The GRIT project
Granularity, Resolution, Identification, Transparency

Report for the Scientific Council of in2p3
June 26th, 2019

1. Summary

Direct reactions are recognized as a unique tool to supply crucial information on nuclei and on the related astrophysical processes. Their implementation with radioactive ion beams represents a challenge, requiring the development of powerful and sophisticated devices. The GRIT European collaboration proposes to build a new generation Silicon-based detector array for optimal study of direct reactions at present and future European Nuclear Physics facilities. The first developments worldwide of a new instrumentation designed for the study of direct reactions with Radioactive ion beams started in the mid 90's. French teams have up to now played a major role in this move. The present development capitalizes on the accumulated scientific know-how and the present competitiveness in technical aspects of these teams.

This new device consists in a new type of compact, high granularity, $\sim 4\pi$ acceptance Silicon array, with new electronics allowing seamless integration inside the Advanced Gamma Tracking array AGATA, as well as in the PARIS scintillator detector. Light charged particles and gamma-rays emitted in reactions induced by radioactive beams will be detected in coincidence by such a combination. For improved reaction channel separation, the new Silicon array is also meant to offer unsurpassed particle identification (PID) capabilities, by implementing state-of-the-art pulse-shape discrimination technique made possible by the high sampling rate specifications of the new digital electronics. Owing to a dedicated R&D program, the GRIT collaboration has established the relevance of this method for light particles detected with highly segmented Silicon detectors. Native integration of special targets such as a pure and windowless Hydrogen and ^{3,4}He cryogenic targets is also planned. The project includes an important milestone consisting in the implementation of an intermediate configuration called MUGAST recently commissioned and currently under operation at GANIL with AGATA in its 1π configuration. This first step has been recognized as pertinent through scientific evaluations and presently represents a core program of GANIL.

In terms of performances, the coupling with AGATA will allow a resolution < 5 keV on the excitation energy of the populated states in the studied reaction, a factor of at least 5 with respect to existing particle-gamma combinations. Gamma spectroscopy (e.g. lifetime measurements) of the selectively populated states will also be possible. The study of reactions in which high energy gamma rays are emitted will take advantage of the coupling with PARIS. The improved PID capabilities will be a crucial advantage for standalone operation when the γ-detection is irrelevant or when projectile-like residue detection is absent or limited. The versatility of targets will also make GRIT a unique device allowing the study of reactions with e,g, ^{3,4}He probes.

The development phase of the project will span over the coming 6 years. The first experiments with the are foreseen at the end of 2023. The principle developments are on electronics (new ASICs) taken in charge mainly by in2p3 labs, the associated boards, and their integration in a new dedicated chamber.

*Related documents are accessible at http://grit.in2p3.fr/login (**ID**: guest   **pwd**: guest#in2p3#grit)*
Once logged in, click on "grit", then on "ressources"

2. Scientific issues

Understanding the properties of nuclei away from the valley of stability (the "*terra incognita*") accessible owing to the modern facilities is the central theme of nowadays Nuclear Science. These properties are difficult to predict as the nuclear interaction is still largely unknown. It is established that Nuclear Physics plays a key role in Astrophysics as governing the creation of elements in the various stellar and interstellar environments, in the observational properties of stars,... and nuclei of the *terra incognita* are often involved in astrophysical processes. Their study is then mandatory in the quest to understand the universe from its origin up to nowadays. In this endeavour, our collaboration is implementing an approach based on the study of direct reactions (mainly transfer reactions) induced by radioactive-ion beams (RIB). A large part of our present knowledge on stable nuclei comes from direct reaction studies performed in the 70-80's with light-ion beams. Their implementation using RIB is the purpose of the GRIT project. Besides selective spectroscopy of nuclear states, these reactions are well-established as providers of crucial information on the *wave-function* of the populated states through their quantum overlaps with the initial states, which intervene as the nuclear structure input in cross-section calculations.

A broad range of scientific issues can be tackled with GRIT by means of direct reactions, i.e.:
- The Shell structure and shape evolution away from stability
- Microscopic structure of new excitation modes
- Nuclear pairing far from stability and neutron stars
- Neutron-proton pairing
- Mirror symmetry breaking
- Transfer reaction near driplines : haloes and clusters
- Indirect measurements of reactions involved in astrophysical processes

For a large part of the Physics case, GRIT is thought to be used in combination with the AGATA array and the related topics are reported in the Physics Case booklet of AGATA to which our collaboration contributed. Some specific cases are presented in more detail in the document "GRIT Physics case" accessible on the GRIT website (see access on page 1). In the elaboration of its physics program, GRIT takes advantage of the activities of the recently set-up RESANET GDR for which the first meetings started last Autumn. As an example, nuclear reactions of interest for astrophysics were discussed during the first meeting of the working group GT4, and the possibility to simulate them with present/future beams and devices were investigated.

The first developments worldwide of a new instrumentation designed for the study of direct reactions with RIBs started in the mid 90's. French teams played a major role in this move by proposing and building the first high-granularity, large acceptance recoil, Silicon-based particle detector named MUST [Blum99], an IPNO, CEA-Saclay, CEA-Bruyères collaborative project, based on the concept of independent telescopes with embedded multichannel front-end electronics, this pioneering detector system allowed the first direct reaction measurements at GANIL induced by the radioactive ion beams delivered by SPIRAL and the SISSI device. A few years later, a new device, MUST2 [Poll05], based on an improved solid angle and the implementation of new innovative electronics, while keeping the same concept of independent square-shaped telescopes was proposed and built, leading to successful campaigns at GANIL and RIKEN.

Along the years, with the availability of heavier beams and the perspective of new SPIRAL1 beams at GANIL and of fission fragment beams at Isolde and SPES, the concept of particle-gamma detection systems emerged in the community. In such measurements, the energy of the populated states is deduced from the energy of the gamma-rays emitted in their decay. A large gain in excitation energy resolution as compared to particle detection only is obtained. With e.g. AGATA, resolutions better than 5 keV can be obtained, that is, 2 orders of magnitude better than typical resolution obtained from recoil particle detection.

Several such first-generation systems are now operating in Europe, e.g. the T-REX/MINBALL at Isolde, and the TIARA-MUST2/EXOGAM combination at GANIL. With respect to the existing systems, the GRIT project aims at taking a major step forward by proposing a new array allowing a greatly improved performance level in every aspect of a detection system for DR studies, e.g. resolution, efficiency, PID capabilities and special target integration. The device is described in the next section.

The project structure reported below underlines the major contribution of in2p3 labs. Their strong implication in the technical developments required for completion of the device is evidenced in section 3.

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Working Groups:	Detectors (F.Flavigny, IPNO), R&D on PSA (M.Assié, IPNO), Electronics and DAQ (D.Mengoni, INFN), Simulations (A.Matta, LPC Caen), Physics case (S.Leoni, INFN), Special targets (A.Gillibert, CEA Saclay)

Collaboration structure of the GRIT project

The global strategy of the collaboration is as follows. An intermediate configuration of GRIT called MUGAST (see below) combined with AGATA in its present 1π version installed at GANIL/VAMOS will be used in 2019-21 at GANIL. In 2022-23 an upgraded version of MUGAST will be implemented for campaigns at LISE using EXOGAM for γ detection. Then, the exploitation of the final GRIT array will start at GANIL or SPES.

