Presentation of the activities of the JANNuS-Orsay / SCALP platform

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Outline

1. Summary

The JANNuS-Orsay/SCALP platform at IJCLab combines various machines (ion accelerator, ion implanter, transmission electron microscope, isotope separator) into a unique facility mainly used for ion beam modification (implantation/irradiation) and ion beam analysis of materials, and isotope and target production. The facility benefits of many years of technical and scientific expertise and operates various machines and dedicated end-stations, providing ion beams of most of the stable elements in a wide energy range from 50 eV to 11 MeV, in a temperature range from -170°C to 1000°C on the target. The particularity of the platform is the *in situ* techniques available for materials structure and chemical characterization (i.e. *in situ* Rutherford Backscattering Spectrometry in Channelling geometry (RBS-C), and *in situ* Transmission Electron Microscopy (TEM) with single/dual ion beam irradiation) that are unique in the world. It is worth noting that developments and upgrades are continuously needed to keep the facility at the state-of-the-art level (e.g. buying a new microscope within the next years). The isotope separator SIDONIE is one of the few isotope separators in Europe that still produce high purity isotopes, although it is not any more reliable and needs an upgrade.

The JANNuS-Orsay/SCALP platform has been offering its facilities and services to users from academic research and industry for more than 35 years. Since 2005, JANNuS-Orsay is closely linked to the triple ion beam JANNuS-Saclay at CEA/DEN/DMN Saclay (French Alternative Energies and Atomic Energy Commission), France, through the Scientific Interest Group (GIS) JANNuS[1]. JANNuS-Orsay/SCALP is a founding member of the EMIR&A[2] French network of accelerators for irradiation and analysis of molecules and materials. The platform was labelled as an IN2P3 platform in 2018.

[1] http://jannus.in2p3.fr
[2] http://emir.in2p3.fr
[3] https://www.csnsm.in2p3.fr/Materiaux-et-Irradiation Now in the Energy and Environment pole of the IJCLab

2. Description of the platform

The JANNuS-Orsay/SCALP platform is located in the building 108 on the campus in Orsay, and was attached to the CSNSM lab (Centre for Nuclear Science and Materials Science, joint research unit of CNRS/IN2P3 and Université Paris-Sud). Since January 2020 it is one of the platforms at the IJCLab (Laboratoire de Physique des 2 Infinis – Irène Joliot-Curie).

Equipments of the platform

The SCALP platform (**S**ynthesis and **C**haracterization using ion **A**cce**L**erators for **P**luridisciplinary research) is composed of (i) a 50 kV isotope separator called SIDONIE, (ii) an ensemble of a 190 kV ion implanter IRMA, a 2 MV Tandem-Van de Graaff ARAMIS, and a 200 kV Transmission Electron Microscope, called JANNuS-Orsay. An overview of the facility is shown in Figure 1. Detailed description can be found in the next paragraphs and in Ref. [Bacri 2017].

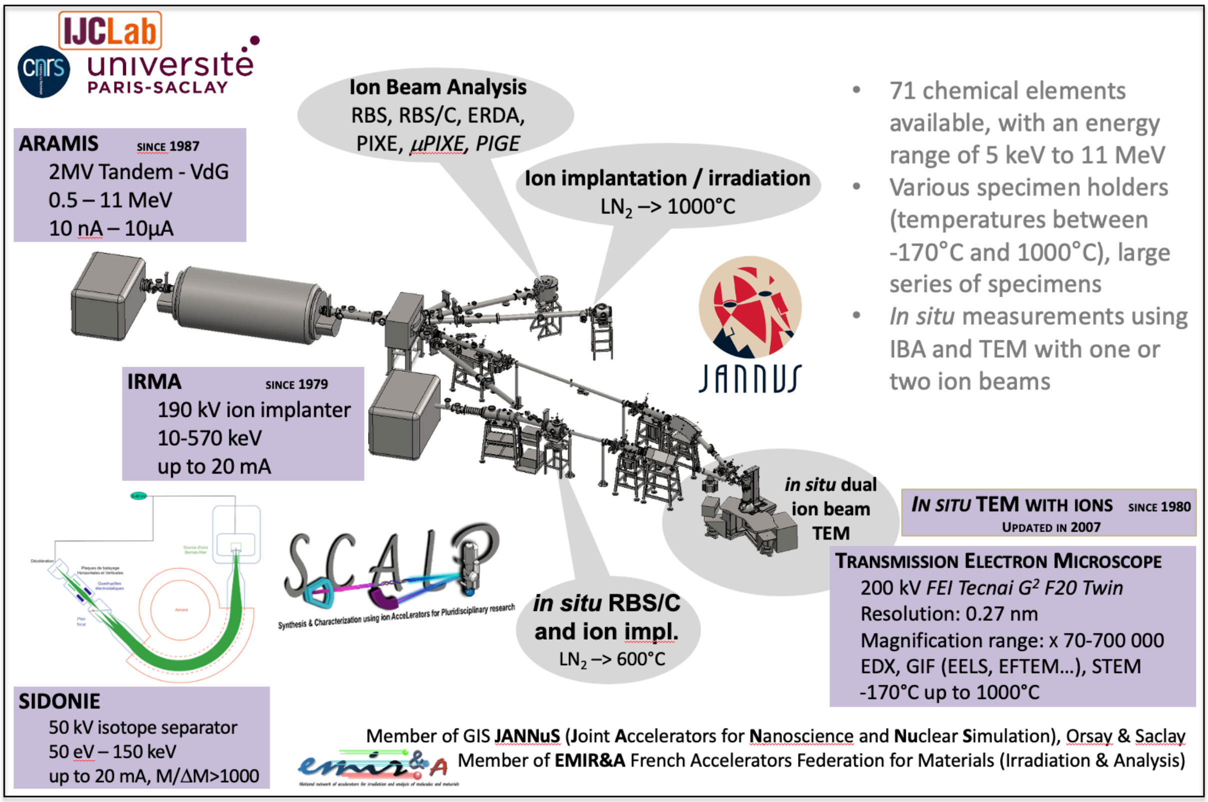


Figure 1 – Overview of the JANNuS-Orsay / SCALP platform

SIDONIE is a homemade electromagnetic separator operational since 1967 [Camplan 1970, Alexandre 1970, Chauvin 2004]. It mainly consists in a Niers-Bernas source, followed by a 135° magnet. Its nominal voltage is 50 kV and it is equipped with a slowing down device allowing to make deposits at energies going from 50 keV down to few tens eV. Its separation power is M/ΔM = 2000. The source type allows accelerating almost all ions (see Figure 2) with high current (some mA), except radioactive and toxic chemicals (for safety and security reasons). SIDONIE is mainly used to produce pure isotopes for various applications, going from nuclear physics and astrophysics (to make pure targets), to geosciences (to produce standards), or any study which need high purity isotopes or low energy beams.

