Fast Advanced Scintillator Timing

A COST ACTION (TD14101)

Joao Varela, LIP Lisbon

Prague, 8-10 June 2015

WORKSHOP ON PICOSECOND PHOTON SENSORS

Objectives of Action

FAST is a multidisciplinary network that brings together European experts from academia and industry to ultimately achieve scintillator-based detectors with excellent time precision.

- Establish the ultimate achievable limits for fast timing for scintillators, photodetectors, electronics
- Facilitate the increase of competitiveness of European industry; provide input for future market applications
- Provide training opportunities for a new generation of scientific experts to strengthen their background in the field of fast timing detectors

Added Value of this COST Action

- Enhanced synergies between partners through long term collaboration building

- Access to network of experts and knowledge

- Increased prospects for innovation in fast timing photodetection

- Opportunities for new European research projects

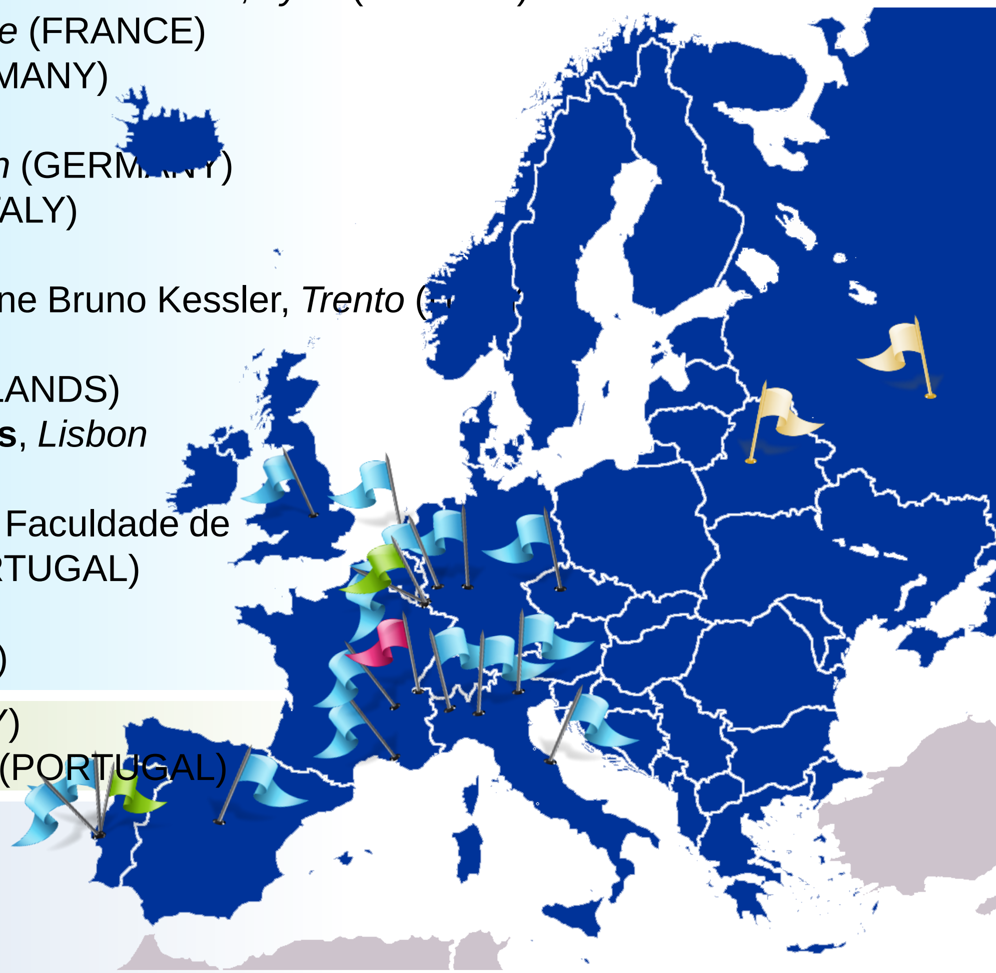
List of 18 Proponents

- **CERN**, *Geneva* (SWITZERLAND)

- **Institute of Physics**, Academy of Sciences of the Czech Republic, *Prague* (CZECH REPUBLIC)
- **Institut Lumière Matière**, University Claude Bernard and CNRS, *Lyon* (FRANCE)
- **Centre de Physiques des Particules** de *Marseille* (FRANCE)
- **Forschungszentrum Julich** GmbH, *Julich* (GERMANY)
- **Justus-Liebig-University**, *Giessen* (GERMANY)
- **Aachen University of Applied Sciences**, *Aachen* (GERMANY)
- **Università Politecnica delle Marche**, *Ancona* (ITALY)
- **University of Milano-Bicocca**, *Milano* (ITALY)
- **Center for Materials & Microsystems**, Fondazione Bruno Kessler, *Trento* (ITALY)
- **INFN** *Torino* (ITALY)
- **Delft University of Technology**, *Delft* (NETHERLANDS)
- **LIP Laboratory of Instrumentation and Particles**, *Lisbon* (PORTUGAL)
- **Instituto de Biofísica e Engenharia Biomédica**, Faculdade de Ciências da Universidade de Lisboa, *Lisbon* (PORTUGAL)
- **CIEMAT**, *Madrid* (SPAIN)
- **University College**, *London* (UNITED KINGDOM)

- **Philips Technologie GmbH**, *Aachen* (GERMANY)
- **PETsys medical PET imaging systems**, *Lisbon* (PORTUGAL)

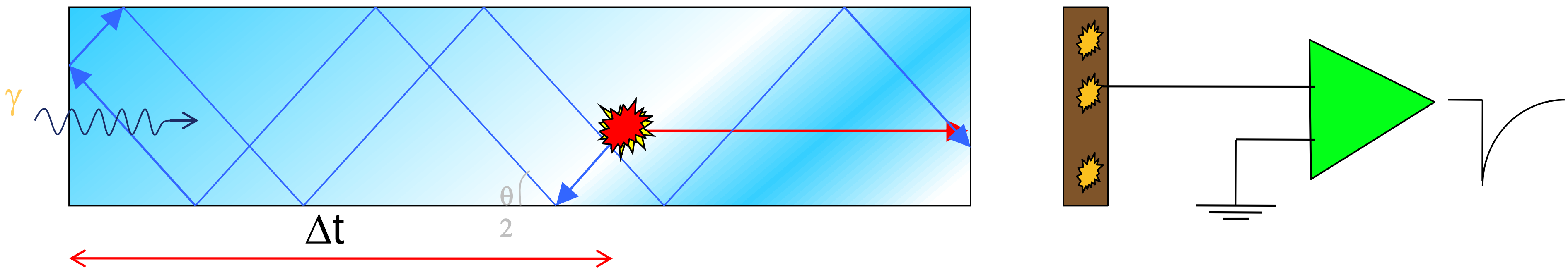
- **Research Institute for Nuclear Problems**, *Minsk* (BELARUS)
- **Lomonosov Moscow State University**, *Moscow* (RUSSIAN FEDERATION)



