Development of Advanced Quality Assurance Instrumentation for Hadrontherapy

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ICTR-PHE 2014
Feb. 11th, 2014

TERA
Fondazione per Adroterapia Oncologica

Advanced QUality Assurance

TERA Overview

Direction: Prof. Ugo Amaldi

<u>AQUA</u>
(Advanced QUAlity Assurance)

- supervised by Prof. F. Sauli
- 1 phD student
- 1 (not anymore) phd student
- 1 post-doc

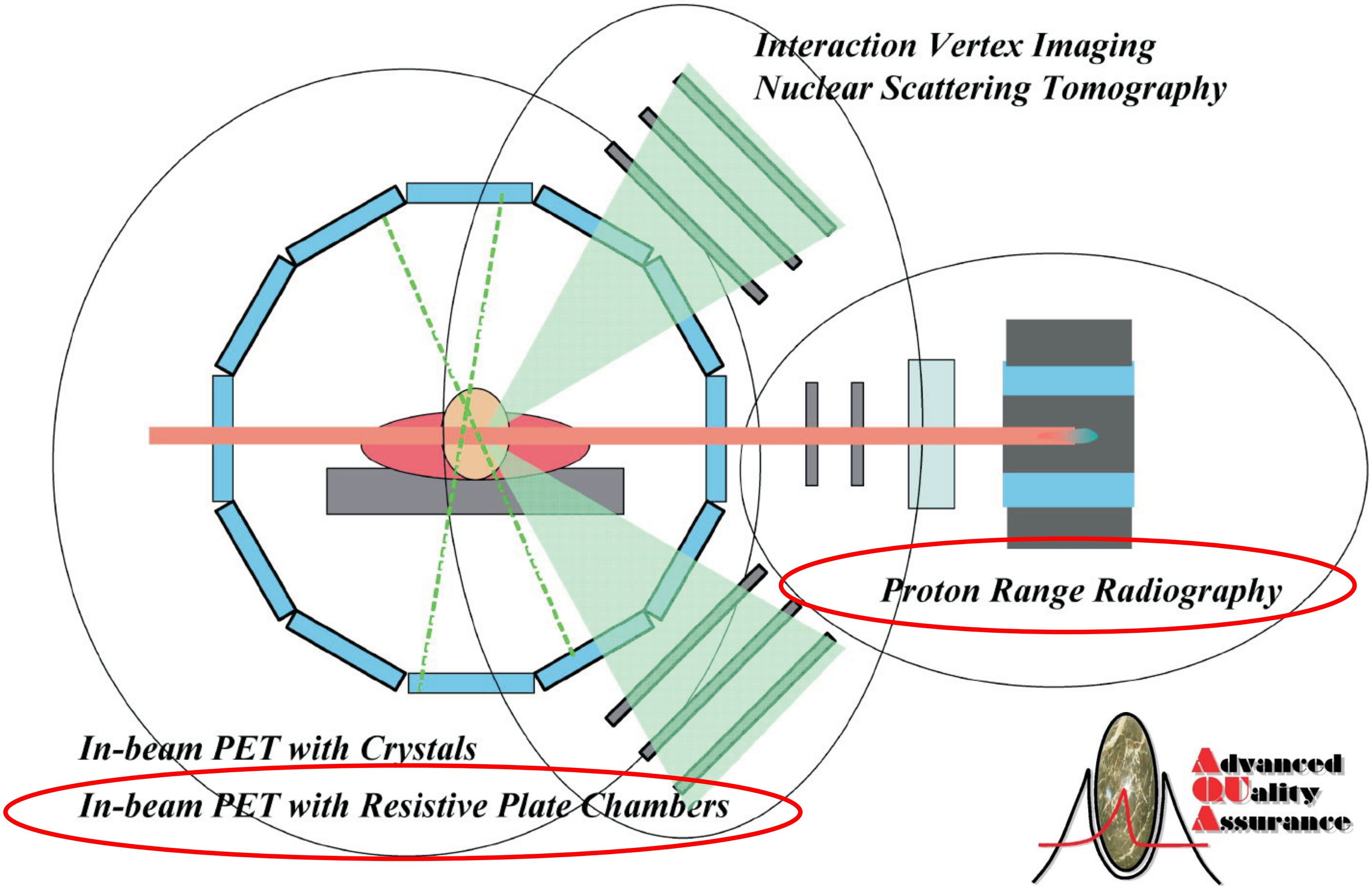
- Also involved in several European projects PARTNER, ENVISION, and INTERVISION

<u>Cyclinac Group</u>

- Main projects are Caboto, TULIP, Idra...
- Involved in European projects... PARTNER

AQUA (Advanced QUality Assurance)

AQUA
ADVANCED QUALITY ASSURANCE



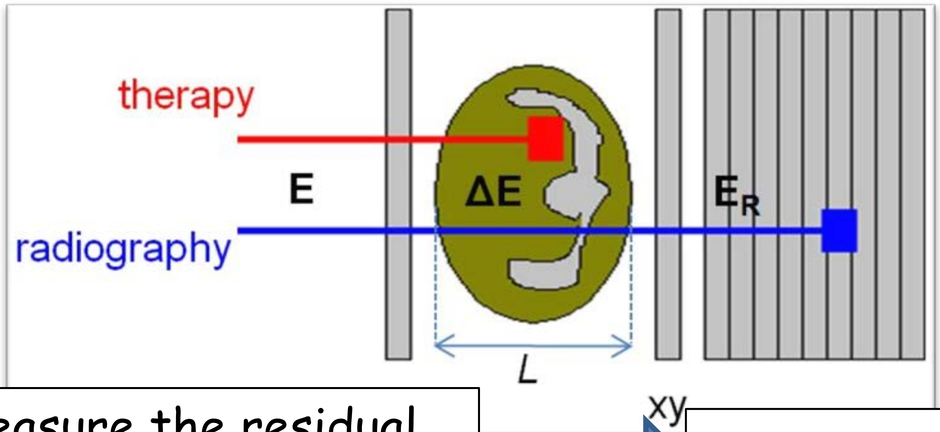
PART I

Proton Range Radiography

Proton Range Radiography

Principle

- Energy loss of protons is proportional to electrons per mm^3



We can measure the residual energy or the residual range

$$R(E) \approx \alpha E^{1.8}$$

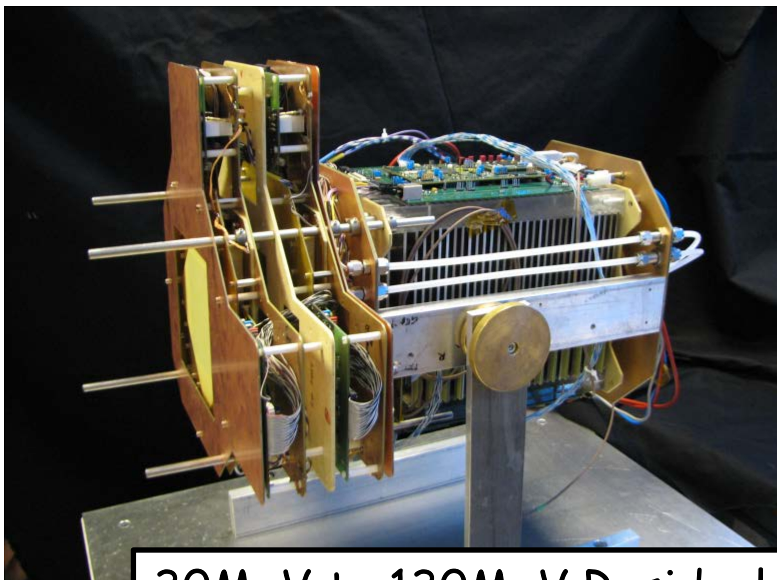
Applications

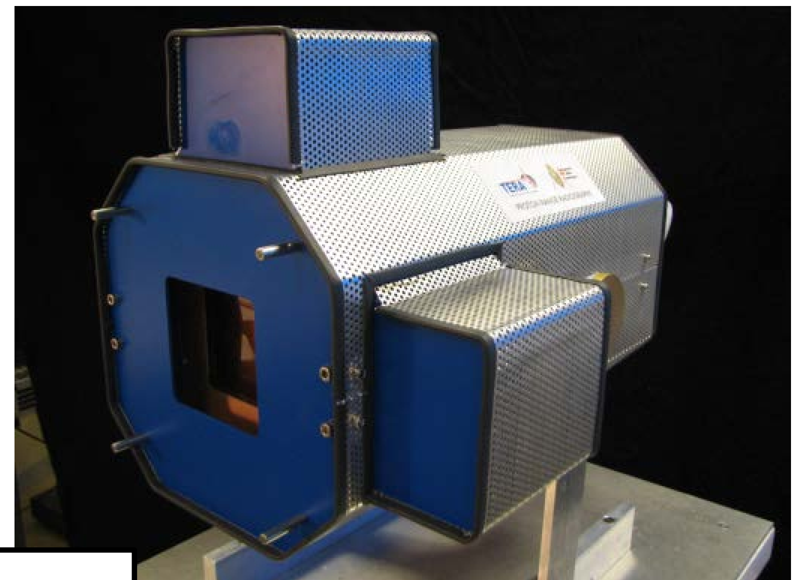
- Conversion of the "greyness" of the CT image to electrons / mm^3
- Online patient positioning (low dose radiography)
- First step towards Proton CT for treatment planning

