ELETTRA IAEA COLLABORATING CENTER: RESEARCH OPPORTUNITIES USING LIGHT GENERATED BY ELECTRON ACCELERATORS

G. AQUILANTI
Elettra – Sincrotrone Trieste SCpA
Trieste, Italy
Email: giuliana.aquilanti@elettra.eu

L. GREGORATTI
Elettra – Sincrotrone Trieste SCpA
Trieste, Italy
Email: luca.gregoratti@elettra.eu

M. KISKINOVA
Elettra – Sincrotrone Trieste SCpA
Trieste, Italy
Email: maya.kiskinova@elettra.eu

Abstract

Large scale synchrotron and free electron laser facilities where the operated versatile experimental stations based on the photon interactions provide access to the state-of-the art techniques are the cradle of multidisciplinary research, spanning over physics, chemistry, material science and engineering to environment, biology, medicine, archeology and cultural heritage. The paper will describe the exciting opportunities offered at Elettra - Sincrotrone Trieste and how as IAEA Collaborating Centre it provides access of Member States to synchrotron-based research and coordinated research activities, fostering also know-how transfer through training, schools and workshops. The selected exemplary systems will address the most recent achievements in basic and applied research in various fields of material and life sciences. Recent activities and achievements in the frame of IAEA-Elettra partnership are outlined.

1. INTRODUCTION: HISTORIC MILESTONES AND PRESENT STATUS OF ELETTRA-SINCROTRONE TRIESTE

The photon emission generated by relativistic electrons in circular or linear accelerators, first observed in 1947 in General Electric Lab in New York and considered 'undesired' loss of electron energy, has been recognized about two decades later as light with exceptional properties. Following the first steps with USA Tantalus Synchrotron opened in 1968 a great number of 2nd generation synchrotron facilities, using only bending magnets, started operation in 1980^{s}, paving the road to scientific discoveries, thanks to the fast developing synchrotron-based techniques. Pressed by the increasing requests for higher brightness in order to make further advances in the performance of the synchrotron-based methods the synchrotron storage rings were ongoing continuous developments and among the first 3rd generation synchrotrons starting operation in 1990^{s} is Elettra - Sincrotrone Trieste in Europe[1].

At present the Italian non-profit company Elettra - Sincrotrone Trieste is classified as a multidisciplinary research center of excellence specialized in generating synchrotron and free-electron laser light and applying the related state-of-the art experimental techniques for fundamental and applied research in all domains of materials and life sciences. Its mission is serving international user communities to promote social and economic growth through basic and applied research, know-how transfer, education and participation in fruitful collaborations and international networks. The scientific and technical performance and developments of the facilities, managed by Elettra - Sincrotrone Trieste, are monitored by international experts, appointed as Members of the Machine Advisory Committee (MAC) and Scientific Advisory Council (SAC). Elettra is located on the Trieste-Basovizza upland zone of AREA science park[2], which hosts many other research and technology institutions, among many also is International Center of Genetic Engineering and Biotechnology, ICGEB, established as a special project of UNIDO.[3]

The name Elettra derives from ancient Greek Elektra, meaning 'shining like amber' and 'electron' has the same origin. The construction of the Elettra synchrotron facility, including accelerator, storage ring, experimental hall, the first beamlines and all infrastructure started beginning 1991. The storage ring Elettra is a double bend achromat with space in the lattice, the so-called long straight sections, to install insertion devices. undulators or wigglers, the distinctive feature of the 3rd generation synchrotrons for providing high photon brightness. In less than 3 years the light shined on October 20th 1993, consenting the first beamlines to start experiments with users in 1994. Elettra synchrotron facility underwent two upgrades – in 2007 the 1 GeV linear accelerator (LINAC) was replaced by a small LINAC and a full energy booster that accelerates and injects electrons with the final energy of 2.0 or 2.4 GeV in the storage ring. Since 2010 Elettra synchrotron operates at both energies in a top-up mode and also has implemented hybrid mode operation for allowing time resolved experiments down to the sub nsec range.[4]

