Particle Detector Applications in Medicine

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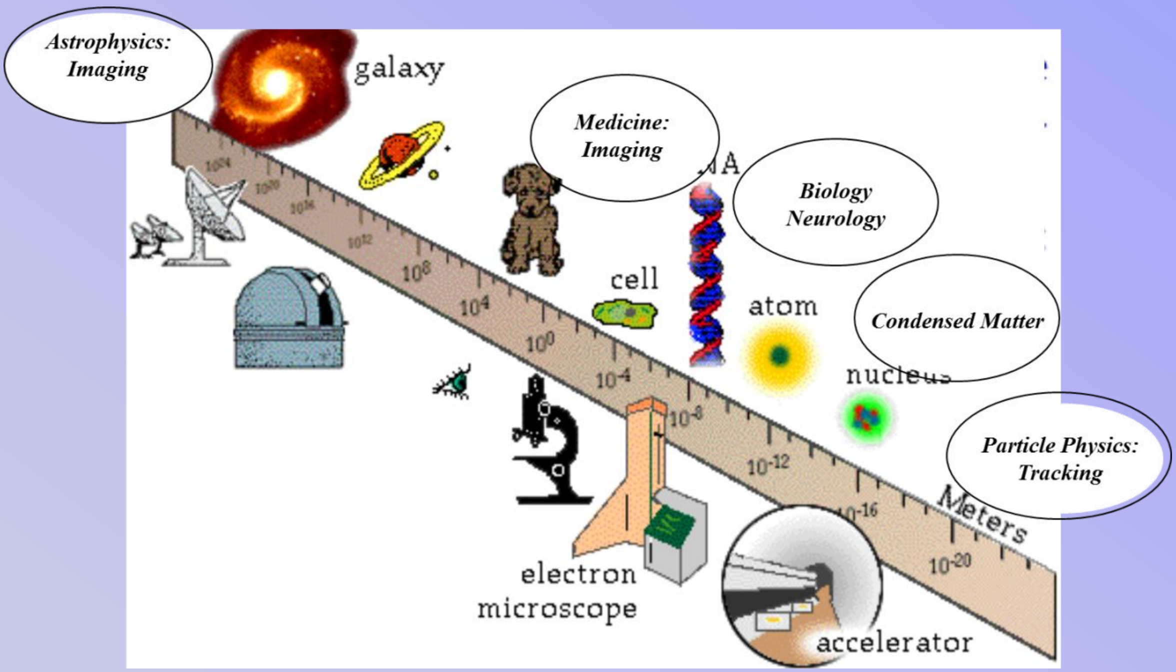
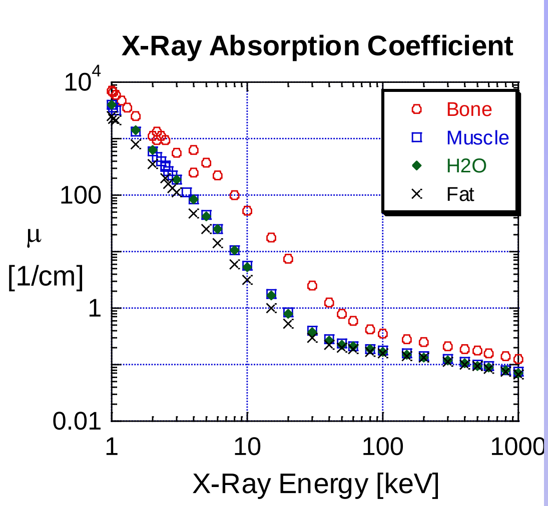


Medical Applications

Low-energy instrumentation,
small systems (until commercialization..) profiting from HEP and (even more so) from Astrophysics heritage
Scintillators & Semiconductors (for WCC heritage: Peskov, Nygren talks)

- Dosimetry, EH&S
- Imaging: Radiography, Tomography
  - Photons
    - X-ray CT
    - SPECT
    - PET & TOF-PET & PET/MRI & PET/CT
  - Hadrons (MedAustron)
    - Intercation Vertex Imaging IVI
    - Proton CT

Absorption of Photons $N(x) = N_o e^{-\mu x}$



Photons of Medical Interest, Energies & Resolution

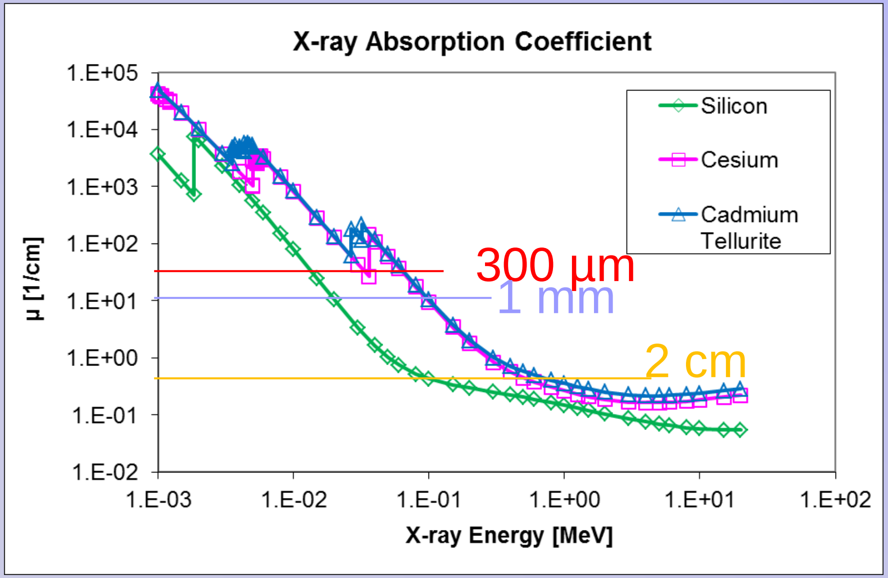
- μ-waves: MRI (10's μm)
- 10-100keV: X-ray radiography and CT (10's μm)
- 500 keV: PET and SPECT (mm)

No directional information with exception of Compton

High bone contrast 1-100 keV

Advantage of high-Z detectors:

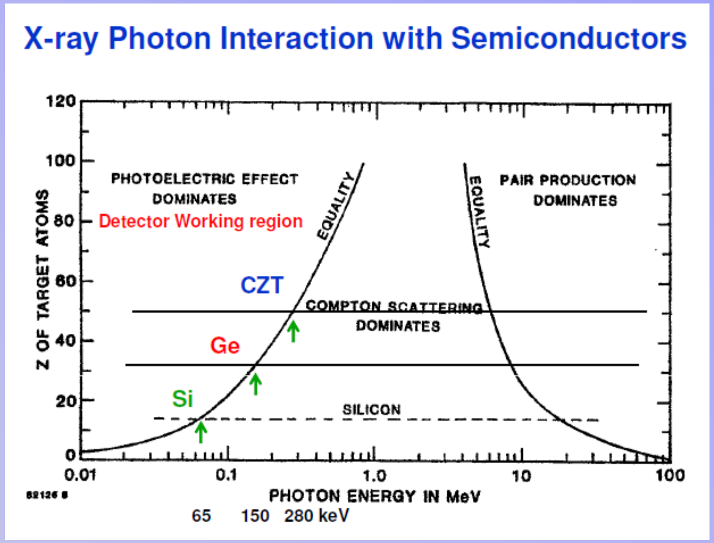
Larger energy reach (depends on thickness)



Shift of Compton region to higher E

reduced range of Compton electrons

reduced range of positron in PET



Clinical Dosimetry

Silicon:

Routinely clinical use for Q/A in X-ray therapy
High sensitivity, very reliable, well established, and low cost technology
Zero bias operation:: no leakage current & in-vivo applications

New developments:
Pre-irradiation (Sensitivity decrease with total dose),
Pt doping (Total dose and dose rate dependence)
P-type, low-resistivity and epitaxial bulk (Dose rate dependence)

Diamond

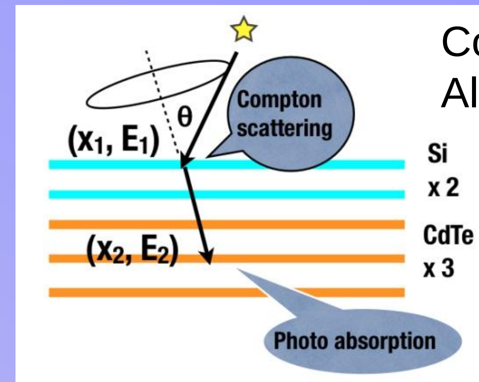
Tissue equivalent
small size and good dosimetric properties, small dose rate dependence

New developments:
Effort to replace expensive natural diamond with CVD grown devices

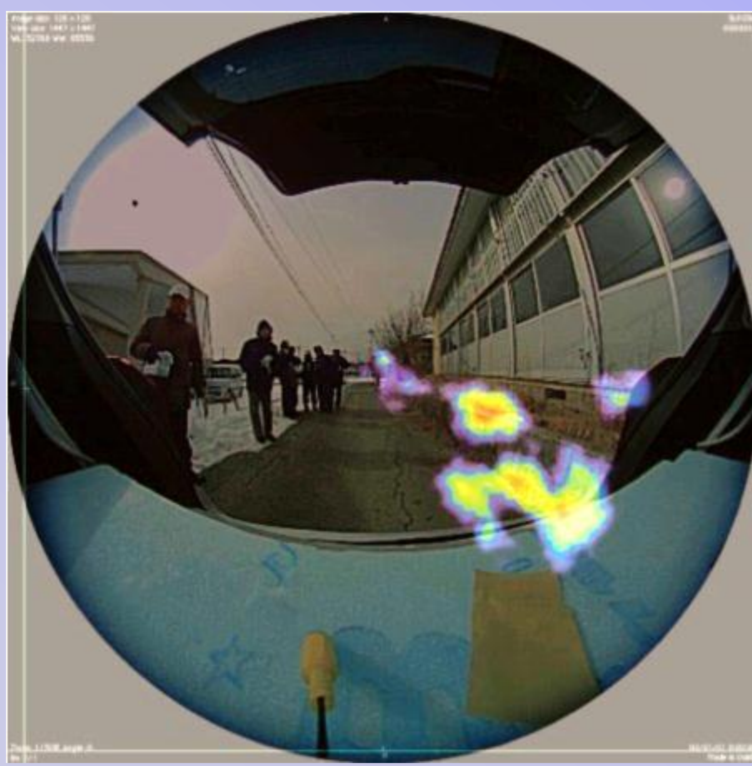
Environmental Health & Safety

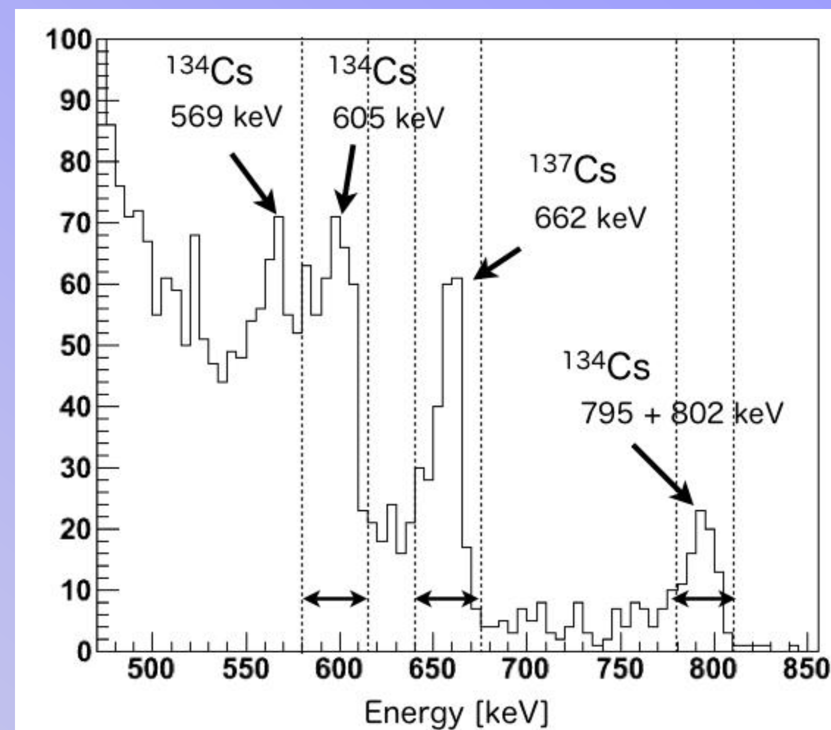
Remote Sensing: Emergency Dosimetry
Compton Camera: Tracking + Spectroscopy
(would have been useful at Fukushima)

@ VCI:
<u>Handy</u> Compton camera (1 kg!)
J. Takaoka, 13 Feb 2013 9:25 AM



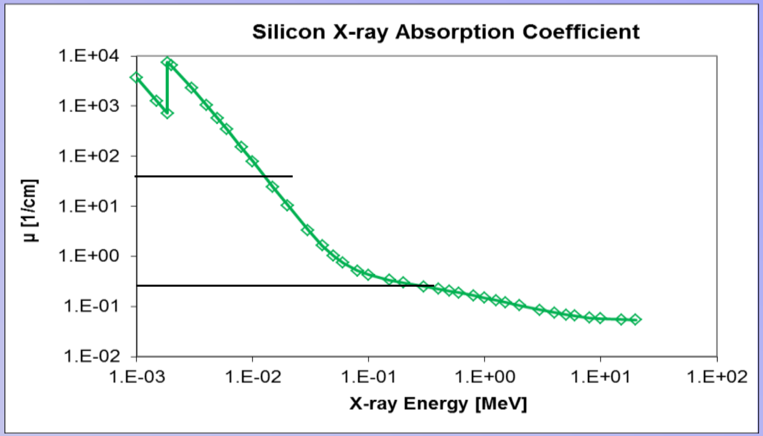
Compton Camera:
Also used in SPECT





T. Takahashi et al., R05-1 2012 IEEE NSS-MIC

Silicon X-ray Detectors?