Proton Range Radiography

Previous PRR10

- 10x10cm^2 active area
- 30 plastic scintillators each 3mm thick

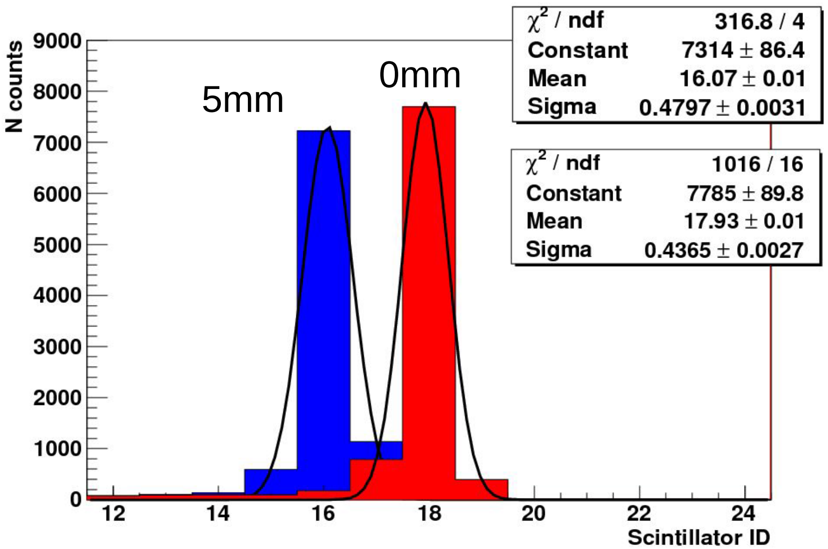




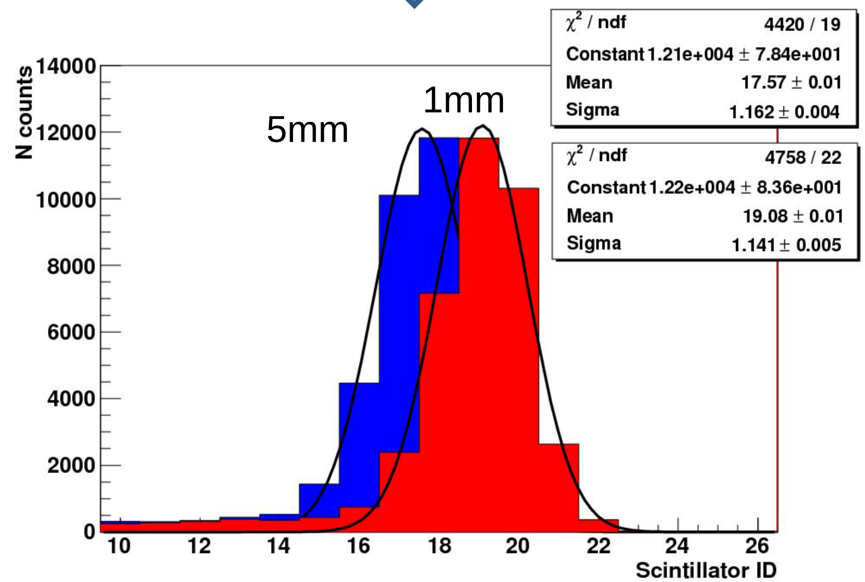
30MeV to 130MeV Residual Energy

PRR10 Beam Tests at PSI

99.7 MeV narrow beam

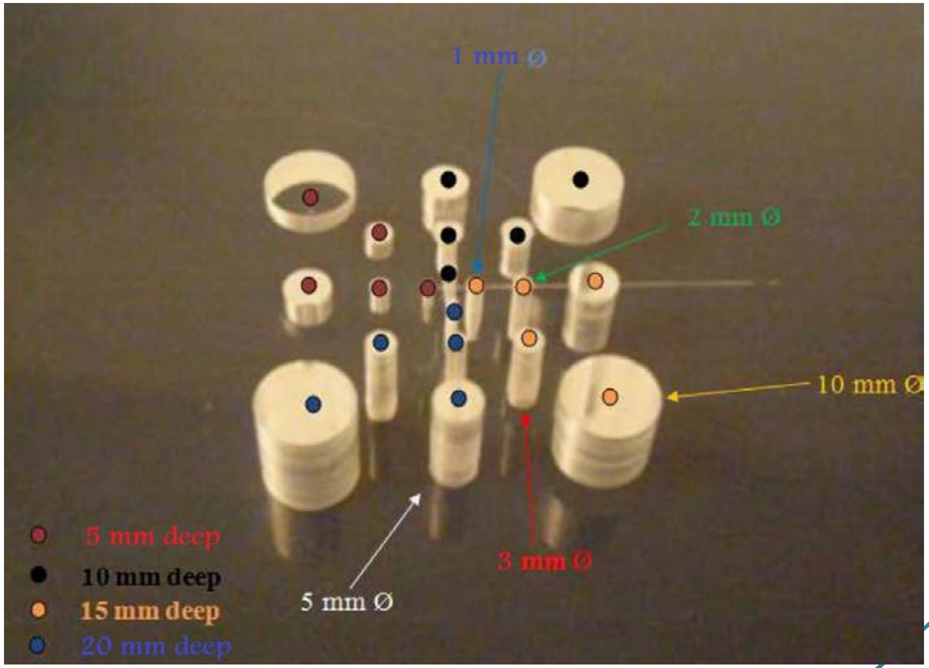


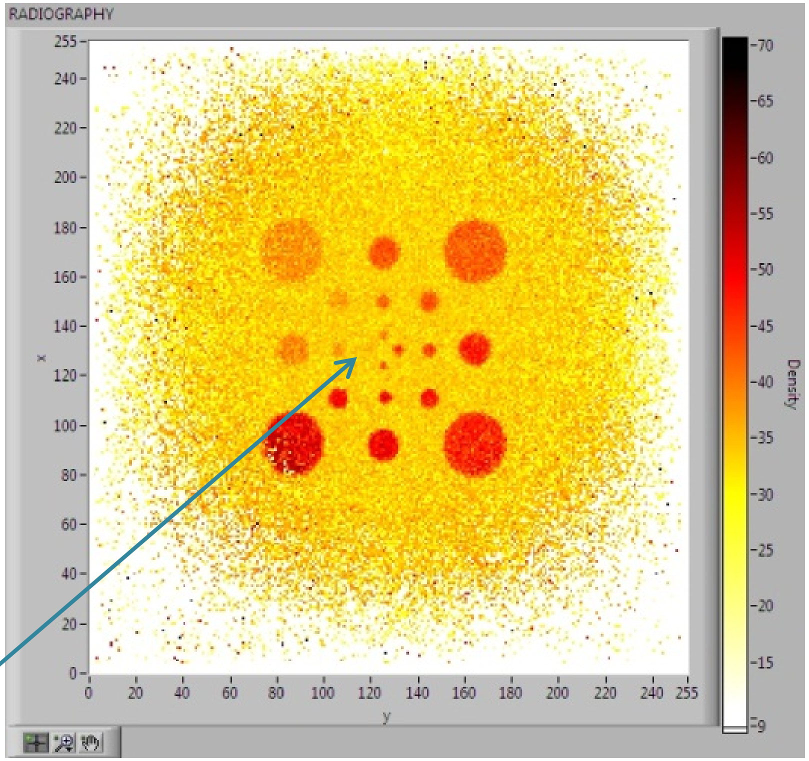
101 MeV wide beam



Range resolution is 1.6 mm WEPL

PSI Beam Tests – Holes Phantom



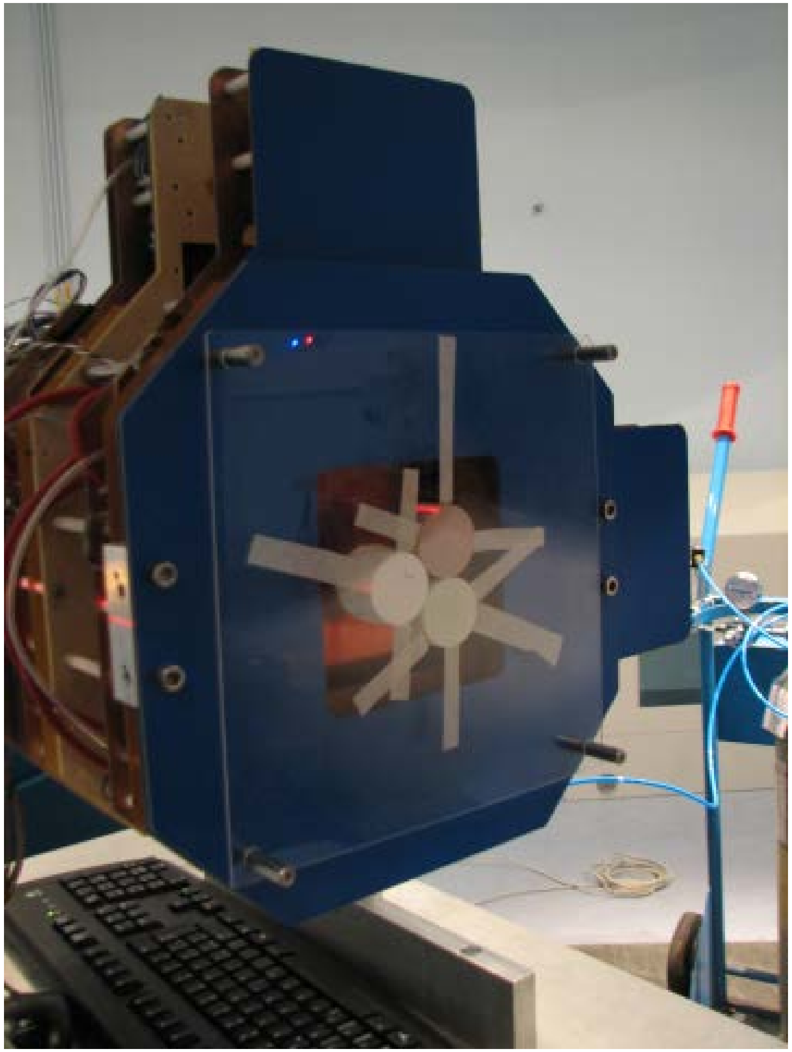


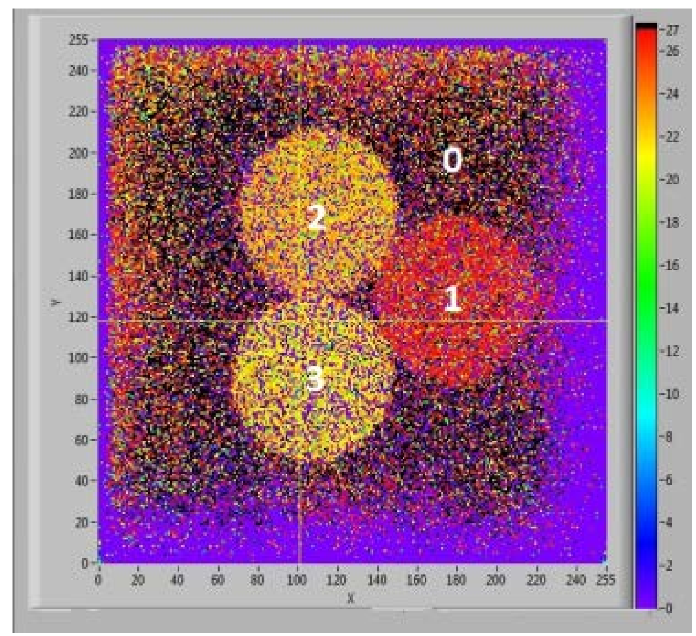
We can see the 1 mm holes

CNAO Beam Tests - Setup

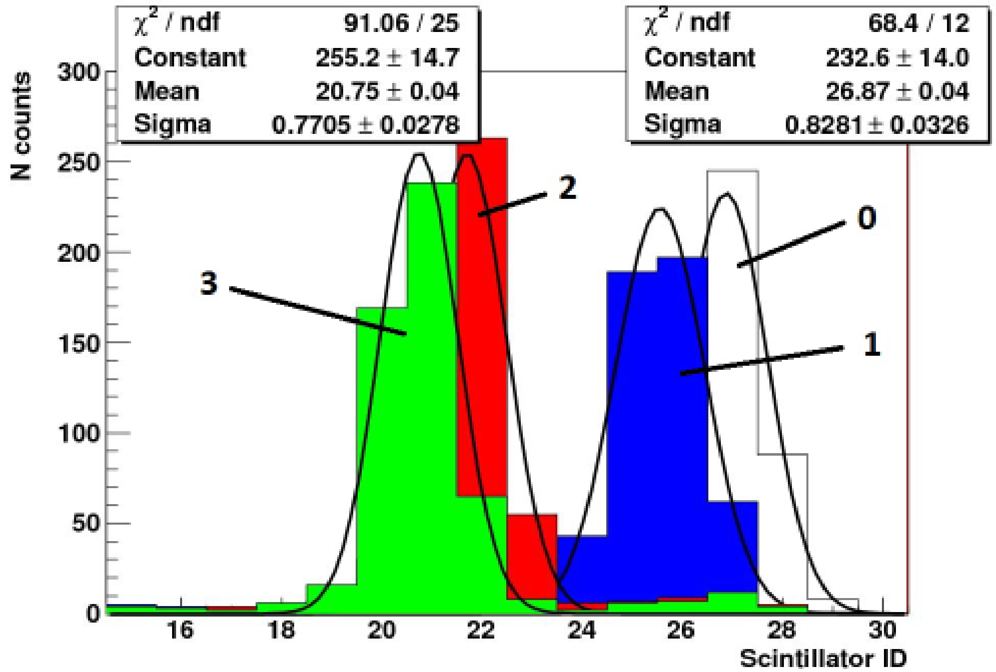
June 2011

CNAO Beam Tests – Tissue-equivalent phantoms





CNAO Beam Tests – Tissue-equivalent phantoms



	ρ_{real}	L	R	ΔR	ρ_{PRR}
	g/cm^3	mm	scint. units	mm WEPL	g/cm^3
No phantom (ref)	0	-	26.87	0	-
Lung	0.20	24.7	25.50	4.987	0.201
Breast	0.99	18.3	21.69	18.86	1.030
Trabecular Bone	1.16	19.5	20.75	22.28	1.142

0.9% error from expected

4.1%

1.5%

Proton Range Radiography

$\frac{\sigma_R}{R}$ = 1.6 mm WEPL or 2.3% at 100 MeV

$\sigma_R/\sqrt{N},$

If 100 event per pixel, actual resolution is 0.16 mm WEPL

$$\sigma_\rho = \frac{\sigma_R}{L\sqrt{N}}$$

= 0.2% (for a 10 cm object)

< 0.3% requirement for clinical PRR system

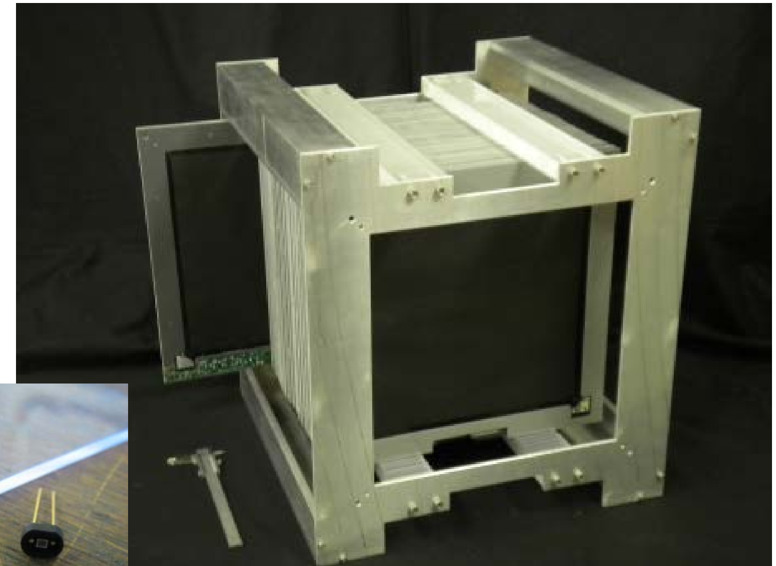
For a 30x30 cm^2 image with 1 mm pixels, 100 events/pixel… you need 10^7 protons. To make this in 10 seconds requires a rate of 10^6 protons per second

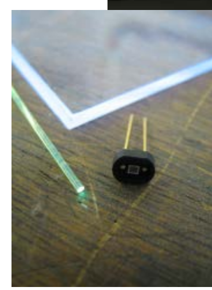
This is FAST!!!!!

PRR30 – Latest Developments

Scintillator stack

- 48 Plastic scintillators 30x30 cm^2 3 mm each (15 cm water equ)
- Same WLS fiber to SiPM



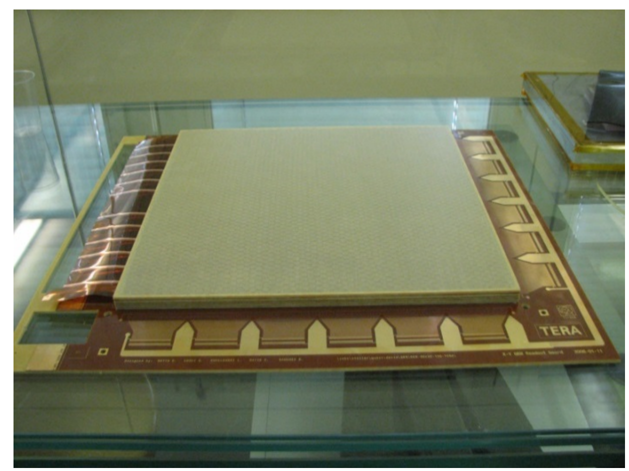


30MeV to 190MeV Residual Energy

Tracker

- Two 30x30 cm^2 triple-GEM detectors
- 2D XY strip readout (400 um pitch)
- Readout electronics capable of 1M events/sec

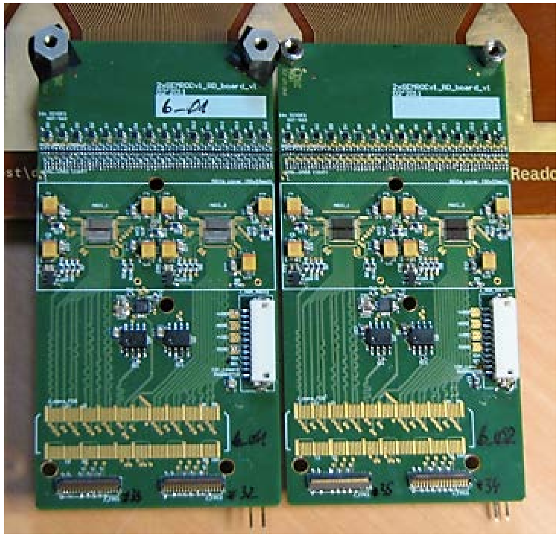
New development was needed!