The old injector was upgraded and was used to build the Free Electron Laser (FEL) facility – FERMI, the first and still the only seeded FEL worldwide. The FEL process at FERMI is triggered by an external seed laser adding full longitudinal coherence of the FERMI-FEL pulses, which are also tunable in wavelength, power, time duration and multiple polarization.[5] The two high gain harmonic generation (HGHG) lines, namely single-stage (FEL-1) and double-stage (FEL-2), cover the wavelength range 100-20 nm and 20-4 nm, respectively. The first FEL light was obtained at the end of 2010 with FEL-1 that started user operation end of 2011, whereas FEL-2 was opened for users in 2016. For pump-probe experiments to explore ultrafast femto-picosecond dynamics along with the possibility to synchronize the FEL pulses with those of an external optical laser, two FEL pulse schemes were implemented in 2015 allowing generation of two FEL pulses with desired wavelengths and temporal separation for multicolor experiments.

The high level of know-how and the accumulated experience in production of synchrotron light during the construction and operation of Elettra storage ring has also been spinned-off; Elettra founded in 2007 the company Kyma S.r.l, which is now designing and fabricating insertion devices for many facilities worldwide.[6]

Elettra storage ring feeds 29 beamlines (FIG. 1) working simultaneously, whereas FERMI-FEL has 6 beamlines, fed alternatively with the beam. Each beamline is designed to transport the photon beam, using proper optical and beam control systems for optimizing the flux density, beam dimensions and wavelength range in order to match best the requirements of the experimental techniques used at the end stations.

Elettra and CERIC-ERIC allocated users by country:

ARGENTINA	3	JORDAN	6
AUSTRALIA	6	MEXICO	6
AUSTRIA	60	MOLDOVA, REPUBLIC OF	3
BELARUS	2	NETHERLANDS	5
BELGIUM	16	NEW ZEALAND	1
BOSNIA AND HERZEGOVINA	1	NORWAY	10
BRAZIL	11	POLAND	15
BULGARIA	5	PORTUGAL	5
CANADA	7	ROMANIA	9
CHINA	10	RUSSIAN FEDERATION	33
CROATIA	34	SAUDI ARABIA	1
CZECH REPUBLIC	18	SERBIA	4
DENMARK	9	SINGAPORE	1
EGYPT	4	SLOVAKIA	1
FRANCE	53	SLOVENIA	28
GEORGIA	4	SOUTH AFRICA	1
GERMANY	116	SPAIN	38
GREECE	15	SWEDEN	18
HUNGARY	7	SWITZERLAND	28
INDIA	68	TURKEY	1
IRAN, ISLAMIC REPUBLIC OF	4	UKRAINE	22
ISRAEL	3	UNITED KINGDOM	29
ITALY	487	UNITED STATES OF AMERICA	12
JAPAN	9	VIET NAM	2
		Grand Total	**1231**

FIG. 1. (Left) Beamlines hosted by the Elettra synchrotron Storage Ring. The stars indicate the hard X-ray beamlines. The beamlines belonging or in partnership with other national, foreign or international institutions are indicated by logos and flags. (Right) Table reporting the number of users from different countries who performed experiments at Elettra beamlines in 2019. It represents the typical number - with small variations for different years. During COVID some experiments were organized with users in remote mode.

The numerous experimental stations host state-of-the art instruments where cutting-edge scattering, imaging and spectroscopic techniques are implemented, using dedicated experimental set-ups for monitoring the relevant signals of the scattered and transmitted photons or emitted photons and electrons. Ten (indicated by red stars in FIG. 1) out of all 28 beamlines use hard X-rays. They are provided by two wigglers, a permanent multipole wiggler shared by the SAXS and XRD1 beamlines and a Super Conducting multipole Wiggler (SCW), reaching 35 keV photon energy, shared by the XRD2 and XPRESS beamlines, and six bending magnets - one of them feeds the XRF (IAEA-Elettra) beamline. Seventeen beamlines work in the UV and soft X-ray range. They get light provided by ten undulators, one elliptical wiggler and two bending magnets. There are also two beamlines using bending magnet (SISSI), which work in the IR-THz range. Eight of the Elettra beamlines are built and operated by the Consiglio Nazionale delle Ricerche (CNR) and another three are operated in partnership with CNR. Two beamlines are funded and operated by foreign institutions, namely the SAXS beamline belongs to the Austrian Institute of Inorganic Chemistry of the Graz University of Technology and the Material Science beamline to the Institute of Physics of the Check Academy of Sciences and the Charles University in Prague. Another four beamlines have partnership with foreign institutions, namely the XPRESS and XRD2 beamlines are operated together with Indian Institute of Science (IISc), Bengaluru, an XPEEM at the NanoESCA beamline is operated by the Peter Grünberg Institute in Forschungszentrum Jülich, Germany, the CoSmoS station at the SuperESCA beamline is operated by the National Institute of Materials Physics in Magurele, Romania. The monochromator of the XAFS beamline was funded by the International Center of Theoretical Physics (ICTP) of UNESCO and the XRF beamline is operated in partnership with the Physics Section of IAEA. Since Elettra is also one of the eight partner facilities of Central European Research Infrastructure Consortium (CERIC)[7] some beamlines offer dedicated beamtime for international users for synchrotron-based methods complemented with NMR, SEM, TXM and Ion beam analysis available in other partner facilities.

