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Technical Report for the Design, Construction and Commissioning of FATIMA, the FAst TIMing Array

Abstract

The experimental determination of nuclear lifetimes of excited nuclear states is of great importance to understand nuclear structure, since it provides model-independent access to nuclear transition rates. The ultra fast timing method makes use of electronic coincidences between fast scintillator signals for the measurement of level lifetimes using the time difference from the populating and de-exciting radiation from a given nuclear level. The method is applicable in the subnanosecond time range.

Here we describe the technical design of the *FAst TIMing Array* (FATIMA) designed to measure sub-nanosecond half-lives of excited states in exotic nuclei produced at FAIR, and of special importance for neutron-rich nuclei far off stability. The system comprises a large number of $LaBr_3(Ce)$ gamma scintillators coupled to fast photomultiplier tubes. It will be placed in the final focus of the Super-FRS and it is designed to work in conjunction with AIDA. This report includes the details about the tests of the available technologies, the configuration of the detectors for FAIR and the design and construction of the prototype that has already been used at several facilities.

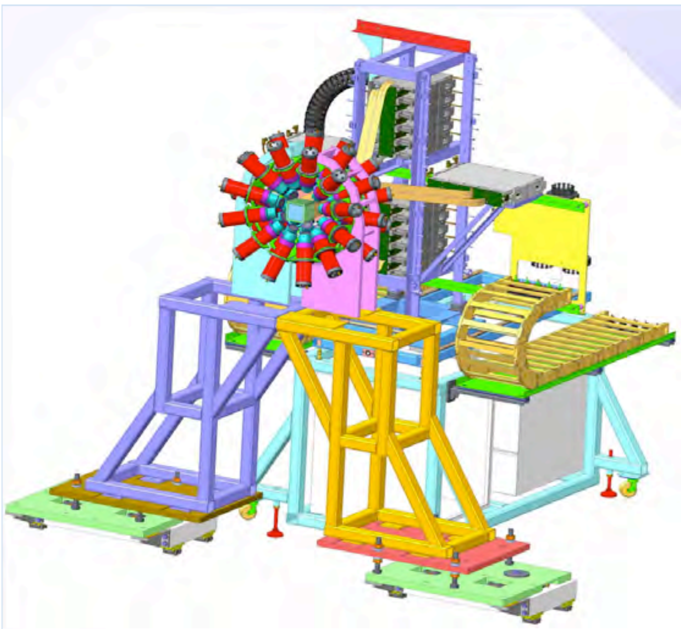

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Table of contents

1. Introduction

The collaboration for NUclear STructure, Astrophysics and Reactions (NUSTAR), is one of the four Physics pillars of FAIR, the Facility for Antiproton Ion Research [FAIR]. The HISPEC/DESPEC (High-resolution In-flight SPECtroscopy/DEcay SPECtroscopy) experiments [DESPEC] are aimed at performing high resolution and high efficiency spectroscopy measurements with radioactive ion beams. They address key questions in nuclear structure, reactions and astrophysics for nuclei very far from the valley of stability. In these experiments the radioactive beams will be delivered by the energy buncher of the Low Energy Branch (LEB) of the Super-FRS (the new Superconducting Fragment Separator). DESPEC is a modular experiment, in which the radioactive ions are slowed down and are stopped in AIDA, a stack of a highly segmented silicon-based, implantation and decay detectors. A variety of other devices will be placed around this DSSSD array according to the experimental needs, such as a compact Ge array, a total absorption spectrometer, several neutron detector arrays, and other systems. FATIMA is the apparatus devoted to the measurement of excited level lifetimes in the sub-nanosecond regime.

The Super-FRS in combination with a high intensity primary beam will allow access to neutron-rich nuclei along the r-process path. At the focal point of the low-energy branch of the Super-FRS a 'stopped beam' set-up for charged particle, γ-ray and neutron detection will be installed. Decay studies will be of the outmost importance for the understanding of these exotic nuclei. Lifetimes of excited nuclear levels span many orders of magnitude, from femtoseconds to billions of years, while the energy of emitted γ -rays may be as low as a few keV or as high as several MeV. The total transition rate for an electric or magnetic (X=E or M) transition of multipolarity λ from an initial to a final nuclear state can be expressed in terms of the reduced transition probability, B(Xλ). The measurement of the partial mean life from a level provides direct and model independent access to this magnitude. Lifetimes down to a few ns are generally measured by time-delayed methods using Ge detectors. Shorter lifetimes, in the nanosecond and sub-nanosecond range, were measured by the Ultra Fast Timing Method developed by Mach, Moszynski and Gill [MAC89, MOS89, MAC91]. The method is schematically depicted in Figure 1.

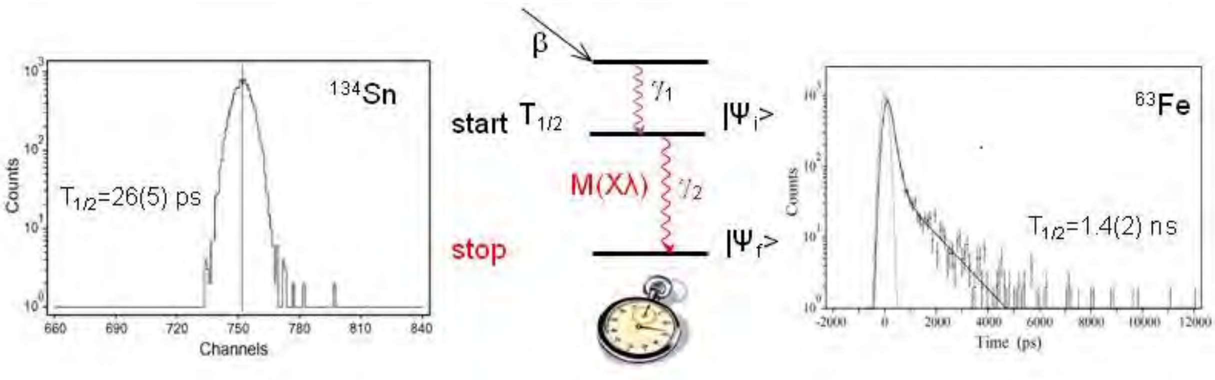


Figure 1: Schematic decay scheme and the applicable time ranges.

The study of excited level lifetimes is of great interest, given that it provides important information on the evolution of shell structure far off stability, nuclear shapes and shape coexistence, nuclear phase transitions, conservation of the K quantum number, etc. Despite the strong interest in obtaining accurate lifetime measurements in the 10 ps to several ns regime, data is still scarce and new high quality measurements are needed. The new FAIR facility will contribute to this quest by providing access to exotic nuclei previously out of reach. In this report we discuss the research and development towards the construction of FATIMA, the *FAst TIMing Array* for DESPEC. The core subject is the technical specifications and design details, given in Chapter 3.

2. Physics requirements for the system

We aim at understanding the interplay between single particle states and collective phenomena in neutron-rich exotic nuclei by performing fast-timing experiments in large-scale radioactive beam facilities. The *FAst TIMing Array* FATIMA has been designed for FAIR as an integral part of the DESPEC setup within NUSTAR@FAIR. FATIMA will be used for the measurement of lifetimes below isomers, in combination with the AIDA implantation detectors, and for lifetimes populated in beta decay, where the beta timing measurement will be performed with ancillary detectors combined with AIDA. In decay spectroscopy measurements the ions from the separator will be implanted into AIDA, acting as an "active catcher" made of highly segmented double-sided silicon-strip detectors. The exotic nuclei then disintegrate by β-decay (or α-decay) and the emission of gamma rays. The high pixellation of the silicon detectors allows the correlation of the time and the position of the implantation of the heavy ion with the signal produced in the same detector from the subsequent β-decay.

The main Physics requirement for FATIMA is a good time resolution over an extended energy range. Sufficient detection efficiency and reasonable energy resolution are also required. Inorganic scintillators are the right choice for this type of measurement. Traditionally, BaF_2 crystals were used for timing due to their fast response, in spite of their poor energy resolution ($\Delta E/E \sim 9\%$ at 662 keV) [MAC14]. Recently, a large advance took place with the introduction of $LaBr_3$(Ce) scintillators [LOE02], which unites very good time response with energy resolution of the order of 3% at 662 keV. This is a suitable material that can be taken as reference for the technical study and the design of the array.

FATIMA is designed to be used as a standalone or a hybrid γ-ray array, able to operate in coincidence with the Super-FRS tracking detectors and the DESPEC charged particle detectors, AIDA in particular. In the hybrid version of the setup, auxiliary detectors such as HPGe detectors can be employed. For beta-gamma timing a plastic detector system is envisaged to provide the timing signals from the beta particles emitted by the β-decaying parent nuclei.

A limiting factor inherent to fragmentation facilities arises due to the prompt flash that occurs during the slowing down of the beam in matter on its way to the implantation point. The main component is associated to the final degrader and AIDA and occurs in the time range o a few ns. Depending on the available energy of the ions, electromagnetic radiation up to several hundreds keV with very high X- and gamma-ray multiplicity is emitted. This sets a limit for very short-lived isomers, but due to the high FATIMA granularity and the fast detectors with short recovery times, it will be minimized. An effect on the EDAQ system due to the prompt flash should also be expected.

In order to fulfil its function, the FAst TIMing Array needs to be modular and flexible, with large solid angle coverage around AIDA. The size of the crystals needs to balance good intrinsic timing resolution, which deteriorates with the crystal size, and detector efficiency, which increases with the crystal volume and the proximity to the source. A suitable crystal shape is the one that allows building rings of detectors around the source, strongly increasing the solid angle. In this way, the light collection in the crystal, and therefore the time resolution, is improved, and simultaneously the intrinsic efficiency losses can be compensated. Additionally it is desirable to have sufficient efficiency for the detection of gamma rays with energies up to about 4 MeV. The ability to measure short lifetimes is defined directly proportional to the time resolution and inversely proportional to the statistics. This can be quantified by a figure of merit that can be defined as $FoM = FWHM / \sqrt{N}$, where FWHM is the coincidence time resolution and N is the number of counts in the time peak. Thus the optimization of the detector time resolution and the enhancement of the statistics are needed in order to maximize the figure of merit.

The fast-timing array will be installed at the final focus of the Super-FRS, where highly charged exotic nuclei will be implanted in the AIDA detector and β-delayed or isomeric delayed γ-rays will be detected by FATIMA. A reduced version of the AIDA stop detector will be used, with an acceptance size of 8 x 8 cm^2, to stop the beam with a size of the order of 40 cm^2. The use of the wide version of AIDA, covering the full focal plane of the Super-FRS with 24 x 8 cm^2, does not offer many benefits since the efficiency of double coincidences is only moderately enhanced at the expense of a much enlarged and costly fast timing array.

