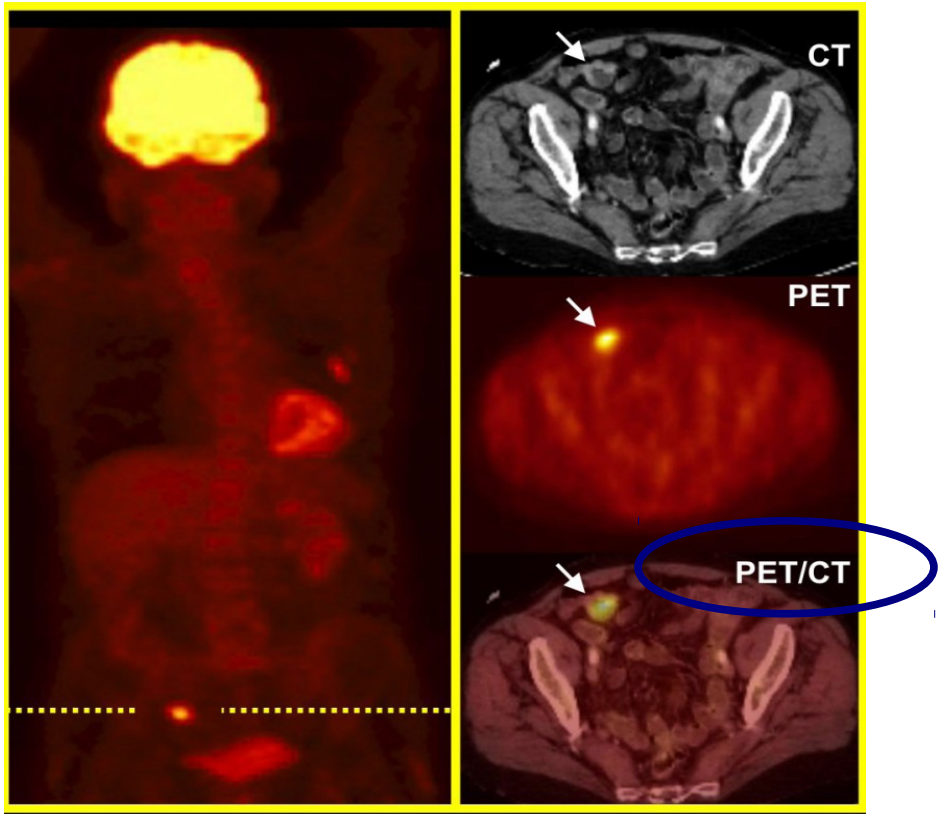
Application of novel semi-conductor based photo-detectors to PET

Martin Göttlich
DESY

(1) Brief reminder on Positron Emission Tomography
(2) Silicon Photomultiplier and their application to PET
(3) Projects with contributions from DESY

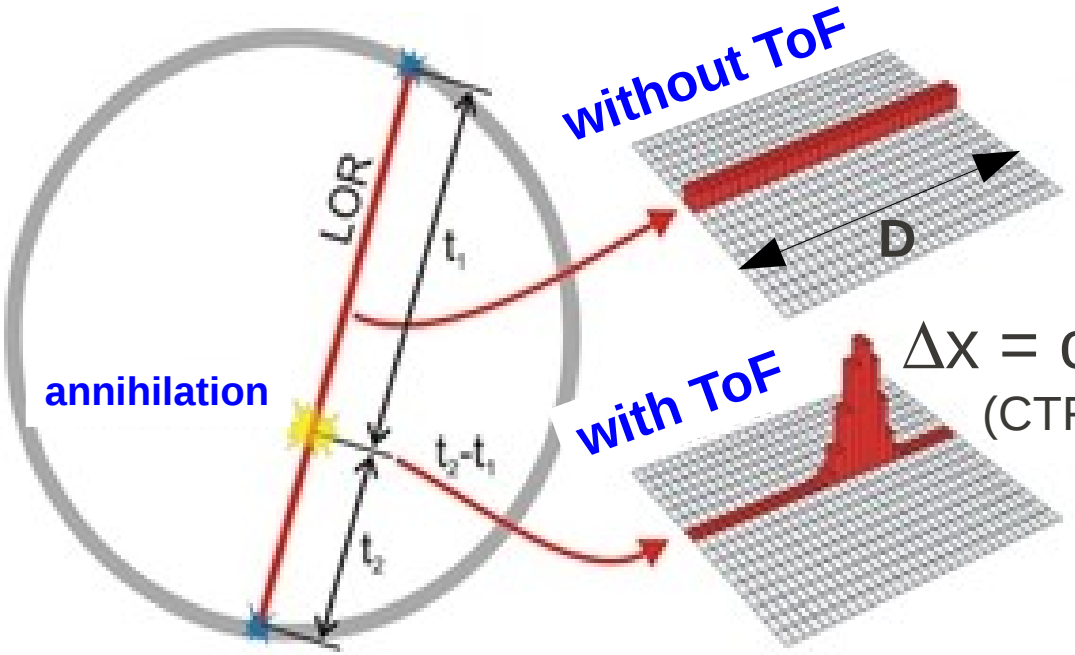
Introduction to PET

- nuclear medicine imaging
- measure distribution of radiolabeled biomolecules (i.e. glucose)
- functional imaging
- oncology/research



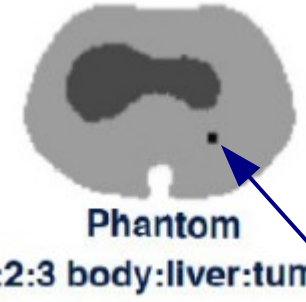
Metastasis of a malignent melanoma
D.Townsend, 1995

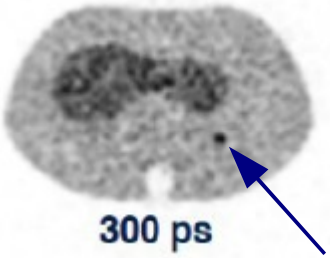
Time of Flight PET



$\Delta x = c\ \Delta t/2$
(CTR)

simulation study





(CPS Innovation)

ToF information enhances image contrast:

$$SNR_{TOF} \cong \sqrt{\frac{D}{\Delta x}}\, SNR_{conv}$$

Significant enhancement of image contrast with ToF.

Application of SiPM to PET

- **small size** → highly granular detector with high spatial resolution (PMT/APD/SiPM 1cm^2/0.5cm^2/0.1cm^2)

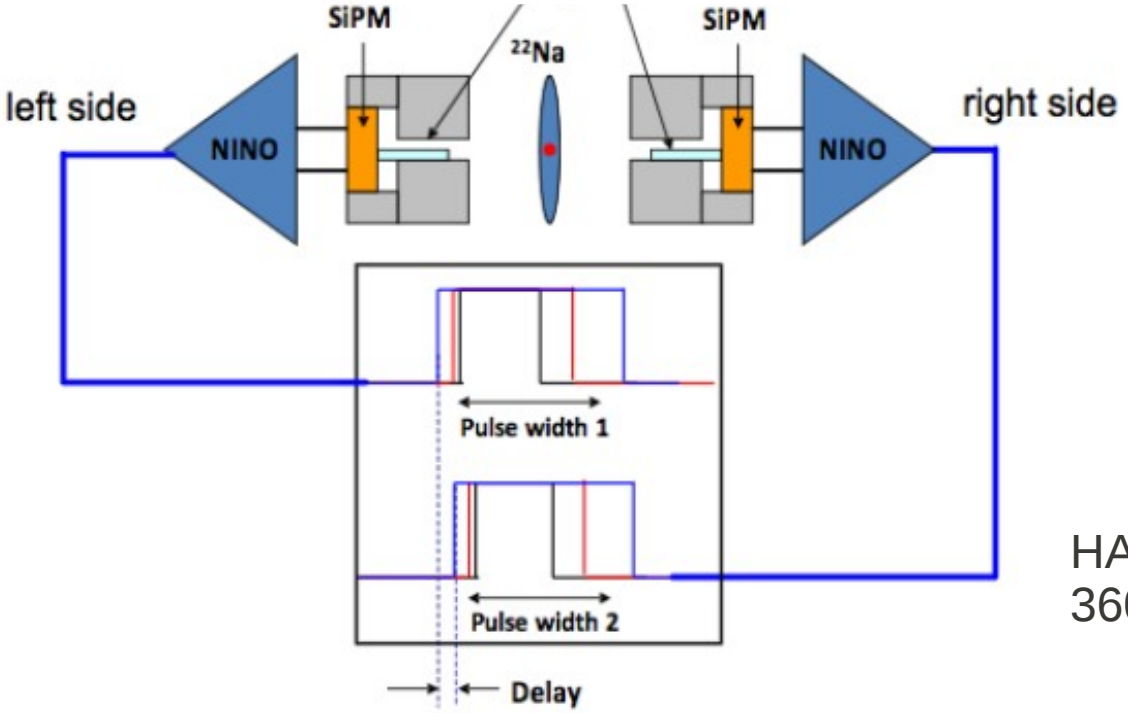
- **fast rise time** → excellent timing properties → ToF (comparable to PMT, both superior to APD)