About 80% of the total, both synchrotron and FEL beamtime, on average ~ 270 days/annum for Elettra synchrotron and ~150 days/annum of FERMI-FEL, is dedicated to the users who have to submit their project proposals the semester before the requested beamtime. The beamtime is granted on the basis of the scientific merit and/or technological impact of their projects, graded by independent international panels consisting of specialists in all research fields. On average about 50% of the projects are granted synchrotron beamtime and ~30% are granted FERMI-FEL beamtime. Materials, solid state physics and life science studies are still the most requested but the last years also energy, environmental and cultural heritage requests are continuously growing. On average annually over 1200 scientists conduct investigations using Elettra synchrotron and, as illustrated in FIG. 1b, more than 50% of the Elettra synchrotron users come from abroad with increasing number from Central-Eastern European countries, Asia, South America and Africa. In the last decade in the frame of the collaboration with IAEA and ICTP the request for using synchrotron techniques from ‘so-called’ developing countries is rising. For the case of FERMI the international participation is much higher with ~80% of users from Europe, North America and Asia. This difference between the origin of the synchrotron and FEL users is understandable considering the smaller number FEL facilities and the demand of a very advanced knowledge level requested for the FEL-type research. In the last five years (2017-2021) the results obtained at Elettra beamlines are reported in 3140 papers and those of Fermi, where a single beamline can use the beam, in 220 papers with a significant increase of the HI publications.

Elettra - Sincrotrone Trieste also offers access to several laboratories with conventional analytical techniques for production or characterization of samples to add information complementary to that obtained at the beamlines. Among them are Structural Biology[8] and NanoLab[9], both in the biomedical field with instruments used for preparation (production and crystallization), screening and complementary characterization of biomolecules and other types of bio-matter which is an added value to the most frequently used for bio-research XRD, SAXS, IR and IUVX beamlines.

Since decades Elettra is fostering know-how transfer through schools and workshops and on-site experimental training, that have led to continuous increase of the number of researchers using its facilities. Among many we should mention the following annual schools: (i) the “School on Synchrotron Radiation “Gilberto Vlaic”: Fundamentals, Methods and Applications” organized in collaboration with Italian Society of Synchrotron Radiation (SILS)[10] and (ii) the “HERCULES European School”, coordinated by ESRF[11]. Since the beginning of the century Elettra is tightly engaged in organization of the bi-annual ICTP School on Advanced Light Sources and Multidisciplinary Applications[12], where IAEA is also involved. This school is in the frame of cooperation agreement with UNESCO’s International Center of Theoretical physics (ICTP) and targets young scientists with rather advanced basic knowledge to be introduced to the exceptional research opportunities offered by synchrotron and free-electron-laser (FEL) facilities worldwide by lecturers with international recognitions, including visits and demonstrations at Elettra and FERMI beamlines. This school that has been very popular and attracted the best young scientists from Asia, Africa and South America, unfortunately was cancelled in 2020 due to COVID but is expected to be re-started soon.

