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[1] IAEA Accelerator Knowledge Portal (https://nucleus.iaea.org/sites/accelerators/Pages/default.aspx)

[2] Handbook entitled International Access to Nuclear Physics Facilities in Europe (6th Edition), published by NuPECC (see in http://www.nupecc.org/?display=pub/publications)

[3] See in https://indico.ific.uv.es/event/2824/

[4] See in http://www.ensarfp7.eu/activities/networking-activities/ensaf/2nd-ensaf-workshop-1

LIST OF ACRONYMS AND ABBREVIATIONS

AIFIRA	Applications Interdisciplinaires de Faisceaux d’Ions en Région Aquitaine
CACTUS	Name of an array of 28 Sodium-Iodine detectors installed at the Oslo Cyclotron Laboratory
EBS	Elastic (non-Rutherford) Backscattering Spectrometry
ENSAF	European Network of Small-scale Accelerator Facilities
ERDA	Elastic Recoil Detection Analysis
HORUS	High efficiency Observatory for γ-Ray Unique Spectroscopy
IAEA	International Atomic Energy Agency
LINAC	Linear Accelerator
LNGS	Laboratori Nazionali del Gran Sasso
NCSR	National Centre for Scientific Research
NRA	Nuclear Reaction Analysis
PAPAP	Petit Accélérateur Pour l’AstroPhysique
PIGE	Proton Induced Gamma-ray Emission
PIXE	Proton Induced X-ray Emission
RBS	Rutherford Backscattering Spectrometry
RUBION	Ruhr-Universität Bochum Ionenstrahlen (Central Unit for Ion Beams and Radionuclides of the University of Bochum)

SiRi	Silicon Ring
SONIC	Name of a silicon-detector array installed at the Institute of Nuclear Physics of the University of Cologne
ToF-ERDA	Time-of-Flight Elastic Recoil Detection Analysis
ZAPS	Zero-degree Auger Projectile Spectroscopy

Executive Summary

D7.1 reports on European Small-scale Accelerator Facilities that offer access to external users to perform nuclear physics research covered by ENSAR2. The 15 facilities listed in this report are installed in 11 European countries. Their in-house programmes cover fundamental research in nuclear structure and/or nuclear astrophysics as well as a large variety of applications based on the use of ion and secondary neutron beams. These are related to key societal problems such as biomedicine, radiopharmaceuticals, environmental monitoring and cultural heritage. In addition, they provide equipment to study the physical processes taking place in materials of technological interest under harsh irradiation conditions. Many of these facilities support also the development and testing of instruments in support of scientific as well as industrial research. All facilities in this report provided access to external users. The scientific community working at these facilities comprises nearly 250 researchers.

Introduction

Low-energy stable-beam facilities contribute to our understanding of nuclei through research in nuclear structure, reactions and nuclear astrophysics. Many of them are strongly linked to the large-scale ENSAR2 facilities that provide Transnational Access (TA), either through active participation in their research programmes or by developing experimental techniques and equipment or both. In many of these low-energy accelerator facilities, multidisciplinary research, based on well-established nuclear techniques, is additionally conducted providing this way a broad spectrum of basic accelerator techniques for the needs of high-level education of students and training of young researchers in nuclear physics. This is the case, especially, for university-based accelerator laboratories.

In addition to the aforementioned category of low-energy small-scale accelerator facilities, there are also many others that focus exclusively on applications with important societal impact such as human health, cultural heritage studies, environmental monitoring, materials analysis, modification and characterisation including fusion plasma facing materials and many others. These facilities were able to develop various innovative approaches in some specific domains like, e.g., forensics and bio-medicine. Many of these have also developed remote analytical services, i.e. they accept samples to analyse without requiring physical presence of the sample owner.

In Europe, there exist currently 72 accelerators, mostly electrostatic machines and to a lesser extent cyclotrons [1,2]. This number does not include large accelerator infrastructures, such as neutron spallation sources, synchrotron light sources or other storage rings, X-ray free electron lasers (X-FELs) and electron LINACs. The current Transnational Access large-scale facilities of the ENSAR2 Integrating Activity are also not included in this number. From these 72 accelerators, at least 2/3 belong to laboratories dedicated almost exclusively to accelerator-based applications without offering beam-time for fundamental research activities (at least on a routine basis). Under these constraints, the present report focuses on the latter category only. The location of these facilities across Europe is presented in Figure 1.

