EUROPHYSICSNEWS

The magazine of the European Physical Society

Research using **European physics infrastructures**

Young Minds
The Photonic Maze

Nobel Prize
in Physics 2023

EPS Historic Sites
in 2023

EPS edp sciences

2023 I VOLUME 54 I NUMBER 5 I EUROPEAN COUNTRIES PRICE: 113€ PER YEAR (VAT NOT INCLUDED)

europhysicsnews


EUROPHYSICSNEWS
The magazine of the European Physical Society
Research using
European physics
infrastructures
Young Minds
The Photonic Maze
Nobel Prize
in Physics 2023
EPS Historic Sites
in 2023

Cover picture: Old electron spectrometer of which the ATOMKI institute in Hungary was the owner. Courtesy László Z. Nagy

EPS EDITORIAL

YOUNG MINDS

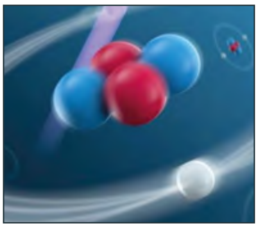
EPS NEWS

IN THE SPOTLIGHTS

OPINION

FEATURES

ANNUAL REPORTS



▲ PAGE 08

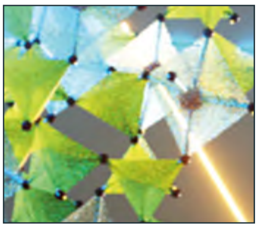
Nobel Prize in Physics 2023

▲ PAGE 13

Current developments in LNGS underground physics

▲ PAGE 25

high-performance laser science to the world at ELI



▲ PAGE 36

Non-linear X-ray Science

Celebrating 20 years SEENET-MTP Network

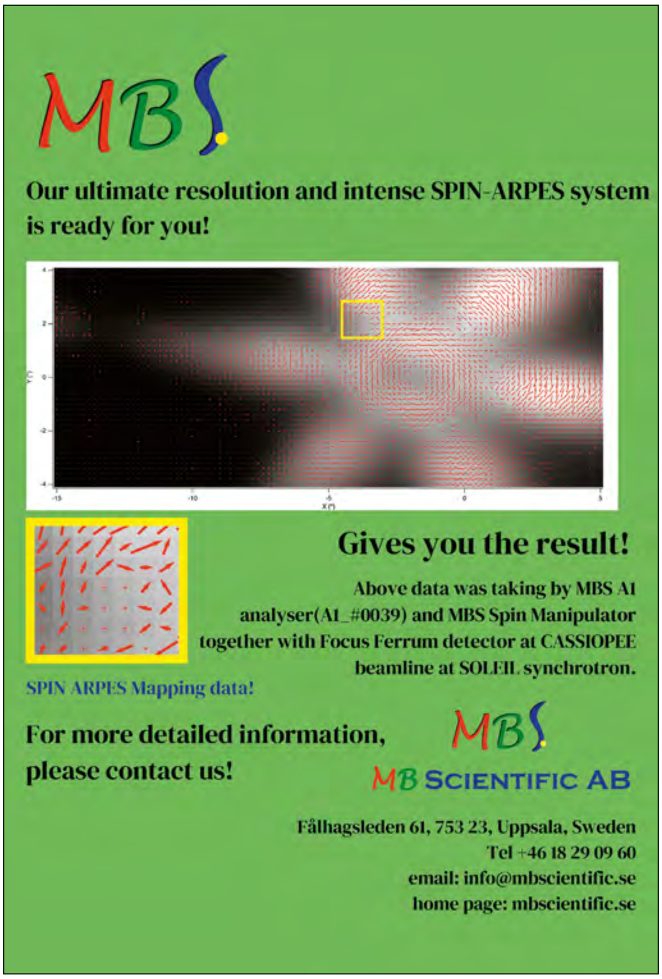
Twenty years ago, with the hope of bridging the gap between the Southeastern and Western European scientific communities, the participants of the UNESCO-sponsored Balkan Workshop BW2003 in Vrnjačka Banja, Serbia, reached consensus on initiating the creation of the Southeast European Network in Mathematical and Theoretical Physics (SEENET-MTP). This initiative was a natural extension of the WIGV (Scientists in Global Responsibility) initiative, which had been launched by the renowned Austrian theoretical physicist Julius Wess in 1999. Since its inception, the network has grown to include 24 institutions from 12 different countries, along with more than 450 individual members. Additionally, the network has received support from 13 partner institutions worldwide, furthering its efforts.

The primary objectives of SEENET-MTP have been: to provide a regional framework for building institutional capacity in Mathematical and Theoretical Physics, to strengthen cooperation among institutions, groups, and individual scientists in South-East Europe, to promote joint research and training activities at regional, interregional, European, and worldwide levels, and to facilitate the exchange of students, physicists, and the broader scientific community. The Network has successfully executed more than 20 projects. The primary patrons and partners of the Network, both within the Balkans and the SEE region, have included UNESCO (Paris and Venice Office), the European Physical Society (EPS), CEI and ICTP Trieste, CERN, as well as the German foundations DAAD and DFG during the initial decade of SEENET-MTP's mission.

The cooperation between the EPS and SEENET-MTP dates back to the year 2005 and had a further reinforcement at the Kick-off Meeting of the EPS Committee of European Integration (EPS-CEI) during the BW2013 workshop. The EPS and SEENET-MTP have ever since collaborated in many domains and established the Memorandum of Agreement in 2019. Scientific collaboration in the SEENET-MTP framework resulted in the publication of more than 350 joint papers, as well as around 20 monographs and Network conference proceedings. More than 360 scientific exchanges were realized in this period, and 30 Network meetings took place, with about 2000 participants in total. The Network was also involved in training activities for teachers and pupils. The joint CERN – SEENET-MTP PhD Training Program (2015-), actively supported by the EPS, as well as the ICTP, is approaching the start of its third cycle. More than 150 PhD and MSc students already took part in this program.

The Network marked the 20 years of its existence during its recent event – the BWXX workshop, August 29-31, Vrnjačka Banja, Serbia. The Workshop topics covered open problems in particle and quantum physics, cosmology and gravitation, and (inter)regional cooperation too. This event was organized by the SEENET-MTP Office and supported by the EPS. EPS, SEENET-MTP and Balkan Physical Union agreed to continue and enforce cooperation in several, recently established programs as Balkan Physics Olympiad (BPO), cooperation in physics education at university level in the region, training programs and schools in theoretical and applied physics. ■

Goran Djordjevic



[EPS EDITORIAL]

The EPS at the IAEA General Assembly

It is not common for international learned societies to be invited to participate in meetings of decision-making bodies, and even less so when it comes to highly sensitive issues such as nuclear energy, its use and developments in the civil or military sectors.

Exception confirming the rule, the European Physical Society (EPS) was invited by the Secretariat of the International Atomic Energy Agency (IAEA) to be represented as an observer at the 67th ordinary session of its General Conference, held at the Vienna International Center, Austria, from September 25 to 29, 2023. As the highest decision-making body of the IAEA, the General Conference brings together high-ranking officials and representatives from Member States, non-Member States, as well as international and regional organisations. The 2023 edition of this event welcomed 2835 participants from all around the world, including 2589 representatives of Member States and 242 members of NGOs and international organisations, among which the EPS.

After having experienced a strict registration procedure (monitored by the United Nations Pass Office), I had the pleasure, from my observer seat, to listen to the welcoming words from IAEA Director General Rafael Mariano Grossi, the message from the Secretary-General of the United Nations, as well as numerous debates and votes on extremely varied resolutions. These included the approval of reports concerning strengthening of IAEA's activities on nuclear science, technology and applications, implementation of the Non-Proliferation Treaty (NPT) safeguards agreement with, for instance, the Democratic People's Republic of Korea, application of IAEA safeguards in the Middle East, Israeli nuclear capabilities, the status of Palestine in the IEAE, the transfer of the nuclear materials in the context of AUKUS military agreement, or still the nuclear security in Ukraine. It was interesting to note, on each resolution, the votes of highly nuclear countries (in particular those equipped with nuclear weapons) opposing those of non-aligned countries, or to observe the almost systematic confrontation of the East-Western blocs on issues related, *e.g.*, to the crisis in Ukraine. On the whole 142 statements were delivered in plenary sessions and 111 side events were proposed, addressing sustainable cooperation and development among nuclear across regions, decommissioning of Fukushima's facilities, nuclear safety at a time of war, accelerating energy system decarbonisation, woman's work in nuclear sector, the battle around childhood cancers, nuclear waste management *etc.* I had the chance to attend the session dedicated to the new efforts by the USA to prevent non-State actors from acquiring weapons of mass destruction and weapons-usable radioactive materials, organised by a panel of US senior government officials. It was also interesting to learn about recent developments in accelerator facilities (electron accelerators and electrostatic ion accelerators) in Iran for… agricultural applications, wastewater treatment or even treating baby's milk.

As an important event hosted by this General Conference, the EPS participated in the IAEA Scientific Forum (September 26-27, 2023), focused on nuclear innovations for a net zero balance. This forum enabled interactive discussions between high-level politicians, leading scientists, experts in the field and the attendees. It was emphasized that nuclear power, with a proven low carbon footprint, can provide an alternative to replace fossil energy-based plants, in particular through the development of small modular transportable reactors dedicated to specific needs such as supplying backup power to the modern electricity grid, heating cities and industries, or producing hydrogen to decarbonise the transport sector. In four sessions over two days, leading experts highlighted the role of new nuclear reactors for energy production and showcased the importance of artificial intelligence, digitalisation, robotics and advanced manufacturing to improve technology avoiding greenhouse gases in future industrial applications. Among the 35 speakers delivering talks or participating in topical round tables in front of 700 attendees were, besides scientific experts and program directors, the President of Ghana, the US Secretary of Energy, several European ministers committed with the ecological transition and even … Miss America 2023, student in nuclear engineering at Wisconsin University and fervent defender of the atomic energy.

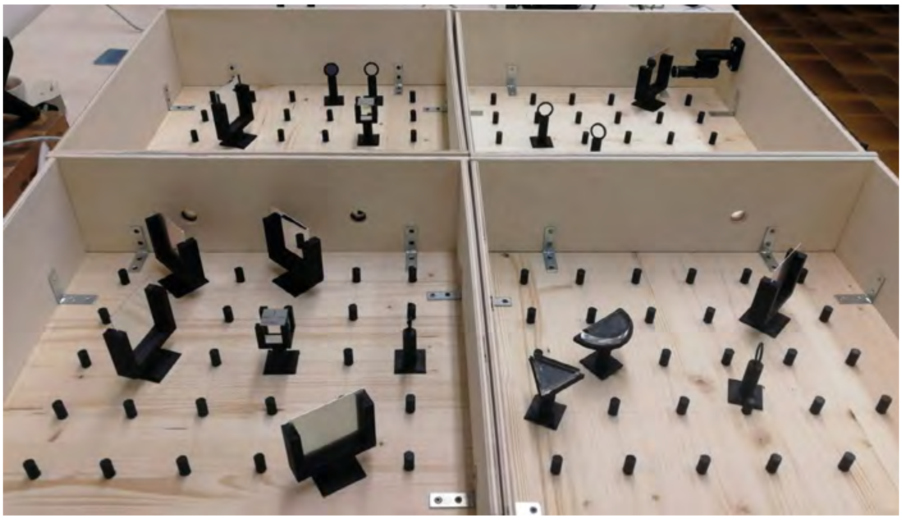
At a time when the Middle East is being torn apart once again, the IAEA General Conference reminds us of the urgent need to know how to use the atom for peace and the development of our nations, and to push our efforts for global cooperation in the nuclear field. ■

Luc Bergé,
EPS President

The Photonic Maze

Sofia Cano Castro, Agostino Di Francescantonio, Pasquale Barbato, Federico Sala, Hugo Nobrega and Giuseppe di Blasio

During the last year, as a part of our outreach projects from the OPTICA, EPS, and SPIE Chapters of Politecnico di Milano, we introduced "The Photonic Maze", an initiative to allow people of different ages and backgrounds to get acquainted with optics and photonics in a fun and interactive way.



The set-up pretends to give an insight into what a scientist does in a photonic laboratory equipped with a laser and an optical table. We arranged a kit consisting of a wooden breadboard divided into four boxes, which can communicate through an aperture on each one. Plastic pins fix the positions on the board in a regular square pitch, where 3D-printed holders for optical elements like mirrors, prisms and lenses can be placed; just as the holes in an actual optical table.

It allows people to have a hands-on experience based on very simple laws of optics, like reflection, refraction and focusing. The goal of the participants is to direct a laser beam through the four rooms to hit a target placed in the last one. A user can place elements to change the beam direction on the dummy optical table and the variety of pieces allows one

to complete the task in various ways. The game can be further complicated from the simplest case of only using mirrors by employing prisms, fibers and diffractive elements. An introductory yet useful activity was performed to understand the working principle of lenses with the construction of a telescope. To this end, the user employed a different board equipped with fixed slits to place lenses with different focal distances and should come to the solution by reaching a defined laser spot size.

The underlying simple physics rules make the activities suitable for people of all backgrounds, leaving room for more advanced scientific discussion about further topics and technological applications.

After some months of work on the prototype development, the Photonic Maze premiered in May of 2022 as a workshop activity in the framework of CARLA Camp, an event addressed for bachelor and master students interested in a career in Photonics. It allowed us to test the format in an environment where people were already familiar with some topics and got a first feeling of the public response. Then, in October of 2022 it was proposed for the "Festival della Scienza" in Genova. The experience was deployed as a two-week exhibition with more than 2000 participants, including groups from elementary schools and families. The Photonic Maze enabled a thematic showroom on the topic of "Light-Glass Interaction". After a brief introduction about light and the history of optics, we presented the principles that allow the use of glass to modify the path of light with an outlook on how light can alter the properties of glass, introducing the cutting-edge technology of femtosecond laser micromachining. Finally, given the positive response of the young audience, a last event was organized in a high school, where students attended an elective workshop. We arranged a short and interactive lecture for those interested in science and engineering to provide some knowledge on photonic science. Some challenges were presented on the "Photonic Maze" to test their comprehension on the matter.

The response from the public was great. All three experiences allowed us to see not only the potential of the initiative but also an unexpected level of engagement from the audience. A very pleasant result was to see interest and discussion arising from the participants, especially among kids and young students, where curiosity sparked and further inquiries were presented. Interest in the technological implications of laser science and photonics was stimulated as well. In conclusion, the "Photonic Maze" represented a very versatile tool to share physics and science with a broad audience, from a relaxed environment to an innovative classroom approach, with the potential to involve people of non-scientific backgrounds. Bearing in mind the easy-to-fabricate prototype that requires very simple and low-cost materials we hope the experience can be replicated and reach an even bigger audience. ■

EPS Council in Porto

The Council of the European Physical Society (EPS) took place in Porto this year. In the beautiful premises of the Fundação Dr. António Cupertino de Miranda, representatives of EPS Member Societies, Individual Members, Associate Members, chairs of Divisions, Groups and Committees gathered to exchange about the Society's activities.

The first day was dedicated to reports from the EPS president, the treasurer and various work groups. Discussions were launched around changes in the EPS constitution and participants had the opportunity to discover the candidates for several elections. The day concluded with a dinner in the impressive contemporary building of Casa da Musica in the centre of Porto. A tribute to David Lee, former EPS Secretary General, was presented by the current EPS President Luc Bergé and several of his predecessors: Luisa Cifarelli, Maciej Kolwas, Ove Poulsen, Christophe Rossel, Petra Rudolf and Rüdiger Voss.

The second day revealed the results of elections for a renewed EPS Executive Committee. Mairi Sakellariaou, is the EPS President-Elect. A professor of Theoretical Physics at King's College London, former co-editor at the EPL journal and current chair of the EPS Gravitational Physics Division, Mairi will succeed Luc Bergé as EPS President in 2024.

The members of the renewed Executive Committee you can find in the EPS Directory at page 45.

Presentations of the activities of ISBSSD (International Year of Basic Science for Sustainable Development) and the congress of the French Physical Society, celebrating its 150th anniversary this year were also on the agenda. The attributed Society's Awards were are listed at page 44.

The Council ended with an online meeting with our colleagues from the Ukraine physical Society (UPS): Prof. Maksym Strikha Taras Shevchenko, Kyiv National University Ukraine, UPS Board Member, UPS President (2013-2016) and Prof. Mikhail Belogolovskii Comenius University, Bratislava, UPS Vice President. Both described the harsh living conditions and the losses among the scientific community who stayed in the country and carried on their work despite the war. They thanked the EPS for its support and encouraged the assembly to work on further common actions. ■

Introducing the European strategy for accelerator-based photon science

Through new plans detailed in ESAPS 2022, the LEAPS consortium aims to strengthen Europe as a global leader in accelerator-based photon science.

The League of European Accelerator-based Photon Sources (LEAPS) is made up of 19 large-scale synchrotron (SR) and Free-electron Laser (FEL) facilities, situated across 10 European countries. A pan-European plan formulated by LEAPS aimed at addressing the future challenges and needs in science and innovation, which strengthens Europe as a global leader in many areas of research and technology. Through the plans set out in the European Strategy for Accelerator-based Photon Science (ESAPS 2022) [1], LEAPS could soon provide valuable new resources for more than 35,000 researchers using its facilities today, spanning fields as wide-ranging as materials science, drug design, biochemistry, quantum technology, geology, and planetary science.

The advanced research facilities (SR and FEL) use particle accelerators to produce intense beams of electromagnetic radiation. By measuring how this light interacts with matter, researchers across numerous fields can access a diverse array of advanced techniques: including detailed mapping of molecular and electronic structures, damage-free probing of exotic new materials and biological samples, and high-resolution imaging of complex systems.

First formed following a collaboration of European facilities in 2017, LEAPS aims to expand cooperation with research infrastructures and partnerships across its member states and beyond. The consortium is developing schemes to better manage advanced infrastructures and offer improved services to users, industry and stakeholders, while also helping its users to share their expertise in photon science and technology. Through ESAPS 2022, the consortium lays out its plans for expanding these efforts in the coming years. The areas detailed [2] include ambitious facility upgrades, plans for technological development, and timelines for the future use of its facilities. ■

References

[1 R. Abela *et al., Eur. Phys. J. Plus* **138**, 355 (2023). https://doi.org/10.1140/epjp/s13360-023-03947-w

[2] *EPJ Plus Focus Point on Accelerator-based Photon Science Strategy, Prospects and Roadmap in Europe: a Forward View to 2030,* https://link.springer.com/journal/13360/topicalCollection/AC_fac84a078611bd831b60883453038270

An overview of the management structure of the AGATA collaboration

The AGATA project could eventually lead to a deeper understanding of the strong nuclear force. To achieve this a sophisticated project management structure is essential.

The Advanced Gamma Tracking Array (AGATA) is a European gamma-ray spectrometer that is already achieving unparalleled levels of sensitivity in nuclear gamma-ray spectroscopy. AGATA promises to make major breakthroughs in our understanding of the strong nuclear force and nuclear structure in the coming decades. Eventually, AGATA will be able to track the trajectories and origins of gamma rays produced by nuclei created by intense, stable beams of rare radioactive isotopes. To achieve this, its future design will feature 180 segmented detectors made from high-purity germanium, arranged in a spherical structure. Since 2010, the project has been hosted by several different major facilities in Europe, and has seen its number of detectors steadily increase. Such deeply complex logistics required AGATA to constantly adapt to new instrumentations and to exploit efficiently the local infrastructures coupled to it – which has now led to a comprehensive, efficient management structure during construction and operation, encompassing all of its scientific, technological, and financial aspects [1].

AGATA is governed by a Memorandum of Understanding (MoU), which guides crucial aspects of the project including its planning, funding, construction, and operation. It also specifies an overarching management structure which aims to maximise the breadth and quality of its scientific output at each facility. The latest MoU was signed in 2021 by 11 different countries, involving 38 institutions. The four main committees of the MoU's management structure and their relationships are explained in detail in [2]. Their main aim is to realise the best experiments to unveil the still unknown nuclear structure properties. ■

References

[1] E. Clément *et al., Eur. Phys. J. A* **59**, 152 (2023). https://doi.org/10.1140/epja/s10050-023-01057-w

[2] EPJ A topical collection on AGATA: Advancements in Science and Technology. https://link.springer.com/journal/10050/topicalCollection/AC_7c4e6a5494d6fa3624a6b34de562c441

The Nobel Prize in Physics 2023

– DOI: 10.1051/epn/2023501

The Nobel Prize in Physics was awarded to Pierre Agostini of Ohio State University, Ferenc Krausz of the Max Planck Institute of Quantum Optics and the Ludwig-Maximilian University of Munich and Anne L'Huillier of the Lund University for „experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter" The Prize acknowledges the tremendous experimental progress in the past 35 years that eventually enabled the investigation of the fastest electron transition processes in atoms, molecules and solids by using state-of-the-art femtosecond laser technology. As a result, a new field of research emerged and shortly after the establishment of the field of femtochemistry, attophysics came of age.

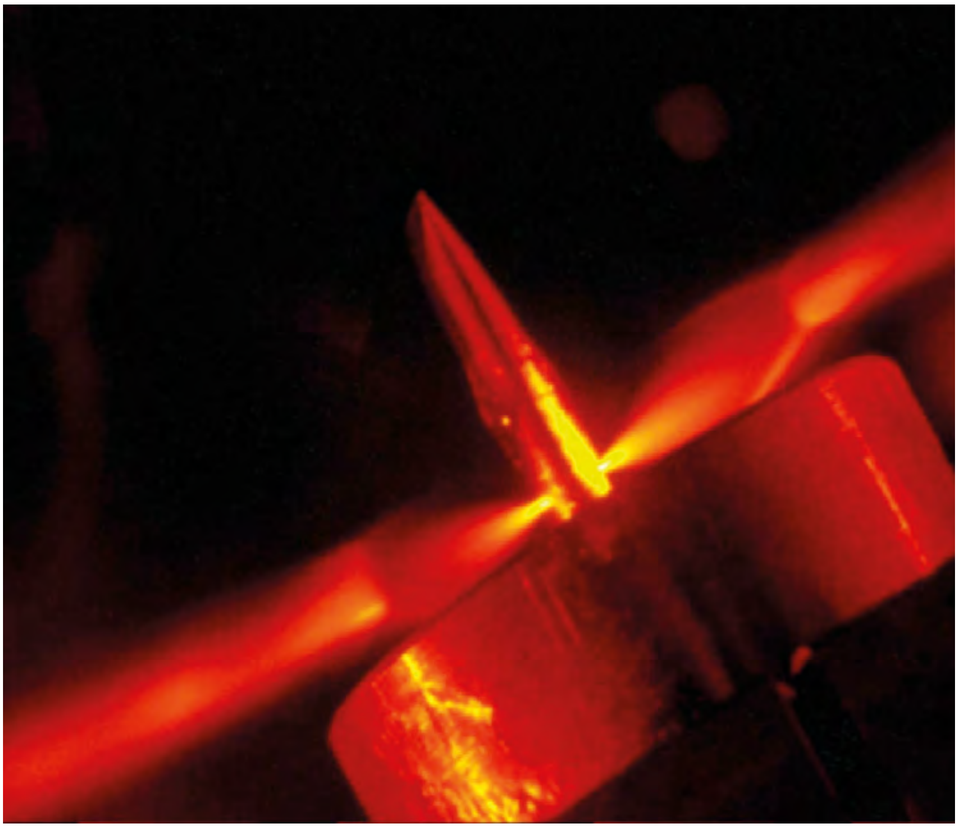
Progress in the generation of ultrashort laser pulses enabled fundamental research on light-matter interactions to enter a new realm. With tens of gigavolt per meter electric field strengths and pulse durations comprising only a few oscillation periods of light, extreme nonlinear phenomena could be explored – an ongoing era of strong-field physics full of surprises ensued.

