DIAGNOSTIC METHODS IN HADROTHERAPY

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TERA Foundation and CERN

PART 3
IN-BEAM POSITRON EMISSION TOMOGRAPHY

CONVENTIONAL PET

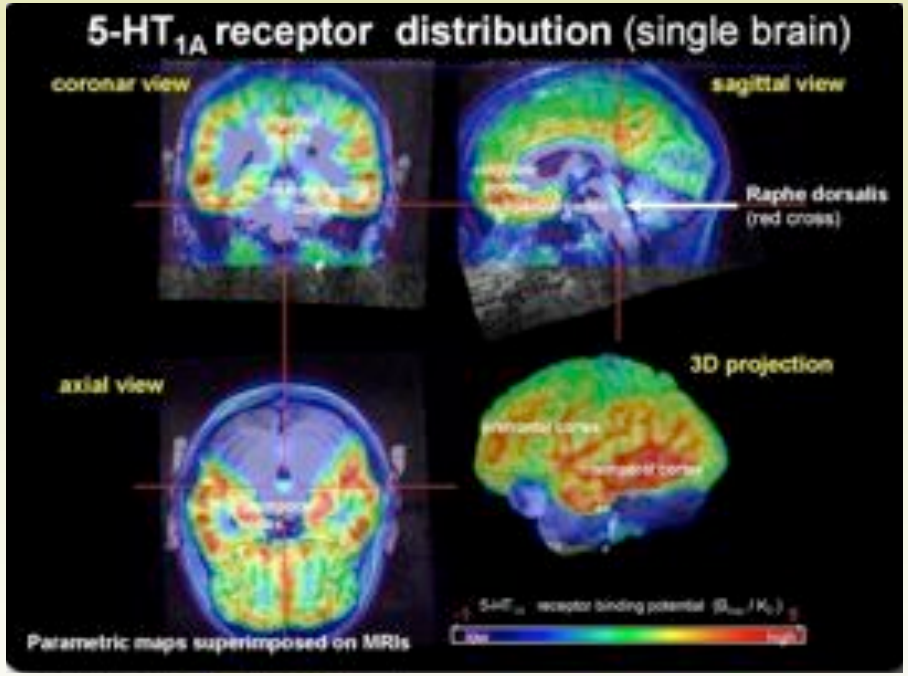
- Positron emitting tracers injected
- Detection of the pair of co-linear 511 keV photons emitted by a positron annihilation
- Computer reconstruction and imaging

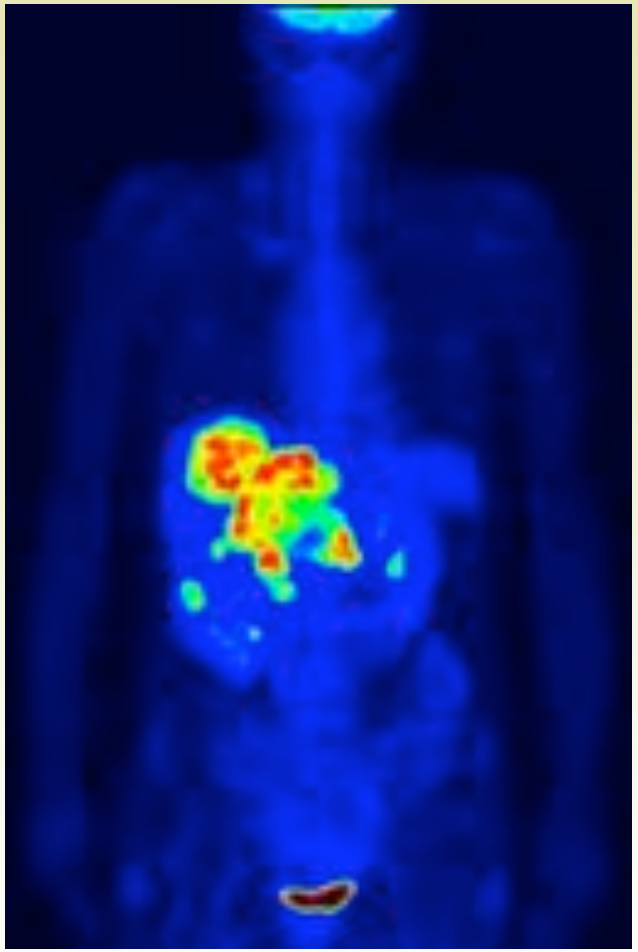
Common β^+ emitting radioisotopes:

Isotope	Half life (min)	Range (mm)
^{11}C	20.4	1.7
^{13}N	10.0	2.0
^{15}O	2.0	2.7
^{18}F	109.8	1.4

Most common molecular tracer: Fluorodeoxyglucose FDG (contains ^{18}F positron emitter)
- Lifetime 110 min
- Typical activity 200-400 MBq

EXAMPLES OF CONVENTIONAL PET IMAGES





PROTON BEAM: β^+ EMITTING ISOTOPES PRODUCTION

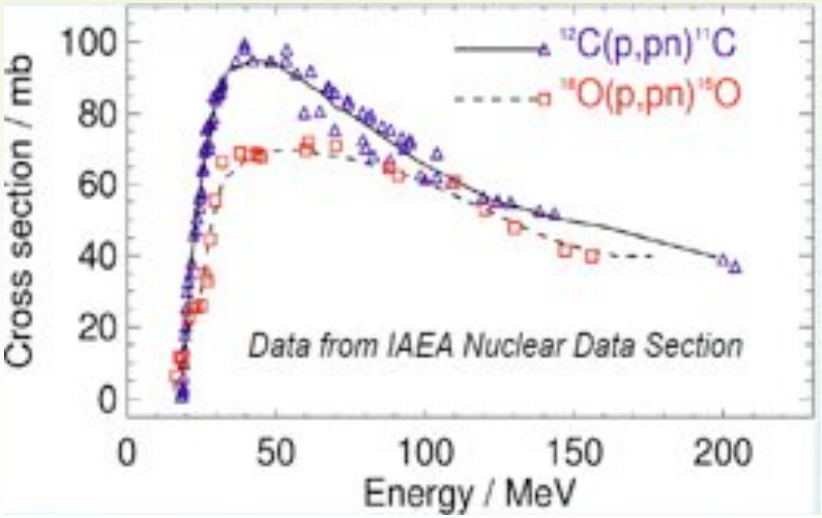
TABLE I
RELEVANT POSITRON-EMITTER PRODUCTION REACTIONS

Nuclear Reactions	Threshold Energy (MeV)	Half-life Time (min)	Positron Max. Energy (MeV)
^{16}O (p, pn) ^{15}O	16.79	2.037	1.72
^{16}O (p, 2p2n) ^{13}N a)	5.66 c)	9.965	1.19
^{14}N (p, pn) ^{13}N	11.44	9.965	1.19
^{12}C (p, pn) ^{11}C	20.61	20.39	0.96
^{14}N (p, 2p2n) ^{11}C a)	3.22 c)	20.39	0.96
^{16}O (p, 3p3n) ^{11}C b)	27.50 c)	20.39	0.96

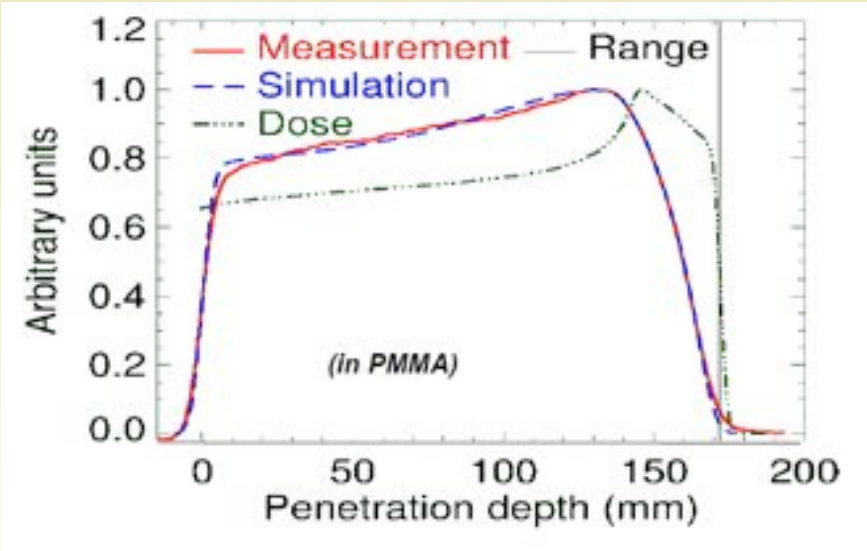
a): (p,2p2n) is inclusive of (p,α)
b): (p, 3p3n) is inclusive of (p, α pn)
c): The listed thresholds refer to (p, α) and (p, α pn)

J. Beebe-Wang et al, IEEE Conf. Rec. (2003)

(p, pn) CROSS SECTIONS:



ACTIVATION VS DOSE (14O MeV p):

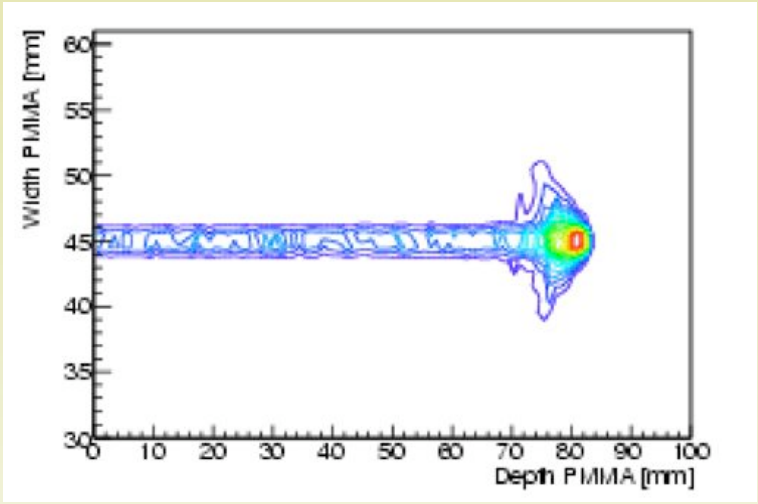


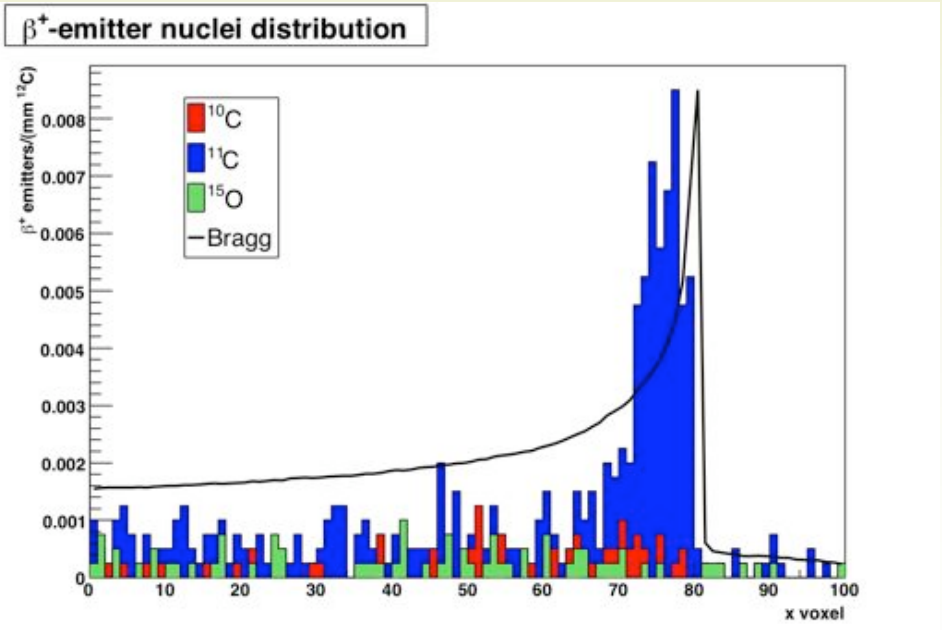
K. Parodi et al, IEEE Trans. Nucl. Sci. 52(2005)778

CARBON BEAM: β^+ EMITTING ISOTOPES PRODUCTION

INDUCED ACTIVITY AT THERAPEUTIC BEAM INTENSITIES:
~ 200 Bq $cm^{-3}Gy^{-1}$concentrated near end of range

(Compare to 200 MBq $cm^{-3}Gy^{-1}$in standard PET)

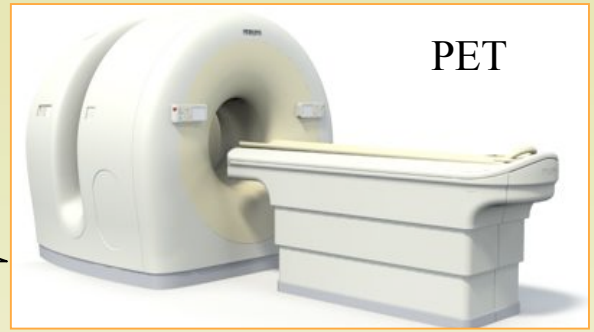




P. Solevi, PhD Univ. Milano (2007)

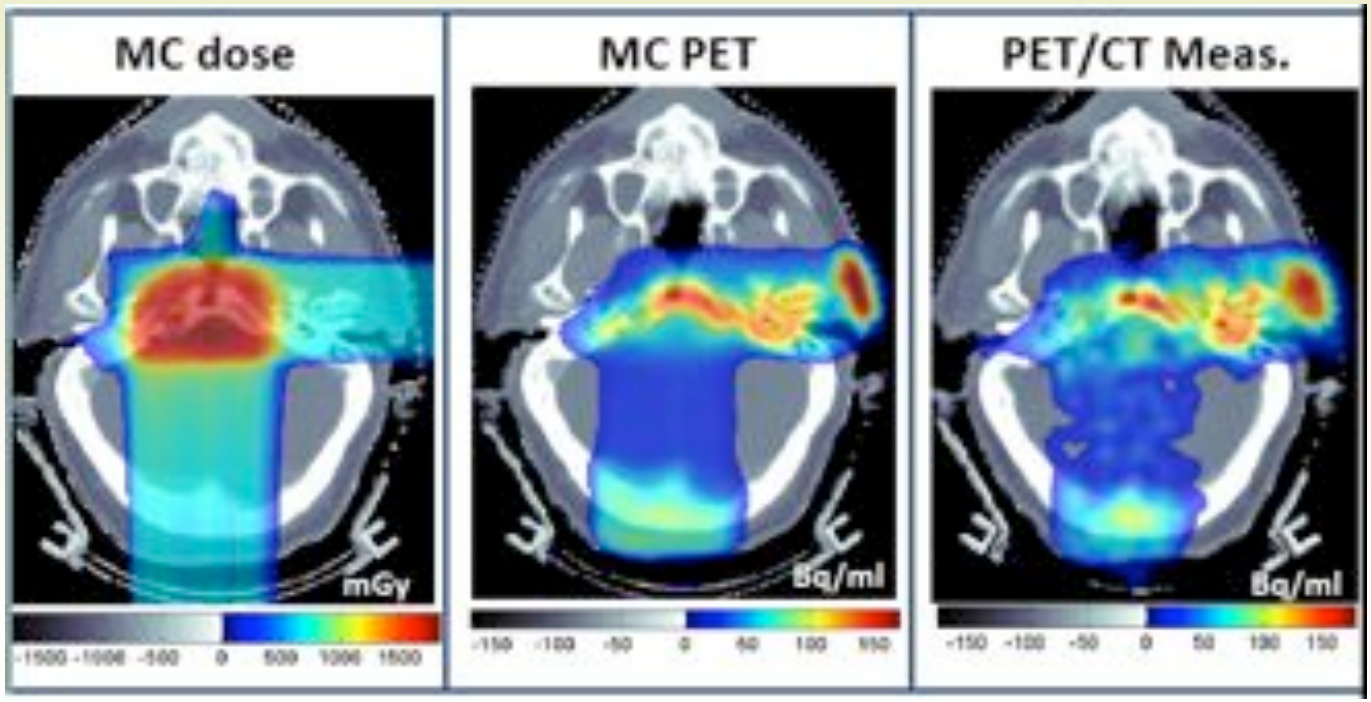
NEAR-BEAM PET

~10 min



- Commercial PET scanners
- Lower activity and wash-out

MGH Boston



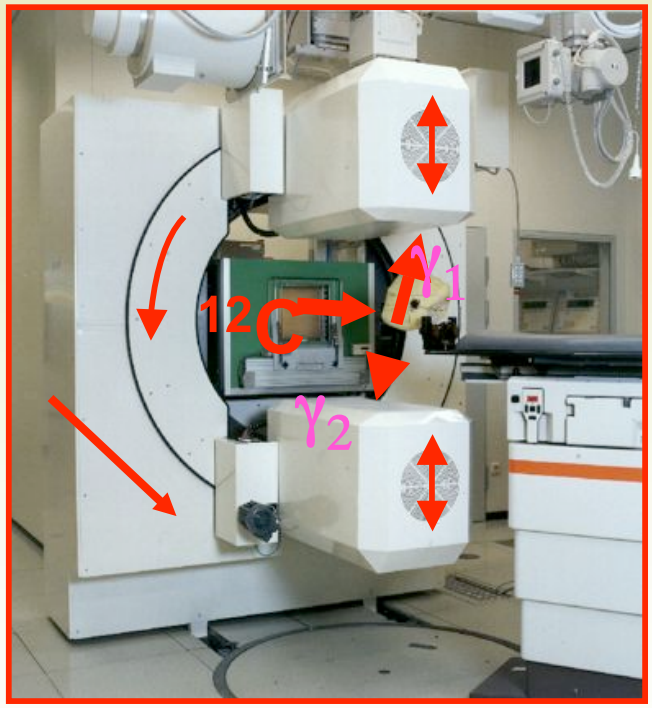
K. Parodi et al, Nucl. Instr. and Meth. A591(2008)282