To achieve its goals and prepare its deliverables, ENSAF has so far organised two workshops. The first [3] was held on October 19-21, 2016, in Seville, Spain, entitled "International Workshop on Accelerator Operation and Management" and the second one [4] on October 3-4, 2018, in Athens, Greece. Both workshops were open to all scientists from European small-scale accelerator facilities interested in presenting research and training activities, as well as EC-funded projects together with lessons learnt in operating their facility and facilitating access to external users. This document is one of the ENSAF deliverables entitled "Physics Opportunities and Innovation at European Small-Scale Accelerators". It was drafted based on the information provided by the participants of the two ENSAF Workshops [3,4] as well as through independent inputs from scientists working at the listed European small-scale facilities.

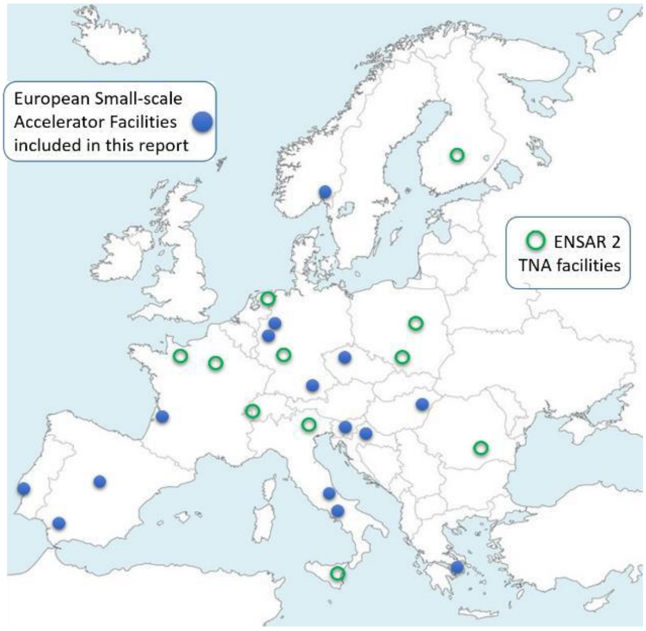

FIGURE 1: European small-scale accelerator facilities offering beam time for nuclear physics experiments and ENSAR2 large-scale TNA facilities.

SECTION 1: Overview of accelerators at European Small-scale Accelerator Facilities

In the following, a brief description of the accelerators installed at small-scale facilities offering beam-time for nuclear physics experiments is presented. They all refer to electrostatic ion-beam accelerators spread across Europe. The laboratories are listed in alphabetical order of their location (city or region)

1.1 LUNA (Laboratory for Underground Nuclear Astrophysics), Assergi, Italy

LUNA is one of the laboratories of LNGS, the Italian Laboratori Nazionali del Gran Sasso, located in Assergi, L' Aquila. LUNA is one of the worldwide leading nuclear astrophysics laboratories since 1992, when the first 50 kV single-stage accelerator was installed followed in 2000 by a second 400 kV Van de Graaff. A new 3.5 MV tandem accelerator is planned to be installed during 2019.

1.2 Tandem Accelerator Laboratory, NCSR "Demokritos", Athens, Greece

The Tandem Accelerator Laboratory of NCSR "Demokritos" is equipped with a 5.5 MV T-shaped Tandem accelerator and a 250 keV single-stage high-current accelerator (PAPAP) for proton and deuteron beams. The Tandem provides a variety of ion beams ranging from protons up to tin produced with Cs sputter and a Duoplasmatron ion sources. By means of the d+d, d+T and ^{7}Li+p reactions, secondary quasi mono-energetic neutron beams are produced with energies up 20 MeV.

1.3 Dynamitron-Tandem Laboratory, RUBION, Ruhr-Universität Bochum, Germany

RUBION is a central unit for Ion Beams and Radioisotopes of the Ruhr-University, Bochum, Germany. It hosts a 4 MV Dynamitron Tandem accelerator providing a wide spectrum of ions, typically from protons up to iron by means of three ion sources, i.e. a Cs-sputter, a Duoplasmatron and a TorVIS for negative He-ions.