Ultra-intense and ultrashort laser pulses have been at the core of this development.

Advanced laser Q-switching and mode-locking techniques enabled continuous rapid growth of the electric field strength of ultrashort laser pulses already in the 1970s. An early example of the new type of bewildering experimental observations is the discovery of above threshold ionization by Pierre Agostini and his colleagues in 1979. Focussing intense ultrafast laser pulses into a cloud of Xe atoms placed inside a photoelectron spectrometer, they observed that the laser is not only capable of ionizing the atoms. Remarkably, they demonstrated that the electrons can absorb several more photons of 1.2 electronvolt (eV) energy than the absolute minimum of 11 required to overcome the ionization potential of 12.3 eV.

Subsequently, considerable research effort was invested in experiments about laser-matter interaction studies and strong-field physics emerged as a substantive field of research comprising experimental and theoretical research teams inspecting the beauty of nonlinear light-matter interaction phenomena. The year 1988 marked an important milestone when under comparable strong-field conditions Anne L'Huillier and her colleagues observed the generation of high-order harmonic radiation of laser light. In their experiment, intense laser pulses emitted by an Nd-doped YAG laser interacted with Ar atoms. This led to the emission of radiation up to the 33rd harmonic of the fundamental frequency, just shy of 40 eV photon energy. This high photon energy and peculiarities of the emitted spectrum including the counterintuitive similarity of the amplitudes of individual harmonics suggested a connection to the findings of Agostini and colleagues. However, a clear quantum mechanical

▼ Attosecond light source driven by ultrashort laser pulses. Ne atoms used for HHG stream into a vacuum chamber and emit (invisible) attosecond pulses that co-propagate with the laser light. (credit: attoworld.de)

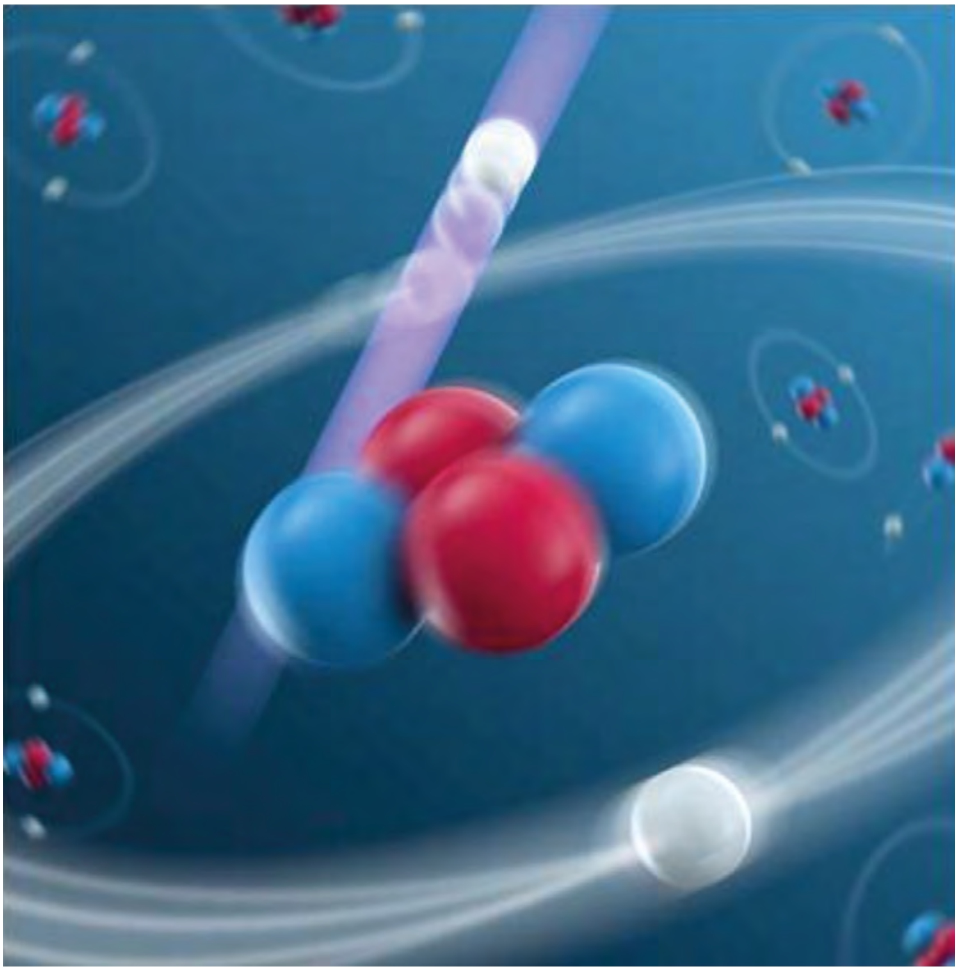


picture of the involved processes was pending at that time.

In the 1990s, much discussion was devoted to the mechanism of the high-order harmonic generation (HHG) process and to whether the emitted high-frequency light was coherent and the observed spectral features could correspond to attosecond pulses in the time domain. However, at that time experimental tools to investigate the radiation were limited to extreme ultraviolet grating spectrometers, incapable of sampling the temporal evolution of the emitted UV light and leaving unclear if the spectral phase of the high harmonic radiation would allow to form short pulses.

While it had been recognised that the spectral bandwidth of the emitted radiation in principle would support pulses of attosecond duration, for a time domain characterisation fundamentally new experimental tools had to be developed. An experimental long-distance race resulted in two experiments demonstrating the feasibility to generate attosecond duration bursts of light via the HHG process. In Vienna, Ferenc Krausz and his team developed a time-domain sampling technique in which co-propagating high-harmonic XUV and near-infrared laser pulses photoionised Ar atoms. The team detected the kinetic energy of the emitted photoelectrons and found it to be modulated by the presence of the near-infrared laser in a way that proved beyond doubt that a single 650-attosecond duration pulse (isolated in time) had caused the photoionisation. At the same time, Pierre Agostini and his colleagues employed a novel frequency-domain technique enabling access to the spectral phase information of the XUV radiation and verified the existence of a train of 250-attosecond pulses in their experiment.

Advancing time-domain and frequency-domain attosecond techniques formed a toolbox capable of scrutinising quantum mechanical processes on their natural time-scale. Suddenly, the treatment of electronic transitions as



▲ How long does it take a Helium atom to notice it got photo-ionized? Attosecond measurements have sparked the development of high-level quantum theories that include multi-electron correlations and boosted the understanding of transient states of matter. (credit: A. Gelin)

virtually instantaneous became a too simplistic model. Fundamental discoveries include the observation and control of electronic wavepacket motion in matter, recording the time photoemission and photoexcitation take and inquisitions on the time domain implications of quantum tunnelling.

The quick progress in fundamental research triggered by attosecond science also fostered a tremendous advance in femtosecond laser technology in the past 30 years. Laser systems used for this research were developed based on the chirped pulse amplification principle (see the work of Gérard Mourou and Donna Strickland, Nobel Laureates in Physics in 2018) and ultrashort, amplified laser pulses are now available that contain only one oscillation cycle of the electromagnetic wave. Next to advances in ultrafast opto-electronic and magneto-optical technology, novel laser sources are nowadays employed in biomedical analysis techniques that will permit early-stage cancer and cardiovascular disease detection in human blood serum. These developments, in the spirit of the Nobel prize dedication, evidence how the continuous interaction between fundamental physics research and the application of state-of-the-art lasers continue to serve "for the greatest benefit to humankind". ■

■ **Peter Dombi,**
Wigner Research Centre
for Physics, Budapest, Hungary
■ **Martin Schultze,**
Graz University of Technology, Institute
of Experimental Physics, Austria

(both authors completed their
PhD under the supervision
of Ferenc Krausz)

Discovery experiments and demonstration experiments

Michael Berry[1] **and Sandu Popescu**[2] – DOI: 10.1051/epn/2023502
University of Bristol, UK – [1] asymptotico@bristol.ac.uk – [2] s.popescu@bristol.ac.uk

Science is distinguished from other creative activities by the central role played by experiment (in which we include observation). Experiments enable us to discover new things, to confirm or falsify our theoretical expectations, and suggest new directions for exploration and analysis. Our aim here is to identify two kinds of physics experiment that are philosophically very different.

The first kind is what we will call *discovery experiments*. Realms previously inaccessible become open to exploration with a new instrument. For example, telescopes (Galileo's, Hubble, James Webb…), microscopes (Hooke, Leeuvenhoek…), and particle accelerators. Each observation reveals something surprising. Sometimes, there are theoretical expectations, and the aim of experiments is to decide between alternatives. The Michelson-Morley interferometer failed to detect an absolute reference frame. The Large Hadron Collider discovered the Higgs boson. The Laser Interferometer Gravitational-wave Observatory discovered merging black holes. The Aharonov-Bohm fringe shift, and the violation of Bell inequalities, established quantum nonlocality, in two qualitatively different forms. Antimatter falls down.

In a subclass of discovery experiments there is no doubt that an underlying theory applies but its implications are either unanticipated or beyond current abilities to compute or conceptualise. In condensed matter, the theory is quantum mechanics: the Schrödinger equation for an assembly of many electrons and nuclei. As Philip Anderson declared: 'More is different'. This was behind the discovery of completely unexpected phenomena such as high-temperature superconductivity, and the integer and fractional quantum Hall effects.

Common to discovery experiments is that the result is not known in advance. Underlying fundamental theory is lacking, or ambiguous, or has not been tested or fully explored in the regime being investigated. The popular understanding of scientific experiments is of the discovery type.

The second kind is what we will call *demonstration experiments*. Existing well-established theory, correctly and uncontroversially applied, unambiguously predicts a new phenomenon, and the aim of experiment is to confirm that it occurs. Such experiments can be regarded as analogue computations. Into this category fall, for example, nonhermitian optical effects in systems with PT symmetry, optical and neutron interference effects revealing geometric phases, and random-matrix spectral statistics of quantum energies of classically chaotic systems and their counterparts in optical and acoustic modes. Common to demonstration experiments is that the result is known in advance. If the experiment fails to conform to theoretical expectation, this means it was wrongly conducted, either through a failure of correct modelling or insufficiently sensitive instrumentation. Such experiments are repeated until they give the correct result.

We do not underestimate demonstration experiments. We are delighted when our theories, and the mathematics underlying them, are brought to life in the physical world. And they have scientific value, beyond educating students in physics laboratories. They are often difficult, and experience gained when they fail to give the expected result guides the development of new instruments and the search for disturbing influences not initially included in the modelling. And demonstration experiments often lead to new technology.

We have emphasised discovery and demonstration, but of course this demarcation is not exhaustive (thought experiments and numerical experiments come to mind), and there is a large literature discussing experimentation, in physics and science more generally, from different perspectives. We simply draw attention to the fact that in the everyday practice of physicists, discovery and demonstration experiments are often conflated. Knowing the subtle differences between them may make little difference to how experiments are done. But if we want to conceptualise our efforts to understand nature, it is worth highlighting the distinctions between them. ■

[EDITORIAL OF THE GUEST EDITORS]

Good infrastructures, happy physicists

A common effort by all European Countries has been developed in the last 20 years through the European Research Infrastructures Strategic Forum, and this allows researchers from all scientific fields to use some "open access" research infrastructures supporting world leading research.

In this issue we have focused on few examples in the physical sciences without trying to be omni-comprehensive. We asked our authors to convey to our readers the information from two main points of view: the senior scientists who make these infrastructures available and attractive and the junior scientists who have early experience of what it means to access them and do exciting research.

The examples cover several exciting fields of physics which recently reached major milestones in the search of new knowledge such as Rare Event Detection, Astronomy, Particle Physics and Condensed Matter Physics. This allows also to give an idea on which kind of "infrastructure" can be necessary for cutting-edge research: very large and localized observatories or particle accelerators using single "probes" (particles or photons) with very high energy or very high collection and detection power, or a very varied and complementary set of analytical instruments allowing to study the phenomena in the condensed matter with many probes and ever increasing definition at atomic level.

In all fields, the capability to explore the phenomena in the right "phase-space" and with the maximum sensitivity requires the development of other physical phenomena and their transformation into "techniques and technologies", from the use of superconductivity to generate very high magnetic fields for the CERN Magnets, to the use of the Laser effect to generate very intense photon beams, or the use of the photoelectron effect to build advanced detectors. Most research infrastructures are, therefore, both generators of scientific as well as of technical knowledge, and this has convinced many Governments in supporting their operations and to host them.

One major result of research infrastructures is to be "meeting and exchange places" in which researchers from different regions and, in some cases, disciplines, interact and spend time together by joining forces to solve the big challenges posed by the effort to advance knowledge in ever-increasing difficult fields. This has been a strong driver, together with the need to join forces to achieve capabilities which would be, otherwise, impossible to reach in isolation even within the largest Countries or Research Institutions.

Though modern scientific discoveries are difficult to get without modern infrastructure, the heart of discoveries are the scientists themselves. Without great ideas even the best infrastructures are useless. ■

■ **The guest editors, Carlo Rizzuto[1] and Zsolt Fülöp[2]**
■ [1] Chair of the CERIC-ERIC General Assembly (formerly Chair of ESFRI)
■ [2] Chair of the National Research Infrastructure Committee, Hungary

THANK YOU!

The EPN Editors are very grateful to Carlo Rizzuto and Zsolt Fülöp, who as Guest Editors used their networks to select the authors which introduce you in the research infrastructures and enthusiastically describe their research projects. The result is a highly attractive special issue.

We highly appreciate your work and endeavour for EPN. Thank you! ■

The Editors

Research Infrastructures: the contribution of ESFRI

The establishment of the European Research Area (ERA) in 2000 marked a significant advance in integrating research efforts within the European Union. This initiative emerged as a strategic response to the existing fragmentation of Europe's research and innovation landscape. Its impact was especially pronounced in the field of research infrastructures (RIs), particularly the very large ones in physics and astronomy that had previously struggled with the absence of a pan-European coordination framework. In its absence, international RIs such as CERN, Institute Laue-Langevin and the European Synchrotron Radiation Facility were established through ad-hoc engagement of various countries.

Within a mere few months following the European Commission's proposal of the ERA concept, a conference to deliberate on developing a cohesive EU-centric approach to RIs was convened in France.

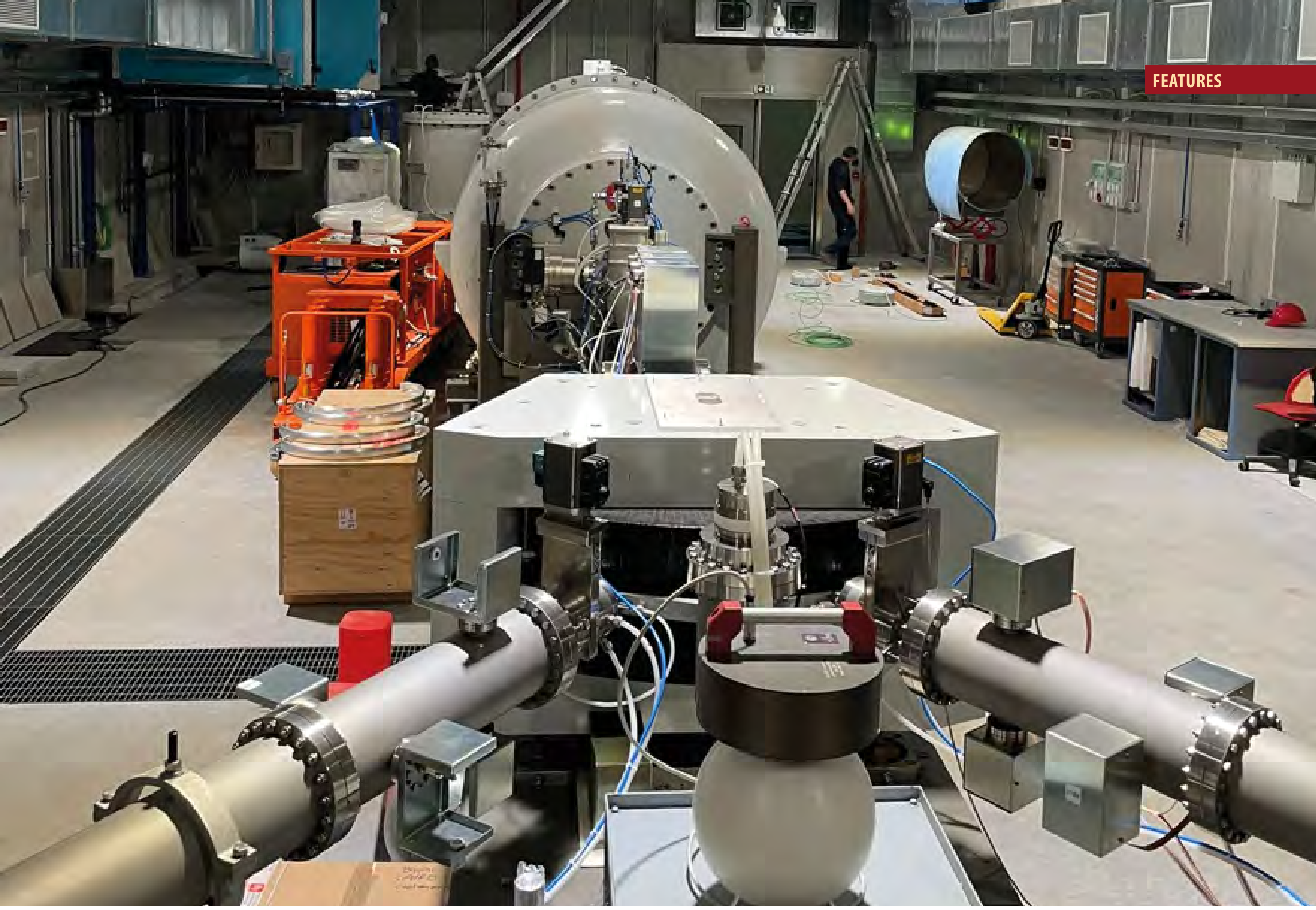
These efforts led to the founding of the European Strategy Forum on Research Infrastructures (ESFRI) in 2002 and the unveiling of ESFRI's first European Roadmap for Research Infrastructures in 2006. This roadmap catalysed the harmonisation of European infrastructure development, ensuring an aligned vision for priority settings and investments across member states, and supported by the European Commission's funding calls. The results of this integration were far-reaching, with the vast majority of EU Member States embracing the road-mapping strategy on a domestic scale and self-organisation of the research communities across Europe to establish RIs in their domains. Perhaps most strikingly, the collective endeavours of the ESFRI Member States and the European Commission over the past two decades have fostered a robust ecosystem of European RIs, with the establishment of 41 ESFRI Research Infrastructures and the progression of 22 RI Projects into their preparatory stages. The collective investment in these often-unique facilities is set to surpass 20 billion EUR. Yet the work of ESFRI goes well beyond roadmapping, for which it is best known. Its policy coordination of the domain of research infrastructures, addressing topics such as financing, energy and supply challenges, and cooperation with industry, has far-reaching effects on the development and functioning of Europe's research infrastructure landscape.

Although impressive, RIs are resources which only achieve their aims when used by scientists to accomplish their research aims. To this end, I warmly welcome the special issue of Europhysics News, which highlights some of Europe's top RIs, their capabilities and potential, promoting the use of the RIs among its vast readership.

I extend my gratitude to Europhysics News for continuously emphasising the topic of research infrastructures, and look forward to our future collaborations. ■

by Jana Kolar

ESFRI Chair – **DOI: 10.1051/epn/2023503**



▲ Bellotti Ion Beam Facility of LNGS, a 3.5 MV Singletron machine (courtesy of M. Junker (LNGS)

CURRENT DEVELOPMENTS IN LNGS UNDERGROUND PHYSICS

A. Formicola[1], A. Ianni[2], G. Imbriani[3], M. Laubenstein[2], S. Pirro[4] and E. Previtali[4]

[1] INFN, Sezione di Roma, Italy

[2] INFN, Laboratori Nazionali del Gran Sasso (LNGS)

[3] INFN, Sezione di Napoli and Università degli Studi di Napoli Federico II,Italy

[4] INFN, Laboratori Nazionali del Gran Sasso (LNGS) and Università degli Studi di Milano Bicocca, Italy

DOI: https://doi.org/10.1051/epn/2023504

The Gran Sasso National Laboratory in Italy (LNGS) is at present the largest deep underground laboratory in the world. LNGS has been in operation for 35 years. It has a rock overburden of 1.4 km which reduces the muon flux from cosmic rays by a factor of one million.

The core purpose of LNGS [1] is frontier research in the domains of Astroparticle Physics: low energy solar neutrinos, neutrinoless double-beta decay, dark matter searches, rare nuclear decays, and of Nuclear Astrophysics. LNGS is operated as a research infrastructure open to international users. The laboratory is equipped with several laboratories and facilities to support the experimental activities, in this contribution we have selected four of them.

