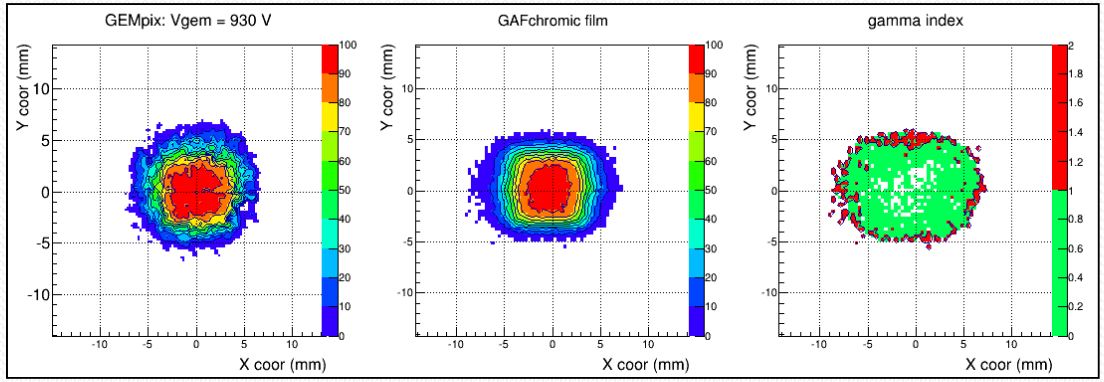
An optimal linearity is observed at the three energy spectra of the LINAC.

GEMpix detector and EBT gafcromic comparison through γ test

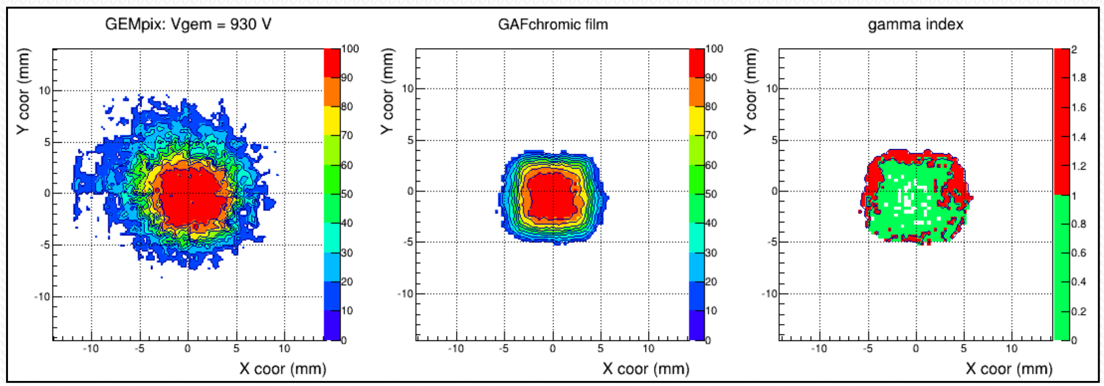


8x8 mm² irradiating field

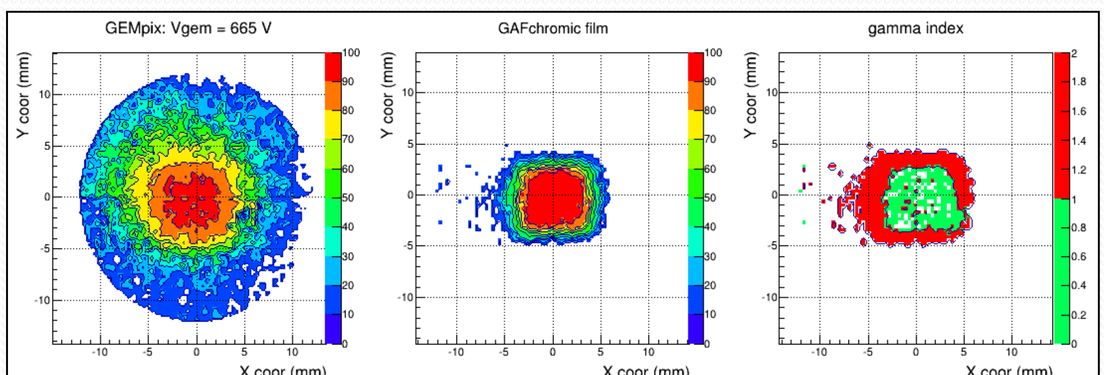
Detector has been used in the convetional configuration with all three GEM switched on, but with electric drift field switched-off. Gamma test shows that matching with gafchromic film is not in the percetage limit for higher energies.