Elettra - Sincrotrone Trieste is involved in numerous international projects[13] and coordinated research activities, e.g. founder of the LEAPS Consortium[14], partner of FELs of Europe[15] and has played an active role in several European strategic programs, listed in ESFRI Roadmap, and many others[16]. The long collaboration and partnership activities with IAEA, which stated with the first nomination of Elettra as an IAEA Collaborating Center in 2005 will be described in more details in the last section.

Elettra was an IAEA Collaborating Centre in the period 2005-2014 and became partner at the XRF beamline in 2014 installing and operating in partnership the experimental end station. Along with the ongoing XRF partnership Elettra was again nominated IAEA Collaborating Centre in 2020. More details of the ongoing research education and training activities in the frame of Elettra-IAEA partnership are reported in the last section.

2. RESEARCH OPPORTUNITIES USING ELETTRA-SINCROTRONE TRIESTE FACILITIES

The synchrotron light generated by Elettra storage ring and FERMI-FEL has the appealing characteristics as high brightness (ph/mm^2/s/mrad^2, 0.1% bandwidth), broad wavelength range - from THZ to hard X-rays, tunability, multiple polarization options and coherence. The photons interact with the electrons of the atoms in the matter and have higher penetration power compared to charged particles that is controlled by the photon energy. The photon-matter interactions are very sensitive to the local structural organization and environment of the matter under investigation and compass redirection (scattering) and absorption, which result in scattered and transmitted photons, and electron and photon emission, as schematically illustrated in FIG. 2. Monitoring selectively, the photon and electron signals can be used for characterization of the spatial and electronic structure, chemical composition and function of matter down to atomic length scales and fs time scales.

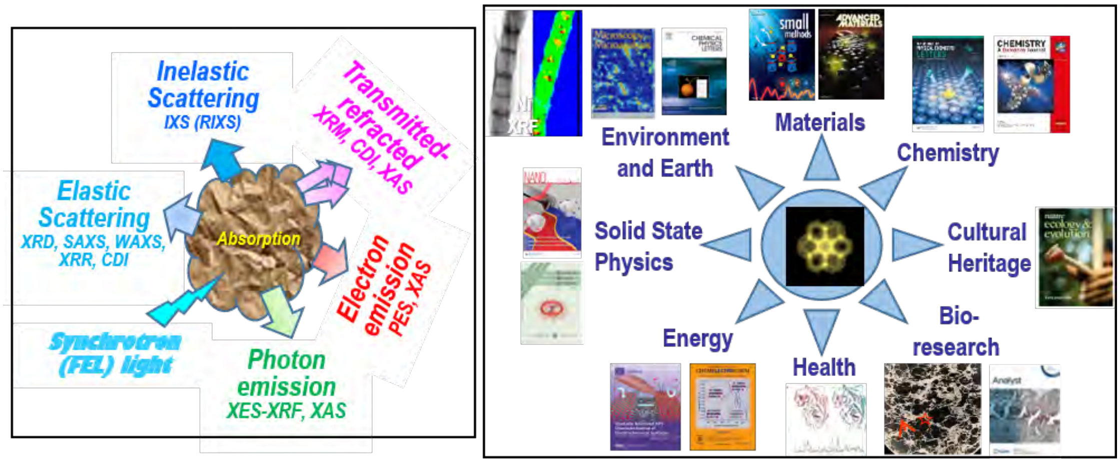

FIG. 2. (left) Photon-matter interactions; (right) Applications fields with examples using studies carried out at Elettra synchrotron and FERMI beamlines.

