Summary of the results obtained during the COST Action TD1401 (FAST)
November 2014 to November 2018

The Fast Core group:

E. Auffray (Action chair), M. Paganoni (Action vice-chair),
P. Lecoq (WG1 leader), D. Schaart (deputy WG1 leader), M. Nikl (WG2 leader),
C. Dujardin (deputy WG2 leader), C. Piemonte (WG3 leader), E. Charbon (deputy WG3 leader),
J. Varela(WG4 leader), C. Morel (deputy WG4 leader), P. Almeida (WG5 leader),
S. Tavernier (deputy WG5 leader), K. Ziemons (industrial coordinator), G. Loudos (STSM coordinator),
H. Tsoumpas (dissimeniation coordinator), M. Georgiou (ESR coordinator),

I. Introduction:

The main objective of the Action was to establish a multidisciplinary Network that brings together European experts from academia and industry to ultimately achieve scintillator-based detectors with time precision of better than 100ps, in particular to enable significant breakthroughs in diagnostic medicine and high luminosity particle physics.
In order to achieve this objective 5 working groups were set-up:

- WG 1 Physics, Specifications & Supervision
- WG 2 Scintillators
- WG 3 Photodetectors
- WG 4 Electronics
- WG 5 Applications
-

In the following sections, the activities of the five working groups and coordinated activities in industrial, events, short term scientific missions (STSMs) and for earlier scientific researchers (ESR) are presented.

II. WG1 summary report

The role of WG1 was to coordinate the scientific program of the Action, to define the technical and physical specifications/parameters of the project and determine the roadmap for achieving the Action's objectives of time coincidence resolution below 100ps.
This was going along the three following objectives:

Objective 1: ***Full detector chain modeling and optimization***

In the frame of the project a very detailed modeling of the full detector chain (figure 1) has been made and all the critical parameters influencing the time resolution have been analyzed and quantified.

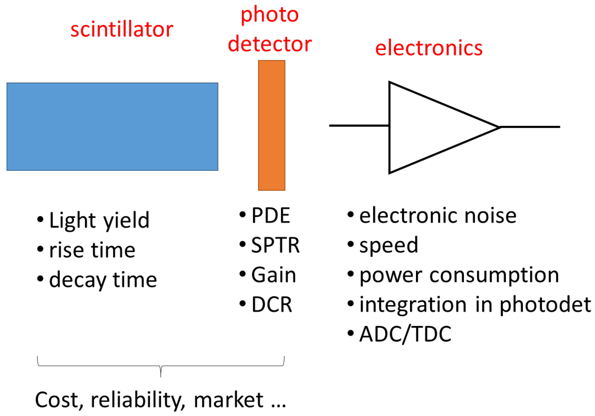


Figure 1: Full detection chain

An important conclusion is that the efforts towards 100ps timing resolution or less have to be concentrated along 3 directions:
- light production in the scintillator
- light transport to the photodetector

- photodetction and readout electronics

Objective 2: ***Definition and supervision of the specifications and the roadmap for achieving the objectives of a coincidence time resolution below 100ps***

A roadmap has been established along four research directions:

- Improve the timing performance of existing scintillators to evaluate the possibility for scintillators to produce at least 1 photon per picosecond and per MeV of deposited energy in the leading edge of the scintillation pulse. This was going through two main actions:
    - Understand charge carrier relaxation to luminescent centers
    - Develop co-doping strategies for faster rise/decay time and higher light yield
- Study mechanisms for the production of ≥ 200 prompt photons @511keV, focusing in particular on the 3 following mechanisms:
    - Cross-luminescence
    - Hot Intraband luminescence
    - Quantum confined luminescence in nanocrystals
- Decrease by a factor ≥ 2 the absorption light loss in long pixels through a systematic investigation of:
    - Scintillator surface state and wrappings treatments
    - Photonic crystals for enhancing the light extraction efficiency from high refractive index scintillators.
- Improve photodetectors and electronics performance with the following objectives:
    - Reduce SiPM Single Photon Time Response (SPTR) by a factor of ≥ 5
    - Reach a system resolution of ≤ 100ps for a 64 integrated readout chip

Objective 3: Throughout all project phases, to interact with each working group and follow up on the progress of the activities, milestones and deliverables.

Throughout the whole duration of the project regular contacts have been established with members of all the working groups, at the occasion of the regular annual meetings and dedicated working groups meetings 2,3,4,5, STSM exchanges and direct bilateral interactions. A detail of these interactions with different partners in the frame of each working group is given below:

- WG2: strong interaction on:
    - Theoretical aspects (Minsk, Moscow)
    - Co-doping actions (Prague, CERN)
    - Hot Intraband Luminescence (Tartu, Minsk, Moscow, CERN)
    - Nanocrystals (Lyon, Prague, CERN)
    - Characterizations in different partner institutes
- WG3: Many discussions on:
    - Criteria for a new generation of SiPM (FBK, Ketek, CERN)
- WG4: many discussions on:
    - System issues for the integration of a large number of high performance channels (Petsys, LIP, Torino, Barcelona)
    - 3D electronic designs for SiPM readout integration (LIP, CERN, Delft, EPFL)
- WG5: discussions on:

– Identification of different domains of interest for fast timing and possibility to define a common R&D roadmap (all)

III. WG2 summary report

Working group 2 covered the scintillation materials topics.