In the fast-timing experiments which will be performed at FAIR the fragments will be implanted in different positions in the dispersive plane, with a spread in the range of the maximum longitude of 8 cm. Depending on the implantation position, the flight path of emitted γ-rays to the FATIMA detectors can vary by roughly this distance, leading to time differences between detectors of the order of 250 ps, similar to the coincidence resolving time of the individual detectors. To maintain the good timing properties of the array a position sensitive detector such as AIDA is needed to correct for the different flight paths. Hence, one of the main constraints on the timing precision of the system will be the position resolution of the implantation detector, which will be used in conjunction with FATIMA. AIDA has an excellent position resolution, which is expected to be as good as 0.05 cm. Such high position sensitivity will help reduce the systematic uncertainty arising from the implantation position down to 2 ps, which is well within the timing properties of FATIMA.

In the cases where high-multiplicity γ-ray events occur, auxiliary detectors will be needed in order to select the desired decay branch. The solution, which has been used by the FATIMA collaboration in the past years, is to use hybrid arrays comprising $LaBr_3(Ce)$ and HPGe detectors [MAR10,REG14]. Such arrays gain from the excellent timing properties of the scintillator detectors and the superior resolution of the HPGe detectors. In the DESPEC configuration coupling to the DESPEC Germanium Array Spectrometer (DEGAS) can be achieved by integrating FATIMA detectors into the DEGAS geometry around the wide version of AIDA, by using suitable connecting flanges.

3. Technical specifications and design details for FATIMA

In order to define the optimal FAst TIMing Array for DESPEC research and development has been done in several areas, as described below. Much of this work is based on the previous experience of the fast-timing collaboration, gathered over twenty-five years of expertise, and includes several key aspects of the array. The crystal material was of crucial importance for the FATIMA design. A large effort has been devoted to the study of the response of halide materials having a variety of sizes and shapes, and equipped with different photosensors. These studies include test experiments and Monte-Carlo simulations using GEANT4 and were performed to identify the optimal size, shape, and arrangement of the detectors. In addition the experimental studies were carried out with shielded and unshielded detectors. The front-end and signal processing electronics has also been studied in detail. Several timing modules were used and optimized to achieve the best time response for the measurement of subnanosecond half-lives. Data analysis procedures, the software at the acquisition stage for the off-line analysis, and sort codes have been developed. Finally the mechanical support has been designed and built and the integration into the DESPEC infrastructure has been designed.

3.1. Choice of crystal type

As mentioned above, a new generation of inorganic scintillators, mostly halide compounds, has revolutionized gamma-spectroscopy. They unite large effective atomic number, excellent timing properties and a good energy resolution. The most prominent example is $LaBr_3$(Ce), commercially available for a decade [SG09]. It is a very fast crystal (see Fig. 2), with a relatively high effective Z and high photon yield of 63 000 photons/MeV (see Table 1). The energy resolution at the ^{137}Cs 662-keV gamma energy is 3%, much better than the very fast BaF_2 crystals that were previously used for fast-timing measurements.

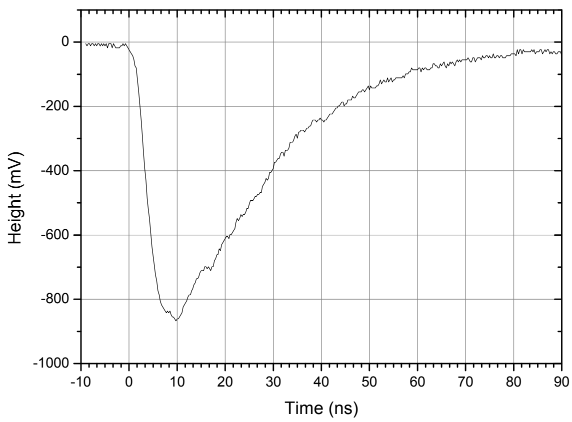


Figure 2: Anode signal of a "Studsvik" design $LaBr_3$(Ce) coupled to the R9779 Photomultiplier taken with a 4 Gs/s oscilloscope. The rise time of the signal from the 20% to maximum is below 6 ns.

The enhanced energy resolution of $LaBr_3$(Ce) entails a big advantage in fast timing measurements such as those proposed for FATIMA at DESPEC, given that complex decay schemes, with a large number of transitions and transitions of overlapping energies need to be unravelled. This is the case for exotic nuclei with large beta-decay Q-values. Moreover, a better energy resolution provides a better ratio between the full-energy peak and the Compton continuum underneath, and thus results in smaller time corrections due to Compton background under the full-energy peaks [MAC91].

Also, it has been reported that the time resolution of $LaBr_3$(Ce) crystals depends on the amount of Ce doping [GLO05] and that it improves with higher doping. Standard crystals commercially available at present have 5% doping. The time resolution given as the full width at half maximum (FWHM) for an individual crystal was reported to be 107(4) ps [MOS06] for ^{60}Co peak-to-peak coincidences for a cylindrical crystal 1 inch in height and 1 inch in diameter. Recently our collaboration has reported FWHM values below 100 ps [VED15] in the same conditions. The coincidence resolution time (CRT) for a pair of similar crystals at the same energies is of the order of 150 ps [MAR10].

This makes $LaBr_3$(Ce) an attractive inorganic material to use for γ-ray spectroscopy and sub-nanosecond half-live measurements. In the fast timing measurements performed over the last years the fast timing collaboration has used three types of $LaBr_3$(Ce) crystals: cylindrical in shape with the diameter and height of 1 in. x 1 in., cylindrical with dimensions 1.5 in. x 1.5 in., and conical with base diameter of 1.5 in. and height of 1.5 in. [WHI07].

It should be noted that $LaBr_3$(Ce) is an expensive crystal and therefore the FATIMA collaboration has investigated several other alternatives. The recently developed $CeBr_3$ is a good candidate (see Table 1), owing to its fast rise time, decay constant of 17 ns and high photon yield of about 68 000 photons/MeV [SHA05]. A good energy resolution, of the order of 4.3% at 662 keV has also been reported. A further advantage of this crystal over BaF_2 and $LaBr_3$(Ce) is that it does not possess internal activity. We have performed a detailed study of this type of crystal to assess whether it is a viable alternative to $LaBr_3$(Ce) [FRA13]. For this work we have investigated the time response of a $CeBr_3$ crystal of 1 in. in diameter and 1 in. in height, commercially available from *Scionix*, with two 2-inch fast-response photomultipliers. The best results were obtained with the R9779 Hamamatsu phototube. Very good time resolutions of 119(2) ps and 164(2) ps were obtained at ^{60}Co energies and for 511keV photons from a ^{22}Na source, respectively, for the combination $CeBr_3$ crystal with Hamamatsu PMT operated at ~1300V. The time resolution stays constant over the high voltage range from 1100 to 1450 V. At the operational voltage the response of the $CeBr_3$–Hamamatsu detector was very linear in energy, and good energy resolution was preserved. Nevertheless the energy (and also timing) performance of $LaBr_3$(Ce) is still superior to $CeBr_3$. Moreover, $LaBr_3$(Ce) is manufactured in shapes and sizes suited for FATIMA, which compensates the slightly higher cost per cm^3.

Material	$LaBr_3$(Ce)	$CeBr_3$	LuAG(Pr)
Density (g/cm^3)	5.29	5.10	6.73
Light yield (photons/keV)	63	60	22
Emission peak (nm)	380	380	310
Decay constant (ns)	25	17	<25
$\Delta E/E$ (% at 662 keV, PMT)	~3.0	~4.0	~4.5
Radiation Length (cm)	1.88	1.96	1.41
Internal activity	Yes	No	Yes
Hygroscopic	Yes	Yes	No

Table 1. Properties of the scintillators studied in this work.

Several other inorganic options have been explored. It is worth mentioning LuAG(Pr) scintillator material, which shows good potential in terms of high effective Z (density) and having a decay constant below 25 ns (see Table 1). Being a promising candidate, the exhaustive tests performed with 1-cm^3 crystals [FRA13b] reveal that the full width at half maximum (FWHM) time resolutions is 147(2) ps for a single crystal measured for ^{60}Co gamma energies. This is far from the best values for the Ce-based inorganic compounds.

3.2. Choice of photosensor

The requirements for the FATIMA readout photodetection are mainly defined by the fast time response required to achieve the best time resolution. Since no strong magnetic fringe fields are expected and the dynamic range is limited, standard photosensors such as fast photomultiplier tubes (PMTs) or Silicon Photomultipliers (SiPMs) may be used. In addition, a good linearity and stability with respect to temperature and voltage variations is requested.

A test bench, depicted in Figure 3, has been set up at Universidad Complutense in Madrid for detailed studies of photosensors, the selection of crystals and the optimization of their operational parameters. First the feasibility to read out fast scintillating crystals, of relatively large size, with Silicon photomultipliers has been explored. Different combinations of Hamamatsu MPPCs and SenSL SiPMs have been investigated in combination with fast scintillators. For $LaBr_3(Ce)$ with the dimensions required for FATIMA, the readout via the optical coupling window yields an energy resolution larger than 5% at 662 keV, and the time resolution is not competitive with commercially photomultiplier tubes neither. Moreover, the available sizes are not sufficiently large to couple to the chosen scintillator crystals, thus requiring building arrays and coupling the SiPMs electrically, deteriorating the time response. With the introduction in the market of new Silicon photomultipliers having reduced cross talk, improved quantum efficiency and increased area, this type of photosensor might nevertheless become an option for future use.

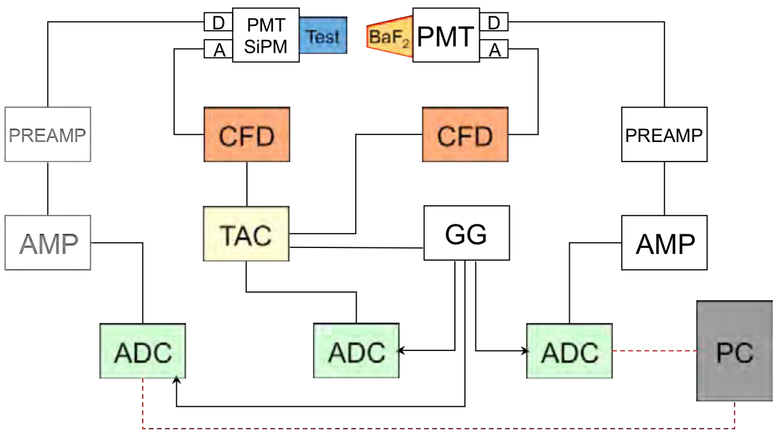


Figure 3. Schematics of the electronics for the timing test bench.

