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I.FAST and EURO-LABS Perfect Legacy of ARIES

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***Abstract*—CERN hosted on May 2-6, 2022, the first annual meeting of the H2020 I.FAST project to support innovation in the field of science and technology of particle accelerators. The project has a completely different character from its predecessors in this area of research. It was approved for implementation a year ago by the EC with the highest marks. It is worth looking at why projects such as ARIES, I.FAST and EURO-LABS are so easily accepted. This alleged ease of acceptance is an appearance. Behind the acceptance, in conditions of extremely tough competition, is the excellent organization of the submitting community that has been developed over the years, as well as the perfect, well-thought-out preparation of the material. The author, a participant in the ARIES and other EC projects in the field of particle accelerator science and technology, presents here, on specific examples, his subjective opinions on how to prepare materials for high-output projects for the EC FP. The author hopes that these remarks may be useful in the process of submitting research projects from Poland in international cooperation to the EC in the best possible way. The science and technology of particle accelerators is an excellent area of showing such examples because it is interdisciplinary and includes the following components: building of research infrastructure, applied physics, mechatronics, materials engineering, automation and robotics, electronics, ICT, innovation, cooperation with industry, and social.**

***Keywords*—particle accelerator science and technology; EC Innovation Pilot projects; H2020 projects**

I. Introduction

FUTURE discovery-class particle accelerators for basic research face critical challenges related to their dimensions, energy consumption, real research capabilities, and downscaling limitations of current technological solutions. In the pursuit of ever-increasing energies, accelerator research infrastructures become gigantic and very energy-intensive. Another group of correlated challenges is related to the growing demand for accelerators for applied research, and applications in medicine, environment and industry.

The aim of the I.FAST project [1], the successor of the ARIES [2,3], in scientific and technical terms, is to search for adequate innovations common to the various acceleration platforms, which can address some of the challenges. The directions of research on the architecture of future accelerator infrastructures should concern greater research usefulness, the possibility of miniaturization of structures, increased energy efficiency, energy recovery from large infrastructures, environmental aspects, usability and social acceptance, and active cooperation with industry [4].

In the most general terms, the goal of the I.FAST project, intentionally involving a very diverse consortium environment, is the effective generation of the process of creating and maintaining an open innovation ecosystem around large research infrastructures based on particle accelerators. The result, according to the assumptions, is to provide accelerator science with new tools adapted to the next challenges on a scale of decades. And at the same time, the most effective connection of these infrastructures with the changing social requirements.

These directions are implemented through the study of alternative particle acceleration concepts [5], the design and testing of new accelerator models, the development of advanced superconducting technologies for magnets and accelerating cavities, rapid prototyping of key technologies, the development of technologies that increase energy efficiency, and massive development of industrial and social applications [6,7]. It is about developing social applications of accelerator technology in such a way that they make the most efficient use of fast and capital-intensive scientific advances and adapt them as innovations in socially useful market products.

The article is an attempt to look at the process of effectively submitting a massive, high-cost, scientific-social pilot project for EC funding under the FP. There are no secrets to being successful. However, what counts is the precise fulfilment of a number of the most important guidelines, called pillars, announced both by EC and expected by the broader community circles, as well as careful elaboration of details regarding numerous civilizational, economic, social and environmental aspects and conditions. This view is implemented on the concrete example of several EC H2020 projects recently successfully completed and currently being efficiently implemented, such as ARIES, I.FAST, EURO-LABS. As before [3], the article was also prepared in Polish version for Elektronika - a key national journal for engineers [8].

Although limited to specific examples, it seems that the arbitrary line of reasoning applies to a wider class of phenomena related to high-cost research funding in Europe and especially in Poland. According to the author, at least several well-organized research communities with good social connections are ready to undertake such large-scale projects in Poland. Such designs have several great advantages. One of them is very efficient attracting young people to great scientific challenges. Another advantage is the inclusion of national environments in a unique class of owners of large research infrastructures.

