INSTITUT JEAN LAMOUR

UNIVERSITÉ DE LORRAINE

HIGHLIGHTS 2020

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2020 was a special year in many ways. The advent of the Covid-19 pandemic messed up our every-day lives, impacting by the way our scientific projects and our relationships with the rest of the world. This period of hardship taxed our resilience but IJL's staff members demonstrated a remarkable capability to adapt to this one-of-a-kind situation. The beginning of the second decade of IJL's existence will be forever marked by this incredible context.

The lock-down period was favourable to researchers released from teaching to gather unpublished materials and submit new contributions. Meanwhile, teachers were rather struggling with video-conferencing facilities, trying to write equations on virtual blackboards for invisible students. In the first entry of these highlights, we have selected a bunch of high-quality publications illustrating some outstanding works chosen among the various fields dealing with materials science as viewed from IJL. Fitting the broad scope of the laboratory's expertise, the made selection spans over different research domains from quantum materials to corrosion.

DAMAS is a laboratory of excellence created to bring together metallurgists interested in the design of alloy metals for low-mass structures. The outcome of 8 years of intensive works on this topic was deemed exceptional and it led to the extension of this laboratory for another 5 years, the total investment amounting to 10.5 M€.

The CERTAIN project was selected to outline a brand-new activity created at IJL in 2020 on metamaterials and phononics. With the support of NATO, new studies devoted to electromagnetic protection with metasurfaces are presented in a nutshell.

2020 was also unusual as IJL was honoured by the CNRS twice the same year with one silver medal and one bronze medal. Vanessa Fierro and Carlos Rojas Sánchez were awarded for their first-rate contributions to porous carbon materials and spintronics.

And even though the whole year was not propitious to human encounters, we could introduce magnetism from its basic concept to "science in the making" before a large audience in a temple dedicated to this purpose: "Le Palais de la découverte" in Paris. Built around a narrative story told by moving from one stand to another, the exhibition "Magnetic" escorts the visitor from the compass to the IJL's Tube, a 70-m long equipment gathering around 30 devices under ultra-high vacuum, made accessible thanks to a virtual animation.

All in all, and despite the difficult times we had to go through, we could find in 2020 good reasons for staying hopeful and optimistic. I wish here to thank all the Institute's people for their support and understanding during this very difficult year. I would also like to acknowledge the constant trust of our institutional partners and in particular of both the CNRS and the Université de Lorraine. Their constant help was precious for all of us.

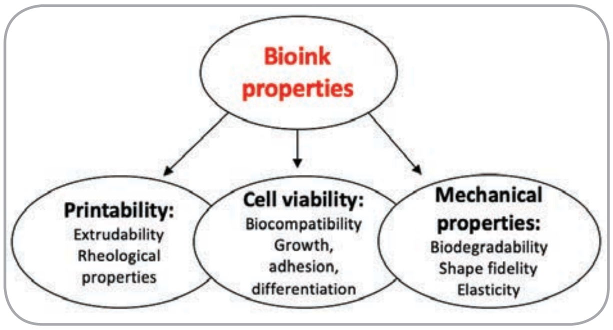
We all have to stay confident: with so many talented people, IJL is destined for a bright future.

Thierry Belmonte
Head of Institut Jean Lamour

NOVEL CHITOSAN / GUAR GUM BIOINK FOR HEALTHCARE APPLICATIONS

3D bioprinting is an attractive technology which aims to recreate tissues and organs in the laboratory. It is based on the use of cells, biomaterials and bioactive molecules, which together constitute the so-called "bioink".

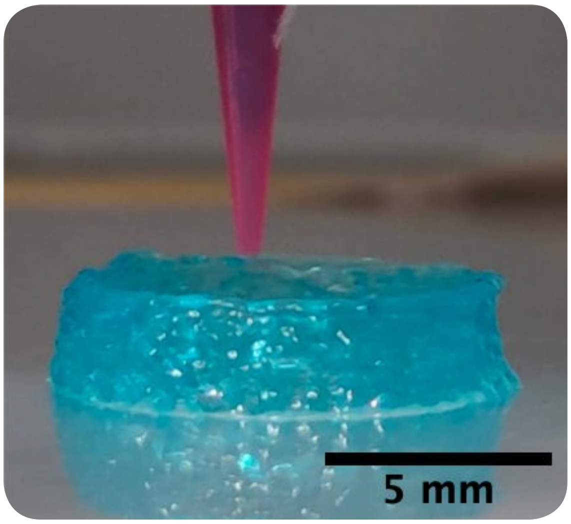
One of the main limitations of 3D bioprinting is the lack of optimal materials which, in form of hydrogels, meet the requirements to be used as bioinks. Natural polysaccharides, such as chitosan, have already been extremely used in tissue engineering applications, thanks to their morphological similarity to the natural extracellular matrix. However, because of the lack of strong mechanical properties and slow rate of gelation, chitosan alone is not suitable for a proper and easy printing.



Summary of the properties studied for the development of bioinks

In this work, for the first time, guar gum was mixed with chitosan for the development of a new bioink for 3D bioprinting applications.

In particular, chitosan has been combined with different concentrations of guar gum and the potential of the different mixtures to be used as bioinks for extrusion-based 3D bioprinting has been evaluated. Printability and rheological tests were conducted to investigate the influence of the gum on the chitosan solution. These tests revealed that the addition of guar gum improved the printability of chitosan solutions, thanks to its ability to form viscous gels in water. Furthermore, guar gum was responsible for an increase of the mechanical properties and consequently, of the shape fidelity of the printed structures.



Example of 3D bioprinted structure fabricated using the extrusion-based bioprinting and a polysaccharide based bioink

In conclusion, guar gum has proved to be a great candidate as a new component of chitosan based bioinks.

Biological studies are in progress to assess the potential of this bioink to be used for healthcare applications.

Reference:

Development of novel chitosan / guar gum inks for extrusion-based 3D bioprinting: process, printability and properties
F. Cleymand, A. Poerio, A. Mamanov, K. Elkhoury, L. Ikhlef, J.P. Jehl, C.J.F. Kahn, M. Ponçot, E. Arab-Tehrany, João F. Mano
Bioprinting 21 (2021) e00122
https://doi.org/10.1016/j.bprint.2020.e00122

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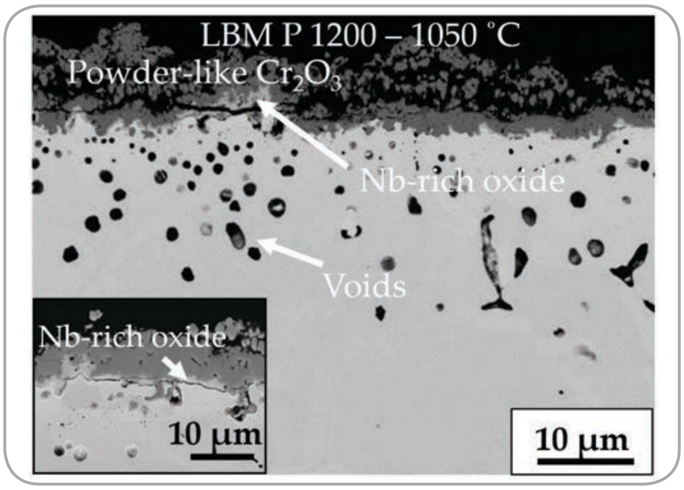
LASER BEAM MELTED (LBM) INCONEL 625 PRESENTS ACCELERATED OXIDATION RATE AT HIGH TEMPERATURE (1050°C)

Manufacturing of components with complex geometries requires time-consuming machining operations or welding treatments. These operations can today be avoided by using three-dimensional additive manufacturing that enables complex designs and material cost saving. Various techniques are now available and used in industry to manufacture large technological pieces: electron beam melting, laser beam melting, direct metal deposition, and powder bed binder jet-printing. More than any other technique, 3D manufacturing produces specific microstructures and high surface roughness. The influence of these on the high-temperature resistance should be determined.

The work led in collaboration with Centre Interuniversitaire de Recherche et d'Ingénierie des Matériaux (CIRIMAT) in France in the framework of the FAIR BPI founded project (Additive Fabrication for the Intensification of Reactors), mentions the impact of microstructure on the high temperature oxidation resistance of 3D manufactured Ni-based alloys.

In their work, the researchers perform isothermal experiments in air on as-manufactured Inconel 625 and grounded materials coupled with high resolution characterization to evidence the influence of micro segregation induced by fast cooling on the oxidation behavior.

The employed laser-beam melting technique induces a high surface roughness of the skin area of the samples that severely affect their reactivity. Nevertheless the degradation rate of these 3D materials, once they have been ground, is similar to wrought products at 900°C. At 1050°C, the impact of the microstructure, characterized by sub-micrometric cells delimitated by Nb- and Mo- rich walls, induced an unexpected modification of the oxide scale that develops. As a consequence the oxidation resistance dramatically drops at 1050°C.



