Fast Advanced Scintillator Timing
COST ACTION TD1401

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CERN, Geneva, Switzerland
On behalf of FAST Action

EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

COST Actions

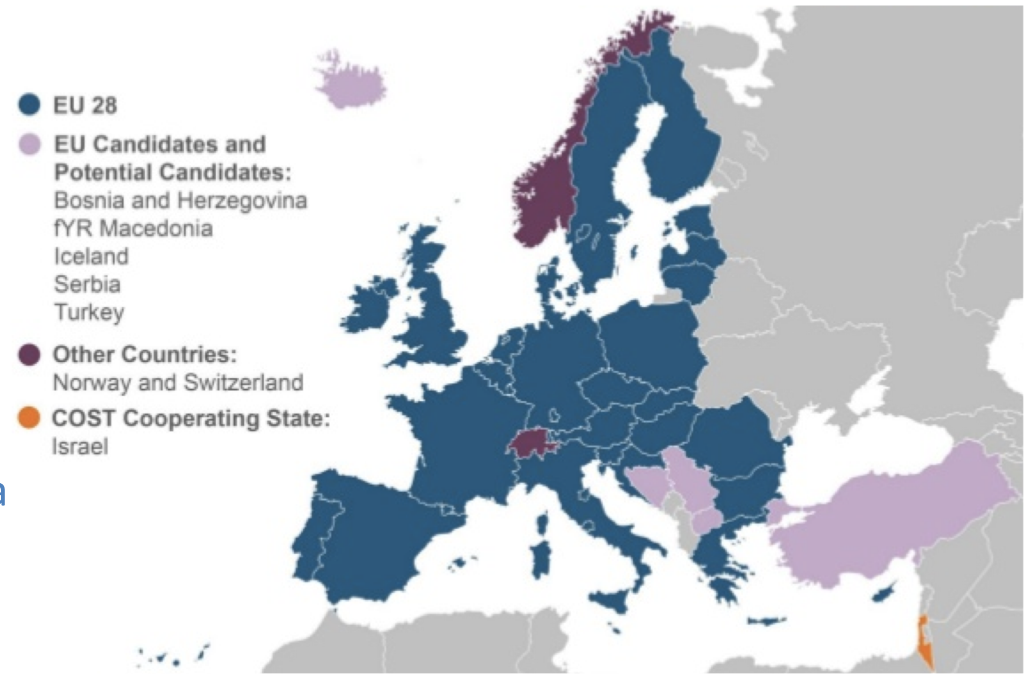
What is COST?

European international framework for Cooperation in Science & Technology (est. 1971)

Based on networks called COST Actions

Regular call: next one: 29/11/2018

36 Countries



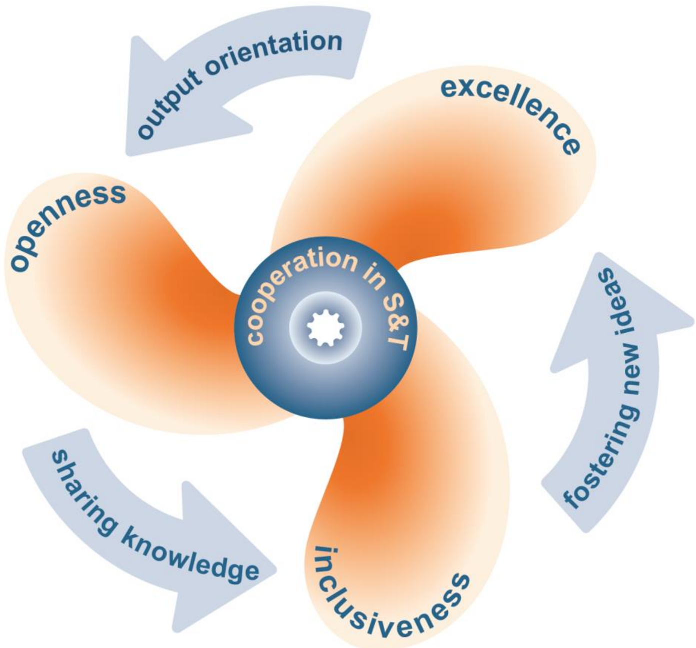
COST Objectives:

- Accelerate breakthrough scientific developments via collaboration
- Strengthen Europe's research and innova capacities
- Build capacity by connecting high-quality scientific networks
- Provide networking for Early Stage Researchers & monitor gender balance
- Address societal questions: connect policy makers, regulatory bodies and decision

COST is supported by the EU RTD Framework Programme

ESF provides the COST Office through a European Commission contract

COST Key Features for H2020



COST Key Principles

- Supporting excellence
- Being open
- Being inclusive

COST Driving Forces

- Fostering new ideas
- Sharing knowledge
- Output orientation

Courtesy COST office

Objectives of the FAST Action
COST Action TD1401

FAST Action is a multidisciplinary network that brings together European experts from academia and industry to ultimately achieve scintillator-based detectors with timing precision of better than 100ps, in particular to enable significant breakthroughs in diagnostic medicine and high luminosity particle physics..