The type of information is first determined by the fundamental issue whether the photons loss energy when interacting with matter or not. If the photon is elastically scattered or refracted at an interface of materials with dissimilar refraction index, it is redirected preserving its energy and wavelength. The monitored scattered intensity as a function of the incident and scattered angle provides structural information, from short range, with atomic resolution for ordered lattices, called X-ray diffraction (XRD) to longer range, 1-100 nm probing the structural variations in disordered systems - Small Angle X-ray Scattering (SAXS), Wide Angle X-ray Scattering (WAXS) and X-ray Reflectivity (XRR). Grazing Angle SAXS (GISAXS) and XRR are adding enhanced surface sensitivity for exploring multilayer systems. The collected photon signal after passing through the specimen depends on the absorption of the X-rays, determined by the local density and composition, where the refraction at interfaces adds also the phase contrast, which improves the resolution and is further enhanced using more coherent X-rays. Here it should be noted that lateral resolution when doing X-ray imaging is also determined by the beam size, de-magnified using focusing optics. The optics limitations can be overcome by Coherent Diffraction Imaging (CDI), using highly coherent light, already achievable at the 3rd generation synchrotrons and provided by the fully coherent FELs. In CDI the real image is reconstructed from the obtained speckle diffraction patterns via algorithm, retrieving the lost phase information. CDI approaches are already widely used at FERMI-FEL and also at TwinMic beamline at Elettra synchrotron. Inelastic scattering is occurring when the scattered and transmitted photons loss energy due to the generated electron excitation in specific atom and is accompanied by electron and/or photon emission. The detected and filtered photon and electron signals are the base of the Inelastic X-ray Spectroscopy (IXS), X-ray Absorption Spectroscopy (XAS), PhotoElectron Spectroscopy (PES) and X-ray Emission Spectroscopy (XES) or better known as X-ray Fluorescence Spectroscopy (XRF). Here should be outlined that XAS, also called X-Ray Absorption Fine Structure (XAFS), is the spectroscopy that requires tunability for scanning the photon energy is also the only one that can use both the emitted or transmitted photon signal and also the emitted total electron signal for obtaining the spectra. Reference 17 can be used as one of the exemplary recent books describing in details all photon-matter interactions and synchrotron-based techniques that have opened unique opportunity to reveal the geometric and electronic structure, chemical composition and other many other phenomena controlling the properties and functionality of the studied matter.

Twelve of the Elettra beamlines and one of the FERMI-FEL beamlines host experimental stations equipped with instruments and techniques based on detection of the electron emission, which provides the possibility for examination of the electronic structure, elemental and chemical composition of molecules in gas phase and of solid specimen with surface sensibility. Dedicated beamlines are capable to execute high resolution PES and XAS, angular-resolved PES (ARPES), time-resolved PES and XAS, PES and XAS microscopy with few tens nm spatial resolution. Thanks to the brightness, tunability and polarization of the synchrotron light these techniques have become state-of-the art and have provided new information about properties of strongly correlated electron and 2D materials and for surface and interface phenomena at gas/solid liquid/solid and solid/solid interfaces, which is highly requested for selecting the best materials used in electronic devices, sensor devices with broad applications fields, including biomedical appliances as well and in catalysis, the core of chemical industry, fuel and energy production, conversion and storage. Among the main targets for understanding the functionality of such systems is the response to operating conditions and external stimuli – temperature, radiation, electric and magnetic. Using total electron yield for XAS and versatility of X-ray Magnetic Circular Dichroism (XMCD) and X-Ray Magnetic Lineal Dichroism experiments using both Elettra and FERMI-FEL beamlines have allowed to observe the evolution of magnetic nanostructures, as domains, domain walls and skyrmions, the key for advances in development of new magnetic devices. Six Elettra synchrotron and three FERMI-FEL beamlines use photon-in/photon-out spectroscopies, namely XES-XRF, XAS, IUVS-Raman and InfraRed (IR), including XRF, XAS and IR microscopy and imaging. Among them is the IAEA-Elettra XRF beamline, using XRF and XAS, where the present focusing optics allows for a few micrometer spatial resolution. Five hard X-ray beamlines use scattering techniques – XRD, SAXS-GISAXS, WAXS and XRR. Another two hard X-ray beamlines (LILIT and DXRL) are lithography beamlines with strong technological impact for nano-structuring, requested for fabrication nanoparts of devices. The sixth hard X-ray beamline is SYRMEP dedicated to X-ray tomography. Elettra is the first synchrotron facility that started two decades ago a clinical program based on X-ray tomography phase contrast imaging. Now SYRMEP is a cradle of multiscale biomedical imaging bridging the gap between preclinical research and patient application.[18]

