SIEMENS

Positron emission tomography (PET)

- past, present and future

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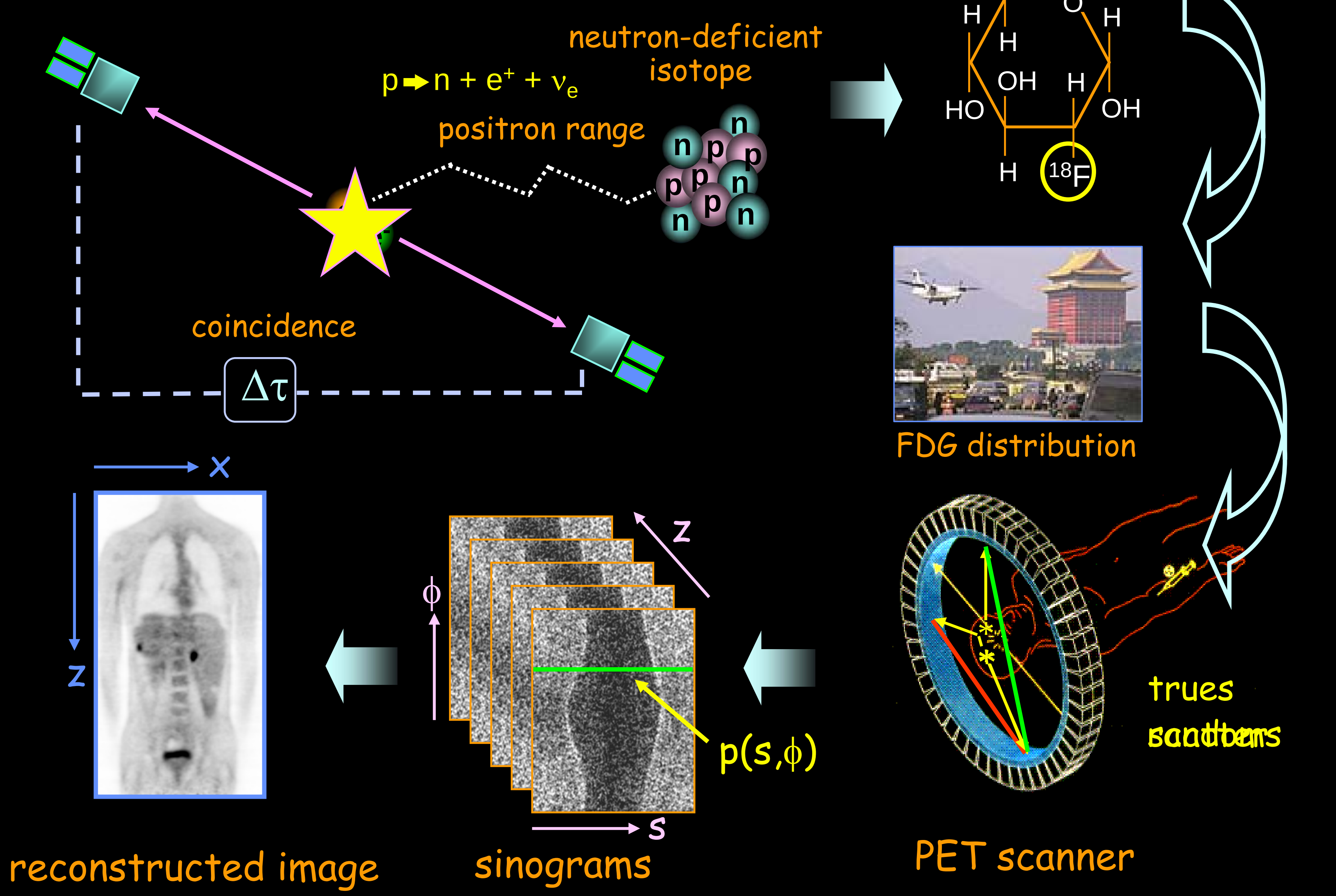
Presentation Overview

- **Basic PET Principles**
- **The earlier four PET generations**
- **Detectors for PET- scintillators combined with photo sensors**
  - scintillators
- **Current (5th?) generation of whole body PET/CT systems**
  - The HiRez block detector
  - PET/CT systems
  - PET/CT examination
  - Clinical image information
- **Brain studies**
  - The HRRT system
- **Future PET systems**
  - Search for higher spatial resolution and sensitivity
  - Improved image reconstructions
- **Time of Flight (TOF) issues**
  - TOF sensitivity gains
- **Conclusions**

Clinical imaging with PET

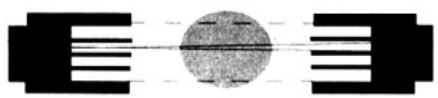


Positron Emission Tomography

Four generation of PET systems

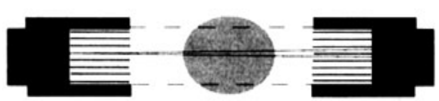
First generation PET (1975-1980)
- NaI(Tl) systems;
- 1 image slice
- spatial resolution ~ 10-15 mm

Examples: PETT3, ECAT2, KS_PET



Second generation PET (1981-1987)
- BGO multiring systems;
- 7 image slices
- spatial resolution ~ 7-8 mm

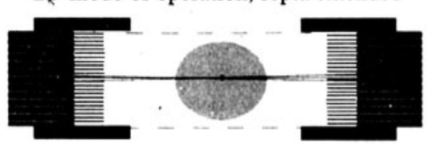
Examples: NeuroECAT, SCX PC384-7B



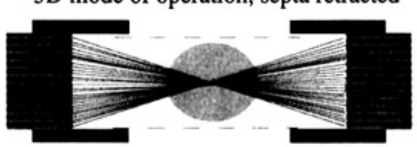
Third generation PET (1988-1992)
- block-detector concept
- 15 -31 image slices
- increased spatial resolution (5-6 mm)

Examples: PC2048-15B, ECAT 853

2D mode of operation, septa extended



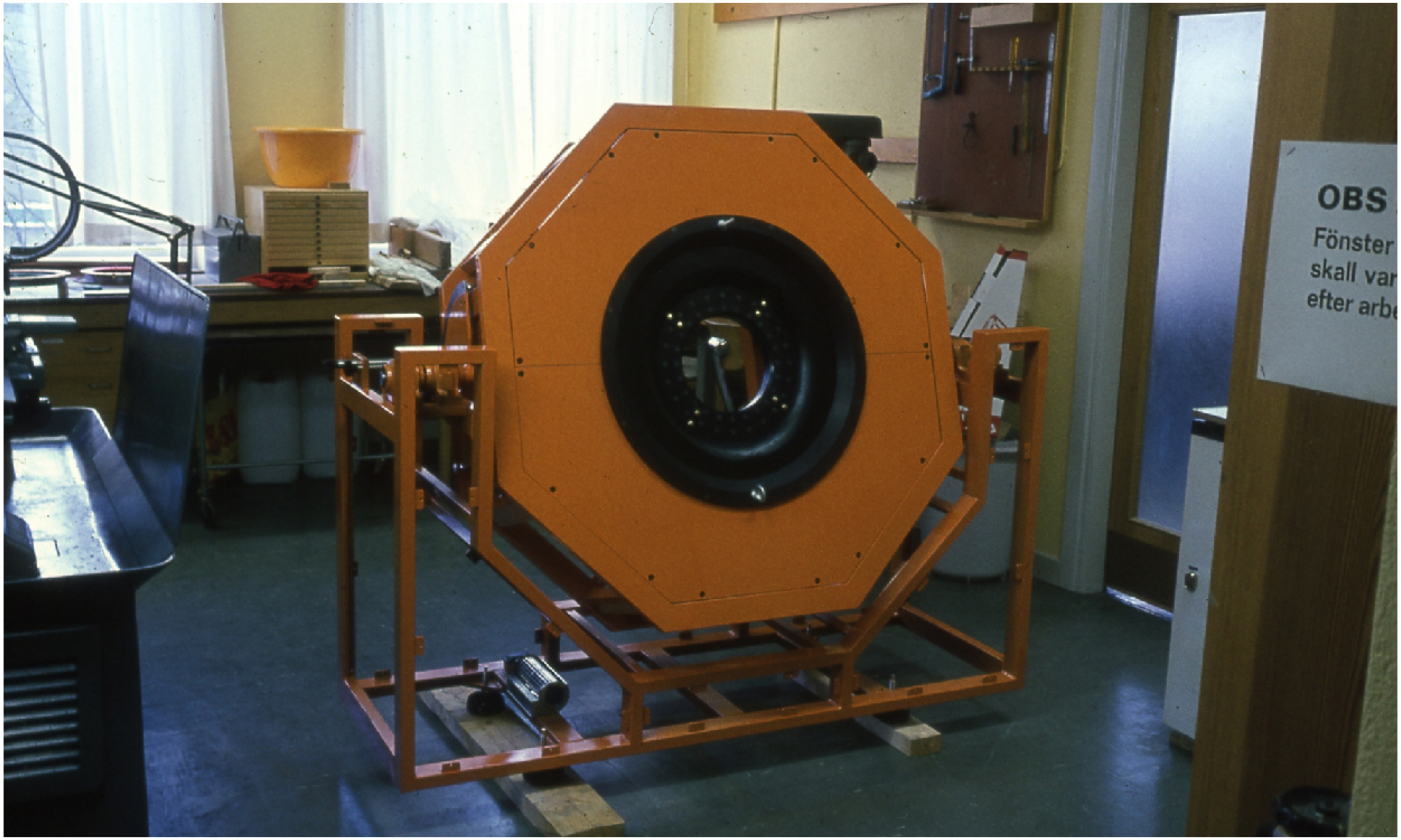
3D mode of operation, septa retracted



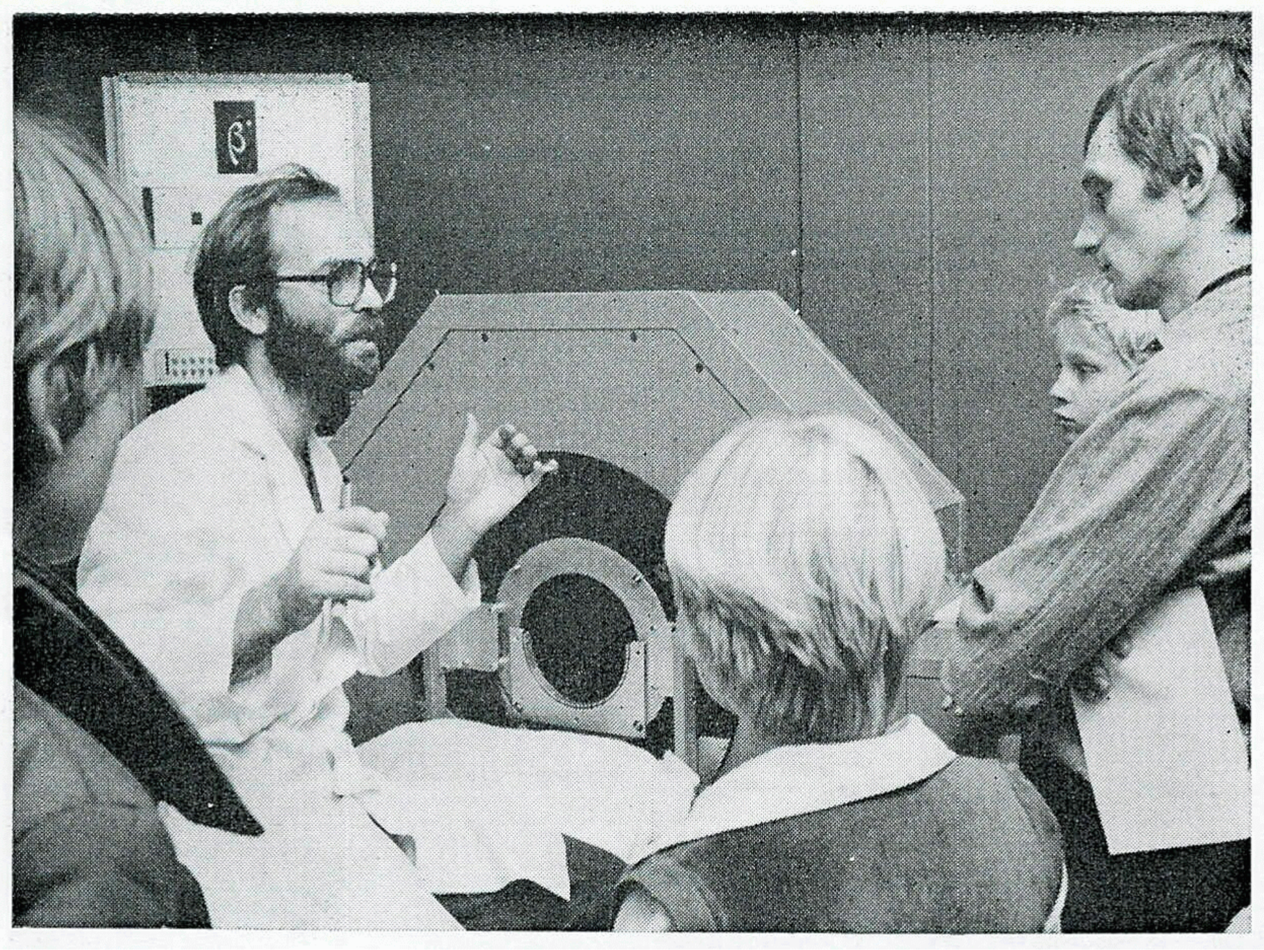
Fourth generation PET (1992-)
- block-detector concept
- retractable septa
- increased axial extension - 15 cm
- increased spatial resolution - 4 mm
- 3D data collection
- 3D image reconstruction