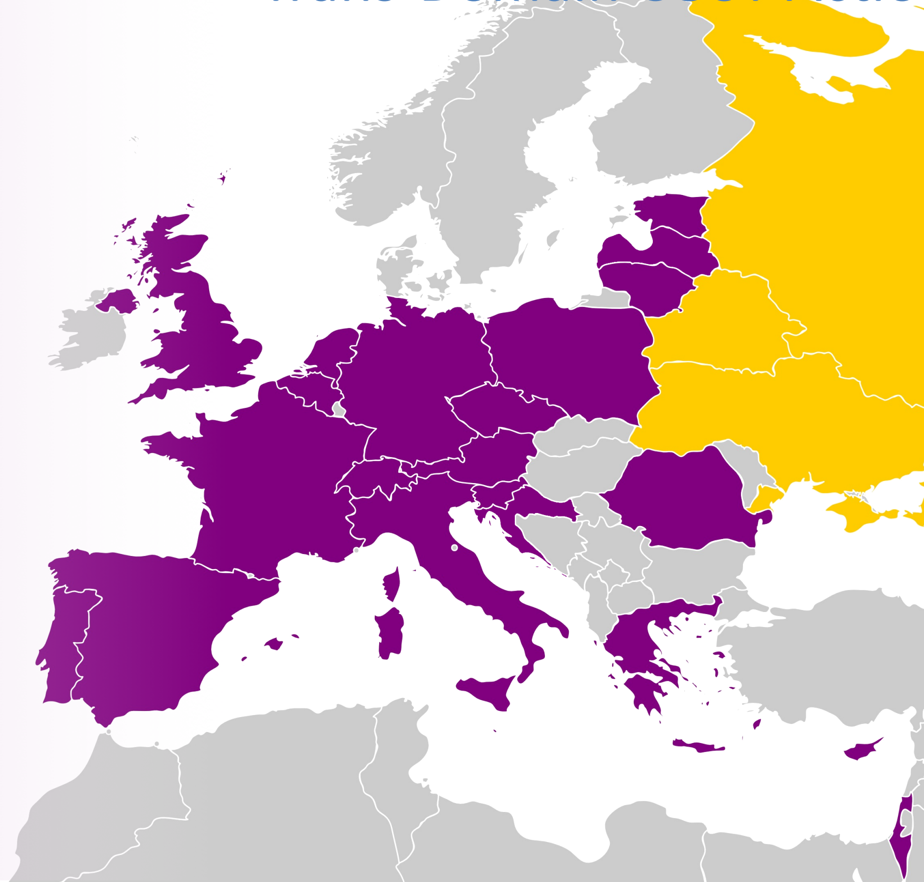
- Establish the ultimate achievable limits for fast timing for scintillators, photodetectors, electronics
- Facilitate the increase of competitiveness of European industry;
  provide input for future market applications
- Provide training opportunities for a new generation of scientific experts to strengthen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

Website: http://fast-cost.web.cern.ch/fast-cost/

FAST Participant countries
(21 COST and 4 Near Neighbours countries)

COST countries
- Austria
- Belgium
- Croatia
- Cyprus
- Czech Republic
- Estonia
- France
- Germany
- Greece
- Israel
- Italy
- Latvia
- Lithuania
- Netherlands
- Poland
- Portugal
- Romania
- Slovenia
- Spain
- Switzerland
- United Kingdom

Trans-Domain COST Action

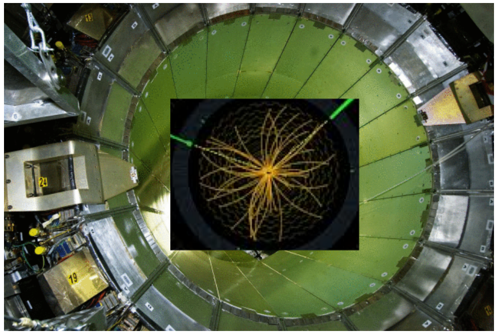


COST Near Neighbour Countries
- Armenia (1 institute)
- Belarus (1 institute)
- Ukraine (1 institute)
- Russian Federation (5 institutes)

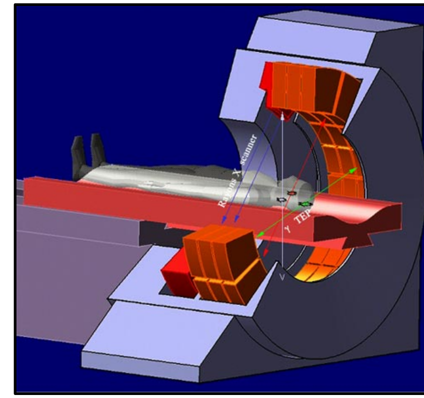
59 institutes/industries participating

November 2014 – November 2018

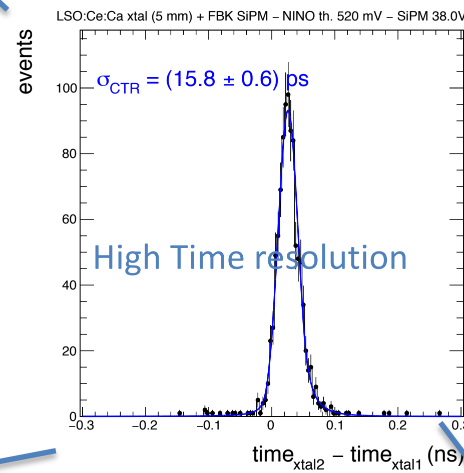
Potential Beneficiaries from FAST Advanced Scintillator Timing



