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sense and simplicity

Digital Photon Counters as Scalable Building Blocks for Various Applications

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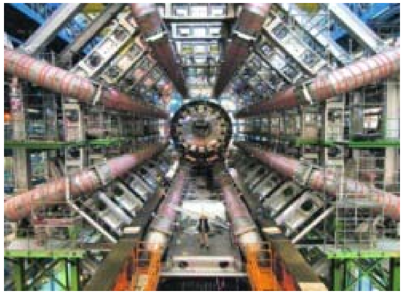
Heraeus Seminar Bad Honnef
May 23rd, 2013

What is Philips Digital Photon Counting (PDPC) doing ?

Philips Digital Photon Counting is designing and manufacturing **scalable** detectors based on **digital Silicon Photomultiplier (dSiPM) technology** – a new type of advanced solid state light detector, now called **Digital Photon Counter (DPC).**

Potential Applications

- **Medical Imaging**
- **Life Sciences**
- **High Energy Physics**
- **Material Testing/Detection**
- **Process Control**



Solid State, Digitization & Integration Win

Transistor

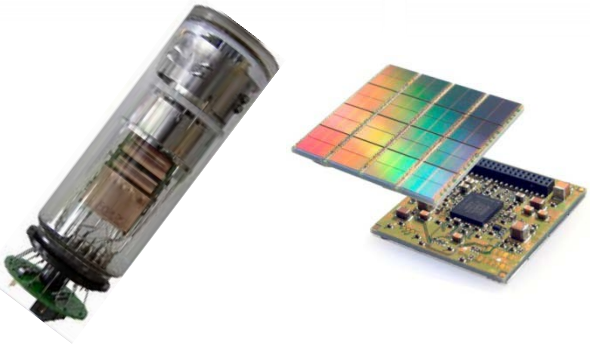
Television

Photography

Telephony

X-Ray imaging

Next: Light Detection



Disruptive Technology: Example TV/displays

- ***size/format:***

- just standing on support	- wall hanging
- big 3D box	- almost 2D, displays everywhere
- size limited by tubes	- flat, no size limitation

- ***image quality:***

- 60/100/200 Hz flickering	- no flickering anymore
- initially higher resolution	- resolution nearly unlimited
- limited contrast	- real life contrast

- ***functionality:***

- just TV or PC display	- internet, TV and PC merge
- single medial	- multi-medial

- ***safety:***

- HV	- no HV
- vacuum, risk of implosion	- no risk of implosion

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Outline

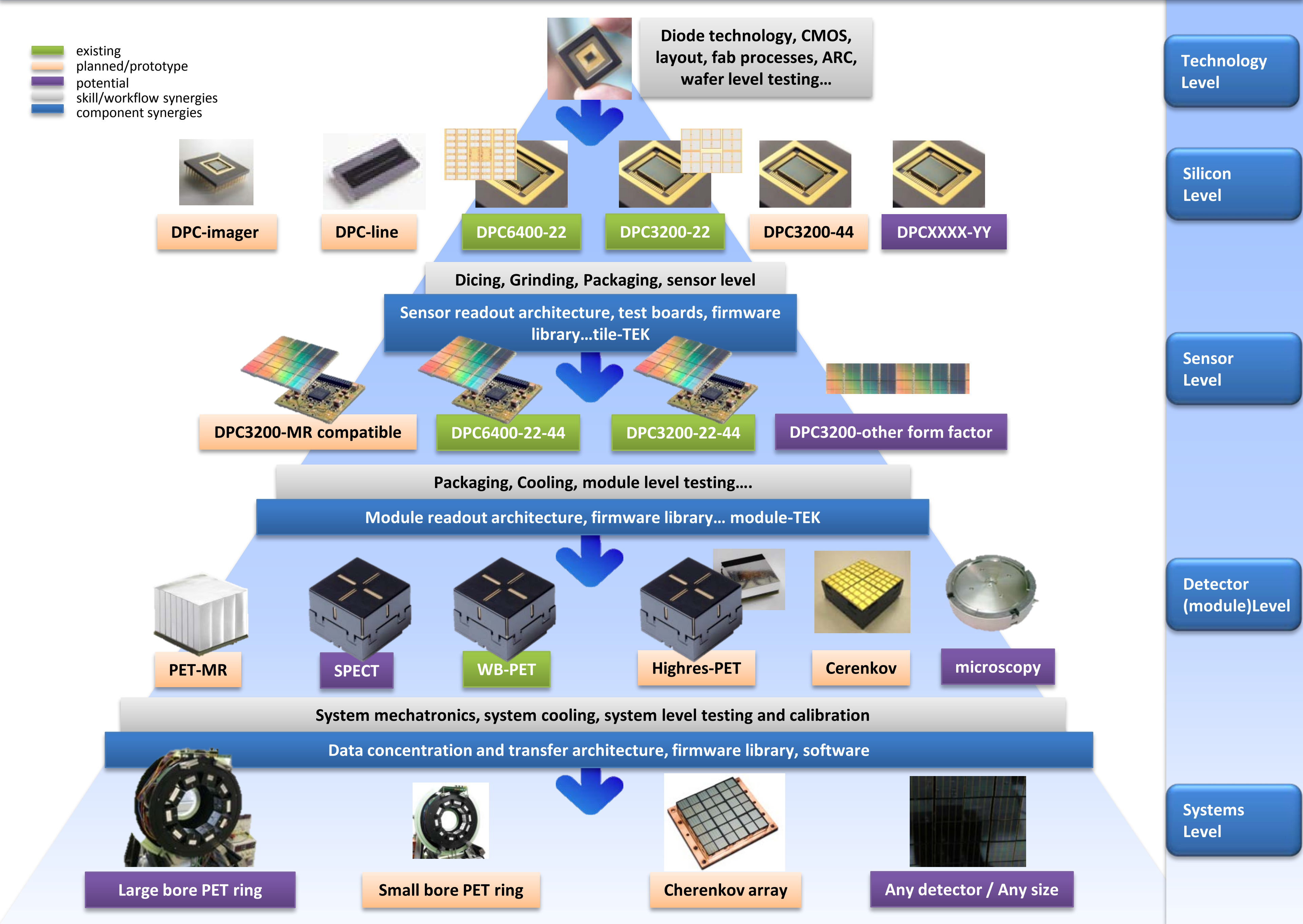
Concept of scalability, from pixels to systems

Applications

- Positron Emission Tomography
- Cerenkov light detection

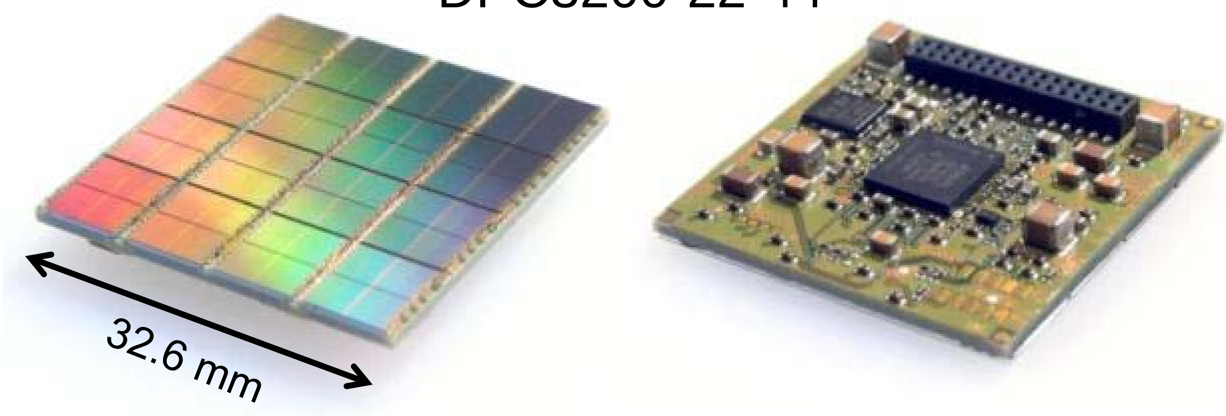
Outlook

The Philips tree of scalable DPC technology



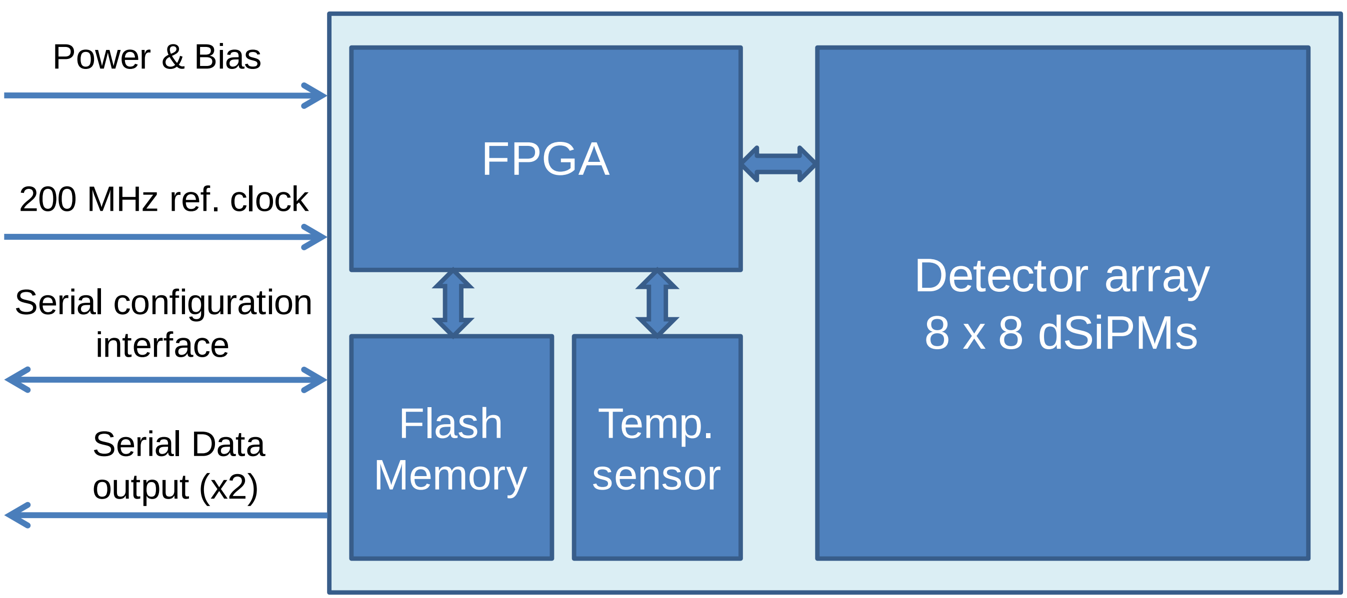
Digital Photon Counters enable Integrated “Intelligent” Sensors

DPC3200-22-44



FPGA
- Clock distribution
- Data collection/concentration
- TDC linearization
- Saturation correction
- Skew correction

Flash
- FPGA firmware
- Configuration
- Inhibit memory maps



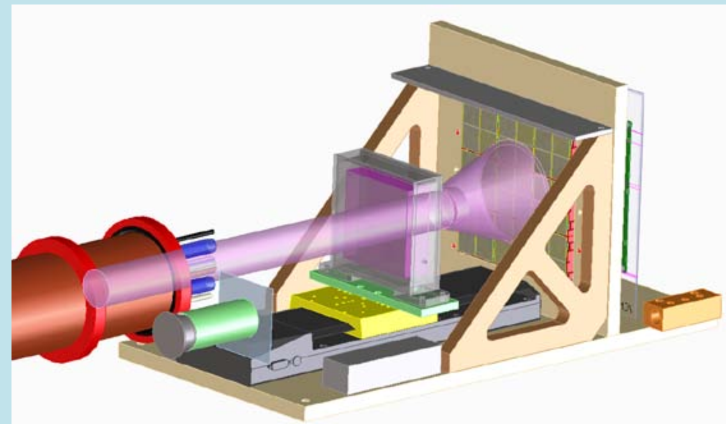
Further integration: Detector Module

- Modular design incl. 2 x 2 tiles, approx. 6.6 x 6.6 cm²
- Module PCB for power supplies, data concentration, processing & corrections
- Designed for easy cooling

Integration into Systems

Medical Imaging: Positron Emission Tomography

High Energy Physics: Cerenkov detector



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Application Example

Positron Emission Tomography (PET)

Positronen-Emission-Tomography (PET) as an application for DPCs

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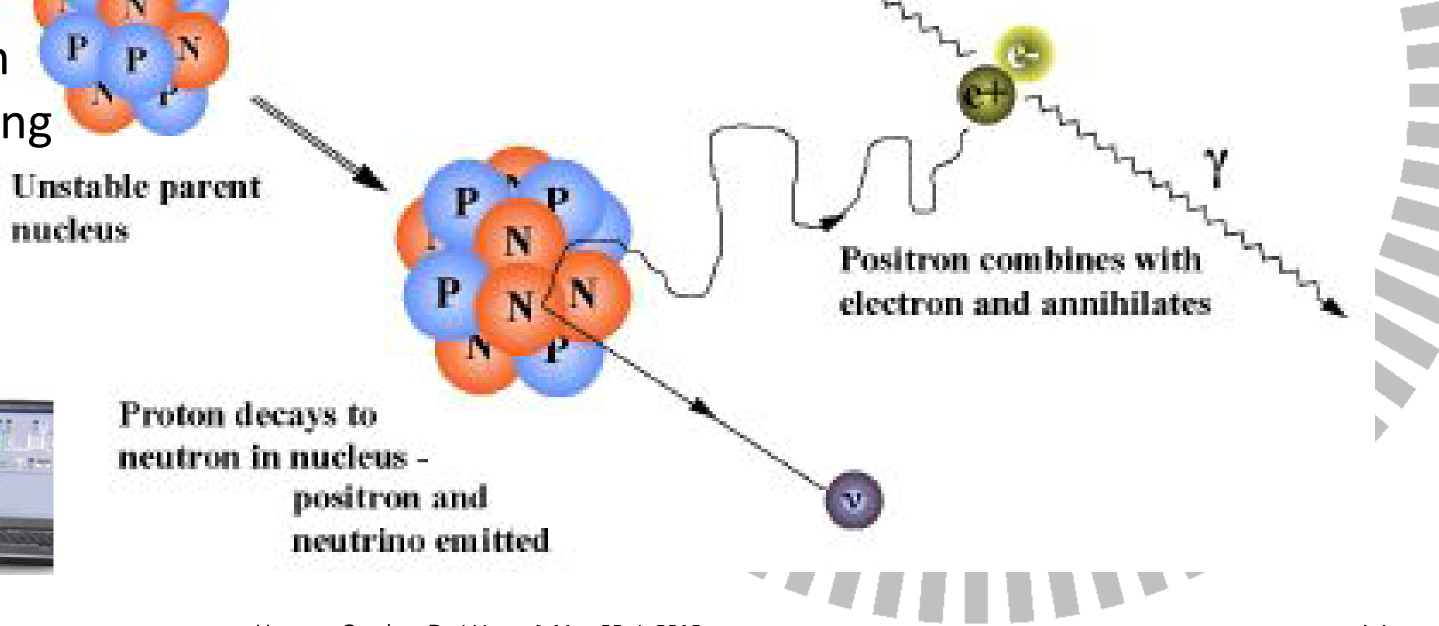
Positron-Emission-Tomography (PET)