II. Large Research Infrastructures in Europe and in Poland

Achieving a success related to the submission, acceptance and effective maintenance of a big research project on an European scale is possible only if a large and sufficiently mature

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community is involved in the process. It seems that the best way to integrate large research communities is to bring them together around the development of smaller and larger discovery-class infrastructures. I.FAST performs such a task in a specialized research section. It is about searching for common denominators of such development and creation of complementary, developing and synergetic activities, and avoiding competitive and duplicating experimental possibilities, already existing in other infrastructures. It is often necessary to overcome local ambitions and notice the necessity of the benefits of acting on a broader research front. Without a more precise coordination of activities related to investments, division of research tasks, development of scientific staff potential on a European scale, we are doomed to inevitably lose emerging opportunities. In this team game, the players in different positions are countries and their functional attributes are available valuable research infrastructures. It is impossible to play in such a team as an equal partner without attributes. On the European scale, the activities have to be coordinated globally. It is neither possible nor does it make sense to build several parallel ILCs or FAIR class infrastructures in several places around the world.

Going a few coordination levels down to the national level, specific conclusions can be drawn. The situation is completely different in countries with large infrastructures and countries without such infrastructures. And it is not just about the size of the country and the level of its development and finances. Valuable infrastructures of potentially discovery class or functionally important are being developed throughout Europe: ESS in Lund, ELI in the Czech Republic, Romania and Hungary, MYRRHA in Belgium, etc. In Poland, investments were made in Krakow in the construction of Solaris [9] and in NCBJ's POLFEL infrastructure [10]. The fate of these infrastructures is affected by the current global energy and economic crisis. The scaling down of these infrastructures is a worrying phenomenon. The construction of a laser infrastructure related to ELI [12] is potentially being considered in Poland, but here a strong polarization of relevant decision-making circles in these matters is manifested. Significant polarization of the community is visible in the blockage of the decision-making factor. This blockage is nothing new. In the USA, many years ago, at the political level, the SSC infrastructure built near Dallas was blocked. In Germany, a large TESLA infrastructure planned near Hamburg was blocked, also at the political level. Currently, the FAIR [13] infrastructure in Darmstadt is experiencing serious problems due to the current political situation in the world. Large research infrastructures are inevitably heavily anchored politically, due to the commitment of significant financial and human resources.

In Poland, we can undoubtedly afford medium-sized, highly specialized, but at the same time sufficiently universal, infrastructures that strongly add research value to large global-class infrastructures. So they are infrastructures entering the network and in this way into the discovery class. Only then do we enter the game as a real infrastructure network node and acquire full club member rights. Such rights are also acquired by our talented scientific youth. Otherwise, perhaps, some people have the feeling that we send young people to study always at the better ones, and we do not exchange resources on an equal footing and actively participate in the global carousel of educating the most highly specialized scientific staff. The persistent polarization of opinion-forming circles regarding the construction of larger research infrastructures in Poland blocks almost everything. A similar polarization blocked a dozen or so years ago a massive, seemingly well-prepared, project related to the launching in Poland of extensive training of personnel for nuclear engineering and energy in cooperation with Ukraine. In a similar way, POLFEL could become a significant, multidimensional centre of laser technology, and not just a location for a relatively small FEL laser [10, 11].

III. EC Strongly Indicates Innovations in Projects – I.FAST as an Innovation Pilot

The European project I.FAST Innovation Fostering in Accelerator Science and Technology is implemented as part of the EC H2020 program, as the so-called Innovation Pilot, in the years 2021-2025. Unlike infrastructural and research projects, the core of the project is the innovation and implementation layer, around which the entire structure of the architecture is built. The possibility of proposing such a project and the chances of its acceptance by EC are closely correlated with the existence of a strong community of advanced technology providers and recipients of innovations and their readiness to take the risk of development and implementation in a specific area of technology with significant innovation potential. Particle accelerator technology undoubtedly has such potential.

In other words, the European Innovation Pilot is a kind of strong and very specific, well-financed, pressure of the relevant EC authorities on innovation and implementation. The I.FAST project, implemented by 49 European partners, has as many as 17 industrial companies as beneficiaries. From Poland, the IChTJ institute participates in the I.FAST. In addition, a group of 32 scientific institutions that are not its direct beneficiaries, and also from outside the EU, with the status of Associated Partners, are associated with the project. This group has special privileges in cooperation with I.FAST.