IRMA is a homemade 190 kV ion implanter [Chaumont 1981], equipped with a reduced version of Bernas-Nier positive ion source which can deliver a large variety of ion beams, with energies in the range 5-570 keV depending on the charge state of the ion produced. More than 40 elements from H to Bi are produced from the IRMA ion source (see Figure 2).

ARAMIS is a homemade 2 MV ion accelerator [Cottereau 1990, Bernas 1992] which can be used either as a Tandem, by injecting negative ions from an external Cs sputtering source (SNICS), or as a single-ended Van de Graaff accelerator, using a positive Penning ion source located at the high voltage terminal. In tandem mode, more than 35 elements can be produced and accelerated to energies between 400 keV and 11 MeV; the single-ended operating mode is used to produce H, He or noble gas ion beams from 200 keV to 3 MeV. Figure 2 shows the elements that are available.

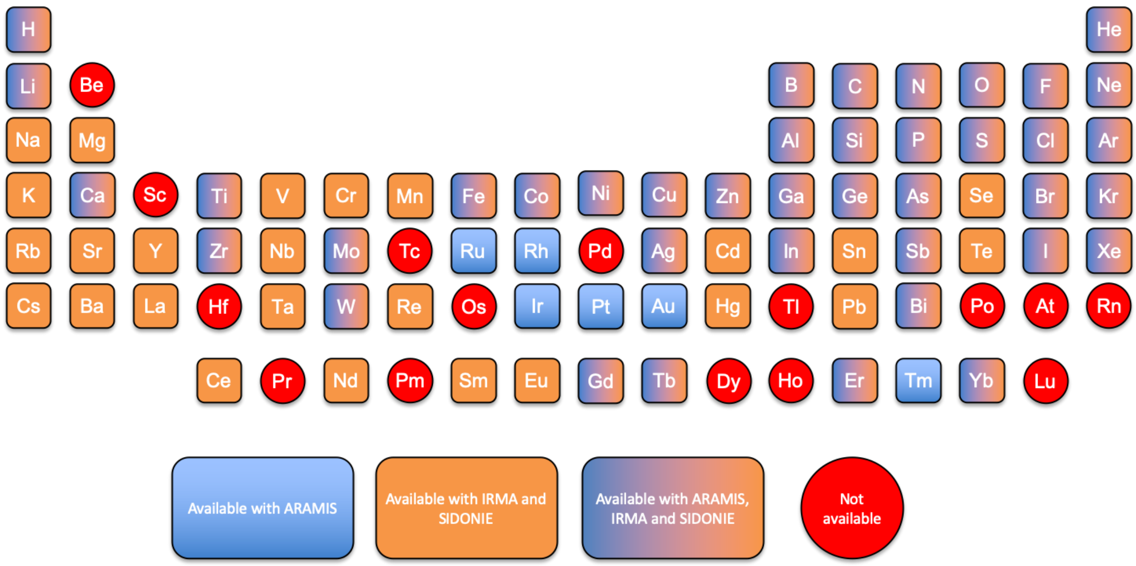


Figure 2 – Available elements that have been tested so far using IRMA, ARAMIS and SIDONIE.

Both **IRMA and ARAMIS ion beams** are rastered during ion implantation/irradiation, which ensures a full, uniform implantation fluence at the surface of the specimen up to 100×100 mm^2. Five beam lines are connected to IRMA and ARAMIS accelerators (see Figure 1). Two beam lines are dedicated to ion implantation/irradiation, and one for Ion Beam Analysis (IBA) including Rutherford Backscattering Spectrometry (RBS, RBS/C), Elastic Recoil Detection Analysis (ERDA), and Particle Induced X-ray Emission (PIXE), allowing structural and chemical characterization of materials. The two other lines are used for the coupling of IRMA and ARAMIS accelerators with the Transmission Electron Microscope (TEM), see below.

The **TEM (JANNuS-Orsay)** is a 200 kV FEI Tecnai G^2 20 Twin equipped with a LaB_6 filament, with a spatial resolution of 0.27 nm, coupled to IRMA and ARAMIS ion accelerators. Several analytical techniques are coupled to the microscope, *e.g.* Electron Energy Loss Spectroscopy (EELS), Energy-Filtered TEM (EFTEM), Scanning TEM (STEM) and Energy-Dispersive X-ray Spectroscopy (EDXS), allowing for example a chemical analysis of the specimen. Details can be found in Ref. [Gentils 2019]. The *in situ* TEM with ions at JANNuS-Orsay is now operating according to three modes: i) TEM + IRMA ion implanter, ii) TEM + ARAMIS ion accelerator and iii) TEM in dual ion beam mode (TEM + IRMA + ARAMIS), at a chosen temperature in the range 77 - 1300 K, allowing *in situ* observation and analysis of the material microstructure modifications induced by single or dual ion implantation/irradiation. Inside the TEM, the typical range of ion beam energies available depends on elements and is within 10-500 keV for the IRMA 190 kV ion implanter and 0.5-6 MeV for the 2 MV ARAMIS ion accelerator. *In situ* simultaneous dynamical TEM observation is possible when using one or two ion beam lines, depending on the geometry used (i.e. tilt angle values, shape of the thin foil, location of the transparent area, use of an ultra-thin specimen holder to minimize shadowing effects, nature and energy of the ion, etc.).

Governance structure

The JANNuS-Orsay/SCALP platform is led by the Operating Manager, who is in charge, with the technical staff (all IN2P3-CNRS employees) of the operation and technical developments of the platform. The scientific leader(s) define(s) the scientific strategy, promote(s) the visibility of the platform in the scientific communities, and define(s), with the help of experts if appropriate, the priorities of the platform in terms of use and evolution.

An internal programme committee (composed of the lab direction or its representative, the operating manager, the scientific leader(s), representatives of the internal users and of the technical staff) meets every three months to discuss about the proposals programming for the next three months, and about general news of the platform (update on operation/developments, and discussion about future developments).

A steering committee (IN2P3, Université Paris-Saclay) meets once a year, to provide an update on scientific and technical activities, along with financial and human resources aspects.

