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ARIES Crowns Two Decades of Particle Accelerators Infrastructure Development in Europe

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***Abstract*—On 2-3 May 2022 ARIES – Accelerator Research and Innovation for European Science and Society held its last annual conference in CERN summarizing 6 year long effort on the smart development of particle accelerator infrastructures in Europe. The whole series of Integrating Activities on accelerator infrastructures started in 2003 with preparations of CARE, then followed by EuCARD, TIARA, EuCARD2 and culminating with ARIES.**

***Keywords*—particle accelerator science and technology; EU Integrating Infrastructure projects; H2020 projects**

I. Introduction

ARIES [1] was the last EU Integrating Activities project funded in the area of particle accelerator infrastructures. The immediate predecessor of ARIES was EuCARD2 [2] and the follower is I.FAST [3]. One of the superb products of EuCARD2 was a monograph on appllications of particle accelerators in Europe [4]. Future accelerators will need higher energy and luminosity to enable scientists to continue exploring the fundamental building blocks of the universe. To achieve this goal, new technologies and materials must be developed to enable accelerator infrastructures to meet the demands of future research. Accelerators and related technologies are used in many different scientific disciplines and have wide applications in areas such as industry, healthcare, energy, environment, security and cultural heritage. ARIES has combined an innovative research and development program with the wider involvement of the scientific community to ensure the development of new technologies and practical applications.

The report on ARIES activities relies on material from ARIES web and especially on particular WP reports provided during the final annual meeting AM in CERN, with a perfect introduction to the particular reports given by the Project Chair dr Maurizio Vretenar [5]. This report is a continuation of author's previous reports on ARIES [6] and its predecessors projects like CARE, TIARA and EuCARD [7].

Author had a unique chance to take part actively as a beneficiary in all of these projects during the years of 2003-2022. This was a really fascinating journey across the vividly developing European large accelerator infrastructures. This was not just a purely theoretical journey, but workshop type, busy hands-on at every working laboratory visit. There were tens of such professionally profitable working visits, sponsored by networking activities of these projects, and full of practical experiences. The experience gathered during these nearly twenty years by all participants of these projects would not have been possible without active and perfect self-organization of the European research and technical community of particle accelerators.

In the last 10 years EUCARD2 and ARIES have seen a shift from a community driven in majority by HEP projects, network and R&D to a community based in majority on light sources. Transition from High Energy Physics to Photon Science is highly justified nowadays and does not mean abandoning the HEP experiments. The project of gamma factory simply opens new paths to HEP experiments. Photon science includes many more discovery class research subjects like subattosecond pulses, exawatt and zettawat pulses, single photon, diphoton and multiphoton experiments, multiphoton multilevel correlation states, particle acceleration based on entangled photon states, gravitational waves sensing and generation, and many more.

To communicate these unique experiences with accelerator science and technology and photon science and technology to the local research and technical communities involved in research and maintenance of large research infrastructures, the author has also published this paper in Polish in the local popular engineering journal Elektronika [8].

II. ARIES overview

ARIES project [5] was extended by one year, till May 2022, due to the pandemic. Prepearations were started in 2014 for a project under the name EuCARD3 as a continuation of successful projects EuCARD and EuCARD2. The project was submitted by a very well organized and very advanced community. The final name of the project ARIES – Accelerator Research and Innovation for European Science and Society was selected in January 2016, to underline widening of the objectives to include a strong interaction with industry and a wealth of societal applications.

The path to success run via the properly chosen project highlights and deep changes vith respect to previous editions. Essentially expanded transnational access, as a part of the project, included a cluster of 14 test facilities in European laboratories and universities used for accelerator research and development. A lot of fully supported access units were declared by the infrastructure owners. More than 20 key accelerator technologies were declared to be developed within the project, after precise consultations with accelerator community coordinators ESGARD and TIARA, as well as with industry. Six technologies out of these were developed directly, or in cooperation, with the industry.

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Innovation JRA were directed to industry and strictly focused on applications and energy efficiency. Improved links were established with the currently developed infrastructures like synchrotron light sources and ESS/Lund. Sustainability of accelerator research was strongly emphasized and a big network on Education, training and outreach was solidly embedded in the project. The consortium was essentially widened to include more than 40 partners from 18 European countries, plus CERN and ESS.