3. The GRIT project

3.1 The GRIT charged particle array

The GRIT array is based on the abovementioned concept of particle-gamma detection. It consists in a new type of compact, high granularity, ~4π acceptance Silicon array, with a new electronics allowing seamless integration inside the Advanced Gamma Tracking array AGATA, as well as with the PARIS scintillator array. This new array is also meant to offer unsurpassed particle identification capabilities, by implementing state of the art pulse-shape discrimination technique using high sampling rate digital electronics, for improved reaction channel separation hence physical background reduction. Native integration of special targets such as the pure and windowless hydrogen target production system CHYMENE or the Orsay ^{3,4}He cryogenic target is also planned. The initial project included an important milestone which consists in the completion and implementation of an intermediate configuration called MUGAST discussed later.

The design of the GRIT array is presented in Fig.1. It is based on a conical-shaped set of 8 trapezoidal telescopes in both the forward and backward hemisphere with respect to the beam direction assembled with a ring of squared-shape silicon telescopes around 90°, achieving ~4π solid angle. The radius is compatible with the insertion in the 4π AGATA array(23cm). The first layer, made of small-pitch DSSD for position measurement, is also meant to perform PSD of low energy particles. The second layer is dedicated to residual energy measurements. Very forward/backward angles will be covered by annular-type detectors..
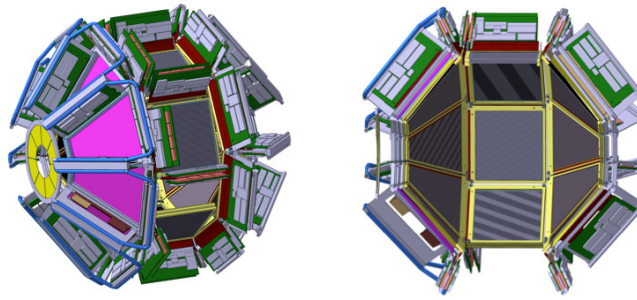
Fig.1: Present design of the GRIT array

The status of the various components of the device is presented below after a summary of the R&D program which was undertaken to validate the PSA technique for light particle identification with highly segmented detectors.

3.2 R&D on pulse-shape analysis (PSA) and electronics specifications

Particle identification (PID) is of key importance for reaction channel determination. The kinematics of direct reactions is such that the energy of light recoiling particles is typically low (few MeV), although for each reaction also exists a "high energy branch" corresponding to larger values of the center of mass angle. Particle identification of very low energy particles usually requires very thin (and often inhomogeneous) ΔE detectors and/or cumbersome time of flight measurements which cannot distinguish particles of the same mass (t and ^{3}He for example) The implementation of pulse shape analysis techniques which exploit the signal's shape would allow particle identification in a single layer of Si thus greatly simplifying the device.

PSA technique for PID has been studied extensively for medium-mass nuclei by the FAZIA collaboration [Bard09, Barl09] with pad detectors of large surface. In these studies the detectors are made of nTD (neutron transmutation doped) Silicon, random cut (to avoid channeling along the axis of the crystal) and reverse mounted (ions enter through the N-side). The effectiveness of this technique with highly segmented strip detectors is *a priori* questionable as distortions of the electric field within the wafer might reduce the signals differences between particles. Technically, the PSA method relies on the digitalization of the charge and/or the current signal with a frequency that should be adapted to the rise time of the registered signal. In the case of light particles the rise time in Silicon detectors is very short (typically a few ns) and a high sampling rate is mandatory to obtain a good discrimination. As this latter point sets strong constraints on the electronics, a determination of the minimum sampling rate required is mandatory.

Our group engaged in an R&D program on the applicability of the PSA technique for highly segmented Si arrays (see publication list below). Several test experiments have been performed at the Orsay Tandem. The initial prototype detector was a 500um thick DSSSD made of nTD wafer cut at 8 degrees.. The strip pitch of this detector was 485 um for a surface of 62 mm x 62mm. Four strips on each side of the detector were read by PACI preamplifiers [Hamr04] which give a current and charge signal output that were read by the MATACQ digitizers at 1 GHz sampling rate with a time window of 2,048 us. The ^{7}Li + ^{12}C reaction at 35 MeV was used to produce Z=1 and Z=2 particles.
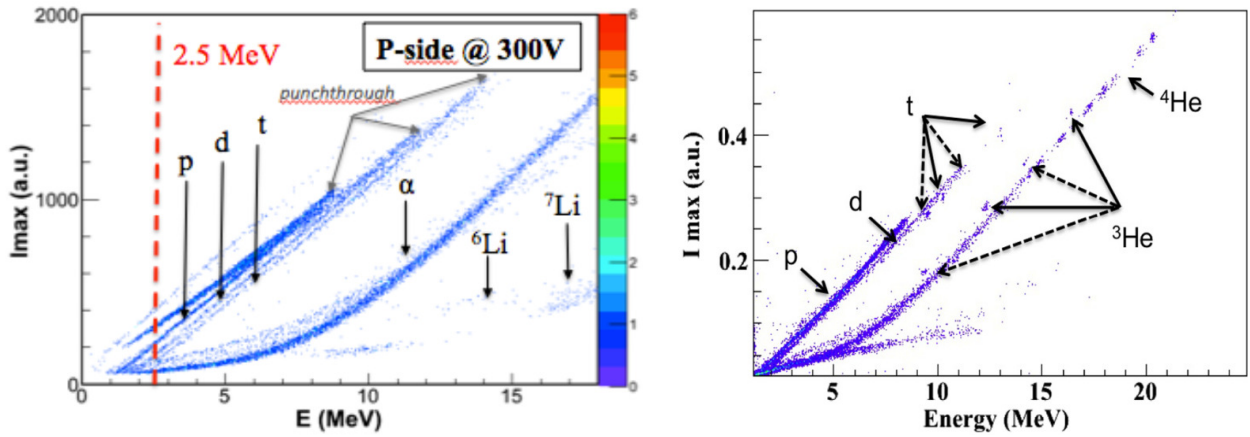
Fig. 2: Imax vs E correlation plots for light particles (see text)

Fig. 2 (left) shows for a single strip the correlation plot between the measured energy E of the particle and *Imax*, the maximum of the current output of the preamplifier. A Bias voltage of 300V, slightly lower than the depletion voltage (350V) was used in the measurement. Three well-separated lines corresponding to the hydrogen isotopes are observed down to around 2.5 MeV. Punch-through proton (E>9MeV) events are also clearly visible. Alpha particles are extremely well-separated from the hydrogen particles (hence triton and ^{3}He). A follow--up experiment aiming to investigate the separation of He isotopes was performed with the same detector and using a beam of deuterons at 24 MeV impinging on a mylar target. The result is displayed on Fig 2. (right), illustrating the discrimination between ^{3}He and ^{4}He can be nicely achieved [assi18]. In a recent test experiment performed at the Orsay tandem in 2017, the same study using a finalized prototype of GRIT, of trapezoidal shape was conducted and similar results on the separation capabilities of were obtained.
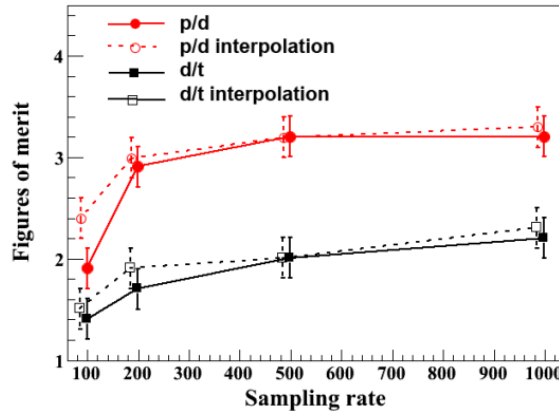

Fig. 3: Figure of merit for Hydrogen isotopes separation

Crucial information could be also obtained on the sampling rate issue by decreasing the number of signal samples from 1GHz down to 100 MHz. Results on the figure of merit parameter quantifying the separation of Hydrogen isotopes are reported in Fig.3. Below 200 MHz, the quality of the discrimination is dramatically reduced. The requested sampling rate for GRIT was then set to this value.