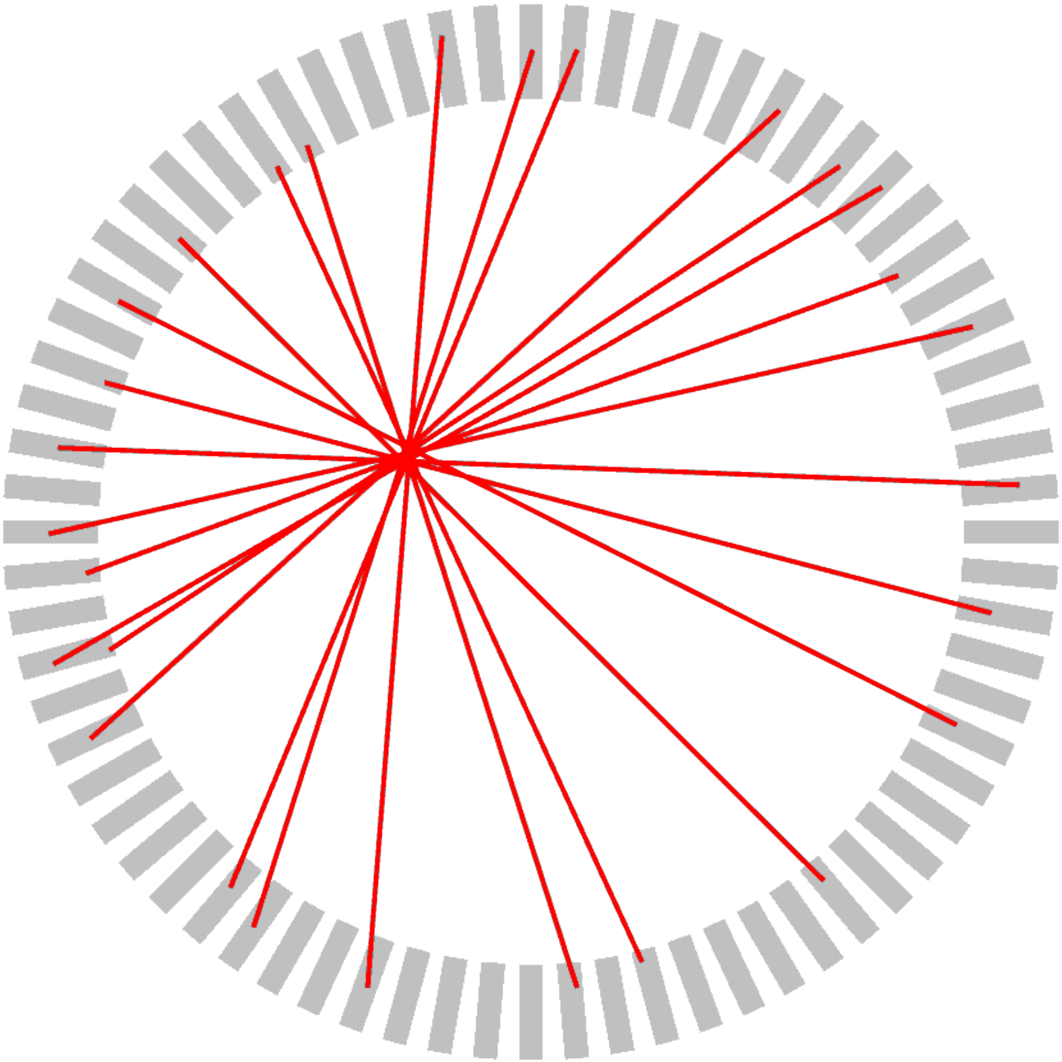
1.) **Production of isotopes** with proton excess in compact cyclotrons (e.g. ^{11}C, ^{13}N, ^{15}O, ^{18}F)

2.) **Labeling of organic molecules** with positron emitting isotope (e.g. ^{18}FDG) - **tracer**

3.) **Detection of 511 keV** annihilation γ-radiation with ring of scintillation detectors (e.g. BGO, LSO, LYSO)



PET – The Principle



Inject tracer

Wait (~60 min)

Marker accumulates

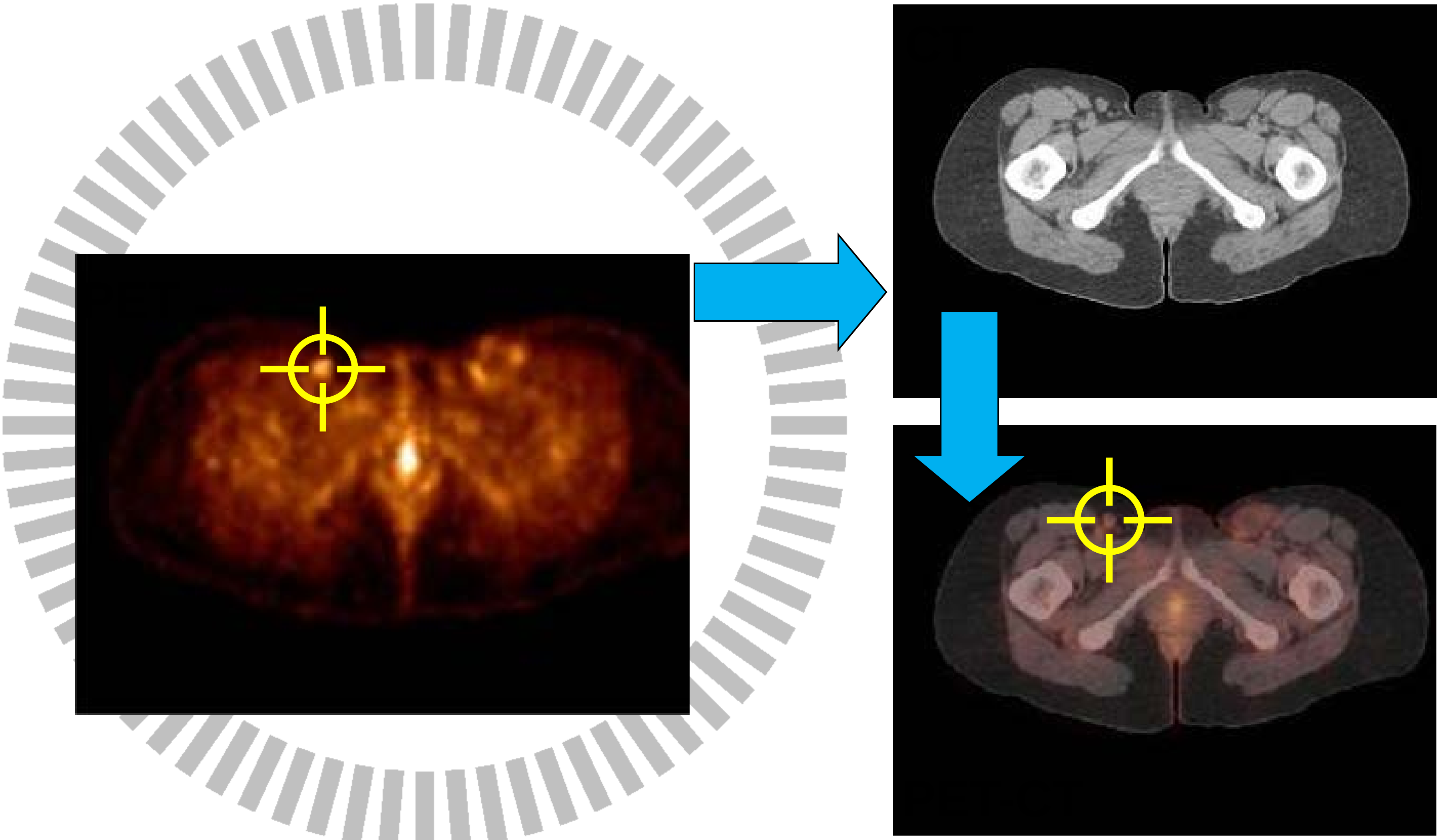
β^+ annihilation emits two γ under 180°

Detect coincident γ with ring detector

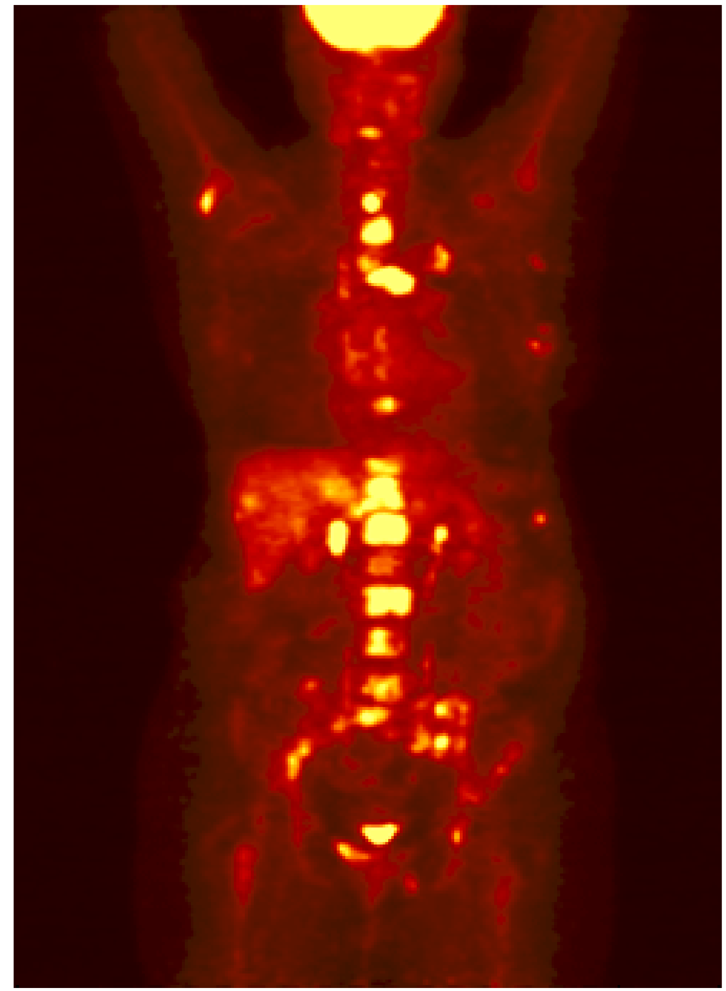
Acquire ~10^8 LORs (lines-of-response)

Reconstruct 3D tracer distribution

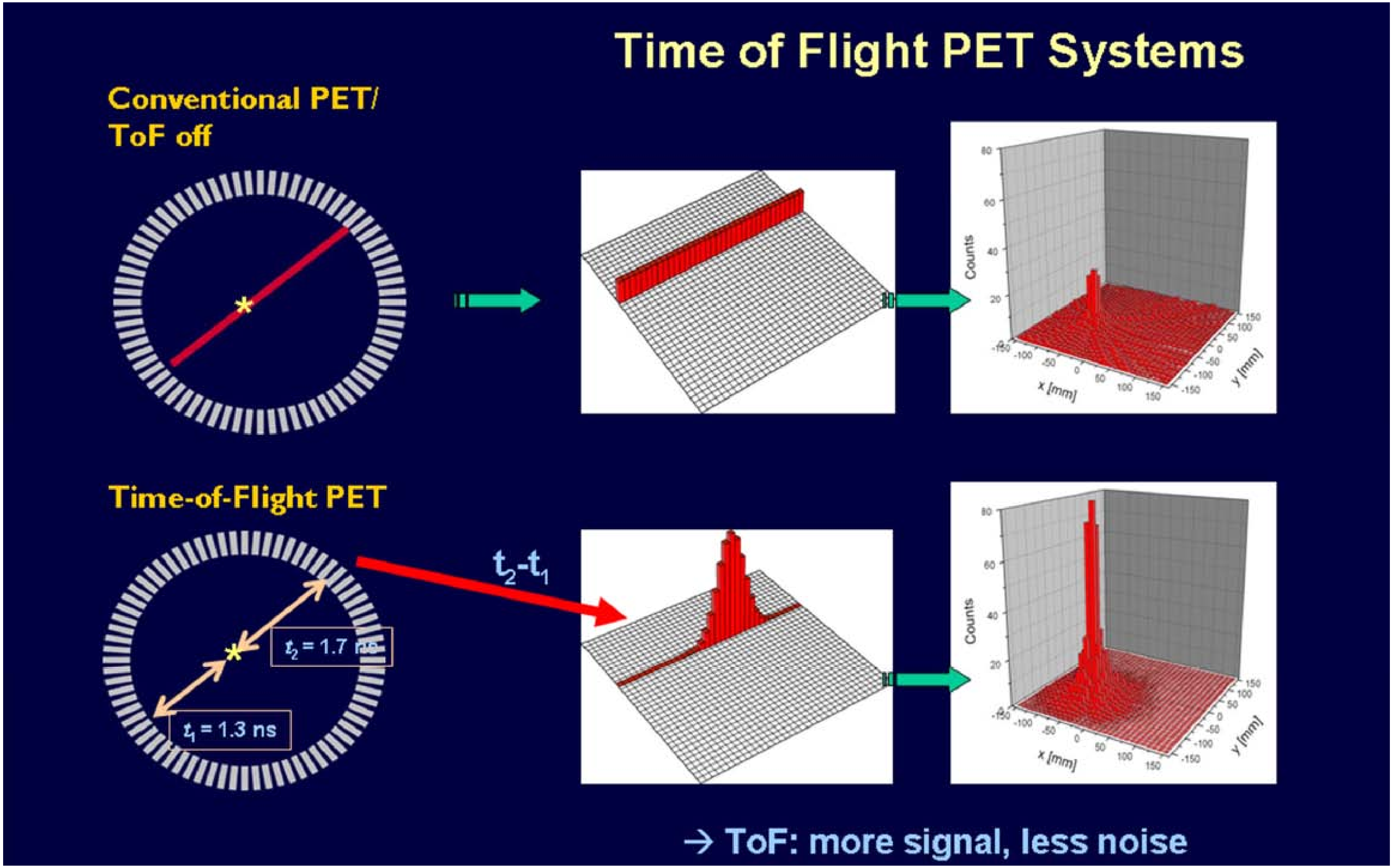
PET – The Principle



PET – The Principle



Time-of-flight (TOF-) PET



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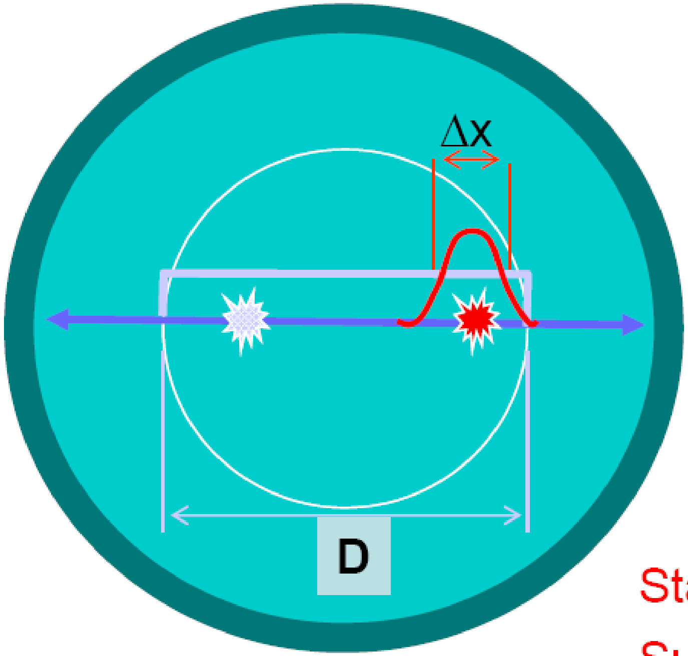
(TOF-) PET effect increases with reduced CRT and for larger objects

The accuracy of source position localization along line of response depends on the *coincidence resolving time (CRT)*



Δx = uncertainty in position along LOR = c · CRT/2, where c is the speed of light.