ARIES proposal was submitted on 4 April 2016 and included completely new aspects like more industry, the innovation fund, education, enlargement towards south and east of Europe. On 26 August 2016 ARIES obtained very favourable evaluation report and on 1 may 2017 ARIES was officially started. The ARIES kick-off took place at CERN on 4-5 may 2017, with 134 participants. The first ARIES annual meeting took place in Riga in May 2018. The rest of the ARIES annual meetings were organized virtually or in a hybrid way.

ARIES rests on four solid pillars: excellence, access, innovation, and sustainability. Excellence is understood as developing key accelerator technologies to make more performant, affordable, reliable and sustainable the present and future accelerators. The aim is to improve the European accelerator infrastructure. Access is related to new schemes of transnational access opening much more accelerator test facilities to the research, technical and industrial partners. Enlarged consortium means activation of many more research teams from European countries.

Innovation is associated with enhanced industrial participation, including individual industries and industrial associations. It is also related to development of co-innovation programmes with industry and strong emphasis on industry supported societal applications in medicine, production industry, environment, etc. TIARA (Test Infrastructure and Accelerator Research Area) coordinates particle accelerator infrastructures development efforts in Europe. A joint programme was established within ARIES with TIARA to develop a model for sustainable accelerator science in Europe. Training programs were designed for the new generations of accelerator scientists and engineers.

The success of ARIES was embedded in an exceptionally broad reach of subjects covered by networking activities NA, transnational access TA, joint research activities JRA, promoting innovation, training, communication and outreach for accelerator science in Europe, dissemination, enduring sustainability and excellent management of all these items. Networking activties embraced: industrial and societal applications, sustainable accelerator technology, European network for novel accelerators, accelerator performance and concepts, rings with ultra low emittance, and advanced diagnostics at accelerators.

Transnational access opened a number of unique facilities to interested research teams. Laboratory research grants were funded for magnet testing, material testing, electron and proton beam testing, radio frequency testing and plasma beam testing. JRAs were carefully chosen to close any delays in the research front and included: SRF area with thin film for superconducting RF cavities, intense RF modulated E-beams, materials for extreme thermal management, and very high gradient acceleration techniques.

The ARIES final annual meeting was summarized by the Coordinator [5] with a personal list of success stories, with which all participants unanimously agreed. ARIES teams have successfully contributed to a large number of key technologies across the particle accelerator fields. ARIES contributed to promote plasma and laser based acceleration, creating the environment for the success of EuPRAXIA project [9]. ARIES contributed to relaunching, after many years, the study in Europe on the Muon Collider. ARIES has continued actively magnet studies in Europe on high temperature superconductivity HTS.

ARIES has started the Proof-of-concept innovation fund and an efficient scheme for internal selection and support of innovative projects. ARIES has identified and supported new applications to society, in particular for biomedicine and environment. ARIES has investigated many new concepts and perspectives for accelerators like muon collider and gravitational waves. ARIES supported assembling, launching and testing a number of key accelerator subsystems, including and electron gun for electron lenses. ARIES innovative TNA facilities have provided access to a variety of users, producing science and enlarging the European accelerator user community.

III. ARIES: TRAINING, COMMUNICATION AND OUTREACH FOR ACCELERATOR SCIENCE

ARIES assumed broad activities in the area of TCO in Europe [10]. These included coordination, support and enhancement of communication, outreach and training activities for accelerators in Europe. ARIES provided an e-learning course, using MOOC technology and platform, embracing introduction to accelerator science, engineering and technology. ARIES ensured a smooth transition to next set of TCO actions in I.FAST, focused on industrial training and knowledge transfer scheme. ARIES and previous projects EuCARD and EuCARD2 have based on a broad plan which was developed by TIARA PP project in 2013. TIARA established a vision for longer-term structural support for TCO. ARIES and I.FAST have addressed some of the high-priority actions within the available resources. ARIES has gathered a lot of experiences in the area of TCO which is richly shared with the accelerator research community and transferred to I.FAST. TIARA recommendations stressed on improving the supply of trained personnel and opportunity access for and to trained personnel. MOOC courses were organized by ARIES basing on these recommendations. The community and many EU accelerator related projects started to be keenly interested in TCO.

Integrating Activity projects such as ARIES and predecessors provide a framework for cooperation, sharing of knowledge and resources, and coordination of activities, that serve the European accelerator community very broadly, at an under-pinning level. ARIES provided a platform that helps to nurture the community and also provided an incubator environment for development of other focused projects and proposals, like design studies, INFRA-TECH projects, MSCI training networks, and more. Even though resources for the TCO are limited, the value of the activities in this area is very high.

