ANALYTICAL RESEARCH INFRASTRUCTURES IN EUROPE

A KEY RESOURCE FOR THE FIVE HORIZON EUROPE MISSIONS

JOINT POSITION PAPER

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European Magnetic Field Laboratory

Laserlab Europe

LEAPS League of European Accelerator-based Photon Sources

LENS League of Advanced European Neutron Sources

RADIATE

ANALYTICAL RESEARCH INFRASTRUCTURES IN EUROPE PRESENT A JOINT POSITION PAPER TO MEET THE 5 HORIZON EUROPE MISSIONS

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Research and Development with Ion Beams – Advancing Technology in Europe (RADIATE)
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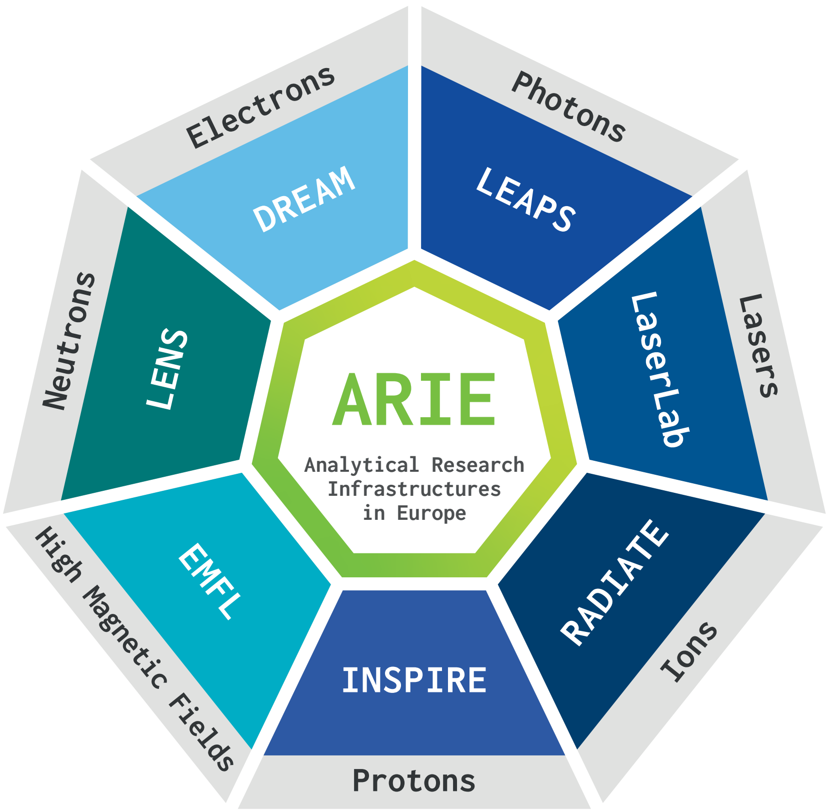
AT A GLANCE

The Analytical Research Infrastructures of Europe (ARIEs) provide unique windows into the workings of the world around us. They include powerful photon sources, such as synchrotrons, laser systems and free-electron lasers; sources of neutrons, ions and other particle beams; and facilities dedicated to advanced electron-microscopy and high magnetic fields. They are centres of scientific and technological excellence, delivering services, data and know-how to a growing and diverse user community of more than 40,000 researchers in academia and industry, across a range of domains: the physical sciences, energy, engineering, the environment and the earth sciences, as well as medicine, health, food and cultural heritage. The insights into materials and living matter made possible by their collective tools underpin the advanced research necessary for the success of the Horizon Europe Missions. The ARIEs provide free access to the scientific user community based upon scientific excellence and open data.



The seven networks in the ARIEs family, providing state-of-the-art analytical facilities for Europe's researchers.

Within the Horizon Europe Missions, there is an unprecedented opportunity to deploy the analytical techniques, skills and know-how of the ARIEs on a large scale, targeting the Missions' individual research needs. Thanks to the nature of Europe and the ease of multi-disciplinary, cross-border partnerships, the many varied and complementary analytical techniques of the ARIEs can be brought together in coordination with the Horizon Europe Mission specialists. As a result, the unique value of the ARIEs can be added to the Missions, accelerating research and driving solutions for Europe's citizens.

MISSION 1: ADAPTATION TO CLIMATE CHANGE, INCLUDING SOCIETAL TRANSFORMATION

Anthropogenic global warming demands adaptation and transformation across a range of sectors, as well as decoupling economic growth from greenhouse gas emissions. This requires large-scale innovation – not least in manufacturing, processing, depollution and decarbonisation. Experiments at the ARIEs are leading the development of novel materials and processes, and are already serving a huge spectrum of societal needs. Introducing a new level of collaboration enables the ARIEs to provide an even more collective and complementary approach.

MISSION 2: CANCER

Cancer is a large family of complex diseases with a plethora of underlying molecular mechanisms. The ARIEs tackle this diverse range of science in a threefold approach: understanding, prevention and treatment. Understanding involves studying the molecular basis of the different forms of cancer; prevention involves the development of specific, powerful methods of diagnosis; and finally treatment involves the innovation of therapies to kill tumours without surgical intervention.

MISSION 3: HEALTHY OCEANS, SEAS, COASTAL AND INLAND WATERS

Every year, eight million tonnes of plastic are discarded into our oceans. Meanwhile, the residues of antibiotics and pesticides are leaking into our water systems and ending up in the food chain. To find a sustainable solution to this challenge, we need a complete understanding of the past and present condition of the water cycles and pollutants, as well as predictions of future scenarios. The mission-oriented questions need an integrated approach, in which the ARIEs are ready to play a crucial role with their unique analytical capabilities.

MISSION 4: CLIMATE-NEUTRAL AND SMART CITIES

Europe is aiming to have 100 climate-neutral cities by 2030, a goal that requires a revolution in sustainable and recyclable materials. At the heart of materials innovation is an understanding of material structures from the atomic and microscopic scales upwards, to full-scale devices and systems – batteries for electromobility, for instance, or eco-friendly concrete for construction. This is the core business of the ARIEs, which allow real materials to be studied under real working conditions, across the full range of length scales.

MISSION 5: SOIL HEALTH AND FOOD

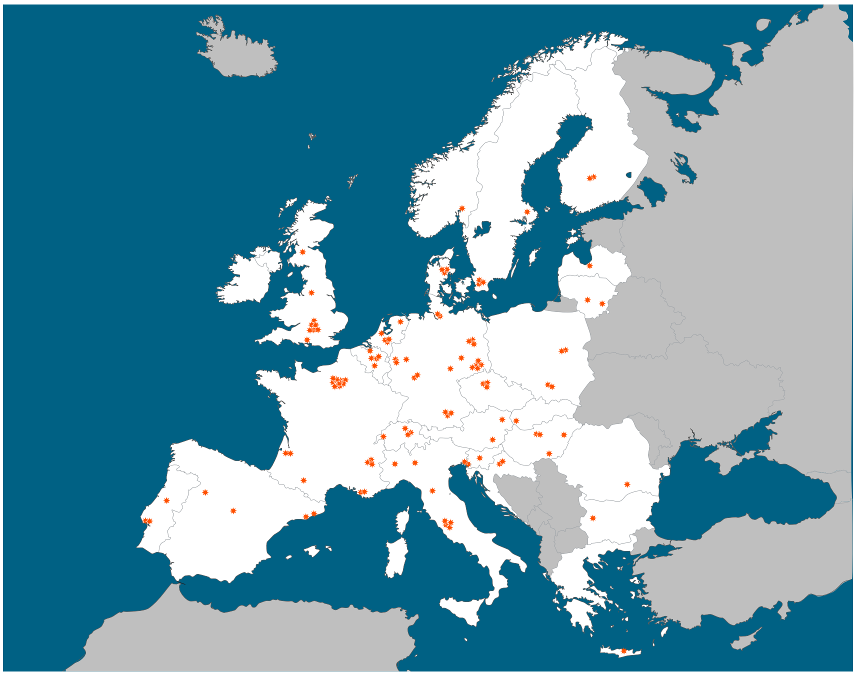
Soil health and food are intertwined and essential for life processes on our planet. Healthy soil functions as a living system to support plants and animals, to maintain water and air quality, and to sustain a diverse community of soil organisms that help our crops grow. Food cannot come at cost to the soil, therefore – but also it needs to be of sufficient quality for us, in terms of its safety and nutrition, for example. Through their advanced, complementary analytics, the ARIEs accelerate research on healthy soil and tomorrow's agri-food systems, and thereby contribute to the prevention of environmental pollution, the mitigation of climate change and the conservation of biodiversity.

