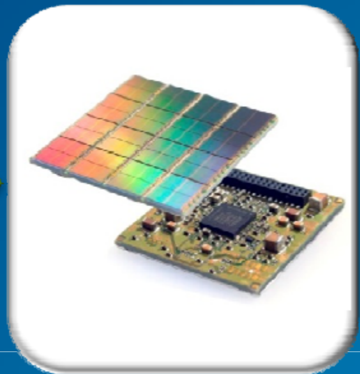
TIPP '14

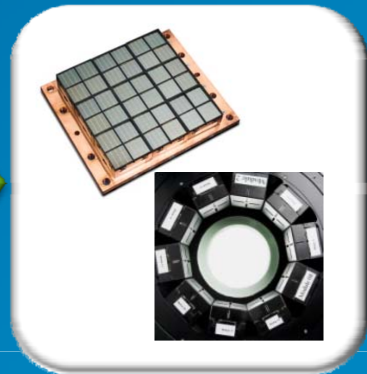
International Conference on Technology and Instrumentation in Particle Physics

2 – 6 June 2014 / Amsterdam, The Netherlands

The Digital Photon Counter (DPC, dSiPM)

a scalable, disruptive technology for application in medical imaging, high energy physics and beyond





York Haemisch, Ph.D., M. Sc. Eng., Senior Director

Philips Digital Photon Counting, Aachen, Germany

Amsterdam, June, 3rd , 2014

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Outline

- DPC (dSiPM): a  ?

- Motivation: Positron Emission Tomography
- Advantages of the digital concept
- DPC technology beyond the sensor
- First user experiences, first PET imaging results
- Future Developments

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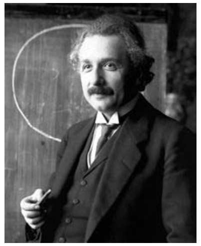
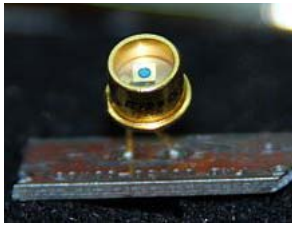
> 120 years of light detection: From **Photomultiplier Tubes** (PMTs) to **Photodiodes** (PDs), **Avalanche Photodiodes** (APDs) to Arrays of Geiger-Mode APDs (**Silicon Photomultipliers** (SiPMs))

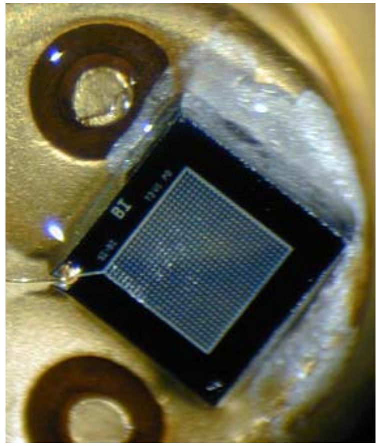
1887 **1905** **1934** **1960's** **Late 1960-1990's**

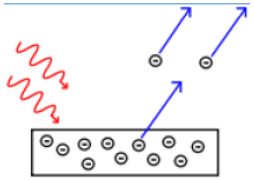

Lenard

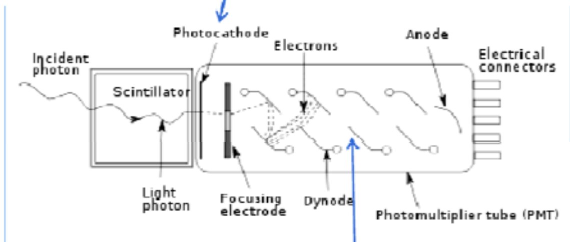

Hertz


Einstein

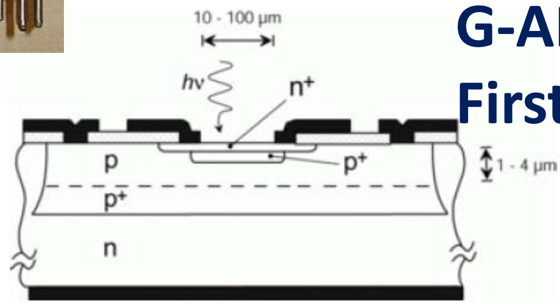

PD, APD


G-APD, SPAD
First SPAD arrays


Photoelectric Effect



Secondary electron emission



Digitization, Miniaturization, Integration…

Transistor

Television

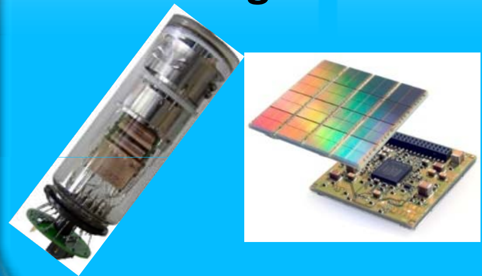
Photography

Telephony

+ SOFTWARE !

X-Ray imaging

Next?: Light Detection



DPC is in sync with current technology trends

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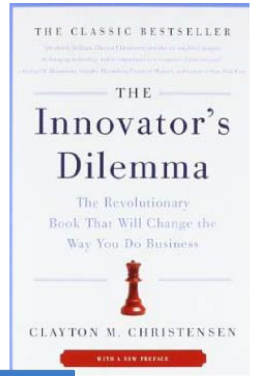
Characteristic innovation patterns



Continuous Improvement ("Kaizen" = good change)

- Long-term approach to work that systematically seeks to achieve **small, incremental changes**
- Low risk
- Often geared towards **reducing costs.**
- improving position in **existing markets**

Disruptive Innovation

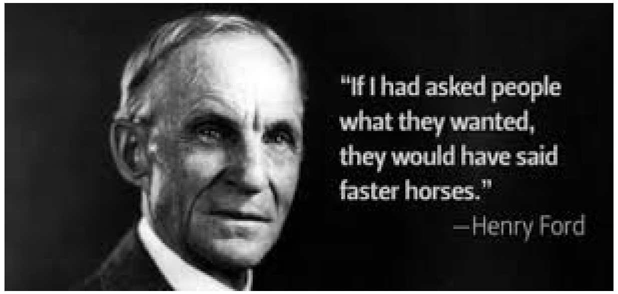
- Introduction of new technologies, products or services in an effort to **promote change and gain advantage** over the competition.
- **Risky** because it requires employees to embrace a radically different approach to product development or marketing.
- Calls for **investments** rather than cost savings.
- Creates **new market opportunities** where none existed before.

Bower, Joseph L. & Christensen, Clayton M. (1995) "Disruptive Technologies: Catching the Wave" *Harvard Business Review*, January-February 1995
Christensen, Clayton M. (1997) "The Innovator's Dilemma" *Harvard Business School Press*, ISBN 0-87584-585-1

TECH DISRUPTIVE NOLOGY

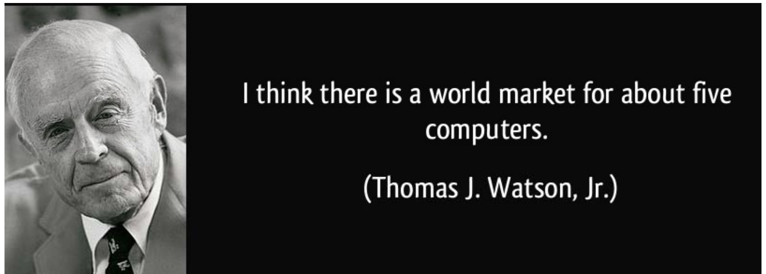
Displacing

- **Displaces** incumbent technology in phase transition
- Mostly **same applications**
- Users adopt over a **period of time**



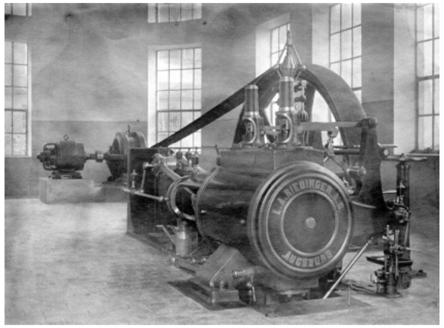
Market Creating

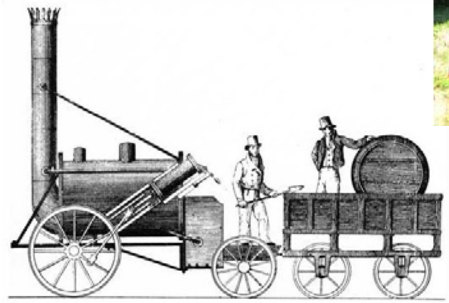
- **Creates a new market or capability** where none had previously existed
- Opens road to **new applications**
- Often **explosive growth** of markets

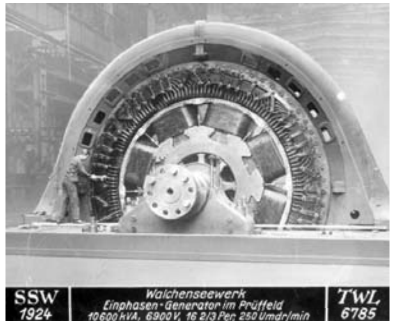


Persistent Forecasting of Disruptive Technologies. THE NATIONAL ACADEMIES PRESS, Washington 2009

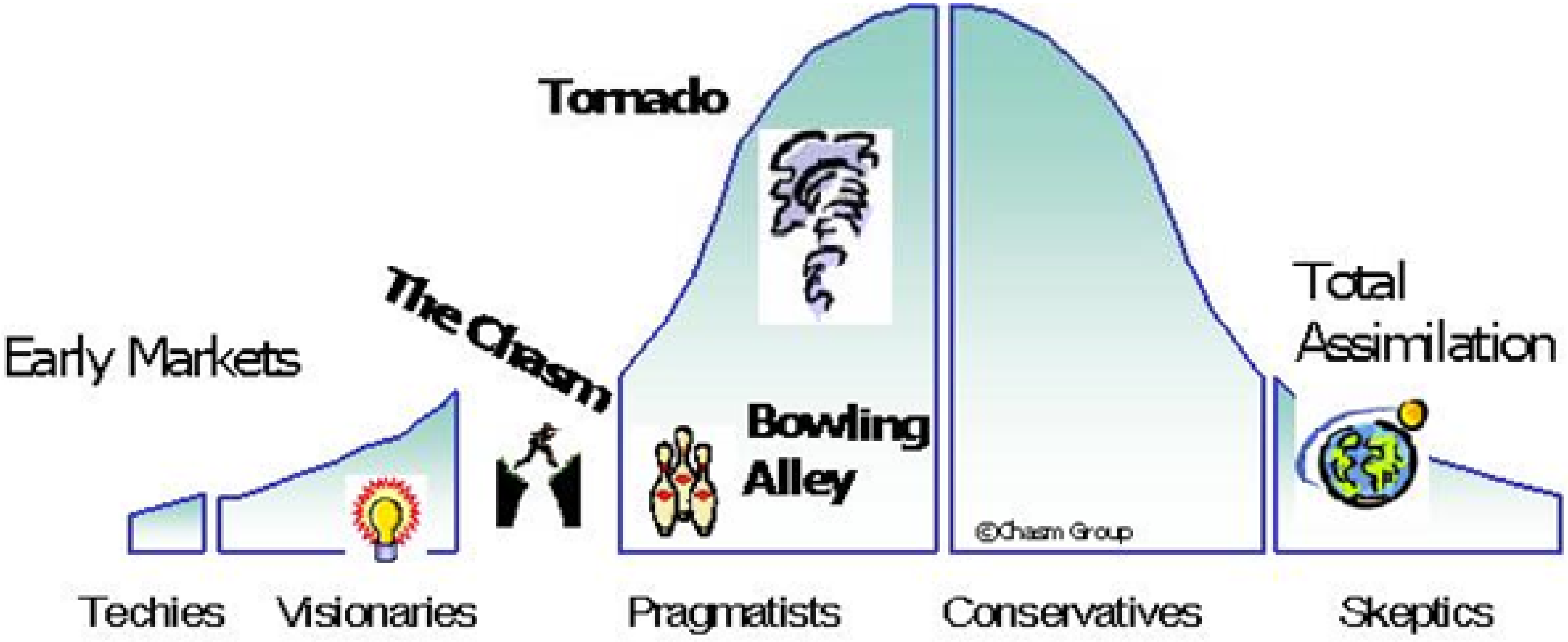
TECH DISRUPTIVE NOLOGY examples







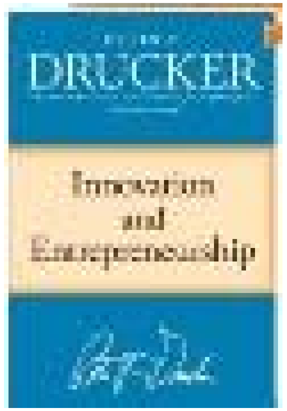
Disruptive technology adoption (Moore)



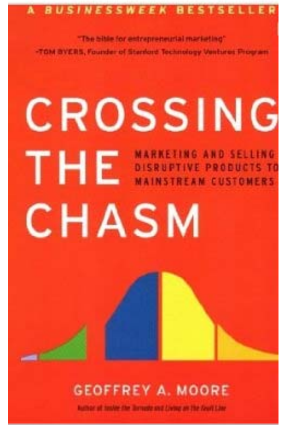
- Disruptive innovation – early adopters are universities, luminary research sites
- Market growth can only be expected AFTER crossing the Chasm

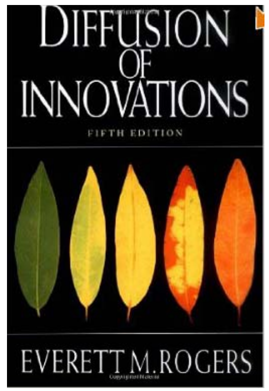
Moore, Geoffrey A.: "Crossing the Chasm: Marketing and Selling high-tech products to mainstream customers" Harper Business Essentials (1991) ISBN 0-06-051712-3

Disruptive Technology: How to cross the chasm



- Understand your **PRODUCT CONCEPT**
- Make the disruptive technology **EXPERIENCABLE**
- Demonstrate **SCALABILITY**
- Demonstrate **IMPACT** on applications
- Select your **TARGET MARKET(S)**





Peter F. Drucker: „Innovation and Entrepreneurship“ Harper Business; Reprint (2006)
ISBN-10: 0060851139

Geoffrey A. Moore: “Crossing the Chasm”, Harper Business; 2nd Edition (2006)
ISBN-10: 0060517123

Everett M. Rogers: „Diffusion of Innovation“, Free Press; 5th Edition (2003)
ISBN-10: 0743222091

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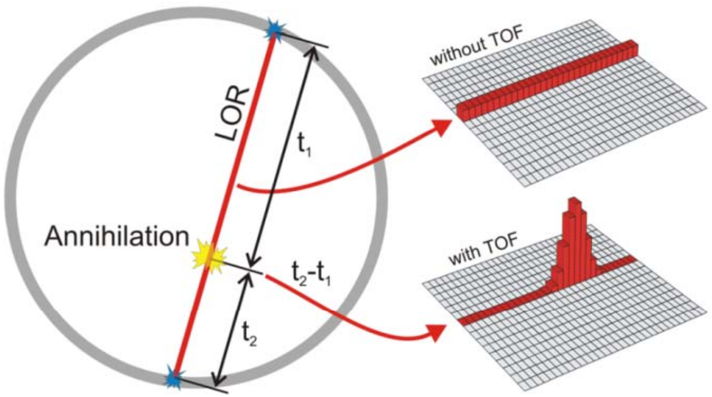
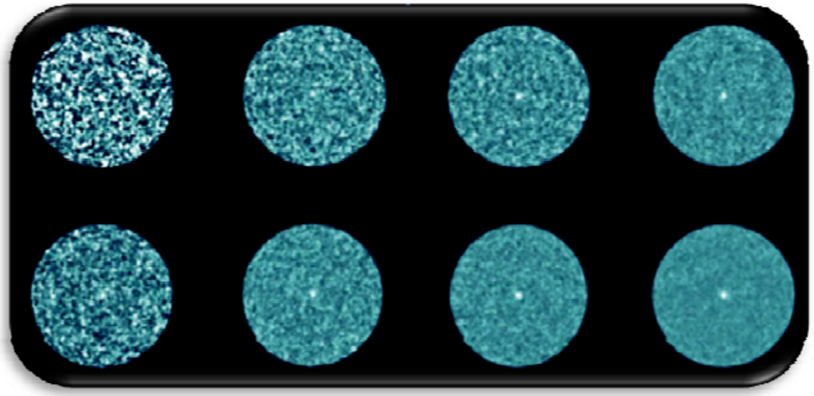
Motivation PET: towards the 100 ps PET device

Positron-Emission-Tomography (PET) with Time-of-Flight (TOF)



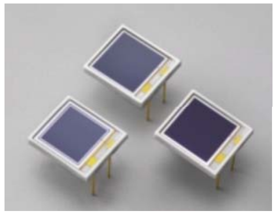


CRT >1ns 500 ps 250 ps 100 ps

> 1 ns

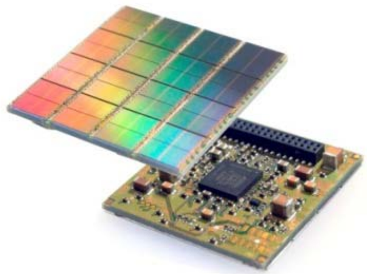
~ 400 ps (limit)

~ 250 ps ---> ~100 ps (potential)