6 MV
γ < 1,
97.57 %

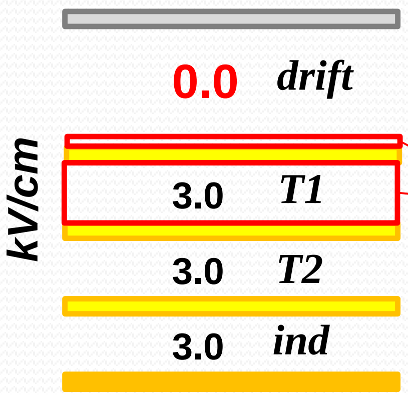


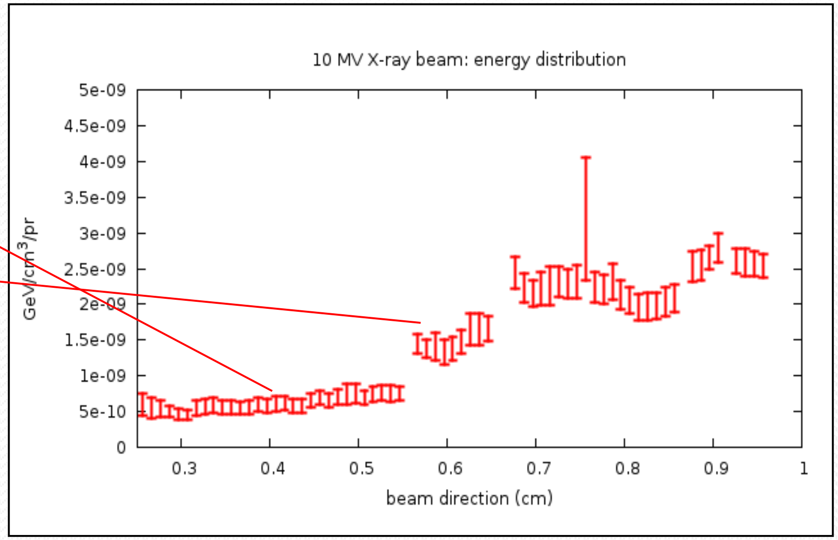
10 MV
γ < 1,
69.16 %

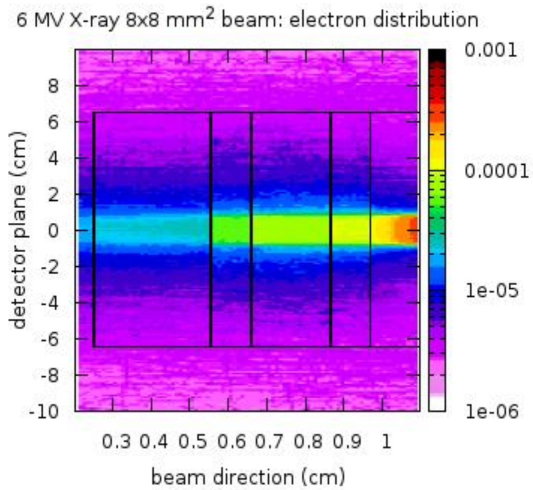


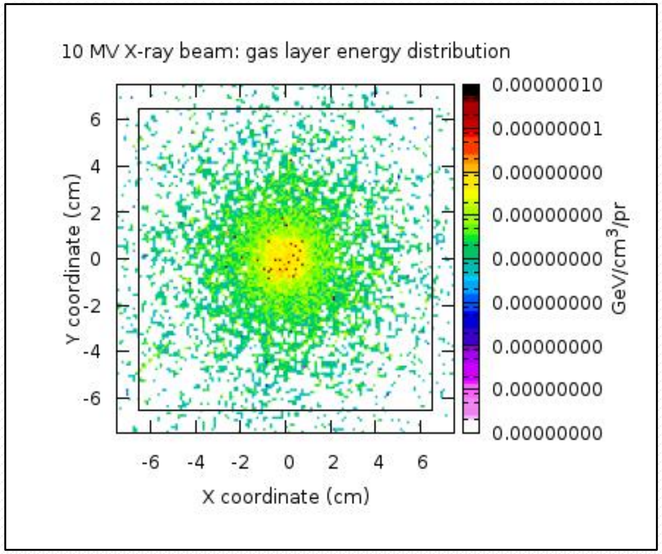
18 MV
γ < 1,
43.04 %

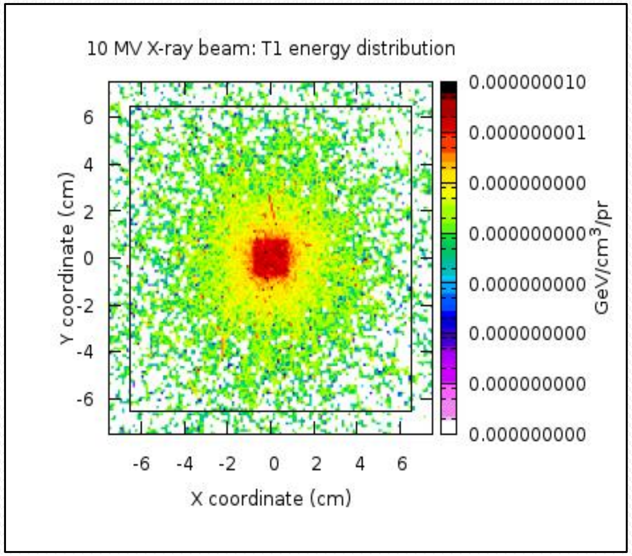
Il rivelatore GEMpix: configurazione tripla-GEM e bi-GEM









