CIRIL: Interdisciplinary Research at GANIL

Jimmy Rangama, C. Grygiel, A Méry, Patrick Rousseau, Hermann Rothard

Nuclear Physics News

Volume 32/No. 1

Contents

Cover Illustration: Aerial view of IJCLab - see article on page 4.

CIRIL: Interdisciplinary Research at GANIL

CIRIL: 40 Years of Interdisciplinary Research at GANIL

Soon after the decision was made in 1975 to construct the Grand Accélérateur National d'Ions Lourds (GANIL) in Caen, Normandy, France, it became clear that in addition to nuclear physics, interdisciplinary research (atomic physics, solid-state and materials science, radiobiology, and chemistry) could benefit from the unique heavy ion beams available. Consequently, the Centre Interdisciplinaire de Recherche avec les Ions Lourds (CIRIL) was established in 1982 [1] and the first experiments were conducted in February 1983 [2]. The buildings are situated close to the GANIL beam-lines within the campus Jules Horowitz. CIRIL is the welcoming platform of the Centre de Recherche sur les Ions, les MAtériaux et la Photonique (CIMAP). The beam-lines available at the advent of the new millennium were already presented in *Nucl. Phys. News* [1]; here we focus mainly on available experimental equipments.

In 2013, a colloquium held in Caen celebrated 30 years of interdisciplinary research at CIRIL, and the proceedings of this meeting offer an overview of interdisciplinary research with GANIL beams [3]. To date, more than 1,200 publications (about 3,000 different authors) and about 200 related theses point out the importance of interdisciplinary research at GANIL. An important mission of CIRIL is to foster the scientific community by means of numerous French and European networks, currently EMIR&A [4] (a federation of accelerator facilities in France) and RADIATE [5] (research and development with ion beams in Europe). The CIRIL platform has played a major role in networks around the world (PAMIR, NEEDS, EMIR, France hadron, LEIF, ITS LEIF, SPIRIT, RADIATE).

Interdisciplinary proposals for experiments are evaluated by the GANIL interdisciplinary Program Advisory Committee (iPAC) organized by CIRIL. Depending on the available beam time to be distributed, iPAC takes place once or twice a year. A fraction of beam time (about 20–30%) is distributed via the EMIR and RADIATE networks after evaluation by their respective committees. CIRIL hosts on average about 70 experiments per year in which more than 150 scientists from national, European, and international scientific communities participate. The need for accelerator facilities worldwide was already discussed in Ref. [6]. During the last five years, human and financial investments (CPER E2S2 2016-2020 in partnership with GANIL for the renovation of beam-lines) brought significant spinoffs for innovation and research. Table 1 highlights milestones of the development of interdisciplinary research at CIRIL–GANIL.

Irradiation Facilities

CIRIL manages and coordinates the scientific, administrative, and technical activities of multiple experimental areas with several beam-lines. The importance of this activity has regularly increased with the growing number of possibilities offered to users: the high-energy line in 1983, the medium-energy line in 1989, the laboratory for the radiobiology research (LARIA) in 2003, the IRRadiation SUD (IRRSUD) line in 2004, the Ligne d'Ions Multichargés de Basse Energie (LIMBE) facility in 2000, and its extension, Accélérateur pour la Recherche avec des Ions de Basse Energie (ARIBE), in 2005 (Figure 1). The constant development of new beam-lines, which can operate in parallel (or independently) from GANIL's high-energy beam, has made it possible to multiply the available beam-time and the range of accessible energies.

The most frequently used experimental areas for interdisciplinary research (Figure 2) are: (1) ARIBE, offering five beam-lines for multiply charged ions from an ECR source. The ions extracted with a charge state q + are accelerated to kinetic energies of $E = q\ U$ with an acceleration voltage $3\ kV < U < 20\ kV$; (2) IRRSUD delivers carbon to uranium beams (0.25 to 1 MeV/u) from the C0 cyclotrons; and (3) the D1 cave, which features ion beams accelerated by the CSS1 cyclotron (sortie moyenne énergie; SME) to the irradiation chamber IRASME, and the high-energy (HE) beams by the CSS2 cyclotron delivered to IRABAT. The IRRSUD, IRASME, and IRABAT lines are equipped with a sweeping device for uniform irradiation (typical irradiation field 5 cm × 5 cm) and dedicated dosimetry [7]. This latter feature is particularly important for materials science and radiobiology (research on hadrontherapy cancer treatments).