- **high PDE in the blue** (MPPC) → direct read-out of fast crystal scintillators (LSO, LYSO) and high light yield → time resolution → ToF (30% for 410nm, comparable to PMT, both inferior to APD)

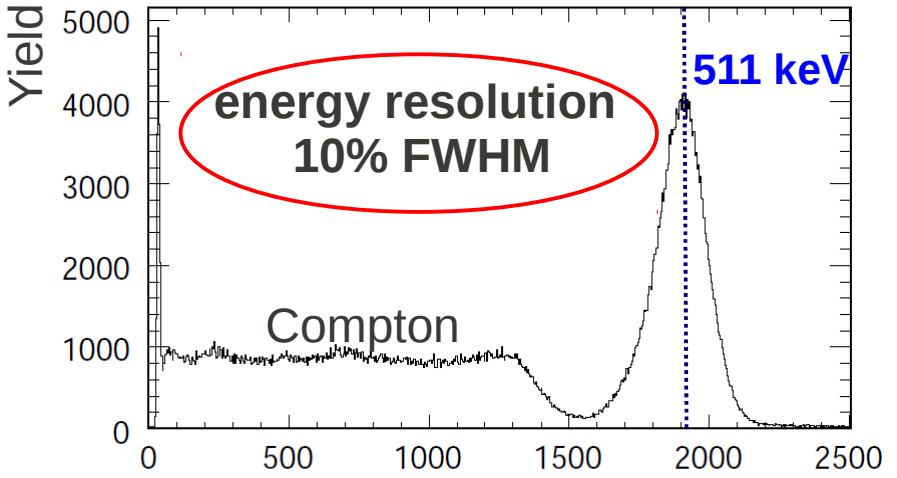
- **insensitive to high magnetic fields** → multi-modal MRI-PET imaging (unlike PMT but similar to APD)

Application of SiPM to PET

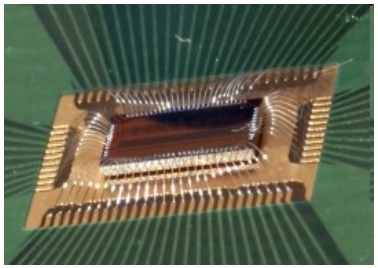
LSO 2x2x10mm^3



3x3x15mm^3 LSO



HAMAMATSU MPPC 3x3mm^2
3600 pixels



- NINO (CERN) - An ultra fast low power front end amplifier discriminator chip (ToF system of ALICE experiment @ LHC)
- Front end time jitter <10ps (design)
- 8 channel
- differential r/o of SiPM

Coincidence time resolution 220 ps FWHM

(CERN, Thomas Meyer et al.)

PET spin-off projects with contributions from DESY

Where can we make an impact?

1) Multi-channel ASIC for SiPM r/o with ToF capabilities

- Building and comissioning of a ToF-PET test device to test multi-channel r/o electronics.
- Profit from experience with the CALICE HCAL (SPIROC)
- Collaboration with CERN and University Heidelberg
- Synergy with ENDO-TOFPET-US project

2) Specialized (organ specific) multi-modal imaging detectors

ENDO TOFPET US
Endoscopic TOFPET & Ultrasound

- **ENDO-TOFPET-US** project
- Funded as an FP7 project
- From design to pilot clinical studies, interdisciplinary
- Combining endoscopic ultrasound probe (EUS) with PET detector
- DESY is work package leader for WP5, and is responsible for the detector integration.
- *http://endotofpet-us.cern.ch*

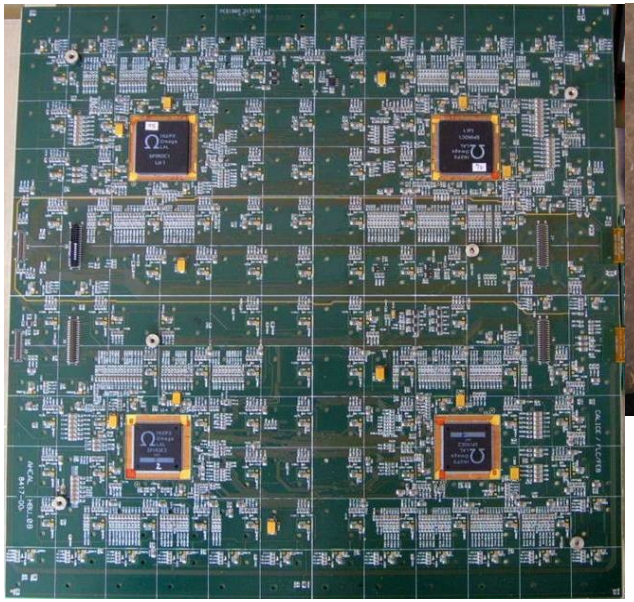
Multi-channel ASIC for Calorimetry

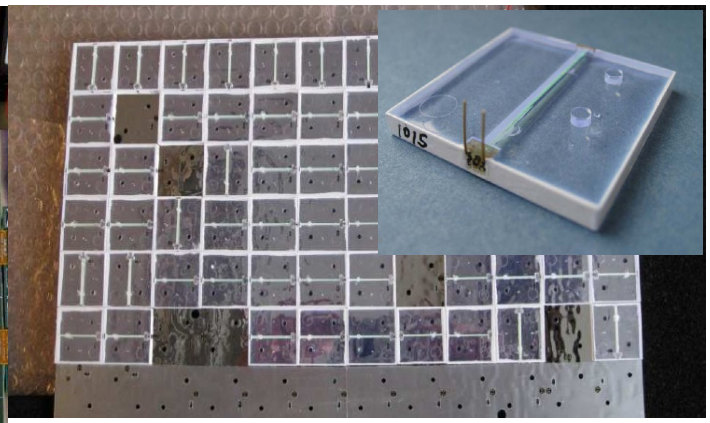
CALICE collaboration: investigating high granularity calorimeter systems for the the ILC

CALICE group at DESY:

- AHCAL Fe/plastic scintillator sandwich calorimeter with SiPM r/o
- First prototype: ~8000 SiPM operated for 4 years at various testbeams
- Next generation prototype:

HCAL Basic Unit:





- 4 ASICs per PCB
- 144 scintillator-SiPM tiles on each board
- LED calibration system

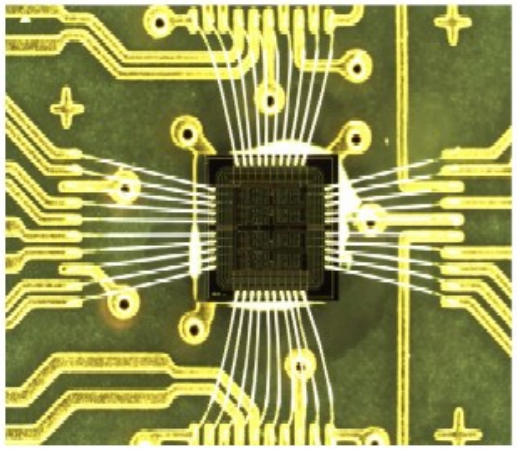
SPIROC:

- Specific chip for SiPM r/o: channel wise bias adjustment
- 36 channels
- Designed for ILC operation:
  - Low power (power pulsing)
  - fully digital output signal from ADC and TDC (1ns time resolution)

TOFPET ASIC for SIPM r/o

STiC: SiPM Timing Chip (**Wei Shen, Uni Heidelberg**)

(fast discriminator ASIC for ToF-PET application)