IN-BEAM PET

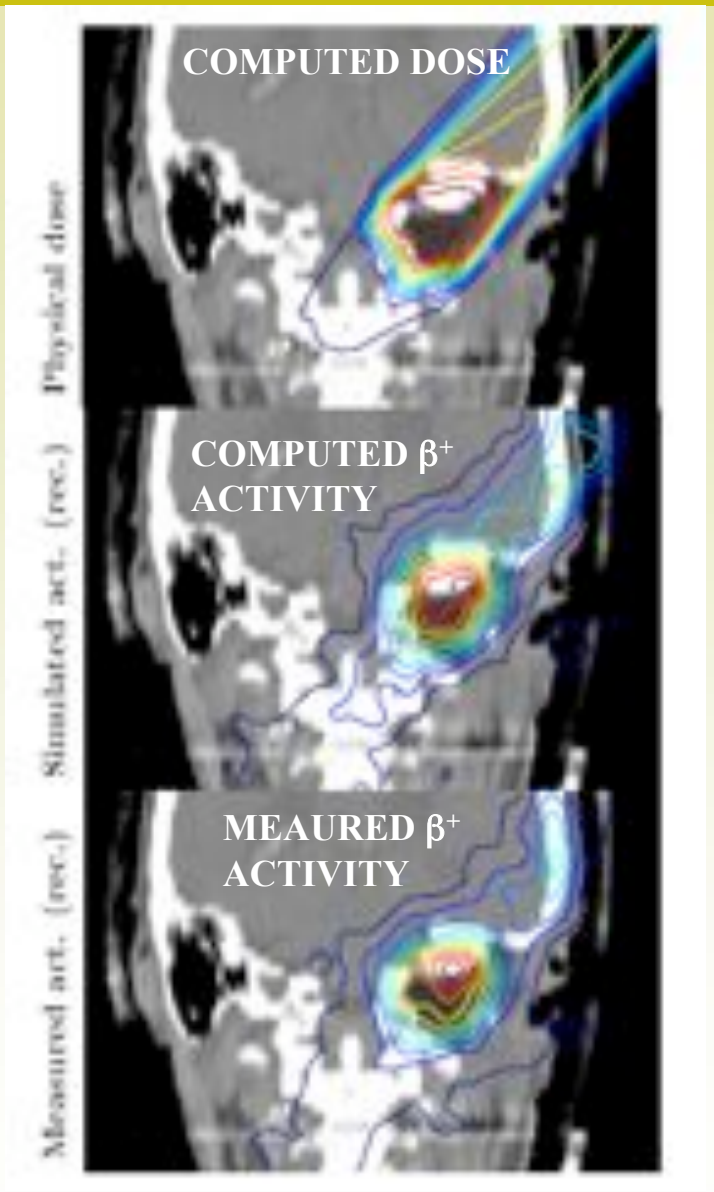
Not possible during therapy (background radiation)

- After treatment
- Gated operation: 1 s spill - 3 s extraction

GSI DARMSTADT:



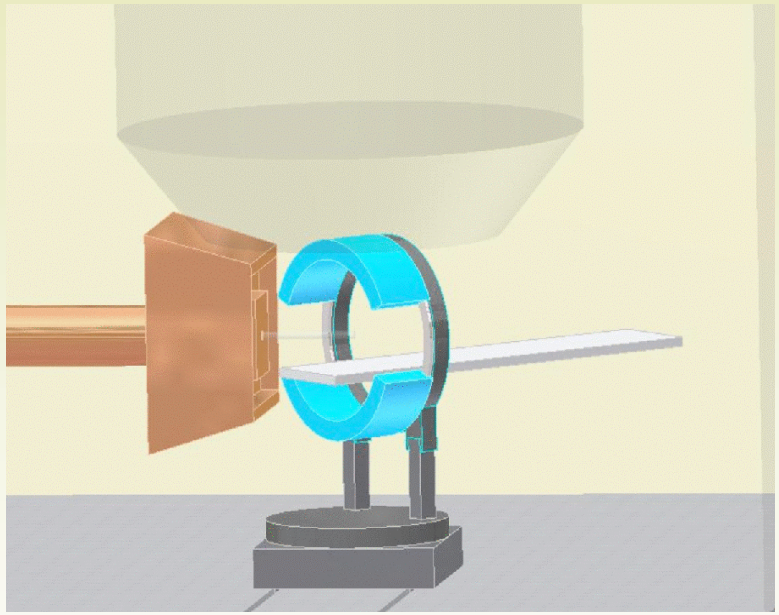
W. Enghardt et al, Nucl. Instr. and Meth. A525 (2004) 284



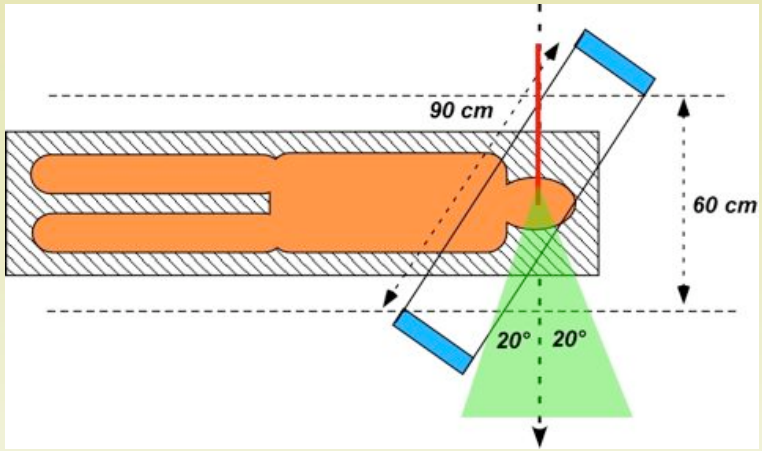
P. A. Crespo, PhD Thesis (Darmstadt Univ. 2005)

IN-BEAM PET: DETECTOR GEOMETRY

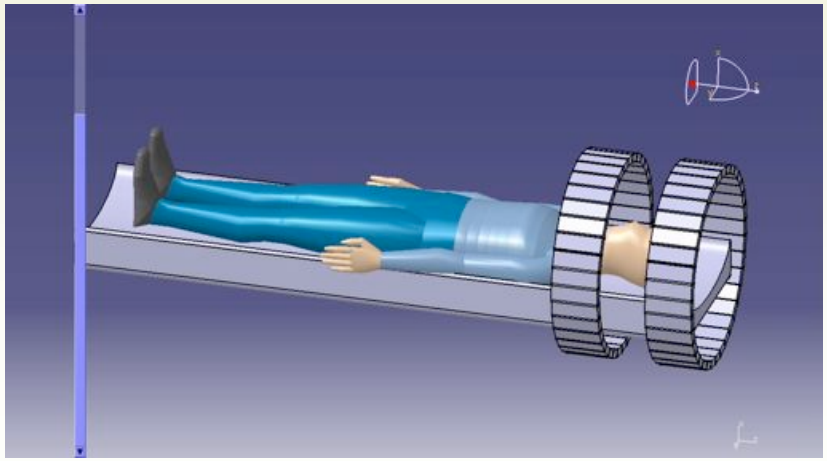
OPEN RING



INCLINED RING



DUAL RINGS

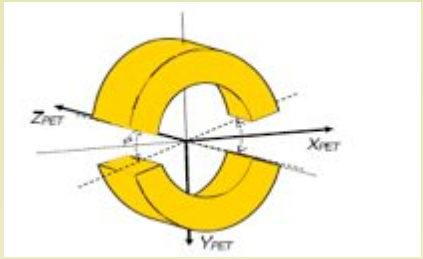


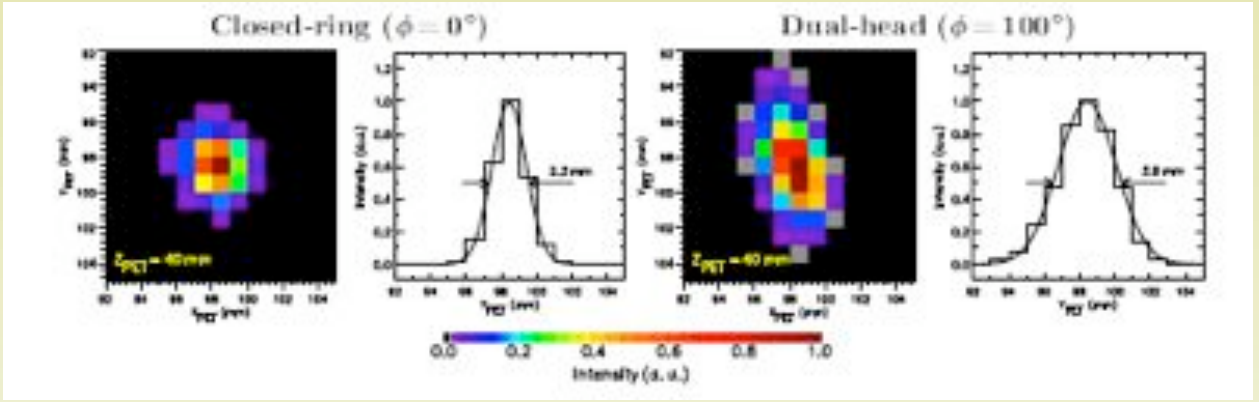
- Reduced efficiency
- Artefacts
- Background radiation?

P. Crespo, G. Shakirin and W. Enghardt, Phys. Med. Biol. 51(2006)2143

IN-BEAM PET PROBLEMS

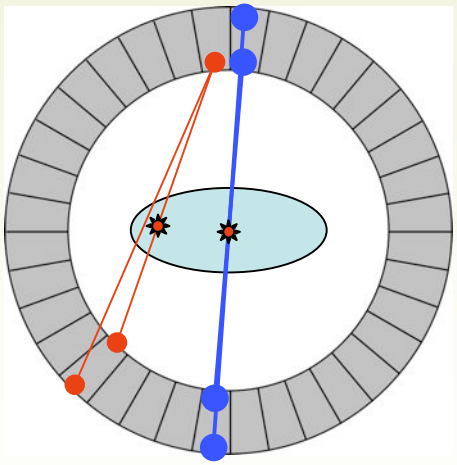
DUAL HEAD ARTIFACTS



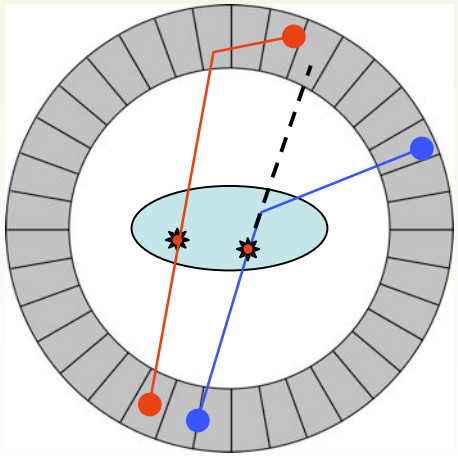


P. A. Crespo,
PhD Thesis (Darmstadt Univ. 2005)

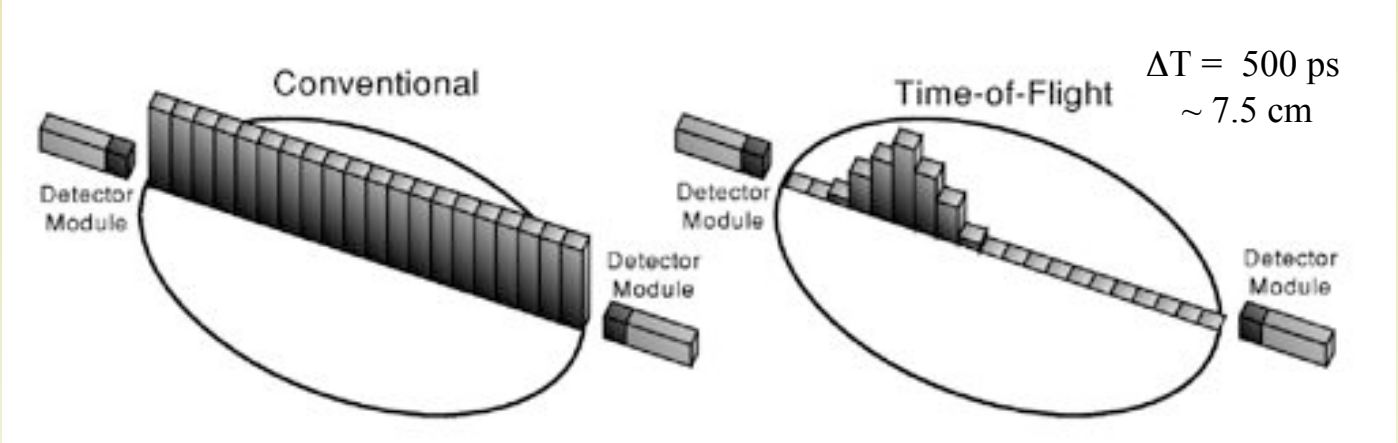
DEPTH OF INTERACTION PARALLAX ERROR

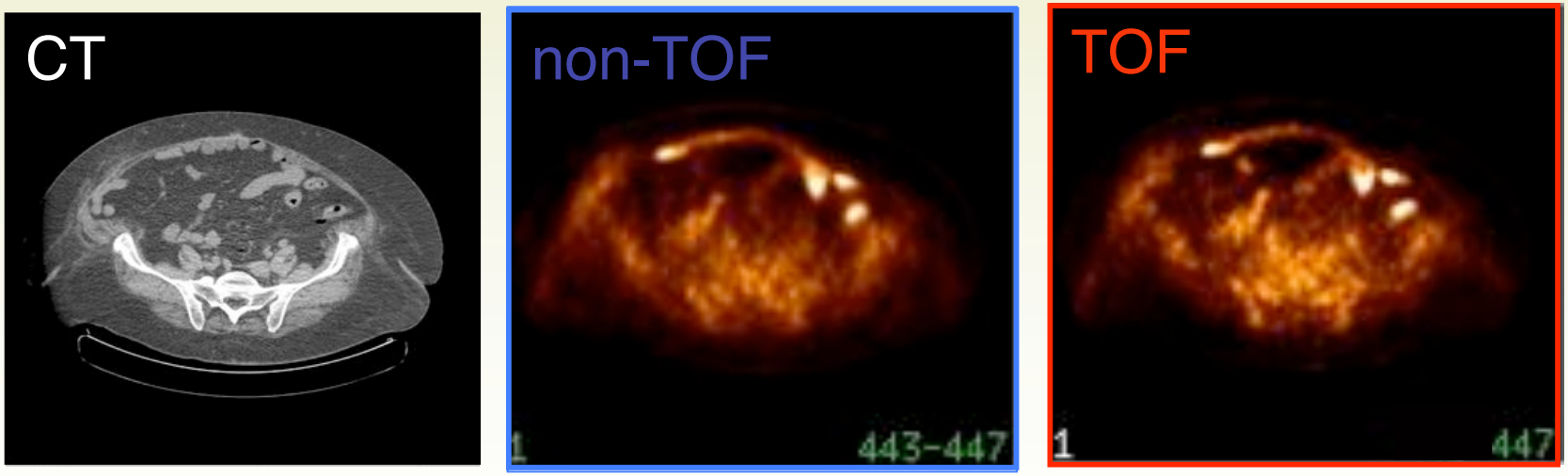


FALSE COINCIDENCES DUE TO SCATTERED PHOTONS:

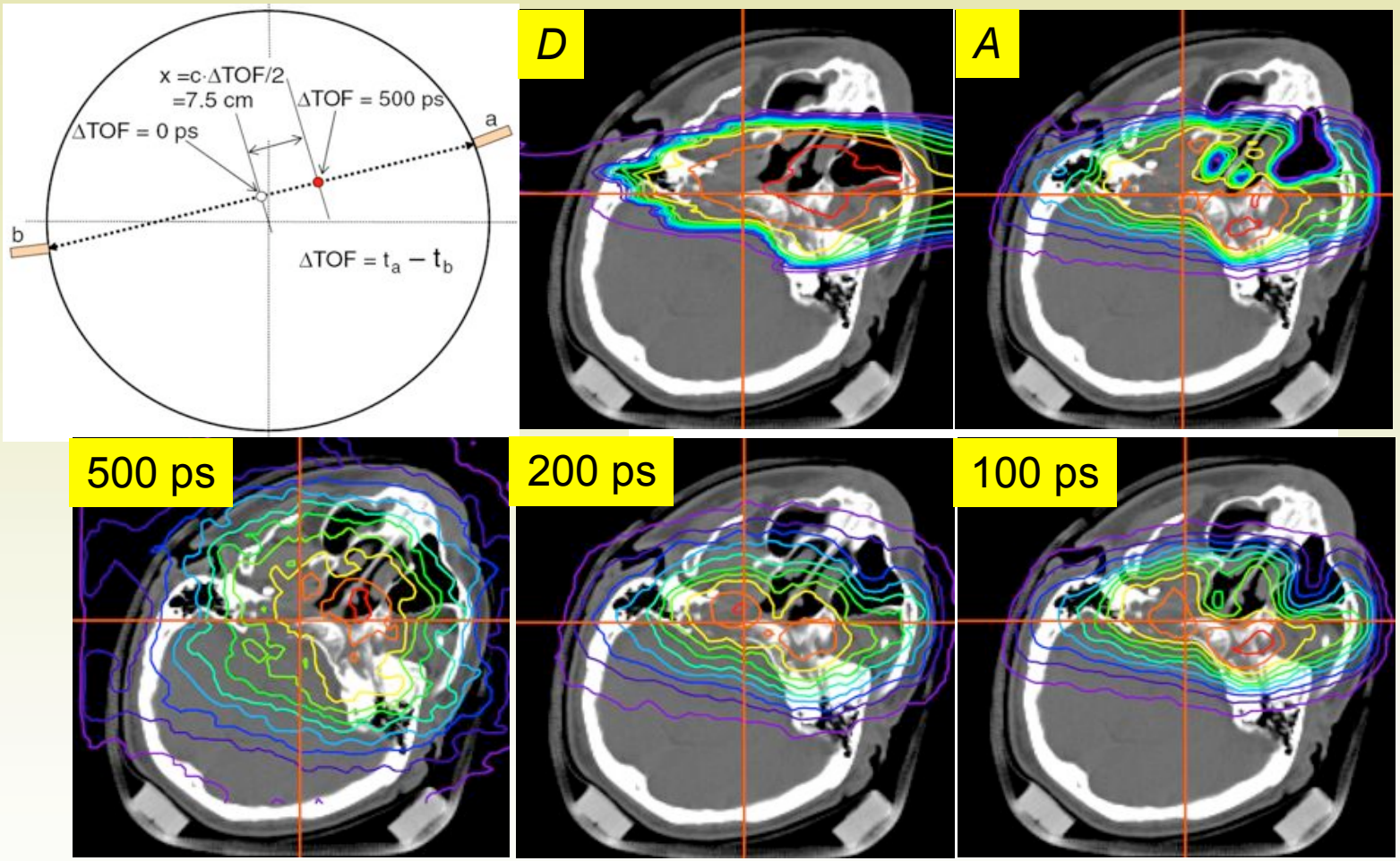


RESTRICTED REGION OF INTEREST: TIME OF FLIGHT



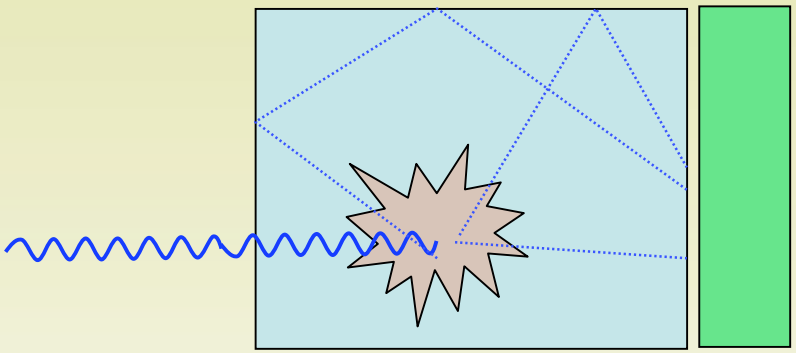


TIME OF FLIGHT PET SIMULATIONS



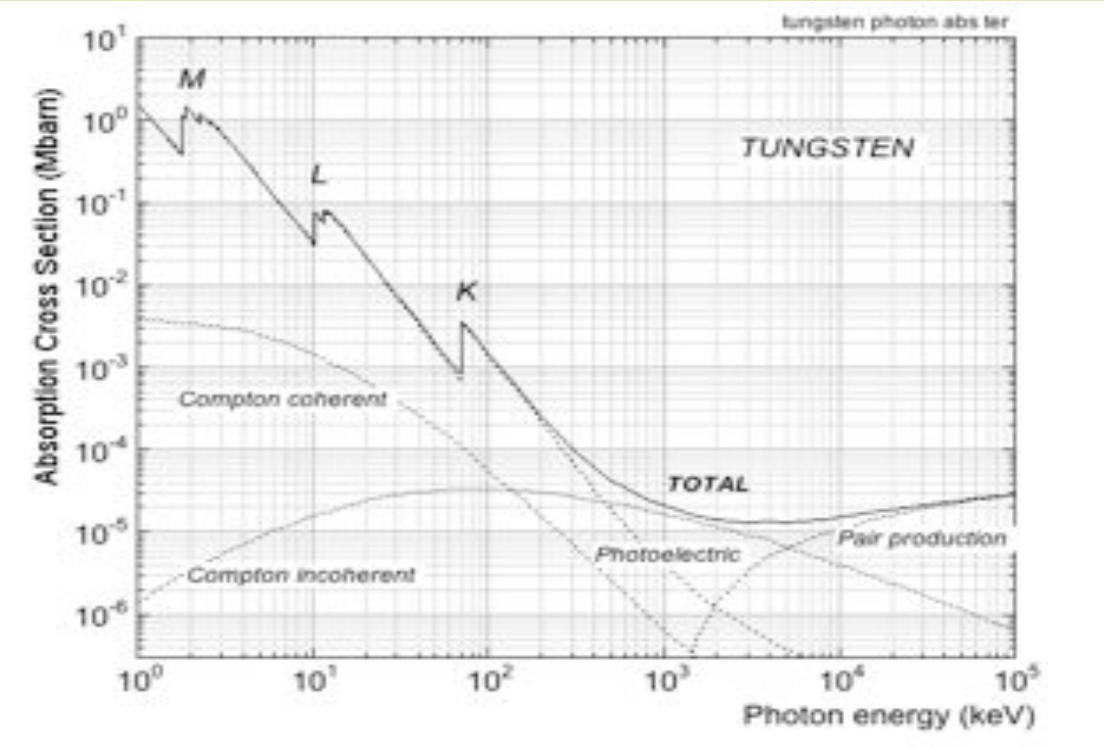
P. Crespo et al., Phys. Med. Biol. 52 (2007) 6795

IN-BEAM PET TOOLS



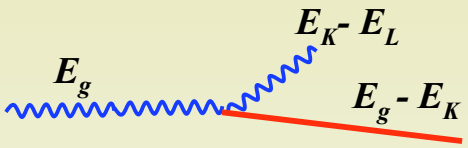
- HIGH ENERGY PHOTONS DETECTION
- HIGH-Z CRYSTAL SCINTILLATORS
- SENSORS: PHOTOMULTIPLIERS, SOLID STATE

PHOTON DETECTION: ENERGY DEPENDENCE

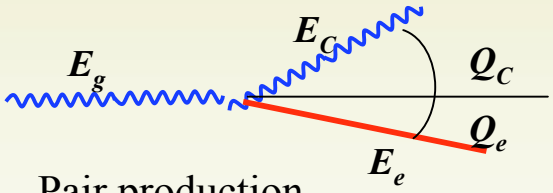


CONVERSION PROCESSES:

Photoelectric



Compton scattering



Pair production

A. Thompson et al, X-RAY DATA BOOKLET (2001)

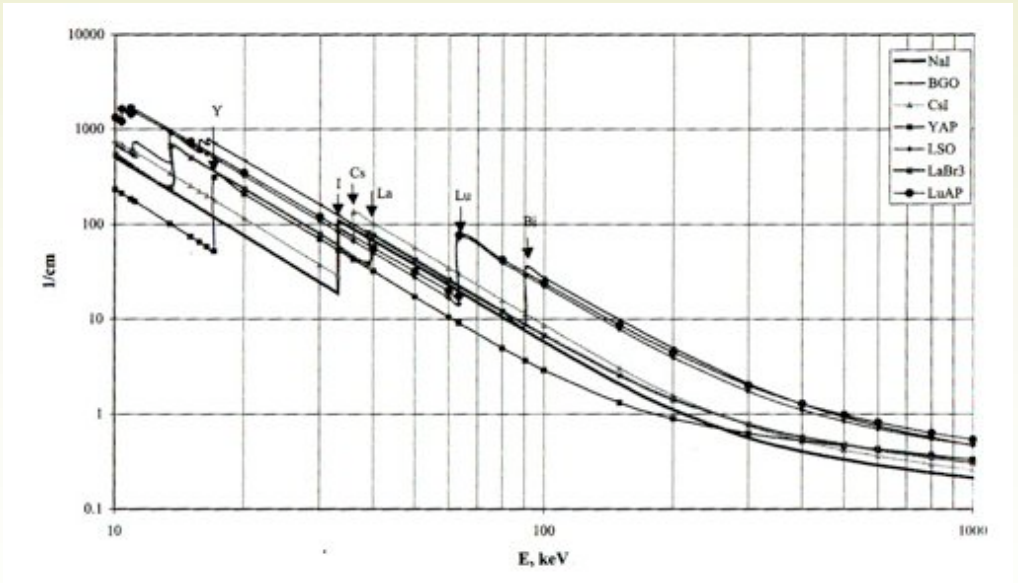
http://xdb.lbl.gov/
http://henke.lbl.gov/optical_constants/

INORGANIC SCINTILLATORS

	NaI	BGO	LSO:Ce	LYSO:Ce	LuAP:Ce
Density (g/cm^3)	3.67	7.13	7.40	7.1	8.34
Photofraction	0.17	0.35	0.32		0.30
Decay time (ns)	230	300	35-45	41	17
Light output (photons/MeV)	43000	8200	27000	32000	11400
Peak emission (nm)	415	480	420	420	365
Refraction index	1.85	2.15	1.82	1.97	1.97

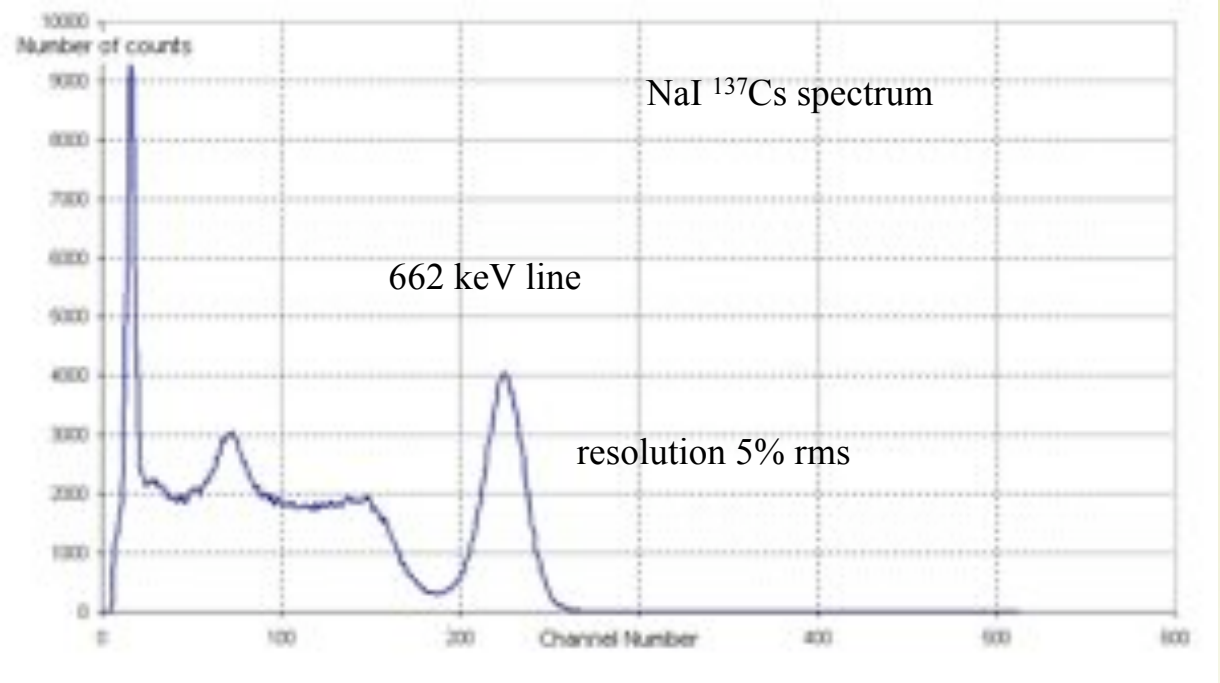
Gadolinium orthosilicate
Gd_2SiO_5 (GSO)
Lutetium orthosilicate
Lu_2SiO_5 (LSO)
Lutetium-yttrium orthosilicate
$Lu_{2(1-x)}Y_{2x}SiO_5$ (LYSO)