X-ray Radiography with Silicon Sensors:

300 μm:	~10 keV
1 mm:	~30 keV
3 cm:	~500 keV

N.B. typical Si wafer thickness 300 μm

"Pixels" on "edge-on" strip sensor:
Depth: ~ strip length (cm's)
Area: pitch * wafer thickness

IEEE TRANS. NUCL. SCI, VOL. 45, NO. 6, (1998) 3059
High Resolution X-ray Imaging Using a Silicon Strip Detector
E. Beuville**, R. Cahn**, B. Cederstrom, M. Danielsson , A. Hall, B. Hasegawa, L. Luo, M . Lundqvist, **D. Nygren**, E. Oltman, J. Walton,

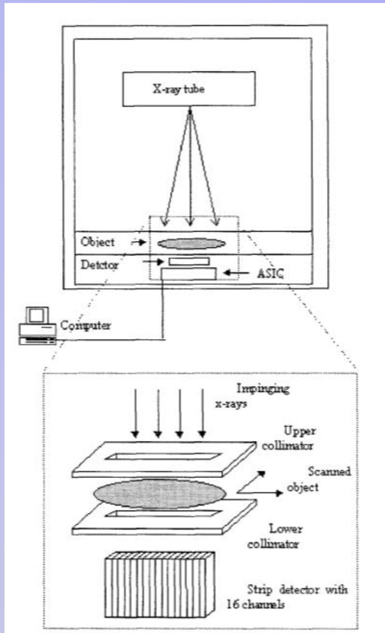
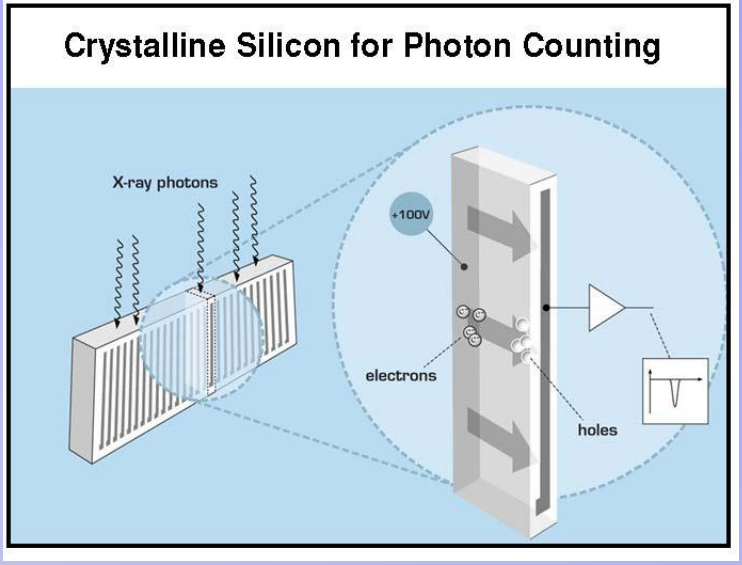


Figure 2
Outline of our system for X-ray imaging

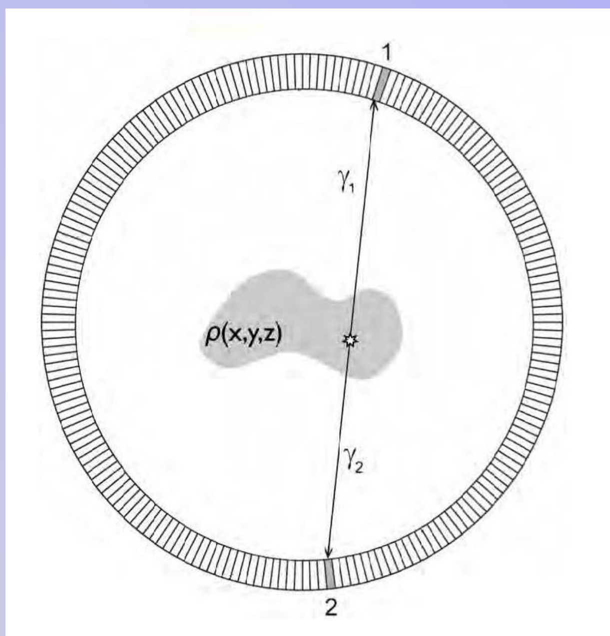
Commercialized
by Sectra Mamea AB (Philips)



Positron Emission Tomography PET

Study accumulation of radioactive tracers in specific organs.
The tracer has radioactive positron decay, and the positron annihilates within a short Distance with emission of 511 keV γ pair, which are observed in coincidence.

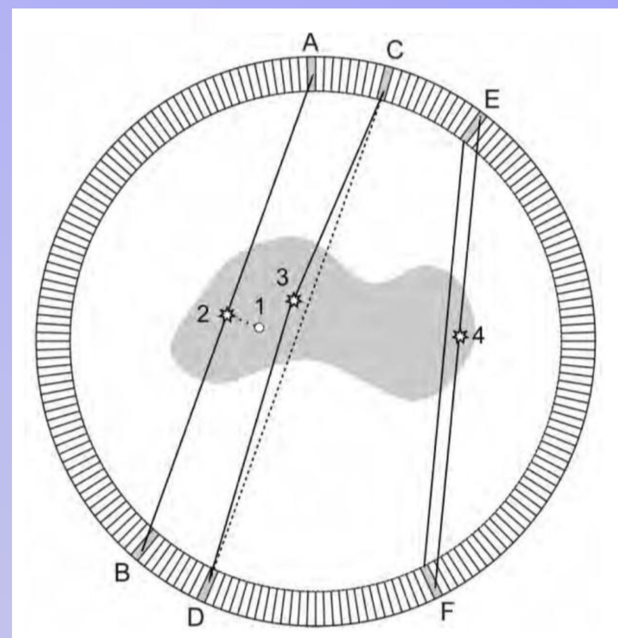
Perfect Picture:



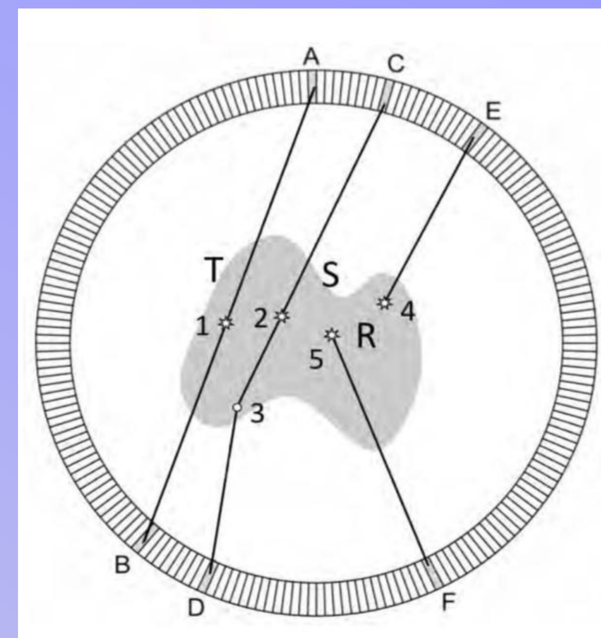
$$FWHM = 1.2\sqrt{\left(\frac{d}{2}\right)^2 + b^2 + (0.0022D)^2 + r^2 + p^2}$$

1.2	from analytical algorithm (FBP)
d/2	from the detector pitch
b	from the coding
0.0022D	from the 2 photon a-collinearity
r	from the positron range
p	from parallax

Resolution and S/N Effects:



Resolution of detector (pitch)
Positron range
A-collinearity
Parallax (depth)



T: true event
S: Compton Scatter
R: Random Coincidence

A. Del Guerra, RESMDD12

Improving Spatial Resolution in PET

Combination of a standard PET scanner with finely segmented silicon sensors to record the impact position of one or both photons from the annihilation pair.

The high-resolution Si detector is expected to capture a relatively small portion of emitted radiation (**2%**).

The standard PET image can be **locally** improved in areas where there is a substantial probability that at least one of the photon pair will interact in a high-resolution detector.

Si detectors 1mm thick, 1 mm x 1 mm pads
vs. cm size crystals.

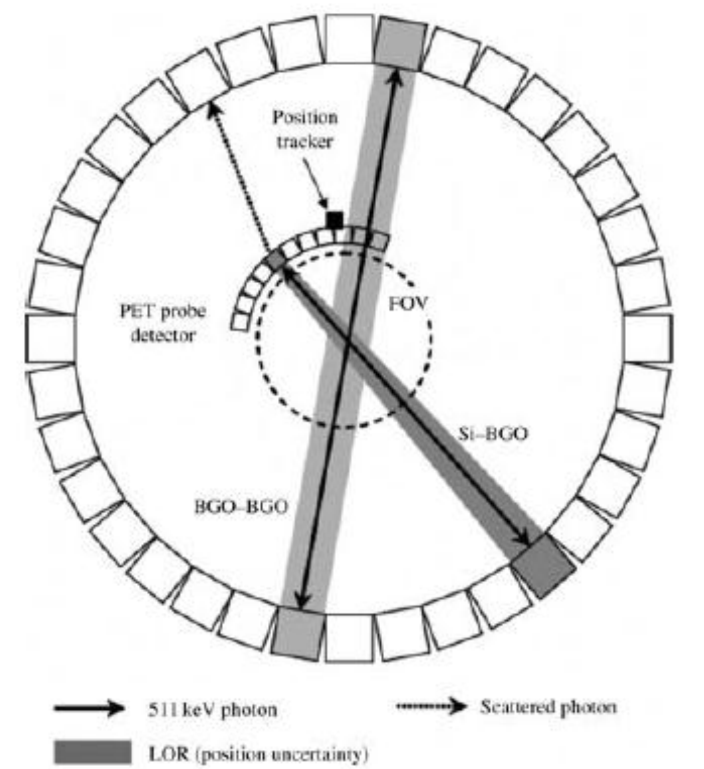
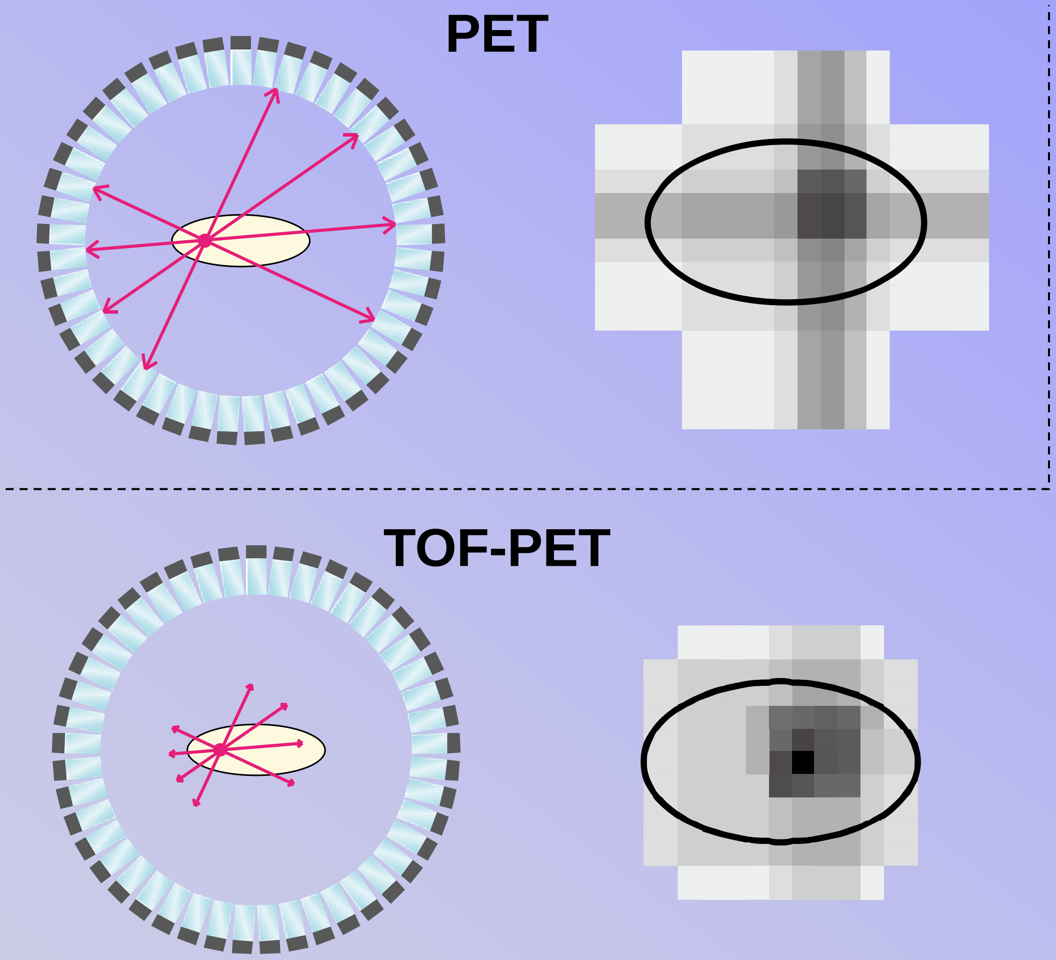
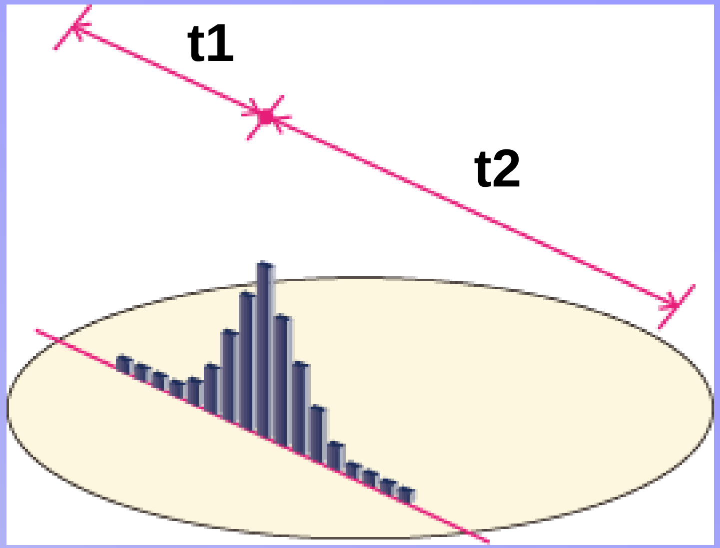


Figure 1. Schematic drawing illustrating the PET probe principle.