Fundamental science

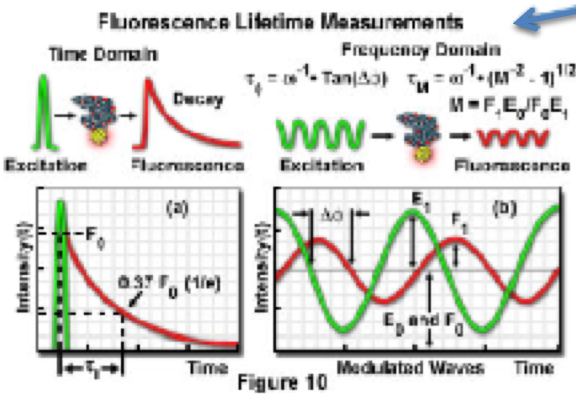


Medical Imaging

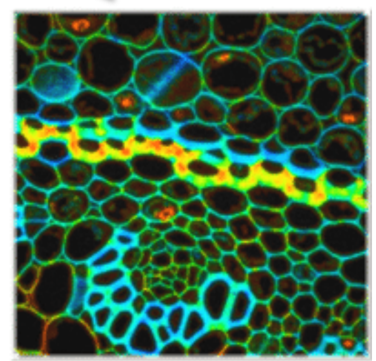


High Time resolution

Quantum Cryptography

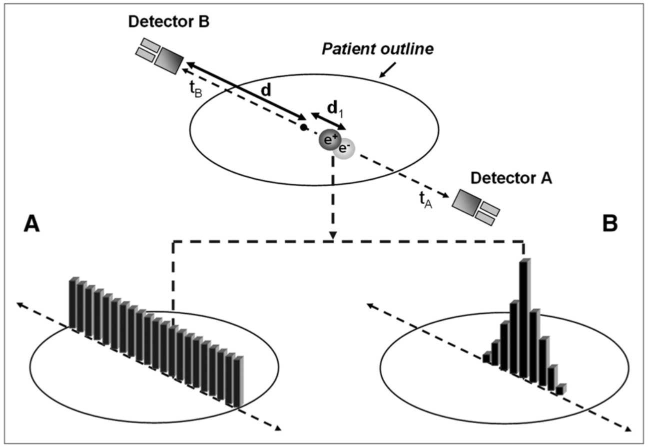


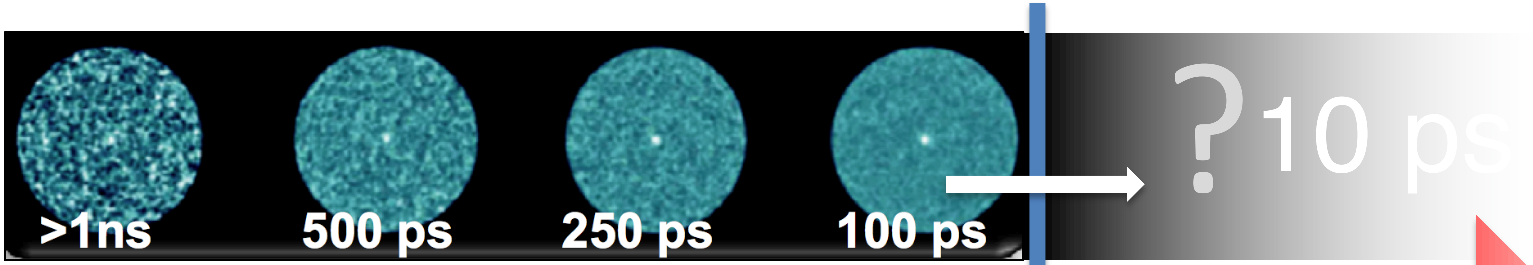
FLIM: Fluorescence Lifetime Imaging Microscopy
FRET: Forster Resonance Energy Transfer



Why FAST is important in PET imaging?

- In vivo: More precise, less invasive, more compact systems
- In vitro: Faster analysis of disease biomarkers
- Ultimatelly: Pave the way into precision medicine





Commercial systems

Effective event collimation
→ Background rejection
→ cm resolution along LOR (EndoTOFPET-US)

Five-fold S/N improvem.
→ Sensitivity gain of 25
→ Dose reduction

Direct 3D image reconstruction with:
→ mm resolution along LOR, and
→ Allow limited field of view

Commercial TOFPET today
550ps (250ps)