Scientific themes and users

The scientific themes that take advantage of the JANNuS-Orsay/SCALP platform are diverse, including nuclear materials, materials for microelectronics, nuclear astrophysics, and geology. The beam time distribution per theme is shown in Figure 3(a) for IRMA, ARAMIS and the TEM for the year 2019. More details are given in paragraph 3.

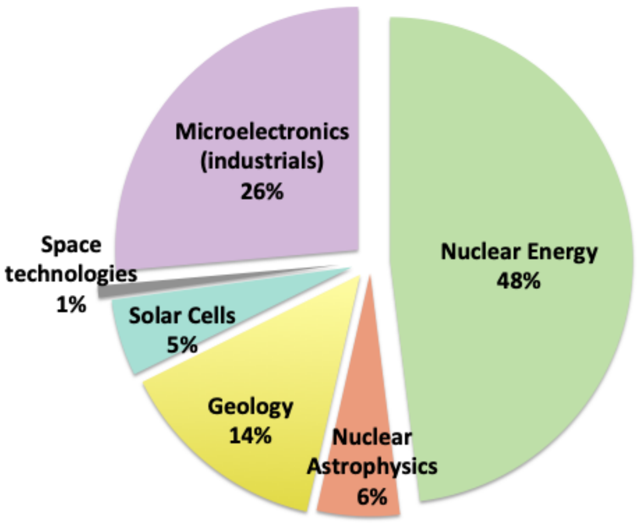


Figure 3 (a) Distribution of the ion beam time per theme (year 2019) for the ensemble IRMA-ARAMIS-TEM (JANNuS-Orsay)

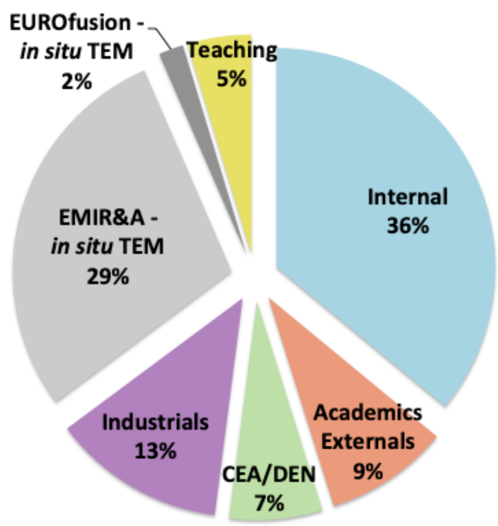
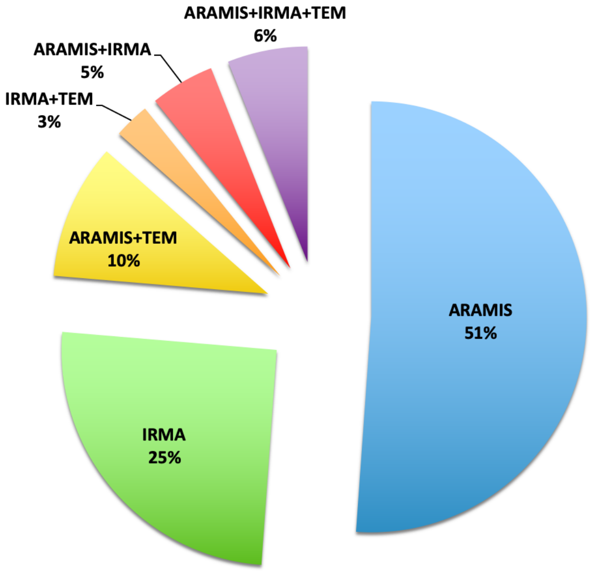


Figure 3(b) Average distribution of ion beam time per users (years 2016-2019) for IRMA – ARAMIS- TEM (JANNuS-Orsay)

Users of the JANNuS-Orsay/SCALP platform are coming both from the IJCLab and outside. The average distribution of the beam time for the years 2016-2019 per users is shown in Figure 3(b) above for the ensemble IRMA-ARAMIS-TEM (JANNuS-Orsay). Internal research (36 %) is mainly related to the studies of the *Materials and Irradiation* team[3] (89 %), to the studies of the *Astrophysics* team[4] (8 %), and to the *Cryogenics detectors* team[5] (3 %). The beam time allocated for external research is either for academic labs (9%), *in situ* TEM experiments selected through EMIR&A network (29%) and EUROfusion European programme (2%), or for CEA/DEN (7%) and industrials (13 %). Beam time is also used for maintenance and development of the facility (not mentioned in the Figure) as well as for training and education, currently lab work for Masters of Université Paris-Saclay (5%).



The total of user beam time (for IRMA, ARAMIS and JANNuS TEM) was in 2019 170 days of experiments per year, corresponding to 130 distinct experiments for around 30 users per year. The average distribution of ion beam time between the machines and their different combinations is shown in Figure 4, for the years 2016-2019.

Figure 4 – Average distribution of ion beam time per machine (IRMA, ARAMIS and TEM) and their combinations for the years 2016-2019

The scientific themes that use SIDONIE are shown in Figure 5(a). They will be later described in paragraph 3. The distribution of beam time per users is shown in Figure 5(b), for years 2017-2019 (in average 36 days).

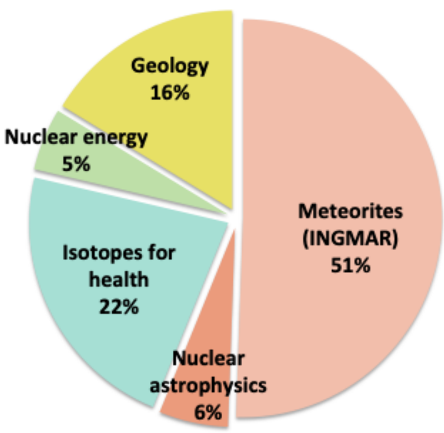


Figure 5(a) - Distribution of SIDONIE beam time per scientific theme

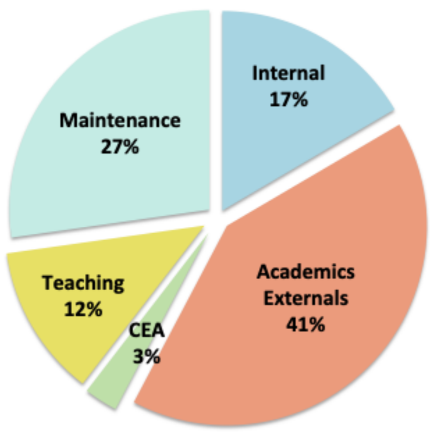


Figure 5(b) – Distribution of SIDONIE beam time per users for 2017-2019

[3] https://www.csnsm.in2p3.fr/Materiaux-et-Irradiation Now in the Energy and Environment pole of the IJCLab
[4] https://www.csnsm.in2p3.fr/Astrophysique-nucleaire and https://www.csnsm.in2p3.fr/Astrophysique-du-solide Now in the *Astrophysics Astroparticles and Cosmology (AAC)* pole of the IJCLab
[5] https://www.csnsm.in2p3.fr/Equipe-Detecteurs-Cryogeniques Now in the *AAC* pole of the IJCLab