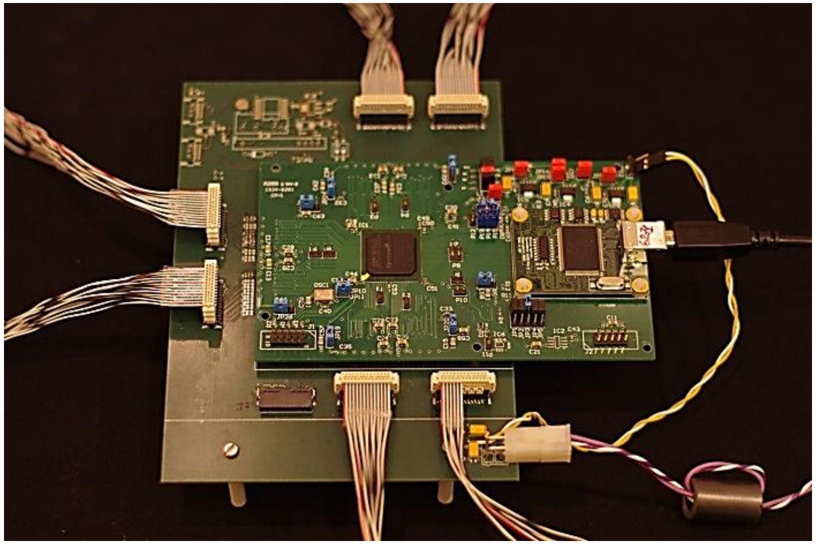


PRR30 High Speed GEM Readout

New developments in GEM readout technology

Main goal: ~ 1 MHz EVENT THROUGHPUT



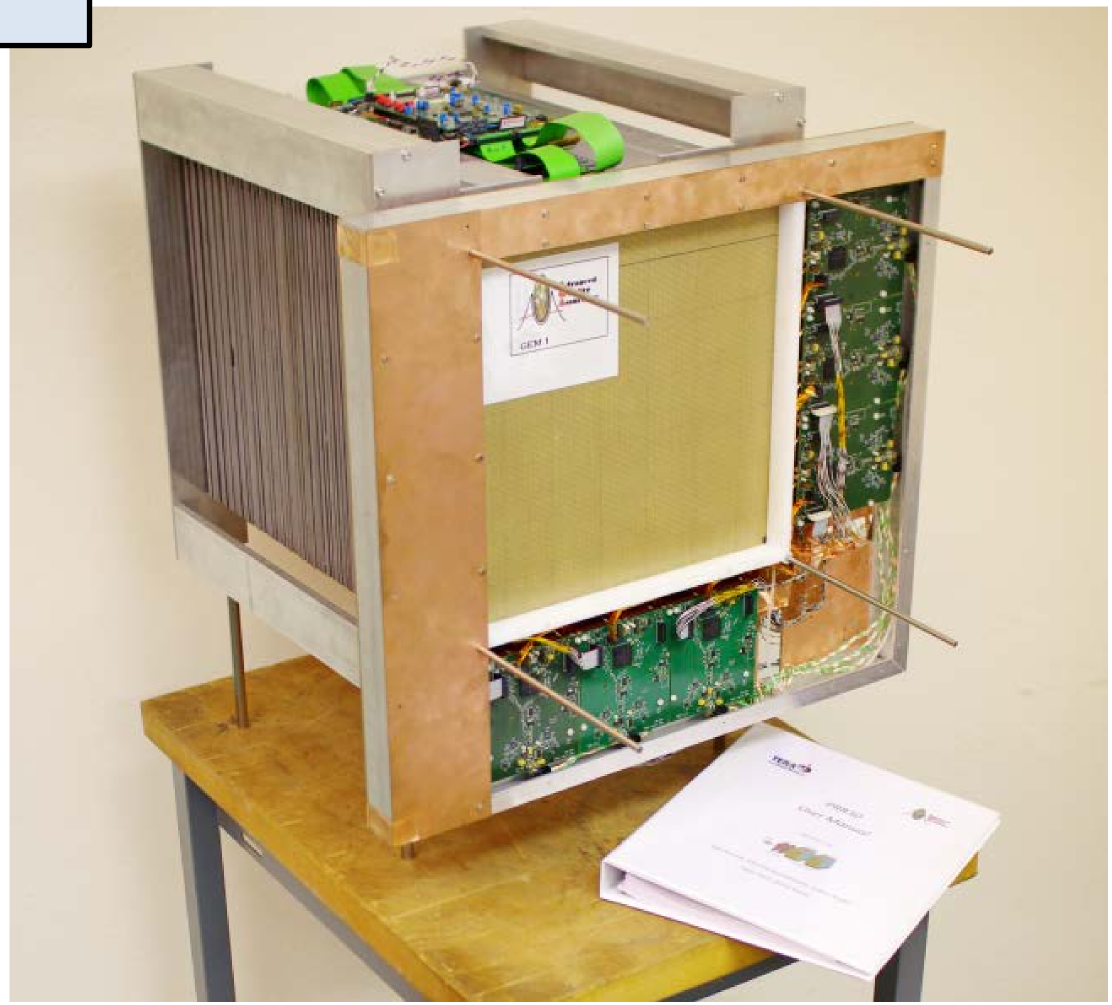


Novel dedicated ASIC for GEM chambers
GEMROC Hybrid Front End board

developed by AGH Cracow University in collaboration with TERA

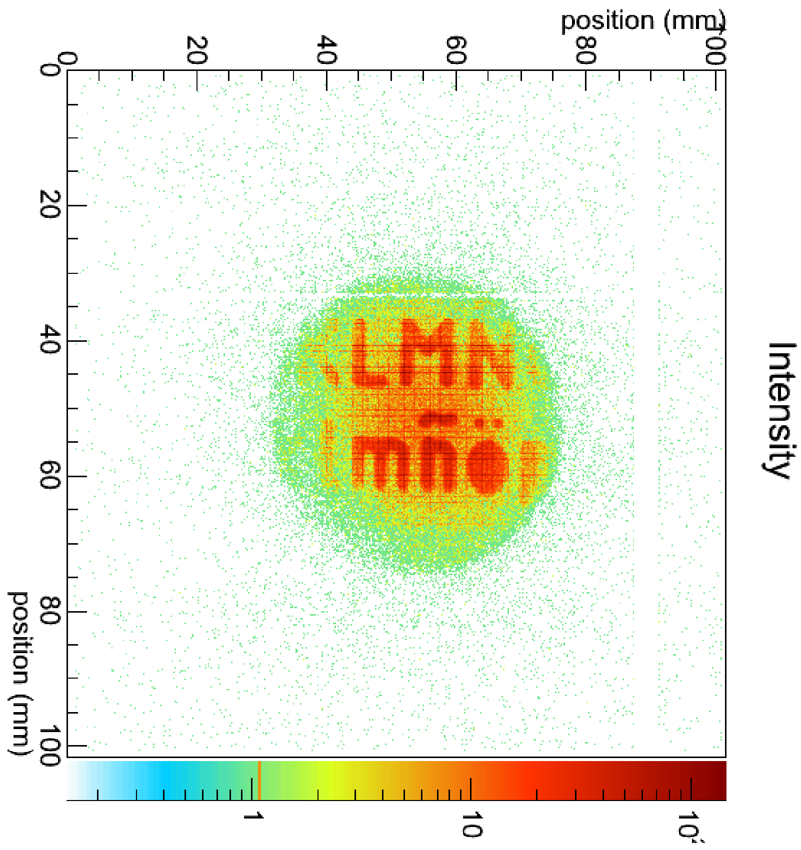
PRR30 Status

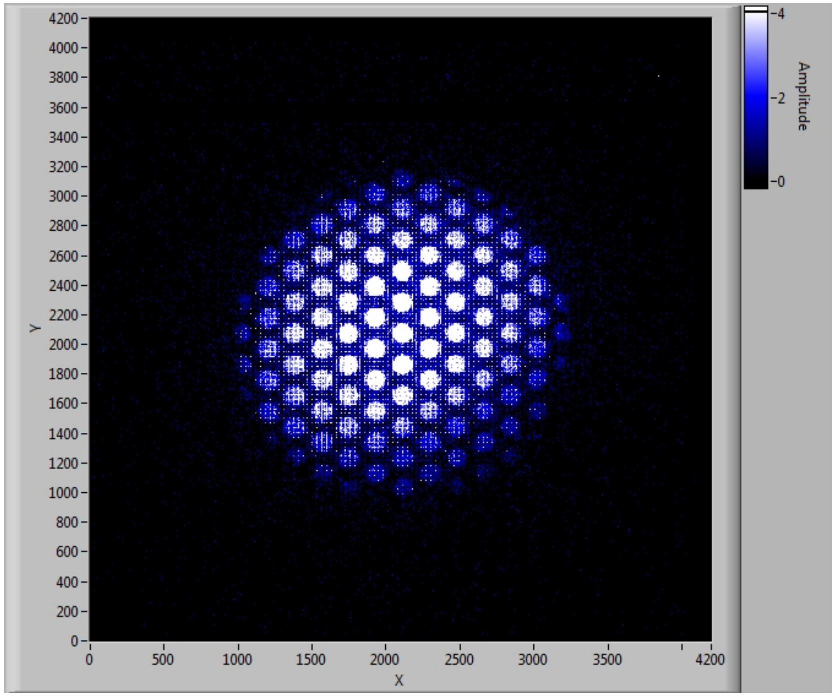
Jan 2014



PRR30 Status

X-ray images acquired
with 1 MHz rate





PRR30 Status

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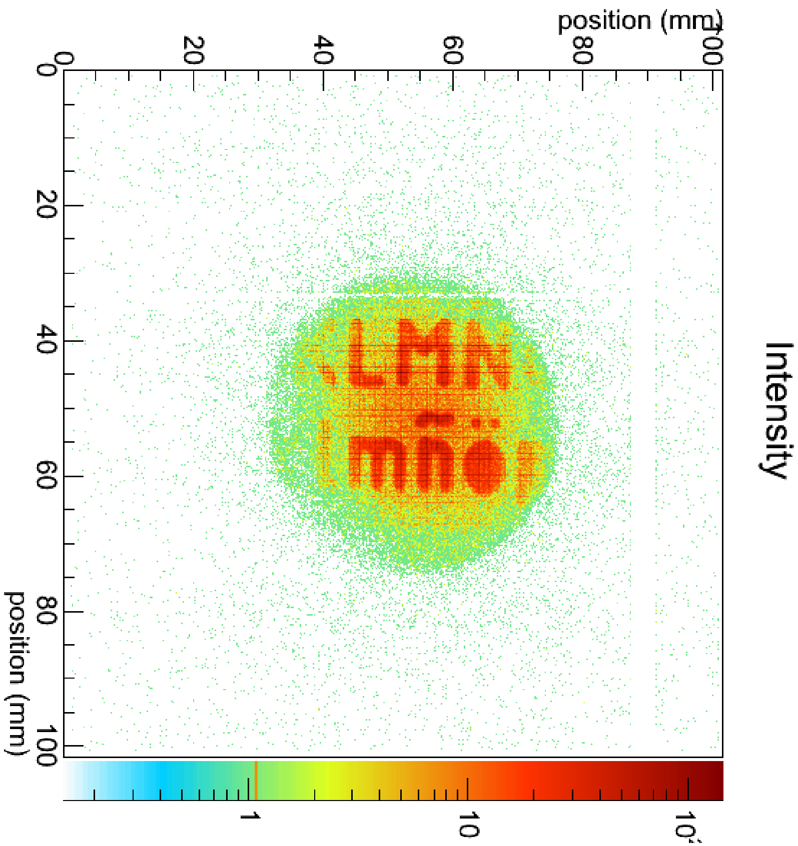
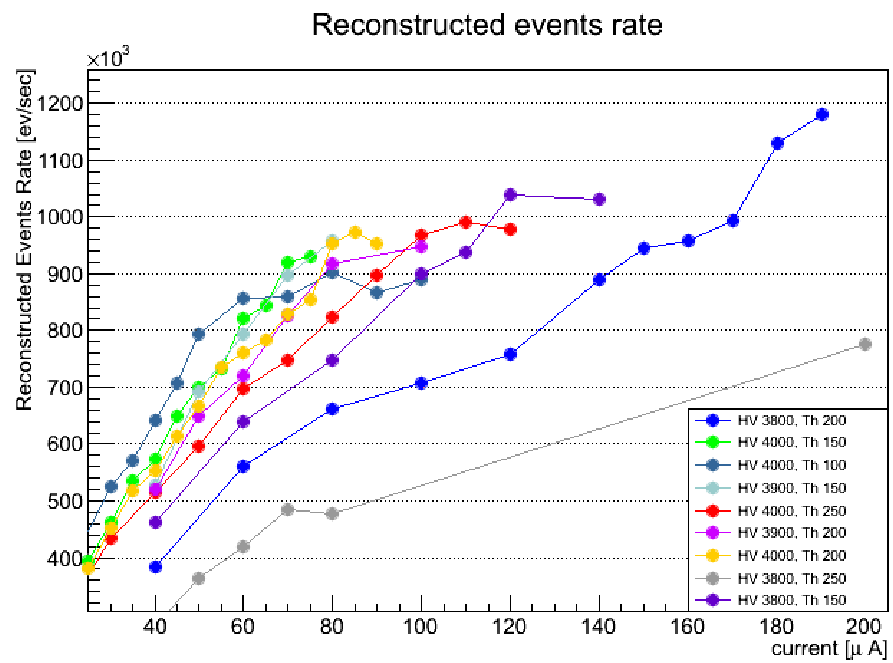