IV. ARIES EDITORIAL SERIES ON ACCELERATOR SCIENCE AND TECHNOLOGY

ARIES continued successfully from CARE, EuCARD and EuCARD2 projects edition of a series of monographs on Accelerator Science and Technology [11]. The first volume in the series issued in 2008 was: J.Sekutowicz, Multi-cell Superconducting Structures for High Energy e+ e- Colliders and Free Electron Laser Linacs.

The last ten volumes 51-60 issued during 2017-2022 were: C.Accettura, Ultra-high vacuum characterization of advanced materials for future particle accelerators; A.G.Chmielewski, Z.Zimek, Electron Accelerators for Research, Industry and Environment − the INCT Perspective; E.Belli, Coupling impendance and single beam collective effects for the Future Circular Collider; F.Zimmermann et al. ed., Beam Tests and Commissioning of Low Emittance Rings Proceedings; Y.Charles, et al., ed., The 1st Workshop on Efficient Neutron Sources; P.Ebermann, Relevance of the irreversible degradation of superconducting Nb3Sn wires and cables caused by transverse stress at room temperature within the FCC study at CERN; E.Felcini, Analysis of a Novel Toroidal Configuration for Hadron Therapy Gantries; M.D'Andrea, Applications of Crystal Collimation to the CERN Large Hadron Collider (LHC) and its High Luminosity Upgrade Project (HL-LHC); C.Acettura, Investigation of radiation damage effects in HL-LHC collimator materials; J.G.Valenzuela, Optimisation of Graphite-Matrix Composites for Collimators in the LHC Upgrade.

The volumes contain Ph.D. theses by young researchers associated with the mentioned projects, scientific monographs from particular WPs, advanced laboratory reports, and general or final project reports. The autor of this paper had a unique chance to be a co-editor of this exceptional, 60 volume, monographic editorial series together with the Chairs of the mentioned projects, drs.: Jean-Pierre Koutchouk and Maurizio Vretenar. Some of the volumes of this series are still available via the CERN Library, or via the WUT Publishing Office [wydawnictwopw.pl]. List of the volumes published with ARIES is available either on CERN's Zenodo or via the EuCARD2 and ARIES web pages – monographs. Editorial series of monographs on accelerator science and technology was a novel idea wich has started with the CARE project, and was continued till ARIES. The volumes were sent to all projects beneficiaries and to a number of accelerator laboratories around the globe.

V. INDUSTRIAL AND SOCIETAL APPLICATIONS OF ACCELERATORS

ARIES was a unique project to include, apart from infrastructure development issues and applied research, straightforward, practical interaction with societal needs. This was realized exceptionally actively by a devoted WP on societal and industrial applicatons [12]. The focused efforts on effective and useful proliferation of societal accelerator applications realized in ARIES was a successful continuation of similar endeavours during its predecessor program EuCARD2 [4].

New applications and technology developments were considered for low (300 keV – 10 MeV) and medium energy (over 100 keV) electron beam (EB) applications. Essential issue in the medical field is radioisotope production, especially ^{99m}Tc for therapeutic purposes. There were reviewed curent applications of e-beam accelerators up to 10 MeV, medical applications of high energy electron beams, different options for PET isotope production, design of a compact 140 MeV electron linear accelerator, applications of electron beams in the environmental area, and new technologies for electron beam accelerators. The exemplary applications under study were new environmental applications, document preservation, food irradiation, virus inactivation and high beam power usage for high dose rates. Breaking environmental application application was related to dirty residual marine ballast water treatment, sewage sludge treatment and biogas production, as well as marine diesel exhaust treatment.

Novel method of inactivation of viruses for vaccine production relies on low energy, high dose rate e-beam irradiation for minutes to hours. In comparison with classical methods based on chemical inactivation the loss of antigens is much lower while the virus RNA/DNA is inactivated. The accelerator based method is fast, safe, and effective. First prototype machine, basing on 300 keV accelerator of compact design, developed by Fraunhofer consortium, works well and produces inactivated suspensions. Industiral licensing was acquired. Similar e-beam machines are iused for preservation of cultural heritage, where archives, documents, books etc. are effectively hygenized by irraditation.