Post-oxidation cross-sections for the laser beam melted Inconel 625 after 50 h at 1050°C showing the unprotective oxide scale and the voids formed at high temperature

The researchers also note that the high oxidation rate of the laser melted samples induces a strong modification of its subsurface with a high density of voids present after exposure. This study proves that these 3D materials should not be used at temperature as high as 1050°C.

Reference:

A comparison of the high-temperature oxidation behaviour of conventional wrought and laser beam melted Inconel 625
Nicolas Ramenatte, Annabelle Vernouillet, Stéphane Mathieu, Aurélie Vande Put, Michel Vilasi, Daniel Monceau
Corrosion Science volume 168, 108347(2020)
https://hal.archives-ouvertes.fr/hal-02972156

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Mechanical properties

THE MECHANISMS BEHIND UNSTABLE DEFORMATION IN METALS

Although metals have been used and worked by humans for millennia, they still hold many secrets! The ways in which metals can be deformed or, on the contrary, resist deformation depend on the details of the chemical composition and the structure of the metal at the atomic scale. In particular, it is well known that the permanent deformation of most metals occurs when a certain type of line defect called 'dislocations' moves like squiggly strings leading to changes in shape in the material. However, metals are still largely designed by the old method of 'heat and beat', which is inefficient, costly, and even leads to excessive carbon footprints! Thus, it is important to understand the details of how dislocations interact with other defects to design advanced metallic alloys with superior mechanical properties.

Here, a team of researchers from University of California Los Angeles - UCLA (USA) and IJL has investigated the interactions between dislocations and oxygen atoms in tungsten, the top candidate to serve as plasma-facing material in future nuclear fusion reactors. The researchers used atomistic methods in conjunction with dislocation line models to study how dislocations interact with oxygen atoms in tiny concentrations resulting from contamination from air exposure.

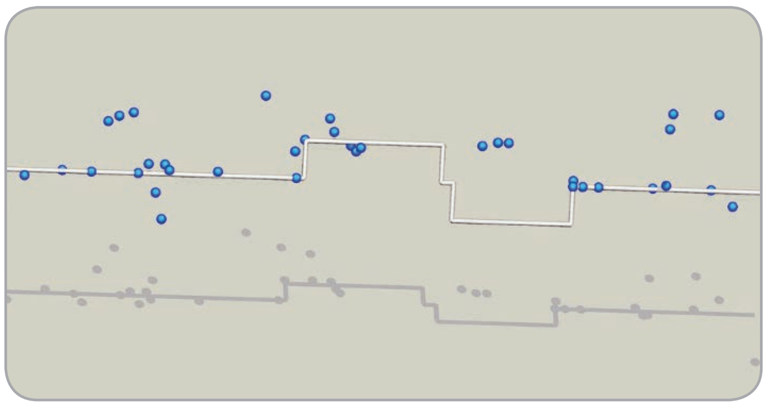

Illustration from the computer simulation of the dislocation line interacting with oxygen atoms in tungsten

Despite such low oxygen content, the researchers found that oxygen atoms control how dislocation behave in certain conditions, leading to a phenomenon known as 'serrated' deformation, in which the response of the material to stress becomes unstable and is characterized by oscillations in the stress-strain curves.

These simulations are extremely challenging because atomic-level resolution is needed to capture oxygen atom motion, yet one has to be able to see their effect on the macroscopic material response. UCLA and IJL researchers were able for the first time to combine such disparity in behavior in a unified model. This could help set the stage to model similar behavior in other systems, particularly those containing carbon or hydrogen, thus helping researchers and engineers understand and target mechanical properties of various alloyed metals.

Reference:

Simulating the mechanisms of serrated flow in interstitial alloys with atomic resolution over diffusive timescales
Yue Zhao, Lucile Dezerald, Marta Pozuelo, Xinran Zhou and Jaime Marian
Nature Communications volume 11, page 1227 (2020)
https://doi.org/10.1038/s41467-020-15085-3

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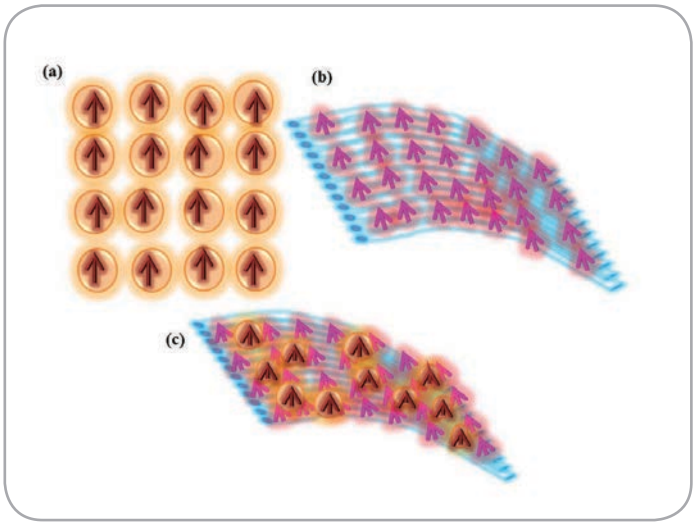
POLYMER-CERAMIC FERROELECTRICS FOR FLEXIBLE ELECTRONICS

Ferroelectric polymer-ceramic nanocomposite systems are considered as emerging materials in the fields of nanoelectronic, microelectromechanical and macroelectronic device applications. It possesses applications in diverse fields such as energy storage, harvesting, energy conversion, etc. Among them, ferroelectric polymer-ceramic system for high energy density storage system has gained huge attention among researchers. Polymer-ceramic system combines the property of both ferroelectric polymer and ceramic fillers.

PVDF polymer has light weight, larger chain flexibility, good mechanical properties, chemical and electrical resistance, availability and good processability. On the other hand the inclusion of high dielectric constant ceramic fillers in the ferroelectric polymer matrix enhances the dielectric and ferroelectric behavior. Hence polymer-ceramic composite system combines higher dielectric constant (ε) and stiffness of ceramics along with better flexibility, elasticity and high dielectric breakdown of ferroelectric polymer.

This is a collaborative work, which is jointly carried out between Mahatma Gandhi University, Kottayam, Kerala, India and Institut Jean Lamour. In this work three different ferroelectric fillers ($BaTiO_3$, $BaTiZrO_3$ and $BaZrO_3$) were introduced in the ferroelectric polymer matrix in order to evaluate the enhancement in the dielectric and ferroelectric performance of the polymer nanocomposites. In order to attain better compatibility between the filler and the polymer matrix, ferroelectric ceramics were functionalized with dopamine hydrochloride. Nanocomposites with dopamine functionalized ferroelectric ceramics were prepared by means of electrospinning method.



Schematic of electric dipole orientation in (a) ferroelectric ceramics, (b) ferroelectric polymer, (c) ferroelectric polymer-ceramic nanocomposites

From this work it is evident that after the addition of ferroelectric filler in the polymer there is a substantial improvement in the ferroelectric and dielectric performance of the composite nanofibers. Among the three fillers dopamine functionalized $BaTiO_3$-PVDF nanofibers possess comparatively excellent response with the others. Also it is evident that the prepared nanocomposites possess excellent mechanical strength. Hence this ferroelectric ceramic-polymer nanocomposite system can be used for the development of flexible ferroelectric energy storage devices.

Reference:

Flexible dopamine-functionalized $BaTiO_3$/$BaTiZrO_3$/$BaZrO_3$-PVDF ferroelectric nanofibers for electrical energy storage
A. Mayeen, MS. Kala, S. Sunija, D. Rouxel, RN. Bhowmik, S. Thomas, N. Kalarikkal
Journal of Alloys and Compounds (2020) 15549
https://doi.org/10.1016/j.jallcom.2020.155492

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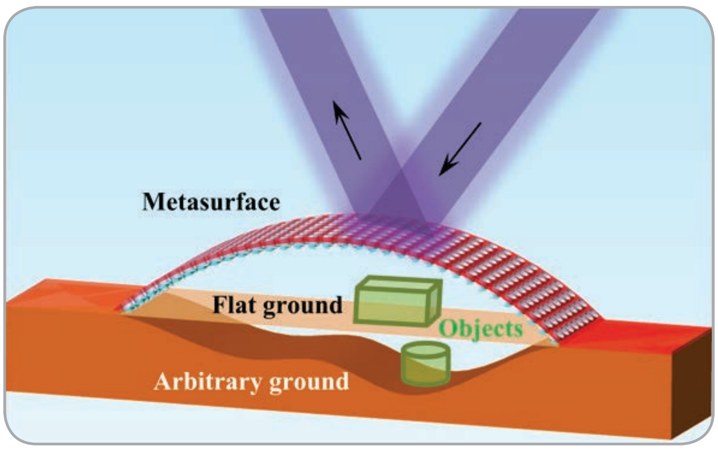
RECONFIGURABLE CURVED METASURFACE FOR ACOUSTIC CLOAKING AND ILLUSION

Acoustic metasurfaces derive their characteristics from the interaction between acoustic waves and specifically designed materials. The field is driven by the desire to control acoustic wave propagation using compact devices and is governed by fundamental and physical principles that provide the design rules and the functionality of a wave. A severe limitation of current acoustic metasurfaces remains in their modest tunability to meet multi-frequency requirements and alterable functionalities on demand.