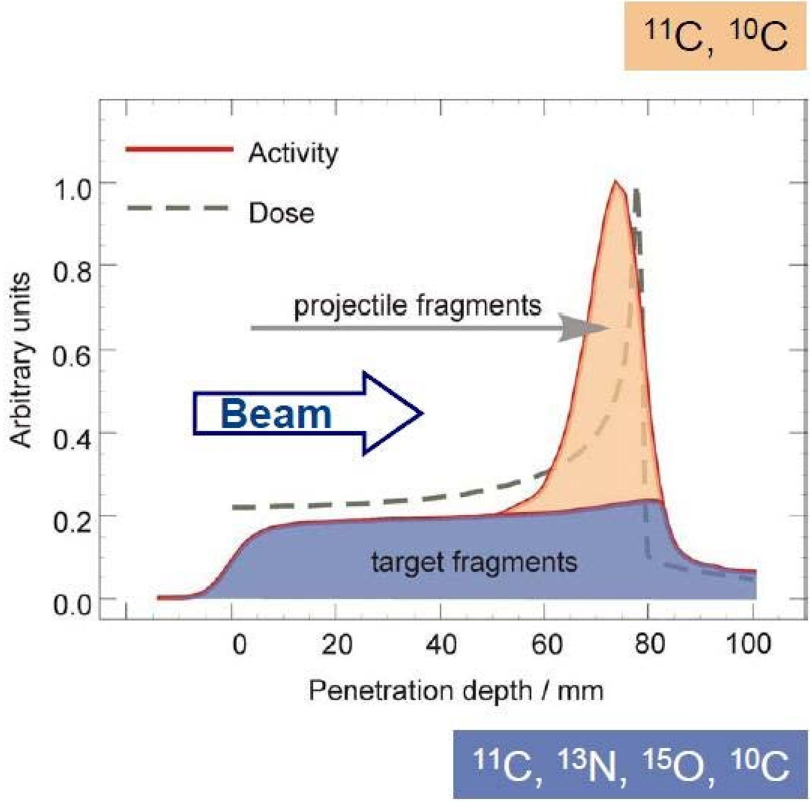


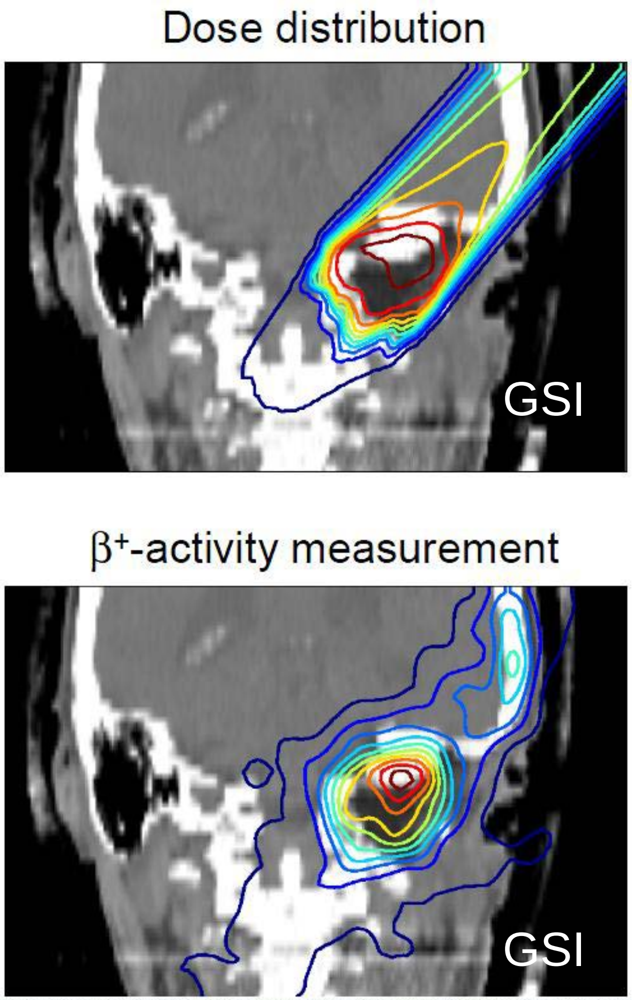
PART II

In-vivo dosimetry with MRPC-PET detectors

In-vivo PET Dosimetry

Proton and ion therapy results in β+ activation of tissues which can be measured by a PET detector and used to verify the treatment plan immediately following irradiation





In-beam PET

Advantages

- Real-time dose and range monitoring

Challenges

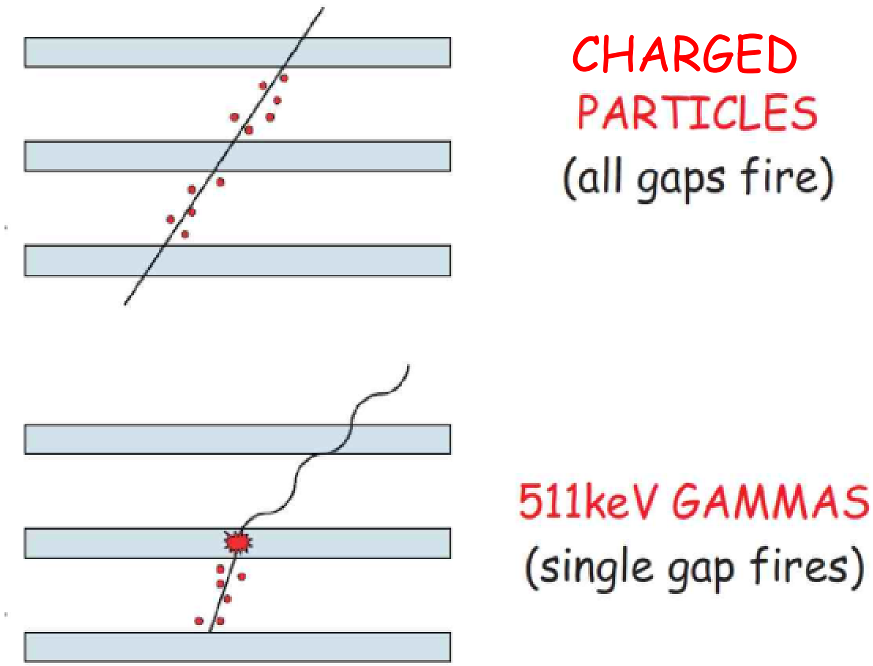
- Very low statistics (100x less than in nuclear medicine)
- In-beam PET requires partial ring geometries (loss in sensitivity)
- Gating on beam structure (too much background during beam on!)
- Biological washout

→ Improve upon existing PET hardware!!!

→
- TOF-PET
- DOI
- …

MRPC application to PET

Multi-gap Resitive Plate Chambers are used in HEP for tracking charged particles with high spatial resolution and TOF capability



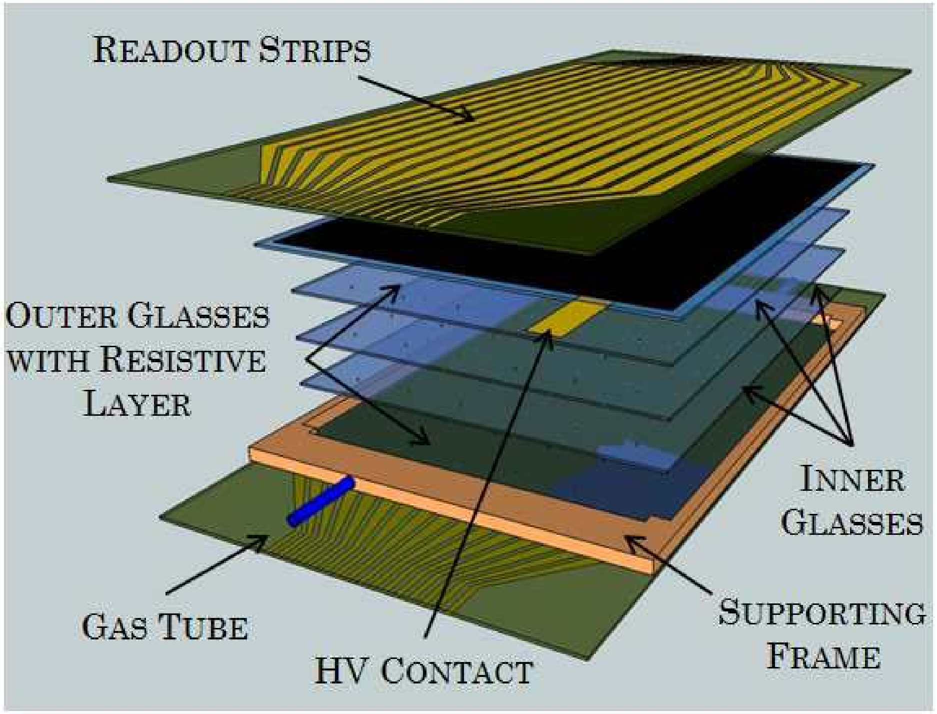
MRPCs give no energy resolution and poor efficiency to 511keV gammas!

So what's the motivation?

- Cheap (in principle)
- TOF-PET
- DOI…

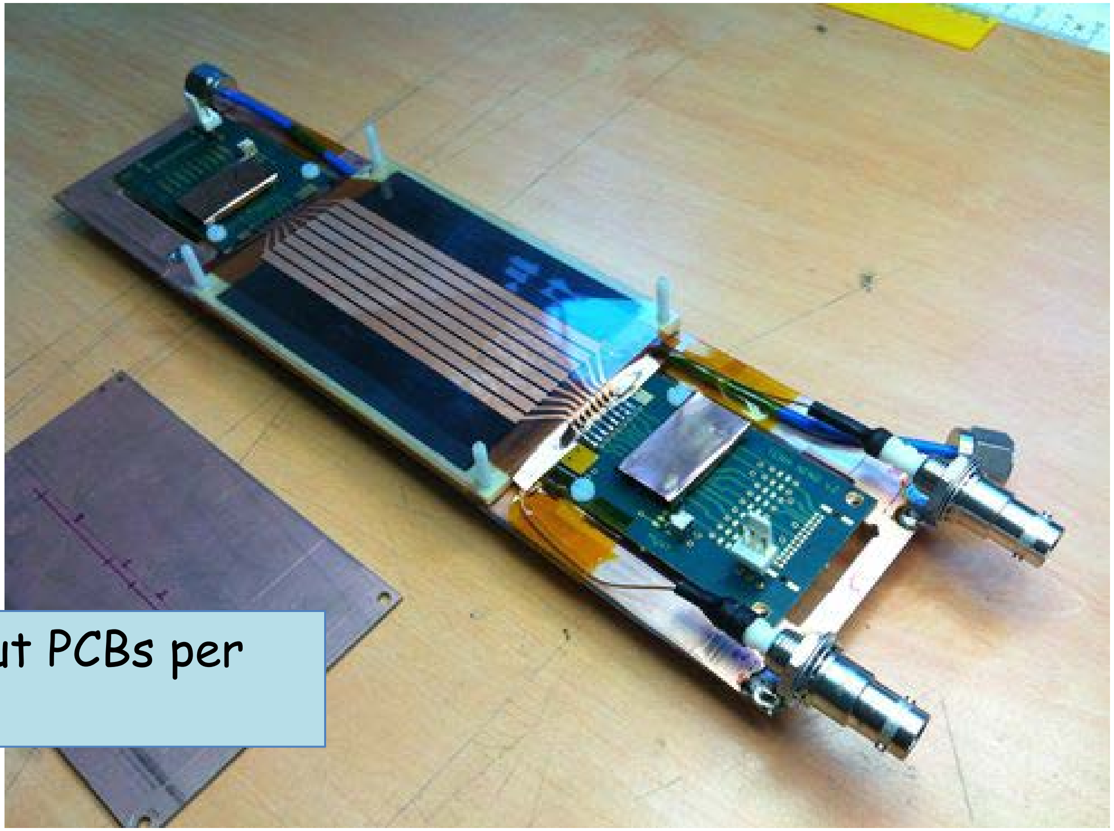
AQUA's proposal for a MRPC module for PET application

A real MRPC design for PET must be compact!!



Axial interaction position is resolved by measuring timing between events arriving on either ends of readout strips