N. Studen 2012 IEEE NSS-MIC

Reduce Accidentals & Improve Image: TOF-PET





Localization uncertainty:
Δd = c x Δt /2
When Δt = 200 ps
➔ Δd = 3 cm

@ VCI
K. Yamamoto 2012 IEEE NSS-MIC

TOF – PET SNR Improvement

The improved source localization due to timing

$$\sigma_x = c \cdot \sigma_t / 2$$

leads to an improvement in signal-to-noise

$$SNR_{TOF} = \sqrt{\frac{D}{\sigma_x}} \cdot SNR_{Non-TOF}$$

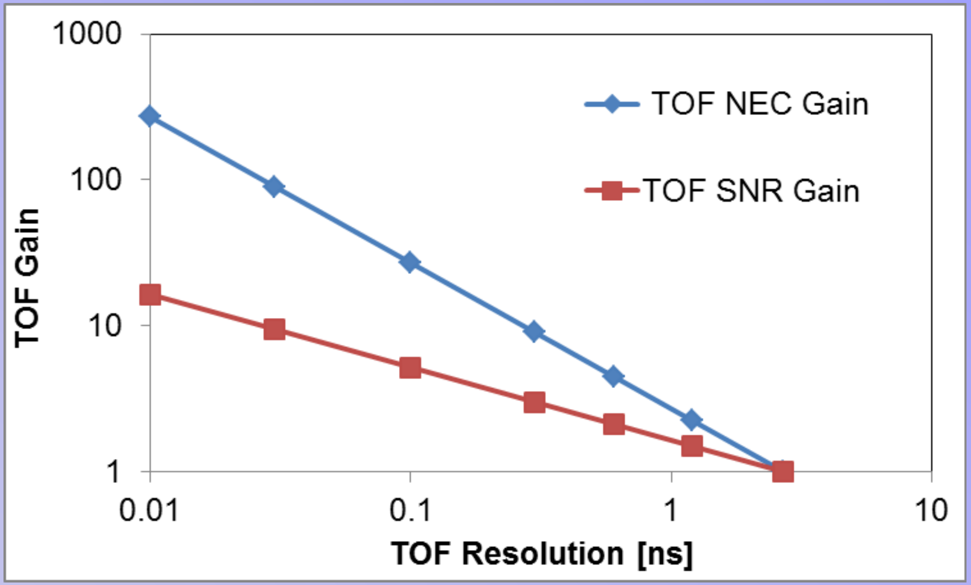
and an increase in Noise Equivalent Count NEC

$$NEC \cdot Gain = \frac{D}{\sigma_x}$$

1. For a given acquisition time and dose to the patient, TOF can provide better image quality and improved lesion detection.

   OR

2. with TOF the scan time and dose can be reduced while keeping the same image quality (better clinical workflow and added comfort for the patient).

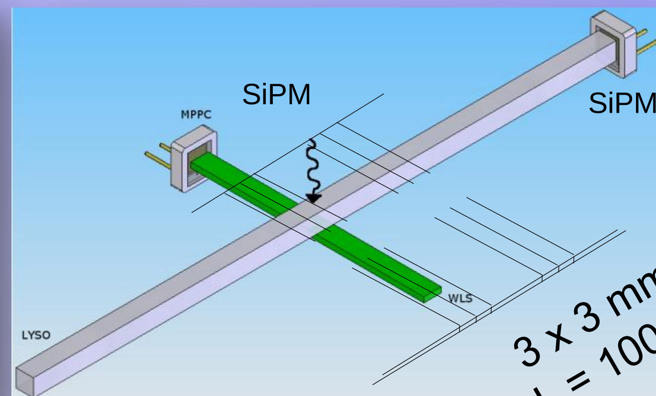


M. Conti, Eur. J. Nucl. Med. Mol Imaging (2011) 38:1147-1157

AX-PET

- Long axially oriented crystals + orthogonal WLS strips, individually read out by SiPMs
- High resolution **and** high sensitivity, **no** parallax error

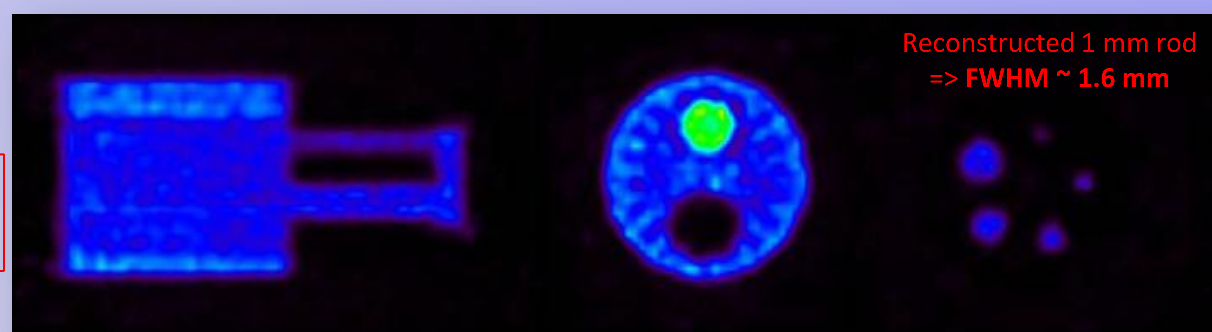
cern.ch/ax-pet



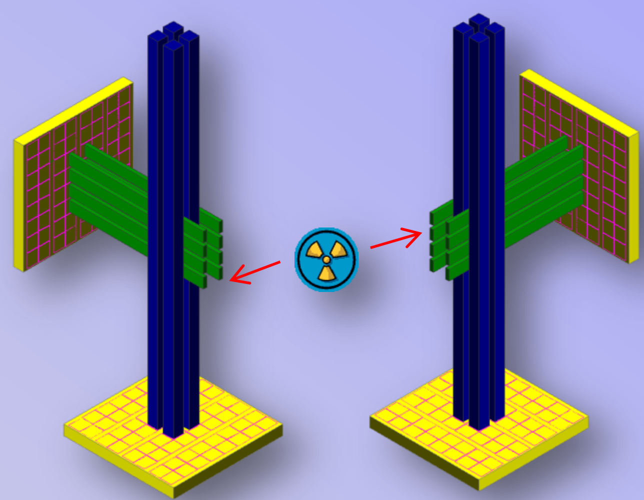
3 x 3 mm^2
L = 100 mm

- Fully operational **Demonstrator** with two detector modules (96 LYSO crystals, 312 WLS strips).
- Evaluated with **point sources, phantoms** and finally also by imaging **small animals**

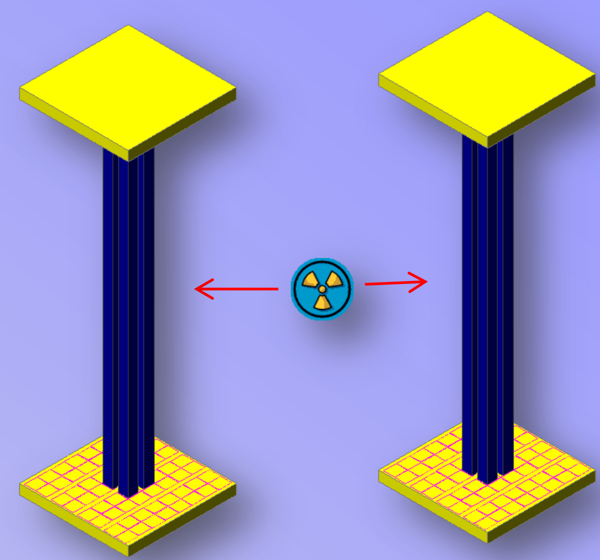
NEMA mouse phantom, imaged with F-18. (AAA Saint Genis, France).



TOF – PET with AX-PET



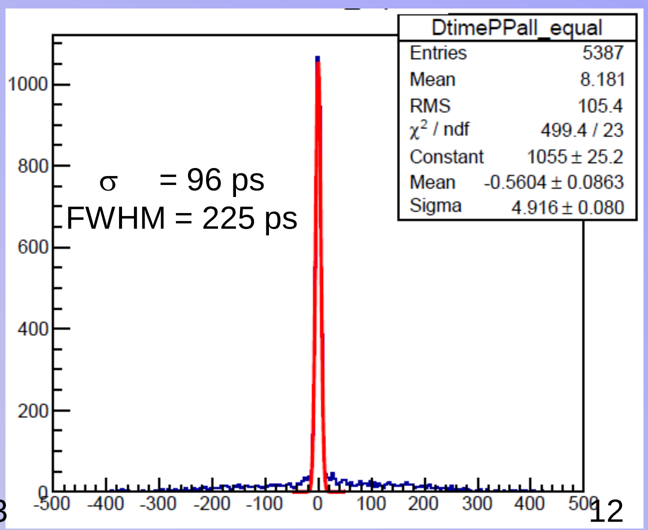
Single sided readout + WLS strips



Double sided readout

Mini AX-PET like set-ups with very fast Digital SiPM
→ AX-PET with TOF extension.

Excellent coincidence time resolution even with 100 mm long LYSO crystals, constant over full field-of-view.



@VCI
C. Joram, Friday 15 Feb 2013 4:20 PM

TOF-PET with Cherenkov Light

Cherenkov Light from electrons in the photon conversions
High Z: high electron speed

	ρ (g/cm^3)	n	Cherenkov threshold (v/c_0)	e^- Cherenkov threshold (keV)	Cutoff wavelength (nm)	Radiation length (cm)
PbF_2	7.77	1.82	0.55	101	250	0.93
PWO	8.28	2.2	0.45	63	320	0.89

Hamamatsu MCP-PMT (prototypes for Belle II TOP): intrinsic resolution ~ 20 ps

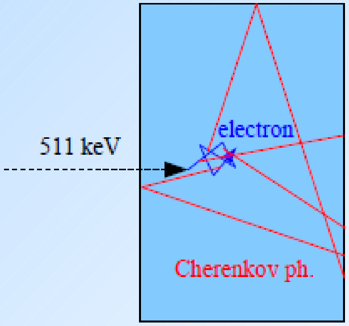
The time resolution obtained with such a system was 116 ps FWHM, with the single detector efficiency of 4.3%.

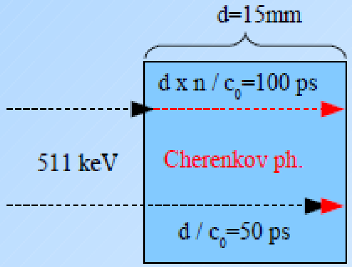
@VCI
S. Korpar Thu 14 Feb 4:30 PM

Estimates of expected number of Cherenkov photons produced and timing spread assuming n=2, electron path length 100 μm, Cherenkov photon energy interval 3 eV, 15 mm thick crystal.

$$N \approx \frac{370}{eV\,cm} \cdot l \cdot \Delta E \cdot \sin^2 \vartheta_C$$

$$N \approx 370 \times 0.01 \times 2 \times 0.75 \approx 8$$





Even for Cherenkov photons going strait to the photodetector the time spread of 50 ps results from depth of interaction.