The TOF benefit is proportional to D/Δx, where D is the effective patient diameter.

=> The smaller the CRT, the better.

State-of-the-art: CRT ≈ 500 ps ⇒ Δx ≈ 7.5 cm

Suppose CRT = 100 ps ⇒ Δx = 1.5 cm

Graph courtesy of D. Schaart, Technical University of Delft, The Netherlands

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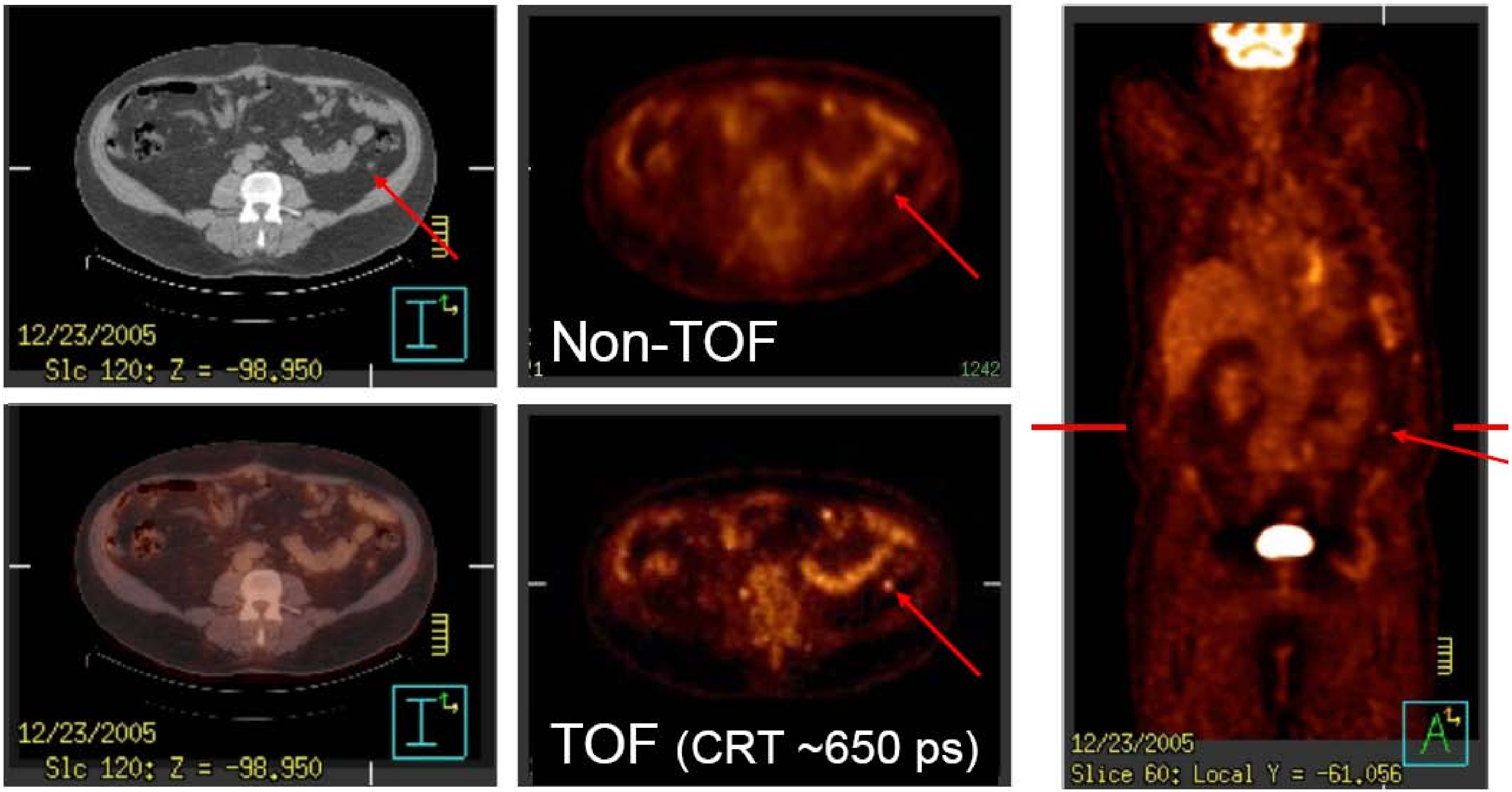
Time-of-flight (TOF-) PET: IQ improvement

Colon cancer, left upper quadrant peritoneal node

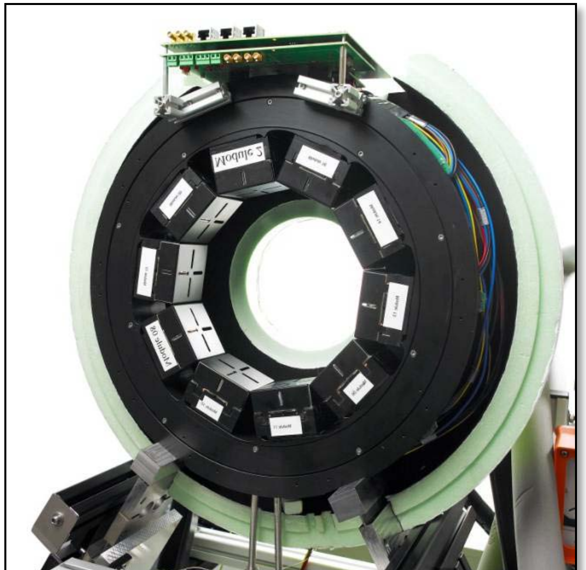
114 kg; BMI = 32.2
13.4 mCi; 2 hr post-inj



State-of-the-art clinical PET: coincidence resolving time (CRT) ≈ 500 ps

Images courtesy of J. Karp, University of Pennsylvania, Philadelphia

Prototype PET Scanner



- 10 modules
- 20 cm transverse field-of-view
- 6.6 cm axial field-of-view
- 4x4x22 mm^3 LYSO crystals, 1:1 coupling to DPC pixels
  (not intended to be a high resolution scanner)
- Integrated cooling (5 – 10 °C operating temperature)

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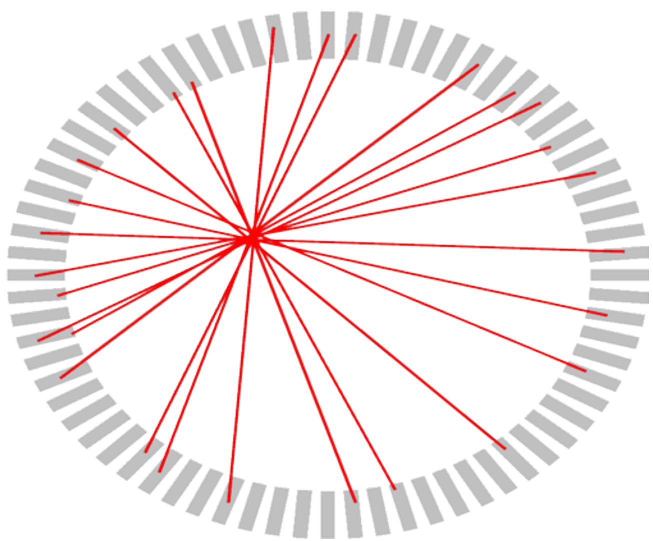
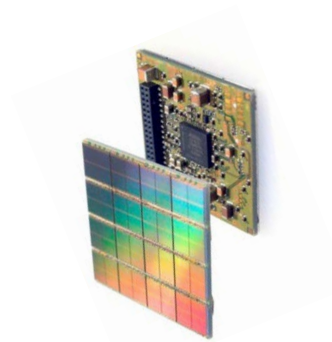
The challenge: information density

PMT-PET:
O(100) channels





Solid state PET:
O(10^4 – 10^5) channels

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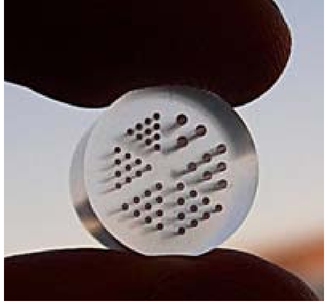
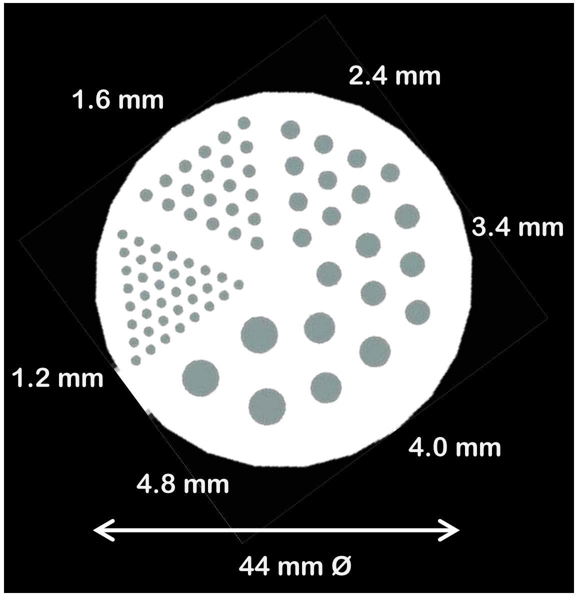
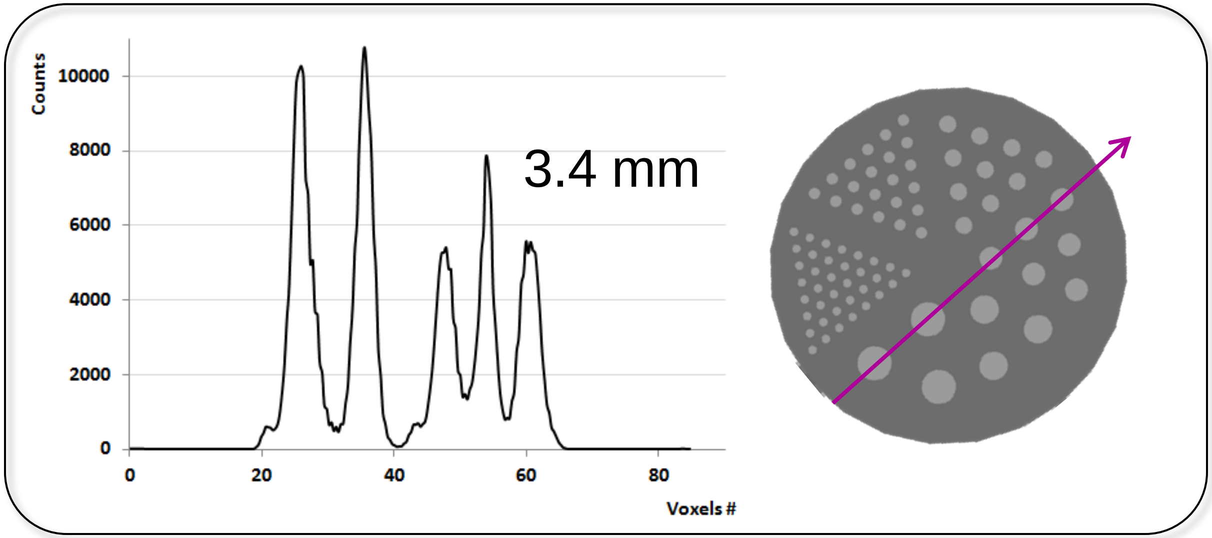
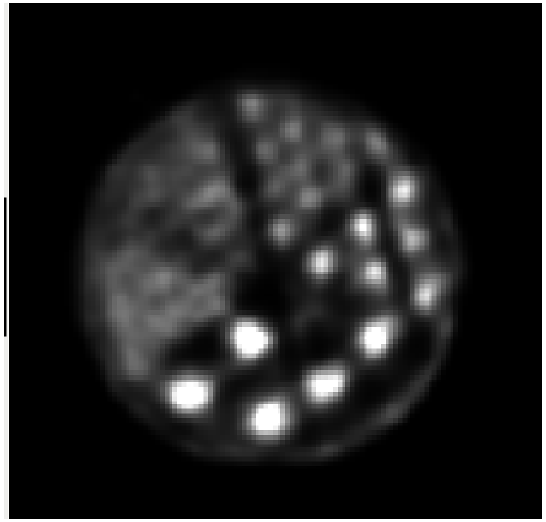
Spatial Resolution of Prototype Ring

