The Spanish participation in the Facility for Antiproton and Ion Research

3-06-2016

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I Executive summary

The international Facility for Antiproton and Ion Research – FAIR is a new international accelerator facility for the research with antiprotons and ions. It is being built in Germany, in cooperation with an international community of countries and scientists. When in operation, it will be a world leading nuclear physics laboratory and offer unique characteristics for extending the frontiers of the nuclide landscape.

FAIR is a host laboratory for basic and applied research for about 3000 scientists from about 50 countries. The FAIR research activity is based on four mayor collaborations or “pillars”, namely:

- **APPA** – Atomic, Plasma Physics and Applications
- **CBM** – Compressed Baryonic Matter
- **NUSTAR** –Nuclear Structure, Astrophysics and Reactions, the largest collaboration formed by 800 registered NUSTAR scientists from over 180 institutes of 39 countries (including Spain)
- **PANDA** – AntiProton ANnihilation at DArmstadt.

FAIR will start its operation in 2018 and increase its capabilities gradually until reaching its full power.

The engagement of the Spanish nuclear physics community in FAIR has been very strong and visible since the earliest stages of the project in 2005. Over 50 scientists from 12 Spanish research institutions are involved in FAIR, many of them as spokespersons of the international teams responsible for the development of advanced detectors:

- *CIEMAT*. **Coordination**, design and construction of the MOdular Neutron SpectromeTER (MONSTER) for β-decay studies (DESPEC).
- *Instituto de Estructura de la Materia – CSIC*. Development and construction of the CALIFA calorimeter *front end-cap* for the R^3B experiment. Development of the Advanced GAmma Tracking Array (AGATA) for in-beam gamma ray spectroscopy at HISPEC (HISPEC).
- *Instituto de Física Corpuscular – CSIC***. Coordination**, design and construction of the DTAS calorimeter for β-decay studies (DESPEC). Development of AGATA and NEutron Detector Array (NEDA) neutron multiplicity filter at HISPEC.
- *Universidad Complutense de Madrid.* **Coordination**, design and construction of the Fast TIMing Array (FATIMA) for β-decay studies (DESPEC).
- *Universidad de Granada.* **Coordination**, design and construction of Penning traps and single-ion detection systems for the MATS experiment (MATS).
- *Universidad de Huelva.* **Coordination**, design and development of a charged particle detector (HYDE) for in-beam gamma ray spectrometry (HISPEC).
- *Universidad Politécnica de Cataluña*. **Coordination**, design and construction of the BEta deLayEd Neutron detector (BELEN) for β-decay studies (DESPEC).
- *Universidad de Santiago de Compostela*. **Coordination**, design and construction of the CALIFA calorimeter for the R^3B experiment (R^3B).
- *Universidad de Salamanca*. Development of the AGATA and NEDA detectors (HISPEC).

- *Universidad de Sevilla*. Development of detectors for the beam diagnostics (HISPEC/DESPEC).
- *Universidad de Valencia – Escuela Técnica Superior de Ingeniería.* Development of electronics for the AGATA and NEDA detectors (HISPEC).
- *Universidad de Vigo***.** Development and construction of the CALIFA calorimeter for the R^3B experiment (R^3B)

About 8% of the senior scientists participating in NUSTAR belong to Spanish institutes and the total investment in instrumentation (in terms of funded equipment or expression of interest) from Spanish institutes amounts to 11.5% of the total NUSTAR cost matrix.

It can be stated without any doubt that the participation of Spain in FAIR is a history of success:

- An important number of Spanish scientists are/have been Spokespersons of detectors, experiments and/or members of the FAIR committees.
- A large effort, both in terms of investment and personnel has been done in R&D. The R&D projects coordinated by Spanish researchers are at the forefront of the available technology and are well distinguished at an international level. In some cases, they are even more advanced than those in countries with much larger funding available for nuclear physics. This has been recognized by independent bodies, such as the FAIR ECE, in its evaluation of TDRs.
- Whenever it has been possible, the research groups have partnered with the Spanish industry in order to maximize the level of the Spanish contributions. Furthermore, the Spanish industry is still in position of winning large contracts and having important industrial returns.
- A number of the detectors compromised by the Spanish institutions are completed or close to completion. Most of the detectors will be ready for FAIR Phase-0, starting in 2018.

The important investments made by the Spanish funding agencies during the last 12 years have lead to functioning detectors, either completed or in construction, and instruments that can be considered as a 2 M€ Spanish in-kind contribution to FAIR.

In order to consolidate the position of Spanish nuclear physics community in FAIR and to maximize the investments made it is necessary to formalize the Spanish participation in the project. The FAIR management is open to discuss with Spanish representatives of the MINECO about flexible solutions for the formalization of the Spanish participation, compatible with the actual Spanish economic constraints and which guarantee at the same time a successful scientific exploitation of FAIR and the high level of scientific excellence and visibility reached by Spain in the past decade.

The Spanish nuclear physics community has prepared the document "*The Spanish participation in the Facility for Antiproton and Ion Researc*h" as a summary of the activities carried out and to provide support for the decision makers.

II Introduction

FAIR, Facility for Antiproton and Ion Research, is a new international accelerator facility for the research with antiprotons and ions. It is being be built in cooperation of an international community of countries and scientists. On October, 4th 2010, the international owners founded the FAIR GmbH and the countries' representatives signed a treaty under international law (Convention, Final Act).

The facility is financed by a joint international effort of so far ten member states. The Federal Republic of Germany together with the State of Hesse is the major contributor to the construction; the current nine international partners - Finland, France, India, Poland, Romania, Russia, Slovenia, Sweden and the United Kingdom - bear ca. 30% of the construction cost.

FAIR will be a host laboratory for basic research for about 3000 scientists from about 50 countries. The FAIR research activity is based on four mayor collaborations or "pillars", namely:

APPA – Atomic, Plasma Physics and Applications

- BIOMAT – Biology and Material Science
- FLAIR – Facility for Low-Energy Antiproton and Heavy Ion Research
- HEDgeHOB – High Energy Density Matter generated by Heavy Ion Beams
- SPARC – Stored Particles Atomic Research Collaboration
- WDM – Warm Dense Matter collaboration
- APPA R&D – Atomic, Plasma Physics and Applications

CBM – Compressed Baryonic Matter

NUSTAR –Nuclear Structure, Astrophysics and Reactions

- DESPEC/HISPEC - Decay Spectroscopy/High-Resolution Spectroscopy
- ELISe - Electron-Ion Scattering in a Storage Ring
- EXL - Exotic nuclei studied in light-ion induced reactions at the NESR storage ring experiment
- ILIMA - Isomeric Beams, Lifetimes and Masses
- LaSpec - Laser Spectroscopy
- MATS - Precision Measurements of very short-lived nuclei with Advanced Trapping System
- R^3B - Reactions with Relativistic Radioactive Beams
- SuperFRS - Super Fragment Separator project

PANDA – AntiProton ANnihilation at DArmstadt.

The Spanish experimental nuclear physics community is involved in NUSTAR.

II.1 The NUSTAR collaboration

The NUSTAR collaboration is aimed at the experimental investigation of nuclear structure, astrophysics, and reactions. Regarding astrophysics, it is assumed that the chemical elements heavier than iron originate from collapsing stars or stellar collisions.

The underlying processes depend on the nuclear forces and symmetries in nuclei very far away from the stability valley, often referred to as “rare isotopes” or “exotic nuclei”.

To investigate the Nuclear Structure, Astrophysics and Reactions (NUSTAR) with intensive secondary beams of such rare isotope experiments the use of the Super-FRS (FRagment-Separator) and a series of complimentary detector set-ups are foreseen. These measurements should clarify relevant details observed in the abundance of heavy elements, provide new knowledge about the interior of neutron stars and other unsolved astrophysical puzzles.

The FAIR-NUSTAR facility will provide beams of radioactive ions with unprecedented intensities. These beams can be used an full energy for secondary reactions at R3B or de-accelerated (HISPEC) or even stopped (DESPEC/MATS)

We will get information on the force acting between the nucleons inside the nucleus, with special emphasis on systems with exotic proton-to-neutron ratios: both proton rich and neutron rich nuclei. In extreme neutron-rich nuclei radical changes in their structure are expected with the possible disappearance of the classical shell gaps and magic numbers and the appearance of new ones.

At present more than 800 registered NUSTAR scientists from over 180 institutes of 39 countries contribute to the construction of advanced instrumentation, the development of experimental methods and the upgrade of the Physics case.

The interests of the Spanish Nuclear Physics community are concentrated in three experiments of the NUSTAR collaboration: DESPEC/HISPEC, MATS and R3B. About 8% of the senior scientists participating in NUSTAR belong to Spanish institutes. The total investment in instrumentation (in terms of funded equipment or expression of interest) from Spanish institutes amounts to 11.5% of the total NUSTAR costs.

The NUSTAR collaboration is governed by the NUSTAR Council and the NUSTAR Board of Representatives (BR) as its executive committee. It acts as the linking body between the NUSTAR collaboration and FAIR and co-ordinates the use of the different set-ups and surveys the strategy behind the physics programme of the collaboration. The BR consists of five regular members plus ex-officio members. Spanish scientists have been or are part of the NUSTAR Board, including J. Benlliure (USC), B. Rubio (IFIC), D. Cortina (USC) and L.M. Fraile (UCM) [1].

II.1.1 DESPEC/HISPEC

DESPEC/HISPEC addresses the kind of questions mentioned above using radioactive beams delivered by the energy buncher of the Low Energy Branch (LEB) of the Super Fragment Separator with energies of 3-150 MeV/u for reaction studies or stopped and implanted beam species for decay studies. The project focuses on those aspects of nuclear investigations with rare isotope beams which can be uniquely addressed with high-resolution setups.

DESPEC (DEcay SPECtroscopy)

Decay studies lie at the very frontier of the field of exotic nuclei, since once the existence of an isotope has been demonstrated, the next elementary information we seek is how it decays, even an imprecise number on the half live of a new isotope can tell us a lot about the allowed or forbidden character of the decay. At the same time decay spectroscopy often provides primary information on excited states of nuclei far from stability. The advantage of the decay experiments is that they can be based on a relatively small number of events. A unique feature of the FAIR Super-FRS will be the access to regions where the waiting points for the r-process occur. For our understanding of the r-process nucleosynthesis of heavy elements in supernova explosions we need to know the beta decay half-life, the neutron branching ratios and the neutron (or two-neutron) separation energy of these nuclei. At the DESPEC set up we will be able to measure the first two quantities while the last will be measured either at ILIMA or at MATS. If the number of decays is sufficiently high, detailed spectroscopy will be possible and then questions such as isospin symmetry can be tested in mirror nuclei or the long-standing Gamow Teller quenching problem in beta decay can be addressed in combination with charge exchange reactions performed at R^3B or EXL.

All of the experiments anticipated at DESPEC involve deep implantation of the ions in an active stopper prior to the decay. The detector will be highly pixelated, which allows us to correlate in time and space the signal of the initial pulse from implantation of the heavy ion with the signal produced in the same detector in the subsequent beta decay. Neutron and high-resolution gamma-ray detectors in a compact arrangement around the active stopper in a highly flexible and modular geometry will be at the heart of this set-up. Complementary measurements using the Total Absorption Gamma technique and measurements of nuclear g-factors and quadrupole moments as well as level half-lives are also foreseen.

The following detector systems are foreseen for the DESPEC experiments:

- Implantation detector AIDA
- Ge array DEGAS
- Gamma Total Absorption Spectrometer DTAS
- Neutron 4pi detector BELEN
- Neutron Time of Flight detector MOSTER
- Fast Timing set-up FATIMA

Spain has played and plays a leading role in the definition of the Physics case for DESPEC and in the design, research and development, and construction of the advanced instruments. The spokespersons of the BELEN (F. Calviño), DTAS (J.L. Taín), FATIMA (L.M. Fraile) and MONSTER (D. Cano-Ott) collaborations belong to Spanish institutions and Prof. B. Rubio has been spokesperson of HISPEC/DESPEC between 2005 and 2012.

<u>HISPEC (HIgh-resolution In-flight SPECtroscopy)</u>

The HISPEC (High-resolution in-flight SPECtroscopy) project aims at in-beam nuclear structure and reaction studies, using high-resolution γ-ray spectroscopy as its main tool. HISPEC will be installed at the “Low Energy Branch”, an experimental line where secondary ions from hundreds to few MeV of energy/A are expected to be available.

HISPEC will take advantage of the in-flight produced exotic species, impinging in a secondary target, to perform in-beam experiments aiming to nuclear structure and reaction mechanism research. Additionally the relativistic energy beams are for the most exotic species a unique tool for the investigation, since the extremely low production requires high reaction rates at the secondary target, only reachable with techniques involving relativistic energies.

Single step Coulomb excitations and fragmentation reactions at intermediate energies as well as inelastic scattering, transfer reactions and fusion evaporation reactions at lower energies will provide information about transition probabilities, single particle spectroscopic factors, high spin states, etc.

The advantage here is that one can use high-resolution Ge detectors to measure the gamma de-excitation of the levels populated. The HISPEC set-up has at its core AGATA, the next generation γ-ray tracking array, with a resolving power hugely exceeding the presently available Ge-arrays. In addition, the setup will comprise beam tracking and identification detectors placed before and behind the secondary target, charged particle detectors, a plunger, a magnetic spectrometer and other ancillary detectors.

HISPEC and DESPEC are complementary in terms of both the physics and the instrumentation, for instance they will use the same suite of ion identification and tracking detectors. There is also a large overlap in terms of the community involved and, in a very natural way, they have decided to join forces. The two set-ups will be combined for specific recoil decay experiments, with the DESPEC detectors placed at the end of the magnetic spectrometer.

Several HISPEC detectors have been build and commissioning experiments are taking place since 2010. Experiments using the mentioned techniques and HISPEC instrumentation have been performed from 2012 to 2014 at the PRESPEC project at the existing GSI.

The following detector systems are foreseen for the HISPEC experiments:

- Beam tracking detectors
- The AGATA tracking Ge array
- Other detectors devoted to high-energy γ-rays
- Instruments and detectors for precision lifetime measurements – Plunger devices for RRDS measurements and others.
- HYDE charged-particle Si detector array optimized for reaction and structure studies
- NEDA high efficiency neutron tagging detector array
- LYCCA (Lund–York–Cologne Calorimeter) for reaction product identification, based on TOF-ΔE–E measurements.
- Magnetic spectrometer. In order to identify heavy (A > 100) reaction products magnetic rigidity measurements combined with the TOF–ΔE–E provided by LYCCA

The Spanish nuclear physics community is working and contributing to the construction of several of these detectors, i.e. the beam tracking detectors, AGATA, HYDE and NEDA.

II.1.2 MATS

The mass and its inherent connection with the nuclear binding energy constitute a fundamental property of a nuclide, a unique "fingerprint". Thus, precise mass values are important for a variety of applications, ranging from nuclear-structure studies like the investigation of shell closures and the onset of deformation, test of nuclear mass models and mass formulas, to tests of the weak interaction and of the Standard Model. The required relative accuracy of the mass measurements ranges from 10^{-5} to below 10^{-8} depending on the specific nuclei, which most often have half-lives well below 1 s. Substantial progress in Penning trap mass spectrometry has made this method a prime choice for precision measurements on rare isotopes. The technique has the potential to provide high accuracy and sensitivity even for very short-lived nuclides. Furthermore, ion traps can be used and offer advantages for precision decay studies.

The MATS collaboration is aiming to apply Penning-trap and Multi-Reflection Time-Of-Flight (MR-TOF) techniques to exotic nuclei beyond the reach of the present Radioactive Ion Beam (RIB) facilities. Although there are other facilities worldwide that have developed similar experimental concepts, the uniqueness of MATS will be preserved. Only a few masses have been measured for isotopes with half-lives below 100 ms, and in all these cases these isotopes have been produced at ISOL facilities. The most remarkable example is the halo nuclei ^{11}Li (with T1/2= 8.8 ms), which mass has been measured with TITAN at TRIUMF with a relative mass uncertainty of 6.3 x 10^{-8}. The production rate at TRIUMF is about three orders of magnitude smaller compared to the one expected at FAIR. This difference in production can be projected to many nuclei, particularly; key nuclei like the doubly magic ^{78}Ni and ^{100}Sn, which are not practicable at any of the existing Penning trap at radioactive beam facilities. A survey of measurements and the uniqueness of MATS was described in the Advanced Trapping Facility MATS at FAIR [3]. The uniqueness of MATS at FAIR was very well evaluated in 2015.