STELLA a laboratory for large-scale-state-of-the-art-material screening

The study of rare events with a specific experiment requires a very low level of radioactivity in all

●●●

● ● ● detector components to disentangle the signal from the background. Therefore, in addition to locating the experiment deep underground, radio-purity assay of used materials is essential. The activity is carried out in dedicated facilities. For this purpose STELLA (Fig.1) was built at LNGS [2]. STELLA is equipped with 15 high-purity germanium (HPGe) detectors, which allow very sensitive measurements by means of gamma-ray spectrometry. Four of these HPGe detectors are custom-made ultra-low background detectors built by the Max-Planck Institut für Kernphysik (MPI-K) in collaboration with LNGS. They can reach a world record sensitivity of the order of 10 μBq kg^{-1} on natural radioactive isotopes. In addition, STELLA also hosts four detectors for alpha spectrometry as well as two liquid scintillator counters. The main task of STELLA is to offer a professional and unique laboratory for material selection to all experiments installed at LNGS, and to provide support to research activities carried out in other underground laboratories. The radio-purity assay is performed in synergy with the Chemistry laboratory at LNGS, which uses inductively coupled plasma mass spectrometry (ICP-MS). To clearly identify the various contributions to the source of materials background they are divided into three categories: *primordial radionuclides and natural decay chains* (40K, ^{232}Th, ^{235}U, ^{238}U, ^{87}Rb …); *cosmogenic radionuclides*, produced through interaction of secondary and tertiary cosmic-rays with matter (^{3}H, ^{14}C, ^{7}Be, ^{11}C, ^{57}Co, ^{39}Ar…); and *anthropogenic radionuclides*, artificially produced mainly through nuclear reactions (^{60}Co, ^{85}Kr, ^{137}Cs, …). A complete radio-purity assay requires the use of different complementary techniques, which are working in synergy. Primarily, these techniques are gamma-ray spectrometry, ICP-MS, alpha/beta spectrometry, and Radon emanation measurements [3]. In STELLA on average the analysis throughput is 100 samples per year. At present, an important upgrade for STELLA is ongoing. It aims at making available underground laboratory space surrounded by neutron shielding and 5 cm of steel for background reduction purposes. It is expected that this, together with other small modifications on the HPGe detectors themselves, will further decrease the environmental natural background of detectors in order to reach enhanced sensitivities needed for next-generation experiments for rare events.

▼ **FIG. 1:** Stella Laboratory equipped with 15 HPGe detectors (courtesy of Massimiliano De Deo (LNGS))

The NOA innovative low background infrastructure

NOA is a new infrastructure of the outside laboratories of LNGS. NOA which is funded in the framework of PON Ricerca e Innovazione 2014-2020 and RESTART CIPE n. 49/2016, is a unique facility worldwide. worldwide. It comprises a 421 m^2 ISO 6 clean room (Fig.2) which can be operated in virtually Radon-free mode using a Radon abatement system. For this reason, it was built with stainless steel walls, ceiling and floor to reduce possible emanation or diffusion of Radon. In addition, the air ventilation system is engineered to reduce Radon emanation. The design is similar to that of other Radon-free clean rooms operated underground at LNGS [4]. NOA is equipped with a custom-made Radon detector with 1 mBq m^{-3} sensitivity for monitoring the activity concentration. A Radon-free clean room is crucial for dark matter experiments to avoid plate-out of ^{210}Pb on surfaces during the assembly of crucial parts of the detectors. NOA is divided into two main volumes: one with 3.0 m in height and 353 m^2 dedicated to testing and packaging of photodetectors based on SiPMs; another with 5.8 m in height and 68 m^2 area for large volume detector assembly. The two main volumes can be operated separately both in normal and Radon-free mode. The packaging area is equipped with a flip chip bonder, a wire bonder, a dicer, and a cryoprobe to test SiPMs at liquid nitrogen temperature where their intrinsic noise is strongly reduced. The activity is crucial for next-generation cryogenic experiments where SiPMs will be commonly used. Right now, NOA will be used for the mass production of photosensors for DarkSide-20k.

The Bellotti Ion beam Facility

The Bellotti Ion beam facility is a new 3.5MV accelerator devoted to nuclear astrophysics and applied physics. It is the result of the synergy between the LUNA (Laboratory for Underground Nuclear Astrophysics) collaboration[1] and the LNGS, thorough a funding of the Italian Ministry of Research[2]. The Bellotti Ion beam facility is equipped with a 3.5 MV Singletron machine [5] manufactured by High Voltage Engineering Europe (HVEE). The machine can deliver intense proton, helium, and carbon beams (about 1, 0.5 and 0.15 mA respectively) with excellent energy resolution and stability, optimal for precision nuclear astrophysics measurements. The new accelerator is

▲ **FIG. 2:** A detail of the SiPM packaging facility in NOA equipped with a flip chip bonder, a wire bonder, a dicer, and a cryoprobe, which can be operated at 77 Kelvin.

currently installed in the hall B of the underground laboratory (see full page picture). A key research area of this facility is the experimental Nuclear Astrophysics studies, the exploration of low energy nuclear reactions related to various stages of stellar evolution and nucleosynthesis. The LUNA collaboration was the first to propose a new approach to nuclear astrophysics, by exploiting the extremely low background inside the LNGS. A pioneering experiment was proposed 1992 to LNGS and a 50 kV accelerator (LUNA-50kV) was installed underground. A 400 kV Singletron accelerator - LUNA-400kV – is in operation since 2000 and still plays a fundamental role for experimental nuclear astrophysics. The LUNA experiments have established underground nuclear physics as a powerful tool for determining nuclear reaction rates at Gamow peak energies, which represents the energies where most of the reactions take place in the interior of a star at a given temperature. Thanks to the presence of the two accelerators with complementary energies and taking advantage of the many years of LUNA collaboration in managing experiments with underground accelerators, the new Bellotti Ion Beam facility, which has a Program Advisory Committee to select and monitor the experiments, will open new frontiers in astrophysics nuclear power and nuclear physics research.

Ieti, the low noise - low radioactivity milliKelvin cryostat for Qubits characterisation

An increasing number of experimental evidence is suggesting that environmental radioactivity could be a limiting factor for the performance of future quantum computers based on the technology of superconducting circuits. Cosmic rays, as well as the decay products of radioactive isotopes naturally present in the laboratory environment, can interact with the chip hosting the quantum processor (Qubit). Such an interaction would limit the ●●●

---

[1] https://luna.lngs.infn.it

[2] Progetto Premiale 2012 and 2013

▸ **FIG. 3:** Ieti cryostat hosting a Superconducting Qubit. The Qubit is framed inside the second magnetic shield just below the inner Lead shield of the cryostat.

● ● ● coherence of the quantum system, *i.e.*, the time in which it retains its quantum behaviour. Moreover, it would induce simultaneous errors on multiple Qubits deposited on the same chip, spoiling the protocols for quantum error corrections.

The Ieti facility[3] is the first cryogenic platform enabling the test of superconducting qubits in an ultra-low radioactivity environment (Fig.3). Ieti offers the ideal environment to test novel qubit prototypes with an experimental volume of 5500 cm^3, a dual magnetic shield to prevent disturbances in quantum processors caused by fluctuations of the magnetic field, and a lead/copper shield system to reduce significantly the influence of environmental radioactivity inside the laboratory. In 2021 the facility hosted the first underground measurement showing the impact of radioactivity on a quantum circuit [6]. In 2022 Ieti was used to benchmark a Qubit fabricated with a new material (Granular Aluminum) by the Karlsruhe Institute of Technology [7]. The Ieti facility is presently hosting members of the SQMS (Superconducting Quantum Materials and Systems) Center, led by Fermilab, to develop a novel quantum processor. Thanks to Ieti, it will be possible to test the SQMS prototypes in an extreme "low noise – ultra-low radioactivity" environment and push their performance to new limits.

Some new improved facilities were realised during the last few years at LNGS aiming at the improvement of experimental sensitivities for Astroparticle physics experiments and to explore new fields of research. At LNGS the development of beyond-state-of-the-art instrumentation, combined with the implementation of novel and original approaches will provide a unique support for future advanced experiments in fundamental physics researches. ■

About the Authors

Alba Formicola is senior scientist at INFN Rome and served as Head of Research Division at LNGS from 2015 to 2021. Since 1998 she is a member of the LUNA collaboration working mainly in nuclear astrophysics.

Aldo Ianni worked as Director of the Canfranc Underground Laboratory from 2015 to 2018. In 2019 he became manager of research at LNGS and head of Office for Scientific Strategy and International Collaboration between underground laboratories.

Gianluca Imbriani is full professor of Experimental Nuclear Physics at the University of Naples Federico II (https://www.docenti.unina.it/gianluca.imbriani). He is currently spokesperson for the international collaboration LUNA.

Matthias Laubenstein is head of the underground ultra-low level laboratory STELLA of LNGS.

Stefano Pirro is senior researcher at LNGS. Currently, he works on the Cryogenics on the Cryogenics of ET and in the Qubit underground characterisation.

Ezio Previtali, PhD in Physics (1993), in 2019 full professor at Univerisità degli Studi Milano Bicocca. From 2021 to present he is Vice President of the HPC4ND consortium on High Performance Computing. Currently, he is Director of Gran Sasso National Laboratory of INFN.

References

[1] A. Ianni, *SciPost Phys.Proc.* **12**, 007 (2023)

[2] M. Laubenstein, *International Journal of Modern Physics A* **32-30**, 1743002 (2017)

[3] M. Laubenstein *et al.*, *Frontiers in Physics* **8** (2020, Volume 8), Article 577734.

[4] V. Di Marcello *et al.*, *JINST* **17**, 06 (2022) , P06033

[5] A. Sen *et al.*, *NIM B* **450**, 390 (2019)

[6] L. Cardani *et al.*, *Nat. Commun.***12**, 2733 (2021)

[7] D. Gusenkova *et al.*, *Appl. Phys. Lett.* **120**, 054001 (2022)

---

[3] https://ieti.sites.lngs.infn.it/index.html

STUDYING STARS FROM THE DEEP UNDERGROUND: THE LUNA EXPERIMENT AND THE CASE OF ^{13}C(α,n)^{16}O REACTION

László Csedreki[1] and **Giovanni Francesco Ciani**[2] – DOI: https://doi.org/10.1051/epn/2023505

[1] HUN-REN Institute for Nuclear Research (ATOMKI), Debrecen, Hungary
[2] INFN- Bari, Italy.

Understanding the stellar evolution and the origin of chemical elements are the main goals of Nuclear Astrophysics. In the last century, many collaborations worked to develop experiments and accelerators to study in Earth laboratories the main nuclear processes taking place in stars at their relevant temperature. As an example, we present the measurement of the ^{13}C(α,n)^{16}O reaction performed by the LUNA collaboration.

Production of chemical elements in the Universe

Everything around us, from our body to the entire Universe, is made by all the chemical elements of the periodic table. Their abundance, the percentage of presence of different nuclei, varies by several orders of magnitude. For example, in Fig. 1 the abundance of chemical elements is shown, normalised with respect to the silicon, as a function of atomic number in the Solar System. Light elements are the most abundant (Hydrogen and Helium are the 98% of the Solar System) and their dependence is almost a decreasing exponential, with 13 orders of magnitude difference for the heaviest elements.

Elements are synthetised in astrophysical environments: the lightest and most abundant elements, hydrogen and Helium, are created in the Big Bang Nucleosynthesis (BBN). The valley for Li, Be and B comes mainly in cosmic-ray induced nuclear reactions in the interstellar medium. All other nuclei, from carbon to uranium, were born inside Stars at the different stages of Stellar evolution. Moving from carbon to heavier elements along the abundance curve, a reduction can be observed, with exception of an evident peak around iron. These elements are produced in a sequence of fusion reactions towards higher atomic numbers [1]. Above the isotopes of the iron group, nucleosynthesis cannot occur by fusion reactions between charged particles for two reasons. Firstly, the reactions become endothermic and that means that they cannot happen spontaneously. Moreover, with the increasing atomic number, the electric repulsion increases, thus at typical stellar temperature, well below the Coulomb barrier, the reaction cross section becomes extremely low. Of course, neutral particles, as neutrons, are not affected by repulsive Coulomb forces. According to recent knowledge, heavy element synthesis is based on neutron capture processes. There are *s(slow)*- and *r(rapid)*- processes. If the produced radioactive nuclei can decay before the next neutron capture, it is a slow process. In general, it takes place in an environment with a low neutron density in AGB stars. On the other side, if a daughter nucleus can capture more than one neutron before decaying, it is a rapid process that takes place in a stellar environment with high neutron density such as stellar neutron mergers. In Fig. 1 nuclides synthetised by r- and s process are indicated with blue and green curves, respectively. Only a minority of nuclei beyond iron is synthetized by the so-called p-process that involves a proton capture (red dots in Fig. 1).

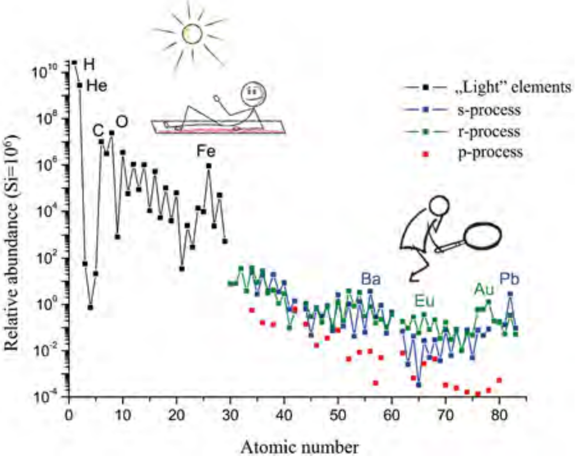
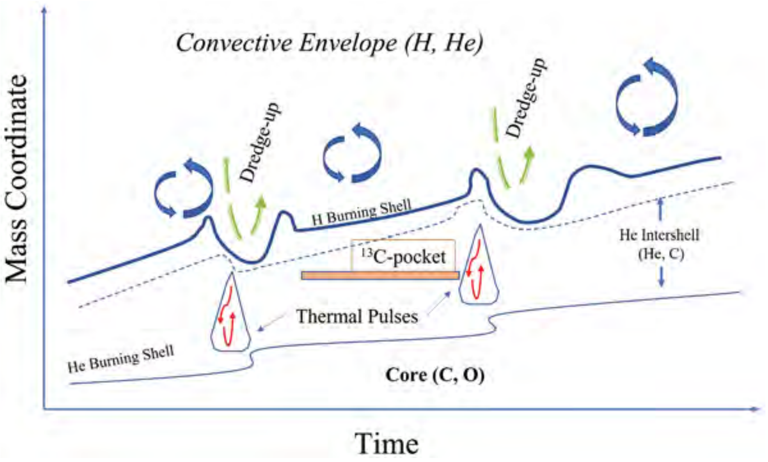


FIG. 1: Abundance of chemical elements in our Solar System (the contributions of the different processes of heavy element nucleosynthesis are labeled separately).



▲ **FIG. 2:** Temporal evolution of the different layers during the thermally pulsing AGB phase. The convective regions generated by two subsequent thermal pulses are also shown.

The study of the neutron sources and the origin of astrophysical s-processes

As mentioned before, we know that elements beyond iron are produced in the slow and rapid processes. Where do neutrons come from? For the s-process, it is well known that they are emitted from charge particle fusion reactions taking place during complex convective motion in stars of the Asymptotic Giant Branch which are stars in an advanced stage of their life. In Fig. 2. the internal structure of an AGB star is shown. Helium-burning takes place in the He burning shell covering the carbon-oxygen core of AGB stars. The helium is reproduced continuously in the hydrogen-burning phase in a separated shell and at a critical density the helium-burning is ignited. The energy released in this process causes the expansion of the star. When the helium runs out, the star contracts and the hydrogen-burning phase continues. The timescale of such an event is a couple of decades, which is repeated after some thousands of years. The material of the AGB star is mixed during the expansion (labeled as Dredge-up in the Figure) and the hydrogen from the convective envelope transported in deeper layers is captured on ^{12}C nuclides, which produce ^{13}N. Finally, the beta-decay of ^{13}N leads to ^{13}C nuclides forming the so-called ^{13}C-pocket. With the subsequent dredge up phase, Helium enters in the pocket that causes the ^{13}C(α,n)^{16}O reaction emitting neutrons that later are captured by the s-process nuclides. Therefore, knowledge of the ^{13}C(α,n)^{16}O cross section at the relevant energy region (Gamow-window, see box) allows for a better understanding of the synthesis of heavy elements.

In the last decades, several experiments have been performed in surface laboratories all around the world, but all of them were limited by the neutron background coming from secondary cosmic rays. It caused high uncertainties that did not allow for extrapolating data towards low energy and reaching the requested precision for stellar models.

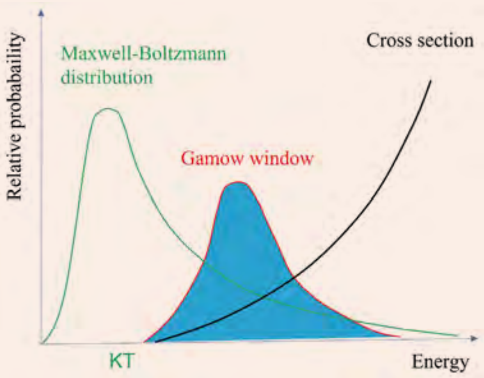
The LUNA experiment at Gran Sasso National Laboratory

In 2015, the LUNA (Laboratory for Underground Nuclear Astrophysics) collaboration decided to run the race towards the ^{13}C(α,n)^{16}O measurement, taking advantage from the intense alpha beam provided by the LUNA400 accelerator, from the neutron background reduction by three orders of magnitude of LNGS with respect to surface laboratories. The participation of LNGS to an international network allowed for building synergies with surface laboratories all over the world, such as ATOMKI (Debrecen, Hungary) and HZDR (Dresden, Germany) to collect experience in all the fields necessary to keep under control all the critical aspects of the measurement: the target production, the design and characterisation of the detection setup, data taking, data analysis for R-matrix extrapolation to lower energies and research for possible astrophysical consequence. All the steps are summarised in Fig. 3.

The four main aspects, which basically determine the available precision of the cross-section measurements are the intensity of the ion beam, the target properties, the detection efficiency of the neutrons and neutron background of the experimental apparatus. In particular, the ideal situation demands to have, together with the very intense alpha beam provided by the LUNA400 accelerator, targets with a very high density of ^{13}C nuclei. Therefore, targets were produced at ATOMKI by evaporation of 99% enriched ^{13}C powder on tantalum disks. The composition of the target was periodically checked using dedicated

GAMOW-WINDOW

The main challenge of nuclear astrophysics is to provide precise information of nuclear reactions mainly in a relevant energy region: the so-called Gamow-window, where the fusion most likely occurs. Its value (blue area) depends on the stellar temperature and the interacting particle. This comes from the convolution of two functions: the Maxwell-Boltzmann distribution (green line) that model the energy distribution of stellar gas, and the probability to overcome the Coulomb barrier (black curve). For the 13C(α,n)16O in an environment of T=0.9GK, the Gamow window is between 130 and 240 keV and the LUNA experiment successfully reached this energy range for the first time ever in the measurement described here.



techniques, that we do not describe here but those interested can find it in [2]. A huge work was done also for the research of the best setup to use in terms of material and design. ^{3}He counters have been used because of their intrinsic high detection efficiency. In order to maximise the geometrical efficiency, 18 counters have been arranged in two concentric rings (6 and 12 in the inner outer ring, respectively) in order to cover a 4π angle around the target. Another peculiarity was that the LUNA collaboration chose stainless steel counters instead of typical aluminum ones to reduce the radioactivity of the material in the setup and consequently its intrinsic background. A devoted paper on the setup construction was published in 2021 [3]. Because ^{3}He counters are sensitive to slow neutrons (E_n = 25 neV) and neutrons emitted by the reaction have energy $E_n > 2.5$ MeV, counters were inserted in a polyethylene moderator that slowed down neutrons. The detection efficiency in these conditions was estimated around 35% thanks to complementary measurements at particle accelerator of ATOMKI and neutron source measurement at University of Naples, Italy. Combining the background reduction of LNGS, the intense alpha beam provided by LUNA-400 accelerator and the experimental efforts mentioned above, in a three year experimental campaign, the LUNA collaboration measured the ^{13}C(α,n)^{16}O cross section directly inside their s-process Gamow window for the first time, reaching an overall uncertainties lower than 20%. Based on the calculated reaction rate from the theoretical extrapolation of the measured cross-section data, the astrophysical impact has been also estimated. Sizeable variations of some isotopes were found, whose production is influenced by the activation of close-by branching points that are sensitive to the neutron density, in particular, the two radioactive nuclei ^{60}Fe and ^{205}Pb, as well as ^{152}Gd [4]. The unprecedented results obtained by the LUNA collaboration have been confirmed by another measurement performed at China Jinping Underground Laboratory by the JUNA collaboration [5]. Although the community recognised the importance of this results, there is still a lot to do to improve the knowledge of s-process. Future prospect is to perform measurements in a wide energy range with angular distribution measurements completed with multi-channel R-matrix calculations considering the other reaction channels of ^{13}C+α. Stay tuned!

About the authors

László Csedreki is a Senior Research Fellow of the HUN-REN Institute for Nuclear Research (ATOMKI), Hungary. He studies low-energy nuclear astrophysics reactions at particle accelerators. He spent 4 years as a Postdoc at the LNGS laboratory, Italy. csedreki@atomki.hu

Giovanni Francesco Ciani is a Staff Technologist at INFN- Bari, Italy. His main research topics are low-energy nuclear astrophysics and detector development. giovanni.ciani@ba.infn.it

References

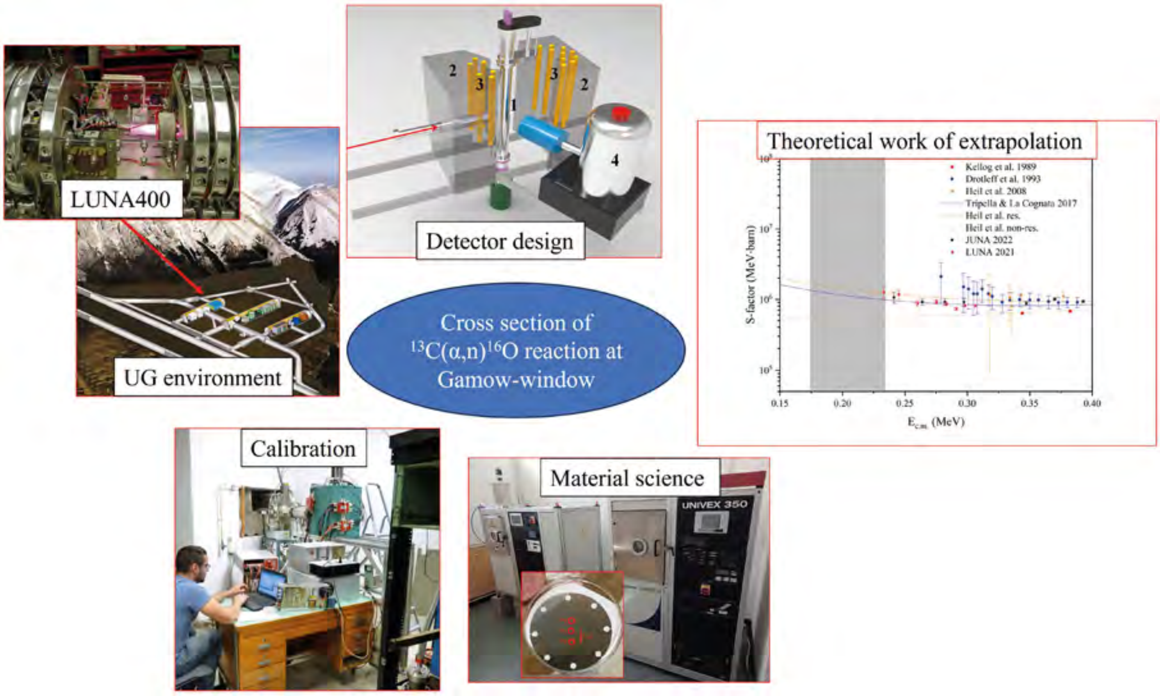
[1] José *et al.*, *Europhysics News* **47/4**, 15 (2016)

[2] Ciani *et al.*, *Eur. Phys. J. A* **56**, 75 (2020)

[3] Csedreki *et al.*, *Nucl. Instr. and Meth. A* **994**, 165081 (2021)

[4] Ciani *et al.*, *Phys. Rev. Letters* **127**, 152701 (2021)

[5] Gao *et al.* , *Phys. Rev. Letters* **129**, 132701 (2022)



◂ **FIG. 3:** Flow-chart of the ^{13}C(α,n)^{16}O reaction measurement represents the complexity of an Nuclear Astrophysics experiment.