EUROPE'S ANALYTICAL RESEARCH INFRASTRUCTURES:

WORKING TOGETHER FOR SCIENTIFIC EXCELLENCE AND SOCIETAL CHALLENGES

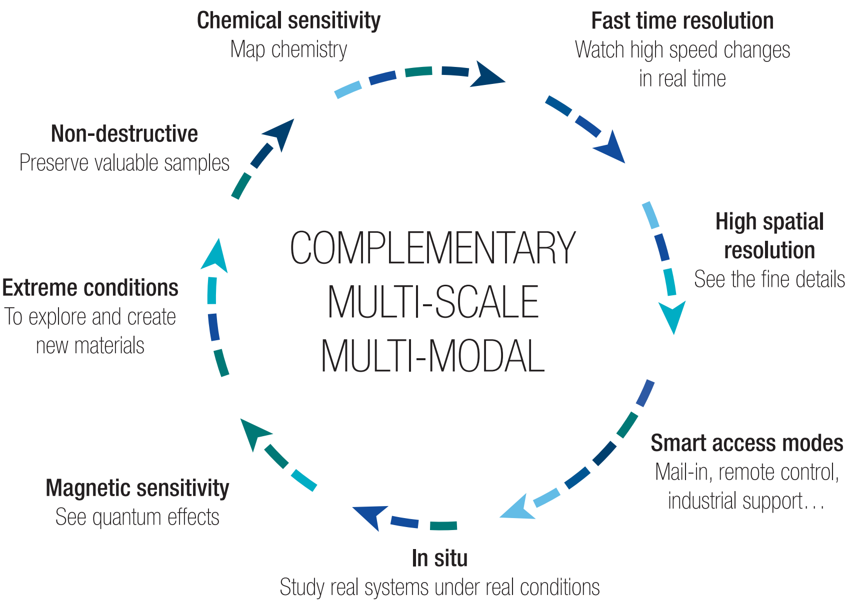
Europe has the world's broadest range of advanced analytical research infrastructures (RIs), both national and international; many of the latter RIs are listed on the European Strategy Forum for Research Infrastructures (ESFRI) Roadmap. Europe is also world leader in their construction and operation, a status that needs to be protected and built upon in the future. Often large or distributed, these scientific facilities provide unique insights into materials and living matter, helping us to understand the world, develop products (as well as processes associated with their manufacture, use and recycling) and invent breakthrough technologies to solve challenges such as those of the Horizon Europe Missions. Accessed by tens of thousands of researchers every year, the ARIEs are centres of scientific and technological excellence that drive cutting-edge fundamental, applied and industrial research. They also serve as interdisciplinary training platforms for students, future scientists, engineers and technicians, and are paradigms for European collaboration in large, high-tech projects.

This paper gathers seven Europe-wide networks as the ARIEs – which in total represent around 120 individual research facilities (see map below) – to highlight their importance for the five Horizon Europe Missions. Their impact is made all the stronger by the innate complementarity of their unique analytical techniques, which in combination offer an unrivalled and complete view into the heart of real materials under real conditions, at unprecedented spatial and temporal resolution and sensitivity. This is how we understand how materials and living matter function; it is how we innovate.



The ARIEs shown in their host countries (highlighted in white). Each dot represents one ARIEs facility.

Europe's analytical research infrastructures provide advanced and complementary characterisation capabilities which add up to a unique vision into materials and living matter.



The European Commission has asked the different research infrastructure networks to comment on how their common, complementary approach will help address the societal challenges of the Horizon Europe Missions framework programme starting in 2021. The five missions already listed above are cemented in Pillar II of Horizon Europe, Global Challenges and European Industrial Competitiveness. Each is a portfolio of cross-disciplinary actions intended to reach a bold, inspirational and measurable goal within a set time frame, one that will impact policy-making and in turn the daily lives and living standards of the European population.

With this in mind, representatives of the seven research infrastructure networks met in Brussels on 21 February 2020 to discuss how they could best serve the Missions. Transversal working groups were formed to assess the opportunities, and how the specific strengths, capabilities and core skills of the ARIEs are relevant. The result of this exercise is summarised below in five sections, each one addressing a Horizon Europe Mission and providing concrete examples of how the ARIEs overcome research challenges related to it.

The multiple-scale analytics and characterisation in Mission-driven research will be not only demanding, but also changing. In looking ahead towards Horizon Europe, therefore, the ARIEs will become ever more agile and proactive in responding to collective research efforts as they arise. They will work together as never before, joining with Mission researchers to provide efficient and timely access to services. Such services include both highly demanding experiments and more routine, high-throughput measurements; provision of advanced instrumentation; appropriate sample environments; and data delivery and archiving according to the FAIR principles.

This collective power of the ARIEs, made possible by long-held European ideals and openness, will be harnessed to deliver on the ambitions of the Missions, supporting Europe, its research, its economic development and its citizens, in solving the challenges central to a future fair and tolerant global society.

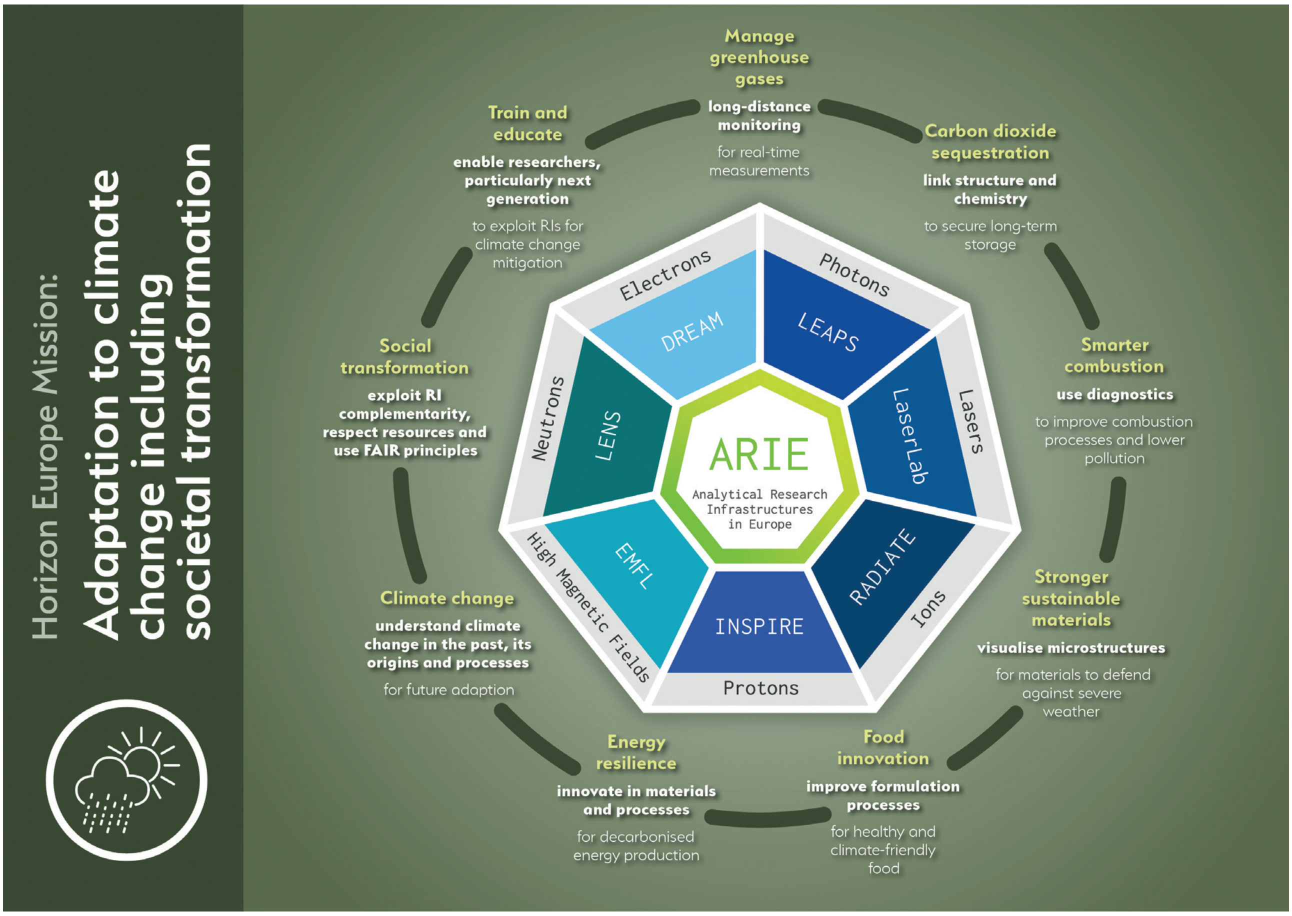
ANALYTICAL RESEARCH INFRASTRUCTURES AS KEY RESOURCES FOR THE FIVE HORIZON EUROPE MISSIONS

Moon-shot missions, such as those of Horizon Europe, require exceptional solutions, and the world-leading ARIEs are one of the key places those solutions can be sought. But individual analytical techniques are of limited use by themselves. It is the cross-border cooperation within Europe that allows us to harness the power of its analytical research infrastructures collectively, to fuel the cutting-edge R&D required by the five Missions. Nowhere else in the world is this readily possible.