S. Korpar, TIPP2011

Progress in Photon Detectors

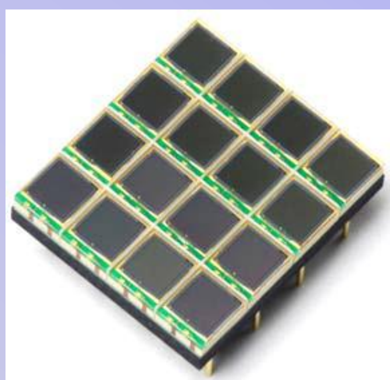
SiPM (Silicon PM) **or MPPC** (Multi-Pixel Photon Counter)

Solid State Devices good match for Photon Detection

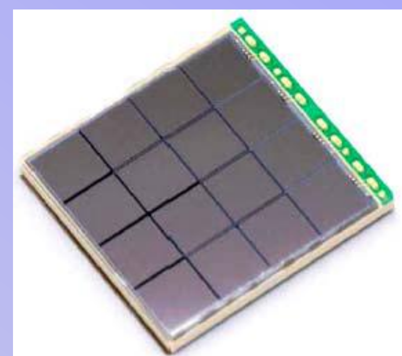
Feature Size, Speed, Power, Low Bias Voltages, Ruggedness, Magnetic Field Insensitivity

Integration: (HPK)

4x4ch discrete array



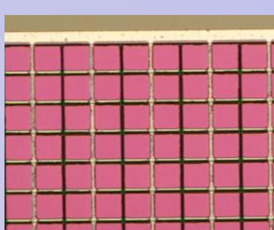
3x3 mm2 monolithic array



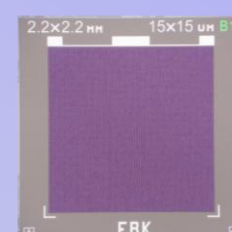
@ VCI:
MPPC (HPK)
K. Yamamoto
H. Sato

Red-Green-Blue High Density SiPM (SRS)

4x4mm2
cell size: 30x30um2
cells: ~17000
Fill factor = 74%
High Efficiency



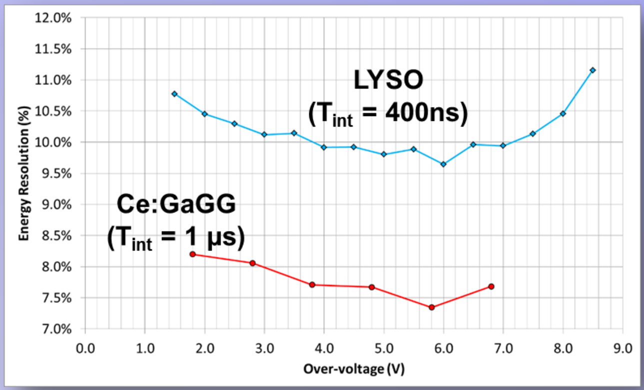
2.2x2.2mm2
cell size: 15x15um2
cells: 21316
Fill factor = 48%
High Dynamic range

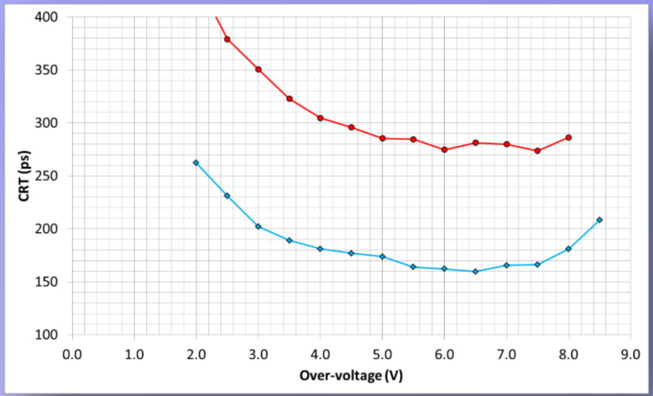


@ VCI:
SiPM (SRS)
M. Boscardin
C. Piemonte

Progress in SiPM: Overvoltage

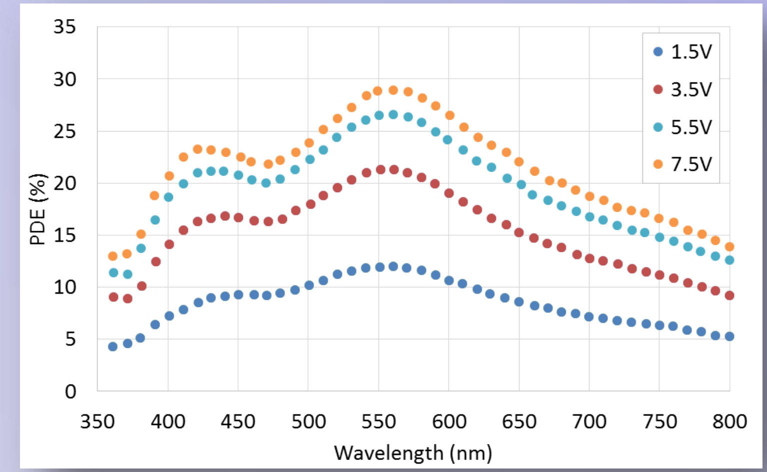
Resolution in energy and coincidence timing (depence on crystal !)





4x4mm2

:Photon Detection efficiency



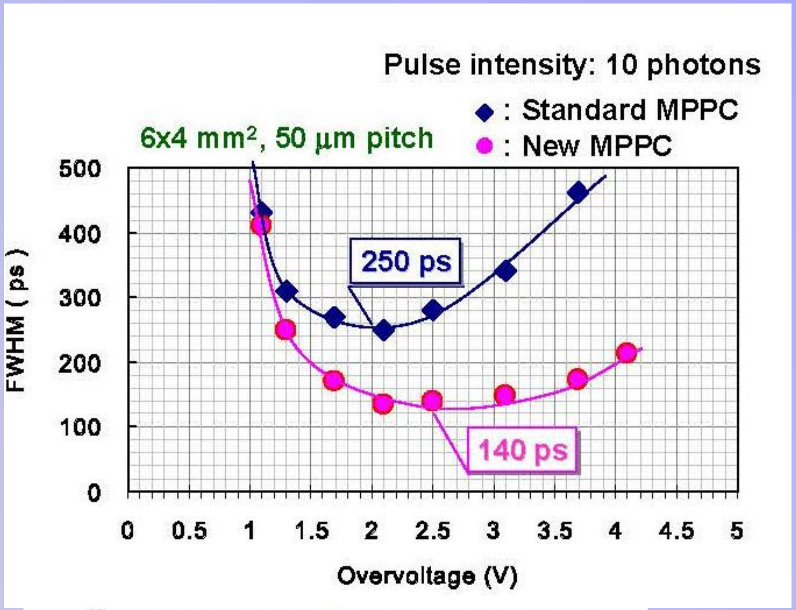
$2.2 \times 2.2 mm^2$

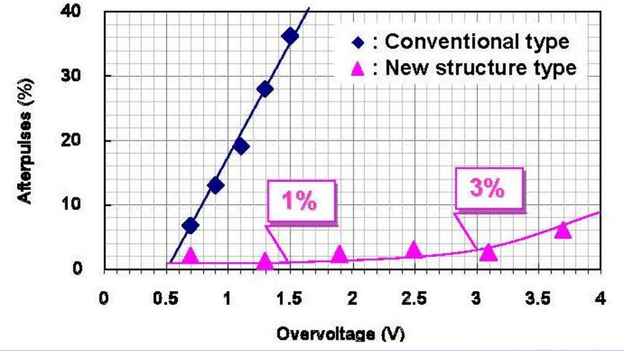
@ VCI:
SiPM (SRS, FBK)
M. Boscardin
C. Piemonte

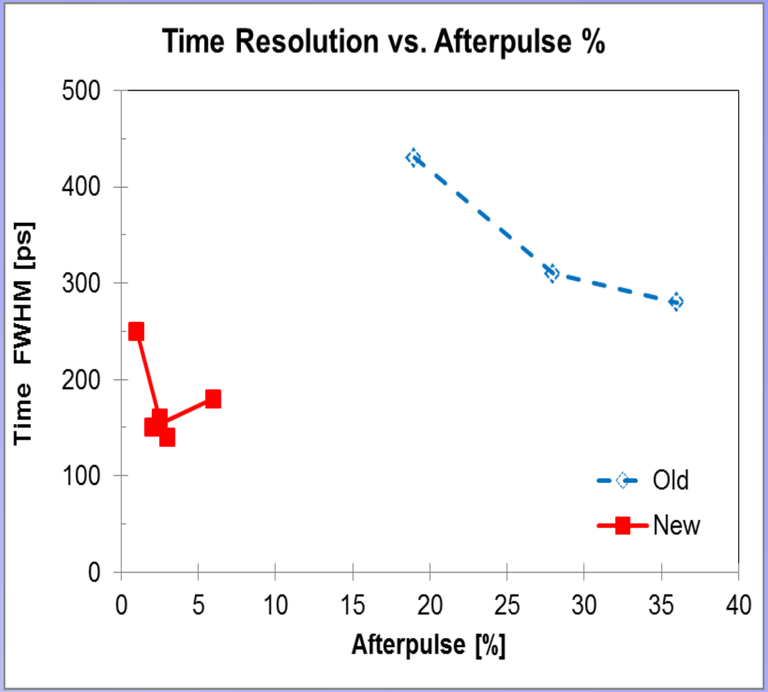
Is there a free lunch?
No:
Need to control
the noise rate and the after-pulsing

Progress in MPPC: Overvoltage

- Expand acceptable overvoltage range
- Timing resolution improves from 250 ps to 140 ps



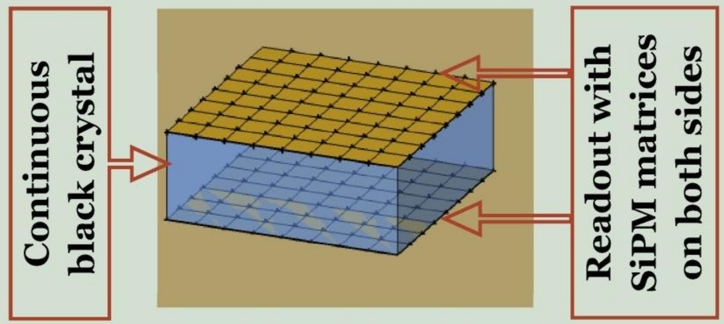




@VCI:
K. Yamamoto (HPK)

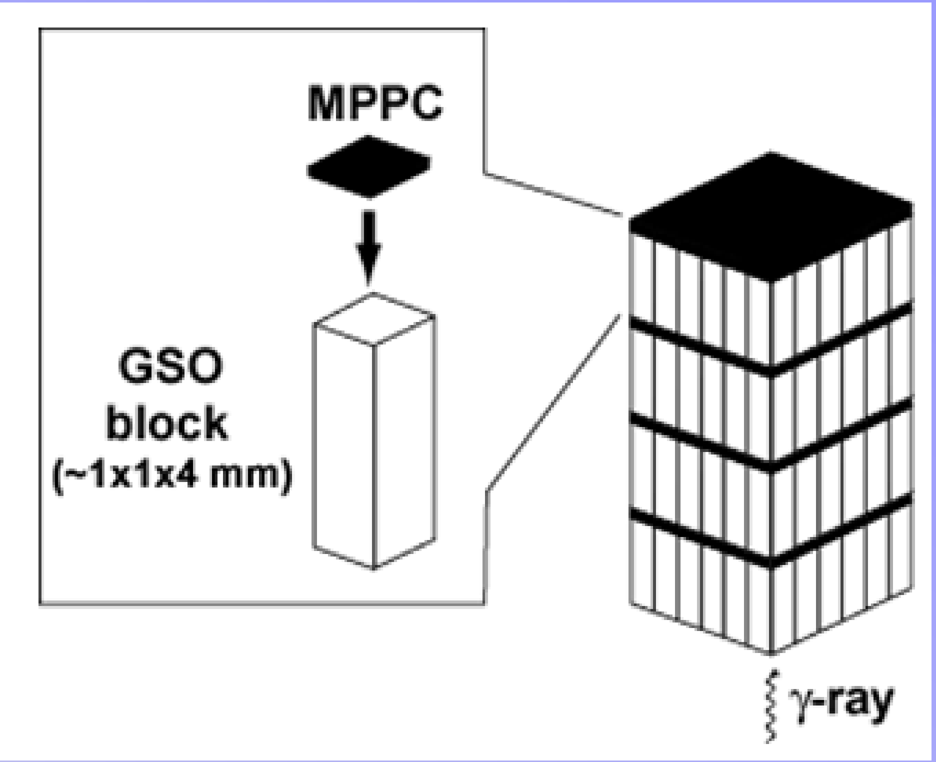
T. Nagano et al., 2012 IEEE NSS-MIC.

PET Parallax: Depth of Interaction (DOI)



DoI measurement: innovative layout

- Asymmetry in the up – down light distribution allows DOI measurement.
- Dual-side readout improves also *x-y* and energy measurement because of the increased statistics.
- Continuous crystal reduces the costs.
- Drawbacks: low single channel signal.



Expected DoI resolution 1 – 2 mm

@ VCI:
M. Morrocchi et al.
Thu 14 Feb, 16:55

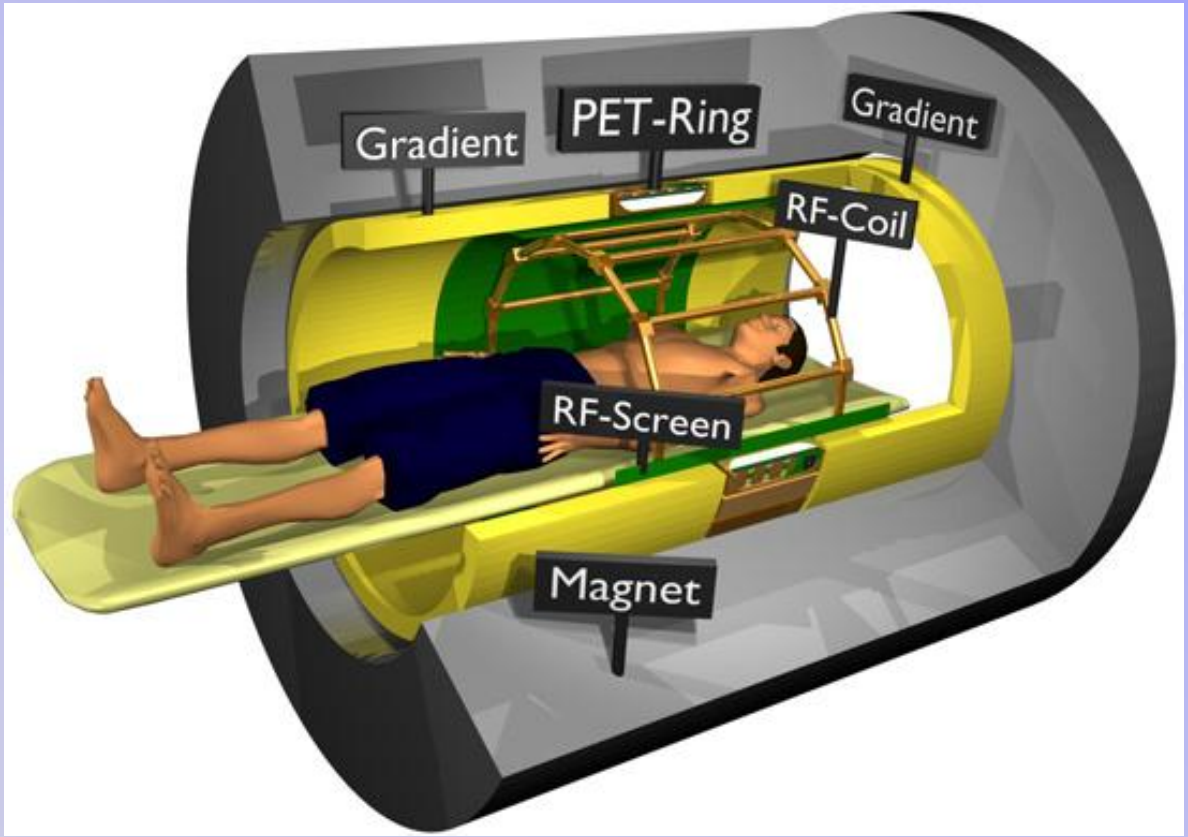
DoI resolution 1.3 mm

@ VCI:

K. Yamamaoto (HPK)

Multi-Modal: PET/CT and PET/MR

PET needs CT data to locate and delineate the tumor and correct for attenuation. Use of PET in conjunction with MRI has the added advantage that the range of the positrons is greatly reduced in the large magnetic field



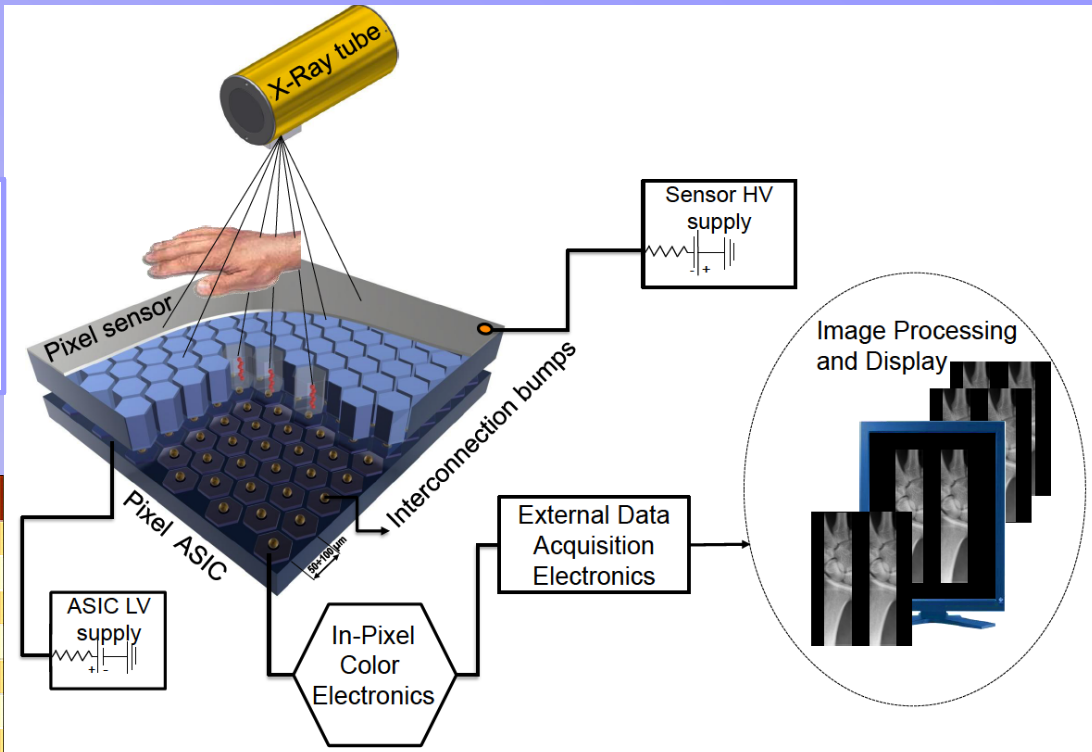
HYPERimage consortium: http://www.hybrid-pet-mr.eu/

@ VCI:
J. NEVES Thu 14 Feb 14:00

Chromatic X-Ray Counting

Pseudo-analog recording with two counters per pixel with 2 thresholds

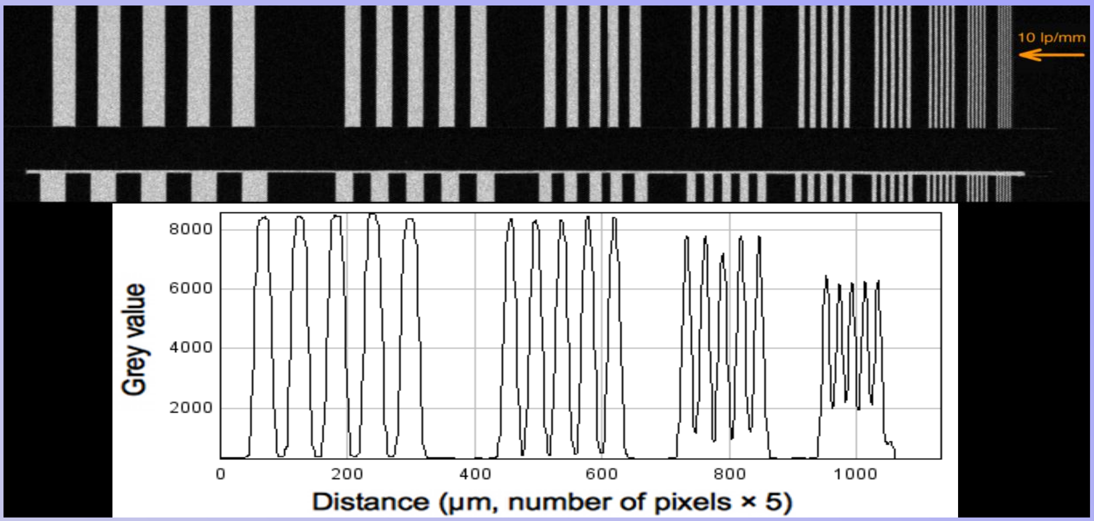
- CdTe pixel sensor (ACRORAD Co., Ltd.):
- Schottky type diode, electron collection on the pixels
- Large area: 30.96 × 24.98 × 0.65 mm
- Pixel pitch: 60 µm (on hexagonal matrix)
- Very low leakage current @400-500V bias



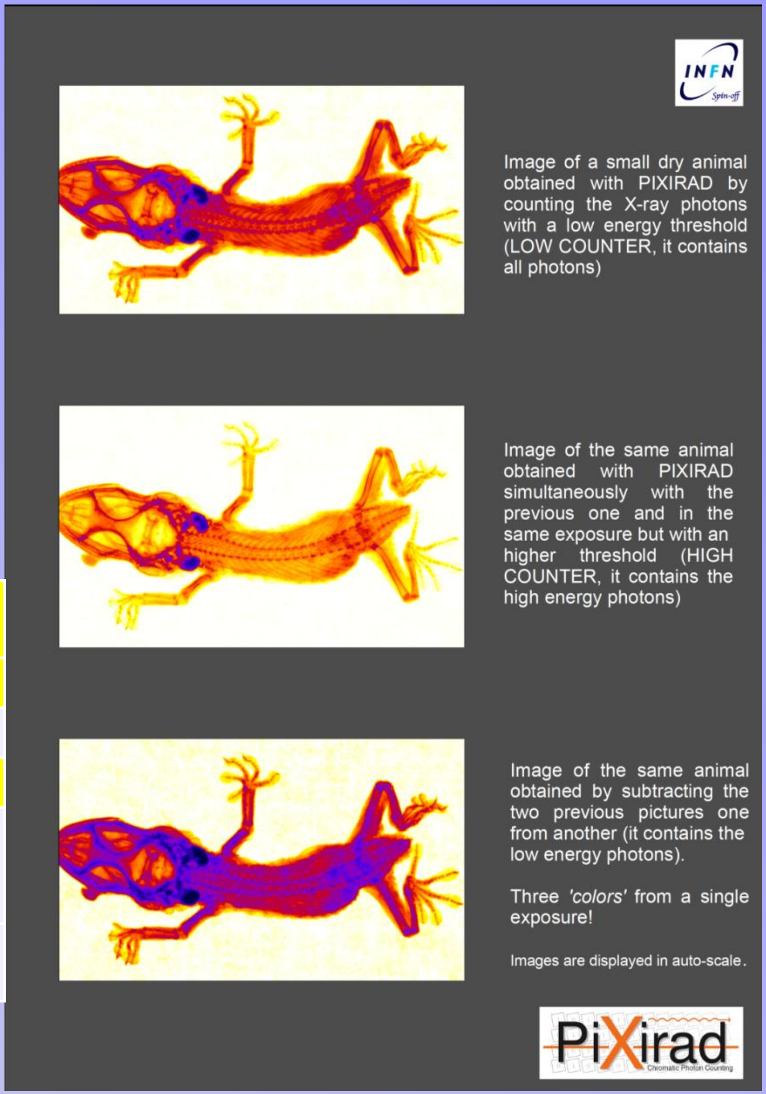
Pixel characteristics	
Shaped pulse duration (at the base)	1 µs (adjustable)
Linear range	> 3000 electrons
Saturation level	> 6000 electrons
Equivalent noise (ENC)	50 electrons (rms)
Residual offset after auto-calibration	± 30 electrons
Maximum number of counts before reading	32768
Input signal	positive or negative
Possibility to disable, swap, by-pass pixel	user-selectable
Pixel reading	
Serialization of columns for best readout time	16, 32, 64, 128
Max readout clock frequency	200 MHz
Readout time for 32 data outputs = 16 columns serialized (16 columns x 476 pixels x15 bits x 5 ns)	< 0.6 ms
Readout time for 16 data outputs = 32 columns serialized	<1.2 ms
Readout time for 8 data outputs = 64 columns serialized	<2.3 ms

2 color reading (2 thresholds, 2 counters) or, alternatively, counting in one counter while reading the other one (dead-time free)

Imaging with Chromatic X-Ray Counting



Pixel rate capability	10^{6} counts/pixel/s (dead-time corrected)
Global rate capability	2.4´10^{11} counts/s (1 chip)
Pixel dead-time	300 ns
Position resolution	11 LP/mm at 50% MTF
Energy range	1-100 keV (with pulse height saturation above 30 keV)
Detection efficiency @10 keV, 50 keV, 100 keV	100%, 98%, 45%



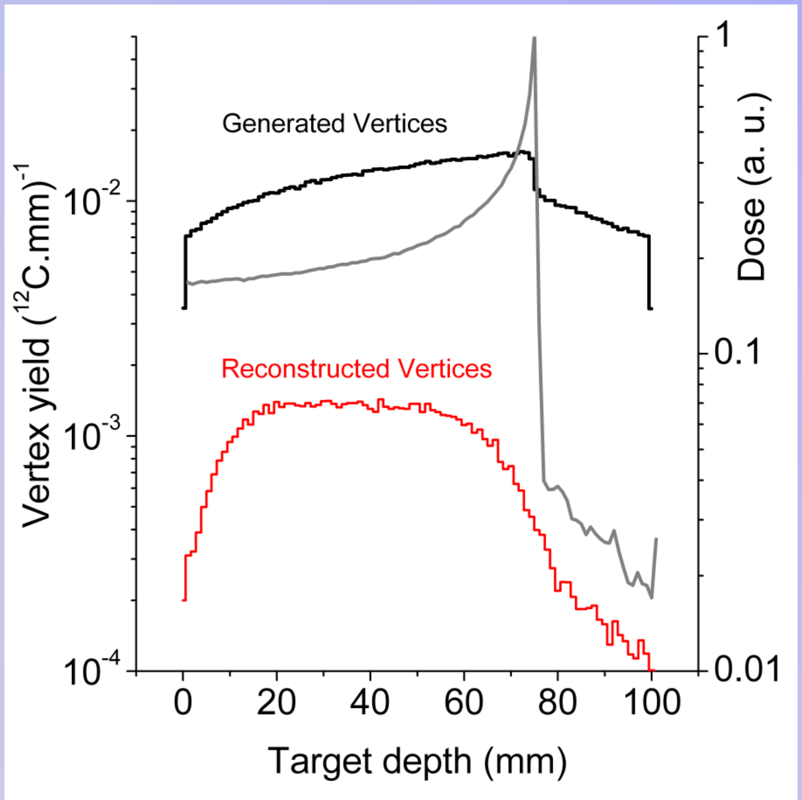
@ VCI:
R. Bellazzini, Thu 14 Feb 5:45 PM

Instrumentation for Hadron Therapy

Highly precise treatment modality due to the Bragg peak is compromised by:

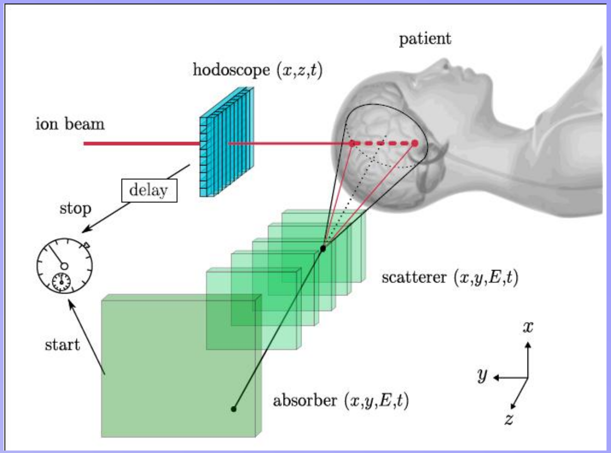
1. Uncertainties localizing patient or beam: ► Interaction Vertex Imaging IVI
2. Patient Stopping power calibration: ► Proton CT pCT

Interaction Vertex Imaging IVI in Carbon Hadron Therapy

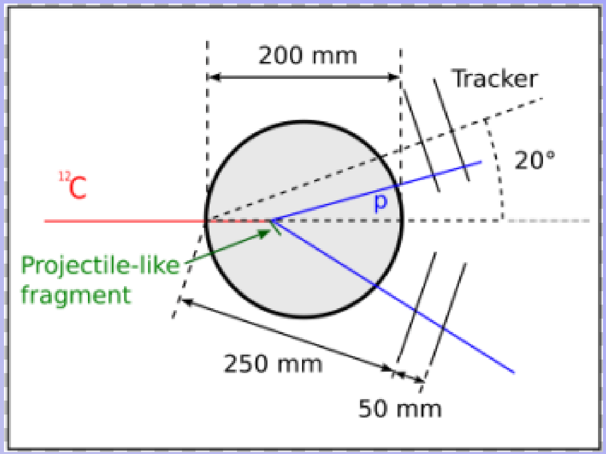


P. Henriquet et al., Phys. Med. Biol. **57** (2012) 1–15

γ IVI :
No Range/ MCS Limitations
Compton Camera

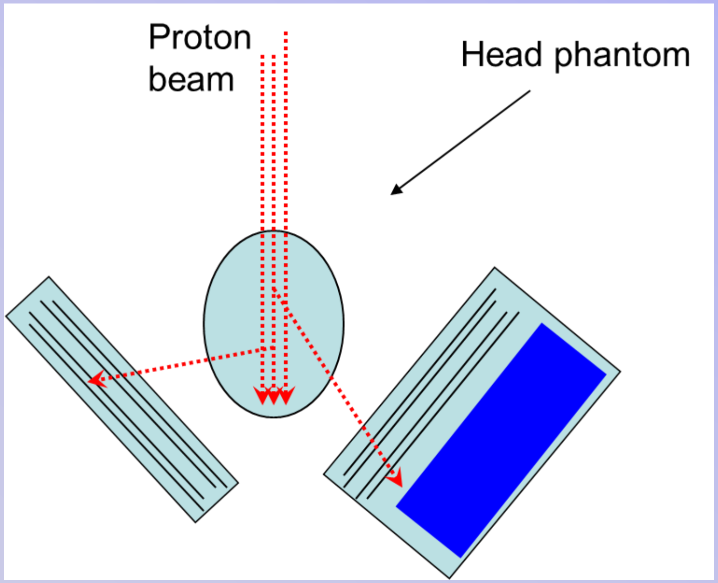


p IVI :
Range and MCS Limitation:
Thin sensors!