Beam time allocation

Experiments at the ion accelerators are usually running 8h per day from Monday to Friday. Information on beam time allocation is available at: https://www.csnsm.in2p3.fr/Les-demandes-de-faisceaux. The machines of the JANNuS-Orsay/SCALP platform are available at present to internal and external users through various accesses:

- Access is provided based on a beam time proposal procedure. Proposals for IRMA, ARAMIS, SIDONIE and the TEM are examined each three months by the SCALP internal committee for academic external users (excluding *in situ* TEM and coupling of ARAMIS+IRMA beam time, that is reviewed through EMIR&A - see below), and for internal users of the lab.
- To allow more flexibility, urgent requests can be exceptionally addressed by the committee outside the scheduled quarterly meetings.
- For external users, beam time proposals using *in situ* TEM or ARAMIS+IRMA coupling for *in situ* RBS/C must be submitted to the EMIR&A[6] annual call, usually in October. The international committee of the EMIR&A French federation for irradiation and analysis of materials selects the proposals depending on the beam time offered each year by the facility (usually 5-6 weeks).
- For industrial users, the platform offers fast and direct access to the equipments based on quotation.

Financial model

The platform is mainly funded by own resources coming from chargeable services for industries and external users (~85%), that mostly cover operational costs. The other part is coming from IN2P3 each year (~15 k€). Depending on years, some funded projects (ANR, Europe, Labex, …) also help in the development and upgrade of the platform. It is important to note that the funding model of the platform is really dependent upon chargeable services for industries and external academic users, meaning that the funding is not fixed and is very dependent on the economical context. The operation costs are in average 100 k€ per year. Details can be found in paragraph 6.

3. Scientific issues

Materials for nuclear energy

Ion accelerators have been used by material scientists for decades to investigate radiation damage formation in nuclear materials and thus to experimentally simulate the irradiation effects induced by energetic particles (e.g. fission fragments, alpha decays and neutrons) on the structure and microstructure of materials. The versatility of conditions in terms of particle energy, flux, fluence, etc., is a key asset of ion beams allowing for fully instrumented analytical studies. In addition, very short irradiation times and handling of non-radioactive samples dramatically curtail the global cost and duration of experiments as compared to in-reactor testing. Coupling of two or more beams, use of heated/cooled sample holders, and implementation of *in situ* characterization and microscopy pave the way

[6] Réseau National d'accélérateurs pour l'irradiation et l'analyse des molécules et matériaux, créé en 2009, Infrastructure de Recherche (Fédération CNRS FR 3618 depuis 2014) http://emir.in2p3.fr

to real time observation of microstructural and property evolution in various extreme radiation conditions that reproduce as closely as possible the nuclear environments (fission, fusion). Several classes of materials are of interest for the nuclear industry ranging from metals and alloys, to oxides, carbides or glasses. Approximately 50% of the beam time is used per year for these studies (see Figure 3), either for internal or external users.

The Materials and Irradiation (MIR) team[7], now included in the Energy & Environment pole of the IJCLab, performs most of its experiments on the platform since the 90's, using either IRMA, ARAMIS (for both irradiation and ion beam analysis), and the *in situ* TEM with ions at JANNuS-Orsay. Their research projects related to nuclear materials are addressing various issues listed below:

- Radiation effects in oxides, carbides and nitrides, mainly related to fuels, confinement and/or transmutation of radioactive waste, *e.g.*:
    - Oxidation mechanisms of the nuclear fuel [Garrido 2006]
    - Radiation tolerance of fluorite-derived rare-earth-based oxides that are used or envisaged to be used in hostile, radiative nuclear environments [e.g. Sattonnay 2016].
    - Experimental simulation of High Burnup Structure in urania: the effect of impurities (Xe, He, La) in uranium dioxide and its behaviour under irradiation were studied for different conditions using both in situ RBS-C and *in situ* TEM [Haddad 2018], giving insights in the exact role played by the various relevant parameters in the formation of a specific microstructure and on the final destabilization of the solid observed at high doses of irradiation.
    - Radiation tolerance and effect of gas on aluminium nitride: insulating and optical materials, such as AlN, will be used in future fusion reactors diagnostic systems [Jublot-Leclerc 2019].
- Behaviour of steels under ion irradiation and ion beam synthesis, related to structural materials for current and future fission and fusion reactors:
    - Ageing of austenitic steels in the framework of actual Pressurised Water Reactor (PWR) reactors lifetime extension up to 60 years, and in particular the potential swelling of austenitic stainless steels representative of PWR vessel under the co-influence of irradiation and helium gas presence (CoIrrHeSim project ANR-11-BS09-006) [e.g. Jublot-Leclerc 2017].
    - Behaviour of ferritic-martensitic steels and Oxide Dispersed Strengthened (ODS) ferritic steels under ion irradiation and gas presence: they are excellent potential candidates for Generation IV fission and fusion reactors. Research focuses either (i) on the understanding of elementary radiation damage mechanisms (primary dislocation loops, role of alloying elements) in the framework of several European programmes [e.g. Bhattacharya 2019], or (ii) on the influence of the accumulation of He and H on the microstructure, or (iii) understanding the Cr-enriched alpha prime phase formation observed under neutron irradiation in reactors.
    - Ion beam synthesis in metallic alloys, to better understand the precipitation mechanisms of nano-oxides in Oxide Dispersed Strengthened (ODS) ferritic steels [e.g. Zheng 2017].

Their research projects are not only dedicated to radiation effects in nuclear materials, but also give an important part in a better understanding of the fundamental

[7] See publications list of the team at https://www.csnsm.in2p3.fr/Publications_Equipe_MIR

processes of the ion-solid interactions. One typical example is the effect of combined electronic and nuclear energy deposition on the atomic network of materials [e.g. Thomé 2015]. Besides, tools and models for quantitative description of the radiation-induced effects are required, e.g. [Debelle 2018].