In addition to sample irradiation with *ex-situ* sample analysis, a variety of *in-situ* experimental setups are available. In many cases, they are mobile and can be mounted on different

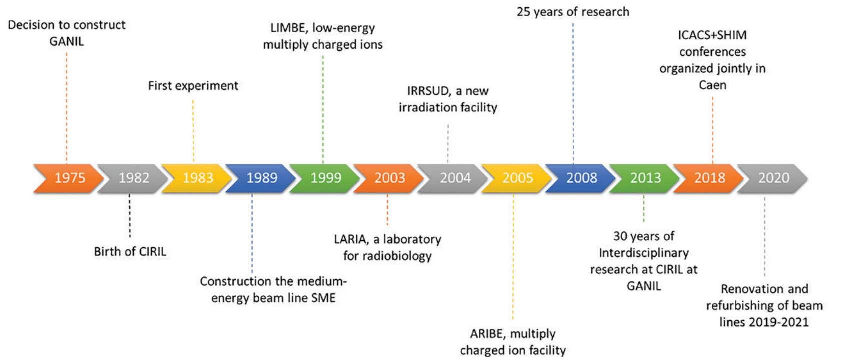

Figure 1. *Chronology of the extension of the GANIL facilities devoted to interdisciplinary research.*

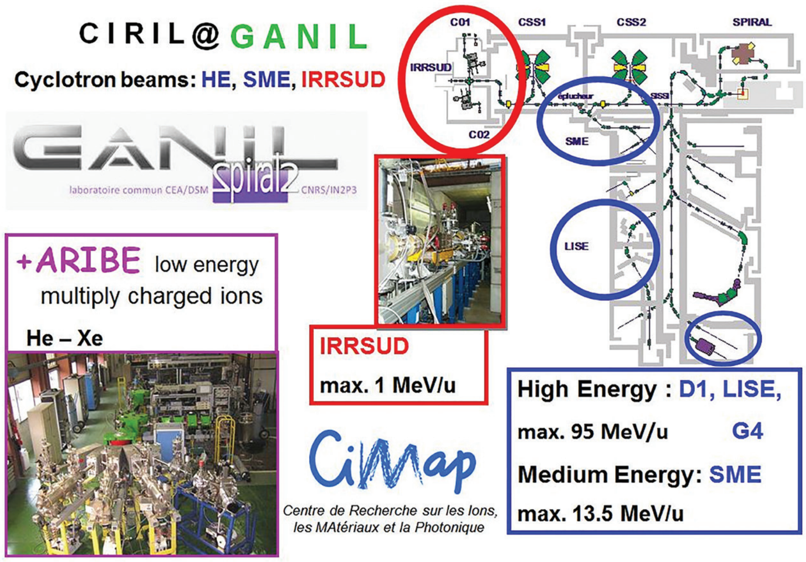

Figure 2. *Available ion beams at GANIL (Cyclotron beams: IRRSUD and SME/HE, low-energy ECR beams: ARIBE).*

beam-lines. The possibility to perform experiments on different beam-lines covering several regimes of microscopic energy deposition mechanisms, from elastic collisions to electronic excitations, including regimes were both come into play, is an unique feature of GANIL. It allows establishing scaling laws for different processes (e.g., fragmentation, sputtering, amorphization) as a function of projectile energy loss. More than 20 online experimental devices, some of which are presented in the next section, have been developed.