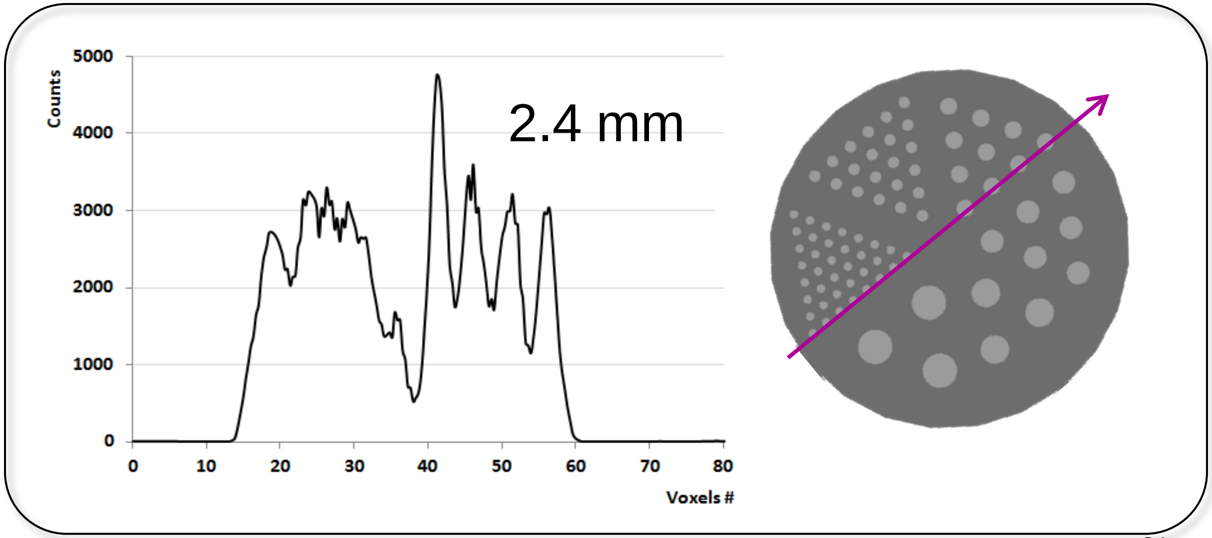


Mini Deluxe Derenzo Phantom





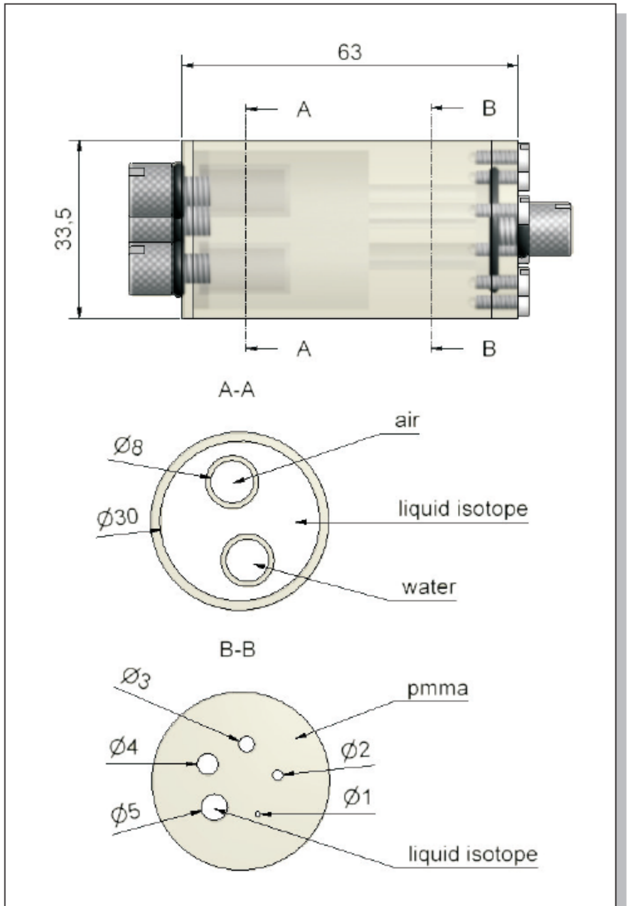




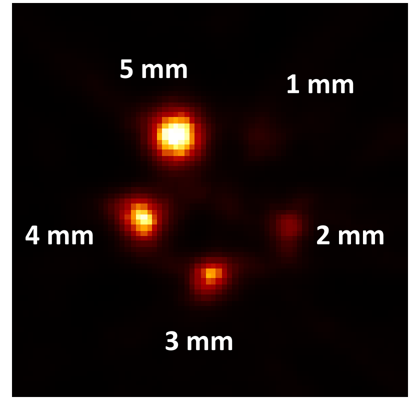
Spatial Resolution of Prototype Ring

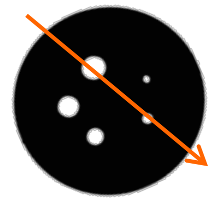
NEMA NU-4 quality phantom

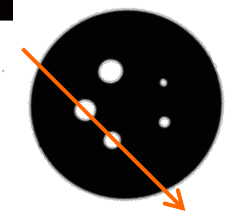
Micro-PET IQ Phantom
(according to NEMA NU 4-2008)

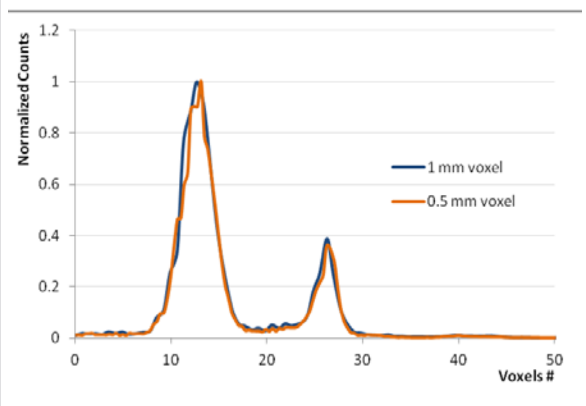


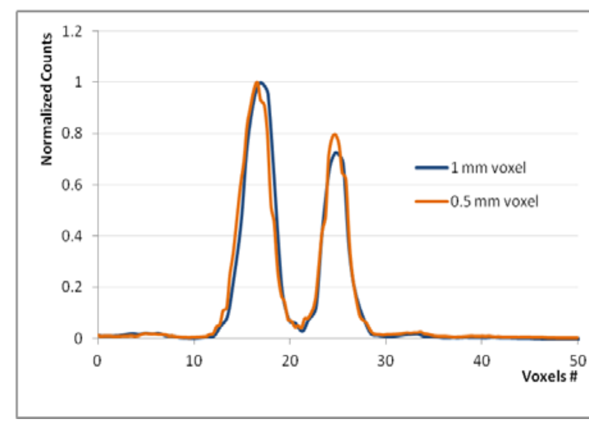
Dimensions of the phantom (in mm)







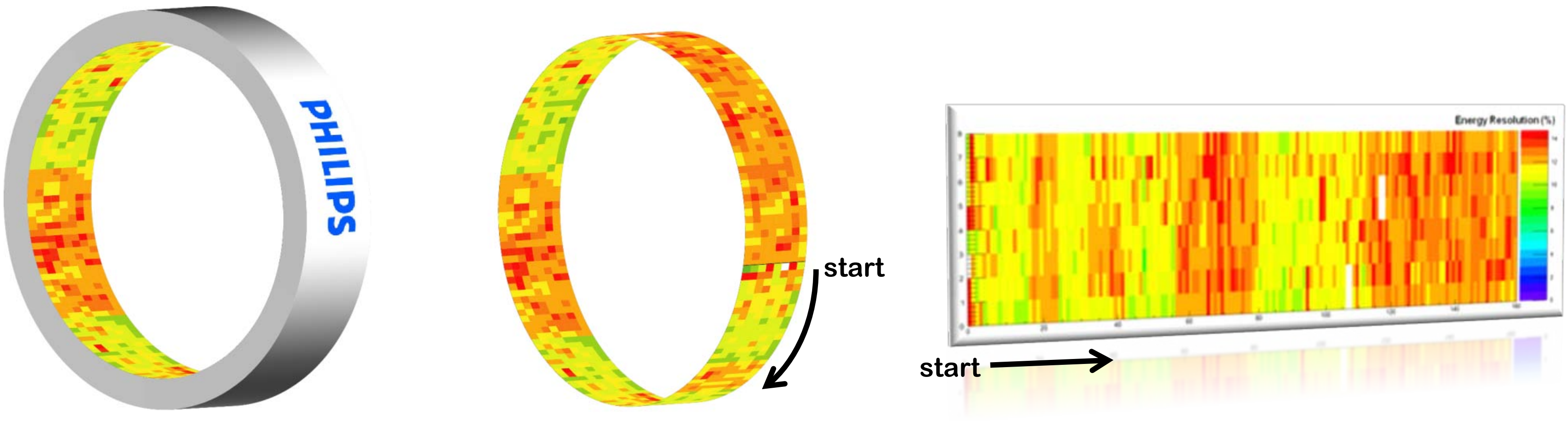


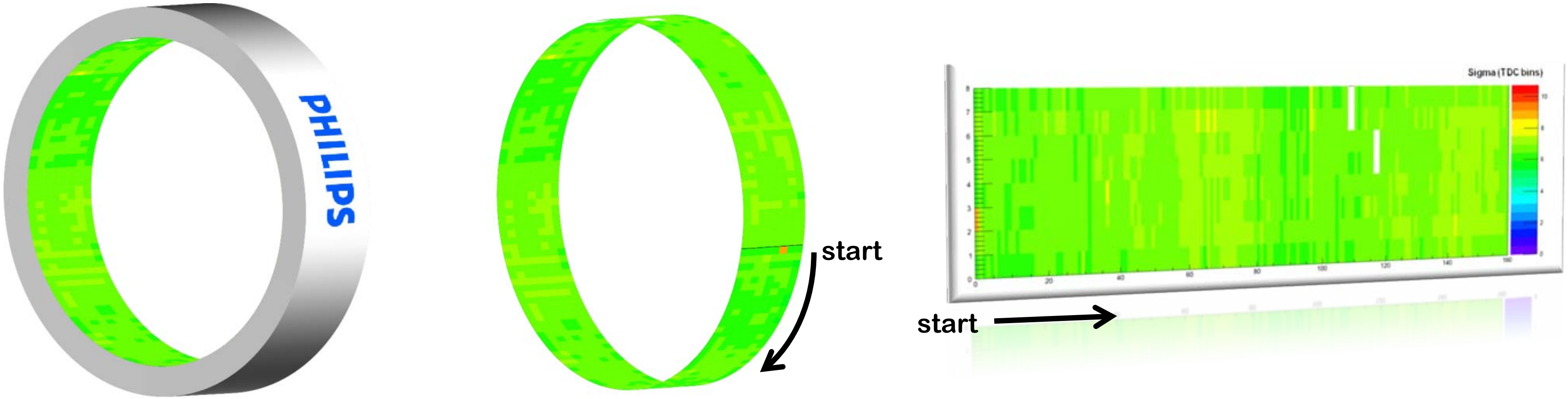


80% contrast recovery for 3mm insert

Interpreting the Plots

Crystals Occupancy Map | **Unfolded Map**





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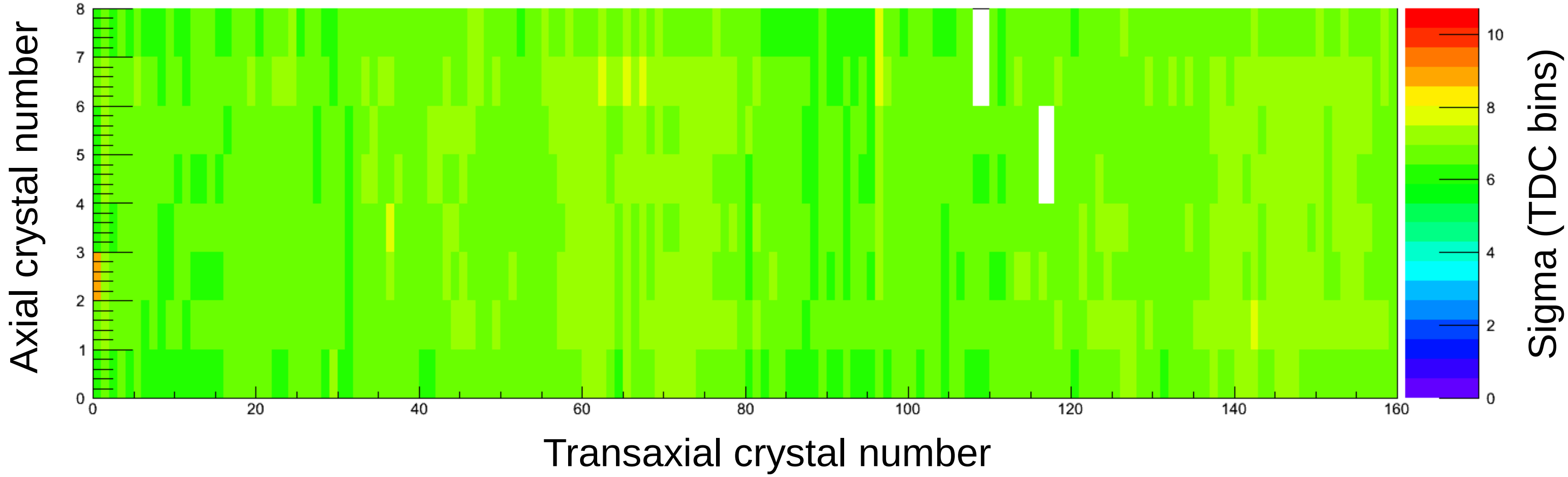
Timing Resolution of Prototype Ring



- 3.7 MBq ^{22}Na pointsource
- Coincidence timing resolution (FWHM): 263 ps (≙ 3.9 cm)

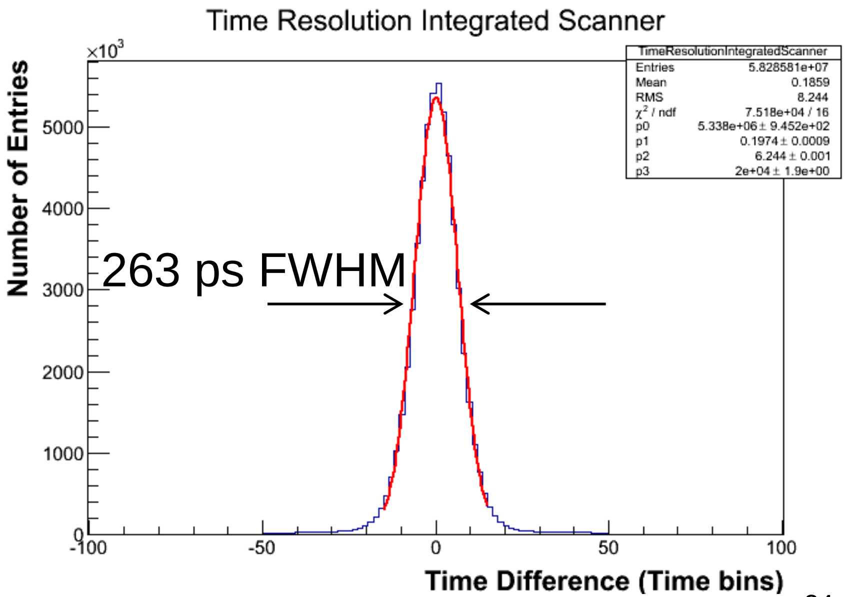
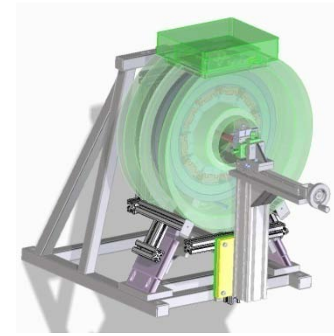
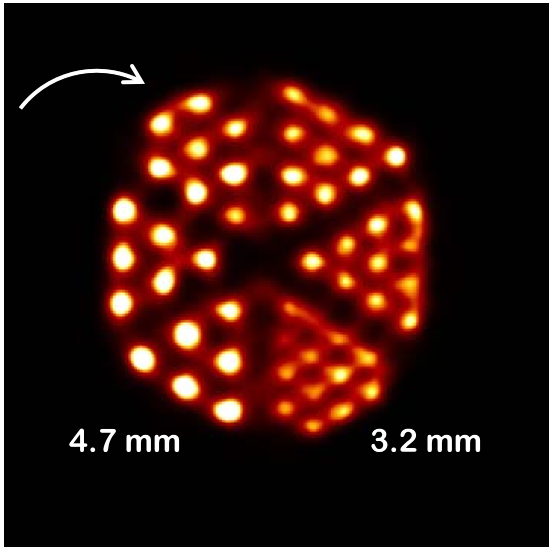