Several external users are also using IRMA and/or ARAMIS and/or JANNuS-Orsay for their research related to nuclear materials, and especially CEA/DEN (Saclay, Marcoule, Cadarache) in France, IP2I Lyon (France), Shimane University (Japan), ETH Zürich (Suisse), IIT (Italy), Queen's University (Canada), University of Wisconsin-Madison and North Carolina State University (USA), etc. A lot of experiments deal with radiation effects, and more precisely study the defects creation at the nanoscale (size, nature, distribution, chemistry, and their evolution vs fluence, temperature, flux…) in metals and metallic alloys such as austenitic steels [*e.g.* Malaplate 2019], ferritic-martensitic steels [*e.g.* Schaublin 2017], Oxide Dispersed Strengthened steels [*e.g.* Lescoat 2012, Yao 2017], zirconium alloys [*e.g.* Tournadre 2012], aluminium [Flament 2017], tungsten [*e.g.* Hasanzadeh 2018], advanced coatings for Liquid Metal Fast Reactors [Garcia Ferre 2016]. Experiments in ceramics were also performed: as an example, the evolution of extended defects in polycrystalline ion-irradiated UO_2 was studied using the *in situ* JANNuS-Orsay TEM as a function of the fluence and temperature parameters [Onofri 2016]. Recently, as a given example among other studies, the behaviour under irradiation of a new type of neutron absorber for future fission reactors, such as boron carbide, has been studied using the JANNuS-Orsay facility, and the threshold fluence of amorphization has been determined, amongst other things [Victor 2018].

Nuclear physics and astrophysics

Detectors tests for nuclear physics, e.g. [Gottardo 2017] were performed using ARAMIS: the response function and energy linearity of a $LaBr_3$ detector were investigated up to 11 MeV with the $^{27}Al(p,\gamma)^{28}Si$ reaction.

Recently experiments have been performed on ARAMIS to try to provide elements related to the first evidence of an anomaly in the emission of e^+e^- pairs from the reaction $^7Li(p,e^+e^-)^8Be$ at a proton energy E_p ~ 1 MeV recently observed [Krasznahorkay 2016], and that could bring a hint to physics beyond the standard model. Indeed, this anomaly can be interpreted as an evidence of a new light gauge boson. These experiments have been performed through collaboration between CSNSM, GANIL, IPNO, INFN/LNS [Kiener], and promising results lead to propose an ANR project, named New Jedi (New Judicious Experiments for Dark sectors Investigations, PI B. Bastin, GANIL, coll. IJCLab, IAP, USA, CZ Rep., Belgium, Italy), part of the IN2P3 prospective.

IRMA was also used for detectors realization in the LUMINEU[8] project [Navick 2016], e.g. the metallization of electrodes using ion implantation.

Pure isotopic deposits (^{11}B, ^{12}C, ^{13}C, ^{29}Si, ^{30}Si, ^{38}Ar) have also been produced using SIDONIE in the last past years. Targets were produced for astrophysics measurements (collaborations between the *Astrophysics* team at CSNSM with many different international laboratories as for instance, INFN, Catania, Italy [Constantini 2009], Stuttgart, Democritos,

[8] LUMINEU (Luminescent Underground Molybdenum Investigation for NEUtrino mass and nature), part of the CUPID project, preparation of the construction of a next-generation Neutrinoless Double Beta Decay experiment, capable exploring the inverted hierarchy region of neutrino mass ; http://lumineu.in2p3.fr

[Assuncao 2006]), and doping of ^{11}B was performed for studies related to Si junction at CNRS-CEMHTI, Orléans, France [Xu 2010].

Low energy beams delivered by SIDONIE are used also to study space weathering of different interstellar objects such as meteorites for instance, through the simulation of low energy solar wind and/or cosmic rays. For that purpose, SIDONIE is coupled with an infrared spectrometer called INGMAR[9]. An example is given in [Lantz 2017].

Radionuclides production for health

SIDONIE was recently used for a first proof of concept experiment for production of high-purity radioisotopes for medical purposes. The goal is to propose an alternative for the production of some isotopes by the irradiation of a pure stable isotope produced by SIDONIE. Initiated through a collaboration with ARRONAX and ILL [Koster 2020], we are mainly working on the production of ^{155}Tb (SPECT imaging), through the ^{155}Gd(p,n) reaction. See paragraph 5 for more details.

Miscellaneous

The platform is also used for a wide range of studies related to various scientific themes (energy, geology, solid state physics, spatial…). The mean beam time distribution for all these scientific themes is roughly 20 % per year (cf. Figure 3), excluding industrials that use the beam time either for development or production. Some examples are given in this paragraph concerning experiments performed in the last few years mainly using the ion implanter IRMA and the ion accelerator ARAMIS. This is not exhaustive and can significantly vary from year to year.

Materials for solar cells were studied using the platform, such as Ar ion implantation in a-Si:H/c-Si heterojunction solar cells to enhance their efficiency [Defresne 2015] or He ion implantation in hybrid perovskites [Plantevin 2019], implantations of K, Na and F ions in Cu(InGa)Se_2 reference samples to quantify the existing impurities [Béchu], and MeV proton irradiation [Park 2018] to understand its influence on lattice-matched GaInP/GaAs/Ge triple junction solar cells under low intensity, low temperature conditions.

Mineral materials for geology applications have been studied for example using ARAMIS to detect He in apatites [Gerin 2017] or irradiation of clay minerals [Allard 2018], or using the JANNuS *in situ* TEM to observe irradiation and recovery effect in monazites [Seydoux-Guillaume 2018].

Another example is materials for spintronics like ferromagnetic TbFe and TbFeCo amorphous alloys, that have been characterized using ion beam analysis (RBS) on ARAMIS to obtain their in depth-chemical composition which is not homogeneous and affects their magnetic properties [Haltz 2018].

[9] INGMAR is a joint CSNSM-IAS equipment funded by the French Programme National de Planétologie (PNP), by the Faculté des Sciences d'Orsay of the Université Paris-Sud (Attractivité 2012), by the French National Research Agency ANR (contract ANR-11-BS56-0026, OGRESSE), and by the P2IO LabEx (ANR-10-LABX-003).

4. Place of the platform in the panorama

SIDONIE

SIDONIE is an electromagnetic separator, home-made built and operational since 1967 [Camplan 1970, Alexandre 1970]. It is a unique electromagnetic separator in Europe regarding its separation power and its capability to produce pure isotopes. It is possible to collect separated isotopes either at the focal plan (40 keV), with dedicated collectors, or at lower energy, after an electrostatic slowing-down device, allowing homogeneous implantation of the isotope into a foil at a given depth (depending of the chosen energy).