In this work conducted in collaboration with Beijing Jiaotong University in China, we tackle one of the novel applications enabled only by acoustic metamaterials and metasurfaces, i.e. acoustic cloaking and illusion. Based on a cleaver design of a curved metasurface composed of tunable helical systems, we structure and manipulate the reflected wavefront emanating from the designed metasurface, so that phase shifts cover a full 2π span. We then successfully hide objects from acoustic waves by restoring the disturbed reflected field or mimicking an arbitrary shaped ground with continuous tunability. The proposed metasurface is also able to operate for a wide-angle detection with oblique incidences.



3D schematic view and working principle of an arc metasurface carpet cloak based on a tunable matched helical units

In this proposed research, we put forward the concept of reconfigurable broadband acoustic cloaking and illusion. Theoretical, numerical and experimental evidences have been provided to demonstrate the properties and functionalities of the conceived curved metasurface over the frequency range from 2 to 7 kHz.

By utilizing the proposed design strategy based on tunable helical systems, it should be fairly straightforward to conceal or imitate objects with different sizes and shapes, and to construct a metasurface for 3D cloaking of sound. Adopting higher spatial resolution of phase discretization may further enhance the performances of the cloak or illusion around the region with abruptly changing object or ground profiles. All these remarkable advantages bring the acoustic metasurfaces a step closer toward the realization of practical cloaks.

Reference:

Reconfigurable curved metasurface for acoustic cloaking and illusion
Shi-Wang Fan, Sheng-Dong Zhao, Liyun Cao, Yifan Zhu, A-Li Chen,Yan-Feng Wang, Krupali Donda, Yue-Sheng Wang and Badreddine Assouar
Physical Review B 101, 024104 (2020)
https://hal.archives-ouvertes.fr/hal-03043135

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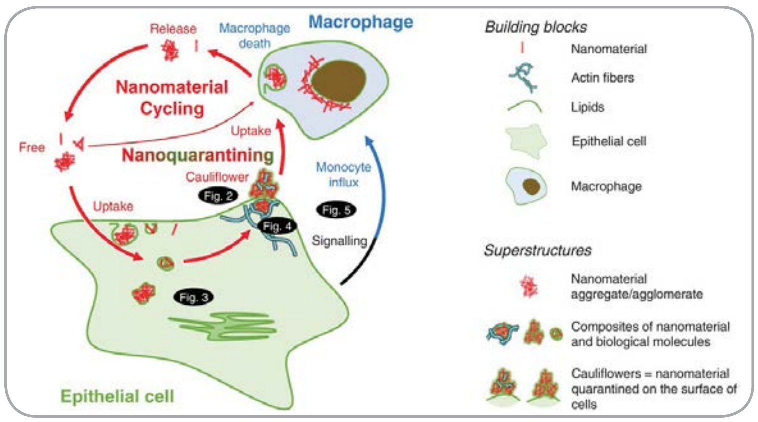
Nanotoxicity prediction

PREDICTION OF CHRONIC INFLAMMATION FOR INHALED PARTICLES: THE IMPACT OF MATERIAL CYCLING AND QUARANTINING IN THE LUNG EPITHELIUM

On a daily basis, people are exposed to a multitude of health–hazardous airborne particulate matter with notable deposition in the fragile alveolar region of the lungs. Hence, there is a great need for identification and prediction of material–associated diseases, currently hindered due to the lack of in–depth understanding of causal relationships, between acute exposures and chronic symptoms.

By applying advanced microscopies and omics to *in vitro* and *in vivo* systems, together with *in silicio* molecular modeling, a European consortium including IJL's Nanomaterials and Health group discovered new molecular key events and their causal relationships for respiratory toxicity of inhaled materials:

- The process of nanomaterial quarantining (nanoquarantining) driven by enhanced lipid metabolism and resulting in immobile composites of nanomaterial and biological molecules on the cell surface that are termed cauliflowers
- Nanomaterial cycling between different lung cell types, fueled by a pro-inflammatory lipid-metabolism-associated influx of new leukocytes



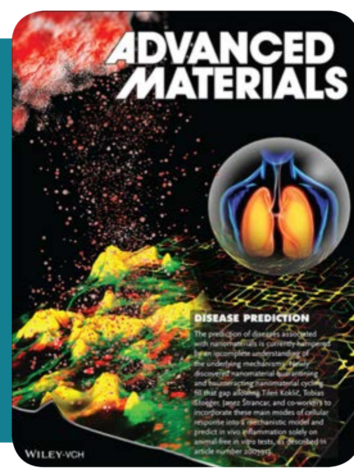
Scheme of the discovered cycle of nanomaterial on the lung alveolar surface model with associated key molecular events that drive chronic inflammation following the exposure to nanomaterials together with a legend of graphical elements (pictograms)

This new insight finally allows prediction of the spectrum of lung inflammation associated with materials of interest using only *in vitro* measurements and *in silicio* modeling, potentially relating outcomes to material properties for a large number of materials, and thus boosting safe-by-design-based material development.

Because of its profound implications for animal-free predictive toxicology, this work paves the way for a more efficient and hazard-free introduction of numerous new advanced materials into our lives.

Reference:

Disease prediction: prediction of chronic inflammation for inhaled particles: the impact of material cycling and quarantining in the lung epithelium
Hana Kokot, Boštjan Kokot, Aleksandar Sebastijanović, Carola Voss, Rok Podlipec, Patrycja Zawilska, Trine Berthing, Carolina Ballester–López, Pernille Høgh Danielsen, Claudia Contini Mikhail Ivanov, Ana Krišelj, Petra Čotar, Qiaoxia Zhou, Jessica Ponti, Vadim Zhernovkov, Matthew Schneemilch, Zahra Doumandji, Mojca Pušnik, Polona Umek, Stane Pajk, Olivier Joubert, Otmar Schmid, Iztok Urbančič, Martin Irmler, Johannes Beckers, Vladimir Lobaskin, Sabina Halappanavar, Nick Quirke, Alexander P. Lyubartsev, Ulla Vogel, Tilen Koklič, Tobias Stoeger, Janez Štrancar
Advanced Materials 47/20202020
https://doi.org/10.1002/adma.202003913



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MELTING MOFs PRODUCE DERIVATIVES USEFUL FOR NONLINEAR NANOPHOTONICS

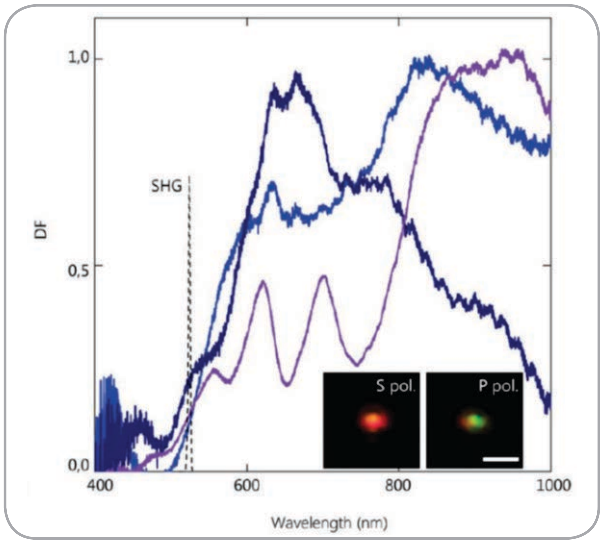
Femtosecond IR laser pulses are used for ultrafast melting of 3D interpenetrated MOFs with flexible alkali-chained ligands. Unique nanometer-scale derivatives thus produced exhibit complex morphology and enhanced nonlinear optical response.

This work is an international contribution gathering laboratories from 8 institutions in Russia (Ioffe Institute, Faculty of Physics and Engineering and TheoMAT Group ChemBio Cluster, ITMO University, Saint Petersburg ; Faculty of Natural Sciences, State University and Institute of Inorganic Chemistry SB RAS, Novosibirsk), the United Kingdom (School of Chemistry, University of Manchester), the Netherlands (Inorganic Systems Engineering Group Department of Chemical Engineering, Delft University of Technology) and France (Institut Jean Lamour).

