INRIM

Metrology towards 2030

INRIM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

Developing relevant measurement science and technology


ISTITUTO NAZIONALE DI RICERCA METROLOGICA
INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

Foreword from the president

INRiM is the national metrology institute of Italy and therefore responsible for the development of measurement science and technology, and its application for the benefit of industry and society, both on national and international level.

Our industry and society, however, is rapidly changing. The recent progress in neural networks has allowed for efficient implementation of machine learning algorithms which will change, for instance, the way we drive cars, perform medical diagnoses, control industrial processes, and take strategic decisions in general. The full impact that the current digital revolution will have on our lives in the near future is difficult to foresee.

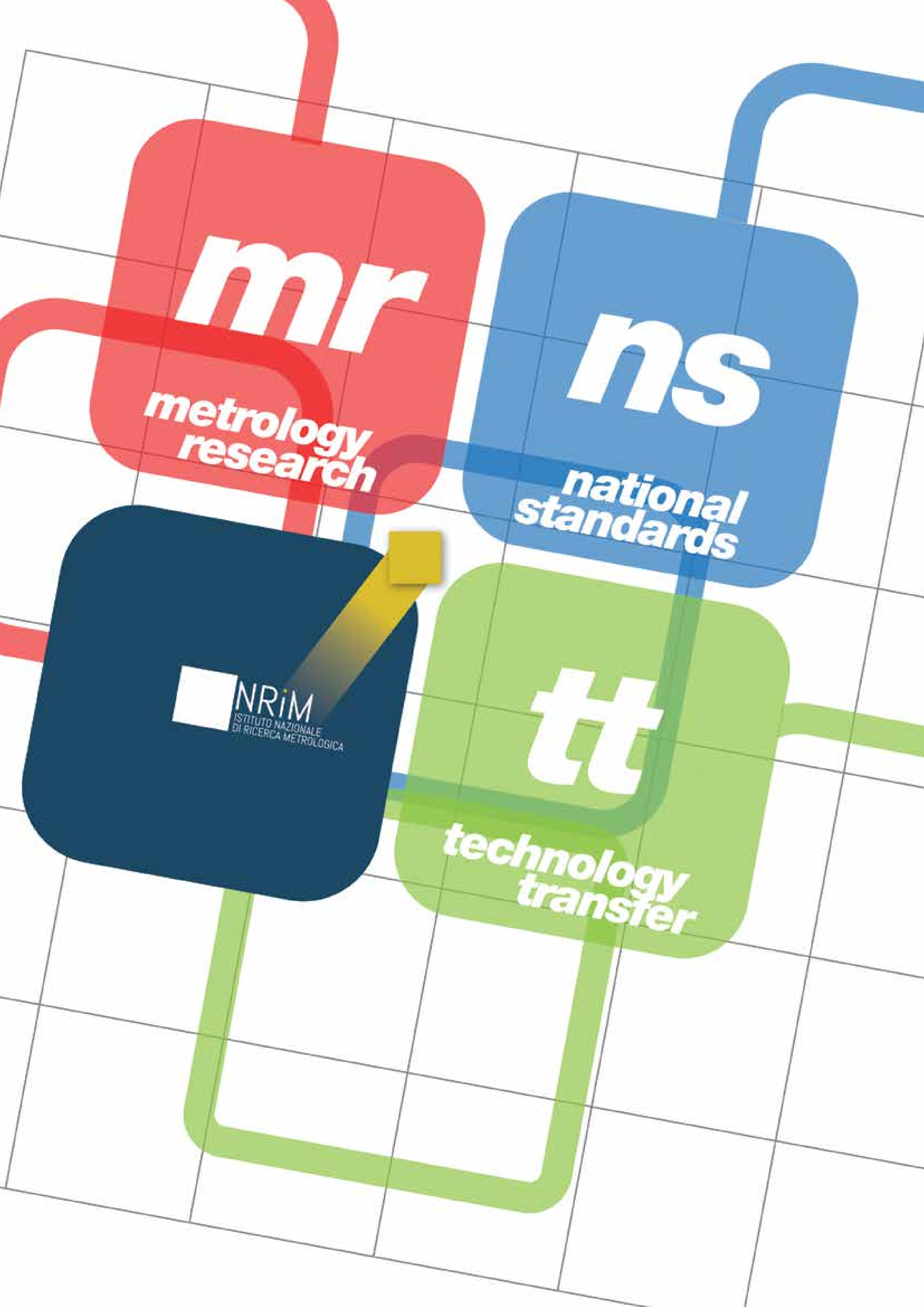
At the same time humanity has put unprecedented pressure on the resources offered by our planet, which means we have to deal with important global challenges including climate change induced by global warming, environmental pollution on various scales, and potential scarcity of resources such as energy, food, and drinking water.

Within this rapidly changing context one can ask the question how metrology research and technology can and should develop such that its impact for industry and society can be maintained and further improved. The new international system of units (SI) has just become into force and this completes an important chapter in the history of metrology research and technology. This also means we have the opportunity and responsibility to ask ourselves how to move forward from here.

This document will discuss the above points and provide a vision for the role that INRiM can play in the coming decade, based on its three major pillars: metrology research, national standards, and technology transfer, and within the current national and international context.

Diederik S. Wiersma
President INRiM

Torino, 23 July 2020.


mr
metrology research
ns
national standards
tt
technology transfer
NRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

Metrology provides the knowledge and technology that allows to perform measurements accurately and in a way that people trust. It also provides a form of language which is relevant for the organization of our society, for industry, and for other fields of science.

The relevance of metrology in the coming decade

A - Impact for industry

An important role for metrology has been, and will remain, to ensure the adequate functioning of industry on national, European, and world-wide level, enable high quality standards and thereby create trust. INRiM will be more proactive in the coming decade in creating opportunities for industrial involvement, and at the same time increase its activities in technology transfer. The high level technology which is developed by INRiM for metrology purposes can provide a precious resource for both national and world-wide industries.

Major changes are taking place in industry, including a pervasive digital transformation which aims to use large sensor networks with wireless connectivity for taking better decisions as part of the Industry 4.0 concept. This enhanced metrological capability goes together with automation and with the extremely rapid development of neural networks and machine learning algorithms. Hence metrology tools will have to be developed that can deal with large amounts of data and virtual entities, and that can provide trust in decisions taken by artificial intelligence. Information technology security has to be assured in this process.

B - Impact for society

Metrology plays an important role in our society and provides, for instance, a common language for trade. Moreover, it provides the tools for reliable measurements and certifications related to food, drinking water, and health. INRiM will help apply and develop new metrology useful for dealing with global challenges on energy conversion and storage, environment and pollution, and support the initiatives within the European Green Deal aiming to make Europe climate neutral in 2050. In some cases the development of new metrology tools is challenging, like for instance in the case of lifetime and efficiency studies of batteries and photovoltaic solar cells where the parameters are currently not fully understood. Others include the definition and implementation of reliable indicators that consumers can use to understand the environmental impact of a product, both during its use and production phase.

C - Impact for other fields of science

The technology developed for the science of measurement is of great value for fundamental science, and scientific research in general. By measuring with greater accuracy, new physical phenomena can be discovered and theories tested. It is of the benefit for INRiM to strengthen more ties with other scientific communities. The cross fertilization that can follow will allow to explore better the use of measurement science for other fields of research while at the same time provide inspiration to develop new and better measurement technology.