Conclusions of the R&D program
The PSA method is established for the case of light particle detected by highly segmented detectors.
- The best PID results are obtained from observables based on the current signal. The rise time of the charge signal does not provide good enough figures of merit (see [Assi15]). Hence the GRIT electronics is designed to record both the charge (E) and current signals (PID)

- From [assi15] we retain two "simple" observables of interest for particle identification: 1) the amplitude of the current signal with the detector biased at depletion voltage and 2) the time over a threshold set at 10% of the amplitude of the current after filtering the signal with a bipolar filter (equivalent to zero--crossover technique) when the detector is biased at nominal bias (+350 V).
- The PSA technique can be applied for particle energy down to about 2 MeV. Below that energy, PID will be based on standard method TOF-E, while punch-through particles will be identified by E-DE using a second layer of Silicon chosen to be of 1.5mm thickness, referred below as thick layer.

3.3 Detectors

The guiding line of Silicon detector's geometrical design was the requirement to tend towards a 4π solid-angle coverage in order to optimize the geometrical efficiency of particle detection. This implies a maximization of active areas, by reducing dead surfaces induced by detector's packaging and supports. It was then opted for a packaging inspired by the BB13-kapton detector of MICRON SL, (similar to the one used in the above R&D) consisting of a thin PCB frame with kapton readout. Kapton bonding allows them to be placed in nearly orthogonal direction with respect to the detector frontface, with almost no extra-thickness induced. Detectors for the first layer of GRIT, developed by MICRON SL., are shown on Fig. 4. For PSD purpose, these detectors are from nTD type Silicon cut at 4 degrees off axis and reverse mounted. They were made from 6'' wafers with two types of geometry (trapezoidal and squar) according to the design of Fig.1. The strip pitch is a crucial parameter for both excitation energy and angular resolution. Full physics simulations were performed for the representative reactions. The strip pitch of the first layer was fixed to 0.8 mm in order to maintain a sufficient energy resolution (typically a few 100 keV) when the excitation energy is deduced from the recoil particle (for e.g. unbound resonances).

6 trapezoid and 2 squared detectors have been delivered and fully tested on a bench at IPNO. These detectors are mounted in the MUGAST setup currently running with AGATA on the VAMOS beam line at GANIL. In 2019, the collaboration is planning to develop detectors of the second layer (see section 6.).
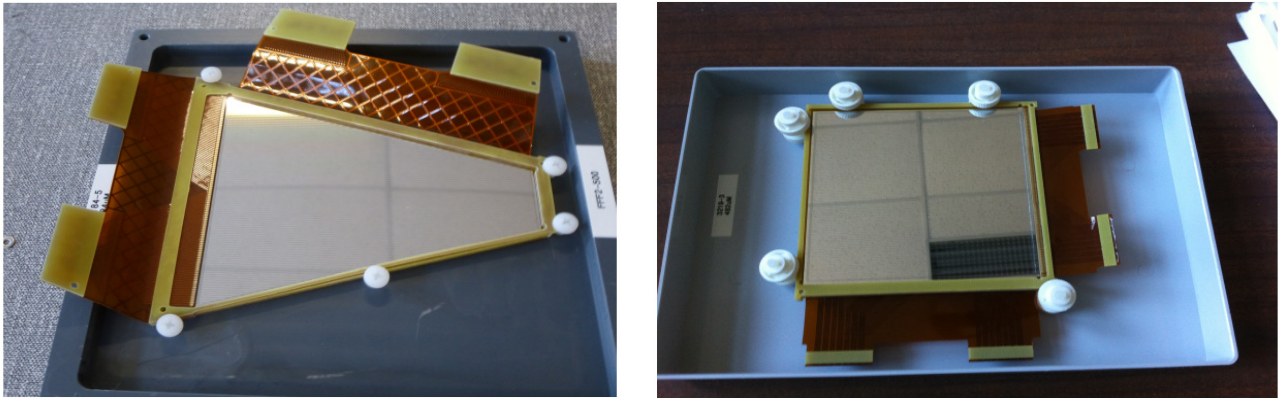

Fig. 4: Detectors developed at MSL for GRIT. Length of both types is nearly 10cm.

3.4 Electronics and DAQ

3.4.1 Overview
The read-out system of GRIT has to handle about 7000 channels with an overall triggering rate which will reach several thousands per second with intense RIB at e.g. SPES. The typical multiplicity of the events is

low. Hence zero suppression is an important feature to reduce the data flow. Captured information should be transmitted serially in order to keep cabling and feedthroughs to minimum. For current and charge signal sampling, our R&D studies mentioned above have shown that a minimum time window of 1 µs is needed (mostly for base line suppression), and that the sampling rate (for the current signal in particular) should not be lower than 200 MSa/s (Fig. 3).
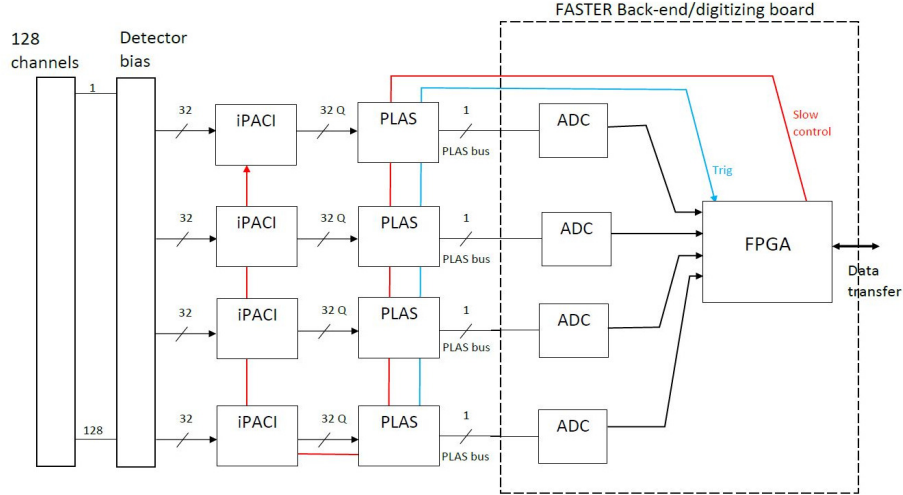

Fig. 5: Electronics block scheme single-face readout of first layer detector

The global scheme of the block electronics for the readout of a single detector face of the first layer (128 channels) is shown in Fig 5. 128 detector channels (N or P) are connected to 4 iPACI's, a charge sensitive pre-amplifier ASIC with additional current outputs developed at IPNO. IPACI outputs are connected to an analog memory chip called PLAS, initially developed at Valencia university (Spain) for the TRACE project. PLAS output bus is an analog differential bus. The chip merges numerical information (such as time stamp, channel hit Identification, etc...) and samples analog waveforms. All data are digitized with an ADC. Digital information is sent to FPGAs (1 or more depending on ADC characteristics and number). The LPC Caen is now in charge of PLAS and of the backend Electronic Boards including ADCs and FPGAs. They will have the same architecture as boards of the FASTER system [ref 4]. FPGA will also treat trig signals from iPACI or/and PLAS. FPGA will also send slow control information to iPACI and PLAS integrated circuits (for example to modify iPACI gains, etc...). Numerical filters are implemented in FPGA for time, energy measurement and pulse shape analysis. The architecture of the electronics will be similar for detectors of the second layer, with the exception of the preamp ASIC which will be the TOT circuit developed at Milano.