Cerium-activated:
$LaBr_3$:Ce, $Lu_2Si_2O_7$:Ce



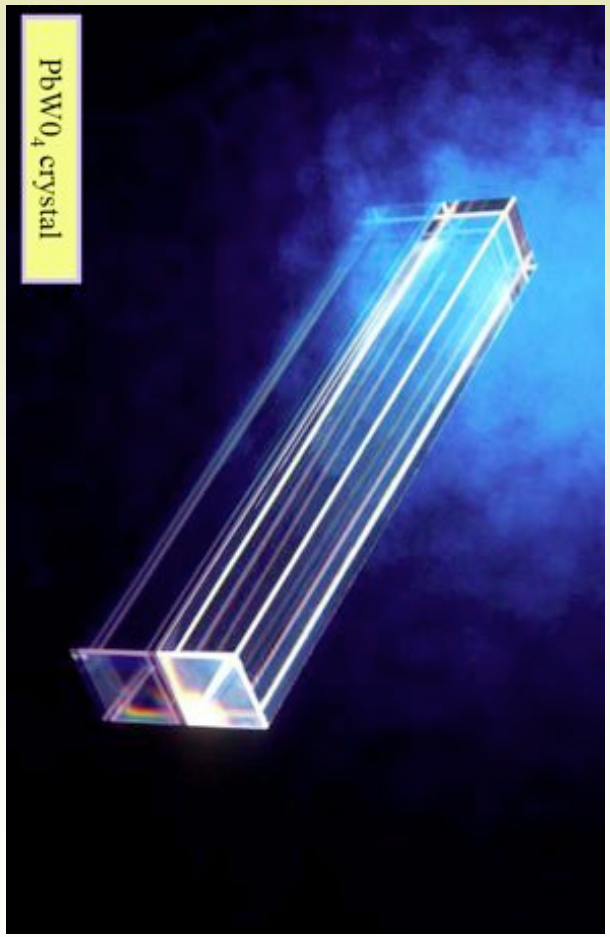
P. Lecoq et al, Inorganic Scintillators for Detector Systems (Springer 2006)

BEST SCINTILLATOR: SODIUM IODIDE

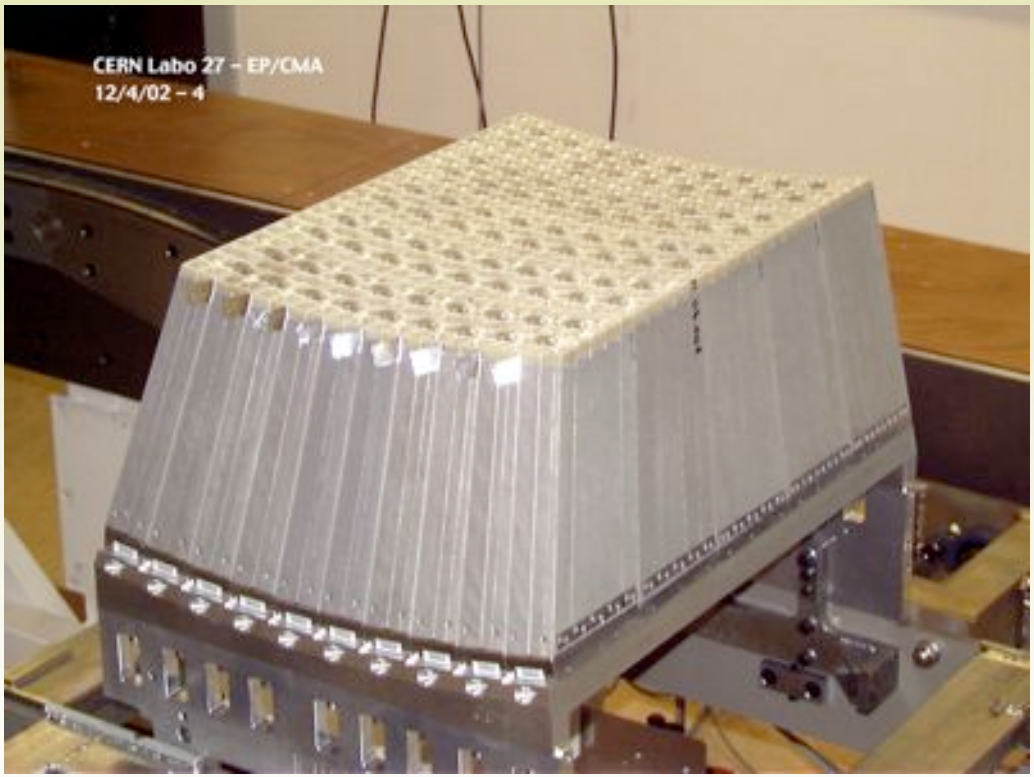


- HIGH LIGHT YIELD ~ 40,000 photons/MeV For 511 keV γ : ~ 20,000 photons
- HYGROSCOPIC
- LOW Z: X_0=2.6 cm -> THICK CRYSTALS -> DEPTH OF INTERACTION

HIGH-Z CRYSTAL SCINTILLATORS
LEAD TUNGSTATE ($PbWO_4$)



CMS ELECTROMAGNETIC CALORIMETER

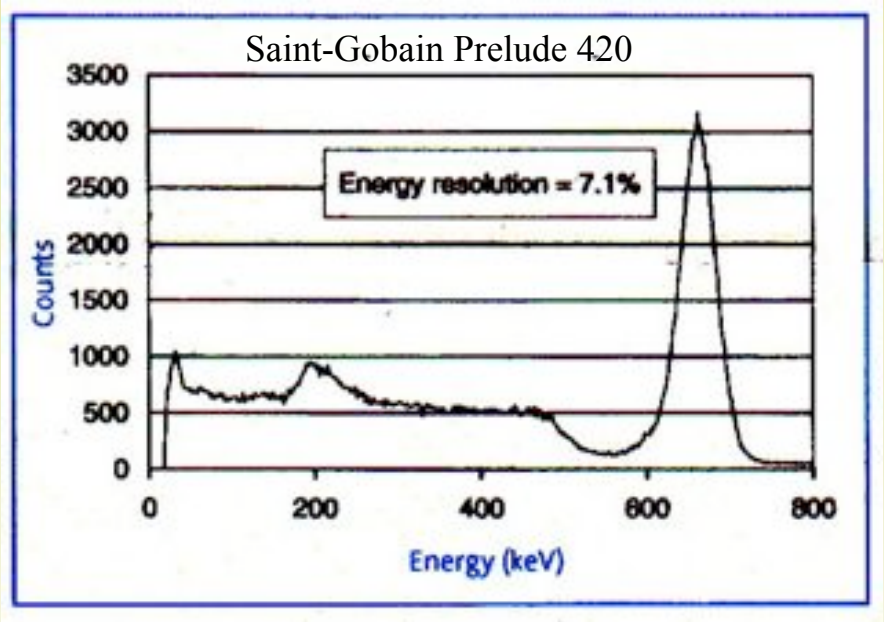


- HIGH Z: X_0 = 0.92 cm
- LOW LIGHT YELD: ~ 200 photons/MeV)

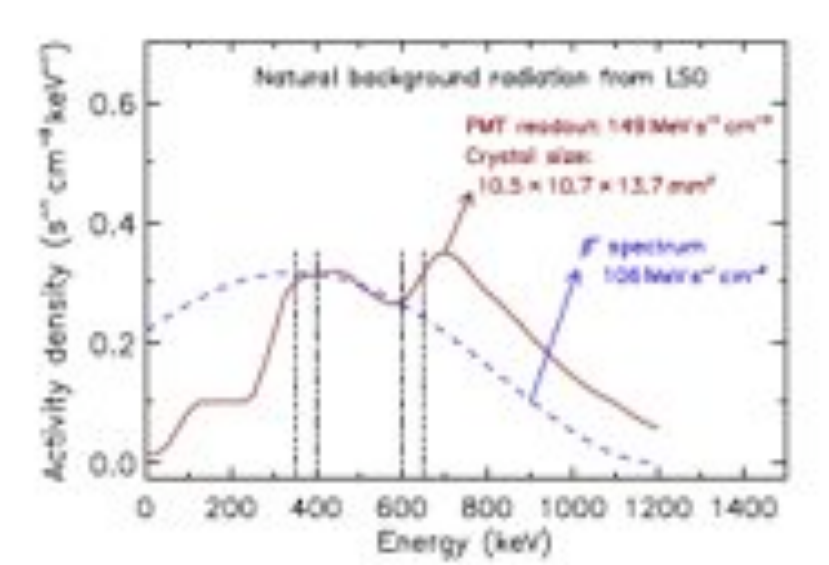
LYSO

$Lu_{1.8}Y_{.2}SiO_5$:Ce

- Density: 7.1 g/cm^3
- Attenuation length at 511 keV: 1.2 cm
- Emission peak: 420 nm
- Light yield: 32 photons/keV
- Decay time: 40 ns



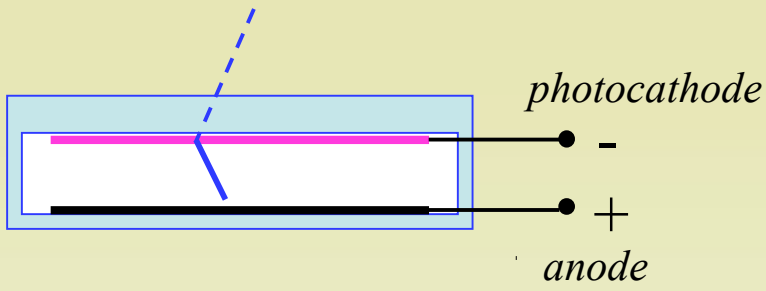
Radioactivity (from 2.6% ^{176}Lu)



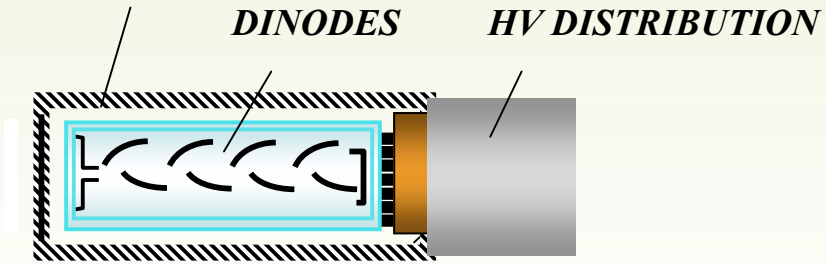
J. S. Huber et al, Phys. Med. Biol. 47(2002)3535

VACUUM PHOTODIODES

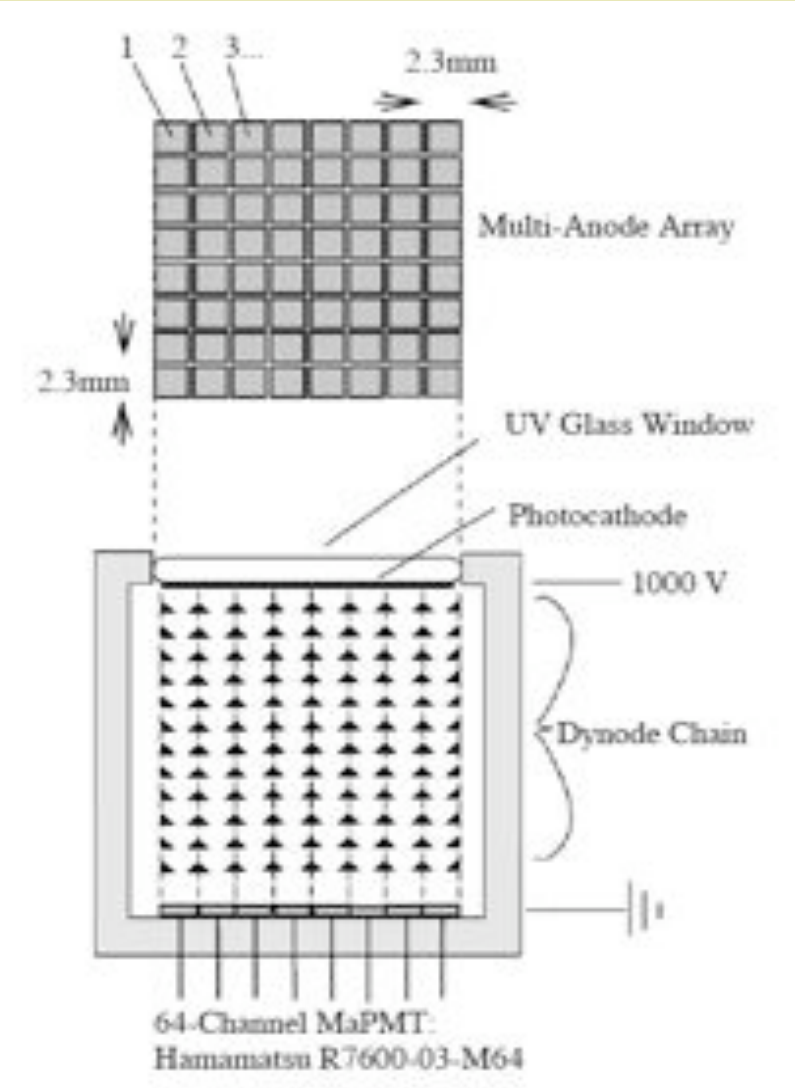
No gain



PHOTOMULTIPLIERS
High gain (> 10^5)

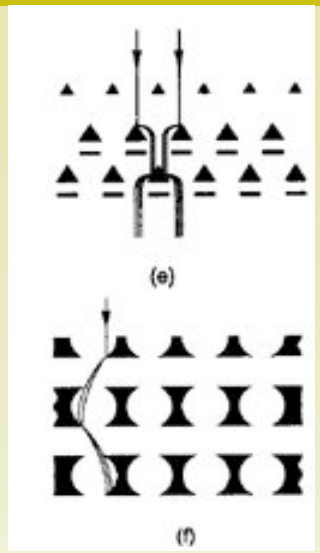


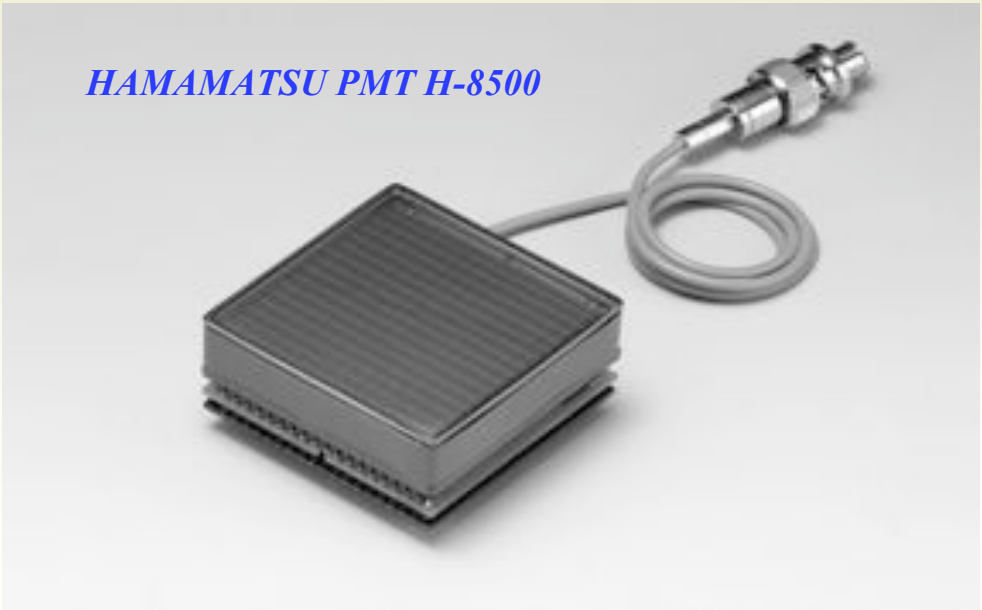
PLANAR MULTIANODE PHOTOMULTIPLIERS



- Square flat window
- Position-sensitive

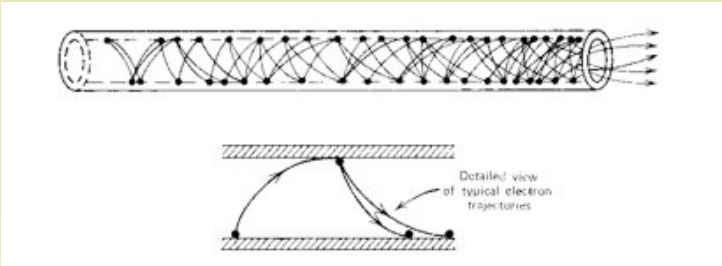
Amplification by collisions in a set of specially shaped metal grids