▲ CERN Science Gateway.

CERN: EUROPE'S VOYAGE TO THE INFINITELY SMALL

Ursula Bassler – Institut National de Physique Nucléaire et de Physique des Particules IN2P3 – CNRS

DOI: https://doi.org/10.1051/epn/2023506

Over the nearly 70 years of its existence as an intergovernmental scientific organisation, CERN has become a landmark of scientific research in particle physics. In a changing geopolitical and societal context, CERN is shaping its future program where large research infrastructures are the necessary cornerstones to continue to investigate the infinitesimally small.

It is summer at CERN, the European Organization for Nuclear Research, close to Geneva. Many young people from all over the world are talking and laughing around the tables on the cafeteria terrace in the warmth of an evening. After a pause due to Covid-19, the summer students are back! CERN's yearly summer internship programme attracts more than 300 students from over 100 countries spreading a joyful atmosphere around the site. After all, one of the core missions of CERN is to train young people, and to promote peace and international collaboration through scientific research.

Building together

It has been nearly 70 years since CERN's foundations were laid in a European landscape marked by the experience of World War II. CERN was founded to provide world-leading research infrastructures, which no European State could afford by itself, through an intergovernmental scientific organisation; to promote scientific collaboration among countries who were at war less than 10 years earlier; and to stop the scientific brain drain. Discussions among the proponents of *big science* and *traditionalists, youngsters and establishment, experimentalists and engineers* and *theorists* spanned over two years before the CERN Convention was ratified and a first research programme established. The stakes were high to build such a laboratory from scratch, on a green-field site, and the outcome was quite uncertain - it was even difficult to find a Director-General ready to take on the task. Large research infrastructures are at the heart of the CERN model: from the Synchrocyclotron in 1957 and the Proton-Synchrotron in 1959 to the first hadron collider ISR in 1971, followed by the first proton-antiproton collider $Sp\bar{p}S$, the Large Electron-Positron collider LEP, and now the Large Hadron Collider LHC. CERN's track record is filled with pioneering instruments: from construction to operation and the final physics results, working on the common goal to unravel the world of the subatomic particles has motivated many physicists, engineers and technicians to engage with CERN and to develop the necessary ground-breaking technologies. As an international treaty organisation, CERN has established a robust framework for scientific cooperation, including financial stability, that has allowed major investments over many years.

Spreading International collaboration

The CERN model has inspired the creation of sister organisations such as ESA, ESO and EMBL, further strengthening the collaboration among the European countries in various areas. The Joint Institute for Nuclear Research, JINR, in Dubna (Russia), was the first international organisation to follow the CERN model in 1955, facilitating by then collaboration between East and West. The latest example is SESAME, the Synchrotron-light for Experimental Science and Applications in the Middle East, which has eight member states and operates a common infrastructure in Jordan since 2017. Starting with twelve founding nations, CERN's membership expanded rapidly in the 1990s towards the Eastern European Countries, and later to Israel. Today, CERN has twenty-three Member States, some 10 Associate Member States, including non-European countries such as India and Pakistan, and close to 50 international cooperation agreements with non-Member States. Nearly 12 000 users with 100 different nationalities are currently registered as CERN. About a third of the users are affiliated with institutes in non-Member States, North America accounting for the largest fraction. Yet, the geopolitical context has changed. For the first time in its history, CERN revoked the Observer Status of the Russian Federation and JINR in 2022 following the Russian invasion of Ukraine, one of CERN's Associate Member States.

Preparing the Future

Since the 2013 update of the European Strategy for Particle Physics, CERN has been working on the concept of a 100-km collider. This "Future Circular Collider" (FCC) could follow a similar development path as LEP and LHC, hosting an electron-positron collider first, FCC-ee, and later a hadron collider, FCC-hh, in an underground tunnel more than three times longer than the LHC tunnel. An accelerator R&D roadmap, coordinated by Europe's largest particle physics laboratories, has emerged as the vehicle for new technologies for the FCC and other accelerator concepts to be investigated. National laboratories in the United States, such as FNAL, BNL and SLAC, as well as KEK in Japan, are also involved in these R&D endeavours. China has started studies of a similar machine, the Chinese electron-positron Collider, or CEPC, if approved slated to start construction in the late 2020s.

Beyond Europe

Even though the LHC attracts scientists from all over the world, the facility was essentially constructed and operated with European funds. Since the FCC-ee will be about twice as expensive as the LHC, discussions about possible financial scenarios have started among the Member States of CERN: if major contributions came from outside the CERN budget, such contributors would certainly expect to have a closer involvement in CERN's governance. Are the Member States ready to invest to maintain European leadership in particle physics? Or should CERN become a "global" laboratory?

"All men by nature desire to know", said Aristotle. It is this desire that motivates us to study the intimate properties of matter and their behaviour in the earliest moments of the Universe. The question is: do we still have this desire to know in the societies of today? National science policy often extols the virtues of targeted research as a means of strengthening economies and addressing societal challenges. Physicists are as eager as anyone else to contribute to the challenges which lie ahead, but if we still want to explore unchartered territory, we need to build the necessary research infrastructures, and to continue to collaborate all over the world. ■

▲ **FIG. 1:** "I don't know if we were particularly lucky, but I really enjoyed every aspect of the summer student program: work, lectures and social life (a lot!)." CERN Summer Students 2023. © CERN

About the Author

Ursula Bassler, former CERN Council President (2019-2021), is currently scientific director at the French National Institute for Nuclear and Particle Physics (IN2P3-CNRS). As particle physicists, she worked at the HERA collider (DESY, Hamburg) and at the Tevatron (FNAL, US), before heading CEA's Particle Physics division and joining the IN2P3 directorate.

▼ **FIG. 2:** A scematic view of the possible implementation of the nearly 100 km FCC tunnel. © CERN

SHEDDING LIGHT ON THE BUILDING BLOCKS OF MATTER AND THE EARLY UNIVERSE AT CERN

Katharina Behr – Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany – DOI: https://doi.org/10.1051/epn/2023507

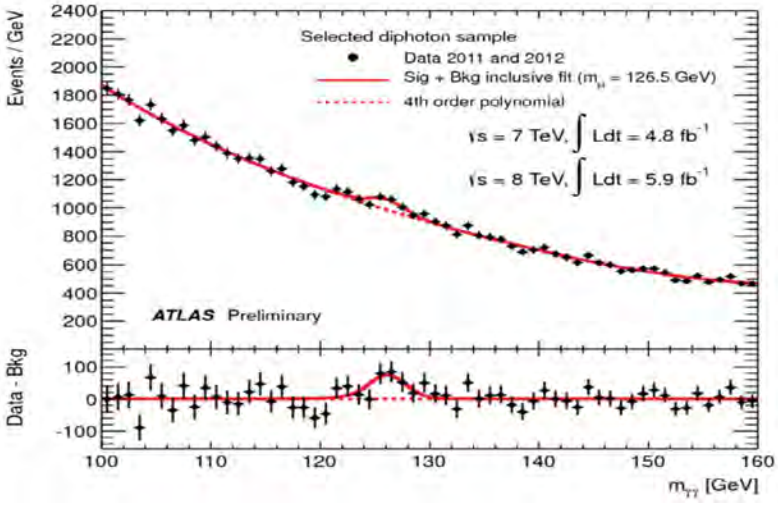
From its early beginnings, the scientific activities at CERN have been driven by the desire to uncover the fundamental constituents of nature and their interactions, and to understand how they shape the evolution of our universe. This article provides an overview of past and current research at CERN.

Prologue

It is 6 am on Wednesday, 4th of July 2012: A long, steadily growing queue has formed outside CERN's main auditorium, winding through the foyer, down the staircase, into the adjacent restaurant. Many of the younger researchers gathered here have camped outside the auditorium doors to make sure to get a seat for the announced scientific seminar. Rumour has it that two of the large experimental collaborations here at CERN will announce the discovery of a new particle that appears to be the long-sought-after Higgs boson, postulated by Peter Higgs, Francois Englert, and Robert Brout some 50 years ago to explain how elementary particles acquire mass. Peter Higgs and Francois Englert, who will be awarded the 2013 Nobel Prize for Physics, are greeted by the crowds like rockstars.

The Higgs boson discovery is one of the great achievements of the thousands of particle physicists, computer scientists, engineers, and technicians at CERN who designed, constructed, and now operate the Large Hadron Collider accelerator complex and its experiments; who engineered the world-wide LHC Computing Grid used to process petabytes of detector data; who designed the algorithms to reconstruct the raw data, to filter out the rare collision events that would indicate the production and subsequent decay of the Higgs boson.

▼ FIG. 1: The invariant mass from pairs of photons (γ) selected in the Higgs to γγ analysis, as shown at the seminar at CERN on 4 July 2012. The excess of events over the background prediction around 125 GeV is consistent with predictions for the Standard Model Higgs boson. (Credit: ATLAS Collaboration)

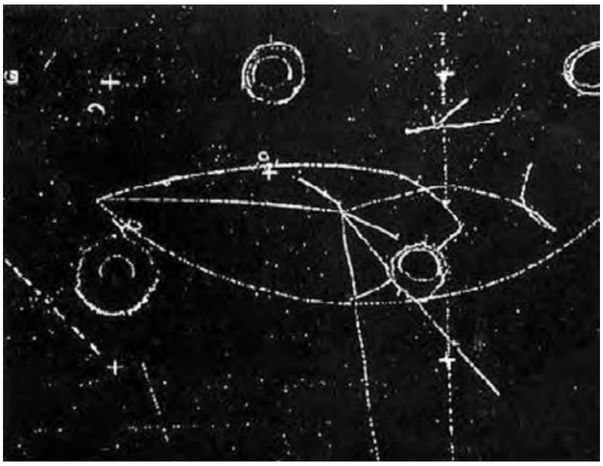


CERN's scientific profile

The discovery of the Higgs boson was not the first scientific breakthrough in the 70-year long history of CERN. From its early beginnings, the scientific activities at CERN have been driven by the desire to uncover the fundamental constituents of nature and their interactions, and to understand how they shape the evolution of our universe. When CERN was founded in 1954, only a fraction of the elementary particles we know today had been discovered. CERN made vital contributions to the understanding of the particles and interactions described in what today is known as the Standard Model of Particle Physics, the theory that describes all known elementary particles and three of the four forces of nature. A major breakthrough in the development of the Standard Model was the realisation that the weak force, which governs, for example, radioactive decays, and the electromagnetic force are in fact two aspects of a unified electroweak interaction.

Discovery of the neutral current

It was a discovery made at CERN that provided crucial experimental support for this new electroweak theory. In 1973, data from the Gargamelle bubble chamber provided the first direct evidence of weak neutral currents predicted by the new theory in events in which a neutrino scattered off a proton or neutron without turning into a muon, a process in which no electric charge is exchanged. Such reactions are the result of an exchange of a neutral vector boson, Z, which mediates the weak interaction together with the charged bosons, $W^{\pm}$. It would, however, take another decade before these particles would be observed in experiments - again at CERN.



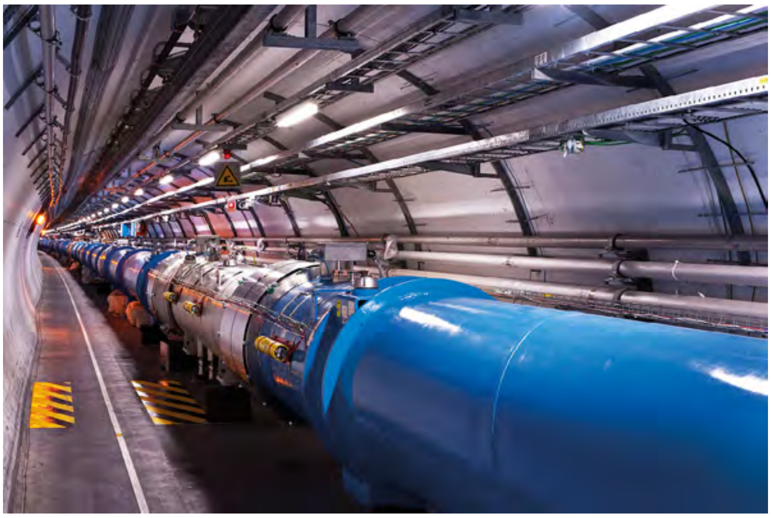
▲ **FIG. 2:** A neutral current event recorded at Gargamelle in which the interaction of the neutrino coming from the left produces three hadrons. No muon is produced. (Credit: CERN)

Discovery of the W and Z bosons

The high masses of the W and Z bosons of roughly 80 and 90 times the proton mass, respectively, meant that highly energetic particle collisions would be required to produce them. These were achieved at the proton-antiproton collider $Sp\bar{p}S$, an accelerator specifically adapted for this purpose under the direction of particle physicist Carlo Rubbia. The discovery of the W boson was presented to a packed CERN auditorium in January 1983, much as would be that of the Higgs boson 30 years later. The Z boson discovery was announced in June of the same year. Both discoveries would not have been possible without significant advancements in the field of accelerator technology, most notable the technique of "stochastic cooling", which reduces the energy spread and angular divergence of the antiproton beam, a prerequisite for the intense particle collisions needed to produce W and Z bosons at measurable rates. It was developed by CERN physicist Simon van de Meer who shared the 1984 Nobel Prize with Carlo Rubbia.

The LEP precision era and the WWW

The properties of the newly discovered bosons were studied with unprecedented precision at the Large Electron-Positron Collider (LEP), which operated between 1989 and 2000 in the same tunnel that would later house the LHC. This precision machine allowed researchers to put the theory of electroweak interactions to rigorous tests. The experimental measurements were found to be in excellent agreement with the Standard Model predictions. The increasing size and internationality of CERN's collaborations - around 1,500 physicists were involved in the LEP experiments alone - made it necessary to share information fast and efficiently across borders. It was this international research environment that prompted CERN fellow Tim Berners-Lee to develop the World Wide Web (WWW), a network browsable by hypertext links, made available to the public in 1991.



▲FIG. 3: View of the LHC (Credit: CERN)

The Higgs boson - ten years later

The Higgs boson discovery in 2012 marked the beginning of a new era of research at CERN with attention shifting to precise measurements of the properties of this new particle to understand whether it really was the Standard Model Higgs boson or a more exotic sibling. In the over ten years following the momentous discovery, tremendous progress has been made in measuring the properties of the Higgs boson, all of which so far are in excellent agreement with the Standard Model predictions. A key missing piece in our understanding of the Higgs mechanism is the question how Higgs bosons interact with each other. Higgs-Higgs interactions are extremely rare but have crucial implications for the evolution of our universe. Their observation is one of the main goals of the upcoming High-Luminosity LHC phase (2028-2038) when the LHC will operate at unprecedented beam intensities, thus producing a dataset an order of magnitude larger than the dataset that will be available at the end of its current third period of operation (2022-2025).

The puzzles that remain

The Higgs boson discovery answered the long-standing question of how elementary particles acquire mass but many others remain: What is the particle nature of dark matter, which makes up 85% of all matter in our universe? Why is there significantly more matter than antimatter in the universe, an imbalance crucial to our existence? The Standard Model fails to address these and other questions. Physicists continue to seek answers at the energy frontier during the on-going LHC run, using ever more sophisticated analysis techniques, which nowadays commonly rely on machine learning, for example to better suppress background noise. Additionally, recent and planned detector upgrades as well as a new forward detector, which started taking data in 2022, open up new possibilities to search for very light or weakly interacting particles, associated for example with dark-matter interactions, to which the experiments would previously have been insensitive.

Not just the LHC

The research programme at CERN has never been limited to large-scale colliders but comprises a diverse set of experiments covering a wide range of topics such as the study of exotic isotopes, cosmic rays, antimatter, and the search for dark matter. Notably, in 2000, experiments in which a highly energetic heavy-ion beam was shot into a fixed target, revealed the existence of a new state of matter known as a "quark-gluon plasma", a state of matter that existed about 10 microseconds after the Big Bang. It was also at CERN that the first antihydrogen atom was created in 1995 at the Low Energy Antiproton Ring (LEAR). In 2011, CERN broke further records when scientists at the ALPHA experiment succeeded in trapping antihydrogen atoms for over 16 minutes, a prerequisite for precision measurements of antimatter atoms.

Dark matter searches at the LHC are complemented by the on-going CAST and OSQAR experiments, which are sensitive to hypothetical light particles called axions in a mass range not accessible at the LHC.

The future

In parallel, scientists at CERN are pursuing advanced accelerator research for possible future colliders such as the FCC, which would initially operate as an electron-positron collider, covering an energy range similar to that of the LHC while providing a much cleaner experimental environment. This would allow researchers to study exotic or rare interactions of the Higgs boson, which itself could be a portal to dark matter, and other particles at much higher precision than achievable at the LHC. Such a precision machine could provide sensitivity to new phenomena beyond the energy reach of the LHC, which would manifest themselves as minute deviations from the predicted interactions of known particles at lower energy scales, allowing researchers to address open questions of particle physics beyond the reach of current experiments. ■

About the Author

Katharina Behr is a particle physicist and leader of a Helmholtz Young Investigator's Group at DESY, Hamburg, studying the structure of the vacuum in the data collected by the ATLAS experiment at CERN. A particular focus of her work is the search for dark matter, additional Higgs bosons, and Higgs-boson self-interactions. Katharina completed her PhD in Particle Physics at the University of Oxford on a Rhodes scholarship, following an undergraduate degree in physics at the LMU Munich.

OPENING UP HIGH-PERFORMANCE LASER SCIENCE TO THE WORLD AT THE EXTREME LIGHT INFRASTRUCTURE (ELI)

Andrew Harrison[1], **Victor Malka**[2], **Daniele Margarone**[3] and **Katalin Varjú**[4],
[1] The Extreme Light Infrastructure ERIC, Dolní Břežany, Czech Republic
[2] ELI Nuclear Physics Facility, Măgurele, Ilfov, Romania
[3] ELI Beamlines Facility, The Extreme Light Infrastructure ERIC, Dolní Břežany, Czech Republic
[4] ELI ALPS Facility, The Extreme Light Infrastructure ERIC, Szeged, Hungary

DOI: https://doi.org/10.1051/epn/2023508

The Extreme Light Infrastructure (ELI) is a research facility that provides for a wide range of scientists access to the largest and most diverse set of high-performance laser systems in the world.

▲ ELI ALPS building.

The laser systems of ELI [1] are used to study the fundamentals of interaction between matter and high-intensity, ultra-fast light pulses, including plasma physics and relativistic acceleration of electrons and protons; or drive secondary sources of ultra-fast (down to attosecond pulses), high-intensity beams of light, or particles, including ions, electrons and neutrons which are used for imaging, diffraction and fast spectroscopic studies of materials and biological systems. Such technology is also developed to explore potential applications in laser-driven compact accelerators that could provide alternatives to current central facilities for synchrotron radiation and neutron beams on a scale that could be located more readily in university departments, industrial laboratories or hospitals. ELI operates as a single multi-site organisation with ●●●

▲FIG. 1: Selected laser and target areas currently offered to ELI ALPS users (from left to right): the HR (100kHz, 1 mJ) laser in combination with NanoESCA endstation, the Mid Infrared laser (100 kHz, 0.15mJ) with experimental platform (centre) and the SYLOS (1 kHz, 30mJ) driven beamline for attosecond science.

● ● ● complimentary facilities: (i) the ELI Attosecond Light Pulse Source (ALPS) facility in Szeged, Hungary for the exploration of ultra-fast processes with uniquely high time resolution; (ii) the high-energy ELI Beamlines facility in Dolní Břežany near Prague in the Czech Republic, with a particular emphasis on high peak intensity; and (iii) the Nuclear Physics (NP) facility in Măgurele near Bucharest in Romania for the combination of ultra-intense lasers with brilliant gamma beams. A particular feature and potential strength of ELI is the complementarity of the facilities, allowing for the support of a particularly wide range of multi-disciplinary science and enabling the co-development of new, enabling technology – for example in laser optics, diagnostics or targets for secondary sources. The three ELI Facilities have been available to user access on the basis of peer-reviewed excellence through open calls for proposals since 2022. To date the ELI facilities have attracted scientists across 27 countries requesting access to 30 different instruments.

ELI ALPS

The ELI ALPS Facility[1] is dedicated to the study of extremely fast dynamics. The parallel existence of state-of-the art lasers with secondary sources and end-stations, offers unique time-resolved investigation possibilities for nonrelativistic and relativistic interaction of light. Installation of research technology started in 2017, when the specially engineered buildings were completed, including 4,000 m^2 cleanroom facilities with vibration isolation, thermal and humidity control and radiation protection. In 2023, the main construction phase of ELI-ALPS is being concluded. The priority focus is shifting from installation to commissioning and user offers. ELI ALPS provides beamtime as well as technical and scientific support for the experiments. To support a wide variety of laser based fundamental and applied research in physical, biological, chemical, medical and materials sciences, the facility hosts a combination of eight specialised primary lasers, operating in NIR and MIR regimes, from 10 Hz to 100 kHz in few cycle pulses. The laser combination drives nonlinear frequency conversion and acceleration processes in twelve different secondary sources. The attosecond secondary sources are based on advanced techniques of high-order harmonic generation in optically ionised gases or oscillating surface plasmas. Other secondary sources provide THz radiation via optical rectification or electron beams via laser wakefield acceleration for spectroscopic and structural studies, plasma physics or radiobiology. End-stations enable investigation techniques to be applied for the study of various samples: *e.g.* a reaction microscope enables the measurement of momenta of photo-fragmented molecules in coincidence; the NanoESCA characterises photoelectrons from surfaces in real and k-space, and spin. Furthermore, high-field physics experiments with the PW laser, particle irradiation of radiobiological samples, photochemical studies or time resolved nanoscience are enabled in advanced setups. Thus at ELI ALPS a uniquely broad spectral range of the highest average and peak power and shortest light pulses with specialised end-stations and a wide portfolio of diagnostics devices becomes available for the study of dynamic processes on the attosecond and femtosecond timescale in atoms, molecules, condensed matter and plasmas.