WG leaders

- **WG 1: Physics, Specifications & Coordination**:
  - WG Leader: Paul Lecoq
  - Deputy WG leader: Denis Schaart
- **WG 2**: **Scintillators**
  - WG Leader: Martin Nikl
  - Deputy WG leader: Christophe Dujardin
- **WG 3: Photodetectors**
  - WG Leader: Claudio Piemonte
  - Deputy WG leader: Eduardo Charbon
- **WG4: Electronics**
  - WG Leader: Joao Varela
  - Deputy WG leader: Christian Morel
- **WG5: Applications**
  - WG Leader: Pedro Almeida
  - Deputy WG leader: Stefaan Tavernier

Technological areas



$$t_{kth\ pe} = \Delta t + t_{k'\ ph} + t_{transit} + t_{SPTR} + t_{TDC}$$

Conversion depth | **Scintillation process** | **Transit time jitter** | **Single photon time spread** | **TDC conversion time**

WG 2

Scintillator R & D

- Particle Interaction
- Light generation
- Light transport
- Light transfer
- Light collection

WG 3

Photodetector R & D

- Reduce SPTR and DCR
- Increase fill factor (PDE)
- Digital SiPM
- MCP for PET & HEP

WG 4

Electronics R & D

- TDC < 10ps bins
- Monolithic architecture
- High bandwidth
- Low noise
- Massive parallel data
- High number of channels

WG-2 Scintillators

Objectives

Define and understand the key parameters to obtain the best timing properties:

a) Fundamental understanding of scintillation mechanism

b) Light production, light reabsorption, light transport and light collection

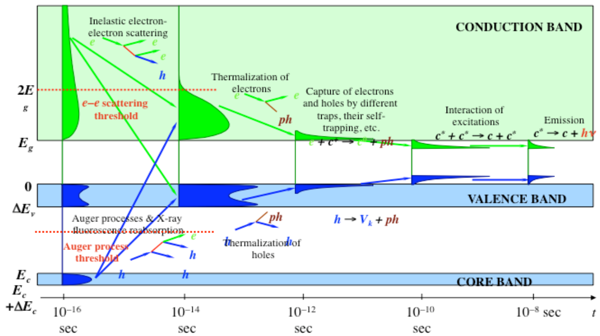
Study processes beyond the classical scintillation mechanism and useful for fast timing:

- Cherenkov radiation
- Intraband luminescence
- Absorption of free charge carriers
- Other processes occurring in the stage of hot carrier existence
- Quantum size effect in nanomorphological materials – quantum wells and dots

Factors influencing scintillator time resolution

The scintillator contributes to the time resolution through:

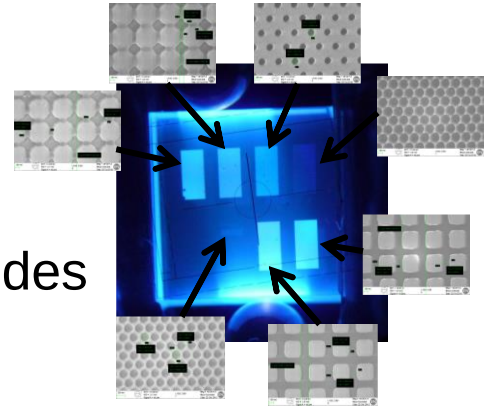
1. The scintillation mechanism
   - Light yield,
   - Rise time,
   - Decay time



A. Vasil'ev, SCINT2001 proceedings, NIMA 486 (2002) 367

2. The light transport in the crystal
   - Time spread related to different light propagation modes

3. The light extraction efficiency (LY➔LO)
   - Impact on photostatistics
   - Weights the distribution of light propagation modes



Types of emission in scintillating crystals

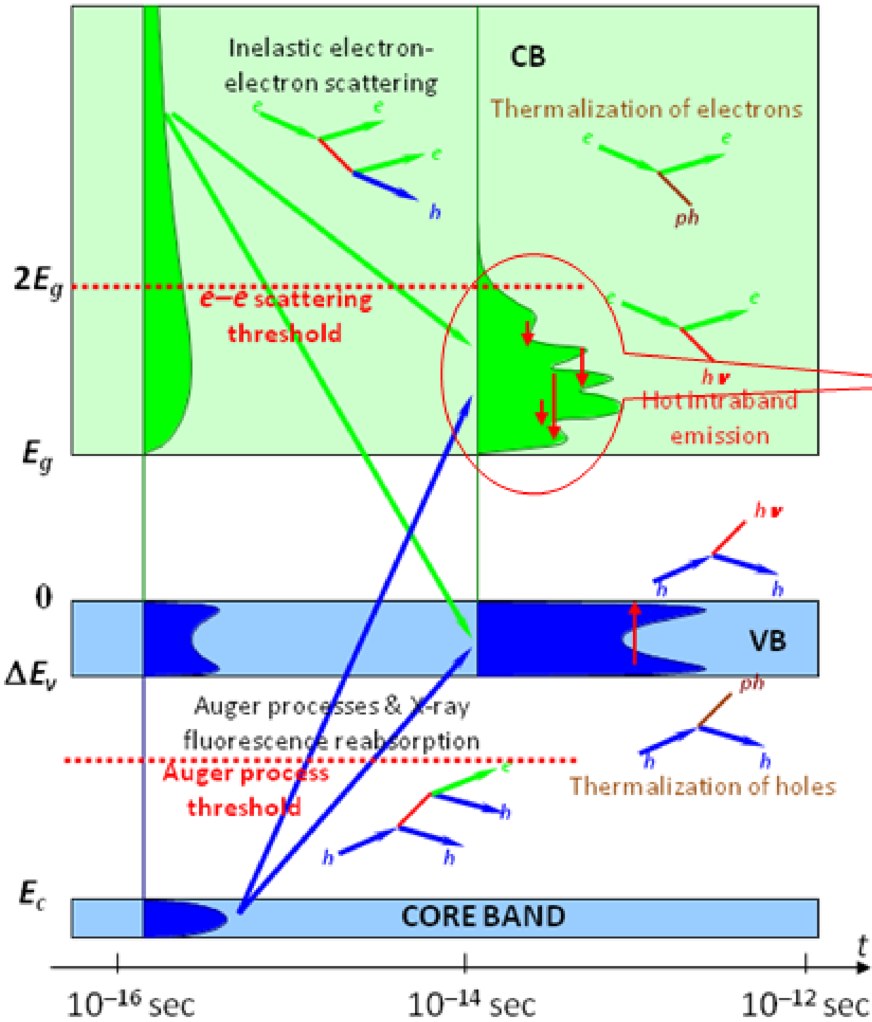
- Excitonic emission (STE, excitations of anion complexes)
- Emission of activators (Ce, Pr, …)
- Emission of quantum dots
- Crossluminescence
- Intraband hot luminescence
- Cherenkov radiation