Together, these more than eighty partners in the I.FAST project constitute a significant coordinated research and technical force with the potential to be of great importance for the development of innovation in the area of science, technology and particle accelerator applications. Such a significant accumulated research potential, and a well-prepared project emphasizing broadly social aspects, as well as properly conducted lobbying, are hard to ignore such arguments. However, it is also difficult to compete with this method of preparation if some aspect of other applications have been developed less well or have been omitted in the preparation cycle.

The guidelines for preparing your own project submission materials to the EC, currently already under FP9, seem trivial at first glance. The basic conditions are: mature core initiating community with significant documented achievements submitting the project; complementing the core community with missing topics and appropriate representing institutions; closing the thematic area as fully as possible in terms of key research, application potential, innovation, industry involvement in research, component delivery, implementation; staff training, activities attracting young people to the subject of the project; documented plans towards pro-social activities, e.g. in such areas as strengthening the involvement of industry, health protection, natural environment, and safety.

However, how does it work in detail, in the case of the European scientific, technical and industrial community of accelerator technology, and how can it possibly be translated into activities in Poland? Over twenty years ago, this community, then only partially integrated on an European scale, noticed its chance to significantly strengthen the level of integration, so that in some products of significant social usefulness could be offered. The key issue was the assumption that the key to the future is the social potential of research, including health, the environment, prosperity and security. The research and scientific-technical potential in this direction existed in individual canters of this research community, but there was no clearly and strongly centrally defined social demand, such as it is today.

At that time, the community was rather focused on upgrading large research infrastructures and adding to those pieces that were necessary and missing to keep them in the discovery class. The modernization concerned the core components and accelerator structures as well as all instrumental layers, including: laser technology, photonics, mechatronics, automation, robotics, electronics, ICT, ultra-precise synchronization, metrology and diagnostics, new materials, all layers of software, and processing large amounts of data. For this reason, quite numerous research and engineering teams from Poland participated in these projects. It was a real success of our scientific and technical community, which could concretely contribute to joint achievements, which are really at the frontier of science.

IV. I.FAST Continues Integration, Research, Technical and Managerial Ideas of ARIES

The I.FAST project is to a large extent a continuation of the H2020 ARIES Integrating Activity project, completed in April 2022 and realized in 2017-2022 covering the difficult pandemic period. In the ARIES project, a path of openness, accessibility and innovation has already been created, which is a direct interface to Innovation Pilots projects. This greatly facilitated the proper preparation of the I.FAST and its acceptance success. The Promoting Innovation path was related to the allocation of part of the ARIES funds for an open competition of mini internal projects concerning the use of the results of research and technical works to produce a socially useful product or key components for such a product.

ARIES has appointed a committee to evaluate applications for financing innovation promoters. Part of the funding under the idea of openness of ARIES was allocated to the Proof-of-Concept fund awarded in a competition to teams proposing to test the assumptions of the most interesting innovative solutions. Practice has shown that the preparation of the I.FAST project framework turned out to be easier after the experience in this direction in the ARIES. Yet another expression of the openness of the ARIES project was the creation of a network of available accelerator test infrastructures in Europe and the competition funding of the proposed experiments with project funds. This openness of ARIES under the Transnational Access initiative meant that despite the strictly defined and frozen by EC framework of total funding, the project was still a source of funding for many innovative, research and testing ideas submitted ad hoc. All these features of ARIES, in the appropriate additions and extension, have been used in the I.FAST project.

ARIES has left behind an excellent legacy of a well-integrated ecosystem of collaborating accelerator centres, with research facilities much more readily available, a significant degree of inter-centre synergies and new plans to improve existing technologies and infrastructures. The European transnational exchange involved the opening of several accelerator and instrumental research infrastructures and thus was raised to a completely new level of cooperation. Open infrastructures enable much easier research in the field of magnets, materials, electron and proton beams, RF and SFR devices, and classically, laser- and plasma-accelerated particle beams.