For the mass measurements, MATS offers both a high accuracy potential and a high sensitivity. A relative mass uncertainty of 10^{-9} can be reached by employing highly-charged ions and a non-destructive Fourier-Transform-Ion-Cyclotron-Resonance (FT-ICR) detection technique on single stored ions. This accuracy limit is important for fundamental interaction tests, but also allows to study the fine structure of the nuclear mass surface with unprecedented accuracy, whenever required. The use of the FT-ICR technique provides true single ion sensitivity. This is essential to access isotopes that are produced with minimum rates and that very often are the most interesting ones.

Decay studies using ion traps as a high-resolution separator will become possible with MATS.

Spain has been strongly involved in the MATS collaboration. D. Rodríguez was the coordinator of the Technical Design Report, a reduced version of which was published as a review with the same title as the TDR manuscript “MATS and LaSpec: High-precision experiments using ion traps and lasers at FAIR” [5]. Daniel Rodríguez has been also spokesperson of the MATS collaboration from December 2010 to March 2015, and he is currently deputy spokesperson.

II.1.3 R^{3}B

During the past decade it has been demonstrated that reactions with high-energy secondary beams are an important tool to explore static and dynamic properties of nuclei far off stability. Relativistic beam energies allow a quantitative description of the reaction mechanisms, while also having experimental merits, such as the possibility of using relatively thick targets (in the order of 1 g/cm^2). Moreover, due to the kinematical forward focusing full-acceptance measurements are feasible with moderately sized detectors. This makes it possible to gain nuclear-structure information from reaction studies even with very low beam intensities, as low as about 1 ion/s. An excellent place to perform such type of studies will be a next generation experimental setup for studies of Reactions with Relativistic Radioactive Beams (R^{3}B).

R^{3}B has an extended scientific program comprising nuclear structure and dynamics as well as different astrophysical aspects and technical applications. Measurements of ground-state properties (radii, masses of unbound nuclei beyond the drip line, single particle structure, fission barriers), nuclear excitations (giant and pygmy resonances), reaction mechanisms including fission, and astrophysical reaction rates are foreseen. It will also study asymmetric nuclear matter by measurements of the neutron-skin thickness or the dipole polarizability of neutron-rich heavy nuclei and by studying nucleon-nucleon short-range and in particular tensor-force induced correlations in nuclei as a function of isospin.

For $^{208-222}$Pb and the tin isotopic chain beyond N=82, extended experimental campaigns are planned addressing several of the topics mentioned above. Fission barriers of heavy neutron-rich nuclei, which are of utmost importance for r-process modeling, will be measured in (p, 2p) fission reactions. In the lighter mass region, quasifree scattering reactions at high beam energies and large momentum transfer with nuclei of extreme $N - Z$ will be measured to study many of the above-mentioned effects.

The R^{3}B program takes advantage of the fact that all these reactions will have been studied with lower luminosities at an earlier stage before the Super-FRS is operational. Through concentrating on reactions with high-energy radioactive beams up to 1 GeV/u, provided only by FAIR, and by optimizing the detection system covering very large parts of the available phase space, the R3B program is in a unique position with little competition.

The R^{3}B experimental setup is a versatile reaction setup with unprecedented efficiency, acceptance, and resolution for kinematically complete measurements of reactions with high-energy radioactive beams. The experimental configuration (initial setup, see Figure), is based on a concept similar to the existing R^{3}B/LAND reaction setup at GSI introducing substantial improvement with respect to resolution and an extended detection scheme, which comprises the additional detection of light (target-like) recoil particles and a high-resolution fragment spectrometer.

The setup will be located at the focal plane of the high-energy branch of the Super-FRS and is adapted to the highest beam energies (corresponding to 20 Tm magnetic rigidity) provided by the Super-FRS, capitalizing on the highest possible transmission of secondary beams. The development of several state-of-art detection subsystems and sophisticated DAQ system are planned and being built. This work is done inside the R^{3}B collaboration, which includes more than 50 different institutes from all over the world.

Spain has been strongly involved in the R3B collaboration since its conception. O. Tengblad is the collaboration Technical Coordinator. H. Alvarez coordinates the collaboration Analysis and Simulation Working Group and D. Cortina is the convener of the design and construction of the CALIFA (CALorimeter for In Flight detection of γ-rays and high energy charged pArticles) detector, in which the Spanish groups participating in R3B have focused their main interest. This detector system, surrounding the reaction target of the R3B set-up, down-stream from the Super FRS, is a unique detector. It will serve as high-resolution γ-ray spectrometer, high efficiency γ-ray calorimeter and provides also information on the energy of protons emitted from the target. The CALIFA TDR was approved in 2013 and 2015 and is currently under construction. As the rest of the R^3B key detectors (Neuland and Si-Tracker) the construction is foreseen in a stage mode. This would allow the collaboration to run experiments since the early FAIR Phase 0 in 2018.

II.2 Timeline of the construction of FAIR

The FAIR facility will start its operation in different phases:

- **Phase 0**. The R&D and experiments will be carried out with the present facilities and the FAIR/NUSTAR equipment. The experiments will benefit from the advanced equipment built.
- **Phase 1**. All the core detectors and subsystems will be completed. The first measurements with FAIR/Super-FRS beams will be carried out. In particular, experiments with highest visibility as part of the core program and within the FAIR modularised standard version (MSV) will be performed.
- **Phase 2**. FAIR will have evolved towards full power. All the experiments of the MSV will be completed. Essentially the full scientific program of MSV will be performed.
- **Phase 3**. FAIR will include moderate projects that have been initiated on the way and outside the MSV. As an example, experiments related to return line for rings.
- **Phase 4**. Major new investments and upgrades for all experiments will take place.

As it can be seen in the timeline in Figure 1, the first beams with FAIR/NUSTAR detectors will be available in 2018.

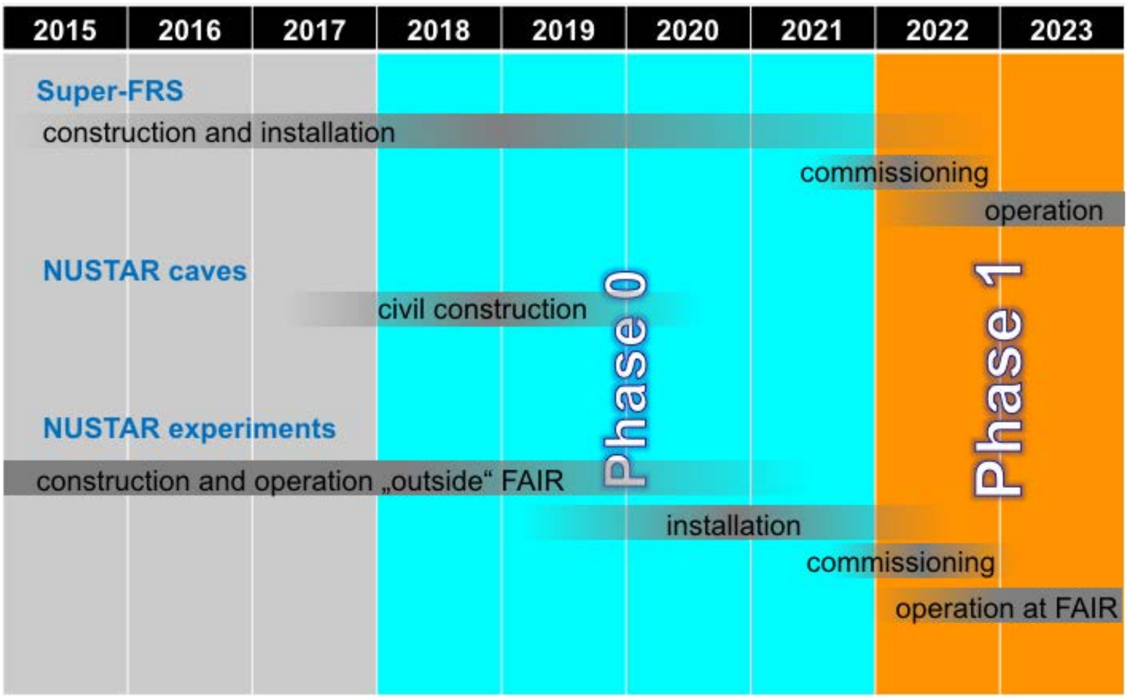


Figure 1. Timeline for the Phase 0 and Phase 1 of FAIR.

III Spain at FAIR

III.1 Spain at FAIR: a history of success

As a result of extensive discussions about the future research opportunities between the GSI community and various international users' communities, FAIR Conceptual Design Report came to light in November 2001. This document presented a major international research facility in the areas of science concerned with the basic structure of matter. It was built on priority recommendations made over previous years by various high-level science committees worldwide that have reviewed the areas of research addressed. The Spanish nuclear physics community, present already at that time at GSI was part of this germinal discussions and start slowly but firmly to get structured and around the scientific program of FAIR.

In 2004, it took place in Santiago de Compostela the official kick-off meeting of the Spanish participation in FAIR. This meeting counted on the participation of GSI/FAIR managers and representatives of the Ministerio de Ciencia e Innovación. The Spanish nuclear physics community proposed a bottom up participation approach that had the support of the Ministry. The proposed participation of Spain in the project it is summarized in 2007 in an official letter from Carmen Andrade (General Director of Technological Policy in the Spanish Ministry) to Beatrix Vonkorn-Rudolph (Director of Large Facilities, Energy and Basic Research form the German Ministry), an represents a contribution of 2% of the project (i.e. 22 M€). This contribution was based on scientific and industrial pillars. CIEMAT was identified as the leading Institution of the Spanish contribution to FAIR and contributed to the design of various FAIR elements: super-ferric dipoles and multiplets for the SuperFRS and additional magnets for the storage rings. CDTI supported also the proposal and helped to structure the industrial contribution.

In 2004 Spain agrees to make the design of the quadrupole and dipole magnets for the FAIR NESR ring. This initiative is financed 50% between two parties, GSI and Spain through an agreement between the CSIC (IFIC) and GSI. The Spanish contribution is financed by an "Acción Complementaria" of 200 k€. The company coordinating the study is ELYTT Energy.

In 2005 a CSIC working group is created composed by B. Rubio, M.J. G. Borge and G. Garcia from the CSIC and J. Benlliure (U. Santiago de Compostela). As a result of the negotiations with CSIC five permanent positions are created in the following years whose profile has integrated the name of FAIR: two experimental positions of "Investigador Científico", A. Jungclaus (IEM), Andrés Gadea (IFIC), one theory position, J. Nieves (IFIC), one "Científico Titular" position, A. Algora (IFIC) and one "Titulado Superior" position, E Nácher (IEM).

In the period from 2005 to 2008 the Ministry nominated Spanish representatives to various FAIR committees and pointed J. Benlliure y B. Rubio as scientific representatives of Spain in FAIR (STI committee). At the same time other Spanish researchers were elected by the international scientific community to hold relevant scientific and technical positions. The visibility and responsibility of Spanish researchers has been very high until nowadays since the beginning of the FAIR project. In 2006 MICINN includes FAIR in his roadmap as high priority ESFRI installation [2]. This successful history reaches its greatest achievement in 2009, in the Kick off ceremony of FAIR whit the attendance of L.E. Ruiz as a Ministry delegate to corroborate the Spanish participation in FAIR.

Along this period (2005-2010) the Ministry strongly supported the community through the FPA program and various infrastructure calls. Different Institutions, Universities and Regional Autonomies also supported the development of the project with specific grants, refurbishments of infrastructures and creation of Scientific and Technical positions with FAIR profile. It is also worth to mention that this period coincides with the existence of a deputy manager (J. Benlliure and M.J. Borge) in the FPA program for nuclear physics.

More recently Ministry pointed G. de Córdoba (representing the Ministry) and B. Rubio (Scientific Advisor) as Spanish representatives in the FAIR Resource Review Board. Even though the difficult administrative and economical context, Spanish scientists have been able to keep their scientific engagement towards this exciting project, consolidating their participation in the intense R&D program related to the design and construction of new experiments, keeping an outstanding scientific production and holding relevant positions that confers them a significant international visibility.

Last but not least, the CIFPA committee has included all the experiments in which the Spanish Scientific community participates, HISPEC/DESPEC, MATS and R^3B, within their priorities.

In summary, the Spanish nuclear physics community at FAIR (see Section VIII for details) has been extremely active since the conception of FAIR.

Spanish scientists participate in 3 FAIR experiments within the NUSTAR collaboration, with a strong implication and very high international visibility. Spanish scientists are leading scientific and technical projects and conveners in 5 Technical Design Reports of various detectors for different NUSTAR experiments: CALIFA, BELEN, DTAS, FATIMA and MONSTER.

III.2 Participation in DESPEC/HISPEC

The Spanish experimental nuclear physics community is heavily involved in the HISPEC/DESPEC experiment and has a high visibility: Prof B. Rubio has been Spokesperson of the experiment from 2004 until 2010 and 4 Spaniards are Spokespersons of 4 detectors HISPEC/DESPEC. A summary of the HISPEC/DESPEC instruments is given in Table 1. The instruments with a Spanish contribution are marked in blue.

Detector	Spokesperson / Institution	Status of the TDR
AIDA	T. Davinson / University of Edinburgh	Approved

AGATA (not in-kind to FAIR)	AGATA Collaboration	Existing since 2008
BELEN http://www.fair-center.eu/fileadmin/fair/publications_exp/TDR_HISPEC_DESPEC_BELEN_public.pdf	F. Calviño / Universidad Politécnica de Cataluña	Approved 2014
DEGAS http://www.fair-center.eu/fileadmin/fair/publications_exp/TDR_HISPEC_DESPEC_DEGAS_public.pdf	TIFR, Mumbai, India R. Palit	Approved 2015
DTAS http://www.fair-center.eu/fileadmin/fair/publications_exp/TDR_HISPEC_DESPEC_DTAS_public.pdf	J.L. Taín / IFIC	Approved 2013
FATIMA http://www.fair-center.eu/fileadmin/fair/publications_exp/TDR_HISPEC_DESPEC_FATIMA_public.pdf	L.M. Fraile / Universidad Complutense de Madrid	Approved 2015
LYCCA	D. Rudolph / Lund University	Approved
MONSTER	D. Cano-Ott / CIEMAT	Approved 2014
NEDA (not in-kind to FAIR)	J.J. Valiente / Laboratori Nazionali di Legnaro	Approved 2016

Table 1. List of DESPEC/HISPEC detectors in which the Spanish institutions are involved.

As it can be seen in Table 1, AGATA and NEDA are key instruments to be used at HISPEC but at present time cannot be considered as an in-kind contribution to FAIR since they are being built by external collaborations and will move together to different laboratories.

At present, no running costs have been established within the HISPEC/DESPEC experiment. Both the HISPEC/DESPEC and NUSTAR MoU are still under preparation.

III.2.1 The participation in AGATA

In connection to FAIR/NUSTAR as well as other Radioactive Ion Beam facilities, the experimental nuclear physics community has developed exciting ideas for new equipment, key to the future research effort. Among these instruments are the γ-ray tracking arrays, i.e. the arrays of high-energy resolution Ge detectors with position sensibility capabilities.

Since the mid 90's European groups are working actively on the R&D on highly segmented coaxial germanium detectors and the tracking technology because the experimental conditions at the future facilities for intense radioactive and high-intensity stable ions beams are expected to be extremely challenging, requiring unprecedented levels of sensitivity and count-rate capabilities. The required performance figures are clearly out of reach with conventional arrays. Besides the highly segmented Ge detectors, the realisation of a tracking array requires digital sampling electronics to extract energy, time, and position information using pulse-shape analysis. This radically new device constitutes a dramatic advance in γ-ray detection that will have wide ranging applications in medical imaging, astrophysics, nuclear safeguards and radioactive-waste monitoring, as well as introducing a new plateau of detection capability for nuclear-structure studies.

The characteristic mentioned above are especially important for in-flight facilities with intermediate energy relativistic beam as HISPEC, in which the position sensitivity of the detectors is of paramount importance for the high-resolution γ-ray spectroscopy.