Slow

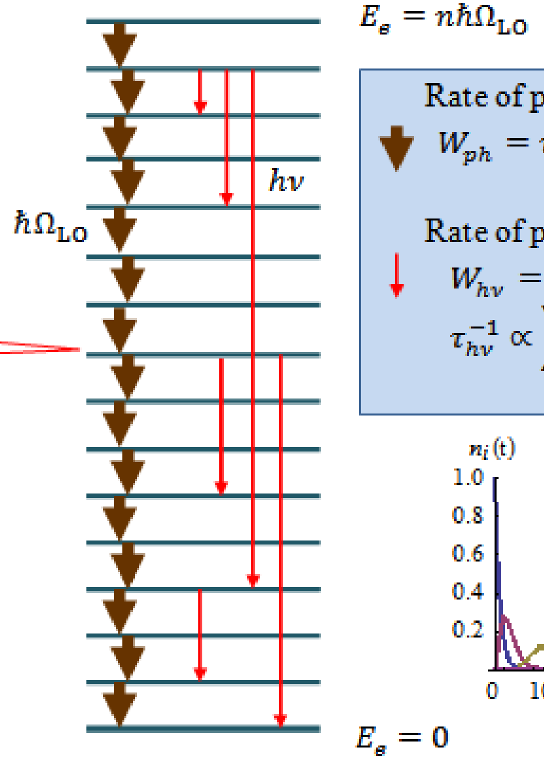
↓

Short

Scheme of intra-band luminescence



Simplified scheme of equidistant levels



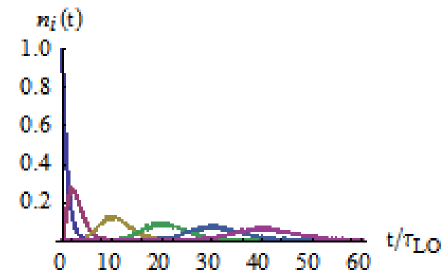
Rate of phonon emission

$W_{ph} = \tau_{LO}^{-1} = 10^{12} - 10^{14}\ \text{sec}^{-1}$

Rate of photon emission

$W_{h\nu} = \tau_{h\nu}^{-1} = 10^{9} - 10^{8}\ \text{sec}^{-1}$

$\tau_{h\nu}^{-1} \propto \sum_f (h\nu_{fi})^2 \left|\langle i|\hat{M}|f\rangle\right|^2$

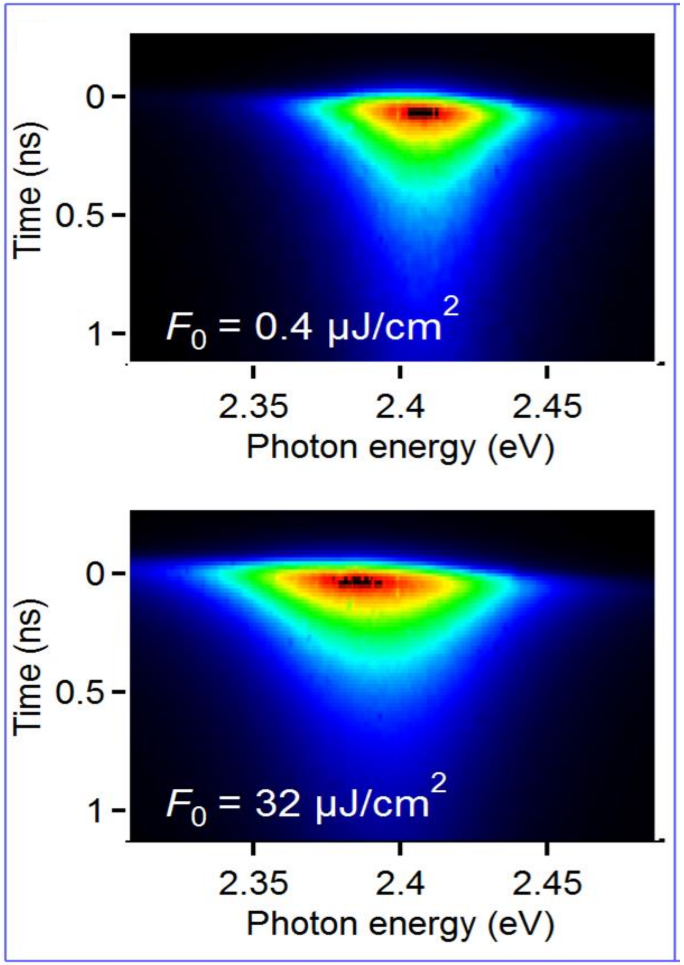


Intra-band luminescence duration is controlled by the fast phonon emission process, the yield is about $W_{h\nu}/W_{ph} \leq 10^{-4}$

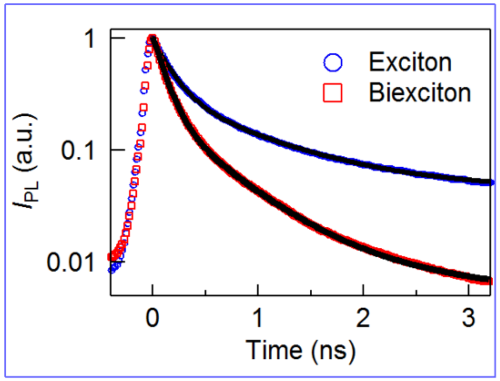
Spectral range from 0 to e-e scattering threshold (about E_g)

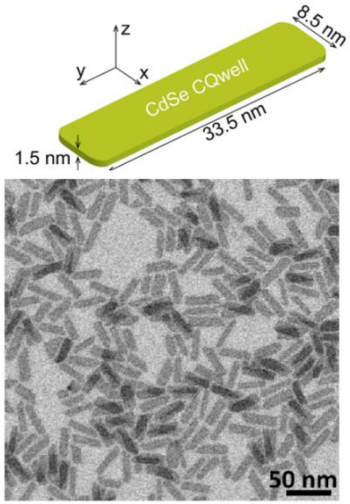
5

Properties of colloidal quantum wells



Exciton lifetime: **440 ps**
Biexciton lifetime: **125 ps**





- 1D Quantum confinement implies strict selection rules
- In-plane delocalization implies fast exciton recombination rate (giant oscillator strength transition).
- Strongly suppressed Auger recombination in 2D CQwells.