Lab today
100-200ps

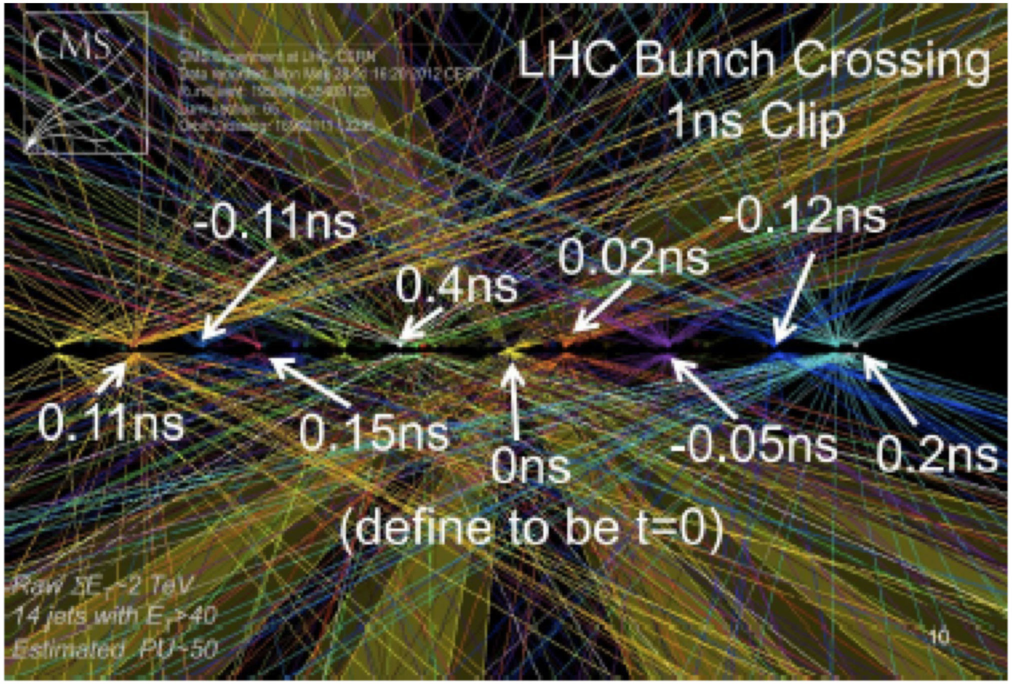
Why FAST is important in HEP

Search for rare events implies high luminosity accelerators

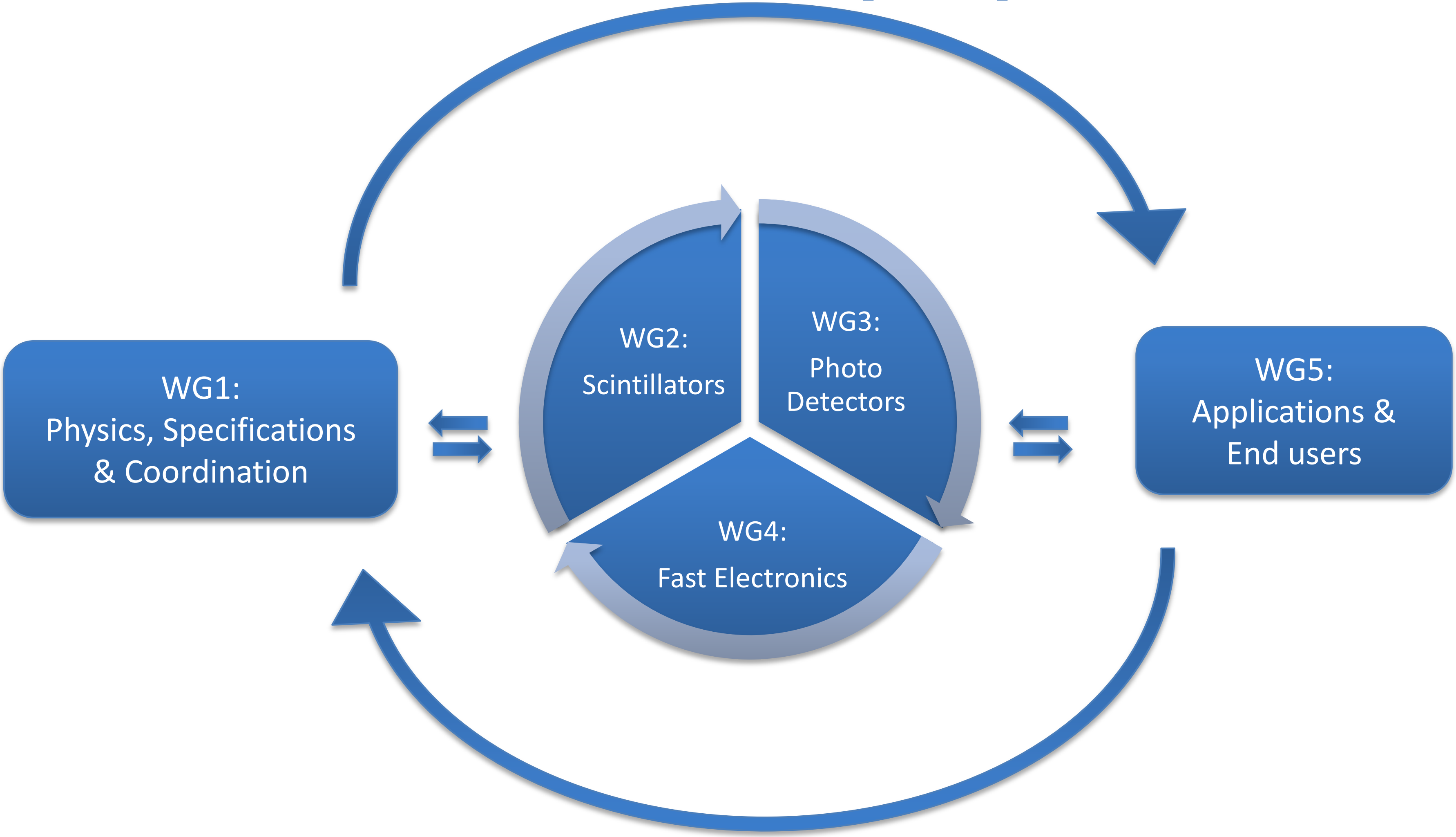
→ Rate problems;

→ Pileup of >140 collision events per bunch crossing at *High Luminosity-LHC;*

→ Pileup mitigation via TOF requires TOF resolution < 50ps.