1.4 AIFIRA, CENBG, Bordeaux-Gradignan, France

AIFIRA is the accelerator laboratory of the Centre d'Etudes Nucléaires at Bordeaux-Gradignan (CENBG). It is equipped with a 3.5 MV single-stage electrostatic accelerator (HVEE Singletron) that delivers H^+, D^+, and He^+ ions with an intensity up to 50 µA, for neutron production.

1.5 Tandem Accelerator Laboratory, CIRCE, Caserta, Italy

CIRCE that stands for Centre for Isotopic Research on Cultural and Environmental heritage. It operates an AMS system based on the 3 MV Tandem accelerator.

1.6 Institut für Kernphysik, Universität zu Köln, Cologne, Germany

The Institute für Kernphysik (IKP) operates a 10 MV FN-Tandem accelerator and 6 MV Tandetron AMS accelerator for mass spectrometry. The Tandem is equipped with a Duoplasmatron, a sputter source capable of delivering ions with atomic masses up to A=127 and a special source ("Phoenix") for Accelerator Mass Spectrometry (AMS).

1.7 Atomki-HAS, Debrecen, Hungary

The Institute for Nuclear Research of the Hungarian Academy of Sciences ATOMKI in Debrecen, hosts a number of accelerators: a 1 MV and a 5 MV single-ended Van de Graaff accelerators, a MGC-20E cyclotron, a 2 MV Tandetron accelerator and a 200 kV Accelerator Mass Spectrometry (AMS) accelerator for radio-carbon dating.

1.8 MLL, Garching, Germany

The Maier-Leibnitz Laboratory (MLL) is a central academic institution of LMU Munich and is the successor to the Accelerator Laboratory. At its 14 MV Tandem Van-de-Graaff accelerator, research programmes in nuclear structure and nuclear astrophysics as well as applications in other fields are implemented. The accelerator is equipped with a single-cathode sputter source for most ions with moderate intensity, and a multicusp ion source for intense hydrogen beams. Polarised hydrogen as well as helium beams are available.

1.9 Laboratory of Accelerators and X-Rays diffraction, IST- Universidade de Lisboa, Portugal

The Laboratory of Accelerators and X-Ray Diffraction hosts two electrostatic accelerators and an implanter. A 2.5 MV Van de Graaff with three beam lines, with all IBA-relevant setups. A 3 MV Tandem has recently been installed equipped with a micro-AMS beamline and a dedicated line for nuclear physics experiments.

1.10 Jožef Stefan Institute (JSI), Ljubljana, Slovenia

JSI operates a 2 MV Tandetron accelerator equipped with three ion sources, i.e. a Duoplasmatron, a Cs sputter source and a high-brightness multicusp-type source for negative hydrogen ions.

1.11 CMAM, Universidad Autónoma de Madrid, Spain

CMAM stands for Centre for Micro Analysis of Materials. It hosts a 5 MV Tandetron accelerator equipped with a Duoplasmatron and a sputtering source.

1.12 The Oslo Cyclotron Laboratory (OCL), Oslo, Norway

OCL is a university-based small-scale cyclotron laboratory. It operates a Scanditronix MC35 Cyclotron providing beams of *p*, *d*, ^{3}He, and α-particles with energies up to 48 MeV (^{3}He).

1.13 Centre of Accelerators and Nuclear Analytical Methods - CANAM, Nuclear Physics Institute – CAS, Řež near Prague, Czech Republic

CAMAM operates a U-120M isochronous cyclotron, a TR-24 cyclotron and 3 MV Tandetron accelerator. The U-120M cyclotron provides beams of accelerated H^+, H^-, D^+, D^-, $^{3}He^{2+}$, and $^{4}He^{2+}$ in a wide range of energies (1–55 MeV). The TR-24 cyclotron delivers proton beams in the 18-24 MeV range.

1.14 CNA: Centro Nacional de Aceleradores, Sevilla, Spain

The Spanish National Centre of Accelerators, CNA, operates a 3 MV Van de Graaff Tandem accelerator, an 18/9 MeV Cyclotron, a 1 MV accelerator for Accelerator Mass Spectrometry and a 200 kV radiocarbon dating system (MiCaDaS). Additional facilities at CNA are: a ^{60}Co irradiator, used for photon irradiations, a PET-CT human scanner, along with micro-PET and nano-CT scanners for preclinical research.