WG 3: photodetectors

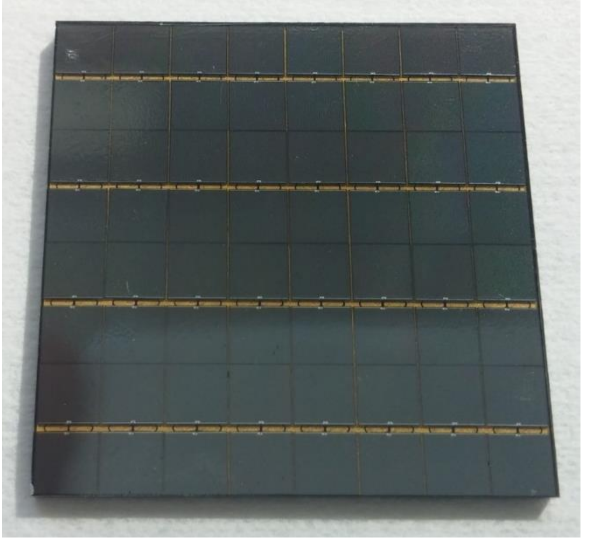
State-of-the-art

- **Scintillator-based detector**
  Depending on scintillator and geometry
  we get a coincidence time res.: 80-200ps FWHM.
  All three elements have to develop together to reach ~10ps so it is very important to have interdisciplinary network.

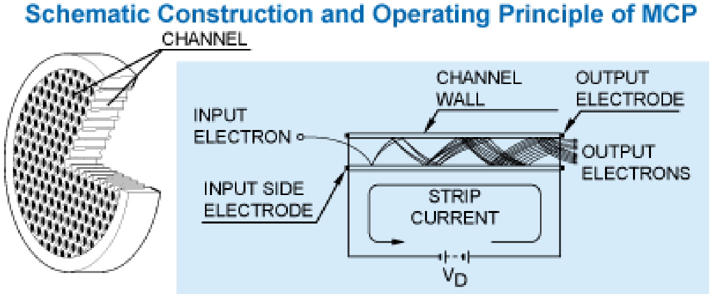
- **Scintillator-less detector**
  we already have ~10-20ps FWHM with SPAD/MCP at the single-photon level.

Competing technologies

PMT



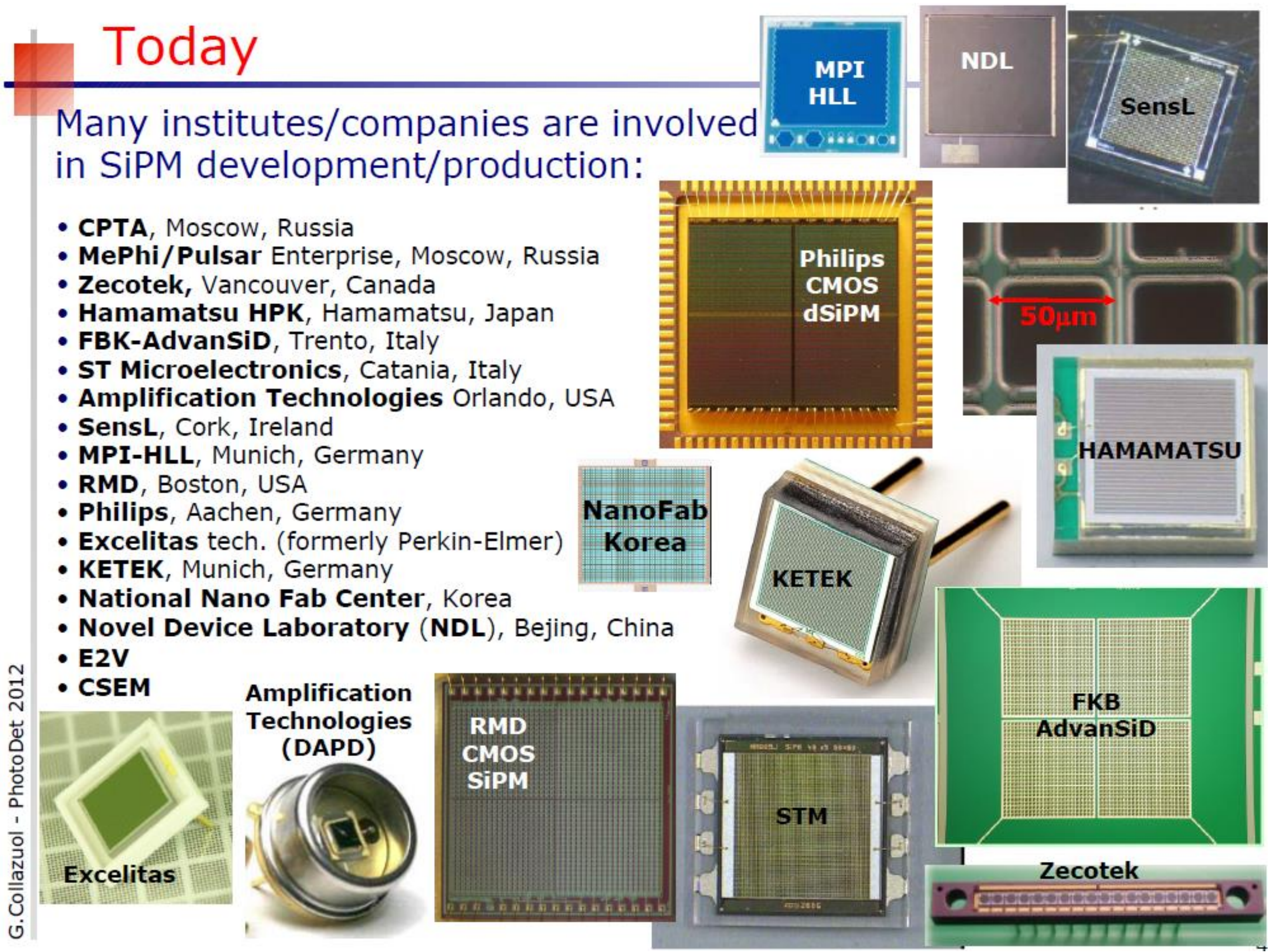
SiPM



MCP

Else?