Examples: Ecat Exact (HR+), Advance

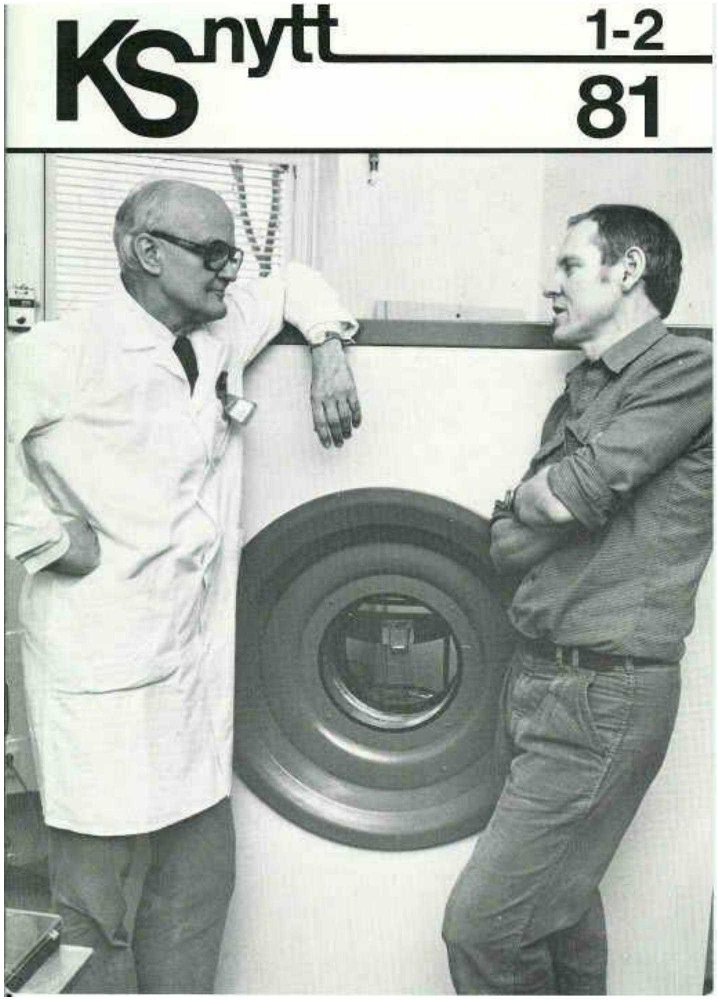
First generation PET as being built at the Karolinska and the Dep of Physics (SU) in 1976-1978. A 95 NaI(Tl) detector ring system



First generation PET system at Karolinska Hospital in 1980. Professor Mats Bergström shows the system.



Second generation PET system at the Karolinska Hospital. This was a four detector ring BGO system built by KS and SU in collaboration with Scanditronix. The KS-PET group during 1976-1990 was headed by Professor Lennart Widén(left).



Professor Christian Bohm working with detectors for future PET system (~ 1985)

Detectors for PET

- **Scintillation detectors**
  - Past – (sodium iodide) NaI(Tl) scintillators
  - Past to present – (bismuth germanate) BGO scintillators
  - Present to future – (Lutetium-ortho-silicate) LSO scintillators

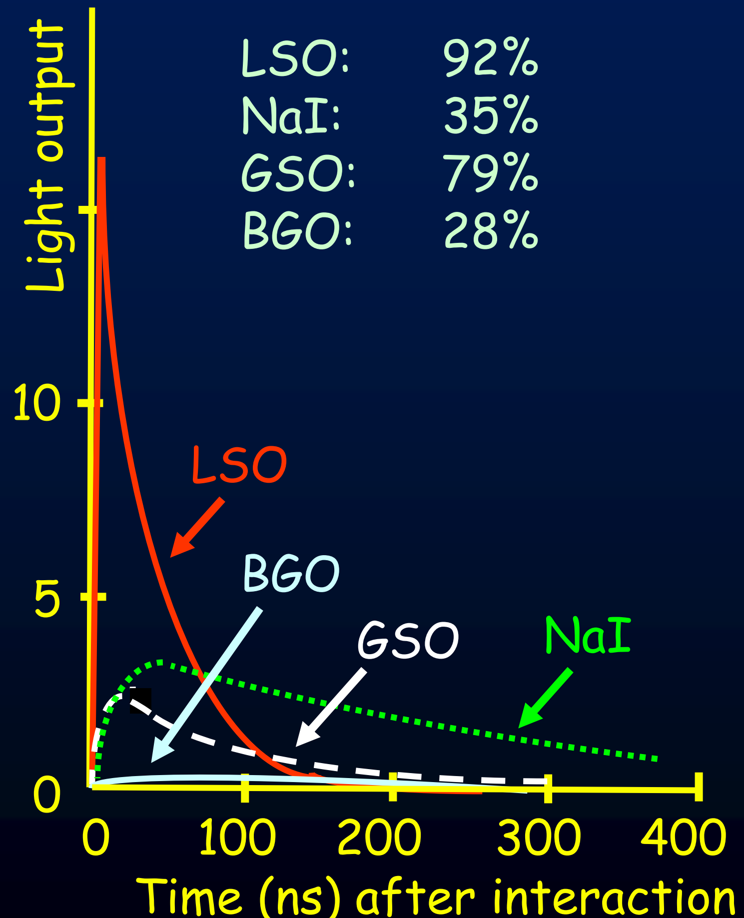
Scintillator material for PET

	NaI	BGO	LSO	GSO
density (g/ml)	3.67	7.13	7.40	6.70
effective Z	51	74	66	61
rad length (cm)	2.56	1.12	1.14	1.38
decay time (ns)	230	300	40	60
hν/MeV	38,000	8,200	28,000	10,000
light yield (%NaI)	100	15	75	35
hygroscopic	yes	no	no	no

General impact of scintillator properties:

Light fraction emitted in first 100 ns:

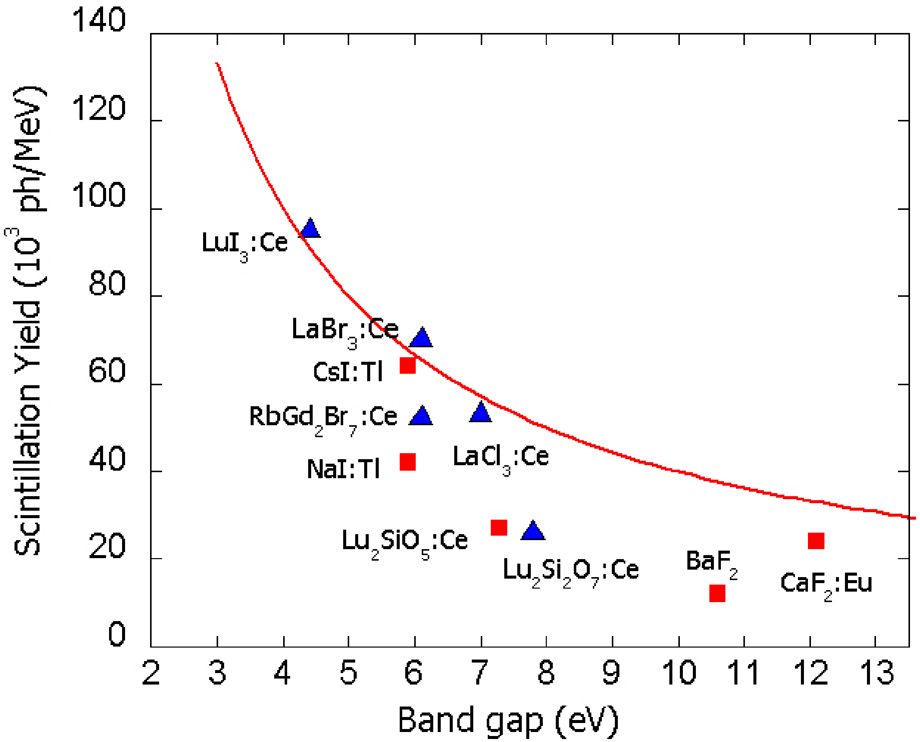
LSO:	92%
NaI:	35%
GSO:	79%
BGO:	28%



physics		effect	
• density	↑	stopping power	↑
• photo fraction	↑	sensitivity	↑
• light output	↑	energy resolution	↑
		scatter fraction	↓
		spatial resolution	↑
• decay time	↓	dead time	↓
		count rate	↑
• rise time	↓	randoms rate	↓

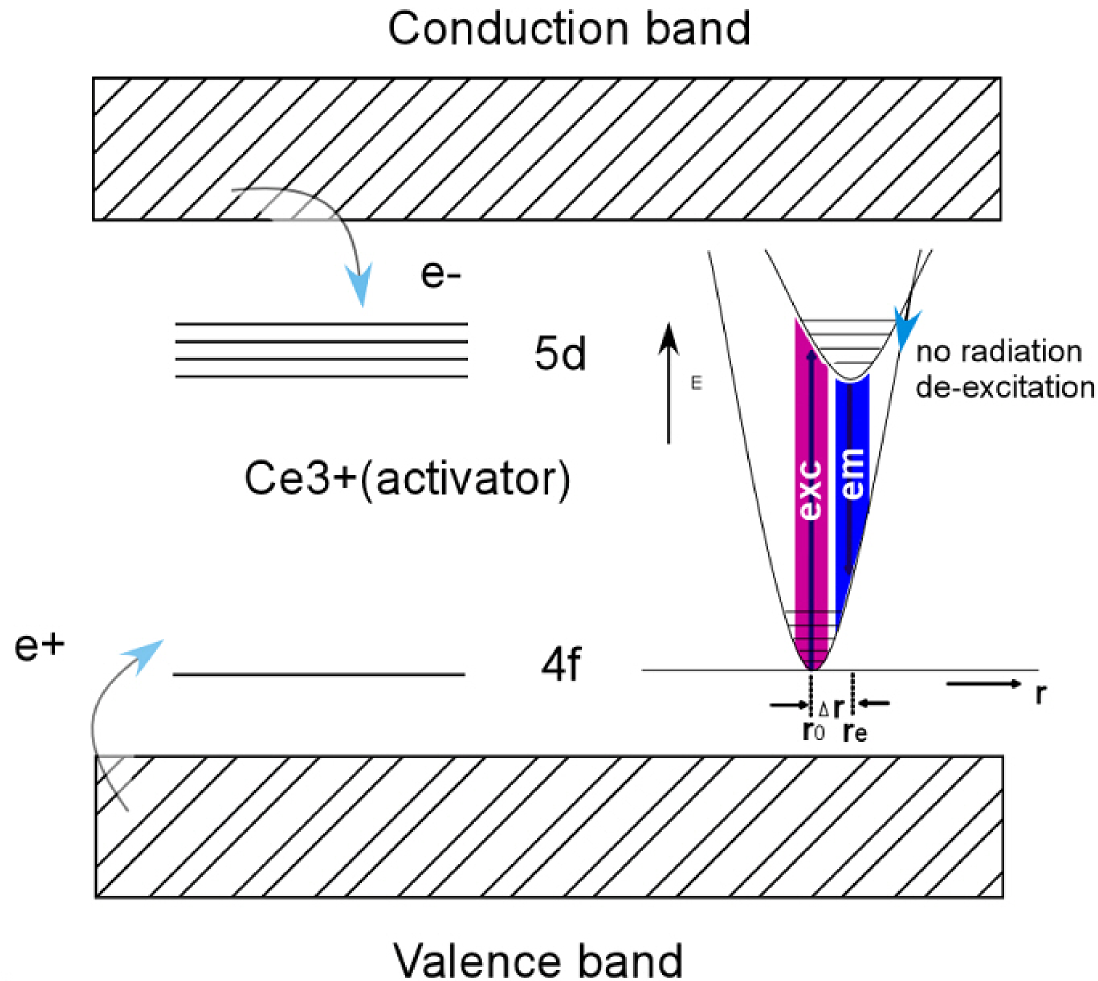
Scintillators continued…
Realized light output for different scintillators
(P. Dorenbos, TUDelft, Puerto Rico Presentation)