The researchers used three different metal-organic frameworks (MOFs), a class of molecular crystals stand out by their unconventional hierarchical structure based on weak and strong interactions between various building blocks such as organic ligands, metal nodes, and solvent molecules.

MOFs were melted by femtosecond infrared laser pulses and characterized next one by one both structurally and optically. The interaction of light with single derivatives was performed after structural analysis by linear and nonlinear optical micro-spectroscopy. Two morphologically different types of particles were produced: amorphized drops with metal–organic composition and spherical particles with a core–shell structure. The analysis of the optical response of these objects reveals an enhanced second harmonic generation and three-photon luminescence (see image) due to resonant interaction of the 100–1000 nm spherical derivatives with light.

Possible applications on catalysis and energy storage are still to be investigated.



Second Harmonic Generation (SHG) and three-photon luminescence (3PL) spectra from the derivatives formed by femtosecond laser melting of [Cd(dmf)(sdc)(L6)]· dimethylformamide (L6 is a imidazolyl-based ligand). Insets: Optical images of SHG-3PL signal from single derivative. Scale bar: 2 µm

Reference:

Ultrafast melting of metal–organic frameworks for advanced nanophotonics
Nikita K. Kulachenkov, Stéphanie Bruyère, Sergey A. Sapchenko, Yuri A. Mezenov, Dapeng Sun, Andrei A. Krasilin, Alexandre Nominé, Jaafar Ghanbaja, Thierry Belmonte, Vladimir P. Fedin, Evgeny A. Pidko, Valentin A. Milichko.
Advanced Functional Materials, volume 30, reference 1908292 (2020)
https://hal.archives-ouvertes.fr/hal-02988373/

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HOW TO PUSH 4f INSTABILITY QUANTUM CRITICAL EFFECTS TO ROOM TEMPERATURE

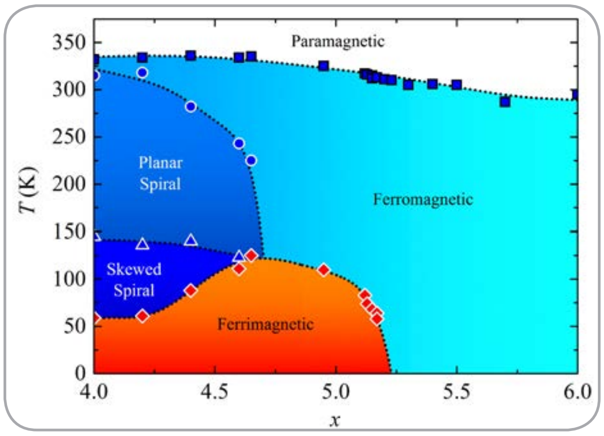
Quantum criticality is investigated within various families of materials notably high-temperature superconductors, quantum magnets or heavy-fermion systems. Most of the heavy-fermion intermetallic systems studied so far combine an unstable 4f shell element, such as Ce or Yb, with non-magnetic elements. Quantum criticality then manifests itself most often at low temperature in the vicinity of the 4f magnetic instability. In the $YbMn_6Ge_{6-x}Sn_x$ series, where the Mn sublattice is strongly magnetic (Fig.1), the persistence of quantum criticality at high temperature is due to the higher energy scale of the Mn-Yb interaction.

Through X-ray absorption and X-ray magnetic circular dichroism measurements, researchers from IJL, Paul Scherrer Institute (Villigen, Switzerland) and ODE beamline (SOLEIL Synchrotron) have identified in a heavy-fermion system changes in the charge state and magnetic moment of ytterbium associated with quantum criticality that persist up to room temperature.

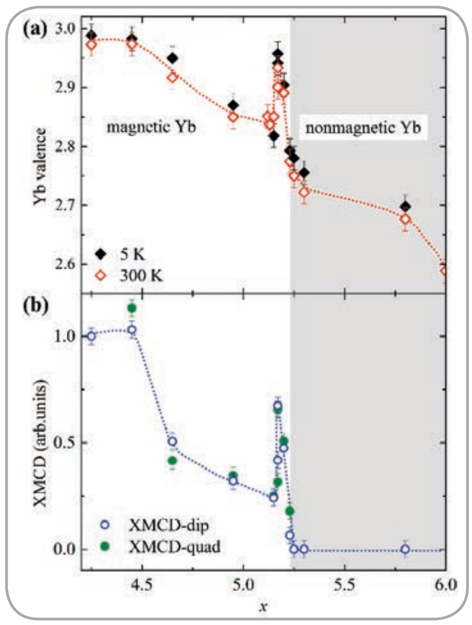
Quantum criticality is usually revealed through thermodynamic or transport measurements. Electron spectroscopy techniques [X-ray Absorption Spectroscopy (XAS) and X-ray magnetic circular dichroism (XMCD) at the Yb L3 edge] were used here. These measurements revealed a peak in the composition dependence of the ytterbium valence (extracted from the XAS measurements) and its magnetic moment (linked to the XMCD signal) near the magnetic instability (Fig. 2). These observations are consistent with recent theoretical predictions in unconventional quantum criticality.

These results suggest that rare-earth intermetallics with a magnetized 3d sublattice form a distinct group of heavy-fermion metals where the high energy of the exchange interactions can bring quantum criticality up to high temperature.

The project was partly co-financed by Campus France and the Schweizerische Akademie der Technischen Wissenschaften SATW as part of the Germaine de Staël programme.



The (x,T) magnetic phase diagram of $YbMn_6Ge_{6-x}Sn_x$ (x ≤ 4.0)



(a)Composition dependence of the Yb valence at 300 K (red diamonds) and 5 K (black diamonds) extracted from the XANES spectra. (b) Composition dependence of the dipolar (blue circles) and quadrupolar (green circles) XMCD signals at 5 K extracted from the XMCD spectra

Reference:

Possible room-temperature signatures of unconventional 4f-electron quantum criticality in $YbMn_6Ge_{6-x}Sn_x$
L. Eichenberger, A. Magnette, D. Malterre, R. Sibille, F. Baudelet, L. Nataf, and T. Mazet
Physical Review B - Rapid Communications 101 (2020) 020408(R)
https://doi.org/10.1103/PhysRevB.101.020408

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Solidification

ISOMORPHIC GRAIN INOCULATION IN Ti-6Al-4V DURING ADDITIVE MANUFACTURING

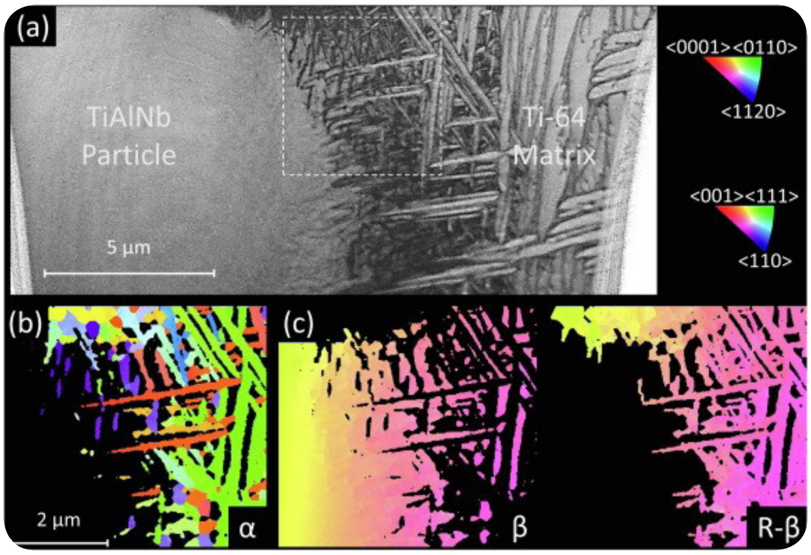
The concept of "isomorphic inoculation" developed at IJL consists in adding soft but unstable particles to the melt, in order to promote heterogeneous nucleation and produce grain refined microstructures with improved mechanical properties. Initially designed for titanium aluminides, which are used for the low-pressure turbine blades of the last generation of aero-engines, it is shown to be also efficient for titanium alloys produced by additive manufacturing.

In their work, the researchers have developed a process to incorporate the inoculant particle into the melt pool by adhering them to the surface of each layer, premixed with polymer lacquer.

This work, in collaboration with Laboratoire d'Etude des Microstructures et de Mécanique des Matériaux (LEM3) in Metz, France, Cranfield University and the University of Manchester, United Kingdom showed that nucleation is suppressed and replaced by epitaxial growth, leading to a grain refined microstructure.