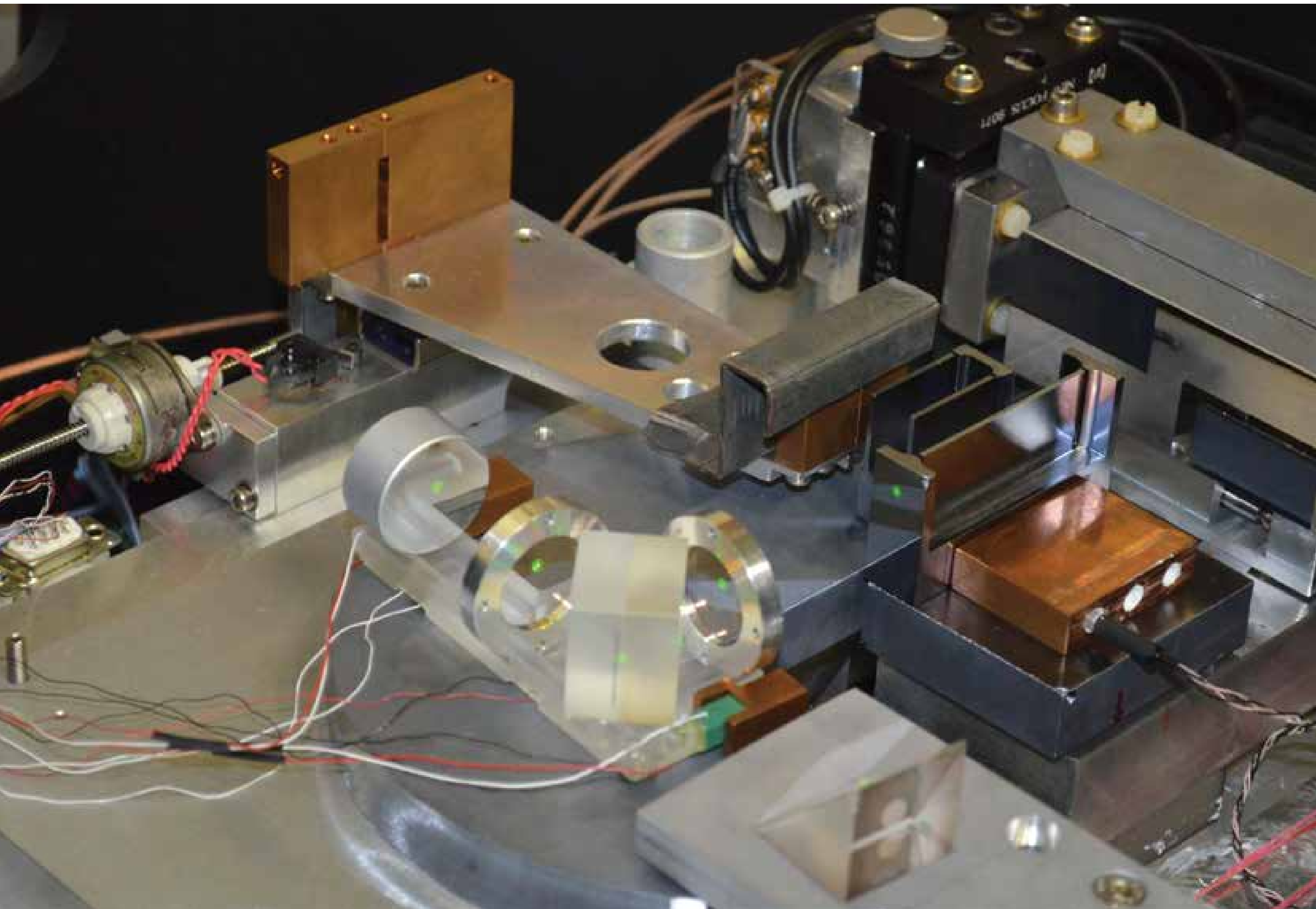
Measurement technologies

Measurement technologies – which can be classified by their technology readiness levels (TRLs) – range from **classical technologies** (high TRL), to **quantum** (medium-low TRL), and further down to those technologies for **chemical and digital metrology** (typically low TRL) that mostly have to be developed. Classical measurement technologies have been in use for long time. The document "Metrology – in short" (EURAMET, 3rd edition) includes an exhaustive list, which goes beyond the purpose of this short section. The focus here is to highlight some challenging trends, which will dominate metrology during the next decade.

Advanced functional materials, nanotechnology, biotechnology, and space technology require enhancing metrology at the atomic and nanometer scale. Enhanced precise metrology relies mainly on optical techniques and quantum optics, which uses quantum mechanics to investigate phenomena involving light and its interaction with matter. For example, quantum entanglement can be used to beat the diffraction limit and to pave the way towards quantum metrology for high-resolution and highly sensitive measurements. Moreover, these technologies offer the possibility to extend our fundamental understanding of materials at the atomic and nanometer scale.

The realm of metrology will be substantially enlarged by dealing with novel challenges in assessing the quality of chemical measurements used to preserve the environment, and improve the energy infrastructure and public health system. Environmental monitoring, energy commodities, clinical diagnostics, health status markers, and food safety are all examples requiring better chemical metrology. Typical challenges here include the need to measure multiple physical quantities at the same time, the dependence of chemical measurements on the considered batch, and the intrinsic variability of biological/biomedical samples. These challenges have profound metrological implications. For example, they explain the need of Certified Reference Materials (CRMs), which are used to check the quality and metrological traceability of products, to validate analytical measurement methods, or for the calibration of instruments. Moreover, biomedical research and the healthcare industry require biobanks, which are biorepositories that store biological samples (usually human) for use in research.

Finally, during the next decade, we cannot underestimate the role of digital transformation. The use of novel digital technology leads to a highly interconnected economy, industry, and society. Measurement results, data, algorithms, mathematical and statistical procedures, as well as communication and security architectures form the basis of digital expansion and transformation. In this context, it is essential that metrology embraces this paradigm shift. In particular, among many others, there are two significant challenges, namely improving the underlying mathematical, computational, and statistical sciences used in testing and measuring, and developing standardization and calibration protocols for a digital metrological infrastructure.



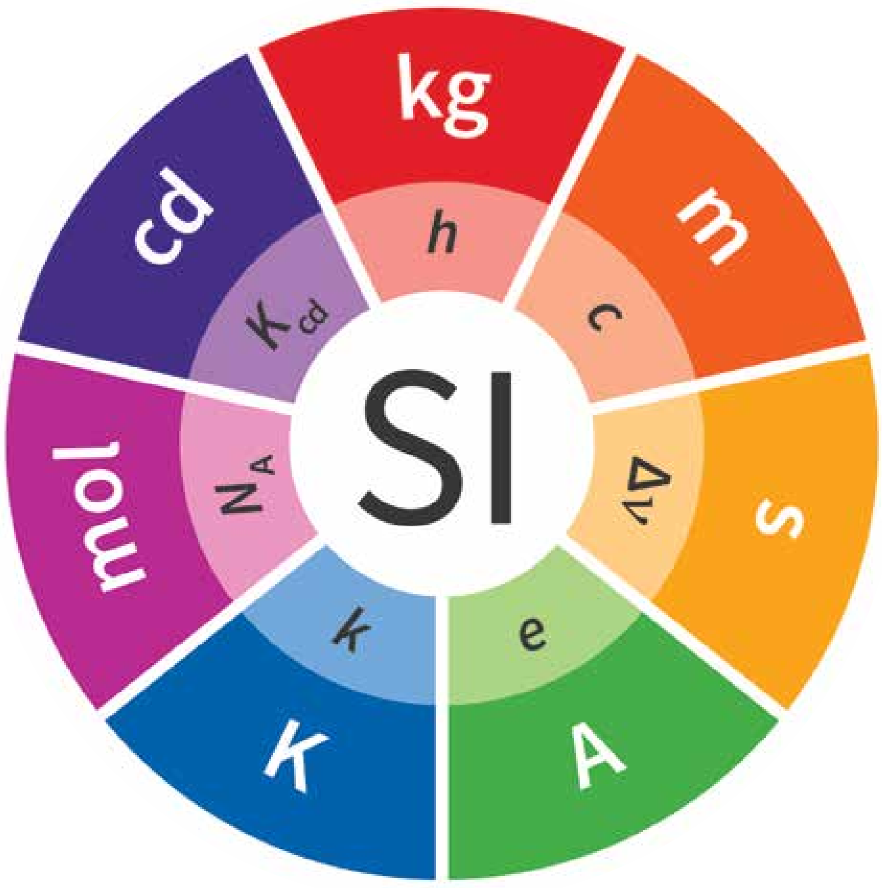
Implementation of the new SI

Italy is a founding member of the Metre Convention – the international treaty that, since 1875, is the basis of the international agreement on units of measurement. The International System of Units (the SI) is the system adopted by the Metre Convention. It is the basic language for measurement in science, technology, industry, and trade since it was established in 1960.

The SI is a practical and dynamic system, evolving to exploit the latest scientific and technological developments. In November 2018, the 26th *Conférence Générale des Poids et Mesure*s approved a complete revision of the SI: the tremendous advances in atomic physics and quantum metrology of the last decades are now fully incorporated in the SI.

Each of the seven SI base units is now linked to a corresponding fundamental constant of nature, to which a fixed value with zero uncertainty is assigned. The *mise en pratique*, or practical realization, of an SI unit is a physical experiment that performs a measurement of a quantity in terms of one (or more) fundamental constants.

INRiM is in charge of implementing the practical realization of the SI units, their scaling to multiples and submultiples, and the continuous availability of these realizations using artifact standards periodically calibrated to the *mise en pratique*. For each unit, this entire process is what constitutes the corresponding Italian national standard.