To address the Missions, these transversal platforms of ARIEs will collaborate amongst themselves and with the Mission specialists at unprecedented levels. They will build and exploit open networks to share knowledge and skills, to coordinate access, to prepare samples, and to create the sample environments required for experiments under real conditions; in doing so, they will use the new European Open Science Cloud. Meanwhile, access to the ARIEs is being made simpler and smarter, more democratised and less reliant on travel, with many facilities implementing options for remote access and full-service via “mail-in” of samples.

The sections below outline, and illustrate with examples, how the ARIEs will support the exceptional goal-oriented science behind each Horizon Europe Mission.

ADAPTATION TO CLIMATE CHANGE INCLUDING SOCIETAL TRANSFORMATION



Adaptation to climate change involves moving towards lifestyles that limit anthropogenic global warming, and decouple economic growth from greenhouse gas emissions – and doing both of these without leaving behind any geographical region or economic sector. Meanwhile, societal transformation requires innovation to improve the ecological well-being of our planet, and to give humans a place within it without leaving too great a footprint. Whether purely academic or in collaboration with industry, research has to come up with novel technologies and processes, from recyclable materials to new methods of manufacture and energy production – and urgently. Here, the ARIEs are key players. As user-based facilities, they act as inclusive, cross-cultural technology, training and information hubs to capture and transfer scientific results and data. They also have well-established networks between academic scientists and industrial sector researchers, which can accelerate the innovation needed for climate change adaptation.

The experiments at ARIEs are at the forefront of materials and processing developments, and are already serving a broad spectrum of societal needs. The Missions will push them to introduce a new level of collaboration, to harness their capabilities further. To help in the transformation to a carbon dioxide neutral society, with more efficient use of resources and climate adaptation, the ARIEs will focus some of their research on overcoming the related technical and socio-ecological problems. Such research will also lead towards a better understanding of the global climate system and the processes influencing it.

SNAPSHOT

NEW FUNCTIONAL MATERIALS

The development of new functional materials is essential for a circular economy in Europe. Here, analytical measurements contribute to the development of improved materials and processes for solar, wind and other sources of renewable clean energy; energy storage, including hydrogen technology; carbon-negative insulation; carbon capture and storage; additive manufacturing (3D and 4D printing) with recycled materials; lighting; and protection for areas that are prone to flooding, erosion and other symptoms of a warming Earth. Again, the advanced analytical methods provided exclusively by the ARIEs are complementary to one another, with each providing a different window onto the material or process so that we can obtain a full description.

KEY EXAMPLE

PHOTOCATALYSTS FOR SUSTAINABLE PROCESSES

Photocatalysis can exploit natural light as a sustainable energy input to drive useful chemical reactions, and has a wealth of applications related to climate adaptation, the efficient use of resources and investment, the cleaning of water and improving human well-being. Such applications include: cleaning water by degradation of chemicals, drugs and antibiotics; converting CO_2 into useful chemicals and fuels; solar cells that also clean polluted air; self-cleaning surfaces; hydrogen production by splitting water; and artificial photosynthesis.

A large variety of compounds and formulations, including nanoparticles and thin films, are already under use or exhibit auspicious properties. Nevertheless, scientists using ARIEs are seeking ways to boost the materials' catalytic efficiencies via changes in constituent elements, stoichiometry, appearance or the application of magnetic fields. The techniques available at ARIEs expose material properties at the atomic scale, and thereby allow those properties to be tailored according to end-use needs. Photon, neutron and electron microscopy are particularly well-suited. Meanwhile, ion beams and magnetic fields allow scientists to engineer the morphological, structural, optical and photocatalytic properties where appropriate – for example in nanocomposite thin films.

SNAPSHOT

ATMOSPHERIC MONITORING

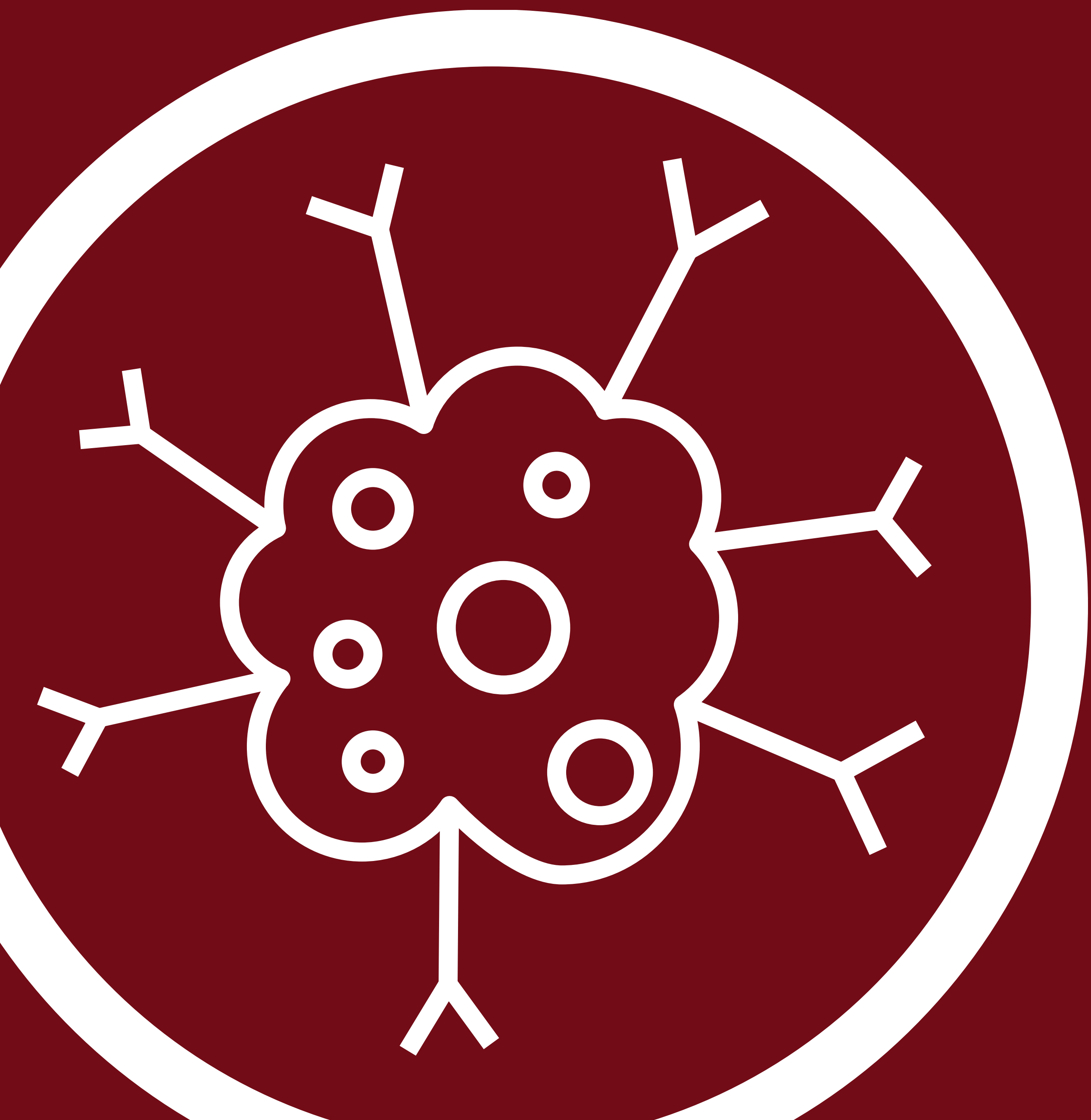
When considering climate change, the Earth's atmosphere is clearly an indispensable part of the discussion. The composition of our atmosphere can influence clouding, and in turn the reflection of sunlight and the level of precipitation. Understanding the atmosphere enables better management and prediction of these different influences, and here, the impact of the ARIEs is wide ranging. Neutron scattering provides information on the early stages of ice cloud formation, for example, while photons, neutrons and lasers provide atmospheric monitoring to cut pollution from combustion processes. The ARIEs are even playing an important role in the upcoming revolution in quantum computing, which could allow high-resolution, processor-hungry climate models to improve predictions of the human influence on climate change.