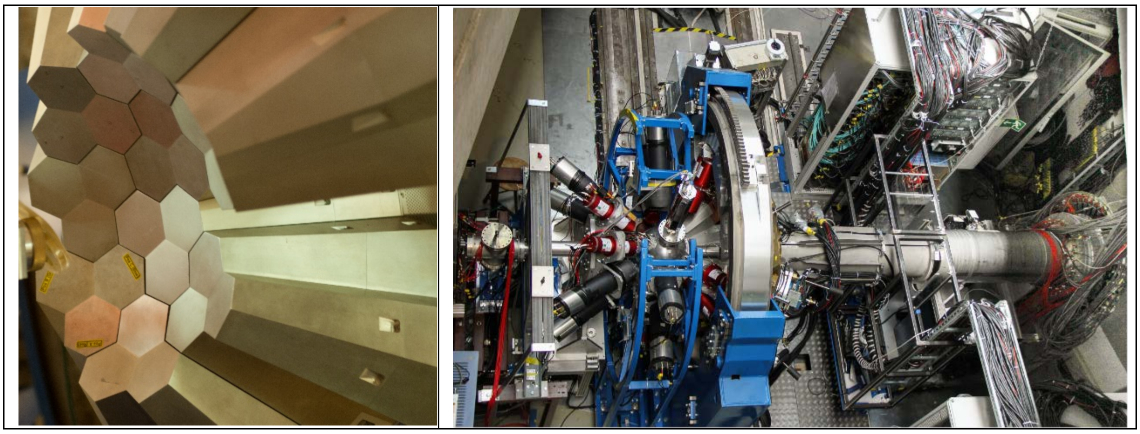


Figure 2. The present AGATA subsystem and the PRESPEC installation at GSI as test bench for the HISPEC instrumentation and concept.

A European collaboration currently consisting of over 40 institutions from 12 countries has been established to develop and construct a European 4π tracking spectrometer called AGATA (Advanced GAmma Tracking Array). Several Spanish members of the nuclear physics community have a long-standing contribution to the AGATA project and are even crucial members of the international AGATA collaboration.

Country	**Institutions**
Bulgaria	Univ. Sofia, INRNE Sofia
Finland	Univ. Jyväskylä
France	GANIL Caen, LPSC Grenoble, IPN Lyon, CSNSM Orsay, IPN Orsay, CEA/DRF/IRFU Saclay, IPHC Strasbourg
Germany	GSI Darmstadt, TU Darmstadt, Univ. zu Köln, TU München
Italy	INFN-Firenze, INFN-Genova, INFN-Legnaro, INFN-Milano, INFN-Napoli,INFN- Padova, INFN-Perugia (Camerino)
Poland	IFJ PAN Krakow, University of Warsaw (HIL)
Spain	Consejo Superior de Investigaciones Científicas – Instituto de Física Corpuscular, Consejo Superior de Investigaciones Científicas – Instituto de Estructura de la Materia, Universidad de Salamanca – Laboratorio de Radiaciones Ionizantes, Universidad de Valencia – Escuela Técnica Superior de Ingeniería
Sweden	Chalmers Univ. of Technology Göteborg, Lund Univ., Royal Institute of Technology Stockholm, Uppsala Univ.
Turkey	Univ. Ankara, Univ. Istanbul, Technical Univ. Istanbul

UK	Univ. Brighton, STFC Daresbury Laboratory, Univ. Edinburgh, Univ. Liverpool, Univ. Manchester, Univ. Surrey, Univ. West of Scotland, Univ. York

Table 2. List of Collaborating Institutions in AGATA per country.

The AGATA project aims to the construction and exploitation of the European Advanced GAmma Tracking Ge detector array, as forefront instrument for the Nuclear Structure research in Europe. The construction of AGATA, as moving instrumental facility is among the recommendations of the NuPECC Long Range Plan 2010 for Nuclear Structure and Dynamics instrumentation [33]. The AGATA web page is http://www.agata.org/ (the old one http://www-win.gsi.de/agata/).

AGATA is being built in phases. The AGATA Demonstrator (phase 0) lasted from 2003 to 2007. Presently we are in the Phase 1, aiming to build ~1/3 of the array. The current MoU was expected to last till 2015, but finally it has been extended to 2020.

The AGATA project has always given high priority to the scientific activity, thus as soon as some AGATA units were available, experimental campaigns were started, always considering the limited performance of the sub-systems. The first campaign was hosted by the INFN-Laboratori Nazionaly di Legnaro (LNL), Italy, from 2009 to 2011. The second one was hosted at HGF-Gesellschaft für Schwerionenforschung (GSI), Darmstadt Alemania, from 2012 to 2014, in the called PRESPEC campaign. The third campaign is ongoing at the CEA-CNRS - Grand Accélérateur National d'Ions Lourds (GANIL), Caen, France, since late 2014.

The Spanish groups are contributing both to the technical developments as well as to the scientific activity of AGATA, at a very high level.

The Participation of the Spanish industry is presently limited to the contribution to the front-end electronics development. The company Teydisa has produced the control card of the Phase 1 Digitizer of AGATA. Several companies coordinated by IFIC and University of Valencia have worked on the production of the mechanical parts for the mentioned Digitizers.

The cost of the AGATA array in the present phase includes 6.6 M€ from the prototyping and phase 0 and 12.8 M€ for the Phase 1. Spain is contributing to 1 detector Module, i.e. ~1/20 of the present AGATA configuration. AGATA will be ready with a configuration up-to 60 detector (AGATA Phase 1 MoU) capsules for the Phase 0 of NUSTAR/FAIR.

Institution name	Researchers (staff)
IEM-CSIC	A. Jungclaus
	E. Nácher
IFIC	A. Gadea
	C. Domingo
UAM	L. Egido
	A. Poves
U Salamanca	B. Quintana
U Valencia - ETSE	V. González
	E. Sanchis

	M.A. Sáez
U Valencia	J.M. Blasco

Table 3. List of Spanish scientists and institutions currently involved in AGATA.

AGATA as a moving facility is not considered an "in-kind" contribution for FAIR and thus the funding dedicated to AGATA cannot be accounted as in-kind. The reason is that it will work in three major European facilities for re-accelerated radioactive beams and an "in-kind" structure for the investments is excluded for the other facilities.

Institution		2016	2017	2018	2019	2020	2021	2022	2023	2024
IEM/IFIC USAL/ETSE	Investment	14		200			New AGATA MoU Required investment 2021-2030 could be approximately 5% of the new instrumentation			

Table 4. Investment profile of AGATA in k€.

AGATA has as well established operational cost (see Table 5) related with the maintenance of the instrumentation. The operational costs are defined for each country in the MoU. The operation costs are independent of the host laboratory where AGATA is installed and at the moment are defined only till 2020.

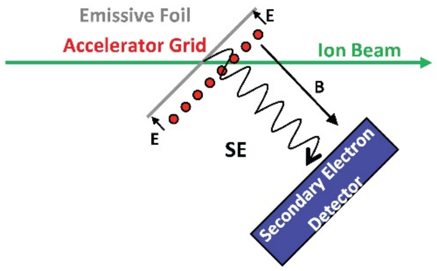
Year/ Country	**2016**	**2017**	**2018**	**2019**	**2020**	**Total**
Bulgaria	13,7	14,7	17,1	17,6	20,1	83,2
Finland	13,7	14,7	17,1	17,6	20,1	83,2
France	70	77,7	90,6	93,1	106,2	437,6
Germany	70	77,7	90,6	93,1	106,2	437,6
Italy	70	77,7	90,6	93,1	106,2	437,6
Poland	13,7	14,7	17,1	17,6	20,1	83,2
Spain	23,6	26,2	30,6	31,4	35,8	147,6
Sweden	39	43,4	50,6	51,9	59,3	244,2
Turkey	23,6	26,2	30,6	31,4	35,8	147,6
UK	43,5	55	70,6	78	93,8	340,9
External resources	16,3	18,1	21,1	21,6	24,7	101,8

Total	**397,1**	**446,1**	**526,6**	**546,4**	**628,3**	**2.544,5**

Table 5. AGATA Operational Costs per year until 2020 in k€.

III.2.2 Beam tracking detectors

The beam tracking detectors are fundamental elements of HISPEC. They have to provide, on an event-by-event basis, position and direction information of the ions impinging on the secondary target. Several detection systems have been built to cope with the different energy regimes expected at HISPEC. In the case of the intermediate energy experiments (E~100 MeV·A) they will be the same as the ones used at the Super FRS. However, for experiments using radioactive beams slowed down to Coulomb barrier energies, special detectors have been developed.



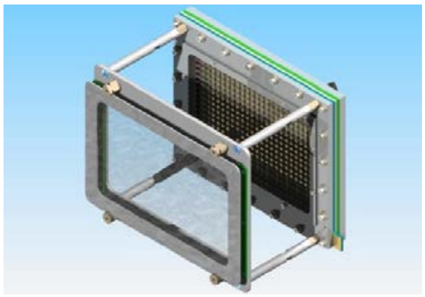


Figure 3. Left: scheme of the interaction of the beam with the detector. Right: image of the detector.

In order to avoid excessive energy and angular spread very thin detectors have to be used. The developments concentrated on secondary electron emitting carbon foil detectors (SeD). In addition of being the thinnest detectors, they are fast and have good position resolution. Such detectors, have been built in a collaboration between the University of Seville – Centro Nacional de Aceleradores (CNA) and the University of Köln. Since 2007 the Basic Nuclear Physics Group of the CNA-University of Seville started a collaboration with GANIL and CEA-Saclay in R&D on SeD at low pressure for beam tracking. Several prototypes of SeD at low pressure with a small active area (7x7 cm2), based on wire PPAC chambers and Micromegas, were constructed and tested.

Finally the best performance was obtained with the SeD based on PPAC wire chambers and a full size detector with an active area of 200x120 mm2 was build and commissioned in 2014. The full commitment of University of Seville – CNA on efforts and investments is now completed.

Institution name	Researchers (staff)
U.Sevilla / CNA	B. Fernández
	J. Gómez-Camacho

Table 6. List of Spanish scientists that contributed to the Beam Tracking Detectors.

III.2.3 The BEta deLayEd Neutron detector – BELEN

The BEta-deLayEd Neutron detector (BELEN) is being developed for experiments at the future FAIR facility within the NUSTAR-DESPEC (DEcay SPECtroscopy) collaboration. BELEN will be used to measure the probability of neutron emission after β-decay of very neutron-rich nuclei. The study of beta-delayed neutron emission probabilities is of interest for different fields, such as nuclear structure, nuclear astrophysics and nuclear technology applications. Improved experimental data from delayed neutron emission represents an important input for the astrophysics r-process calculations. Furthermore, in nuclear structure, β-delayed neutron emission constitutes an important probe for the structure of neutron-rich nuclei far away from the valley of stability where other measurements are not yet possible. The technological interest of beta-delayed neutron measurements is related to nuclear power generation. This research is fundamental for the design of safer and more efficient nuclear reactors. In this sense in year 2011, the IAEA (International Atomic Energy Agency) boosted the creation of a Coordinated Research Project on β-delayed neutron emission evaluation to study the need for Compilation and Evaluation of β-delayed Neutron Probabilities, define β-delayed neutron precursors as "standards" for the purpose of data evaluation and measurements, and elaborate a list of priorities for evaluation and new experiments for reactor physics and nuclear structure/astrophysics.

Units in mm	Central hole	Rings		
		Inner	Central	Outer
Diameter	160	220	340	420
Counter holes diameter	-	27.5	27.5	27.5
Number of He-3 counters at 10 atm	-	10	0	0
Number of He-3 counters at 8 atm	-	0	12	26

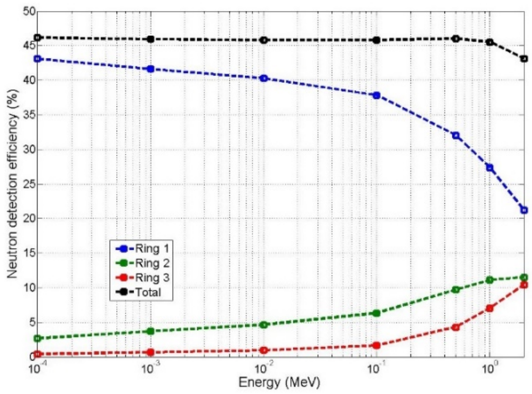
Table 7. Configuration details of BELEN-48 detector (48 ^{3}He tubes distributed in three different rings and at different atm). The dimensions are expressed in mm.

The detector consists on a set of ^{3}He tubes embedded in a polyethylene matrix. Different prototypes of the detector have been employed at JYL and GSI facilities for the study of β-delayed neutron emitters and in particular the determination of the neutron emission probability. The detector concept is a modular one, which allows an easy adaptation to different experimental environments and the optimization of the detector efficiency. The design of these detectors, has served to develop a methodology to facilitate the process and assist in obtaining the optimal design. The purpose of this methodology is to find the best combination of the position of the tubes in the polyethylene matrix to obtain a maximum efficiency and a flat response for a range of initial neutron energy values.

Counter	Property of	Gas	Amount available	Length (mm)	Diameter (mm)	Gas pressure (atm)	Operating voltage (v)	Cathode material
252248 LND	UPC	^{3}He	42	675.9	25.4	8	1500	Stainless steel
252248-10 LND	GSI	^{3}He	10	675.9	25.4	10	1500	Stainless steel

Table 8. Characteristics of the 52 ^{3}He counters available today. The few extra counters are spare units.

Figure 4. 3D view of the BELEN-48 detector polyethylene moderator matrix placed on its supporting structure. The ^{3}He counters will be inserted in the small holes located around the big central hole.



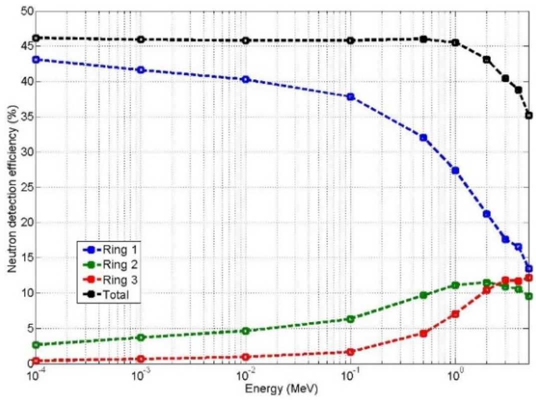


Figure 5. Left: neutron detection efficiency of BELEN-48 up to 2 MeV. Right: neutron detection efficiency of BELEN-48 up to 5 MeV.

The detector design for DESPEC, known as BELEN-48, consists of a polyethylene matrix and 48 ^{3}He proportional gas counters. The proportional gas counters are distributed in three rings around a beam hole (see Table 7). The High Density Polyethylene matrix hosting the tubes have is composed of 8 slices or blocks of 10 cm thickness that are assembled together to conform the central block with dimensions 50x50x80 cm^{3}. A supporting structure for the polyethylene block has been designed and constructed at the workshop of the UPC. This structure will be adapted to the facility and the implantation detector. The design of BELEN-48 is shown in Figure 4 and the counters specifications are detailed in Table 8. The neutron detection efficiency obtained with MCNPX simulations is presented in Figure 5. The total efficiency stays almost flat up to 2 MeV neutron energy. A detailed view of the total efficiency is depicted in figure 2b. To conclude, the following criteria are accomplished, an average neutron detection efficiency around 45 % and the planarity of the efficiency, defined as the maximum value of the neutron detection efficiency divided by the minimum value, is 1.07.