Rich activities in WG2 were focused into three directions, namely the materials R&D itself (bulk crystals, nanocrystals and quantum wells, composites) and specific luminescence and scintillation mechanisms which can be exploited for fast timing. Furthermore, various experimental methods (time coincidence resolution measurements, picosecond scintillation, luminescence and absorption spectroscopies, double beam excitation, photo-elastic spectroscopy) have been further developed and tailored for the performed experiments. Finally, theoretical calculations and phenomenological modeling focused onto specific aspects of scintillation and luminescence mechanism have been carried out.

Main results

R&D of scintillation materials was generally aimed in squeezing luminescence photons to arrive to photodetector in the **as short as possible** time window to provide a time tag in the time scale of a few tens of picoseconds. To reach such a goal, i.e. to produce few hundreds of photons at photodetector within first 100 ps, high light yield, short decay time and negligible rise time are the prerequisites.

To reduce rise time, specific codoping was applied in the case of garnets scintillators: optically inactive Mg^{2+} or Ca^{2+} codopant was embedded in aluminum and multicomponent garnets to stabilize Ce^{4+} which successfully competes with electron traps and converts very slow components of scintillation response into the immediate scintillation component. As a result, rise time is shortened down to a few tens of picoseconds and light yield is noticeably increased in aluminum garnets for low codopant concentrations (few hundreds of ppm). In multicomponent GAGG garnet its high light yield is a little degraded even for small Mg concentrations which is explained by the unwanted energy transfer from Gd^{3+} towards Ce^{4+} charge transfer absorption band creating a pathway of energy loss. At high codopant concentration light yield is degraded in all the garnet group and scintillation response is noticeably accelerated even below the photoluminescence decay time. Explanation of such an effect has not been convincingly found yet.

To reach a superfast scintillation response of the order of a few nanosecond or even less the direct gap semiconductor materials have been explored in the form of nanocrystals (quantum dots) and quantum wells. Such a fast radiative lifetimes of the excitonic emission are enabled by the microscopic superradiance effect which is further strengthened by the quantum confinement of excitonic state in a nanocrystal (quantum well). Nanocrystals of CdSe, Zn(Mg,Cd)O and most recently $CsPbX_3$ (X = Cl,Br) have been synthetized by different techniques including a novel radiation method and their structure, morphology and luminescence and scintillation properties were characterized. In case of ZnO-based materials, the solid solutions of (Zn,Mg)O and (Zn,Cd)O were prepared to tune the fast excitonic emission wavelength within some 370-430 nm. Ga-doping and two-steps annealing with the second step in a reduction H-containing atmosphere was applied to completely suppress the unwanted slow defect emission in the visible spectral range. Multiple quantum wells of GaN-GaInN were grown by MOVPE method and up to seventy quantum well and total thickness over 1.5 micrometer (world record!) was obtained. Excitonic emission within 400-450 nm shows analogous timing characteristics as the nanocrystals of other compounds mentioned above and

a slow defect emission is also present in visible spectral range. Its suppression is critically needed to achieve superfast and intense scintillation response, but a recipe for its complete suppression has to be found yet in the technological process.
In exploration of other, yet faster luminescence processes and mechanisms, the crossluminescence, hot intraband luminescence and Cherenkov radiation have been addressed. Especially hot intraband luminescence was measured in quite several compounds from the group of complex halides and oxides. Using theoretical tools incl. electronic band structure calculations the material parameters have been defined to obtain higher yield of this process. So far, the number of photons which can be obtained from this mechanism is too low for time tagging in the intended applications especially in the medical field.
All these subjects were discussed deeply during the several meetings organized in frame of WG2:
During the 4 years projects, meetings where activity plans and survey of results in WG2 have been discussed were organized during four annual meetings in Prague (April 2015), Trento (May 2016), Larnaca (March 2017) and Bucharest (March 2018). In addition, separate WG2 meetings were organized in-between the annual meeting in Tartu (December 2015), Vilnius (October 2016), Torun (October 2017) and Prague (June 2018). Final report was provided in final project meeting in Athens (September 2018). In June 2018 meeting, it was joined with Summer school of H2020 project ASCIMAT the program of which includes also activities related to fast scintillators explored for fast timing purposes. The list of WG2 meetings is list in table 1.

Table 1: list of WG2 meetings:

Place and time	Types
Prague, April 2015	First meeting to define the objectives
Tartu, December 2015	WG2 meeting: presentation of the activities of each partner
Trento, March 2016	Annual meeting report on WG2 activities
Vilnius, October 2016	WG2 meeting: presentation of the activities of each partner
Larnaca, March 2017	Annual meeting report on WG2 activities
Torun, October 2017	WG2 meeting: presentation of the activities of each partner
Bucharest, March 2018	Annual meeting report on WG2 activities
Prague, June 2018	WG2 meeting in collaboration with ASCIMAT Twin project

Within WG2, we had 42 STSM mainly by young researchers. The topics of the STSMs were the characterization of different materials using experimental set-up existing only in some partner laboratories like optical differential absorption measurement with pump and probe configuration in Vilnius, time resolved spectroscopy with picosecond pulsed Xrays at CERN. It was also the opportunity to initiate new collaborations between groups.
During the 4 years project we achieved the objectives of this working group
1 Define and understand, under the supervision of WG1, the key parameters for scintillators to obtain the best timing properties, and define the ultimate time resolution achievable with inorganic and semiconductor scintillators