KEY EXAMPLE

AEROSOL MONITORING AND ANALYSIS

Aerosols are complex and often dilute, making their analysis challenging. Aerosols include those from fuel combustion and the reaction of ozone, the latter of which can result in particles of complex mixtures of organic species. Photons from light sources, and electron microscopy facilities, are able to identify the organic compounds in aerosol particles from the large down to the ultra-fine, partially in real-time analysis. In addition, ion-beam studies support the analysis of particulate air filters used for both local pollution measurements and for larger scale atmospheric monitoring and the establishment of extensive databases. These studies can provide important base information for global air- and water-circulation modelling and monitoring (including that looking for traces of human impacts), as well as long-term information streams that enable the effects of extreme events – large volcanic eruptions, massive wild fires, ice-cap melting, asteroid impacts, tsunami, nuclear accidents and others – to be measured against local pollution.

CANCER



Cancer is a large family of complex diseases with a plethora of underlying molecular mechanisms. Currently, most treatment involves the surgical removal of the tumour followed by different therapies to kill rapidly dividing cells.

Tackling such a diverse set of complex diseases requires a threefold approach. The first is understanding: that detailed knowledge of the cancer's molecular basis which is essential for the development of proper diagnostics and therapy. Then comes prevention: that is, the development of preventative measures based on powerful and specific methods of diagnosis. Finally comes treatment: the development of therapeutic options that remove tumours (ideally) without surgical intervention, in combination with a stimulation of the patient's immune system to prevent relapse.

The ARIEs have unmatched capabilities in advanced medical- and bio-imaging and super-sensitive analytics, allowing the identification of specific biological markers and interactions of biomolecules within tissues. They have already provided the basis for successful, non-invasive cancer treatment regimes, and are fostering the development of new technologies – for instance molography, a novel, biophysics-based analytic. The ARIEs are unique in their ability to produce any conceivable radioisotope with medical potential, and have been instrumental in the development of non-invasive imaging technologies based on radiotracers for cancer diagnosis. Moreover, they are critical to the development of particle-based treatments – notably proton therapy, a highly successful non-invasive cancer therapy that is being commercialised worldwide. Other modalities based on research at ARIEs and demonstrating potential for clinical adoption include microbeam radiation therapy (MRT) and high dose-rate FLASH therapy.

When addressing different forms of cancer with the technological capabilities of the ARIEs, a key challenge is integrating experts into efficient teams from both biomedical fields (such as radiology, pharmacology, immunology, structural biology, cell biology) and the more physical sciences (such as clinical radiotherapy, physics and engineering). We believe that the Mission "Cancer" within the new Horizon Europe programme provides a unique opportunity for the formation of international, cross-disciplinary teams of world-leading experts that is beyond the scope of any individual member country. We are convinced that technology development, research programmes and know-how within the ARIEs will continue to play a critical role in addressing the societal challenge of cancer – understanding, prevention and treatment – and that the multinational scope of the Horizon Europe programme will be a critical driver for their success.

SNAPSHOT

UNDERSTANDING CANCER

Innovative technology developments at the ARIEs network facilitate the development of integrated, multi-parametric and multiscale analytical imaging approaches with spatial resolutions ranging from sub-nanometre (X-ray, NMR, neutron, electron- and ion-based, nano-SIMS) to mm (X-ray, laser), including mesoscopic resolution (photoacoustics, spectroscopies) and temporal resolution from femtoseconds (fs) to weeks. These technologies will be critical for understanding processes on a molecular, cellular and tissue level that lead to cancerogenic alterations in cells that escape detection by the immune system.

The ARIE facilities are eager to make their infrastructure accessible to the cancer research community through the UNCAN.eu platform, which has been proposed by the Mission Board for Cancer, as it is a main driver for the development of essential methods for the analysis of molecular structures, dynamics and interactions in biological systems, which underlie the development of cancer. We foresee, for example, within the the ARIE facilities on-site development of new integrative structural biology approaches, combining X-ray, electron and neutron methods, which will provide the basis for structure-based drug development. Similarly, the ability to understand the impact of different radiation modalities on both tumour and normal tissue at a nano, cellular, tissue and patient scale will enable a translational pipeline leading to the development of more efficient cancer therapies. A key element for the success of such efforts are interdisciplinary consortia and platforms like UNCAN.eu, which could be an excellent tool for connecting the different communities in cancer research.

SNAPSHOT

PREVENTION

Non-invasive medical imaging technologies play a key role in cancer detection, and the ARIEs provide unique opportunities for their development. Non-invasive, high-resolution, highly sensitive, targeted 3D imaging of specific cancer bio-markers to achieve early detection of tumours in patients is one example. Meanwhile, the remarkable success of radiotracer-based positron emission tomography (PET) and single-photon emission computed tomography (SPECT) imaging is now routine clinical practice. Henceforth, different high- and low-energy radionuclides, which can be used for diagnostics and therapy, respectively, are of particular interest. Also, high-resolution imaging of biological structures at a macroscopic level can be addressed by novel laser sources in new wavelength regions, technologies that integrate adaptive wavefront control, hybrid technologies such as photoacoustics, and methods for reconstructing coherent properties (for example, phase retrieval tomography).

Many researchers would like highly zoomable, "Google Earth" capabilities for imaging biological tissues – for example, tissue imaging that has a resolution capable of exposing molecular cancer markers. Such capabilities demand cross-fertilisation between different technologies, for which the ARIEs provide a unique environment. Importantly, while current methods usually detect only labelled targets, novel methods are increasingly exploiting the "labels" present naturally in the contrast in biological tissues. Further dramatic progress is likely in this area in coming years, particularly in the combination of existing methods with 3D imaging technologies such as X-ray and electron-based tomography, which are being developed at the ARIEs.

SNAPSHOT

TREATMENT

The different facilities within the ARIEs have always been centred around the development of non-invasive treatment options and are very well aligned with the priorities set out in the recommendations set out by the Mission Board for Cancer. In particular, they can be used to study drug development and delivery, and to develop different forms of radiotherapy, including combined protocols (multimodal drugs with radiation).

KEY EXAMPLE

DRUG DEVELOPMENT AND DELIVERY

Rational drug design requires an understanding of drugs and their targets at a molecular level – and of this understanding, the ARIEs are the main provider. Here, integrative structural-biology approaches that combine different technologies will play an increasingly critical role in the design and delivery of nano-medicines, such as immunotherapeutics and RNA therapeutics. Such therapeutic nanoparticles have great potential for cancer treatment, either as drug vectors – they can be enhancing agents in radiotherapy, or contrast agents in medical imaging – or in themselves as multimodal agents; they also are being explored to increase the effect of immunogenic responses in cancer immunotherapy. The ARIEs play a fundamental role in the development of nanoparticles by providing photon, electron, neutron and other particle-based technologies for structural and functional characterisation, and for advanced 3D and 4D imaging for tracking in biological tissues. Drug-device combinations, such as in photodynamic therapy and photo-immunotherapy – which employ lasers to activate otherwise non-toxic molecules – can overcome the limitations of drug targeting, providing new opportunities for instrumentation and in drug design. Basic research on high-energy magnetic fields indicates that the use of magnetic fields as external stimuli is also a promising new venue for targeted in vivo drug delivery (in which the drug-release system is magnetically triggered). In addition, new avenues of research are opening up in the use of proton and heavier ion beams in combination with drug and immunotherapeutic agents. These beams are particularly suited to inducing "hibernation" in radio-resistant hypoxic tumours, so that their progression – as confirmed in recent vivo studies – is temporarily halted.

KEY EXAMPLE

INTERNAL RADIOTHERAPY

Targeted radionuclide therapy (TRT) is an important tool in precision medicine due to its high specificity and minimal side effects in cancer treatment compared with chemotherapy. In TRT, suitable high-energy radioactive nuclides bound to a biologically active targeting molecule are used to selectively target specific disease sites while sparing surrounding healthy tissue. These nuclides are produced currently in high-flux reactors or in accelerator-based infrastructures – such as those in the ARIEs. Although high-energy beta-emitters are commonly used, recent data indicate that alpha particle emitters have strong potential in TRT. Isotopes suitable for diagnostics and therapy (so called "theragnostics") such as terbium and scandium are of particular interest. The production of these radionuclides requires significant investment over the coming years to build up the production capacities required for clinical applications.