EB system for hybrid biogas generation was developed at IChTJ/Warsaw. Wastewater is treated in a plant to obtain purified water. The process includes primary treatment, biological treatment and secondary sedimentation with extraction of sludge. The sludge goes to the biogas production plant where undergoes hydrolysis and anaerobic fermentation. Biogas is used for or in co-generation processes of heat and electricity. The fermented sludge undergoes separation and is used as a microbiologically safe fertilizer due to electron beam hygenization. Technology can be applied in any place with sufficient supply of biomassconsumption resources, while there is no need for external electric energy supply. Technology shows potential also for processing modern contaminants like microplastics, etc.

Ballast water discharge typically contains a variety of biological materials, including plants, animals, viruses, and bacteria These materials often include non native, nuisance, exotic species that can cause extensive ecological and economic damage to aquatic ecosystems, along with serious human health issues. Green dock for ballast water discharge consists of: tank, separator of oil fraction, filter for sludge and water, accelerator processing sludge, sludge settler, removing of heavy metals, and post-process water release. A separate ARIES monograph was written on this subject [11].

Accelerator based system designs for environmental applications resulted in several mutli national proposals: Hybrid exhaust gas cleaning retrofit technology for international shipping, Production of high-quality organic fertilizer using EB, Advanced technology as a solution to halogen-based persistent and mobile chemicals, Reduction in AMR transmission by the destruction of AMR microorganisms, gees and antibiotics in sewage sludge and animal waste treated using EB. This topical track is continued in I.FAST as: Strategy for implementing new societal applications of particle accelerators, Environmental applications of EB, and Design of advanced electron accelerator plant for biohazard treatment.

Medium energy EBs, in the energy range 70 – 140 MeV, are used for new radiotherapy applications. EB parameters in the relevant machines are: charge up to 2 nC, normalized emittance 3-10 mm mrad, RF 3 GHz, repetition rate 50 Hz, bunch length less than 10 ps, energy spread less than 0,2%, single bunch per pulse. High performance E-linacs are required for these biomedical purposes, together with relevant detectors – diamond, MAPS, HV-CMOS, DEPFETs, beam instrumentation, laser plasma lenses, THz radiation instrumentation. Challenges and new approaches in radiotherapy RT are associated with the Very High Energy Electrons (VHEE) compact accelerator designs, in particular for Grid mini-beam and FLASH ultra-high dose rate delivery modes. The available beams for single or multiple fractions in biological and preclinical applications should offer: dose rates 2 Gy/min – 100 Gy/sec, beam sizes 0,5 mm – 10 cm, beam homogeneity +/- 2-3%.

Several existing and relevant accelerators for VHEE RT, normal conducting RF, superconducting RF, and laser –plasma, were tested including: eRT6-Oriatron/CHUV, EFlash/IC, CLEAR/CERN, CLARA/Daresbury, AWA/ANL, ELBE/HZDR, PITZ/DESY, DRACO/ELBE, LOA/IPP. High-gradient RF structures for compact designs offer accelerating field intensities more than 100 MeV/m. The research on accelerator technologies for VHEE RT includes: distributed coupling accelerating, use of cryogenic copper, use of higher frequency millimeter waves of 100 GHz and higher repetition rates using THz sources. Tests are carried on possible designs for compact E-linacs for VHEE RT applications including linacs working in S-band, C-band, and X-band. The subject from ARIES is continued in I.FAST project.

Development of efficient radioisotope production goes into direction of research on compact mini-cyclotrons to be installed in, or near the hospitals. Machine compactness requires high magnetic field, low maintenance costs and low power consumption. Advanced Molecular Imaging Technology (AMIT) Cyclotron is used for in-situ ^{11}C and ^{18}F single doses production. Optimization of AMIT cyclotron includes: ion source validation and characterization, beam dynamics control, and maintenance of the autonomous cooling supply system, machine compactness around 1 qubic m.

Development of AMIT is a key issue for the RT. Devoted ion source test bench was assembled at CIEMAT. The measurements of the discharge characteristics and extracted ion current have provided relevant information for the final operation of the compact synchrotron. The ion source IS characterization include: discharge characteristics curves, beam extraction regimes, influence of plasma conditions, optimizing IS input parameters, cathode lifetime, plasma expansion gap research. AMIT beam dynamics includes fine tune analysis of different cyclotron configuration parameters. Determination of the adequate beam extraction positions is required for a suitable beam transportation to the target. Assessment of the beam residual stripping interactions in AMIT cyclotron and optimizing the beam injection conditions are necessary to control the pressure level and minimize the stripping losses.