2. *Develop new ideas or exploit properties of existing materials to get the bestpossible time resolution;*
3. *Investigate other light producing modes like Cerenkov radiation or transient processesoccurring in the crystal prior to the standard light generation, i.e. in the stage of hot carrier existence;*
4. *Investigate (theoretically and experimentally) the mechanical and structural properties of scintillating materials in various forms (bulk crystals, films and fibers).*

IV. WG3 Summary report

Working Group 3 covered the photodetector part of the detection chain.
This element of the radiation detector system has a crucial role in the timing performance. Parameters like photodetection efficiency (PDE) and single-photon response are essential to catch the photons with lowest jitter from the scintillator and provide and electrical signal with the lowest jitter as well.
In the past few years, we have been assisting to a revolutionary change of this component: from the classical photomultiplier tube (PMT) to a silicon device working in avalanche regime, i.e. the silicon photomultiplier (SiPM). Besides improving drastically the timing performance, the SiPM is enabling also new system solutions and ideas for a potential higher benefit. Due to this high impact, a large portion of the working group activities have been directed to this technology: understanding its physical limits, aspects of improvement and best coupling with the other parts of the system, i.e. the scintillator and the read-out electronics.
On the other side, we also tried our best to monitor the evolution and assess potential benefits of both existing and new photodetectors: the classical photomultiplier tube, the multichannel plate, photodetectors based on transmission dynodes, superconducting nanowires. We also followed the progress of single-photon avalanche diodes produced in different materials than silicon, such as Silicon Carbide and Indium Gallium Arsenide. In our meetings and discussions, we could assess the steps forward made in all these technologies and compare one to the other. Application wise, main focus has been devoted on scintillator-based detection systems and in particular TOF-PET. For this particular application, we have seen a huge improvement in terms of time-of-flight capabilities thanks to the use of silicon photomultipliers. According to our analysis (WG1 and 3), the benefit can be much larger and revolutionize the PET concept if we will be able to fully exploit the potential given by the single-photon avalanche diodes (SPADs), which are the building block of the SiPMs.
We tried to extend our view to other application fields in order to understand the requirements on the photodetector. For example, an emerging topic is direct-TOF Lidar. The operation conditions in this case are completely different, for example: use of near infrared light, high noise due to background light, triggered acquisition. All this poses new and different challenges to the photodetector which are very interesting to understand and monitor.
WG3 organized (or was deeply involved) several workshops/meetings. They are listed in the table 2.

Table 2: list of WG3 meetings:

Place and time	Main focus
Prague, April 2015	WG3 meeting: Evaluation and comparison of the main photodetector technologies for fast timing
Corsica, May 2015	Not sponsored by WG3.

	Understanding critical parameters of photodetectors for fast timing
Aachen, September 2015	FAST Industrial workshop mainly focused on photodetectors and PET producers
Trento, March 2016	WG3 meeting Silicon photomultipliers
Strasbourg, November 2016	Industrial workshop held in the framework of the Nuclear Science Symposium/Medical imaging conference
Lisbon, January 2017	Joint WG3/WG4 workshop. Interaction of photodetector with electronics
Lubljana, January 2018	Joint WG3/WG4/WG5 workshop. Interaction of photodetector with electronics. MCP: improvements and applications.
Schwetzingen, ICASIPM, June 2018	International workshop on SiPMs, in which WG3 organized the session on timing and participated in the discussion for test standardization of SiPMs.

In each workshop/meeting we tried to cover different topics giving plenty of time for discussion. It is worthwhile noting that we had 3 joint workshops between WG3 and WG4. This decision was taken to enhance the collaboration between these two critical and strongly linked parts of the system. The last workshop was part of the ICASiPM conference (International conference on the Advancement of Silicon Photomultipliers:
http://www.icasipm.physics.gatech.edu. Many members of FAST were actively involved in the organization of this event. The matching between the scope of the workshop and FAST was very relevant because the focus was on the characterization techniques and standardization of SiPMs. The result of the workshop will be summarized in a paper. Overall the participation on the WG3 activities was very high. Many people from academy, research institutes and companies actively contributed to the events and to the discussion.
Within WG3, we had 12 STSMs by young researchers. The main topics of the STSMs were the characterization of Silicon Photomultipliers in different conditions: new scintillators, radiation damage, new device concepts.

Analyzing the objectives of this WG, we can certainly state that
objective 1 (*define and pursue the key parameters of current and/or novel photodetectors, leading to the best timing properties*) and objective 2 (*Investigate the different existing state-of-the-art photodetection technologies and evaluate their merits and disadvantages with main emphasis on timing*) have been completely reached. We had several events, discussions, and also published papers on the key parameters of the photodetectors and compared in-depth the different technologies. As mentioned much of the attention was given to the SiPM because of the impact it is currently having and the potential still to be exploited (for example by using highly integrated packaging techniques between sensor and electronics). Concerning objective 3 (*Industrial cooperation to assure (or rule out) feasibility of proposed ideas and methods*), we

involved all main companies producing photodetectors for fast timing and we tried to trigger collaborations and development projects. As mentioned above the participation was quite successful. We were able to trigger few small projects as well. On this latter aspect we expected and tried to reach a better result within the duration of FAST. We think we established the seed and created a network to create more collaborative projects between academia and industry in the next future.