3.4.2 The ASIC Preamplifier iPACI

The iPACI (integrated Charge and Current preamplifier) ASIC is being developed at IPNO for the DSSSD readout. It is an updated and integrated version of the single channel PACI [Hamr04] widely used for pulse-shape analysis studies. It will be fed with the DSSSD outputs and will embed the required hardware to extract the charge, current and time information. The current version of iPACI (version 2) is a 16-Channel particle detector read-out chip integrating several common functions, *e..g.* slow shaper, serializer, fast shaper, discriminator and Time to Amplitude Converter. The ASIC embeds slow control circuitry, enabling real-time tuning. Fig. 6 shows the chip's architecture. Two ranges in energy are implemented in order to read out detector signals for light and heavier particles. Other features like fast and slow shaper have been implemented. A summary of the simulated performance of iPACI v2 is given in table 1. The circuit was delivered in early 2019 and commissioning tests are now underway at IPNO.
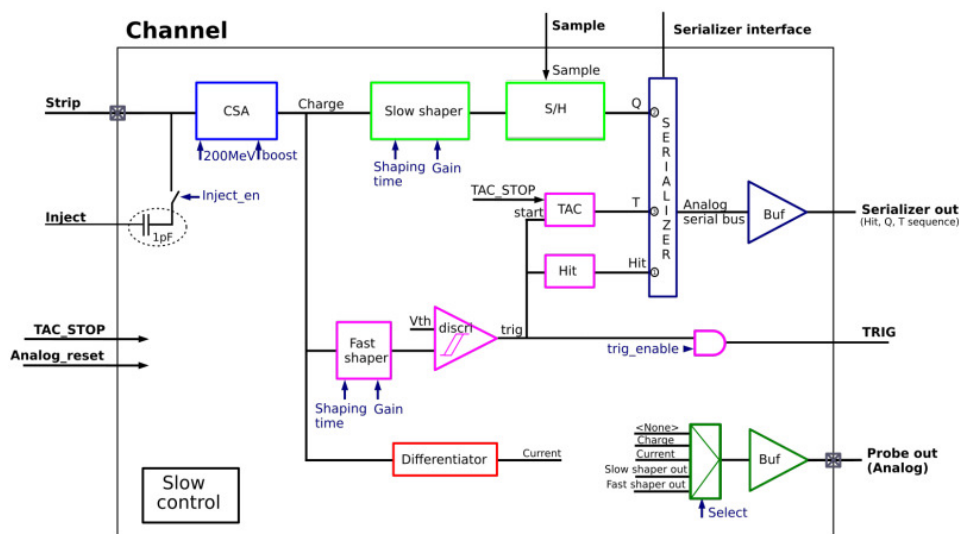
Fig. 6: Architecture of iPACI v2

Charge output		Current output	
Energy max	70/200 MeV (slow control)	current gain	7 kΩ
Equivalent noise Charge	15 keV (FWHM)	current swing	1.5V single ended
Charge non-linearity	<1%	current BW	150 MHz
Charge output recovery	100 µs	**Time signal**	
Input capacitance	[10pF .. 40pF]	Trigger jitter	500 ps FWHM
Current consumption	32mW / Channel		

Table 1: Simulated characteristics of iPACI v2.

3.4.3 The ASIC Preamplifier TOT

A collaboration was initially established between INFN-PADOVA and University and INFN of Milano to design a low-noise low-power multichannel charge-sensitive preamplifier with fast-reset technology.

The first integrated multichannel CSP prototype was realized by the end of 2014 with four channels for hole signals (front channels) and one designed specifically for electron signals (back channel). For the front channels of the detector the fast-reset device acts only as a dead-time reduction system. For the back channel it works as a range-booster, incrementing the dynamic range from 40 MeV to 700 MeV and enabling high resolution spectroscopy in this range. The device is designed in AMS 0.35 m 5V technology and is operated with a ±2.6V dual power rail. A second version of the chip was submitted to the foundry at the end of 2016 and received in January 2017. It comprises eight channels for holes and one channel for electrons. On the back channel a custom Time-to-Amplitude Converter (TAC) was added to the Fast-Reset device. This circuit is activated only during Fast-Reset events and provides an analog signal with amplitude proportional to the energy. The peculiarity of this circuit is its ability to correct the Fast-Reset energy measurements from their dependency on the baseline value. In this way the output signal provided can be directly sampled and requires no special digital processing in order to extract the energy value. A third submission consisting of 8 channels for both holes and electrons is underway.

3.4.4 The Analog memory circuit PLAS

Although achieving very good performances, digitizers such as MATACQ or WaveCatcher that we used for the beam tests cannot be extended to such a large number of channels. As mentioned above, for current and charge signal sampling, a minimum time window of 1 µs is needed for proper base line suppression, and the sampling rate should not be lower than 200 MSa/s.

Our collaborators from the University of Valencia (R. Aliaga, V. Herrerro-Bosch) have developed a concept and the first version of an analog memory ASIC called PLAS (for Pipe Lined Asymmetric Switch Capacitor Array) [Alia2015], initially for the TRACE project.

PLAS is a novel 32-input analog memory, with self-triggering channels for the sampling of detector pulses and their transmission at slower pace. PLAS reduces the number of SCA cells needed by a factor of 7 with respect to single full SCA, thus decreasing the size of the chip and power consumption. The operating principle is divided in three main blocks (Fig.7). The pre-trigger memory block samples continuously the waveform with a 32-samples circular buffer logic, and discards the data when no signal is present. Once a pulse is detected, the channel is locked and a free slot in the second SCA (Switched Capacitor Array) called "post-trigger memory" on Fig.7 is assigned where pulse capture continues. 192 samples are available for the capture of the waveform. During the pulse capture, the content of the pre-trigger memory is transferred sequentially onto a buffer in the assigned channel (called storage buffer in Fig.7). Simultaneous capture of several signals is possible (up to 8 per 32 channels). When pulse capture ends, the input channel is immediately ready to start sampling again. Thus there is no deadtime. The captured pulse and information can be further read out at a slower rate. Captured signals are timestamped and transmitted serially to the back-end by means of single analog output, reducing considerably the number of feedthroughs. They are digitzed remotely and processed by FPGA (FASTER back--end) that controls the readout process at 50 MHz. The 100 MHz sampling clock is handled by the back-end electronics. Both clock edges are used for the sampling to reach 200 MSa/s. A summary of the main characteristics of the PLAS ASIC is given in Table 2.