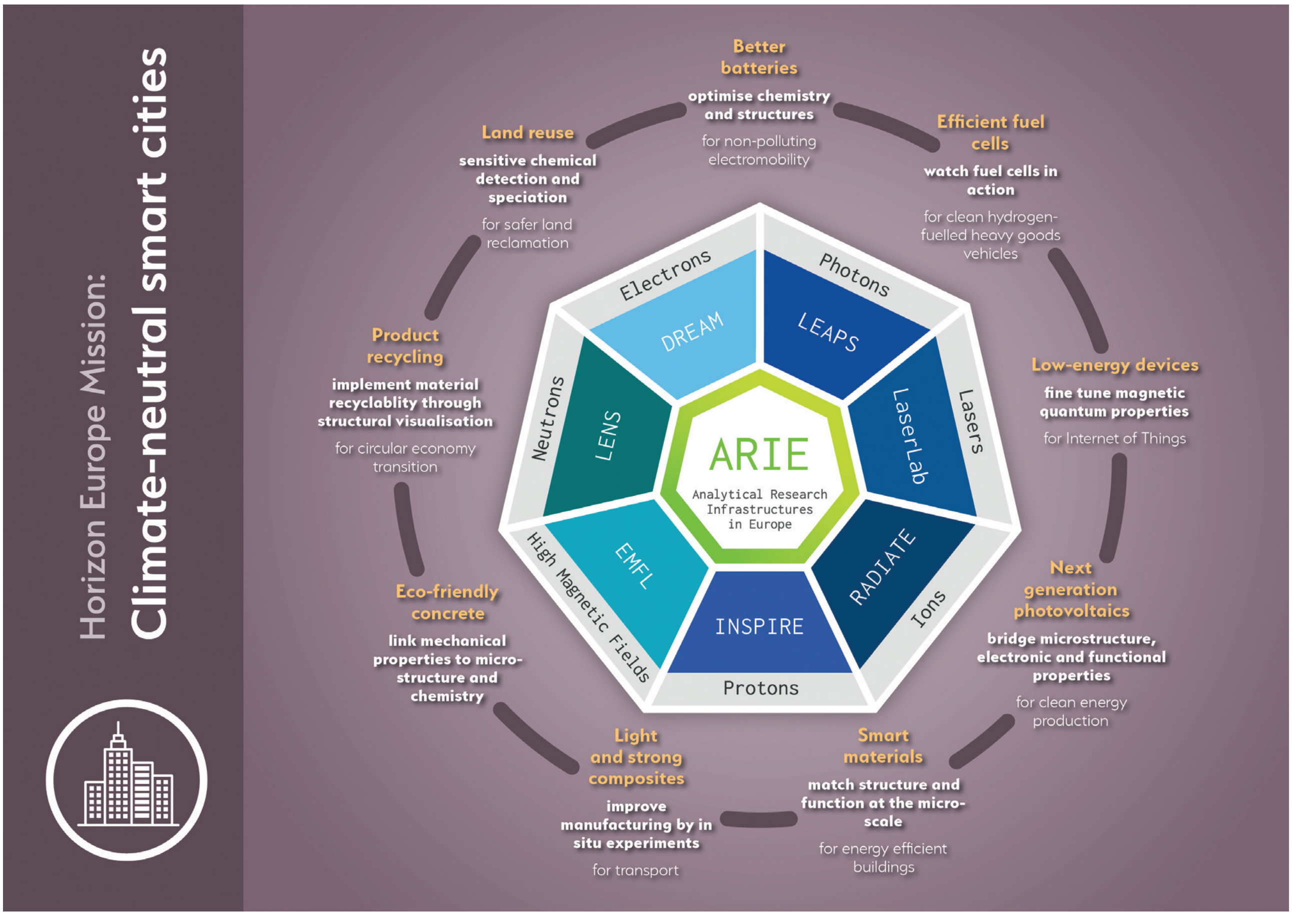
KEY EXAMPLE

EXTERNAL RADIOTHERAPY

High-energy particle-based cancer treatment, in particular electron, proton and heavy ion therapy, has already become a highly effective method for cancer treatment. Major advances in the past at some ARIE facilities triggered the establishment of proton therapy as the therapeutic option of choice for an increasing number of cancers. The technology is currently commercialised and deployed in all major economies around the globe. Nevertheless, there are a number of scientific and technological challenges that need to be addressed in order for proton therapy to reach its full potential. These include simulating the biological effects of the treatment, combined with clinical validation, range verification and imaging. Henceforth, there are a number of novel electron- and hadron-therapy approaches being developed at infrastructures within ARIEs that will enhance tumour control and reduce side effects, in particular optimised proton and heavy-ion therapy plants and innovative laser-driven particle sources. High dose rate FLASH therapy and spatial fractionation by particle mini-beams and X-ray microbeams (MRT) offer a further reduction in side effects. These treatments have the potential to maintain tumour control while dramatically reducing short- and long-term side effects for patients; they could also improve patient quality of life, and cut treatment times. ARIEs facilities are working with commercial partners to develop new technologies to measure the FLASH effect and to plan how it can be implemented in the clinic. All partners are fully committed to involving patients in enabling them to have full control over their medical data as well as integrating patient feedback into their research efforts by reaching out to patient organisations. Any efforts by the EU to facilitate such exchange is highly welcomed.

A detailed understanding – ranging from the particle interaction with DNA and the latter's subsequent repair, to the biological impact at the cellular, tissue and patient level – will enable the development of combination therapies. The ARIEs are in a unique position to provide the required irradiation (for example at ion microprobes, using light and heavy ions), imaging and biophysical capabilities, and expertise, to explore such approaches.

CLIMATE-NEUTRAL AND SMART CITIES



Our future cities are predicted to become home to over 80% of the world's population by 2050 (50% today). Europe has set itself an ambitious, but necessary, goal of 100 climate-neutral cities by 2030; the European Green Deal is seeking a carbon-neutral Europe by 2050. The ecosystems of these citizen-friendly cities must have circular economies; readily available carbon-neutral and mobile energy; efficient energy use for clean transport, healthier air and living conditions; and integrated services, infrastructure and utilities. This vision requires a revolution in the development of innovative, sustainable and recyclable materials, for use in the energy, building, transport and healthcare sectors, some of which rely today on increasingly scarce raw supplies from politically unstable regions. At the centre of materials innovation is an understanding of structure from the atomic- and micro-scale to entire devices and systems, in their real working environments.

The ARIEs are central to support this understanding, and will be especially so when they work hand-in-hand with the Mission science experts. Each type of ARIE infrastructure has unique capabilities and, combined, they provide researchers with an unrivalled view into the heart of objects by studying real materials under real conditions, at unprecedented resolution and sensitivity. It is only such complementarity that can provide answers to complex material problems; moreover, joining forces improves the efficiency of access to services, the tailoring of instrumentation (for example, sample environments), the development of analysis software and the effectiveness of data management. In delivering the key knowledge of how materials and products function, we can innovate the better and more sustainable materials required for climate-neutral and smart cities.

The selected examples below illustrate how specifically the combined power of analytical research infrastructures can enable the clean- and sustainable-energy value-chain as part of the carbon cycle required for climate-neutral and smart cities, from energy production (Example 1 - photovoltaics), to energy storage and conversion (Example 2 – batteries and fuel cells) and energy consumption (Example 3 – low power quantum-enabled devices).

Beyond these examples, ARIEs help the design of smart building materials, recyclable materials and eco-concrete, as well as light composites and alloys for transport, among the wide range of materials and technologies required for Climate-Neutral and Smart Cities.

SNAPSHOT

CLIMATE-NEUTRAL ENERGY GENERATION

Climate-neutral cities are looking to exploit clean, local-scale power generation as a central component of their energy mix. Within this context, Europe's Strategic Energy Technology Plan puts renewable and carbon-neutral approaches at the heart of the energy transition, and as part of the solution to climate change, urban air quality and other issues. But the path to clean-energy production depends upon having the right materials, and the right materials depend on cutting-edge characterisation and in-depth analysis. This is where the ARIEs and their unique capabilities come to the fore, providing the science that underpins next-generation photovoltaics, such as perovskites; green hydrogen or biomass generation; and cycling carbon through capture and reuse.