SiPMs


Today
Many institutes/companies are involved in SiPM development/production:
• CPTA, Moscow, Russia
• MePhi/Pulsar Enterprise, Moscow, Russia
• Zecotek, Vancouver, Canada
• Hamamatsu HPK, Hamamatsu, Japan
• FBK-AdvanSiD, Trento, Italy
• ST Microelectronics, Catania, Italy
• Amplification Technologies Orlando, USA
• SensL, Cork, Ireland
• MPI-HLL, Munich, Germany
• RMD, Boston, USA
• Philips, Aachen, Germany
• Excelitas tech. (formerly Perkin-Elmer)
• KETEK, Munich, Germany
• National Nano Fab Center, Korea
• Novel Device Laboratory (NDL), Bejing, China
• E2V
• CSEM
MPI HLL
NDL
SensL
Philips CMOS dSiPM
50µm
HAMAMATSU
NanoFab Korea
KETEK
FKB AdvanSiD
Amplification Technologies (DAPD)
RMD CMOS SiPM
STM
Zecotek
Excelitas
G.Collazuol - PhotoDet 2012

State-of-the-art

	PMT*	SPAD	aSiPM	dSiPM	MCP
PDE	35% (blue)	70% (green)	~45% (blue)	~25% (blue)	35%
SPTR	200ps	20ps	200ps (3x3mm2)	180ps	20ps
Gain	1e8	1e6	1e6	-	1e6
DCR	<100 Hz/cm2	10Hz 100um	100 kHz/mm2	>1M Hz/mm2	<100 Hz/cm2
ENF	1.1	1.0x	1.1	?	1.05
Radiation hardness	Good	lower	lower	lower	Good
Reliability/Life	Good	Good	Good	Good	moderate
magnetic field tolerance	bad	Good	Good	Good	moderate
Temperature sensitivity	Good	Good	Good	Good	Good

Possible improvements for the next future

	PMT	SPAD	aSiPM	dSiPM *	MCP
PDE	**45%**	70/80%	**60-70%**		**45%**
SPTR	100ps	10ps	<200ps (?)		
Gain	1e6	1e6	1e6		
DCR	100Hz	100Hz	**~10kHz/mm^2**		
ENF	1.05	1.0x	1.1		1.05
Size					200x200mm^2

New approach:

3D integration :
SPAD/SiPM custom technology
+
high-end electronics

Scientific goals of WG3 in the FAST project

Understand where we are and where we can go with the different photodetector technologies.

Promote networking to foster the technological development.

WG 4: electronics

Motivations

The development of electronics with picosecond time resolution is challenging

- ASIC design
- system level.

Front-end systems with

- very large bandwidth
- very low noise
- very low-power

Various architecture options are being investigated:

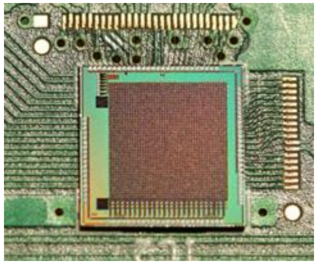
- low level discrimination and fast TDCs
- high frequency ADC sampling
- no solution will fit it all

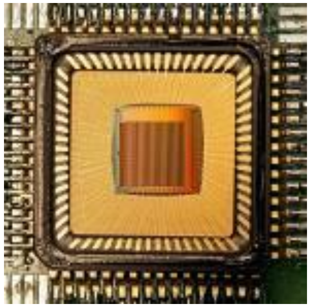
Creating the FAST electronics community

Wednesday, 15 April 2015

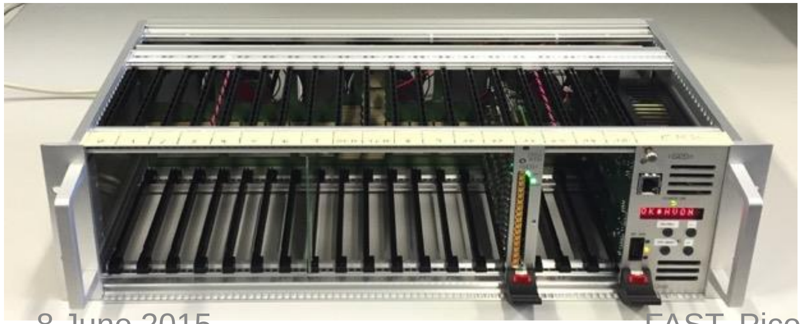
09:00 - 09:10	Introduction *10'* Speaker: Joao Varela (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part)
09:10 - 09:35	Developments at PSI *25'* *Developments at PSI* Speaker: Dr. Stefan Ritt (Paul Scherrer Institute)
09:35 - 10:00	3D Single Photon Modules for Fast Timing Detectors *25'* *Developments at University of Sherbrooke* Speaker: Jean-Francois Pratte (Universite de Sherbrooke)
10:00 - 10:25	Development at University of Barcelona *25'* Speaker: David Gascon (University of Barcelona (ES))
10:25 - 10:45	Coffee break
10:45 - 11:10	Developments at Omega and Weeroc *25'* *Developments at Omega and Weeroc* Speaker: Julien Fleury (CNRS/IN2P3)
11:10 - 11:35	Developments at University of Heidelberg *25'* Speaker: Wei Shen (Kirchhoff Institute for Physics)
11:35 - 12:00	Developments at LIP, Lisbon *25'* *Developments at LIP, Lisbon* Speaker: Joao Varela (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part)