V. WG4 Summary report

Working Group 4 covered the electronic part of the detection chains and is dedicated to foster the development of electronics with picosecond time resolution with the aim to preserve detector intrinsic performance, i.e. providing large bandwidth and low noise for a large number of electronic channels at low consumption power. Several meetings, listed in table 4) were organized with the aim to review on-going activities in the field of fast data acquisition ASICs for the readout of SiPMs.

Table 3: list of WG4 meetings:

Place and time	Main focus
Prague, April 2015	WG4 meeting: definition of the objectives review of existing devices
Trento, March 2016	WG4 meeting review of existing devices
Lisbon, January 2017	Joint WG3/WG4 meeting. Interaction of photodetector with electronics
Lubljana, January 2018	Joint WG3/WG4/WG5 meeting. Interaction of photodetector with electronics.

Activities in WG4 were focused on 4 objectives:

Objective 1: *Understand the key parameters and microelectronics technologies required for time precision < 10 ps*

Various architectures have been investigated which use either single level discrimination and fast TDCs, or constant fraction discrimination (CFD), or high frequency sampling (GHz). The following ASICs have reviewed and discussed during several FAST workshops/meetings:

(i) Nino chips based on time-over-threshold analysis (CERN.) (1st and 2nd meeting)
(ii) DRS4 chip based on switch capacitor arrays to perform high bandwidth fast timing (PSI, Villigen), (1st meeting)
(iii) FlexToT chip based on time-over-threshold analysis (Barcelona Univ.),(1st, 2nd and 3rd meeting)
(iv) PETIROC chip implementing high precision fast ADCs and TDCs (Weeroc, Palaiseau), .),(1st, 2nd 3rd and 4th meeting)
(v) TOFPET2 ASIC implementing a fast frontend associated to high precision TDC and ADC (LIP Lisbon and PETsys), .),(1st, 3rd and 4th meeting)
(vi) STIC and PETA ASICs with performance similar to PETIROC and TOFPET2 (Heidelberg Univ.), 1st (STIC) and 2nd (PETA) meeting

(vii) SAMPIC ASIC (LAL/IN2P3, Orsay) a high performance waveform TDC, (2nd and 4th meeting)

(viii) TOFFEE ASIC an amplifier and discriminator chip for LGAD sensors (INFN Torino and LIP Lisbon), (3rd meeting)

(ix) FastIC a flexible architecture ASIC for fat timing applications (Barcelona Univ.), (4th meeting)

(x) ALTIROC ASIC dedicated to fast timing of MIP particles with LGAD sensors (LAL Orsay and Omega Microelectronics), (4th meeting)

(xi) TOFHIR ASIC for precise timing of MIP particles with SiPMs at high rate (LIP Lisbon and PETsys). (4th meeting)

The WG4 extended the scope of the activities beyond the crystal-based PET application. The ideas around Liquid Xe scintillation presented at the second WG4 meeting raised new issues and created new challenges. In particular the exploitation of prompt Cherenkov light would require improved SiPMs sensitive in the VUV region. Fast timing with accuracy of the order of 10 ps is of interest to a number of different applications, in particular the possible application to automotive LIDAR (Light Detection and Ranging). The timing of charge particle detection is particularly relevant in the new detectors being developed for the HL-LHC collider. Ultra-fast timing for tracking charged particles with silicon detectors can be extended beyond the scope of crystal-based detectors for PET. Interestingly, crystal-based detectors are now also being applied to the fast timing of charged particles. Actually, there are a number of applications in the field of particle tracking and calorimetry, e.g. using Cerenkov light or liquid Xenon fast UV scintillation. In particular, charged particle tracking is likely to reach the 10 ps frontier sooner that 511 keV annihilation pair detection for PET.

Objective 2: *Conception and design of an ASIC in deep submicron CMOS technology based on specifications established with other working groups*

The lines being pursued in the direction of the new ASIC designs were reviewed in the joint meeting organized between WG3 and WG4 that took place in Lisbon on 23-24 Jan 2017. In general ASICs are needed for systems with large number of channels but the range of different applications is quite large. The choice of the photo-sensor, the coupling between the scintillator crystal and the photo-sensor, the number of channels in the system, the performance versus cost optimization, are among the factor that influence the chip design.

Three categories of ASIC are now available from the scientific community and continue to be improved:

- analog: amplifiers, amplifier+discriminators (NINO, FlexTOT, FastIC)
- analog-digital: amplifier, discriminators, ADC, TDC (PETA, PETIROC, STIC, TOFPET2)
- waveform sampling (DSR, SAMPIC)

All the groups developing these ASICs have been associated or in contact of the FAST action. These groups have been pursuing new designs or several improvements of current ASICs, which have been presented and discussed in the WG4 group meetings.

Objective 3: *Organize common Multi-Project Wafer (MPW) productions*

Not needed since in particular CERN is already organising regular MPW productions for various CMOS technologies.