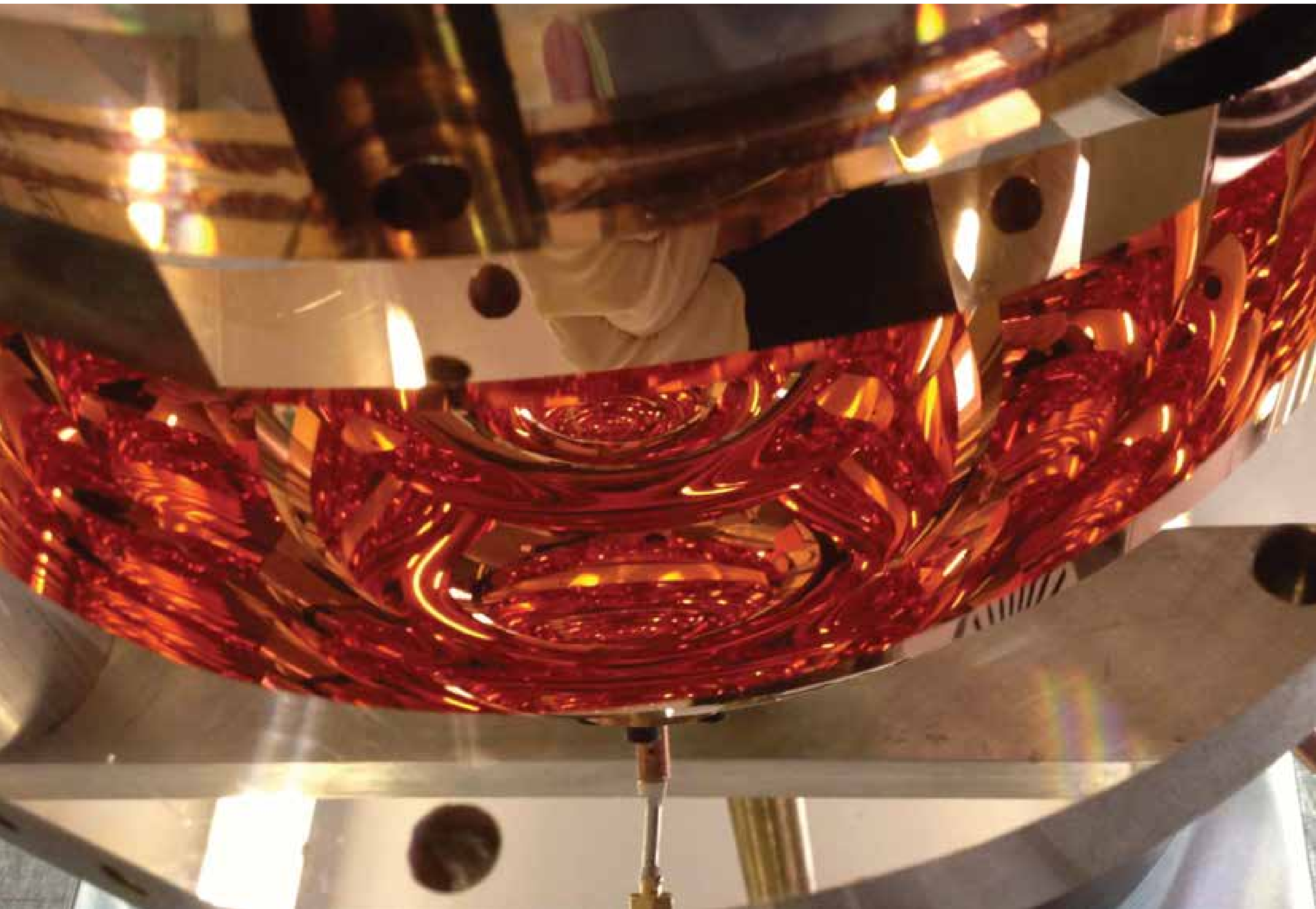
Several **scientific and technical challenges** are posed to INRiM by the SI revision.

The fundamental constants chosen for the definition of the units include the elementary charge *e*, the Planck constant *h*, and the Boltzmann constant *k*. These constants underpin quantum electrodynamics; the realization of a unit requires to exploit the manifestation of the quantum behavior – typical of elementary particles – in macroscopic physical phenomena. The experiments for practical realizations involve reaching extreme physical conditions (ultra-low temperatures, intense magnetic fields, ultrahigh vacuum), detecting individual elementary particles (electrons, photons), extremely fine control of the probing parameters (microwave or optical frequencies, temperature, …), and managing experimental noise down to, or even below, the quantum noise level.

Although suggested *mises en pratique* of the SI units are available, the revised SI imposes specific phenomena or experiments to achieve the definition of a unit. Any experiment that links the unit to its defining constant is a realization. The same unit can be realized in different ways and at a different magnitude level. In these years new physical phenomena are being discovered, and others are becoming practically exploitable because of scientific and technological improvements. Investigating which of these phenomena will provide accurate and convenient practical realizations of SI units is a major challenge, both for INRiM and for metrology research in general.

Hard engineering of the experimental devices is a basic requirement to transform a fragile physical phenomenon in a robust national standard of primary accuracy and which can cover the range of values of practical interest. This proper engineering is in itself cutting edge research involving micro- and nano fabrication, precision mechanics and optics, material science, mixed-signal electronics, vacuum and cryogenic technologies, signal processing techniques, and automation. The engineering process can be further developed to create turn-key standards suitable to be employed in an industrial environment.

Research and development in INRiM has to point towards the implementation of the SI into new Italian national standards. This will be achieved by performing research on the physical phenomena which probe the fundamental constants fixed by the SI, on the design and fabrication of devices and of the corresponding measurement setups capable of a practical realization of the unit, on the generation of scales, and on accurate systems for calibration of artifact standards. These newly developed national standards will be validated by international intercomparisons within the framework of the Mutual Recognition Arrangement, and affordable and efficient calibration services will be provided to ensure the dissemination of the SI units in Italy. Efforts will be made to transfer the newly developed technologies to the Italian research institutions, calibration laboratories, and industry.



(Inter)national position of INRiM

INRiM is the national metrology institute of Italy and depends both financially and legally on the Ministry of Research (MUR), while at the same time it has a link with the Ministry of Economical Development (MISE) – responsible for, amongst others, the Italian delegation at the *Conférence Générale des Poids et Mesures*.

While INRiM has its headquarters in Turin, its ambition is to strengthen its national position through joint laboratories with universities, public research institutes, and private R&D entities, and by exploiting the possibility of creating designated laboratories on topics that cannot be handled by INRiM directly.

Modern metrology has an international vocation – the need for standard measurements emerges from scientific, industrial, and commercial reasons, which clearly transcend national borders. A large part of INRiM's activities is integrated in international collaborations, which is also of immediate benefit to the national community.

The four main international references for the institute are:

- the **CIPM (*Comité International des Poids et Mesures*)**, which is the hearth of the international metrology community and of the meter convention. Italy is signatory of the convention since it's beginning and is actively involved in the CIPM, the Mutual Recognition Arrangement, and in its consultative committees;
- the **BIPM (*Bureau Internationale Poids et Measures*)**, which is the international organization established by the Metre Convention through which Member States act together on matters related to measurement science and measurement standards;
- **EURAMET,** which coordinates the metrology at European level and supports research programs with EU funding;
- the **European Union**, who sets the main direction of scientific research in Europe.

INRiM shares the strategic view of EURAMET to develop an integrated metrological structure in Europe – stimulating synergies among the national metrology institutes – to foster a competitive and sustainable industry for the wellbeing of the EU citizens.

The instruments for this goal are the research programs dedicated by the EU to metrology (EMRP, EMPIR, and EMP). The participation of INRiM in these programs is of fundamental strategic importance since it stimulates international integration and provides significant additional resources.

One of the pillars of EURAMET in the next decade will be the realization of European Metrology Networks (EMNs) as a tool to face the future challenges in measurement science, and to give to European metrology an additional value. INRiM is currently already involved in six EMNs, while others will follow:

- EMN for Quantum Technologies (relevant for space applications, fundamental science, and industrial transitions)
- EMN on Smart Electricity Grids (relevant for clean technologies)
- EMN on Climate and Ocean Observation (relevant for environmental monitoring)
- EMN for Mathematics and Statistics (relevant for digital transformation and fundamental science)
- EMN on Traceability in Laboratory Medicine (relevant for quality of life and health)
- EMN on Advanced Manufacturing (relevant for industrial transitions)

The participation in these networks will increase the capability to deal quickly with industrial requests, internationalize metrology services, and help to focus the activities of INRiM on strategic topics that are consistent with the focal points while, at the same time, will increase the visibility of INRiM at national level.

INRiM is well-integrated in the EURAMET community and aims to strengthen its scientific relations with non-European NMIs and metrological research bodies. Bilateral agreements were signed in the past and new ones are foreseen. Among them we highlight the relations with NIST (U.S.A.), NMISA (South-Africa), NIM (China), BGU (Israel), and NPLI (U.S.A.).

Metrology services and quality infrastructure

The Quality Infrastructure – according to the definition provided by the United Nations Industrial Development Organization – is the system comprising the organizations (public and private) together with the policies, relevant legal and regulatory framework, and practices needed to support and enhance the quality, safety, and environmental soundness of goods, services, and processes. A properly functioning Quality Infrastructure, which relies on metrology, standardization, accreditation, conformity assessment, and market surveillance, is essential for the effective operation of the domestic market of a country, as well as for the accessibility to foreign markets.

In Italy, the national Quality Infrastructure is based on the National Calibration System which provides traceability to the national primary standards and is composed of the National Metrology Institutes (NMIs) and Accredited Calibration Laboratories. The National Metrology Institutes perform the studies and research in order to develop these primary standards, which implement the base, supplementary, and derived SI Units. The NMIs guarantee the highest possible quality of their standards by international comparison and make them available for dissemination.

INRiM is responsible for maintaining the primary measurement standards for all fields, apart from ionizing radiation. As Italian NMI, the mission of INRiM is to provide the measurement capability that underpins science and technology for addressing the global challenges in environmental protection, energy sustainability, healthcare, robust and sustainable industrial development, space technologies, and fundamental science. INRiM works with both the international and European scientific metrology organizations – BIPM and EURAMET respectively – and both contributes to and benefits from the Mutual Recognition Arrangement whereby Institutes worldwide recognize the validity of each other's calibration and measurement certificates.

INRiM offers more than 400 Calibration and Measurements Capabilities (CMCs) recognized by the CIPM Mutual Recognition Arrangement and published in the BIPM key comparison database for physical and chemical measurements in: mass and related quantities; length; electricity and magnetism; time and frequency; thermometry; photometry and radiometry; acoustics, ultrasound, and vibration; and chemistry. INRiM offers measurement capabilities for calibration and testing which meet most of the national science and technology requirements, and world level – tightly controlled – facilities, partly located underground to increase stability. The institute will rationalize its CMCs in the coming period, closing those which have become obsolete and renewing those that are of strategic importance.