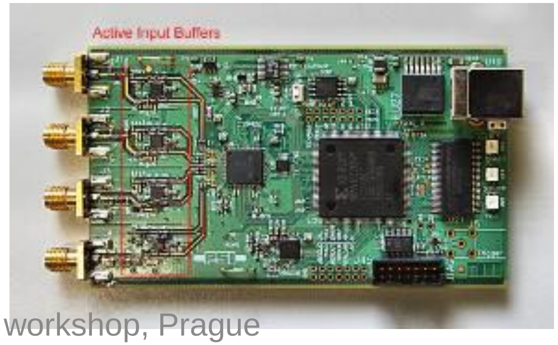
PSI - Villigen



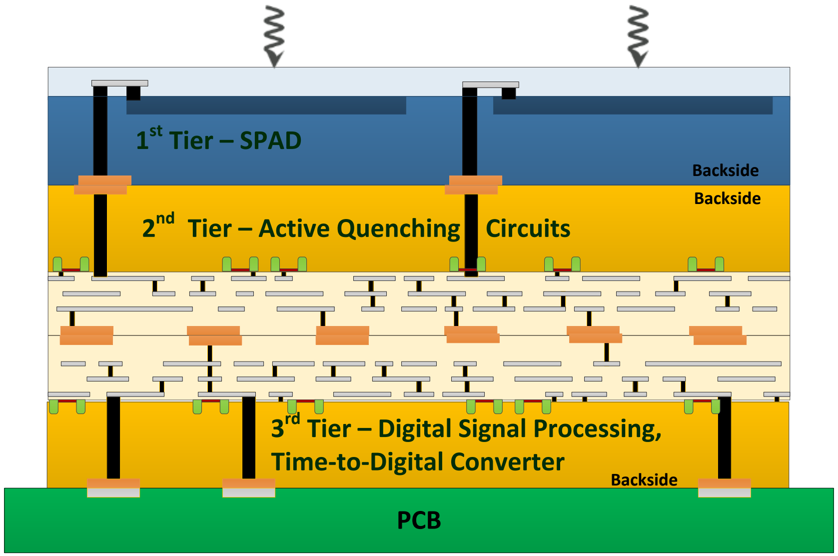


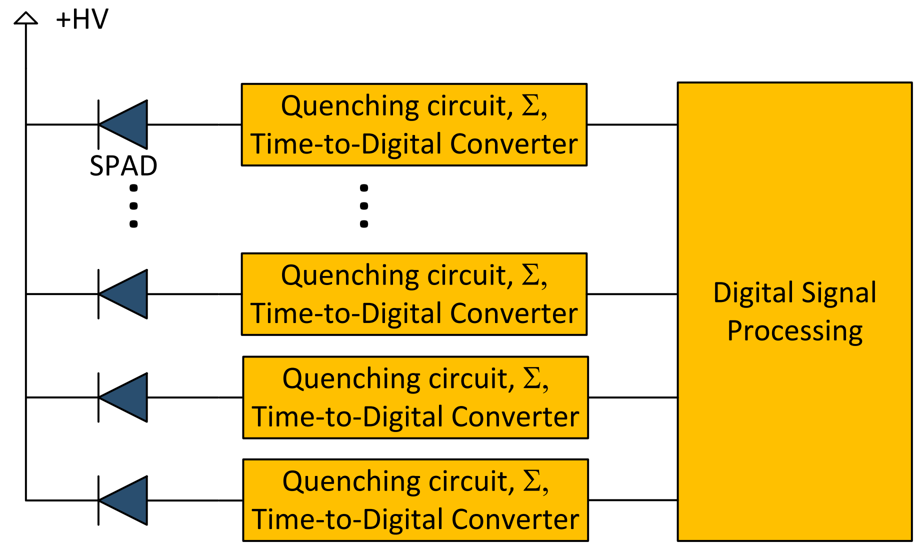
- DRS4 allows timing measurements < 1 ps
- New WaveDAQ systems with ~10'000 channels under construction at PSI
- DRS5 (~2017) will allow dead time less readout up to few MHz





Sherbrooke Univ



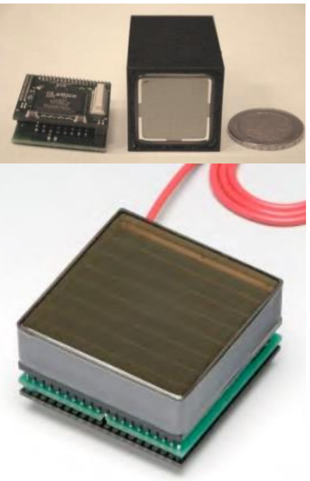


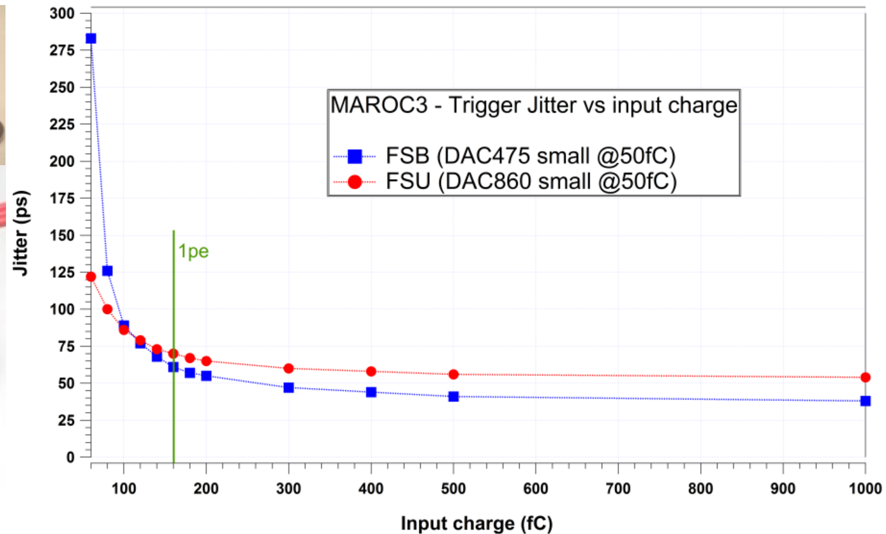
3D Single Photon Counting Modules

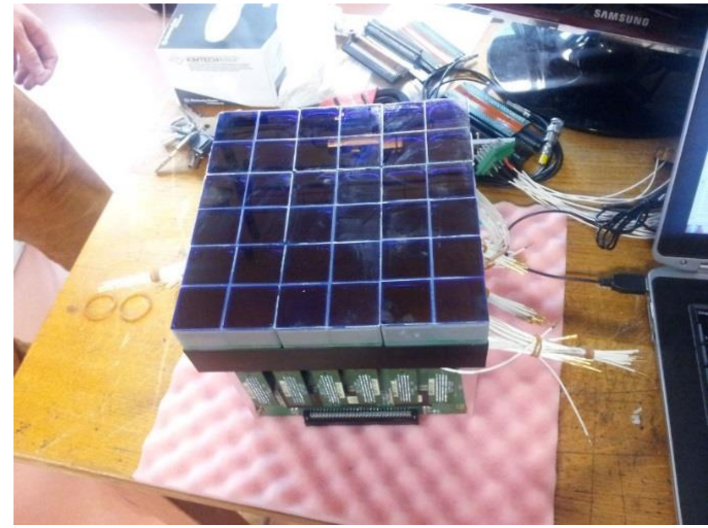
- TSMC 65 nm CMOS process
- 2 tiers only: Tier 1 - SPAD array, Tier 2 - CMOS readout
- 50 x 50 μm^2 pixel
- Quenching circuit with adjustable threshold = optimal jitter
- 1 TDC per pixel = **No more signal propagation skew (SPTR)**
- 5 ps Vernier ring TDC with digital Phase Lock Loop feedback