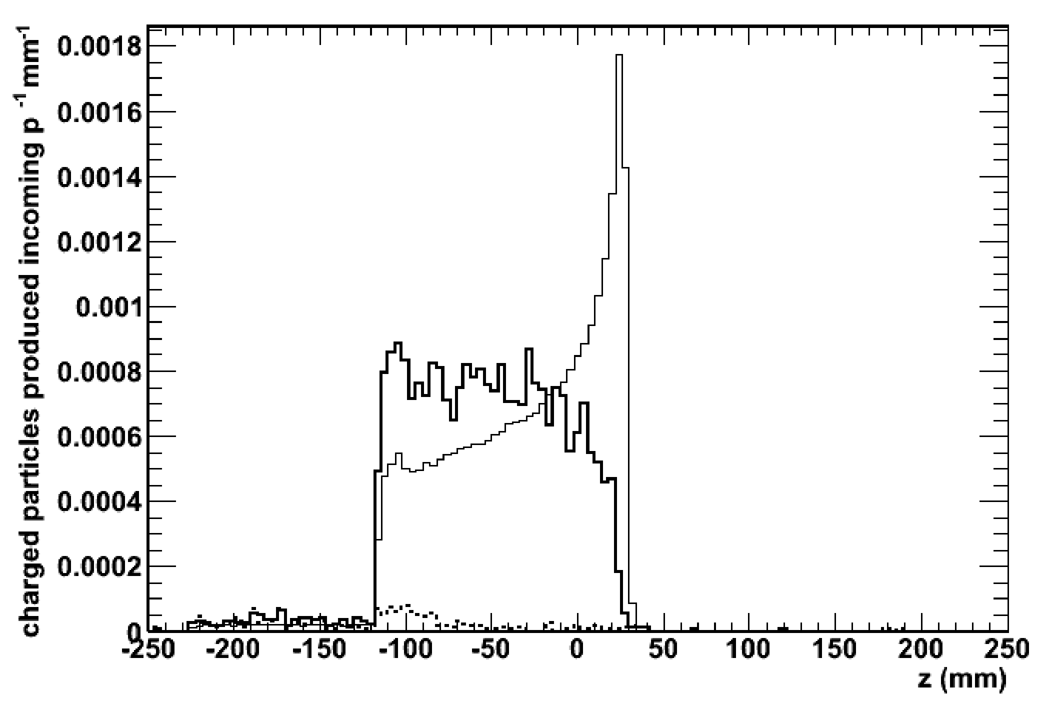


IVI in Proton Therapy

Range and MCS Limitation: Thin sensors!
Single tracks only
Kinematic cut-off at Bragg peak
Small efficiency (but large flux)
Resolution ~ mm
Possibility of Beam line monitoring



M. Battaglia et al.,
2012 IEEE NSS-MIC



Proton CT Basics

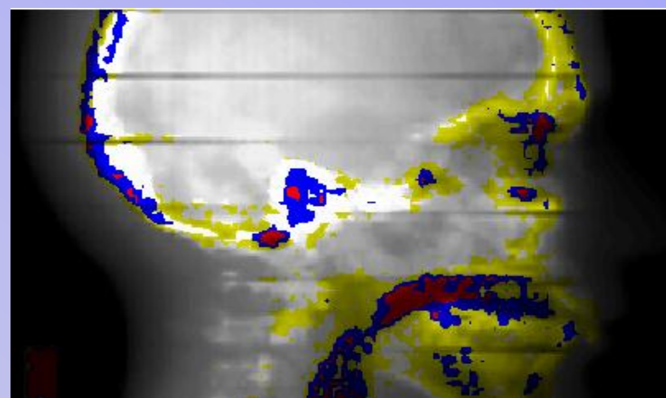
Proton therapy and treatment planning requires the knowledge of the stopping power in the patient, so that the Bragg peak can be located within the tumor.

X-ray CT has been shown to give insufficiently accurate stopping power (S.P.) maps in complicated phantoms or from uncertainty in converting Hounsfield values to S.P.

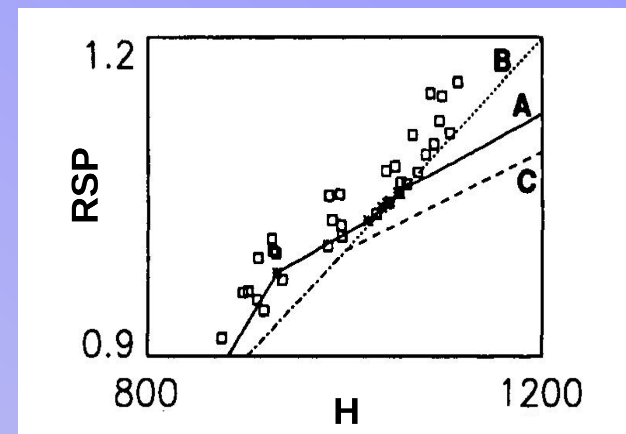
Range Uncertainties (measured with PTR)

> 5 mm
> 10 mm
> 15 mm

Schneider U. (1994), “Proton radiography as a tool for quality control in proton therapy,” Med Phys. 22, 353.



Alderson Head Phantom



The goal of Proton CT is to reconstruct a 3D map of the stopping power within the patient with as fine a voxel size as practical at a minimum dose, using protons (instead of x-rays) in transmission.

In a rotational scan the integrated stopping power is determined for every view by a measurement of the energy loss.

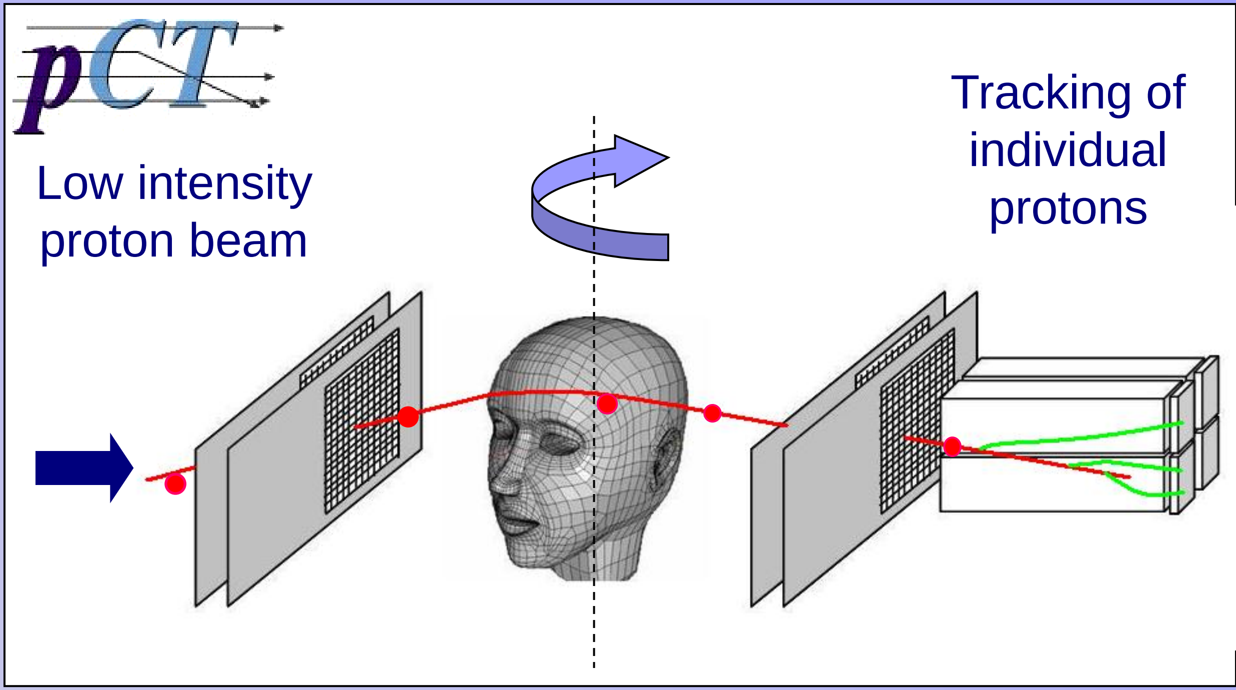
Proton CT (pCT) Concept

Measure Stopping power distribution directly (instead of converting X-ray CT scans

- An energetic low intensity cone beam of protons traverses the patient
- The position and direction (entry & exit) and energy loss of **each** proton is measured
- Proton histories are taken from multiple projection angles (angular "CT scan")
- Minimal proton loss and high detection efficiency make this a low-dose imaging modality

Design of a Proton CT Scanner rotating with the proton gantry

(R Schulte et al. IEEE Trans. Nucl. Sci., 51(3), 866-872, 2004)



Low Contrast in Proton CT

High contrast in absorption of Photons

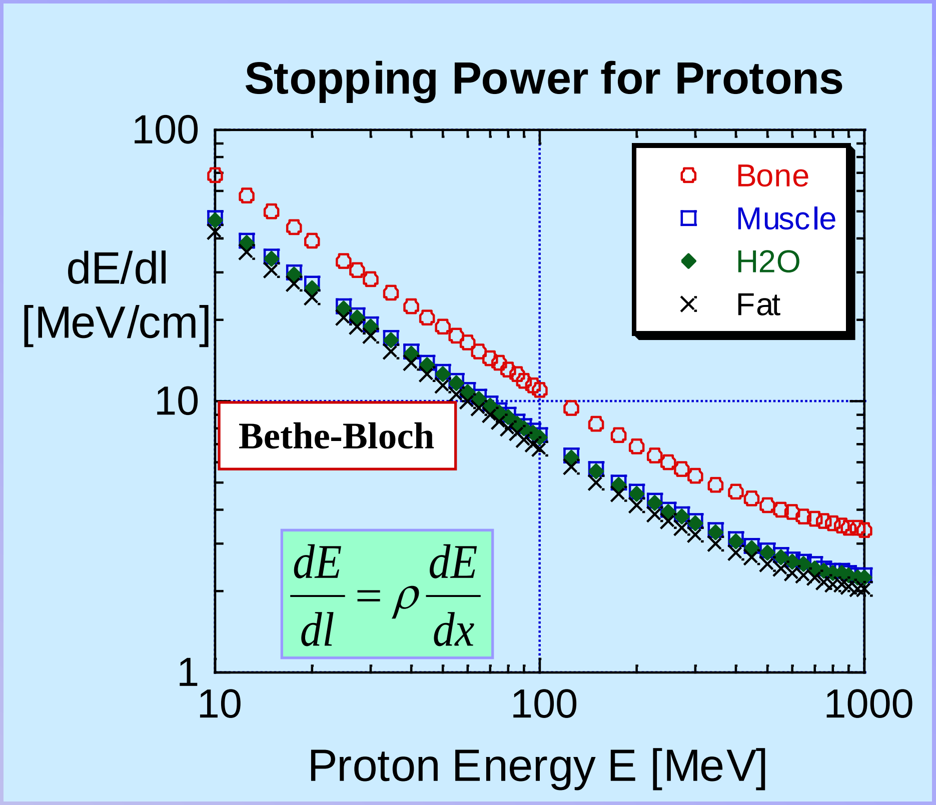
$N(x) = N_o e^{-\mu x}$

with the linear absorption coefficient μ differing by a factor 10 between bone and soft tissue.

Low contrast in energy loss of Protons

$$\Delta E = \int \frac{dE}{dx} dx \approx \sum \rho \frac{dE}{dx} \Delta l = \sum \frac{dE}{dl} \Delta l$$

with the stopping power dE/dl only 50% larger for bone than for soft tissue.