KEY EXAMPLE

NEXT-GENERATION PHOTOVOLTAICS

An in-depth understanding of the systematic interaction of microstructures, compositions and electronic properties is critical to improving solar cells. In particular, their efficiency is governed by structural features such as defects, secondary phases and interface properties. Visualising these features in real devices with multimodal analytical research infrastructure measurements is therefore critical to tailor next-generation solar technology, such as thin-film perovskites or even artificial photosynthesis, with high stability, long lifetimes and sustainably sourced raw supplies. Electron microscopy, for example, is a unique tool to probe the structure and the chemical composition of thin-film solar cells at atomic resolution and to strictly correlate the atomic structure of their interfaces to their electrical and optoelectronic properties. Meanwhile, ultrafast laser facilities work with very fine time resolution to unravel obstacles in the photo-generation cycle, and high magnetic fields are key to understand and tailor the quantum nature of the photovoltaic process.

SNAPSHOT

ENERGY STORAGE AND CONVERSION FOR CLEAN TRANSPORT AND MOBILITY

A central component of clean, carbon-neutral energy use, particularly in cities, is effective energy storage and conversion. Urban mobility for people and transporting products to cities needs clean, efficient and safe vehicles. Electromobility and hydrogen-powered utility vehicles are part of the solution. Lower air pollution from clean cars will also encourage people to walk and cycle more, improving their health. The ARIEs are studying the materials required for the future high energy-density batteries, super-capacitors and fuel cells (a key component of the hydrogen economy) at the heart of this electrification, across an unprecedented multi-scale range from atoms to devices.

KEY EXAMPLE

BETTER BATTERIES AND FUEL CELLS

Electrochemical devices for energy storage and conversion, such as batteries and fuel cells, are layered-systems in which the bulk properties of each component (mainly electrodes and electrolytes) as well as their interfaces determine the overall performance in terms of autonomy, lifespan, cost, energy density and power. For that reason, breakthrough high-energy technologies – such as platinum-free fuel cells or lithium-metal-based batteries, which are less reliant on rare materials – require advanced materials characterisation. The problems involved are extremely complex, involving multiple phases and multiple length and time scales, from atomic-level details up to large objects. Bridging information – whether spatial, temporal or chemical – from sensitive X-ray, neutron and electron-beam analytics, is vital to predict the behaviour and to guide the design of new devices. Such analytics are all available at the ARIEs, but they must be combined – along with modelling and electrochemical characterisation – as no single probe is able to grasp all relevant features at all relevant scales.

SNAPSHOT

EFFICIENT ENERGY CONSUMPTION FOR THE INTERNET OF THINGS (IOT) AND DIGITAL CONNECTIVITY

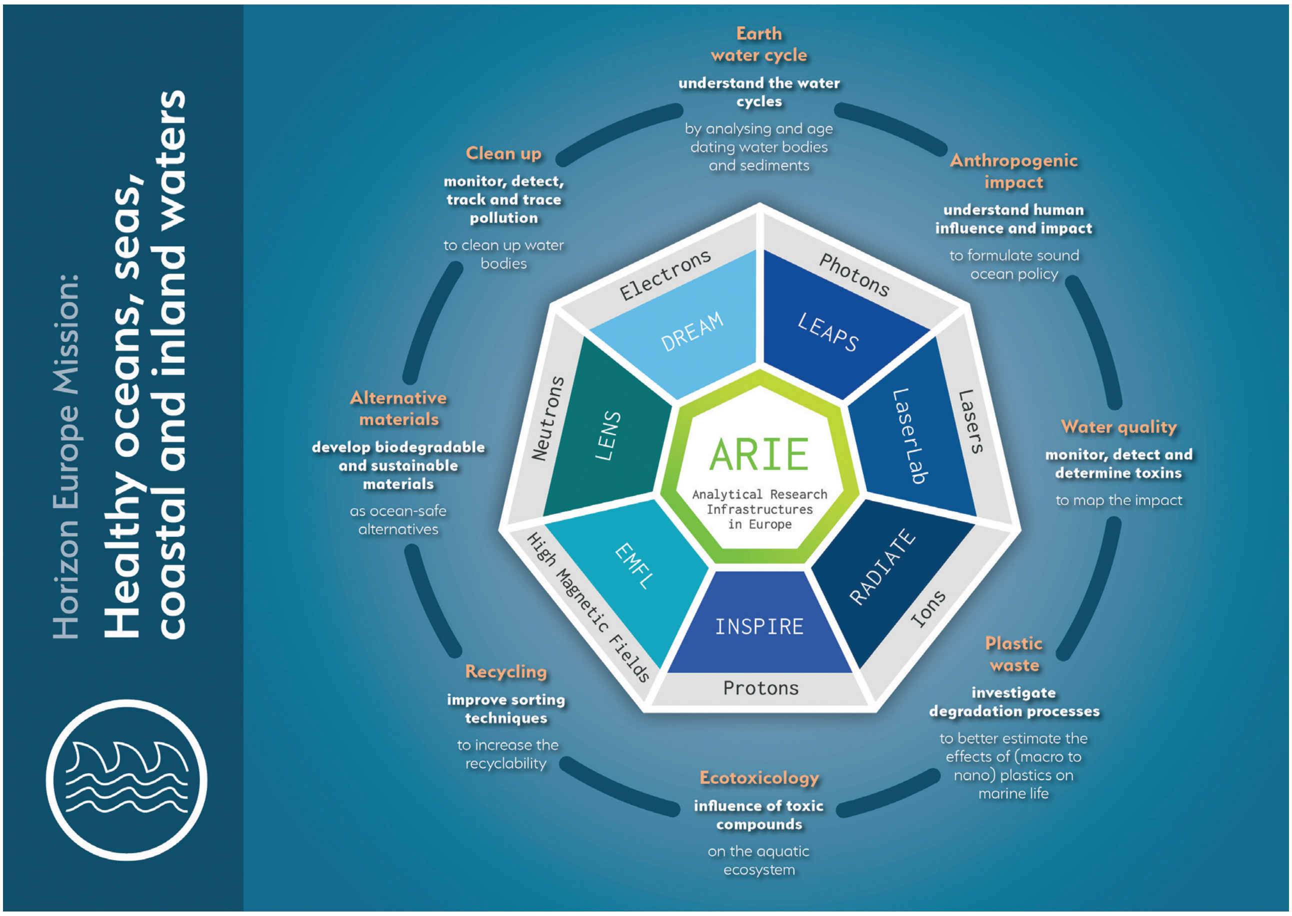
The growth of our digital society and the Internet of Things (IoT) – a critical component of climate-neutral and smart cities, with connected sensors and devices – is projected to demand more than 20% of global energy production by 2030. That is a doubling of today's 10%; indeed, the sector's energy requirements are growing faster than total energy production. With the pressing need to conserve energy and to reduce our environmental footprint, this expanding power use is a major source of concern and demands new energy-efficient approaches, such as the use of nano-structured materials for information generation, processing and storage. Research infrastructures are ideally suited to studying objects at the nanoscale, and thereby help us understand and drive new science and materials development.

KEY EXAMPLE

LOW-POWER QUANTUM-ENABLED DEVICES

One promising route for reducing power consumption in information technology is to transmit information on chips not by electrical currents but by quantum-level magnetic excitations, which do not heat up the device and waste energy. To understand the underlying physical processes and to design working devices, research using attosecond X-rays, magnetic fields and probes sensitive to magnetism is needed. The ARIEs provide the highest magnetic fields available, either alone or in combination with complementary probes such as neutron, ion or synchrotron X-ray beams, to probe the fundamental properties of next-generation materials; meanwhile, ultrafast laser and attosecond facilities provide the required temporal sensitivity. The collective "ultrafast magnetic spectroscopy" that results is laying the path for the rational design of smart materials for energy and quantum technologies.

HEALTHY OCEANS, SEAS, COASTAL AND INLAND WATERS



Healthy oceans, seas, and coastal and inland waters are vital for our societies and the future of our planet. They also present a major challenge. The health and recovery mechanism of our oceans has always been taken for granted, but right now eight million tonnes of plastics are being discarded into the oceans every year. Meanwhile, antibiotic and pesticide residues are leaking into our water systems, and from there into in the food chain.

Any effective solution to this Mission requires a complete understanding of the past and present condition of the water cycles and pollutants, as well predictions of future scenarios. Large research infrastructure consortia such as Euro-Argo ERIC are monitoring the oceans' physical parameters, while LifeWatch ERIC monitors their biodiversity. The ARIEs offer important assistance in the form of a wide range of unique tools to analyse and image the structure, chemistry, and optical magnetic and electronic properties of organic and inorganic (nano) materials, including advanced radioactive dating. Thanks also to that broad base of knowledge which arises in the assembling of many scientific disciplines, the ARIEs can highlight relevant information on the various types of pollutants and their possible degradation processes, as well as support the development of alternative non-polluting materials.