In a second stage, a study has been performed on the commercial photomultiplier tubes. After the discontinuing of the production of Photonis photomultipliers, a viable alternative to the Photonis fast 2-inch photomultiplier needed to be found. The 8-stage Hamamatsu R9779 appeared to be a good option. This photomultiplier has an accelerator ring at front-end, with anode rise time of 1.8 ns and Transit Time Spread (TTS) of 250 ps. We have compared its time response to the fast XP20D0 Photonis photomultiplier, which has also 8 dynodes, anode rise time of 1.6 ns, and 520 ps TTS. Tests were performed with a very fast

NE111A plastic disk of 25 mm diameter and 5 mm height, which is known to provide very good time response of about 60 ps with the XP2020Q PMT [MOS89]. In our tests a FWHM time resolution of 75(4) ps for NE111A plastic is obtained for the XP20D0 PMT, whereas better time resolution of 50(3) ps is achieved with the R9779 PMT [FRA11]. In addition, measurements of the $LaBr_3$(Ce) [REG12] and $CeBr_3$ [FRA13] crystals coupled to the Photonis XP20D0 photomultiplier have revealed a strong non-linear energy response and a much worse time resolution than detectors equipped with the same crystals but coupled to the R9779 PMT. Earlier, the XP20D0 PMTs had shown relatively good performance with $LaBr_3$(Ce) crystals, in particular good timing resolution [MOS06], but much worse energy linearity.

It should be also noted that the coupling of R9779 to $LaBr_3$(Ce) shows excellent performance in terms of time response and good linearity [REG12]. In our investigation with $LaBr_3$(Ce) coupled to Hamamatsu R9779 PMTs it is shown that at the normal operation voltages, where the best time resolution is achieved, the non-linear effects at low energies can be neglected [VED13].

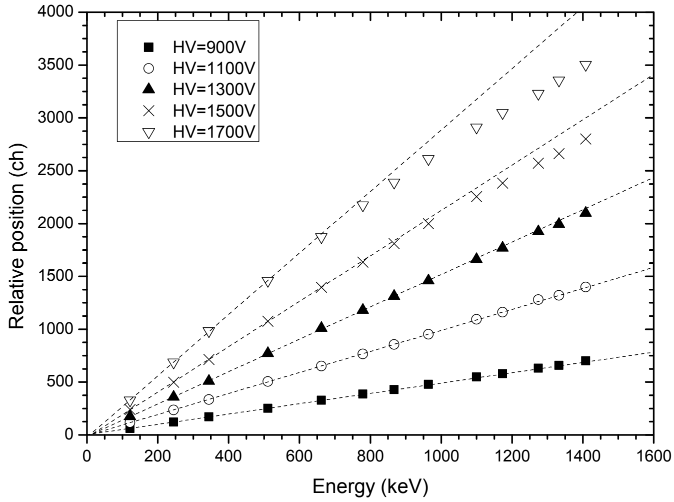


Figure 4. Linearity of the $LaBr_3$(Ce)+R9779 combination as a function of voltage.

Based on the above considerations it was concluded that the Hamamatsu R9779 PMT is ideally suited for fast crystals with high photon yield, such as $LaBr_3$(Ce), and in therefore for FATIMA at DESPEC.

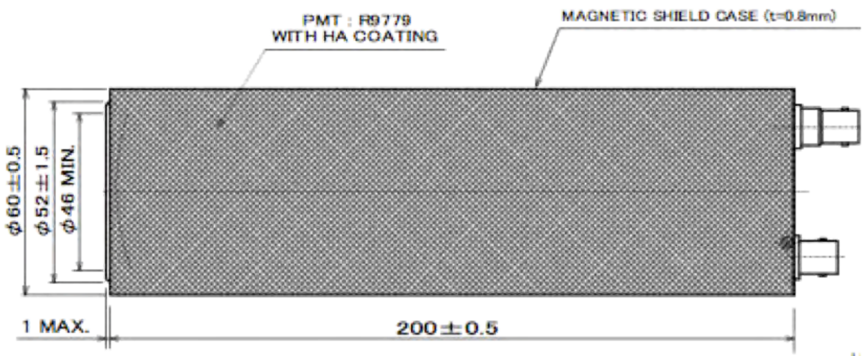


Figure 5. Sketch of the Hamamatsu R9779 PMT with basic dimensions.

3.3. Selection of crystal shape and detector evaluation

Test measurements have been performed with $LaBr_3(Ce)$ crystals of different sizes and shapes to determine the best crystal geometry. The time and energy responses have been studied in a number of experiments where the crystals where coupled to two different models of PMT that initially showed very similar parameters, the 8-stage Hamamatsu R9779 and the Photonis XP20D0 discussed above. An optimization of the operation parameters for fast timing applications using analog signal processing via CFD (ORTEC 935) and TAC (ORTEC 567) has been done. The time resolutions are given for the optimized parameters, namely the external CFD delay and the CFD zero-crossing value (Z). Several of the detector configurations have been tested in detail in order to assess the stability against variations in high voltage. The time walk as a function of energy has also been studied.

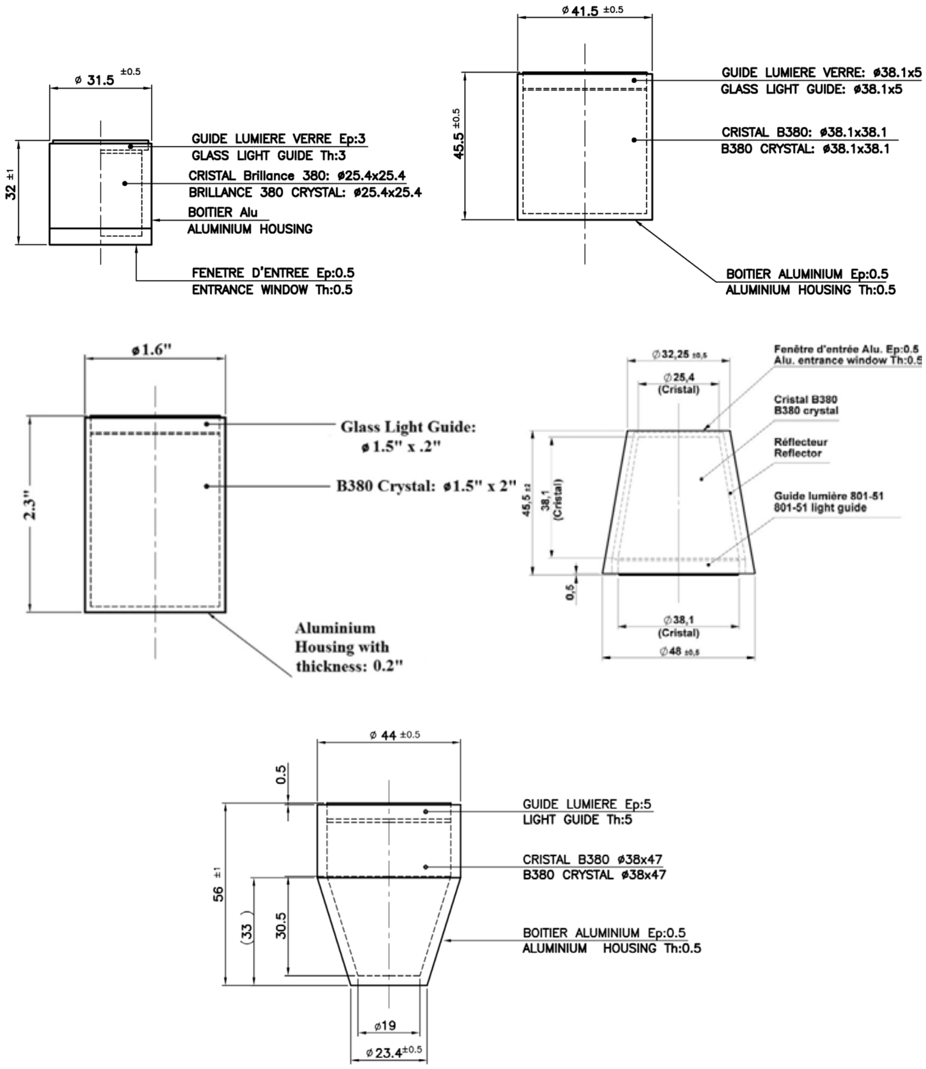


Figure 6. Cross sections of the different $LaBr_3(Ce)$ crystals under consideration for this study.

The main shapes and sizes under consideration in this TDR are depicted in Figure 6. The small 1-inch x 1-in. cylinder is taken as reference. Two cylindrical crystals are considered, one with 1.5 in. base and 1.5 in. height and the second with 1.5 in. base and 2 in. height, having a higher efficiency. A truncated cone shape, with 1 in. height and bases of 1.5 in. and 1 in. has been specially designed by the FATIMA collaboration, owing to expected better timing response and ease to construct rings around AIDA. It has been developed by Saint Gobain. A second especially designed crystal, developed for FATIMA, is based on the advantageous "Studsvik" design for BaF_2 crystals [MAC14], a tapered "hybrid" crystal, with a cylindrical section 1.5 in. in the base and 0.65 in. in height and a 1.2 in. long conical section, i.e. with a total height of 1.85 in. (see Figure 6).

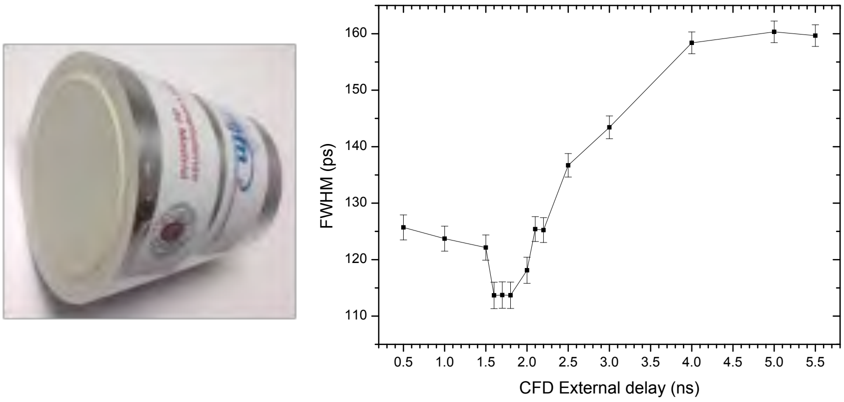


Figure 7. FWHM time resolution of $LaBr_3$(Ce) truncated cone coupled to Hamamatsu R9779 as a function of the CFD external delay, at 1150 V operation.