1.15 Ruđer Bošković Institute, Laboratory for Ion-Beam Interactions, Zagreb, Croatia

The Laboratory for Ion-Beam Interactions (LIBI), of the Ruđer Bošković Institute (RBI), operates two accelerators, i.e. a 1 MV Tandetron and 6.0 MV EN Tandem Van de Graaff. Research equipment are installed at 8 beam lines with one of them being accessible simultaneously for ion beams from both accelerators. The Tandem accelerator has an RF source with charge exchange for He ions and a multi-cathode sputtering ion source for variety of ion species

SECTION 2: Complementarities of research activities and scientific instruments at European Small-scale Accelerator Facilities

Between the listed European small-scale facilities, the following overlapping activities and complementarities exist:

a) Apart from LUNA-Assergi, IKP-Cologne, MLL-Garching and OCL-Oslo, all other accelerator facilities implement successfully almost all basic IBA techniques. These include RBS, EBS, ERDA, PIXE, PIGE, NRA and Channelling. Some of these labs provide, additionally, setups for ToF-ERDA analyses.

b) Research activities focusing on Nuclear Astrophysics are implemented by LUNA-Assergi, Demokritos-Athens, CIRCE-Caserta, Atomki-Debrecen, MLL-Garching, IKP-Cologne, JSI-Ljubljana, OCL-Oslo and CANAM-Prague. For these activities, a large variety of instruments are available.

c) Secondary neutron beams are provided by NCSR “Demokritos, AIFIRA-Bordeaux, MLL-Garching, CANAM-Prague, and CNA-Seville. These beams are used either for nuclear structure studies or for calibration and testing of nuclear instrumentation.

d) In some of the facilities, there exist unique instruments for specific research activities, such as:
   - ZAPS spectrometer for the study of ion-atom collisions (Demokritos-Athens),
   - Three 4π calorimeters (a 12"x12" BGO summing spectrometer at LUNA-Assergi, a two-fold segmented 14"x14" NaI(Tl) summing spectrometer at Demokritos-Athens and a 12"x12" NaI(Tl) summing monocrystal at RUBION-Bochum),
   - Recoil mass separator ERNA (CIRCE-Caserta),
   - HORUS multi HPGe-detector array with BGO shields (IKP-Cologne)
   - A 15-folded LaBr array for γ-spectroscopy (Atomki-Debrecen)
   - Orange spectrometer (IKP-Cologne)
   - CACTUS multi NaI-detector array (OCL-Oslo)
   - Particle ΔE-E telescopes (SiRI at OCL-Oslo, SONIC at IKP-Cologne)
   - BGO-ball multiplicity filter (80 BGO crystals at 4π geometry; under installation at Demokritos-Athens)
   - Plunger device (IKP-Cologne)
   - Q3D magnetic spectrograph (MLL-Garching)
   - GAMS: Gas-filled Analysing Magnet System (MLL-Garching)
   - Array of 16 ^{3}He counters for neutron detection (Demokritos-Athens)
   - SNAKE heavy-ion microprobe (MLL-Garching)
   - Chopper and buncher system to produce pulsed beams of 1-2 ns spread for neutron time of flight measurements (CNA-Seville)

e) Apart from LUNA-Assergi, IKP-Cologne, MLL-Garching and OCL-Oslo, all other facilities offer the possibility for surface analysis with beam spots of micron or even sub-micron diameter, as they are equipped with proton micro-beam systems.

f) Accelerator Mass Spectrometry (AMS) is provided by CIRCE-Caserta, Atomki-Debrecen, IKP-Cologne, IST-Lisbon, and CNA-Seville.

g) CNA-Seville hosts a ^{60}Co irradiator, used for photon irradiations, a PET-CT human scanner, along with micro-PET and nano-CT scanners for preclinical research.

h) Atomki-Debrecen operates a standalone Electron Cyclotron Resonance (ECR) Ion Source with a platform voltage between 50 V and 30 kV, used for plasma diagnostics, atomic physics (ion guiding) and surface-modification studies relevant to industrial and medical applications.