The ensemble IRMA-ARAMIS-TEM (JANNuS-Orsay)

IRMA is a home-made 190 kV ion implanter that was operational in 1979 [Chaumont 1981]. The *ex situ* ion implantation beam line of IRMA has existed since the beginning. Several specimen holders were produced over the years, and are still used at various temperatures from -170°C to 1000°C, including a variable temperature goniometer allowing Rutherford Backscattering analysis in Channelling geometry (RBS/C). In the early 80's IRMA was also connected to a Transmission Electron Microscope, see below. At the time of its creation, the beam time was devoted to astrophysical simulations (solar winds) [Borg 1980], metallurgy experiments [Pivin 1980] and various applications (semiconductor detector production, silicon nitride layer fabrication, etc). Throughout the years the ion implanter has been upgraded to maintain it at the state-of-the-art level.

ARAMIS is a 2 MV Tandem-Van de Graaff homemade electrostatic accelerator built in the late 80's and operational in 1989 [Cottereau 1990, Bernas 1992]. It is dedicated for ion beam analysis, and MeV ion implantation/irradiation in metals and insulators to modify materials over a depth of a micrometre range. In addition, at this time, nuclear astrophysics needed also MeV heavy-ion beams to measure cross sections of reactions of the CNO cycle that catalyse the combustion of hydrogen in stars. Several experimental lines were designed (see Figure 1). One line sends the ion beam from ARAMIS into the implantation chamber of IRMA, and is devoted to characterization using Rutherford Backscattering spectrometry (RBS). This equipment is unique in France and exists only at HZDR (Germany) in Europe. As an example, the evolution of the ion-induced damage at a given temperature (up to 600°C) has been studied using this peculiar setup in several oxides for nuclear applications (uranium dioxide [Nguyen 2014], cubic zirconia [Gentils 2002], magnesium aluminate spinel [Gentils 2005], apatites (*on-going*), …). Another line is dedicated to ion beam analysis (RBS-C, NRA, PIXE, PIGE): the chamber and the goniometer have been developed in the early 90's, and updated in 2017 (thanks to P2IO and Master Nuclear Energy funding). It is mainly used for chemical analysis as a function of the depth of materials such as thin films (e.g. [Haltz 2018]), and for structural and elemental characterization of nuclear materials (*e.g*. measurement of damage [*e.g.* Thomé 2004] and location of impurities [*e.g.* Thomé 2001]). A microPIXE setup has been also developed recently on this beam line to determine distribution of elements in materials, and first results are promising.

The team is part of the IBAF (Ion Beam Analysis Francophone) network since its creation, and participates to the annual workshop. In October 2019, the 24th international conference IBA[10] (Ion Beam Analysis) was organized in Antibes, France, by the French/Belgium IBAF consortium, and chaired by Frederico Garrido (IJCLab), gathering more

[10] https://www.iba2019.com

than 250 researchers from 30 countries. The *Materials and Irradiation* team at CSNSM also organized the 19th REI[11] (Radiation Effects in Insulators) international conference in July 2017 in Versailles, France (chair: Gaël Sattonnay, Co-chairs: Aurélie Gentils, Lionel Thomé, all from IJCLab), bringing together 200 persons of 27 countries, and 60 proceedings in Nucl. Instrum. Methods B. The IRMA and ARAMIS ion accelerators are also well established worldwide thanks to numerous posters, oral presentations and invited talks of users at international conferences, and publications in peer-reviewed journals.

***In situ* Transmission Electron Microscopy** is a speciality of the laboratory since the early 1980's [Ruault 1983]. A 120 kV Philips EM400 Transmission Electron Microscope (TEM) and the 190 kV ion implanter IRMA (described above) were connected together under the guidance of Dr. Marie-Odile Ruault, allowing *in situ* observations of modification of materials under ion beam. Several research projects were developed that mainly focused on ion beam synthesis in semiconductors and metals using this peculiar equipment [e.g. Ruault 1988, Lin 1987, Zheng 1991, Fortuna 1993]. A new 120 keV Philips CM12 microscope equipped with Energy-Dispersive X-ray Spectroscopy was installed in 1994 [Ruault 2005]. Part of the research still focused on ion beam synthesis in silicon for microelectronic applications [*e.g.* Ruault 2008], whilst other projects emerged that were dedicated to nuclear materials [*e.g*. Soulet 2001, Monnet 2004, Gentils 2008]. The facility was updated in 2006 [Chauvin 2007] with the arrival of a new FEI Tecnai 200kV G^{2}20 TEM and the construction of a second new ion beam line connected to the 2 MV Tandem-Van de Graaff accelerator ARAMIS (described above).

This exceptional facility that includes the TEM and the two ion beam lines coming from the IRMA ion implanter and the ARAMIS ion accelerator has been called **JANNuS-Orsay** since 2007. This *in situ* dual ion beam TEM is nowadays mostly used for fundamental researches related to nuclear industry for fission and fusion applications [Gentils 2019], although some experiments are performed on superconductors, or mineral materials for geology applications. It is unique in France, and was the only such facility in Europe until the construction of the MIAMI-2 facility at the University of Huddersfield, UK [Greaves 2019]. JANNuS-Orsay is a founder member of the EMIR&A[12] French accelerators network for irradiation and analysis of molecules and materials, and provides 5 to 8 weeks per year of *in situ* dual ion beam TEM experiments to worldwide academic users since 2008 (through EMIR&A and European programmes). We participate actively in the annual meetings of the FEI-ThermoFisher electron microscope consortium (named GUMP[13]) in France, and organized two of them (in 2010 and 2019). We also organized in 2016 the 4th international Workshop On TEM With In Situ Irradiation (WOTWISI[14]) that gathered 50 users and representatives of current *in situ* TEM facilities worldwide (USA, UK, Japan, France) to discuss about recent advances in electron microscopy and ion irradiation techniques, and we are member of the scientific committee of this workshop. JANNuS-Orsay is known worldwide thanks to numerous posters, oral presentations and invited talks at international conferences, publications in peer-reviewed journals, and it is in particular recognised for the precision of the flux and fluence measurements inside the TEM, and the wide range of elements and energies available.