With the increase in world trade and the implementation of new regulations regarding safety, health, and environment, metrology in chemistry has grown in importance in recent times and will keep doing so in the next decade. Metrology in chemistry consists of the development of reference methods, the production of certified reference materials, and the provision of proficiency schemes. A certified reference material is a reference material for which one or more property values are certified by a procedure that establishes traceability to a realization of the unit in which the property values are expressed. Each certified value includes an uncertainty statement. Metrology in chemistry will be essential for developing national measurement standards for health, pharmaceuticals, agriculture, food safety, environment, climate change and clean air, chemicals, metals, and energy.

INRiM issues about 1800 calibration certificates per year which is multiplied by the accredited calibration laboratories into 120.000 calibrations and through the large network of accredited testing laboratories results in 5 million tests per year. It is the vision of INRiM that the number of calibration certificates per active CMC can be doubled in the coming decade. Supporting this significant effort within the context of a growing National Calibration System requires the development of a digital metrological infrastructure – thereby taking maximum advantage of novel digital technologies in a world where the economy, industry, and society will be increasingly interconnected. In particular, this digital transformation requires developing standardization and calibration protocols which are specific for digital technologies.

Capacity building

Capacity building forms an essential part of the activity of INRiM and it is our vision to intensify our activities in this respect.

We intend to do this by:

- increase the training of young researchers and technicians;
- continue active involvement in the organization of the "Enrico Fermi" summer school in metrology together with the BIPM and the Italian Physical Society;
- support PhD programs;
- active participation in metrology networks;
- stages at INRiM of high school students and students from technical schools and internships by bachelor's and master's students.

The PhD program in metrology provides an excellent opportunity to train future researchers and will be further supported. Financial coverage should be guaranteed both from institutional and project funding. Within the context of EURAMET it is beneficial to explore the extension of this program on European level.

Among the tasks of metrology networks, it is important to highlight the activity of capacity building – aimed towards smaller metrology institutes worldwide to help develop their metrological capabilities and improve international integration. This activity is based on training and hosting of young researchers, to provide them with the most advanced technical competences and capabilities.

The "Enrico Fermi" summer school on metrology is an initiative of great international resonance, including the participation of Nobel laureates coming from academia and metrology institutes from all over the world. A broad range of topics is covered including the most recent developments in metrology research. INRiM will maintain its proactive role in the organization of this school. The engagement of students from countries traditionally less represented is an important goal for the future editions.

Public engagement

INRiM has an important responsibility, and a unique opportunity, to generate knowledge outside the institutional environment which will benefit social, cultural, and economic development, and generate broader interest for the topic of metrology.

Current activities which INRiM intends to continue and strengthen include the participation in public events (like e.g. the *Notte dei Ricercatori, Settimane della Scienza, Onda di Scienza, Festival della Scienza*, Open Days), and tutorial lectures at schools, academic environments, and public places. An activity of strategic importance is that of short term stages and training events for (high school) students and people from industry.

With the new definition of the SI, it has become important to offer training activities for high school teachers and develop instruction tool-kits. INRiM will dedicate an important effort to this. Hands-on training will be made available at all levels, from children to high school students, teachers, people from industry, and the general public. INRiM will explore the possibility of setting up a dedicated training and outreach facility. Scientific courses for the general public, like the training courses called "Protons For Breakfast" currently organized by NPL (the NMI of the UK), can be developed by INRiM in a similar way. Site visits to the laboratories will remain to be a pillar of the outreach activities of INRiM, open to any age category and background whereas the historical site in Corso Massimo d'Azeglio in Turin will be further developed within the context of outreach and training.

It is important that INRiM does not limit itself to local outreach activities but develops initiatives in all regions of Italy with particular focus of important strategical cities as Rome, Naples, and Milan. To that end, portable material will be further developed to promote the new SI throughout Italy. In addition, high quality contributions on the internet are foreseen, including to existing scientific outreach websites, simisura.it, dedicated Wikipedia pages, and social media.

Focal Points

- Monitoring the environment and supporting the development of clean technologies
- Supporting sustainable energy conversion and clean storage
- Supporting the quality of life and health
- Accelerating digital transformation and supporting industrial transitions
- Developing technology for space applications and research
- Improving the quality and impact of fundamental scientific research

Monitoring the environment and supporting the development of clean technologies

The state of our environment poses a major concern in our rapidly changing world. Research programs at national, European, and worldwide level dedicate special attention to environment technologies and the protection of the fragile environment in which we are living. Metrology can play an important role, for instance in assessing climate change and pollution.

Monitoring the environment requires a huge amount of data, collected by different sources (satellites, air-based, marine-based, terrestrial networks, etc), which require careful traceability, calibration, uncertainty evaluation, and conformity assessment for instruments and procedures. Moreover the global environment is very complex and hence monitoring initiatives must deal with the specific requirements of atmosphere, sea, and land under investigation, including those under extreme environments (e.g. mountains, polar regions, etc).

Monitoring the environment is not only a scientific challenge per se, but it is also a trigger to supporting the development of clean technologies. Efficient and reliable assessments of pollution and greenhouse gas emissions in each step of a value chain or during a product life cycle is crucial. In recent years, various methodologies have been developed to quantify and report greenhouse gases emissions, among other things, (i) for companies during the whole value chain, (ii) for products life cycles, (iii) for emission-mitigation projects. Standard protocols are important for planning, comparisons of strategies, products and companies, and for transparent public reporting. However, whereas such a holistic approach is becoming ever more common at the corporate level, end-users tend to focus on very few steps, neglecting large parts of the product life cycle. Faithful measurements of the emissions and clear communication and explanation to the citizens is therefore very important.

INRiM will strengthen its activity in both metrology for the environment and the detection of pollution and greenhouse gas emissions. INRiM supports the European satellite navigation system (Galileo), which is a key component also for Earth observations, and further developments can be foreseen in the calibration of space borne equipment like spectro- radiometers. INRiM will apply, and further develop, atmospheric measurements (like temperature, humidity, wind anemometry), metrology for ocean observations, and geophysics measurements using high precision frequency metrology.

To address pollution and greenhouse gas emissions, INRiM will further develop its gaseous primary standards to determine the isotopic composition of carbon dioxide, apply thermodynamic characterizations of new refrigerants with low global warming potential, develop techniques for the identification and quantification of micro-/nano-plastics in food and environmental matrices, and develop certified reference materials for the quantification of technology-critical elements (e.g. rare-earth elements, antimony, etc).

INRiM will perform the above activities in synergy with international institutions for climate and environment like the UN Commission for Climatology, the World Meteorological Organization and its programs on Global Climate Observing System and Global Cryosphere Watch, and standardization bodies (ISO).

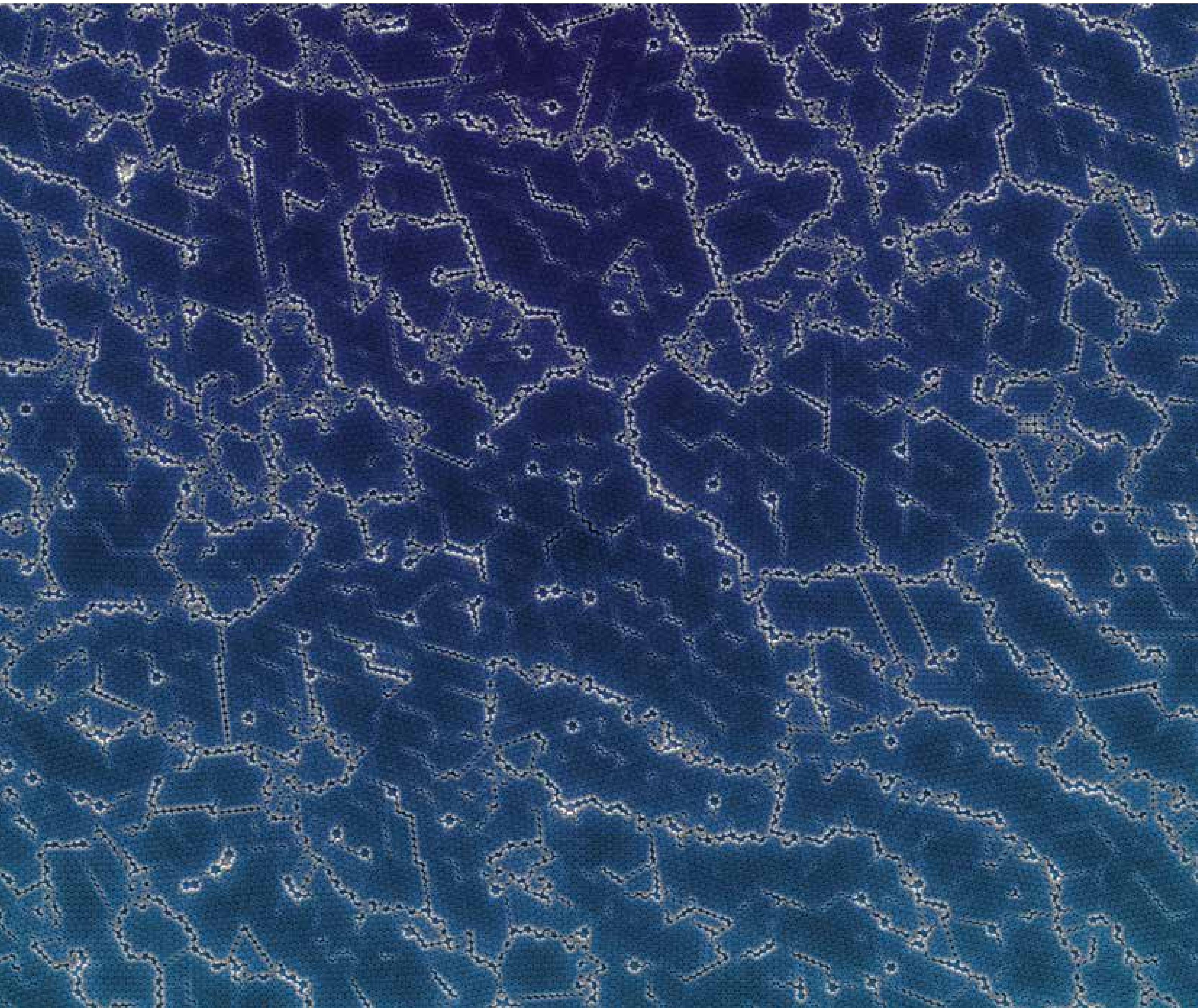
Supporting sustainable energy conversion and clean storage

The public concern with environmental consequences of energy conversion and storage has increased rapidly in recent years. Effects on the environment happen at all stages, from extraction of raw materials, through manufacturing, distribution, consumption and disposal, and include the depletion of natural resources, pollution, and the degradation of soil and forests.