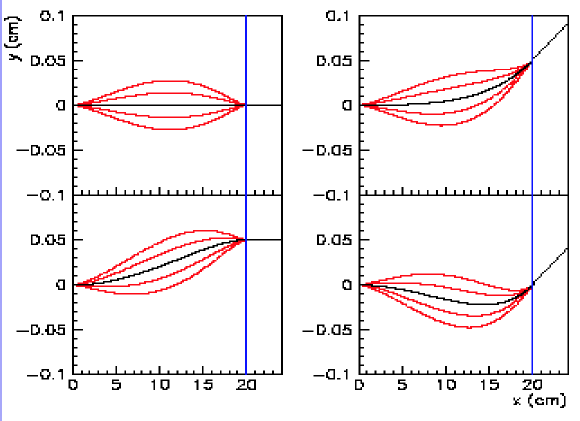
NIST Data

Instrument Solutions to pCT Challenge

Experiment	Tracker	Energy Detector	Typical Proton Energy [MeV]
TERA / CERN U. Amaldi et al., NIM A 629 (2011) pp 337-344	GEM ~100 μm	Range (3mm) + WLSF + MPPC	100 upgrade
Firenze / LNS **(@ VCI: M. Bruzzi, 14. Feb 5:20 PM)**	SI SSD 80 μm	Fast crystal calorimeter + P.D.	68 - 200
LLU / UCSC / NIU F. Hurley et al., MEDICAL PHYSICS 39 (2012) 2438-2446	Si SSD 80 μm	CsI + P.D.	100 - 200
NIU / FNAL **(@ VCI: A. Dychkant Poster 69)**	SciFi +MPCC 0.3-0.5 mm	Range (3mm) + WLSF + MPCC	100 - 200 under construction
LLU /UCSC H. Sadrozinski et al., NIM A 699 (2013) pp:205-210	Si SSD “Slim edges” 80 μm	Polystyrene Calorimeter + PMT	100 - 200 under construction

pCT Challenges

#1: Multiple Coulomb Scattering



D C Williams Phys. Med. Biol. 49 (2004) 2899–2911

The proton path inside the patient/phantom is not straight
→ the path of **every** proton before and after the phantom
has to be measured and its path inside
the patient reconstructed.

From deflection and displacement, calculate the "Most Likely Path MLP"

#2: Proton Data Rate

Data Flow math:

Assuming 100 protons / 1mm voxel and 180 views requires ~ $7*10^8$ protons.
A scan with a proton rate of **2 MHz** takes 6 min with a dose of 1.5 mGy.

Image Reconstruction

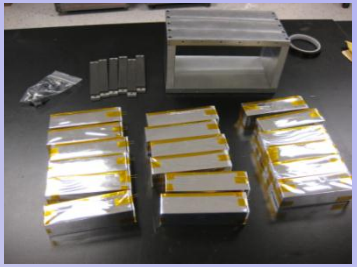
To reconstruct images with > 10^7 voxels using ~10^9 protons is NOT trivial.
Our reconstruction code is already running on GPU's in anticipation of the much higher data rates of the future.

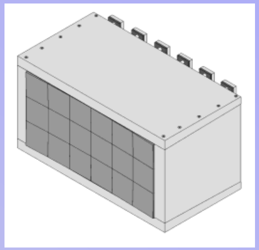
pCT Challenge #4 : Range Straggling

Measure WEPL = Water equivalent Path Length (of proton in phantom)

Range straggling ~ 1% of range ~ 1mm for 100 MeV, ~ 3mm for 200 MeV

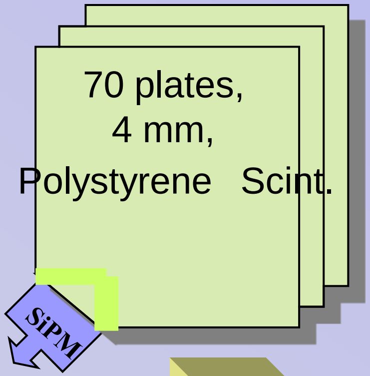
Low contrast requires uniform response of WEPL detector

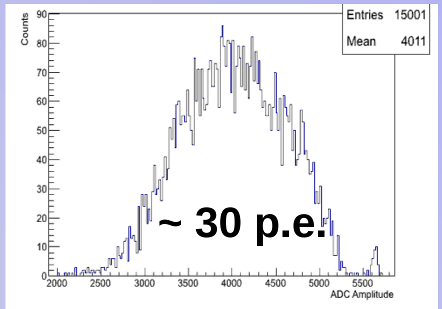




Too slow!
Calibration elaborate

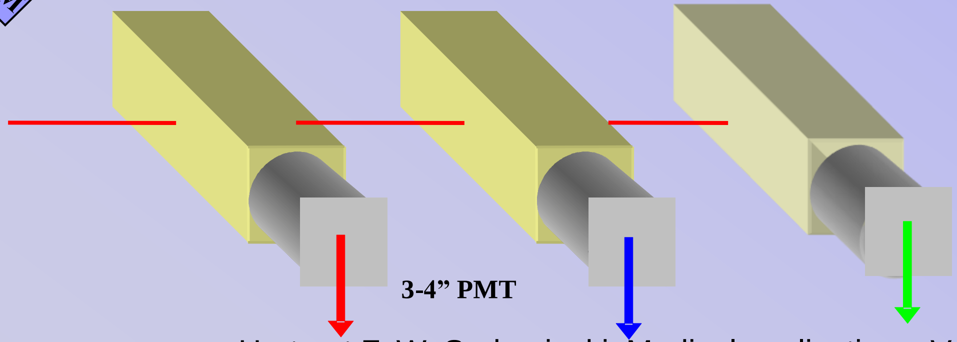
Existing Hodoscopic CsI Calorimeter
P.D. Readout





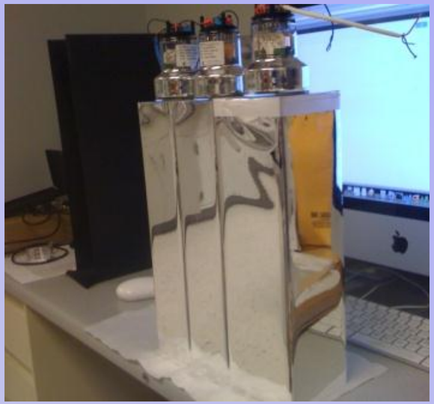
Good performance on S/N

Range Counter
Direct MCPP readout
(signal 3-5x of 3mm+WLSF)



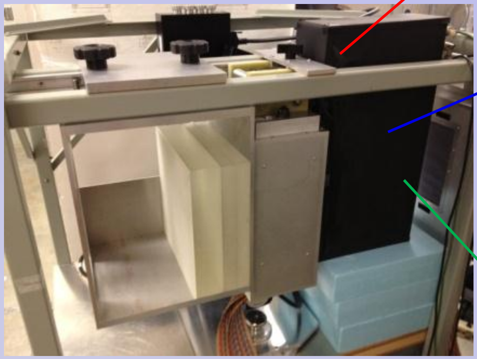
Multi-stage Scintillator Counter
3 Polystyrene 10cmx10cmx40cm + PM
Uniform Response.

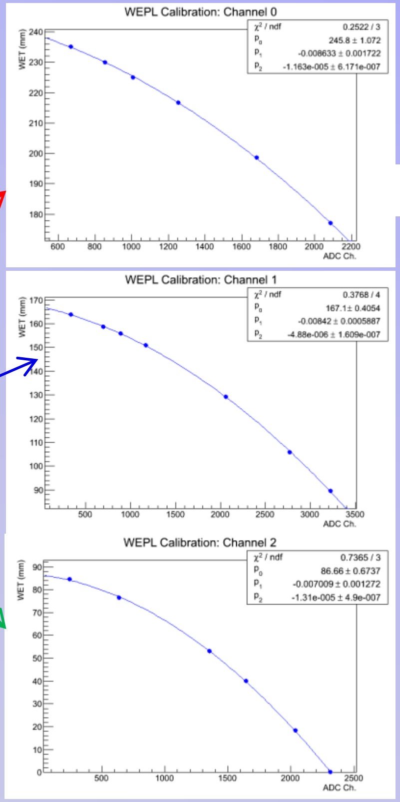
3-Stage Multi-Stage Scintillator



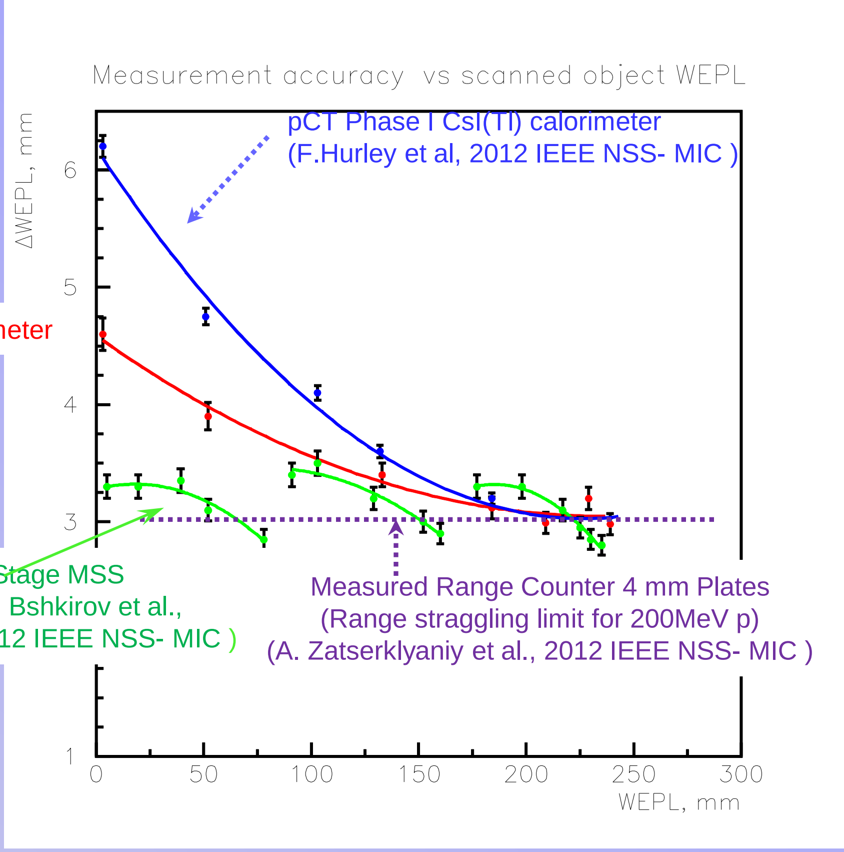
10x10x36cm Polystyrene
3' PMT via light-guide

WEPL Calibration of each stage with Polystyrene degraders

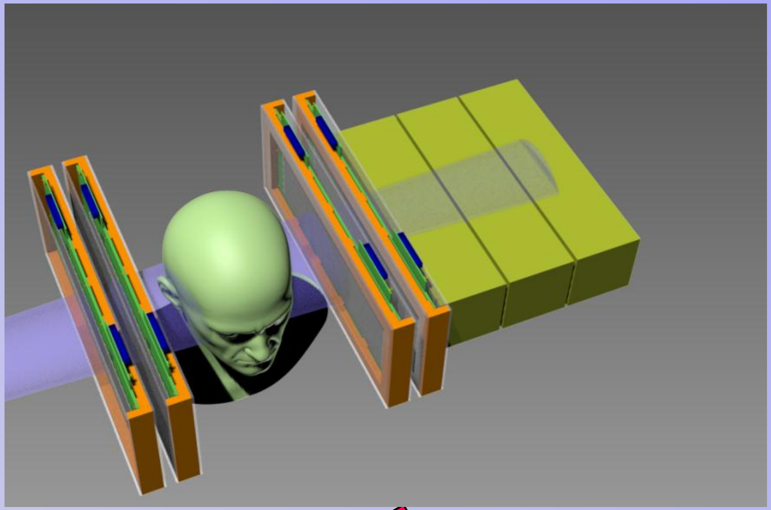




WEPL Resolution [mm]

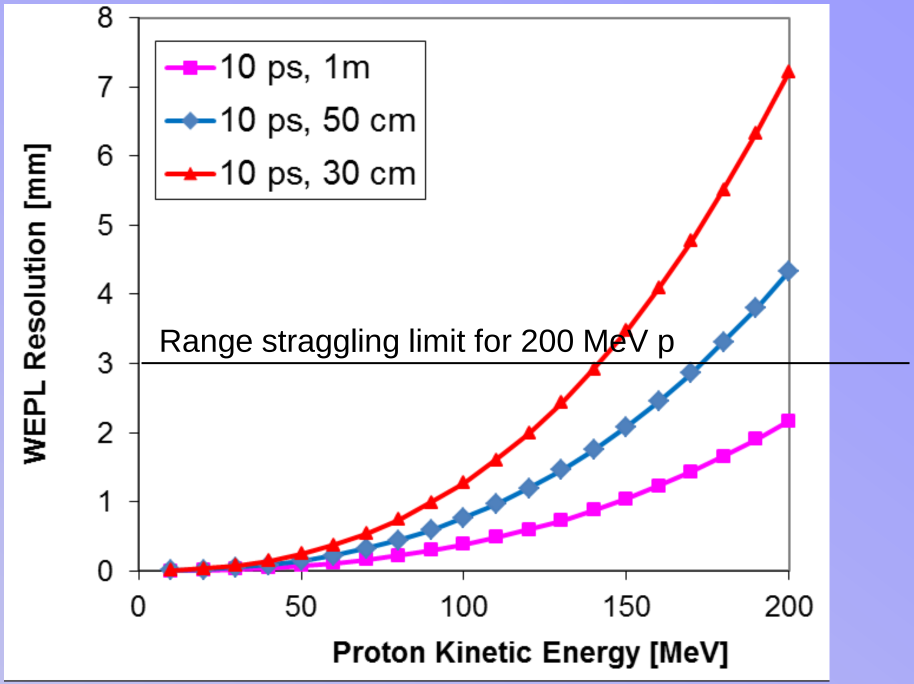


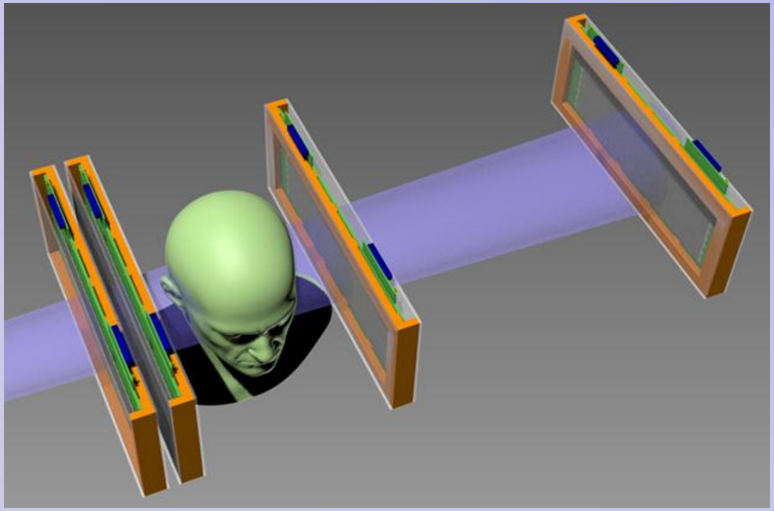
Future: 4-D Ultra-Fast Si Detectors ?