The opening of infrastructures significantly increases the community of their users. Such an opening also resulted in the generation of completely new projects successfully opened under H2020, e.g. EuPRAXIA as part of particle acceleration driven by laser excited plasma [14]. It was ARIES that started intensive cooperation with the industry, which is now continued and systemically extended by I.FAST. A prime example in this regard was the launch of a prototype accelerator system for removing harmful exhaust gas emissions from ship engines. More developed work in this direction is carried out by I.FAST. An industrial version of the accelerator treatment of exhaust gases of large marine diesel engines is being built in cooperation between the Riga University of Technology, IChTJ and industrial companies. A similar project concerns the accelerator higienization of contaminated ballast water.

V. EURO-LABS – Integration of European Subatomic Research and Technology Around Accelerator Infrastructures

Apart from the I.FAST, another consequence of the well-prepared and perfectly realized ARIES, continuing its part of transnational access, is the infrastructural project H2020 Transnational Access EURO-LABS [15]. The project implements the idea born during the implementation of ARIES to be more powerful, effective, infrastructural, and an open connection of different but strongly associated research communities - nuclear physics, science and technology of particle accelerators and detectors for high energy physics experiments. EURO-LABS - European Laboratories based on accelerator science and technology is a project funded by EC in 2022-2026 and coordinated by INFN Bologna. EURO-LABS is a consortium of 39 accelerator research infrastructures from 12 European countries, including Poland. Polish institutions formally participating in EURO-LABS are IFJ PAN, UW, and IChTJ. The opening conference of the project was held in Bologna on October 2-5, 2022.

EURO-LABS groups 14 large research infrastructures available for experiments for European scientific and technical teams and for innovative SMEs. The project supports access to infrastructures in the following areas: stable and radioactive ion beams, neutron beams, pulsed beams, material irradiation, magnets, RF testing, RF cavities, electron beams, laser beams, detector characterization, beam tests. The qualification criteria are: an application from an international organization, and participation in the activities of JRA, ERIC and other scientific units. The majority of the research group should be from outside the country providing the infrastructure. The dissemination of the results of activities on the shared infrastructure should be published in open access conditions. The activities of SME companies are exempt from this obligation. The assessment of the application and the allocation of beam time is carried out by statutory supervisory bodies associated with the given infrastructure.

The goals of the project seem obvious now, in the era of the necessary integration of European science and consolidation in the face of strong global competition. The means to achieve these goals is to fund synergies of users from different research communities. A large and diverse community of particle accelerators users has an easier option to choose the right research infrastructure tailored to the nature of the experiment. Conducting research of the exploratory class requires supporting the processes of sharing knowledge and developed technologies across slightly separate science disciplines. Interdisciplinary activities in related areas facilitate the implementation of good practices in data management and improve services for the management and provision of research infrastructures. Opportunities for expanding and targeting joint staff training and staff exchange between canters are improving.

Optimal training of staff enables the development of various skills of young scientists, necessary to conduct research in advanced and new infrastructures. For the first time, the EURO-LABS project contributes in a unique way to building a very specific, super-specialized community of researchers and technical services in a wide subatomic area. Never before has a project been built in this way, combining in one common group of tasks such a wide area of science, with different research requirements, where infrastructure is the common denominator. EURO-LABS hopes to start building a new, unprecedented type of synergy and cooperation in Europe between the nuclear research and high energy physics environments - sources and detectors, as well as instrumental equipment for these areas. Such cooperation should extend Europe's research potential in subatomic areas to the upcoming new research challenges in the coming decades.

VI. Innovative Structure of I.FAST Project

I.FAST launches a number of internal initiatives unprecedented in this type of projects. The internal competition innovation fund IIF of the I.FAST project has separate funds of 1 MEuro, intended for continuous evaluation and launching of new applications for research and technical activities related to new solutions for accelerators and their functional subsystems, high-brightness accelerators for light sources, innovative solutions of superconducting magnets, thin superconducting layers, advanced technologies and accelerator materials, infrastructures and social applications. Individual projects receive funding in the range of 100-200 kEuro. Applications accepted, on a monthly basis, must come from two partners, the beneficiary of the I.FAST project and the industrial partner. Participation in such a dynamic form of additional funding for scientific-industrial cooperation enjoys considerable interest within the I.FAST and among the industrial partners cooperating with the project [16] .