Realized values for the light output



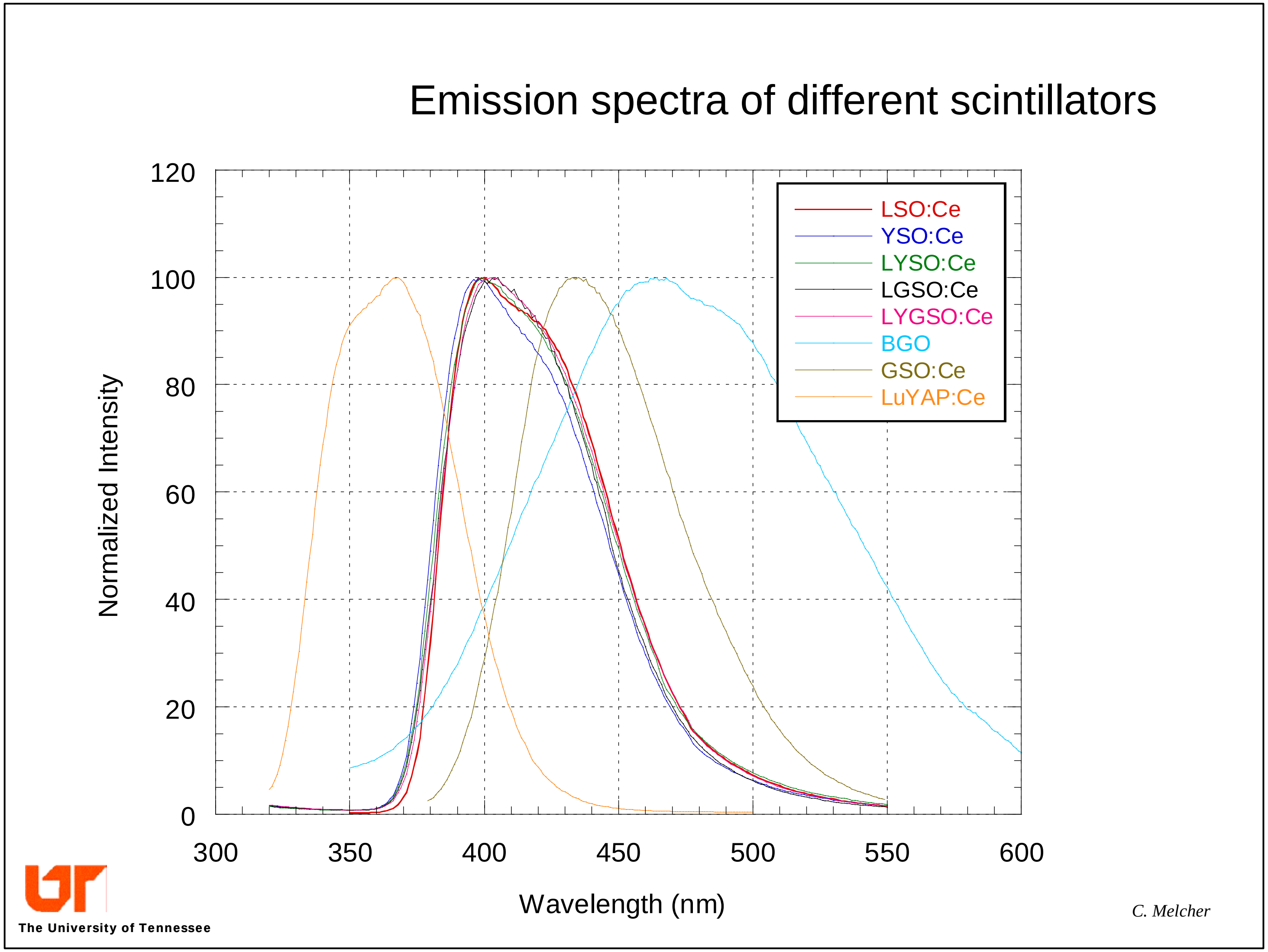
TU Delft

Possible model of the LSO:Ce scintillator. Ce3+ emission.

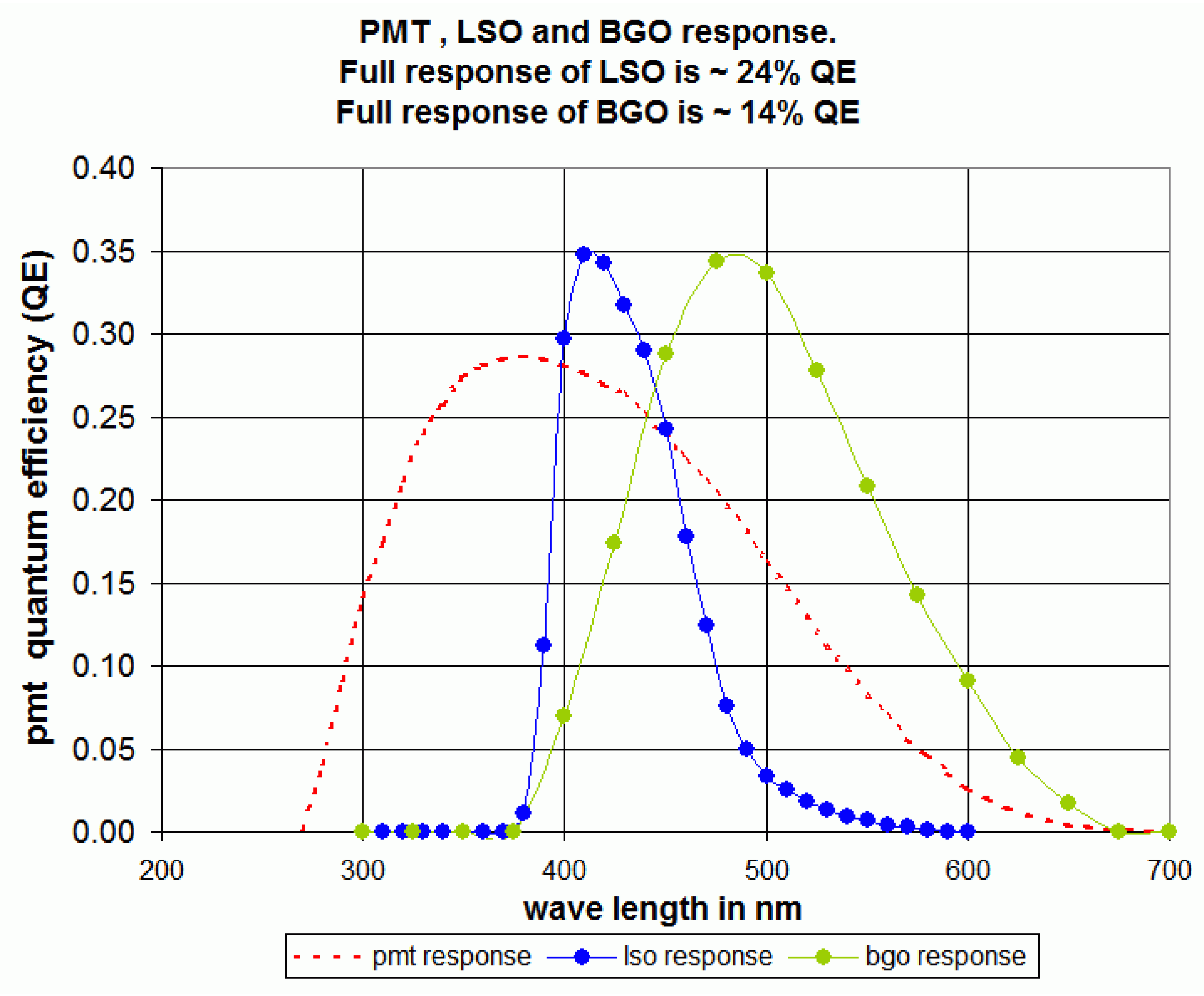


C. Melcher

Emission spectra of different scintillators



Matching of PMT response with scintillator response- for BGO a slight mismatch when using conventional PMTs



scintillator non-linearity (Moszynski)

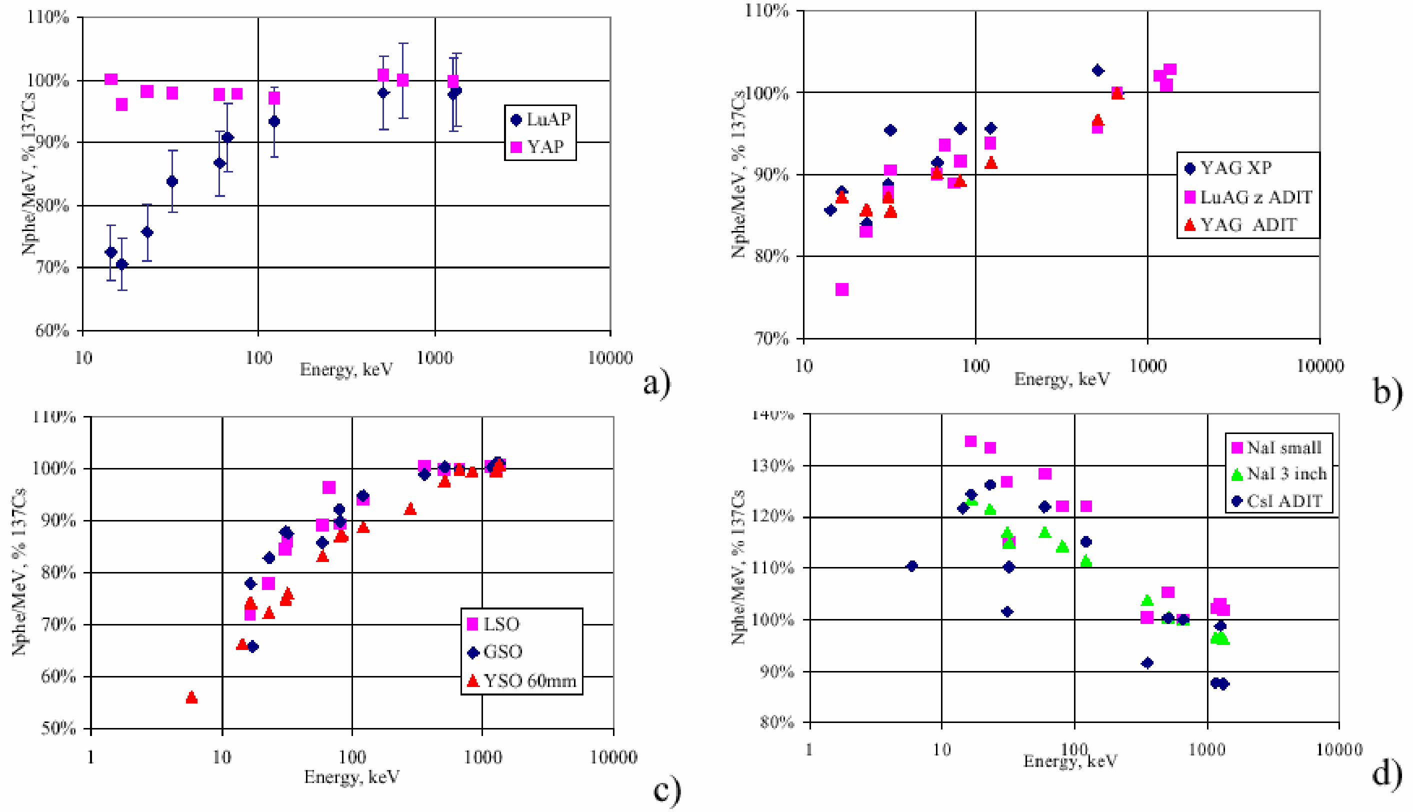
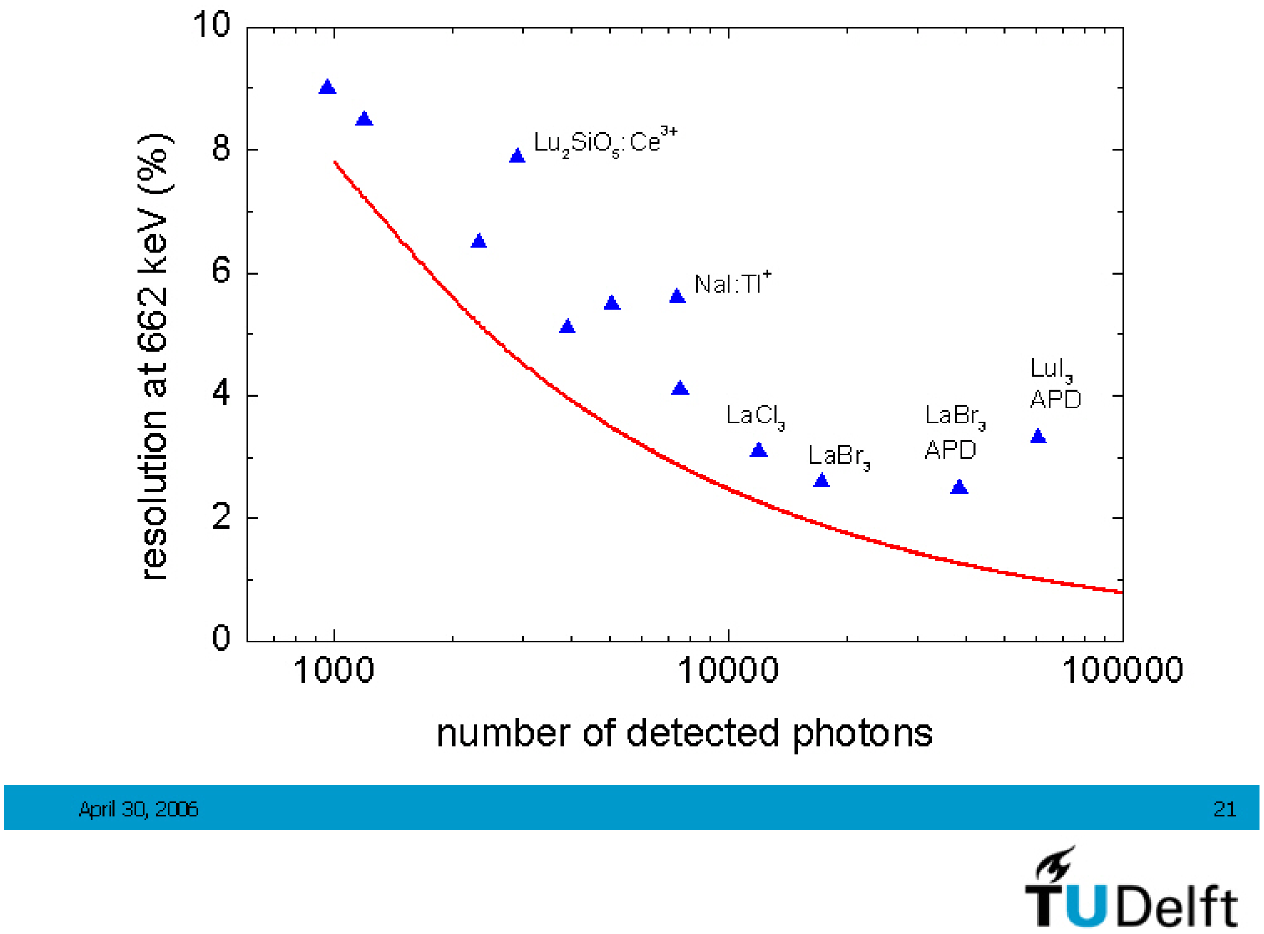