APD

(special) PMT



DPC

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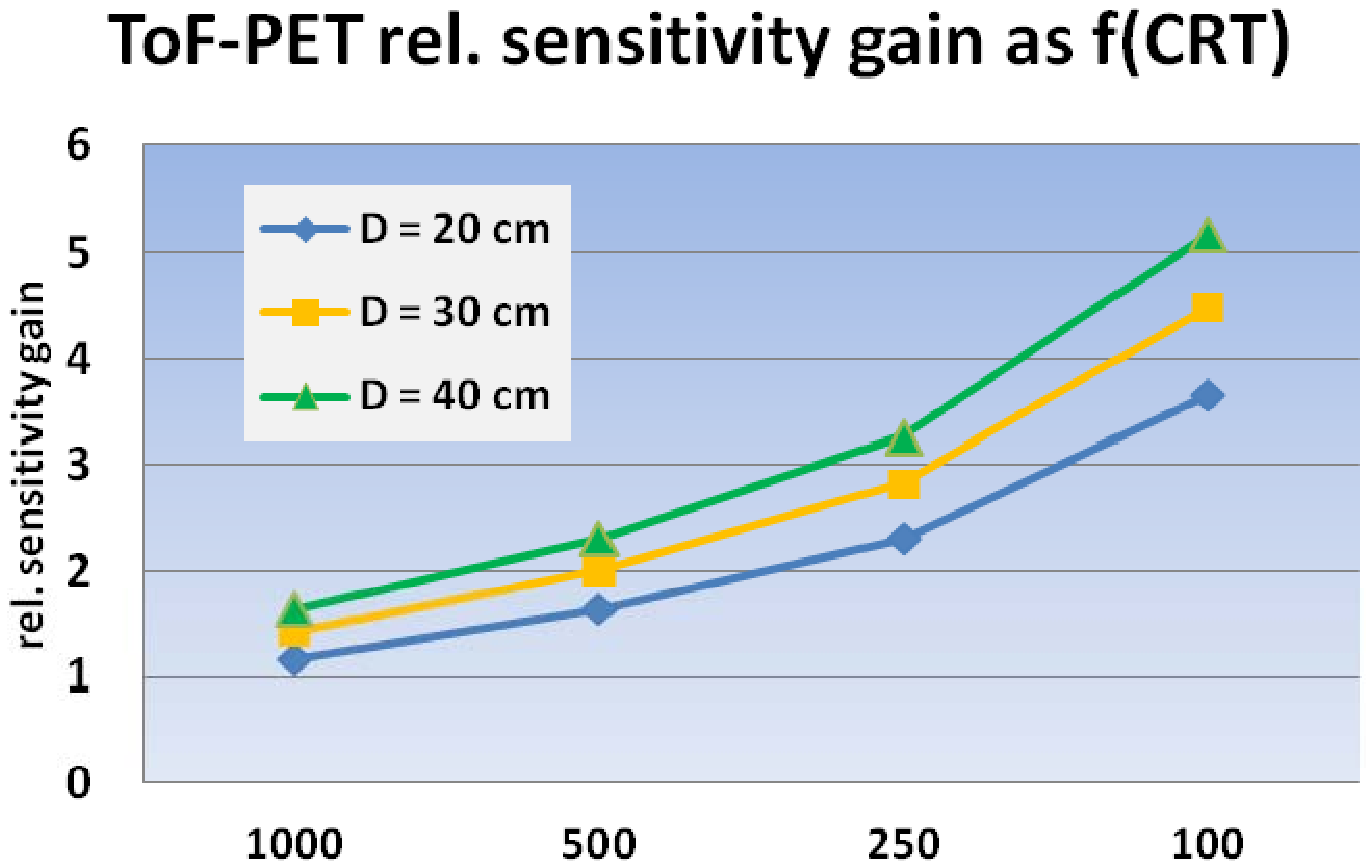
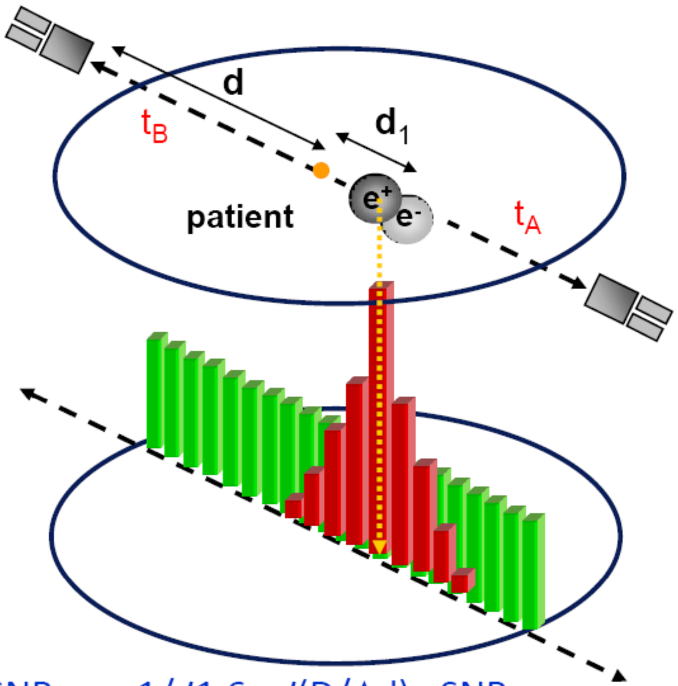
ToF impact: clinically useful sensitivity gain



*Data calculated after: J.S. Karp et.al. JNM, **49/3**, 462-470, 2008*

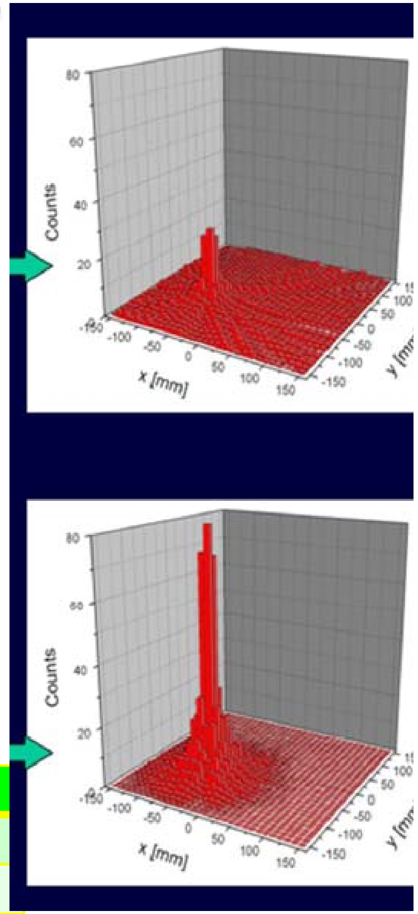
PET: ToF improves signal-to-noise (SNR)

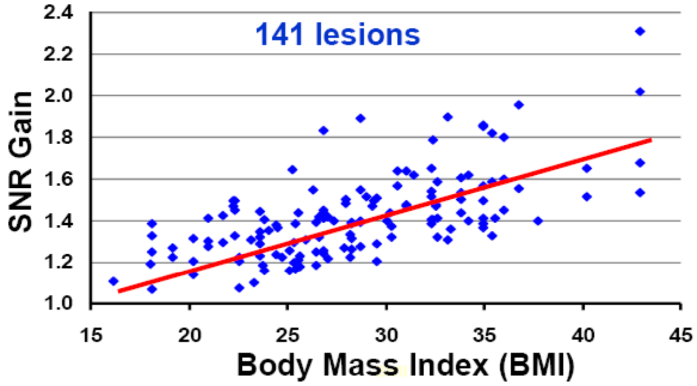
Time-of-Flight (TOF)



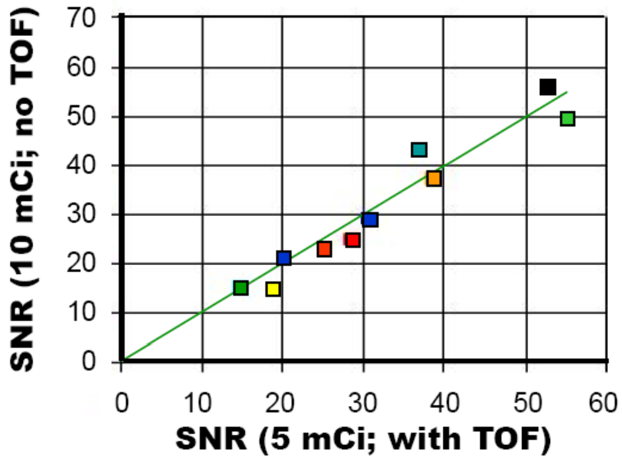
$SNR_{TOF} = 1/\sqrt{1.6} \cdot \sqrt{(D/\Delta d)} \cdot SNR_{conv}$

Δs (ps)	Δx (cm)	SNR gain
100	1.5	5.2
300	4.5	3.0
500	7.5	2.3
1200	18.0	1.5





✓ Improved signal-to-noise



✓ Reduced radiation dose

Data courtesy of D. Townsend, Singapore

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From PMT to solid state: more motivation (Nucl. Imag.)

performance

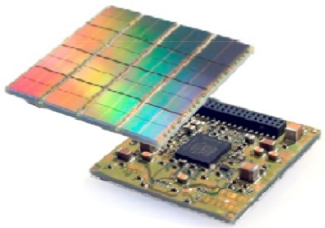
- 1:1 coupling (CR, NEC, linearity)
- Time-of-Flight (SiPM)
- Depth of Interaction (DOI)-3D

application

- MR compatibility
- compactness/low voltage

industrialization

- scalability/stability?
- compactness/low voltage
- (lower) cost?, serviceability etc.



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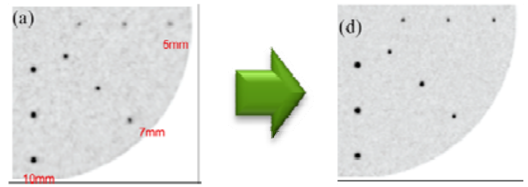
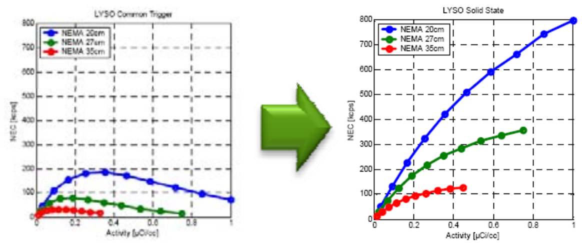
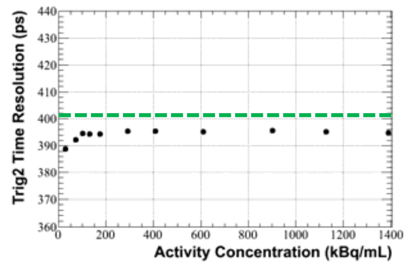
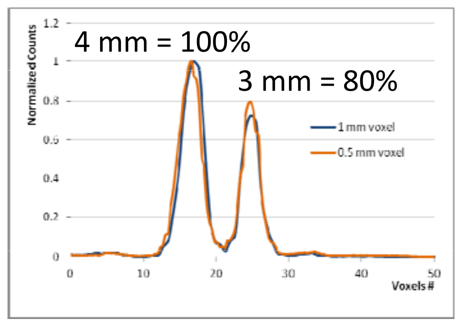
Desired: 1:1 coupling of crystal & photo detector

- Homogenous **spatial resolution** and contrast across FOV (incl. DOI)
- Much **enhanced Noise Equivalent Countrate** (NEC)
- Less/no **dependence** of PET-performance **on** injected **dose**
- Improved **linear response** over a wide dose range
- Improved spatial resolution and **contrast recovery**









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- DPC (dSiPM): a TECH DISRUPTIVE NOLOGY ??
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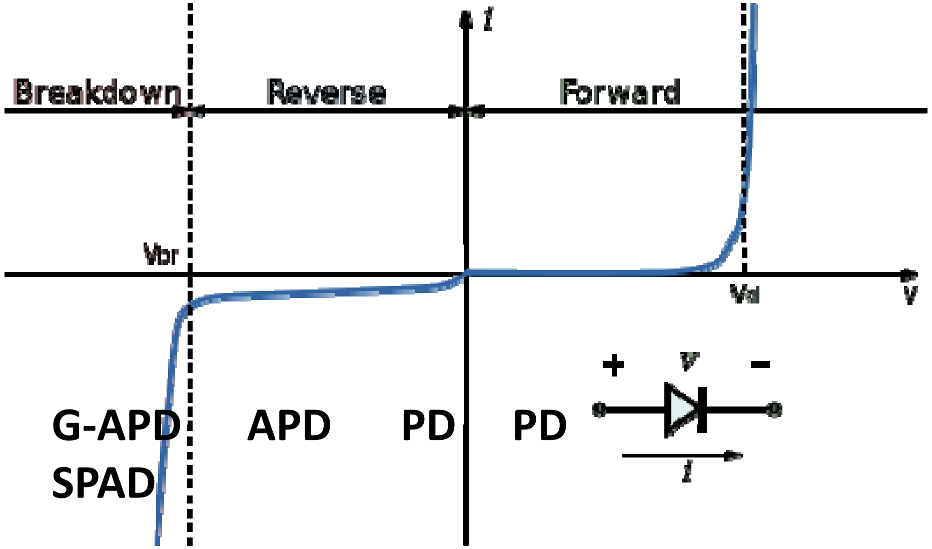
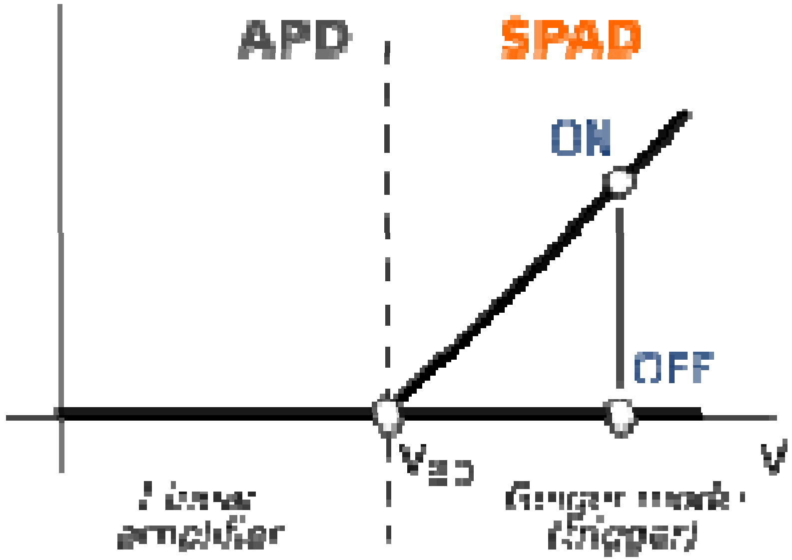
A G-APD or SPAD intrinsically is a <u>digital device</u>

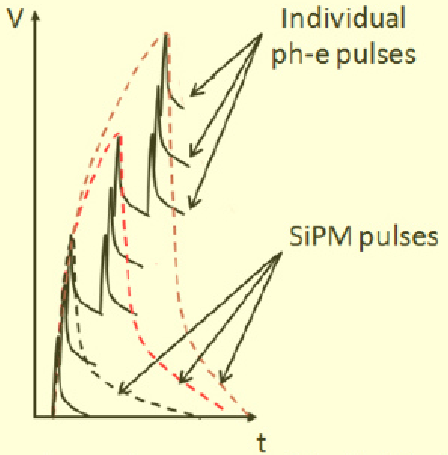




"Therefore, while the APD is a linear amplifier for the input optical signal with limited gain, the SPAD is a trigger device so *the gain concept is meaningless**."*
(source: http://en.wikipedia.org/w/index.php?title=Single-photon-avalanche-diode&oldid=603577212)

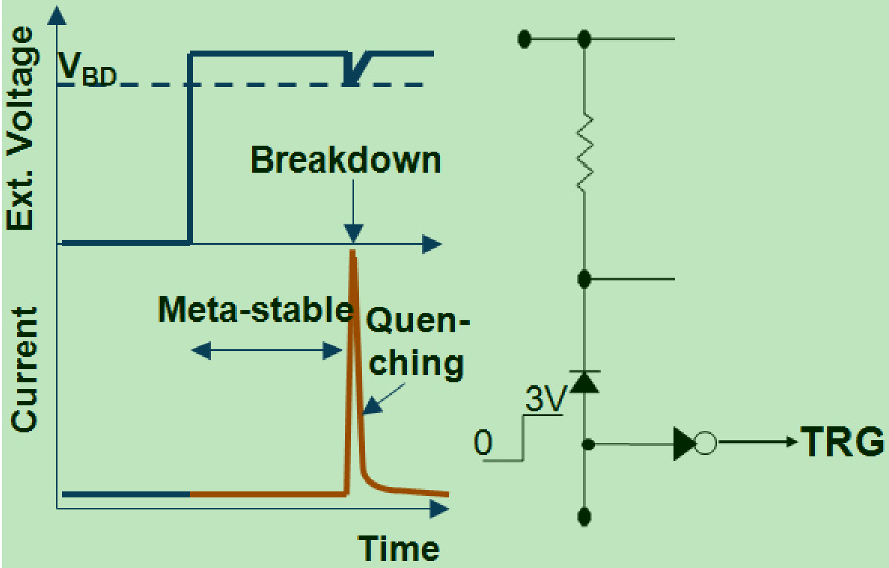
DPC uses intrinsic binary nature of SPADs

Analog SiPM



- Signal: analog sum of individual pulse amplitudes
- amplitudes depend on gain
- gains depend on temperature
- temperature drifts: 2-8%/K