A summary of the result of the time resolution measurements with the different crystals, after the optimization of the parameters, is shown in Table 2. It can be concluded that the best performing crystals in terms of time resolution and efficiency are the 1.5" cylindrical and the truncated conical ones, specially the Studsvik design.

Nevertheless, the energy resolution of the Studsvik design crystals is not up to the specifications. This problem has been addressed with the provider, but no solution has been found until now. Therefore this option has not been considered further, although if the energy problem could be solved and given its size, it is the best in terms of time resolution.

$LaBr_3$(Ce) shape	$LaBr_3$(Ce) dimensions	$LaBr_3$(Ce) volume (cm^3)	ΔE/E (%) @ 662 keV	FWHM (ps) 511 keV	FWHM (ps) ^{60}Co
Cylinder	⌀1" x 1"	12.87	2.9	145	100
Cylinder	⌀1.5" x 1.5"	43.10	3.3	170	140
Cylinder	⌀1.5" x 2"	57.46	3.5	380	185
Truncated cone	⌀(1"/1.5") x 1.5"	30.49	3.5	160	115
Studsvik (tapered)	⌀(0.75"/1.5") x 1.2" + 0.65"	38.89	4.2	160	115

Table 2. Description of the crystals and measured time resolution, given as the de-convoluted FWHM for an individual crystal against a fast BaF_2 reference detector, from our measurements with R9779 PMT and R6231 for energy resolution. For the ⌀1.5" x 2" cylinder taken from [ROB14].

3.4. Summary of Monte Carlo simulations

In order to fulfil its intended purpose, the FAst TIMing Array needs to be both modular and efficient, covering as much of the solid angle as possible. A complete Monte Carlo simulation of the setup has been carried out, in order to understand the overall efficiency and performance.

Since newer packages are able to simulate light yield and optical photons, the simulation of the time response is in principle feasible. This would allow optimizing detector shape and size, together with geometry, efficiency and resolution, in a single package, making it possible to provide realistic physics generators. We have explored this possibility by employing the GEANT4 toolkit [Geant]. For the test we have used the reference cylindrical shape of 1 inch, and compared it to the conical and tapered geometries described above. In the simulation the optical photons, created after impact of gamma radiation, were tracked until the PMT photocathode. Delays arising from the fluorescence process and photomultiplier transit time were included to obtain a realistic time signal from the photomultiplier. The constant fraction value of events generated this way was then histogrammed. Unfortunately the results of the simulation show non-physical components, with strong non-Gaussian behaviour in the time peak, which has not been observed experimentally. In spite of GEANT4 being very useful for the prediction of detector efficiencies, we conclude therefore that the simulations do not predict the time resolution of our scintillators with sufficient accuracy as required for fast timing.

A second attempt has been done by developing optical photon simulations with Detect2000 [Detect], a Monte Carlo package devoted to optical materials [FER13]. It allows for a realistic modelling of the geometry of the detectors and then generates individual emission of photons in specified locations. An interface to the PENELOPE Monte Carlo code [Penel] has been written in order to connect the optical photon simulation with realistic gamma interactions of photons in the scintillator materials. Although the results are more realistic, still the accuracy is not sufficient for our purposes.

Therefore, in order to assess the Figure of Merit of the different configurations, the time resolution of the $LaBr_3$(Ce) crystals was taken as the measured values (the individual crystal resolution values given above), and Monte Carlo simulations of the efficiencies were performed using GEANT4. The aim is to study the arrangement of the fast timing detectors around AIDA to achieve the maximum detection efficiency, while keeping a good timing resolution. GEANT4 has been used to determine the full-energy peak efficiencies for different arrangements of a variety of shapes and sizes of $LaBr_3$(Ce) crystals over an energy range from 0.1 to 4 MeV. An extensive report is presented in reference [ROB14]. In the simulations the full-energy peak efficiency of the system was studied. Configurations built of crystals with cylindrical shapes and sizes of 1 in. x 1 in., 1.5 in. x 1.5 in, 2 in. x 2 in. and 1.5 in. x 2 in. were used. The efficiency of a system built of cylindrical crystals was then compared to the efficiency when conical and Studsvik design ("hybrid") detectors were used.

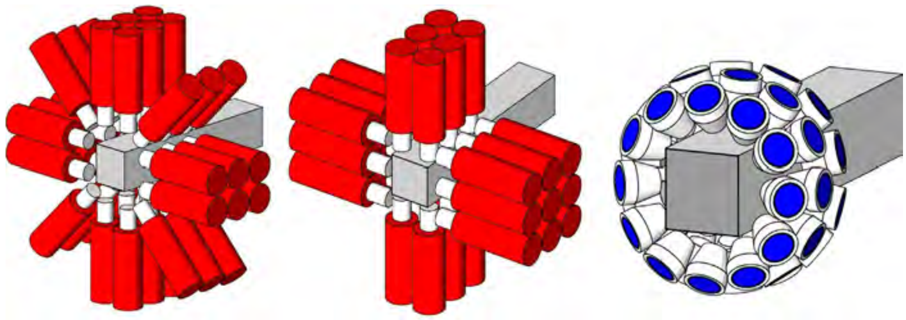


Figure 8. Star, cross and ring configurations studied in this work. Taken from [ROB14].

The centre of the tenth DSSSD in the AIDA 8x8 cm^2 version, was chosen as the implantation point and treated as an isotropic point source. The simulation includes the aluminium chamber with dimensions 10 x 10 x 50 cm and a thickness of 0.2 cm. The distance from the implantation point to the corners of the can is 7.07 cm. For the simulations an inner radius of 8.3 cm is considered to give an integer number of all the proposed detector sizes. Different geometries of the set up have been investigated, including cross geometry with detectors pointing to the side of the AIDA chamber, a star (cross plus supplemental detectors at 45 degrees) and spherical-like geometries, where the detectors are arranged in rings tilted with respect to the beam axis, as depicted in Figure 8. Rings are constructed with the maximum packing density for each of the detector types, namely 8 2 in. x 2 in. cylinders, 10 1.5 in. x 1.5 in and 1.5 in. x 2 in. cylinders, and 12 conical, 1 in. x 1 in. and Studsvik design crystals. The efficiency for a point like source in the centre implantation detector is shown in Figure 9. It is shown that the best-suited configurations are achieved with rings of 12 detectors. This is true both for the ball-like configuration with Studsvik or conical detectors, and for the star configuration with long cylindrical detectors.

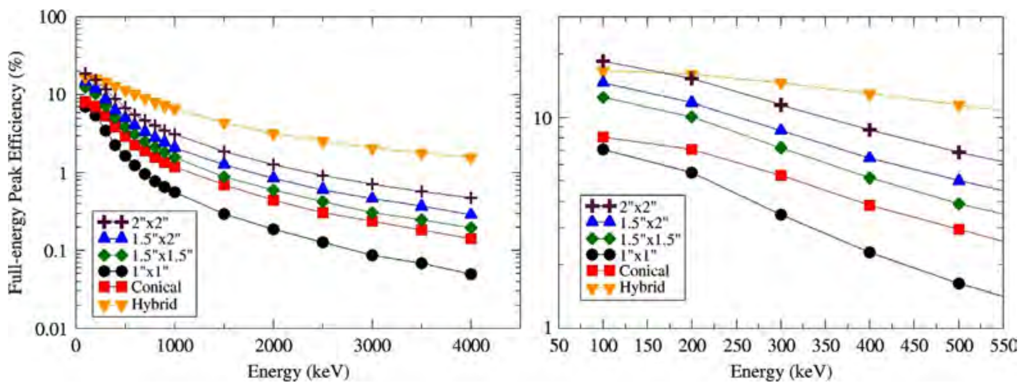


Figure 9. Simulated FEP efficiencies for detector rings of different $LaBr_3(Ce)$ crystal sizes and shapes. Taken from reference [ROB14].

The simulations reveal that the optimal efficiency of FATIMA can be obtained in the cases where the detectors are arranged in several rings around AIDA. The best efficiency is obtained for a system in ring assembly with the Studsvik design ("hybrid") crystals, as shown in Figures 9 and 10. The simulations show also the use of these crystals increase the efficiency of the system by reducing the non-active space between the individual crystals, and with a very good time response owing to the improved light collection. Unfortunately this option, which otherwise will be optimal, is not viable due to the deterioration of the energy resolution of the crystals as provided by the manufacturer.

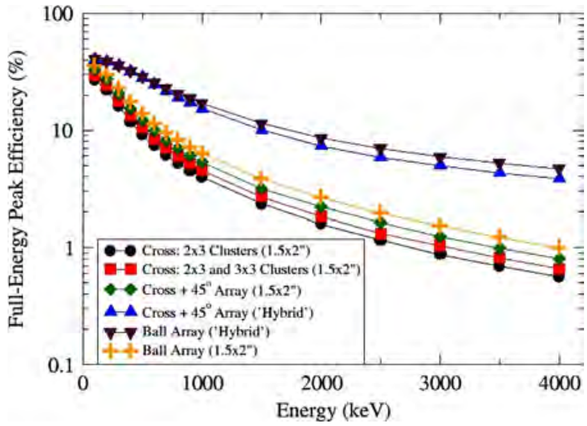


Figure 10. Simulated FEP efficiencies for several detector configurations, using the long cylinders and the Studsvik design (hybrid) $LaBr_3$(Ce) crystals [ROB14].

Both the 1.5 in. x 2 in. and the conical $LaBr_3$(Ce) crystals have a reasonable efficiency and good timing properties up to a few MeV, with better Figure of Merit for the conically-shaped crystals at low energies and better FoM for the larger crystals at 1 MeV and above. Given the volume and price constraints it has been decided to use both types of detector geometries, i.e. ⌀ 1.5 in. x 2 in. cylinders and ⌀ (1 in. / 1.5 in.) x 1.5 in. truncated cones, on FATIMA. This also makes the system more flexible to adjust to different geometries, and in particular to adjust for the use of high-resolution gamma detectors in a mixed array.