Innovations based on challenge based innovation CBI for particle accelerators and related technologies are related to the idea of educating young scientists [17]. The foundation for the development of such a broad and massive discipline of accelerator science and technology in terms of necessary infrastructural investments is the education of the staff. The beginning of such a process comes from encouraging young people to work in this area. I.FAST launches a project-related initiative to finance projects submitted by scientific youth teams. The idea is related to the implementation by CERN of a long-term program of combined university science schools of accelerator technology. The I.FAST-CBI initiative will finance several interdisciplinary teams of young researchers, composed of 6-8 students from different countries, in such disciplines as: economics, law, environment, as well as physics, technical and engineering sciences. The intention is to try to generate new ideas in such unusually mixed teams, giving such teams a chance to present their ideas in the form of a conference before the jury after a 10-day stay in the selected infrastructure at CERN and familiarizing themselves with its operation. Every year the topic of I.FAST-CBI will be changed. The leading theme of I.FAST-CBI in 2022, which took place on July 26-August 4, was Accelerators for the Environment. The annual I.FAST-CBI program is carried out in cooperation with the Geneva-based ESI - European Scientific Institute, Archamps. Applications for the I.FAST-CBI program in 2023 are accepted until the end of February 2023. The CBI initiative is cyclical and will be implemented until the end of the I.FAST project.

I.FAST operates in an open science infrastructure. It uses the open large-scale repository system ZENODO [18] and the Invenio RDM [19] scientific data management system created by an international consortium of academic and research institutions such as Brookhaven NL, Caltech, NYU, CERN, Helmholtz, INFN, and many others. In this regard, I.FAST works in line with the initiatives taken in Europe and in the USA to open up science and free it from closed large and often monopolistic global publishers. The NASA TOPS - Transform to Open Science initiative is a type of funded mission and community initiative aimed at strengthening the processes of opening up science to publication. In Europe, projects are implemented under the OpenAIRE initiative [20], funded by EC, based on 35 national NOAD open access canters.

In this way, I.FAST avoids creating a proprietary resource of information, data and knowledge, and contributes to joint large initiatives that create global trends that support open science in the best possible way. A strong recommendation is to encourage the use of OpenAIRE in your own R&D projects and other research result generating initiatives. You can log in to individual OpenAIRE functional blocks in many ways, e.g. through the scientific library of your own institution, but also through your own account, via ORCID, LinkedIn, Facebook, etc. OpenAIRE functional blocks are linked to European projects, which enables the automation of project reporting. OpenAIRE consists of a number of practical blocks. Use of these functionalities by research projects, such as I.FAST, is in line with the idea of EC and global tendencies to open science financed from social funds, and at the same time strengthens the role of the submitted project.

During the implementation of the infrastructural accelerator projects preceding I.FAST, the Accelerating Newsletter was created in 2012, related to these projects, but of a much wider nature and scope. The initiative was created within the EuCARD project, and in April 2022 the Newsletter celebrated its 10th anniversary [21]. The EuCARD project was the first to create an internal newsletter, which then evolved into a global newsletter. At that time, the Accelerating Newsletter became a popular global publication with thousands of subscribers and significant readership. Properly edited, cooperating with other projects such as EuCARd2, ARIES, EuroNNAC [22] and currently I.FAST has become a kind of important hub fulfilling the role of fast, current, public information exchange in the global environment of science and accelerator technology. The existence of such a strictly professional, yet friendly, open and popular forum not only serves the community well, but is also appreciated when evaluating a project submission declaring co-creation with such a global information platform.

It is the duty of a large-scale project such as I.FAST to actively participate in the most important life events of the professional community. Global research communities such as HEP have their platforms for exchanging scientific and social information, established for decades. One of them is the IPAC conference - International Particle Acceleration Conference [23]. The IPAC22 conference [24] was held in Bangkok with over 800 personal participation. During this key conference, the I.FAST project was represented in the form of several papers and during the plenary discussion session. I.FAST Project Coordinator Dr Maurizio Vretenar spoke about the new role of industry in the innovative ecosystem of science and accelerator technology.