Organization in 5 Working Groups (WG)



Exchanges through meetings, short serm scientific missions, workshops, projects

Organization in 5 Working Groups (WG)

Chair: Etiennette Auffray (CERN); Vice Chair: Marco Paganoni

WG 1: Physics, Specifications & Supervision

Leader: Paul Lecoq; Deputy: Dennis Schaart

WG 2: Scintillators

Leader: Martin Nikl; Deputy: Christophe Dujardin

WG 3: Photodetectors

Leader: Claudio Piemonte; Deputy: Eduardo Charbon

WG 4: Electronics

Leader: Joao Varela; Deputy: Christian Morel

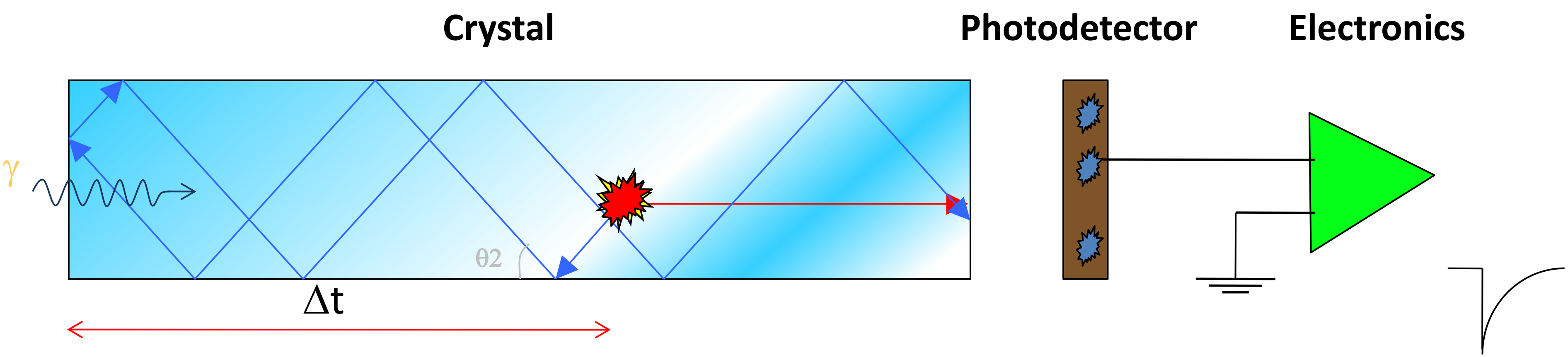
WG 5: Applications

Leader: Pedro Almeida; Deputy: Stefaan Tavernier

WG1: Physics, Specifications & Supervision

Objectives:

- Detector chain modelling and optimization
- Design the roadmap for coincidence timing resolution towards 10ps
- Interact with each working group (WG) and follow up progress



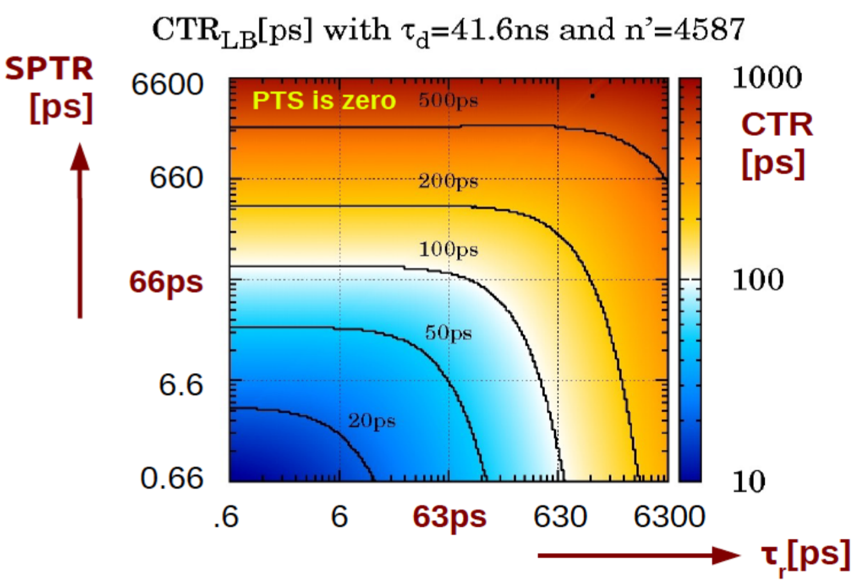
$t_{kth\ pe} = \Delta t + t_{k'\ ph} + t_{transit} + t_{SPTR} + t_{TDC}$

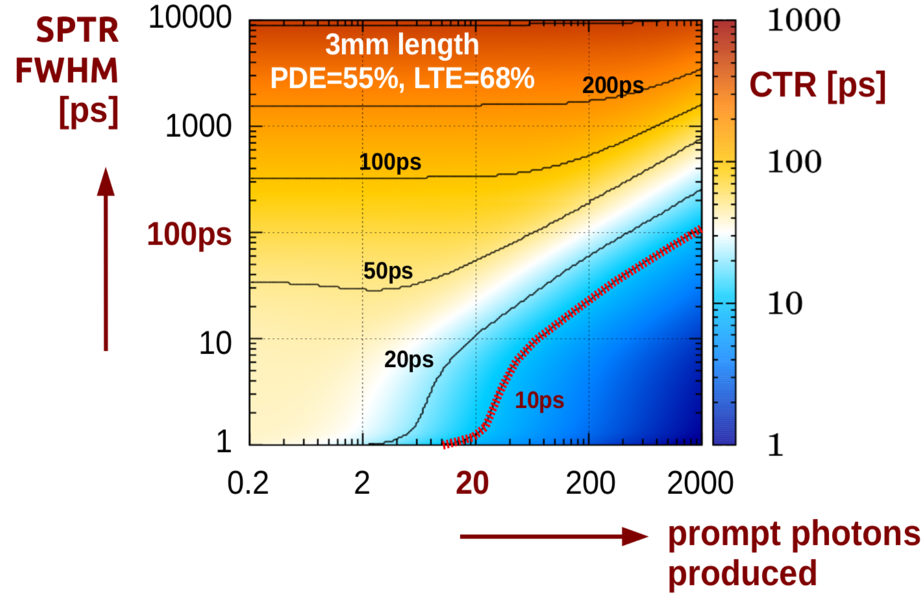
Conversion depth	Scintillation process	Transit time spread	Single photon time spread	TDC conversion time