Dedicated Experimental Setups: A Selection

IRABAT

The heavy ion beams of GANIL are a tool to simulate the effects of cosmic rays on matter with applications in space science (exposure of materials, in particular electronic devices) and biological targets, such as organic molecules and living cells, to help optimize radiation protection in space missions (astronauts, on-board equipment). Also, damage induced by incorporated radioactive atoms or the treatment of cancer by radiotherapy with heavy ions (hadrontherapy) can be studied. In this vein, the radiobiology laboratory LARIA was installed at the CIMAP–GANIL site. Together with the Centre Baclesse (a world-leading clinic for cancer treatment) and the hadrontherapy center Cyclhad (operational since 2017), the importance of CIMAP's and GANIL's investment in this area has contributed to the recognition of Caen as a leading place in this domain. CIMAP–CIRIL designed a sample changer (Figure 3) on which biologists can install up to 32 vials containing cell cultures. A control system manages automated irradiation remotely.

IRASME

IRASME (Figure 4) derives from IRABAT and allows completely controlled irradiation (flow, fluence, surface) of all types of samples. It contains all the technical specificities of IRABAT with a vacuum chamber allowing also experiments carried out under controlled atmosphere (e.g., oxygen). Also, *in-situ* experimental setups can be mounted downstream and profit from uniform irradiation fields due to the sweeping device and precise dosimetry. A large community of physicists and chemists interested in the effects of electronic excitations in materials profits from the increased beam time than that possible in IRABAT alone, between 2,500 and 3,000 hours of beam for IRASME (i.e., 10 times more than in IRABAT).

IGLIAS and CASIMIR

The mobile experimental setups CASIMIR and Irradiation de Glaces d'Intérêt AStrophysique (IGLIAS), Figure 5 allow studying the interaction of ion beams with solid samples in a wide temperature range, from 9 K to 300 K. IGLIAS, developed by CIMAP in collaboration with IAS Orsay [8] allows reproduction of space conditions like ultrahigh vacuum, low

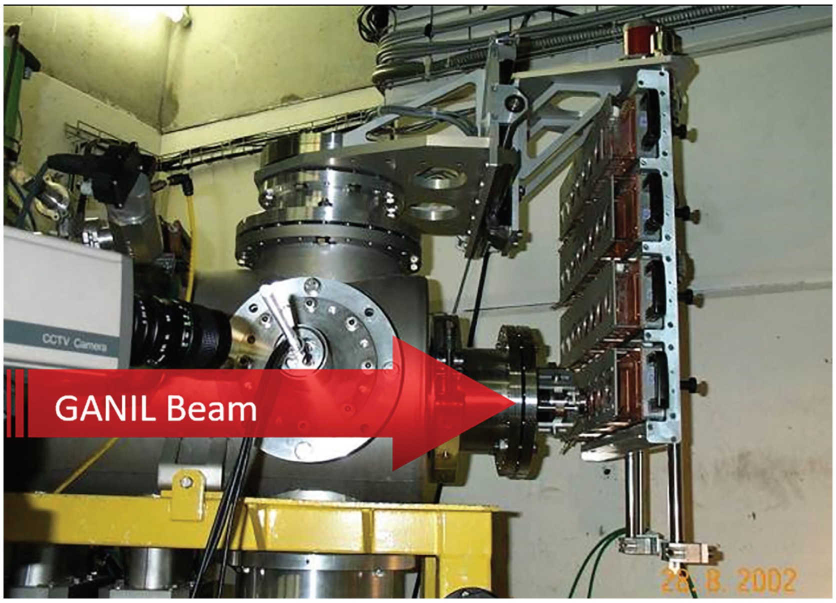

Figure 3. *Biological sample holder for automated irradiation of 32 vials containing living cells at the IRABAT irradiation chamber.*