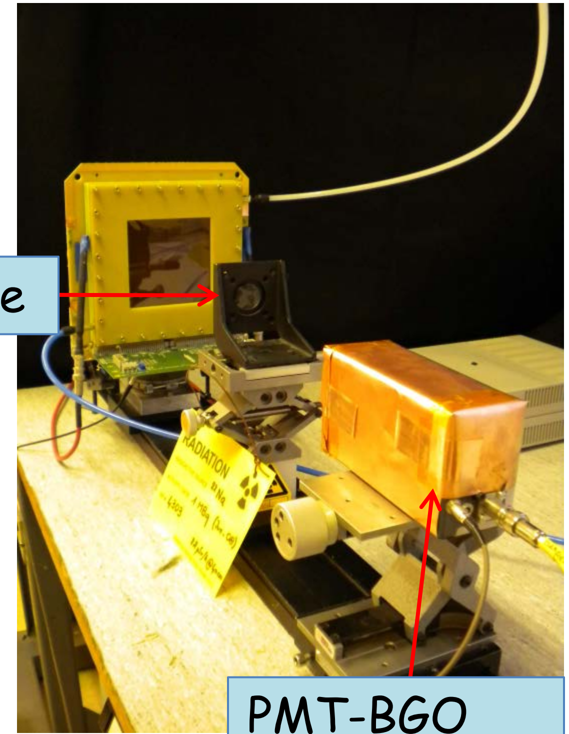
Partially equipped MRPC-PET module

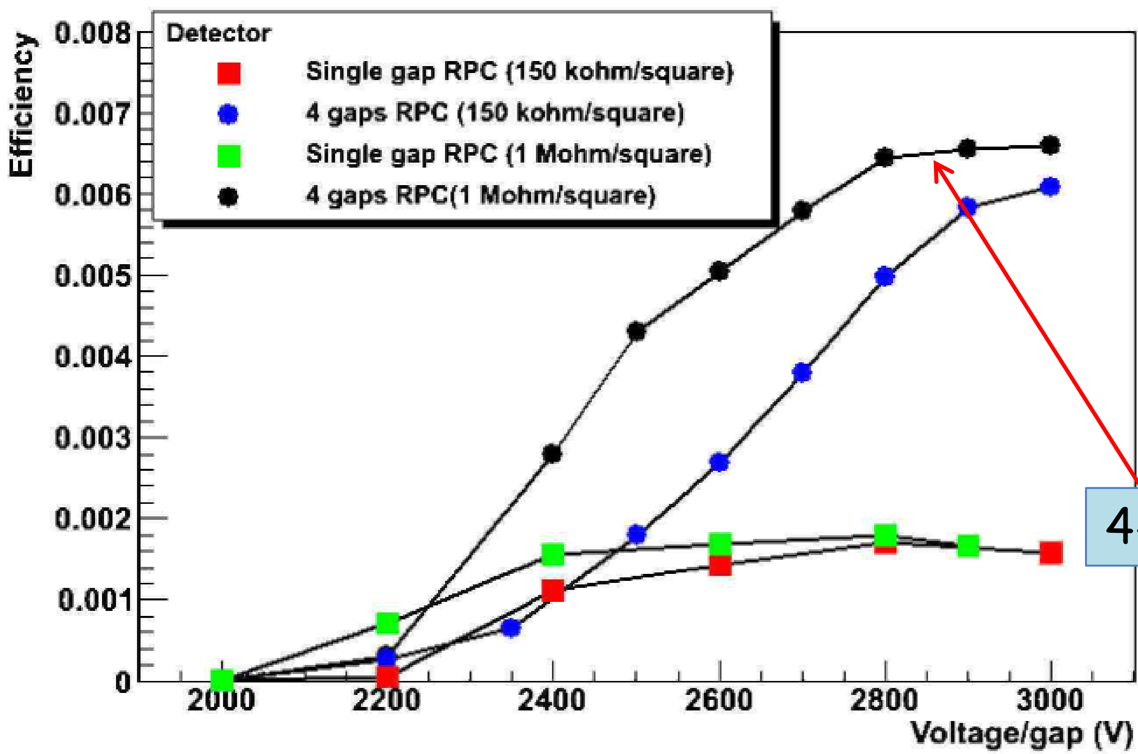


Two readout PCBs per module

MRPC-PET: Efficiency Study

Efficiency setup

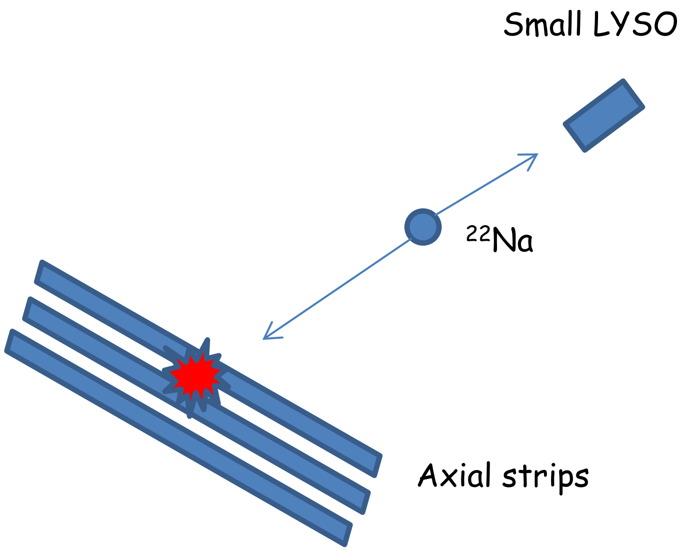


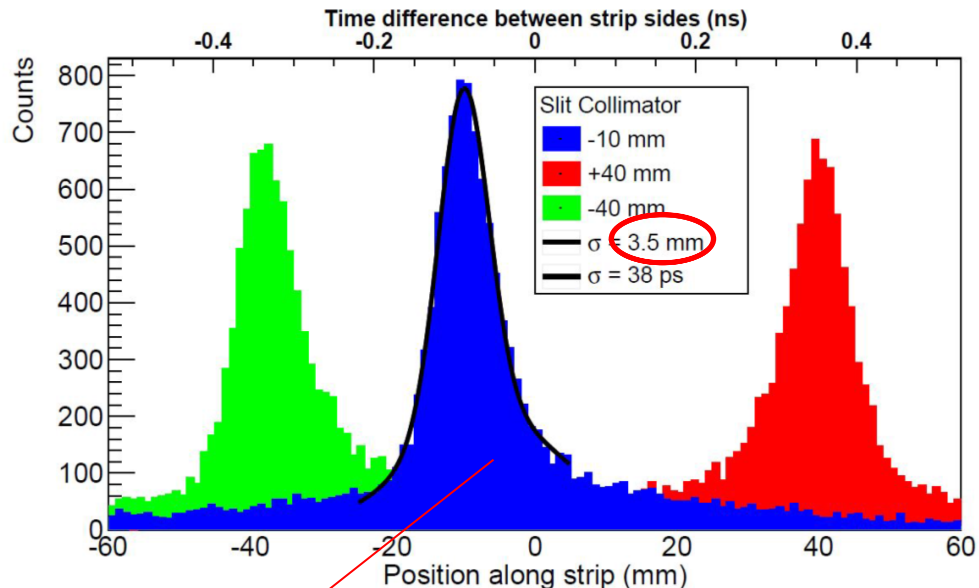


4-gap MRPC (0.66 ± 0.05)%

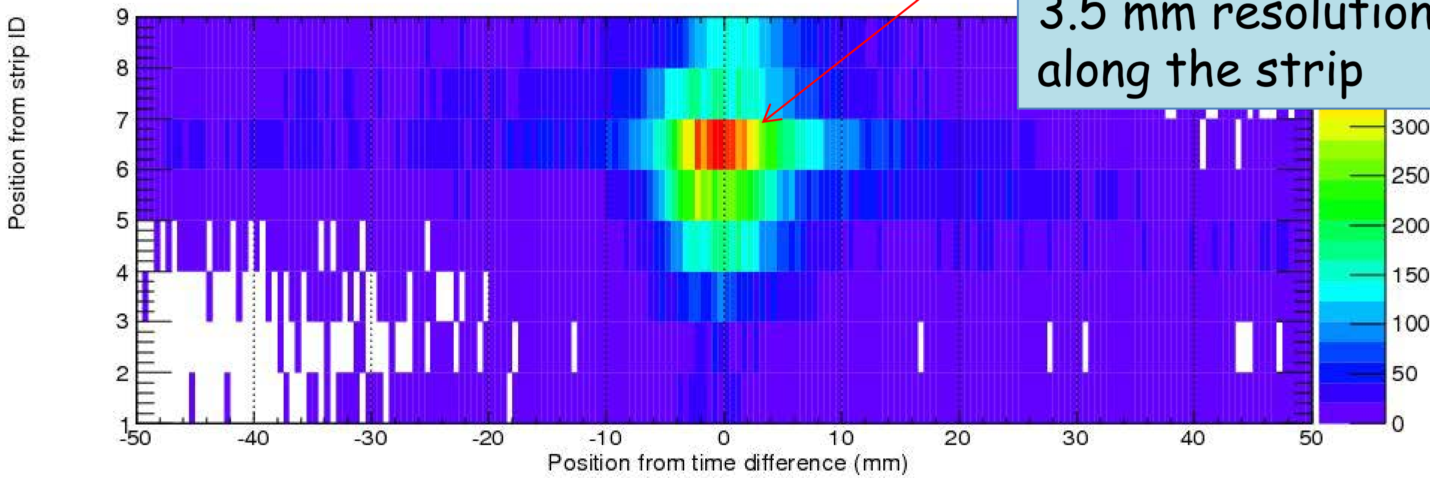
Monte Carlo: 0.77%

MRPC-PET Compact Module: Axial localization

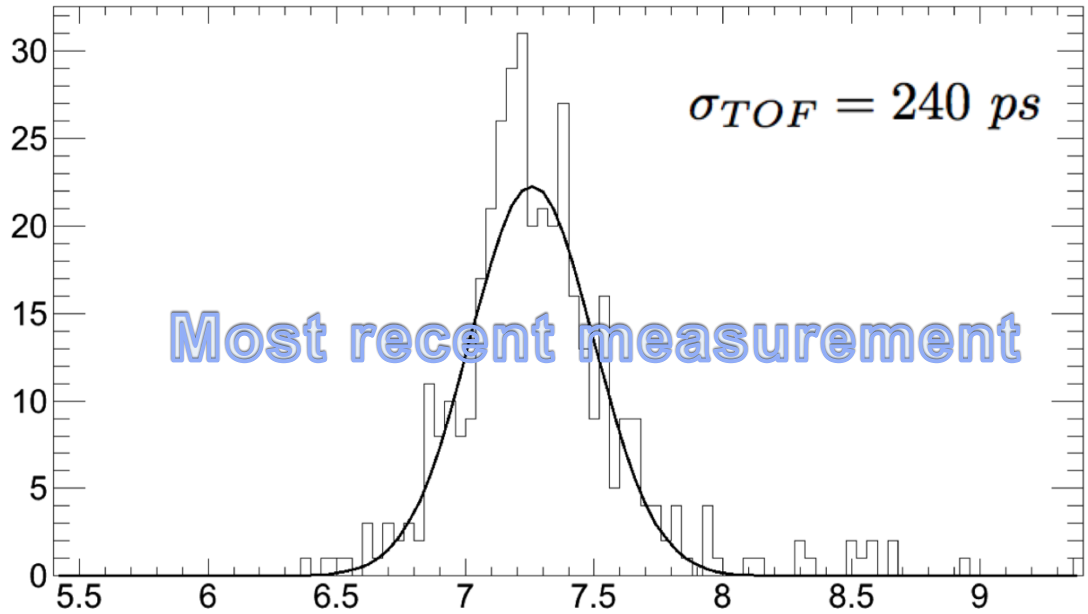




3.5 mm resolution along the strip



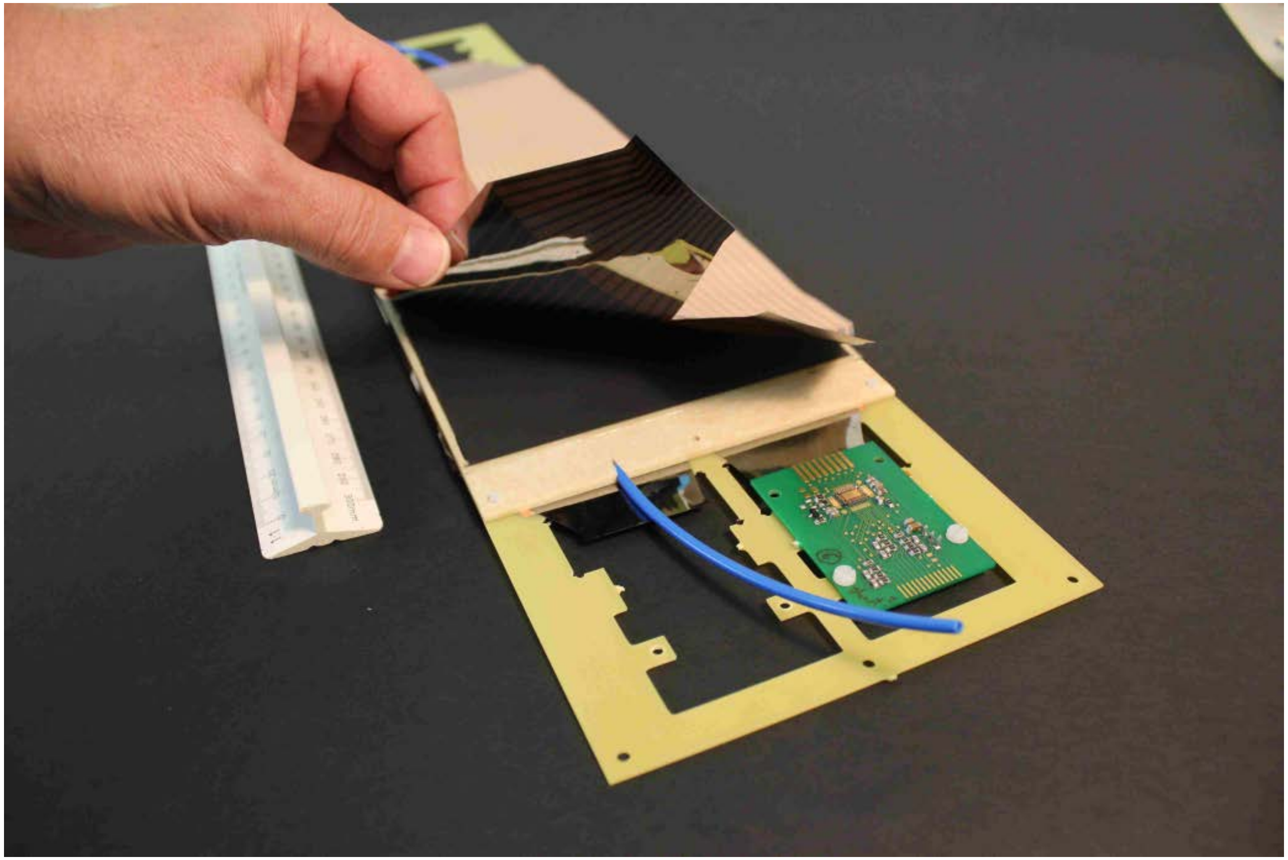
MRPC-PET Compact Module: Time-of-flight resolution



Single detector resolution = 170 ps sigma

FWHM of coincidence = 550 ps   i.e: 8.5 cm along LOR

MRPC-PET Compact Module: 12cm x 30cm



Target dimensions for MRPC-PET demonstrator and simulation studies

Conclusions

- The AQUA (Advanced QUality Assurance) group of the TERA Foundation aims to build radiation detectors for QA in hadrontherapy

- Two main projects presented here: proton range radiography (PRR) and *in-vivo* dose monitoring with Multi-gap Resistive Plate Chambers (MRPCs)

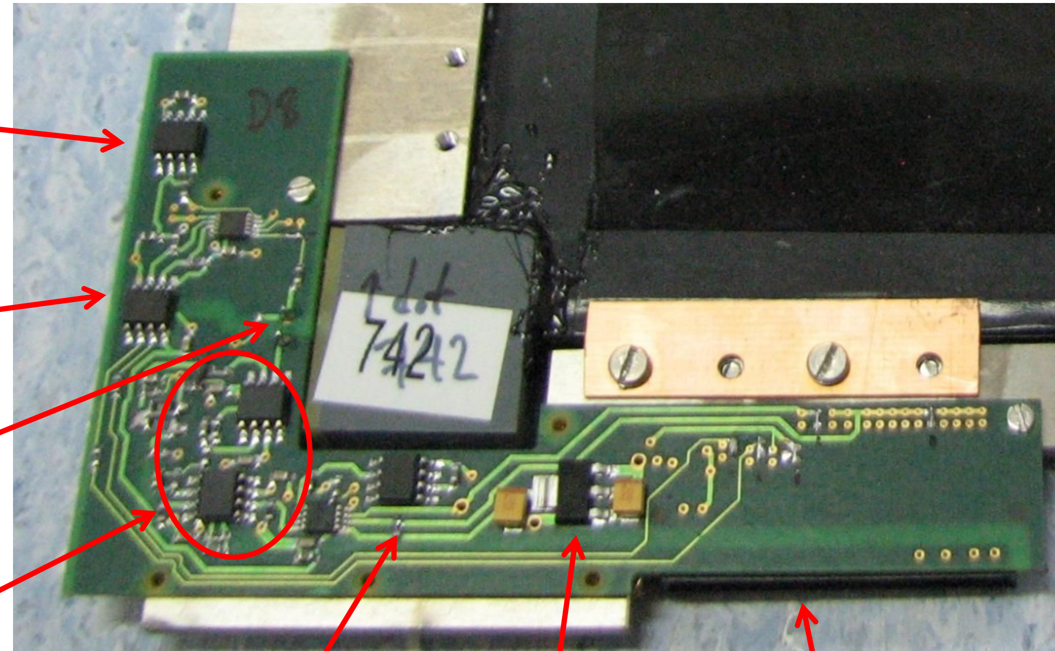
- A 10x10cm^2 PRR instrument has been completed and tested with proton beams at PSI and CNAO → A new device, 30x30cm^2 PRR is being built, scheduled for beam testing during summer 2014.