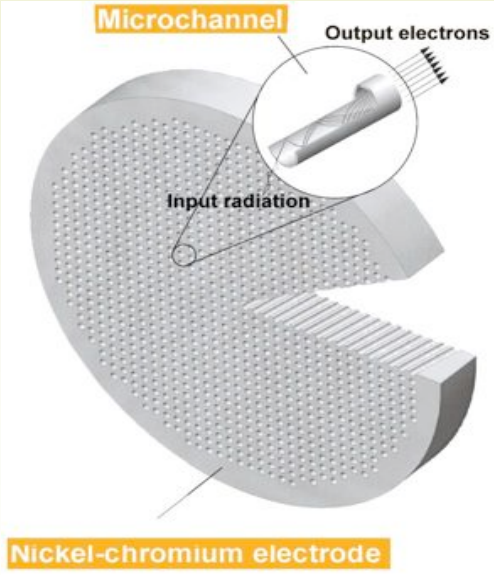


MICROCHANNEL PLATE MULTIPLIER (MCP)

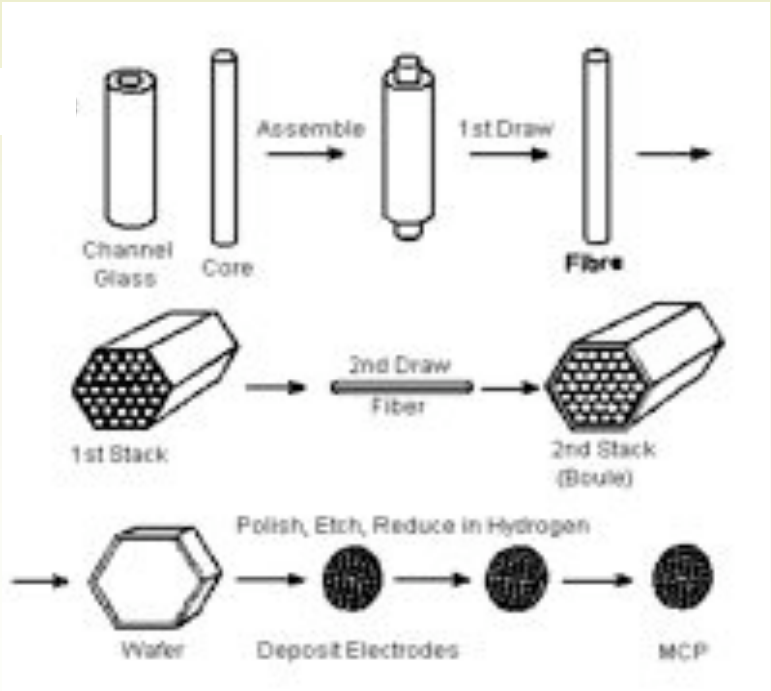
SINGLE CHANNEL:



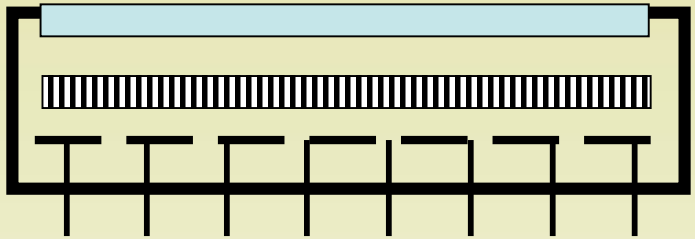
MULTIPLE CHANNELS:

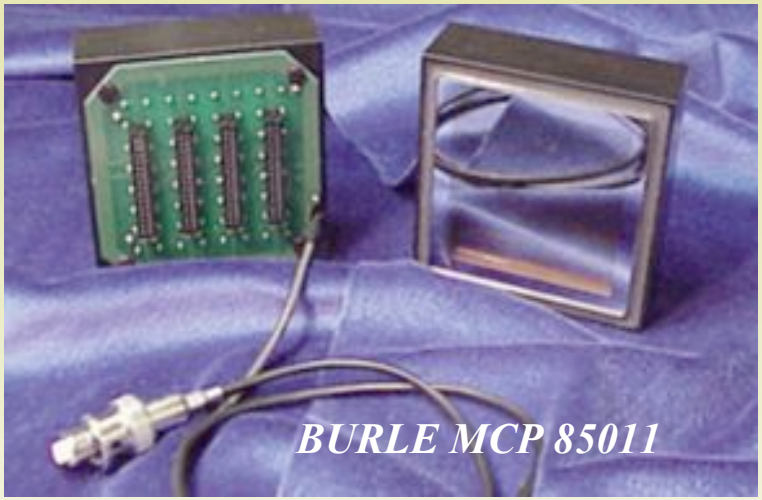


MCP MANUFACTURING:

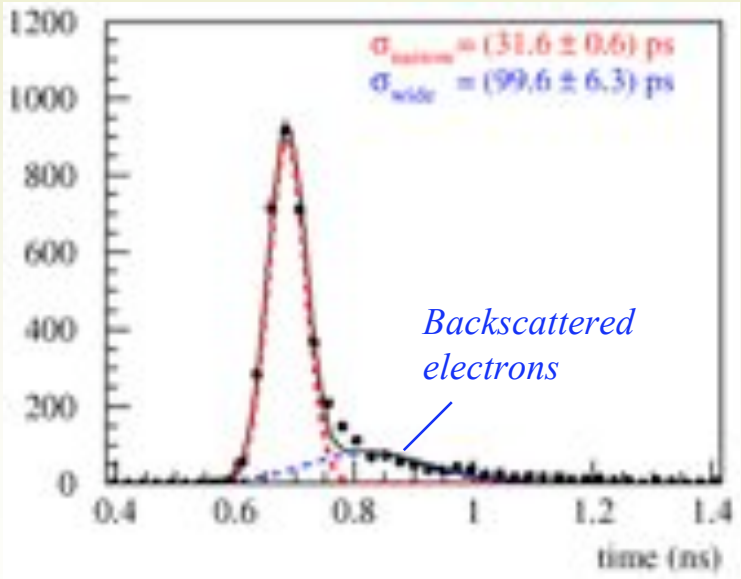


MULTIANODE PHOTOMULTIPLIERS WITH MICROCHANNEL PLATE AMPLIFIER

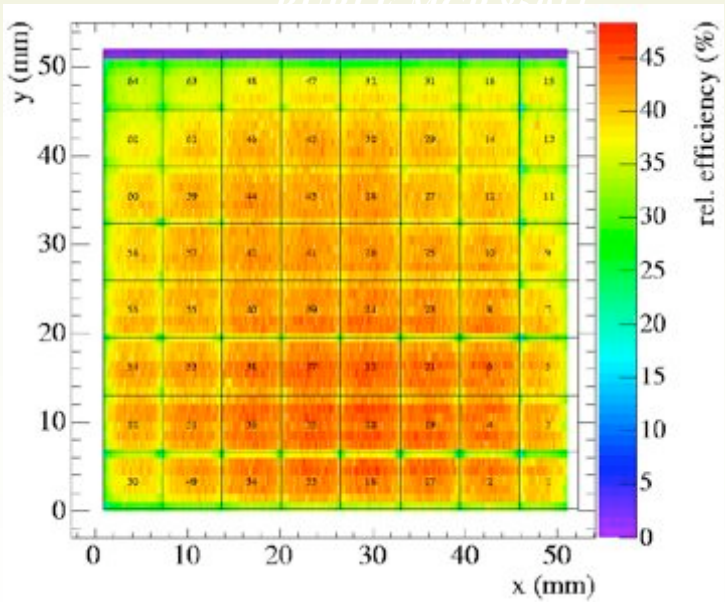




TIME RESPONSE (ON LASER PULSE):



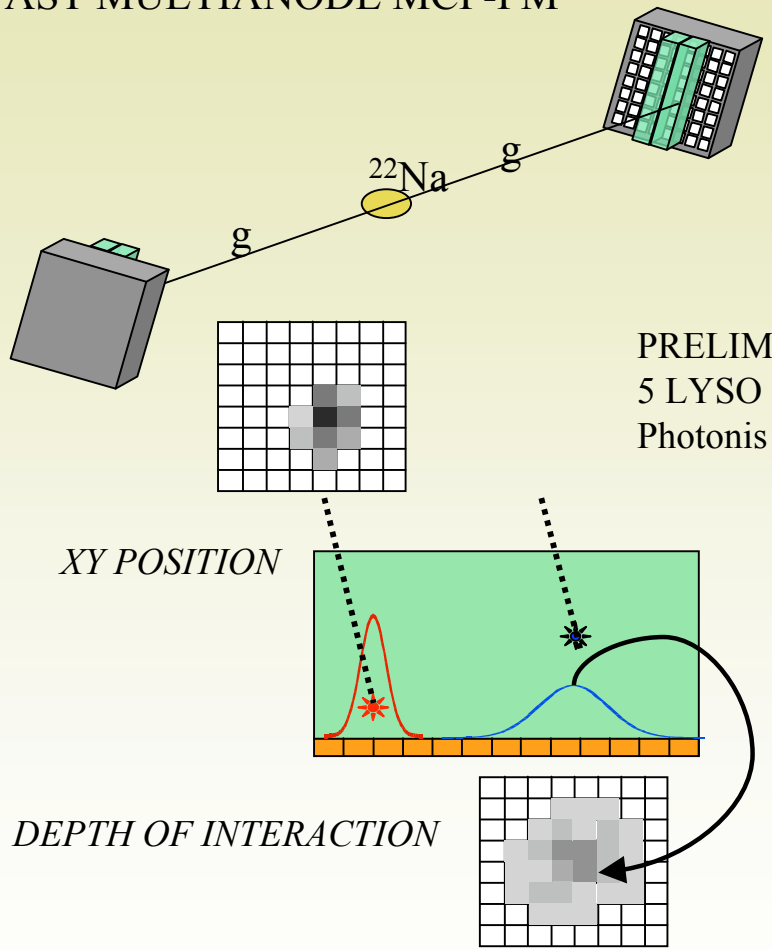
RELATIVE RESPONSE (QUANTUM EFFICIENCY)



T. Hadig et al, IEEE-NSS04 (N35-2)
C. Field et al, Nucl. Instr. and Meth. 518(2004)565

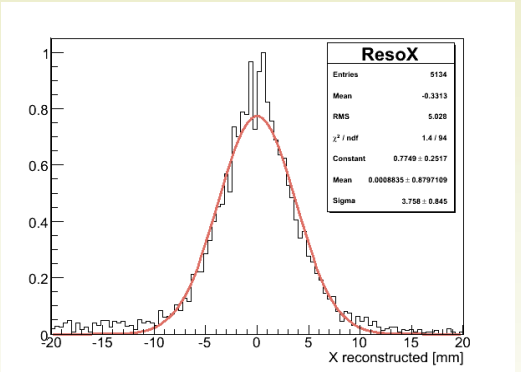
DEPTH OF INTERACTION DETERMINATION

POSITION AND DOI DETERMINATION
FROM PULSE HEIGHT ON SEGMENTED
FAST MULTIANODE MCP-PM



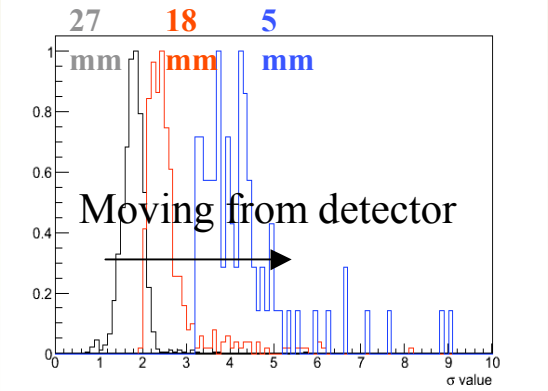
TERA-AQUA SETUP

PRELIMINARY RESULTS
5 LYSO Crystals 12x30x60 mm^3
Photonis XP85013 MCP-PMT



X-position:
2 mm rms

DOI:
10 mm rms

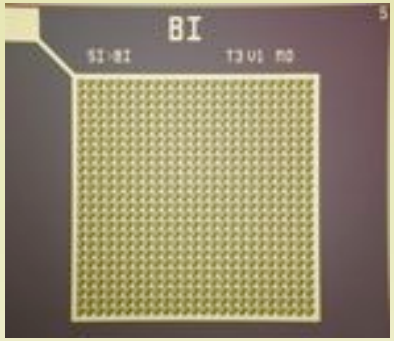


D. Watts, ENVISION WP2 Meeting (CERN 2.2.10)

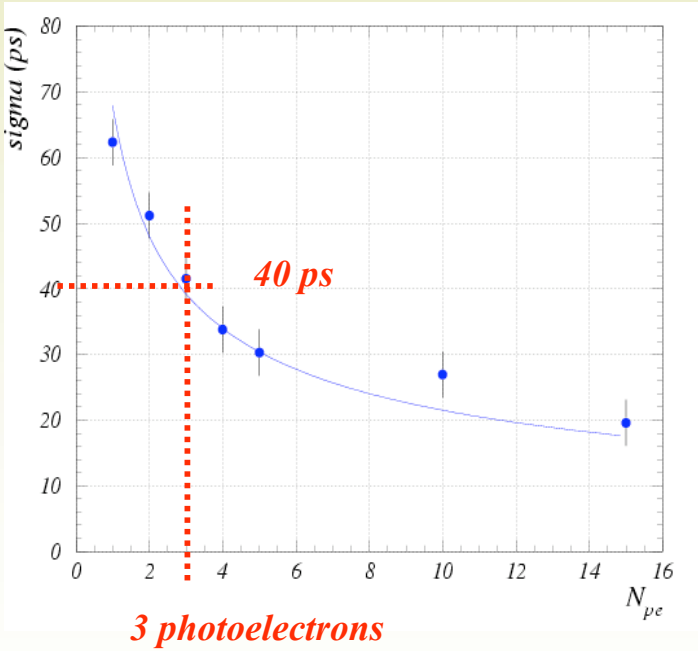
SILICON PHOTOMULTIPLIER/MULTI-PIXEL PHOTON COUNTER

Light sensors: Silicon Photomultiplier (SiPM, MPPC)
Multi-cell Geiger mode:

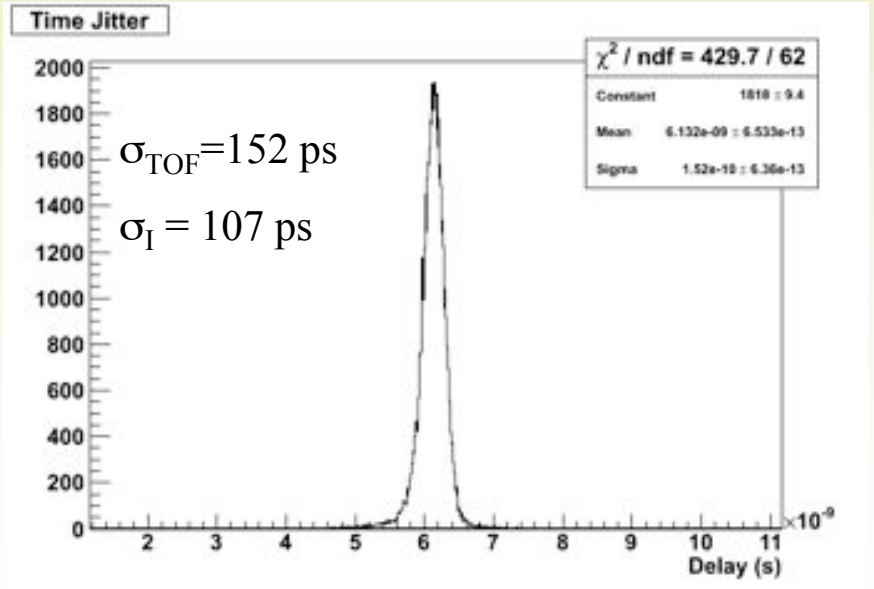
- High QE (70%)
- High gain ~ 10^6
- Single photon counting - linear response



INTRINSIC TIME RESOLUTION VS NUMBER OF PHOTOELECTRONS (PULSED LASER SOURCE):



LSO:Ce, Ca doped

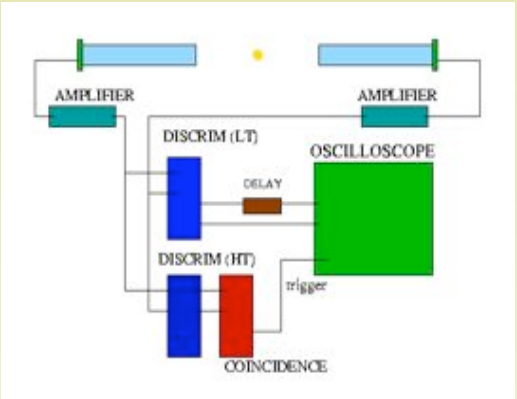


G. Collazuol et al, Nucl. Instr. and Meth. A581(2007)471

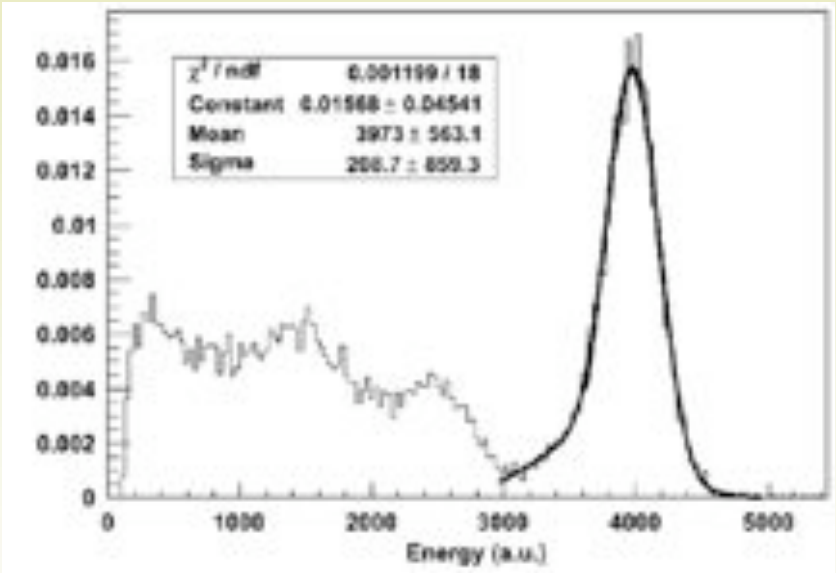
A. Del Guerra et al (INFN Pisa)

SILICON PHOTOMULTIPLIER PERFORMANCES

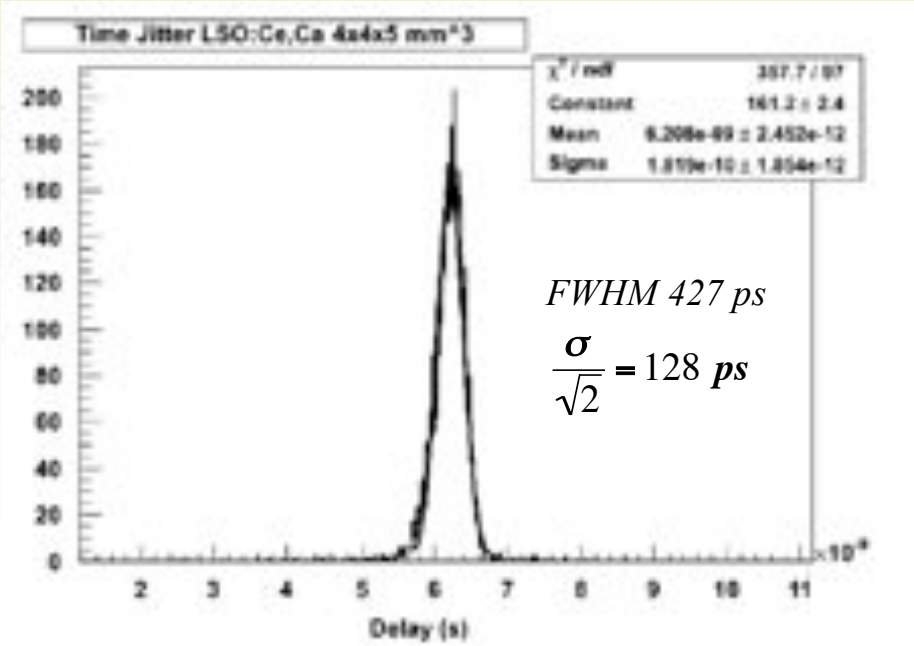
FAST SMALL SIZESCINTILLATORS
LSO:Ce-Ca 4x4x5 mm^2



ENERGY RESOLUTION ON ^{22}Na (511 keV)



TIME RESOLUTION:

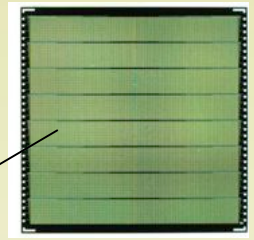


M.C. Bisogni et al,
Subm. Nucl. Instr. and Meth. (2010)

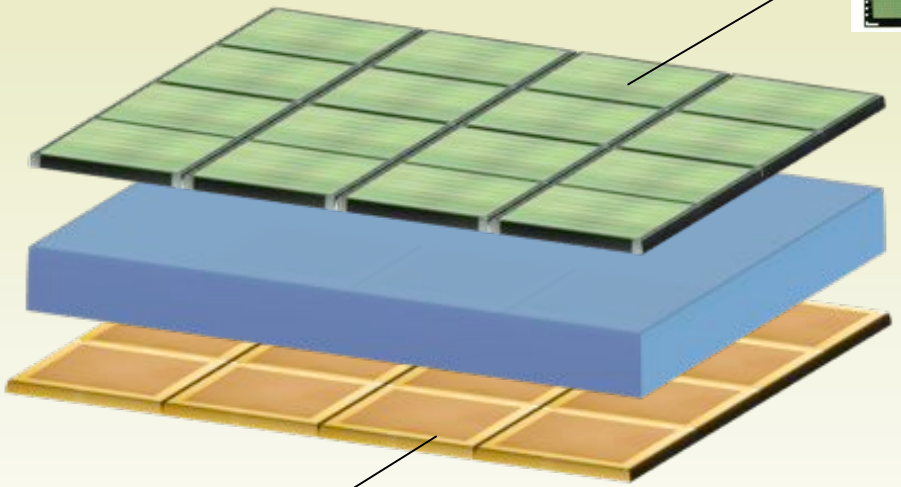
INTEGRATED SCINTILLATOR+SiPM

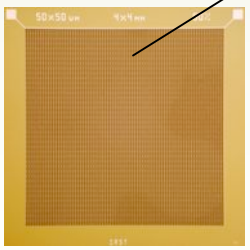
$LaBr_3$ SCINTILLATORS WITH SiPM SENSORS

INFN Pisa - IFIC Valencia (ENVISION WP2)

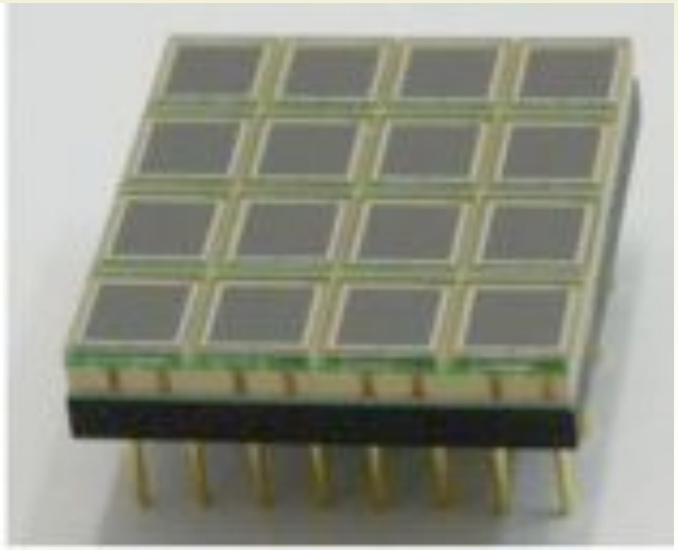


SiPM matrix
8x8 pixels 1.5 mm pitch
High granularity
High spatial resolution





Single SiPM 4x4 mm^2
Low granularity
High time resolution



STATISTICAL LIMIT ON TIME RESOLUTION

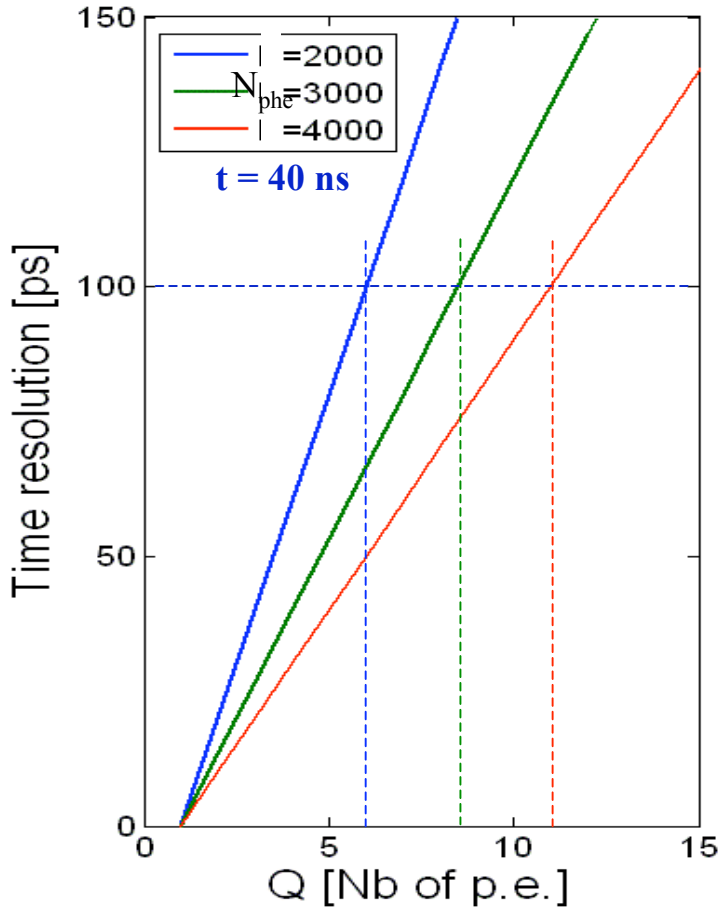
$$\Delta t \propto \frac{\sqrt{\tau}}{\sqrt{N_{phe}/ENF}}$$

Decay time

Photodetector excess noise factor

Nunmber of photorelectrons

LYSO 2x2x20 mm^3, 511 keV g
N_{phe}/ENF ~ 2200

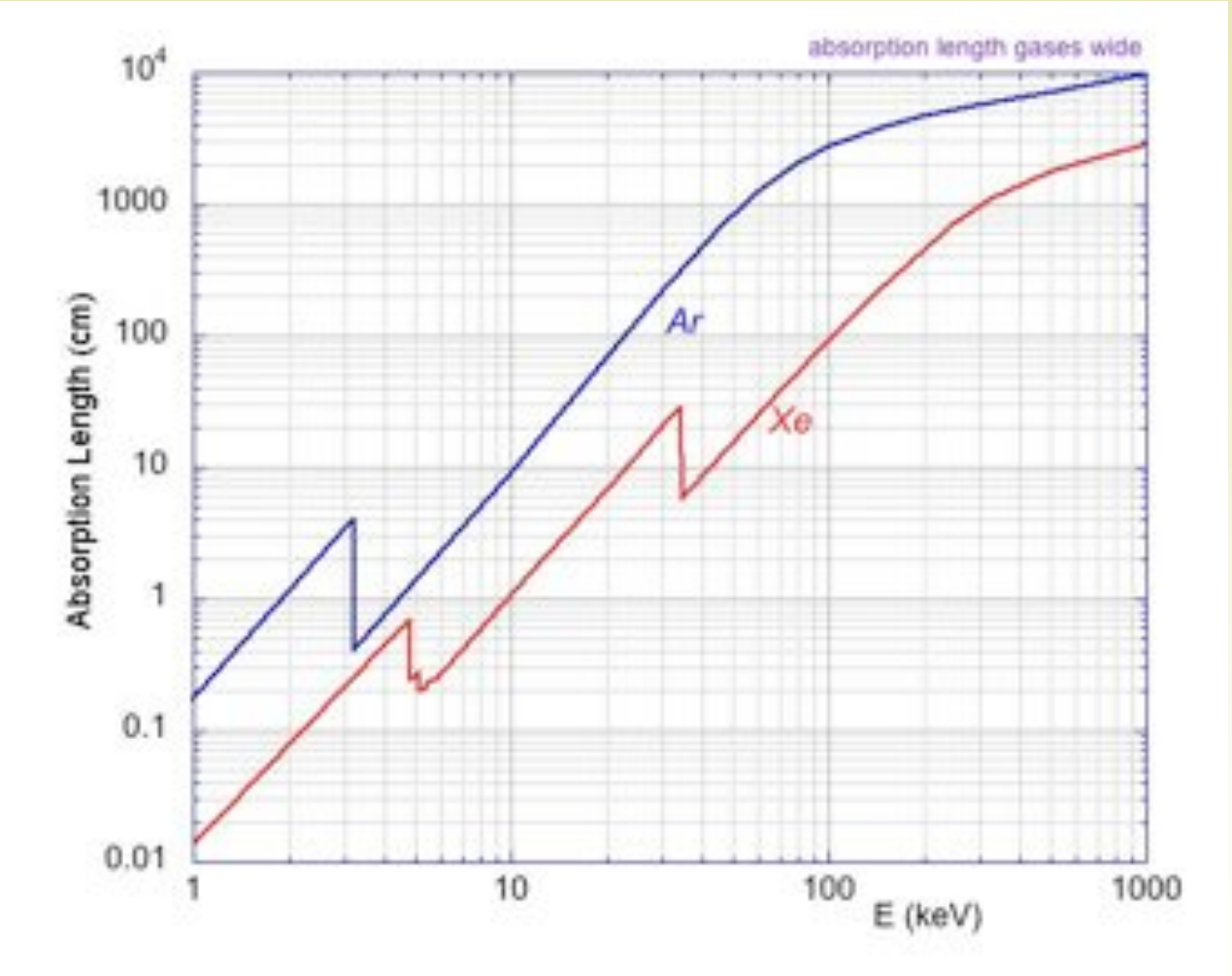


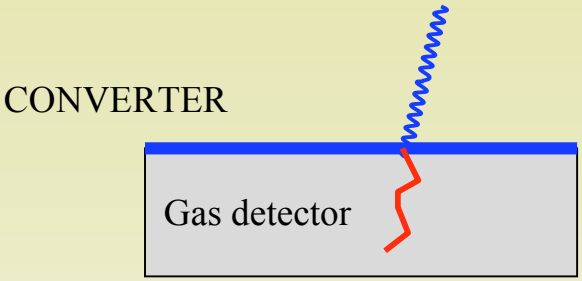
- SCINTILLATION RISE TIME LIMIT
- INTERNAL LIGHT TRANSPORT LIMITS

For a 2x2x20 mm^3 LSO crystal the intrinsic time spread due to travel path is 342 ps peak to peak (142 ps FWHM)