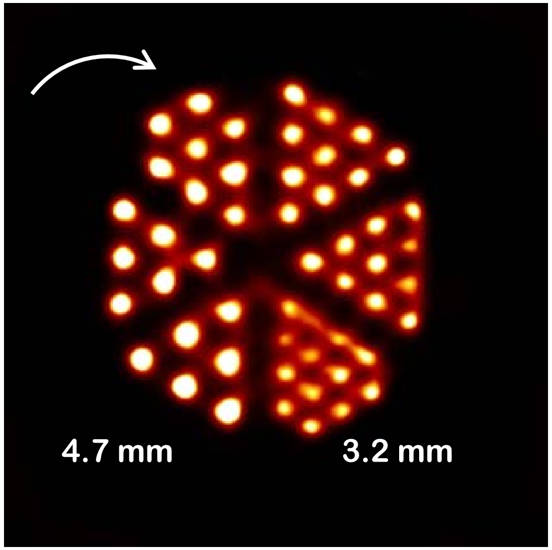
Image Quality Overview

- Hot rod phantom (70 mm diamater)
- 1h data acquisition (10-15 MBq ^{18}F)
- Trigger 2 at 7-9°C (internal tile temperature)
- Energy (RE 13% & clustering) and time (TR 390 ps) calibrations applied
- Energy window of [440;660] keV and time window of 3 ns [-1.5;1.5]



Without TOF **With TOF** 263 ps (≙ 3.9 cm)





PURE/OSEM (0.5 mm voxels), no norm., no decay time, all other corrections applied.

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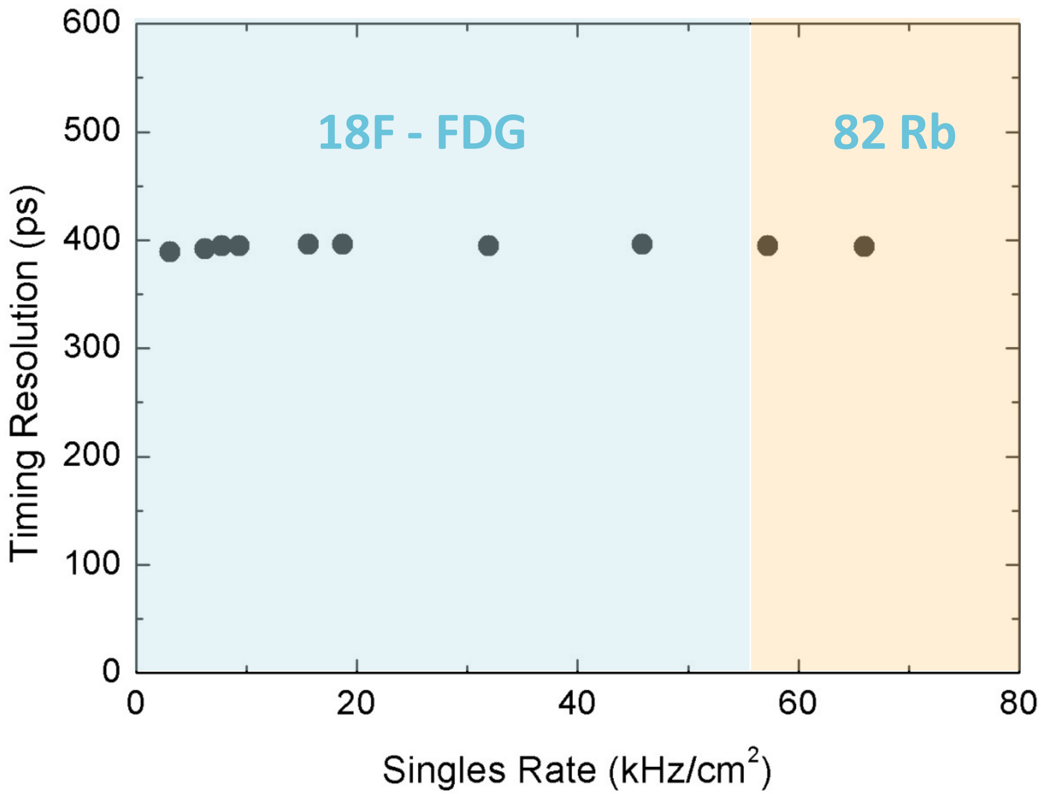
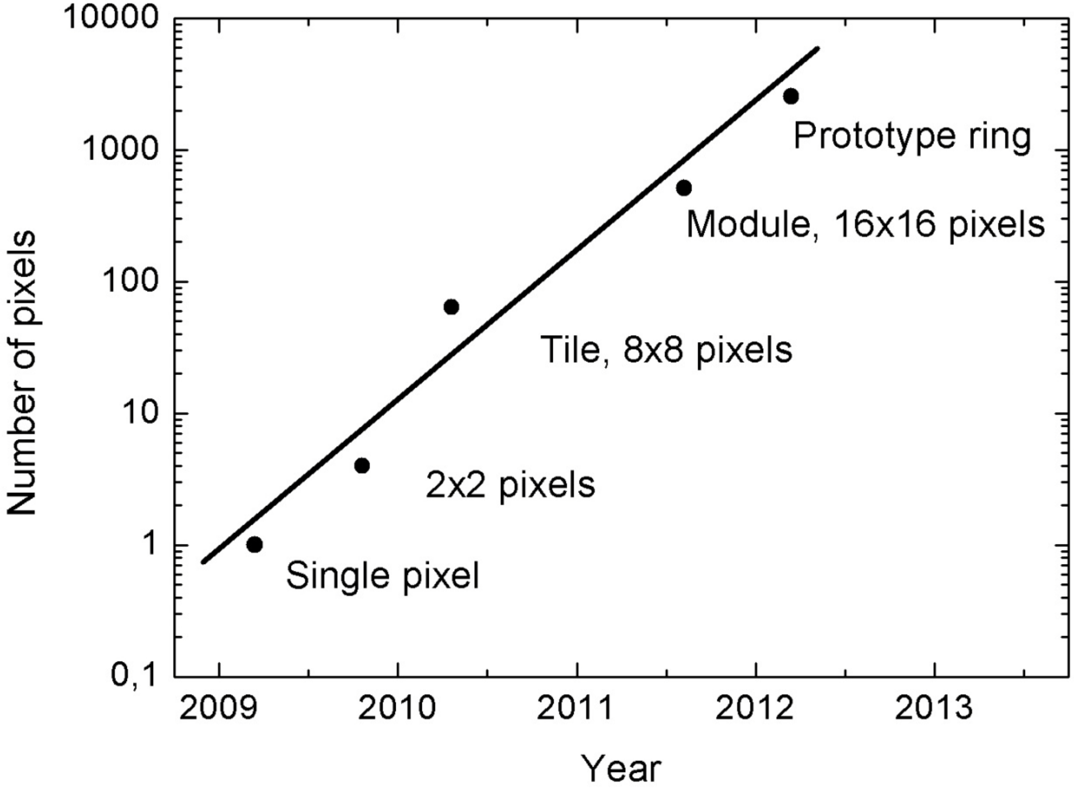
Count Rate Performance of Prototype Ring



- 1:1 coupling between scintillator and detector eliminates pile-up
- No degradation of timing, energy and spatial resolution with activity

Moore‘s law for PDPC



Coincidence timing resolution FWHM

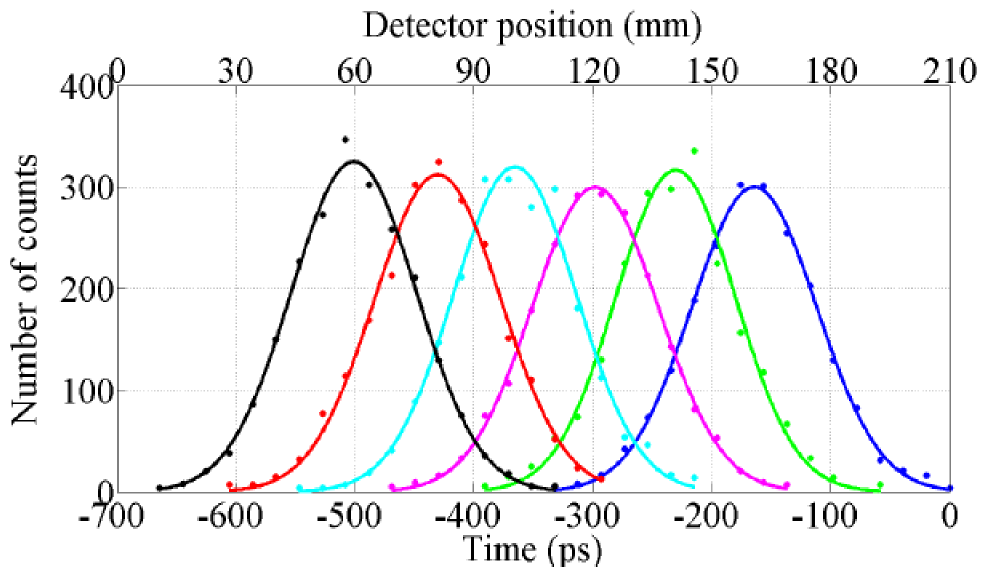
Single pixel	250 ps
Ring	263 ps

Number of pixels doubled every 3 months, while maintaining performance

Timing Resolution with Single Short LSO:Ca Crystals

Timing resolution

Two coincident detectors:
- DPC-3200-44-22 dSiPM arrays
- 3 x 3 x 5 mm^3 LSO:Ce,Ca crystals



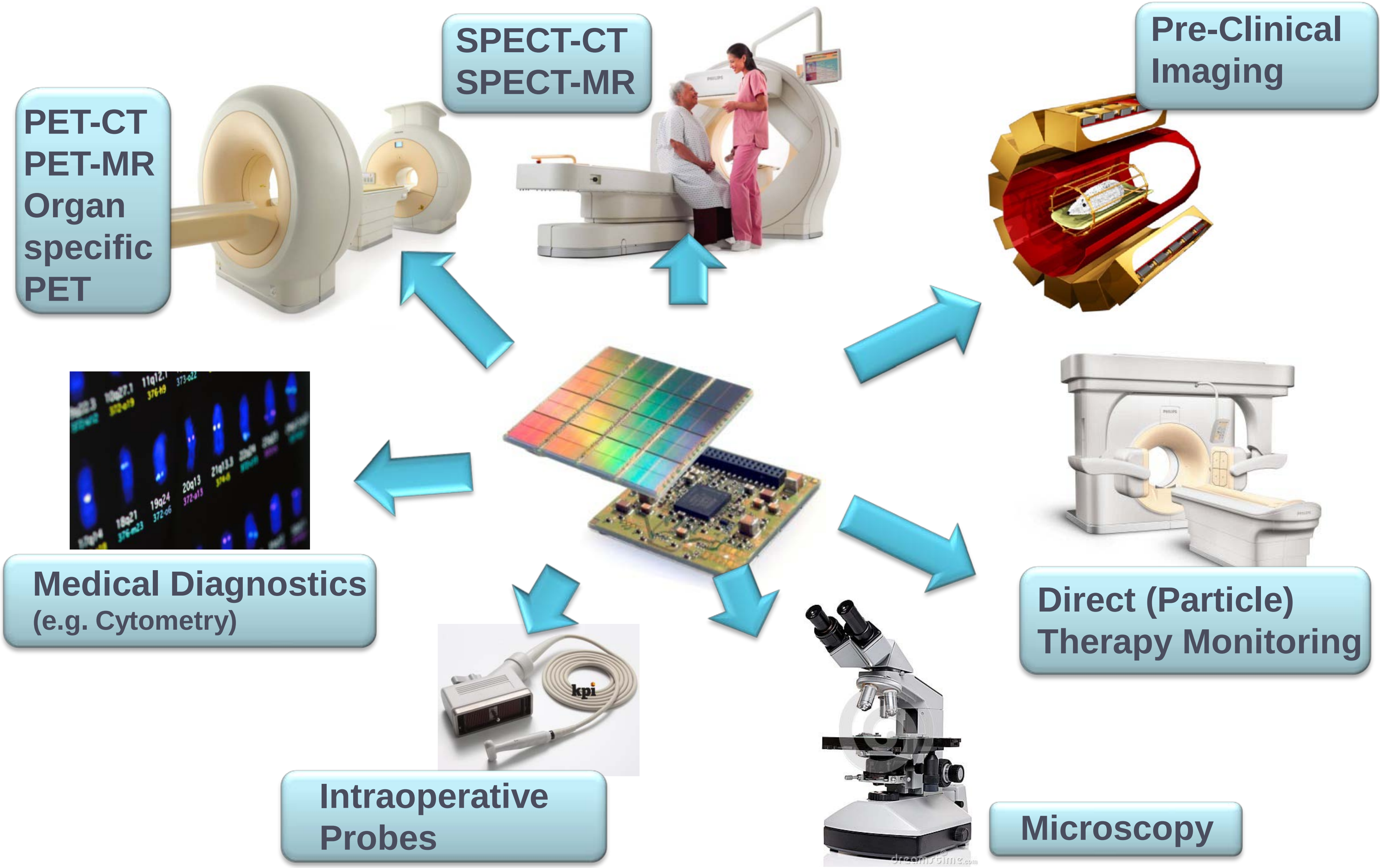
Timing spectra at different positions of one of the two detectors. The step size is 20 mm. The average coincidence resolving time (CRT) is **123 ps FWHM**.