Sampling rate	200 MSa/s
Resolution	12 bits ENOB
Nb of entrance channels	32
Post-trigger slots	8
Cells depth	32+192
Trigger	internal
Time stamping	[10pF .. 40pF]

Table 2: designed specifications of PLAS

A first version of PLAS (v1) with 32 channels has been submitted in 2016 in 0.18um technology. Tests have been performed with pulser signals simulating the output of our preamplifier. These tests showed that the maximum achievable sampling rate was lower than expected (of about 80 MHz) and evidenced issues with pre-trigger information and channel ID. Corrections have been applied to solve the problems. of the first version. However PLAS v2 could not be submitted in 2018 due to manpower issues on the project at the University of Valencia. In 2019, in agreement with the collaborators from the University of Valencia, the collaboration took the decision to transfer the development of PLAS to LPC Caen. The possibility to submit PLAS v2 in 0.18um technology has been confirmed by the engineers of LPC Caen. The submission is foreseen at the end of 2019 after minor modifications will be achieved.
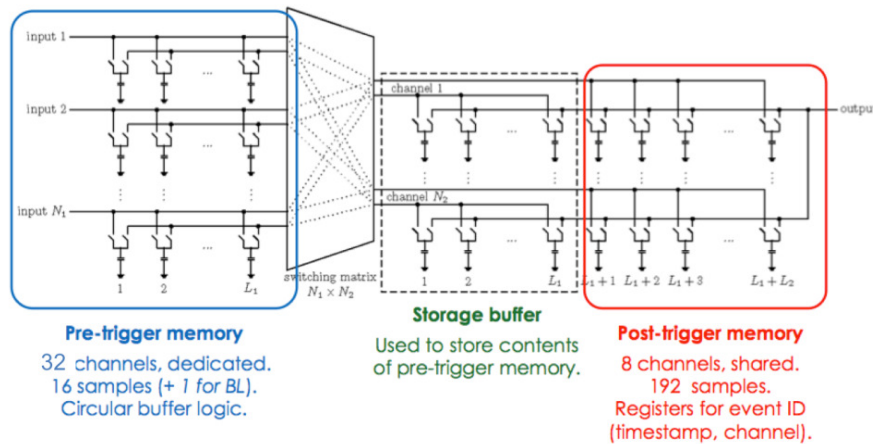

Fig.7: Principle of pipelined asymmetric SCA for PLAS

The issue of signal/noise ratio of PLAS has been raised during the review of the GRIT project the Scientific Council of IPNO (report on GRIT webite). The commissioning of PLAS in mid-2020 will provide the relevant information and possibly trigger important modifications of the circuit such as a change of inner connectics from present single-ended to differential one.

3.4.5 The FASTER backend/DAQ

FASTER is a modular digital acquisition system developed at LPC Caen. The system is currently designed to handle small to medium size experiments, from one to few hundred detectors. FASTER is a n-ary tree in which each node performs the following functions: synchronize and aggregate data streams received from the children nodes, make decision on the resulting data stream, send the resulting stream to the parent node. The current version of FASTER proved itself over the years, with increasing number of channels, and higher data bandwidth, reaching 100MB/s during the last LICORNE campaign at ALTO, reading out the signal of 180 Nuball detector. Working with the GRIT collaboration, FASTER will integrate the no-dead time analog memory, PLAS, allowing the acquisition of ten thousand channels with a reduced number of digitizers. The FASTER back-end will be coupled to the AGATA acquisition through the use of the SMART* uTCA card developed at GANIL to synchronize the internal clock of both systems.
(* The SMART system is currently developed at GANIL to replace the current GTS triggering system used by AGATA. It is designed to overcome the current limitation of the GTS in term of number of trigger inputs).

3.5 Mechanical design

Integration issues constitute a major challenge of the project. Detectors and their supporting structure, the FEE and its cooling system, the connectors and feedthroughs need to be integrated in a small radius chamber (23cm) with the strong constraint of minimizing shadowing and scattering of gamma-rays emitted over nearly 4π. An important design work has been undertaken at IPNO to produce a preliminary though detailed mechanical design of GRIT. Images of this design are presented in Fig.8. Fig.8.(left) shows a unit module of detection with an extension for embedding the front-end and intermediate boards. A special chamber with "ear-shape" extensions (Fig.8 right) houses these unit telescopes. This chamber is also designed to integrate the CHyMENE target as well as the Orsay Helium target to be operated soon in a forthcoming MUGAST experiment (see below).
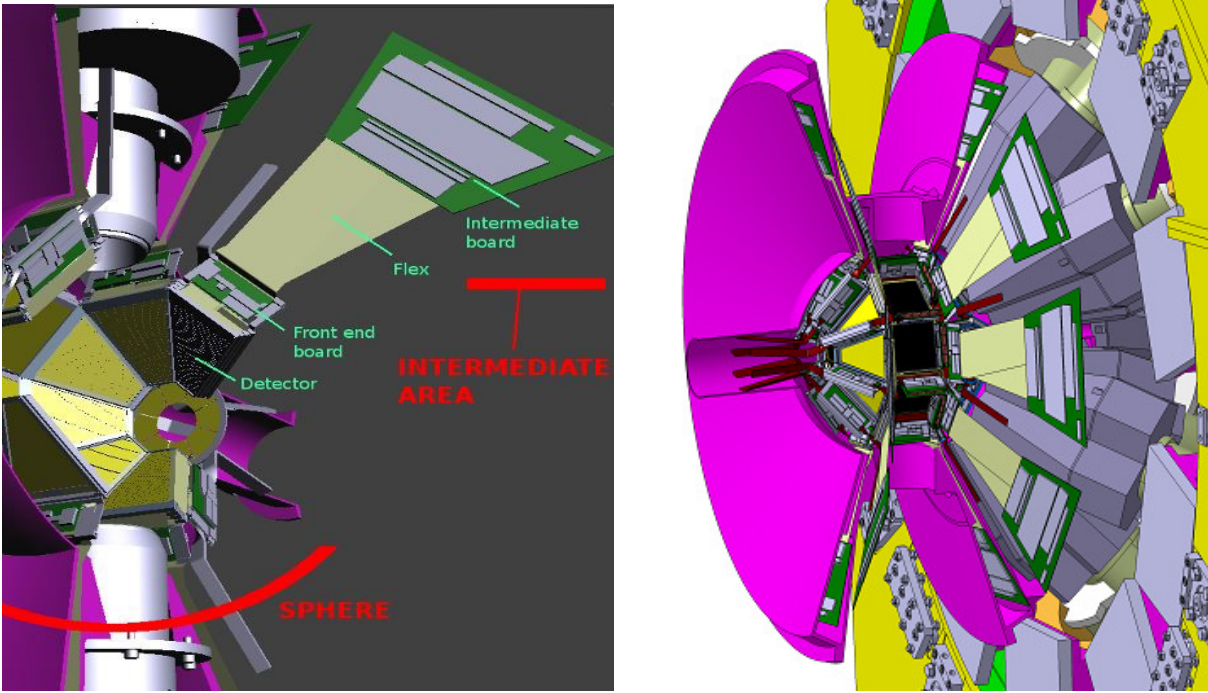
Fig. 8: Schematic views of GRIT mechanical design

3.6 Special targets

CHYMENE is an independent project but natively designed to be integrated in GRIT. CHYMENE is dedicated to the production of a thin windowless hydrogen target. The framework of the CHYMENE Project is a joint effort between CEA/IRFU, CEA-DAM and CNRS/IPN Orsay (financed by the French funding agency ANR), in relationship with a private company, the PELIN laboratory in St Petersburg. The system allows continuous extrusion of hydrogen ice (that can be ^{1}H or ^{2}H) through a nozzle that defines the thickness of the target. The target will be windowless, and so completely remove the background of the spectra due to scattering in Carbon. The system has been tested successfully in beam in April 2019 using two different extruders for production of 20um and 100um, respectively.

The Orsay Helium target was developed by the Accelerator division at IPN Orsay, initially for the study of reaction of RIBs with ^{4}He. It consists in a cryostat system allowing production of a cooled gas cell, at a temperature just above the fusion (typically 4K). An update of the system for production of an ^{3}He target has been recently developed. This target will be used in a forthcoming MUGAST experiment at GANIL. Finally, integration of a tritium target in GRIT is also planned.