3.5. Background and shielding

The stopping of the heavy charged particles in medium creates a burst of Bremsstrahlung, which is mostly directed in forward direction. To reduce the background component, the FATIMA detectors will be placed in rings separated from the beam axis. In the cases where possible, i.e. in the experiments where high-energy gamma rays populate and de-excite the state of interest, lead shielding can be placed in front of the detectors to attenuate the low energy background.

A significant contribution to the background in compact detector arrays such as FATIMA, come from scattered and back-scattered gamma rays from the experimental surroundings. This is in addition to the Compton continuum originating from high-energy gammas, which is the background to the full energy peaks of interest and carries different time properties [MAC89]. For lifetime measurements in the picosecond range the reduction of the background is thus essential. The low-energy background is mainly due to scattering in material around the detector array, including scattered gamma rays in other detectors, which are known as cross-talk events. This low-energy background is largely delayed and needs to be suppressed as much as possible in order to reduce contributions to the time-spectra of full energy peak (FEP) events of γ-rays below 300 keV. The use of active BGO shielding reduces considerably the background for energies below 300 keV [REGPhD], with reduction factors of the order of 3 at around 100 keV. This effect can be decisive for lifetime measurements in the low-energy region, since the background is generated from coincident gamma rays and thus contributes to the time-spectra of the FEP events. For higher energies the background is due to Compton events of higher energy γ-rays in the $LaBr_3$(Ce) crystal where the scattered γ-rays leave the crystal and therefore are faster. In this case the use of active BGO shielding only reduces the high-energy background by 10 to 20%.

Due to the cost and space limitation of BGO shields it is customary to use passive shielding made of a few millimetre thick layer of Pb and mounted around the crystals. We have explored this solution in our test experiments. It has to be noted that, even though it reduces the low-energy background, the shielding has the drawback of γ-ray scattering from the Pb shield into the $LaBr_3$(Ce) crystal, and the production of X-rays by the high-energy γ-rays, which show up at low energies. Moreover, the gamma-ray efficiency is a key factor for DESPEC experiments, and then the use of a compact FAst TIMing Array is desired. The use of active or passive shields reduces the γ-ray efficiency due to space constraints. In experiments performed using a mixed array of HPGe detectors and unshielded $LaBr_3$(Ce) detectors (see Section 4) a good background suppression was achieved by defining the best coincidence conditions in order to minimize the cross-talk events, e.g., by excluding triple events with doubles in two neighbouring $LaBr_3$(Ce) detectors. This is a proven method that has already been put in practice [REG14].

3.6. Beta detection

For the investigation of excited states in exotic nuclei populated after the beta decay of mass-separated ions at the LEB, the high granularity of the AIDA implantation detector allows a spatial correlation to be performed between a detected ion and an electron from its beta decay. Since AIDA is based on Si detectors, its time resolution is around 5 ns and the signal processing time is of the order of 10 μs. Hence, its time response is several orders of magnitude slower than the $LaBr_3$(Ce) and makes it needed to use auxiliary detectors for measurements of lifetimes of excited nuclear states, directly populated from the parent nucleus. The solution is based on our experience in beta decay studies at ISOLDE and at the Lohengrin fission fragment separator at ILL (Grenoble), where the characteristics of an extended beam are similar to those of the stopped DESPEC beam in the AIDA detectors, and also in the tests experiments performed at RIKEN.

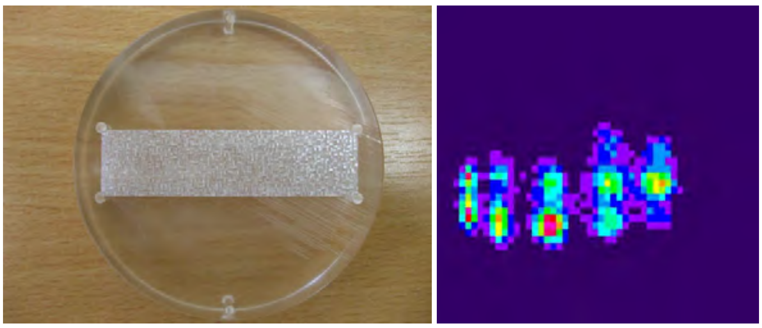


Figure 11: End-on view of the fibre optic detector element for the identification of ions and beta particles (left), and the obtained position resolution of about 3 mm (right).

Fast plastic scintillators are commonly used for precise timing of electron emission. In this case they will be mounted around the DSSSDs of AIDA to register the beta particles, emitted after implantation. This solution has already been used in the RIKEN setup [BROPhD]. The WAS3ABi stopper comprised 5 layers of DSSSDs placed 0.5 mm apart, each with an active area of 60 x 40 mm^2. The cross-sectional area of each strip was 1 mm^2 giving a segmentation of 60 x 40. For beta timing plastic scintillators of 2 mm thickness and area 65 x 45 mm^2 were installed upstream and downstream of WAS3ABi. Each of them was optically coupled to two photo-multiplier tubes, and the mean of the time signals was used as the beta-electron detection time. The efficiency of each of the beta plastics was of the order of 30%.

Another option that we have explored for FATIMA is the use of an array of fibre optics read out by a photomultiplier tube equipped with a resistive gridded anode. This scenario was tested at the Lohengrin spectrometer, where a position resolution of ~3 mm was achieved. The detector element is an array of 15 x 36 plastic scintillating fibre optics (see Figure 11) with a 1 mm x 1 mm square cross-section and consists of a BCF-12 fibre, with a double external multi-cladding. The fibres face the beam end on, and ions are implanted in to the open face of the fibre optics. The scintillation light, generated by ions or electrons implanted into the fibre optics, is then transmitted to a Hamamatsu R2486 PMT, with active area of its window is 50 mm in diameter. In the test custom-made preamplifiers were used to optimize the shape of the signals out of the PMT for use with the acquisition system. The results of the test illustrate the position resolution capabilities and show good timing response of the fibre. This represents a feasible solution for the timing of beta particles.

3.7. Layout of the fast timing array

The FATIMA collaboration has long-standing experience with scintillator detectors including $LaBr_3$(Ce) crystals. Successful campaigns have been held at several international facilities, including ILL (France), ISOLDE (CERN), RIKEN (Japan), IFIN-HH (Romania) and University of Cologne (Germany). In addition, the collaboration is very experienced with radioactive beam experiments at GSI. The FATIMA design is based on the R&D activities described above, which have been performed over several years, the detailed simulations of the setup, and the experience with actual data taking and analysis at several facilities.

As discussed above the modular configurations include arrangements of 12 detectors each, combining either long cylindrical (1.5 in. x 2 in.) crystals, or truncated cone crystals (closer to the chamber), with the Hamamatsu R9779 PMT. In the case of the future DESPEC experiments, the minimal configuration around the AIDA Si-array for isomer measurements with these crystals consists of 3 rings with 12 detectors in each, providing a total of 36 detectors. More complex configurations will consist of 5 rings with 60 detectors in total placed around AIDA. It has been decided to proceed in two phases for the array. In **Phase 1**, three rings of ⌀1.5 in. x 2 in. crystals (N38x51/B380) will be implemented. In **Phase 2**, two more rings with 12 conical detectors each will be constructed. The total number of detectors will therefore be 60.

3.8. Mechanical supporting structure

The FATIMA mechanical support will be modular in order to be used with auxiliary detectors. It will comprise five rings of 12 detectors, that is, 60 detectors. The middle ring is mounted at 4 degrees with respect to the beam axis. Two of the rings will be installed at 44 degrees with respect to the beam axis, both on forward and backward angles. Two more rings are mounted in forward and backward angles. All detectors will be focused towards the centre of AIDA. The Phase 1 structure consists of the 3 middle rings, as shown in Figure 12. Phase 2 will include 2 more rings.

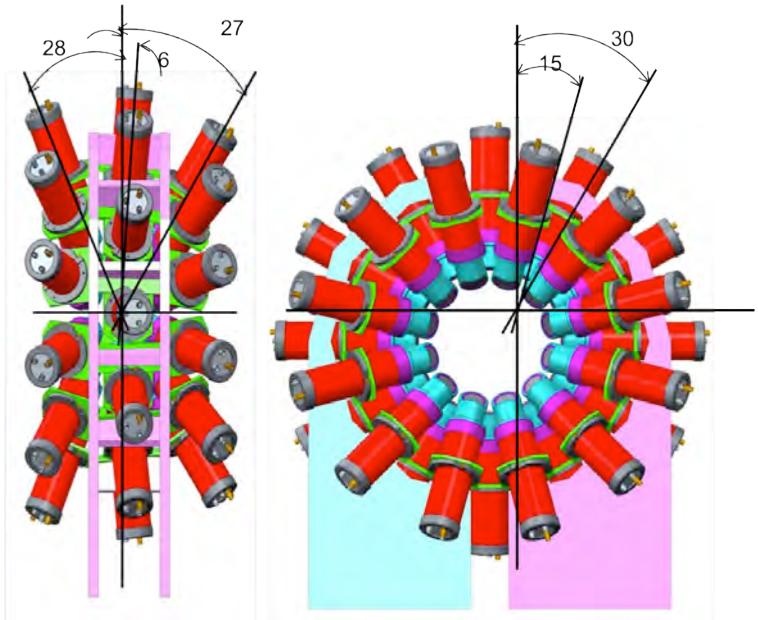


Figure 12. View of the arrangement with 3 rings for the long cylindrical crystals.

The mechanical structure has been built at Daresbury STFC, UK. The holding structure, comprising two semi-circular modules, is made of aluminium. The detectors are fixed on their positions by aluminium clamps. The aluminium structure is mounted on two iron frameworks which will be bolted into the DESPEC infrastructure trough two metallic plates. The weight of each of the framework parts plus its base is 175 kg, and the aluminium assemblies are 28 kg, i.e. the total weight of the mechanics without the $LaBr_3(Ce)$ detectors is 378 kg. The mechanical structure was delivered to Surrey in June 2014 and mechanically tested with half of the $LaBr_3(Ce)$ detectors.

The mechanical structure has a footprint of 2.5 x 1.5 m^2 and needs to be bolted to fixed structures on the floor of the low energy branch cave. This structure is common for the installation of fixed experimental setups and will need to be provided within the general infrastructure of the facility. With standard alignment a precision of 2 mm can be routinely achieved. Features on the side plates allow accurate positioning of the structure using a laser tracker and spatial analyser software. The detectors can be positioned to within 1 mm precision.