- Compact MRPCs modules have been tested using a production technique which could be scaled to large volumes. Current TOF measurement is 240 ps (sigma) and we are still working to improve it!

Thank you for your attention!

Backup Slides

PRR10 – Scintillator module PCB



5V DAC working at decoupled base voltage (67V)

I2C ground decoupledchip

SiPM

2 stage pre-amp (80ns shaping time)

12-bit high-speed ADC

Voltage regulator

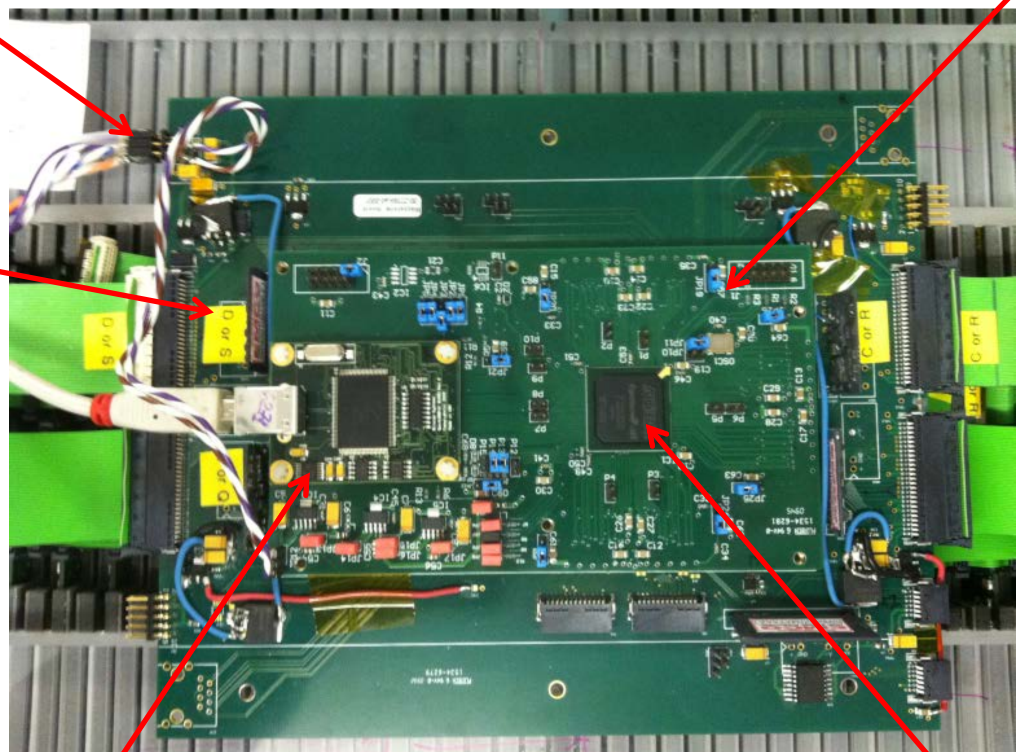
Low-profile ERNI connector

PRR10 – Scintillator DAQ

Trigger modules

Central DAQ on top of mezannine (fan-out plus HV)

HV modules (67 V for SiPMs)



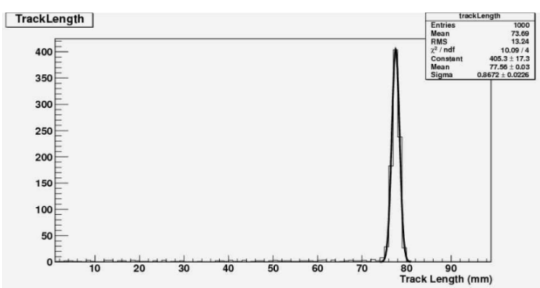
Bitwise Systems Quick USB module

ALTERA Cyclone III FPGA

Uncertainty in Range Determination

$$(\sigma_R)_{measured} = \sqrt{(\sigma_R)^2_{straggling} + (\sigma_R)^2_{beam} + (\sigma_R)^2_{detector}}$$

1.1% for protons at these energies



Energy spread of beam (translated to a range uncertainty)

$$\left(\frac{\sigma_R}{R}\right) \approx p\left(\frac{\sigma_E}{E}\right)$$

For thin absorbers $\frac{\Delta d}{\sqrt{12}}$

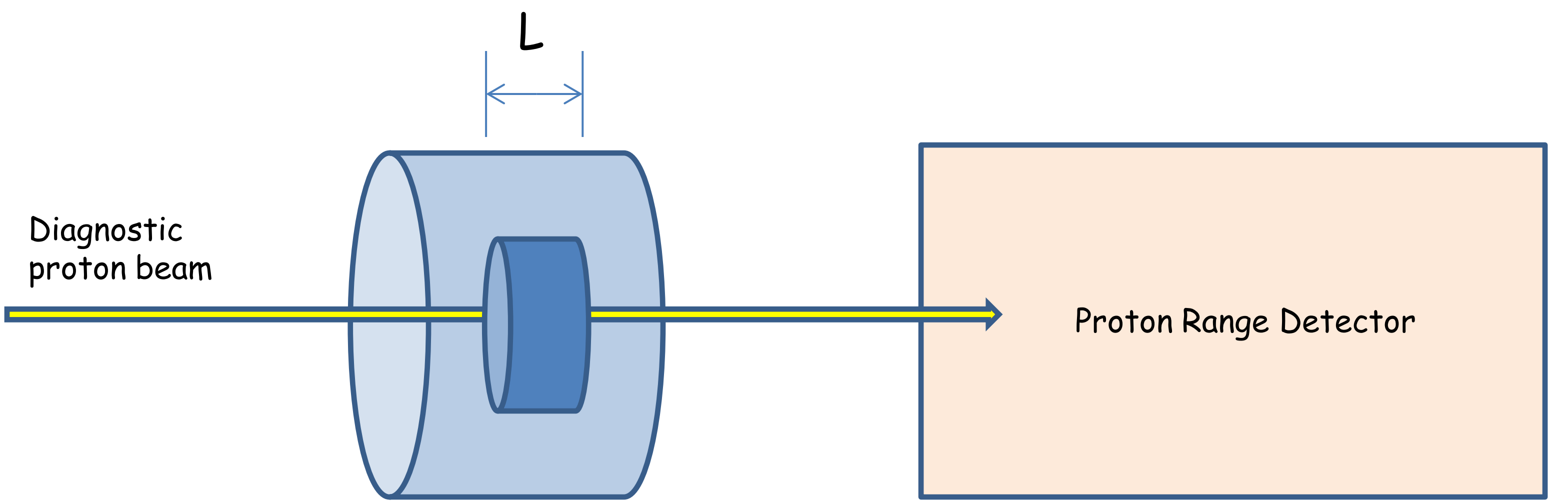
Uncertainty in Range Determination

Actual uncertainty depends on number of protons sampled per image element (pixel)

$$\sigma_R/\sqrt{N},$$

Uncertainty in density of an object with length L within a target of near-water density

$$\sigma_\rho = \frac{\sigma_R}{L\sqrt{N}}$$



MRPC-PET Simulation Studies with GATE

Can be found in my thesis entitled: “Detectors for Quality Assurance in Hadrontherapy” (among other things!)

Simulation Study Goals

Simulating EVERYTHING would take too long and my work is predominantly hardware related (and there was a lot of it!)

→ Limit the simulation study to the sensitivity of PET scanners based on the technologies developed in the laboratory

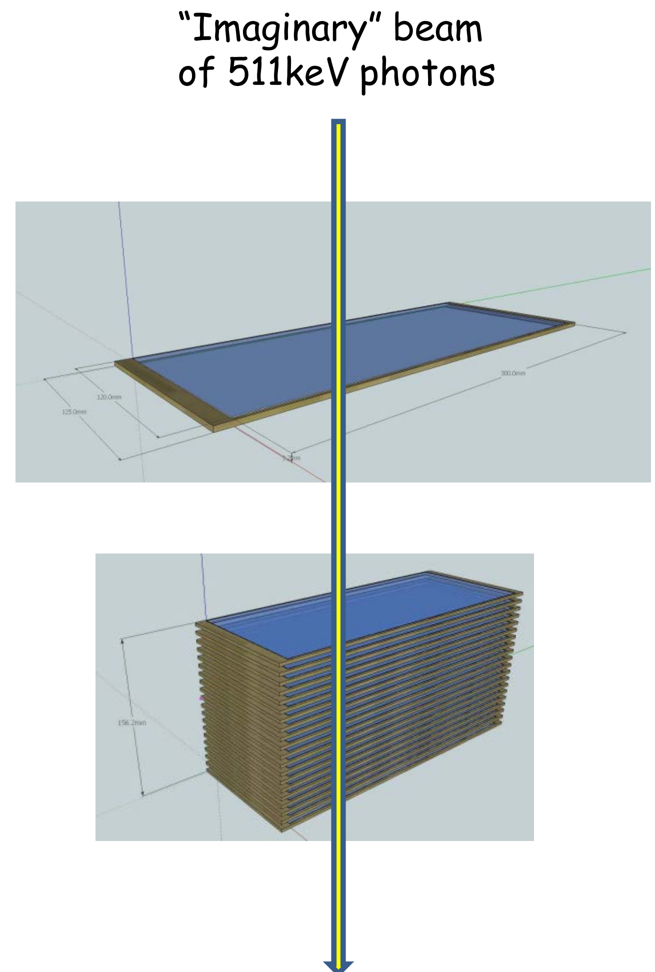
Reasons this is a good idea:

- Main drawback of RPCs to PET is their extremely low sensitivity to 511 keV gammas (makes proving merit of MRPC-PET very hard in real life!)
- Research suggests that even an excellent TOF resolution cannot compensate for a poor sensitivity
- Requirement for many hundreds of modules may be practically unrealistic
- Since the other aspects of MRPC performance should be equal (if not better) than crystal technologies, then optimizing sensitivity is the logical first step
- Phase space (number of parameters) is already HUGE!

“Basic” simulation study overview

Parameters to investigate:

- Glass thickness
- Material of absorber
- Energy dependence
- Number of module per stack
- e- cuts
- Gas thickness

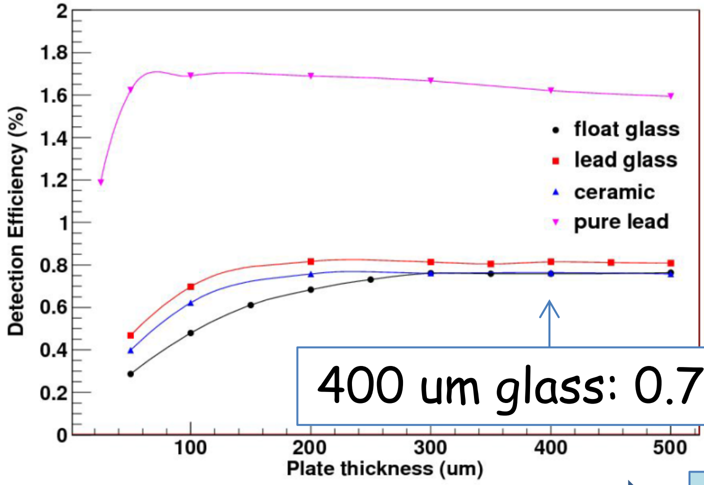


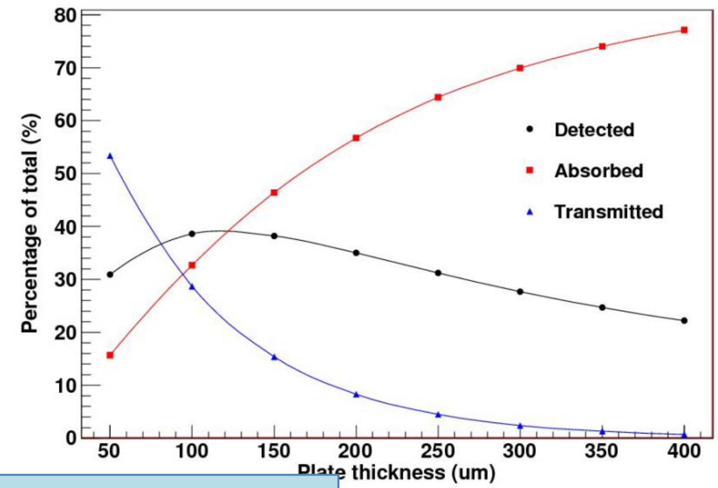
Simplifications:

- Avalanche mechanism ignored
- Only active detector elements modelled
  (no mechanical supports)

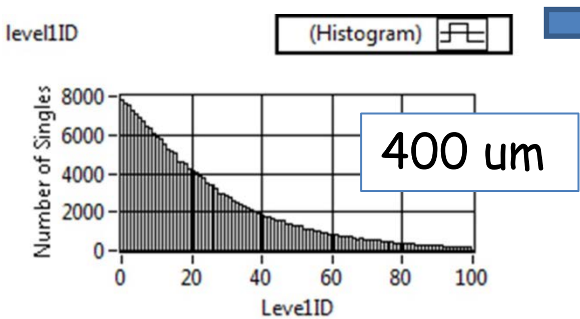
Any energy deposition (>100ev) in the gas volume is deemed a ‘hit’