Using the listed nuclear methods and scientific instruments, built around these accelerator facilities, the scientific community, with almost 250 researchers and technicians, covers a broad range of nuclear physics research topics. At the same time many graduate and post-graduate students are trained by conducting research for their theses.

SECTION 3: Research Opportunities at European Small-scale Accelerator Facilities

Up to date, small-scale accelerator facilities could demonstrate a list of excellent research activities in various fields. Nuclear Astrophysics has a prominent position in this list. Hence, the LUNA Collaboration has been directly measuring, for almost 25 years, cross sections of nuclear reactions taking place in the hydrogen-burning phases of stars and in primordial nucleosynthesis in the underground laboratories of LNGS. The current facility will continue to play a leading role worldwide in these research topics, especially when the new 3.5 MV Tandem will be installed.

Demokritos-Athens, Atomki-Debrecen and IKP-Cologne are leading laboratories in the study of explosive stellar nucleosynthesis, especially in measuring via direct methods the cross sections of capture reactions relevant to the modelling of the p-process. The scientific instruments installed at these facilities in combination with the intensities of ion-beams provided by their accelerators are best-suited to perform this type of measurements. AMS-based investigations can often play a complementary but crucial role in nuclear astrophysics research. Excellent paradigms have been delivered by MLL-Garching and IKP-Cologne.

The recoil mass separator ERNA at CIRCE-Caserta is a unique instrument in Europe for the study of nuclear reactions of paramount importance in stellar evolution studies, such as $^{12}C(\alpha,\gamma)^{16}O$ or $^{7}Be(p,\gamma)^{8}B$. Indirect methods, such as the asymptotic normalisation coefficients (ANCs) have proven to be useful for determining reaction rates of interest in nuclear astrophysics. These methods are implemented at CANAM-Prague using the in-house U-120M cyclotron providing new information on the processes in stellar *p-p*, CNO and NeNa cycles. The instruments offered by OCL-Oslo and the “Oslo” method developed to extract nuclear level densities and γ-ray strength functions from primary γ spectra are also at the forefront of research conducted at small-scale accelerator laboratories. These quantities are essential to calculate nuclear reaction rates for astrophysical applications as well.

IKP-Cologne plays a prominent role worldwide in nuclear structure studies. The “Cologne plunger” is one of the most wanted devices in this research field and has been “copied” by many laboratories hosting multi-detector arrays for γ-spectroscopic studies in order to determine the lifetimes of excited nuclear states in the pico-second range and test with the highest possible accuracy various collective nuclear structure models. The Q3D magnetic spectrograph at MLL-Garching is a worldwide unique instrument for precision measurements in nuclear structure physics. Using Q3D, excellent results have been obtained regarding fissioning hyperdeformed states in actinide nuclei, or the clustering phenomenon of α-particles in light nuclei.

On top of the research topics discussed above, small-scale accelerator facilities provide the necessary beams and equipment for the development and testing of important scientific instruments, such as detectors and sensors used not only for scientific research but also in a variety of applications with technological importance. Hence, neutron irradiations relate to nuclear-waste transmutation, and charged-particle irradiations contribute to the understanding of processes in materials required in the energy production via fusion or the shielding of devices in space exploration.

IBA setups, available in most of the facilities listed above, together with AMS and micro-beam systems are key tools in materials and surface science, monitoring of environmental pollution, studies related to human health and the development of radiopharmaceuticals, dating of artefacts and understanding processes behind cultural heritage objects. A list of successful applications of accelerators in these domains can be extremely long and is beyond the scope of this report.

CONCLUSION

The 15 facilities presented in this report are installed in 11 European countries. Their in-house programmes cover fundamental research in nuclear structure and nuclear astrophysics as well as a large variety of applications based on the use of ion and secondary neutron beams. These are related to key societal problems such as biomedicine, radiopharmaceuticals, environmental monitoring and cultural heritage. In addition, they provide equipment to study the physical processes taking place in materials of technological interest under harsh irradiation conditions. Many of these facilities support also the development and testing of instruments in support of scientific as well as industrial research. All facilities in this report provided access to external users to perform nuclear physics research covered by ENSAR2. The scientific community working at these facilities comprises nearly 250 researchers.