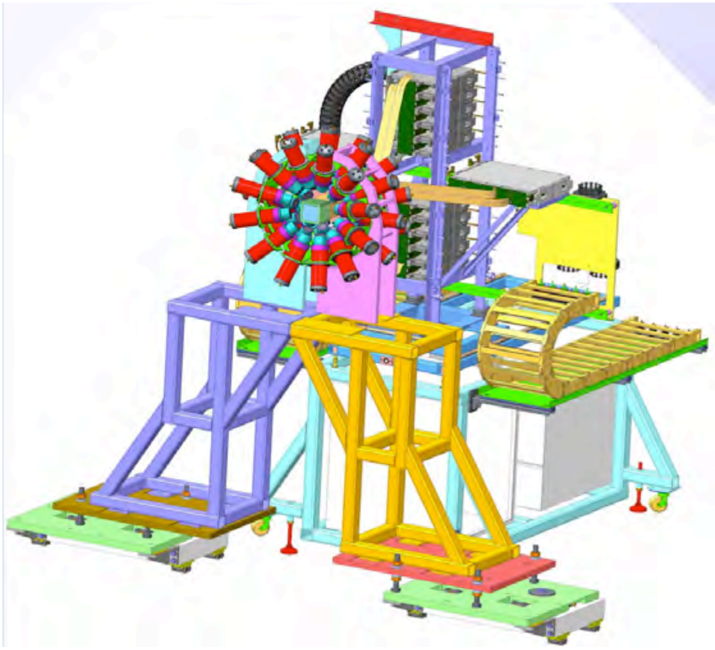


Fig. 13. Supporting structures integrated with AIDA and 3 rings of detectors.

3.9. Electronics and Data Acquisition System

The FATIMA array has the main requirement of high precision timing between channels, be it $LaBr_3$(Ce) detectors for γγ timing of fast plastic and $LaBr_3$(Ce) detectors for βγ(γ) timing. As discussed above the $LaBr_3$(Ce) crystals are coupled to PMTs with dynode and anode output, one for energy and the other one for timing,

The high voltage supply for the PMTs is provided by a CAEN SY1535D modular power supply with a maximum output power of 2.5 kW. The rack can be equipped with 8 units each of which can bias 8 channels. The system can power individually each of the channels in the range of 0 to 3.5 kV. Each of the units is equipped with a microprocessor and the bias parameters are set and remote controlled via Ethernet. It can be linked to the general EPICS interface. Standalone and NIM low-ripple HV units have been also purchased and extensively used for tests.

For the proper handling of the time signals, in order to achieve the best timing resolution, a well-established solution is based on the use of analog fast TAC units. Each individual detector signal is processed by a CFD that serves as a start to a TAC module. The TAC is then stopped by another fast signal issued from a second detector and processed by a second CFD channel. For arrays involving large number of detectors, a common stop is made by the combination of the rest of detectors, with the particularity that only detectors in increasing number are used for the stop (to reduce the number of channels). The TAC signals (together with energy signals from the PMT dynodes) are afterwards processed by ADCs or digitizers. A VME-based digital system, equipped with 8-channel 14-bit digitizers at a sampling rate of 100 MS/s has been used in tests experiments. This is a working solution that has been already used in the EXILL-FATIMA experiments (see below), but is difficult to extend the TAC-based method to a very large number of detectors. Nonetheless, for the operation of a few channels and comparison with the alternative methods, electronics for 8 channels (2 quad ORTEC 935 CFDs and 8 ORTEC 567 TAC units) have been purchased.

An alternative way of processing is based on TDCs, whereby the signals from the anodes are processed by high quality CFD units to preserve good timing and minimize the time walk, and then send to high resolution TDCs. The preferred solution for FATIMA is based on 4-channel ORTEC 935 200-MHz CFD on the NIM standard, with ultra low walk below 50 ps for a 1:100 dynamic range, in combination with CAEN VME TDC modules, model V1290, which accepts signals from 32 independent channels. The V1290 TDC has a time resolution of 25 ps (LSB), 52 μs full-scale range and output buffer for storage and data output in event or continuous mode. This is a working solution that can be readily implemented. TDCs model MTDC-32 by Mesytec on VME standard with maximum 10 ps RMS resolution are also under consideration. For Phase 1 CAEN V812B CFD 16-channel modules have also been purchased for a compact VME-based solution to be possible.

A related acquisition method is based on the use of a 16-channel FPGA-based VFTX TDC [GSIVD], with intrinsic FWHM resolution (RMS) below 20 ps, competitive with analog systems. It includes multi-hit capability, it is available at GSI and has been tested and recently used in experiments. On the PCI-Express interface on a PC, a solution also exists: the TAMEX2 boards can be used for high precision timing measurements in multi-channel systems while keeping compatibility to the GSI/FAIR data acquisition system. These units use leading mode and can operate time over threshold to achieve proper walk correction.

For the processing of the energy digital systems can readily be used, in our case VME-based solutions have been chosen for FATIMA. A trapezoidal algorithm used in several existing data acquisition systems (XIA, CAEN) can be employed to extract energy without deterioration of the energy resolution. The chosen solutions are based on VME boards from CAEN [CAEN]. The 8-channel 14-bit 100 MS/s V1724 digitizers have already been successfully used at EXILL-FATIMA. The 8-channel 10-bit 1 GS/s Flash ADC V1751C waveform digitizers, are the alternative. They support multi-board synchronization, allowing all ADCs to be matched to a common clock source and ensuring trigger time stamps alignment. Once synchronized, all data will be aligned and coherent across multiple boards. The advantage of using ADCs with high sampling rate is that they may eventually allow for fully digital processing for the timing signals as well. A PCI solution here would be FEBEX3 [FEB] from GSI, which can work at 14 bits with 100 MS/s and it is very cost effective. In combination with the TAMEX2 board for timing, it will allow for a fully PCI-based system.

The second acquisition method is based on a fully digital system, both for the timing and energy signals. Digital electronics offer new possibilities for pulse-shape analysis of detector signals as a range of algorithms can be applied to a set of samples to potentially give improved resolution, when compared to analogue signal processing. We have already evaluated some of the modules available in the market. The V1742 32 channel 12-bit switched capacitor digitizer, with sampling capacity of 5 GS/s, does not completely fulfil the requirements for sufficient throughput. Nevertheless it has proven useful to test several algorithms to extract timing information from fast scintillators. The timing performance of different algorithms was compared by looking at the time distributions when setting gates on the 1173- and 1332-keV transitions from the ^{60}Co source. Several algorithms have been applied, including trapezoidal filter, constant fraction algorithm, and a simple leading-edge model. The results are around 50 % worse than those obtained with an analog system. Using a digital oscilloscope we have investigated processing algorithms capable of obtaining reliable time and energy values from the raw fast scintillator signals [ORT13], with promising results. In conclusion, at the present stage the analog solutions are preferred for time processing in FATIMA, since they are well proved and safer to implement, but digital solutions are not excluded for future use.

The VME based solutions can be hosted on a VME crate, which also includes a V2718 6U VME master module, which is interfaced to the CONET (Chainable Optical NETwork) and controlled by a standard PC equipped with the PCI card CAEN A3818. The A3818 is a PCI Express (v1.1 or higher) card that can plug into both x8 and x16 PCI Express slot and allows the control of up to 4 CONET2 independent networks, with sustained data transfer rate up to 80 MByte/s. In addition, the integration of VME solutions into the NUSTAR DAQ can be readily achieved by using a RIO4/RIO5 with TRIVA and VETAR modules [GSIVD]. This will assure the full compatibility and control for data collection and merging into the general trigger scheme.

Synchronization to the White Rabbit system will be required from the VME (or PCI) solutions; this will be achieved via the standard synchronization VETAR module mentioned above. Correlation to the implanted ions in AIDA is needed, and scintillator energies will be required in coincidence with time differences (gamma-gamma or beta-gamma). Rates of 15 kHz for an individual $LaBr_3(Ce)$ have been sustained in the neutron-induced fission experiments on ^{235}U at the EXILL&FATIMA campaign [REG15]. These are the highest count rates one can envisage for this type of detector array, and the expected rates at FAIR are much lower. With double-coincidence driven data acquisition, FATIMA will not be the bottleneck in the data transfer. Data logging is expected to occur via the general NUSTAR DAQ framework.

3.10. Development of analysis procedures

An important characteristic of the ultra-fast timing technique introduced in the 1980s [MAC89,MOS89] is the analysis procedure involving accurate calibrations of the time response of the systems. This is of particular important to measure lifetimes of nuclear excited states down to about 3 ps accuracy when the centroid shift method is used. The good energy resolution of $LaBr_3(Ce)$ crystals has made it possible to extend the technique for gamma-gamma lifetimes [REG12]. The mirror symmetric centroid difference method takes advantage of the symmetry achieved for pairs of almost identical fast scintillators. In particular the crossing point of the prompt time calibration curves can be used as calibration point, since it does not depend on energy or on the timing properties of the detectors. The centroid differences can then be obtained by reversed gates on the gamma transitions, which is of interest for the calibration of the response curve (see Figure 14).

Due to the mirror symmetry of the centroid differences (prompt response differences, PRDs) and the universal prompt calibration point at the zero crossing, additional data points can be obtained for a more precise PRD curve calibration. The PRD curve is calibrated as a function of energy for any combination of energies in the range of 200–1500 keV with accuracy below 10 ps, resulting in a lifetime determination limit in the order of ps. This limit is increased by statistical uncertainties of the centroid determinations. For good peak to background ratios above 5, the additional error induced by background correction procedures is often negligible.

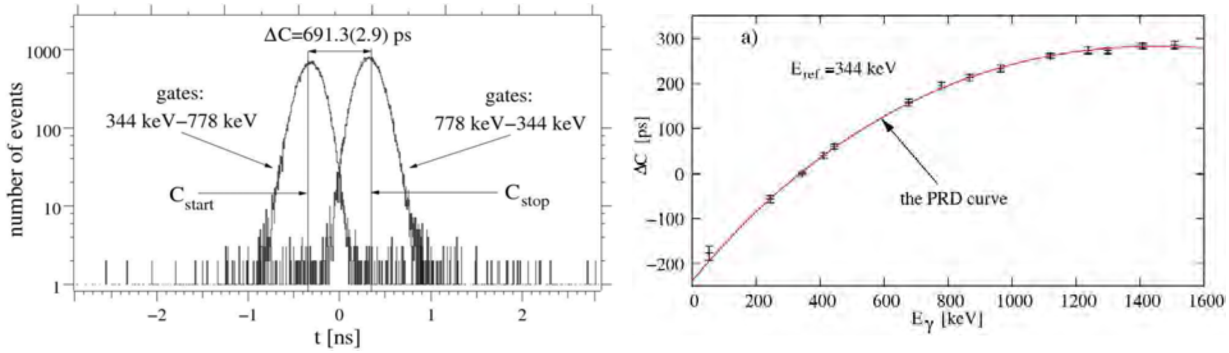


Figure 14. The prompt curve as a function of energy of the $LaBr_3$(Ce) scintillator detectors measured with a standard ^{152}Eu source, taken from [REG10].