The designed Ti-Al-Nb inoculant alloy and associated concept of isomorphic self-inoculation are shown to be viable for most titanium alloys, and applicable to additive manufacturing processes.

A technical challenge remaining is how best to add the inoculating particles and control their survival during the brief high temperature exposure in the melt pool, to ensure a consistent level of grain refinement within the deposited metal.



Transmission Kikuchi Diffraction (TKD) analysis of a particle/matrix interface. (a) band contrast image, (b) TKD IPF ND orientation maps of the indexed α phase, and (c) a composite image showing the directly indexed β associated with the particle (left) and the reconstructed parent β orientation in the matrix (right)

Reference:

Isomorphic grain inoculation in Ti-6Al-4V during additive manufacturing
J.R. Kennedy, A.E. Davis, A. Caballero, A. Garner, J. Donoghue, S. Williams, J. Zollinger, E. Bouzy, E.J. Pickering, P.B. Prangnell
Materials Letters, volume 8, 100057 (2020)
https://doi.org/10.1016/j.mlblux.2020.100057

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Spin optoelectronics

SPIN INJECTION AND RELAXATION IN p-DOPED (In, Ga)As/GaAs QUANTUM-DOT SPIN LIGHT-EMITTING DIODES AT ZERO MAGNETIC FIELD

Spin light emitting diode can transfer binary information encoded within the spin of carriers into corresponding right- or left-handed circularly polarized photons emitted from an active semiconductor medium via carrier-photon angular momentum conversion. In order to attain maximized spin injection at out-of-plane magnetic remanence, a number of material systems have been explored as possible solid-state spin injectors. However, the circular polarization (P_c) of emitted light was often limited at remanence.

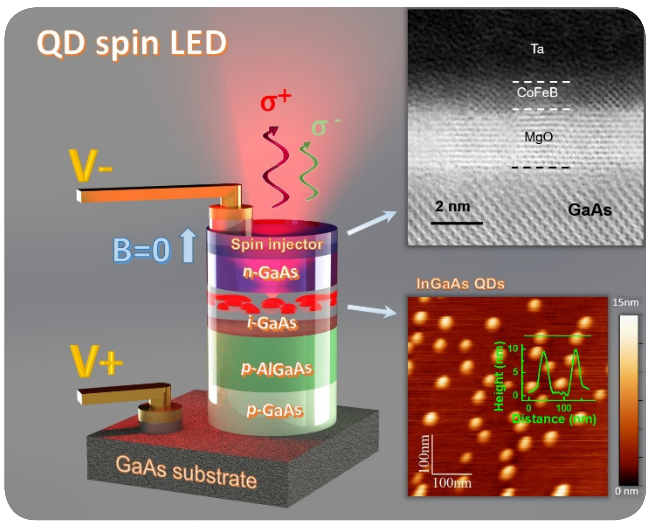
The work is a collaboration with Institute of Semiconductor (China), Laboratoire de Physique et Chimie des Nano-Objets – LPCNO (CNRS/Insa Toulouse/UT3-Paul Sabatier), Unité Mixte de Physique CNRS/Thales (France) and National Institute of Advanced Industrial Science and Technology (Japan).

We report on efficient spin injection in p-doped (In, Ga)As/GaAs quantum-dot (QD) spin LEDs under zero applied magnetic field. A high degree of electroluminescence circular polarization (Pc)~19% is measured in remanence up to 100 K.

This result is obtained thanks to the combination of a perpendicularly magnetized Co-Fe-B/MgO spin injector allowing efficient spin injection and an appropriate p-doped (In, Ga)As/GaAs QD layer in the active region. By analyzing the bias and temperature dependence of the electroluminescence circular polarization, we evidence a two-step spin-relaxation process.

The first step occurs when electrons tunnel through the MgO barrier and travel across the GaAs depletion layer. The spin relaxation is dominated by the Dyakonov-Perel mechanism related to the kinetic energy of electrons, which is characterized by a bias-dependent Pc.

The second step occurs when electrons are captured into QDs prior to their radiative recombination with holes. The temperature dependence of Pc reflects the temperature-induced modification of the QD doping, together with the variation of the ratio between the charge-carrier lifetime and the spin-relaxation time inside the QDs.



Schematics of the stack structure of the QD based spin-LED which can emit circularly polarized light at zero applied magnetic field. Upper inset: HR-TEM image of the spin injector layer which contains 5nm Ta/1.1nm CoFeB/2.5nm MgO. Lower inset: AFM image of the InGaAs QD layer before capping with GaAs layer. The InGaAs QDs have a density of 1.6×10^{10} cm^{-2}. The inset of the AFM image shows the average lateral dot diameter of about 30 nm and the height of about 9 nm

The understanding of these spin-relaxation mechanisms is essential to improve the performance of spin LEDs for future spin optoelectronic applications at room temperature under zero applied magnetic field.

Reference:

Spin Injection and Relaxation in p-Doped (In, Ga)As/GaAs Quantum-Dot Spin Light-Emitting Diode at Zero Magnetic Field
Alaa E. Giba, Xue Gao, Mathieu Stoffel, Xavier Devaux, Bo Xu, Xavier Marie, Pierre Renucci, Henri Jaffrès, Jean-Marie George, Guangwei Cong, Zhanguo Wang, Hervé Rinnert and Yuan Lu
Physical Review Applied 14, 034017 (2020)
https://hal.archives-ouvertes.fr/hal-02999545/document

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Spintronics

SHORT ELECTRICAL PULSES MAY INCREASE THE WRITE-SPEED OF MAGNETIC MEMORIES

The combination of electronics with magnetism known as spintronics has led to a number of extraordinary discoveries such as the Nobel-prized giant magneto-resistance effect. Spintronic phenomena have thereafter resulted in groundbreaking technology too, such as ultra-sensitive magnetic sensors and high-density memories. Now, magnetic memory shows great potential to tackle the energy bill in the processor-level memory of our computers. However, such types of magnetic memories still suffer from speed limitations.

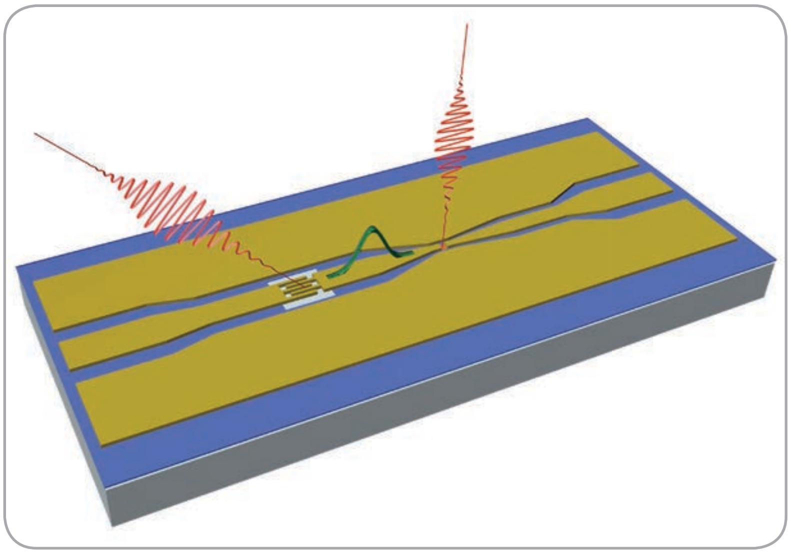
The work led by in collaboration with the University of California Riverside, the University of California Berkeley (United States) and Centre de Nanosciences et de Nanotechnologies – C2N (CNRS / Université Paris-Saclay), France, pushes the speed of magnetic control to the single-digit picosecond level (a trillionth of a second), almost two orders of magnitude faster than previous attempts.

In their work, the researchers used laser-triggered 6 picosecond-wide electrical current pulses to switch the magnetization of a thin cobalt film by exploiting a mechanism known as spin-orbit torque.

The after-pulse magnetization direction is then set by the polarity of the current flow and a fixed external magnetic field. Interestingly, the researchers note that at such short time scales, heat dissipation can actually be beneficial as it may assist the reversal.

Moreover, the first energy usage estimates are incredibly promising.

The experimental methods used by the researchers also offer a new way of triggering and probing various spintronic phenomena at ultrafast timescales, which could help better understand the underlying physics at play.