Fig. 1 Proportionality of scintillators a) YAP:Ce and LuAP:Ce, a) YAG:Ce and LuAG:Ce, b) GSO:Ce, YSO:Ce and LSO:Ce and d) NaI(Tl) and CsI(Tl) in % of number of photoelectrons for 662 keV of ^{137}Cs. Error bars are representative for all measurements.

Energy resolution of LSO limited by non-linear response for low electron energies => photopeak due to full absorption via Compton is shifted to a lower energy relative to the photopeak due to photo-electric effect => photopeak widened to approx 9-10 % as best. Typical on system level ~ 12-14% (slide below P. Dorenbos, TUDelft)

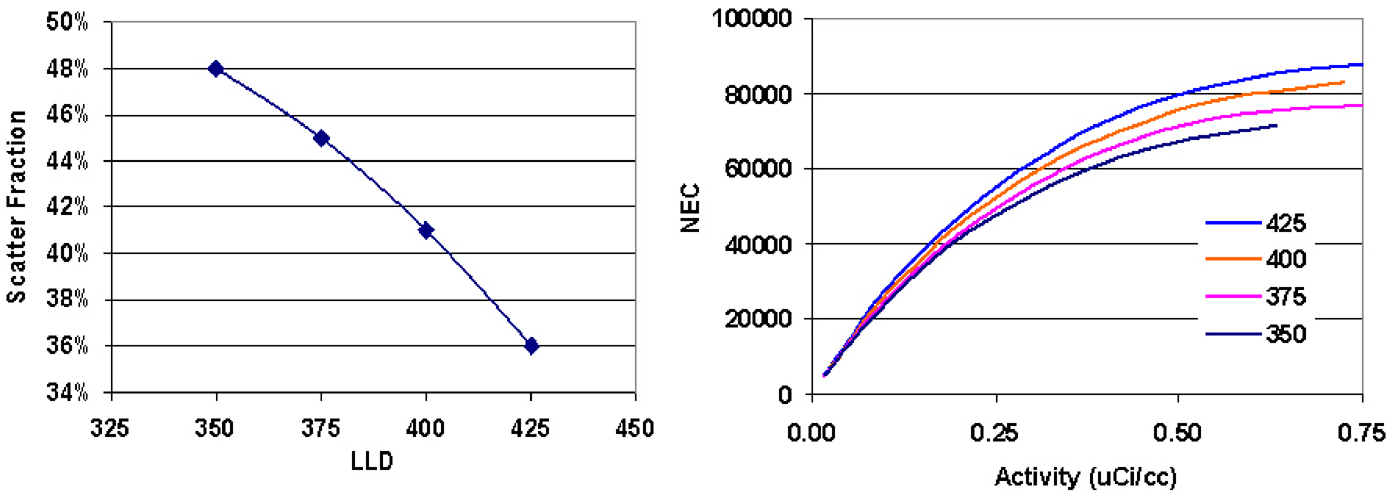


Importance to have a good energy resolution
- to control scatter fraction by making a narrow energy selection around the 511 keV photopeak

lld = lower level discriminator setting ~ 425 keV
uld = upper level discriminator setting ~ 650 keV
NEC=trues*trues/(trues+scatter+randoms) – SNR estimate

NEC Performance versus LLD

Improved scatter rejection (along with decreased event processing time) improves the Noise Equivalent Counts, which represents and improvement in the signal to noise ratio.



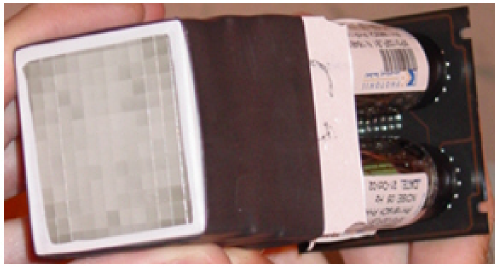
Whole Body oncology studies

Siemens current whole body systems based on the HiRez block.

Almost all clinical PET/CT studies for tumor diagnosis are F-18 FDG based (glucose metabolism).

Current status of PET/CT systems.
The PET/CT HiRez (for example the Karolinska system)
Three block rings, 48 blocks/ring. Multi-slice CT (6-64)

		LSO HI-REZ PET/CT
Block matrix		13 x 13
Crystal size		4.0 mm x 4.0 mm
Crystal Thickness		20 mm
Number of blocks		144
Total # crystals		24,336
Axial FOV		16.2 cm
Number of rings		39
Number of planes		81
Plane spacing		2.0 mm
Ring Diameter		83 cm

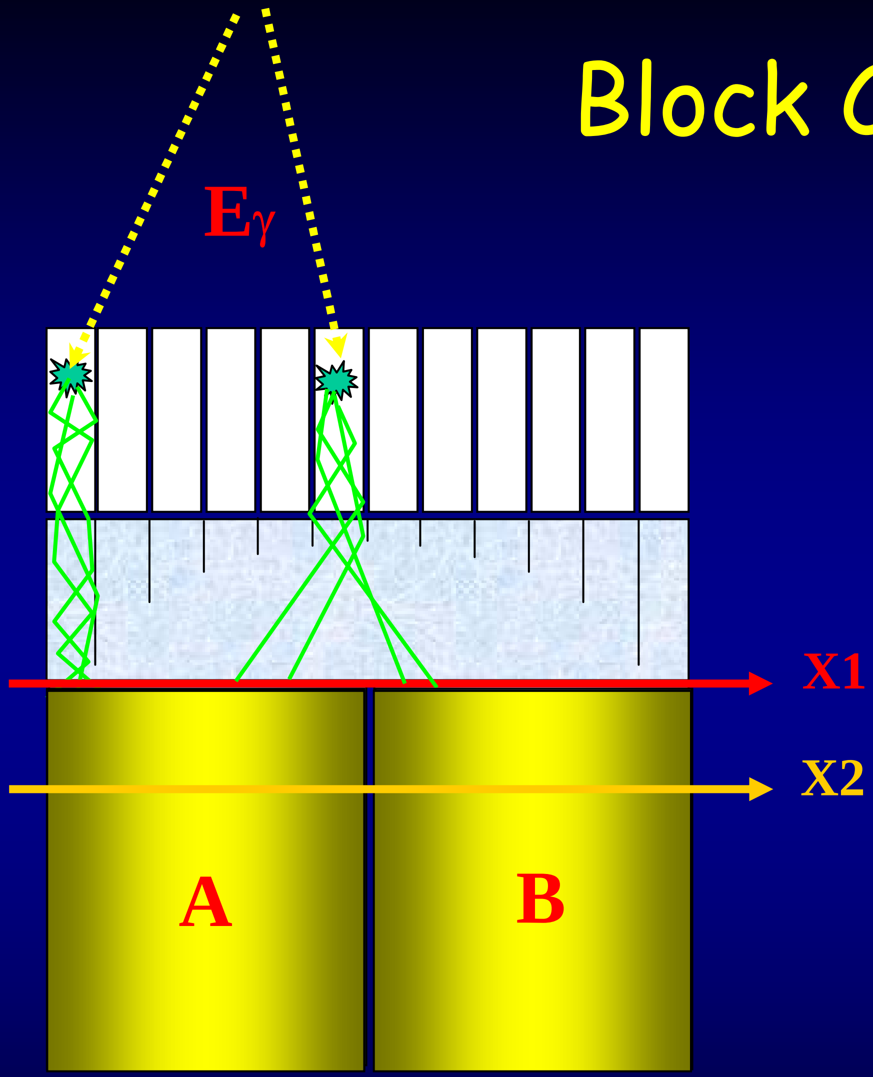


LSO HI-REZ

- >2.5x more crystals
- 2x More planes (slices)

Spatial resolution HiRez system ~ 4.5 mm FWHM

Block Concept



$X = A / (A + B)$

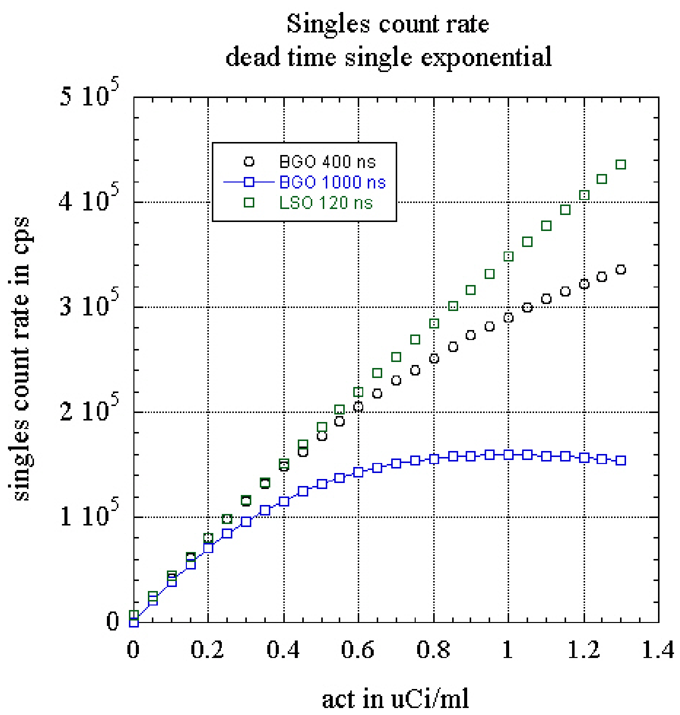
$X1 = 100 / (100 + 0) = 1.0$

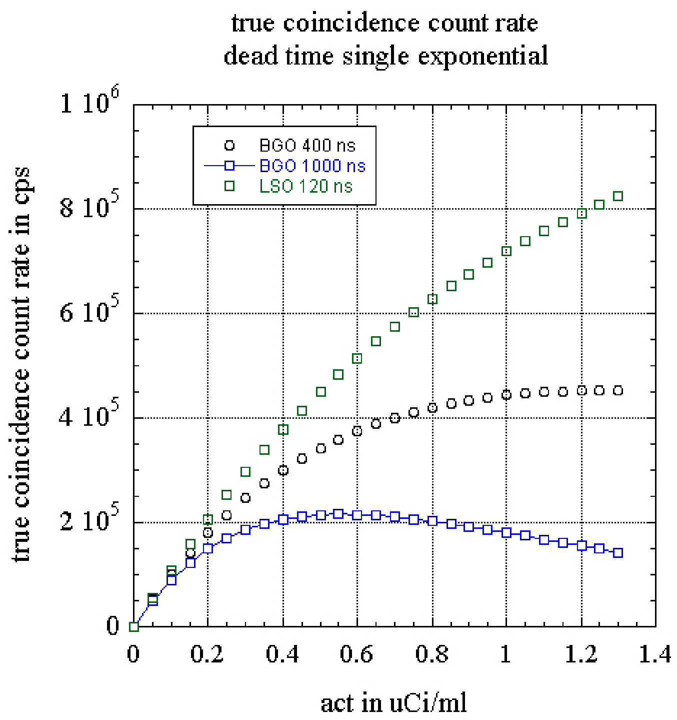
$X2 = 55 / (55 + 45) = 0.55$

Some dead-time issues with BGO and LSO

Block detector 52*52 mm2 assumed with 2 cm deep scintillator

LSO with 120 ns integration - reset time (scint decay 40 ns)
BGO with 400 ns and 1 μs integration - reset time (scint decay 300 ns)
Most of system dead-time comes from the block detectors