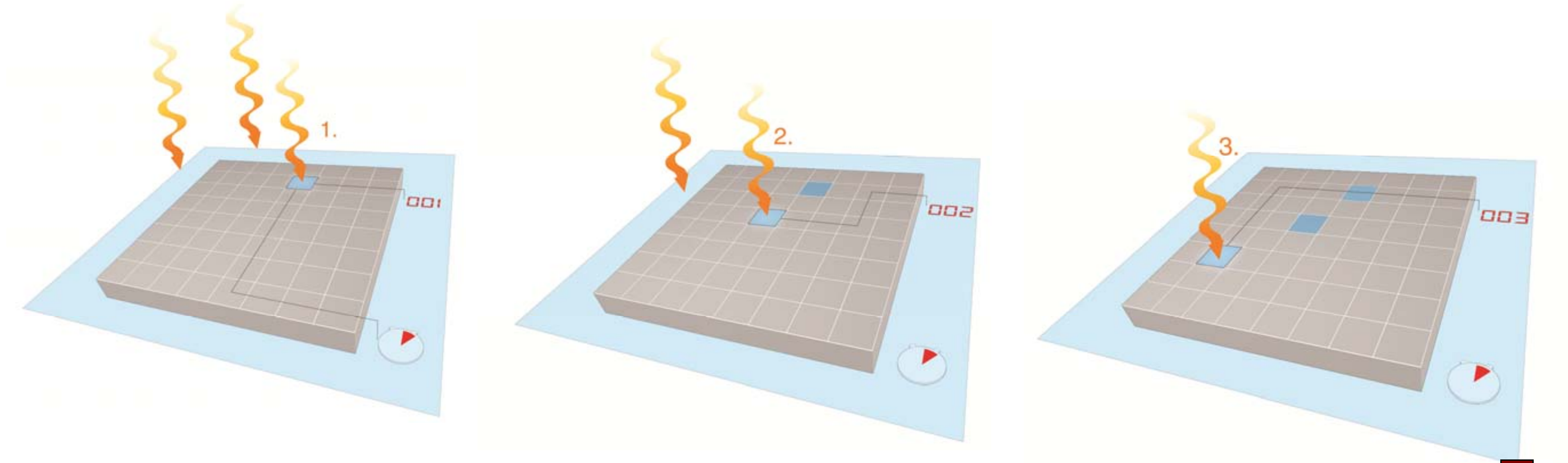
Digital Photon Counter (DPC)

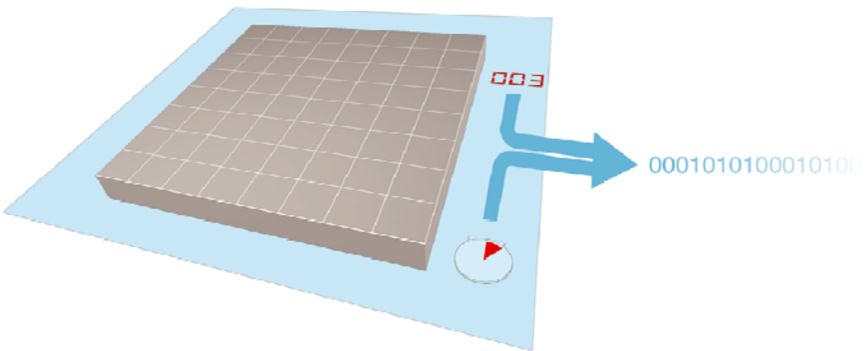


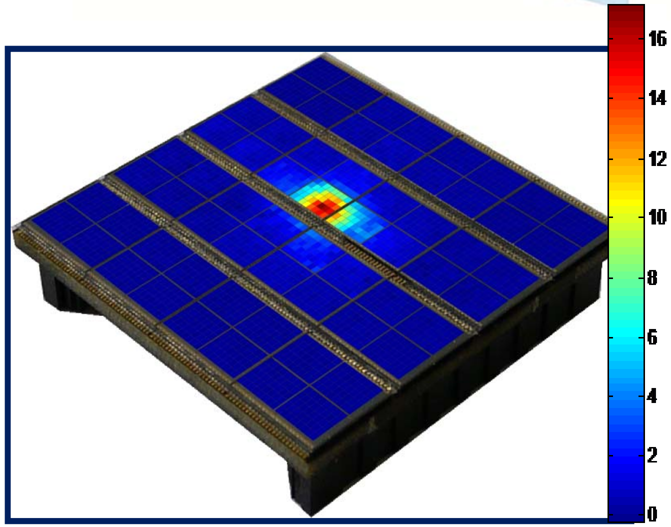
- Signal: digital sum of trigger bins & digital time stamp from TDC
- amplitudes are not relevant
- no gain dependency, reduced temp. drift: 0.33%/K

- DPC: combination of diode- & CMOS technology (lateral integration)
- Voltage drop at breakdown is used to generate trigger signal

With DPC photons are counted directly







Output: → no. of photons
→ time stamp(s)
No analog post-processing necessary!

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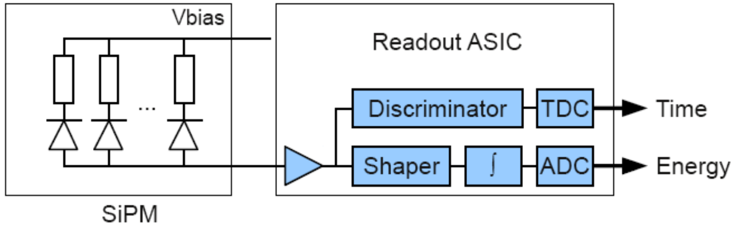
DPC is an integrated, scalable solution

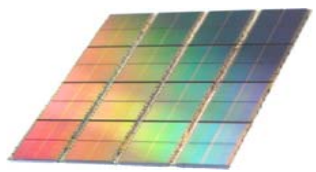
Analog SiPM

Analog Silicon Photomultiplier Detector

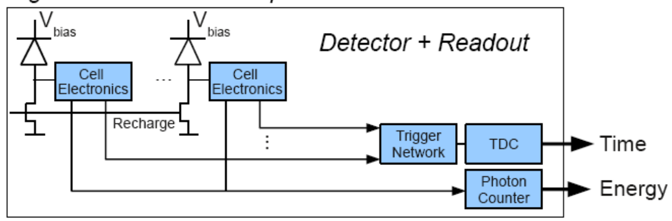


- discrete, limited integration
- analog signals to be digitized
- dedicated ASIC needed
- difficult to scale

Digital Photon Counter



Digital Silicon Photomultiplier Detector



- fully integrated
- fully digital signals
- no ASIC needed
- fully scalable

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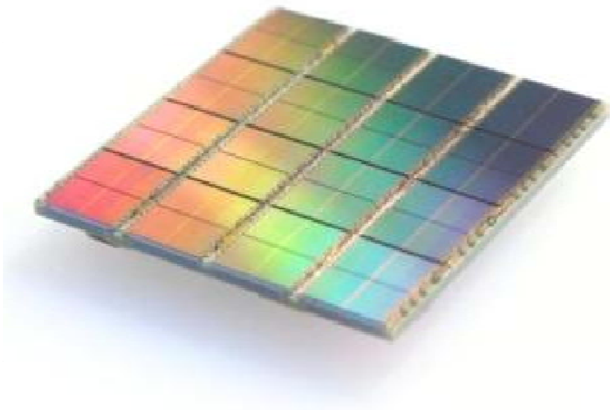
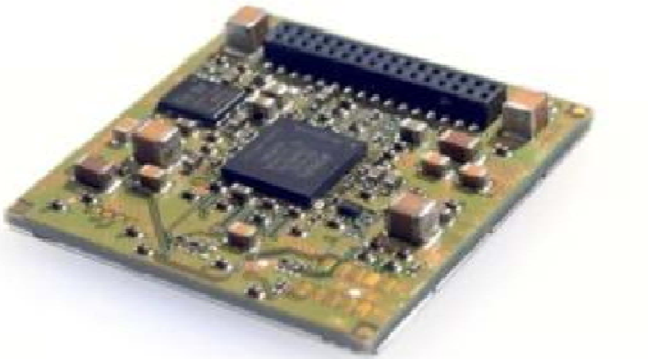
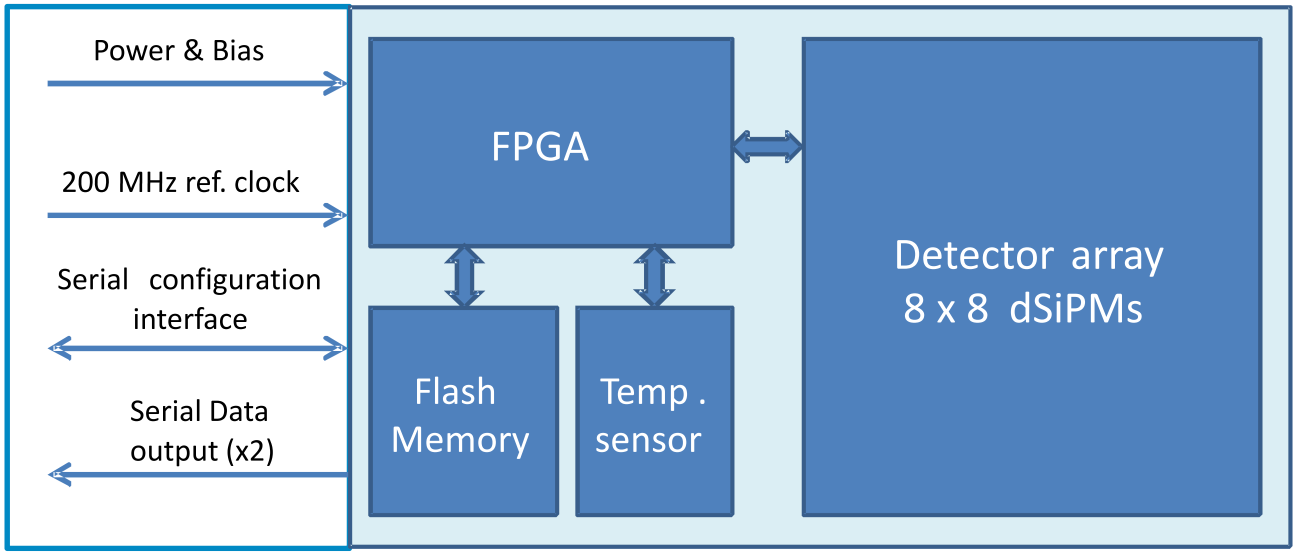
DPC: “intelligent” sensor with 4-layer interface







FPGA

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

Flash

- FPGA firmware
- TDC calibration data
- Configuration
- Inhibit memory maps

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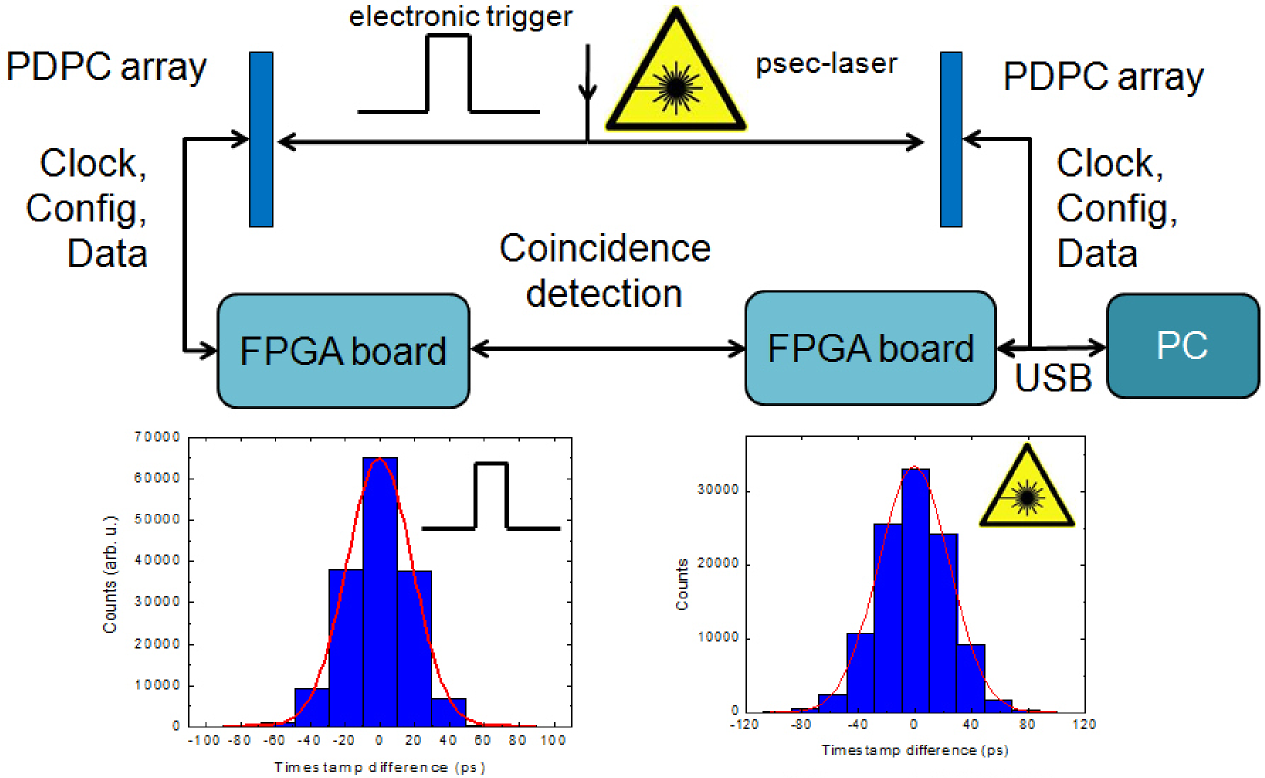
On-chip integration of TDC provides superior timing across arrays



Timing jitter: **44 ps FWHM** **59 ps FWHM**

Contribution of: **TDC network** **TDC network + diodes**

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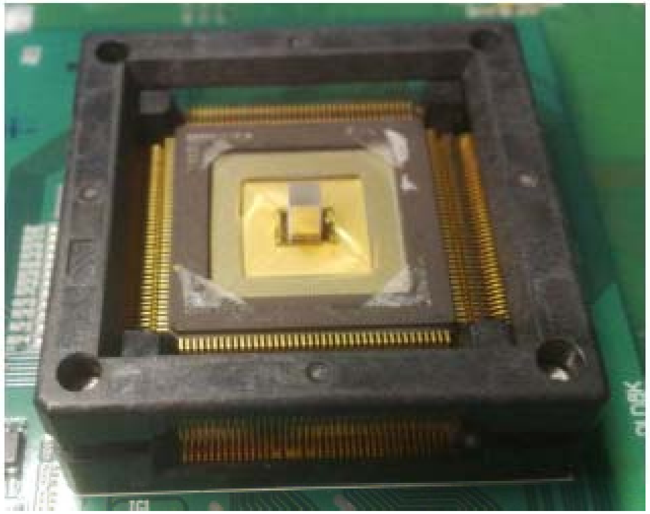
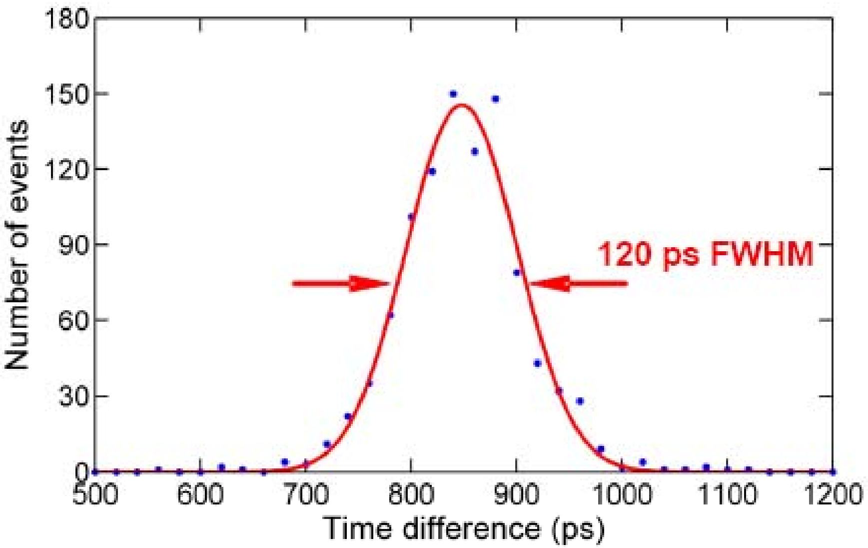
Ultimate timing with short LSO co-doped crystal

3 mm x 3 mm x 5 mm Ca co-doped LSO:Ce on PDPC demonstrator chip



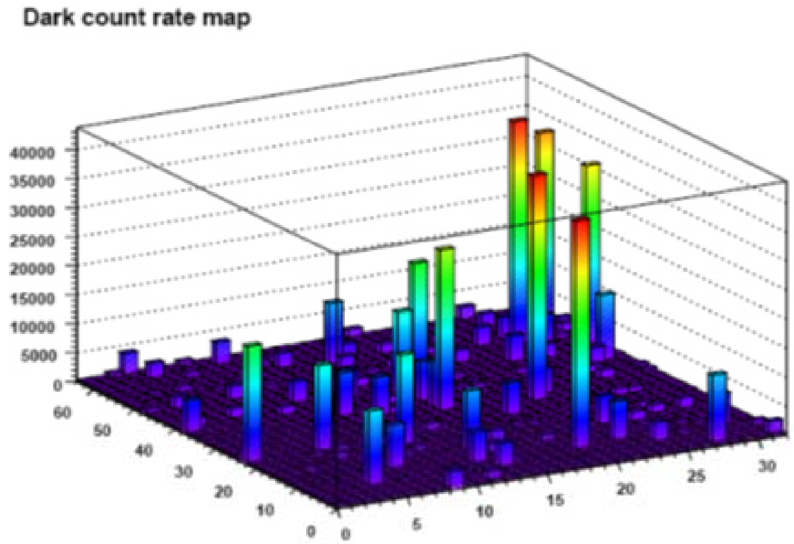
Photograph of Ca co-doped LSO:Ce crystal mounted on dSiPM demonstrator chip

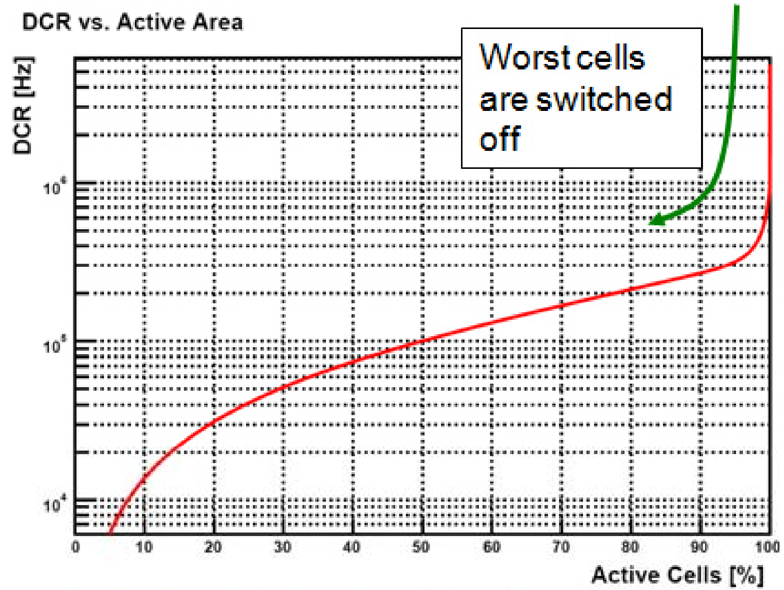


- Time difference spectrum measured with a Na-22 point source
- CRT = 120 ps FWHM (for two detectors in coincidence) at room temperature

TUDelft *D.R. Schaart et al, NSS-MIC 2011, MIC15.S-137* 11

DPC: dark count management by digitization





- Silicon based light sensors have background noise (dark counts), varying with temperature.
- In digital SiPMs every cell can be addressed individually.
- Cells with high dark counts can be switched off.
- A few cells switched off (1-5%) reduces dark count levels by orders of magnitude.