Protons of 200 MeV have a range of ~ 30 cm in plastic scintillator. The straggling limits the WEPL resolution.

Replace calorimeter/range counter by TOF:
Light-weight, combine tracking with WEPL determination

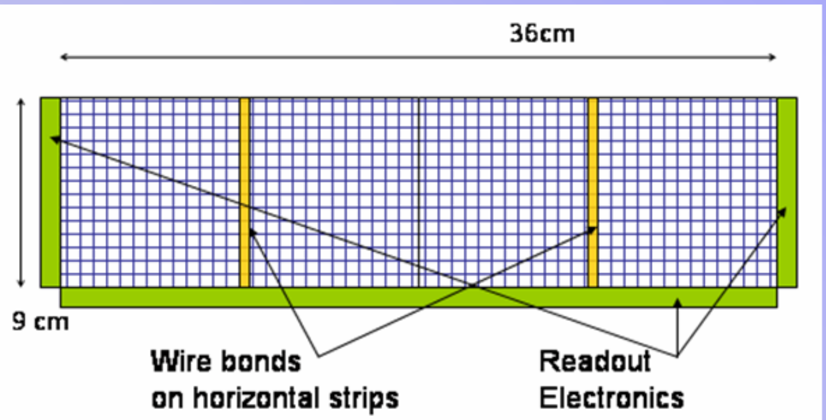




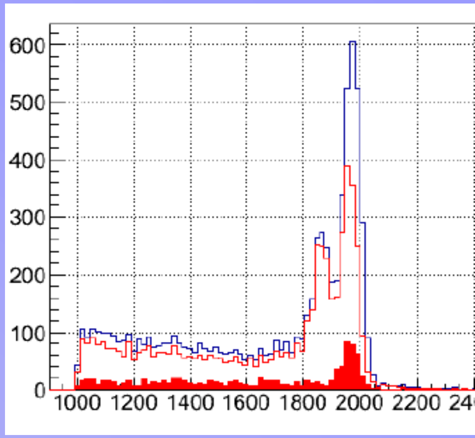
We started a program to develop ultra-fast silicon sensors based on internal charge multiplication, investigated by RD50, with the goal of thin sensors with moderate gain.

pCT Challenge #5: Large Area Si Tracker

Large area coverage requires tiling of 4 sensors,
having ~ 1mm inactive edges which create image artifacts.

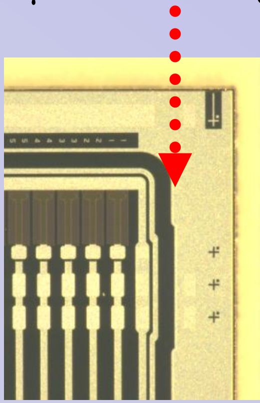


Overlapping sensors introduces artifacts requiring additional, non-uniform energy corrections



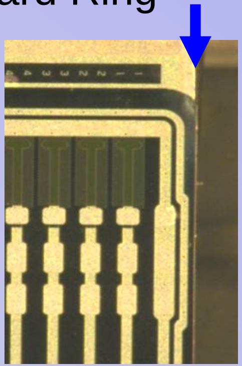
For Tiling with no Overlap: "Slim Edges"

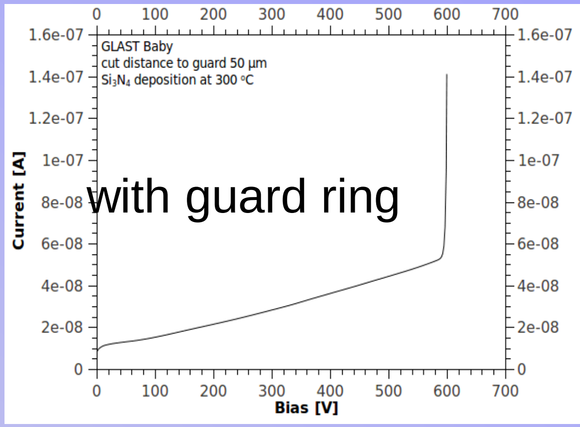
Si SSD with
900μm dead edge



S-C-P:
Scribing (XeF_2)
+ Cleaving
+ Passivating
(N_2 PECVD)

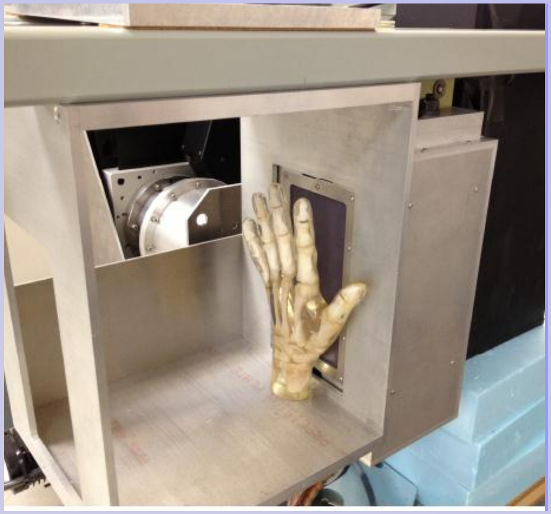
Cut within 50 μm
of Guard Ring



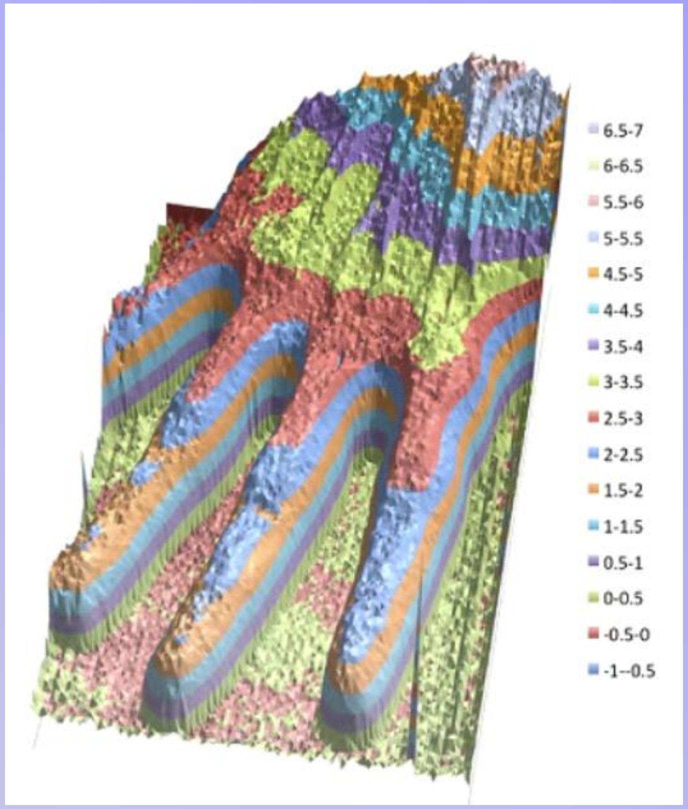


M. Christophersen et al.,
SSE 81, (2013) 8–12

Hand Radiography: Something New (?)



Hand Phantom imaged with 200 MeV protons
at the Loma Linda Synchrotron,
using the existing pCT scanner.



Color-coded image
of the summed-up
stopping power
in terms of
water-equivalent
thickness [in mm].

Note the varying thickness of the hand
and clear structural details.

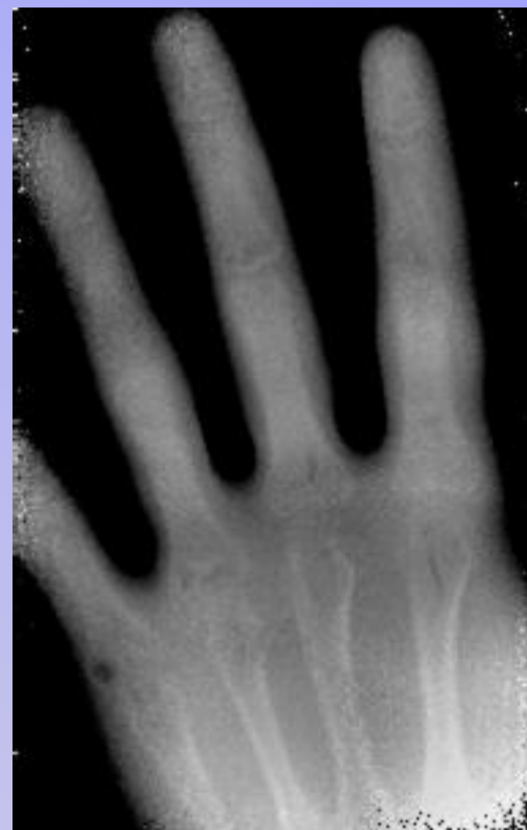
A step forward into Imaging History..

X-Rays

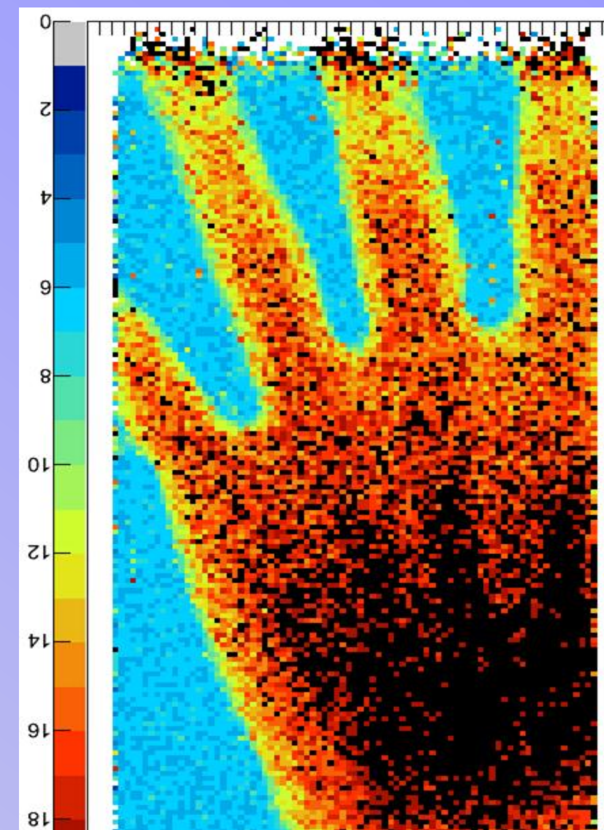
Wilhelm Roentgen,
Laboratory Radiology (1895)

200 MeV Protons

Stopping Power



Multiple Scattering



UCSC-LLU-CSUSB 2012, T. Plautz et al., 2012 IEEE NSS-MIC

Final Remarks

With heritage from HEP and Astro, medical applications are supported by active targeted R&D.

New Materials & ASICS:
There are new scintillators being developed, and impressive application specific modes for read-out..
SiPM / MPPC:
Very active commercial developments because of the many advantages, like their feature size and insensitivity to magnetic fields.
Multimodality
PET/CT, PET/MR etc combine high-resolution structural delineation and localization with the organ specific information. Much like multi-wavelength campaigns in Astrophysics.
Instrumentation in support of Hadron Therapy (MedAustron).
Both Interaction vertexing and proton CT are being pursued to reduce the uncertainty in treatment.
Time measurements:
Evolution towards elevating the 4^{th} dimension to equal status, providing a tool for remote sensing.
Presentations @ VCI
2 sessions on Medical Instrumentation, & posters, but scour all sessions for ideas, which at the next VCI might appear in the "Medical Application" sessions.
Steady interest in medical applications
(It is our body, after all!)
Working on small systems in a small group is very attractive so is the prospect of commercialization!

	Monday 11 February	Tuesday 12 February	Wednesday 13 February	Thursday 14 February	Friday 15 February
08:00	Registration				
08:30		Registration	Registration	Registration	Registration
09:00		PLENARY	Semi / Cher / Scint	Semi / Calorim	PLENARY
10:00	Opening				
11:00	PLENARY	Calorimeter Discussion	Poster B	Poster A	
12:00			EI7 / EI8 / EI9	EI7 / EI8	
13:00					
14:00	PLENARY	Semi / Gas / Astro	free afternoon (excursion)	Electron / Medical	PLENARY
15:00					
16:00		Poster A		Poster B	Award Ceremony
17:00		EI7 / EI8 / EI9		EI7 / EI8	Summary Talk
18:00	Art & History of Vienna				
19:00					
19:30	Welcome Reception (Conference Venue)	Classical Concert (Austrian Academy of Sciences)		Conference Dinner (Palais Ferstel)	
20:00					
21:00					
22:00					