Schematic of the "picosecond spintronics platform". A femtosecond laser pulse (red) generates a picosecond current pulse (green) on the left-side of the circuit, and a second laser pulse detects the dynamics induced by the current pulse on the small magnetic region (orange)

Reference:

Spin–orbit torque switching of a ferromagnet with picosecond electrical pulses
Kaushalya Jhuria, Julius Hohlfeld, Akshay Pattabi, Elodie Martin, Aldo Ygnacio Arriola Córdova, Xinping Shi, Roberto Lo Conte, Sébastien Petit-Watelot, Juan Carlos Rojas-Sánchez, Grégory Malinowski, Stéphane Mangin, Aristide Lemaître, Michel Hehn, Jeffrey Bokor, Richard B. Wilson and Jon Gorchon
Nature Electronics volume 3, pages 680–686 (2020)
https://doi.org/10.1038/s41928-020-00488-3

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Thermoelectrics

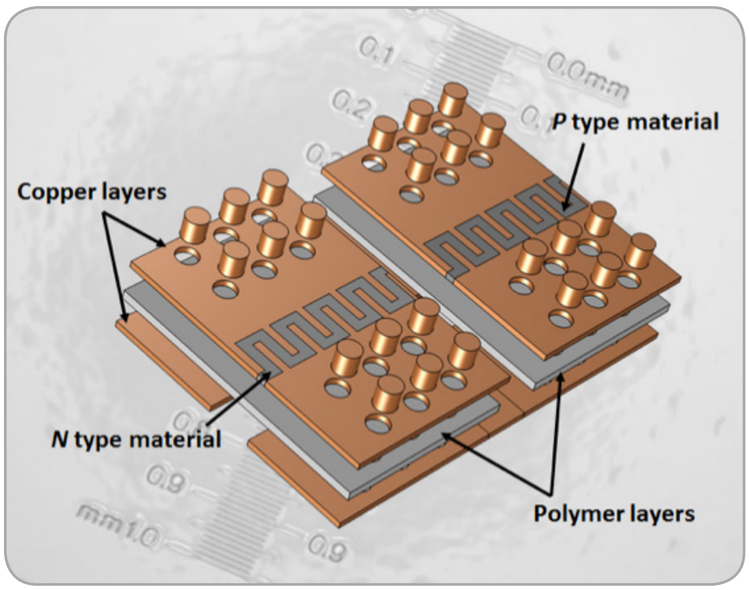
A NOVEL DESIGN OF FLEXIBLE THERMOELECTRIC GENERATOR LEADS TO A SIGNIFICANT INCREASE IN THE ELECTRICAL POWER PRODUCED FOR LOW TEMPERATURE DIFFERENCE

Thermoelectric micro generators offer an elegant way for producing electrical power from waste heat. Around room temperature, they may provide an interesting solution for powering wireless sensors. However, the low electrical power produced by current generators still limits their widespread use in real applications.

The work carried out in collaboration with Mahle Thermoelektronik in Germany led to the successful fabrication of a novel generation of micro-thermoelectric generators (µ-TEG) ranked among the best micro-generators currently available.

In their work, the researchers used a combination of finite-element analysis to design and optimize a novel µ-TEG architecture with thermoelectric materials deposited in wavy-shaped paths. The fabrication of the µ-TEG with optimized geometry was realized using an easily-scalable process based on the technology currently used in the semiconductor industry.

This novel design enables a high electrical power generation per thermocouple under temperature differences of only 5 K. Thanks to its versatile design, the delivered output power can span the range from few µW up to several mW, a power range particularly useful in many applications (sensors, IoT, etc.).



Schematic, in perspective view, of the design of µ-TEG. n- and p-type thermoelectric materials form a wavy-shaped path, separated by a gap, which are deposited on polyimide, itself residing on Cu plates. The upper and lower Cu plates are connected by Cu rivets to ensure a good thermal coupling

Reference:

Innovative design of bismuth-telluride-based thermoelectric micro-generators with high output power
Soufiane El Oualid, Francis Kosior, Anne Dauscher, Christophe Candolfi, Gerhard Span, Ervin Mehmedovic, Janina Paris and Bertrand Lenoir
Energy and Environmental Science, volume 13, pages 3579–3591 (2020)
https://hal.archives-ouvertes.fr/hal-03027363/

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DESIGN OF ALLOY METALS FOR LOW-MASS STRUCTURES (DAMAS)

DAMAS is a laboratory of excellence (LabEx) cofounded by Institut Jean Lamour and Laboratory of Microstructure Studies and Mechanics of Materials (LEM3). Created in 2012 with the support of the French State through the "Investment for the Future" programme, it has been extended for another 5 years in 2020. It is also one of the structuring projects of Lorraine University of Excellence (LUE).

LabEx DAMAS brings together the driving forces of research in chemical, physical, mechanical and numerical metallurgy from LEM3 in Metz and IJL in Nancy, amounting to 85 researchers.

Its activities have enabled the Université de Lorraine to finish 43rd in the Shanghai Ranking in the field of metallurgical engineering and 15th in international partnership in metallurgy.

Fundamental research in metallurgy for the lightening of metal structures by metallurgical means is at the heart of this LabEx, with 4 focuses:

- Innovative metallurgical processes
- Development of alloys and microstructures for weight reduction
- Advanced characterization techniques
- Multi-scale modeling and simulation (from the ab-initio to the process)

LabEx DAMAS devotes its resources to the recruitment of doctoral and post-doctoral students, and attracts high-level researchers from all over the world thanks to its collaborations with 118 foreign laboratories.
It is also active in metallurgy training, international outreach and the transfer of its results to the industry.
Two examples of LabEx DAMAS success stories can be given:

- A European patent on new nano-structured alloys with high mechanical and thermal resistance for the aerospace industry
- The contribution to the production implementation in the Groupe PSA of low pressure carbonitriding of gearbox pinions in order to extend their service life (a first in Europe) in collaboration with IRT M2P

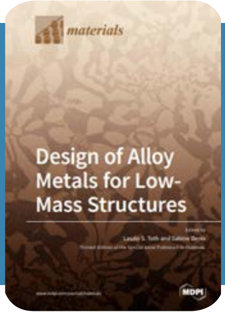
Nazca cup, art work in damask steel by the artist Jean-Louis Hurlin

Key figures (2012-2020):

- **85** researchers and lecturers - researchers
- **30** PhD defended, **52** post-doctoral researchers recruited and **31** guest researchers
- **626** publications (including 1 book)
- **111** invited conferences
- **118** partner laboratories
- **4** excellency researchers (regional support)
- **1** prof@lorraine
- **2** industrial chairs
- **1** start-up
- **3** patents

Further reading:

Design of alloy metals for low-mass structures
Laszlo S. Toth and Sabine Denis (Eds.)
Published: July 2020
https://doi.org/10.3390/books978-3-03936-159-5
This book is a printed edition of the Special Issue Design of Alloy Metals for Low-Mass Structures that was published in Materials
Download PDF: https://www.mdpi.com/books/pdfdownload/book/2464
Website : http://labex-damas.univ-lorraine.fr/



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METASURFACES FOR DATA PROTECTION: A PROJECT FUNDED BY NATO

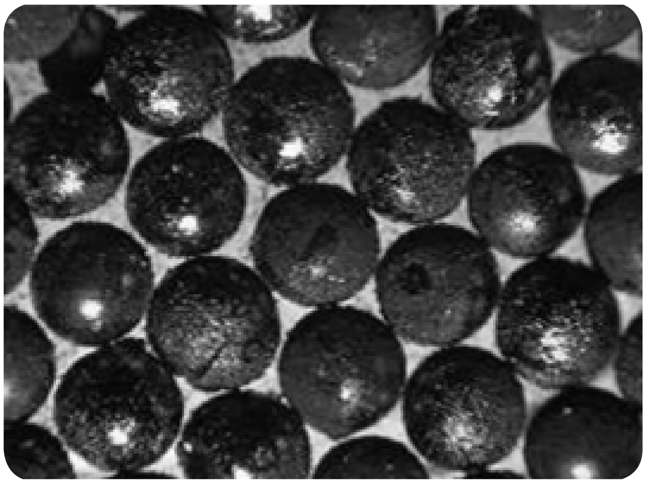
In 2020, the project "Globular carbon-based structures and metamaterials for enhanced electromagnetic protection (CERTAIN)" was launched, coordinated by IJL and funded by NATO under the Science for Peace and Security (SPS) programme*.

CERTAIN lasts 3 years and deals with the development of innovative technologies related to security, such as data protection through the production of metasurfaces with improved electromagnetic properties: microwave absorption and frequency dispersion, allowing effective guidance and trapping of high frequencies.

This project brings together IJL's Bio-sourced Materials group and researchers from 4 countries: Ukraine (Taras Shevchenko National University in Kiev), Lithuania (Vilnius University), Belarus (Belarus State University), United Kingdom (University of Exeter).

The objective is to design and implement new types of artificial magneto-electric materials for applications in radio frequency and microwave technology. Designed with the metamaterials approach, they will combine the advantages of the electrical and magnetic properties of carbon-based magnetic globular structures, leading to multifunctional 2D structures to the concept of a perfect electromagnetic absorber or wave concentrator.