ELI Beamlines

The combination of high repetition rate capability and high energy in a single pulse of the laser systems at the ELI Beamlines facility[2] is a unique feature which allows users to explore the interaction of light with matter (plasma) at relativistic and ultra-relativistic intensities and simultaneously sustain unprecedently high repetition rate operations of about 10^{23} W/cm^2 at 1 shot/min, about 10^{22} W/cm^2 at 10 Hz, and more than 5×10^{18} W/cm^2 at 1 kHz. Such cutting-edge technologies enable pioneering research in plasma physics, nuclear fusion, strong-field physics, and laboratory astrophysics. Experiments on nonlinear quantum electrodynamics, positron, muon and gamma-ray beam generation, and planetary science are conducted by users or planned in the near future. Furthermore, laser driven particle accelerators have gained interest in recent years thanks to their versatility and innovative features, which has pushed forward the development of beamlines

---

[1] https://www.eli-alps.hu

[2] https://eli-beams.eu

where users can exploit the unique parameters such as ultrashort bunch duration and ultrahigh dose rate of laser-driven particle (ion and electron) and radiation (XUV to gamma-ray) sources for a wide range of applications in material science, AMO (atomic, molecular and optical) science, chemistry, biology, medicine, and pump-probe capabilities for high energy density physics. User experiments on probing ultrafast relaxation dynamics of atoms, irradiation of cancer cells, mimicking space radiation for testing electronics, and non-destructive surface analysis techniques for cultural heritage are conducted at the facility. The potential combination of optical, X-ray, and particle beams is also offered to users to conduct experiments related to inertial confinement fusion and shock physics thanks to the availability of a unique kJ-class, nanosecond laser beam operating at unprecedented repetition rate of about 1 shot/min and having temporal shaping capability and narrow/broad band options. A range of advanced target delivery solutions and diagnostics in operation under extreme laser-plasma conditions and unprecedented repetition rates is in continuous development and is provided to ELI Beamlines users.

ELI NP

The focus of the ELI-NP research infrastructure[3] is on research activities of laser- and gamma-ray driven nuclear physics and ultra-high intensity laser interaction and related applications. The facility aims to deliver secondary high energy radiation and particle beams with unprecedented brightness suitable for studying fundamental processes of relevance for domains such as high-energy-density physics, light sources such as betatron, Compton and FEL (Free Electron Laser), and nuclear physics. ELI-NP consists of two major divisions with state-of-the-art equipment: one related to the gamma beam system in which the radiation source is generated from Compton backscattering of laser light on a very intense beam of electrons accelerated to relativistic velocities for high sensitivity nuclear physics studies; the second one related to the high-power laser system for Ultra-High Field science studies aims at the exploration of relativistic laser-matter interaction in a range of extreme laser power and intensity; here new phenomena become significant dominated by the radiation pressure such as the acceleration of the extreme thin foil that allows for the production of a quasi mono energetic ion beam or by the radiation reaction force that affects the dynamics of charged particles and its efficient conversion to γ photons. In the last week of October 2023, a symposium was held to celebrate the 10 years of ELI-NP that is now delivering the most powerful laser beams in the world with two arms of 10 PW each that are reaching intensities of more than 10^{23}W/cm^2. The different *modi operandi* of the laser system allow users to propose a large diversity of experiments. The commissioning of the laser experimental areas was carried out through several experimental campaigns by the ELI-NP teams with the support of expert users from institutions abroad. Many challenges have been successfully tackled resulting in the delivery of multi-GeV electron beams, proton beams with energy over one hundred MeV, and bright gamma beams. ■

The scientific breakthroughs on which ELI's transformative technology is based have now been recognized by two recent Nobel Prizes in Physics: in 2018 to Mourou and Strickland for Chirped Pulse Amplification, and in 2023 to Agostini, Krausz and L'Huillier for experimental methods generating attosecond pulses.

▾ FIG. 2: (Top) Selected lasers currently offered to ELI Beamlines users in connecting experimental areas: the L1 5TW (1kHz) laser, the L3 1PW (10Hz) laser (centre), and the L4n kJ (ns) laser. (Bottom) The laser bay at ELI-NP housing lasers capable of delivering up to 10 PW.

---

[3] https://www.eli-np.ro

About the Author

Andrew Harrison is Director of Science for ELI ERIC and was previously Director General of the Institut Laue-Langevin in Grenoble and CEO of the Diamond Light Source, the UK's national synchrotron facility.

Victor Malka is Professor at the Weizmann Institute of Science in Israel and Science Director at ELI-NP. He is an expert in atomic physics, inertial fusion, and laser plasma interaction.

Daniele Margarone is Director of Research and Operations of the ELI Beamlines Facility (Czech Republic) and Visiting Scholar at Queen's University Belfast (UK).

Katalin Varjú is the Science Director of ELI ALPS, responsible for the implementation and operation of the facility. She has been engaged with the ELI programme since 2008. Katalin also holds an associate professorship at the University of Szeged. Her main research interests are in optical, atomic physics and attosecond science.

Reference

[1] Whitebook ELI – Extreme Light Infrastructure; Science and Technology with ultra-intense lasers, Mourou, Korn, Sandner and Collier (Eds) (2011) Andreas Thoss

---

OPPORTUNITIES FOR NEW SCIENCE AT ELI

A. Arefiev[1], Mihail Cernaianu[2], Florian Condamine[3] and Balázs Major[4]
[1] UC San Diego, Mechanical and Aerospace Engineering, USA
[2] ELI Nuclear Physics Facility, Măgurele, Ilfov, Romania
[3] ELI Beamlines Facility, The Extreme Light Infrastructure ERIC, Dolní Břežany, Czech Republic
[4] ELI ALPS Facility, The Extreme Light Infrastructure ERIC, Szeged, Hungary

– DOI: https://doi.org/10.1051/epn/2023509

The technology that ELI provides and is developing at a very rapid pace, so the opportunities to study new phenomena in a wide range of scientific areas are also advancing very quickly[4].

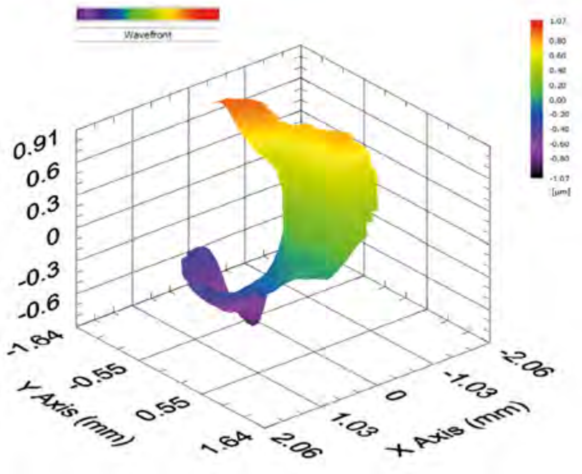
High-intensity laser-plasma interactions

Mihail Cernaianu, ELI-NP

The extraordinarily high power of the lasers and associated equipment at the ELI-NP Facility offers exceptional opportunities to explore the fundamentals of laser plasma interactions for ion acceleration and applications. Energies up to hundreds of Joules, delivered in pulses of the order of tens of femtoseconds and focused down to a few microns provide intensities of more than 10^{22} W/cm^2. However, reaching clean and controllable interaction conditions with a dense target at such intensities is very challenging due to the difficulty of achieving high temporal contrast, in which the intense peak in intensity has minimal pre-peak intensity that might stimulate undesirable phenomena. Understanding how this influences the laser-plasma interaction and finding means to control it is crucial to achieving efficient laser – plasma coupling, and will ultimately unlock the potential of high power lasers for applications such as cancer therapy involving tumour irradiation. A particular area of research into laser-plasma interactions is the production and exploitation of beams with a helicoidal phase structure – so called Laguerre - Gaussian beams. The helicity of such beams could influence and perhaps even control aspects of laser – plasma interactions [1], and nuclear physics, for example by conferring some aspects of the helicity to beams produced. Here the need to have a "clean" temporal contrast profile over many orders of magnitude in intensity

---

[4] Scientific publications at http://www.eli-np.ro/scientific_papers.php



◂ **FIG. 1:** Measurement of a laser pulse wavefront that is compressed down to 25 fs (FWHM) pulse duration. The laser pulse possesses a helical wavefront with topological charge 3 (*i.e.* three twists in one wavelength), generated by the novel technique at ELI-NP.

is even more acute, to help distinguish between the influence of the helicity of the beam on the laser-plasma interactions and potential effects due to deviations from a clean profile.

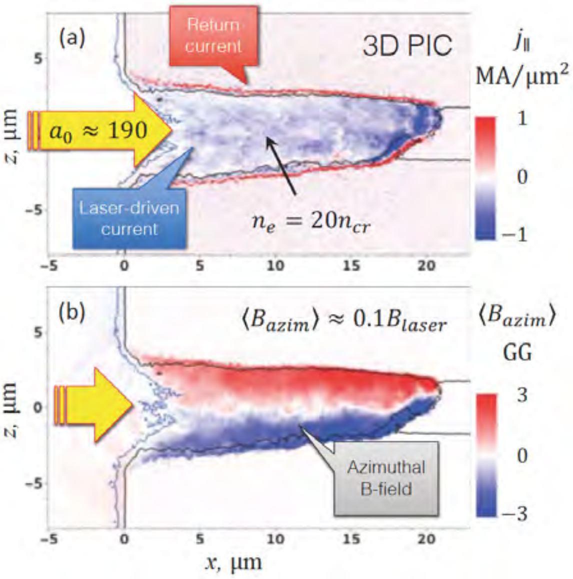
ELI-NP provided the right facilities and environment to perform such high-risk, high-gain experiments. A novel approach to produce helical laser light that could be used for multi-PW ultra-short pulse laser beams was first tested with simulations and then experimentally with some of the very first shots of the ELI-NP lasers. This work also took advantage of the very diverse skills and experience of staff and collaborators at the facility, bringing together scientists from a wide range of physical and engineering sciences, stimulated by the prospect of playing a role in ground-breaking research. The complex measurements require the support of large teams with complementary knowledge for designing and building optical setups, plasma diagnosis, detectors, controlling laser parameters, analysing data or performing simulations to understand the underlying physics and optimize the experiments. This exciting period was rewarded after four years of research with vindication of theoretical work and simulation of the nature of Gaussian-Laguerre beams on laser-plasma interactions and pointed to further improvements to experimental set-ups to control and improve the laser contrast to better understand and improve the laser – target interaction. It also became apparent that helical beams could also be used to provide further control of the parameters of the accelerated particles produced in plasmas. In addition to the significance of this fundamental science, the research also has important applications based on the improvements it could make to the technology of laser accelerated particles or secondary radiation (X-rays) for biomedical research (*e.g.* cell irradiation or hadron therapy) or applications such as X-ray imaging.

Study of gamma-ray generation in multi-PW laser-plasma interactions

Florian Condamine and Alex Alefiev

The development of high-power lasers and pulsed power devices has advanced experimental plasma physics research into regimes relevant to astrophysics. Among many topics, the direct creation of matter and antimatter from light remains elusive in laboratory research [2] This process is crucial for various phenomena, from filling the magnetosphere of a pulsar with plasma to determining the opacity of our universe. To achieve this process, a high photon density of at least multi-MeV energy (known as gamma-rays) is needed. The most suitable mechanism involves deflecting ultra-relativistic electrons (E > 100 MeV) with a strong static magnetic field, leading to the emission of MeV photons. The advent of ultra-high intensity (UHI) lasers offers a promising approach. By driving a strong magnetic field in a dense, laser-irradiated plasma, an optical laser with a peak intensity of 5.10^{22} W.cm^{-2} can induce the generation of tens of MeV photons. The field is generated through a high electron current density $|j|$ within the plasma through relativistically induced transparency a regime, accessible by UHI lasers. Figure 2 illustrates a 3D Particle-In-Cell (PIC) simulation of a plasma penetrated by a the beam and the resultant strong current and magnetic field.

In such magnetic fields, electrons are radially confined and accelerated after being injected into the the laser beam from the ambient plasma. This process, called Direct Laser Acceleration (DLA) assisted by the plasma magnetic field leads to the emission of synchrotron radiation with typical critical energies in the order of several MeVs. Considering the high density of gamma-rays generated, the two-photon process for pair production becomes achievable and measurable at state-of-the-art UHI facilities such as ELI Beamlines. Indeed, the • • •



◂ **FIG. 2:** 3D PIC simulation of a UHI laser propagating through a plasma-filled channel (a) driving a strong current and (b) generating a static magnetic field.

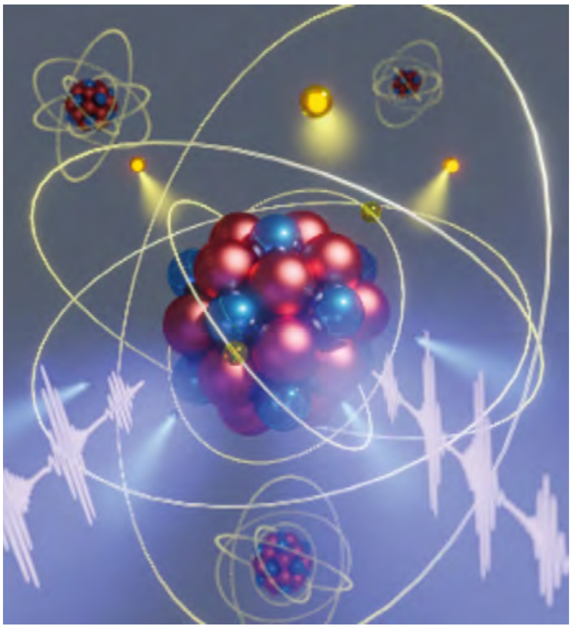
● ● ● L3-HAPLS (1 PW, 3.3 Hz repetition rate) and L4-ATON (10 PW, 1/min repetition rate) offer ultra-high intensity levels on target, up to 10^{23} W.cm^{-2}, while their repetition rates enable significantly increased statistics. This is an entire change of paradigm compared to what high-power lasers were able to provide before. But, many experimental challenges must be solved in order to generate gamma-ray beams in a reliable and reproducible way. First, the higher repetition rate necessitates mass production of targets. Very low density solid targets are required, leading to the use of complex foams to ensure known interaction parameters. While these targets reduce the number of shots per experiment, ELI Beamlines also offers a multi-beams configuration where the L3 laser is coupled with the L4 ns-kJ class laser. In this setup, the ns-kJ pulse creates a low-density plasma, into which the PW laser pulse is shot with adjusted delays to scan various densities and plasma sizes. Also, implementing active gamma-ray diagnostics in highly constrained environments (*e.g.*, EMPs, radiations) presents challenges. One solution involves using scintillators coupled with a CCD camera to capture the light emitted by gamma-rays upon interaction with the scintillators. Utilising different layers and types of scintillators, it is possible to deduce the MeV photon spectrum through unfolding techniques.

In conclusion, cutting-edge, ultra-high-intensity laser sources pave the way for studying physics phenomena encountered in the most extreme environments in the universe, such as pulsars and the gamma-ray induced pair creation mentioned here. Many challenges have to be solved to use the full-potential of such lasers. In the next decade, combining sophisticated 3D PIC simulations and complex engineering, these technologies will undoubtedly usher in a new era for laser-matter interaction studies.

Selected directions in current attosecond science

Balázs Major, ELI ALPS

The use of laser pulses to capture snapshots of superfast processes is the underlying principle of the technique of pump-probe spectroscopy at femtosecond (10^{-15}s) timescale, and was recognised with a Nobel prize in 1999. ELI ALPS aims to push the limits and applications of this method up to three orders of magnitude further – into the attosecond (10^{-18}s) regime – and make it accessible to users from around the world. This will take dynamic studies of materials well beyond following the nuclear motion that occurs in a chemical reactions as the atoms rearrange within molecules. Rather, it will allow scientists to follow the reorganisation of the electrons associated with the atoms during such processes, as the much lighter electrons move considerably faster. Understanding their motion is critical to understanding the reaction paths molecules are taking and key to answering important open questions in attochemistry.



▲ **FIG. 3:** Schematic illustration of an attosecond experiment: two intense attosecond pulse trains (white) interact with an atom, resulting in the emission of three electrons (yellow); during this process four photons (blue) are absorbed.

Attosecond pump –probe measurements nowadays allow one to study directly what happens when one or more electrons are removed from an atom through the absorption of extreme ultraviolet photons. First a train of attosecond pulses – the pump – excites the material, while the second train of pulses, each with a short, variable delay compared to the initial pulses – the probe – provides information about the resulting processes through changes in their spectral content. Such experiments have recently been carried out that even revealed multi-electron multi-photon dynamics (Figure 3) [3]. Of course, the world surrounding us does not only consist of gas-phase atoms or molecules. We should not forget about condensed phase materials, in which although different bonds are making the connection in between atomic elements, the cohesive force is also formed by the electronic cloud. Since the velocity with which particles travel is strongly correlated with their mass, the mechanisms through which condensed matter reacts to its environment happens on a time scale defined by the electron motion. As a result, the same "cameras" can be used to gain new insights in surface science or nanophysics.

A common feature of all the above is quantum phenomena. With the faster and faster measurements, one may observe the dynamics of yet smaller physical entities. The dynamics of these are inherently governed by quantum physics, and a brand new direction of science starts to blossom as the quantum aspects of attoscience begin to be unraveled. While one of the first quantum optical signatures in a strong laser pulse after interaction with semiconductors were measured in a user experiment at ELI ALPS, most recent experiments are working with non–classical light states, like squeezed light, having important potential applications in quantum information science or detection of gravitational waves. It is generally true - independent of the research field - that underlying technologies always limit what can be measured, achieved or resolved. By pushing the frontiers of ultrafast laser science ELI also extends the parameter range in which its secondary sources – such as femtosecond-laser driven attosecond beamlines – can operate. Substantial work is also put into improving the capabilities of existing attosecond beamlines at ELI ALPS and providing access to so far unobservable dynamical phenomena in all types of matter regardless of whether it is organic or inorganic. And as a user facility ELI is particularly distinctive in offering advances in cutting-edge tools for attosecond science to researchers around the world, whether they are expert in such techniques or not.

About the Authors

Alexey Arefiev is Professor at the University of California San Diego where his group studies high-intensity laser-plasma interactions using supercomputer simulations.

Mihail Cernaianu joined ELI-NP in 2013 and is responsible for the 1 PW laser driven experimental area. His research interests are in the field of laser – solid plasma interactions and applications.

Florian Condamine is an instrument scientist at the plasma physics and ultra-high intensity interaction platform at ELI Beamlines. Since 2022 he is co-PI with A Arefiev on a project to study gamma ray sources using multi-PW beams.

Balázs Major is senior research fellow, group leader at ELI ALPS, and assistant professor at University of Szeged. He chairs the Short Wavelength Sources and Attosecond/High Field Physics Technical Group of Optica.

References

[1] D. R. Blackman *et al.*, *Commun Phys* **5**, 116 (2022)

[2] G.Breit *et al.*, *Phys.Rev.* **46**, 1087 (1934)

[3] M. Kretschmar *et al.*, *Optica* **9**, 639 (2022)

thanks to the H2020 project NFFA-Europe PILOT

nffa.eu
research infrastructure

FREE ACCESS FOR ACADEMIA & INDUSTRY

LITHOGRAPHY & PATTERNING

Nanoengineered devices

High-resolution lithography for pattern generation; physical and chemical processes for pattern transfer and development. Ancillary processes for device making.

APPLICATIONS
Integrated circuits and microdevices
MEMS/NEMS (micro/nano electro-mechanical systems)
Lab-on-chips, sensors, molecular detectors,
bio-electronics, microfluidics

GROWTH & SYNTHESIS

Nanostructured materials and surface functionalisation

Layer-by-layer growth of thin films, multilayers and nanowires; synthesis of self-assembled monolayers, hybrid materials and nanoparticles; design of soft matter composites.

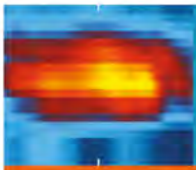
APPLICATIONS
Semiconductors, polymers and biomaterials
Electronics, optoelectronics, magnetic systems
and spintronics
Catalysis
Energy conversion & storage

STRUCTURAL & MORPHOLOGICAL CHARACTERIZATION

Including methods for atomic and nm-resolution microscopy

Structural and morphological features

APPLICATIONS
Materials structure and device engineering
Interface behaviour analysis and design
Failure analysis and quality control



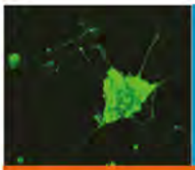
ELECTRONIC, CHEMICAL & MAGNETIC CHARACTERIZATION

Including nanolab-based tools and techniques

Electronic and chemical properties

Magnetic and electric transport

APPLICATIONS
Materials surfaces and device engineering
Fine analysis and Metrology
In-operando analysis



FROM NANO TO MICRO/MACRO

Pool of techniques from the nano-, micro- up to the macroscale

2D/3D shaping of materials, including 3D printing and 2D/3D bioprinting

Rheological, mechanical and thermal properties analysis

Electrical and thermal characterization at wafer or device level

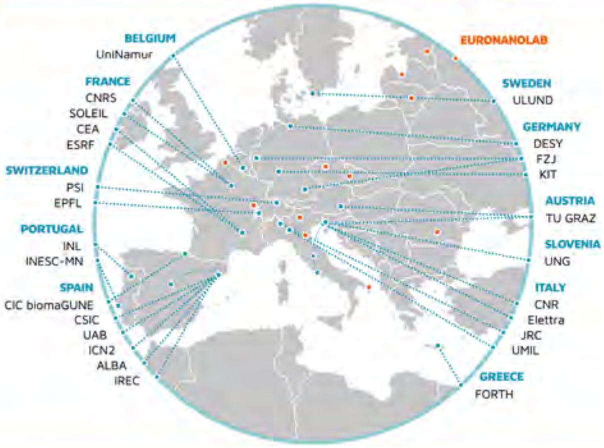
APPLICATIONS
Development, synthesis, characterization, functionalization and validation of organic, inorganic or hybrid materials

THEORY & SIMULATION

Atomistic computer modelling of materials

Scientific software, technical competences, and high-performance parallel computing for modelling the ground- and excited-state properties of nanostructured systems.