Current PET/CT scanners

BGO, LYSO
6 x 6 x 30 mm^3
2D/3D (septa)
8, 16, 64 slice CT
70 cm port
dual-position bed

***Discovery* ST, STE, RX**

GSO, LYSO
4 x 6 x 30 mm^3
3D only (no septa)
6, 10, 16 slice CT
70 cm port
6 ns coincidence
bed supported

Gemini GXL, TF

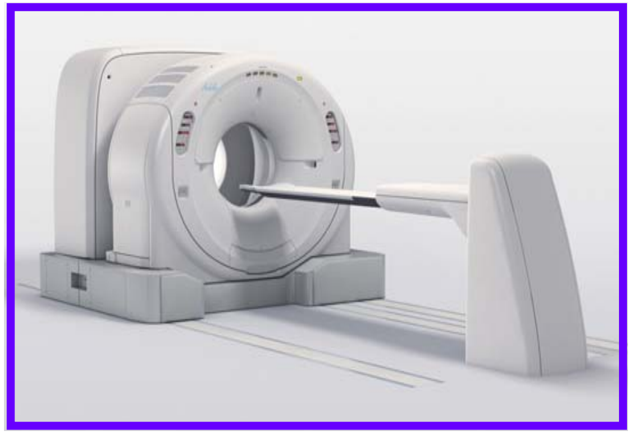
LSO
4 x 4 x 20 mm^3
3D only (no septa)
8, 16, 64 slice CT
70 cm port
4.5 ns coincidence
bed on rails

***biograph* 6, 16, 64**

LSO
6 x 6 x 25 mm^3
3D only; rotating
4 slice CT
70 / 60 cm port
4.5 ns coincidence
bed on rails

SceptreP3

Current PET/CT scanners (continued)

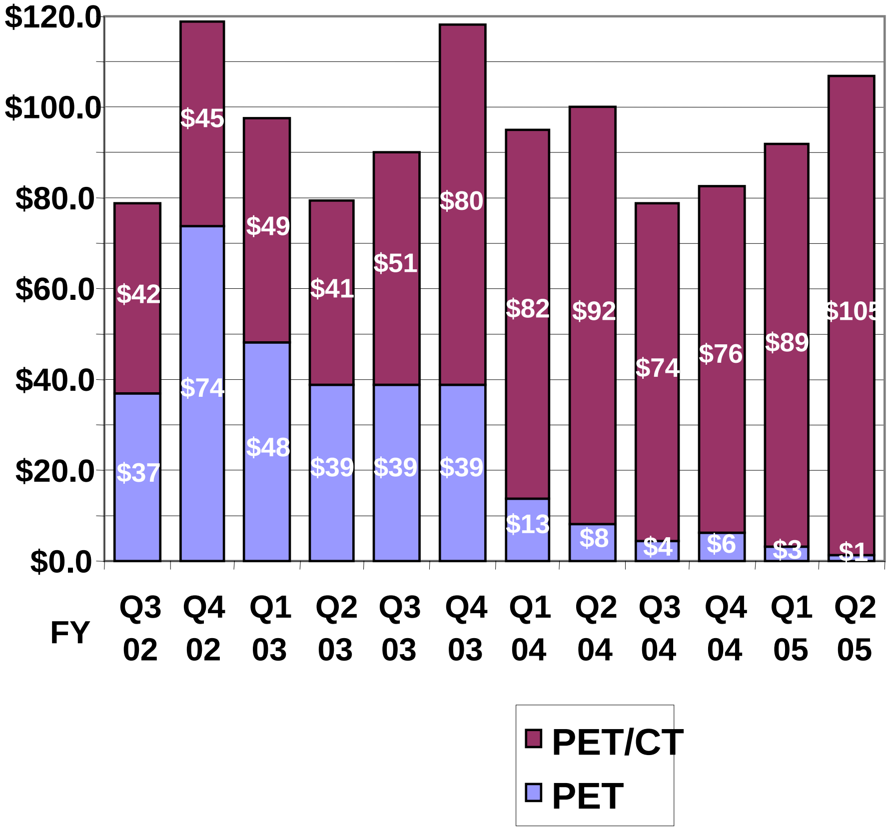


Aquiduo

LSO

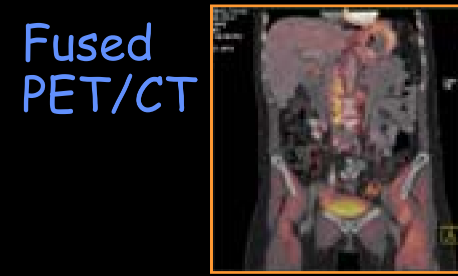
4 x 4 x 20 mm^3
3D only (no septa)
16 slice CT
70 cm port
4.5 ns coincidence
gantry on rails

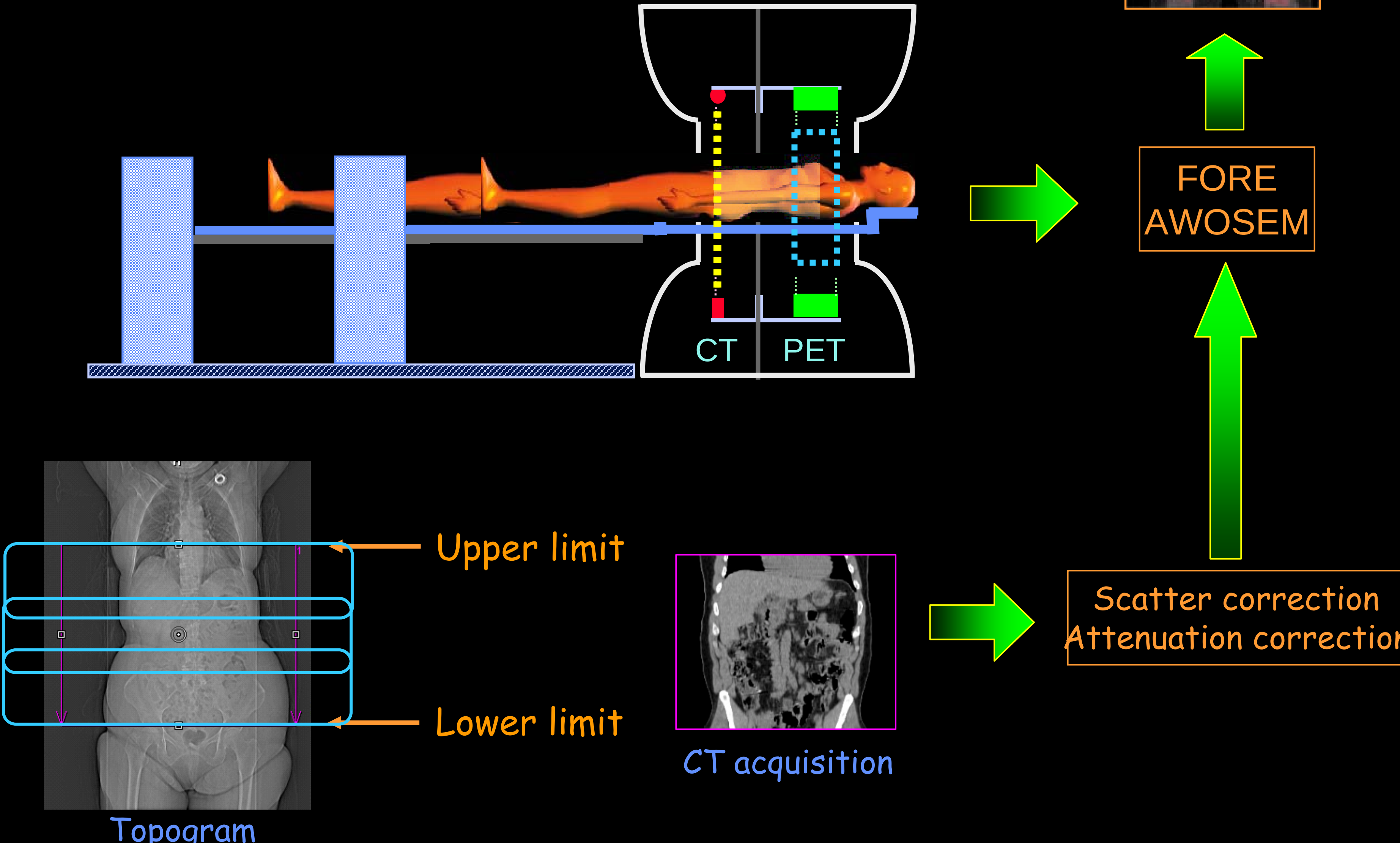
NEMA - US Shipments ($M)



PET/CT clinical impact

PET/CT standard protocol

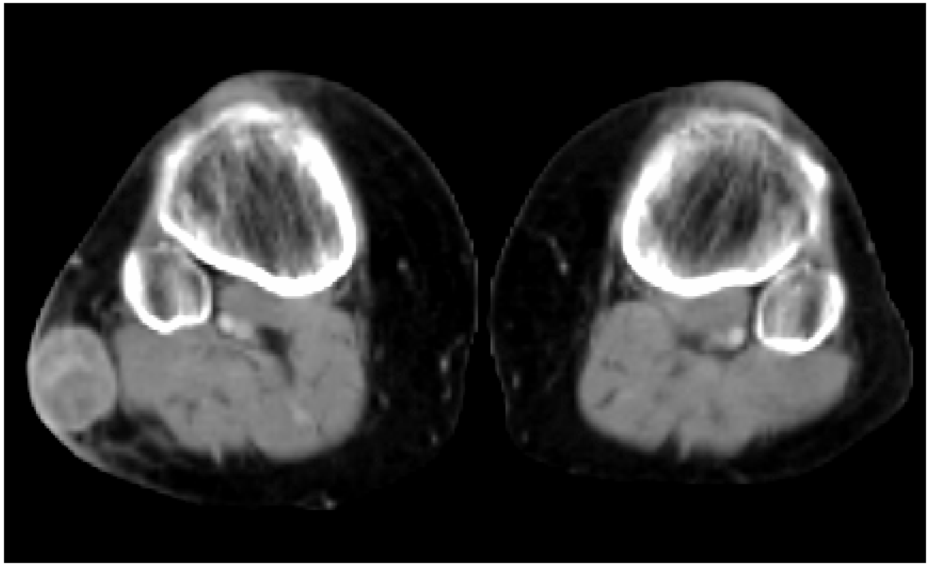


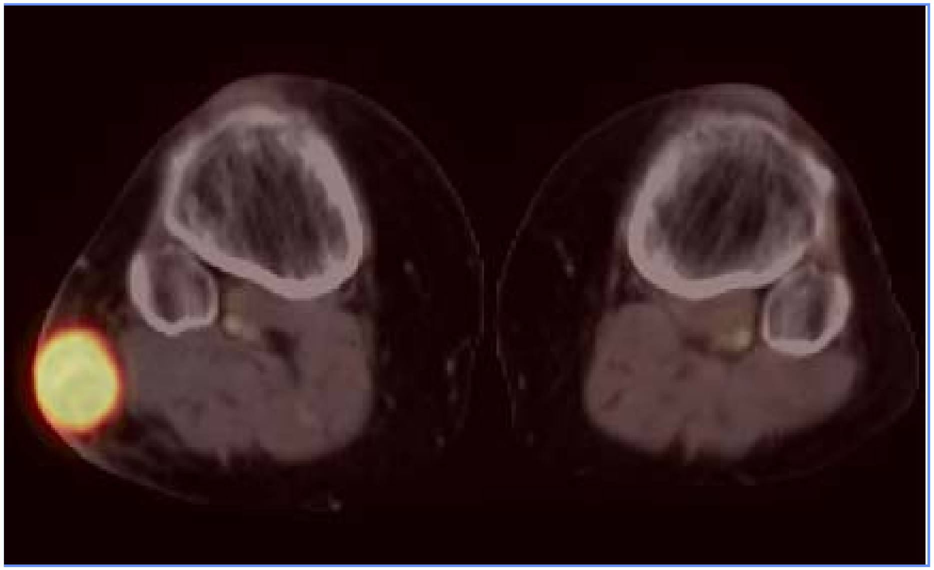


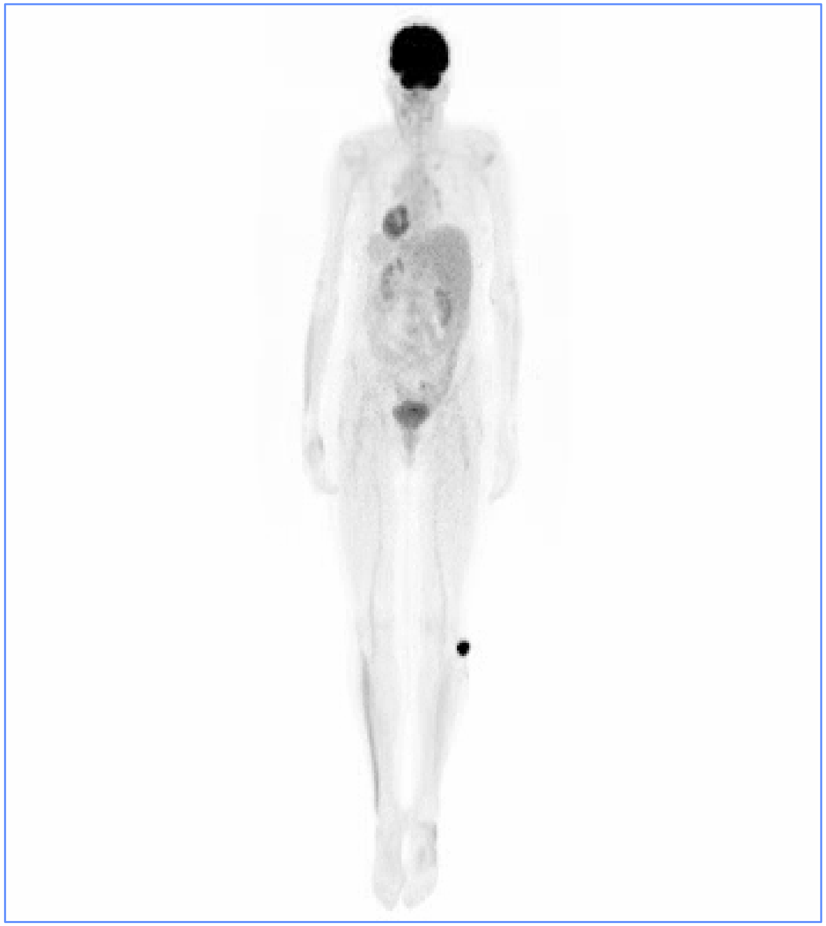
Restaging melanoma

biograph 6

Cancer Imaging and Tracer Development







CT: 102 mAs, 130 kV, 5 mm slices at 0.75 mm
PET: 9.8 mCi FDG, 108 min pi, 2 min/bed, 11 beds