TU Delft Dennis R. Schaart Delft University of Technology 9 SUBLIMA

D. R. Schaart, G. Borghi, H. T. van Dam, G. J. van der Lei, S. Seifert, V. Tabacchini

SNM 2012 Annual Meeting, Miami, FL, 11-Jun-2012

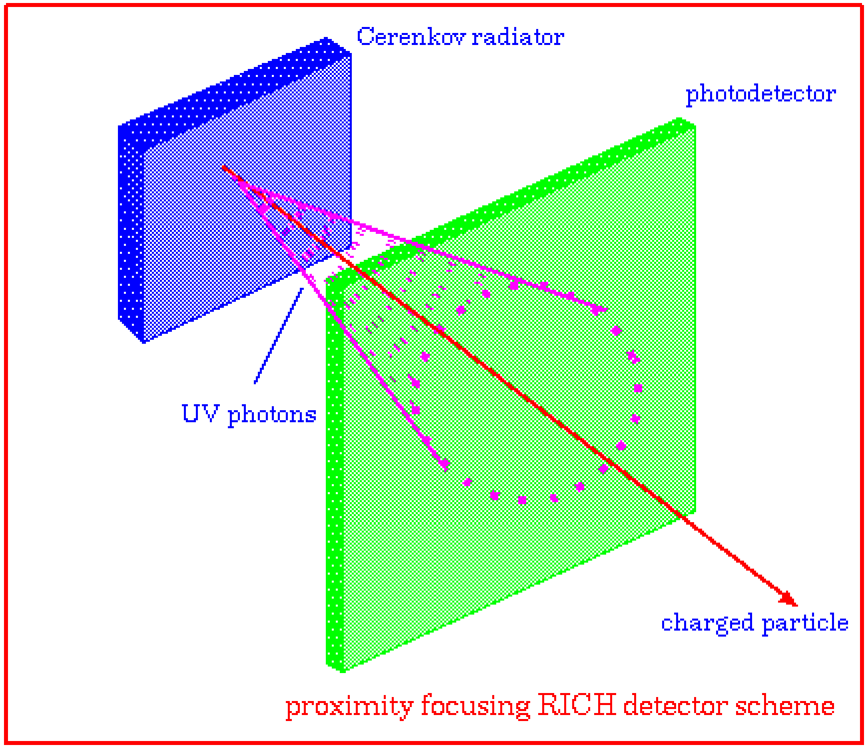
Philips DPC technology: potential in Healthcare

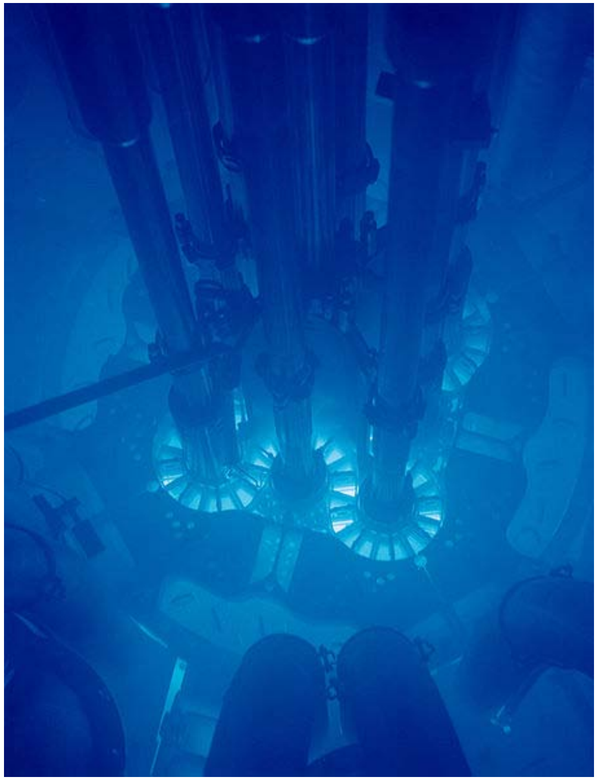


Application Example

Cerenkov Light Detection

Ring Imaging Cerenkov (RICH) Detector



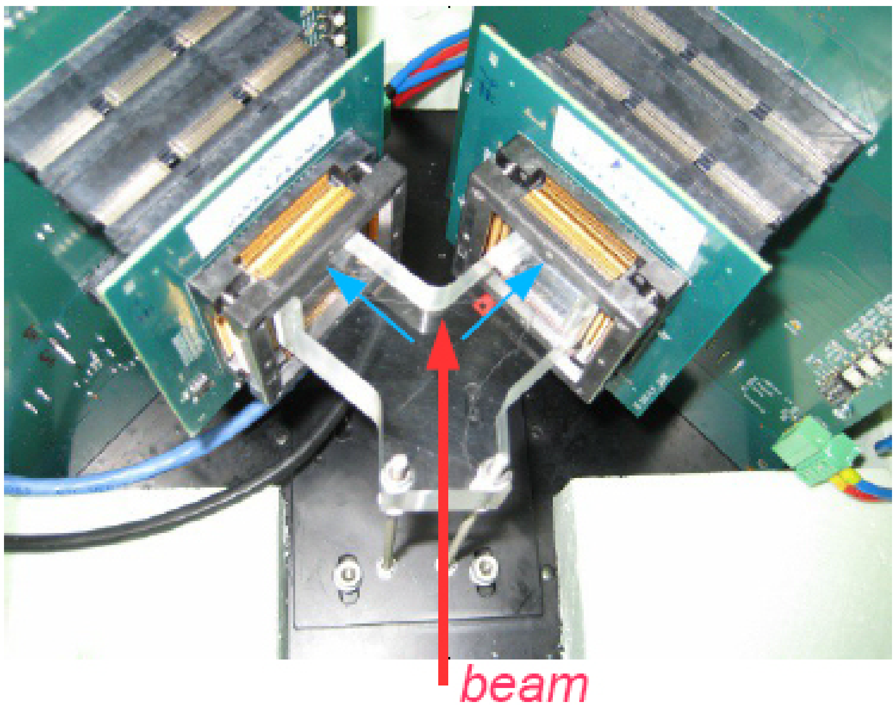


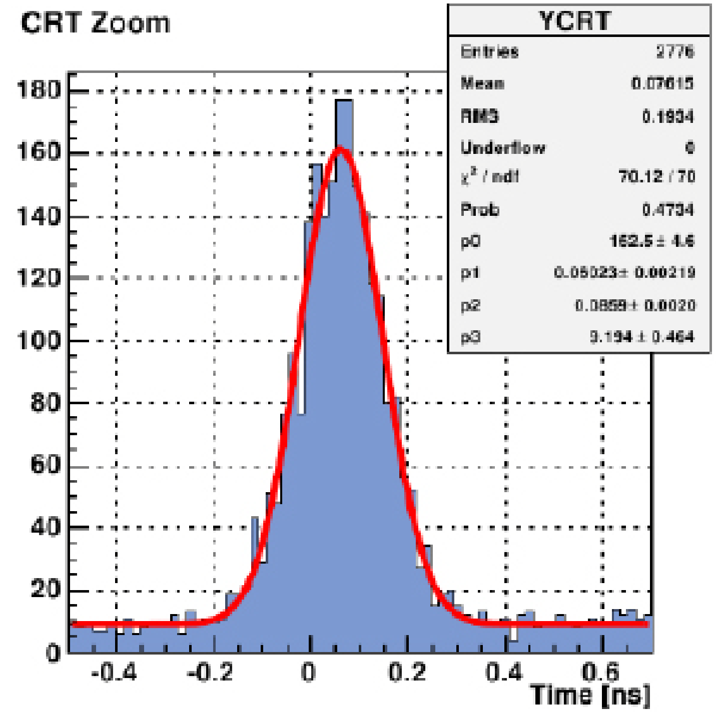
Use Cerenkov radiation for particle identification

Challenge: Detect low number of photons with high timing resolution

Source: Wikipedia

DPC: First Use for Cerenkov Detection 2011





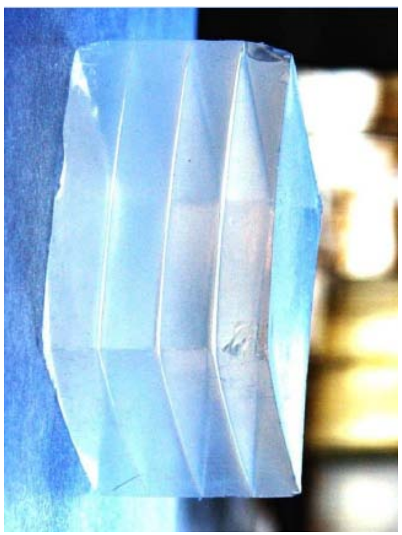
- PMMA radiator coupled via air gap to two dSiPMs (DLD8K) in coincidence
- Box isolated and temperature-controlled with a TEC to 2 – 3°C
- Cooperation between Giessen University (Prof. Düren) and Philips DPC
- First measurements at CERN SPS: **σ = 60.7ps**

DPC in High Energy Physics: FARICH Detector

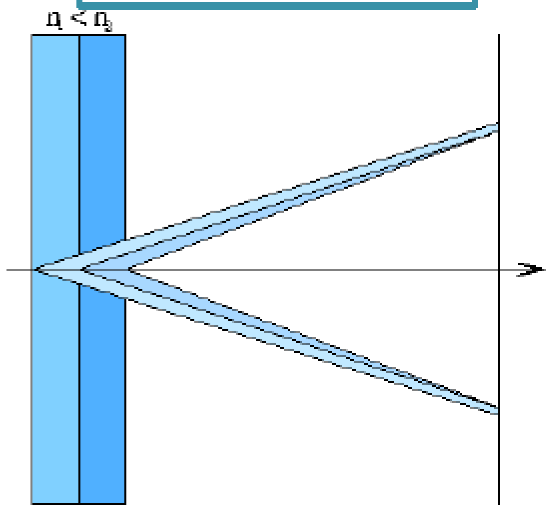
FARICH concept

Focusing Aerogel RICH – FARICH

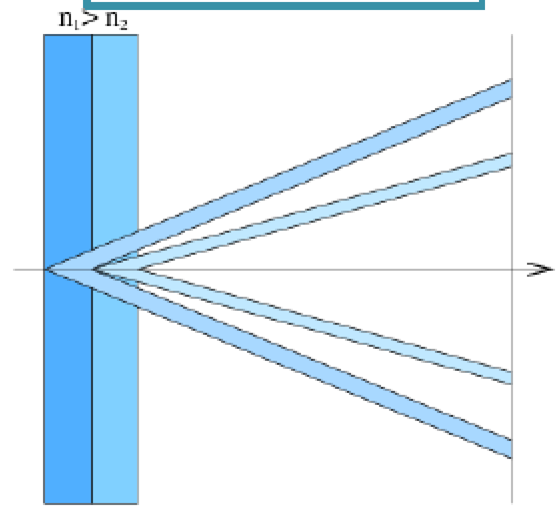
Improves proximity focusing design by reducing radiator thickness contribution into the Cherenkov angle resolution



Single ring option



Multi-ring option



T.Iijima et al., NIM A548 (2005) 383
A.Yu.Barnyakov et al., NIM A553 (2005) 70

First test of DPC in High Energy Physics: FARICH Detector @ CERN, June 2012

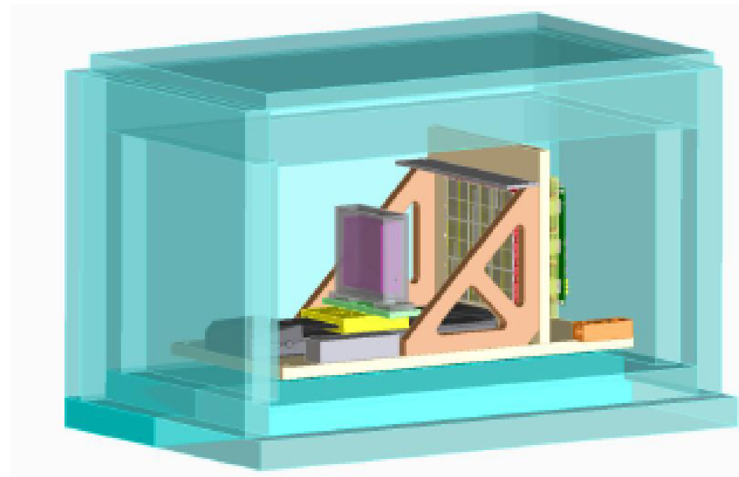
Main objective:

Proof of concept: full Cherenkov ring detection with DPC array

Timeline:

- Started to envisage: **28/02/12**
- Requirements for the FARICH prototype test setup fixed: **30/04/12**
- Prototype operational @ Aachen Labs: **03/06/12**
- Installed @ CERN: **12/06/12**
- Subsequent beam runs for 12 days until **25/06/12** with smooth setup operation

Fast prototyping!