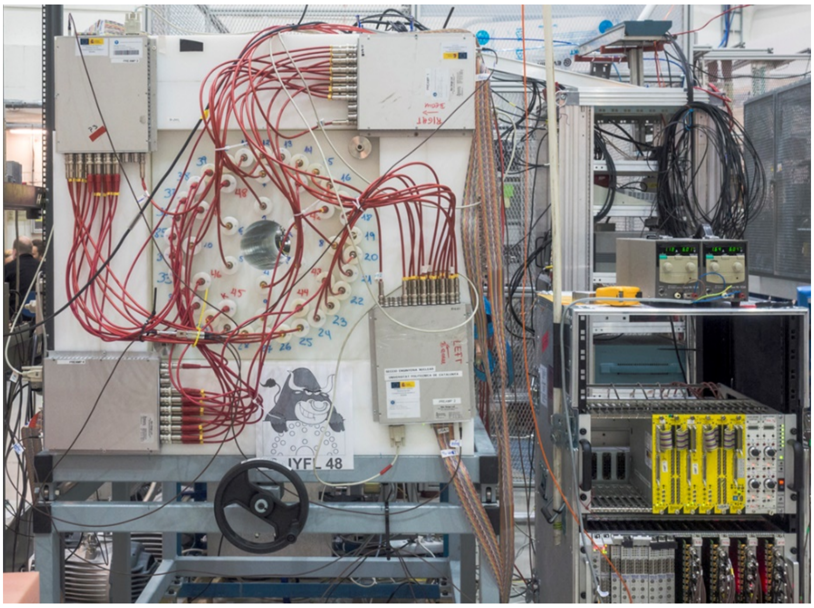


Figure 6. BELEN-48 used at JYFL in Nov 2014.

Institution name	**Researchers (staff)**
UPC	R. Caballero
	F. Calvino
	G. Cortes
	B. Gomez
	V. Gorlychev
	A. Tarifeño
IFIC	J. Agramunt
	A. Algora
	C. Domingo
	J.L. Taín
CIEMAT	D. Cano-Ott
	A.R. García
	T. Martínez

Table 9. List of scientists that have been involved in the construction of BELEN.

BELEN has already been used at JYFL, GSI and PTB. The settings of each prototype have been made to meet the initial specifications of each facility. The number of tubes, the number and location of the groups of counters (usually in the form of ring), the type of tubes in each group, and the spacing between tubes and rings has been designed by Monte Carlo simulations in order to achieve the best compromise between high efficiency and flat response for the neutron's energy range of each measurement.

The first two prototypes used 20 counters (BELEN-20) and were tested in two experiments at JYFL in 2009 and 2010. The next prototype BELEN-30 was tested at GSI in 2011 and was composed by 30 counters. BELEN-48, similar to the design for FAIR as part of the DESPEC setup, has been tested at PTB in 2013 and JYFL in 2014 (see Fig. 4). The last prototype is part of a larger delayed neutron detector (160 ^{3}He tubes), known as BRIKEN, and it is near to be commissioned (Jul 2016) at RIKEN.

The list of Spanish Scientists involved during the R&D and construction phases of BELEN is given in Table 9.

The list of institutions involved in the R&D and construction phases of BELEN is given in Table 10.

Institution	**Investments secured 2014 (k€)**
UPC	310
IFIC	26
GSI	165
CIEMAT	0 (only R&D)
Total	**501**

Table 10. Total cost and level of investment already accountable as in-kind contribution of the different partners in the construction of BELEN.

The TDR is finished and approved and the detector is constructed and ready to be used at FAIR Phase-0. Since the detector has been completed, no future funding for construction will be necessary.

III.2.4 DEGAS

The DESPEC Germanium Array Spectrometer (DEGAS) is a high-purity germanium array for high-resolution spectroscopy of electromagnetic decays from exotic nuclear species. It is a key instrument of the Decay Spectroscopy (DESPEC) experiment at FAIR. As mention before, at DESPEC rare isotopes produced by the Super-FRS will be stopped in an active implanter (AIDA) surrounded by DEGAS measuring gamma rays with high resolution from α, β, proton, neutron and isomeric decays. These measurements are complementary to DTAS measurements where the emphasis is put in the high efficiency of the spectrometer paying the price of a modest energy resolution.

The construction of DEGAS will proceed in three phases. For phase I it is planned to re-use EUROBALL Cluster detectors previously employed at GSI in the RISING stopped beam campaign. The detector units will be comprised of three crystals in a common cryostat. The cryostats will be electrically cooled to facilitate a compact detector arrangement.

In phase II AGATA-type γ-ray tracking detectors are planned to replace the most background affected EUROBALL detectors. Contrary to the conventional EUROBALL coaxial Ge detectors, tracking detectors enable efficient detection and rejection of both particle and γ-ray background.

The third phase is planned to include the results of long-term developments of highly segmented planar Ge detectors for the ultimate "imaging" array. The third phase is not included in the current funding scheme for DESPEC.

The Spanish groups have actively work in the R&D phase including the prototyping of a planar detector and the acquisition of one AGATA capsule which can be included as in-kind contribution at the DEGAS phase II stage.

III.2.5 The DESPEC Total Absorption Spectrometer – DTAS

The purpose of the Decay Total Absorption Spectrometer (DTAS) is to obtain for each exotic isotope of interest an accurate map of the beta decay transition probabilities to the states in the final nucleus, the so-called beta-strength distribution [8].

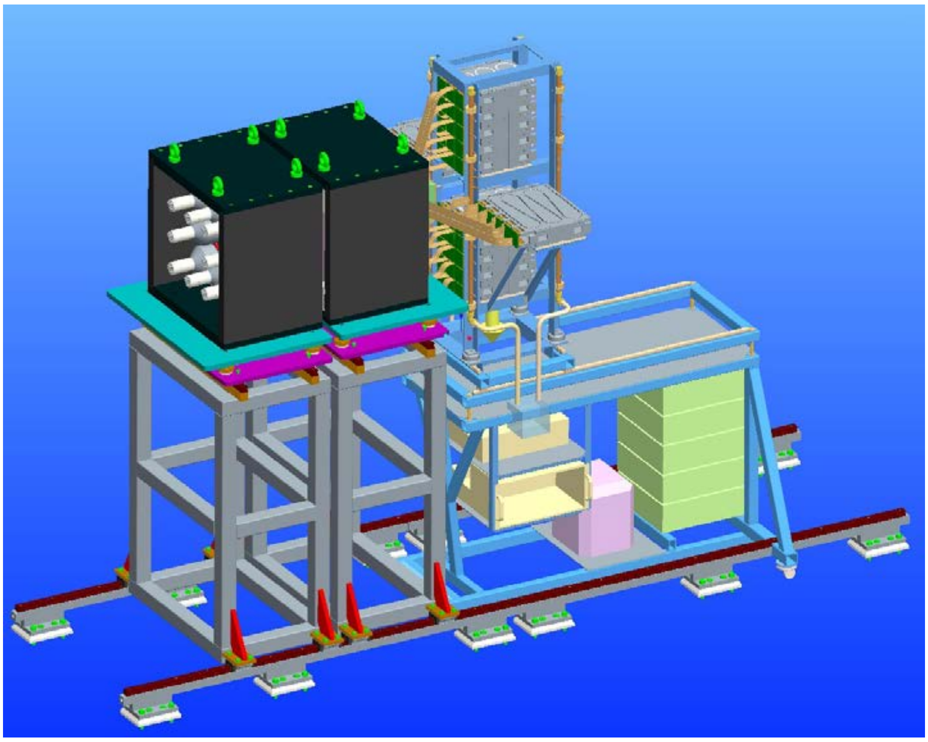


Figure 7. Assembly of DTAS surrounded by the lead-steel background shielding and coupled AIDA.

The beta strength is very sensitive to the nuclear wave function, thus it is an optimum tool to investigate the structure of exotic atomic nuclei [9][10]. It determines the emitted beta and gamma radiation fields and is thus of practical relevance (decay heat in reactor technology) [ALG10]. It determines also the neutrino field and is thus a key parameter in the analysis of reactor antineutrino oscillation experiments [12].

The beta strength distribution determines the decay half-life. Thus verification of theoretically calculated beta strength distributions for very exotic nuclei is determinant for the accuracy of half-life prediction for nuclei not accessible to experiment today as for instance nuclei involved in r-process calculations. .

DTAS measurements will be complementary to direct delayed neutron measurements performed with the BELEN and MONSTER setups. Moreover, very recently a novel approach [15] to the determination of neutron capture cross-sections in very unstable nuclei has been proposed, based in a combination of total absorption gamma ray spectroscopy and neutron measurements of beta delayed neutron emitters. As can be seen there is a large degree of synergy in the physics goals of the three instruments.

DTAS will be employed also at the MATS installation in the Low Energy Branch of FAIR [16]. This allows very precise measurements of beta strength distributions in some key exotic nuclei.

Institution name	Researchers (staff)
IFIC	J. Agramunt
	A. Algora
	B. Rubio
	J.L. Taín
Univ. Surrey	W. Gelletly
	Z. Podolyak
	P. Regan
CIEMAT	D. Cano-Ott
	T. Martínez
	E. Mendoza
Univ. Jyväskylä	A. Kankainen
	A. Jokinen
	I. Moore
	H. Pentillä
	S. Rinta-Antila
GSI	J. Gerl
	M. Gorska
	C. Scheidenberger
Petersburg NPI	L. Batist

Table 11. List of scientists and institutions currently involved in the design and commissioning of DTAS.

DTAS is a gamma-ray calorimeter. The principle of operation is the absorption of all the energy released in the decay in the form of a beta particle and gamma rays. A sophisticated deconvolution procedure allows the extraction of the beta strength function. This requires a precise characterization of the spectrometer and the accurate calculation of the response. The group at IFIC-Valencia has established the appropriate approach to the problem and demonstrated the level of accuracy that the technique can attain [17][18]. Thus it has become the technique of choice for this type of studies, since high-resolution gamma-ray spectroscopy is affected by serious systematic errors.

For operation at FAIR, DTAS will be coupled to the AIDA detector [19], where the high-energy ions are implanted and identified with the help of the information provided by the Super-FRS. After extensive simulation studies, taking into account physical and technical constraints, prototyping work took place on two options, one based on NaI(Tl) and the other on LaBr3:Ce [20][21]. Finally, mostly on budgetary grounds, the NaI(Tl) option was chosen with a modular design based on sixteen large crystals (15x15x25 cm^3). Figure 7 shows the assembly of DTAS, surrounded by the lead-steel background shielding, coupled AIDA is shown in the figure below:

The TDR was submitted on April 2012 and approved by FAIR management on January 2013 [22][20]. Construction of the detector proceeded, including the adjustable support structure and the radiation shielding. A gain stabilization system using a calibrated LED light source was developed. Both a data acquisition system with front-end analog electronics and a fully digital DACQ were developed to fulfill different experimental requirements.

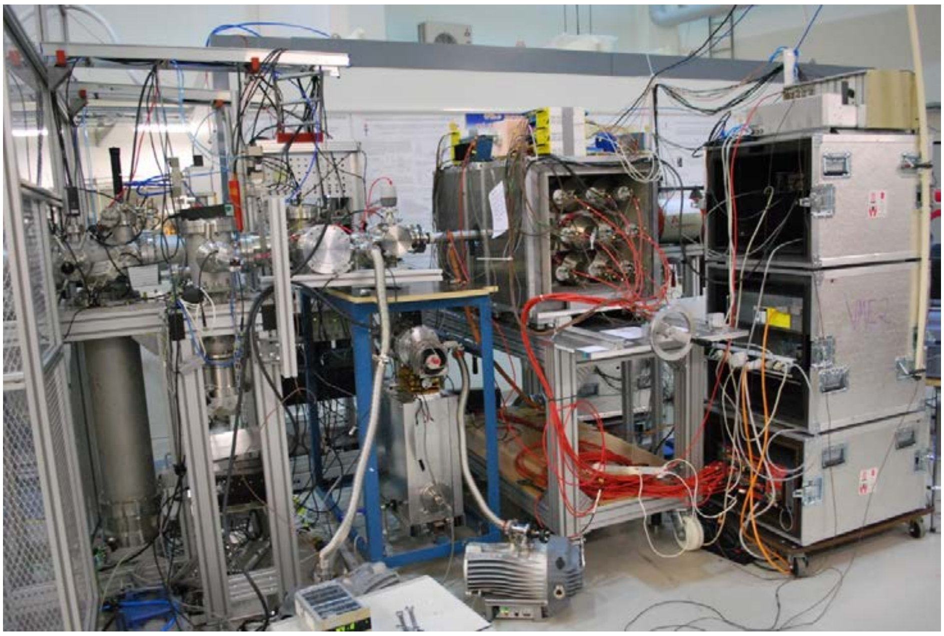


Figure 8. Photo of the experimental arrangement at the JYFL-IGISOL facility.

The full spectrometer was commissioned in the laboratory by the end of 2013. The efficiency to detect one decay is close to 100%. Single gamma-ray full peak efficiencies are larger than 60% in the energy range of interest (<10 MeV). An energy resolution of 8.8% is obtained for the 662 keV peak and a value of 4.4% is obtained at 2.5 MeV. The timing resolution is around 12 ns. All parameters are according to design values. The commissioning of the spectrometer (in an eighteen module version) with low energy ion beams, followed by the first physics experiments, took place at JYFL-IGISOL (Jyvaskyla, Finland) on March 2014 [23]. Figure 8 shows a photograph of the experimental arrangement.

The detector is awaiting the restart of the GSI/FAIR complex to carry out the commissioning with high-energy beams and perform the first physics experiments (Phase-0). The design, construction and commissioning of DTAS has been led by IFIC-Valencia (Project leader: J.L. Tain), and has been carried out the institutions and researchers (main contributors) given in Table 11.

Thus from Spain both IFIC and CIEMAT were involved, with the participation of a total of 7 physicists and engineers and the additional contribution of 5 students.

The Spanish industry (several small companies) was involved in the construction of the supporting structure for the detector and radiation shielding, with a weight of two tons, which allows the manual swift and precise positioning of the two detector halves.

The cost of DTAS eligible for in-kind contribution in the FAIR Cost Matrix escalated to 2014 values amounts to 510.7 k€. The distribution between the different institutions of eligible investments until now (in hardware, not including R&D or personnel costs) is shown in the Table below:

Institution	**In-kind (2014 values)**
IFIC-Valencia	346.7 kEur
CIEMAT-Madrid	0 (only R&D)
Univ. Surrey	14.9 kEur
Total	**361.6 kEur**

Table 12. Total cost and level of investment already accountable as in-kind contribution of the different partners in the construction of DTAS.

The share from Spain has been funded by "Plan Nacional I+D" through two FPA Grants and one ICI Grant. The resources for R&D, including additional personnel, have been funded through FPA Grants.

Institution		2016	2017	2018	2019	2020	2021	2022	2023	2024
IFIC	In-kind	-	-	40	40	40	-	-	-	-

Table 13. Funding scheme of the remaining funds for the completion of Spanish contribution to DTAS.

The current DTAS setup is fully functional. However in the TDR we proposed, and it was endorsed by the scientific review panel, to expand its capabilities with the addition of high resolution $LaBr_3(Ce)$ modules. Thanks to its modular design they can be added without loss of efficiency providing a new resolution spectroscopy tool. We contemplate the acquisition of four $LaBr_3(Ce)$ modules in a first stage, amounting to 120 k€ (in-kind).

III.2.6 The FAst TIMing Array – FATIMA

The experimental determination of nuclear lifetimes of excited nuclear states is of great importance to understand nuclear structure, because it makes it possible to determine 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 sub-nanosecond time range.

The FAst TIMing Array (FATIMA) is designed to measure sub-nanosecond half-lives of excited states in exotic nuclei produced at FAIR, and of special importance for the neutron-rich nuclei far off stability that will be unique at FAIR.

Figure 9. Left: Assembly of the FATIMA array in an experiment at the Institut Laue-Langevin in Grenoble. Right: demonstrator assembled at the University of Surrey.

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. With this in mind the system is designed with 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. The detailed conceptual and technical design of FATIMA can be found in the Technical Design Report (TDR), coordinated by Luis Mario Fraile (Universidad Complutense de Madrid).

Institution name	Researchers (staff)
Universidad Complutense	L.M. Fraile (coord.)
	M.C. Martínez
	J.M. Udías
	V. Vedia
Univ. Surrey	P. Regan
	Z. Podolyak
	M. Rudigger
Univ. Brighton	A. Bruce
IFIN-HH Bucharest	N. Marginean
	D. Ghita
	R. Marginean
	C. Mihai
Univ. Cologne	J. Jolie
	J.-M. Régis
Daresbury	J. Simpson
	I. Lazarus
Univ. Manchester	D. Cullen
U. West Scotland	J.F. Smith

LPSC Grenoble	G. Simpson
Univ. Sofia	S. Lalkovski

Table 14. List of scientists and institutions currently involved in the design and commissioning of FATIMA.