APPLICATIONS
Prediction and characterisation of structural, electronic, optical, magnetic and functional properties
Simulation and interpretation of spectroscopy and microscopy data
Insight and guidelines for the design, growth and synthesis of novel functional materials



A NETWORK OF OUTSTANDING EXPERTISE AND WORLD-CLASS FACILITIES

A pan-European infrastructure of 27 participants providing access, with a core of 12 nanofoundries co-located with Large Scale Facilities. More than 180 techniques are currently available to our users in the field of nanoscience and nano-microtechnology.

APPLY & GET FREE ACCESS JUST 4 EASY STEPS

WWW.NFFA.EU

1
BROWSE & CHOOSE
Visit www.nffa.eu, browse the offer & select the tools you need

2
SUBMIT YOUR PROPOSAL
on our single-entry point

3
HAVE IT EVALUATED
& ranked by an international peer-review panel

4
GET FREE ACCESS
and receive a contribution for travel & subsistence costs

Take advantage of our cutting-edge data services

DATA SHARING AND COLLABORATION PLATFORM

FAIR METADATA REPOSITORY

ONLINE DATA ANALYSIS TOOLS

This research project has received funding from the EU's H2020 framework programme for research and innovation under grant agreement NFFA-Europe-PILOT (n. 101007417 from 1/03/2021 to 28/02/2026)

RESEARCH INFRASTRUCTURE FOR NANO FOUNDRIES AND FINE ANALYSIS

Giorgio Rossi – Università degli Studi di Milano, Italy – DOI: https://doi.org/10.1051/epn/2023510

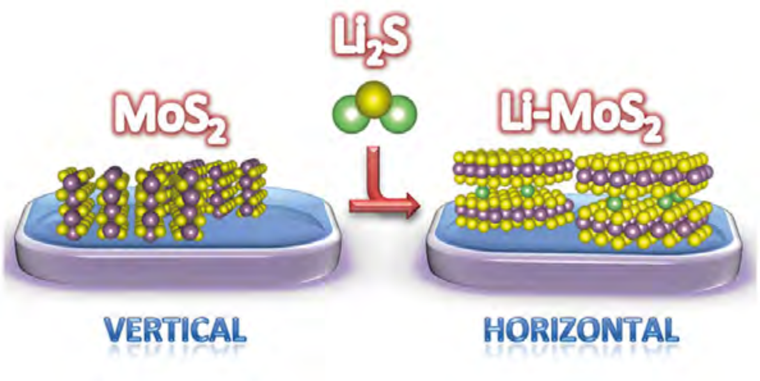
The research infrastructure for Nano Foundries and Fine Analysis (NFFA) was designed under FP7 to become a European research infrastructure on nanoscience based on integrated access of co-located foundry-type nanoscience laboratories and large-scale facilities for fine analysis. Those facilities are generally not mutually integrated nor run by the same organisations, albeit co-located in key European science campuses.

The concept of NFFA (see page 32) has been to offer project-based access to the ensemble of sample preparation, theoretical simulation, microscopic characterisation, and advanced spectroscopies based on synchrotron radiation, free-electron lasers, and neutron sources. The concept has expanded including co-location with large laser and electron microscopy facilities as well as access to academic laboratories offering unique complementary experimental and theoretical methods. 24 calls for access (4 per year) have yielded insofar 2400 laboratory sessions (8h) to be exploited by about 500 accepted integrated proposals. NEP (NFFA-Europe PILOT H2020) is the current consortium of 23 members, and a MoU among partners has been signed by 11 of them setting the foundations for long term sustainability. Advanced research projects have been run by young scientists who, based on their own talent and scientifically appealing proposals, could carry out competitive research entirely, or substantially, based on access to NFFA.

NFFA-Europe/NEP is a unique infrastructure for integrated nano-material science and physical analysis through combined access to over 180 methods and 650 instruments belonging to unique state of the art academic laboratories as well as to dedicated large scale facilities[1]. The cross-linked expertise of the access providers optimizes the research workflow for the users and provides FAIR data commons. About 800 integrated multi-method proposals have been submitted to NFFA-Europe, and about 2500 eight-hour laboratory sessions have been delivered leading to scientific publications on quantum matter, novel nano-material growth protocols, innovative methods, and practices for interoperability of instruments and data. Nanoscience defines the domain of physical phenomena that occur in matter when the lateral dimensions of the sample are reduced to the nanometric scale in one or all dimensions. Solid matter with nanometric extension displays peculiar properties that modify all order parameters present in semi-infinite solids and the associated quasi-particles display full quantum behaviour due to geometric confinement. The study of the electronic properties of solids based on band-theory has expanded first to the low dimensionality of surfaces and surface modified layers, interfaces, patterned ultrathin films, then nanoparticles and nano-domains of low-dimensional matter where topology, highly anisotropic bonding configurations, surface terminations and reconstructions, bonding to organic overlayers, display peculiar ground states and excitation properties of interest in the general quest of low-energy switchable order parameters, potentially exploitable for functionalities. Fine analysis methods are currently available to probe electron energy states at sub meV resolution and to address transient phenomena down to the fs / sub-fs time scale. Concerning sample/nanoparticle synthesis and growth, the atomic control is reached either in ultrathin films by epitaxy methods or laser-ablation deposition, or in the single quantum dot by advanced lithography, self-aggregation or single atom manipulation by tips. Concerning computational theory, the successful implementation and continuous enrichment of codes based on Density Functional Theory has also created powerful means for integrating experimental data and simulated data at the relevant level of energy, momentum, and spin resolutions to guide the researchers to robust analysis and interpretation of fine analysis data. Multiscale/multiphysics approaches support the analysis of the crossover between nano e meso scale. The mentioned resources and facilities are developed and operated nowadays by the ensemble of advanced academic •••

---

[1] www.NFFA.eu



▲ **FIG. 1:** Lithium induces the reorientation of few-layer MoS2 films. Measurements at the BACH beamline of CNR at the Elettra synchrotron facility in Italy attest to the presence of lithium in interstitial sites in Li-MoS2 films prepared by a new approach. Copyright under CC-BY 4.0

● ● ● laboratories: electron beams from meV to MeV energies, scanning probes and electron microscopy with pm resolution, laser sources for pump-probe optical magneto-optical and Raman spectroscopies. Large scale sources for fine analysis provide pulsed X-ray beams and neutron beams and highly specialized beamline instruments. Lithography, nanopatterning and growth are also available in academic laboratories and nanofabrication technologies in academic clean-rooms. Not all the above resources are designed or operated by their owners to provide users access. Nevertheless all of those have capacity for allowing significant amount of user access, under proper conditions and rules, warranting scientifically excellent usage and realizing optimal return on investment. NFFA has added to the landscape of European users' facility for physics of matter and nano-materials science an *integrated research infrastructure service organization* that enables European researchers to formulate comprehensive integrated proposals seeking combined access to all the required methods and instruments needed for carrying out their research programme.

Science enabled by NFFA

Scientific highlights examples that prove the unique value of NFFA users integrated proposals are:

1) the experimental evidence of dynamic covalent chemistry in 2D frameworks by combining in-situ variable-temperature scanning tunnelling microscopy (IOM-CNR) and X-ray photoelectron spectroscopy (ALBA) at near ambient pressure [1].

2) the fabrication of 3D superconducting nano-helices using H+ focused beam induced deposition by means of the Orion NanoFAB He+ microscope, the Omniprobe multi-gas injection system and electron microscopy at the Center de Nanosciences et de Nanotechnolgies of CNRS [2].

3) generation of optical Schrodinger cat states in intense laser-matter interactions through theoretical and experimental study: an international team of researchers (from ICFO/ICREA-Spain, Technion-China, MBI-Germany, ELI-ALPS-Hungary, and FORTH-Greece) led by Maciej Lewenstein (ICFO -Spain) and Paraskevas Tzallas (FORTH-Greece), demonstrates the generation of optical Schrödinger cat states using intense laser–matter interactions using the attosecond science and technology laboratory at FORTH, Heraklion, Greece [3].

The overall yield of impactful publications exceeds 50% of performed proposals, with a standard time delay distribution after completion of access.

Perspectives

At this time new aggregations of facilities are being explored, mostly based on methodology and technology commons as the LEAPS for accelerator-based photon sources, e-Dreams for electron microscopy, LENS for neutron scattering, RADIATE for ion sources. These aggregations may lead to common strategies in the upgrades of the services to users, but remain confined in their own, very relevant indeed, methodology/technology paradigm. NFFA is foreseeing a long-term structured research *Integrated Distributed Research Infrastructure on Nanoscience* (IDRIN) aiming to support nano-science in all its main aspects, with important intersections with the large scale facilities, but no redundancy with those as the proposals considered by NFFA are only integrated research projects requiring multiple methods and techniques at the forefront of European capabilities. The rationale is that a large part of the research community does not have sufficient in-house resources to complete advanced nano-science research project just with own methods and the competitive access to *e.g.* a synchrotron beamline. The integrated access offer of NFFA is convenient because it optimizes the exploitation of the most appropriate research resources in a time effective workflow including methods and instruments that cannot be otherwise reached unless in the framework of a scientific collaboration with the owners. From the point of view of efficient use of the LSF one can note that access through NFFA warrants high quality preparation and broad complementary information on samples and physical properties enhancing the overall outcome of the beamtime. The creation of a FAIR open repository of nanoscience data, protocols and research workflows is also an objective of NFFA aiming to increase reproducibility, data quality and robustness of the insights obtained through the infrastructure. This will spread the FAIR data culture also to the academic world. A memorandum of understanding has been signed by 11 partners of the NFFA-Europe/NEP consortium aiming to expand the action of NFFA beyond the time and scope of the EC Pilot project, due to end in 2026. The interest of the research performing organizations (mostly large RPOs from 7 EU Member States plus CH) is to consolidate the model of a research infrastructure that complements the activity of their own research laboratories realizing their full productivity potential and enlarging through external usage the science return on investment. There are clear advantages of academic research laboratories in providing a quota of access

(20-50%) to science selected external projects that combine the distributed resources of NFFA. The advantages are in the full exploitation of the resources with well-prepared access, in the continuous benchmarking of those facilities by the users that can help orienting the upgrade strategy and new investments, as well as in the possibility of science collaboration on novel research lines brought in by the users. There is therefore a two-way gain for the European research system: a unique integrated offer to users, only based on excellent science criteria, and a broad community feedback to the participating RPOs, as well as the push to make overall coherent investments to the advantage of the ERA. The most adopted legal statutes of distributed research infrastructures are of the European Consortium type, *i.e.* ERIC, or of the international association type, under a MS national law as the Belgian AISBL. In spite of a clear indication of the European Parliament there is not yet an operational instrument for a non-profit European Association, an existing status is the European Grouping of Territorial Cooperation (EGTC) but this has not yet been adopted by fully European RIs. The ERIC consortium implies the responsibility of the participating Governments and medium-term support engagements. The Association, or EGTC, on the other hand are participated by RPOs according to a statute and could be a more flexible model for adding new associates, including from the private sector.

Work is in progress for establishing a long-term sustainable NFFA-type service research infrastructure for advanced nano-science. ■

About the Author

Giorgio Rossi is Professor of Physics at the Università degli Studi di Milano. He leads an experimental research group on the physics of matter at low dimension, exploiting and operating instrumentation at synchrotron radiation facilities in collaboration with CNR and Elettra in Trieste, Italy. He coordinates NFFA-Europe since 2008. He chaired the ESFRI Physical Sciences and Engineering Strategy Work group in 2013-2016 and served as ESFRI Chair in 2016-2018. He chaired in 2019 the High-Level Expert Group on Long Term Sustainability of Research Infrastructure. He coordinated the expert group which wrote the Italian National Plan for Open Science that became effective in 2022. He represents Italy in the EOSC Steering Board and contributes as co-chair to the Policy sub-group.

References

[1] P. Leidinger *et al.*, *Nanoscale* **15**, 1068 (2023)

[2] Rosa Córdoba *et al.*, Nano Letters, DOI:10.1021/acs.nanolett.9b03153

[3] M. Lewenstein *et al.*, *Nat. Phys.* **17**, 1104 (2021).

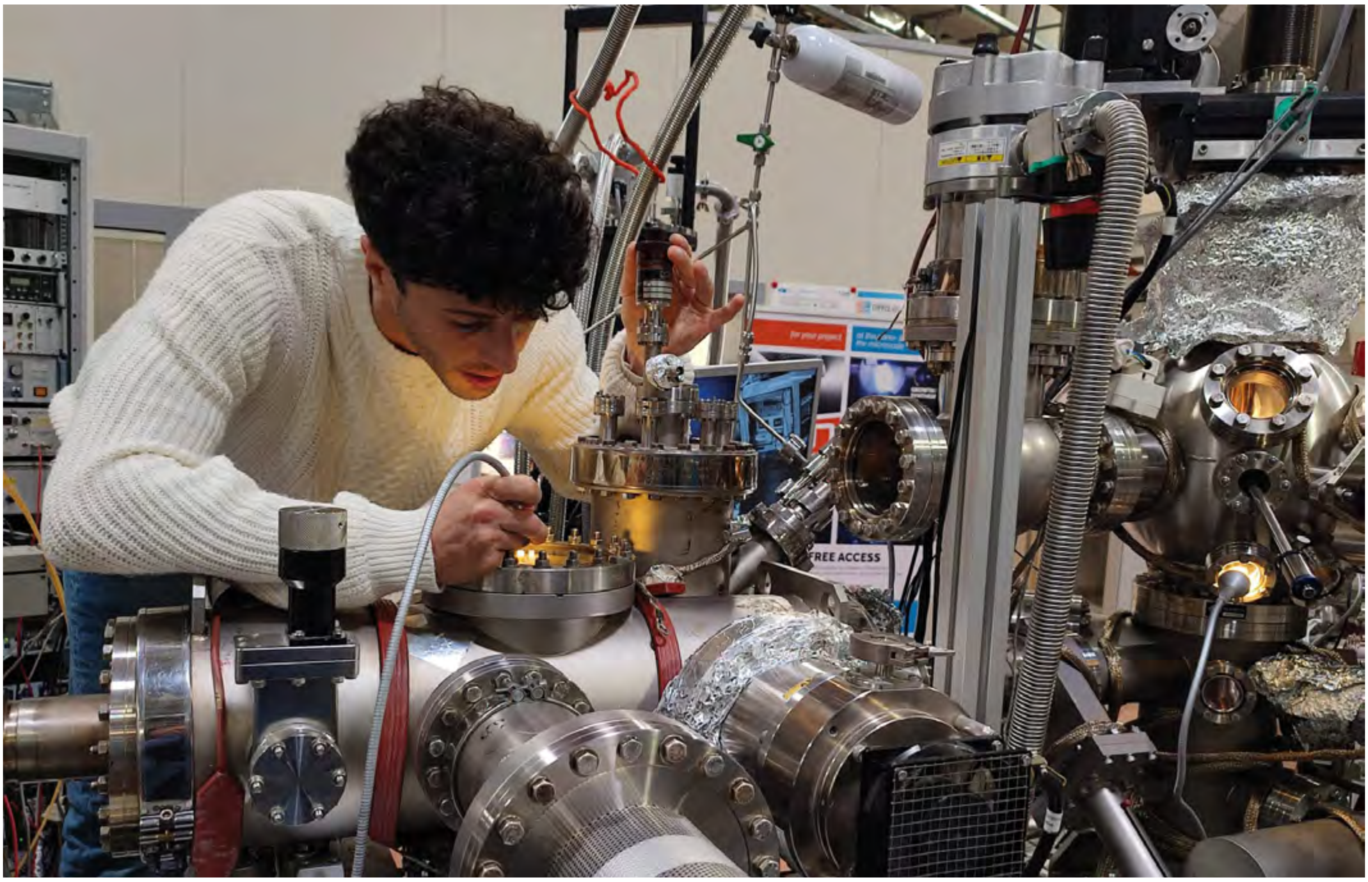
DECENTRALISING SCIENCE: A MORAL DUTY AND A HUGE OPPORTUNITY

Federico Mazzola – University of Venice Ca' Foscari and iom-CNR, Italy – DOI: https://doi.org/10.1051/epn/2023511

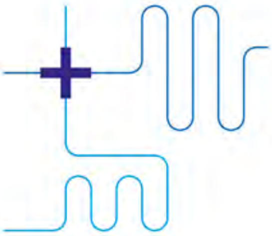
Symmetries have always been important in the description of natural phenomena. From the structure of various materials and the ordered fashion of the atoms, many properties can take place and many others can be modulated. In particular, the electronic properties of a certain system are tightly connected to the system's crystal structure. Hence, magnetism, transport of carriers, and the intertwining between these effects strongly rely on the underlying symmetries of a material.

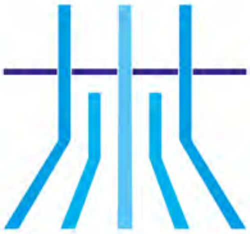
Understanding such symmetries is a goal of paramount importance because it can help us in discovering new hidden physical parameters and to use these for targeted applications.

My current research focuses on uncovering the deepest relationship between symmetries and electronic properties of quantum systems. In particular, I am interested in understanding the role of the electron spins, topology, and unconventional forms of transport in mediating a particular behaviour of the charges. To do this, I use photoelectron spectroscopies: X-rays shines on a surface and the electrons which reside in the material can be emitted. This process exploits the photoelectric effect, which was introduced by Einstein in 1905 and reason for ● ● ●



▾ **FIG. 1:** Author at work.






SHFQC
Qubit Controller
8.5 GHz
Zurich Instruments

which Einstein won the Nobel prize in 1921. The main idea is to take "snapshot" of the electron states and to decode the information that such photographs contain. As a matter of fact, the electrons in a lattice can interact with each others, can couple to lattice vibrations (called phonons), can couple to magnetically induced spin-waves (called magnons), can scatter against the material's impurities and defects. All these interactions are responsible for a very complex picture which deviates from the behaviour described by standard textbooks. We are spectators of a many-body problem, which from the one hand complicates the understanding of certain phenomena, from the other hand it paths the way to discover new physical quantities. NFFA has been a beneficial tool to develop this kind of research, helping me with resources and infrastructures to perform high quality scientific research. This was particular important in the context of infrastructures: I used NFFA to access synchrotron radiation, which compared to standard laboratory has the enormous advantage of being focused, variable in energy, and variable in polarisation. These are all necessary elements for the research I am carrying out, which, as mentioned above, is aimed at understanding the role of symmetries in mediating the electronic (and magnetic) properties of quantum materials.

In general, all crystals have some symmetries which are a reflection of the ordering of the atoms which form them. Examples are inversion symmetry, rotational symmetry, mirror symmetry, and combinations of these. If the system is non-magnetic it also has time-reversal symmetry. When a symmetry is broken, physical phenomena can occur. One example is the well-known Rashba effect: at the surface of a bulk material the inversion symmetry is broken and the electronic states lose the spin-degeneracy. Effectively, electrons redistribute by separating themselves according to their spins. If the system is non-magnetic, the time-reversal symmetry is preserved and the overall magnetisation is zero. Instead, when magnetism is turned on, the time-reversal symmetry is broken and a net magnetisation can form. When symmetries break, there is an effect on the charges, on the electron spins, on the transport, and on the magnetic properties of a system. Identifying the hallmarks which describe a symmetry breaking is often very challenging. Sometimes, such a certain phenomenon is only local and macroscopically not observable. One can think that there are hidden parameters which are not easy to access with standard tools. Recently, we have developed a methodology to tackle these ordered parameters, which combines the use of photoelectron spectroscopy and synchrotron radiation. Ultimately, the physics I am interested in resides in many degrees of freedom which are sensible to small changes of the underlying symmetries: spins, orbitals, and many-body effects. In order to achieve information from these degrees of freedom we need to develop strategies to measure them. To probe the orbital character, for example, I change the light polarisation vector which couples effectively to the parity of the orbitals of a material. One project that was recently developed undertaken the NFFA project was aimed to tackle the spin-Berry curvature in a family of kagome metals. The spin-Berry curvature is a quantity which contains information about the topology of the system. In particular, the aim was to probe the topological nature of a spin-orbit induced gap which opens in the system between spin-degenerate bands. For the current work [1] we used circularly polarised light from the synchrotron to couple to the orbital and angular momentum of the material, Lz, and thought the use of a VLEED spin detector we were able to separate the single contributions from the electron spin.