Understand key limiting factors of timing resolution & Propose routes towards 10ps

Time resolution limit

Simulation of all detection chain





=> Need good timing properties both for scintillator and photodetector

S. Gundacker, PhD thesis
S. Gundacker et al, Phys. Med. Biol. 61 (2016) 2802-2837
S. Gundacker et al., JINST 11P08008

WG2:Scintillators

Objectives

- Define & understand key parameters for scintillators with best timing
- How fast inorganic and semiconductor scintillators can be?
- Develop ideas/exploit properties of materials for better possible timing resolution
- What light producing modes prior to standard light generation exist?

Key parameter for scintillator's time resolution:

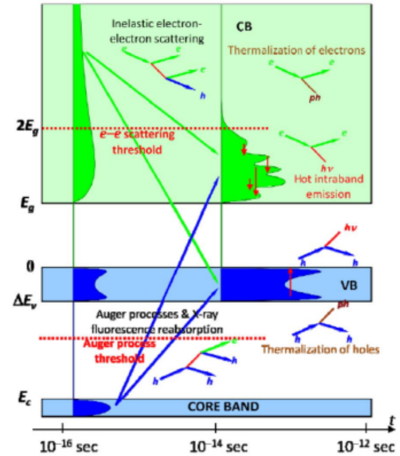
1. Scintillation mechanism
2. Light transport in crystal
3. Light extraction efficiency

WG2:Scintillators

- **Study of emission types:**
  - Excitonic emission (STE, excitations of anion complexes)
  - Emission of activators (Ce, Pr, ...)
  - **Crossluminescence**
  - **Quantum confinement driven luminescence**
  - **Hot intraband luminescence (HIL)**
  - **Cherenkov radiation**

Slow → Ultra fast

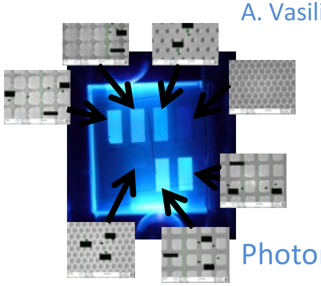
HIB mechanisms



A. Vasiliev

- **Study of Light transport and collection**
  - R&D on innovative ways to transport the light
  - R&D on increase light collection

    surface treatment, photonic crystals, light guide



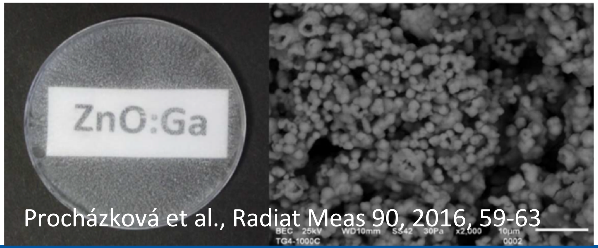
Photonic crystals

⇒ Multifunctional metamaterial concept for fast timing

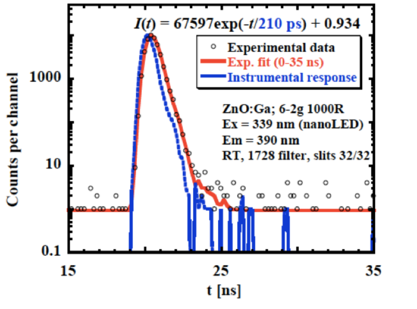
Exploit prompt photon

Eg Combined bulk material with nanomaterial

ZnO:Ga nanopowders embedded in a thin layer of SiO_2



Procházková et al., Radiat Meas 90, 2016, 59-63



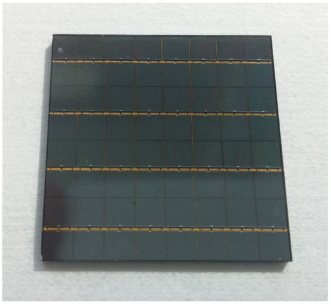
WG3: Photodetectors

Objectives

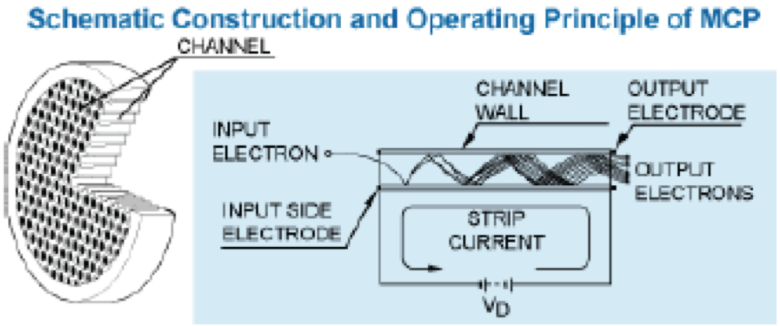
- Define key parameters for best timing performance
- Investigate the timing of different detector technologies
- Cooperate with industry to reassure feasibility of ideas

Competing technologies

PMT



SiPM



MCP

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

State of the art

	PMT	SPAD	aSiPM	dSiPM	MCP
Cost of device/area	depends	Low	Low	Low	expensive (custom)
Market	stable, large systems, low noise applications	small	Increasing, various types of systems, custom applications	Increasing, miniaturized systems, PET, imaging	physics experiments, military
Competition	mainly not	Y	Y	Y – different markets	Y