Tackling the mission-oriented questions needs an integrated approach, in which the ARIEs can play a crucial role. The ARIEs are user facilities open to all scientific disciplines and experts, and can contribute to fields of (palaeo) oceanography, biology, material research, (eco) toxicology, etc., and therefore have an important contribution to the development of sustainable environments – and, indeed, a healthier blue planet overall.

SNAPSHOT

THE PAST

To understand the current condition of our oceans, seas, and coastal and inland waters it is important to have a reliable reference. As water circulation patterns in oceans and groundwater systems are relatively slow, we can chart the condition of our oceans and seas going back well before the industrial revolution, defining a baseline for oceanographic and climate-change research. Combining the analytical techniques of the ARIEs with advanced dating techniques will contribute to a better understanding of how the physical properties of our water system change over time.

KEY EXAMPLE

WATER CIRCULATION PATTERNS

Anthropogenic radioactive releases into the environment have proven potential as tracers and for dating applications of ocean current, sediment cores and groundwater patterns. Measured by accelerator mass spectrometry (AMS) at the ARIEs, long-lived radionuclides such as ^{99}Tc, ^{129}I and ^{236}U, ^{233}U and Pu isotopes and ^{14}C allow us to spatially and temporally map the Earth's major water cycles. Combining AMS dating with chemical analyses of inland, coastal and oceanic sediment cores gives us a better understanding and quantification of anthropogenic influences. Meanwhile, palaeo-temperature reconstructions and measurements of the acidification of oceans will contribute to our understanding of history of climate change, while sediment profiles incorporating traces of (for example) anthropogenic generated pollutants – including microplastics and (banned) pesticides, drugs and chemicals – expose the human influence on our vital water environment and ecosystems.

SNAPSHOT

THE PRESENT

Monitoring the current "health" of the oceans, seas, and coastal and inland waters needs a global approach. The size of plastic debris in the oceans ranges over several orders of magnitude, from fishing nets to plastic carrier bags to micro- and even nano-scale plastics. Inland waters show increasing concentrations of pharmaceuticals, antibiotics, pesticides and hormones. All these pollutants eventually end up in the food-chain and should therefore be monitored and investigated.

KEY EXAMPLE

POLLUTION DEGRADATION PROCESSES

Pollutants are physically and chemically degraded in the environment under the action of sunlight (that is, its ultraviolet component) and salt water, sometimes combined with that of bacteria. The ARIEs offer the possibility of studying these pollutants and their degradation processes by analysing and determining their molecular structure, size, morphology and composition, as well as their electronic, magnetic and optical properties, etc. The number of small plastic particles (micro- to nano-scale) present in ocean water is largely unknown as they require special detection techniques. Recently, a laser-based microscopy technique based on stimulated Raman spectroscopy was developed at one of the ARIEs to identify and quantify microplastics; in a harbour sediment, some 12,000 particles per kilogram were discovered [1]. The advanced tooling of electron microscopy, X-ray and Raman spectroscopy, optical and free-electron lasers allows us to detect and characterise such particles down to the nanometre scale.

SNAPSHOT

THE FUTURE

To improve the quality of the oceans, seas, and coastal and inland waters, pollution should be addressed at the source. Recyclable materials are one of many ways to improve on current levels of pollution, or at least maintain the quality of different water systems, and ARIEs can characterise solutions in the form of new recycling processes, and new materials themselves, such as biodegradables. In addition, the degradation processes and products of these new materials must be understood to identify and assess potential environmental risks.

KEY EXAMPLE

BIODEGRADABLE PLASTICS

Degradation to non-toxic / environmentally safe compounds by natural and/or biological processes is the key feature of biodegradable plastics, and is how they can contribute to a more sustainable society. The ARIEs offer the tools to investigate and assist the development of new biodegradable plastics (for example, cellulose- or lignin-based polymers), and to determine their degradation products in detail by means of synchrotron X-rays, free-electron lasers, transmission electron microscopy or laser-based spectroscopies. In particular, AMS measurements of ^{14}C content can be used to distinguish bio-based plastics from fossil-based plastics, and thereby monitor the percentage of bio-based plastics in product or waste streams.

KEY EXAMPLE

OPTIMISED RECYCLING

Currently, the recycling of plastic household waste is based on sorting with near-infrared spectroscopy. A circular economy, however, will require better sorting and higher quality recycling. Developed at the ARIEs, laser-based spectroscopic techniques for multimodal analysis, and techniques such as magnetic-density separation, could be effective solutions. In just one example of the important contribution of ARIEs to recycling processes, a recent paper [2] described the remarkable efficiency with which an optimised enzyme could hydrolyse the most abundant polyester plastic (polyethylene terephthalate, or PET): up to 90% into monomers, as measured by synchrotron X-rays.

KEY EXAMPLE

WATER DESALINATION AND PURIFICATION

Ion beams can be used for the production of etched ion-track membranes. Thanks to the characteristics of these membranes, ions can be transported in such a way as to desalinate and purify water, as well as sense of harmful substances.

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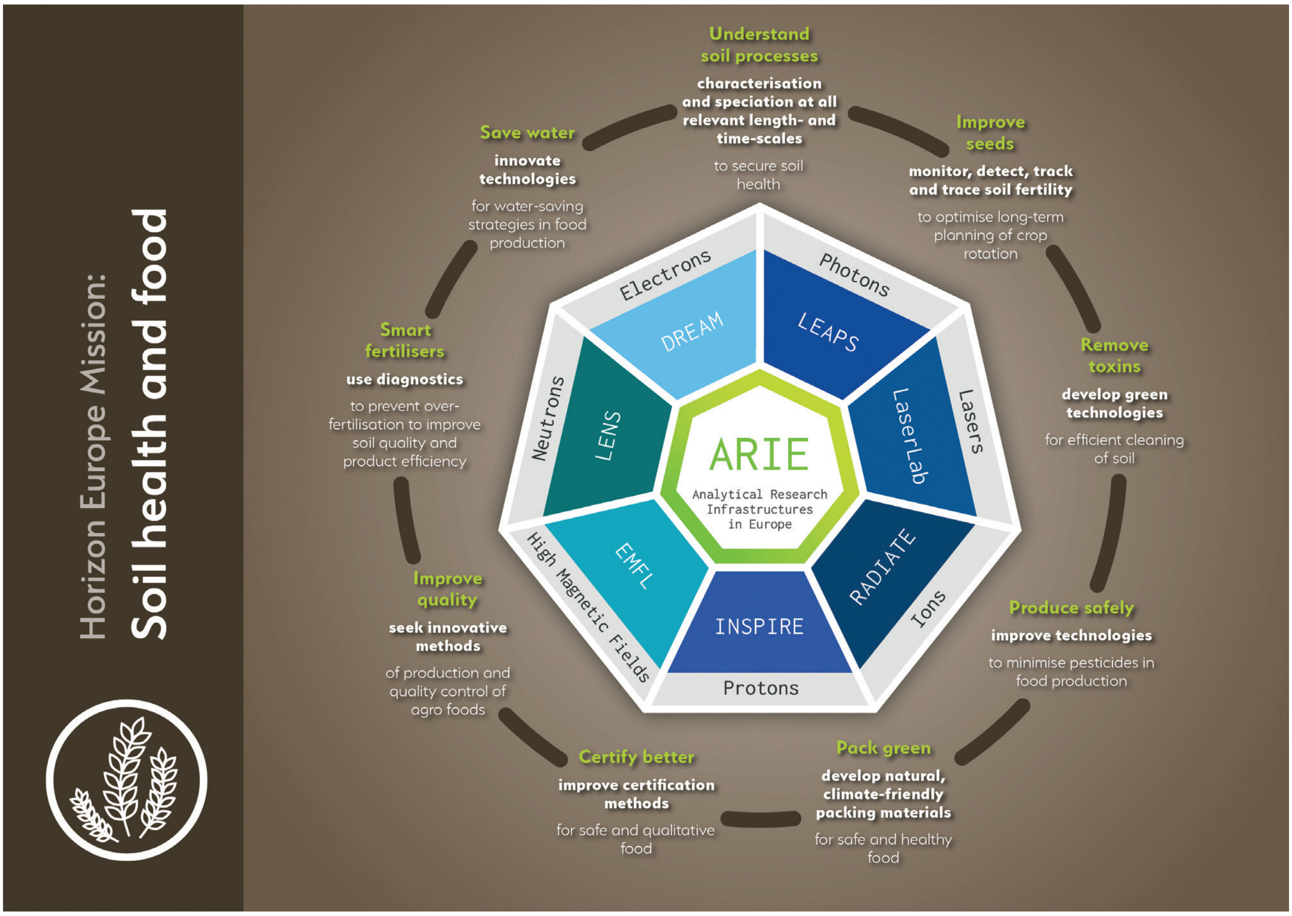
[1] Zada, L, Leslie, HA, Vethaak, AD, et al. Fast microplastics identification with stimulated Raman scattering microscopy. J Raman Spectrosc, 49, 1136– 1144 (2018). doi.org/10.1002/jrs.5367