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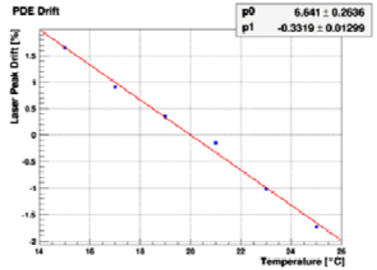
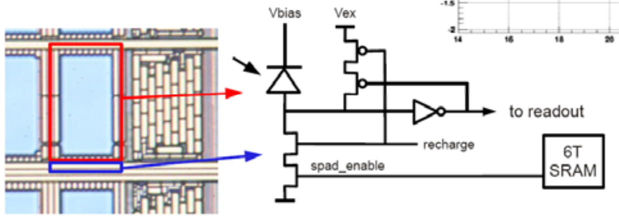
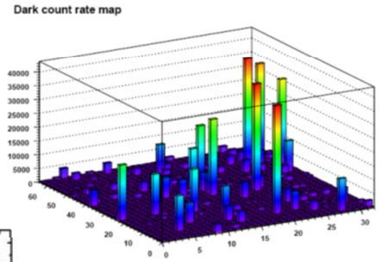
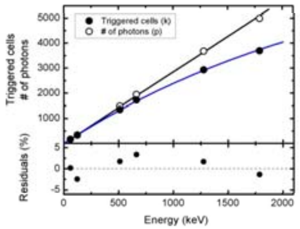
Sub-summary: Advantages of DPC vs. analog SiPM

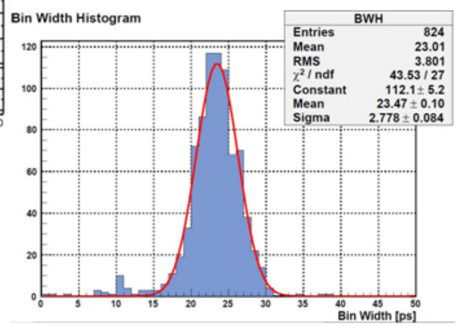
- Significantly **reduced temperature sensitivity** (~10^{-1})
- Active quenching **reduces afterpulsing & crosstalk** (~10^{-1})
- Individually addressable cells enable **DC control** (~10^{-2})
- Better **linearity** (&correction)
- Better **intrinsic timing resolution** due to integrated TDCs (~ factor 5)
- **No analog electronics**, no ADCs, no ASICs









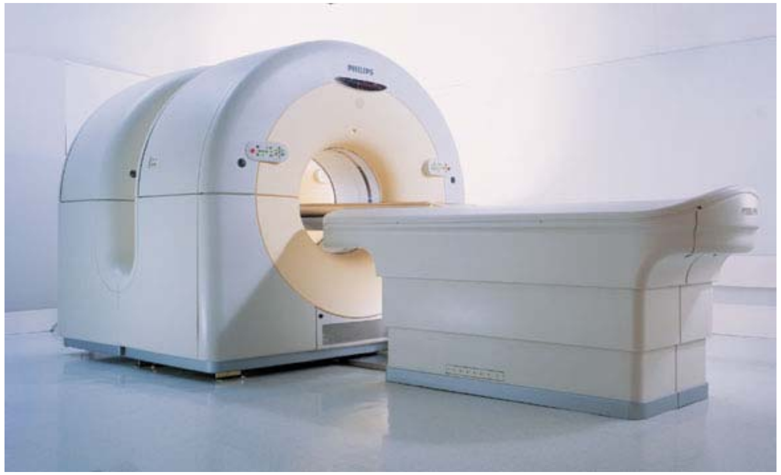


Outline

- DPC (dSiPM): a  ?

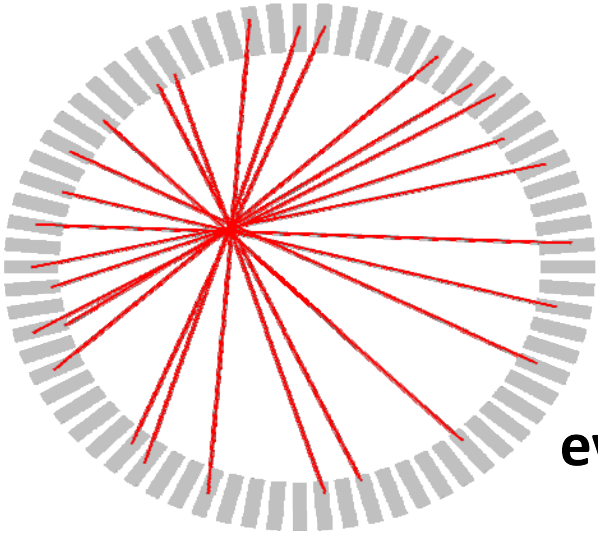
- Motivation: Positron Emission Tomography
- Advantages of the digital concept
- **DPC technology beyond the sensor**
- First user experiences, first PET imaging results
- Future Developments

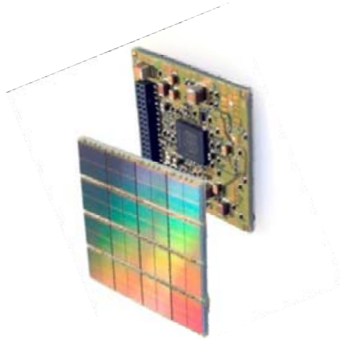
Challenge: significant increase in information density



- **bandwidth requirements**
- **data reduction**
- **front end correction/data processing**
- **calibration**

PMT-PET:
420 channels
(current Philips PET)

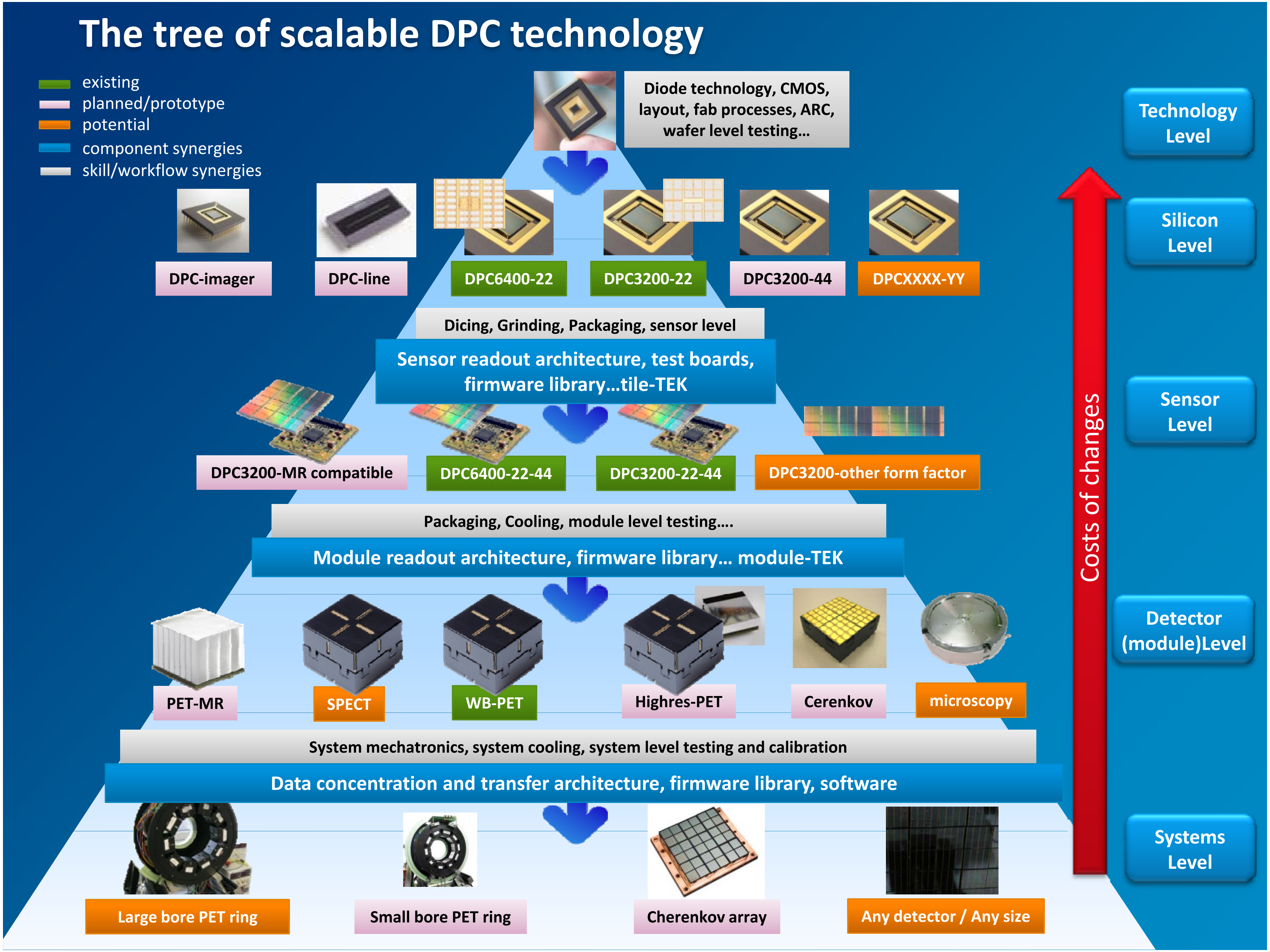




Solid state PET:
evtl. > 35.000 channels

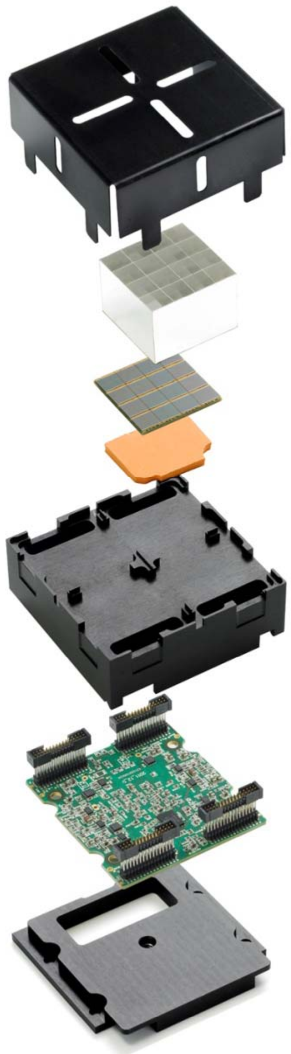
Lines-of-response (LOR)

PHILIPS



The tree of scalable DPC technology
existing
planned/prototype
potential
component synergies
skill/workflow synergies
Diode technology, CMOS, layout, fab processes, ARC, wafer level testing…
Technology Level
DPC-imager
DPC-line
DPC6400-22
DPC3200-22
DPC3200-44
DPCXXXX-YY
Silicon Level
Dicing, Grinding, Packaging, sensor level
Sensor readout architecture, test boards, firmware library…tile-TEK
DPC3200-MR compatible
DPC6400-22-44
DPC3200-22-44
DPC3200-other form factor
Sensor Level
Costs of changes
Packaging, Cooling, module level testing….
Module readout architecture, firmware library… module-TEK
PET-MR
SPECT
WB-PET
Highres-PET
Cerenkov
microscopy
Detector (module)Level
System mechatronics, system cooling, system level testing and calibration
Data concentration and transfer architecture, firmware library, software
Large bore PET ring
Small bore PET ring
Cherenkov array
Any detector / Any size
Systems Level

DPC: from sensor to detector module

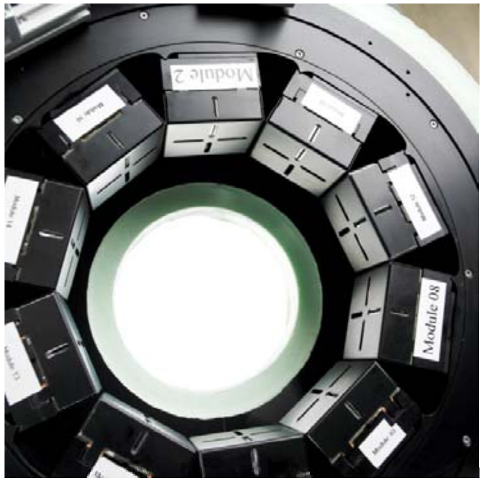


- 4 DPC sensor arrays (tiles)
- ~ 6.6 x 6.6 cm^2
- usable with or w/o scintillator crystals
- variable scintillator geometries
- Module board with FPGA, pre-processing capability & well defined interface
- local power supply
- experimentally cooled to - 40°C

PHILIPS

Rapid PoC: PET prototype, tested @ FZ Juelich

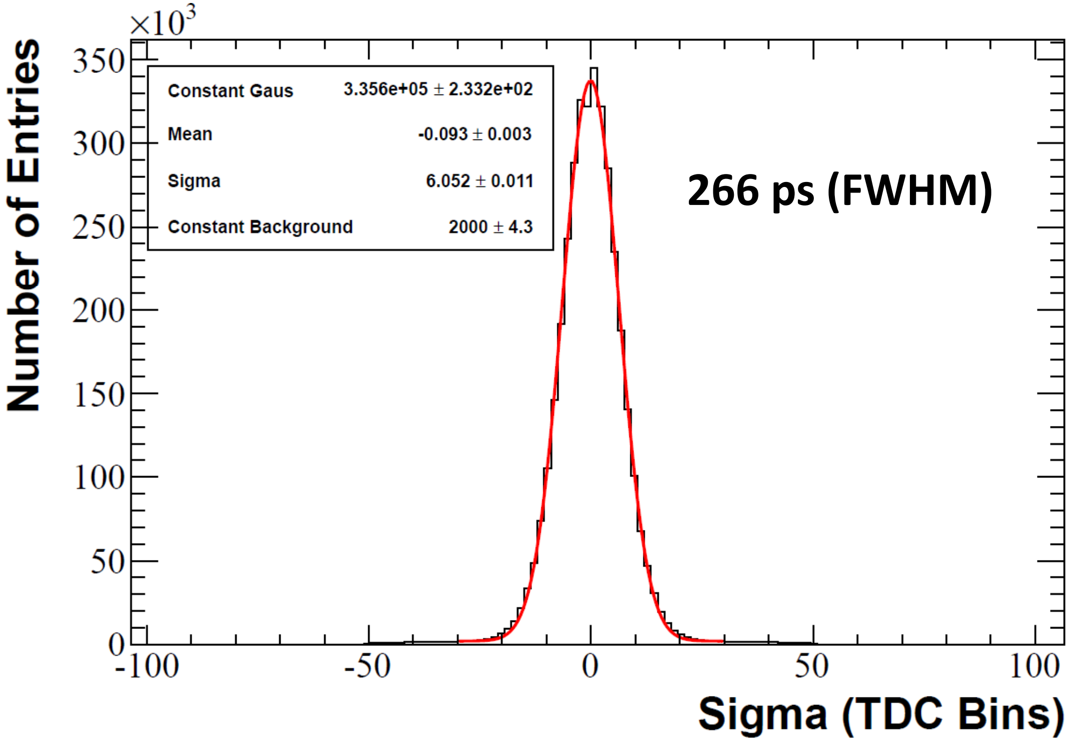
- Inner Diameter (face-to-face): 20 cm
- 10 modules a 4 sensors
- LYSO 4 x 4 x 22 mm²
- Coolable down to 0°C
- Sensor temp. : ~ 5-10°C