*NATO's Science for Peace and Security (SPS) programme aims to enhance cooperation and dialogue between NATO and partner countries through civilian science and innovation. The SPS Programme funds activities related to NATO's strategic objectives that address key SPS priorities. The programme provides grants for collaborative research and development projects, workshops, institutes and training involving scientists and experts from NATO nations and partner countries.



2D array of hollow, magnetic monodisperse carbon spheres

The magnet attracts the carbone spheres against the glass wall of the vial

Reference:

Website: http://nano.bsu.by/certain/

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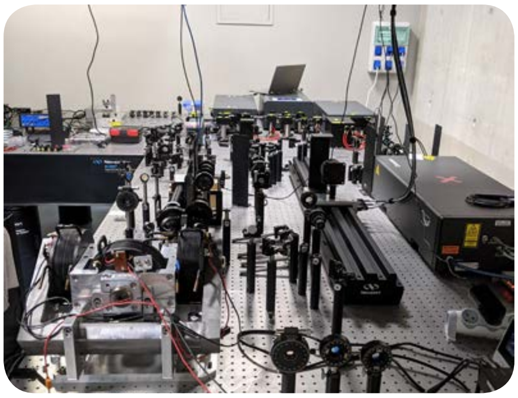
PLUS CHAIR - ULTRAFAST LASER PULSE TO STORE INFORMATION

"For the past forty years, we have witnessed a profound transformation of our society, which leaves an increasingly important place in the digital world. The need for information storage continues to grow. The digital data generated annually around the world is now counted in zettabytes, or thousands of billions of billions of bytes. This is equivalent to delivering hundreds of millions of books of data every second. Consequently, the explosion in the production of data, requiring increasingly important storage and analysis means and, consequently, an increasing use of materials, for some rare, and always more energy, poses a real problem in terms of environmental impact."*

The creation of the PLUS Chair within the IJL with the support of the NIT Foundation is primarily aimed at developing research knowledge to move from proof of concept to its use in electronic devices such as hard disks.

The second objective is to disseminate this new knowledge to students of Master, engineering schools and PhDs, as well as to anyone interested in the fields covered. Indeed, this collaboration allows us to show not only the academic but also the industrial interest of our research and training, while reinforcing our international visibility.



Finally, the third objective is to mobilise cross-disciplinary skills by associating all the university's scientific fields that can contribute to scientific progress. Organised in project mode, the chair is managed by a holder, Julius Hohlfel, granted with both academic and industrial skills.

In the context of the PLUS Chair, ultrafast laser equipment, partially funded by the Pulse FEDER project and Nano for Sensors Lorraine University of Excellence Impact project, has been set up at IJL (see picture). This experimental device has enabled our researchers to obtain first-rate results, which have been published by Nature Electronics (see page 13), Advanced Science and Nano Letters (see below). These results show that it is possible to make magnetic computer memory units that are faster and consume less energy.

*After an interview given by Julius Hohlfeld, the Chair holder, available on this website:
http://fondation-nit.univ-lorraine.fr/interview-julius-hohlfeld/

Reference:

Energy Efficient Control of Ultrafast Spin Polarized Current to Induce Single Femtosecond Pulse Switching of a Ferromagnet
Q. Remy, J. Igarashi, S. Iihama, G.Malinowski, M. Hehn, J. Gorchon, J. Hohlfeld, S. Fukami, H. Ohno and S. Mangin
Advanced Science 7, 2001996 (2020)
https://onlinelibrary.wiley.com/doi/full/10.1002/advs.202001996

Engineering single-shot all-optical switching of ferromagnetic materials
J. Iigarasi, Q. Remy, S. Iihama, G. Malinowski, M. Hehn, J. Gorchon , J. Hohlfeld, S. Fukami, H. Ohno, S. Mangin
Nano Letters 20, 8654–8660 (2020)
https://pubs.acs.org/doi/10.1021/acs.nanolett.0c03373

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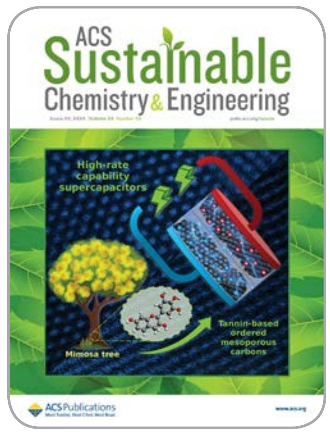
CNRS SILVER MEDAL FOR VANESSA FIERRO

Vanessa Fierro was awarded a Silver Medal by the CNRS in 2020. She is a CNRS senior researcher and her scientific focus is on carbon adsorption and more specifically on hydrogen storage.

After her PhD at the Instituto de Carboquímica iCB-CSiC (Saragossa, Spain) she worked at IFP Energies Nouvelles - IFPEN (Solaize, France), IRCELYON (Villeurbanne, France) and Universitat Rovira i Virgili (Tarragona, Spain). She joined the CNRS in 2006 as a researcher. She has been leading the Bio-sourced Materials group of IJL since 2018.

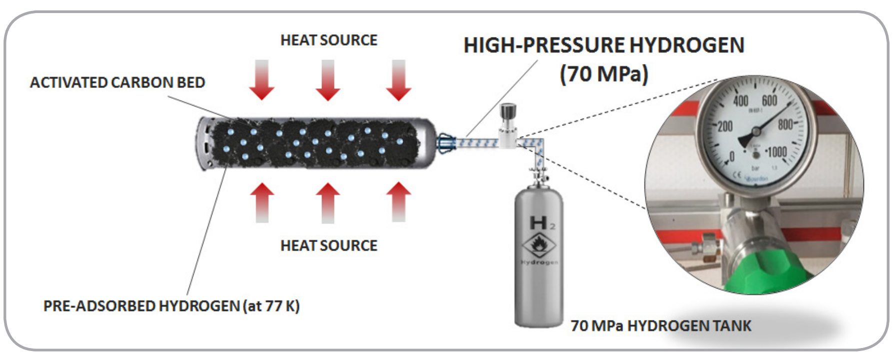
Vanessa is at the origin of many scientific breakthroughs that were successfully transferred (7 patents) such as the development of porous (organic or carbon) materials derived from plant polyphenols: rigid foams, powders, adsorbents, (aero) gels, and other porous, cellular and crosslinked monoliths, or even 3D printed, as well as resins and membranes.



Vanessa has published over 300 scientific papers, is a specialist in gas adsorption for the characterization of porous materials and has extensive experience in porous materials for energy and environmental applications. She was awarded the American Carbon Society's Charles E. Pettinos Prize in 2019. In 2017, she received the Micromeritics Grant awarded for the first time to a scientist in France.

She conducted the work leading to the publication of the article *Synthesis of perfectly ordered mesoporous carbons by water-assisted mechanochemical self-assembly of tannin* published in 2018 in Green Chemistry and *High-rate capability of supercapacitors based on tannin-derived ordered mesoporous carbons* published in ACS Sustainable Chemistry & Engineering in 2019. Both studies were covers of these scientific journals.

Vanessa Fierro collaborates in ULHyS, a research project focused on hydrogen supported by Lorraine University of Excellence. In this framework, researchers from IJL and LEMTA entirely designed a non-mechanical hybrid hydrogen compressor and thus succeeded in compressing hydrogen to 700 bars in 2019. This was an international first! This work gave rise to an article published in 2020 in Carbon journal: *A 70 MPa hydrogen thermally driven compressor based on cyclic adsorption-desorption on activated carbon*.



Vanessa Fierro also co-authored the book *Organic and Carbon Gels*, published in June 2019 by Springer.

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CNRS BRONZE MEDAL FOR CARLOS ROJAS-SÁNCHEZ

Carlos Rojas-Sánchez is a CNRS researcher at IJL. He has been awarded the CNRS Bronze Medal in 2020. His work is predominantly engaged in the area of condensed matter physics and his main research interests span from spintronics to spin-caloritronics and spin-orbitronics. He studies spin current, spin Hall effect, Edelstein effect and spin-orbit torque in 3D and 2D systems with the aim to obtain more efficient, faster and environmentally cleaner devices for memory, energy harvesting, and logic applications.

Carlos has achieved to develop his passion for research through remarkable perseverance such as to be admitted to the university, study physics in Peru, overcome many difficulties and finish his PhD in 2011.