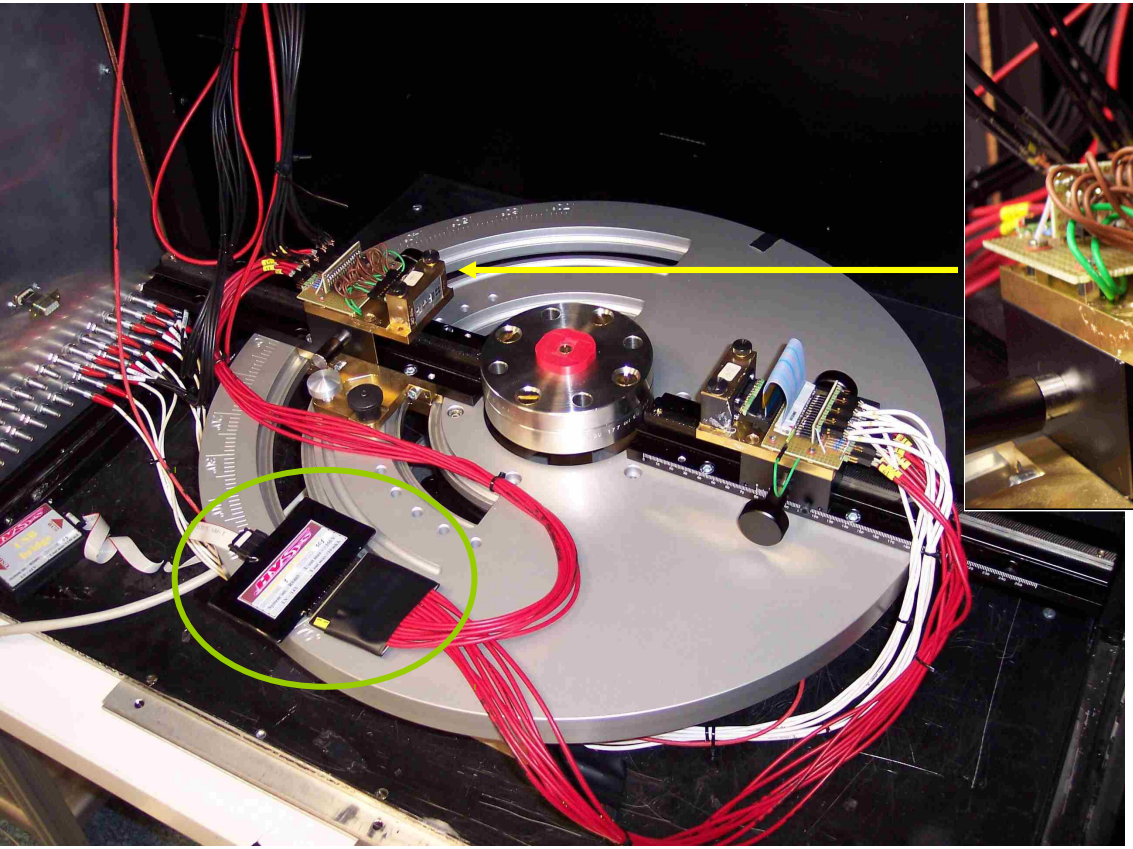
STiC 1.0: AMS 350 nm CMOS , 4 channels;
Leading edge & Constant fraction trigger;
Tunable bias DAC ~ 1 V; power < 10mW/ch
Pixel jitter ~ 300 ps, time of flight capability

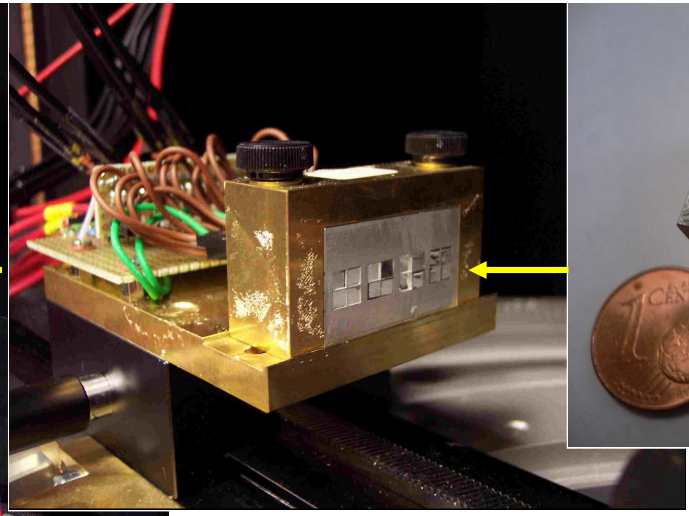
STiC 2.0: UMC 180 nm (in preparation)
Differential design to explore timing limits
Simulation: single pixel time resolution ~ 100 ps.

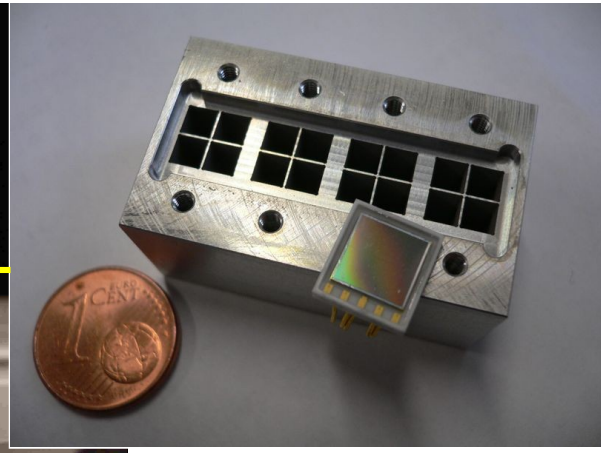
Under development: integrate TDC (ENDO-TOFPET-US project)

W. Shen et. al, IEEE NSS/MIC, 2009; 10.1109/NSSMIC.2009.5401693

Multi-channel ToF-PET test device







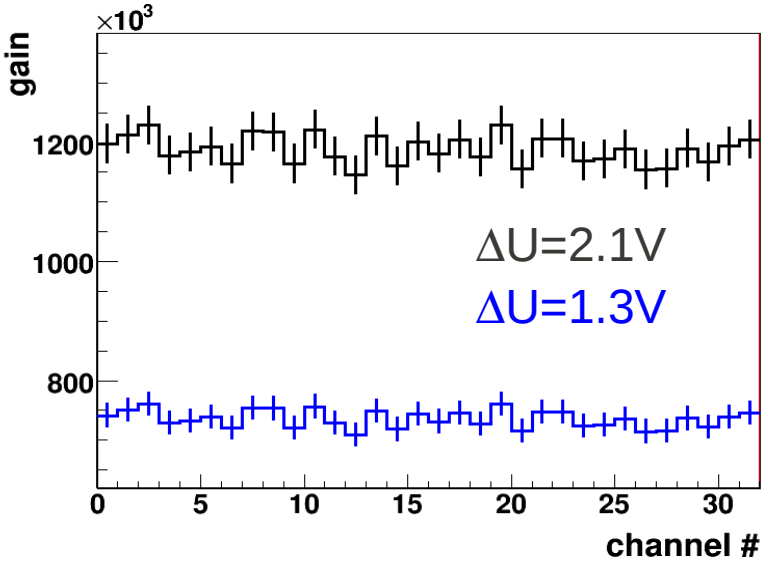
- 2 modules of 16 ch. Each
- 3x3x15 mm^3 LFS crystals
- 2x2 MPPC array

  [3x3mm^2, 50μm^2 pixels, 3600 pixels]

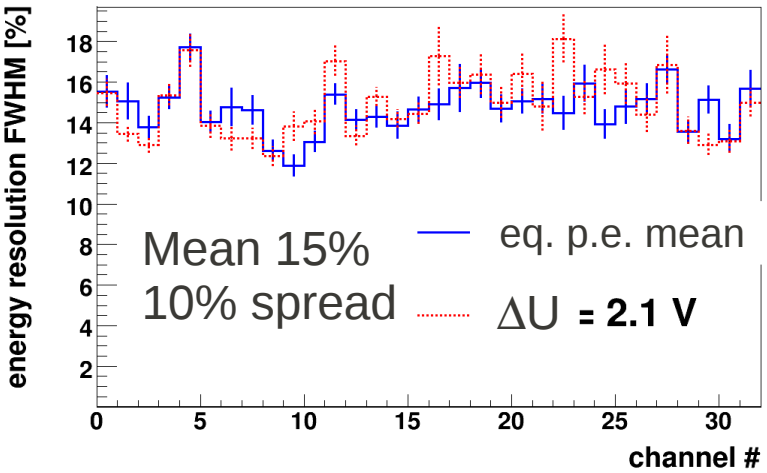
- 2 detector modules with adjustable distance from centre and relative angle
- computer controlled motor for rotation of modules around source
- 2x16 ch. power supply with individual bias steering for each MPPC and temperature sensor for SiPM gain stabilization

Basic Detector Characterization

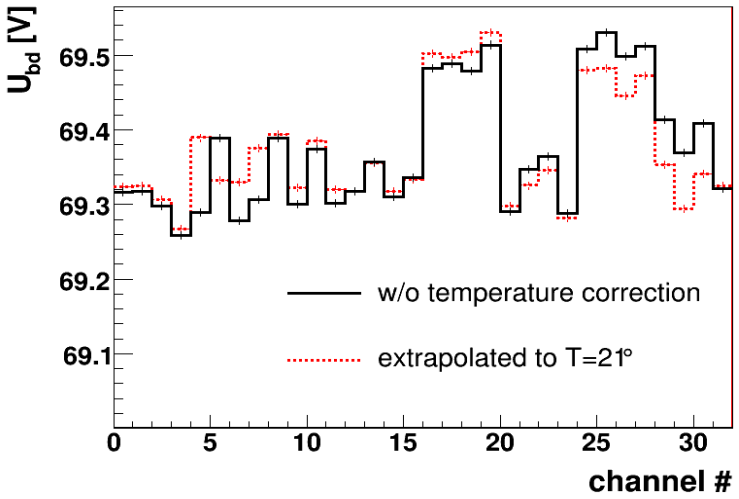
1) MPPC gain



3) Energy resolution

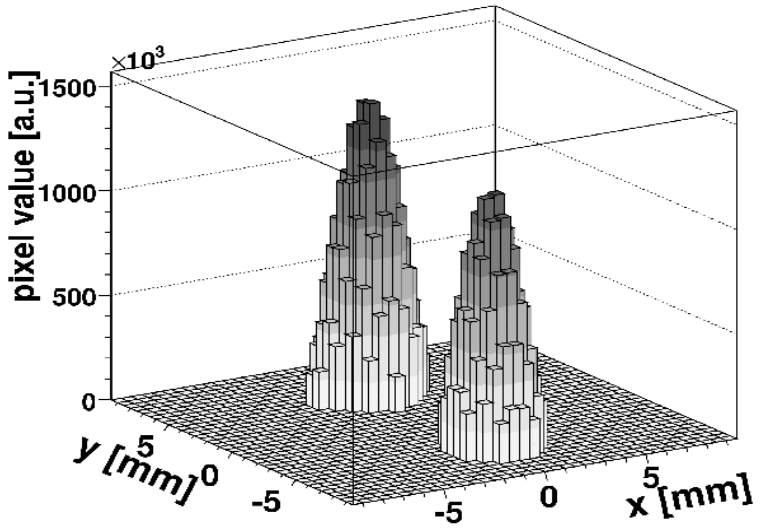


2) breakdown voltage



→ gain stabilization with temperature

4) Reconstructed image (two source d=1mm)