[2] Tournier, V., Topham, C.M., Gilles, A. et al. An engineered PET depolymerase to break down and recycle plastic bottles. Nature 580, 216–219 (2020). doi.org/10.1038/s41586-020-2149-4

SOIL HEALTH AND FOOD



Soil as a resource is currently endangered and its formation, preservation, decontamination and regeneration are vital challenges for society. Healthy soils sustain a variety of organisms that help to control plant disease, as well as insect and weed pests; they also form beneficial symbiotic associations with plant roots; recycle essential plant nutrients; improve soil structure for water and nutrient holding capacity; and ultimately improve crop production. A healthy soil prevents pollution of the environment and helps mitigate climate change by maintaining or increasing stored carbon.

Soils are currently studied on length scales ranging from the molecular to world level and all spatial levels in between. However smaller length scales, extending over eight orders of magnitude from 1 nm to 10 cm, are vital for an improved understanding of the main active soil components, including fine minerals, organic matter, bacteria and others. Research into soil behaviour across this range of smaller length scales is a key point for identifying future solutions.

But the health of soil itself is not the only problem. A growing population demands more food, and moreover food that meets the nutritional requirements of both the elderly and children, whose health is particularly dependent on their diet. Ensuring food quality implies avoiding unwanted additives. Reducing the environmental footprint of food implies replacing animal proteins with those of plants or insects, and better use of resources.

With their various complementary imaging modes, the ARIEs offer a sure route to understanding, giving access to the various soil and food components, and their spatial and functional correlations, at all relevant length scales.

SNAPSHOT

FOOD, PLANTS AND CLIMATE CHANGE

The world's food production is facing unprecedented challenges: climate change and overpopulation, as well as knock-on problems such as drought, rising salinity and soil erosion in areas with intense agriculture. The ARIEs are supporting research dedicated to the mitigation of these processes, for example in their application of a wide range of research methods to determine specific water, elemental and molecular distributions in plants. In addition, the ARIEs support the development of laser-based remote-sensing technologies to monitor agricultural emissions and changes in soil organic carbon content, both of which are important contributors to levels of greenhouse gases.

KEY EXAMPLE

TRACKING AND CHARACTERISING TRACE ELEMENTS AND CONTAMINATION

The sensitive probes of the ARIEs facilities can detect, map and characterise low concentrations of elements and contamination. The chemical imaging of plant tissue and its trace-element composition is one example. Dedicated tomographic techniques also support the selection of drought-resistant and salinity-resistant varieties, as well as the development of strategies to use less water, fertilisers and pesticides in agriculture. What is more, over 30% of the population in the developing and developed world is affected by iron deficiency [1]: our advanced microscopies and highly sensitive, bulk chemical analytical methods support research on the responses of plants to soil mineral fortification, and the selection of (healthier) mineral-rich varieties of crops.

As a result of poor collection and management practices, there is the possibility of food contamination with various pollutants, such as pesticides, mineral oils, heavy metals, antibiotics, toxins, bacteria and viruses. Moreover, products of high commercial and nutritional value (such as olive oil) are the subject of fraud, substituted by cheaper adulterants of lower nutritional value. With their sensitive analytics, our infrastructures can help fight against food contamination, and food fraud and forgery.

SNAPSHOT

SOIL CONTAMINATION AND REMEDIATION

Soil pollution is a worldwide environmental issue that has attracted considerable public attention, largely from the increasing concern for the security of agricultural products. It is estimated that 355,000 people are killed each year globally as a result of soil poisoning [2], through contaminants entering either groundwater or the food chain.

KEY EXAMPLE

HEAVY METAL CONTAMINATION

A particular source of soil contamination comes in the form of of heavy metals. These elements enter the soil agroecosystem both naturally and through anthropogenic activities. Remediation using chemical, physical and biological methods can solve the problem; phytoremediation – the use of plants themselves to clean up contaminants – has proven to be a promising improvement on conventional approaches, as it is cost-effective, environmentally friendly and aesthetically pleasing.

Species of allium have been shown to be effective phytoremediators of Cd, Te and Se, all of which are toxic to most other plant species. Their effectiveness has been linked to their intrinsically high sulphur content; but to understand the precise mechanism by which phytoremediation occurs, the structure and chemistry of the toxic metal species must be characterised within their root cellular system. Nevertheless, even in the most effective phytoremediating plants the concentration of heavy metals is low, and radiolabels are needed to highlight the chemical pathways. This demands a multimodal, multiscale approach – one that exploits the combined strengths of the ARIE X-ray, electron and ion-based spectroscopies and imaging, as well as accurate mass measurement.

[1] WHO Global Database on Anaemia

[2] The world health report 2003 – shaping the future. Geneva, World Health Organization, 2003.

CONCLUSIONS AND PERSPECTIVES

The ARIEs stand together and are ready to respond to the needs of the Horizon Europe Missions. They represent the widest and most mature set of such infrastructures in the world. Their special capacities, skills and cultures – often reflected in their position on the ESFRI Roadmap – provide unique opportunities to support the analytical and characterisation needs across the Missions. The ARIE facilities already support a growing community of some 40,000 researchers across Europe and indeed throughout the world, bridging science disciplines, academia and industry, and functioning as multi-faceted science and technology enablers.

As mentioned above, Europe, like nowhere else in the world, provides a special framework for this type of collaboration which crosses borders, cultures and disciplines, with academic and industrial researchers and stakeholders alike. It is an asset that is worth cultivating through the Missions, in which the ARIEs are fully prepared to play a proactive role. The technical innovations created by the Missions will need prompt, responsive access to the ARIE platforms, with instrumentation to match their needs. The ARIEs will work closely with the Horizon Europe Mission board specialists and within other strategically oriented partnerships to mesh seamlessly with the needs of the Missions, thereby strengthening Europe' s scientific and technological bases and the European Research Area.

This paper has outlined, with examples, the kind of advanced experiments and measurements that the ARIE facilities can perform in support of the Horizon Europe Missions. These are just a taste of the wide-ranging capacities available. Undoubtedly new applications will arise, in particular as new generations of the ARIE facilities are constructed or upgraded, answering the needs of Horizon Europe with ever more powerful techniques and tools. The ARIE Mission approach will promote the integration of the Research Infrastructure ecosystem whereby different RIs cluster for a specific mission and develop joint services targeting complex research questions.

European Magnetic Field Laboratory (EMFL)

emfl.eu

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Hochfeld-Magnetlabor Dresden -HLD	www.hzdr.de	Germany
Laboratoire National des Champs Magnétiques Intenses - LNCMI	lncmi.cnrs.fr	France

DREAM

esteem3.eu

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University of Oxford	www.ox.ac.uk	United Kingdom
Forschungszentrum Jülich	www.fz-juelich.de	Germany
EMAT at University of Antwerp	www.uantwerpen.be/en/research-groups/emat	Belgium
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The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences (IFJ PAN)	www.ifj.edu.pl	Poland
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Coimbra Laser Lab - CLL	www.uc.pt/en/uid/laserlab	Portugal
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Center for Ultrafast Lasers at UCM	www.ucm.es/ulc	Spain

Laserlab-Europe

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Helmholtz-Zentrum Dresden Rossendorf	www.hzdr.de	Germany
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Nanoscience Center, University of Jyväskylä	www.jyu.fi/science/en/nanoscience-center	Finland
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Laboratoire Lasers, Plasmas et Procédés Photoniques – LP3	www.lp3.univ-mrs.fr	France
Laboratoire pour l'Utilisation des Lasers Intenses	portail.polytechnique.edu/luli	France
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Max Planck Institute of Quantum Optics - MPQ	www.mpq.mpg.de	Germany
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leaps-initiative.eu

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www.lens-initiative.org/budapest-neutron-centre-bnc

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RADIATE

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