The objective of this project was to check the robustness of the topology in a charge-density wave material: the spin orbit coupling, which confers non-trivial nature to the gap of this metal, is an adiabatic phenomenon. It is a relativistic effect which couples the electron spin to the orbital motion. However, a lattice distortion occurs in the same system. Such a lattice distortion gives rise to the formation of a charge density wave. The question we wanted to address is: Will the charge density wave suppress the topological nature of the gap? Our study, which was only possible through the combination of infrastructures offered by NFFA, has demonstrated the robustness of the topology in this very emergent class of materials. NFFA, for me, offers a great opportunity to develop high-quality research projects also in the absence of large individual funding as it allows to integrate in situ capabilities of highly controlled thin film growth by pulsed laser ablation and molecular beam epitaxy, structural, morphological and electrical characterization, advanced sample preparation methods (e.g exfoliation in controlled atmosphere and UHV transfer), optical, opto-magnetic, Raman, photoelectron spectroscopy and spin-polarimetry also in time resolved mode (50-300 fs) and the possibility, as European user to access the full network of NFFA-Europe/NEP. I think that it is a great way of decentralising science and offering the opportunity to everyone to perform cutting edge research. ■

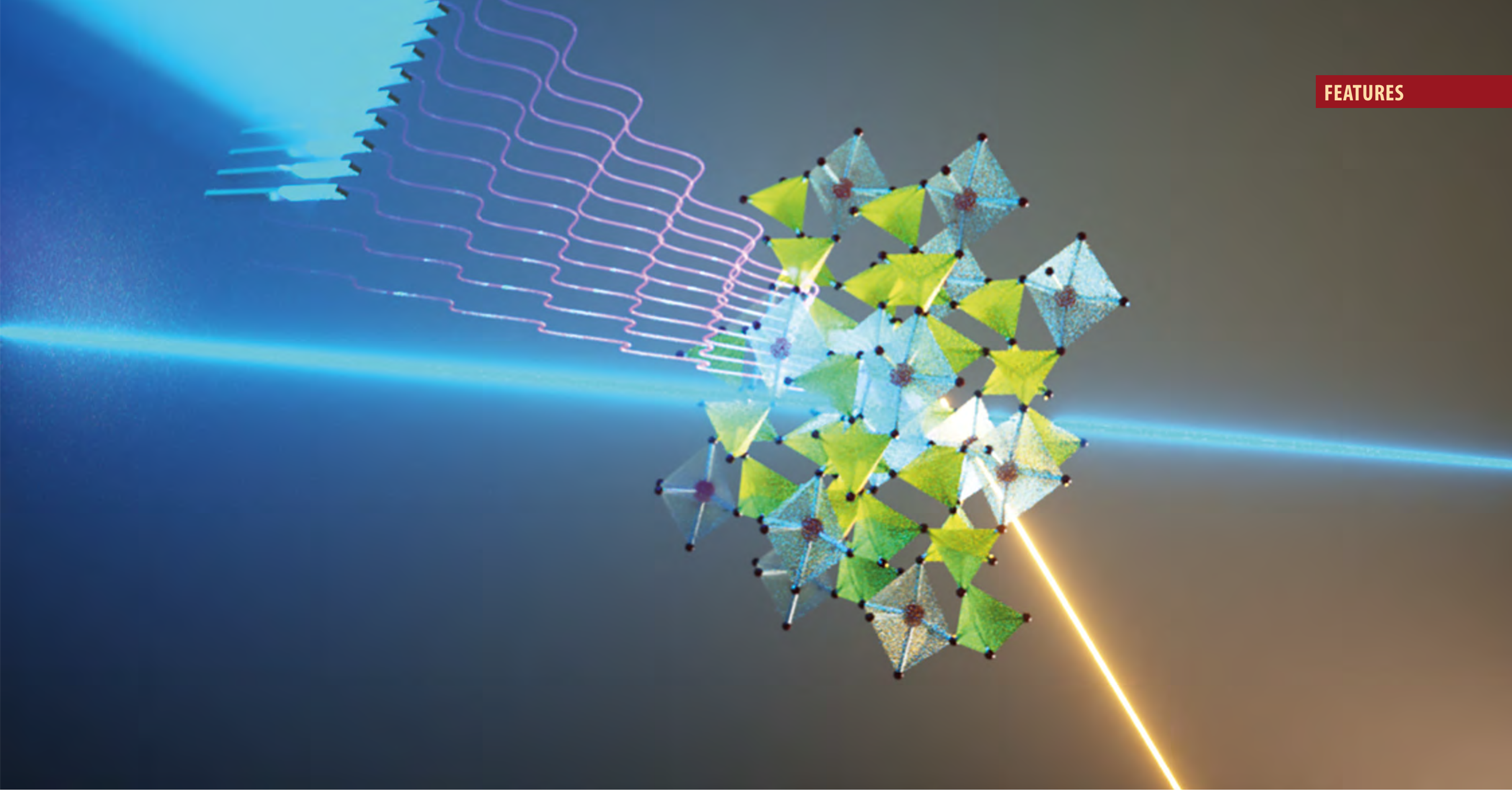
About the Author

Federico Mazzola, University of Venice Ca' Foscari and iom-CNR, Italy.

email: federico.mazzola@unive.it and mazzola@iom.cnr.it

Reference

[1] Di Sante *et al.*, *Nat. Phys.* **19**, 1135 (2023)



NON-LINEAR X-RAY SCIENCE

M. Beye[1,2], **M. Chergui**[3,4], **C. Masciovecchio**[4] and **C. Svetina**[5,6]
[1] Department of Physics, Stockholm University, SE-10691 Stockholm, Sweden
[2] Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany
[3] Ecole Polytechnique Fédérale de Lausanne, Lausanne Centre for Ultrafast Science (LACUS), ISIC, CH-1015 Lausanne, Switzerland
[4] Elettra Sincrotrone Trieste S.C.p.A., 34149 Basovizza, Trieste, Italy
[5] Madrid Institute for Advanced Studies, IMDEA Nanociencia, Calle Faraday 9, Ciudad Universitaria de Cantoblanco, Madrid, 28049, Spain
[6] European XFEL, Holzkoppel 4, 22869 Schenefeld, Germany
DOI: https://doi.org/10.1051/epn/2023512

The advent of the laser in the early 1960s represented a revolution in Optics and Spectroscopy that is still impacting our lives to this day. The availability of coherent and intense beams of laser light enabled the birth of non-linear optics as first demonstrated by the historic experiments in 1961 on second harmonic generation, and the first observation of two-photon absorption. The rapid discovery of diverse non-linear (NL) optical methods had a deep impact in Science that were recognised by Physics (1981, 2018) and Chemistry (1999) Nobel Prizes.

These developments were mainly undertaken in the optical-domain (ultraviolet, visible, infrared and terahertz), and led to the birth of photonics and optoelectronics, along with a myriad of new analytical and imaging techniques. [1] On the fundamental side, NL methods have boosted the spectroscopic study of atomic, molecular and condensed matter systems, but also of surfaces and interfaces, such as those exploiting the second-order susceptibility of the material, namely second harmonic generation and sum/difference frequency generation that are operative in non-centrosymmetric systems (Figure 1). In centrosymmetric systems, the third-order susceptibility becomes the lowest-order non-linearity, leading to phenomena such as third-harmonic generation and the so-called four-wave mixing techniques. These further enhance the above capabilities and allow, *e.g.*, via transient grating spectroscopy, to probe transport phenomena (heat, charge, magnetism, *etc.*) in materials and solutions.

With the femtosecond (fs) and attosecond (as) durations reached by pulsed laser sources, NL methods have benefited from the higher and higher peak powers for driving NL phenomena.

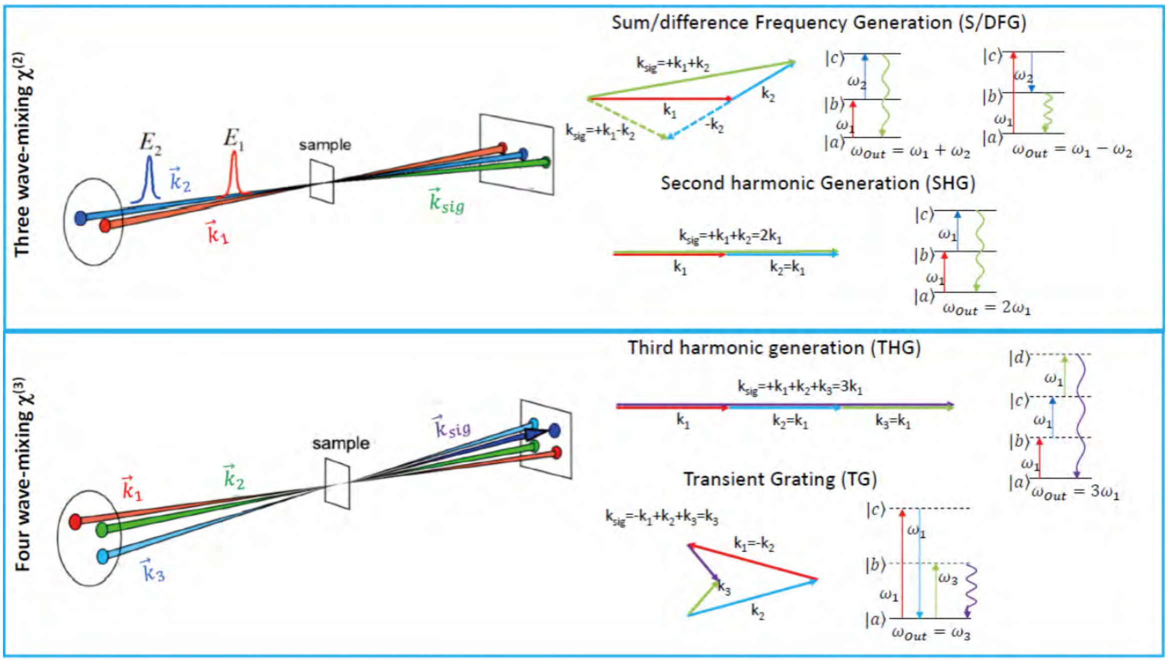
In the past 10-15 years, the advent of Free Electron Lasers (FEL) providing intense, coherent, and ultrashort pulses of short-wavelength radiation in the extreme-ultraviolet (≥10 eV, EUV) to the hard X-ray (≤20 keV) range, brought several orders of magnitude increase in photon flux per pulse (typ, 10^6) compared to the most commonly used X-ray sources that are synchrotrons, along with ultrashort (fs and as) pulse durations. This made FELs game changers for time-resolved EUV/X-ray spectroscopy and scattering methods. [2] Most significant, they are enabling the non-linear revolution in EUV/X-ray science, just as what occurred in the optical-domain lasers with the 1960s. The field of non-linear X-ray science is nascent, but the past ten to fifteen years have already brought a handful of results. The first FEL was FLASH at DESY (Hamburg, Germany) in 2005, which operates in the EUV to soft X-ray range. The first hard X-ray FEL, the Linac Coherent Light Source (LCLS), was launched in 2009 in Stanford, soon followed by the EUV/soft X-ray FEL FERMI in Italy (Trieste) and the hard XFEL SACLA in Hyogo (Japan). In 2017, three additional hard and soft XFELs went into operation: SwissFEL (Paul Scherrer Institut, Switzerland), European XFEL (Germany) and the Pohang Accelerator lab PAL (South Korea) XFEL.

It can be said that almost all the basic non-linear methods have been demonstrated in the EUV/X-ray range, as recently reviewed. [3] Two-photon absorption (TPA) accesses partially or fully dipole-forbidden transitions, thus complementing information to that obtained using one-photon X-ray absorption. The first TPA studies were carried out in the EUV and in the soft X-ray regime on rare gas atoms, and the cross-sections were found to be 2-3 orders of magnitude larger than theoretically predicted and were attributed to contributions from near-resonant states. They were followed by reports on hard X-ray TPA in Germanium and later, in Zirconium, Iron and Copper foils.

Stimulated X-ray emission (XES) and X-ray Raman (XRS) spectroscopy provide information about the energy and dispersion of the elementary low-energy excitations (vibronic, charge, magnon and orbital excitations). Stimulated EUV emission from a single X-ray fluorescence line in a Neon gas was achieved, followed by demonstrations on different solids. In the hard X-ray regime, stimulated XES was demonstrated on copper. $K\alpha$, $K\beta$ emission carry information about the electronic and spin structure of the system, while K_{VtC} (valence-to-core) additionally contains exquisite fingerprints of the chemical bond of the atom with its neighbours, and its oxidation state, covalency, *etc.* By externally stimulating these transitions, the sensitivity of emission experiments, which are inherently weak, was significantly enhanced (by > 10^5 over the conventional $K\beta$ emission).

Resonant inelastic X-ray scattering (RIXS) is an ideal tool for populating electronic valence states that are inaccessible at optical wavelengths. Stimulated RIXS (SRIXS) was first achieved for atoms, and more recently in diatomic molecules such as CO or NO. The use of attosecond X-ray pulses was shown to induce electronic population transfer via SRIXS exploiting their broad spectral bandwidth. Both stimulated resonant elastic (SREXS) and inelastic (SRIXS) X-ray scattering were recently reported near the cobalt L3 edge in solid Co/Pd multilayer samples, with 4 to 5 orders of magnitude enhancement over the spontaneous RIXS signal.

In the X-ray domain, sum- and difference-frequency generation (S/DFG) are akin to optically-modulated X-ray diffraction in which X-rays inelastically scatter from optically induced charge oscillations and therefore, they probe optically polarised charge. This additionally

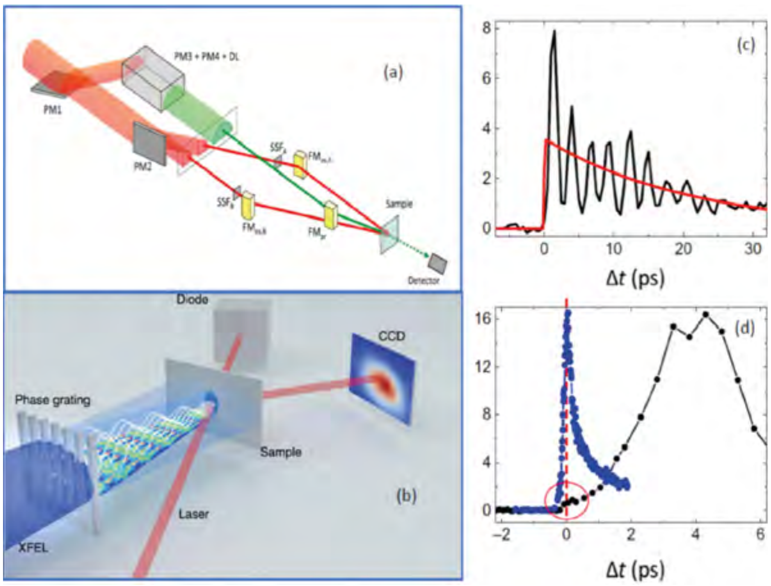


▸ **FIG. 1:** A sample of non-linear optical methods based on the second (top) and third (bottom) order susceptibility allows the optically-induced microscopic field to be determined as it is closely related to the induced charge. The experimental verification was achieved at XFELs combining an optical with a hard X-ray pulse.

In addition to being interface- and element-specific, S/DFG and and second harmonic generation (SHG) can be enhanced by resonance of the relevant photon energies with valence and/or core-level transitions. Extending SHG into the EUV/X-ray domain offers the additional advantage of element-selectivity. There are some important differences with the optical-domain in that non-linearities may be observed in centrosymmetric materials, provided a non-uniform electron density is present. These techniques also allow the monitoring of buried interfaces, in-operando catalytic processes and interfacial electron transfer, to name a few.

Among the Four-wave mixing methods, Transient Grating (TG) spectroscopy is one of the most popular. It consists in crossing two identical incident beams on the sample, where they interfere and produce a grating of excitation (thermal, charges, magnetic, *etc.*) at t=0. The decay of the grating by relaxation, diffusion or other processes, is then monitored by diffracting a third, probe beam on the grating (Figure 2). The grating period is determined by the wavelength and crossing angle of the two incident beams. Going from the visible to the hard X-ray range decreases it from microns to nanometers. This offers a unique approach to access the meso to nanoscopic range of transport phenomena. This is of particular interest as with the miniaturization of optoelectronic devices, nanoscale transport phenomena need to be understood and described, and specifically the changes from ballistic to diffusive transport. The first demonstration of EUV-TG was achieved in 2015 and it used an optical probe pulse. The advantage of mesoscale periods is however cancelled by the use of optical probe pulses, therefore this first achievement was followed by an all-EUV TG experiment (Figure 2a). [4] More recently, demonstration of hard X-ray TG was achieved exploiting the Talbot effect (Figure 2b), with promising perspectives to monitor nanoscale transport, especially when all hard X-ray TG will be demonstrated.

The above account gives a very succinct presentation of the capabilities and achievements in non-linear EUV/X-ray science. Considering the diversity and flexibility of non-linear optics, these breakthrough experiments are heralding the birth of a new era. Just as in the optical regime, non-linear EUV/X-ray science promises highly diverse and versatile applications in the study of interfaces/surfaces, transport phenomena, optoelectronics, *etc.* While all the above-mentioned methods have a high potential for applications, the holy grail is to reach core-level multidimensional spectroscopy, [5] which will allow detecting the cross-talk between atoms in any type of system. ■



▲ **FIG. 2:** a) split-and-delay scheme for all EUV TG spectroscopy; b) Talbot effect to create a TG using hard X-rays; c) all EUV-TG signal of Silicon Nitride showing coherent acoustic modes; d) comparison of the EUV-TG signal of Silicon Nitride probed by an EUV pulse (black) and an optical one (blue). This reflects the fact that the refraction index changes at optical wavelengths are sensitive to electronic excitations in the conduction/valence band, while at EUV wavelengths, they are sensitive to changes in the total electronic density, and are dominated by the lattice response.

About the Authors


M. Beye


M. Chergui


C. Masciovecchio


C. Svetina

The authors are leading figures in X-ray science. MB is known for his contributions to non-linear X-ray science, MC is a pioneer in ultrafast X-ray spectroscopy, CM has been a major driver of NL EUV science and CS is the key architect of its extension into the hard X-ray regime. MC is founder and former director of the Lausanne Centre for Ultrafast Science (LACUS) and CM is director of the FERMI FEL.

Acknowledgements

The authors are members of the steering committee of the WavemiX Network (https://www.elettra.eu/Prj/WAVEMIX/), aimed at fostering non-linear EUV/X-ray science. A COST Action "NEXT" (https://www.cost.eu/actions/CA22148/) dedicated to this field has just been launched.

References

[1] S. Mukamel, *Principles of Nonlinear Optical Spectroscopy* (Oxford University Press, New York, 1995).

[2] M. Chergui and E. Collet, *Chemical Reviews* **117**, 16 (2017).

[3] M. Chergui, M. Beye, S. Mukamel, C. Svetina, and C. Masciovecchio, *Nature Reviews Physics* **5**, 578 (2023).

[4] F. Bencivenga *et al.*, *Science Advances* **5**, eaaw5805 (2019).

[5] P. Hamm and M. T. Zanni, *Concepts and Methods of 2d Infrared Spectroscopy* (Cambridge University Pres, Cambridge; New York, 2011).

europhysicsnews
2023 • Volume 54 • number 5

Europhysics news is the magazine of the European physics community. It is owned by the European Physical Society and produced in cooperation with EDP Sciences. The staff of EDP Sciences are involved in the production of the magazine and are not responsible for editorial content. Most contributors to Europhysics news are volunteers and their work is greatly appreciated by the Editor and the Editorial Advisory Board.

Europhysics news is also available online at:
www.europhysicsnews.org

General instructions to authors can be found at:
www.eps.org/?page=publications

Editor: Els de Wolf (NL)
Email: epn.editor@eps.org - **Twitter** @elsdewolf1

Science Editor: Ferenc Igloi (HU)
Email: igloi.ferenc@wigner.hu

Executive Editor: Anne Pawsey
Email: anne.pawsey@eps.org

Graphic designer: Xavier de Araujo
Email: xavier.dearaujo@eps.org

Director of Publication: Agnès Henri

EPS Secretariat

Address: EPS • 6 rue des Frères Lumière
68200 Mulhouse • France
Tel: +33 389 32 94 40 • **fax:** +33 389 32 94 49
www.eps.org

Secretariat is open 09.00–12.00 / 13.30–17.30 CET except weekends and French public holidays.

EDP Sciences

Managing & Publishing Director: Agnès Henri
Email: agnes.henri@edpsciences.org

Production: Florence Anglezio

Advertising: Bernadette Dufour
Email: bernadette.dufour@edpsciences.org

Address: EDP Sciences
17 avenue du Hoggar • BP 112 • PA de Courtabœuf
F-91944 Les Ulis Cedex A • France
Tel: +33 169 18 75 75 • **fax:** +33 169 28 84 91

www.edpsciences.org

Subscriptions

Individual Members of the European Physical Society receive Europhysics news free of charge.

Members of EPS National Member Societies receive Europhysics news through their society, except members of the Institute of Physics in the United Kingdom and the German Physical Society who have access to an e-version at www.europhysicsnews.org. The following are 2021 print version subscription prices available through EDP Sciences (Prices include postal delivery cost).

Institutions - European Union countries: 113 € (VAT not included, 20%). **Rest of the world:** 136 €

Student - European Union countries: 54.17 € (VAT not included, 20%). **Rest of the world:** 65 €

Contact: Europhysics News, EDP Sciences
17 avenue du Hoggar - Parc d'activités de Courtaboeuf
BP 112 - F-91944 Les Ulis CEDEX A, France
subscribers@edpsciences.org or visit **www.edpsciences.org**

ISSN 0531-7479 • ISSN 1432-1092 (electronic edition)

Printer: Fabrègue • Saint-Yrieix-la-Perche, France

Legal deposit: December 2023

EPN 55th edition in 2024

Every year in September the Editors of EPN together with the External Advisory Board select the focus topics for the year to come. This is our choice for 2024.

EPN 55/1
The first EPN issue in the year is dedicated to 'Nobel prize physics', notably the physics field that was awarded the prize in the preceding fall. Consequently, the focus of EPN 54/1 will be on '**Attosecond Physics**'. Already we have invited a few experts in the field for their contribution.

EPN 55/2
For the second EPN issue to be published in April 2024, we have choosen '**Physics and Transportation**'. A broad field with links to society, but also to chemistry. If interested to submit a contribution, please contact the EPN science editor (see colophon).

EPN 55/3
The third EPN issue will be published in June/July 2024. For this summer issue we selected the focus on '**Active Matter**'.

EPN 55/4
In the September issue, we focus on '**Graphene and 2D materials**'. Are you the person who would like to share your knowledge and research in this attractive 'hard-core-physics' field? Please, contact the Science Editor.

EPN 55/5
A special Issue about '**The Universe**' will contain contributions about astrophysics, telescopes, cosmology, gravitational wave…Early next year, we will meet with established physicists to discuss the contents of the issue. ■

We wish you all a happy, healthy and safe 2024!
The EPN Editors

EUROPHYSICSNEWS
The magazine of the European Physical Society

The editors wish you all a healthy, safe and

HAPPY 2024

New EPS Historic Sites

In 2023, the following EPS Historic Sites have been inaugurated:
19 April 2023 – Racah Institute, Jerusalem, Israel
22 May 2023 – Faculty of Physics at the Alexandru Ioan Cuza University of Iași, Romania
15 September 2023 - Milutin Milankovic's office at University of Belgrade, Belgrade, Serbia
22 September 2023 - Bernoulli's physics cabinet, Basel, Switzerland
13 October 2023 – Institut de Physique Nucléaire (IPN), Orsay, France

Daniel Bernoulli's Physics Cabinet in Basel

On 22nd September, the former home of the Physics Cabinet of Daniel Bernoulli in Basel was inaugurated as an EPS Historic Site.

During his time at the University of Basel, Daniel Bernoulli assembled a large collection of demonstration experiments which he used for teaching and public lectures. These were housed in the Stachelschützenhaus ("house of the crossbow men"). The building is still used by the university and is currently the centre for clinical virology. After the lectures, attendees walked to the Stachelschützenhaus, where they were introduced to the building's history. Anne Pawsey, EPS Secretary General, and Philipp Treutlein, Head of the Physics Department, officially distinguished the house as the 6th EPS Historic Site in Switzerland.

The Mansion of Misa Anastasijevic

Milutin Milankovic (1879-1958) was a doctor of civil engineering, climatologist, geophysicist, astronomer and promoter of science, who taught at the University of Belgrade rational mechanics, celestial mechanics and theoretical physics (1909-1955). He founded an astronomical theory of climate change on Earth and applied it to the problem of the ice ages. Milankovic developed his theory of climate change to solve the problem of the Earth's ice ages during his time at the Mansion of Misa Anastasijevic. He was the first to accurately compute the climate response to insolation forcing, providing convincing evidence that astronomical mechanisms giving rise to the changes of insolation are three: the secular variations of the eccentricity of the Earth's orbit, the precession of the Earth's axis of rotation, and the variations of the obliquity of the rotation axis.