In the case of lifetime measurements of nuclear excited states via γ-γ coincidences with FATIMA where *N* $LaBr_3$(Ce) scintillator detectors are used, this method can be generalized [REG13] to use two independent "start" and "stop" time spectra obtained by a superposition of the *N(N−1)* γ-γ time difference spectra of the *N* detector fast-timing system. Provided that the energy response and the electronic time pick-off of the detectors is similar, the time spectra can be matched using constant shifts, and a mean prompt response difference between start and stop events can be used. The curve can be calibrated and used as a single correction for lifetime determination. These mean γ-γ time-walk can be determined for 40 keV < E_γ < 1.3 MeV with a statistical accuracy below 5 ps using a ^{152}Eu γ-ray source. In this manner the complicated calibration of N detector time-walk curves is avoided and therefore, no correction involving possible systematic errors is applied to the data. The superposition of the *N(N−1)* γ-γ time spectra of FATIMA reduces the possible systematic deviations arising from geometrical effects, and provides an effective symmetrisation of the time response of the array. The only corrections come into play from the possible background contributions to the time spectra, which can be accounted for by generalizing the standard procedures [MAC89] to obtain a generalized time response for Compton events.

4. Previous prototypes and test experiments

Extensive laboratory tests have been performed to characterize detectors and photomultipliers, and to study the background effects. Analysis methods have been developed and already put into operation. In addition, experiments have been performed at several large-scale facilities.

4.1. The ROSPHERE mixed array for in-beam fast-timing

The *ROmanian array for SPectroscopy in HEavy ion REactions* (ROSPHERE) array represents one of the earliest implementation of the in-beam fast timing method using $LaBr_3$(Ce) crystals [MAR10]. It was designed as a multi-detector set-up dedicated to nuclear spectroscopy studies at the Bucharest 9 MV Tandem accelerator, and consist of up to 25 detectors, either Compton suppressed Ge detectors or fast $LaBr_3$(Ce) scintillator detectors.

The array served as a test bench for the various $LaBr_3$(Ce) crystal shapes listed in Table 2, with the exception of the Studsvik design. In its current configuration, the ROSPHERE spectrometer combines 14 HPGe detectors with 50% relative efficiency (1.1% absolute efficiency @ 1.33MeV) with 11 $LaBr_3$(Ce) detectors with a total absolute efficiency of 1.75% @ 1.33MeV.

In order to perform fast-timing experiments with the ROSPHERE array, several effects due to the use of the high light yield $LaBr_3$(Ce) crystals have been investigated, including the CFD time walk amplitude versus energy, the energy linearity, the time resolution as a function of the PMT bias voltage, and the gain stability versus the count rate. An optimal high voltage regime that assures minimum energy nonlinearity and gain stability without affecting the timing properties has been found. Algorithms have been developed for off-line correction of the time walk and gain instability.

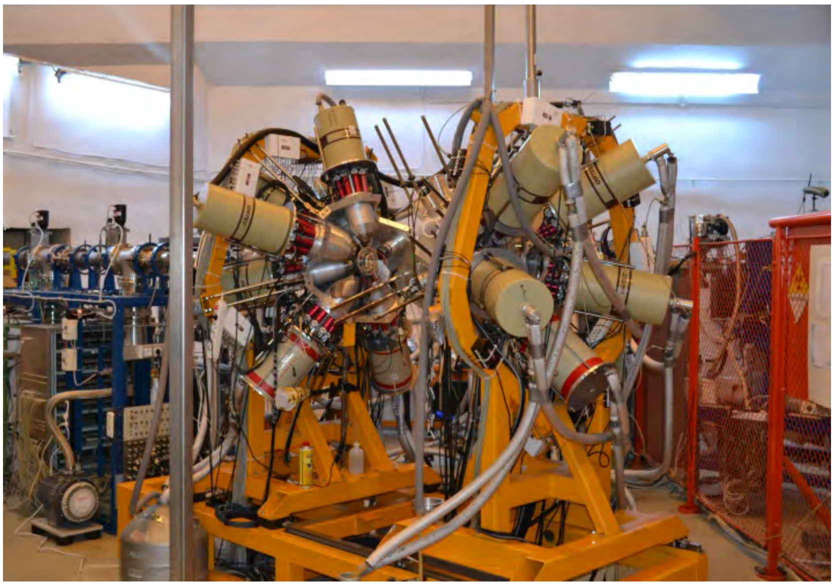


Figure 15. View of the ROSPHERE array in its mixed configuration.

The ROSPHERE is a powerful tool for lifetime measurements using the in-beam fast timing method and it is routinely used for experiments at the Bucharest Tandem studying lifetimes of excited nuclear states down to a few tens of picoseconds [MAR10, KIS11, MAS12, ALH13, NIT14].

4.2. A mixed array of EXOGAM and FATIMA detectors at ILL

One of the recent most extensive tests of the a mixed spectrometer was performed in the EXILL-FATIMA campaign in 2013 [REG14]. A high-granularity mixed spectrometer consisting of high-resolution EXOGAM germanium detectors and $LaBr_3$(Ce) FATIMA detectors was installed around actinide fissile targets at the cold-neutron guide PF1B of the high-flux reactor of the Institut Laue–Langevin, see Figure 15. Exotic nuclei around ^{132}Sn and with A~80 were produced. Lifetimes of excited states in the range of 10 ps to 10 ns could be measured in around 100 exotic neutron-rich fission fragments using Ge–

$LaBr_3(Ce)$–$LaBr_3(Ce)$ or Ge–Ge–$LaBr_3(Ce)$–$LaBr_3(Ce)$ coincidences.

Extensive calibration measurements have been performed to test the precision of such a high-granularity FAst TIMing Array by using the mirror symmetric GCD method described above. Possible systematic errors due to the timing asymmetries and time drifts cancel out due to the geometrical symmetry. Over 5 weeks of operation, no significant change of the prompt response difference curve was observed [REG14], thus making us confident on the FATIMA capabilities at DESPEC. The prompt response difference was measured for the total dynamic range of the FATIMA set-up in the range 40 keV < E_γ < 6.8 MeV with an overall precision of 10 ps. The FWHM coincidence time resolution for γ–γ prompt events ranges from 270 to 500 ps for energies above 100 keV. This provides access to lifetimes of nuclear excited states below 300 ps with precision better than 10 ps with statistics in the order of 1000 to 2000 counts in the (Ge-gated or Ge-Ge gated) time coincidence spectrum. This situation can be extrapolated to FATIMA at DESPEC.

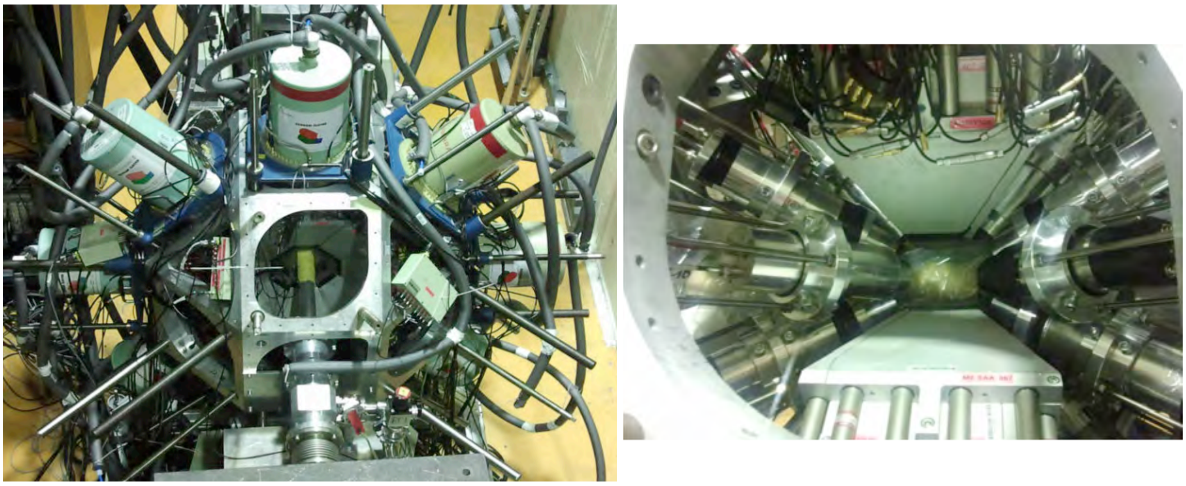


Figure 16. EXILL FATIMA setup at P1FB at ILL.

Moreover, the EXILL-FATIMA campaign has allowed studies on the effect of the background in γ–γ fast timing. Cross-talk γ–γ events due to Compton scattering from one crystal to another has been shown to be important only for adjacent $LaBr_3(Ce)$ detector combinations. Such coincidences have been excluded from the analysis, resulting in a geometrical shielding for the other detector pairs, and thus in Compton suppression. Thanks to the high-resolution gating using EXILL detectors, the Compton background in doubly gated coincidence spectra is reduced, to the point of being negligible in certain cases. Otherwise, time-correction procedures for Compton background underneath the full-energy peak of interest have been shown to be reliable. For peak-to-background ratios larger than 2 and for about 2000 γ–γ events, the error of this time correction is below 10 ps. This value can be used as a good estimate for FATIMA at DESPEC.

The EXILL-FATIMA campaign has made it possible to put into play the operation of a mixed array, with the complexity of the set-up, the data acquisition and the analysis procedures that can be directly translated to FATIMA at DESPEC. The campaign has already produced the first Physics results [JOL15].

5. Radiation environment and safety issues

FATIMA is a gamma-ray multidetector system that will be used in conjunction with low intensity primary and secondary radioactive ion beams. Due to its moderate intensity, no specific radiation safety actions are foreseen except for the implemented restricted access procedure for the site during beam times. Off-beam gamma-ray sources with activity of 10-100 kBq will be used to calibrate the system. These sources must be controlled by the radioprotection service of the laboratory, which will be responsible to provide the dosimeters or the devices needed to control the dose received by personnel.