The FATIMA collaboration strives to continuously follow up new developments in scintillator detector technologies. Strong R&D has been carried out on the on the suitability of new materials for fast-timing measurements [24][25][26]. We have also tight links with the community undertaking these developments and we are ready to test their suitability for fast timing in our facilities. FATIMA has been designed in a modular and flexible manner in order to be able to easily integrate the new technologies in our system. The design in several stages allows for partial modifications of the fast timing array without compromising the overall performance.

The cost of FATIMA eligible for in-kind contribution in the FAIR Cost Matrix escalated to 2014 values amounts to 862 k€. The Spanish share of eligible hardware investments until now is shown in the Table below. The table does not include R&D nor personnel costs, obtained via FPA grants and European projects (FATIMA-NuPNET), which is estimated to amount to about three times the in-kind investment.

Institution	**In-kind (2014 values)**
Univ. Complutense	132.300 €
Total	**132.300 €**

Table 15. Total cost and level of investment already accountable as in-kind contribution for FATIMA, escalated to 2014 values.

The FAst TIMing Array (FATIMA) is co-ordinated by L.M. Fraile, Universidad Complutense de Madrid, and it integrates groups from UK (Surrey, Brighton, Paisley, and Manchester), Romania (IFIN-HH), Germany (Univ. Köln) and Bulgaria (Sofia) and several associated partners. The FATIMA TDR was submitted in 2015 by the international collaboration and was approved [27] with excellent recommendations by the FAIR ECE. The main part of the setup has been constructed and commissioned. Moderate investment is still required for the instrumentation of the beta detection and the data processing.

Institution		**2016**	**2017**	**2018**	**2019**	**2020**	**2011**	**TOTAL**
UCM	In-kind	11,000	23,000	--	25,000	--	--	59,000
TOTAL	In-kind							59,000

Table 16. Funding scheme of the remaining funds for the completion of Spanish contribution to FATIMA.

III.2.7 The MOdular Neutron SpectromeTER – MONSTER

As mentioned in Section III.2.5, the knowledge of the β-decay strength function $S_\beta(E)$ and the properties of nuclei lying far from stability contributes decisively to our understanding of nuclear phenomena in the nuclear structure, astrophysics and nuclear technology fields. One of the important aspects to be studied is the β-delayed neutron probability as a function of the energy in the daughter nucleus. Moreover β-delayed neutron (βdn) emission becomes more important as the neutron drip line is approached. As explained in Section III.2.3, the probabilities and energy spectra of the beta delayed neutrons emitted in the decays of neutron rich nuclei play an important role in the nucleosynthesis r-process as well as in the kinetic control of advance reactors, in particular the determination of the energy spectra contributes to determine the neutron capture cross section rate in nuclei of difficult access by other techniques.

Another important area of interest is the isospin dependence of nuclear level density (NLD). NLD is one of the important ingredients of all statistical model calculation. The excitation energy and angular momentum dependence of nuclear level density is well explored; however very little is known to the isospin dependence of NLD [31][32]. The set-up proposed for DESPEC will give suitable opportunity to study NLD by detecting the evaporated neutrons of neutron rich nuclei in-coincidence with daughter nuclei in the DSSD.

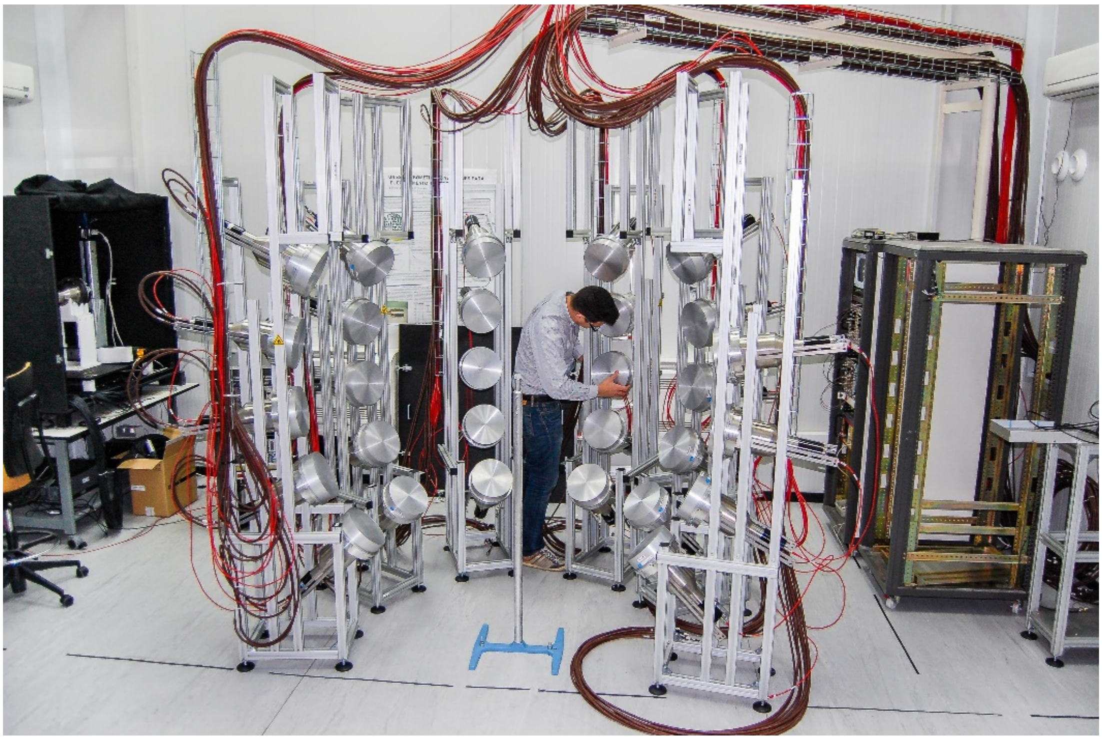


Figure 10. MONSTER demonstrator with 30 detector installed at the Laboratorio de Datos Nucleares – CIEMAT.

In order to determine the neutron emission features, two complementary neutron detectors have been proposed, a high efficiency moderator based 4π neutron counter BELEN explained before and a time-of-flight spectrometer based on scintillation detectors. Here we describe the Time Of Flight (TOF) MOdular Neutron SpectrometeTER (MONSTER) [28] for performing neutron spectroscopy at DESPEC. MONSTER will be also used at the MATS installation in the Low Energy Branch of FAIR [16]. A photo of the demonstrator built at CIEMAT is shown in Figure 10.

MONSTER is an array consisting of 100 neutron detectors made of BC501A/EJ301 liquid scintillator. Each detector has 20 cm in diameter and 5 cm in thickness and is able to detect neutron in the range from 300 keV – 20 MeV with an intrinsic efficiency between 60% (at 1 MeV) and 20% (at 10 MeV). The data acquisition system will consist on 100 high performance flash ADC channels with high resolution (12 or 14 bits) and high sampling rate (>500 Msamples/s). During the R&D phase CIEMAT has developed a high performance digitiser and 10 channels are available as a prototype. However, the fast development of commercial electronics has favoured the solution offered by S&P Devices board, with higher resolution and lower cost per channel. At present, CIEMAT is evaluating a test board on a high performance PC and a Xeon Phi PCI express parallel computer for doing the online pulse shape analysis.

The construction of MONSTER is being carried out within an international collaboration between CIEMAT (coordinator of the collaboration), IFIC, the Universidad Politécnica de Cataluña and the Variable Energy Cyclotron Centre in Kolkata (India) and the University of Jyväskylä institutions. The level of the in-kind contributions of the different partners is given in Table 17. As it can be seen, 80% of the funds of the detector have been secured.

Institution	**Total cost 2014 (k€)**	**Investments secured 2014 (k€)**
CIEMAT	609	391
IFIC	80	80
UPC	21	21
Univ. Jyväskylä	146	120
VECC Kolkata	609	560
Total	**1465**	**1172**

Table 17. Total cost and level of investment already accountable as in-kind contribution of the different partners in the construction of MONSTER.

The R&D and construction of MONSTER has been funded via several FPA grant s(CIEMAT, IFIC, UPC) over the past 10 years, the 7th Framework Programme ENSAR, ANDES and CHANDA projects (personnel) and by ENRESA (CIEMAT personnel). The large additional R&D costs for hardware and personnel have not been included in Table 17.

Instituion name	**Researchers (staff)**
CIEMAT	D. Cano Ott
	T. Martínez
	E. Mendoza
IFIC	A. Algora
	C. Domingo
	B. Rubio
	J.L. Taín
UPC	F. Calviño
	G. Cortés
VECC	C. Bhattacharya

	K. Banerjee
	S.Bhattacharya
	P.Roy
Univ. Jyväskylä	H. Pentillä
	A. Jokinen

Table 18. List of scientists and institutions involved in the construction of MONSTER.

The funding scheme of Spanish institutions necessary for the completion of MONSTER is given in Table. As it can be seen, the fraction pending of 220 k€ for CIEMAT will be dedicated to complete the data acquisition of the detector, still under development.

Figure 11. Left: photo of the new facility for the MONSTER assembly and test at CIEMAT. Right: photo of glove box room for the mounting/filling of the liquid scintillators in N_2 atmosphere.

The modules have been designed and tested entirely by CIEMAT at different European laboratories with reference neutron beams such as the Physikalische Technische Bundesanstalt (PTB) and CEA-DAM (France). As part of the project, CIEMAT has created a new facility for mounting/repairing and testing both organic and inorganic scintillators. The first batch of 30 detectors was manufactured by St. Gobain Crystals following the CIEMAT specifications. Later on, CIEMAT has transferred the detector construction technology to the Spanish company Scientifica Internacional, which has built 21 additional detectors for CIEMAT (15 units), IFIC (3 units) and UPC (3 units). The collaboration between CIEMAT and Scientifica Internacional has led to a patent (50% CIEMAT – 50% Scientifica) on a new type of detector with an innovative expansion volume.

Institution		2016	2017	2018	2019	2020	2021	2022	2023	2024
CIEMAT	In-kind	-	55	55	-	55	55	-	-	-

Table 19. Funding scheme of the remaining funds for the completion of Spanish contributions to MONSTER.

In addition, VECC has built two additional prototypes and will purchase another 42 units. Last, but not least, the University of Jyväskylä has obtained the funding for purchasing 10 additional modules and associated electronics. In both cases, Scientifica Internacional will make an offer and has excellent chances to win the call for tender.

A demonstrator of MONSTER consisting of 30 modules has been completed and tested in 2014 in a pilot experiment at ISOLDE. Recently, a new proposal has been accepted at ALTO (IPN Orsay). This experimental program serves to double purpose of making partial commissioning of the instrument (with increasing number of modules and different types of βand γ-ray detectors) and to its scientific exploitation at a much-reduced cost until the first beam is available at FAIR. MONSTER will be part of the scientific equipment ready during the FAIR Phase-0.

III.2.8 The NEutron Detector Array – NEDA

The neutron detector array NEDA, is a compact neutron tagging detector, recently incorporated to the HISPEC project, to be used together with AGATA and other detectors for measurements of neutrons in the energy range from about 1MeV to 200MeV.

The NEDA detector units will have the shape of uniform hexagonal prisms with a volume of about 3 litres, and will be filled with a liquid scintillator with good neutron-discrimination (NGD) properties. The design of the units was chosen to optimise the efficiency for detection of neutrons and to have a modular setup, allowing for a placement of the detectors in various geometries and distances from the target position. The full version of NEDA will consist up to about 350 detector units, which e.g. can be placed at a distance of 1m from the target position to cover a solid angle of about 50% of 4π.

The main characteristics of NEDA are the following:

- Efficient detection of neutrons in the energy range from 1MeV to about 200MeV.
- Superior neutron-γ discrimination, which allows the detectors to be used in an environment with a high γ ray background, and high count-rate capability.
- Sufficient granularity of the array to minimise the crosstalk of neutrons.
- Modular design, which allows for a placement of the detectors in different geometries around the target, optimising neutron detection efficiency and/or neutron energy resolution.
- Advanced digital front-end electronics, which is fully compatibility with the AGATA electronics and data acquisition system.

NEDA will be used in experiments with radioactive beams at HISPEC in NUSTAR/FAIR as well as at other European accelerator facilities for radioactive and high intensity stable beams, for example at SPIRAL2/GANIL and at SPES/LNL, therefore NEDA will be as well a moving detector associated mainly to AGATA.

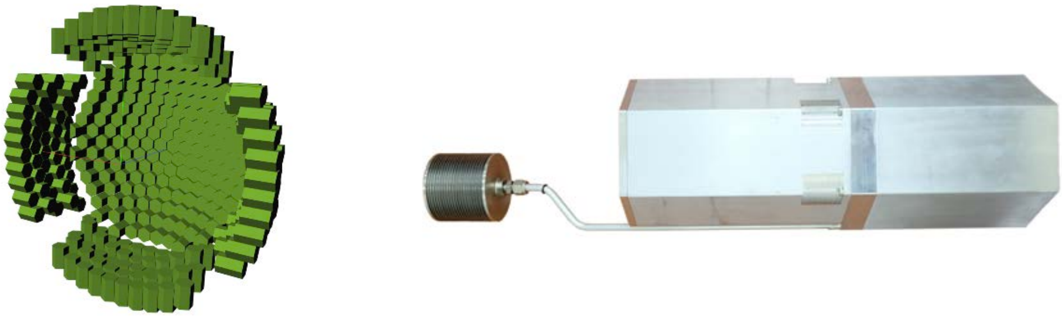


Figure 12. NEDA conceptual design and final detector module.

The present phase of developments and construction of a NEDA array consisting of about detector units, which will be ready for experiments at HISPEC from 2018.

The Technical Design Report (TDR) for NEDA at HISPEC was approved by the FAIR Expert Committee Experiments (ECE) on 22th Jan 2016 [35]. The Spanish groups have a modest contribution to the design and construction of the NEDA array through regional grants financed by the Generalitat Valenciana. It is not defined yet if the contributions to NEDA will be accounted as in-kind.

Country	**Institutions**
France	GANIL Caen
Germany	GSI Darmstadt, TU Darmstadt, Univ. zu Köln, TU München
Italy	LNL (INFN), Università di Padova, INFN-Sezione di Catania LNS (INFN), Università di Napoli and INFN
Poland	University of Warsaw, The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences, National Centre for Nuclear Research, Świerk
Spain	IFIC (CSIC), University of Valencia (ETSE), Politecnical University of Valencia
Sweden	Uppsala University, Royal Institute of Technology, Lund University
Turkey	Istanbul Sabahattin Zaim University Mimar Sinan Fine Arts University, Nigde University Yildiz Technical University
UK	York University, Daresbury Laboratory

Table 20. List of collaborating institutions to NEDA.

III.3 Participation in MATS

MATS, is together with LaSpec (precision laser spectroscopy), the two experiments of the NUSTAR pillar to be carried out after the exotic ions are thermalized in an ion gas catcher at the end of the Low Energy Branch (LEB). The design and construction of the MATS facility is carried out by the MATS collaboration, a large international consortium made of about 90 scientists from over 12 countries [34].

The detailed conceptual layout of MATS can be found in the Technical Design Report (TDR) of MATS and LaSpec, coordinated by Daniel Rodríguez (Universidad de

Granada) which can be downloaded from [3]. A reduced version of this document, excluding the costs matrix, was published as a review with the same title as the TDR manuscript "MATS and LaSpec: High-precision experiments using ion traps and lasers at FAIR" in the European Physical Journal Special Topics, 183, 1-123 (2010).

Institution Name	Contact
Universidad de Granada	Daniel Rodríguez danielrodriguez@ugr.es

Table 21. List of Spanish institutions participating in MATS

Key elements of the MATS system are the RFQ buncher, the MR-TOF device, the two Penning traps (one for preparation and one for precision measurements), the carbon-cluster ion source for absolute mass measurements, the instrumentation to provide highly-charged ions, or the infrastructure to operate new detection techniques like for example the Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) technique or the Fourier-Transform Ion-Cyclotron-Resonance (FT-ICR) for single ion detection, including the operation at cryogenic temperature.