Faculty of Physics at the Alexandru Ioan Cuza University of Iași

On the 22nd May 2023, the Faculty of Physics of the Alexandru Ioan Cuza University of Iași (UAIC) has been named a "Historic Site" by the European Physical Society (EPS). The Faculty of Physics in Iasi is only the second Romanian institution to receive this honour, after the Magurele Physics Campus in 2017. The EPS distinction is a symbol to recognise that the city of Iași has been at the forefront of physics research in the region. Some of the scientific landmarks which shaped the world of physics are "the successful bone X-ray imaging and X-ray experiments (1896-1906) and the first scientific paper describing the effect of magnetic fields on chemical reactions (1894), both published by Dragomir Hurmuzescu.

EPS awards and distinctions **during the year 2023**

The EPS congratulates the 2023 laureates for EPS prizes and distinctions for their outstanding achievements in physics across Europe and around the world. The EPS is grateful to the physics community for submitting the truly excellent nominations received. The EPS highly appreciates the work by the EPS Divisions and Groups in identifying individuals and their research that contribute to the development of physics and our understanding of our world.

EPS Condensed Matter Division

The EPS Europhysics Prize was awarded to **Claudia Felser** (Max Planck Institute for Chemical Physics of Solids) and **Andrei Bernevig** (Professor of Physics at Princeton University and Visiting Ikerbasque Professor at Donostia International Physics Center), for *'seminal contributions to the classification, prediction, and discovery of novel topological quantum materials'.*

EPS Physics Education Division

The EPS Physics Education Division Secondary Teacher Award was awarded to **Sebastian Bauer** (Humboldt-Gymnasium Vaterstetten), for *'his work in developing the Humboldt Academy For Science and Technology'.*

High Energy and Particle Physics Division

The EPS High Energy and Particle Physics Prize 2023 was attributed to **Cecilia Jarlskog** (Technical University of Lund), for *'the discovery of an invariant measure of CP violation in both quark and lepton sectors'* and to **Daya Bay Reno** (KU Lueven), for *'for the observation of short-baseline reactor electron-antineutrino disappearance, providing the first determination of the neutrino mixing angle θ!""', which paves the way for the detection of CP violation in the lepton sector'.*

The EPS Cocconi Prize 2023 was awarded to **PSDSS/BOSS/eBOSS** for *'their outstanding contributions to observational cosmology, including the development of the baryon-acoustic oscillation measurement into a prime cosmological tool.'*

The EPS Gribov Medal 2023 was awarded to **Netta Engelhardt** (Harvard University), for *'for her groundbreaking contributions to the understanding of quantum information in gravity and black hole physics'.*

The 2023 Young Experimental Physicist Prize was awarded to **Valentina Cairo** (CERN), for *'her outstanding contributions to the ATLAS experiment: from the construction of the inner tracker, to the development of novel track and vertex reconstruction algorithms and to searches for di-Higgs boson production'.*

The 2023 HEPP Outreach Prize was awarded to **Jay Armas** (University of Amsterdam), for *'his outstanding combination of activities on science communication, most notably for the "Science & Cocktails" event series'.*

EPS Plasma Physics Division

The EPS Hannes Alfvén Prizes 2023 have been awarded to **Pisin Chen** (National Taiwan University), **James Benjamin Rosenzweig** (University of California) and **Chandrashekhar Janardan Joshi** (University of California) for *'proposing, demonstrating and conducting impressive ground-breaking experiments on plasma wakefield accelerators driven by particle beams'.*

The 2023 EPS Plasma Physics Division PhD Research Award was awarded to **Luis Gil** (Instituto Superior Tecnico, Universidade de Lisboa) and **Maurizio Giacomin** (Swiss Plasma Center, EPLF).

EPS Quantum Electronics and Optics Division

The 2023 EPS Quantum Electronics Prize for Applied aspects was awarded to **Giulio Cerullo** (Politecnico di Milano) for *'pioneering and outstanding contributions to the generation of few-cycle light pulses and for their application to the study of primary photoinduced processes in (bio)molecules and nanostructures'.*

The 2023 EPS Quantum Electronics Prizes for fundamental aspect was awarded to **Vahid Sandoghdar** (Max Planck Institute for the Science of Light) for *'ground-breaking research on the efficiency of light-matter interaction in quantum optics and biophysics, leading to single-molecule strong coupling and label-free detection of small proteins'.*

The EPS Fresnel Prize for fundamental aspects was awarded to **Xiaochun Gong** (East China Normal University) for *'outstanding contributions to the field of attosecond science and for developing attosecond coincidence metrology to ultrafast photonics'.*

The EPS Fresnel Prize for applied aspects was awarded to **Zuo Chao** (Nanjing University of Science and Technology) for *'pioneering contributions to computational phase imaging and metrology, particularly for noninterferometic quantitative phase imaging and high-speed 3D optical metrology'.*

The EPS QEOD - Thesis Prizes were awarded to **Andrea Schirato** (Politecnico di Milano), **Shima Rajabali** (EPFL, Lausanne), **Gur Lubin** (Weizmann Institute of Science) and **Sebastian Ecker** (Quantum Technology Laboratories GmbH).

ESPD - joint European Solar Physics Division

The 2023 ESPD Patricia Edwin PhD Thesis Prize was awarded to **Yutto Bekki** (Max Planck Institute for Solar System Research).

The 2023 ESPD Giancarlo Noci Early Career Researcher (Postdoc) Prize was awarded to **Jack Jenkins** (Postdoctoral Researcher at KU Leuven).

The 2023 ESPD Kees Zwaan Inspirational Community Prize was awarded to **Martina Pavelková** (Astronomical Institute of the Czech Academy of Science).

EPS Statistical and Nonlinear Physics Division

The EPS Statistical and Nonlinear Physics Prize 2023 was awarded to **Amnon Aharony** (University of Tel Aviv) for *'his seminal contributions in the application of renormalization group theory to critical phenomena and classification of universality classes, fractals and percolation, and the theory of disordered magnetic systems' and to* **Amos Maritan** (University of Padova) for *'his seminal contributions in the understanding the physical principles underlying collective behavior in biological systems, including protein folding, DNA organization, ecosystems, and river networks'.*

The early career prize is awarded to **Patrick Pietzonka** (Max Planck Institute for the Physics of Complex Systems) for *'his outstanding contribution the statistics of current fluctuations in active systems and to thermodynamic uncertainty relations',* and to **Ada Altieri** (University Paris Cité) for *'her outstanding contribution to theory of the jamming transition and to inter-disciplinary applications of statistical physics to species-rich ecosystems'.*

EPS Accelerator Group

The 2023 Rolf Wideröe Prize was awarded to **Katsunobu Oide** (CERN / University of Geneva) for *'his many conceptual contributions to linear and circular particle colliders.'*

The 2023 Gersh Budker Prize was awarded to **Mikhail Krasilnikov** (DESY/Zeuthen) for *'his achievements in the development of high brightness electron beams and a high power, tunable THz SASE free electron laser based on those beams, demonstrating lasing at the PITZ facility in 2022'.*

The 2023 Frank Sacherer Prize was awarded to **Xingchen Xu** (Fermilab) for *'his contributions in demonstrating the effectiveness of the internal oxidation method in Nb3Sn wires to strongly improve the performance of this superconductor by using artificial pinning centers, opening the way to the next generation of high field accelerator magnets'.*

The 2023 Bruno Touschek Prize was awarded to **Matthew Signorelli** (Fermilab) for *'his significant contribution to the design of the Electron Storage Ring (ESR) which is part of the Electron-Ion Collider (EIC). His work is aimed at a lattice design maintaining a high degree of beam polarization during collisions'.*

EPS Gero Thomas Commemorative Medal

The 2023 EPS Gero Thomas Commemorative Medal was awarded to **Christophe Rossel** (IBM Research) for *'his inspired, effective and longterm commitment to the EPS'.*

EPS directory: summary and website

EXECUTIVE COMMITTEE

President
L. Bergé
Commissariat à l'Energie Atomique (CEA), France
TEL +33 (0)169 26 7376 (or - 4000)
EMAIL luc.berge@cea.fr

Vice-President
A. Fantoni
INFN - LNF ,Frascati, Italy
TEL +39 347 3352318
EMAIL alessandra.fantoni@lnf.infn.it

Secretary
Ian Bearden
Niels Bohr Institute, Denmark
TEL +45 353-25323
EMAIL bearden@nbi.dk

Treasurer
S. Palmer
IOP Publishing Inc., Temple Circus House, UK
TEL +44 117 929 7481
EMAIL Stuart.Palmer@iop.org

Executive Committee Members
C. Beck
Queen Mary University of London, London, UK
TEL + 44 20 7882 3286
EMAIL c.beck@qmul.ac.uk

R. Caruso
Brookhaven National Laboratory , Coram USA
TEL +16318163542
EMAIL rcaruso@bnl.gov

E. Coccia
Gran Sasso Science Institute, L'Aquila, Italy
TEL +393290524040
EMAIL eugenio.coccia@gssi.it

A. Di Ciaccio
University of Roma Tor Vergata, Roma, Italy
TEL +39 3487826323
EMAIL anna.diciaccio@roma2.infn.it

A. Lipniacka
University of Bergen, Bergen, Norway
TEL +47 95786756
EMAIL anna.lipniacka@gmail.com

K. Lorenz
Instituto Superior Tecnico (IST), Lisboa, Portugal
TEL/FAX + 351-9651 52641
EMAIL lorentz@ctn.tecnico.ulisboa.pt

M. Sakellariadou, President Elect
King's College London, UK
TEL +44 020 7848 1535
EMAIL mairi.sakellariadou@kcl.ac.uk

A. Schopper
CERN, EP-LBD, Switzerland
TEL +41 (0)22 76 73158
EMAIL andreas.schopper@cern.ch

K. Zach
Deutsche Physikalische Gesellschaft
TEL + 49 177 86 01 458
EMAIL zach@vorstand.dpg-physik.de

The Secretary General is a member of the Executive Committee and most Committees ex officio (i.e. by virtue of his office).

COUNCIL

Individual Members Council Delegates
C. Agodi
INFN, Italy
TEL +39 (0)95 542461
EMAIL agodi@lns.Infn.it

W. E. Elsaesser
Technische Universitaet Darmstadt, Germany
TEL/FAX +49 6151 16 20163 / +49 6151 16 20172
EMAIL Elsaesser@physik.tu-darmstadt.de

A. Fontaine
Fondation Nanosciences, France
TEL +33 (0)6 86 55 25 58
EMAIL alain.fontaine@neel.cnrs.fr

I. J. D. Macgregor
University of Glasgow, UK
TEL +44 1413 304468
EMAIL douglas.macgregor@glasgow.ac.uk

E. Scapparone
IINFN, Sezione di Bologna, Italy
TEL +39 (0)51 209 1093 / +41 22 767 7589
EMAIL eugenio.scapparone@bo.infn.it

Associate Members Council Delegates
G. Ghiringhelli
Politecnico di Milano, Milano, Italy
TEL +39 (0)2 2399 6067
EMAIL giacomo.ghiringhelli@polimi.it

P. Giubellino
Gesellschaft für Schwerionenforschung mbH
Darmstat, Germany
EMAIL P.Giubellino@gsi.de

J. P. Glatzel
European Synchrotron Radiation Facility (ESRF), France
TEL +33 (0)4 76 88 29 68
EMAIL glatzel@esrf.fr

T. Jung
Paul Scherrer Institute (PSI), Switzerland
TEL +41 56 310 45 18 / +41 56 310 26 46
EMAIL thomas.jung@ psi.ch

T. Stoehlker
University of Jena, Jena, Germany
TEL +49 3641-9-47600
EMAIL t.stoehlker@hi-jena.gsi.de

PAST PRESIDENTS

P. Rudolf, The Netherlands (2019-21)
R. Voss, Switzerland (2017-19)
C. Rossel, Switzerland (2015-17)
J. Dudley, France (2013-15)
L. Cifarelli, Italy (2011-13)
M. Kolwas, Poland (2009-11)
F. Wagner, Germany (2007-09)
O. Poulsen, Denmark (2005-07)
M.C.E. Huber, Switzerland (2003-05)
M. Ducloy, France (2001-03)
A. Wolfendale, UK (1999-01)
D. Weaire, Ireland (1997-99)
H. Schopper, CERN, Germany (1995-97)
N. Kroó, Hungary (1993-95)
M. Jacob, CERN, France (1991-93)
R.A. Ricci, Italy (1988-91)
W. Buckel, Germany (1986-88)
G.H. Stafford, UK (1984-86)
J. Friedel, France (1982-84)
A.R. Mackintosh, Denmark (1980-82)
A. Zichichi, Italy (1978-80)
I. Ursu, Romania (1976-78)
H.B.G. Casimir, Netherlands (1972-76)
E. Rudberg, Sweden (1970-72)
G. Bernardini, Italy (1968-70)

SECRETARIAT

European Physical Society
6 rue des Frères Lumière
F-68200 Mulhouse, France
TEL/FAX + 33 389 329 440 / + 33 389 329 449
WEBSITE www.eps.org

Secretary general
A. Pawsey • **EMAIL** anne.pawsey@eps.org

PA to EPS Secretary General
O. Fornari • **EMAIL** ophelia.fornari@eps.org

Conference manager
P. Helfenstein • **EMAIL** patricia.helfenstein@eps.org

Graphic designer
X. de Araujo • **EMAIL** xavier.dearaujo@eps.org

IT manager
A. Ouarab • **EMAIL** ahmed.ouarab@eps.org

Accountant
C. Boudeliou • **EMAIL** chahira.boudeliou@eps.org

Communications Coordinator
G. Gunaratnam • **EMAIL** gina.gunaratnam@eps.org

PUBLICATIONS

EPL

Editor in Chief
B. van Tiggelen
EMAIL Bart.van-Tiggelen@grenoble.cnrs.fr

Staff editor EPL
F. Burr • **EMAIL** burr@epletters.net

Editorial Assistants
K. Desse & T. Zede • **EMAIL** editorial.office@epletters.net

EPN

Editor
E. de Wolf • **EMAIL** e.dewolf@nikhef.nl

Science Editor
F. Igloi • **EMAIL** igloi.ferenc@wigner.mta.hu

PUBLISHER

EDP Sciences

Managing & Publishing Director
A. Henri
EDP Sciences
17, av. du Hoggar - BP 112
F-91944 Les Ulis Cedex A, France
TEL + 33 169 187 575
EMAIL agnes.henri@edpsciences.org

Advertising
B. Dufour • **EMAIL** bernadette.dufour@edpsciences.org

HONORARY MEMBERS

V.G. Baryakhtar, Ukraine; **J. Bell Burnell**, Oxford, UK; **S. Bertolucci**, Geneva, Switzerland; **C. Cohen-Tannoudji**, Paris, France; **H. de Waard**, Groningen, Netherlands; **P. M. Echenique**, Donostia-San Sebastian, Spain; **F. Englert**, France; **G. Gehring**, Sheffield, United Kingdom; **T.W. Haensch**, Garching/Munich, Germany; **S. Haroche**, Paris, France; **E. Heer**, Geneva, Switzerland; **S. W. Hell**, Göttingen, Germany; **R. D. Heuer**, Geneva, Switzerland; **P. Higgs**, UK; **M. C. E. Huber**, Zurich, Switzerland; **N. Kroó**, Budapest, Hungary; **K. Langanke**, Darmstadt,Germany; **M. Leduc**, Paris, France; **L. Maiani**, Trieste, Italy; **S. Myers**, Geneva, Switzerland; **P. Nozières**, Grenoble, France; **H. F. Schopper**, Geneva, Switzerland; **G. 't Hooft**, Utrecht, Netherlands; **A. Zichichi**, Lausanne, Switzerland

COMMITTEES

Conferences

CHAIR M. Reiffers
FHPV PU / University of Presov
SK -08116, Presov, Slovak Republic
TEL +421 (0)51 75 70 604
EMAIL reiffers@saske.sk

Distinctions and Awards

CHAIR L.Cifarelli
DIFA - Università di Bologna,
Bologna, Italy
TEL/FAX (+39) 051 2091063/ (+39) 335 7902129
EMAIL luisa.cifarelli@unibo.it

Equal Opportunities

CHAIR P. Rudolf
University of Groningen,
Groningen, Netherlands
TEL (+31) 50 363 4974, (+31) 6 27 86 70 07
EMAIL p.rudolf@rug.nl

European Integration

CHAIR G. Zwicknagl
Institut für Mathematische Physik -
TU Braunschweig, Braunschweig, Germany.
TEL/FAX (0) 531 391 5206
EMAIL g.zwicknagl@tu-bs.de

Historic Sites

CHAIRS K. Grandin
Center for History of Science,
Stockholm University – KVA
SE-10405 Stockholm, Sweden
TEL +46 86739616
EMAIL karl.grandin@kva.se

Forum Physics and Society

CHAIR C. Hidalgo
CIEMAT
ES-28040 Madrid, Spain
TEL +34 (91)3466498
EMAIL carlos.hidalgo@ciemat.es

Young Minds

CHAIR R. Zeltner
FAU Erlangen-Nürnberg, Experimental Physik
D-91054 Erlangen, Germany
EMAIL richardzeltner@gmx.de

DIVISIONS & SECTIONS

Atomic, Molecular and Optical Physics

CHAIR J. Burgdörfer
Technische Universität Wien (TU Wien)
AT-1040 Vienna, Austria
TEL +43-1-58801-13610
EMAIL burg@concord.itp.tuwien.ac.at

Sections

European Group on Atomic Systems (EGAS)
Chemical & Molecular Physics Section
Electronic & Atomic Collisions Section

Condensed Matter Division

CHAIR J. M. de Teresa
IDAEA
Consejo Superior de Investigaciones
Científicas (CSIC)
ES-50009 Zaragoza, Spain
TEL +34 976762463
EMAIL deteresa@unizar.es

Sections

Liquids Section
Low Temperature Section
Macromolecular Physics Section
Magnetism Section
Semiconductors & Insulators Section
Structural and Dynamical Properties of Solids
Surfaces & Interfaces Section

Education

CHAIR S. Schmeling
CERN, Meyrin, Switzerland
EMAIL sascha.schmeling@cern.ch

Environmental Physics

CHAIR J. Orphal
Karlsruhe Institute of Technology (KIT)
D-76344 Karlsruhe /
Eggenstein-Leopoldshafen, Germany
TEL +49 (0)721 608-29120
EMAIL orphal@kit.edu

Gravitational Physics

CHAIR M. Sakellariadou
King's College London - Strand
London WC2R 2LS,
United Kingdom
TEL +44 020 7848 1535
EMAIL mairi.sakellariadou@kcl.ac.uk

High Energy & Particle Physics

CHAIR F. Maltoni
Université catholique de Louvain,
Louvain-la-Neuve, Belgium,
TEL +32 484 360156
EMAIL fabio.maltoni@uclouvain.be

Nuclear Physics

CHAIR A.Fantoni
INFN - LNF ,Frascati, Italy
TEL +39 347 3352318
EMAIL alessandra.fantoni@lnf.infn.it

Physics in Life Sciences

CHAIR F. Ritort
University of Barcelona
ES-08028 Barcelona, Spain
TEL + 34-934035869 / +34-934021149
EMAIL ritort@ffn.ub.es

Plasma Physics

CHAIR R. Dendy
Centre for Fusion, Space and Astrophysics (CFSA)
Department of Physics,
University of Warwick
Coventry CV4 7AL, United Kingdom
TEL/FAX +44 01235 466377 / +44 024 7615 0897
EMAIL R.Dendy@warwick.ac.uk

Sections

Beam Plasma and Inertial Fusion Section
Dusty and Low Temperature Section

Quantum Electronics & Optics

CHAIR G. Cerullo
Dipartimento di Fisica, Politecnico di Milano
20133 Milano Italy
TEL/FAX +39 02 2399 6164 / +39 02 2399 6126
EMAIL giulio.cerullo@polimi.it

Joint European Solar Physics

CHAIR I. Ballai
University of Sheffield
School of Mathematics and Statistics (SoMaS)
S10 2TN Sheffield, United Kingdom
TEL +44 (0114) 2223833
EMAIL i.ballai@sheffield.ac.uk

Statistical & Nonlinear Physics

CHAIR R. Burioni
University of Parma, Parma, Italy
TEL 0521 905492
EMAIL raffaella.burioni@unipr.it

Complete directory online at:
➥ www.eps.org/search/custom.asp?id=298

GROUPS

Accelerators Group

CHAIR P. Mcintosh
ASTeC, Science & Technology Facilities Council
Warrington, UK
TEL +44 (01925) 603899
EMAIL peter.mcintosh@stfc.ac.uk

Computational Physics Group

CHAIR C. M. Bertoni
Università di Modena e Reggio Emilia
Dipartimento di Scienze Fisiche,
Informatiche e Matematiche
IT-41125 Modena, Italy
TEL +39 5920 55288
EMAIL carlo.m.bertoni@gmail.com

Energy Group

CHAIR A. Portone
Fusion For Energy, Barcelona
TEL/FAX +34617974158
EMAIL alfredo.portone@f4e.europa.eu

History of Physics Group

CHAIR K. Grandin
Center for History of Science
Stockholm University – KVA
SE-10405 Stockholm, Sweden
TEL/FAX +46 86739616
EMAIL karl.grandin@kva.se

Physics for Development Group

CHAIR J. Niemela
Abdus Salam ICTP
APP-FDL
IT-34151 Trieste, Italy
TEL /FAX +39 040 2240 607 / +39 040 2240410
EMAIL niemela@ictp.it

Technology and Innovation Group

CHAIR C. Rossel
IBM Research-Zurich
Science and Technology Department
CH-8805 Richterswil
TEL +41 44 7248522
EMAIL rsl@zurich.Ibm.com

NATIONAL SOCIETIES

Albania, Armenia, Austria, Belarus, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, Iceland, Israel, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Moldova, Montenegro, The Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, Russia*, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom

ASSOCIATE MEMBERS

ALBA-CELLS, AMPEGON/OCEM, AYIMI, CAEN SpA, CEA Saclay, CECOM, CENTRO FERMI (Museo Storico della Fisica), CERN, CNR Roma, CONSORZIO RFX, DESY, DIPC, EDP Sciences, EPFL SPC, ENEA, ESRF, EUROfusion, FOM, GSI, HZB, IBA s.a., IBM Research GmbH, INFN Frascati, IOFFE*, IPPLM Warsaw, IST Lisbon, JINR, LSC, MPI Festkörperforschung, MPI Plasmaphysik, MPI Science of Light, NORDITA, POLIMI, PSI, SINCROTRONE Trieste, SISSA, University of Geneva, University of Zurich

RECOGNISED JOURNALS

Europhysics news, E-EPS, EPL, European Journal of Physics, Physics Publishing Alliance, ECA & Conference Proceedings, Society newsletters, Recognized Journals, Annual Reviews.
See website: www.eps.org/publications

* suspended cooperation

ANNUAL INDEX VOLUME 54 - 2023

MATTER INDEX

AUTHOR INDEX


Mag-13MS100
Three-Axis Magnetic Field Sensor
Bartington