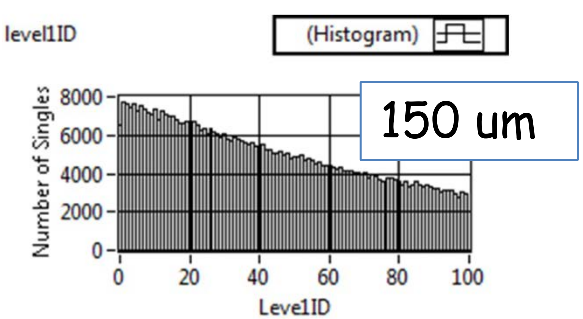
“Basic” simulation results

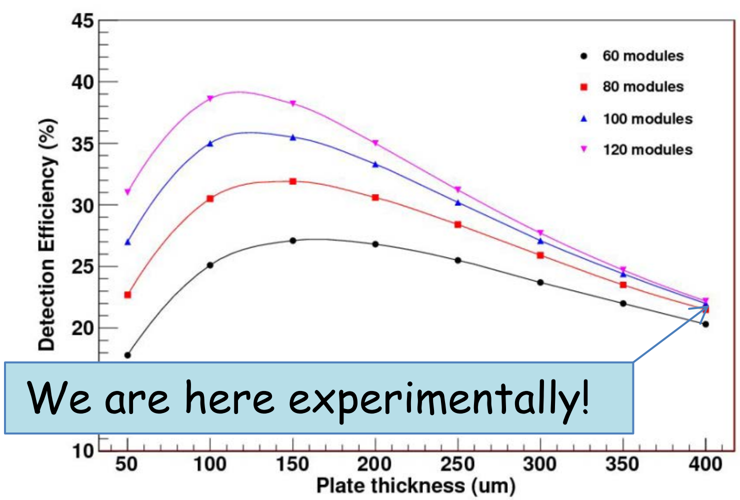




Experimental: 0.66%

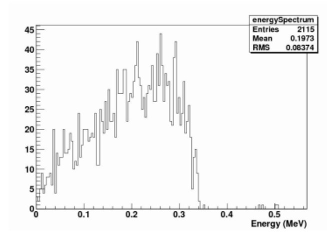




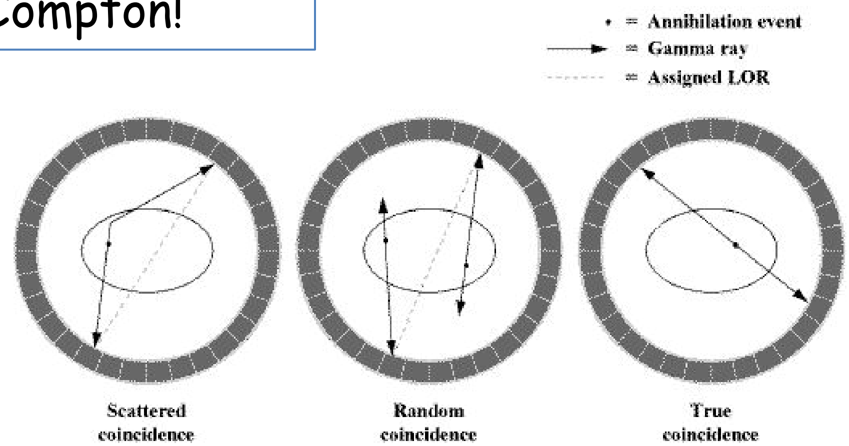


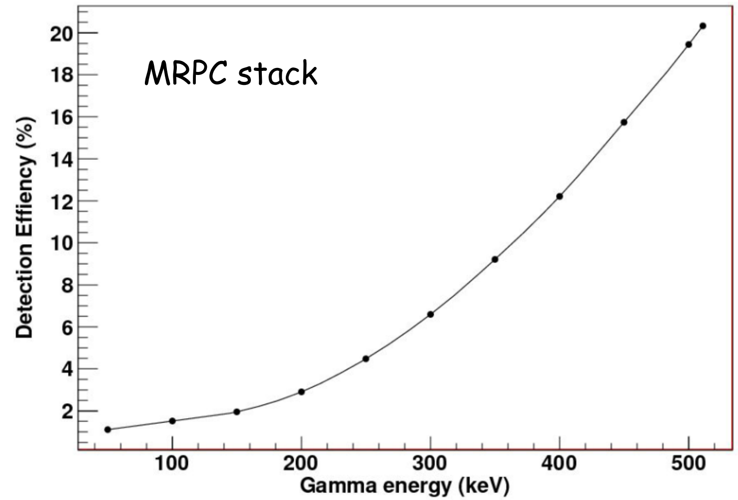
"Basic" simulation results

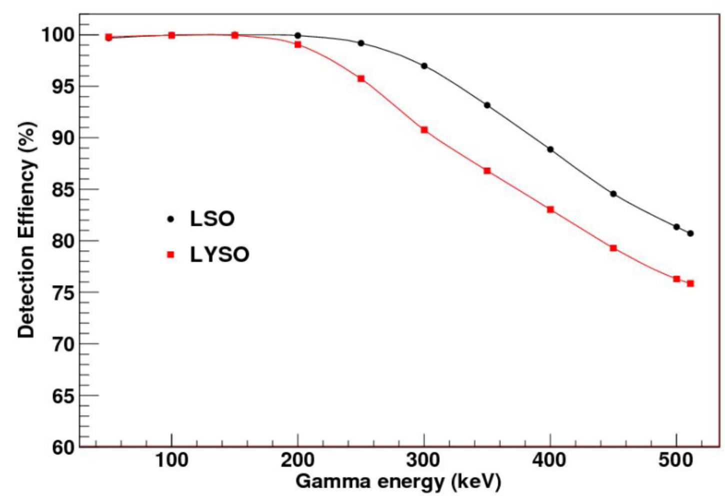
What about the lack of energy resolution in RPCs?



Interaction is Compton!







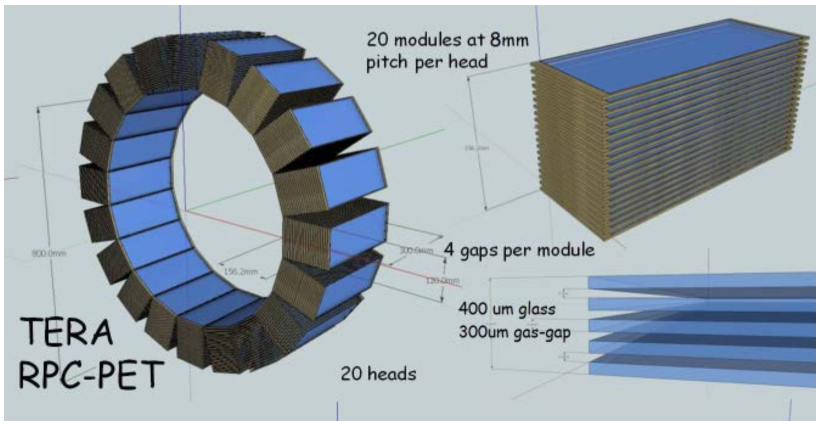
RPCs have an intrinsic rejection of lower energy photons.

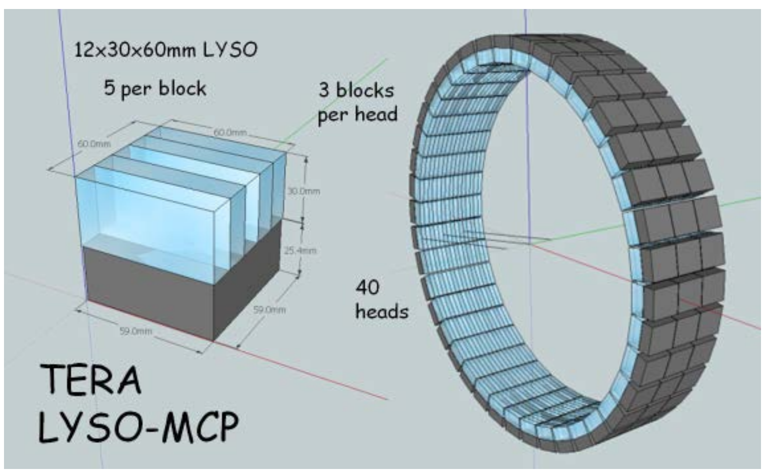
I have recorded the scatter fraction throughout my studies.

Full-ring simulation study overview

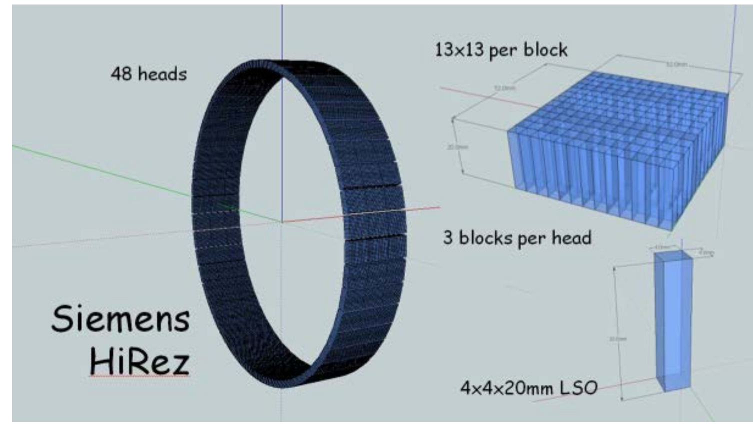
Now that we have some insight as to basic MRPC optimization we can study full-ring scanner designs

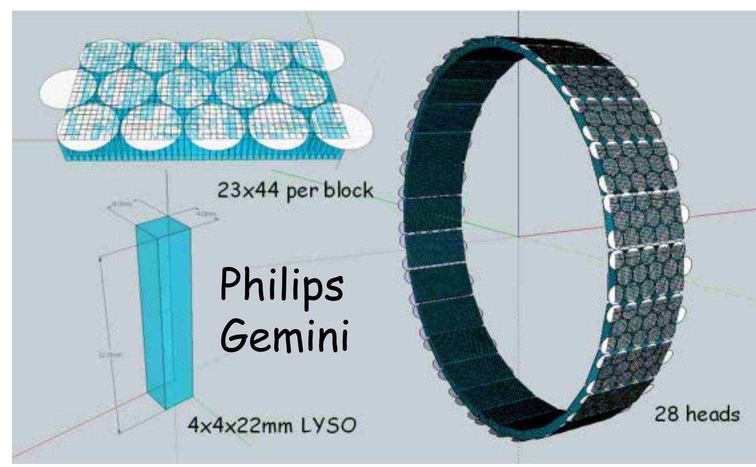
→ Relevant to "in-room" or "off-line" PET and nuclear medicine





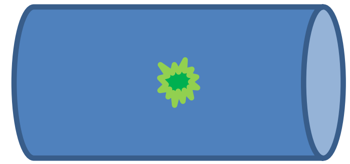
Benchmark



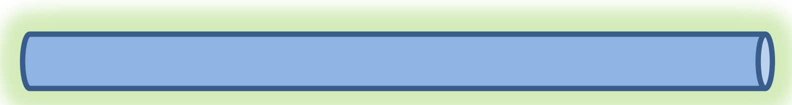


Full-ring simulations - Sources

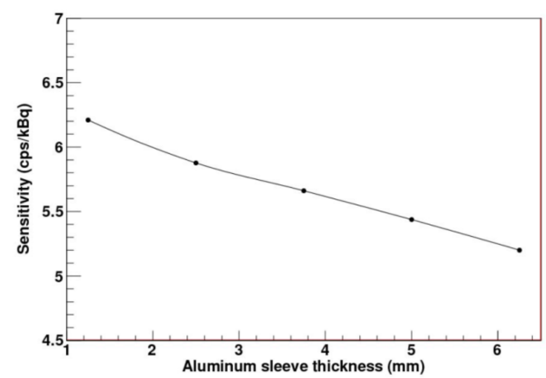
Point source
Back-to-back 511keV point source
1MBq
Spherical 1mm radius



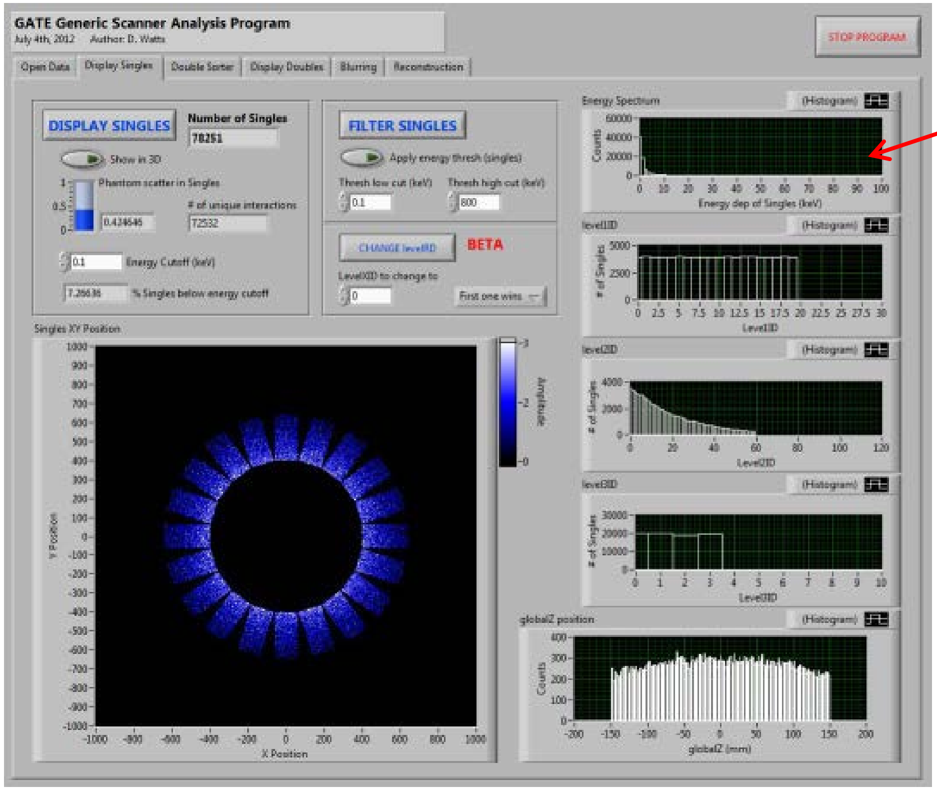
Point source w Phantom
Back-to-back point source
1MBq
20cm diameter,
30cm length water phantom



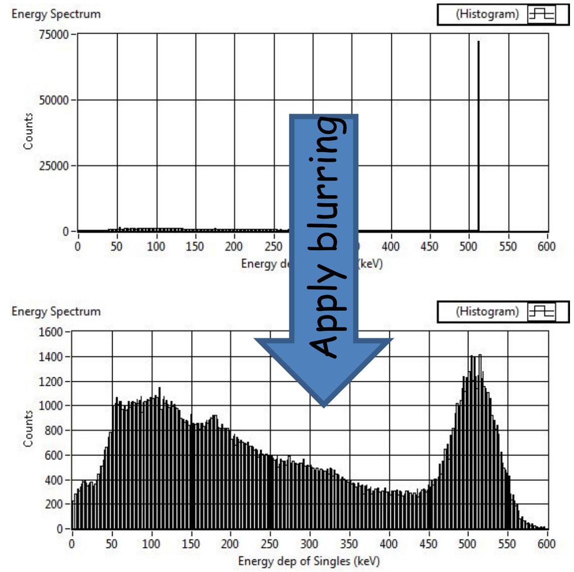
NEMA 2001
1.95mm radius cylinder
70cm long filled with water
Fluor18, 6586.2 s half-life
1MBq total activity
+ 1.25mm, 2.5mm, 3.75mm, 5.0mm, 6.25mm radius aluminium



Full-ring simulation – Analysis parameters



Custom built Labview software for analysis



Scanner	Energy Blur.	Energy win.	Time win.	FOV Filter
	(% FWHM)	(keV)	(ns)	(#Sect/minSectDiff)
MRPC-PET	-	> 0.100	1.0	20 / 5
LYSO-MCP	11.5	440 - 665	3.8	40 / 10
HiRez	15.0	425 - 650	3.8	48 / 12
Gemini	11.5	440 - 665	3.8	28 / 7
BASTEI	15.0	425 - 650	3.8	2 / 1

Full-ring simulation – Results

LYSO-MCP

	Sensitivity (cps/kBq)	Scatter Fraction (%)
Point source	82.4	0
Point source /w phantom	14.69	20.0
NEMA source	10.37	0.72

modules → 60-400-4-30 ← Module spacing

Glass thickness (um) ↗ ↖ Axial length (cm)

Needs to be MUCH better!