Spatial resolution: 2.5 mm FWHM

ENDO TOFPET US
Endoscopic TOFPET & Ultrasound

COOPERATION

Endo-TOFPET-US: Objectives

Medical Objectives:

- improve harvesting of tumoural tissue during biopsy combining the functional biological information of radioactive biomarkers (**PET**) with the morphological information obtained from **EUS**

- image-guided diagnosis and minimally invasive surgery with a **miniaturized bimodal endoscopic probe** with a millimetre spatial resolution and a 100 times higher sensitivity than whole-body **PET** scanners (fast acquisition)

- first target pathologies: **pancreatic and prostatic cancer** (with a clinical pilot study)

- Develop more **specific biomarkers** for pancreatic (severe) and prostatic (frequent) cancer

Technological objectives:

- Energy resolution sufficient to discriminate against Compton events
- 200 ps FWHM coincidence time resolution → 3cm → restrict LORs coming from ROI 3cm
- high sensitivity
- extreme miniaturization of PET head (pancreas)

Endo-TOFPET-US: Organization

- FP7 funded 4 year project
- started January 2011
- Consortium:
  - 3 university hospitals (UnivMed, CHUV-UNIL, TUM)
  - 3 companies (Fibercryst, KLOE, SurgicEye)
  - 4 universities (UHEI, Unimib, LIP, DELT TU)
  - CERN, DESY
- divided into 6 workpackages
- DESY is WP5 leader (Erika Garutti): mechanical and software integration of the system
- DESY group involved in r/o electronics

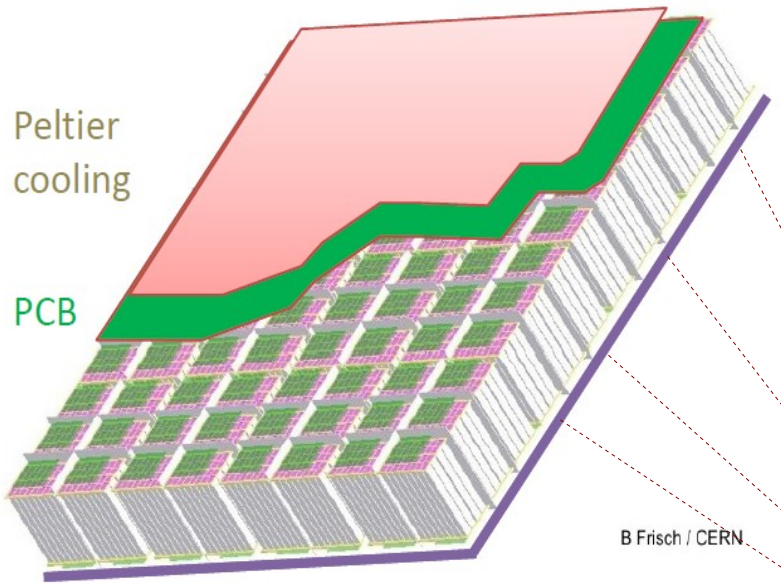
Strong co-operation with UHEI

ENDO TOFPET US
Endoscopic TOFPET & Ultrasound

COOPERATION

Endo-TOFPET-US: Overview

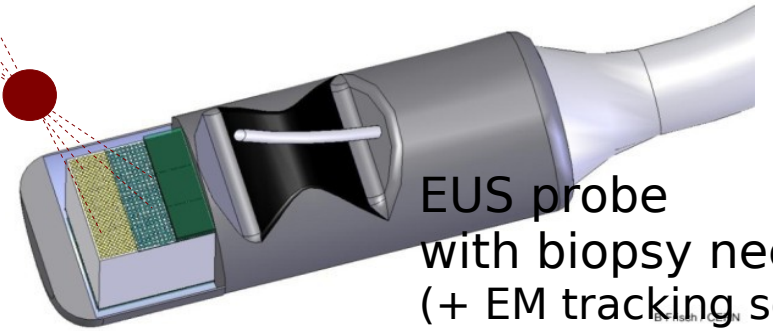
External PET detector



- 64x64=4096 LYSO crystals r/o individually by SiPM devices
- Crystal size 2x2x10 mm^3
- TOFPET ASIC
- Profit from experience with TOFPET test device

coincidences

Endoscopic probe



PET head

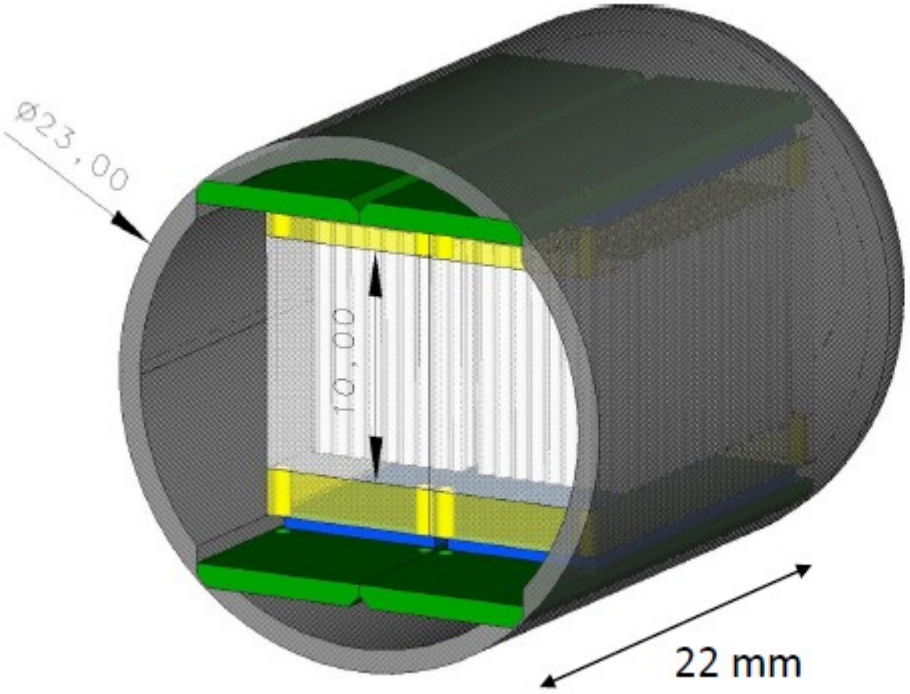
(schematics not to scale)

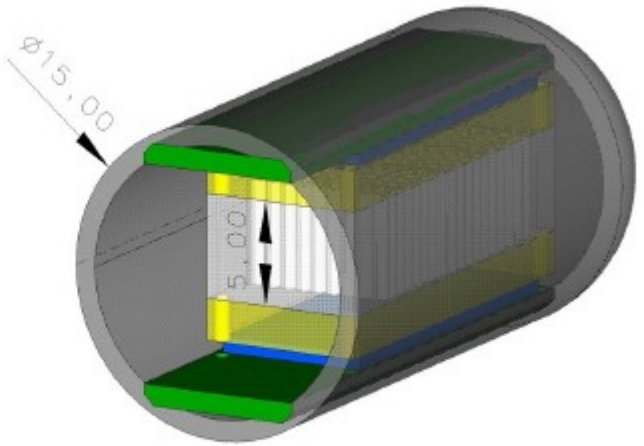
Challenges:

- Miniaturization
- Changing geometry
- Asymmetric geometry
- Position tracking
- High background