Objective 4: *Coordinate a joint characterization of the prototype devices*

Photosensors and readout electronics are tightly coupled and have deserved the organization of the joint meeting between WG3 and WG4 that took place in Lisbon on Jan 23-24 2017. At this meeting, results on comparing the performance of PETA, STIC and TOFPET chips have been presented (ETH Zuerich), namely the results on time resolution in specific configurations the type of crystal, of photodetector (SiPM), the gain and the temperature, and signal rate. Comparative results on the timing performance of several SiPM devices associated to the same readout electronics (based on the NINO chip and a fast external digitizer) were also presented (CERN, Geneva). The influence on the readout electronics on the results was highlighted.
During the Wrap-up session on 24 Jan 2017 in Lisbon, the discussions covered several issues. The first topic was about the question: what is the relevant FWHM CTR (Coincidence time resolution) target for PET ? 100ps is already achieved with short crystals. However, 10 ps is probably the next frontier that will generate a shift of paradigm in PET.
A second issue was on how to measure the intrinsic electronics contribution to SPTR (Single Photon Time Resolution)? State-of-the-art measurements convolute laser, SiPM, electronic and digitizer. More extensive light/SiPM/electronics simulations are definitely needed to better understand this issue.
Then, we discussed where are the further improvements or breakthrough possible or needed in order to cross the 10 ps frontier with scintillators? These improvements have to be focused on light production, light collection and light detection. For light production, research and development lines can be related to the development of new fast scintillation crystals and/or the use of meta-materials capable of lasing thanks to quantum confinement. For light collection, the use of photonic crystals can represent an interesting research track. The importance to get a better knowledge on the interface between the crystal and the photodetector through simulation and cross-validation is underlined. For light detection, it is noted that SiPM may not be the unique solution and that they are other possible alternatives such as micro-channel plate photomultiplier tubes (MCP-PMT).
Moreover, it is of uppermost importance to understand why it is so difficult to improve the timing accuracy of electronics. Is it related to power consumption and/or to the combination of analog and digital circuits? As an example, the NINO time jitter is 3 ps, but it goes up to 10 ps when it is integrated in a system. For photosensors, the SPAD resolution is lower than 20 ps, but within a SiPM, it amounts about 200 ps.
Finally, other applications were also mentioned such as HEP, or automotive LIDAR, that can be very different from the 10 ps TOF-PET paradigm with regards to pixel size, or the detection of single photons. Two examples of such applications are the impact localization imaging of ultra-fast X-ray and the imaging through turbid media, which necessitates to separate ballistic photons from scattered photons. A joint meeting WG3, WG4, WG5 was organized in Ljubljana in January 2018 to get closer links with the work of WG5.
Within WG4, we had 16 STSMs mainly by young researchers. The main topics of the STSMs were the evaluation of different types of ASIC with reference set-ups.

VI. WG5 Summary report

The communities initiating this COST action mainly have their expertise in PET medical imaging and in high energy physics experiments. The main aim of WG 5 was to make the bridge to other applications requiring fast timing. This compelled us, to focus on identifying potential users of fast timing since the beginning of the Action. This was done on the broad area of photon sensing, in particular those using state-of-the art solid state detectors (Silicon Photodiodes) either directly exposed to radiation or used as transducers for pre-occurring scintillation events.

The Action tried to engage effectively with industry from the very beginning and organized industrial workshops (lead by Karl Ziemons see section VII). These events provided evidence, on one hand, on the timings involved in technology adoption and also the industry positioning in the context of this Action.
The identified areas for potential applications were the following:

- Medical Imaging.
- High Energy Physics.
- LIDAR.
- Biology.
- Space Applications.
- Item analysis and sorting.

Requirements for different applications:
Medical Imaging:
It was an obvious application for fast timing. Identified applications include:

Positron Emission Tomography (PET) for accurate ToF imaging (<100 ps)
X-Ray imaging with photon counting (<100 ps)
Cerenkov Imaging (<50 ps)
Precise location of medical intra-operatory medical devices (<100 ps)
Neutron Imaging (<100ps)

High Energy Physics:
Given the characteristics of high energy experiments, extremely fast timing can be of paramount importance. This was, from the beginning of the Action an area of choice. In particular, calorimetry experiments would greatly benefit from very extremely fast timing resolutions (<20ps).
LIDAR:
One obvious application needing fast timing is LIDAR.
In this application, we came to learn that there is a fierce competition between the industrial players in the automotive industry. This is not really compatible with the more open spirit of a COST network. Therefore, later in the action, we have concentrated on applications of the LIDAR principle that are different from the main application of LIDAR in automotive industry. One particularly interesting application is related with artificial intelligence and the need to develop adequate machine vision using LIDAR. Other possibilities include urban aerosol monitoring (<200 ps)
Biology:
The European Molecular Biology Laboratory (EMBL) and the Gulbenkian Institute of Science (Portugal) were approached in order to investigate possible needs for fast timing measurements. We have identified possibilities in:

a. The study of applications like photon counting for very low light imaging, needed in order to keep the integrity of biological samples when performing live imaging. (<1ns)
b. High throughput microscopy (<1ns)
c. Time-gated optical tomography (<500ps)
d. Fast cell sorting(<1ns)
e. Realtime imaging of fresh vegetable products (<10ns)

Space Applications:
The Institute of Astronomy and Astrophysics in Portugal and the Weizmann Institute of Science in Israel were contacted in search of applications. The following possibilities were identified and its use discussed:

– Space Gamma-ray imaging is of interest either for NASA and the ESA.(<1ns)
– Fast detectors allow the possibility of 4D imaging using time information.(<1ns)
– For distance metrology, sub-nanosecond detectors are critical elements.(<1ns)
– For Telecommunications, fast detectors are imperative to archive higher transfer rates.(<1ns)
– Search for dark matter.(<1ns)

Item analysis and sorting.