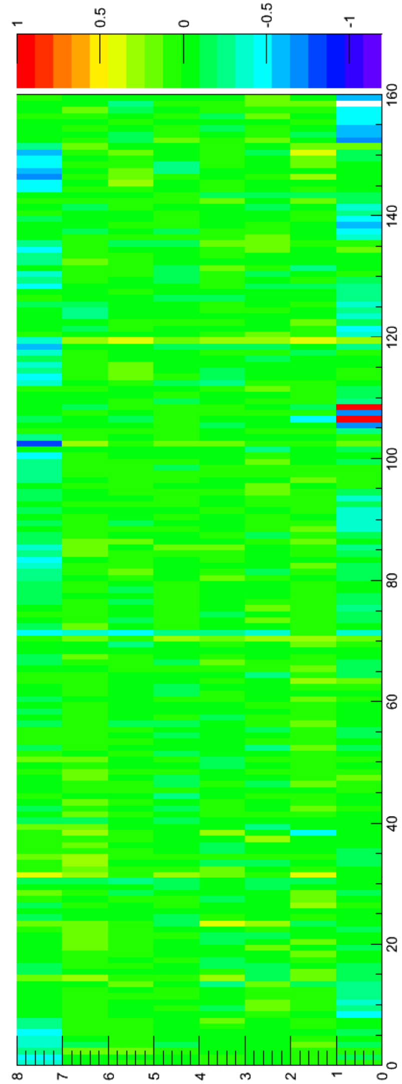
PHILIPS

Rapid PoC: PET prototype – timing (CRT)

- LYSO 4 x 4 x 22 mm²
- Sensor temp. : ~ 5-10°C



Stability of timing signal over 4 months →



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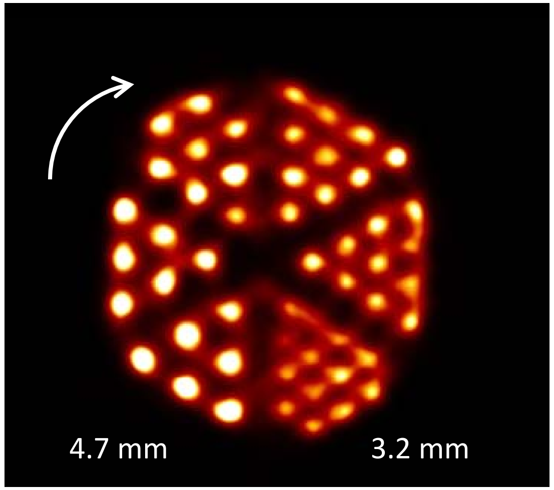
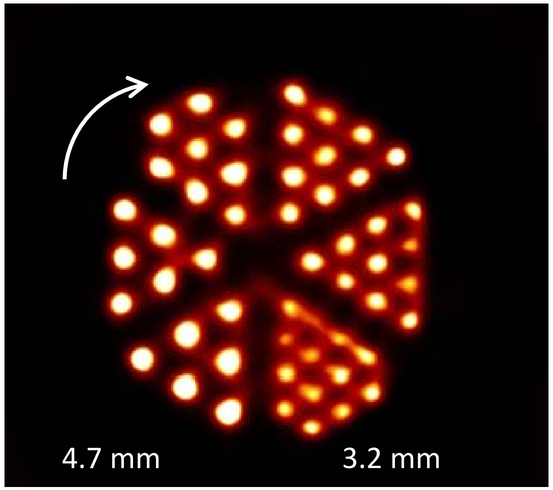
Rapid PoC: PET prototype – image quality (ToF)

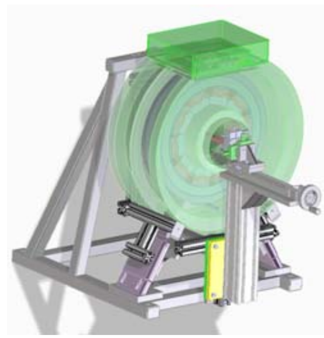
- Hot rod phantom (70 mm diameter)
- 1h data acquisition (10-15 MBq ^{18}F)
- Trigger 2 at 7-9°C (internal tile temperature)
- Energy (RE 13% & clustering) and time (TR 390 ps) calibrations applied
- Energy window of [440;660] keV and time window of 3 ns [-1.5;1.5]

Without TOF



With TOF (~ 390 ps)





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

PHILIPS

Rapid PoC: FARICH prototype detector

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

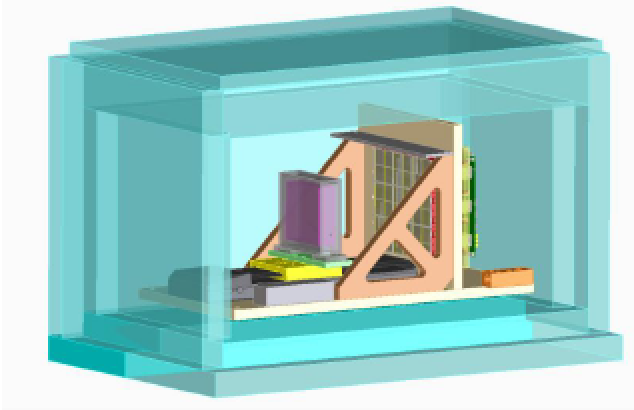
Main objective:

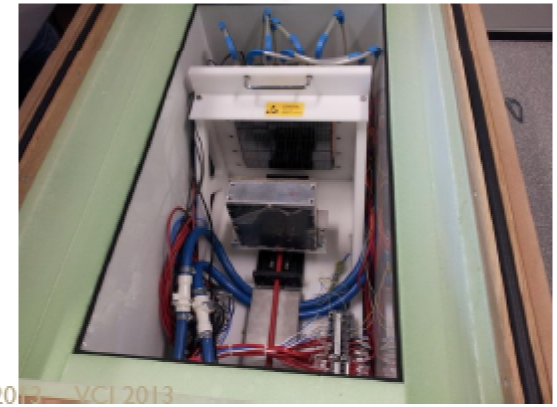
Proof of concept: full Cherenkov ring detection with DPC array

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!





13/02/2013 VCI 2013

Slide courtesy of S. Kononov, Budker Institute, Novosibirsk

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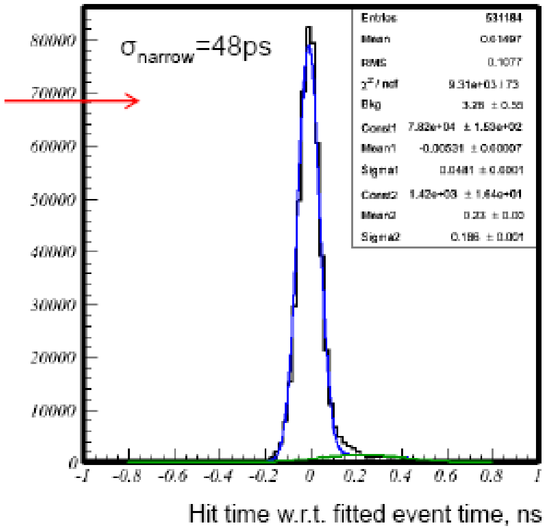
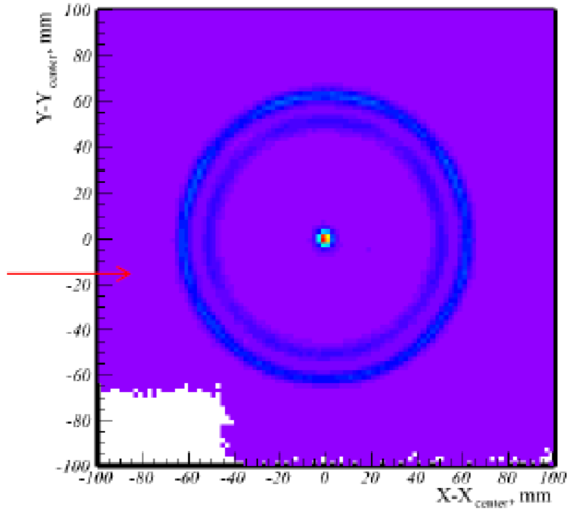
FARICH prototype detector @ CERN

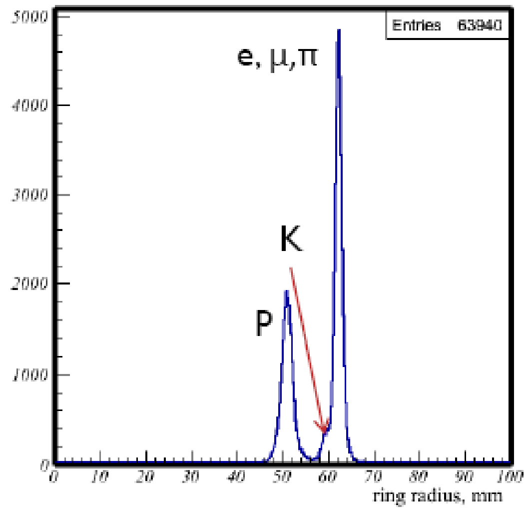
Intrinsic timing



Hit positions



Event distribution on radius



- Intrinsic timing resolution of full (20 x 20 cm^2) detector: **σ = 48 ps**
- Discrimination of protons, kaons and pions with high angular resolution
- Curable damage of sensor at primary beam spot

Data courtesy of S. Kononov, Budker Institute, Novosibirsk

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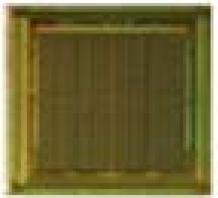
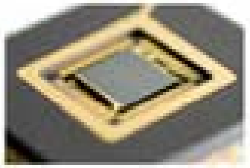
DPC: Scalable Technology Maintains Intrinsic Performance

DEMONSTRATOR:
single pixel
CRT ~ 270 ps*



CHIP:
2 x 2 = 4 pixels
CRT ~ 270 ps*



ARRAYS (TILES):
8 x 8 = 64 pixels
CRT ~ 270 ps*

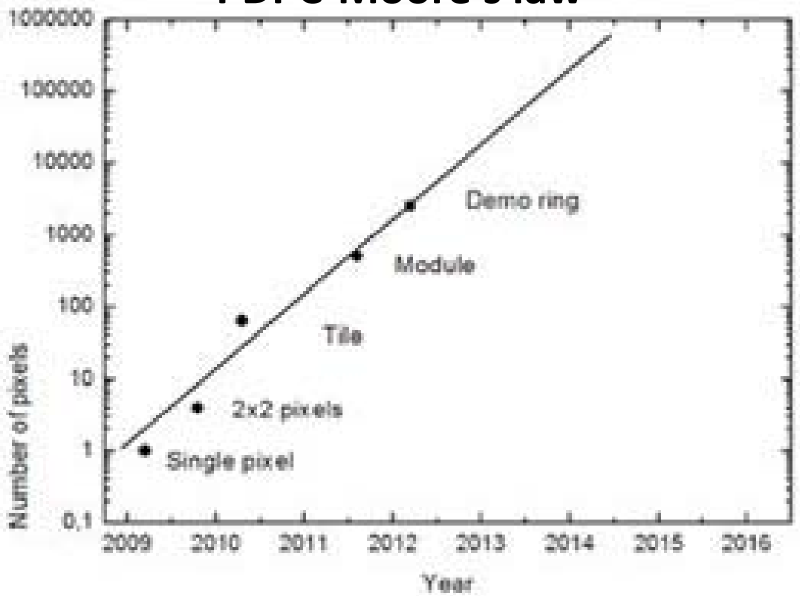
MODULES:
256 pixels
CRT ~ 270 ps*

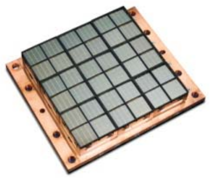
DEMO RING:
2560 pixels
CRT ~ 270 ps*

*Using 4x4x22 mm³ LYSO crystals !!

Many first time rights

PDPC-Moore's law





20 x 20 cm²
Cherenkov detector
with **48 ps σ** !

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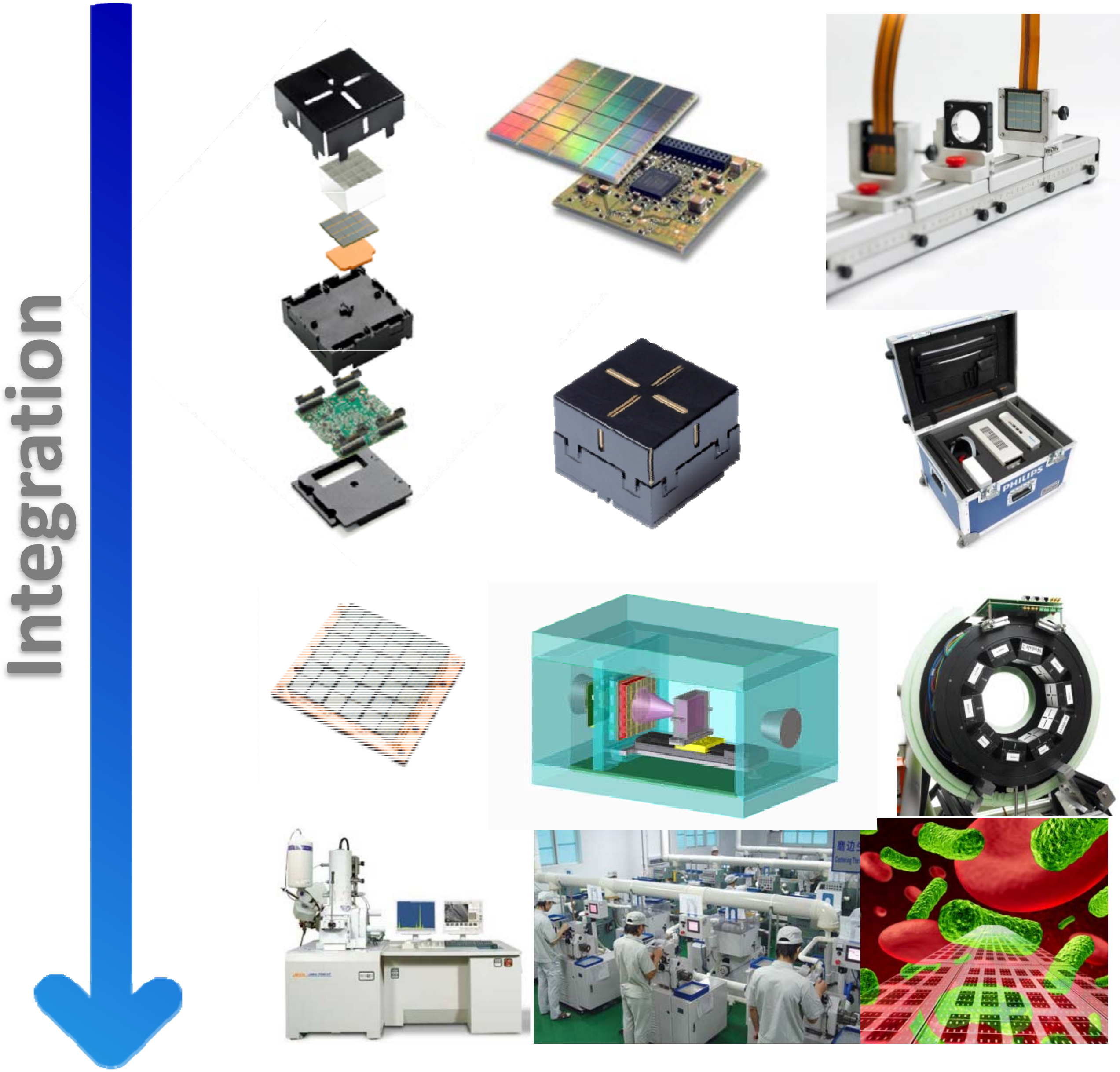
DPC: technology to application ("DPC Lego")



TEK 1 - POP (tile TEK)

POP - proof of principle

TEK 2 - POC (module TEK)

POC - proof of concept

Rapid prototyping

Application/ Industrialization

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Outline

- DPC (dSiPM): a
- Motivation: Positron Emission Tomography
- Advantages of the digital concept
- DPC technology beyond the sensor
- First user experiences, first PET imaging results
- Future Developments

DPC Sensor Technology Evaluation Kit (STEK)

> 30 kits installed

- 3 year contract
- user support by dedicated Ph.D.'s
- regular user meetings

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Rapid PoP of DOI scheme @SNU

Functional & Molecular Imaging System Lab @ SNU

2013/01

- PDPC-TEK evaluation kit arrived

2013/02-03

- Initial evaluation of PDPC-TEK evaluation kit

2013/04-07

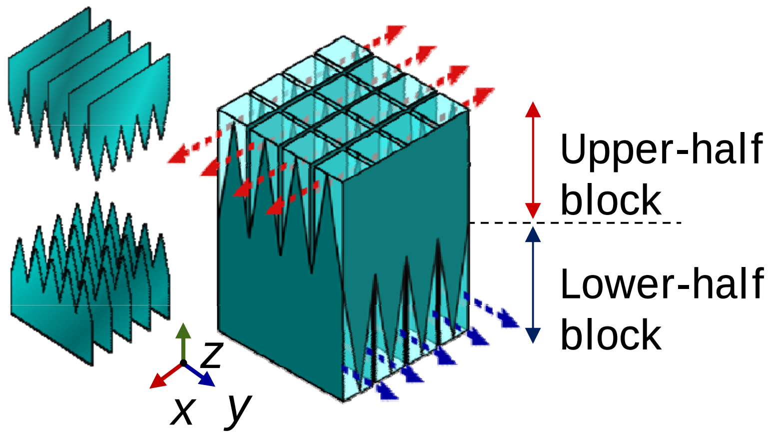
- Preliminary experiment for DOI measurement
  - Changing temperature, tile configuration, several experimental conditions, light guide size, etc.