A limit to the energy that can be made available from renewable sources, which are intermittent and partially unpredictable, is given by the distribution grid and the storage capacity. Various storage approaches are under development that allow for an increase of self-consumption of electricity by small scale photovoltaic systems, support frequency and voltage regulation of the distribution grid, and decouple energy generation from demand over the time scale of one day. However, batteries play a prominent role because they are particularly suited for the car industry, which canalizes large resources for research and development. Battery production is rather expensive and emits large amounts of greenhouse gases, but the longer the life cycle of a battery the lower is the pollution over the whole life cycle, especially if this allows to replace fossil fuels by renewable sources. Introducing renewable sources into the energy infrastructure is extremely challenging for the grids, because of the need to compensate energy intermittency and to balance energy users and producers. This is typically achieved also by smart metering. Smart electrical, thermal, and fluid grids open new challenges, also because they require new paradigms in distributed metrology and user data protection. Thus, the problem is complex and its solution does not depend only on mere technical improvements but also on social habits, organization, and coordination on a national and international level. Hence the metrological challenge includes the development of methods to measure advantages for the community in such a complex context, and measurements of habits of citizens.

INRiM will support the set of initiatives comprised in the European Green Deal with the overarching aim of making Europe climate neutral in 2050. As a public research institution, INRiM has a natural role in research and development of measurements for energy conversion and storage devices, in close synergy with industry. In particular, INRiM has experience in experimentally characterizing and designing new materials which will be applied for the development of solid state batteries and super-capacitors. Moreover, INRiM will apply its experience in energy measurements for the development and operation of smart electrical, thermal and fluid grids, and storage facilities. The institute will also apply its know-how on the thermodynamic characterization of combustion fluids to help develop circular economy solutions including fuel generated out of atmospheric CO_2 and storage via power to gas. The assessment of energy conversion and distribution in e-transport applications will deserve particular interest, as well as measurement technologies for batteries and charging stations.

Because of its technological competences, INRiM will be able to work also on the reduction of primary energy consumption in different applications: solid-state lamps/lights (LED) with high efficiency, low-power data storage and smart devices, and smart energy materials (e.g. with controlled moisture or optical response). Moreover, INRiM will extend these activities by providing also the corresponding metrological services (e.g. services for electrical grids, certified reference materials for thermal and moisture measurements, primary standards for thermal and humidity measurements for energy-related applications, traceability for large gears for windmills, amongst others).



Supporting the quality of life and health

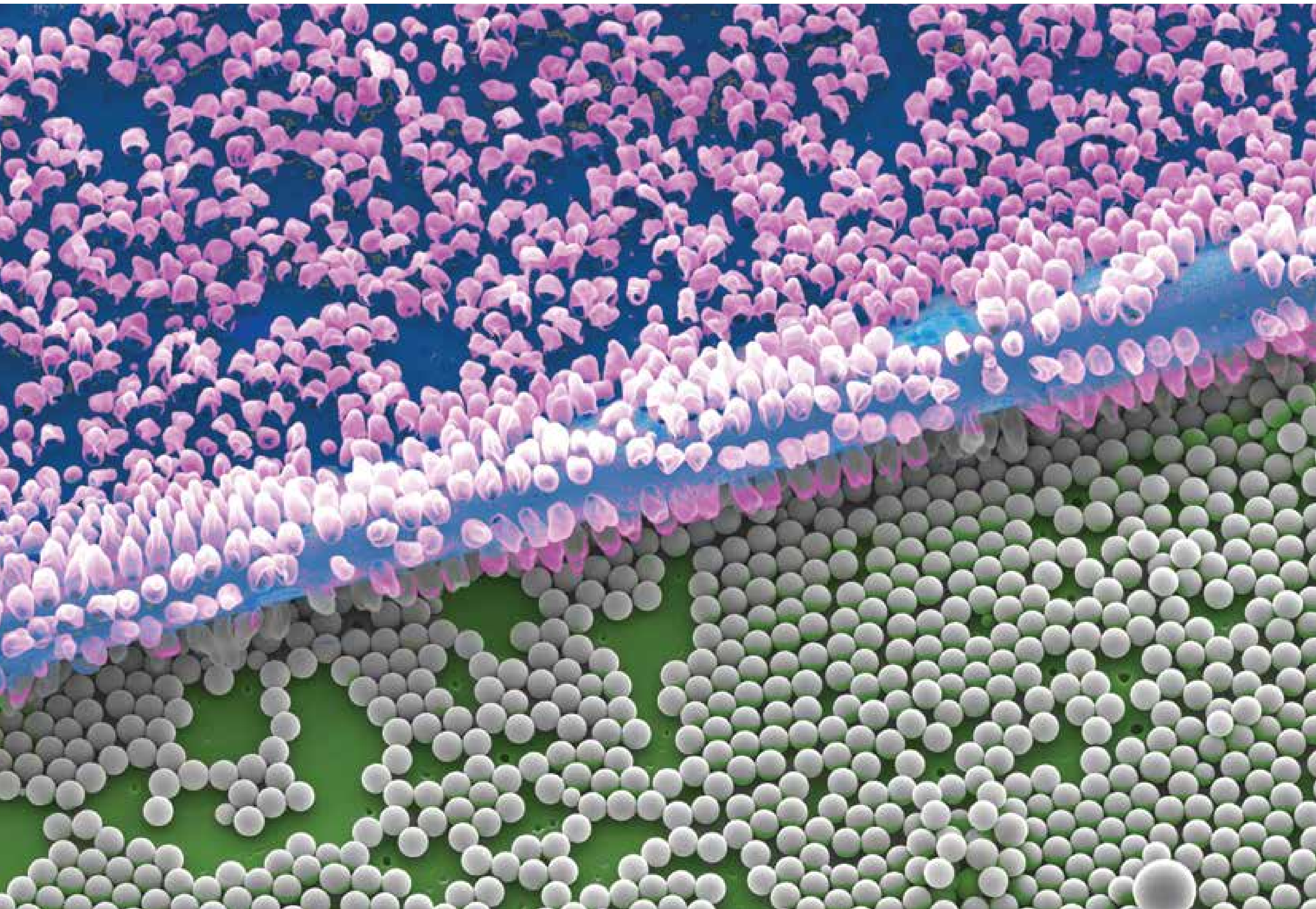
Supporting life quality and health requires that medicines and therapies are assessed, that chronic diseases are monitored over time, and that our food chain is properly protected. If physical metrology has reached its maturity, the situation is much more challenging for chemical metrology and even more for agri-food and biological metrology. In particular, the latter is still actively working on identifying biological markers (biomarkers), which are objective and measurable indicators of normal biological processes, pathogenic processes or pharmacological responses to therapeutics. Once these biomarkers are identified, it is essential to define reference materials, which can be used to ensure the traceability and reproducibility of biological measurements, and to store them in biobanks, namely repositories that store biological samples for use in research and medicine. Similar considerations hold for the traceability and quality assessment of food and medicines.

INRiM will contribute to this topic through its capabilities in the development and characterization of materials, the identification and validation of contaminants and biomarkers, and the development of quantitative methods for the analysis of food, medical imaging methods, and diagnostics tools. Materials include those that are responsive to external stimuli (like for instance external electromagnetic fields or ultra-sound), food packaging, and bio hybrid structures which combine artificially synthesized materials with living cells and which find applications in diagnostics and regenerative medicine. Additive manufacturing will be utilized and further developed for this purpose. INRiM will work on the development of reference materials and primary standards for materials and nano structures.

Quantitative medical imaging methods will be further developed, using, amongst others, ultrasound, magnetic resonance imaging, and light waves, with a particular focus on traceability of measured quantities and the synergy between in vivo and realistic in vitro experiments. Imaging and sensing on biological neurons and neural networks will provide inspiration for the activity on new hardware platforms for artificial neural networks discussed in the next section. INRiM will dedicate metrology tools to access and monitor the health risk of electromagnetic fields which will allow to explore in a reliable way their potential for applications in biomedicine.

INRiM will contribute to the development of metrology in biology by the development of technologies and methods of analysis to identify and validate biomarkers for diagnosis and predictive personalized medicine. The goal will be to design certified measurement capabilities in cell biology and biological nano-metrology. INRiM will explore the possibility to apply metrology tools to reduce, refine, and replace animal experiments in scientific studies.