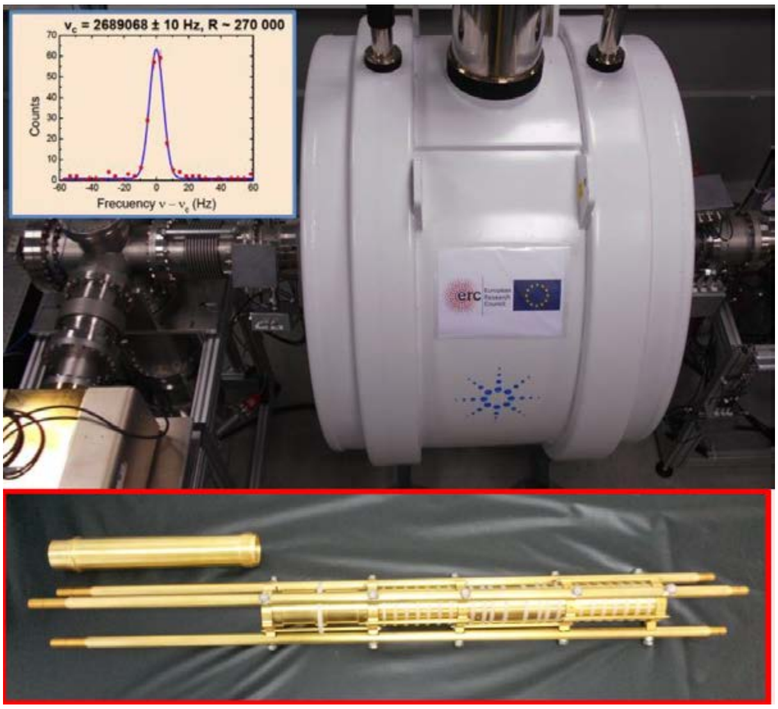


Figure 13. Picture of the 7-Tesla Superconducting solenoid at the University of Granada and the preparation Penning trap (bottom). The magnet provides two homogeneous magnetic field regions. The centre of this trap is located in one of these regions. The inset shows a cooling resonance for $^{40}Ca^{+}$ ions.

Institution Name	Researchers (* Staff)
Universidad de Granada	Juan Manuel Cornejo
	Daniel Rodríguez*

Table 22. Estimated number of Spanish scientists participating in MATS (only Ph. D)

The group in Granada is responsible for the preparation Penning trap and for single-ion detection using FT-ICR. The developments for single-ion detection started after the preparation Penning trap was built, and was coupled to a laser desorption ion source and a transfer section, to simulate the ion injection as it happens in a Radioactive Ion Beam facility. The results from the commissioning of the preparation Penning trap in this experimental arrangement have been published with the title "A preparation Penning trap for the TRAPSENSOR project with prospects for MATS at FAIR" [4]. Developments of electronics for Fourier-Transform Ion-Cyclotron-Resonance Mass Spectrometry started in 2015. Electronics for broadband and narrow-band (single ion) detection has been built by a Spanish company and tested by Juan Manuel Cornejo. This is to our knowledge, the first time a Spanish company develops this kind of circuitry and was funded through the project a FPA grant.

Although MATS at FAIR will be operational from 2020, the groups integrating the collaboration are carrying out measurements at the different facilities if radioactive beams are available. The group in Granada is working on the new facility at the University (TRAPSENSOR) to perform mass measurements on naturally abundant isotopes, in this case to address specific nuclei of interest for neutrino physics.

Facility	**Responsible-coordinator / Institution**	**Status of the TDR**
MATS and LaSpec TDR http://www.fair-center.eu/for-users/publications/experiment-collaboration-publications.html#c4908	Daniel Rodríguez / University of Granada	Approved in 2010
Work package		
RFQ and switchyard	Ari Jokinen/ University of Jyväskylä	Included in TDR Approved in 2010
Precision Penning trap	M. Block/GSI-Darmstadt and University of Mainz	Included in TDR Approved in 2010
Preparation Penning trap	D. Rodríguez/University of Granada	Included in TDR Approved in 2010
Detectors FT-ICR-MS	K. Blaum/Max-Planck Institute for Nuclear Physics	Included in TDR Approved in 2010
MR-TOF system	W.R. Plass/University of Giessen	Included in TDR Approved in 2010
Control system	D. Neidherr/ GSI-Darmstadt	Included in TDR Approved in 2010
In-trap conversion electron spectroscopy	P. Thirolf/LMU	Included in TDR Approved in 2010
Carbon Cluster ion source	Y. Novikov/PNPI	Included in TDR Approved in 2010

Beamline	L. Schweikhard/ University of Greifswald	Included in TDR Approved in 2010
Detectors TOF-MS	L. Schweikhard/ University of Greifswald	Included in TDR Approved in 2010
Tape station	G. Marx/ University of Greifswald	Included in TDR Approved in 2010
EBIT	J.R. Crespo López Urrutia/MPIK	Included in TDR Approved in 2010
q/A Selection	F. Herfurth/GSI-Darmstadt	Included in TDR Approved in 2010

Table 23. List of the MATS components, indicating the responsible person/institutions. The TDR was approved by the FAIR Steering committee in May 2010.

Institution		**2013**	**2014**	**2015**	**TOTAL**
UGR	In-kind	2.680,00	0,00	26.025,00	29.705,00

Table 24. Investment accountable as Spanish in-kind contribution

Institution		**2020**	**2021**	**2022**	**TOTAL**
UGR	In-kind	50.000,00	50.000,00	20.000,00	120.000,00

Table 25. Level of investment accountable as in-kind contribution and amount of investment pending/expected for the University of Granada in MATS.

	Running and Maintenance costs / person /year	**Total /year €**
Phase 0	2.000 (1.000 NUSTAR, 1.000 MATS)	2.000,00
Phase 1	Not yet defined	-
Phase 2	Not yet defined	-

Table 26. Expected yearly running costs for the MATS experiment for the University of Granada.

III.4 Participation in R^3B

R^3B is a major branch of the NUSTAR pillar of the FAIR experimental program. The design and construction of the R^3B facility is being pursued within the R3B collaboration, a large international consortium comprising more than 200 scientists from over 20 countries. R^3B was designed to be the first experiment to allow for kinematically complete measurement of peripheral reactions with heavy ion beams, including coincident detection and identification of the heavy residues in addition to neutrons and photons. There exist other facilities worldwide that have developed similar experimental concepts, however the uniqueness of R^3B will be preserved, being the sole installation that will allow the study of extremely heavy and fully striped ion beams, in particular those approaching the r-process path.

The detailed conceptual layout of R^3B can be found in the R^3B Technical Proposal [36] of 2005. Since then, an extensive R&D program has been pursued, leading to the final design of the different detection components. O. Tengblad (IEM-CSIC) is Technical Director of R^3B.

Key instruments in R^3B include the neutron detector NeuLAND with unprecedented multi-neutron detection (NeuLAND) with high resolution down to 20 keV, the silicon tracker R3B-Si-TRACKER with three-layer surrounding the target allow for particle and gamma detection with highest efficiency and precision in conjunction to the calorimeter CALIFA, and the super-conducting large-acceptance dipole R3B-GLAD with 15 Tm bending power and a huge (+120, −50%) momentum acceptance, together with the high-performance tracking system allow for momentum measurements of heavy fragments with a precision $\Delta p/p = 10^{-3}$. In addition, several charged-particle detectors are used for ΔE and time of-flight measurements.

The Spanish groups participating in R^3B have focused their interest in the development of the calorimeter CALIFA (CALorimeter for In Flight detection of γ-rays and high energy charged pArticles). The international collaboration is led by D.Cortina (Univ. Santiago de Compostela).

Institution Name	**Contact**
Universidad de Santiago de Compostela	Dolores Cortina-Gil
Instituto de Estructura de la Materia	Olof Tengblad
Universidad de Vigo	Enrique Casarejos
Universidad Complutense de Madrid	Luis M. Fraile

Table 27. List of Spanish institutions participating in R^3B

Institution Name	**Researchers (* Staff)**
Universidad de Santiago de Compostela	H. Alvarez- Pol *
	J. Benlliure *
	P. Cabanelas
	D. Cortina-Gil *
	J. L. Rodríguez
Instituto de Estructura de la Materia	M.J. G. Borge *
	E. Nácher *
	O. Tengblad *
Universidad de Vigo	E. Casarejos
	A. Segade *
	J.A. Vilán *
Universidad Complutense de Madrid	L.M. Fraile *

Table 28. Estimated number of Spanish scientists participating in R^3B (only Ph.D.).

Detector	Spokesperson / Institution	Status of the TDR
CALIFA barrel http://www.fair-center.eu/for-users/publications/experiment-collaboration-publications.html#c4908	D. Cortina / USC	Approved in 2013
CALIFA Endcap http://www.fair-center.eu/fileadmin/fair/experiments/NUSTAR/Pdf/TDRs/TDR_R3B_CALIFA_ENDCAP_public.pdf	D. Cortina / USC	Approved in 2015
Neutron ToF spectrometer /NeuLAND)	K. Boretzky /GSI	Approved in 2013
R3B Quadrupole triples	T.Aumann/ TU Darmstadt	Approved in 2011
Large-acceptance Dipole (GLAD)	H.Simon /GSI	Approved in 2008
Tracking Detectors	S. Pascalis/ TU Darmstadt	Approved in 2015
Si Tracker	R.Lemonn/ Daresbury	Expected in 2016
Active Target	P: Egelhof /GSI	Submitted in 2016
R3B High resolution spectrometer	M. Petri / TU Darmstadt	Expected in 2018

Table 29. List with the main R^3B elements, the coordinating institutions, status of the TDR. The Spanish participation concentrates on the CALIFA detector.

Institution		2012	2013	2014	2015	TOTAL
USC	In-kind	79.600	12.6472,16	59.381,1	149.888,7	415.341,96
IEM	In-kind	174.520				174.520
UVigo	In-kind			11.986,5	17.910,0	29.896,5
						619.758,46

Table 30. Level of investment accountable as Spanish in-kind contribution (CALIFA)

The collaboration is since 2013 performing experiments in the existing GSI ALADIN/LAND setup, precursor of R^3B. There are plans to run experimental campaigns starting from 2018 in the so-call FAIR Phase 0. These experiments will benefit from the new FAIR equipment developed. To contribute to the maintenance of the common infrastructure, the collaboration has foreseen the payment of a year contribution that will amount to 1000 € / per PhD and year. This contribution will be added to the equivalent amount that will be paid to the NUSTAR collaboration as stated in Table 31.

	Running and Maintenance costs / person	Total /year €
Phase 0	2.000 (1.000 NUSTAR, 1.000 R^3B)	24.000

Phase 1	Not yet defined	-
Phase 2	Not yet defined	-

Table 31. Expected yearly running costs for the whole experiment and for individual detectors (if any) corresponding to Spanish researchers Table 28.

III.4.1 The CALIFA calorimeter

CALIFA, the R^3B calorimeter, is a versatile device that will play a key role in the realization of full kinematics measurements. It will surround the target in order to detect (normally in coincidence with other R^3B detectors) the emission of γ-rays from 100 keV to 30 MeV and light-charged particles (mostly protons with energies up to 700 MeV) arising from reactions induced by relativistic radioactive beams impinging on the R3B target. The particular kinematics of high-energy reactions (strong forward-focusing due to the Lorentz boost and accompanying Doppler broadening and shift) has, to a large extent, determined the geometry of the detector.

CALIFA will be used in many of the physics cases of the R^3B experiments, even though the required functionality will greatly vary from one case to another. Three different working conditions for CALIFA are foreseen:

- In some cases it will be employed as a high-resolution spectrometer, used for the detection of relatively low-energy γ-rays (0.1 to 2 MeV in the projectile frame), consequently with low multiplicity (2-3). The energy resolution will be in this case the most critical parameter of CALIFA. This value has been set to be of $\Delta E/E < 6\%$ (for a 1 MeV γ-ray), which allows distinguishing most of the simple γ-ray cascades that originate from the de-excitation of exotic heavy nuclei in the vicinity of the shell closures or light exotic nuclei.
- Another case requires using CALIFA as a γ-ray calorimeter for the detection of very energetic γ-rays (up to 10 MeV in the projectile frame), associated with very fragmented decays (high multiplicity events). In this case the key parameters are the total γ-ray absorption (intrinsic photopeak efficiency), the γ-ray sum energy, and the γ-ray multiplicity.
- The most challenging scenario corresponds to the use of CALIFA as a hybrid detector that has to provide simultaneously high-resolution spectroscopic and calorimetric properties to determine the total energy of light charged particles. A typical example of a reaction channel that requires this performance is that of quasi-free scattering (i.e. (p,2p),(p,pn)...). Here, the detection of high-energy light charged particles (protons up to 700 MeV) has to be possible at the same time as the detection of the prompt γ-ray de-excitation of the residual fragment. Both processes need to be measured with good energy resolution over a very large dynamic range. The recoiling protons and also other target-like fragments are to be measured by CALIFA operating in coincidence with the R^3B SiliconTracker, which fulfills the required angular precision.

The demanding requirements are summarized in Table 32.

Intrinsic photopeak efficiency	40% (at E =15 MeV projectile frame)
γ–ray sum energy resolution	Δ(Esum)/<Esum> <10 % for 5 γ-rays of 3 MeV
γ-ray Energy resolution	<6 % ΔE=E for 1 MeV
Energy range for protons	Up to 700 MeV in Lab system $\frac{\sqrt{100MeV}}{\sqrt{E}}$
Energy resolution, protons stopped	<1 % $\Delta E_p/E_p$
Energy resolution protons punch though	<7 % $\Delta E_p/E_p$ (at E_p=500 MeV)
Full energy peak efficiency for protons	>50 % (for all energies)
Proton-γ separation	for 1 to 30 MeV

Table 32. Nominal specifications of the CALIFA R^3B calorimeter (at β=0.82c)

CALIFA consists of two sections, a cylindrical `Barrel' spanning an angular range from 140 to 42 degrees and an `Endcap' covering the angular range up to 7 degrees. The Barrel is formed by 1952 long CsI(Tl) coupled to APD devices and equipped with a digital readout system. The design of the CALIFA Barrel was subject to a Technical Design Report accepted by the FAIR management in January 2013 and is presently under construction.

The CALIFA Endcap has to provide the detection of the most energetic particles in an angular region strongly populated by the light reaction products and gammas. Larger polar angles in the Forward Endcap will make use of high performance CsI(Tl) crystals coupled to Large Area Avalanche Photo Diodes employing the so-called iPhos readout concept. Smaller polar angles, below 19^o, are covered by a ring of Phoswich detectors made from a stack of 7 cm $LaBr_3$ and 8 cm $LaCl_3$.

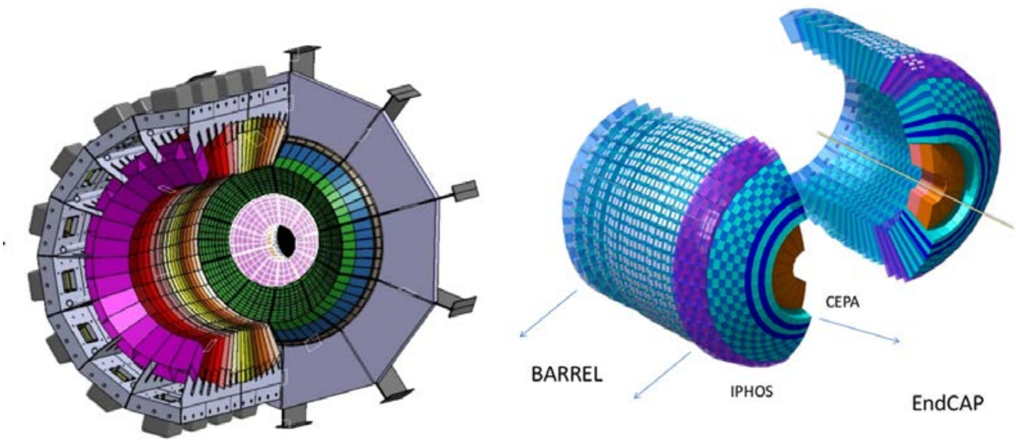


Figure 14. Left: Artistic profile of the CALIFA calorimeter showing part of the mechanical coverage. Right: Detail of the Carbon Fiber structure that holds the CsI(Tl) crystals.