[11] https://rei2017.sciencesconf.org

[12] EMIR&A Réseau National d'accélérateurs pour l'irradiation et l'analyse des molécules et matériaux, créé en 2009, Infrastructure de Recherche (Fédération CNRS FR 3618 depuis 2014) http://emir.in2p3.fr

[13] http://gump.microscopie.org

[14] http://wotwisi4.in2p3.fr

5. Evolution of the platform

SIDONIE

Two main programs are currently developed with SIDONIE:

- Proof of concept experiment for production of radioisotopes for medical purposes: a lot of different programs related to the production of radioisotopes for medical purposes are developed around the world. For some of them, the necessary purity is difficult to obtain and is sometimes prohibitive. At IJCLab, we are starting a new program to propose an alternative for the production of these isotopes, by the irradiation of a pure stable isotope produced by SIDONIE. Initiated through a collaboration with ARRONAX and ILL [Koster 2020], we are working on the production of ^{155}Tb (SPECT imaging), through the ^{155}Gd(p,n) reaction. Cross sections measurements of the reaction of interest are necessary to identify the optimal p energy (high enough to produce large quantities of Tb, and low enough to avoid as possible parasitic reaction producing contaminants). A common internship with ARRONAX is hired for this study.
  In parallel, a similar study is related to the ^{67}Cu (β^- therapy), produced by the ^{68}Zn(γ,p) photoreaction at the ALTO facility, after the production of a ^{78}Zn target on SIDONIE.
  Moreover, we have been contacted very recently by ORANO and CEA/DEN to develop a collaboration for the production of ^{103}Pd (cancer prostate therapy), through the ^{102}Pd(n,γ) reaction. Discussions are in progress to explore the possibility to share a PhD student. These programs require using SIDONIE in the best operating conditions (particularly in terms of high delivered currents), to have robust and reproducible results, which needs SIDONIE to be upgraded to be able to provide the community with a reliable machine. This program related to production of radioisotopes, thanks to the requested performances on SIDONIE, should be used as a “scientific support” to carry out the necessary upgrades.
- In 2020, the project « STANDARD » benefits from a funding through the “défi ISOTOP” of the MITI[15] (CNRS), to continue the program related to the production of rare gas standards.

In order to improve reliability and so to increase the beam request rate, it is necessary to commit higher budget. Indeed, the scientific interest on pure isotopes is renewing, at least for medical purposes and for the production of standards.
At last, it has to be mentioned that INGMAR spectrometer (see part 3. Section Astrophysics, Micrometeorites) will be moved and coupled with ARAMIS after the building extension of SCALP (see below), probably at the end of 2021.

Hall IRMA-ARAMIS-JANNuS-Orsay

In the near future, several developments and upgrades are foreseen to maintain the platform at the state-of-the-art level.

First of all, complementary *in situ* characterization of ion-beam induced modification of materials is needed, such as an *in situ* X-Ray Diffraction setup with heavy ions in the MeV range, that does not exist anywhere else in the world yet, allowing *in situ* structural characterization of materials as a function of the irradiation, at a given temperature. This peculiar equipment will be complementary to other *in situ* characterization techniques already available at the facility (i.e. RBS-C and TEM), as well as to complementary

[15] MITI Mission pour les Initiatives Transverses et Interdisciplinaires (CNRS), http://www.cnrs.fr/mi/

characterization techniques available at facilities through the EMIR&A network in France. Obtained results will be of great importance for research on materials under irradiation, and especially for nuclear materials and ion-solid interactions understanding. The development of an advanced software for crystallographic analysis of a material by ion channeling during RBS-C experiments is also an upgrade that is essential in the next years to improve the capabilities of the facility.

The development of a new irradiation chamber on ARAMIS, equipped with a heating sample holder and a thermal camera, is a key asset for studying materials under extreme conditions (temperature, irradiation), as it allows the accurate measurement of the temperature of the irradiated surface of a specimen *in situ* during ion irradiation. A project has just been submitted to the MITI[15] (CNRS) through the "défi *Instrumentation en conditions extrêmes*".

Moreover a dedicated beam line for nuclear astrophysics and detector tests would be of great help in the future to develop future experiments. The *in situ* Infra-Red Spectrometry INGMAR setup (see paragraph 3) that is today installed at SIDONIE will also need to move to be connected to a new line of ARAMIS to benefit of higher energies ion beams.

Thanks to a CPER-P2IO funding (1.2 M€, 2015-2020), an extension of the experimental hall will allow to build these lines (and existing ones, i.e. ion beam analysis, ex-situ implantation/irradiation for industrials). The building works will start this spring for a duration of 12 months. The new surface to be built is highlighted in orange in Figure 6, that double the surface of the existing experimental hall, allowing:

- ✓ New ion beam lines on ARAMIS, *e.g.*
  - *In situ* X-ray diffraction (line and setup to be built/funded, as described above)
  - Gamma analysis for nuclear astrophysics (setup to be built/funded)
  - *In situ* Infra-Red Spectrometry (setup already existing, named INGMAR, line to be built/funded)
- ✓ Practical work for Master students, with dedicated beam time and room for data analysis (Université Paris-Saclay: Nuclear Energy Master, Master Grands Instruments, Master "Outils et Systèmes de l'Astronomie et de l'Espace", …)
- ✓ Industrials – Valorization

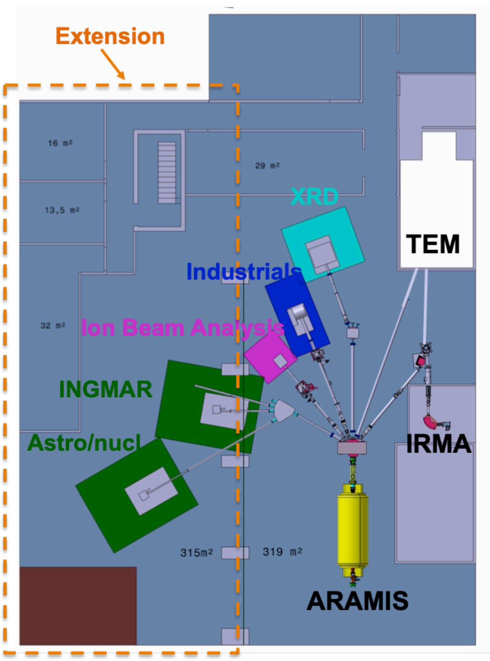


Figure 6 - Scheme of the experimental hall after building extension, showing the different ion beam lines (existing or to be constructed) – the new part is highlighted in orange.