The traceability of measurements related to the quality of life, agro-food, nano medicine, and health in general, will need to be developed in the coming years, in synergy, not only with other metrology institutes worldwide, but in particular also with health care organizations and research institutions that have expertise in chemistry, medicine, and biology. This will be done by proactively seeking synergies on national and international level and through European technology platforms.



Accelerating digital transformation and supporting industrial transitions

Industrial transitions have significantly changed our society throughout the centuries – from the introduction of steam engines, then mass production, and more recently electronics-based automation. Nowadays industry is facing a new transition based on (large amounts of) data and partially autonomous machines – a concept often referred to as Industry 4.0. Metrology can help to make Europe more competitive in this transition.

Clearly, better sensors (smarter, cheaper, and more robust) will play a key role for assessing the quality of measurements. Cheap sensors pave the way towards large-scale sensor networks, which can bring new levels of quality assessment and traceability to primary standards throughout the whole value chain. The use of sensor networks provides a challenge for metrology since it requires a paradigm shift from single, high quality sensors with extremely low measurement uncertainty to the analysis of large amount of data produced by many lower quality sensors. These large amounts of data will also require new types of data processing, analysis, and (automated) decision making. At the same time the data and information infrastructure has to be protected against cyber security threads. Digital transformation is much more than collecting data: it is a way to redesign the industrial production (even dynamically) in order to match a wider set of requirements by the customers. INRiM will contribute on three levels: sensor technology, data sensor networks, and innovative neural networks.

INRiM will make use of its vast experience in the development and characterization of industrial sensors, which range from traditional to highly innovative, and include smart gas meters, trace water sensors for ultra-pure gases, water vapor pressure sensors, next-generation process thermometers, dew/frost point temperature sensors, humidity sensors, non-contact dimensional sensors, thread gauges, digital vibration sensors, electrical sensors, and autonomous vehicle detectors. INRiM will work on the improvement of its existing sensors and at the same time develop new sensor types based on industrial needs. INRiM will be able to guarantee the definition of their reference test environments, traceability, calibration, and working standards, to provide trustable and reliable sensor technology.

Moreover INRiM is committed to develop better metrology for large-scale sensor networks, including manufacturers' in-line control systems, large-scale calibration procedures, resilient and certified time procedures over (secure) optical networks, and the assessment of quantum cryptography and key distributions. To process vast amounts of data and implement – partially automatic – decision making processes, neural networks and artificial intelligence will play an increasingly important role. The current bottleneck in this respect lies in the traditional hardware platforms (computers/electronics) which are inefficient for this task and extremely energy consuming compared to biological neural networks. INRiM will dedicate effort in developing new materials and technologies to find better hardware implementations of neural networks, which, if successful, will constitute one of the major breakthroughs in the field of large scale data processing and machine decision making.

INRiM will work on a wide range of tools for explaining and promoting digital transformation, including digital certification and virtual calibration laboratories, and will disseminate metrology services like calibrations, accreditation, precision measurements, and advanced data post-processing tools.


DIGITAL TRANSFORMATION

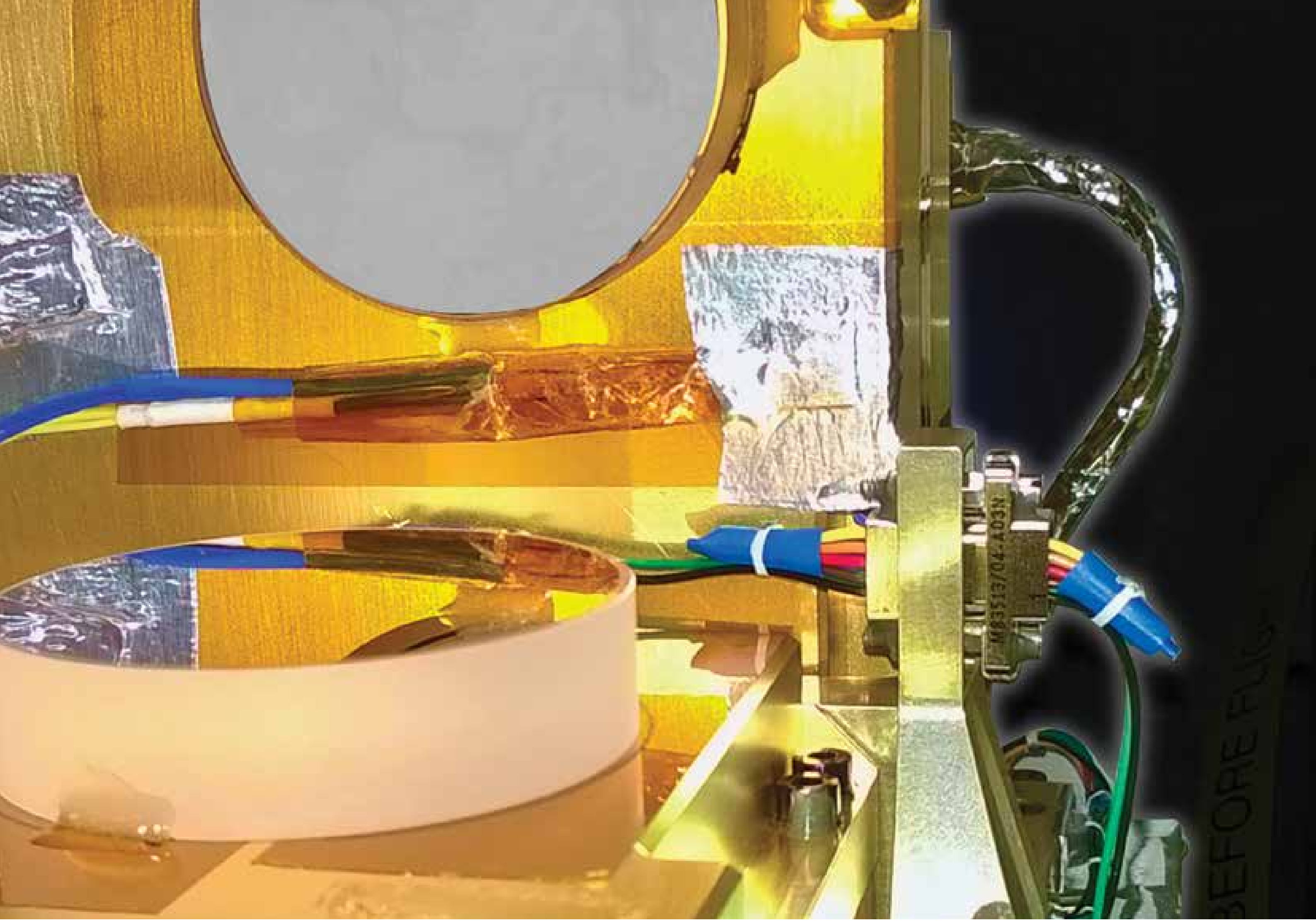
Developing technology for space applications and research

Europe manages today the second largest public space budget (Member States, EU, ESA, and EUMETSAT) in the world with programs and facilities spanning different European countries. Because of this investment, Europe can rely on its own space systems like Copernicus for Earth observations, the European Geostationary Navigation Overlay Service (EGNOS), and Galileo for satellite navigation and geo-positioning. Space technologies, data, and services have become indispensable in the daily lives of European citizens. In particular, Copernicus is the most advanced Earth observation system in the world and Galileo is the first civilian-run navigation satellite system, providing highly accurate global positioning data. In spite of this excellent positioning, Europe has to face new challenges due to global competition and the pervasive integration with digital technologies.

The combination of space data and digital technologies allows to develop novel space services for the benefit of society and the European economy. For these reasons, the new EU space program will integrate current activities and will synergically drive them during the next decade. The European Commission envisions to promote the uptake of Copernicus, EGNOS, and Galileo solutions in EU policies. In particular, the Commission aims to facilitate the use of Copernicus data and information by strengthening data dissemination and setting up platform services, promoting interfaces with non-space data and services. From the metrological point of view, this strategic goal requires a careful assessment of the data quality and their improvement by advanced sensors and their integration. Moreover, the Commission intends to promote measures for introducing the use of Galileo for mobile phones, and critical infrastructures using time synchronization.

INRiM will contribute with its activity on time synchronization and sensors for space applications, from low Earth orbit to space missions. INRiM has been involved since many years in research and design for the Galileo Navigation Satellite Systems, and will develop novel compact atomic frequency samples and emerging quantum key distribution systems for security, advanced measurements, and time synchronization. This will be done together with the European Global Navigation Satellite Systems Agency (GSA) for Galileo, and with the Italian Space Agency (ASI) for on-ground optical fiber link for time and frequency dissemination. This activity will be further strengthened by the development, calibration, and testing of a broad range of advanced detectors, sensors, and supporting equipment for space applications, with emphasis on their metrology aspects.

Moreover, INRiM will support the development of satellites, for instance by providing accurate and traceable measurements of gas flow rates and temperature in satellite engines, space telescopes, and stabilization technologies. INRiM will contribute in the support of space missions through the characterization of space materials and will ensure traceability for large dimension metrology, nano-acceleration, and various types of instrumentation. This work will be done in synergy with space agencies and aerospace industries through research projects, commissioned testing programs, and knowledge transfer.