2013/08

- Several debugging processes to acquire better results
  - Change of coincidence window & irradiation direction, etc.

2013/09-now

- Rotation of two detectors
- Also working to improve the timing resolution



(PMB, Ito et al 2010 & 2013)

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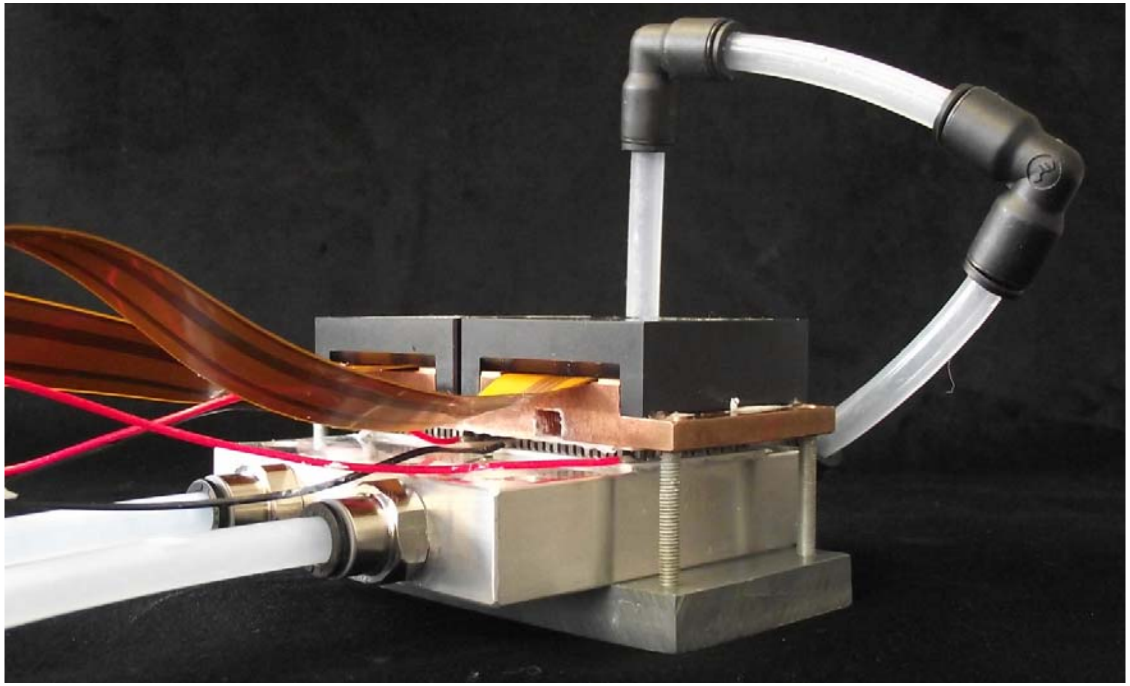
Fast testing of various scintillators @ TUD

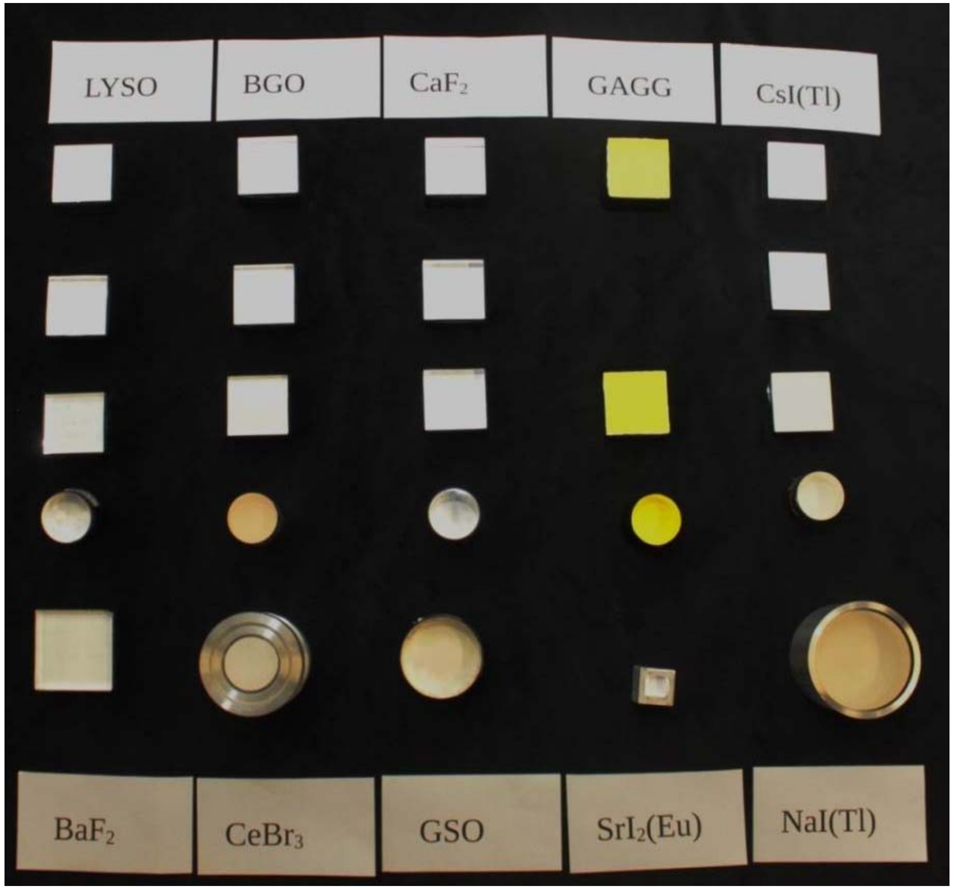
- No fixed scintillation crystals attached – freedom of choice
- Water and Peltier cooling
- Copper heat sink
- Nitrogen flushing
- Stable at 0 C
- Larger cooling plate for 8 sensors



Courtesy of J. Petzold, OncoRay-Technical University Dresden

Fast testing of various scintillators @ TUD

- Coupled different materials in several shapes to DPC
- Monolithic 32x32 mm²
- Additional shapes
- Compared light yield, energy- and timing resolution with standard PMT

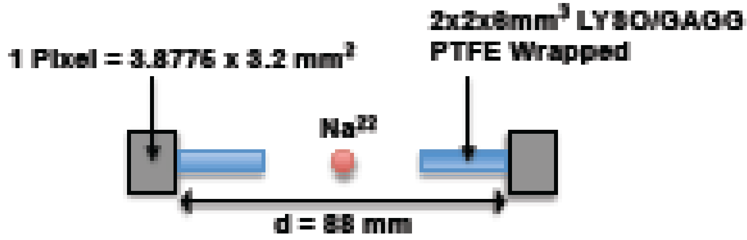


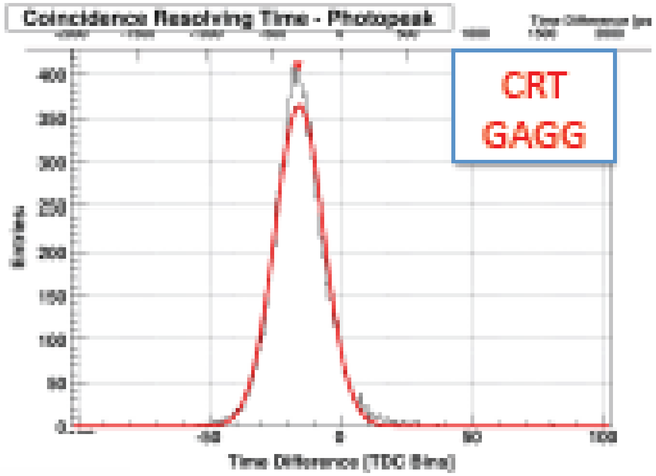
Courtesy of J. Petzold, OncoRay-Technical University Dresden

PHILIPS

Fast and easy test of GAGG scintillator @ TUM

Philips DPC Coincidence Timing





- Parameters
  - 420 < Energy [keV] < 600
  - 10% DC inhibited cells
  - 2°C

Trigger Scheme	1	2	3	4
Avg. No. photons to trigger	1	2.333	3	8.333
LYSO CRT FWHM [ps]	215	280	350	580
GAGG CRT FWHM [ps]	430	600	685	995

Courtesy of K.Shimazoe, Tokio University

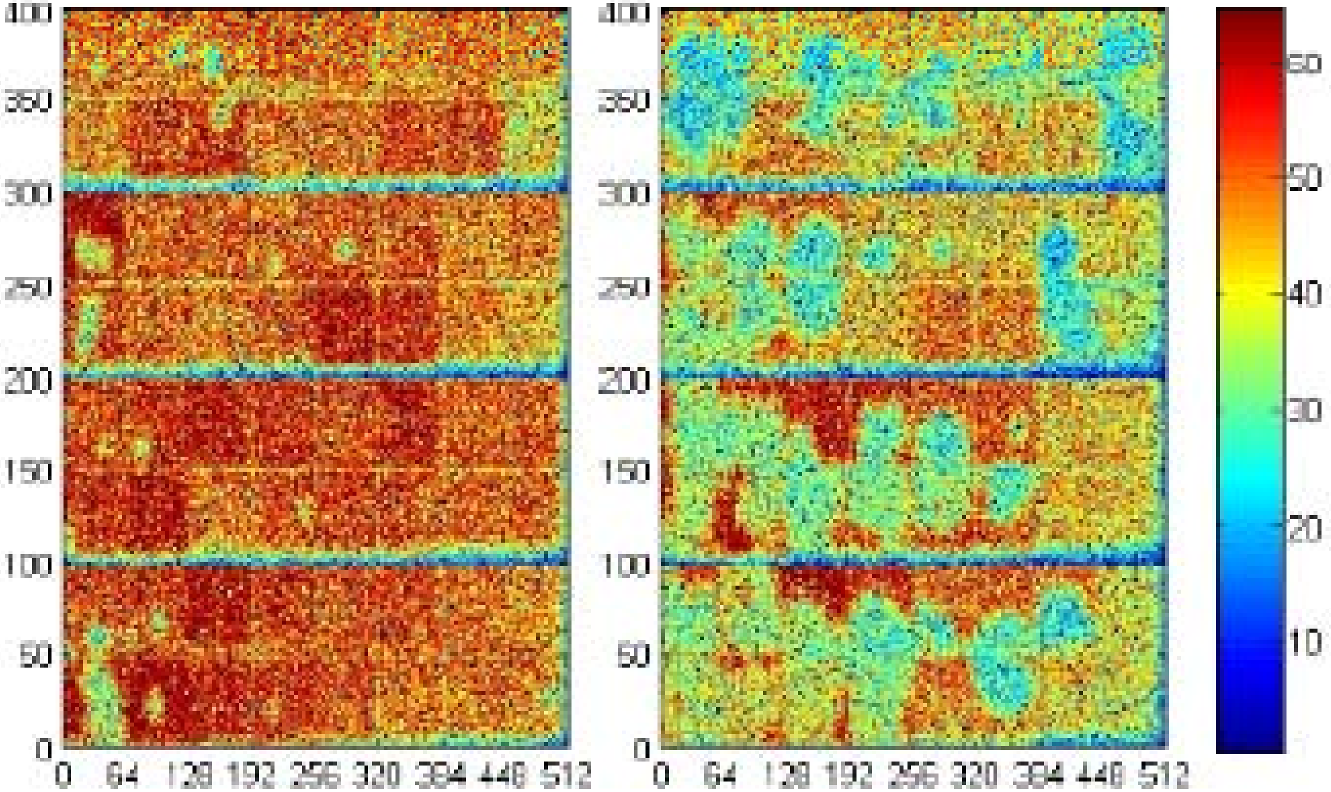
DPC opens new opportunities

Another Usage of DCMs: „Coupling Visualization"

東京大学
THE UNIVERSITY OF TOKYO

TECHNISCHE UNIVERSITÄT MÜNCHEN

- Array of Single GAGG Crystals matching exactly DPC pixel geometry
  - Coupling Evolution from t = 0h to t =24h



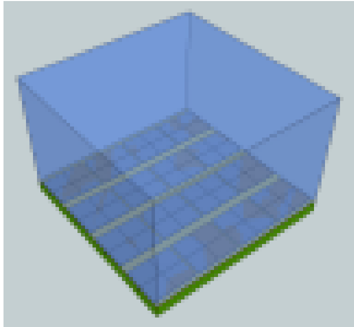
Tokio

PHILIPS

DPC with monolithic crystals@ TU Delft

Performance summary

TU Delft
Delft University of Technology



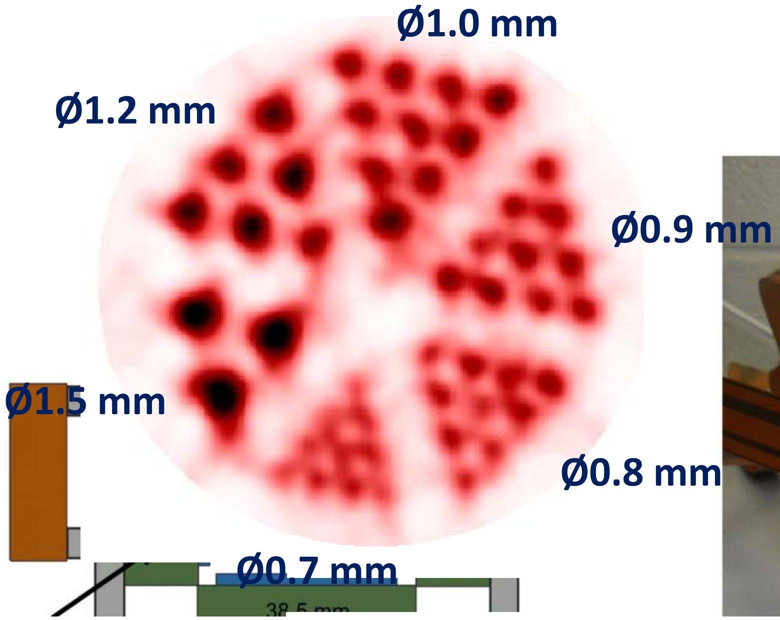
Current results with LSO monolithic scintillators on dSiPM arrays:

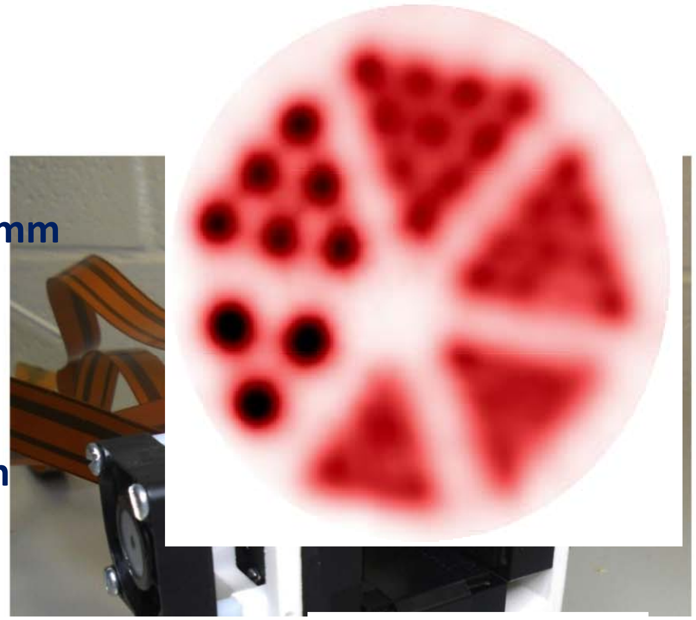
Performance parameter		Monolithic	State of the art
Energy resolution	(% FWHM)	11 - 12	~12
Spatial resolution	(mm FWHM)	1.0 - 1.6	4 - 6
DOI resolution	(mm FWHM)	3 - 5 mm	None
CRT	(ps FWHM)	160 - 185	500 - 650

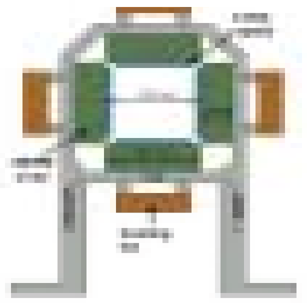
⇒ A highly promising detector for future clinical PET/CT and PET/MRI systems

TU Delft H.T. van Dam et al, Sub-200 ps CRT in monolithic scintillator PET detectors using digital SiPM arrays and maximum likelihood interaction time estimation, PMB 58, 3243-3257, 2013 107