Size of the AMIT depends largely on very compact design of the whole superconducting magnet. Performance depends on stable operation of the magnet, minimal thermal losses for superconducting operation and positioning the cryogenic supply out of high radioactive environment. Machine maintainability is facilitated by easy acesss for particle chamber, target and ion source, and providing removable poles for magnetic shimming. Autonomous cryogenic supply system was modified, from original CERN's design to fit to AMIT. Injection line was added for hybrid usage in closed and/or open circuit. Helium is cooled down by a cryocooler inside CSS, but additional liquid can be injected from external Dewar. Other modifications included: pipes modification to match the cyclotron, additional by-pass valve included to reduce the cool down time, filters were added for particles coming from coils to obtain required helium purity for efficient liquefaction.

VI. Efficient Energy management for Particle Accelerators

ARIES is aware of high level of energy consumtion by large particle accelerator infrastructures [13]. The assumption in this respect of ARIES was that as a science community we should aim at developing solutions and not to be a part of the problem, which involves increasing energy efficiency, introduce smart energy management and adapt to use future fluctuating energy supply. ARIES has addressed energy saving issues with the following topics: networking with energy efficiency workshops, developing efficient klystrons – RF sources as parts of accelerator power conversion, efficient moderators in neutron sources – conversion energy to neutron flux, high Q superconducting cavities – with low losses at 2 K, developing and applying pulsed magnets – for low power beam transport. All these technologies introduced together save a lot of energy in new generations of sustainable infrastructures.

Energy management in large sustainable accelerator research infrastructures is an extremely complex problem involving a multitude of factors: national, international and large laboratory energy strategies; development of energy efficient technologies; infrastructure lifecycle management; ecological diversity; large system energy storage; energy, water and material consumption; global and local energy monitoring; smart energy management at research infrastructurs; sustainable technology developments by research infrastructures, use of waste heat; etc. These general issues involve particular solutions at all infrastructure sites like: usage of fuel cells, MgB_2 superconducting cables, stand-alone superconducting magnet cooling, solid-state modulators, catalysis research, high performance computing, etc.

Research on energy savings and smart management goes through precise analysis of power flow in accelerator based research infrastructures. A lot of chained factors are involved in grid power conversion to specific radiation for research. Conceptual and technological advancements are needed to gain considerable energy savings. Not just primary beam brightness, but also quality of secondary radiation is key in these considerations. Grid power goes to accelerator and auxiliary systems and the primary beam is produced (electrons, protons, ions). The primary beam is conversed to specific secondary radiation which involves conversion targets, undulators, magnets, colliding beam insertions. The radiation which goes to experiments is: X-rays, neutrons, muons, exotic particles. All conversion stages have their own internal efficiencies, which may be influenced by properly directed technological developments.

ARIES obtained a number of particular results increasing the energy efficiency in particle accelerator subsystems in all previously listed energy distribution areas. Design and simulation on a 12 GHz high efficiency kladistron was performed to obtain 65% efficiency in realistic simulations. Extensive simulations were performed on efficient neutron sources with target and moderator geometry optimization, multiphysics simulations, radiation transport, thermo-mechanical simulations to consider target and moderator assembly including two-phase D_2O. New type of two-phase simulations were established with concept for SINQ. Experimental and theoretical work was advanced on flux trapping and magnetic shielding – with preparation of Nb sample test device. A prototype pulsed quadrupole power supply has been set up with circuits recovering almost 30% of energy from pulse to pulse.

VII. European Network for Novel Accelerators

EuroNNAc was started with EuCARD in 2011 as part of ACCNET and was continued with EuCARD2, ARIES, and now is supported by EU viahigh gradientbe achievedcomponents I.FAST [14] as EuroNNAc4. [15]. EuroNNAc is coordinated by DESY, CERN, Ecole Polytechnique, Uni.Oxford, INFN Frascati and CEA. EuroNNAc is a limited network of infrastructure owners. Within ARIES, the network organized European Advanced Accelerator Workshop, International Conference on Laser Plasma Acceleration and CERN Accelerator School on Plasma Acceleration. European Plasma Research Accelerator with excellence in applications - EuPRAXIA project was the outcome of EuroNNAc with a number of practical achievements in the field including: CDR on plasma accelerator facility was published by the EPJ [9], two construction sites were indicated as Frascati for beam driven machine and alternatively ELI Beamlines or EPAC/Rutherford/Pisa for laser driven facility, ESFRI application was submitted for the facilities.