Improving the quality and impact of fundamental scientific research

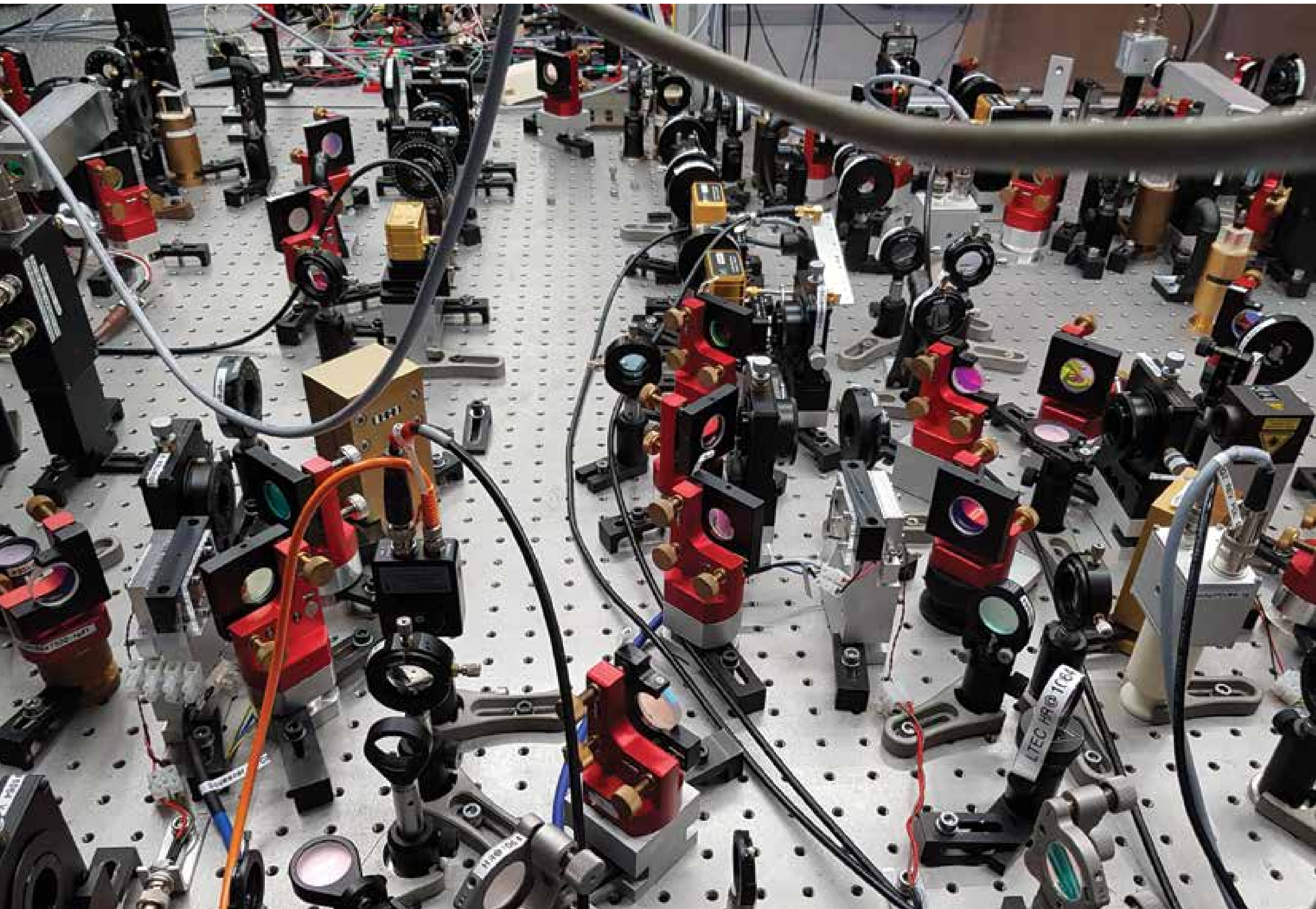
Properly designed and executed experiments constitute an essential pillar of both fundamental and applied scientific research. While much investigation is done to improve metrology, the use of – often very advanced and reliable – metrology tools to improve the quality of measurements in other fields of research is less common. Yet there is a golden opportunity for scientific progress by strengthening cross fertilization between research communities. Science – in addition to industry and society – constitutes in that respect a customer for metrology. It is the intention of INRiM to push this type of synergy further by seeking synergies with other research institutions and academy.

Certain areas of fundamental science intrinsically require high precision measurements. INRiM will contribute in that respect to ultra-sensitive quantum physics experiments, including quantum sensing and imaging, and time synchronization in fundamental physics experiments (including high energy physics, frequency metrology for testing the standard model, and atomic clocks for radio astronomy and geodesy). INRiM will also keep contributing to the determination of fundamental constants.

In addition to the research areas that intrinsically require metrology to achieve the extreme accuracy required for their experiments, there are several fields of research that do not require metrology know-how intrinsically, but that can still benefit enormously from the above describe synergy. Examples of contributions of INRiM in this respect include the development of advanced spectroscopic techniques like surface and tip enhanced Raman spectroscopy, super-resolution spectroscopy with random lasers, metrology for characterizing emerging materials, and the accurate determination of matter in classical states (like the determination of the thermo-physical properties of fluids).

In addition to the experimental capabilities and know-how, INRiM will also be able to provide sophisticated computational post-processing techniques for improved data interpretation which are typical for the metrology community. Examples include the use of digital twins for precision measurements and data analysis, uncertainty quantification and data comparability of measurement methods, suitable metrics for machine learning algorithms, and computational imaging for life sciences.

INRiM aims to improve also its own metrology tools through fundamental research. Examples include the development of advanced devices for metrology that are traceable to fundamental physical constants, realizations of the new SI units (as discussed in the previous section on the "Implementation of the new SI"), the analysis of differences between new SI units and former units, and the use of fundamental physics for more accurate time measurements in the context of a possible future redefinition of the second.



Research Infrastructures

INRiM is involved in several research infrastructures – some existent and many being newly constructed – in synergy with regional, national, and international partners. This will allow to further support the complex and highly accurate technology needed in the context of the focus points. External access will be provided to academia and industry.

The **QR laboratories and Nanofacility Piemonte** is already present at the INRiM campus and comprises a series of micro and nano fabrication laboratories housed in a class 100 clean room and two class 10.000 grey areas. The most recent is the Nanofacility Piemonte Laboratory, where – thanks to support by the foundation "Compagnia di San Paolo" – nanotechnology is developed, mainly by ion and electron beam lithography. The QR laboratories are specialized in nanofabrication by self-assembly of single nano-objects and di-block copolymers on large areas. The laboratories will play an important future role also in rapid testing of new ideas and concepts.

The **Research Infrastructure PiQuET** (Piedmont Quantum Enabling Technologies) will be newly constructed in a 500 m2 clean room (class 100 and 1000) equipped for micro/nano fabbrication and device production and testing. It is coordinated by INRiM with the participation of the universities: "Politecnico di Torino" and "Università di Torino", and co-funded by the "Regione Piemonte" and the European community.

PiQuET will be active in two key sectors: (i) the development of micro / nano structured materials, devices, and sensors; (ii) quantum metrology including atomic clocks and quantum communication devices. The strategy of extensive application of quantum physics laws and miniaturization of devices will be pursued through an inclusive research and knowledge transfer ecosystem where collaboration with industry will play an important role.

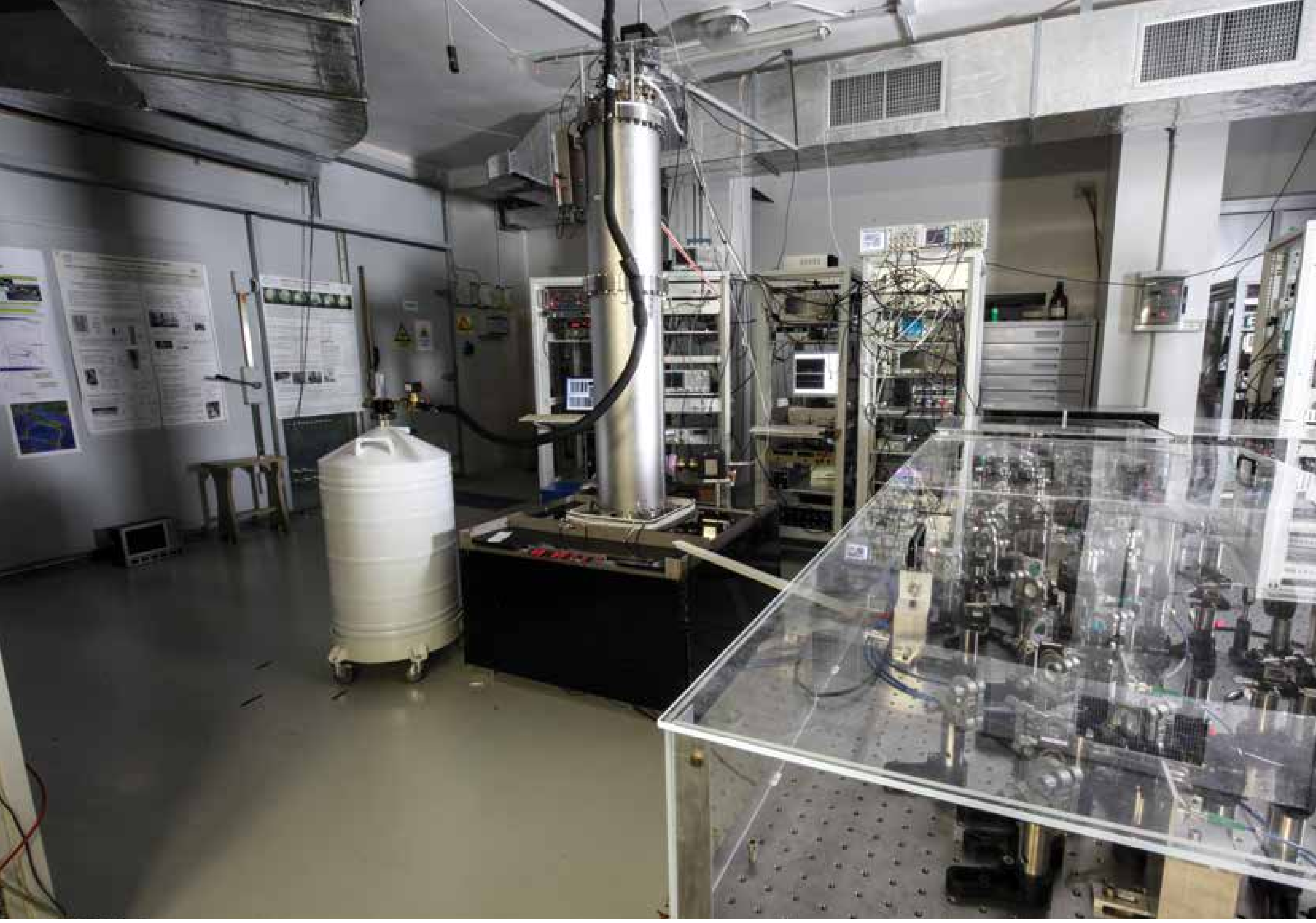
The **Metrological Infrastructure for Food Safety** (IMPreSA) aims to support research and industrial activity in the – traditional and innovative – food packaging sector and thereby helps to comply with international regulations in this field. The Infrastructure will be newly constructed and will allow INRiM to be among the first European metrological institutes equipped with highly technological and innovative instrumentation for both organic and inorganic chemical analyzes.