Improvement for next future

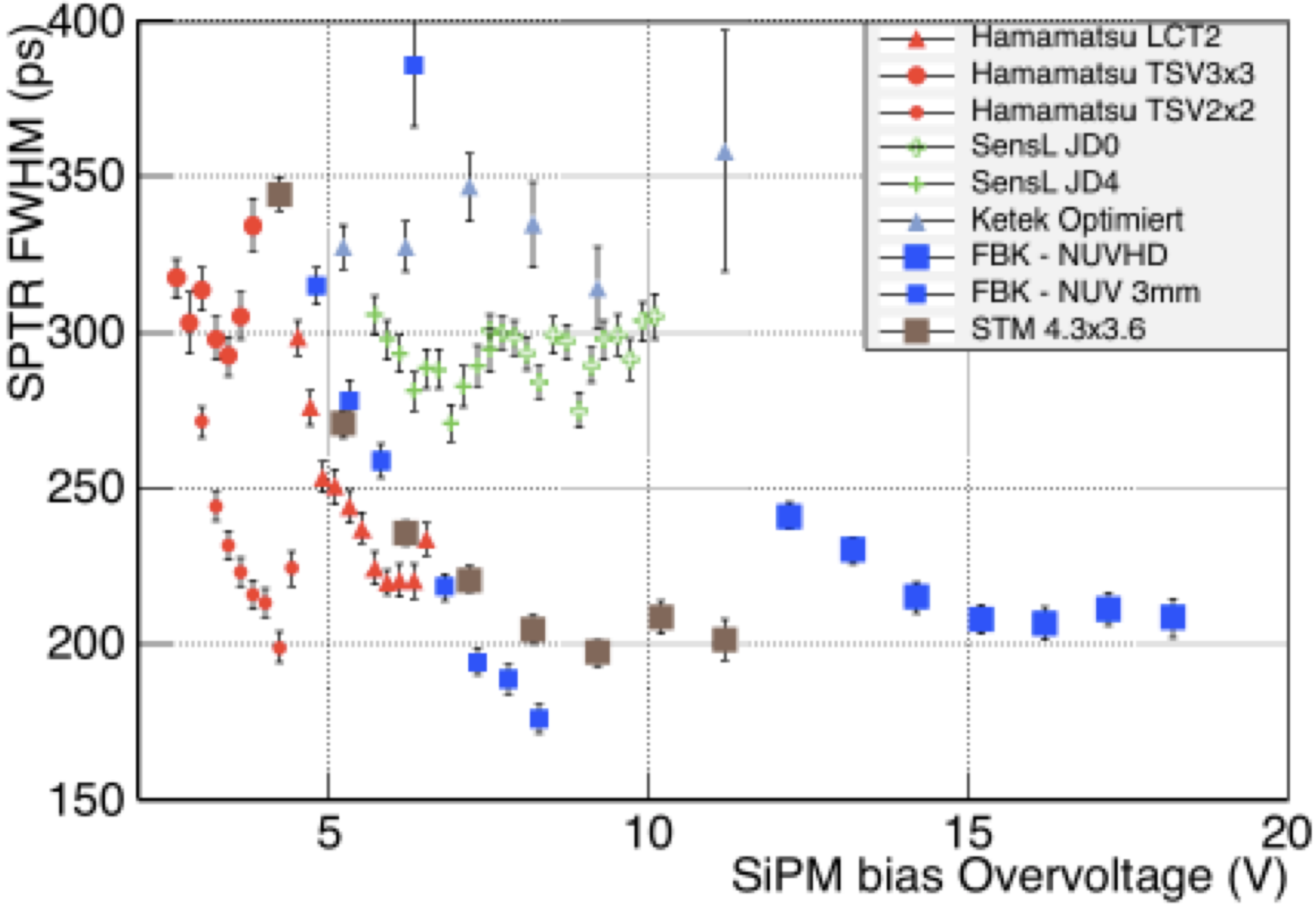
	PMT	SPAD	aSiPM	dSiPM *	MCP
PDE	**45%**	70/80%	**70%**		**45%**
SPTR	100ps	10ps	<100ps (?)		
Gain	1e6	1e6	1e6		
DCR	100Hz	100Hz	**~10kHz/mm2**		
ENF	1.05	1.0x	1.1		1.05
Size					$200x200mm^2$