Rapid Prototyping: DigiPET @ Gent University





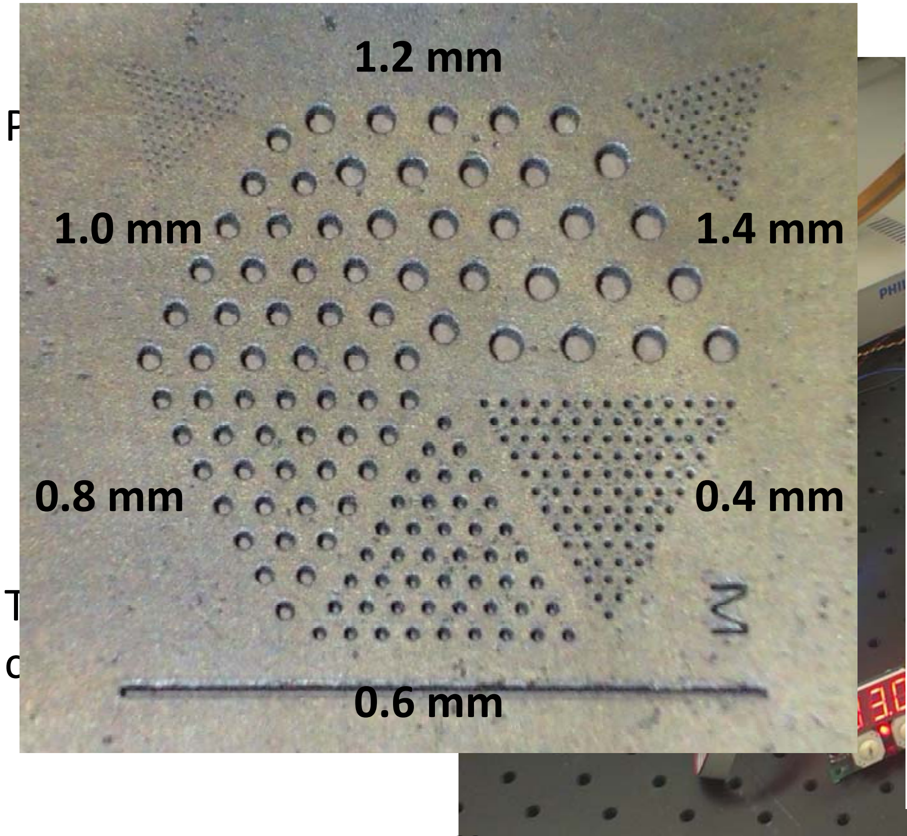


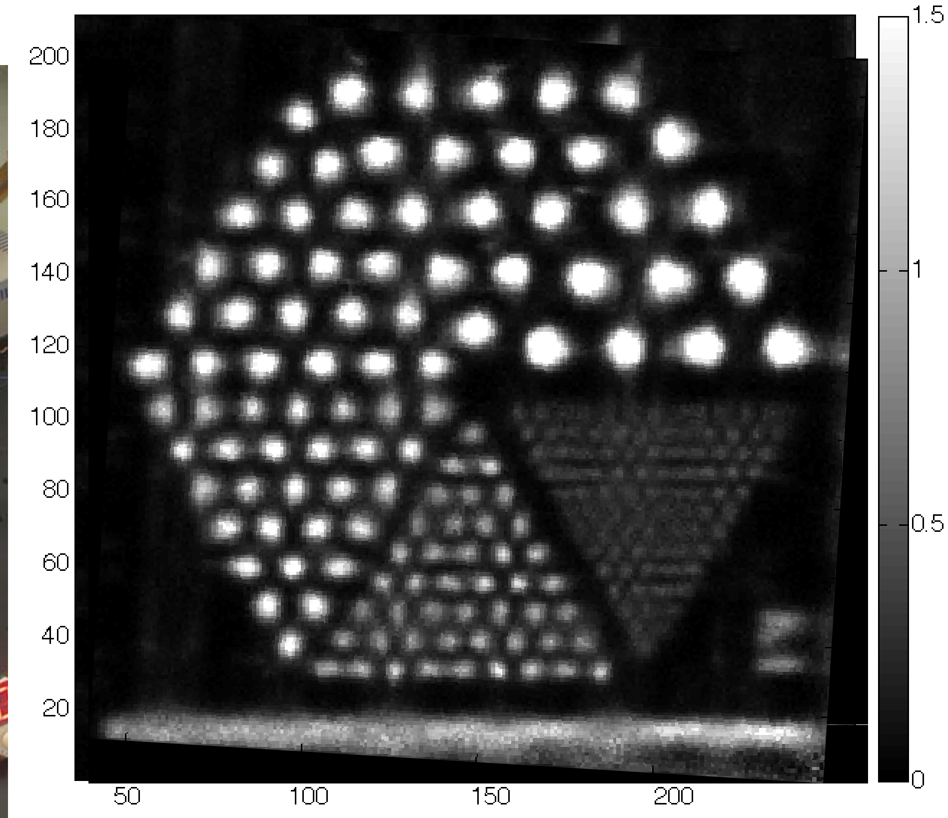
15M coincidences

160M coincidences

S. Espana *et al*, “DigiPET: Sub-millimeter spatial resolution small animal PET imaging using thin monolithic scintillators”, *in preparation*

Evaluation of DPC for SPECT @ UGent

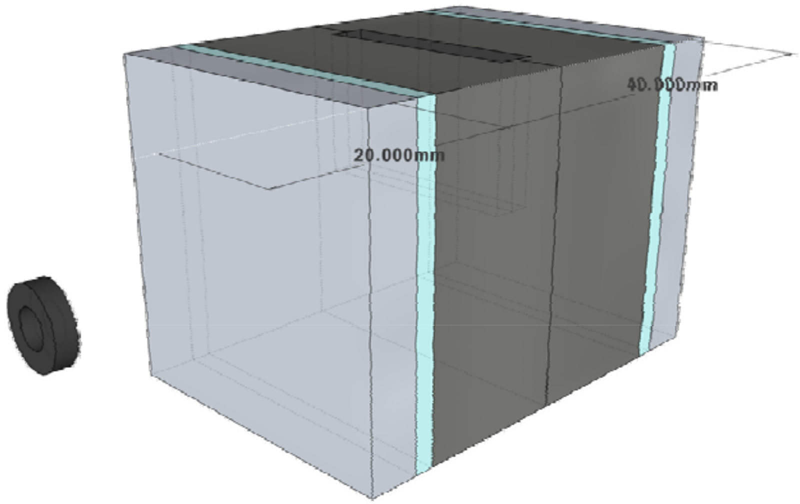


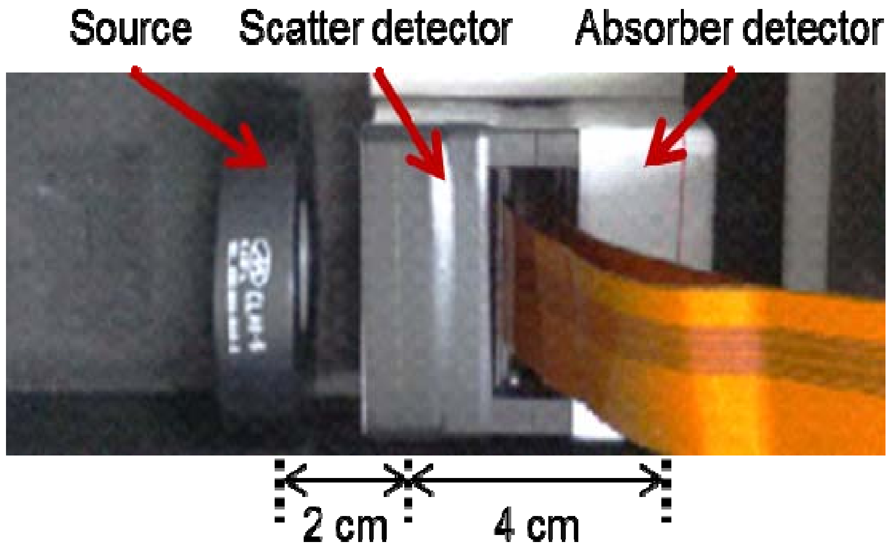


Tungsten collimator **Detector image**

Courtesy of S. Vandenberghe, Gent University

PoP for Compton Camera @ Hanyang





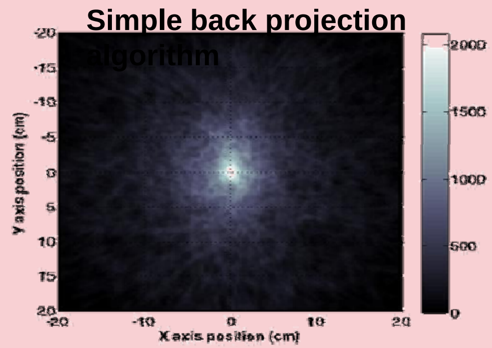
Trigger scheme: 2

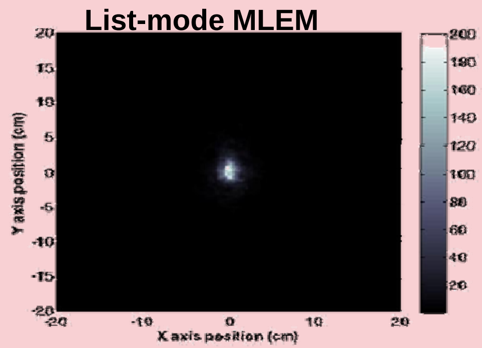
Validation scheme: 4

Integration time: 645 ns (~2.5 tau)

Temperature of the detector: 5°C

Source: ^{137}Cs (662 keV, 8.37 µCi)





Source to detector distance: 2 cm, **inner detector distance**: 4 cm

Measurement time: 180 minutes, **coincidence window**: 80 ns

Courtesy of J.H. Park, Hanyang University, Seoul

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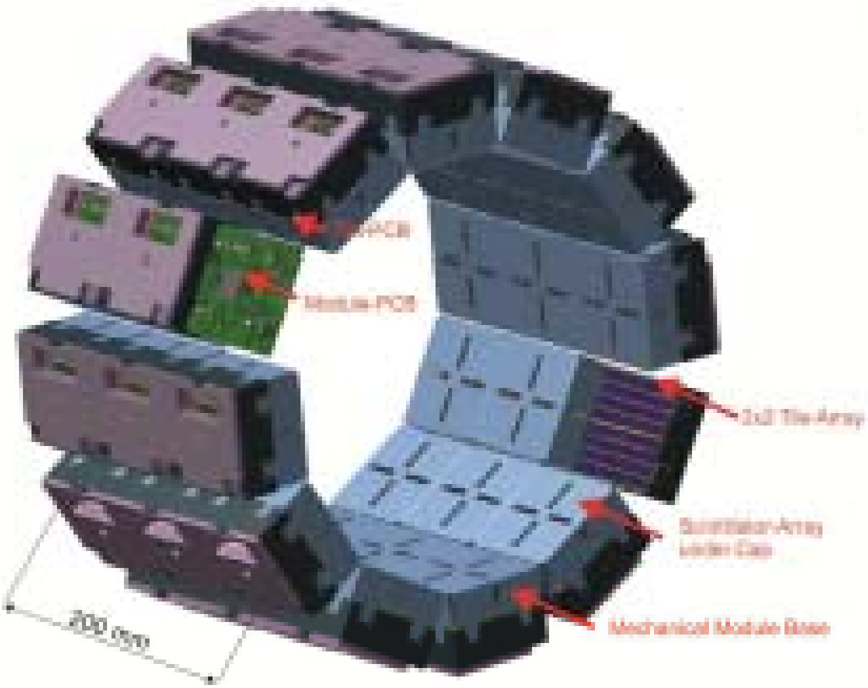
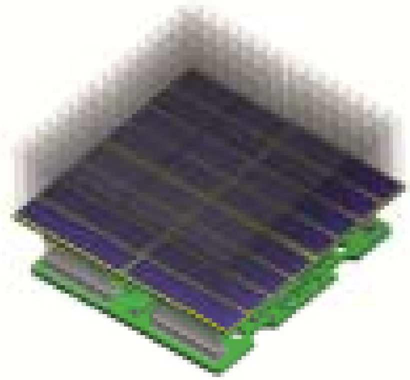
New PET Scanner: phenoPET

JÜLICH
FORSCHUNGSZENTRUM





- 1 Ring: 12 Modules (48 Tiles)
- Scanner: 3 Rings (36 Modules)
- FOV: ~18cm x 18cm

Graph courtesy of H. Noeldgen, FZ Juelich

DPC Module Technology Evaluation Kit (MTEK)

Operation of 2 DPC Modules
- 2x2 tiles per module
- local voltage regulation
- designed for easy cooling

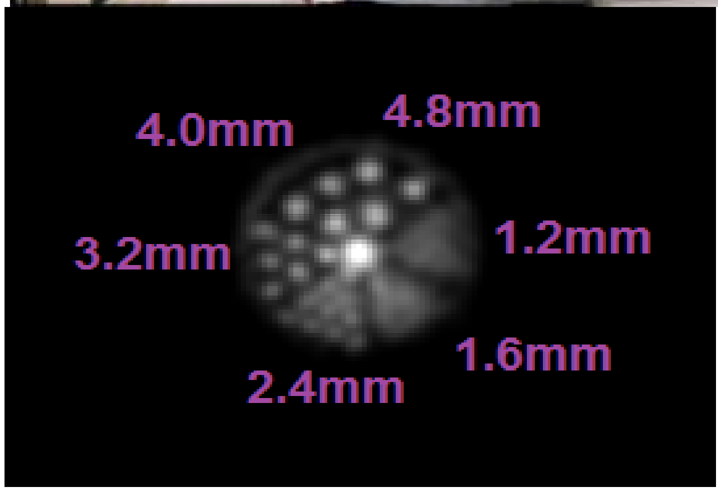
Local voltage supply allows to use longer cabling (1-3 m)

Same sensor control features as in STEK

First kits installed!

- 3 year contract
- user support by dedicated Ph.D.'s
- regular user meetings

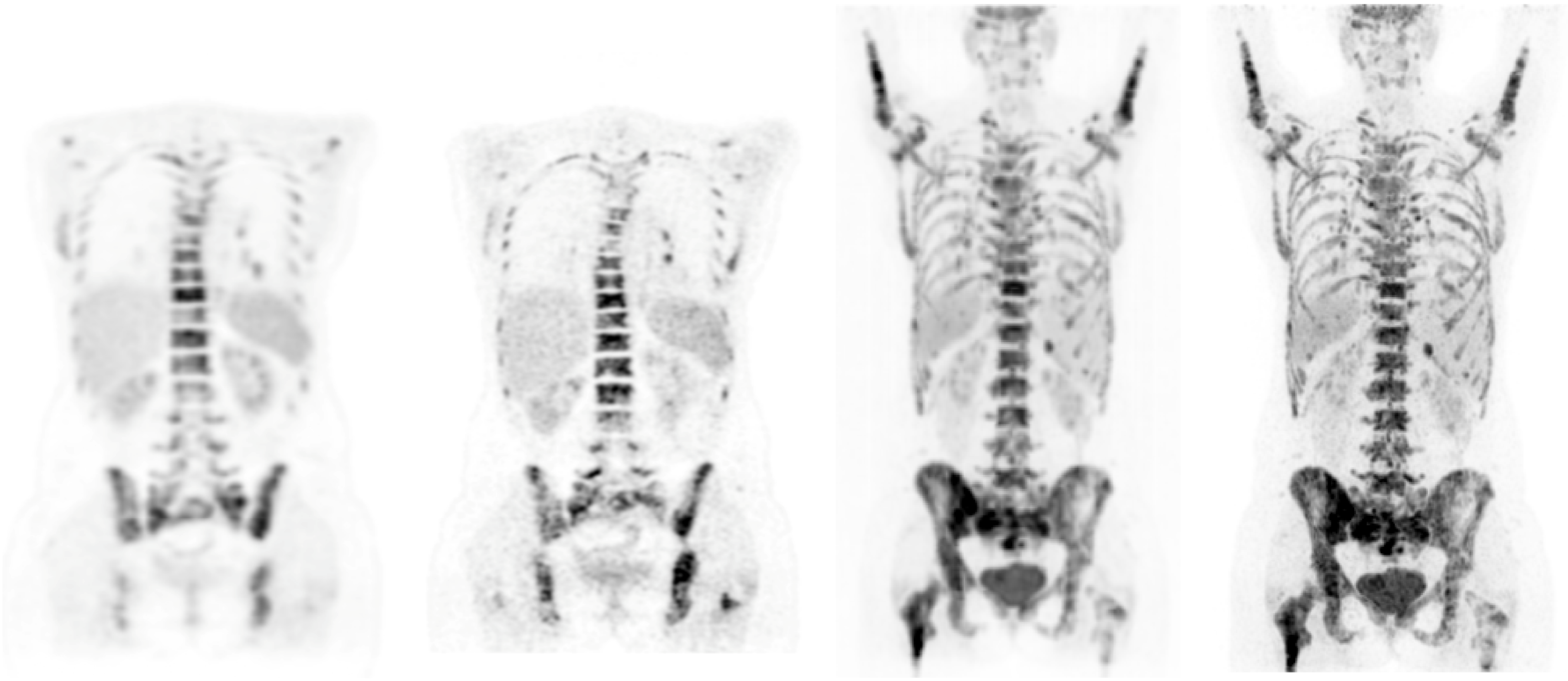
Clinical PET with DPC: towards the first product