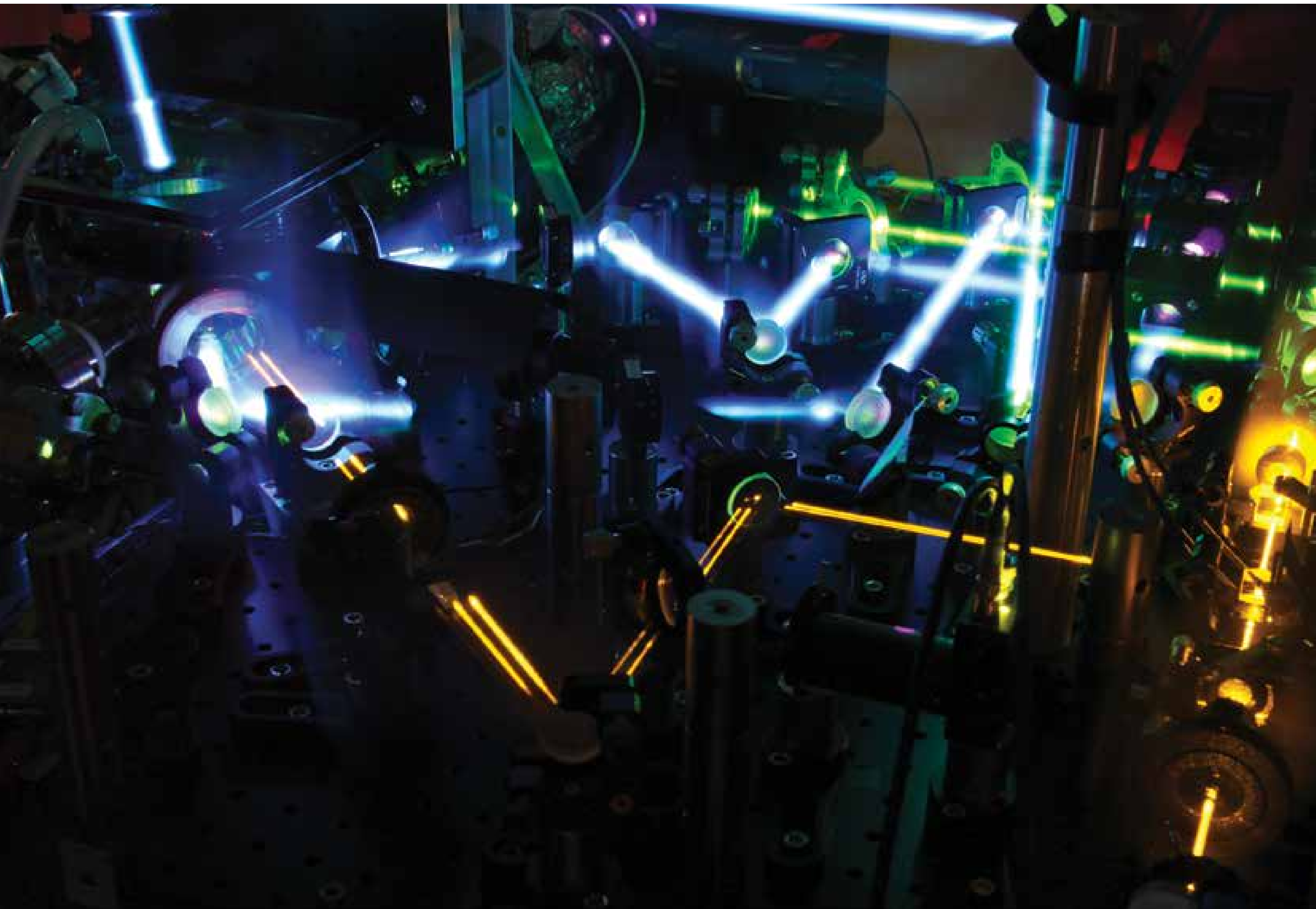
The first objectives include the development and metrological characterization of materials, analysis of migration of possible substances and/or contaminants from packaging to food, and the characterization of organoleptic and nutritional aspects. The infrastructure will support Italian control bodies on food safety and human and animal welfare.

The Time and Frequency Infrastructure of INRiM realizes the national time standard, and contributes to the Universal Coordinated Time (UTC). INRiM is leader in the quest for more accurate timing with its atomic clocks, in particular a laser-cooled Caesium fountain and optical clocks based on Ytterbium and Strontium atoms. The relative frequency accuracy of the Caesium fountain is currently 2e-16, while the Ytterbium optical clock achieves 2e-17. Both the Ytterbium and Strontium optical clocks are candidates for the new definition of the second, expected in this decade.

INRiM contributes to the time standard of the European navigation system Galileo through the design and implementation of the ground segment that synchronizes the on-board clocks and the related timing algorithms. The institute is committed to the Time Service Provider project together with major European industrial players. INRiM designed and realized the Italian Quantum Backbone for the distribution of ultra-accurate timing signals for research on quantum sensors and quantum communication. It currently comprises 1850 km of optical fibre connecting major Italian research centers and industries, as well as metrology institutes in France, Germany, and the UK, which puts Europe in a world leading position towards the redefinition of the international unit of time.

An Advanced Mechanical Workshop in collaboration with the 'Istituto Nazionale di Fisica Nucleare' *INFN* – recognized for its high quality technical design and realization capabilities – will be constructed in support of the development of advanced metrology tools. The collaboration will have the added value of complimentary equipment and highly skilled staff of both institutions and will lead to a unique technical support facility in the region.





Staff and working environment

Research, technology transfer, and all that is related to the role INRiM has as national metrology institute, cannot be done without researchers, technicians, administrative and other support staff. Transparent and fair recruitment policies are therefore crucial for the future development of INRiM, both to attract high level staff to the institute as well as to allow current staff to develop their personal career plan. Rating parameters for the hiring of new staff as well as for career advances should be clear and known in advance. Regular evaluation of the quality of the work and the achieved results is crucial for a meritocratic working environment and is generally stimulating. INRiM intends to be proactive on proposing new and better job selection procedures and job evaluation – unhampered by prejudices or preferences regarding social background, religion, gender, and ethnicity – and will interact with other research institutions and government bodies on this topic.

The INRiM main campus, and working environment in general, can be improved and several buildings require maintenance. Special attention will be given to the realization of more creative spaces and modernization of the architecture. When possible, INRiM will make use of sustainable technologies with low environmental impact and high energy efficiency, by – amongst others – participation in the European project "Supporting The EPC Public Procurement IN Going-beyond". The aim is to collaborate towards world-wide decarbonization and decrease the energy consumption of our campus using various means. The quality of the working environment will be further improved by the construction of a new campus canteen, lecture hall, and an environment in which people can meet and discuss, making use also of the beautiful natural resources that the campus has to offer. The 130 thousand square meter green park in which INRiM is located will be made more useable and accessible for INRiM staff and official visitors, thereby creating a stimulating environment for social integration and exchange of ideas.

Regarding safety of the working environment and health, INRiM has made significant progress in recent years. Within the mission of the institute, INRiM not only aims at reaching and maintaining compliance with regulations, but also will play a proactive role in implementing new concepts and interact with key players like the 'Azienda Sanitaria Locale *ASL*' and other inspection bodies. An important action in this respect will be the organization of a national conference on the various aspects of safety in the complex, and very specific working environment found in scientific research – co-organized together with other research institutions, universities and inspection bodies.

This document is based upon a

SWOT analysis, peer review,
and an institutional workshop.

With input by the staff of INRiM.

(and continuous support by Artù)