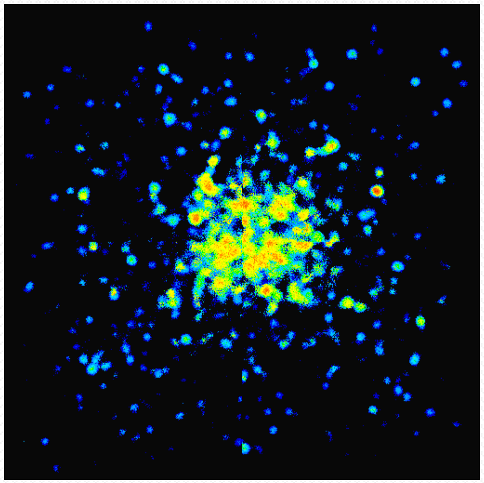


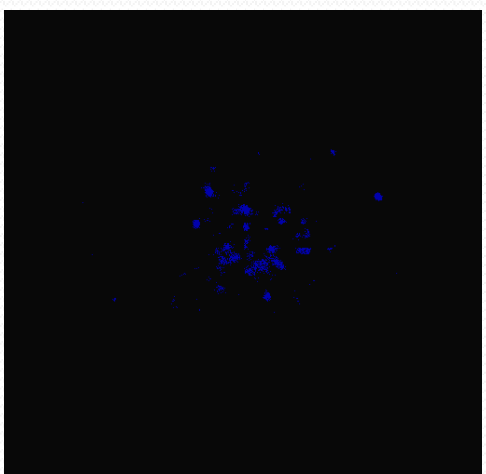
Accordig to simulations detected distribution in a bi-GEM configuration shows an higher contrast respect to the triple-GEM configuration.

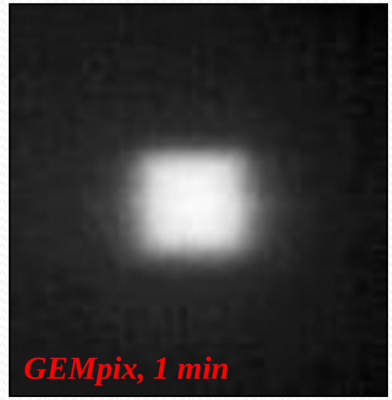
The collected charge comes from the first transition region (T1) and detector can work at a low gain voltage (660 V).