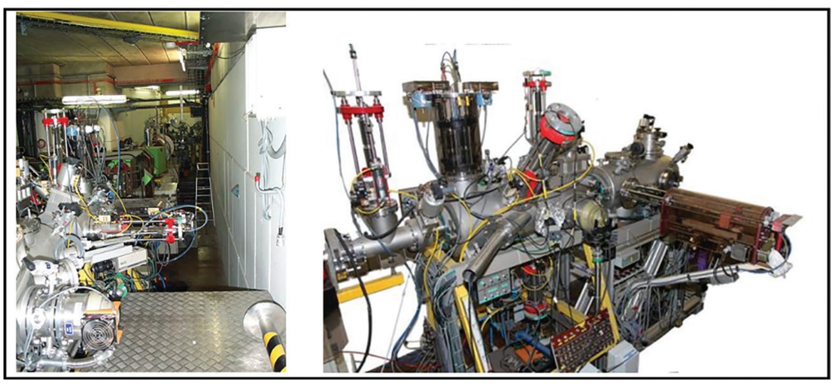

Figure 4. *IRASME at the medium energy beam-line SME in the D1 cave.*

temperatures, and exposure to cosmic radiation. Up to three samples prepared *ex-situ* can be mounted. Thin layers of molecules can be prepared by condensation on cold substrates from gases or vapors *in situ*. Mixtures of up to four different molecules have been prepared. Chemical or physical evolution during ice processing by irradiation with ion beams (simulating, e.g., cosmic rays or ions present in the magnetospheres of the Solar System's giant planets) can be followed *in situ* with several analysis techniques. They include Fourier transform infrared spectroscopy, visible-ultraviolet spectroscopy, and mass spectrometry. Often, residues containing organic matter are produced by slowly heating the irradiated samples to room temperature, which then can be analyzed *ex-situ* by other techniques (micro-SIMS, chromatography, high-resolution mass spectrometry). This allows testing possible scenarios for synthesis of organics in the early outer Solar System and their transport to Earth via micrometeorites. IGLIAS (and CASIMIR, mainly used for polymer and materials science) are open to the scientific community.

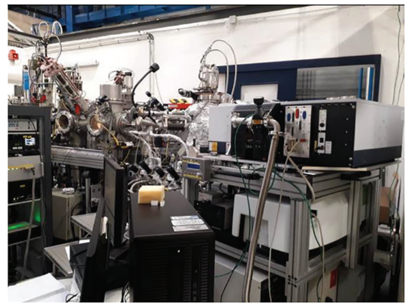

Figure 5. *IGLIAS mounted at IRRSUD.*

ALIX

ALIX (Figure 6) is an X-ray diffractometer set up at IRRSUD for studying defect formation and structural modifications [9] of crystalline materials (oxides, semiconductors, alloys, metals) induced by swift heavy ions. The diffractometer, a Bruker D8 Discover, has been modified and optimized to enable ion irradiation simultaneously to X-ray pattern recording. Thus, *in-situ* experiments at room temperature are possible. Since the penetration depths of IRRSUD projectiles are only around tens of micrometers below the surface, X-ray diffraction measurements under grazing incidence allow the analysis of the topmost part of the sample. Damage depth profiles can be established in irradiated materials. Kinetics of phase transitions and structural modifications (amorphization, strain, grain subdivision) are also studied and associated to energy deposition processes (elastic or inelastic electronic excitations) induced by swift heavy ion irradiation in functional materials.

COLIMACON

The COLission Ion-Molécule/Agrégat Complexe Neutre (COLIMACON) is a crossed-beam collision device to study ionization/excitation of the gas