The high-voltage supplies for the detector assemblies will be below 2.5 kV. FATIMA does not include any cryogenic cooling devices or other mechanical hazards, but will be used in combination with other detector setups that may entail the operation of higher voltage supplies and cryogenic cooling.

FATIMA is conceived as a modular detector array, which can be transported, adapted and reused at other facilities. Therefore all of the components can be reused in new experiments and de-commissioning is straightforward. The electronic components will be reused in other experiments and finally disposed properly according to the Waste Electrical and Electronic Equipment Directive (European Community directive 2002/96/EC).

6. Production, quality assurance and acceptance tests

All components of the FATIMA array have been tested individually by the collaboration. A test procedure is followed for each of the crystals and photomultipliers once they are received. Before the delivery of the FATIMA detector to FAIR, all the system components will be tested with respect to their specifications. Once delivered, further tests will be conducted to verify safe delivery and compatibility with other DESPEC detector systems and FAIR infrastructure. The majority of the parts of the device already exists and has been checked and used at different facilities.

7. Calibration with test beams

Several experiments utilizing fast timing equipment have been performed. These include small beta-decay setups at ISOLDE and JYFL, larger mixed arrays at IFIN-HH and experiments at ILL, both at Lohengrin (where the beam dimensions and characteristics are closer to DESPEC), and at the PF1B (where a large amount of detectors were put in play).

Ideally, test and commissioning experiments with the full system are required at GSI but, due to non-availability of beam time, the whole system will be mounted, tested and commissioned at other facilities. Several members of the collaboration required commissioning of the setup by the end of the first quarter of 2016 and therefore several scenarios are considered. One of them consists in using stable beams, provided by the Tandem accelerator of the University of Cologne where wide FAIR beams can be simulated. Alternatively, exotic beams at Jyväskylä, ISOLDE, RIKEN, and Argonne National Laboratory will be used. Letters of intent at several of the listed facilities have been accepted.

It is worth noting that test experiments with beam are required in order to optimize the algorithms for position correction and their effect on the time response of FATIMA, and to assess the beta timing (when required). Experiments with FATIMA at GSI within the NUSTAR Phase 0 Programme will be of relevance. It is foreseen that once SIS-18 operation starts beam time can be used for FAIR preparation and experiment commissioning. This will open a window for experiments trying to understand exotic nuclei around N=126 by means of comprehensive measurements of masses, level structure, neutron branchings, dipole strengths, and of course nuclear level lifetimes using FATIMA.

8. Civil engineering and cave

FATIMA is part of the DESPEC equipment. As such, it will be located in the Low Energy Branch building, once it is built. The FAst TIMing Array will work in coincidence with the position-sensitive detector AIDA. It is modular and can be easily located inside the cave. It will be placed on a trolley, which will be allowed to move on rails for easy re-arrangement of the set-up. It is requested a suitable area of 3 x 3 m^2 to place the detector, the support structure and the electronics and data acquisition system. In addition there should be space available for the mounting and dismounting. The maximum distance between the FATIMA detector assemblies and the electronics racks is of the order of 5 m.

The weight of the detector array will be around 500 kg, mostly due the support (350 kg), while the weight of 60 crystals with casing is about 20 kg. Room temperature stability must be assured to within 0.2 ºC, since otherwise time measurements will be affected. In addition power supply to the experimental equipment needs to be provided with a high quality ground reference. A crane to lift up and transport the equipment will also be desirable, in case of fine-tuning of the geometry or need for extra shielding. A dedicated Gbit network infrastructure for experimental data transfer and experiment control, and integration to the NUSTAR DAQ is also requested.

9. Installation procedure and logistics

The shipping of the FATIMA components will follow standard procedures for (partially) fragile instruments from the various assembly and test laboratories. The FATIMA detector has been designed as a modular device that can be assembled around AIDA, which is positioned around the beam line. The main steps of the installation procedure could be listed as follows:

- Installation of the two support structures, fixing to the floor, centring and alignment.
- Installation of the detector support structures around AIDA, fixing of the angles.
- Installation of detectors (crystal and phototube assembly) including individual shielding.
- Installation of shielding if required.
- Cabling and connection to the HV supply
- Verification of the individual output signals and connection to the front-end electronics.
- Calibration and signal alignment for energy and time with sources.
- Verification of the acquisition and data output and read-out.

10. Capability to accommodate new technologies

FATIMA aims at providing an optimal fast-timing setup over an extended period of time. It is expected that the setup will be used already at the existing SIS18-FRS GSI facility, where it is envisaged that beams will be available from late 2017. FATIMA will be used within the DESPEC campaign planned for 2017 onwards. Thus FATIMA needs to be ready for optimal operation in the immediate future, and decisions on the choice of technology have been taken keeping this in mind.

Nonetheless the technological evolution in the field of scintillating detectors, photosensors and digital electronics is quite rapid. Concerning scintillator detector technology, new scintillators can be developed by the so-called directed search methodology, where candidate materials are pre-selected based on their effective atomic number, low intrinsic radioactivity and radioluminescence light yield. In addition recent progress in theoretical chemistry using ab-initio methods allows reliable predictions on the properties of new scintillator materials to be made. Hence, the possibility of new materials becoming available with performance superior to $LaBr_3$(Ce) cannot be excluded, although the stringent requirements on time resolution, energy resolution and efficiency make a real breakthrough not so likely.

The FATIMA collaboration strives to continuously follow new developments in scintillator-detector technology, as evidenced by our publications on the suitability of new materials for fast-timing measurements [FRA13,FRA13b]. We have also tight links with the community undertaking these developments and we are ready to quickly test their suitability for fast timing in our test benches and facilities, as addressed in Section 3. Moreover, the setup has been designed in a modular and flexible manner in order to be able to easily integrate the new technologies in our system. In addition, the design in several stages allows for partial modifications of the fast timing array without compromising the overall performance. Thus, we are confident that new technologies can be readily adopted if they become available, maintaining FATIMA as a competitive device.

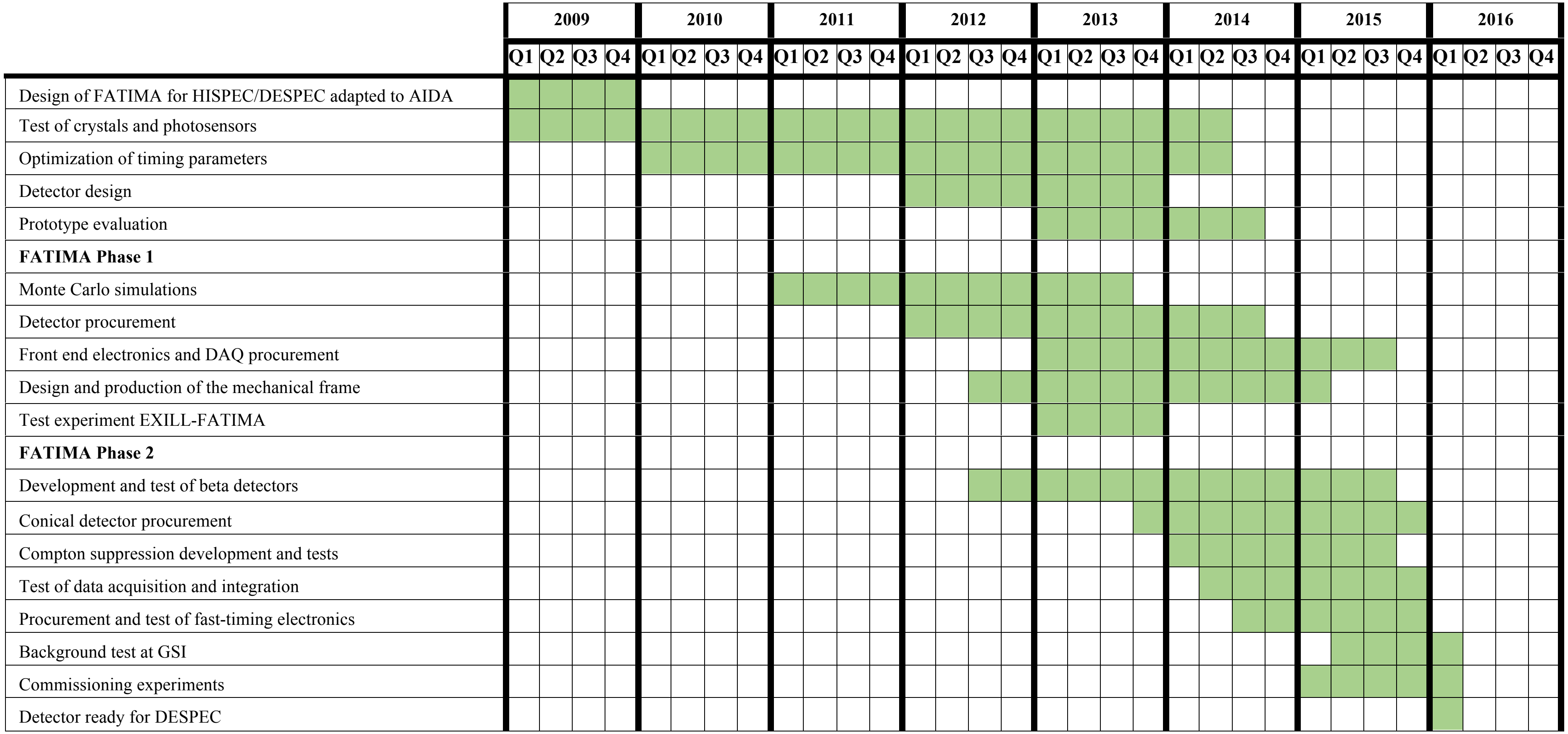
11. Organization and distribution of responsibilities

The DESPEC/HISPEC FATIMA collaboration comprises: University of Brighton (Brighton, United Kingdom), IFIN-HH (Bucharest, Romania), University of Cologne (Cologne, Germany), STFC Daresbury Laboratory (Daresbury, United Kingdom), University of Surrey (Guildford, United Kingdom), Universidad Complutense (Madrid, Spain), University of Manchester (Manchester, United Kingdom), University of West Scotland (Paisley, United Kingdom) and NCBJ (Warsaw, Poland).

Associated members are LPSC Grenoble (France), TU Darmstadt (Germany) and CEA Saclay (France).

The responsibilities of design and construction of FATIMA have been shared among all the active working group members.

12. Time schedule and milestones



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