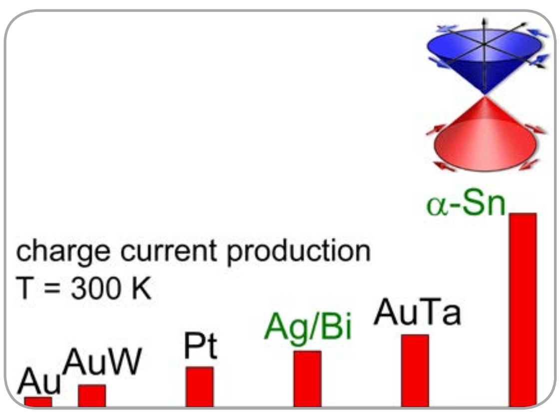
After his PhD in Physics at the Balseiro Institute, Bariloche, Argentina, Carlos worked at INAC and SPINTEC, two laboratories of the French Atomic Energy Commission (Commissariat à l'Énergie Atomique-CEA) in Grenoble, France. He also worked at the Néel Institute in Grenoble. He then spent two years in Albert Fert's group at the Unité Mixte de Physique CNRS/Thales (UMPhy) in Palaiseau. He joined the CNRS in October 2015 as a researcher in the Spintronics and Nanomagnetism group at IJL. In 2018, he also became the head of IJL's micro and nanotechnologies competence center.

His experimental research works focus on the phenomena of inter-conversion of charge current into spin current due to spin-orbit coupling towards the manipulation of the magnetization of magnetic nanostructures. In particular, he studies inter-conversion at Rashba interfaces or surfaces of topological insulators. The latter are new states of matter that are characterized by being metallic on their surface and, ideally, insulators in their inner bulk. He performs a range of experiments such as spin pumping and spin torque ferromagnetic resonances, spin Seebeck, and spin-orbit torque switching of magnetization.

Carlos has published over 42 articles in international peer-reviewed journals such as Physical Review Letters, Nature Materials and Nature Communications. Several of them were co-authored with Albert Fert, such as: *Compared efficiencies of conversions between charge and spin current by spin-orbit Interactions in two- and three-dimensional systems* published in Physical Review Applied in 2019.

In the framework of the European H2020 MSCA RISE programme, Carlos has been active in establishing an international network of collaborations involving 12 partners in 8 countries. He is the local IJL coordinator of this project.

The CNRS Bronze Medal recognizes the work of a promising researcher in her or his field. We can already confirm this with a recent study led by Carlos and published in Advanced Materials: *Current–induced spin torques on single GdFeCo magnetic layers*.



The experimental results of the production of the charge current in different systems. The spin current is injected by spin pumping at the ferromagnetic resonance. Note that the charging current produced by the alpha-Sn topological insulator is by far much higher

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MAGNETIC: AN INTERACTIVE EXHIBITION MADE IN THE LAB

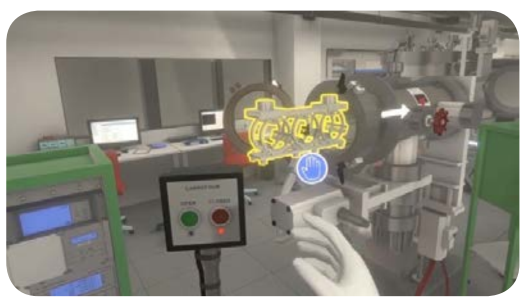
Magnetic is a touring scientific exhibition for the general public designed by IJL's researchers and technicians, with the collaboration of art and engineering students. It was presented for one year at the Palais de la découverte in Paris in 2019-2020 and received around 60 000 visitors.

Through experiments, manipulations and observations, Magnetic invites the public to discover principles and effects of this omnipresent but unknown phenomenon. Its objective is to share with the public the scientific process and the "science in the making", according to the famous expression of Jean Perrin, Nobel Prize in Physics in 1926 and creator of the Palais de la découverte in 1937. This exhibition takes the visitor into the creativity and imagination of the researcher.

Magnetic includes some 60 interactive experiments specifically designed for this exhibition and completed by many videos on touch-screen terminals. Pedagogical experiments are presented to explain the origin of magnetic properties. They are essential to explain some of their applications in everyday life as well as some recent research results. Experiments to do yourself invite visitors to be curious and to answer many questions, in particular about the use of magnetism in computers and data storage. The exhibition is thus organized in a logical and progressive way around 5 thematic blocks:

1. Magnetism, where can it be observed?
2. Magnetism, how can it be explained?
3. Magnetism, how can it be useful?
4. Magnetism, where to find it in a computer?
5. Magnetism, what in research is being done?

This last block shows the experimental universe of our research laboratory, whose facilities allow the development of new nanomaterials with new magnetic properties.
Visitors can therefore observe a 3D model of the platform for Depositing and Analysis of nanomaterials under Ultra-high Vacuum (D.A.U.M.). A spectroscopic analysis chamber used in research is also exhibited. Models show the growth of crystals under ultra-high vacuum, structural and magnetic characterizations of samples and lithography to make three-dimensional nanometric objects. This block ends with experiments illustrating applied research topics: innovative giant magnetoresistance sensors used in ABS, and magnetography as a secure printing technique useful for legal and banking services.



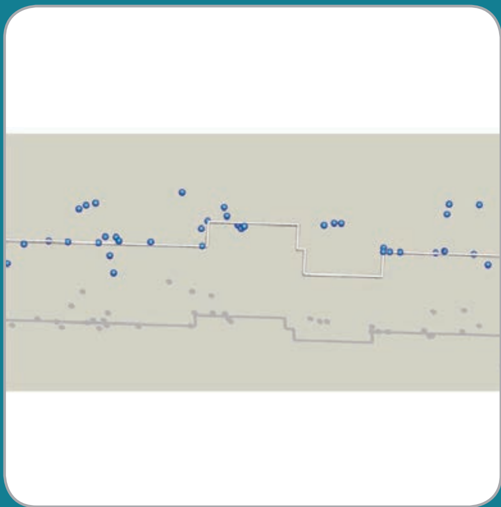
The 5th block is completed by a virtual and interactive immersive approach of the IJL's D.A.U.M platform. The objective of this application is to invite the public inside a virtual laboratory to share an experiment of thin film deposition in order to produce materials with new properties. The scenario is based on a sequence of real experiments in the laboratory: atomic deposition under ultra-high vacuum, in-situ surface characterization of in-situ surfaces, lithography, etc. Visitors are then invited to realize by themselves a virtual magnetoresistive sensor used as position sensor in drones.

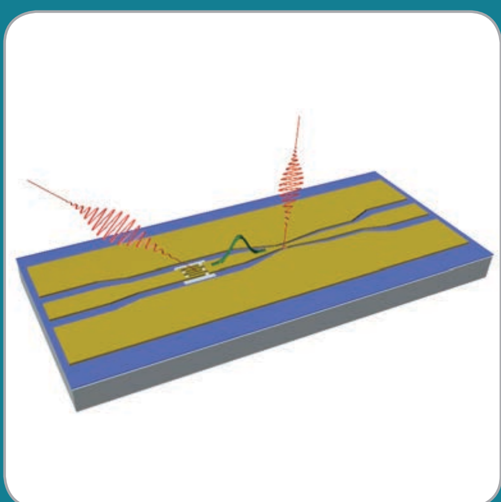
Reference:

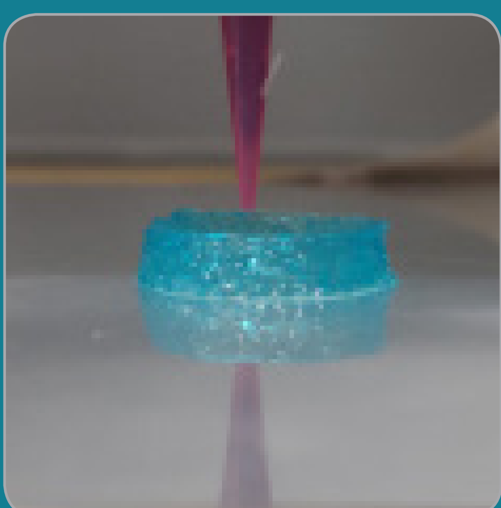
Watch the short video about the exhibition: https://youtu.be/cW6UfIFXtxg
See full description of Magnetic : https://www.teo-exhibitions.com/touring-exhibitions/exhibition/magnetic/

Contact person:

For further information and rental conditions, please contact:
helene.fischer@univ-lorraine.fr







KEY FIGURES 2020

Staff:

166 permanent researchers

70 post-doctoral researchers

171 PhD students

103 support staff

Scientific activity:

360 peer-reviewed articles

54 new research contracts

30 PhD thesis defenses

International:

51 nationalities

200 collaborative actions

30 partner countries

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Production: Communication department of IJL, May 2021 – Photo credit: Ph. Levy, EPPDSCI (cover and page 20). The cover's photo shows an experiment of the Magnetic exhibition presented at the Palais de la découverte in Paris.