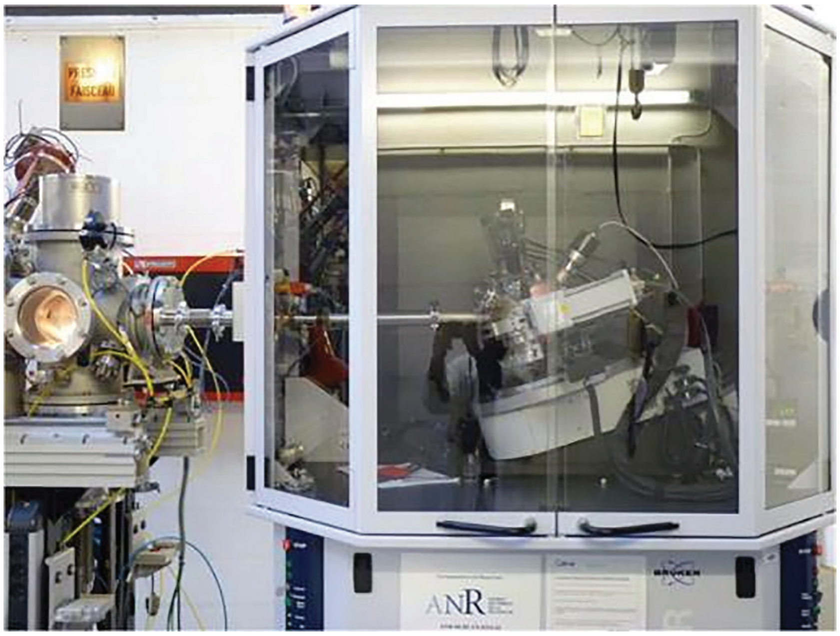

Figure 6. *ALIX setup mounted at IRRSUD.*

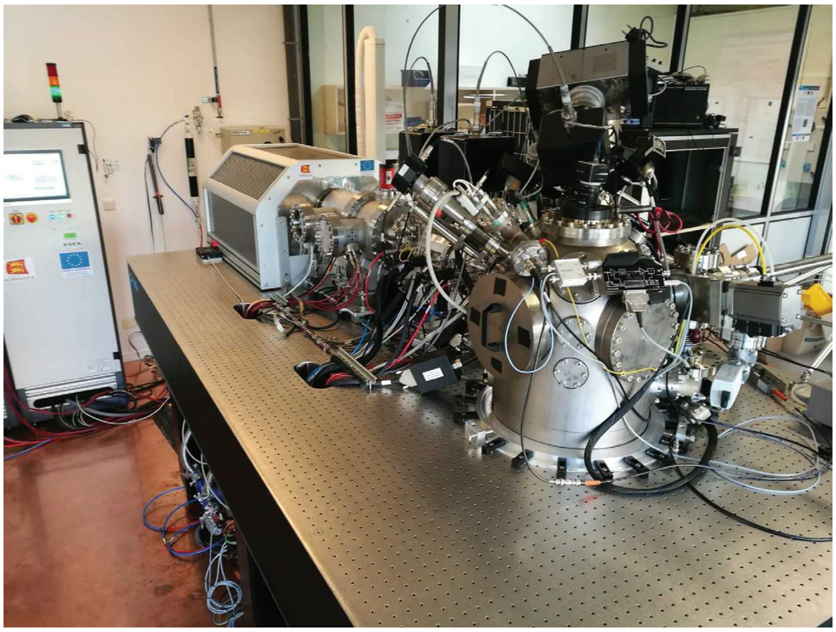

Figure 7 *PELIICAEN - Platform for the Study of Controlled and Analyzed Ion Implantation at Nanometric Scale.*

phase complex molecular system following the interaction with ion beams [10]. The target beam can be made of (a) single isolated molecules obtained from a gas line or a resistively heated oven for samples with low vapor pressure or (b) weakly bonded molecular clusters produced by a gas aggregation cluster source. The cationic products of the interaction are detected in coincidence by a time-of-flight mass spectrometer. The molecular sources available in COLIMACON cover a wide range of molecules, including systems of interest in astrophysics such as the carbonaceous molecules (diamondoids, polycyclic aromatic hydrocarbons, and fullerenes), or the building blocks of biomolecules such as amino acids and nucleobases. With low-energy beams at ARIBE, collision regimes where multiple electron capture is dominant and where the nuclear stopping power is of the same order of magnitude than the electronic stopping power are explored.