Concerning the TEM, it is mandatory to anticipate a new TEM purchase in the near future to stay competitive in a context where *in situ* TEM with ions facilities flourish abroad (4 are now working and open to users, 2 are in construction), while updating the existing TEM (e.g. new faster camera as soon as possible to replace the former one that is dying). This new TEM will allow state-of-the art performances in term of structural and chemical *in situ* characterization of ion-irradiated materials (high resolution and atomic resolved chemical characterization (*e.g.* STEM-HAADF, …)), at a smaller scale that cannot be achieved with the existing one. This will give access to the first stages of damage and defect creation that is of importance to understand fundamental mechanisms occurring in irradiated materials. Moreover, to study materials submitted to fusion environments, the experimental simulation of the synergetic effect of irradiation + helium and hydrogen presence is essential; that can be achieved through a third ion source inside this new TEM, which does not exist anywhere else in the world. Several current or future users have already asked us for having such a possibility.

6. Resources and means

Human resources

The technical team in charge of operating and developing the platform is composed of the persons listed in the table below (as of January 1st, 2020), all employed by CNRS (IN2P3 Institute) and belonging to the *SCALP platform* service of the IJCLab. These 9 permanents and 1 fixed-term IN2P3 employees represent 9.4 FTE.

Name	Position	FTE	Function	Competences
Dr Cyril Bachelet	IR	1	Operating manager, IBA	Experimentation development
Dr Cédric Baumier	IR	1	Responsible of the TEM	Instruments development
Jérôme Bourçois	AI	1	IRMA-ARAMIS, responsible of the accelerators	Instrument and experimental techniques
Philippe Benoit-Lamaitrie	AI CDD*	1	IRMA-SIDONIE (since October 2019)	Instrument and experimental techniques
Laurent Delbecq	IE	1	Infrastructures	Instrument and experimental techniques
Silvin Hervé	IE	1	ARAMIS-IRMA (since October 2019)	Instrument and experimental techniques
Dominique Ledu	IE	1	SIDONIE (Retirement summer 2020)	Experimentals techniques
Florian Pallier	IE	1	Specimen preparation	Materials science developments
Sandrine Picard	AI	0.9	ARAMIS, quality	Instrument and experimental techniques
Christine Oriol	IR	0.5	Materials analysis (using IBA), since Oct. 2019	Materials science and characterization

* CDD means fixed-term contract

Other persons from the IJCLab lab are also working part-time for the platform, and especially Sébastien Pitrel (AI, *On-line* service, *Computing* Department, *Engineering* pole) for the maintenance of the control/command system and associated electronic, representing usually 0.5 FTP or more when an upgrade is needed. Also, the on-going upgrade work of SIDONIE is also done today thanks to Hervé Lefort (IE, *Accelerator* pole, 0.8 FTE), and Tony Viaud (AI, *Engineering* pole, *Computing* Department, 0.5 FTE).

The scientific leader of the JANNuS-Orsay/SCALP platform is Dr Aurélie Gentils (CR HDR, section 15, CNRS, *Energy and Environment* pole of the IJCLab) since January 2020, with the help of Dr Charles-Olivier Bacri (DR, section 01, CNRS, *Physics for health* pole of the IJCLab), scientific responsible of the SIDONIE isotope separator. Dr Stéphanie Jublot-Leclerc (CR, section 5, CNRS, *Energy and Environment* pole of the IJCLab) is also acting as a local contact for some *in situ* TEM experiments at JANNuS-Orsay.

The human resources evolution is as follow. An IE retirement (on SIDONIE) is planned to occur in the 2020's summer; the fixed-term contract will end in November 2020; and finally, 1 or 2 departures (not definitively known when the text is being written) are expected before February. All these departures will fragilize the platform operation and any development/upgrade, such as the renovation of SIDONIE.

Financial balance sheets (investment/operating)

The annual cost of the platform is in the range 85 - 115 k€ depending on years (106.7 k€ in average the last 3 years), mainly used for operational costs and small upgrades (*e.g.* keeping up to date the control-command system). The table below shows the distribution of expenses for the year 2019, and does not reflect the exact needs of each machine each year.

	Total	Common	ARAMIS	IRMA	TEM	SIDONIE
Operation costs (€)	61 714	6 958	7 571	8 157	33 834	5 194
Computer (€)	5069	4 419	0	0	0	650
Overhead (€)	431	431	0	0	0	0
Developments (€)	5 664	741	4 923	0	0	6698
Missions-Colloquium (€)	1 761	1 761	0	0	0	0
Interns-fixed term contracts (€)	9 490	9 490	0	0	0	0
Total	**84 129**	23 800	12 494	8 157	33 834	12 542

Table – Distribution of expenses of the JANNuS-Orsay/SCALP platform for the year 2019

The platform is mainly funded by own resources (~85%), coming from chargeable services for external users and industries. The other part is coming from IN2P3 (15 k€ in 2019). Depending on years, some funded projects (*e.g.* ANR, Europe, LabEx) also help in the development/upgrade of the platform. It is important to note that the **funding model of the platform is really dependent upon chargeable services for external users and industries**, meaning that the funding is not fixed and is very dependent on the economical context.

In the near future, several developments and upgrades are foreseen to maintain the platform at the state-of-the-art level. As detailed in paragraph 5, thanks to the building extension, new beam lines can be built, and especially one to develop an *in situ* X-Ray Diffraction setup with heavy ions in the MeV range. A global estimation for this equipment is

450 k€ (XRD setup + beam line). Concerning the TEM, it is mandatory to update the existing camera as soon as possible (200 k€), and prepare the purchase of a new TEM in the near future to keep the facility competitive with the existing and new facilities in the world (4 are now working and open to users, 2 are in construction). An average price for this specific new TEM is approximatively 5-8 M€. Concerning SIDONIE, the effective cost of the necessary upgrade for future projects is under study and can be estimated today in the approximate range of 100 k€ to 400 k€.

7. SWOT self-analysis

- Strengths
  - Self-sustainability
  - Worldwide recognition – International Network
  - Exceptional pool of machines with unique performances
  - Public area (lab work and training course)
  - Free space for facility improvement
  - Balance between research and benefits
- Weaknesses
  - Quality procedure (ongoing with the *Quality* service of the IJCLab)
  - Development of lab work
  - Improve the external communication
  - Facility with old equipments
  - Maintain the required staff for operation, development and upgrade
  - Fragile industrial funding
- Opportunities
  - Help of the support services (valorization, international partnership, project management office)
  - Support of engineering and accelerators services for upgrade
  - Financial support of the CPER for building extension
- Risks / Threats
  - Difficulties to keep financial support for development and upgrade
  - Difficulties to hire permanent staff

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