EuroNNAc prepared input for 2018 European Strategy for Particle Physics, listing projects EuPRAXIA, AWAKE and ALEGRO. The conclusion was that the ESPP should explicitly list ultra-highgradient plasma acceleration as essential research and development towards a compact alternative for future colliders, what was added in the following update of the ESPP [16]. EuroNNAc also had relevant presentations for ECFA. Expert Panel was established on High Gradient Acceleration Plasma and Laser within the extended Lab Directors Group LDG reporting to the CERN Council. Other targeted accelerator R&D expert panels include: high-field magnets, high-gradient RF structures, Muon beams and energy recovery linacs. ARIES, WP5 and EuroNNAc played an important role in the European and international development of novel accelerators.

VIII. Accelerator Performance and Concepts

ARIES WP6 is somehow associated with the ideas for new accelerators. Here, however, the new ideas are directed towards essential development of classical accelerators like energy recovery linacs, FCC-ee-ERL, LHeC, PERLE, etc. [17]. Accelerator performance and concepts generated a white list of ranked far-future accelerator options. Priority and focus for time scale 10-15 years were: energy recovery, crystal bending and gamma factory; for 15-30 years time scale the priorites were: proton based muon collider, plasma acceleration, positron based muon collider, crystal and nanostructure acceleration, and gravitational wave detection using storage rings; low or no priority topics were: photon collider, crystalline beams, Moessbauer acceleration using photon entanglement, gravitational wave generation using accelerators, and non-electromagnetic acceleration or focusing mechanisms.

Some of these far reaching ideas, which are continued from EuCARDs and ARIES will be pursued in I.FAST and next development projects. Either proton or positron based muon collider designs will be advanced by a dedicated R&D panel. Launching discussions on using storage rings and accelerator technologies for detection or generation of gravitational waves stimulated concrete plans for experiment in the LHC access shaft. Energy recovery based colliders have strengthened their positions as next generation facilities, with a number of advanced experiments exercised across Europe. Proposed gamma factory, super light source, is advancing via developing design, feasibility demonstration and possible operation modes. Applications for bent crystals are researched for future solutions in HL-LHC collimation baseline and for crystal and nanostructure acceleration. Optimal RAMS characteristics are researched for accelerators including: FCC-ee model, availability of cirtical systems, reliability of key systems, modeling platoform at FCC-hh. Research on performance limitations in hadron synchrotrons include: beam loss details, single-bunch instabilities and nonlinearities, review and ranking of mitigations.

Accelerator performance and concepts defines potential impact on science and society as: defining new directions in accelerator science, emphasizing key aspects which will allow designing future accelerators for new discoveries, while considerably optimizing the existing ones, using storage rings and accelerator technologies for gravitational wave research, research on the high precision operation of accelerators and beam diagnostics, increase reliability of accelerator operations, facilitate transferring of research achievements to all types of accelerator applications including for industrial and medical applications.

IX. Particle Accelerator Science and Technology

The research on Ultra-low emittance rings – U-LER has started formally withing these debated projects from EuCARD2 11 years ago, was actively exercised throughout ARIES and is continued with I.FAST [18]. U-LER is associated with design, construction and operation of very high quality accelerator infrastructure for light sources and in HEP for damping rings and colliders. U-LER technology developments are associated with key spects of precise beam dynamics. U-LER issues embrace in ARIES WP7: high brightness accelerator for light sources, injection systems, ring technology, collective effects, diagnostics, beam tests and commissioning, classical and hybrid multiband achromats, optimal sextupoles distribution, longitudinal gradient dipoles, cancellation of nonlinear aberration by sextupole pairing, fast high voltage kickers, high gradient magnets and small chambers issues, vacuum system design for high gradients, minimisation of power consumption in cables, NEG coating, etc. Small bore radius magnet imply the use of small aperture vacuum chamber. Effective vacuum can be achieve with extensive use of NEG coating. Machine models include realistic errors from magnetic measurements and alignment. Possible real life scenarios are extensively simulated years before the start of the commissioning.