PELIICAEN

CIMAP has developed the unique tool Platform for the Study of Controlled and Analyzed Ion Implantation at Nanometric Scale (PELIICAEN, see Figure 7) [11] allowing the use of submicron (<200 nm) mono and multiply charged ion beams and *in-situ* topographic characterization through a scanning electron microscope and an atomic force microscope. Beams (size about 200 nm) with various ions (from He^{+} to Xe^{17+}, Ta, Bi) with energies from 2 to 530 keV can be produced with projectile fluxes up to 10^{17} $cm^{-2}s^{-1}$. These focused ion beams can be used both to modify the physical, structural, and chemical properties of matter, from the extreme surface to a few hundred nanometers deep, but also as a local probe for chemical and structural analyses. By the simultaneous use of these means, it is possible to control and analyze finely the evolution of materials and their properties. This project is the fruit of cooperation between CIMAP and the French company Orsay Physics, one of the world leaders for the development and commercialization of FIB/FEB units and secondary emission imagery. Beam time can be obtained via the EU RADIATE network [5].

Conclusions

The CIRIL platform promotes ion beam science and develops cutting edge on-line equipment, fostered by the excellent cooperation between CIMAP and GANIL. Financial support as part of a RIN (funding by the region Normandy)

"GANIL Innovation Future Project" (2020–2022) allows the renovation of the environment of the ion source at ARIBE installation (safety, radiological protection). Future developments of equipment and joint research programs are discussed at national and international levels (EMIR&A federation, EU RADIATE). A promising project is to acquire an ion accelerator in the intermediate energy range (completing ARIBE and IRRSUD) coupled to the medium energy beam-line of GANIL with the possibility of dual beam irradiation allowing a combination of energy deposition by electronic and nuclear stopping (S_e and S_n, respectively). The uniqueness of this new facility lies in the use of the SME beam-line delivering beams inducing high S_e, around the Bragg peak and above the threshold for latent track formation. Moreover, coupling irradiations with high-energy light ions (C-Ne, from SME) with low-energy light ions (H or He) will allow combining multiple linear energy transfer radial dose distributions. This is crucial for a better understanding of the mechanisms of defect formation in compounds prone to radiolysis, such as polymers. The dual beam will also be a powerful tool to mimic space conditions (complex radiation field including a distribution of ion species in a broad energy range) for astrophysical laboratory simulations. For more information, see the CIRIL website: http://cimap.ensicaen.fr/spip.php?rubrique137

Acknowledgments

It is a pleasure to thank all our colleagues from CIMAP and GANIL, without whom the user's facility CIRIL could not have been such a success. Special thanks to Thierry Been, Franck Dardy, Yann Doublet, Florent Durantel, Claire Feierstein Plancq, Cédric Gendreau, Stéphane Guillous, Toiammou Madi, Jean-Marc Ramillon, Fréderic Ropars, Anthony Sineau, and Patrick Voivenel. We dedicate this article to the memory of our colleagues Daniel Lelièvre and Francis Levesque.

References

1. J. P. Grandin, *Nucl. Phys. News*. 10 (2000) 14.
2. A. Barbu et al., *C. R. Acad. Sci*. 299 (1984) 409.
3. A. Domaracka et al. (Eds.), *J. Phys. Conf. Ser*. 629 (2015).
4. S. Bouffard, Nucl. Phys. News 26 (2016) 14.
5. J. Fassbender and W. Moeller, *Nucl. Phys. News*. 29 (4) (2019) 29.
6. W. Assmann, C. Trautmann, and M. Toulemonde, *Nucl. Phys. News* 15 (2005) 1.
7. F. Durantel et al., *Nucl. Instrum. Meth*. A816 (2016) 70.
8. B. Augé et al., *Rev. Sci. Instrum*. 89 (2018) 075105.
9. C. Grygiel et al., *Rev. Sci. Instrum*. 83 (2012) 013902.
10. T. Bergen et al., *Rev. Sci. Instrum*. 70 (1999) 3244.
11. S. Guillous et al., *Rev. Sci. Instrum*. 87 (2016) 113901.

Jimmy Rangama

Clara Grygiel

Alain Méry

Patrick Rousseau

Hermann Rothard

Centre de Recherche sur les Ions, les Matériaux et la Photonique, Normandie Univ, ENSICAEN, UNICAEN, CEA, CNRS, CIMAP, 14000 Caen, France