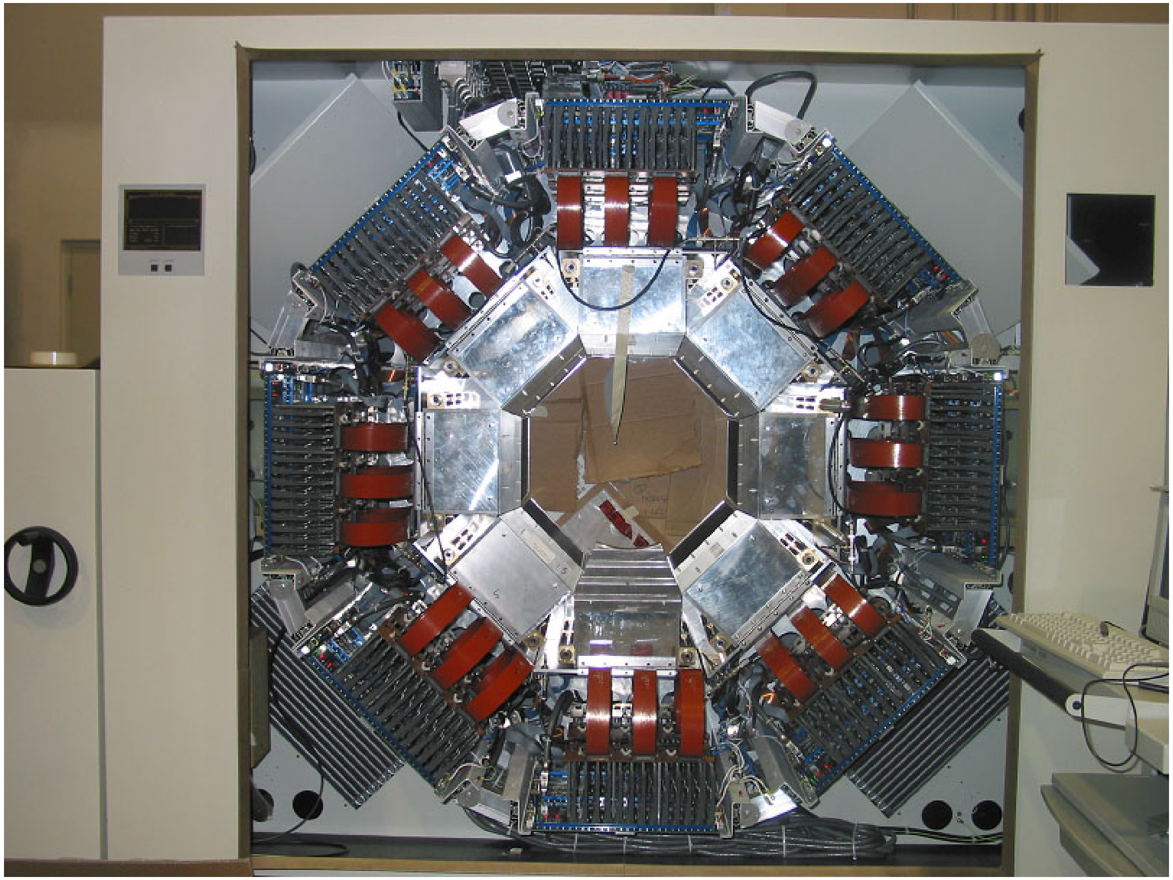
68 year-old female, diagnosed with melanoma in 1999. Restaging following surgery and interferon treatment. Focal uptake close to site of original lesion. Remainder of study unremarkable.

Brain studies

- **Special equipment to optimize brain studies**
  - Smaller detector ring to minimize non-collinearity of annihilation photons and thus increasing spatial resolution (~ c_1*diameter)
  - Smaller ring implies higher sensitivity (~ c_2*diameter)
  - Smaller detector elements to give better spatial resolution
    - ~ 2*2*L mm^3 pixels used (L~10 to 20 mm)
  - List-mode data to provide kinetic studies (multi-frames) for receptor imaging

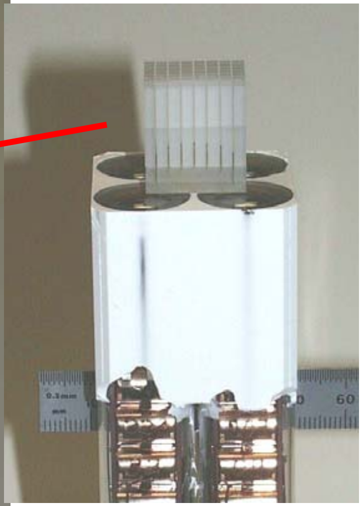
State-of-Art Brain imaging
- the High Resolution Research Tomograph

- **Eight panel system**
  - Each panel has 117 blocks, viewed by 140 PMTs



The HRRT system uses panel technology

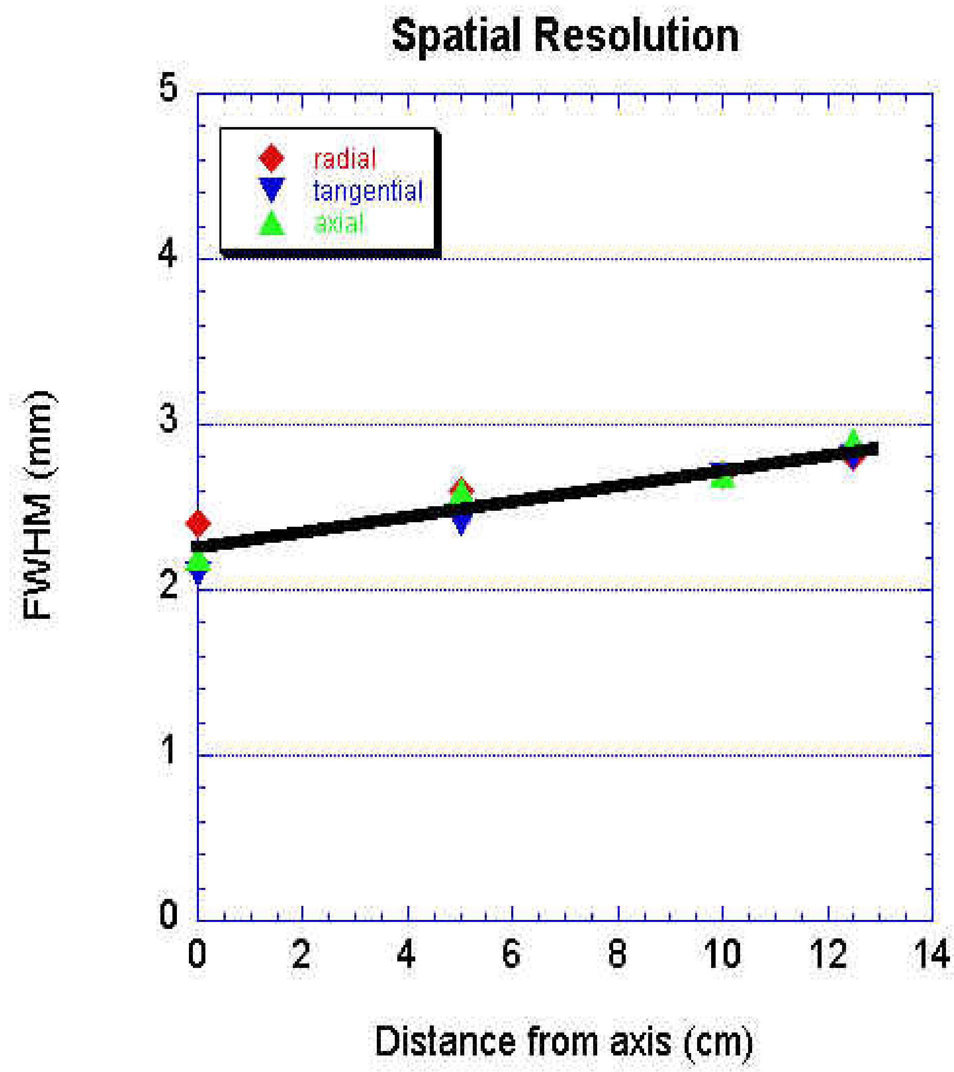
- **One of the HRRT panels**
  - 117 blocks/panel viewed by 140 PMTs
  - Block organization with quadrant sharing read-out
  - Block in 8*8 matrix. Each pixel 2*2*10 mm3. Two crystal layers
  - Top layer is LSO(~42 ns), bottom layer is LYSO(~55 ns). Layer selection via differences scintillation decay times (phoswich).



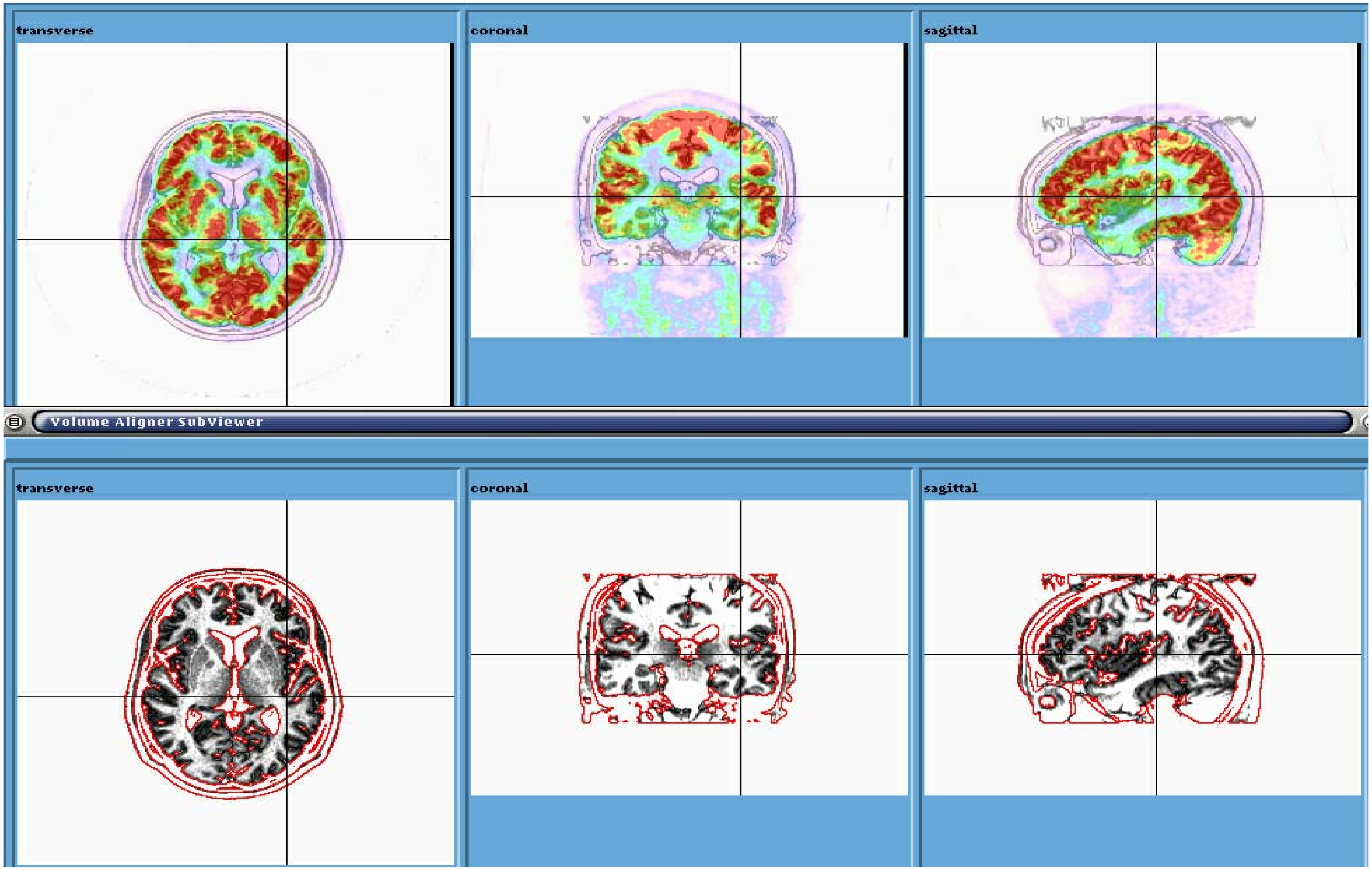
HRRT Performance: Spatial resolution

•3D-OSEM recon

•**~2.5 mm FWHM** in the volume of a human brain



HRRT data integrated with MR data



What will happen with PET in the future?