All synchrotron-based techniques have found multidisciplinary applications very schematically illustrated in FIG. 2-left, where the research examples are from studies carried out at Elettra beamlines. Health and bio-research issues are interconnected and have largely been based on the paradigm from structure to function. The recent advances in photon production and transport have enabled protein micro-crystallography, sub-micrometer X-ray imaging of tissues and cells with speciation information and even in-vivo studies using non-ionizing IR microscopy. The discovered SARS-CoV-2 main protease structure at XRD2 beamline, was recognized as a promising target for the development of effective drugs. The computed X-ray tomography image reveals alveolar dilatation and thickening in lung tissue due to COVID, thanks to the use of synchrotron light allowing to see features in anatomical fine structure and its changes due a decease, invisible with hospital instruments. Megapixel scanning transmission soft X-ray microscopy imaging coupled with compressive sensing X-ray fluorescence have opened new horizons for faster screening of large biological tissues that was advertised at the cover page of Analyst Journal[19]. Energy is another grand challenge of our society and all devices for energy production, conversion and storage are complex functional systems involving multiple energy, time and length-scales. Synchrotron-based spectroscopy, imaging and scattering offer necessary characterization potentials to explore physical and chemical phenomena governing the performance of different energy devices. Micro-PES characterization allowing insights in chemistry of electrochemical surfaces in energy devices is advertises at the Surfaces cover page[20] and XAS Investigation of reversible redox activity cathode material with high capacity deserved ChemElectroChem cover page[21]. In solid state physics understanding spin-orbit coupling effects in quantum materials for electronics has made tremendous steps ahead thanks to the tunability and multiple polarization of the synchrotron light and the observed ferroelectric control of GeTe spin texture by ARPES deserved a NanoLetter cover page[22]. Triggering and switching magnetic moments in thin films is of key importance from spintronics to quantum information and in this respect circular and linear polarization of the beams, used for XAS and resonant imaging made major contributions - the recently reported free electron laser-based scheme for generating atomic-scale charge current loops within femtoseconds, using FERMI-FEL, got a Physical Review Letters cover page[23]. The challenges in environmental studies due to the limits of the available techniques in terms of trace element sensitivity and spatial resolution have been largely overcome using synchrotron light for shedding light on the involved bio-chemical and atmospheric processes. Thanks to the results obtained by X-ray and XRF imaging of cable bacteria at TwinMic beamline it was revealed its electrical conductivity occurs through proteins with Ni-dependent cofactors, which is remarkable and surprising, since biological electron transport typically involves Fe and Cu metalloproteins[24]. X-Ray microscopy and XRF-XAS microscopy analyses revealing the fate of lungs and pleura in the presence of inhaled asbestos in polluted areas got a Microscopy and Microanalysis cover page[25]. The monitored escape of O+ ions from the atmosphere relevant to explanation of the ion density profiles in space monitored with coincidence ARPES at Gas phase beamline got a Chemical Physics Letters cover page[26]. Material research is also linked to manufacturing. An example for advances in the field are the operando XAS studies, showing that Na-Rich Manganese Hexacyanoferrate is a promising candidate for Li and Na Ion storage, advertised at the Small cover page[27]. Recently accomplished by direct X-ray lithography at DXRL beamline nano-patterning of Metal Organic Frameworks (MOF), verified by GISAXS for being used in micro-devices to allow dynamic positioning in magnetic fields, is advertised at Nature Materials cover page[28]. In chemistry the applications are multiple spanning over synthesis of new substances, their characterization and evolution under operation or exposure to various environments. Examples are smart decomposition of cyclic alanine-alanine dipeptide by VUV Radiation marked as seed for the synthesis of biologically relevant species advertised in Journal Physical Chemistry Letters at the cover page[29]. The first stereospecific synthesis of a new class of molecular propeller - polycyclic aromatic hydrocarbons, verified by XRD at MCX beamline got cover page of Chemistry European Journal[30]. Cultural heritage studies, relevant to archaeology, palaeontology and art history are fast expanding using the powerful non-destructive synchrotron-based imaging and spectroscopy methods. As an example is the Nature-Ecology and Evolution Cover page publicizing how micro-spectroscopy analysis of lithic pieces from 40-45,000 years ago revealed their use as weapons by anatomically modern humans. Many other environment-relevant and cultural-relevant studies were performed at XRF beamline in partnership with IAEA and will be notified in the next section.