The design and construction of the CALIFA calorimeter demanded many technical challenges. The Spanish groups (USC, IEM and UVigo) have assumed important management and technical responsibilities in R^3B/CALIFA, developed within the project an important number of technical contributions that are summarized here:

- **Contribution to the general conceptual design**. We have been deeply involved since the beginning of the process on the conceptual design that is in a big extent dominated by the strong Doppler effects suffered by particles emitted by relativistic sources. The kinematics of the process and the characteristics of the reaction and detection technique impose an important granularity in the detector. The dimensions of the crystal entrance faces evolve with the polar angle to better adapt to these effects. The length and in consequence the total volume of the detectors also varies to optimize the efficiency according to the expected Doppler energy boost [37][38][39].

- **Contribution to the definition of the detection units**. A broad R&D program leaded by the Spanish groups was accomplished to define the nature and specifications of the different scintillators and photo-sensors to be used in CALIFA. This program led to the election of finger-like CsI(Tl) crystals coupled to Large Area APD sensors (and developed in partnership between USC and Hamamatsu) for the Barrel and backward angles for the Forward Encap (up to ~20 degrees) (see Figure 5 Left). The development of the USC group in APD has also been the origin of a productive collaboration with the CNMB (U Barcelona) group working in semiconductor sensors. The most forward angles (8-20 degrees) in the Forward Endcap will be covered by an array of Phoswich detectors composed by $LaBr_3/LaCl_3$ and readout by metal-package PMT (right part of Figure 15). This system was developed by the IEM group and the St Gobain crystals company. Several experiments in-beam have been performed using CsI(Tl) and $LaBr_3/LaCl_3$ units in its DEMONSTRATOR version [40][41][42][43][44][45][46][47].

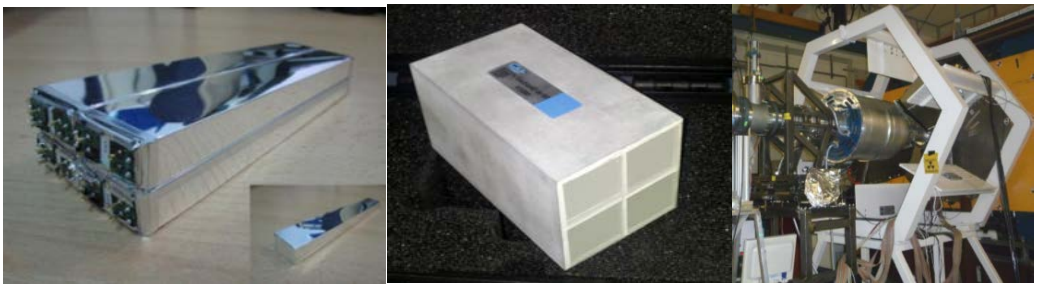


Figure 15. Left: Picture of a bunch of 4 Cs(Tl) (22 cm long) wrapped with VM2000 and couple to the customized LAAPD (S- 8622 of Hamamatsu). Central: Picture of a bunch of four LaBr/LaCl phoswich (St. Gobain). In this prototype the first stage has a length of 4cm and the second one of 6 cm. Left: Several experiments in-beam have been performed using CsI(Tl) and $LaBr_3$/LaCl units in its DEMONSTRATOR version

- **Simulation.** Our team has participated in the development of the analysis and simulation software for the R^3B experiments, R3BRoot (Dr. Alvarez is the convener of the Analysis and Simulation WG and the R3BRoot project coordinator). The analysis and simulation framework, based on ROOT and connected via virtual Monte Carlo to the Geant4 or Geant3 tracking engines, allows the calibration, reconstruction and physical evaluation of the detectors data, preserving in common data structures and parameters both the simulation and the data analysis. A particular effort has been devoted to the simulation of the CALIFA detector. It is very important to determine the capability of the detector design to fulfill the specifications. But it is also relevant to evaluate the effect of the support and wrapping structures on the detector efficiency [48].

It is important to notice that this project has opened the collaboration with the mechanical engineering group of UVigo. This technical group has given support in the important step of going from the conceptual design to realistic and versatile mechanical structures.

- **Mechanical design.** The mechanical design of CALIFA has to deal with the functionality of the detector, the integration of the different systems, and the constrains of its use. The overall constrains for the active core made of almost 2000 CsI(Tl) crystals (BARREL) include a robust and safe structure, a minimum of structural material, and a tight definition of the static positioning and orientation of the crystals.

  The designed solution is an alveolar structure made of carbon fiber (CF) reinforced composites to support the crystals. A three layer concept is proposed, based in the internal CF-structure, a cover structure surrounding the CF-structure, and the external structure to support the active core, as a gantry, allowing for the partition of the system in two autonomous and symmetric halves with relative movements (seeFigure 16).

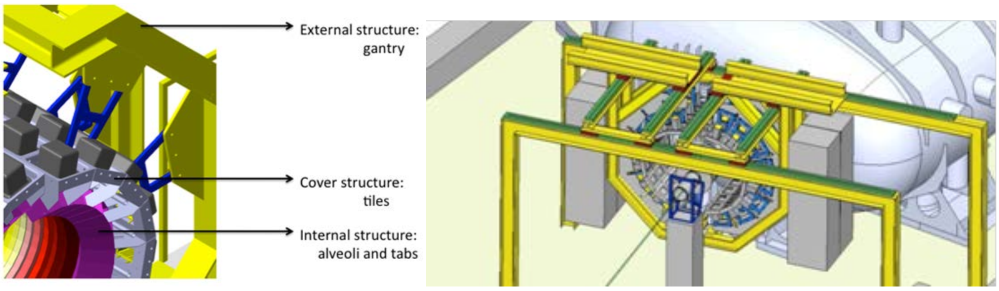


Figure 16. Left: The 3 layers concept. The crystals are hold and positioned within a honeycomb-like CF structure. The cover layer surrounds the crystals and holds the CF-structure. Right: An external structure sustains the system, and allows its displacements.

- **Development of Carbon Fiber internal structure**. One of the major issues is the definition of a support system able to stand the weight of the detector and guarantee the position precision required introducing a minimum quantity of matter. This has been achieved by using thin wall carbon fiber structures, honeycomb-like. Figure 7 shows a picture of a bundle of the pieces made of CF, after mounted into a mechanical cage. The first prototypes holding up to 64 detection units have been produced and successfully tested (right part of Figure 17). The ratio of the mass of the CF-structure and the mass of the active crystals (about 1300 Kg) is below 0.7%.

Figure 17. Left: Picture of the Carbon Fibre Honeycomb structure produced by the UVigo group. Right: Example of the First prototype structures used for transport and experiments

Institution		2012	2013	2014	2015	TOTAL
USC	In-kind	79.600	12.6472,16	59.381,1	149.888,7	415.342
IEM	In-kind	174.520				174.520
UVigo	In-kind			11.986,5	17.910,0	29.896
						619.758

Table 33. Level of investment accountable as Spanish in-kind contribution in CALIFA.

Presently, we are on the process of constructing the detector. The realization of the CF structures to hold the 2014 CsI(Tl) units is ongoing in the UVigo laboratory. The collaboration expects to have 768 from the 1064 CsI(Tl) crystals covering angles between 40 to 90 degrees operatives (fully electronic and DAQ equipped) in Q4 2016 (half of them mounted in USC). Experiments with part of this equipment are foreseen for Q4 2017 in the proton accelerator PNPI (St. Petersburg) and Q4 2018 in R3B/GSI after the intensity upgrade and operating in coincidence with other R^3B new equipment (GLAD, NeuLAND and Si-Tracker). Moreover, the tendering process of the $LaBr_3$/$LaCl_3$ CEPA crystals has also been initiated and the first prototype is expected to be available for Q2 2017.

To summarize, the implication of the Spanish groups in CALIFA is very high. We have been a leading force in the project since the conceptual design, detection definition, electronics and DAQ, analysis and simulations, mechanics and now construction. From the economical point of view our participation can be resumed in a level of investment accountable as Spanish in-kind contribution of 619.758 € (seeTable 31). The total contribution (including personnel and research infrastructures) made largely multiplies these numbers by a factor 3.

Institution	Country	(up to 2015)	Remaining	TOTAL
USC	Spain	415. 341,96	255.120,77	670.462
IEM	Spain	174.520	255.120,77	429.640
UVigo	Spain	29.896,5	100.000	129.896
U Lund	Sweden	589.000	0	589.000
Chalmers	Sweden	850.000	0	850.000
TU Munich	Germany	200.000	260.000	460.000
TU Darmstadt	Germany	130.000	260.000	390.000
Dubna	Russia	0	360.000	700.000
TOTAL		2.388.758,46	1.490.241,54	3.879.000

Table 34. Level of investment accountable as in-kind contribution in CALIFA including all the international partners.

The cost for the four FAIR collaborations (NUSTAR, CBM, Panda and APA) amounts to 180 M€. The R^3B experiment, is the largest investment in NUSTAR and the cost estimates goes up to 25 M€. CALIFA is one of the key detectors in R^3B and amounts up to 3.7 M€. Spain aimed in 2005 for a total contribution of 1.3 M€ to CALIFA. Today Spain has invested ~620 k€ in CALIFA (a bit less than 50% of the envisaged participation, 16% of the CALIFA cost, 2.5 % of the R^3B). Our goal would be to complete the 1.3 M€ Budget originally proposed in the inception of the project.

IV Scenarios for the official Spanish participation in FAIR

Spain has been heavily involved in the FAIR project since its beginning. Spain has also made very important investments during the R&D phase and a significant fraction of them have been materialised as possible in-kind contributions to the project. The summary of the investments already accountable as Spanish in-kind contribution and the funding necessary to complete the Spanish participation (i.e. as it is declared in the FAIR cost matrix) is given in Table 33.

	Detector	Investments made and accountable as in-kind contribution (k€)	Investments pending (k€)	Leading institution
DESPEC	BELEN	336	0	UPC
	DTAS	337	120	IFIC
	DEGAS (*)	179	0	IFIC
	MONSTER (det)	391	0	CIEMAT
	MONSTER (DAQ)	0	220	CIEMAT
	MONSTER (det)	13	0	UPC
	MONSTER (det)	28	0	IFIC
	FATIMA	104	59	UCM
HISPEC	AGATA	not in-kind	not in-kind	IFIC, IEM, UAM, USAL
	NEDA	not in-kind	not in-kind	IFIC
	Beam tracking	45,5	-	CNA
R3B	CALIFA	425	255	USC
	CALIFA	30	100	UV
	CALIFA	174	255	IEM
MATS	MATS	30	120	UGR
Total		**2092,5**	**1129**	

Table 35. Summary of the investments made and pending which can be accounted as in-kind contributions to FAIR. (*) The AGATA capsule is considered as in-kind contribution to DEGAS only if the DEGAS solution includes AGATA capsules.

As it can be seen, a total of 2092.5 k€ can be considered already as a Spanish in-kind contribution to the FAIR project. At present there exist three mechanisms to become an official member of the project:

- Become a full member of FAIR which is achieved after providing an 11 M€ in-kind contribution.
- Become a FAIR associate, which is achieved after providing a 5.5 M€ in-kind contribution.
- Become a FAIR associate in partnership with a second country. The combination of in-kind contributions of two different countries adding up to 5.5 M€ would provide both countries the conjoined status of FAIR associates.

The Spanish nuclear physics community proposes two scenarios for an official Spanish participation to FAIR: a purely scientific participation in the experiments and a more ambitious combined scientific and industrial participation.

IV.1 Scenario 1: a purely scientific participation in the experiments

The Spanish investments made in the construction of the different detectors in which Spain is involved amounts to 3660 k€ (2104 k€ already invested). The weight of such a contribution can guarantee the status of conjoined FAIR Associate if Spain merges its participation with an additional country. Furthermore, it could serve as a basis for a negotiation with FAIR adapted to the specific case of Spain. This scenario would preserve the high level of scientific participation and leadership reached by the Spanish research groups in FAIR.

IV.2 Scenario 2: participation in scientific instruments and FAIR infrastructure

If Spain finds an additional mechanism to fund an industrial participation to the FAIR infrastructure then it could become a FAIR Associate on its own, without closing the path of becoming a full member in case that the industrial participation is increased. As it is detailed in Section V, FAIR offers excellent opportunities for the Spanish industry and important returns could be obtain with a modest contribution to the accelerator infrastructure.

IV.3 Conclusions

The informal contacts between Spanish representatives of the nuclear physics community and the FAIR management have shown that FAIR can offer flexible solutions to the Spanish participation in FAIR adapted to its particular case. For this reason, it is of greatest importance that the Spanish Ministry of Economy and Competitiveness – Secretary of the State for Research, Development and Innovation re-establishes the contacts with the FAIR management with the ultimate goal of defining the formal participation of Spain and its research community in FAIR.

V Participation of the Spanish industry and returns

The large scale and complexity of the FAIR project offers excellent opportunities for the Spanish industry and a large potential for industrial returns, which could exceed the investments. Section IX shows a detailed list of the FAIR items that remained to be built and for which Spanish companies could make an offer.

The Asociación Española de la Industria de la Ciencia (ineustar) [49] has expressed its strong interest in participating in the FAIR project and ineustar representatives will meet with FAIR contacts to explore the possible levels of participation.

Among the large possibilities it is worth to highlight two especial examples of Spanish companies that could have an easy implication in the FAIR project: ELYTT Energy and Seven Solutions.

ELYTT Energy is an innovative company, working in high technology projects, solving the needs of our clients, in the field of the energy and the particles accelerators. It is capable of designing, manufacturing and distributing a large variety of high technology components relevant for FAIR:

- Design and manufacturing of warm and superconducting magnets for particle accelerators, spectrographs, scanners… and accelerators components.
- High precision power supplies, our standard program offers most magnets applications, with low ripple and high stability class.
- Design and manufacturing of Kinetic Energy Storage Systems (KESS, Flywheels) for use as UPS, net quality, energy management, regenerative braking…
- Design and manufacturing drawings of warm and superconducting magnets, coils, support frames, fusion industry, electrical motors...

Type	Sub-type	Total cost k€	Share of the contribution	ELYTT R&D
SFRS super-conducting magnet	Super-ferric dipole	12.000	30% in-kind (3.600 k€) 70% industrial return	-
Power supplies	Group 1	5.350	30% in-kind (1.600 k€) 70% industrial return	Energetic efficiency
Power supplies	Group 3	3.250	30% in-kind (975 k€) 70% industrial return	Energetic efficiency
Total		**20.600K€**	**6.175k€ in-kind**	

Table 36. Possible contributions of ELYTT to the construction of the FAIR infrastructures, investments and returns.

ELYTT has shown a great interest in the FAIR project since 2004 and has participated in the R&D phase of several components. According to the most recent information provided by ELYTT in 2016, the company would be capable of contributing to the construction of important components of the Super FRS getting important returns.

A second example is provided by the Spanish company Seven Solutions [51]. For over 10 years, Seven Solutions has worked successfully in different cutting-edge projects from different sectors such as avionics, telecommunications, Smart-Grid, space, military and scientific facilities as particle accelerators and radio-telescopes providing embedded systems (electronics, firmware and embedded software). Seven Solutions is leader in accurate sub-nanosecond time transfer and frequency distribution for reliable industrial and scientific applications. The company is the original designer of the White Rabbit switch extensively used at CERN.

Between 2012 and 2013 Seven Solutions has delivered to FAIR 20 switches and in 2015 did win an additional contract for additional 50 White Rabbit switches. Due to the massive implantation of the White Rabbit synchronization technology at FAIR, Seven Solutions has estimated important potential returns of 2 M€ from the delivery of White Rabbit switches and 5 M€ from the delivery of White Rabbit nodes.

VI <u>Synergies with other activities of the Spanish nuclear physics community</u>

Experimental nuclear physics has many aspects in common with particle physics and astroparticle physics. There is a large degree of overlap in the fundamental scientific questions to be answered and also in the experimental techniques, methodologies, instrumentation, tools and facilities (i.e. particle accelerators) used.

There are however important differences which can led to a wrong conclusions or misinterpretations when evaluating the activities in the field.

From the scientific point of view, the prediction capabilities of nuclear theories are not sufficient to drive the search of new physics, as it is the case in particle physics. The subject of study of nuclear physics is diffuse and requires a huge experimental activity, in particular for providing the nuclear data (i.e. nuclear properties) required by theory and applications (medical physics, energy, environmental sciences…).

The size of nuclear physics detectors and experiments has increased over the time, gaining in efficiency and sensitivity. However, they are still orders of magnitude below the size of the large LHC detectors and therefore nuclear physicists are still able to organize themselves in smaller groups and smaller collaborations.