ARIES WP11 has offered funding for access to several European facilities under the transnational scheme. The facilities were: ANKA at KIT, with electrons between 0,5 – 2,5 GeV, adjustable e-bunch lengths and operator defined bunch filling pattern; IPHI at CEA, with 3 MeV protons, duty cycle 1ms/1Hz to 100 mA/CW, neutron source at low flux, 352 MHz RF test facility; VELA at STFC Daresbury with electrons of 6 MeV, 10 Hz, pulses of 100 fs; FLUTE at KIT with electrons 7 – 50 MeV, bunch length range 1 – 300 fs, charge range 1 pC – 3 nC per bunch; SINBAD at DESY with electron bunches 0,1 – 20 pC charge to 100 MeV. ARIES WP10 also has provided material testing facilities at CERN-HiRadMat and at GSI M-Branch.

ARIES WP8 concerned advanced diagnostics at accelerators including beam and machines hadron linacs, hadron synchrotrons, circular and linear light sources [19]. Requirements for beam diagnostics at novel accelerators include application of instruments basing on different physics and techniques. The emphasis are on the next generation beam position acquisition and feedback systems, longitudinal diagnostics for free electron lasers, efficient extraction of information from electro-magnetic monitors, emittance measurements for light sources and FELs, simulation design and operation of ionization profile measurements.

ARIES WP12 was related to testing of advanced RF structures [20], related to transnational access. Superconduction RF cavities were tested at two sites: HNOSS/FREIA Uppsala University and XBOX CERN. The following components were tested at HNOSS: ESS high-beta elliptical cavity, validation of a prototype double spoke cavity criomodule, RF and piezo actuators study on spoke cavities, HL-LHC crab cavity cold testing. The following commponents were tested at XBOX: dark current and breakdown spectrometer, X-band pulse compression chain, X-band deflecting structure, average power limitation for high gradient X-band accelerating structures for future light source.

ARIES WP15 was devoted to thin films for SRF. The aim of this work package was to intensify systematic studies and development of the coating technology of superconducting materials to enable the superconducting coated RF cavities with Q(E) characteristics better than for the bulk ones. The main emphasis was on a systematic study of correlation between substrate surface preparation, deposition parameters for: superconducting material Nb, NbN, Nb3Sn, NbTiN and SIS deposited on Cu substrate, film structure, morphology, chemistry, phase, AC and DC superconductivity parameters: such as T_c, H_c, H_{fp}, H_{sh}, RRR, and, finally, the behaviour at RF conditions with the test cavities at CERN, HZB and STFC.

ARIES WP16 was concerned with Intense, RF modulated e-beams [21]. The major aim was to manufacture an RF modulated electron gun for applications in electron lenses of the following parameters: high electron currents up to 10 A, Gaussian shaped transverse electron beam profile, RF modulated at 0.4 to 1 MHz with a bandwidth of up to 10 MHz, Grid modulation to lower power requirements on modulator. The task included operation of a test stand for the RF modulated electron gun, normal conducting solenoids for beam transport, instrumentation for probing transverse and longitudinal electron beam profiles.

ARIES WP17 was concerned with materials for extreme thermal handling [22]. PowerMat was related to identification of relevant materials for accelerator components like: collimators, beam targets, windows and luminescence screens. These materials have to withstand high power impacts and extreme thermal management, and the work included several aims. Develop novel Ceramic Matrix and Metal Matrix Composites based on graphite and diamond reinforcements with various dopants. Simulate and test materials under extreme thermal shocks (particle or laser beam induced) and particle irradiation. Investigate Radiation Damage from theoretical, numerical and experimental standpoint. Explore societal applications in advanced engineering, medical imaging, quantum computing, energy efficiency, and aerospace.

ARIES WP18 concerned very high gradient acceleration techniques [23]. One of the hot topics is generation of hollow channels in plasma. The research is on long term plasma dynamics, in the aftermath of blowout regime, can self-consistently evolve into a hollow plasma channel. The effect was demonstrated in 3D simulations using Osiris. An initial electron bunch is used to drive a plasma wave in the blowout regime. Hollow plasma channel should appear as a result of long term plasma dynamics. Second driver is used to power a wakefield in the hollow channel, which is a requirement for stable electron and positron acceleration. The following questions have to be resolved for exotic beams acceleration. Plasma accelerators driven by exotic beams – what is the role of instabilities in the propagation of higher order laser modes in plasma? Positron acceleration in hollow plasma channels are related with application of channels to positron bunches with properties that are HEP relevant. Generalized superradiance is related to building coherent plasma based light sources. At charge frontier the issue is laser generated waveguide.