3. RECENT ACTIVITIES AND ACHIEVEMENTS IN THE FRAME OF IAEA-ELETTRA COOPERATION

After a break of six years Elettra was again nominated as Cooperation Center in 2020, which is based on the worldwide recognized experience of Elettra in production and application of both synchrotron and free electron laser light for serving international user community. As Cooperation Center Elettra has become a reference hub, enriching the Member State capabilities in construction of Synchrotron and FEL machines and beamlines and implementation of the very powerful synchrotron-based methods in all domains of material and life sciences. This renewed cooperation agreement follows the ongoing XRF beamline Elettra-IAEA Partnership agreement since 2014 for hosting the end-station of the IAEA Division of Physical and Chemical Sciences[31], which allows the execution of different experiments using all type XES-XRF approaches, complemented by XAS. The IAEA-Elettra XRF beamline was officially inaugurated by

DDG Yukiya Amano in 2014 and was later visited by the Mexican Ambassador in Italy Carlos Gracia de Alba Zepeda in 2020 and the present IAEA DDG Najat Mokhtar in 2021.

Along with the on-site user support, instructing how to execute synchrotron-based experiments and process the obtained data using the instruments at the Elettra beamline end stations, dedicated educational and training events are/will be organized for teaching how to design and build synchrotrons including accelerators, storage rings, beamlines and dedicated measurement stations. An asset for such activities as Cooperation Center is the ongoing operation and continuous upgrades of the IAEA end-station and XRF beamline, where 40% of the beamtime - ~100 days/annum is reserved for the IAEA-supported users from the Member States, most without synchrotron facilities. Although the proposals of these Member State users also pass through the International proposal review panel having such reserved beamtime fraction gives higher chance of these researchers to get access for performing experiments. In order to expand the number of the users from the Member States to be granted beamtime at other Elettra beamlines as general users, where they are competing with highly experiences in synchrotron research scientists, focused training sessions how to write good project proposals are considered as well.

In the frame of the Elettra and IAEA partnership annual training workshops are organized – the next will be July 25-29, 2022[32]. Two professional videos describing the XRF beamline, measurement station and the techniques and data handling have been accomplished by the Elettra and IAEA staff. Participation of the researchers from all Member States is also open for all other schools and workshops organized in partnership with Elettra, some already noted in Section 1.

In the last three years (2019-2021) 52 experiments, supported by IAEA were performed at the XRF beamline, one of them also complemented with operando XAS measurements at XAFS beamline. As illustrated by the chart in FIG. 3a the research projects relevant to life sciences dominate, covering the environment, biology, biomedicine and food. In the same period 35 papers are published in refereed journals and some of the results were presented at seven conferences. The three examples in FIG. 3 are selected from published results obtained at XRF beamline for representing the majority studies carried out by the IAEA-supported users, which are relevant to health, environment and earth sciences. Recognizing the great concern for health hazard due to air, water and food pollution characterization of the pollutant content using synchrotron light is of significant importance. Scientists from Egypt, Jordan and Saudi Arabia used XRF and XAFS spectroscopy to exploit the presence and chemical state of arsenic in ambient air particulates collected in different industrial zones of greater Cairo (FIG. 3b). Thanks to the beam tunability and brightness they were able to achieve high detection levels allowing to distinguish also between the different chemical states of the As in the particulate material[33]. Several publications from a Mexican team were dedicated to exploiting giant gypsum crystals of Naica cave and their evolution, focusing on the potential environmental impact including human activity as well. In their most recent papers[34] the extraction of water from the caves was pointed as a reason for the most significant anthropogenic damage, revealed by complementary grazing incidence diffraction, micro-XRF and XAS results for the structure and surface impurities, summarized in FIG. 3 (c). Scientists from Turkey and Slovenia are collaborating in controlling the presence in food of important for health elements, as Fe in seeds in particular. As illustrated in FIG. 3(d) the elemental XRF mapping of seeds, shows Fe accumulation in endosperm and seed coat and also the relevant spatial distribution of other metals[35].

The advantage of having fully tunable X-ray light has also been extensively used for measuring X-ray emission cross section of different elements varying the incident energy starting from the corresponding absorption edge, which is exclusively important experimental validation of the theoretically predicted using different model. These types of studies have been initiated from the IAEA staff and continues with financial support from IAEA, as clearly stated in Ref. 36.