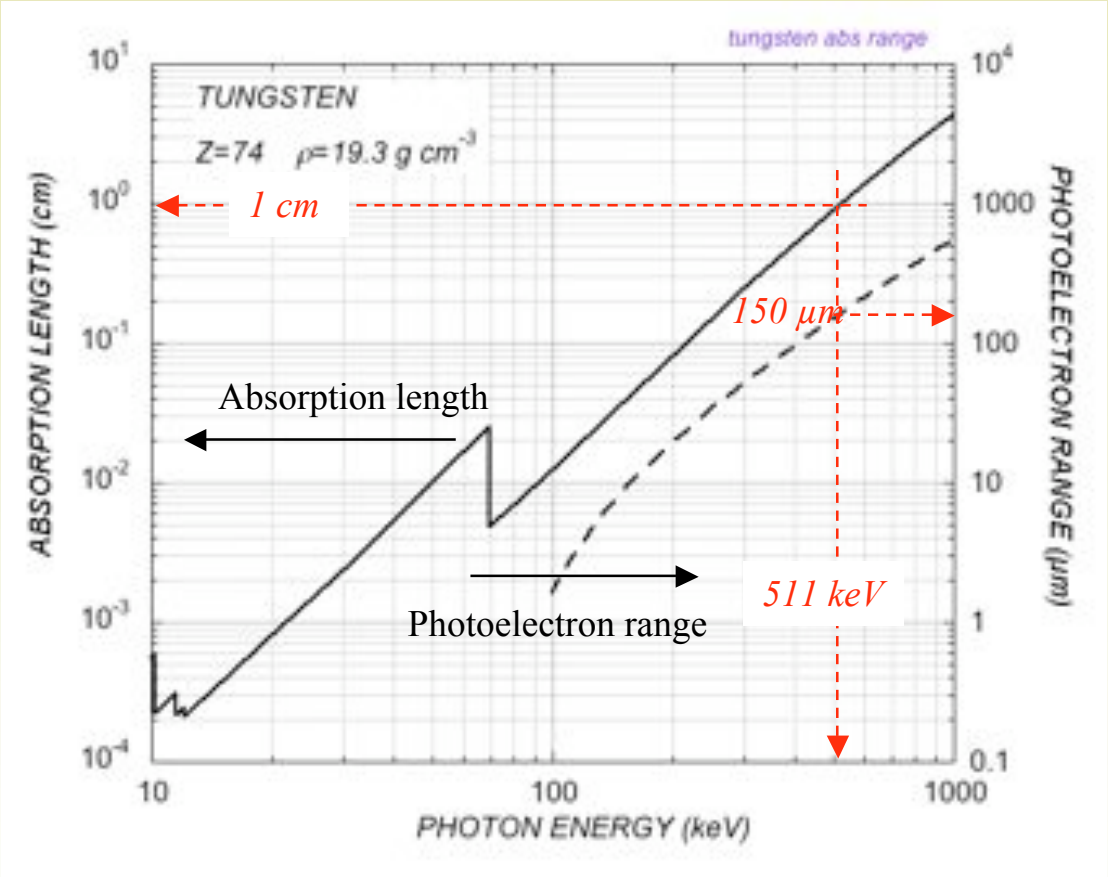
P. Lecoq, ENVISION Meeting (CERN 3.2.2010)

ABSORPTION LENGTH FOR GASES AT NTP:

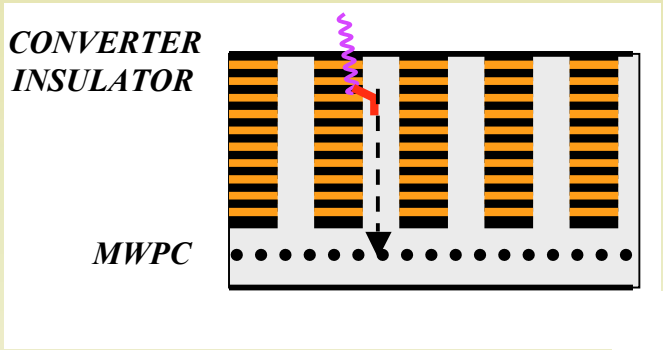




For 511 keV photons the 441 keV photoelectron (511-70) has a range in Tungsten of 150 µm.
The optimum thickness of the converter is around 100 µm, ~ 1/100 of the absorption length, so the theoretical detections efficiency is ~ 1%.

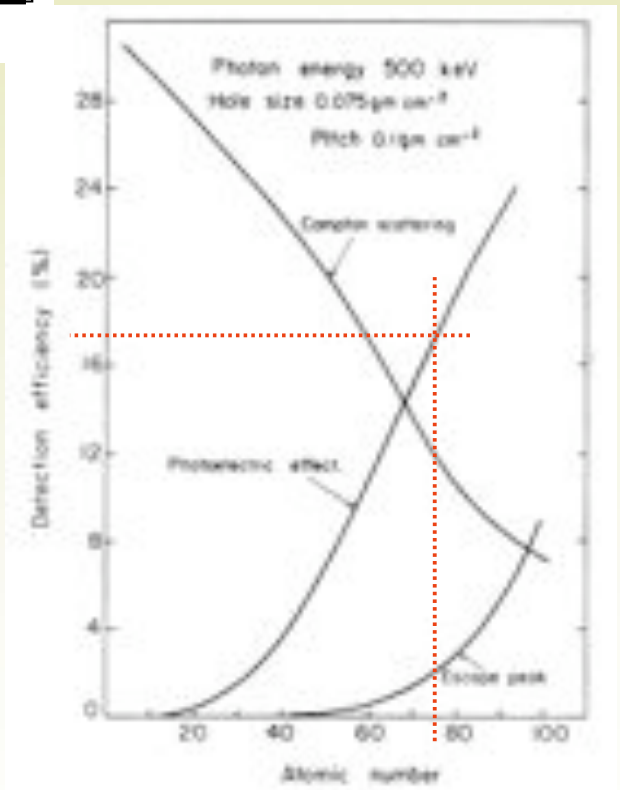


HIGH DENSITY AVALANCHE CHAMBER (HIDAC) 1980-90

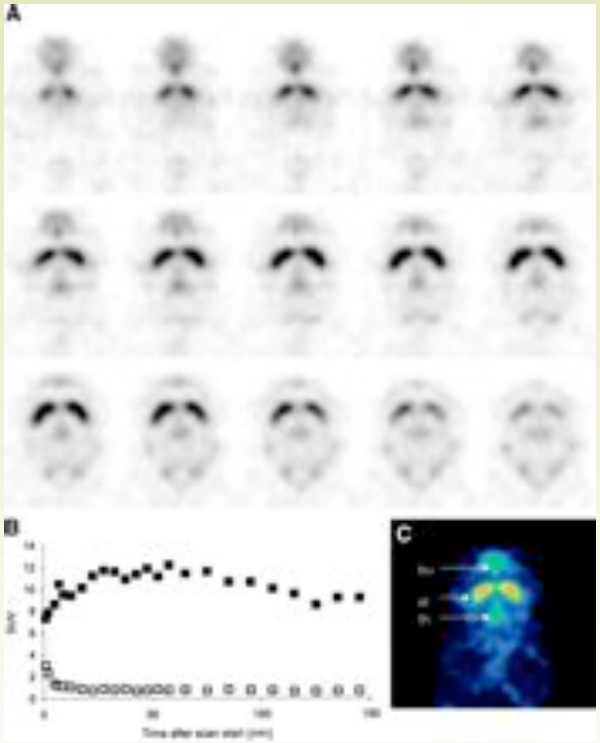


FOR TUNGSTEN (A=74) ε ~ 17%

TIME RESOLUTION 50-100 ns



CORONAL SECTIONS OF A ^{18}F-FALLYPRIDE LABELLED MOUSE
0.3 mm SLICES

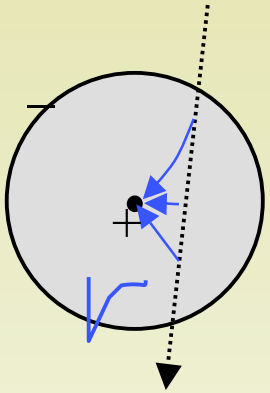


M. Honer et al,
J.Nucl. Med.45(2004)464

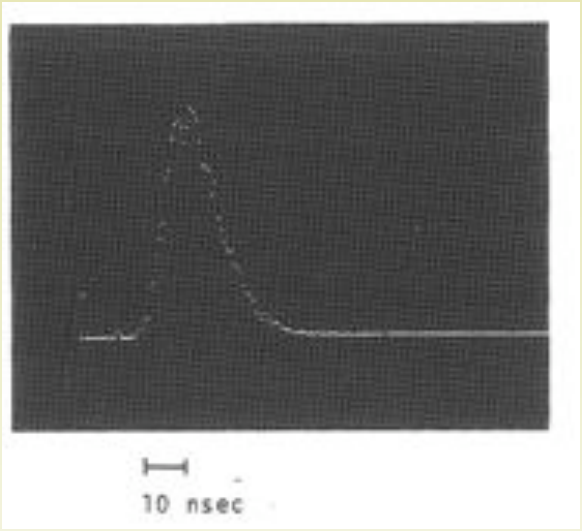
A. P. Jeavons, Nucl. Instr. and Meth, 156(1978)41
D. Townsend, Nucl. Instr. and Meth, A269(1988)443

TIME RESOLUTION OF GASEOUS DETECTORS

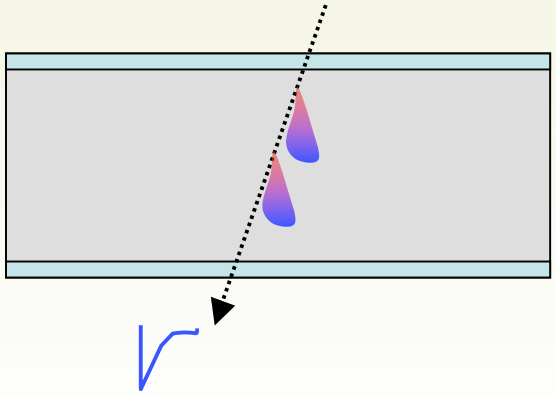
WIRE PROPORTIONAL COUNTERS AND CHAMBERS:



Average distance between ion pairs (MIPS) ~ 300 μm
Drift velocity ~5 cm/μs
Avalanche amplification at wires
Time resolution 5-10 ns



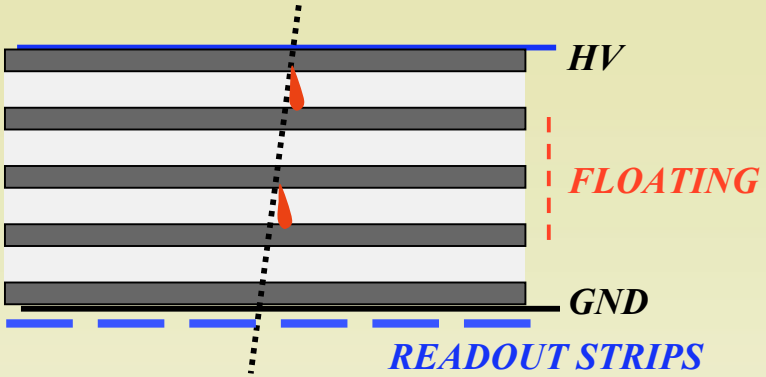
PARALLEL PLATE COUNTERS:



Avalanches start all through the gap
Instant signal induction on electrodes
Time resolution 1-2 ns for ~ mm gaps

WIDE GAP: GOOD EFFICIENCY
NARROW GAP: GOOD TIME RESOLUTION

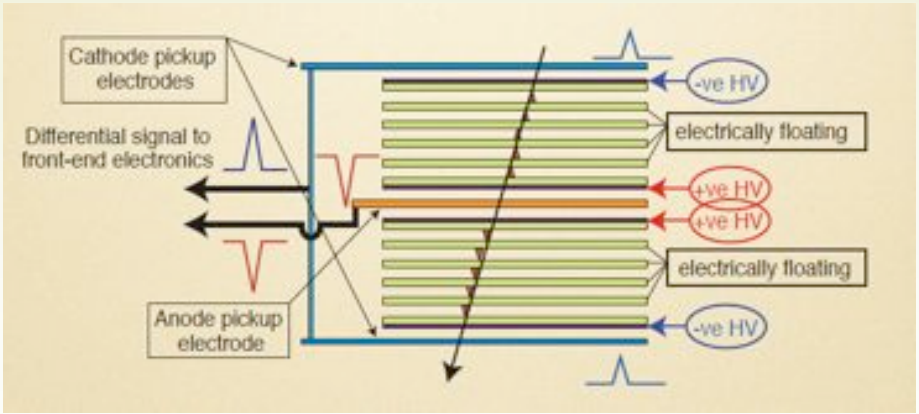
MULTIGAP RESISTIVE PLATE CHAMBERS

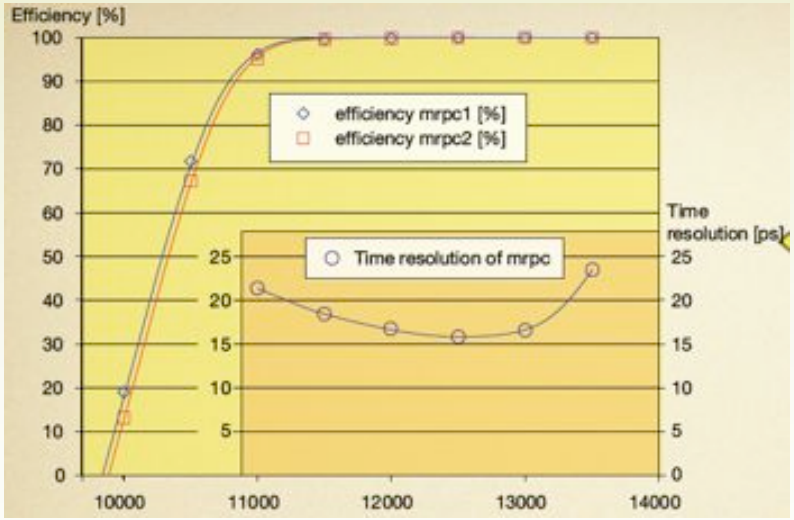


STACK OF INDEPENDENT NARROW GAP PPC
HV AND GROUND ON EXTERNAL ELECTRODES
FLOATING INTERNAL ELECTRODES
COMMON EXTERNAL SIGNAL PICKUP