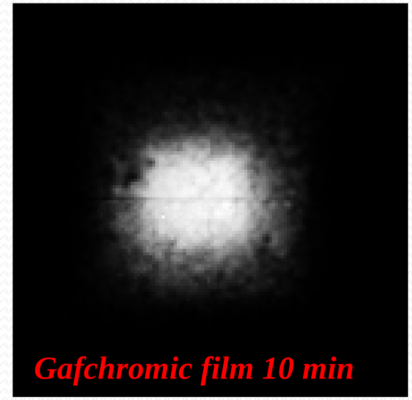
The GEMpix GEMpix: bi-GEM configuration

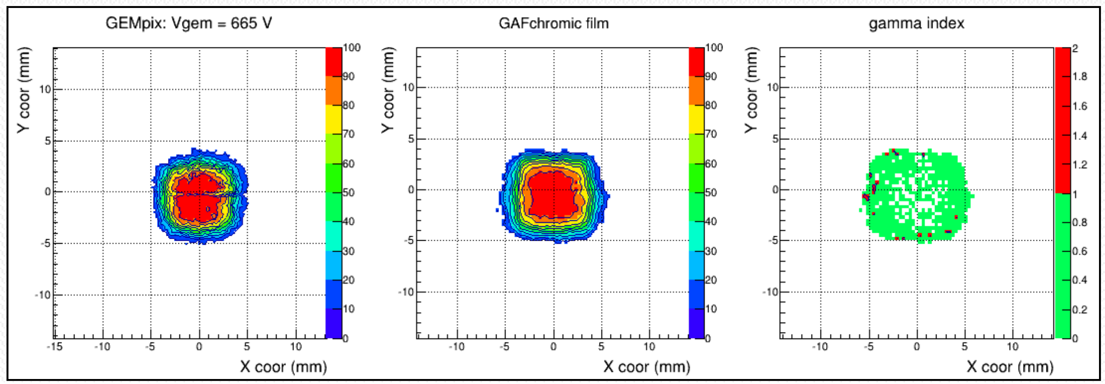
The GEMpix detector is sensitive to the single Linac pulse.