MRPC-PET

60-400-4-30	Sensitivity (cps/kBq)	Scatter Fraction (%)
Point source	9.01	0
Point source /w phantom	2.11	42.4
NEMA source	2.03	-

Siemens HiRez

	Sensitivity (cps/kBq)	Scatter Fraction (%)
Point source	69.8	0
Point source /w phantom	12.7	20.2
NEMA source	7.69	-

Philips Gemini

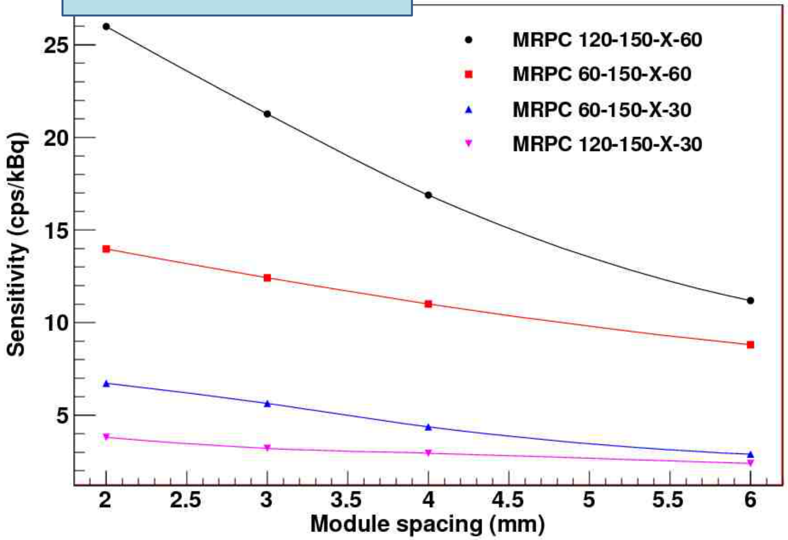
	Sensitivity (cps/kBq)	Scatter Fraction (%)
Point	52.1	0
Point /w phantom	9.33	17.9
NEMA source	6.57	-

What can we do???

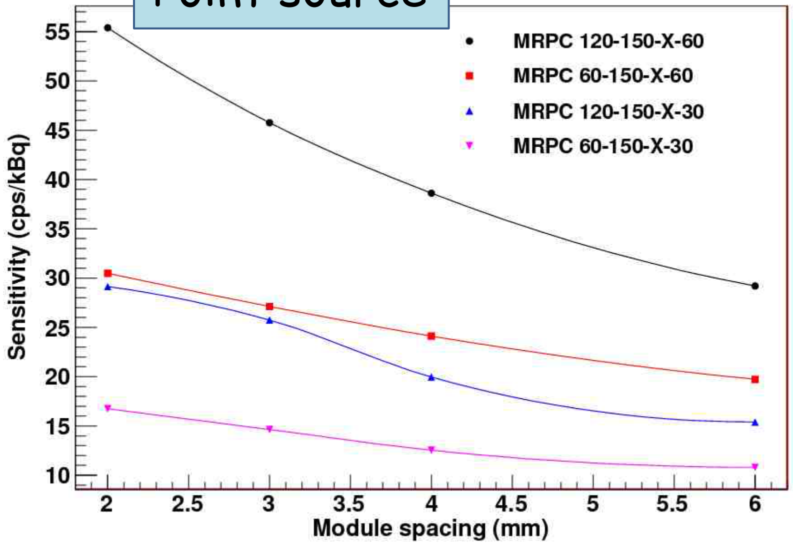
- Reduce glass thickness
- Add modules
- Increase axial length

Full-ring MRPC-PET Sensitivity Optimization

NEMA source



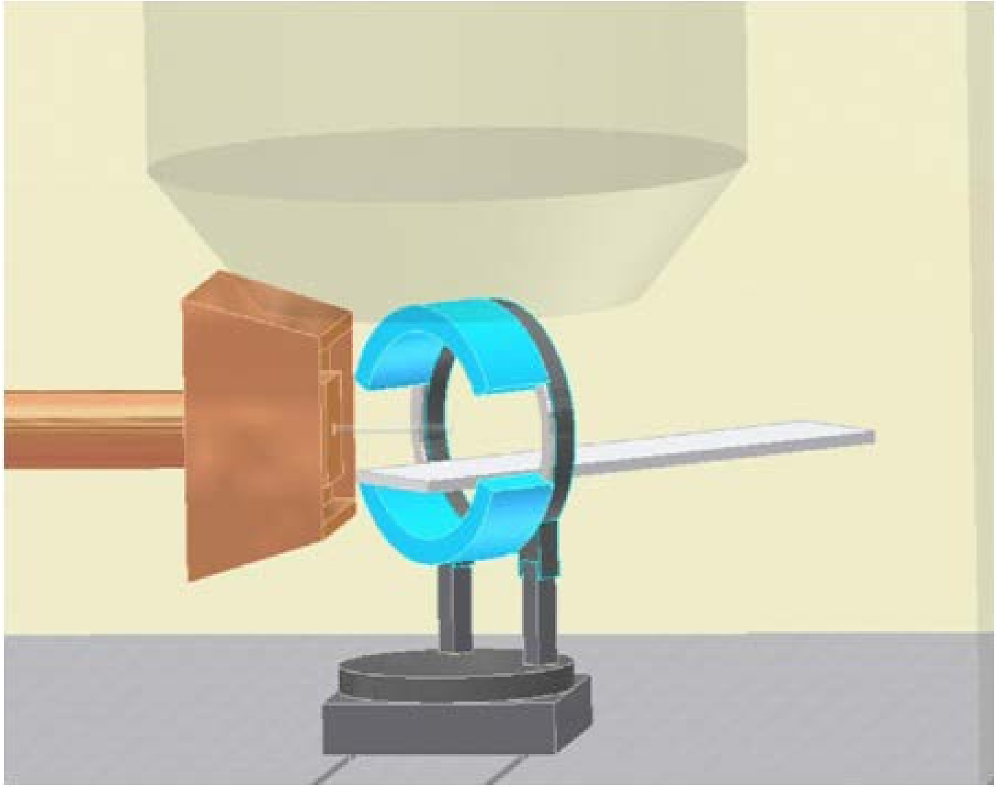
Point source



Scanner type	Sensitivity			Scatter Fr.
	NEMA (cps/kBq)	Point (cps/kBq)	Point w phan. (cps/kBq)	Water phan. (%)
MRPC 60-400-4-30	2.03	9.01	2.11	42.4
MRPC 120-150-4-30	4.37	20.0	4.44	37.8
MRPC 60-150-4-60	11.0	24.1	6.6	52.8
MRPC 120-150-4-60	18.7	38.6	10.4	52.7
LYSO-MCP	10.4	82.4	14.7	20.0
Gemini	6.6	52.1	9.3	17.9
HiRez	7.7	69.8	12.7	20.2

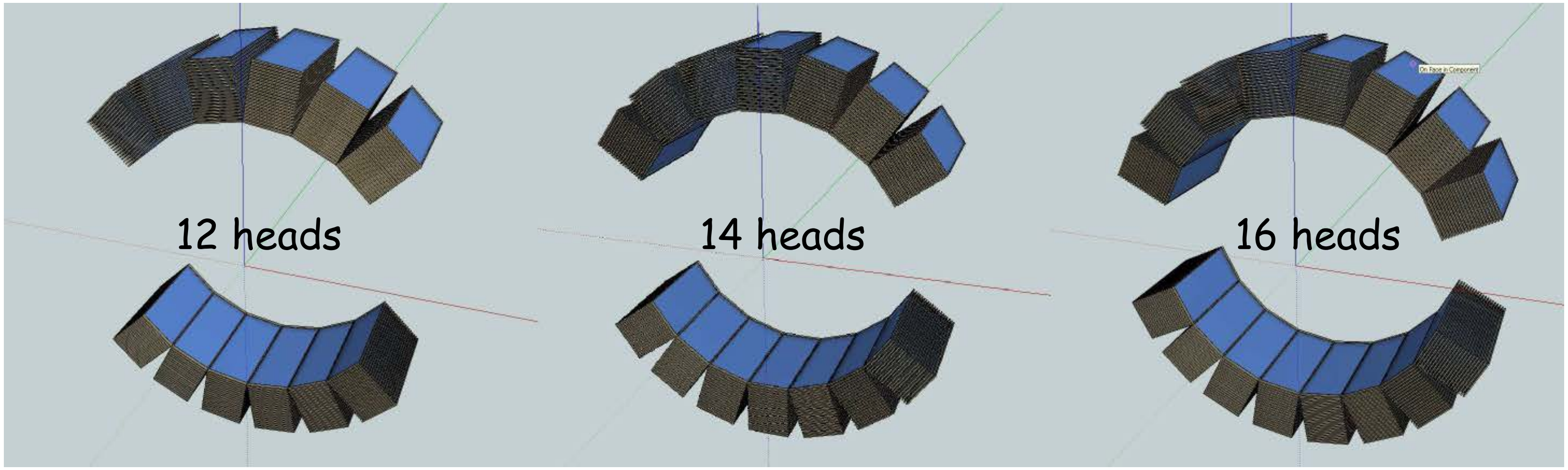
Partial-ring studies

"In-beam" PET for hadrontherapy requires the use of partial ring scanners



Cannot use commercial scanners!

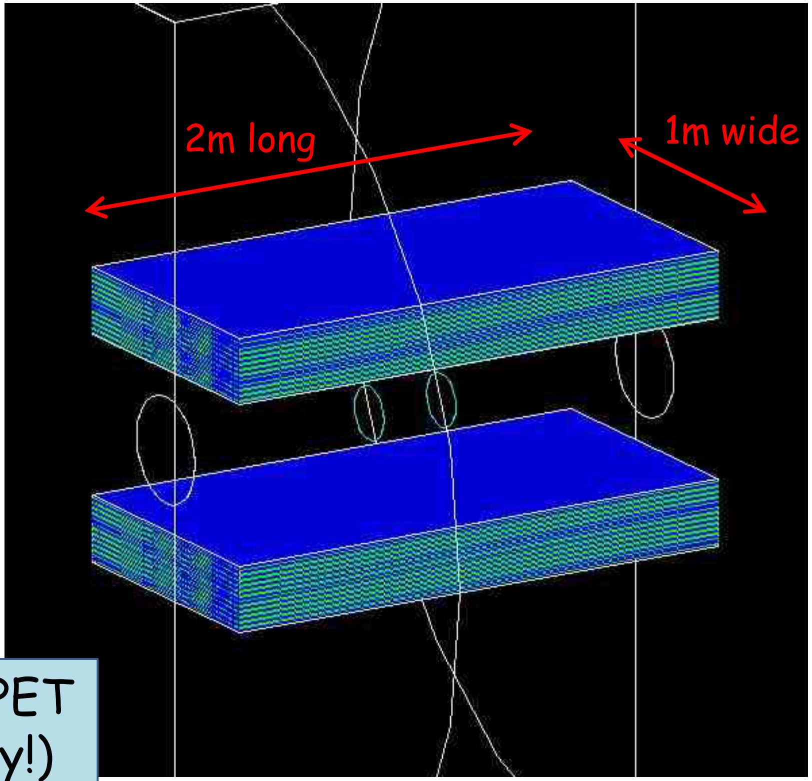
MRPC-PET Partial-ring studies



Since partial-ring geometries apply only to in-beam PET, I simulated only the point sources (NEMA is not relevant since you 'know' where the dose goes!)

Source	MRPC-PET 120-150-4-60	Sensitivity (cps/kBq)	% of full-ring (%)
Point source	20 head	38.6	100
	12 head	23.3	60.3
	14 head	27.1	70.1
	16 head	30.9	80.1
Point w phan.	20 head	10.4	100
	12 head	5.67	54.5
	14 head	6.53	62.7
	16 head	7.81	75.0

MRPC-PET dual-head planar geometry



Relevant to in-beam PET (NEMA does not apply!)

Dual-head planar MRPC $2x1\ m^2$ 60 modules	Sensitivity (cps/kBq)	Scatter Fraction (%)
Point source	43.1	0
Point source /w phantom	12.1	54.5
NEMA source	42.8	-

Full-body PET (≈ 7x better than Gemini!)

≈3x worse than Gemini (effect on image quality remains to be seen in reconstruction)