X. ARIES INNOVATION AND INDUSTRY PROGRAMMES

ARIES WP14 [24] provided unique possibility to evaluate, assess and develop technology inside the project with the final aim to provide society with identified commercial applications of the supported research potential. This was done via: Implementing proof-of-concept PoC for innovative actions; Implementing research projects in industries; Increasing synergies in consortium between laboratories, industries, universities, applied research institutes.

Industrial Advisory Board was appointed with several tasks to advise ARIES on matters relating with industrial collaborations, support managing PoC fund, evaluate the PoC submissions, set-up academia-meets-industry events. General aim of the PoC is: Increase the level of innovation and TT from accelerator science, increase the impact of research, concepts & technology arising from ARIES; To pre-industrialise complex components of particle accelerators and demonstrating to industry the possibility to invest and engage with a target to commercialization, minimizing risks associated with innovation for SMEs.

PoC Fund in ARIES was a unique tool helping to bridge the gap between research infrastructures and marketable innovation, providing incentive to the beneficiaries to get actively involved in TT activities. PoC was a first of a kind such implementation within a H2020 projects. PoC ambition was: To develop and use incentives for academic research groups to collaborate with SMEs and larger industries; To advance the technology readiness levels in order to enable the uptake and exploitation of specific technologies developed in ARIES by the industrial participants in the project or other industrial partners.

ARIES Innovation and industry program ended with several important conclusions. The PoC helped deploying resources in short amount of time. It provided money and more general support (networks, visibility, competences and know how from cross cutting domains) to innovative projects. There have been identified and prospected commercialization, depending on the specific project, at prototype level, and patents were submitted. PoC has helped to develop collaborative R&D at EU level, the creation of communities able to set roadmaps. PoC is a way to engage partners for more demanding developments. EC values the possibilities of engaging into R&D industries together with accelerator community.

XI. THE LEGACY OF ARIES AND CONCLUSIONS

The EC has recently established a new instrument for super-advanced research infrastructure communities – Innovation Pilots. In November 2020, the EC has approved the Innovation Pilot Project I.FAST – Innovation Fostering in Accelerator Science and Technology, submitted to the last call of Horizon 2020. I.FAST is a collection of joint research and development activities with industry and strategy groups to develop ideas and technologies for the next generation of particle accelerators, grouped into relevant thematic areas. Network activities are reformulated as strategy gropus, and the largest fraction of the project is made of JRA-type activities with strong industry participation.

EURO-LABS are newely established European Laboratories for Accelerator Based Sciences. EURO-LABS is a consortium of 39 research infrastructures (RI) from 12 countries spanning all over Europe. EURO-LABS is expected to build the foundations to create synergies and collaboration between the research infrastructures of the nuclear and high energy communities, enhancing Europe's potential for successfully facing the upcoming new challenges of the coming decades. Six pillars of EURO-LABS are: access, infrastructure, data management, RIs, community and physics.

ARIES has contributed directly and indirectly, among other similar projects realized in the relevant field of high energy experimental physics, to the update of the European Strategy for Particle Physics ESPP [16]. The conclusions of the recent update of the European Strategy for Particle Physics fully incorporate the strategic objectives of ARIES, and build many of their accelerator R&D recommendations on the results of ARIES. ARIES has contributed with one of its main goals to strengthen the European ecosystem of research centres for optimal use of the available resources and maximize scientific returns. ARIES has launched a vigorous research and development on innovative accelerator technologies like HTS magnets, muon colliders, plasma wakefield etc, and this is continued in I.FAST.

ARIES has developed a number of effective synergies with neighbouring fields. EuCARD, EuCARD2 and ARIES have launched a strong synergetic effort with synchrotron light sources, neutron sources, industrial and societal applications. One of the key themes of ARIES was to mitigate environmental impact of particle physics. Active key topics in ARIES were: knowledge and technology transfer, training of next generation accelerator researchers, education and communication. All these above mentionad items are visibly present and emphasized in the updated ESPP document. Apart from hard objectives and multitude of deliverables, ARIES possessed and produced a number of soft objectives and deliverables. This was one of the main goals of ARIES, not only to produce science and innovation, but also to create a community including both industry and researchers around that would sustain the science and innovation.

ARIES was the last Integrating Activity project for accelerator research and development funded by the EC. ARIES gained considerable funding with creativity and hard work and opened new avenues for the European community of particle accelerator science and technology [5]. All the particle accelerator oriented Integrating Activity projects gained, during the last two decades, for the European community working on infrastructure development, were very big resources which enabled to put these technologies on new fast rails, to the benefit of us all.

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