The extension of the frontiers of nuclear physics requires the construction of larger facilities such as FAIR (Germany), SPIRAL-2 (France), RIB (USA), TRIUMF (Canada) or RIKEN (Japan). However, small-scale facilities are also necessary for doing complementary experiments and detector tests and calibrations. Indeed, the typical situation is that a research program requires the access to various installations that provide the best experimental conditions for the quantity to be measured.

Nuclear physicists have developed in a natural way a collaborative and competitive modus operandi that exploits the synergies between facilities and research groups:

- An idea for an experiment is materialized as a proposal, which involves the necessary number of collaborators to carry out the experiment, i.e. covers the necessary amount of detectors and human resources.
- The collaboration set around an experiment does not necessarily hold over the time, although long standing links have been established between the groups with common interests, in order to share equipment, resources and complement each other with the specific skills.
- If the experiment is approved by the corresponding advisory committee (PAC), and a TEC (technical advisory committee for feasibility) the set of instruments, which do not necessarily belong to the same institution are combined and the experiment is carried out when the beam time becomes available. The typical duration of a single experiment ranges from days to months.
- Once the experiment has been completed, the setup can be dismantled and used elsewhere. In this way it is possible to optimize the cost of the scientific production since several experiments can be carried out at different places with the same detector.

Even large sized detectors such as AGATA (to give a specific example) can be used at various facilities, thus optimizing the ratio of scientific production over the investment in hardware.

It is realistic to think that when no beam time will be available at FAIR, many detectors will be used at other laboratories such as CERN (ISOLDE and n_TOF), GANIL/SPIRAL-2, Laboratori Nazionali di Legnaro, Cyclotron Laboratory of the Univeristy of Jyväskylä, Institut Laue-Langevin (among others) or even outside Europe, at RIKEN, TRIUMF or RIB. In this sense, it has been mentioned in several occasions that FAIR will establish different collaboration agreements with other facilities.

Last, but not least, smaller local accelerator facilities such as the CNA or the CMAM in Spain, and Spanish ICTS such as LSC, will also benefit from the limited use of Spanish instruments developed for FAIR, besides the key role they have played during the R&D phase.

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VIII List of Spanish institutions and researchers participating in FAIR

The list of Spanish institutions and scientists participating in the FAIR project i.a.o. is:

CIEMAT
Daniel Cano Ott, Trinitario Martínez Pérez
Main activity: coordination, design and construction of the MOdular Neutron SpectromeTER (MONSTER) for β-decay studies.

Instituto de Estructura de la Materia – CSIC
María José García Borge, Andrea Jungclaus, Enrique Nácher, Olof Tengblad
Main activity: development and construction of the CALIFA calorimeter *front endcap* cap for the R^3B experiment (R3B). Development of the Advanced GAmma Tracking Array (AGATA) for in-beam gamma ray spectroscopy (HISPEC).

Instituto de Física Corpuscular – CSIC
Alejandro Algora, César Domingo, Andrés Gadea, Berta Rubio, José Luis Taín
Main activity: coordination, design and construction of the DTAS calorimeter for β-decay studies (DESPEC). Development of AGATA and NEutron Detector Array (NEDA) neutron multiplicity filter (HISPEC)

Universidad Complutense de Madrid
Luis Mario Fraile, María Cristina Martínez, José Manuel Udías
Main activity: coordination, design and construction of the Fast TIMing Array (FATIMA) for β-decay studies (DESPEC).

Universidad de Granada
Daniel Rodríguez
Main activity: coordination, design and construction of ion traps for the MATS experiment (MATS).

Universidad de Huelva
Luis Acosta, José Dueñas, Juan Antonio Gómez, Raúl Jiménez, Ismael Martel, Ángel Sánchez
Main activity: coordination, design and development of a charged particle detector for in-beam gamma ray spectrometry (HISPEC).

Universidad Politécnica de Cataluña
Francisco Calviño, Guillem Cortés, Albert Riego, Ariel Tarifeño
Main activity: coordination, design and construction of the BEta deLayEd Neutron detector (BELEN) for β-decay studies (DESPEC).

Universidad de Santiago de Compostela
Héctor Álvarez Pol, José Benlliure, Pablo Cabanelas, Dolores Cortina, José Luis Rodríguez
Main activity: coordination, design and construction of the CALIFA calorimeter *barrel* for the R^3B experiment (R^3B).

Universidad de Salamanca
María Doncel, Begoña Quintana.
Main activity: development of the AGATA and NEDA detectors (HISPEC).

Universidad de Sevilla
José Manuel Espino, Joaquín Gómez Camacho
Main activity: development of detectors for the beam diagnostics (HISPEC/DESPEC).

Universidad de Valencia – Escuela Técnica Superior de Ingeniería
Vicente González, Enrique Sánchis
Main activity: development of electronics for the AGATA and NEDA detectors (HISPEC).

Universidad de Vigo
Enrique Casarejos, José Antonio Vilán
Main activity: development of CALIFA and RPCs for the R^3B experiment (R^3B).

IX List of FAIR items which could still be delivered by the Spanish industry

Subproject	Description of Elements in Workpackages	Number of items needed
COMMON SYSTEMS	GHE Storage Tanks	1
COMMON SYSTEMS	Interlock Cables	1
COMMON SYSTEMS	Cables for HEBT	46442
COMMON SYSTEMS	Cables for Super-FRS	35200
COMMON SYSTEMS	Cables for CR	7016
COMMON SYSTEMS	Cables for p-Linac	3600
COMMON SYSTEMS	Cables for SIS100	27230
COMMON SYSTEMS	Cables for p Bar Separator	4300
COMMON SYSTEMS	Cables for HESR	23300
COMMON SYSTEMS	Cables for HEBT	14000
COMMON SYSTEMS	Cables for SIS100	2800
COMMON SYSTEMS	AC Cables for HEBT	5210
COMMON SYSTEMS	AC Cables for Super-FRS	3210
COMMON SYSTEMS	AC Cables for CR	1110
COMMON SYSTEMS	AC Cables for p-Linac	2640
COMMON SYSTEMS	AC Cables for SIS100	2640
COMMON SYSTEMS	AC Cables for p Bar Separator	510
COMMON SYSTEMS	AC Cables for HESR	1700
COMMON SYSTEMS	Voltage Signal cable for power supplies	60000
COMMON SYSTEMS	Cable-Trays	1
HEBT	Valve for roughing chamber (warm)	33
HEBT	Valve Control Roughing	1
HEBT	Gate Valve all-metal DN160	5
HEBT	Gate Valve Viton DN160	34
HEBT	Fast Valves others	11
HEBT	Fast Valve Sensor	11

HEBT	Fast Valve Control	11
HEBT	Cable Fast Valve - Control	11
HEBT	Cable Sensor - Control	11
HEBT	Valves	9
HEBT	Valve Control Cryostat	1
HEBT	Stripper: Charge State Stripper (SIS18-SIS100)	1
HEBT	Magnetic field control (Hall probes)	76
HEBT	Detector	49
HEBT	Mechanics others	49
HEBT	Detector	16
HEBT	Mechanics others	16
HEBT	Subsystems others	16
HEBT	Diffusor Block	9
HEBT	Vacuum Chamber	9
HEBT	Mechanics + Pneumatic Drive	9
HEBT	Long Cables	9
HEBT	Pneumatic Drive Control	9
HEBT	Diffusor Block	1
HEBT	Vacuum Chamber	1
HEBT	Mechanics + Pneumatic Drive	1
HEBT	Long Cables	1
HEBT	Pneumatic Drive Control	1
HEBT	Ion getter pumps others	137
HEBT	Ion Pump Controller (for 2 IPs)	69
HEBT	IP & PS connector	132
HEBT	Pumping Station Roughing (Scroll + Turbo)	5
HEBT	Pumping Station Roughing (Scroll + Turbo)	4
HEBT	Power Part + Cabinet + Construction	4
HEBT	Power Part + Cabinet + Construction	3
HEBT	Power Part + Cabinet + Construction	2
HEBT	Power Part + Cabinet + Construction	10
HEBT	Zero Field Control	3
HEBT	Power Part + Cabinet + Construction	1
HEBT	Power Part + Cabinet + Construction	5
HEBT	PCBHD17 Power Part + Cabinet + Construction	1
HEBT	Power Part + Cabinet + Construction	4
HEBT	Power Part + Cabinet + Construction	3
HEBT	Power Part + Cabinet + Construction	1
HEBT	PCBHD24 Power Part + Cabinet + Construction	1
HEBT	Power Part + Cabinet + Construction	1
HEBT	Power Part + Cabinet + Construction	5
HEBT	Zero Field Control	1

HEBT	Power Part + Cabinet + Construction	2
HEBT	Zero Field Control	1
HEBT	Power Part + Cabinet + Construction	5
HEBT	Power Part + Cabinet + Construction	2
HEBT	Power Part + Cabinet + Construction	2
HEBT	Long Cables	24
HEBT	Long Cables	11
HEBT	Long Cables	38
HEBT	Long Cables	49
HEBT	Long Cables	16
HEBT	Long Cables	15
HEBT	Long Cables	30
HEBT	Nuts + Bolts + Gaskets	1
HEBT	Collimator-block	6
HEBT	Vacuum Chamber	1
HEBT	Mechanics + Stepper Motor	6
HEBT	Long Cables	6
HEBT	Stepper Motor Control	6
HEBT	DAQ	6
HEBT	Collimator-block	8
HEBT	Vacuum Chamber	4
HEBT	Mechanics + Stepper Motor	8
HEBT	Long Cables	8
HEBT	Stepper Motor Control	8
HEBT	DAQ	8
HEBT	Detector	11
HEBT	Vacuum Chamber	11
HEBT	Mechanics	11
HEBT	Detector	15
HEBT	Vacuum Chamber	15
HEBT	Mechanics others	15
HEBT	Other	15
HEBT	High-voltage Supply	15
HEBT	Detector Gas	15
HEBT	Detector	30
HEBT	Injection beam dump	1
HEBT	Extraction beam dump	1
HEBT	Beam Dump TNC01 (CBM)	1
HEBT	Beam Dump XPP2 (Plasma Phys.)	1
HEBT	Beam Dump XBM1 (Biomat)	1
HEBT	Beam Dump XAPD (SPARC)	1
HEBT	bakeout jackets (1000€/m)	90
p-Bar	TARGET Fast Valves others	1
p-Bar	TARGET Fast Valve Sensor	1
p-Bar	TARGET Fast Valve Control	1

p-Bar	TARGET Cable Fast Valve - Control	1
p-Bar	TARGET Cable Sensor - Control	1
p-Bar	TARGET Target Station	1
p-Bar	TARGET Transport Vehicle	1
p-Bar	TARGET Flask	1
p-Bar	TARGET Transport Car	1
p-Bar	TARGET Passive target (incl. 4 spare units)	5
p-Bar	TARGET Power Part + Cabinet + Construction	1
p-Bar	TARGET Magnetic horn (incl. 4 spare units)	5
p-Bar	TARGET Stripline	1
p-Bar	TARGET Junction Box	1
p-Bar	TARGET Proton beam dump + off line	1
p-LINAC	Klystron supply system incl. installation	7
p-LINAC	Circulator	7
p-LINAC	Power lines (WG & coax)	10
p-LINAC	Transition (WG - coax)	7
p-LINAC	RFQ 4-vane electrodes	1
p-LINAC	RFQ 4-vane plungers + coupling + misc	1
p-LINAC	RFQ 4-vane tuning	1
p-LINAC	RFQ 4-vane rf-coupling	1
p-LINAC	CCH_Tank_1 from stainless steel	1
p-LINAC	Support structures for electronic connectors	6
p-LINAC	CCH_Tank_2 from stainless steel	1
p-LINAC	CCH_Tank_3 from stainless steel	1
p-LINAC	CH_Tank_7 from stainless steel	1
p-LINAC	CH_Tank_8 from stainless steel	1
p-LINAC	CH_Tank_9 from stainless steel	1
p-LINAC	Beam Dump p-Linac	1
SIS100	Valve for roughing chamber (warm)	25
SIS100	Valve for roughing chamber (cold)	56
SIS100	Valve Control Roughing	1
SIS100	Rf shielded gate valve others	50
SIS100	Fast Valves others	6
SIS100	Fast valves sensors	6
SIS100	Cable sensor	6
SIS100	Fast valve control	6
SIS100	Cable fast valve control	6
SIS100	Valves	60
SIS100	Pumping chambers	35
SIS100	Bellows part 2	575
SIS100	Support frames & adjustment equipment	1200

SIS100	Nuts + Bolts + Gaskets	1
SIS100	Quadrupole Chambers short	28
SIS100	Quadrupole fast	1
SIS100	Warm rad. hard Quadrupole Chambers	2
SIS100	Warm Sextupole	12
SIS100	Detector	6
SIS100	Detector	2
SIS100	Mechanics others	2
SIS100	N.c. Radiation resistant Quadrupole Magnet (Extr.)	2
SIS100	Pumping station roughing fixed	34
SIS100	Pumping station roughing (mobile)	6
SIS100	Power Part + Cabinet + Construction	1
SIS100	Power Part + Cabinet + Construction	2
SIS100	N.c. Gammat-Jumpquadrupole Power Converter: Power Part + Cabinet + Construction	6
SIS100	N.c. Gammat-Jumpquadrupole Power Converter: Embedded Control Unit	6
SIS100	Power Part + Cabinet + Construction	1
SIS100	Power Part + Cabinet + Construction	1
SIS100	Power Part + Cabinet + Construction	1
SIS100	Power Part + Cabinet + Construction	1
SIS100	Power Part + Cabinet + Construction	1
SIS100	Long Cables	86
SIS100	Long Cables	50
SIS100	Long Cables and Electronics	2
SIS100	Proton Collimator incl. stepping motor drive	3
SIS100	Ion Collimator incl. stepping motor drive	1
SIS100	Stepping Motor Controls incl. cabling	12
SIS100	Vacuum Chamber	6
SIS100	Mechanics others	6
SIS100	Long Cables and Electronics	6
SIS100	Detector	6
SIS100	Vacuum Chamber	6
SIS100	Mechanics others	6
SIS100	Long Cables and Electronics + HV supply	6
SIS100	Front End Electronics	2
SIS100	Vacuum Chamber and Mechanics	2
SIS100	Long Cables and Electronics	2
SIS100	Vacuum Chamber and Mechanics	1
SIS100	Long Cables and Electronics	1
SIS100	Detector	1

SIS100	Vacuum Chamber and Mechanics	1
SIS100	Long Cables and Electronics	1
SIS100	Detector	1
SIS100	Vacuum chamber and Mechanics	1
SIS100	Long Cables and Electronics	1
SIS100	Data Acquisition (per channel)	1
SIS100	Bakeout jackets	6
Super-FRS	UHV valves (D=400)	15
Super-FRS	Valves	69
Super-FRS	Cryostat	3
Super-FRS	Yoke	3
Super-FRS	Integration	3
Super-FRS	Cryostat	18
Super-FRS	Yoke	18
Super-FRS	Integration	18
Super-FRS	Cryostat	3
Super-FRS	Yoke	3
Super-FRS	Integration	3
Super-FRS	Dipole 1	2
Super-FRS	Quadrupole 1 Typ 1	1
Super-FRS	Quadrupole 1 Typ 2	1
Super-FRS	Quadrupole 2	1
Super-FRS	Sextupole 1	2
Super-FRS	Multiplet chamber + Energy buncher (long)	1
Super-FRS	Support Dipole 1	3
Super-FRS	Support 2 x Quadrupole 1	2
Super-FRS	Support Quadrupole 2 + Sextupole 1	1
Super-FRS	Pumps (TPU 400 & 1000)	22
Super-FRS	Pumps (IG)	48
Super-FRS	Pumps (Scroll pumps different sizes)	22
Super-FRS	Pumping Station Roughing	60
Super-FRS	Power Part + Cabinet + Construction	4
Super-FRS	Power Part + Cabinet + Construction	3
Super-FRS	Power Part + Cabinet + Construction	3
Super-FRS	Diagnostic elements	1
Super-FRS	Beam extraction components	1

Table 37. List of FAIR items to be constructed, which could still have a Spanish industrial participation.