- Increased spatial resolution
- Increased sensitivity

Factors to be changed to enable future generations PET scanners

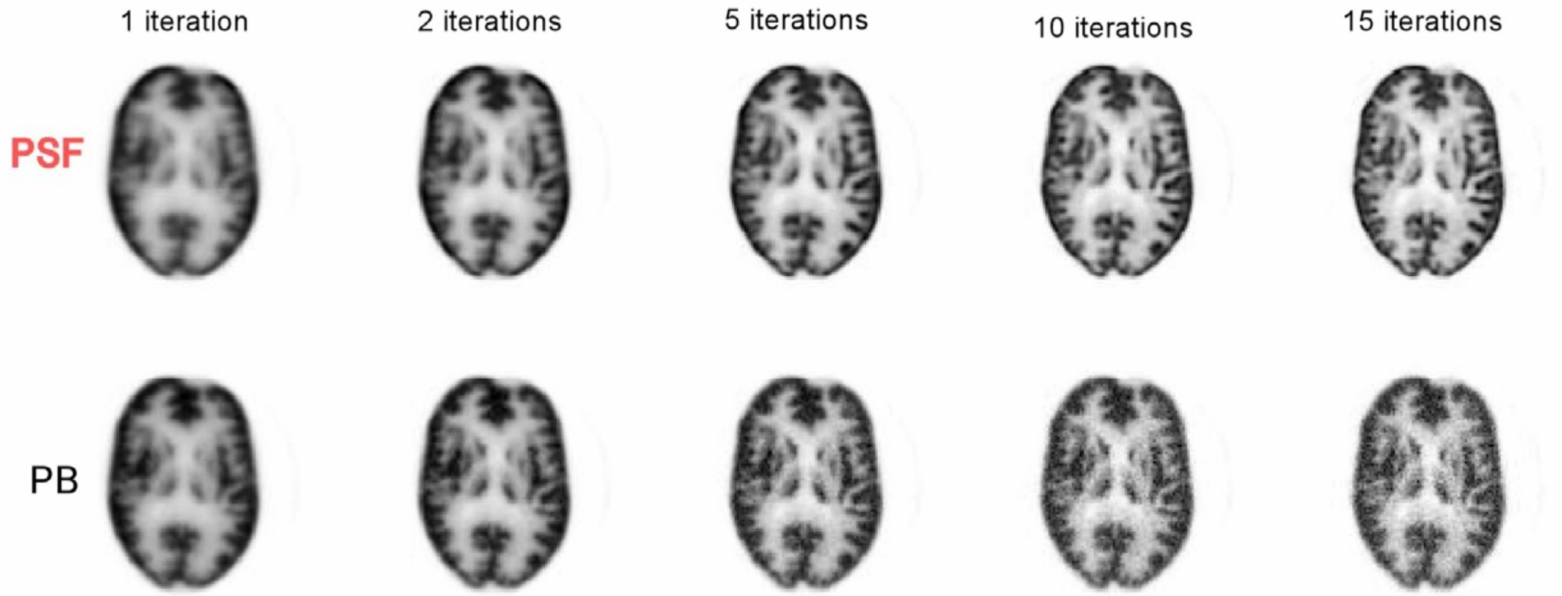
	Factors to change	Direction/Method of change	Predicted improvement
1	*Decreased size of crystals*	Finer grid on detector blocks without packing fraction losses	*Improved spatial resolution and image quality due to improved spatial sampling*
2	Increased packing fraction	Block packing fraction – Minimize gaps between blocks	Higher Sensitivity
3	Decreased system dead time	Reduced to 2x scint decay or 3x scint decay as used in the pico electronics in the HIREZ	Higher count rate capability due to low system dead time
4	Increased solid angle	Axial extension increased	Higher Sensitivity, higher NEC
5	Improved time resolution	Fast electronics to match LSO's intrinsic timing properties	Better time resolution-less randoms and TOF capability
6	Maintain depth of crystals	2 cm (or 3 cm) depth	Awaits data, maintain cost
7	Decreased cost	Reduction of PMTs per block	Lower costs

Spatial resolution limits based on pixels sizes and positron physics

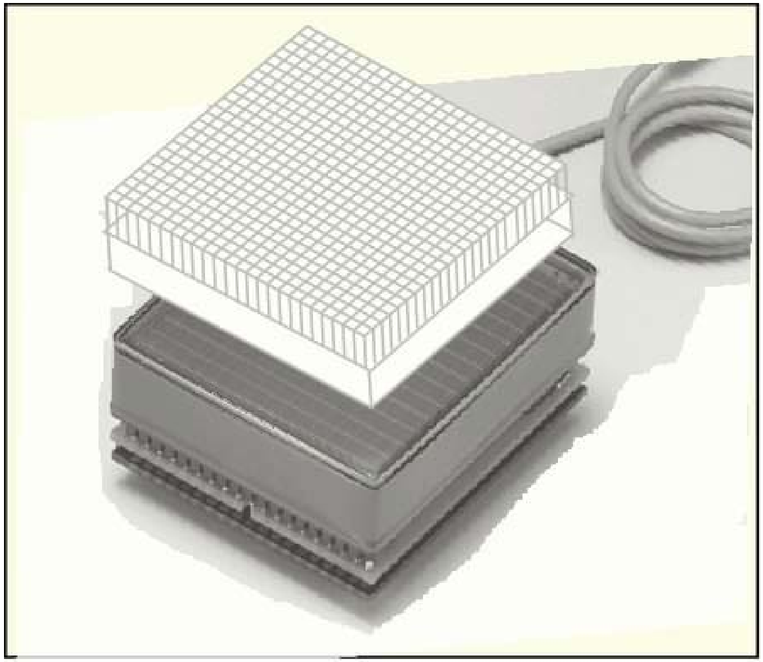
Isotope	Reconstruction technique	detector widths in mm in a 85 cm diameter system			
		1	2	3	4
F-18	3D OSEM/MAP	2.81	3.04	3.40	3.82
	FORE/ 2D OSEM	2.90	3.29	3.88	4.56
O-15	3D OSEM/MAP	3.70	4.04	4.44	4.87
	FORE/2D OSEM	3.75	4.23	4.82	5.47

Image improvements via adequate image reconstructions…

Reconstruction with System matrix modeling (PSF) compared to Parallel Beam (PB) reconstruction (V. Panin, Siemens Molecular Imaging)



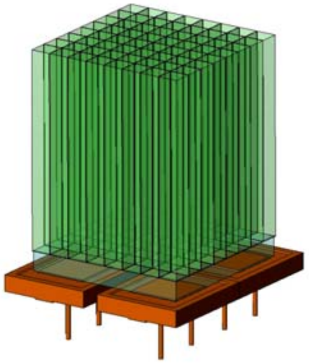
Spatial resolution….PMT based systems

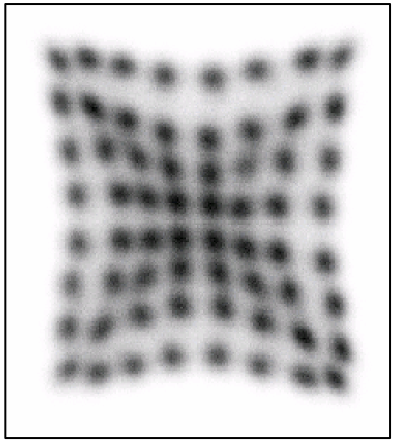


A HIREZ block has 13*13 4*4*20 mm^3 pixels. Assuming a future block with the same block size but with 2*2*20mm^3 pixels, this would imply that we need to identify 26*26 pixels.
We need more photo-sensors than the HIREZ four PMTs for this. One possibility would be to use multi-anode PMTs, for ex. the Hamamatsu H8500 (8*8 anode) or Photonis NONAD (3*3 anode)

Spatial resolution improvements.. APD based systems (Ron Grazioso, Siemens Molecular Imaging)

- Based on Block Technology:
  - 8 x 8 arrays of 2 x 2 x 20 mm^3 LSO crystals read out by 4 APDs (Hamamatsu)
  - Average crystal energy resolution: 17%
  - Average crystal time resolution (vs. plastic/PMT): 1.8 ns





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Sensitivity issues

- **Point source sensitivity = solid angle at the center * packing fraction squared * scintillator efficiency squared**

- **The solid angle at the center** of the cylindrical PET system is ~D/2R' where R' is ~ R the radius of the system plus some distance into the LSO scintillator and D is the axial extent of the scanner

- **The packing fraction** is the ratio between the actual LSO volume of the scanner and the ideal LSO volume

- **Scintillator efficiency** for different thicknesses based on 12% energy resolution and 400 keV LLD setting

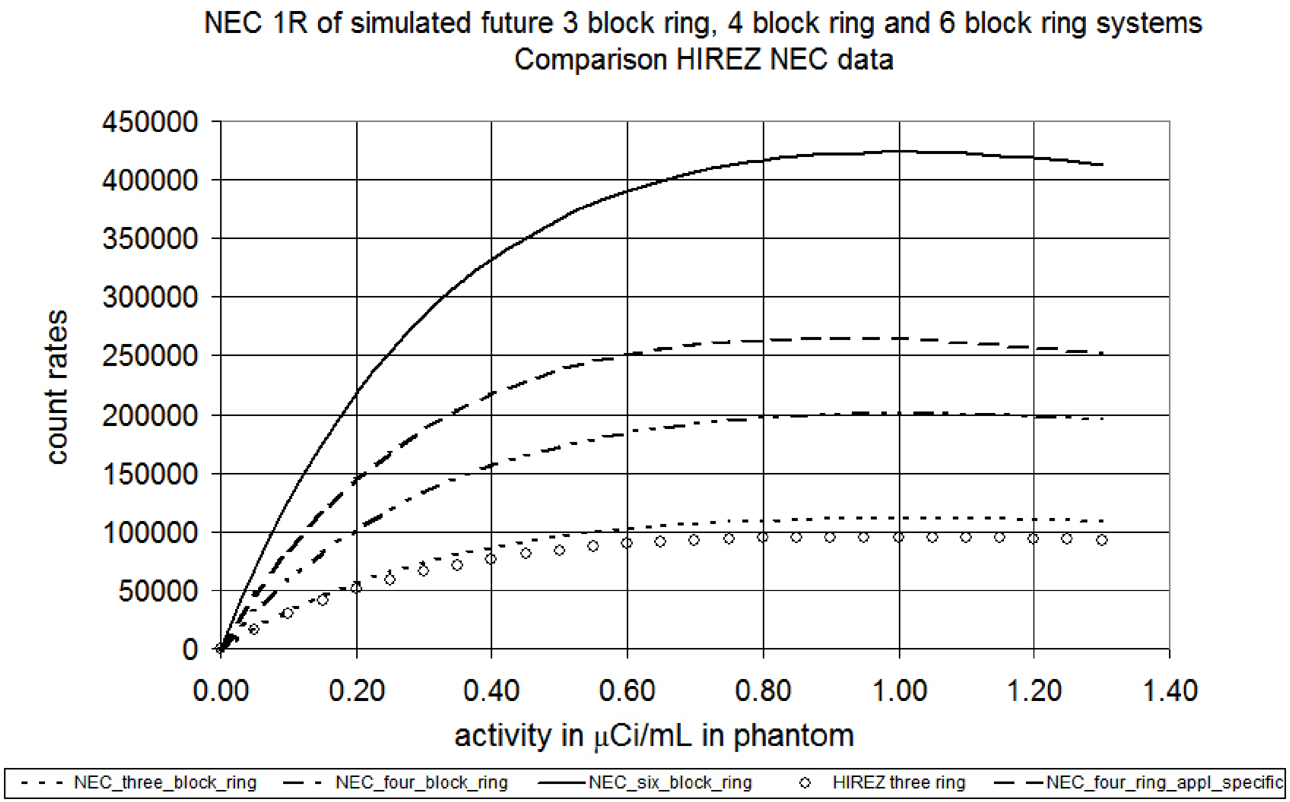
Slab thickness in cm	LSO	BGO
2	0.6978	0.7554
3	0.8388	0.8856

By adding block rings the solid angle increases and thus the sensitivity increases..