In this specific item, we have engaged contacts with the cork industry for the study of performing very fast analysis during the quality control of corks for wine and champagne bottles (<1ns).
Other, not explored applications may be waste sorting and fast quality control of fresh products.

All these applications and requirements were discussed during several meetings, listed in table 4:

Table 4: list of WG5 meetings

Place and time	Main focus
Prague, April 2015	1st FAST meeting
Aachen, September 2015	FAST Industrial workshop mainly focused on photodetectors and PET producers
Ajaccio, May 2016	WG5 session during MEDAMI conference
Koln, May 2016	WG5 session during PSMR2016 conference
Strasbourg, November 2016	Industrial workshop held in the framework of the Nuclear Science Symposium/Medical imaging conference
Lubljana, January 2018	Joint WG3/WG4/WG5 workshop. Interaction of photodetector with electronics. MCP: improvements and applications.

At the onset of the Action we set out to propose a list of requirements and application tradeoffs to WGs 1, 2, 3, 4. This task proved to be extremely difficult due to the small involvement of companies (competition and industrial secrecy). In fact, the main contributions have been made by academic groups.
We were, nonetheless, able to identify at least one interesting application in medical imaging clearly requiring sub ns timing, in line with the technological objectives of the Action, the fast single photon detection for locating medical devices using weak light signals allow to monitor the position of an endoscopic optical fibre (<100 ps)
We have also identified an interesting applications in neutron imaging, and a representative of the group interested in this application has become a regular presence at our meetings (Lior Arasi, Israel) (<100 ps).
Finally, we have also succeeded to obtain a case of cross-fertilisation between fast timing in medical imaging and in fundamental research in physics. The PETsys TOFPET ASIC, that was

initially developed for application in Positron Emission Tomography found its way to an application in High energy physics at HLLHC experiments (<200ps).
Overall, and from the point of view of potential applications, the Action allowed to obtain an overall panorama at the European Level. In addition, the training of students was a particularly important achievement
Within WG5, we had 12 STSMs mainly by young researchers. The main topics of the STSMs were image reconstructions.

VII. Industrial coordination report

The **F**ast **A**dvanced **S**cintillation **T**iming is more than a technology shift. It represents a technical revolution with profound impact on feasible applications in particle physics, accelerator physics, medical & biological imaging, non-destructive industrial processing and electronic design issues. An important objective that this action also embarks on is training young researchers in a very innovative approach. We need change agents from every facet of industry, government, academia and healthcare to harness the full potential of **FAST** and to define what is possible.
In total, following activities with industrial contributions have been organized or co-organized by FAST:

- 1st Industrial FAST Workshop @Aachen, Germany Sept. 24th, 2015
- Technology Frontier for Single Photon Detection and Advanced Scintillator Timing @ IEEE NSS/MIC and RTSD in Strasbourg, France Nov. 4th, 2016
- Industrial Event on Fast Advanced Scintillator Timing - @ SCINT Conference 2017
- ICASiPM 2018 @ Schwetzingen, Germany

These workshops and conferences brought together academics and representatives from the industry to discuss how academia and industry can partner to address the challenges and the opportunities that scintillator-based detectors with time precision better than 100ps presents. Mainly the industrial representatives are coming from following area:

- Crystal growers
- photosensor manufacturers
- readout electronic industries, specially in the field of photosensors
- scintillation crystal manufacturers
- medical imaging and small animal imaging manufacturers

Presentations from the industrial representatives in the field of SiPMs have shown the potential benefit of the new technology with

- 3D-integration layout to couple the sensitive area with an integrated circuit for preamplifying and read out technologies,
- large area readout issues,
- ultra-fast timing better than 100 ps,
- radiation hardness, and
- Ultra-Violet and Vacuum Ultra-Violet sensitivity.

They claim possible applications into High Energy Physics, Medical Imaging, Biology, Security and non-destructive imaging and open for collaborations. In particular in the field of automotive applications with the popular LIDAR technology are under restrictions and industrial representatives are willing to present their effort in this field.
The result of the industrial day events should be a list of following perspectives:

1. A set up of characterization methods of the new solid state photo detectors, called SiPM (Silicon Photomultiplier Tube), for a proper definition of parameters and to start a standardization process. As an outcome of the ICASiPM conference a book on standardization methods for SiPMs would be published next year.
2. The knowledge transfer from academia to industry should be more efficient. The early start of a collaboration between academia and industry was usually an order of research work from academia which was of focused interest of industry, might be accompanied by a focused NDA. If both sides were satisfied with the outcome, a joint research project might be organized. If a long term systematic collaboration was created, overall NDA becomes useful. IPR issues became today critically important at any level.
3. R&D ability and the capacity of academic consortium should be strictly focused on basic research and at the same time attract the interest of industrial partners. Though there were (big) industries, which support and promote the basic research in their field, not so many companies were interested in (or could afford) the support and collaboration with academia at the level of truly basic research.
4. A database of industrial and academic units has to be built with public access which offers dedicated equipment and measurement devices for possible partnerships and cooperations.
5. An important objective of the workshops and conferences were also to provide a training to young researchers in an open and innovative context.

We need involvement from every facet of industry, government, academia and healthcare to harness the full potential of what is available and to define what is possible. Responsible and effective transformation will be ushered in through an alliance of industry and academia. The success of the **Industrial Workshops** and the dialogue that we started should continue in the following years.