4. CONCLUSION

The ongoing upgrades of the storage rings and the growing number of FELs worldwide are opening exciting opportunities for “watching” how matter behaves at ultra-short fs time scales down to the level of nano-units, atoms and molecules. They will enable high-throughput and operando structural, physical and chemical characterization fully integrated with operando syntheses, operation and data processing methods for deepening our knowledge in functionality of the complex matter for addressing key societal health, environment, energy and technology challenges. The continuous advances in accelerator technology added further narrowing of the electron beam increasing the brightness and coherence of the emitted photons and these are the 4th Generation synchrotrons starting since 2016 with Max4 and recently with the upgraded ESRF. Upgrade of Elettra storage ring to become a 4th Generation facility is also funded and expected to start operation in 2026.[37]

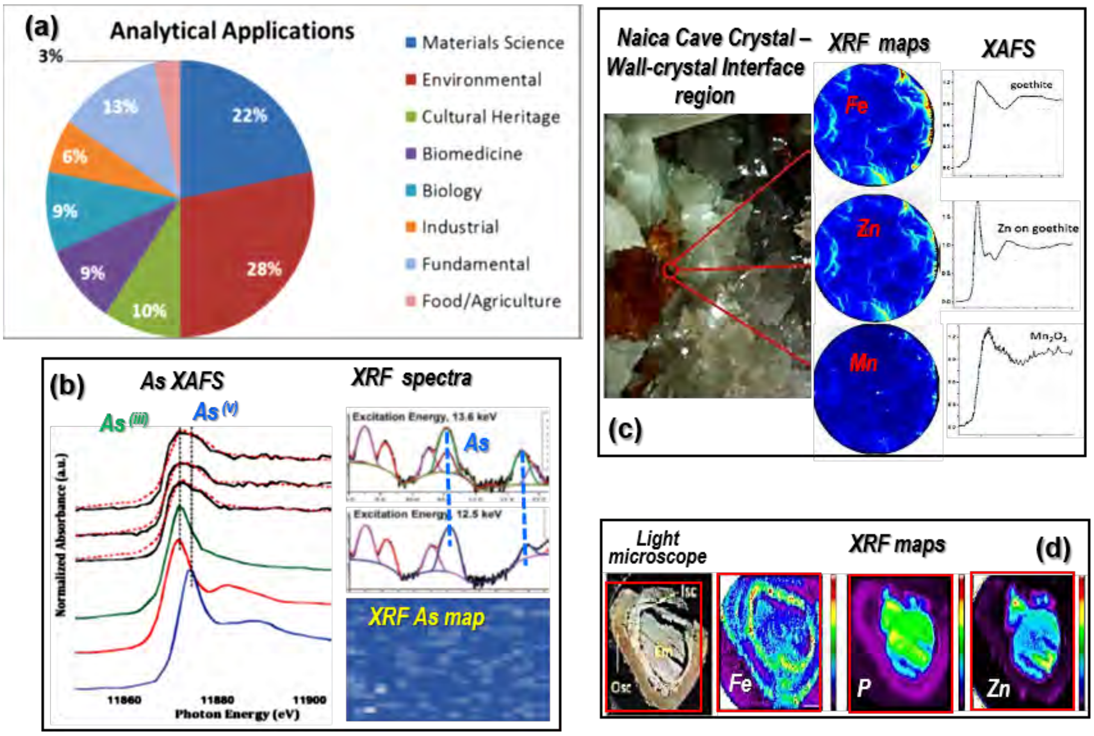

FIG. 3. (a) Chart representing the percentage of XRF beamtime used for different research areas. (b) As content (XRF spectra and maps) and variable chemical state (As XAFS spectra) in different particulate samples collected in industrial zones in Cairo region. The XRF spectra taken at two different X-ray beam energies show the advantage of tunability - by using energy lower than the one required for Br excitation the overlap with Br XRF peak to eliminated; (c) Micro-XRF map showing the distribution of Fe, Zn in Mn in the indicated on the lect zone on a gypsum sample. The corresponding XAFS spectra are fingerprints for the Fe, Zn and Mn chemical state, (d) Micro-XRF maps of a seed shown in the light microscope image on the left showing spatial distribution of Fe, P and Zn.

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