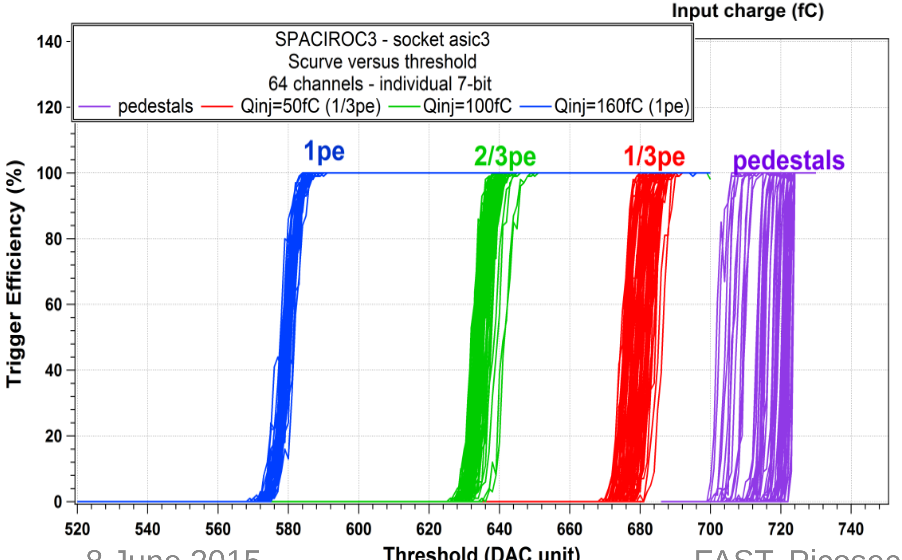
Omega and Weerock - Paris

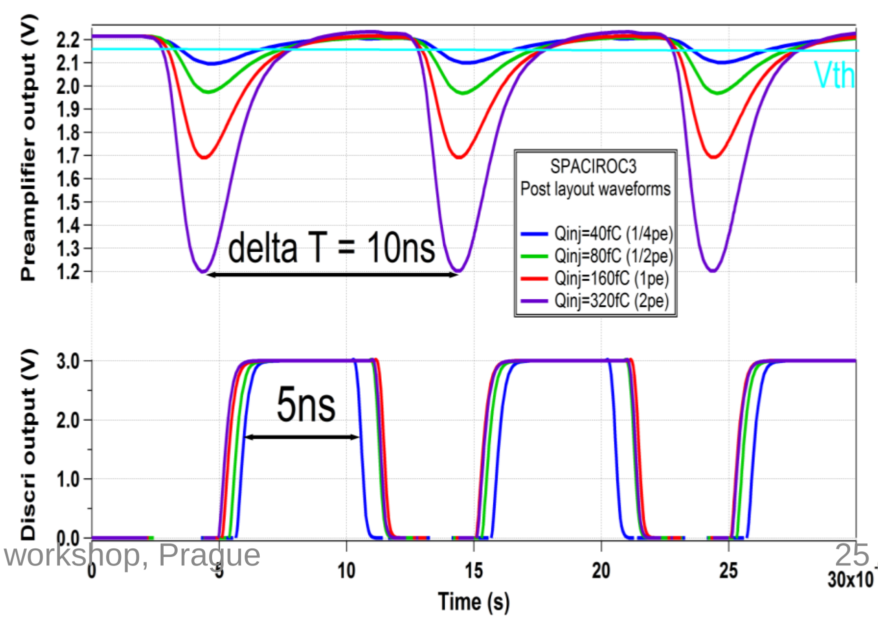
MAROC –SPACIROC -PARISROC







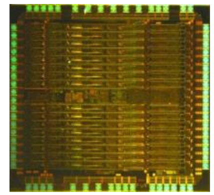


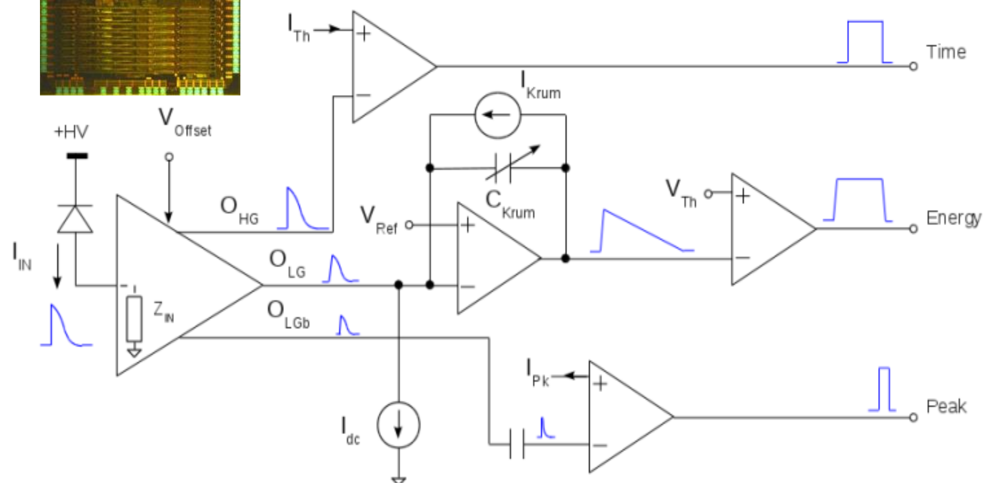


Barcelona Univ

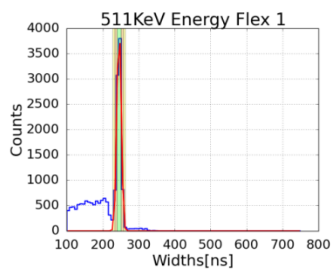
FlexToT ASIC

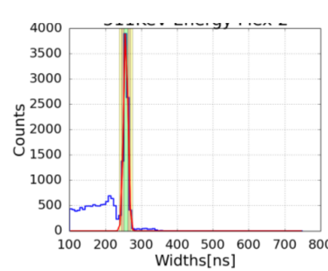
- A Flexible 16 Ch ASIC for SiPM RO (PET, SPECT, Compton)
  - Novel current mode input stage
  - Time resolution for ToF
  - Time over Threshold RO: No ADC
  - SiGe BiCMOS 0.35um
  - 10 mm2, 3.3 V (10 mW/ch)