13/02/20 VCI 2013

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FARICH prototype with DPC…

4-layer aerogel

- n_{max} = 1.046
- Thickness 37.5 mm
- Calculated focal distance 200 mm
- Hermetic container with plexiglass window to avoid moisture condensation on aerogel

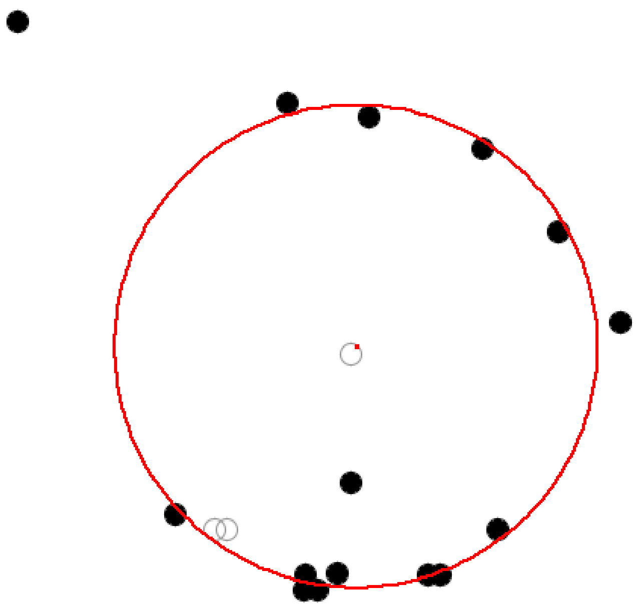
Square matrix 20x20 cm²

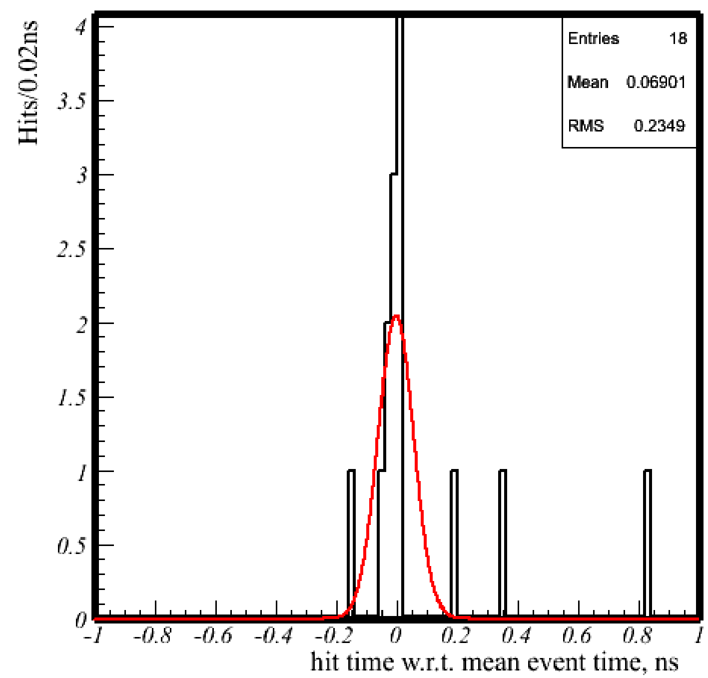
- Sensors: DPC3200-22-44
- 3x3 modules = 6x6 tiles = 24x24 dies = 48x48 pixels in total
- 576 time channels
- 2304 amplitude (position) channels
- 4 levels of FPGA readout: tiles, modules, bus boards, test board

Event-by-event ring fit

<u>Hit selection and ring fit:</u>

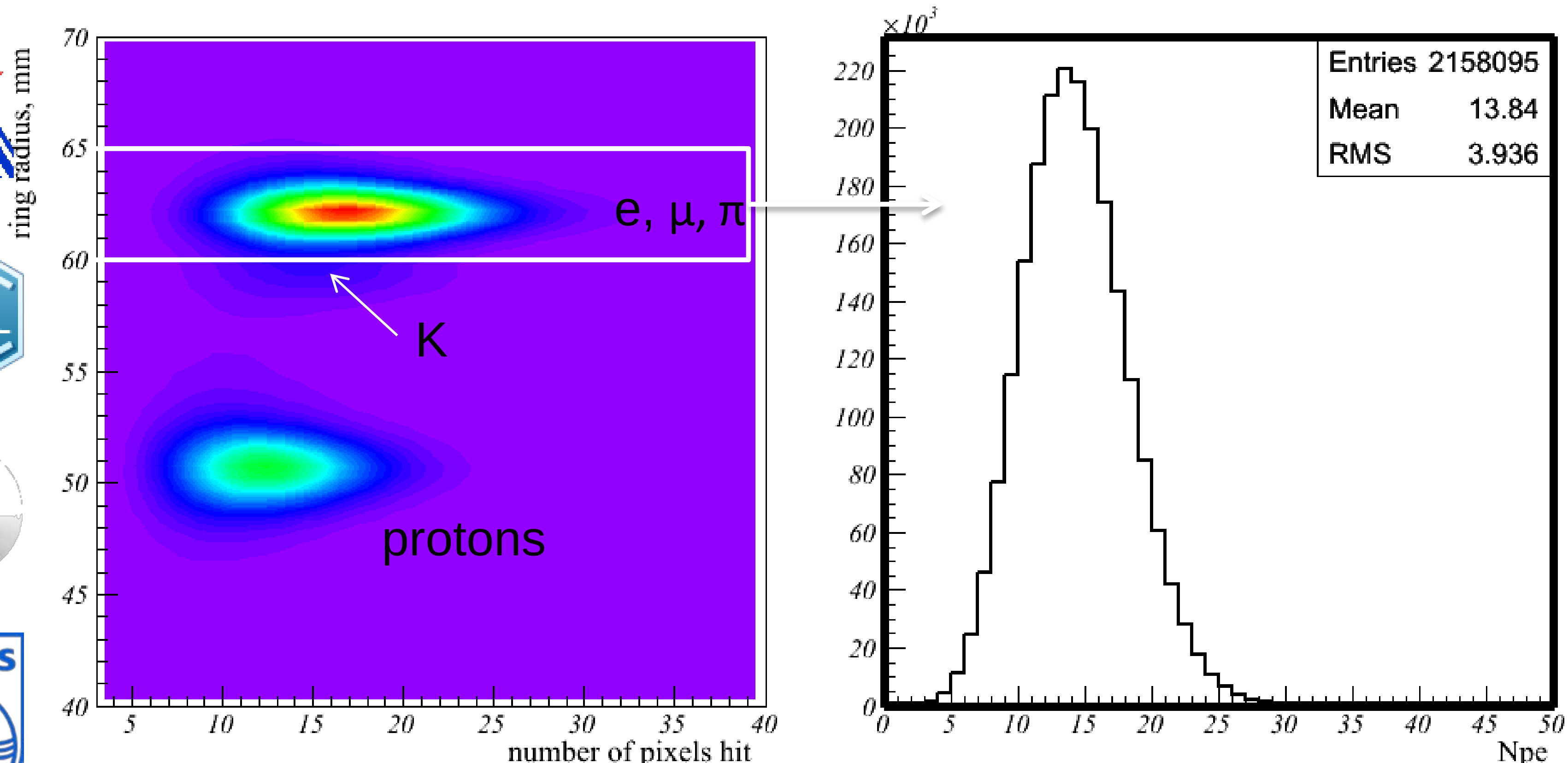
- Reject central hits
- Select hits in 4 ns time window
- More than 3 selected hits per event
- 4 parameters fitted: X_{center}, Y_{center}, R, t_0





S.A. Kononov et al., VCI ´13

Number of photoelectrons

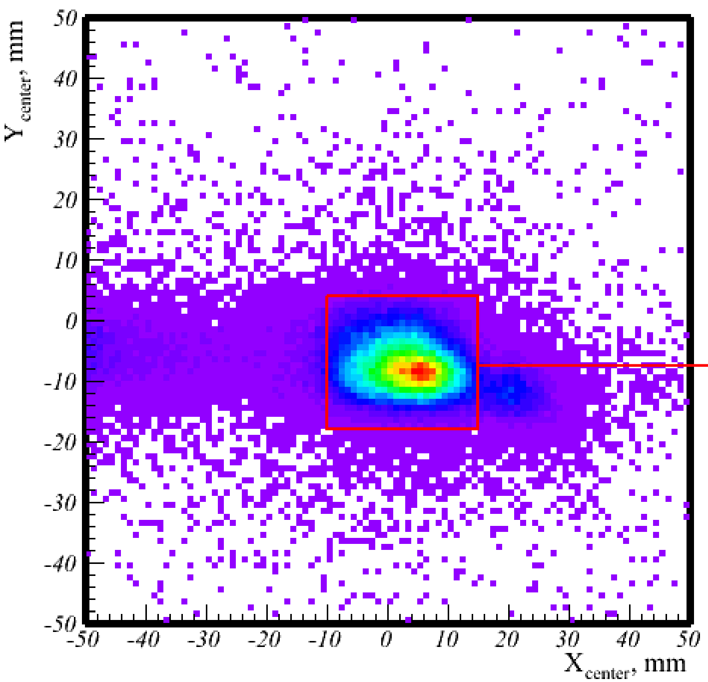


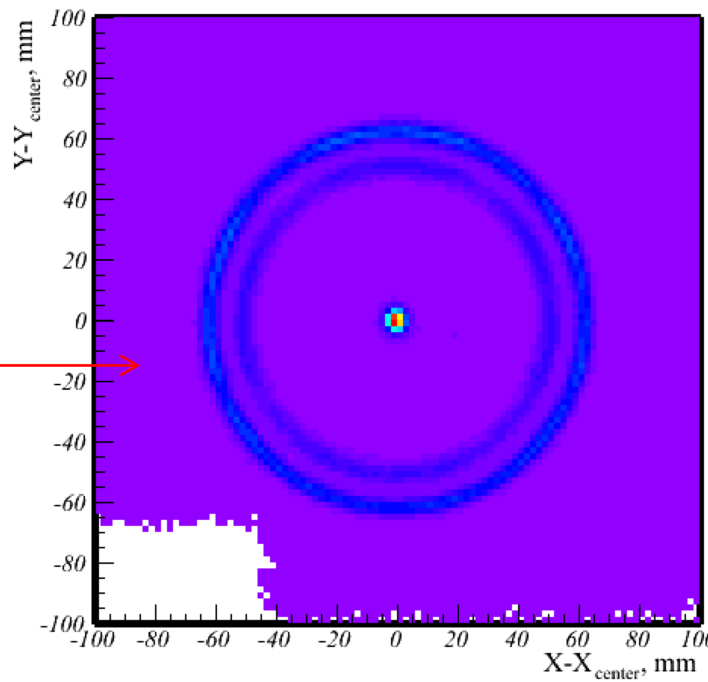
S.A. Kononov et al., VCI ´13

Ring center adjusted distributions P=6 GeV/c, L=200mm

Ring center position in detector plane

Hit positions





S.A. Kononov et al., VCI ´13

Ring radius distribution fit

Fit function

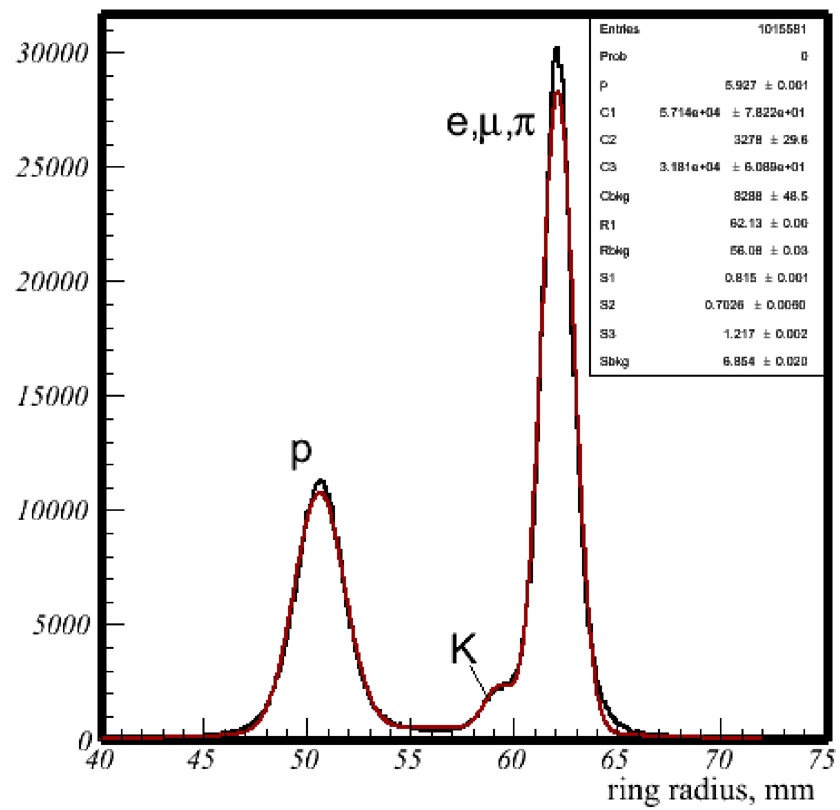
sum of three gaussians for each particle type with distinct radius plus gaussian background (to account for non-monochromatic particles in the beam)

Free parameters:

- Particle momentum
- Ring radius of rightmost gaussian (other radii derived from Cherenkov law)
- Constants and sigmas of all gaussians

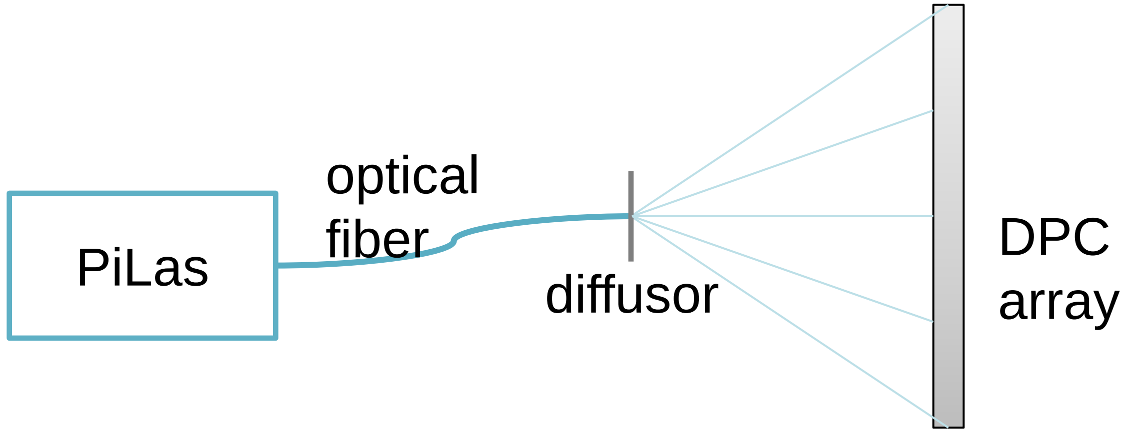
Fixed parameter:

- Effective refractive index $n_{eff}=1.038$

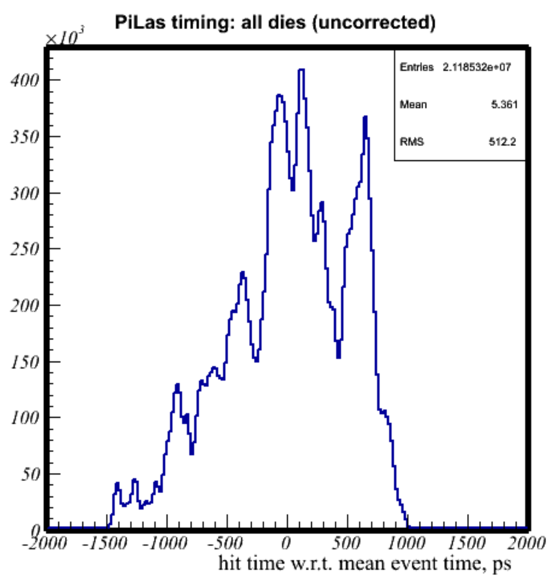


S.A. Kononov et al., VCI ´13

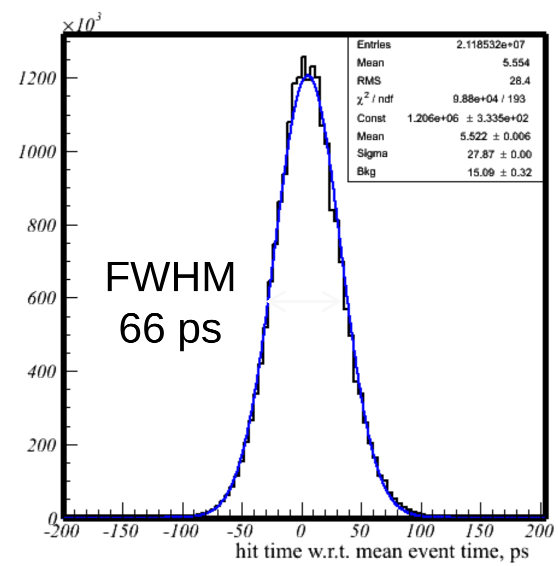
Die-to-die clock skew correction



All dies hit times w.r.t. mean event time



Clock skew correction between dies



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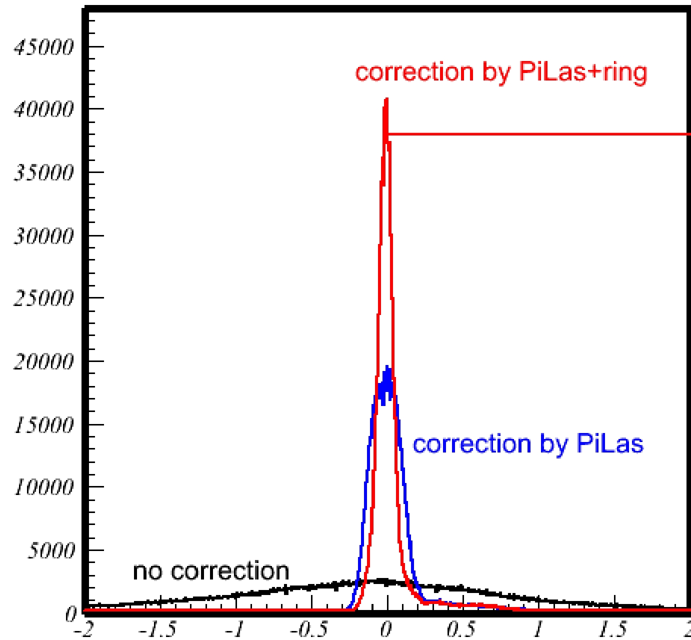
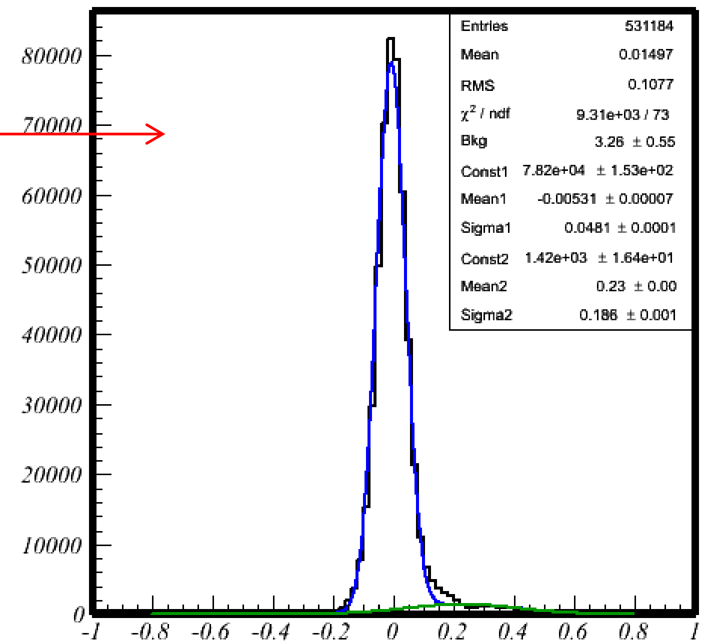
Timing resolution for Cherenkov photons



Hit time w.r.t. fitted event time, ns



Hit time w.r.t. fitted event time, ns

$\sigma = 48\text{ps}$

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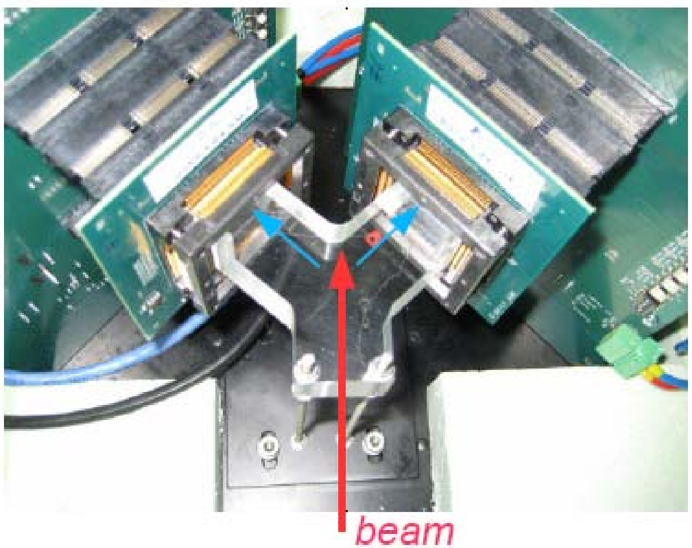
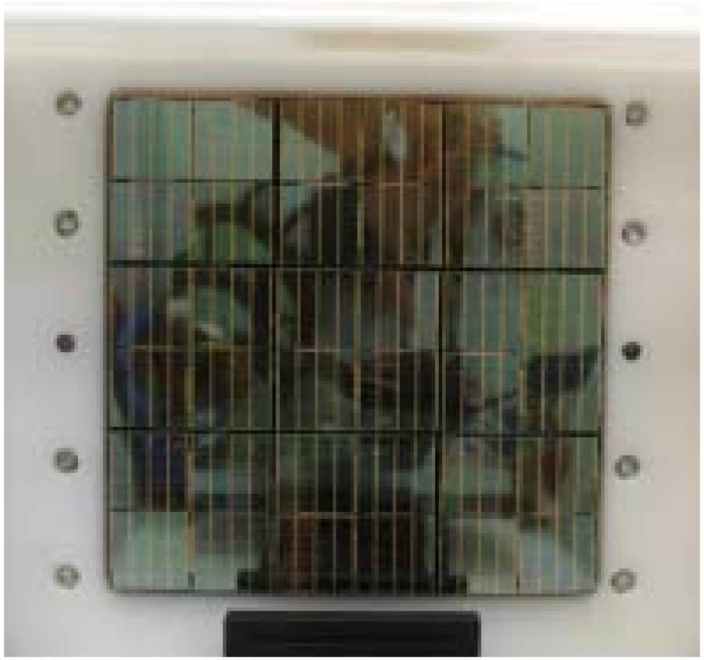
Comparison of timing resolution

Single pixel, 4 x 4 mm^2



System, 2304 pixels, 200 x 200mm^2



σ = 61 ps

σ = 48 ps

Scalability of timing performance shown

There are large detectors (not only) @ CERN

PDPC Technology Evaluation Kit (TEK)

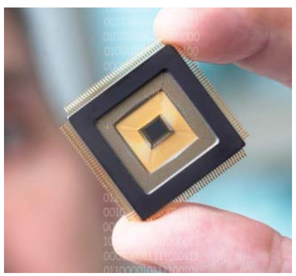
25 kits installed so far

Application Example

Outlook

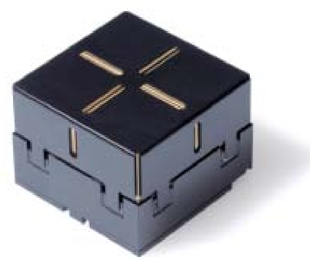
DPC technology concept beyond PET

- The first target application for dSiPM technology is ToF-PET. (Time-of-Flight Positron Emission Tomography).
- The first DPC sensor family (e.g. DPC 6400-22 / DPC3200-22) may be usable in other applications for scintillation light detection.



Die

Tile



Module

PET Ring

How can DPC technology be adapted to other applications?

➡ Pathfinder : design new sensors and modular packaging for new applications using DPC technology

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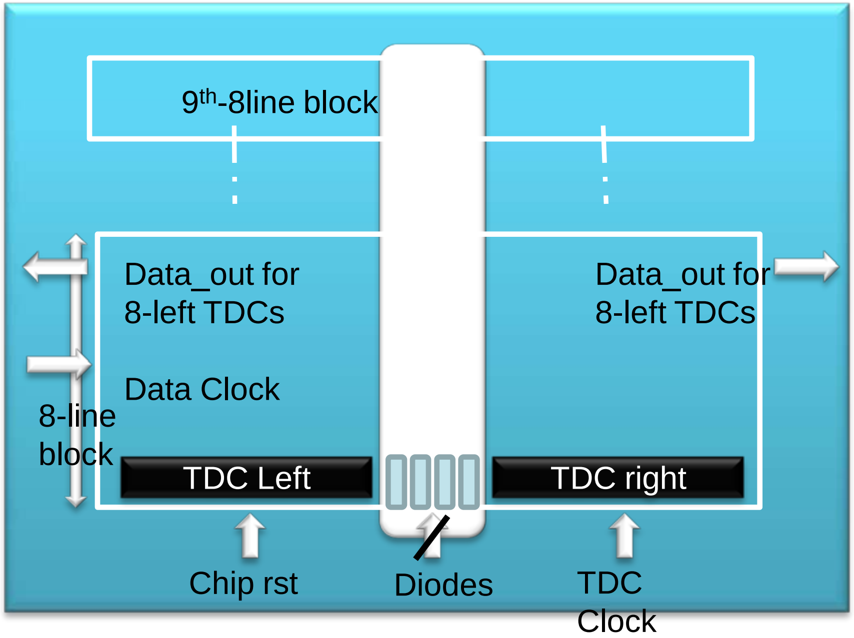
DPC technology concept extension: line sensor

Objective:

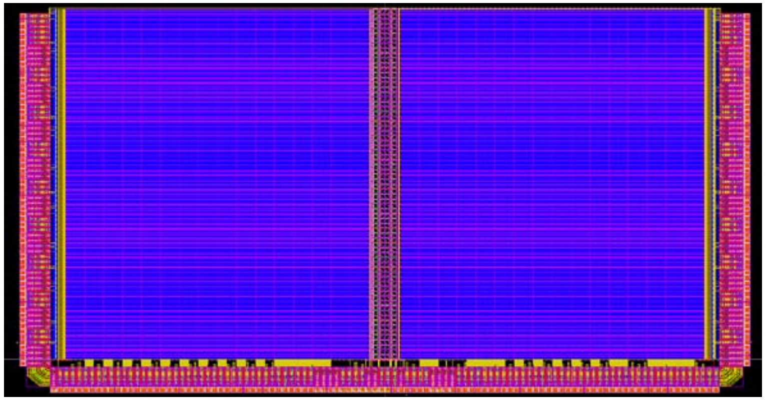
Functional test of a line sensor with SPAD technology suitable for LIDAR **(Light Detection and Ranging)** or 3D scan imaging applications and FLIM (**Fluorescence Lifetime Imaging**).

Features:

- 72-line sensor is implemented
- 1 line = Cell-Diodes + TDCs
- Each 8-lines has its clock and data channels
- stitch-able design for e.g. a 144 line sensor



5.2 mm



8.2 mm

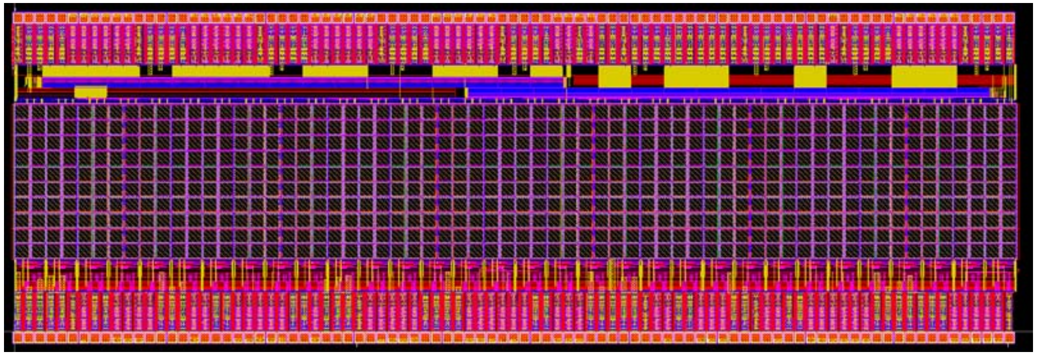
DPC technology concept extension: spectroscopy

Objective:

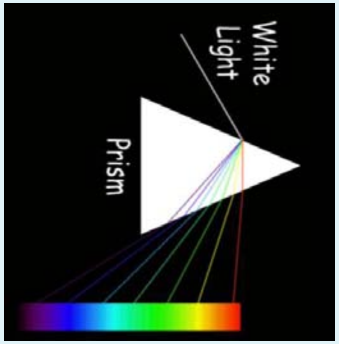
- Functional test of the line sensor with SPADs for **fluorescence detection** and **spectroscopic applications**
- Industrial and Biological **Spectroscopy** applications
- Confocal **Raman Spectroscopy**
- Fluorescent lifetime imaging **(FLIM)**
  (one programmable TDC is implemented to perform the timing measurement of the first photon hit)

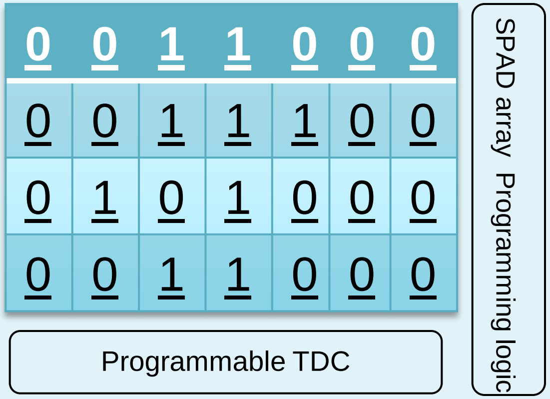
64 x 10 Geiger mode diodes

2.2 mm



6.5 mm





Simplified Architecture
(with example excitation)

Summary/Outlook

- **Demonstrated scalability of Philips DPC technology by maintaining intrinsic performance:**
  - ***- PET test ring***
  - ***- FARICH detector prototype***

OUTLOOK/Next:

- **Expansion of Scale of technology:**
  - ***- detectors with larger number of pixels***
  - ***- additional building blocks of scalable architecture***
- **Improved performance of DPCs (2nd generation):**
  - ***- higher PDE (>50%)***
  - ***- less dead time (factor 10)***
  - ***- better intrinsic timing resolution (factor 2)***
  - ***- subpixel (2x2 mm^2) readout***
- **New designs for new applications**
  - ***- line- and image sensors***
  - ***- LIDAR, FLIM, Spectroscopy***

Thank you very much for your attention!

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