E. Cerron Zeballos et al, Nucl. Instr. and Meth. A 374(1996)132

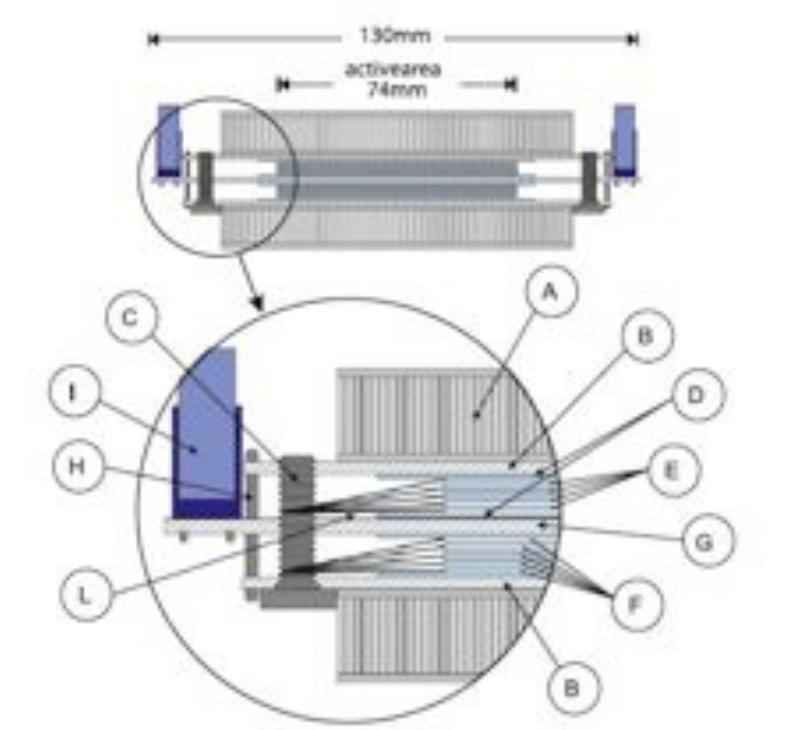
ALICE TOF PARTICLE IDENTIFIER





A. Akindinov et al, Nucl. Instr. and Meth. A533(2004)74

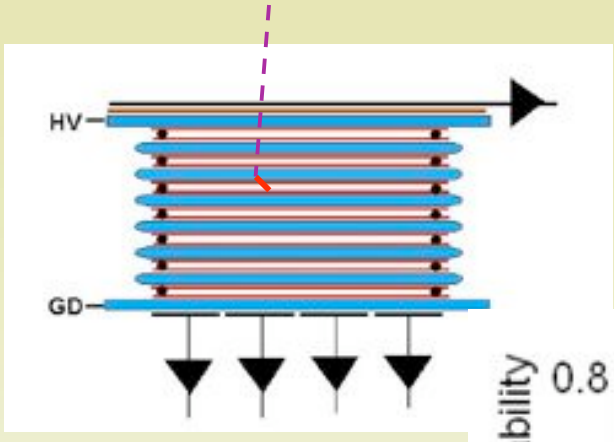
ALICE TIME OF FLIGHT PARTICLE IDENTIFICATION

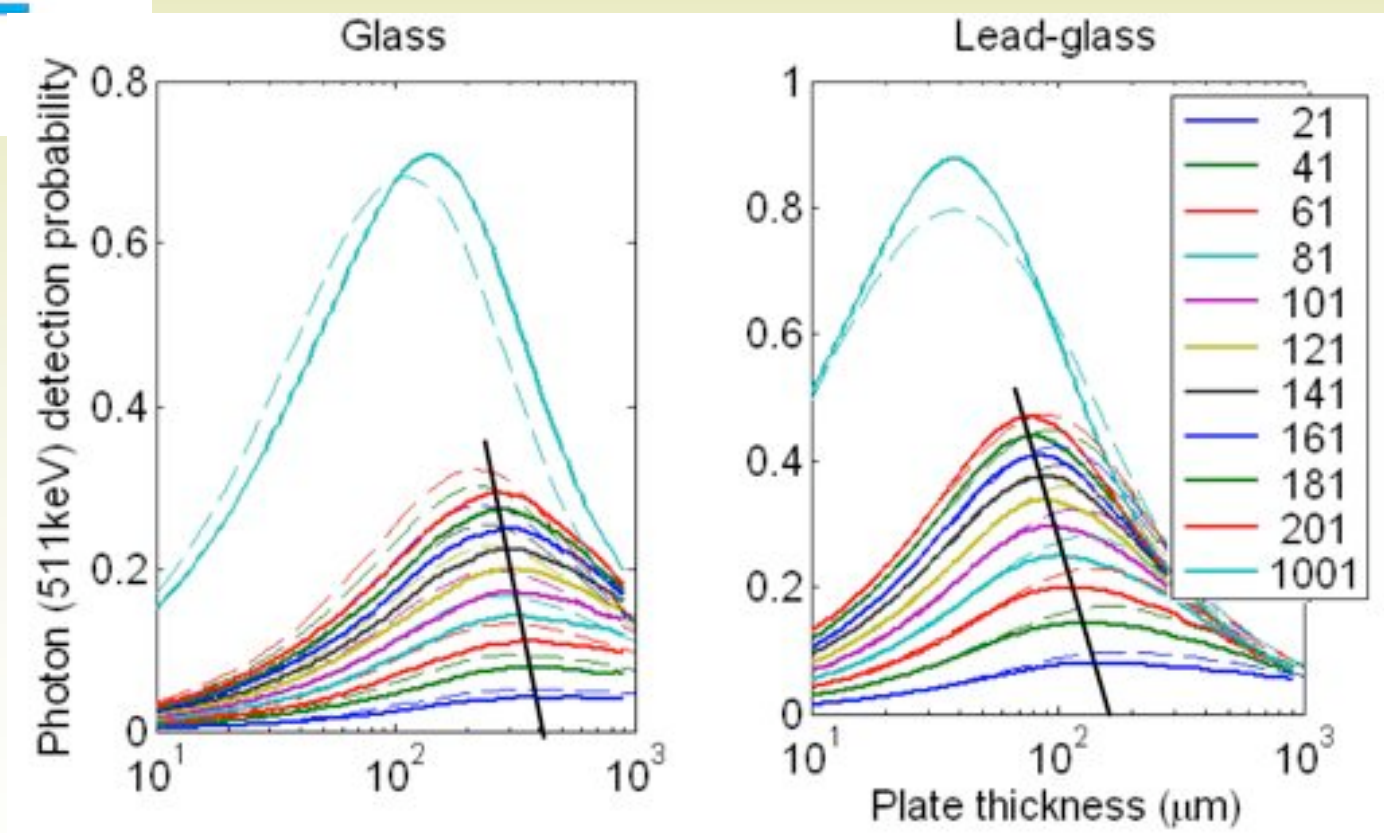


~ 150 m^2 INSTALLED AND OPERATING

TOF RESOLUTION FOR PARTICLES:
σ = 55 ns

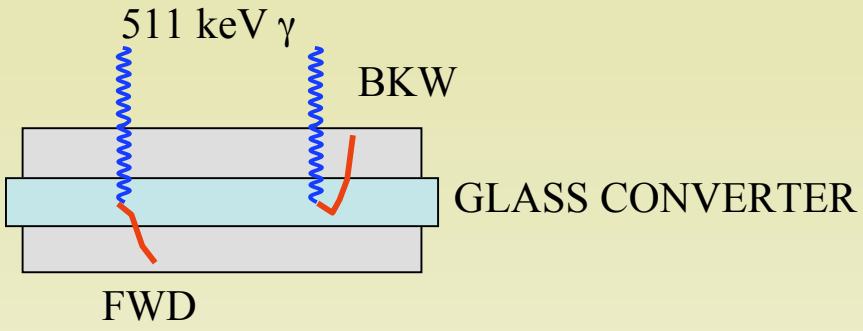
MULTIGAP RPC EFFICIENCY



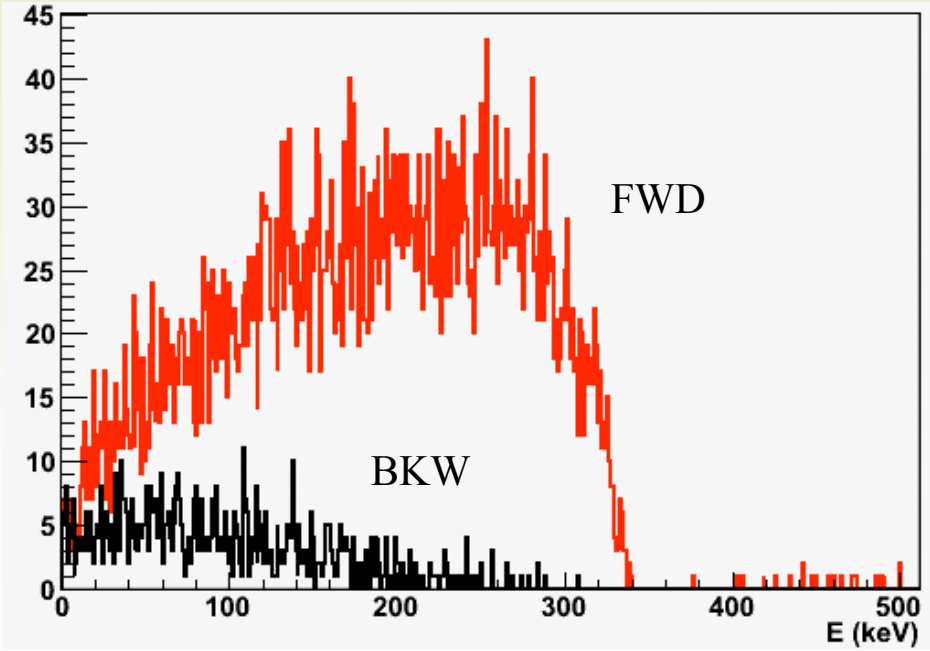


GEANT4 Calculation by P. Fonte (Imaging 2006)

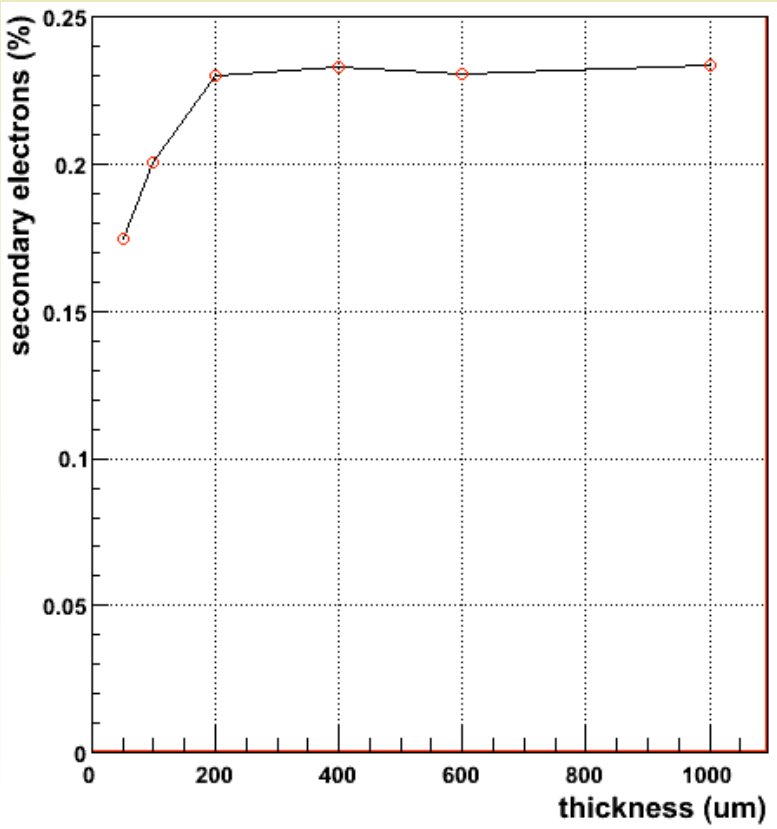
MRPC SIMULATIONS (GEANT4)



EJECTED ELECTRONS ENERGY SPECTRA



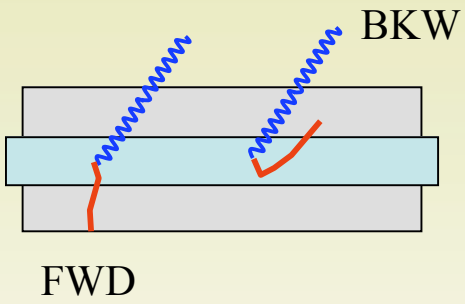
EFFICIENCY VS GLASS THICKNESS (FWD+BKW):



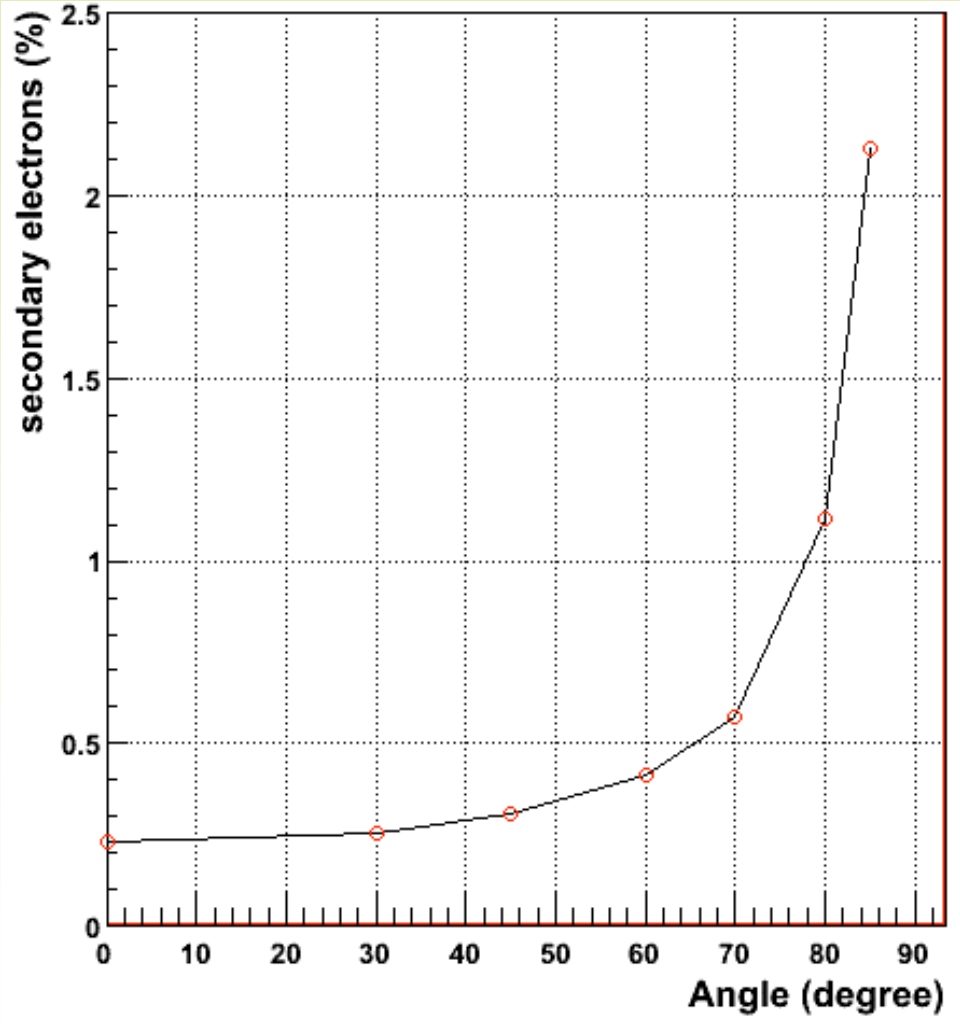
J. Samarati, TERA-AQUA (Sept. 2010)

MRPC SIMULATIONS (GEANT4)

GRAZING INCIDENCE:



EFFICIENCY VS INCIDENCE ANGLE OF PHOTONS FWD+BKW:



J. Samarati, TERA-AQUA (Sept. 2010)

GRAZING INCIDENCE PET DETECTOR DESIGN