VIII. Short term scientific mission report (STSM)

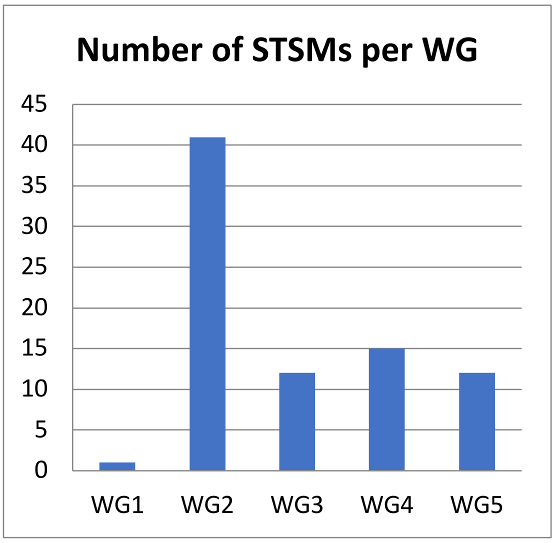
General procedure

Given the interdisciplinary nature of the Action, STSMs were considered as a tool, which will facilitate the collaboration among Action members and especially about different but complementary Working Groups. To better coordinate the procedure, it was decided to have 3-4 open calls for STSMs every year, so that the applications could be collected, evaluated and approved. This procedure was considered as more efficient compared to “first come, first served”. Each interested applicant had to submit a motivation letter, where the main objectives of the STSM are described. Following the acceptance of the application, the participant was allowed to use the e-COST system. Following the end of the STSM, besides the documents requested by e-COST, each participant had to prepare one slide, which summarized the main outcomes of the STSMs and potential future steps.

Main outcomes

In total 81 STSMs were carried out during the Action lifetime and the majority of them was carried out by ESRs. In total 14 calls for STSMs were opened.
In terms of gender balance, 63 were implemented by male researchers and 18 by female (see figure 2 right). Although this number is not well balanced, it corresponds to the gender balance of Action members and ESRs. Given the fact that the Action is mainly technologically driven and focuses on engineering and physical sciences, such a distribution is expected.

From the Action WGs, most of STSMs took place in WG2. Actually the number of STSMs per WG was: WG1: 1; WG2: 41; WG3:12; WG4: 15. WG5:12 (see figure 2 left). The role of WG1 was rather theoretical and coordinating and it was expected that it would sparkle very few STSMs. WG2 focused on the evaluation of crystal materials, which is a dominant component for the achievement of 10ps timing. So, a number of STSMs explored different crystal materials, in combination with new Silicon Photomultipliers or other data acquisition techniques. Although in those STSMs different WGs contributed, in all cases that the primarily focus was on the evaluation of a new scintillator, the STSM was assigned to WG2. Almost equal distribution was observed among the STSMs of WG3 (photodetectors), WG4 (electronics) and WG5 (applications).



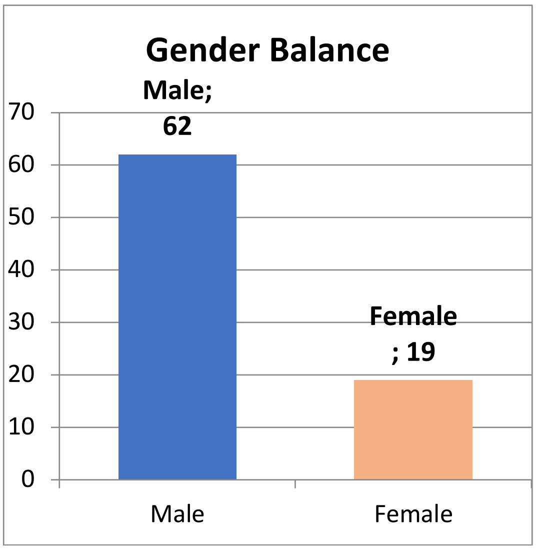


Figure 2: left: distribution of the 81 STSMs by different working groups; right: gender distribution of 81 STSMs

The average duration of an STSM was ~14 days; most of the STSMs were short visits of 5-10 days and in many cases, they were repeated. This happened since some work was initiated during the STSM at the host institution, then continued at the home institution and then a second STSM was required to complete it or continue it. There were few cases that long STSM of 3 or even 6 months took place.

The average budget per STSM was ~880€. Effort was made to fairly support all STSMs taking into account their duration and the average expenses at the host institution country, as well as available travel options. Taking into account that a COST Action supports, but cannot fully cover all research expenses, in cases that a high support was requested this was reviewed taking into account the abovementioned policy. In all cases, Action members agreed with the revised budget.

Although few SMEs participated in the Action it must be mentioned that BET, KETEK and PETsys hosted ESRs for their secondment. Being companies with originally academic background they understood the added value for STSMs and supported this scheme.