Vereos™
Digital PET/CT
Introduced
@ RSNA 2013

PHILIPS

Clinical PET with DPC: significantly improved IQ



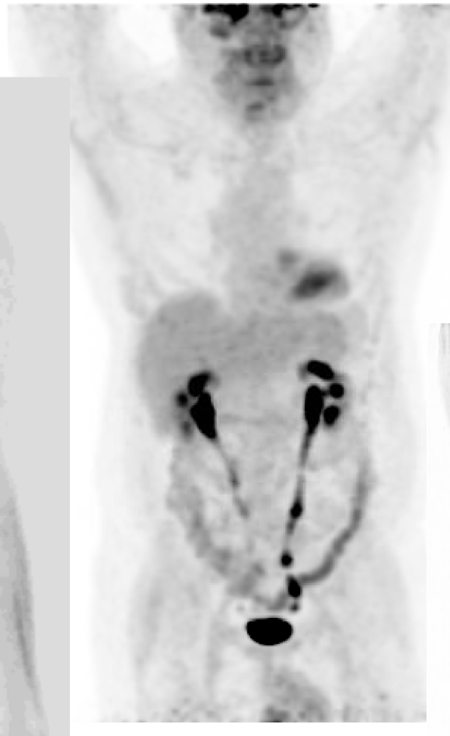
PMT **DPC** **PMT** **DPC**

Images courtesy of Cleveland University Hospitals, Cleveland, OH, USA

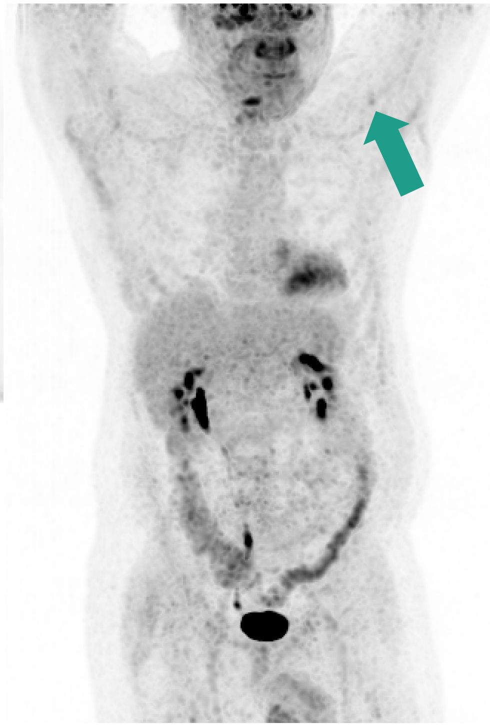
Clinical PET with DPC: significantly improved IQ

PMT

DPC



PMT

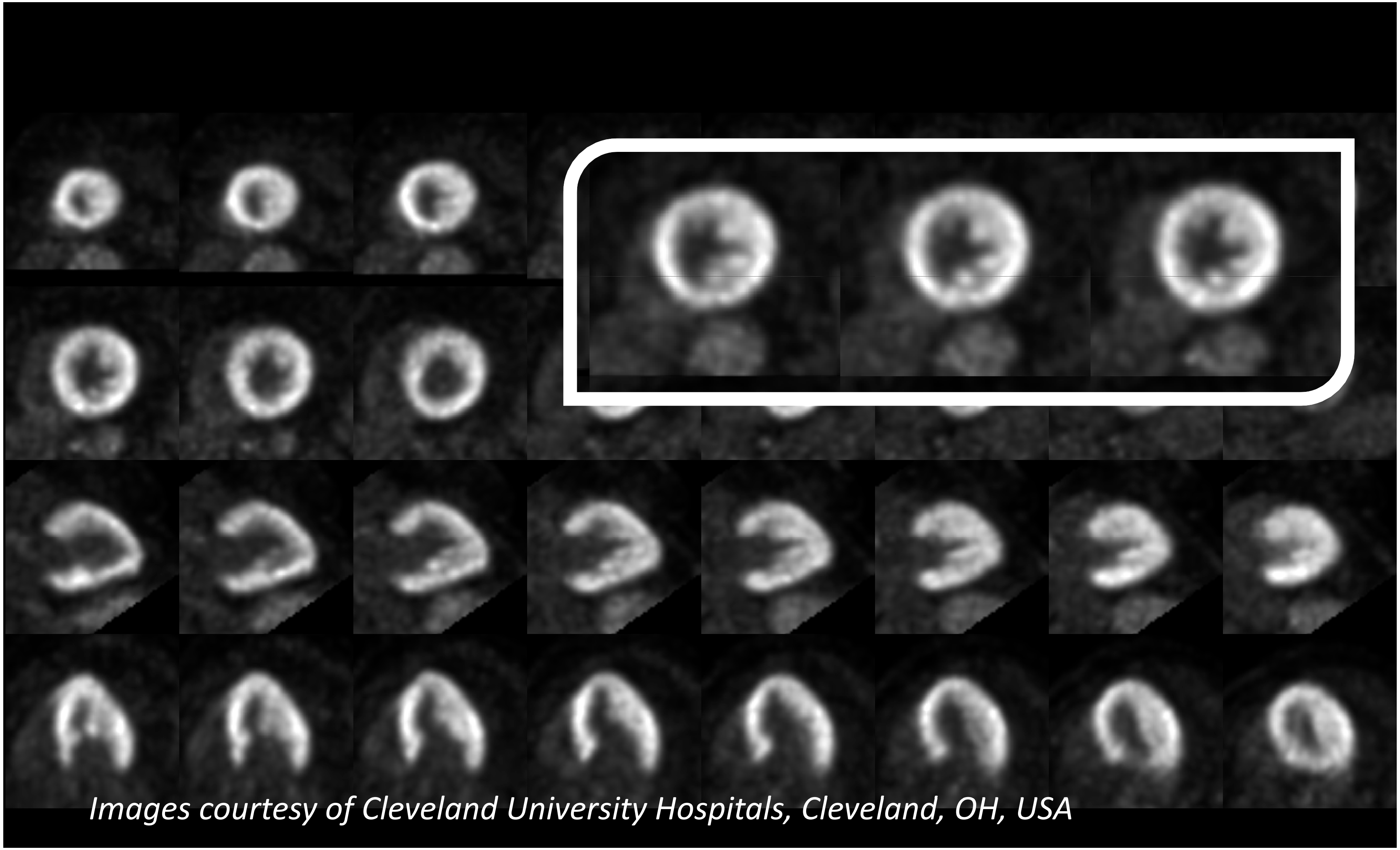


DPC

Images courtesy of Cleveland University Hospitals, Cleveland, OH, USA

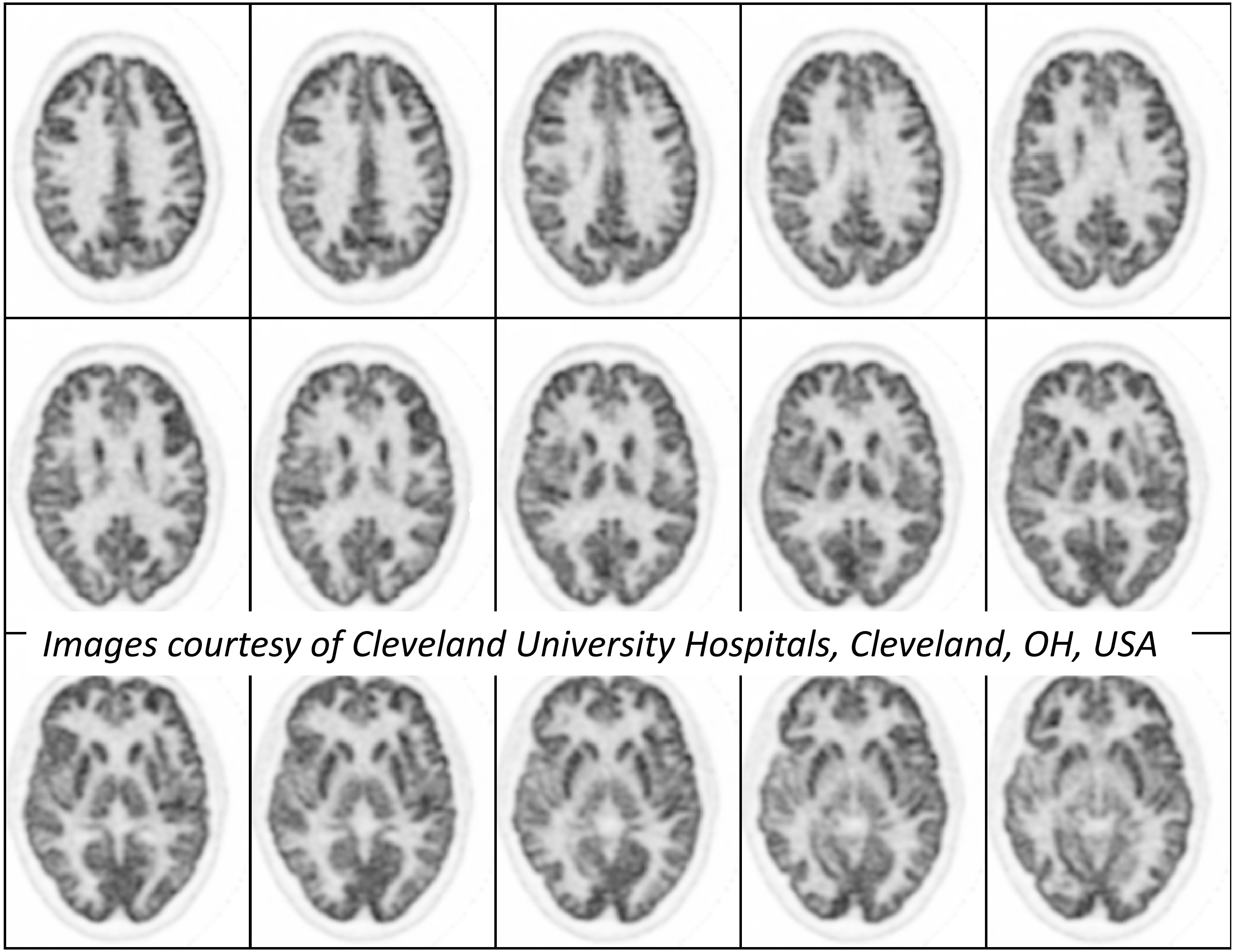
PHILIPS

Clinical PET with DPC: significantly improved IQ



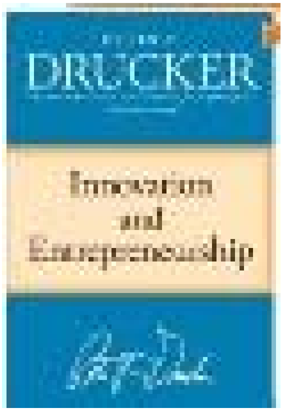
Images courtesy of Cleveland University Hospitals, Cleveland, OH, USA

Clinical PET with DPC: significantly improved IQ

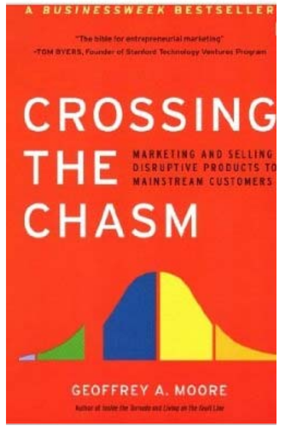


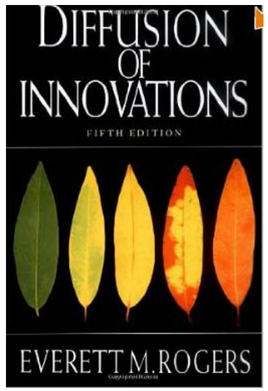
Images courtesy of Cleveland University Hospitals, Cleveland, OH, USA

Disruptive Technology: How to cross the chasm



- Understand your **PRODUCT CONCEPT**
- Make the disruptive technology **EXPERIENCABLE**
- Demonstrate **SCALABILITY**
- Demonstrate **IMPACT** on applications
- select your **TARGET MARKET(S)**





Peter F. Drucker: „Innovation and Entrepreneurship“ Harper Business; Reprint (2006)
ISBN-10: 0060851139

Geoffrey A. Moore: “Crossing the Chasm”, Harper Business; 2nd Edition (2006)
ISBN-10: 0060517123

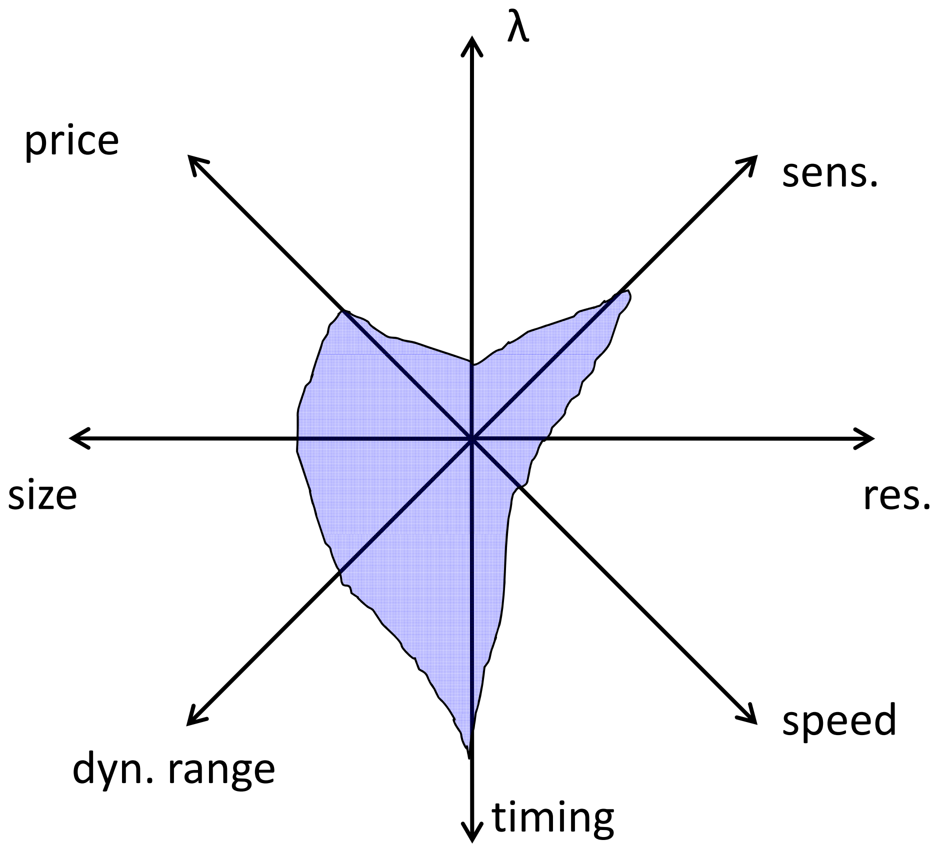
Everett M. Rogers: „Diffusion of Innovation“, Free Press; 5th Edition (2003)
ISBN-10: 0743222091

Outline

- DPC (dSiPM): a
- Motivation: Positron Emission Tomography
- Advantages of the digital concept
- DPC technology beyond the sensor
- First user experiences, first PET imaging results
- **Future Developments**

The future: What direction to go?

DPC: current parameters are optimized for TOF-PET



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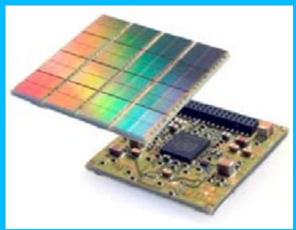
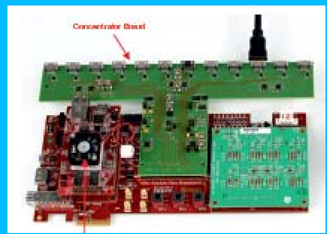
DPC: Directions/Areas of Development

Silicon/ Sensor



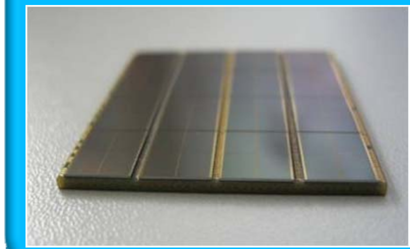
- Performance
  (timing, speed, granularity, PDE)
- MR compatibility
- Radiation hardness

Architecture/ Detectors



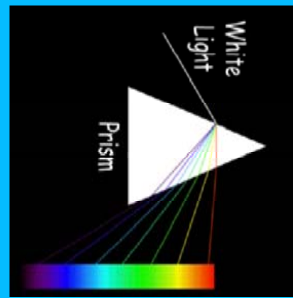
- 1x4 module
- MR compatibility
- Supermodule
- Coinc. board

Packaging



- TSV
- MR compatibility
- Shellcase
- Flexible geometries

Applications



- Spectrometry
- FLIM
- Material testing
- ....?

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Summary

- **DPC is a disruptive technology that will induce changes in applications.**
- **DPC development was triggered by ToF-PET and shows significant improvements for this application.**
- **DPC has shown superior performance and ease of use vs. analog SiPM technology (24 contributions at IEEE2013).**
- **DPC demonstrated scalability of technology in maintaining intrinsic performance in larger systems:**
  - ***PDPC PET test ring***
  - ***FARICH detector prototype***
  - ***many user PoC's***
- **As a CMOS based technology DPC needs volume to succeed, therefore a systems architecture concept was developed.**
- **New application areas for DPC are explored by adapted designs.**

Thank you very much for your attention!

Thanks also to:

PDPC:
Thomas Frach
Mezbah Shaber
Carsten Degenhardt
Louis Meesen
Ben Zwaans
Oliver Muelhens
Ralf Schulze
Sebastian Reinartz
Ralf Dorscheid
Rik de Gruyter
Shu Xu
Anja Schmitz

Philips Research/RWTH:
Andreia Trinidade
Pedro Rodrigues
Andreas Thon
Volkmar Schulz
Torsten Solf
Andre Salomon
Björn Weissler
Pierre Gebhardt
Jakob Wehner
David Schug

FZ Juelich:
Siegfried Jahnke
Gerhard Roeb
Simone Beer
Matthias Streun
Günther Kemmerling
Holger Nöldgen
Marco Dautzenberg

Boreskov Institute, Novosibirsk
A.F. Danilyuk

Budker Institute of Nuclear Physics, Novosibirsk
A.Yu.Barnyakov
M.Yu.Barnyakov
V.S.Bobrovnikov
A.R.Buzykaev
V.V.Gulevich
S.A.Kononov
E.A.Kravchenko
I.A.Kuyanov
A.P.Onuchin
I.V.Ovtin
A.A.Talyshev

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Thank you!

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