PET Head

EUS extension a) prostata version b) pancreas version



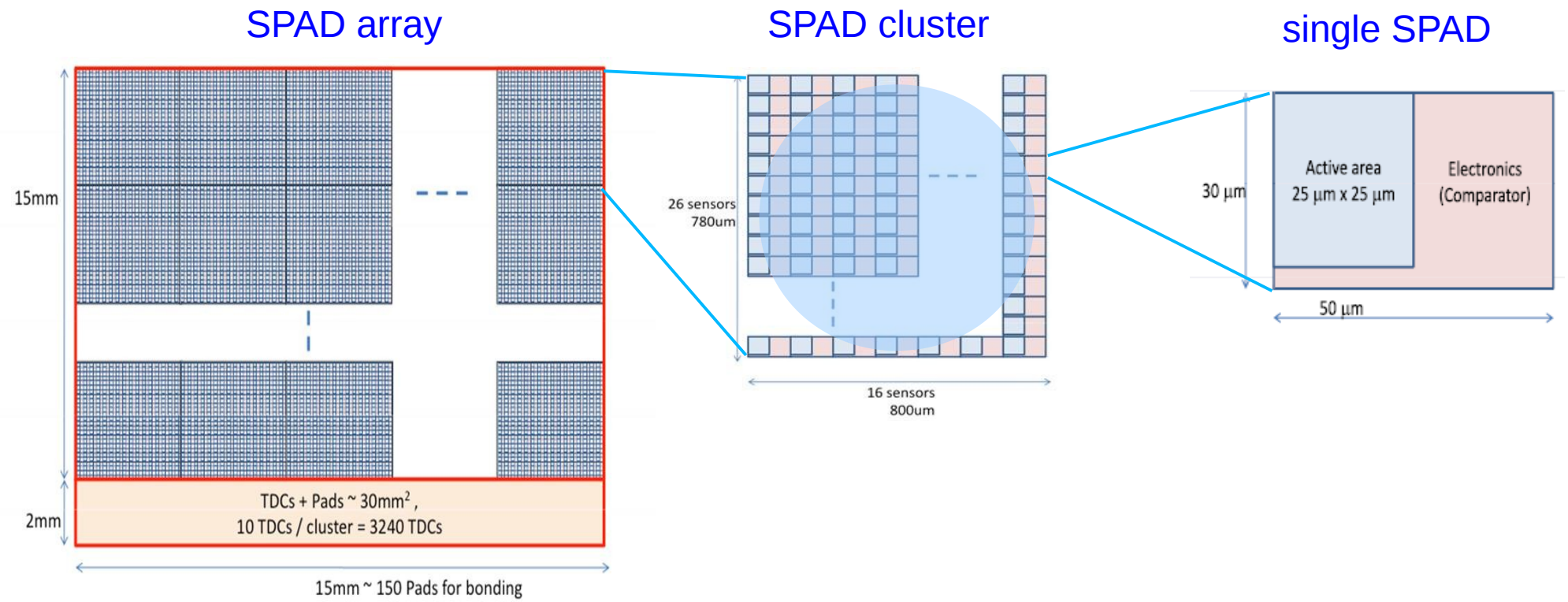


K. Gadow
(DESY)

PCB
Photo-detector (SPAD array)
Diffractive optics film (microlenses)
Fibre crystal matrix (LYSO 750 µm diameter)

Challenges: miniaturization, alignment, diffractive optics, …

PET Head



- SPAD array: CMOS mounted SiPM with integrated TDC
- single SPAD readout
- 416 SPADs = 1 cluster = 1 fiber readout
- 10 TDC per cluster
- 1 SPAD array = 324 fibers readout

Conclusion

- The PET group participates in two interesting and cutting-edge projects:

  1) Testing of multi-channel TOFPET ASIC
  2) ENDO-TOFPET-US (WP5 leader)

- Group size and expertise on the field is growing steadily.
- Group leader + 2 Postdocs + 1 PhD student + 2 diploma students

- Accademia has still a chance to make an impact in PET developments.
  Recepy:
  - stay away from the field of the big enterprices (full-body PET scanner)
  - focus on development and commissioning of multi-channel TOF ASIC for SiPM (expertise of HEP community)
  - explore the organ-dedicated PET detector field

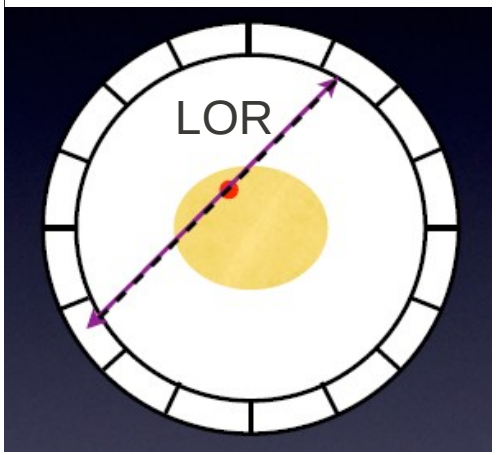
Backup

Basic Principle

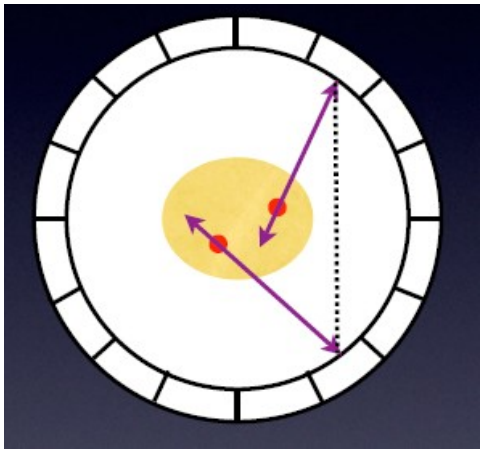
Detecting back-to-back gammas from an e+e- annihilation (positron emitting radionuclide).
Events which are coincidence form a **Line of Response.**

Background

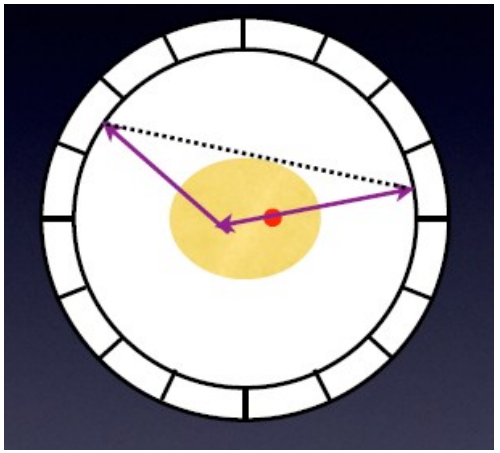
True coincidences



Random coincidences



Scattered coincidences



Background rejection:

- Time resolution: small coincidence window → reject random coincidences
- Energy resolution: discriminate compton events → reject scattered events

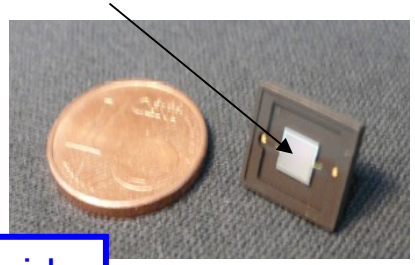
Multi Pixel Photon Counter

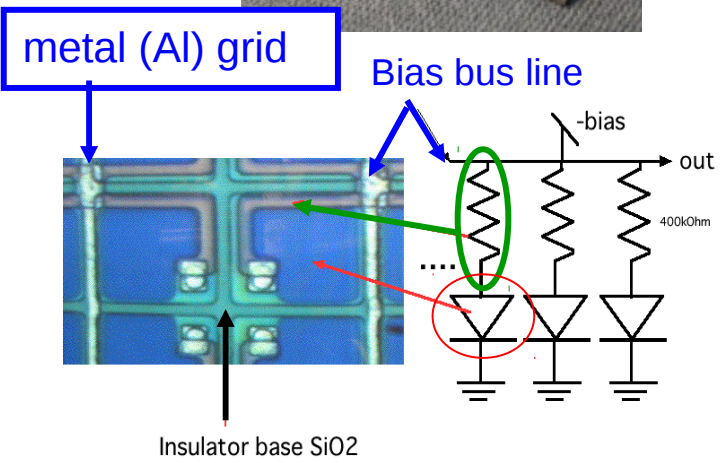
(Hamamatsu)