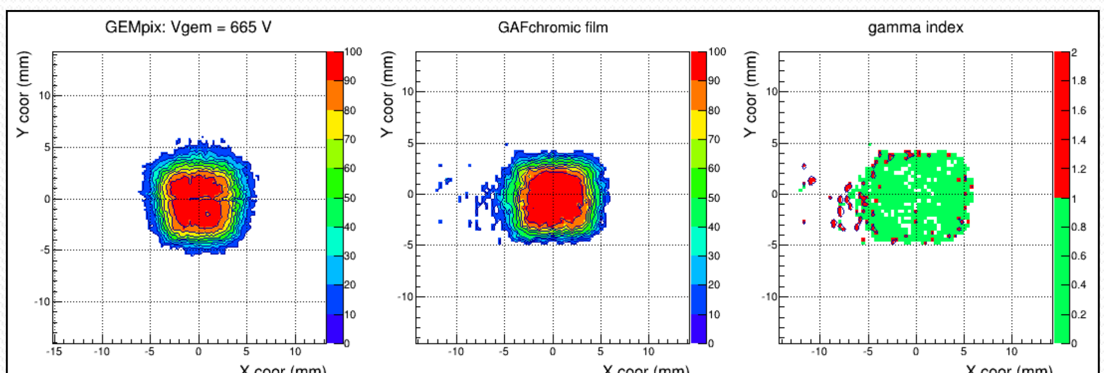




10 MV

$\gamma < 1$,

97.28 %

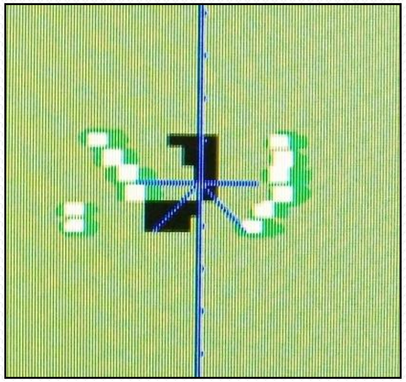


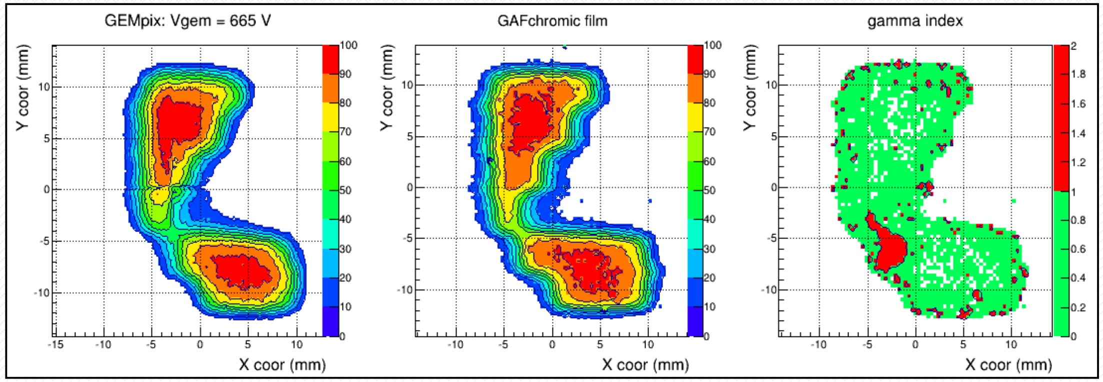
18 MV

$\gamma < 1$,

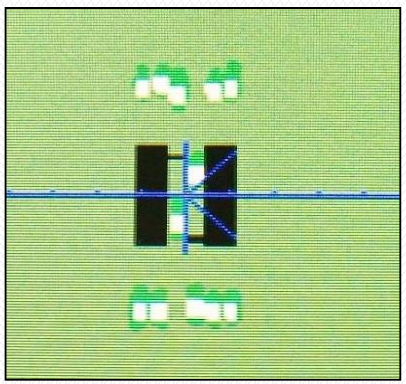
90.14 %

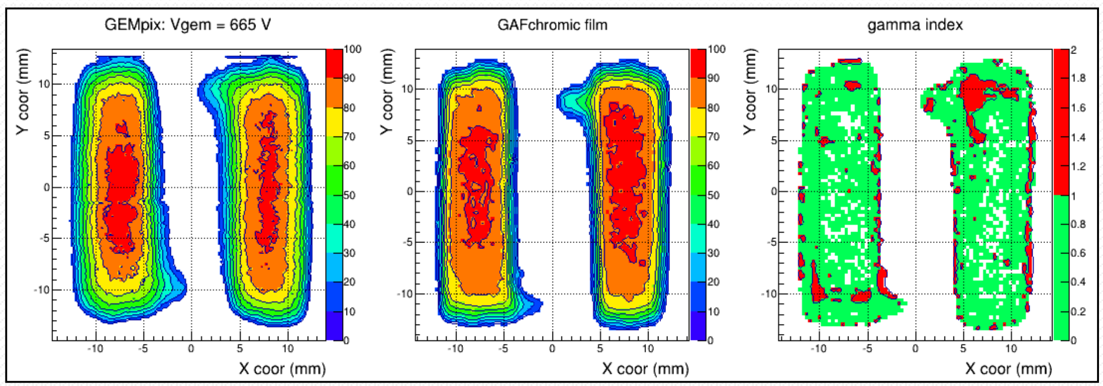
The GEMpix detector: bi-GEM configuration and IMRT fields





6 MV
$\gamma < 1$,
90.50 %





6 MV
$\gamma < 1$,
87.04 %

An optimal accordance between the two detectors is obtained working in a bi-GEM configuration and applying the suitable thresholds to cut the halos around the main beams.

Conclusions

In comparison to the conventional 2D dosimeters, GEMpix detector shows a series of useful advantages:

- an ***higher spatial resolution*** (55 x 55 μm^2 pixels) comparable to radiochromic films
- ***data acquisition is fast and in real time*** (few seconds in comparison to minutes of gafchromic films)
- there is ***no need of post-irradiation processing***
- it has a ***very high sensitivity***: the signal is obtained without material, it can detect the sigle pulse, the minimum detectable dose value is at least 4 order of magnitude lower than that measured by the gafchromic film
- detected ***dose range*** is ***practically unlimited***
- it preserves an ***optimal linearity with dose rate***

The present work has shown optimal results on samll area irradiating fields. The next step will be the realization of:

- Large area GEM foils (at least 20x20 cm^2)
- Larger pixels with their related front-end-electronics

Thanks
for your attention!!!