3.7 MUGAST: an intermediate configuration of GRIT presently in operation at GANIL

The GRIT detectors discussed above are designed for optimal integration in AGATA, with minimized dead areas. While these detectors were being validated, the idea came up to prepare an intermediate configuration offering a sizeable acceptance by combining a pre-series of these detectors with a few MUST2 telescopes, readout of all detectors being insured by the MUST2 electronics. The main motivation to implement this configuration, called MUGAST, was the availability of AGATA in its 1π-configuration at the VAMOS beam line of GANIL. Combining the two systems s offers the opportunity to perform the first high resolution transfer studies with the new SPIRAL1 beams. Technically, the implementation of such a combination represented a valuable step to tackle some of the many integration issues of GRIT.

A view of the MUGAST setup is displayed in Fig.9. The detector's configuration is as follows: 5 trapezoid (plus an annular) detectors (500 um thick) to cover the backward angles, two square detectors placed

around 90 degrees, and 4 MUST2 telescopes to cover the forward angles. Cooled FEE blocks are mounted perpendicularly to the beam direction on a wheel-shape support shown in Fig. 9 (right). A new chamber was designed to host this setup, allowing also the insertion of the Orsay Helium cryogenic target. With this target, MUGAST represents already a unique system allowing the study of e.g. (^{3}He,d) or (^{3}He, p) reactions, which can be used for the simulations of rp-process reactions and the study of neutron-proton pairing, respectively.
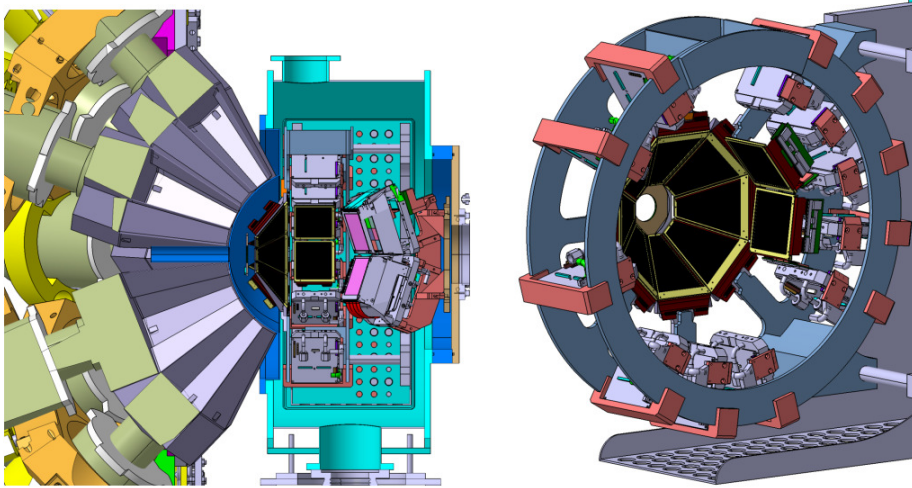

Fig.9: (Left) View of the MUGAST setup in a dedicated chamber and with MUST2 electronic boards. (Right) View of the GRIT--TRACE detectors with the MUST2 electronics and its support.

Four MUGAST experiments have been accepted by the GANIL PAC . In April 2019, the MUGAST-AGATA-VAMOS setup has been commissioned and the first experiment was successfully performed. Two others will run later this year. The call for experiments issued by the GANIL PAC in 2019 includes a further MUGAST-AGATA campaign in 2020.

Although unique and running well, the MUGAST setup presents strong limitations. The use of MUST2 electronics is at its limits with 3000 channels (energy and time), prevents the use of more DSSDs as well as the foreseen increase of solid angle for gamma detection, The poor PID performance due to the lack of PSD and the absence of backing trapezoidal detectors limits the range of reactions accessible. With GRIT, an increase by a factor 3 of solid angle for particles can be reached, while being compatible with any >1π AGATA or PARIS version. Furthermore, GRIT will offer an unsurpassed PID capability for light particles and insure integration of other special targets like CHYMENE.

4. Genesis and timelines

In the late 2000's, three European collaborations (associated to the GASPARD, HYDE and TRACE projects, respectively), aiming to build new generation Si arrays decided to implement a common R&D program focussing on the particle identification techniques by pulse shape analysis using highly segmented Silicon detectors.

GRIT comes from the merge of the GASPARD and TRACE projects in 2016. The fusion of the two projects came as a natural step after 1.the successful implementation over several years of a common R&D program and 2.the co-optation of the present design of the array, making use of squared and trapezoidal detector geometries. A construction MoU is currently under completion. Recently the MUGAST project was reviewed by the scientific council of GANIL, and GRIT by the Scientifc council of IPNO. (GRIT website, see page 1 for access).

The timelines of the project are reported in table 3. The associated detailed workplan can be accessed on

the GRIT website.

Publications
The studies on pulse shape identification of light particles have led to 8 publications from the collaboration, 5 of them corresponding to experiments performed at the ALTO-tandem in Orsay.
J. Duenas et al, NIMA 676 (2012) 70.
J. Duenas et al, NIMA 714 (2013) 48.
B. Genolini, B. Le Crom, et al, NIMA 732, 87 (2013).
J. Duenas et al, NIMA 743 (2014) 44.
D. Mengoni et al, NIMA 764 (2014) 241.
R. Aliaga et al, NIMA 800 (2015),34.
M. Assié, B. Le Crom et al, EPJA 51 (2015) 11.
M. Assié et al, NIMA 908 (2018) 250.
One PhD thesis was partially on GRIT (on the R&D for pulse shape discrimination of light particles) :B. Le Crom, "Etude de l'appariement neutron-¬-proton dans les noyaux instables N=Z par réactions de transfert", Université Paris-¬-Saclay, 2016.

Table 3 : Gantt chart of GRIT

5. State of the art

As mentioned above, mainly two first-generation systems for particle-gamma measurements were extensively operated in Europe in the past decade: 1. The T-REX/MINIBALL at CERN/Isolde, and 2. The TIARA-MUST2/EXOGAM combination at GANIL. With respect to T-REX and TIARA/MUST2, GRIT will offer a largely extended dynamical range over 4π for particle detection as well as a critically improved capability of PID. Concerning targets, with the possibility to insert the cooled ^{3}He or ^{4}He gas cell, GRIT gives access to reactions with the Helium probe such as (^{3}He,d), (^{3}He,p), (^{3}He, α), (α,^{3}He), (α,t), (α,^{6}He)… These reactions typically offer different selectivity than the H probes. For example, high-l neutron orbitals are favourably excited as compared to (d,p), which is of interest for the study of medium-mass or heavy nuclei.   For proton (and deuteron) induced reactions, the CHyMENE target will eliminate the contamination of the spectra due to reactions on the Carbon in CH2 and CD2 standard targets,. Besides, forward scattering of beam particles will be much reduced which may be critical in the case of very intense beams. Concerning gamma-detection, the integration capability of GRIT in the state-of-the-art AGATA array is clearly advantageous in terms of resolution (factor >5) w/r to EXOGAM or MINIBALL, efficiency, and through the possibility of performing in-beam gamma spectroscopy of selectively excited states (as in e.g. the ^{19}O(d,pγ) proposal with MUGAST). As for GRIT coupled with PARIS, the efficiency for detecting high energy gamma-rays (in e.g. PDR decay studies) will reach values as high as 50% when the

whole array will be available. Considering the above arguments, GRIT represents clearly a new generation p-γ system.