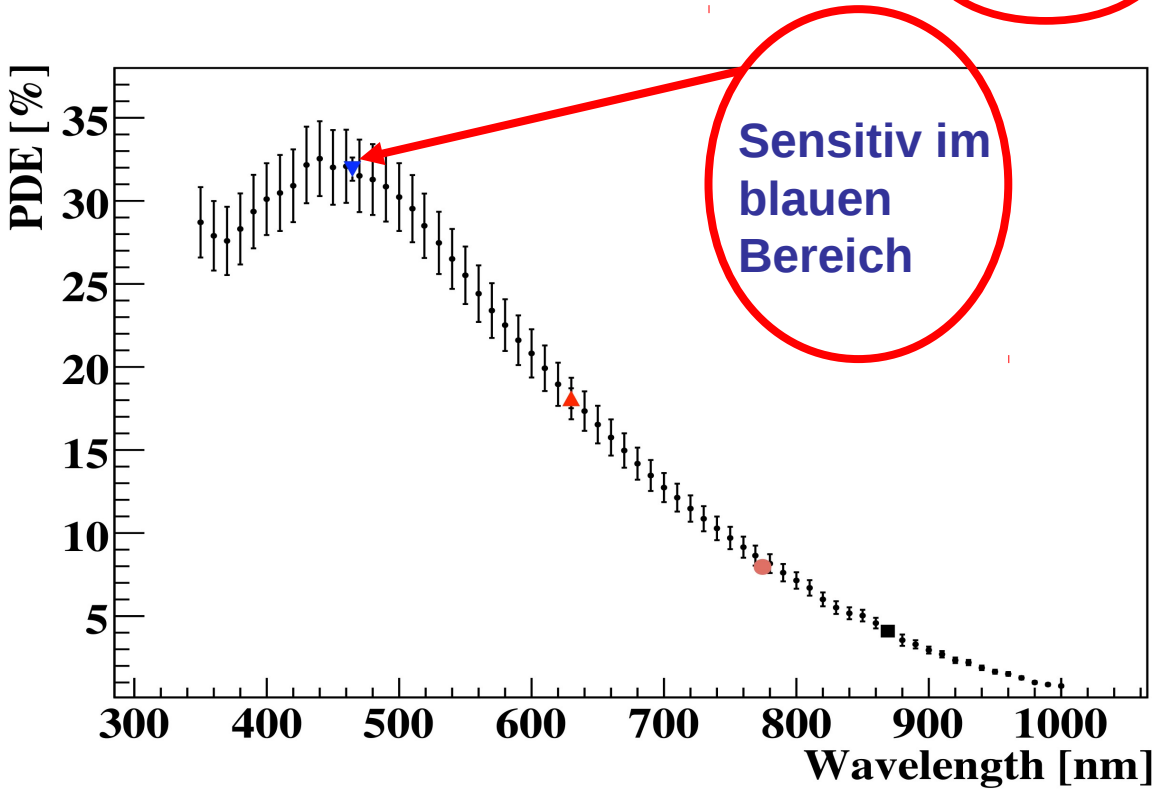
Matrix aus Avalanche-Photodioden, die im Geigermodus betrieben werden.

# Pixel (Größe mm²)	Spannung	Dunkelrate > 0.5 Pixel	Dunkelrate > 1.5 Pixel	Verstärkung (10^5)
3600 (3x3)	70 V	3.2-3.3 MHz	320-330 kHz	7.4-7.5

3x3 mm² aktive Fläche, 3600 Pixel



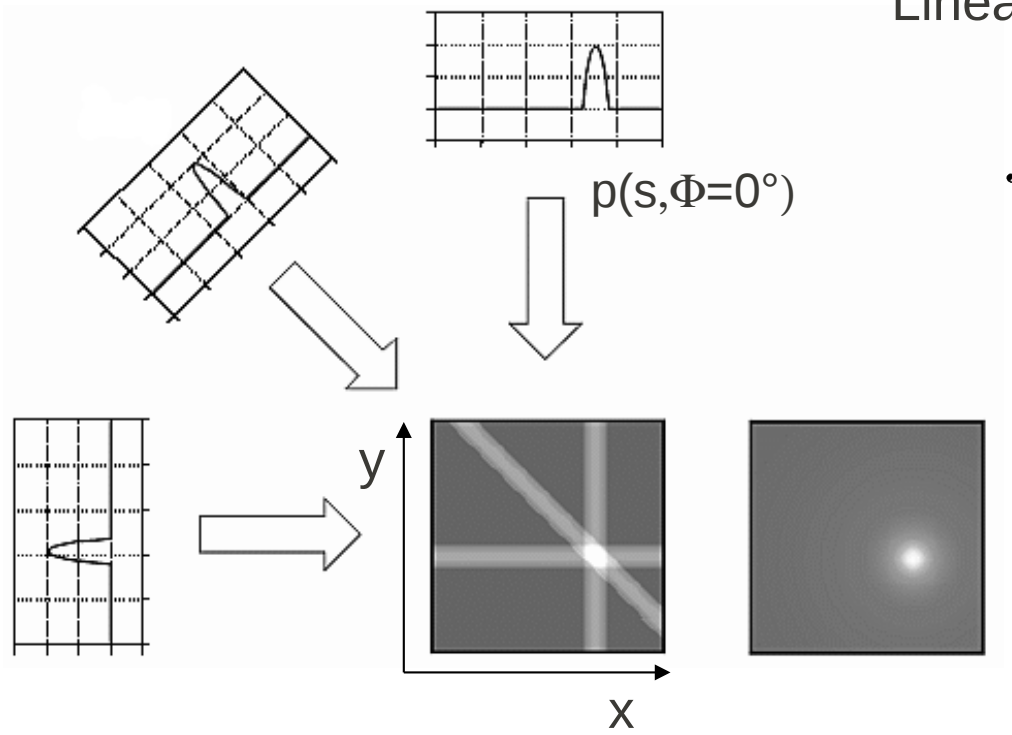




Problem: Sättigung. Aber Pixel-Erholungszeit 4 ns.

Gefilterte Rückprojektion

(**Analytische 2D Bildrekonstruktion**)



3 verschiedene Projektionen

viele Projektionen

Lineare Superposition von Rückprojektionen:

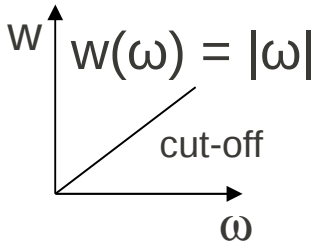
$$f(x,y) = \int_0^{\pi} p[s(x,y),\Phi]d\Phi$$

Integration über alle möglichen Projektionswinkel.

Führt zu einer **1/r** Verschmierung des Bildes, d.h. schlechte Ortsauflösung.

-> Filterung, die langreichweitige Beiträge unterdrückt und daher den Kontrast verbessert.

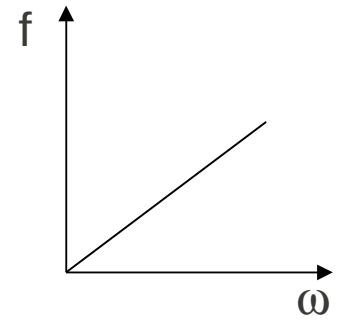
Ramp-filter (Frequenzraum):



Korrekturen:
- Akzeptanz
- Granularität (Smearing)

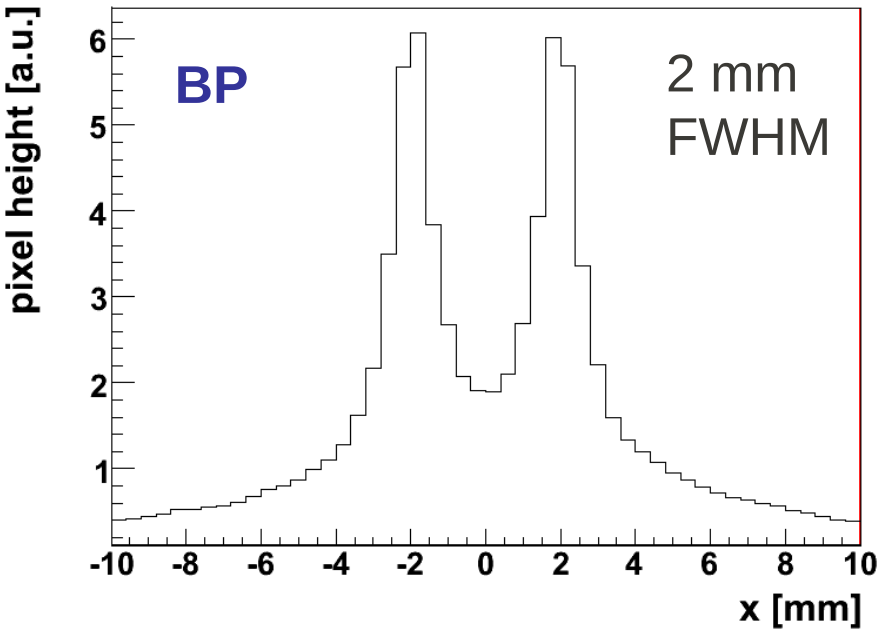
Filterung

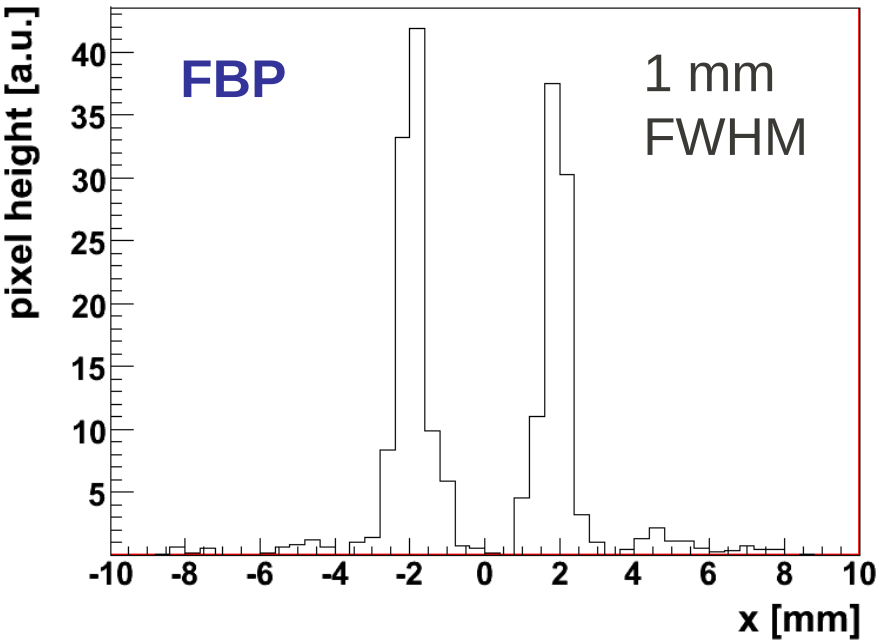
Ramp-filter:



Simulation: Idealer Detektor

$w(\omega) = |\omega|$

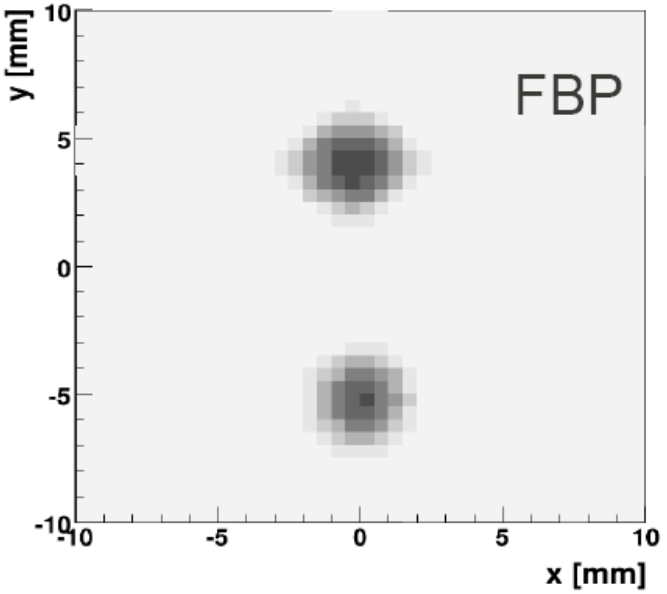




(Durchmesser Quellen d=1mm)

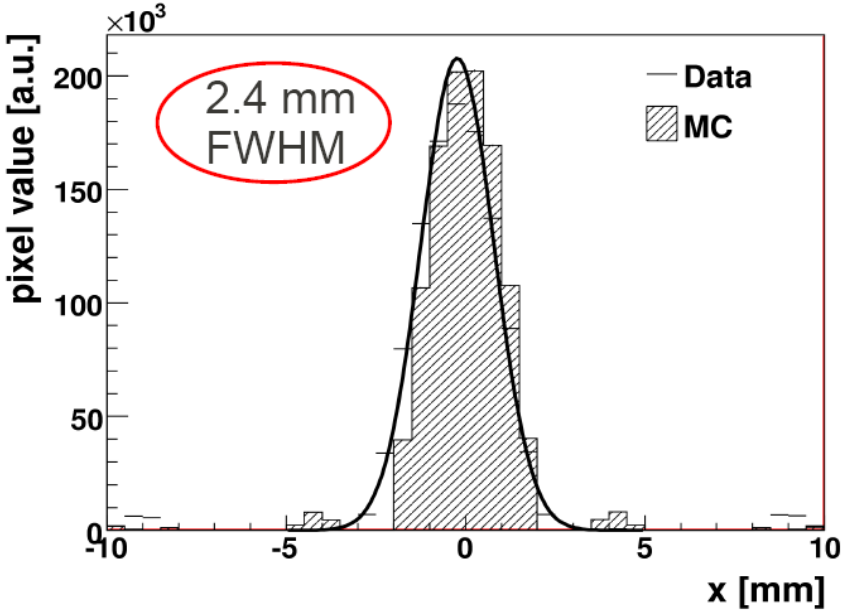
Spatial resolution tested

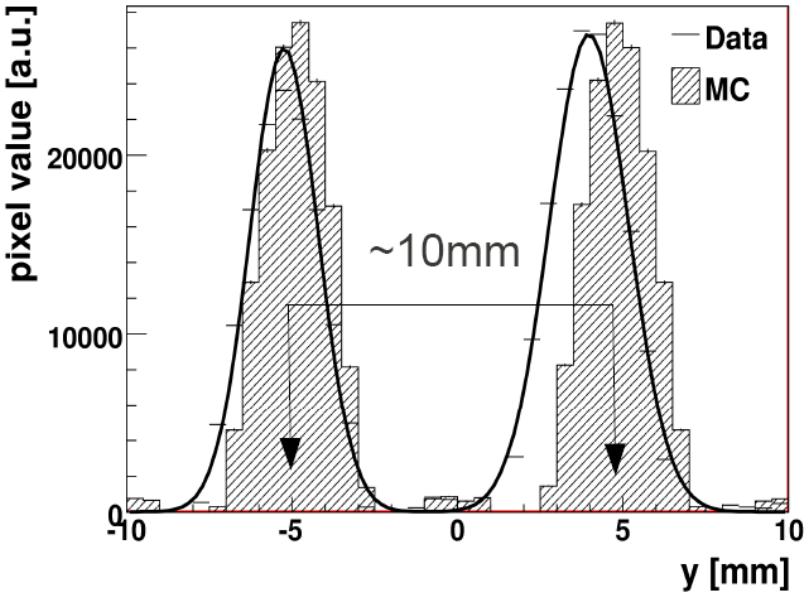
Reconstructed image of two sources (1mm diameter each) ➔



Spatial resolution dominated by crystal size

Resolution of 2.4 mm FWHM in agreement with GATE simulation





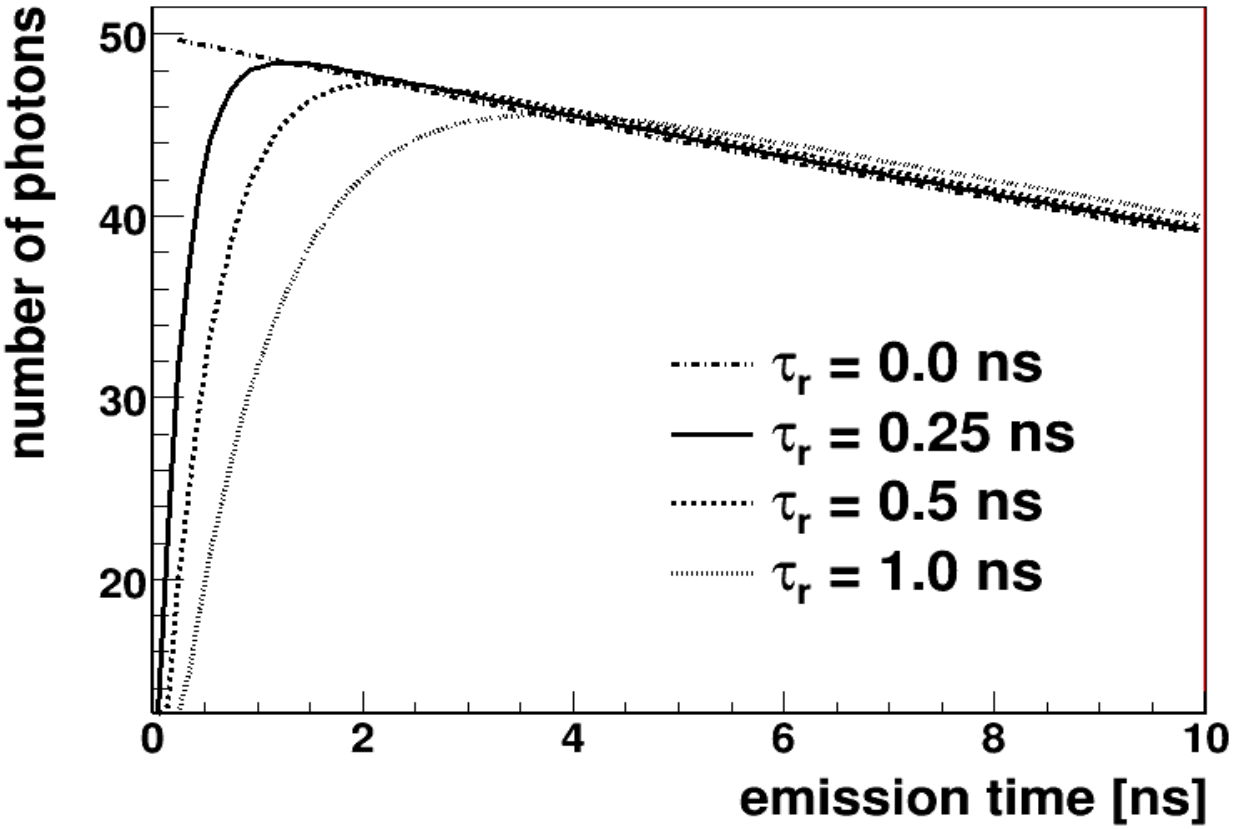
Statistics of the scintillation process

$$n(t) = R\frac{\tau_d + \tau_r}{\tau_d^2} e^{-t/\tau_d}\left[1 - e^{-t/\tau_r}\right]$$