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

* depending on market and Si foundry involvement

SiPM SPTR investigation

SPTR for various types of SIPM

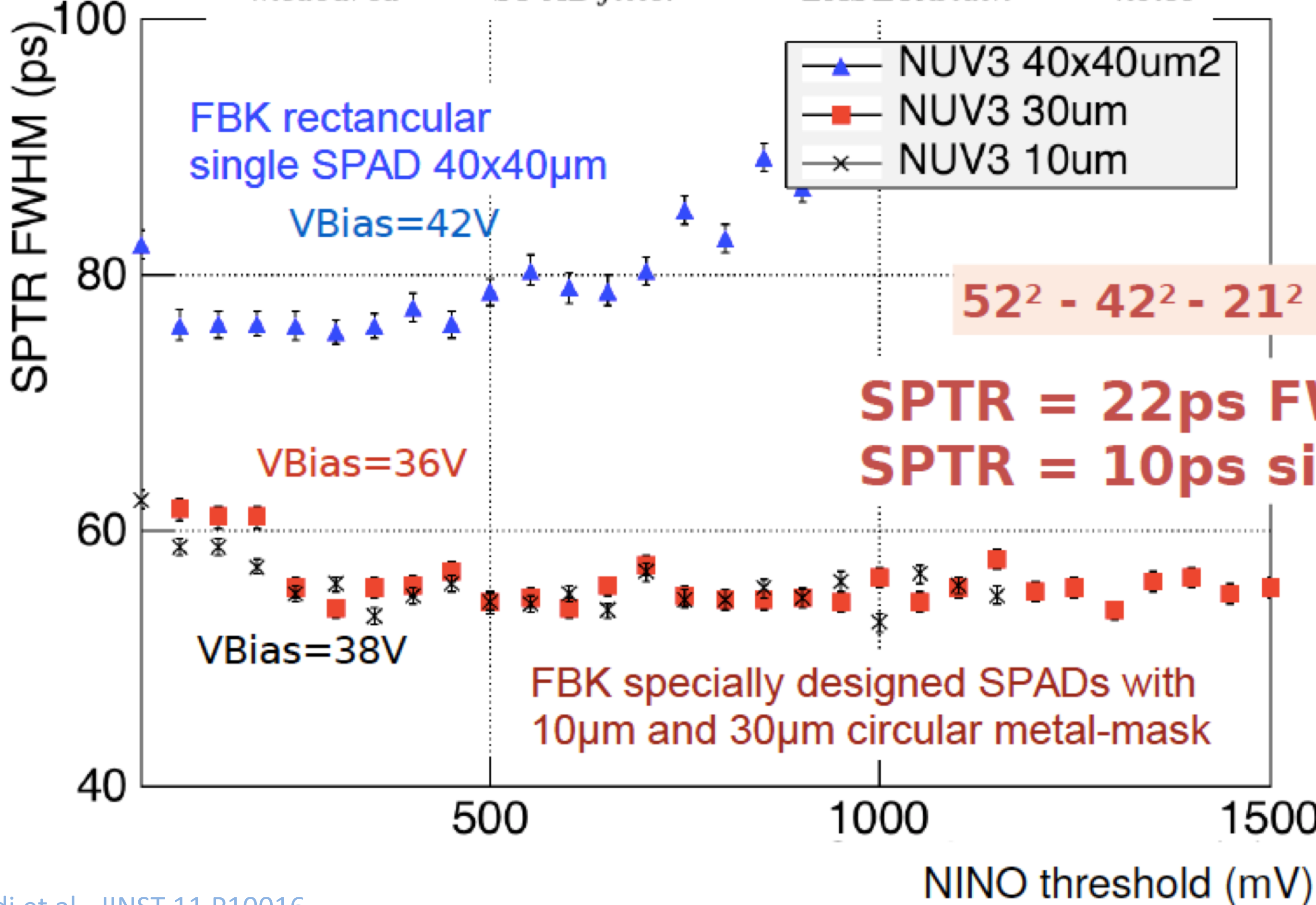


M. V: Nemallapudi et al., JINST 11 P10016

Improvement of SPAD SPTR

Single photon level at optimum bias voltage

$$\sigma^2_{measured} = \sigma^2_{SPADjitter} + \sigma^2_{LASERwidth} + \sigma^2_{noise}$$



$52^2 - 42^2 - 21^2 = 22^2$

SPTR = 22ps FWHM
SPTR = 10ps sigma

M. V: Nemallapudi et al., JINST 11 P10016

Next Step:

Standardization of SiPM characterization:

- Comparison of SiPM measurements done in different groups
- Understanding the difference between the measurements

=> Establish a set of measurement procedures

WG4: Electronics

Objectives

- Define Key parameters required for time precision
- Design novel ASICs based on proposed specifications of the action
- Coordinate a joint characterisation of prototype devices

WG4: Electronics

Development of electronics with ps 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 and used

- single level discrimination and fast TDCs
- constant fraction discrimination
- high frequency sampling (GHz)

WG4: Electronics

Several ASICs for SIPM are now available:

- analog: amplifiers, amplifier+discriminators
  NINO, FlexTOT, FastIC
- analog-digital: amplifier, discriminators, ADC, TDC
  PETA, PETIROC, STIC, TOFPET1, TOFPET2,

Similar results obtained for SPTR and CTR (FWHM)

SPTR for small SiPMs(1x1 mm2): 100 ps
SPTR for large SiPMs(3x3 mm2): 200 ps
CTR for small crystals (2x2x3 mm) around 100 ps
CTR for large (realistic) crystals (2x2x20 mm) around 200 ps

WG5: applications

Objectives

- Identify target applications
- Discuss & evaluate requirements of end users with respect to timing

Possible applications of FAST detection chains

Medical Imaging: TOF-PET, Single-photon X-ray
Biological Imaging: Live Imaging, ballistic imaging, multi-thread flow cytometry, imaging in the mesoscale, laparoscopic applications
Security: Terrestrial border control of large volumes.
LiDAR applications: High-precision remote sensing
High Energy Physics: HLLHC experiment upgrade, Cerenkov Imaging

For all these applications we have established contacts

Conclusion

- FAST Action has created and fostered a multidisciplinary expert network on fast timing detectors
- Significant progress has been made in the understanding of the full detection chain and the key parameters for fast timing resolution
- Main achievements:
  - Possibility to improve the time resolution of light emitted material (exploitation of prompt emission proccess)
  - Much progress has been made on SiPM (PDE, wavelength range, SPTR, etc…)
  - Various readout ASICs for TOF are available
- 100ps time resolution has been reached

=> No physical barrier to go toward 10ps time resolution: Our next Challenge!

Contact details

Web page :

Website: http://fast-cost.web.cern.ch/fast-cost/

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