Alternative systems based on different concepts than the particle-γ systems have been proposed for the study of direct reactions. Active targets such as ACTAR (commissioned in 2017) allow the determination of the reaction point in the gas ("vertexing"), strongly reducing the target effects on the resolution of the populated states. These systems are well-adapted for very low intensity beams, or very low recoil energies (as in the case of giant resonance studies). The efficiency can be close to 100% (while GRIT depends on the gamma efficiency in particle-gamma studies). The overall resolution remains typically ~100 keV, and the maximum acceptable beam rate is a few 10^4 pps. A variant of this system in which the target gas stands in a magnetic field which increases the dynamic range has been developed at MSU (AT-TPC) and more recently at KU Leuven (SPECMAT) mainly for experiments at Isolde/CERN. In SPECMAT, gamma detection using CeBr3 scintillator detectors is included which will determine the resolution. Finally, solenoid systems such as at Argonne and later on the ISS for Isolde/CERN have been developed. The use of a magnetic field offers the possibility to eliminate the kinematical compression encountered in "standard" measurements. However, targets effects are still present so that this system is suitable for use with very thin target and high intensity beams. ISS was successfully used at CERN/Isolde in 2017 for the measurement of the ^{28}Mg(d,p) reaction. A resolution of the order of 50 keV was obtained.

In summary the main advantages of GRIT combined with AGATA over the above alternative systems is the resolution on the populated states, the versatility of targets and the PID capabilities. Conversely, the efficiency is generally lower, depending on the number of available gamma detectors and on the gamma energy.

6. Capital cost and Manpower

6.1 Capital cost

The budget for the MUGAST operation and its distribution over the years by institution for the MUGAST operation is displayed in table 4.

	(2013-2015)					2016		2017				2018	2019
	AP	P2IO	Surrey	Santiago	INFN	Surrey	AP	Surrey	GANIL	RP IPN	INFN	GANIL	GANIL
>> MUGAST mécanique													
chambre à réaction						34480	334						
méca intérieure/ support							998	7023		10749			
traversées étanches											11000		
blocs de refroidissement									6320				
adaptation méca, cible												2218,27	
tuyau adaptation VAMOS												2836,62	
>> MUGAST électronique													
composants/cables							9992					5867	
cartes MUFEE							1318						
ASIC MATE							31500						
boîtier BT/HT									3200				
cartes CAEN BT/HT									3200				
>> MUGAST Détecteurs													
kaptons							6006				13360		
Prototypes trapèze	35000	15000											
Prototypes carrés					50000								
Pré-séries trapèzes		9000	9000	9000									
>> MUGAST Cible cryogénique													
sondes étalonnées										5209			
test en 4He													10800
conversion 3He												5046	6596,22
achat 3He													5000
Autres : transport												369,97	400
TOTAL		59000	9000	9000	50000	34480	50148	7023	12720	15958	24360	16337,86	22796,22
		92000				84628		35701				40697,86	
TOTAL GLOBAL							253026,86						

Table. 4: Capital investment and its distribution for the MUGAST setup

The GRIT budget capitalizes on a large part of the developments achieved for MUGAST. In particular, the detectors of the first layer and the ^{3,4}He target correspond to the final design of the array.

The total capital investment **remaining for completion of the GRIT array** is reported in Table 5. As detailed in section 2, GRIT comprises a large set of DSSDs to cover nearly 4π solid angle with two layers, a

new high-sampling rate low-consumption integrated electronics, and a new reaction chamber. Additionally, a chamber for reaction studies at LISE/GANIL will be built in view of campaigns in 2022-23. Concerning Detectors of the first layer (500 um thickness), Trapezoid (T) DSSDs will be purchased from MSL (UK), while the squared (S) DSSD's will be produced by SCL in India. For the second layer (1.5mm thick), it is planned that all detectors will be produced by MSL. The cost for electronics (~46€ /channel) has been estimated on the basis of the global scheme of the system presented in section 2.2, which makes use of the iPACI, TOT, and PLAS Asics, as well as the FASTER backend. Collaborators from both the Univ. of Santiago de Compostella and Univ. of Surrey will purchase two detectors. Surrey will also put in a bid to the STFC capital equipment fund likely in the period 2021-2022.

The capital cost for the completion of GRIT, and its sharing by the collaboration over the duration of project is presented in table 6. The last years (2024-25) are dedicated to purchasing the last detectors. Detector's provisioning takes into account the already purchased detectors for MUGAST.

DETECTORS	Number of pieces	Cost (k€)
Thin proto (from SCL, India)	2	76
Thick Square proto (1.5mm)	2	40
Thick Trapez. proto (1.5mm)	2	40
First Layer (complete)	10T+8S (x9k€)	162
Second Layer (complete)	16T+8S (x10k€)	240
Annular detectors	1	30
ELECTRONICS	**Number of channels**	
For all detectors	7000	322
MECHANICS		
MUGAST@LISE chamber	1	30
Reaction chamber and supports	1	80
	TOTAL	**1020**

Table 5: Capital costs for completion of the GRIT array

	2019	2020	2021	2022	2023	2024	2025	Total (k€)
Detectors								
Thin DSSD proto (500um, SCL)	76							**76**
Thick Si protos (1.5mm, MSL)	80							**80**
Serie DSSD (1st layer, MSL+SCL)		63	36	45		18		**162**
Serie DSSD (2nd layer, MSL)		60	50			40	90	**240**
Annular detectors						30		**30**
Electronics								
ASICs, boards, modules, power supply, connectics	20	40	82	90	90			**322**
Mechanics								
MUGAST@LISE chamber			30					**30**
GRIT final reaction chamber				40	40			**80**
IN2P3	**10**	**37**	**60**	**65**	**65**	**30**	**31**	**298**
Normandy Region	**40**	**40**	**40**					**120**
GANIL (*)								
INFN	**50**	**59**	**62**	**65**	**65**	**58**	**59**	**418**
BARC	**76**		**36**	**36**				**148**
Univ. of Surrey		**18**						**18**
Univ. of Santiago de Complla		**9**		**9**				**18**
TOTAL (k€)	**176**	**163**	**198**	**175**	**130**	**88**	**90**	**1020**

(*) currently under discussion

Table 6: Capital investment distribution for GRIT

6.2 Human ressources

Physicists member of the collaboration are listed below. Names in bold character correspond to physicists involved in the construction/development of the GRIT device.

IPN Orsay (F): **M. Assié, , D. Beaumel, Y. Blumenfeld**, M. Chabot,, N.De Séréville, **F. Flavigny**, F.Galtarossa (postdoc), J.Guillot, F. Hammache, T. Id'Barkach (student), I.Stefan,
LPC Caen (F)   L.Achouri, F.Delaunay, J.Gibelin, **A.Matta**, N.Orr
GANIL (F)   A.Chbihi, E.Clement, **G.De France**, A.Lemasson, M.Rejmund, O.Sorlin
CEA-Saclay (F)   A.Gillibert, V.Lapoux, M.Zielinska
Padova (INFN&Univ.,Italy) **A.Goasduff, D.Mengoni**, G.Pasqualato, D.Testov
(+**2postodcs+2Stud.(Mst,PhD)**
LNL (INFN, Italy)   G.De Angelis, A.Gottardo
Milano (INFN & Univ., Italy) **S.Capra**, S.Leoni, S.Bottoni, **A.Pullia**
Firenze (INFN & Univ., Italy)   A.Nannini, M.Rocchini
BARC (India) **K.Mahata**, S.K.Pandit, V..V.Parkar. K.Ramachandran, **A.Shrivastava**
Univ. of Santiago de C^{lla} (Spain)   B.Fernandez-Dominguez
Univ. of Huelva (Spain)   J.Duenas
Univ. of Valencia (Spain)   A.Gadea
Univ. of Surrey (UK)   **W.Catford**, G.Lotay
STFC Daresbury (UK)   M.Labiche

The human resources for the completion of GRIT, and its distribution by collaborative institutions over the duration of the project are presented in table 7. Tables 8 show the percentages and FTEs for in2p3 engineers&technicians.