Solid angle, packing fractions and sensitivity for different number of block rings of LSO. Block size 52*52 mm^2, Pixel size 4*4*20 mm^3, ring diameter 83 cm and 48 blocks/ring.

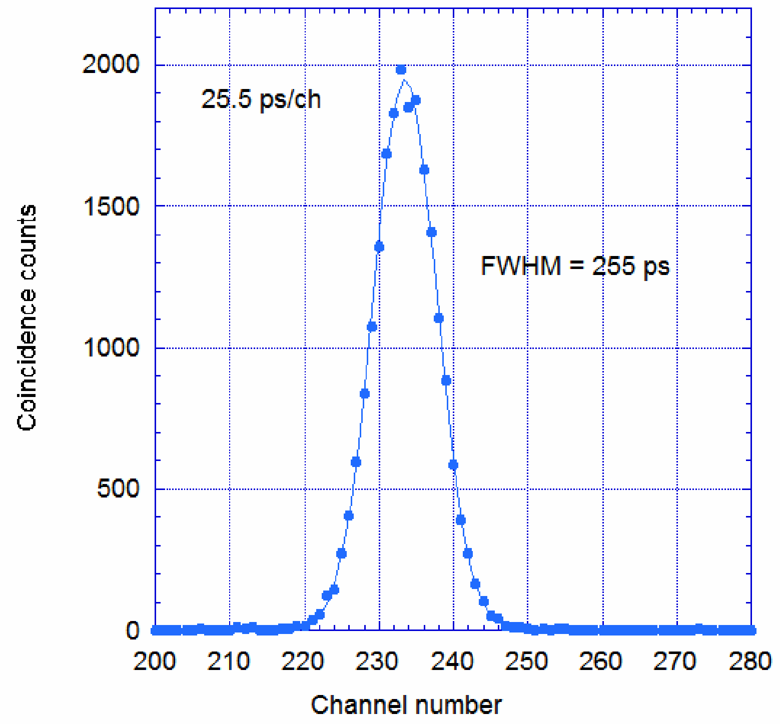
Number of block detector rings	3 block ring system	4 block ring system	6 block ring system
axial FOV in cm	16.2	21.6	32.4
Solid angle	0.187	0.246	0.356
Ideal LSO volume cylinder (cc)	8652	11536	17303
actual LSO volume (cc)	7788	10383	15575
packing fraction squared	0.81	0.81	0.81
point source sensitivity	**0.064**	**0.085**	**0.123**
axial length sensitivity	**0.032**	**0.042**	**0.061**
absolute sensitivity for a 70 cm line source	**0.0075**	**0.0131**	**0.0284**
absolute sensitivity corrected for span and ring difference	**0.0049**	**0.0088**	**0.0190**

Solid angle improvements on NEC data [NEC=T*T/(T+S+R)]



Using LSO, can time-of-flight information be used?

- **LSO – LSO time spectrum.**
  - Two LSO cubes 1 cm^3 and two Photonis XP 2020/Q PMTs



Time-of-Flight continued…

- **Marek Moszynski results for LSO 4*4*20 mm^3 vs BaF$_2$**
  - For LSO-LSO the 295 ps -> appr 380 ps

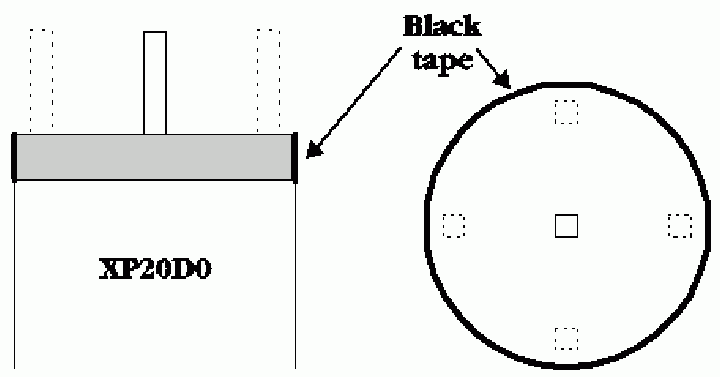


Fig. 2. The position of the light diffuser at the photocathode of PMT and positions of LSO crystals tested in the experiment.

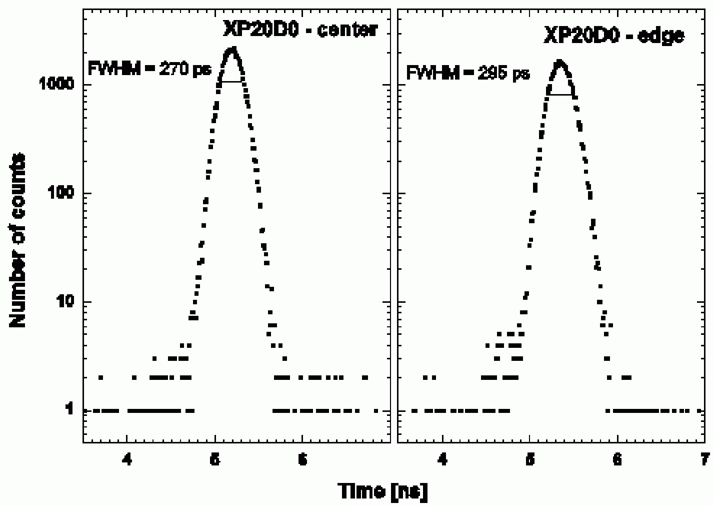
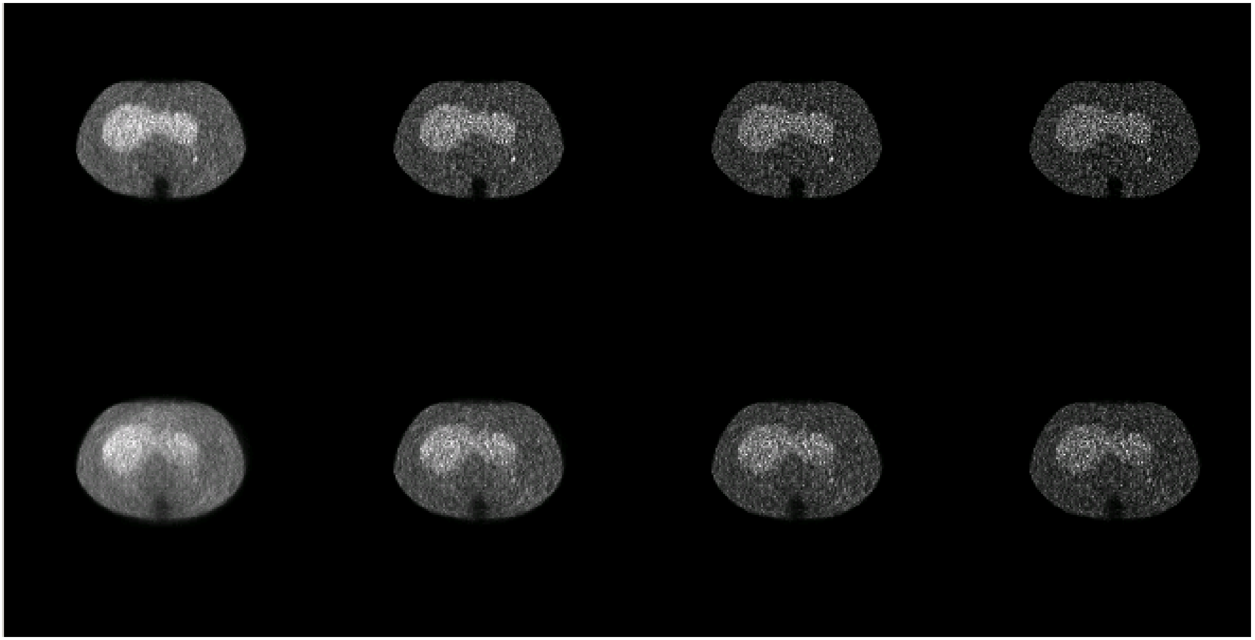


Fig.3. Time spectra measured with 4x4x20 mm^3 LSO coupled in the center and at the edge of the light diffuser.

TOF continued… simulation data based on 500 ps time resolution

Based on our own experimental data with strong support from the results from the Moszynski group we believe that a system time resolution using LSO blocks can be around 500 ps.

1 iteration 2 iterations 3 iterations 4 iterations

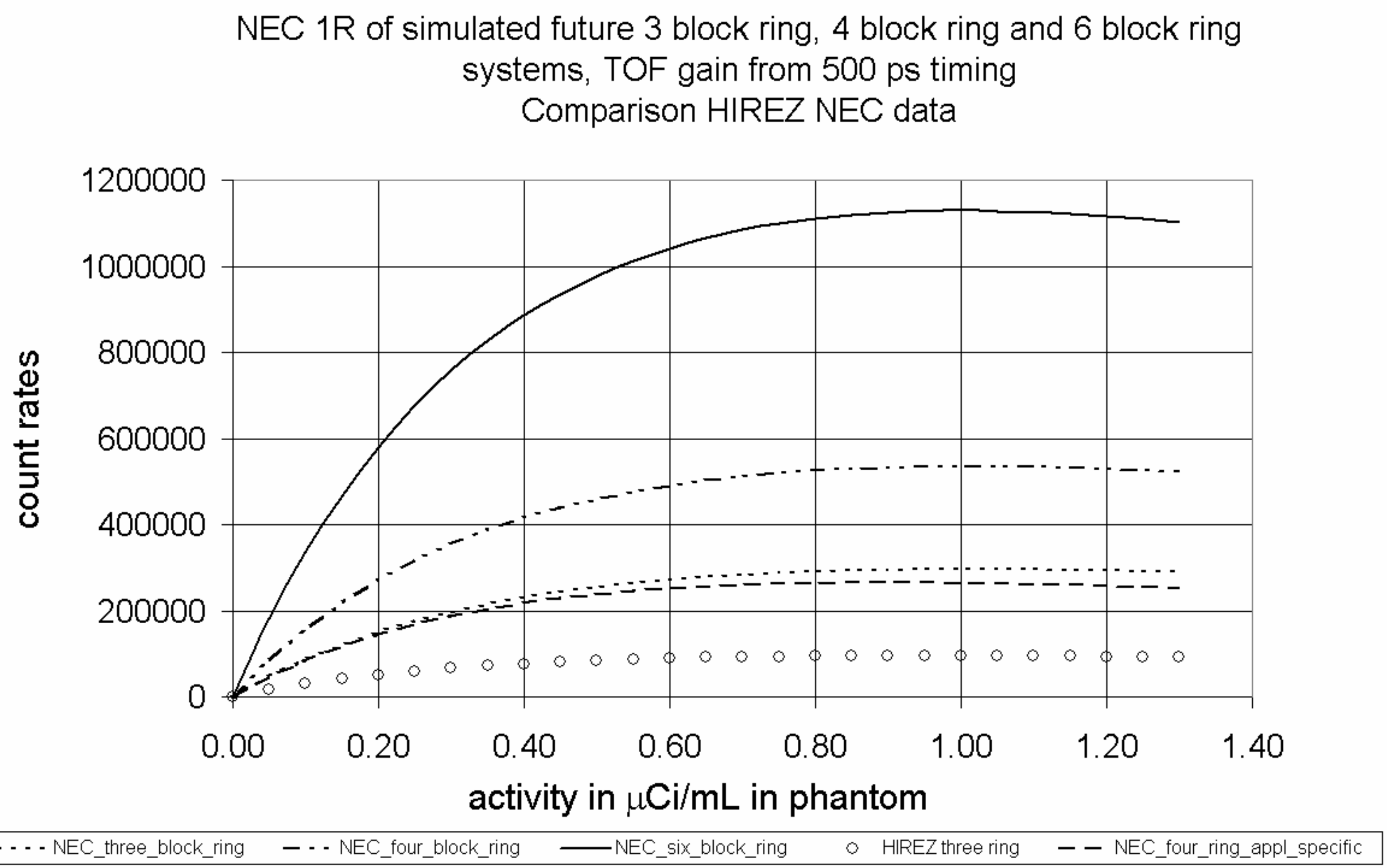


TOF reconstruction

Non TOF reconstruction

Info on this simulation: Phantom: torso phantom, lesion contrast 4:1, size=2 pixel (8mm)
Statistics: 5 million trues, 36% scatter, 100% randoms
Reconstruction: OSEM, conventional and TOF
TOF parameters: TOF bin size = 312 ps, time resolution = 500 ps

TOF gain amplifies the NEC curves...



Conclusions

- **Siemens is building up detector technology based on LSO detectors. LSO has efficiency ~ BGO but ~4× more light output and 7× faster decay time**
- **LSO detectors give:**
  - high detector live time=> high system live time
  - short coincidence time windows < 4.5 ns => low randoms
    - TOF possible
  - large area detector possible => affordable large axial FOV systems.
    - Caveats exist for example dead time problems
  - APD based detectors possible with good timing (< 3ns)
  - high scintillation light allows high resolution capability
- **Whole body systems with ~3 mm LSO pixels feasible**