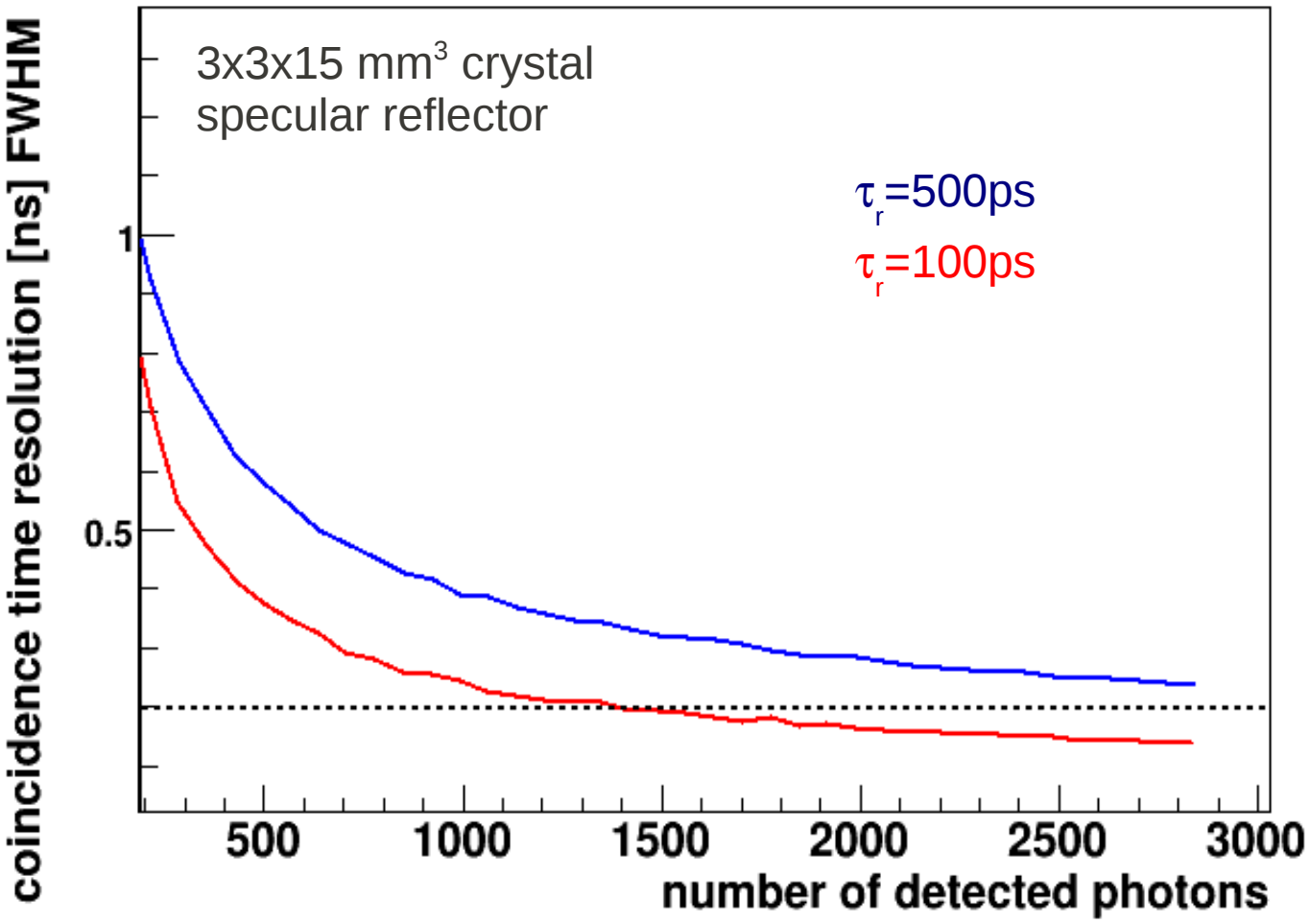
R: detected photons (**1500**)

τ_d: decay time (**40 ns**)

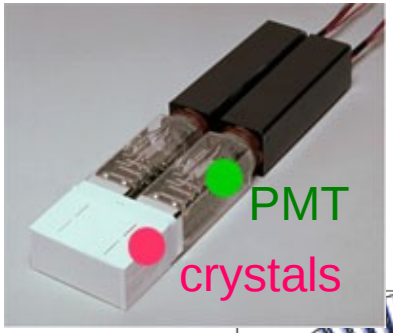
τ_r: rise time (**0.5 ns**)



CTR GEANT4 Simulation

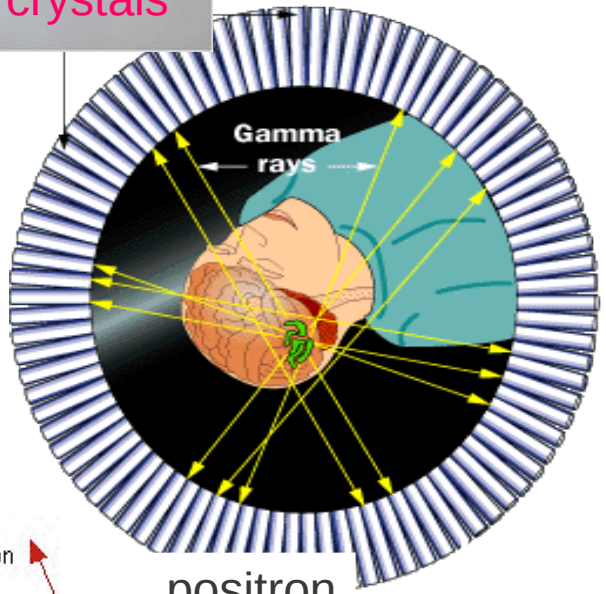


PET – Basic Priciple

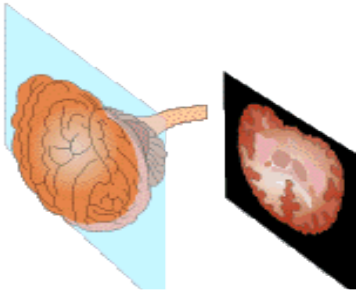


Tracer

(z.B. FDG)



positron



reconstructed image

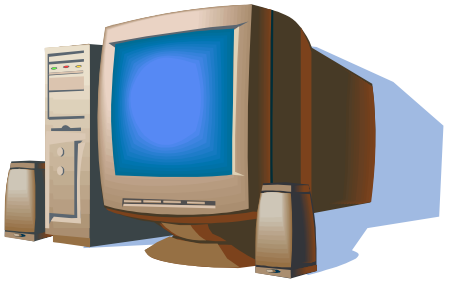
coincidences

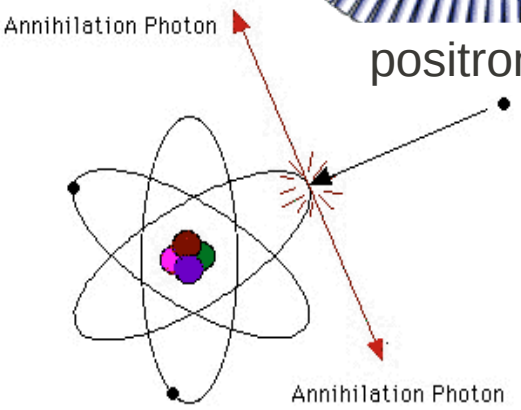
↓

Line of Response (Sinogram)

↓

Image reconstruction





Part. no.	Organisation type	Short Name	Organisation legal name	Principal investigator	City, Country
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2	International Research Organisation	CERN	European Organization for Nuclear Research	P. Lecoq	Geneva, Switzerland
3	University Hospital	CHUV-UNIL	Centre Hospitalier Universitaire Vaudois et Université de Lausanne	J. Prior	Lausanne, Switzerland
4	Research Organisation	DESY	Deutsches Elektronen-Synchrotron	E. Garutti	Hamburg, Germany
5	Higher Education	Delft TU	Delft Technical University	E. Charbon	Delft, Netherlands
6	SME	Fibercryst	Fibercryst	D. Perrodin	Villeurbanne, France
7	SME	KLOE	Kloe SA	P. Coudray	Montpellier, France
8	Higher Education	LIP	Laboratório de Instrumentação e Física Experimental de Partículas	J. Varela	Lisbon, Portugal
9	SME	SurgicEye	SurgicEye GmbH	J. Traub	München, Germany
10	University Hospital	TUM	Technische Universität München Team 10a. TUM/NUK Team 10b. TUM/CAMP	M. Schwaiger M. Schwaiger N. Navab	München, Germany
11	Higher Education	UHEI	University of Heidelberg	H.C. Schultz-Coulon	Heidelberg, Germany
12	Higher Education	Unimib	University Milano Biccoca	M. Paganoni	Milano, Italy