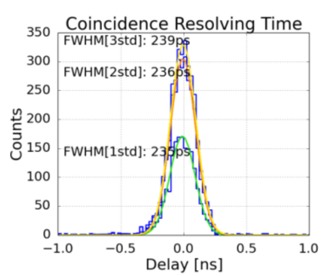


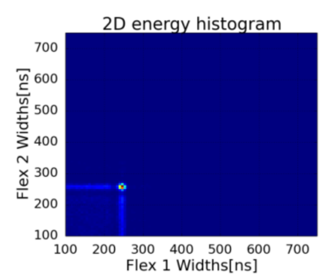


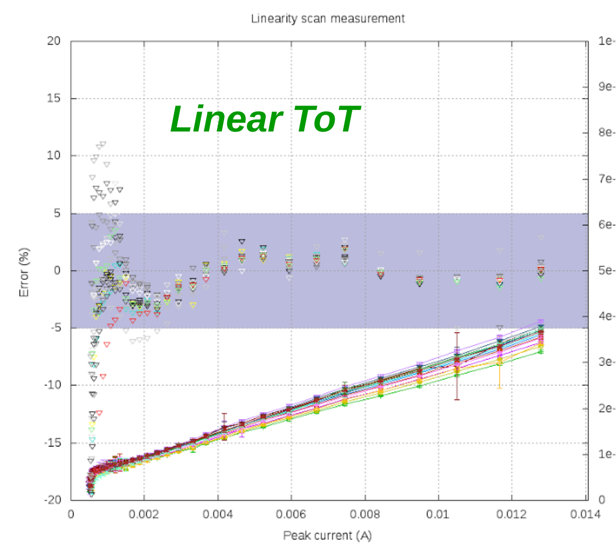
- **Linear ToT**
- **Energy resolution**
  - **@ 511 KeV < 8 %**
- **Time resolution:**
  - **SPTR < 120 (sigma)**
    - **50 um SiPM**
  - **CTR < 250 ps FWHM**
    - **LYSO 3x3x20 mm^3**
  - **Limited by set-up**
    - **Improvement 10-20 % expected**











Heidelberg Univ

STIC ASIC

- 64 channel SiPM readout designed and tested

  Timing based energy readout

  Mixed mode chip, with TDC and serial link
- Coincidence timing resolution < 220ps

  Energy Resolution ≤10%

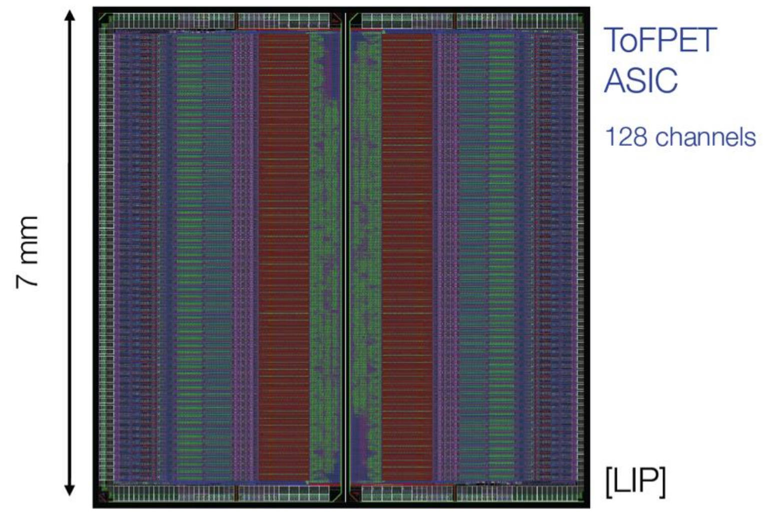
  LSO 3.1 * 3.1 * 15 mm^3 + MPPC s-10632
- Mass production steps established, CTR is good

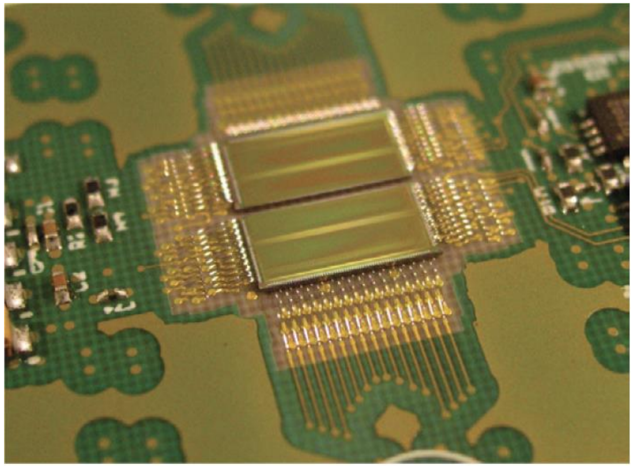
  system commissioning in progress

LIP and PETsys - Lisbon

TOFPET ASIC

- Developed in collaboration with Torino
- 128 channels in 7 x 7 mm^2
  - CMOS 130nm
- Frontend + TDC + Digital readout
- Optimum SNR performance for SiPM capacitance up to 350 pF
- Positive or negative signal polarity
- SNR (Qin = 200 fC): 25 dB
- Interpolation TDC
  - Time binning: 50 ps (option 25 ps)
- Optimized for low power
  - 8-11 mW channel
- Output data rate 640 Mb/s
- On-chip calibration circuitry





WG 5: applications

Possible applications of FAST detection chains:

- Medical Imaging
- Biological Imaging
- Security
- LiDAR applications
- Industrial non-destructive quality control
- High Energy Physics

- Medical Imaging/Diagnostics
  - TOF PET
- Biological Imaging
  - 3D imaging/Live imaging
  - Multi-thread flow cytometry
  - Time-gated optical tomography
  - High troughput microscopy

First meeting of the FAST network was last April (here in Prague…)

The network is opened to the participation of new groups

http://www.cost.eu/COST_Actions/TDP/Actions/TD1401

Contact: Etiennette.Auffray@cern.ch