	2019	2020	2021	2022	2023	2024	2025
In2p3							
Eng./tech.	3.7	3.1	5.1	5.1	3.3	0.5	0.5
Physicists	6.4	6.4	6.	5.	5.	5.	5.
GANIL							
Eng./tech.	2.4	2.4	2.3	0.8	0.8	0.8	0.8
Physicists	1.	1.	1.	1.	1.	1.	1.
INFN							
Eng./tech	1.	1.	1.	1.	1.	0.	0.
Physicists	5.9	4.2	4.0	4.	4.	5.	5.
BARC							
Eng./tech.	1.	1.	1.	1.	1.	0.	0.
Physicists	2.	2.5	2.5	2.	2.	2.	2.

Table 7: Global table of manpower (FTE) for GRIT

	2019	2020	2021	2022	2023	2024	2025
IPN Orsay	1.7	1.7	1.9	1.9	2.1	0.2	0.2
LPC Caen	1.	1.4	3.2	3.2	2.5	0.2	0.2
LAL Orsay	1.	0.	0.	0.	0.5	0.	0.

	Name		Activity	2019	2020	2021	2022	2023
IPN Orsay	JJ DORMARD	IR	Electronicien : 1/ support routage BT iPACIv2, 2/ Test iPACIv2, 3/ test iPACIv1, PLASv1 et FASTER, 4/ Conception iPACIv3 (2020), 5/Schéma carte front-end GRIT (2020)	50	40	50	30	30
	A TORRENTO	IR	Détecteurs : 1/Modélisation Silvaco, 2/ Modélisation COMSOL	30	40	10	0	0
	E RAULY	IR	Electronicien : 1/modélisation MATLAB, 2/ pré-étude méca (prix et consommation),3/test iPACIv1, PLASv1 et FASTER, 4/Schéma carte front-end GRIT (2020-2021)	40	50	40	40	40
	F.DORANGE-VILLE	AI	Magasin : 1/ Achat composants pour BT iPACIv2, 2/ Achat composants cartes front-end	30	30	30	30	0
	BY KY	IR	Electronicien : 1/ Système numérique BT iPACIv2 (2019)	30	10	10	10	0
	G MAVILLA	AI	1/ Mécanique pour banc de test iPACIv2 (2019)	20	20	0	0	0
	E RINDEL	IE	1/ Conception mécanique GRIT (entre 2020 et 2022)	0	20	50	50	0
	Service mécanique	AI	Montage détecteur GRIT	0	0	0	50	50
LPC Caen	D ETASSE	IR	Electronicien : 1/couplage PLASv1 et FASTER (2019-2020), 2/Schéma carte interm. (2021),	40	20	30	0	10
	J HARENG	T	Electronicien : routage carte intermédiaire (2021-2022)	0	0	30	40	0
	B CARNIOL	IR	Electronicien : 1/ FPGA readout PLASv1 (2019-2020), 2/ FPGA readout PLASv2 (2021),3/ FPGA readout PLAS v3 (2023)	40	20	30	0	30
	J HOMMET	IR	Informaticien : Interface PLAS	0	10	20	0	0
	CDD	IR	Electronicien : 1/couplage PLASv1 et FASTER (2020), 2/Conception et caractérisation PLASv3 (2021-2023),	0	45	90	90	45
	S DROUET	IR	Electronicien (micro-électronicien) : 1/Evaluation travail reprise PLASv2 (2019),2/ changement techno et reprise PLASV2 (2019-2020), 3/Conception et caractérisation PLASv3 (2021-2023)	10	20	60	60	60
	L LETERRIER	IR	Electronicien (micro-électronicien) : 1/Evaluation travail reprise PLASv2 (2019), 2/ changement techno et reprise PLASV2 (2019-2020), 3/Conception et caractérisation PLASv3 (2021-2023)	10	20	60	60	60
LAL Orsay	Cablage	AI	Cablage BT iPACIv2	50	0	0	0	0
	Routage	AI	Electronicien : 1/routage BT iPACIv2, 2/ Routage carte FEE GRIT (2022)	50	0	0	50	0

Table 8: Global table for in2p3 technical personnel (in %)

The **detailed workplan** is accessible at the GRIT website (see page1 for access)

7. Technical developments

The technical developments associated with the GRIT project are as follows.

7.1 Detector developments

Trapezoid and square detectors for the first (thin) layer (nTD, high segmentation, 500um) have been developed with MICRON SL during the MUGAST operation. Concerning **square** detectors, the serial detectors should be fully provided by our collaborators from BARC-Mumbai. They will be built by the SCL Institute in Chandigargh. Delivery of the first prototypes is expected at the beginning of 2020 and commissioning will be performed by the BARC group.

The development of the thick detectors (low segmentation, 1.5mm), trapezoid and squared, for the second layer will be launched in 2019, in association with MICRON SL. This company already developed 1.5mm thick DSSDs from 6'' wafers for γ-astronomy purpose. Mechanical design will be finalized at IPNO. Padova and IPNO will take in charge the commissioning.

7.2 Electronics developments

The main task will be the completion of the innovative analog memory ASIC PLAS. As mentioned above, the microelectronics group of LPC Caen is now in charge of the circuit. The second version of PLAS will be submitted to foundry at the beginning of 2020 in 0.18um techno which will be soon obsolete. For 2020-2022, a CDD (contract-engineer) needs to be hired for commissioning of PLAS v2 and pre-design of v3. This last version will probably be designed in a different technology.

Preamplifier ASICs developments are undertaken at Orsay (iPACI) and Milano (TOT). The final version (v3) of these circuit are planned to be submitted in early 2021. The SMART system to be used for the coupling with AGATA is currently under development at GANIL.

The full iPACI+PLAS+FASTER chain will represent a unique system for Silicon detectors. At the moment an application of this system is foreseen for the FRACAS project (hadrontherapy). (http://www.lpc-caen.in2p3.fr/article447.html?lang=fr).

7.3 Mechanics

The mechanical design of the GRIT reaction chamber, cooling system and supports will be taken in charge by IPNO, based on the existing design discussed in section 2.

7. SWOT analysis

S: The group has world leading expertise in the development and exploitation of Si-strip arrays for RIBs (MUST, MUGAST, TiARA)
IPNO and Milano expertise in preamps for Si detectors
IPNO mechanical expertise
Addition of LPC Caen electronics team

W: Delay to Departure of Valencia electronics group from project
Lack of pluri-annual financial support from IN2P3

O: Funding from Normandy region through F. Flavigny
Support of GANIL Scientific Council
Versatility and portability of system and compatibility with AGATA and PARIS

T: Unproven quality of Indian DSSDs
Endemic delays with Micron deliveries.
Novel PLAS concept untested
Possible problems with new SPIRAL1 beams
Delay of SPES post accelerated RIBs

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