IX. Early stage researchers reports

In order to encourage early stage researchers to participate to the FAST Action, several dedicated meetings were organized:

1. An ESR training event was organised in April 21, 22, 2016 in Athens, Greece (18 participants, see http://fast-cost.web.cern.ch/fast-cost/events_ESR_21_22_april_2016.html, https://indico.cern.ch/event/522778/, where ESRs from different countries met, presented their work and discussed possible collaboration. It resulted in the preparation of STSMs.
2. During the second industrial day event on November 4, 206, in Strasbourg, France one full session was dedicated to the presentations of the ESRs work on fast timing detection: 10 ESRs presented their work to the industry and senior scientists in a pitch (see https://indico.cern.ch/event/591739/).
3. During the third annual meeting on March 23-24, 2017 in Larnaca, Cyprus (https://indico.cern.ch/event/594385/), an ESR event was organised the second day. 18 participants from different countries presented their results from the STSMs that they did and also their research progress related to FAST. A questionnaire was filled in from the ESRs answering what is their position they have in their university/research team, their responsibilities, their PhD subject. The most important part of the questionnaire was the answers related to what they can offer in the FAST Action via collaborations and STSMs hosting and what they are missing and trying to find in FAST Action. This event resulted in the strengthening of the ESRs' personal research network and their between relationships.
4. The ESR event was organised in March 9, 2017 in Bucharest it was hosted the second day of the four FAST annual meeting (https://indico.cern.ch/event/681215/). 10 ESRs, mainly from neighborhood countries, presented their research activities. Additionally, 14 ESRs reported on their STSM during the general meeting. The meeting closed with a visit in the host university, National Institute for Laser Plasma and Radiation Physics.
5. During the final meeting of the FAST COST Action, an ESR event was organized in September 26, 2018. The final meeting and the ESR event was held in Athens. The program is announced here: https://indico.cern.ch/event/733582/. In the ESR event, the total participants were 23 while the ESRs were 10 and all of them presented their work related to FAST Action.

In addition to these meetings, a summer school was organized just before the SCINT 2017 conference from Sept 14 to 17 in Chamonix. 56 participated from 19 countries (11 countries members of FAST) to this school among them 40 trainees: 6 master & 25 PhD students, 3 postdocs, 6 “professional” (4 from industry). In addition to the lectures given by senior researchers, each ESR presented its work in an oral or poster presentation (in total 27 short presentations/posters).

All the ESR events were the opportunity for the ESR to create a new network of young researchers in the field of Fast timing detection.

The STSMs were a very tool for ESRs to train and gain experience, out of 81 STSMs 58 were done by ESRs.

X. Dissemination and outreach report

Several actions have been taken to promote the FAST Action.

A public webpage (http://fast-cost.web.cern.ch/fast-cost/) was created, a flyer was realized which was distributed during the different meetings, conference school in which Fast members were involved. FAST Action is present in two social networks :

- research gate https://www.researchgate.net/project/Fast-Advanced-Scintillator-Timing-FAST (73 followers, 927 reads). The increase in reads is 23% the last 7 months.
- Linkedin group: https://www.linkedin.com/groups/8356110 (52 members)

Several dissemination talks were given at different international conferences. The scientific results obtained via the Action were presented at several international conferences and published in peer review.vThe list of publications and presentations is available on the FAST webpage: http://fast-cost.web.cern.ch/fast-cost/articles.html.

XI. Conclusion

In four years, FAST has succeeded to establish a multidisciplinary network bringing together European experts from academia and industry to develop scintillator-based detectors with a timing precision of better than 100ps.This network became an excellent training platform for scientists interested in this domain of research. The Action comprises 21 COST countries and four Neighbor countries. The Action held 16 dedicated working group meetings, five annual meetings and three Industrial Events in various locations. Also, five dedicated events for early stage researchers (ESRs) were organized and one summer school in September 2017. The Action also coordinated 81 short-term scientific missions (STSMs) with 58 made by ESRs and an overall proportion of 22% female scientists had participated.

In the framework of Horizon2020, the network submitted proposals in programs such as 'TWINN', 'Research Infra-structure', 'Individual Marie-Curie Fellowships', 'ERC Grants', ATTRACT. ASCIMAT, an Horizon 2020 TWINN project, has been approved. 16 national programs were submitted.

Many highly beneficial exchanges between academia and industry took place, in particular during the three Industrial Events in Aachen (2015), Strasbourg(2016), Chamonix (2017). These events and the Action's WG meetings have laid the foundation for a trust- and fruitful collaboration between the public and private sector, leading even to some STSMs to the premises of the partner industries.

The collaboration has published more than 50 articles and made more than 100 presentations worldwide at international conferences and collaboration meetings. As part of its dissemination mission, FAST is currently represented in two social networks, i.e. ResearchGate and LinkedIn.

In the scientific area, substantial progress was made in the three key areas devoted to fast and high precision timing (scintillators, photodetectors, electronics). Scientific developments have advanced beyond expectations to the extent that the originally targeted value of 100ps has already been exceeded, thus paving the way towards a new challenge of timing precision of 10ps. New lines of research were endorsed for the investigation of ultrafast, prompt photon signals. Furthermore, different photodetection technologies were examined and compared to identify parameters contributing to the limitations in timing. Similarly, an inventory of existing technologies and architectures for fast electronics has been put on file. WG5 recognized specific applications of fast timing for high energy physics detectors, as well as for TOFPET, LIDAR, and biology.

FAST has accomplished a solid record of timing precision from its concerted efforts in the five WGs. The results have exceeded the original expectations already very challenging at that time. The high level of quality in all domains of FAST makes us approach a new frontier of ultrafast timing, ultimately reaching 10ps, and hence opens new perspectives in fundamental and applied science. Without this COST coordinated and structured approach the stipulated challenges would not have been met at the required scope and scale.