The European HEP and accelerator technology community is organized into several coordination bodies. One of them is ECFA [25] - European Committee of Future Accelerators, and on a global scale it is the international committee of ICFA. The I.FAST project was presented at the ECFA meeting for information, consultation and support purposes. The project was also presented at meetings of other opinion-forming bodies in this area of science and technology. These types of activities are designed to create a positive environment of support as well as consultation and interaction that facilitates the preparation of the best possible material and then good cooperation with the wider communities. It would be a significant mistake to omit such bodies from consultations, lobbying and cooperation.

VII. I.FAST – Key Research Areas, Innovations, and Future Development Directions

Fundamental research in I.FAST is related to future global projects on HEP experiments and the roadmap for research and development of accelerators. Currently, the main accelerator infrastructures for HEP are: LHC/CERN, MINOS and LBNF/DUNE/Fermilab, SuperKEKB and J-PARC/Japan, BEPC-II/China. Large infrastructures are used to test the Standard Model in parallel with: Flavor factory, Higgs and electroweak symmetry breaking, Neutrino and dark sector, and many different smaller-scale experiments. Large-scale infrastructures are designed, built and operated for decades. They require planning on a global scale. I.FAST, in its limited lifetime, addresses these aspects of long-term development, and shows exactly its contribution priorities.

Basic research in the area of HEP is coordinated in the form of the periodically renewed European Strategy for Particle Physics ESPP [26]. On a global scale, similar guidelines are developed and updated periodically in the US, Japan, and China. The last update of the ESPP, noting global updates, was developed and published in 2020. The strategy takes into account a realistic research agenda and synergies with other areas, as well as the social and environmental impact of particle physics. The compliance of the main I.FAST program lines with the current ESPP document of an European nature, but in principle of a global impact, is a strong proof of the project's contribution to the implementation of widely negotiated global guidelines. In description of the general assumptions of I.FAST , this argument is used as a strong support for the power of the application. And this argument was duly appreciated. The update of the 2020 ESPPU document was a massive process that lasted two years and covered wide European communities, including the ones that subsequently submitted, based on the conclusions of such a document, a few large European infrastructural projects. Perhaps the most important argument is that the fundamental document 2020 ESPPU strongly emphasizes the implementation of research projects in the area of accelerator infrastructures in synergy with other areas and the impact of these projects on society and the environment.

The 2020 ESPP document indicates European and global priorities. The I.FAST project is actively addressing these priorities. It is not surprising that the need to effectively use the full potential of the HL-LHC infrastructure under development in the coming years is the most important. Other priorities are to support Japanese and American long-baseline neutrino experiments. In Europe, the infrastructure of a future hadron collider with an energy of at least 100 TeV is being considered. The planned 100 km circular tunnel at CERN is to accommodate the FCC-ee and FCC-pp infrastructures, and possibly the FCC-mm muon afterwards. Among large liniac infrastructures, three options are being considered: ILC in Japan, CLIC in CERN and CCC - cold copper collider. In linacs, it is necessary to recover energy, which however increases their cost of construction. The muon collider avoids synchrotron radiation in the accelerator ring, but muons have a short lifetime. Plasma liniac options with much larger accelerating field gradients are being studied. The next update of the ESPP document, coordinated by the directors of main infrastructures, is scheduled for 2026, after the end of the I.FAST project [4].

Key components of accelerator infrastructures are present in all projects in this area, as well as in I.FAST and EURO.LABS. For the implementation of FCC-ee and FCC-hh group of projects, it is necessary to develop high-gradient SRF technologies, including klystrons with high energy efficiency. The FCC requires the construction of long tunnels, and therefore the use of new, much more efficient technologies for their digging is necessary. In superconducting accelerators, further research is required on magnets with significant field intensities made of high-temperature superconductors. Efficient cryogenics is required to support their work. It is necessary to master the skills of building energy efficient large-scale cryogenic systems. The development of warm RF systems is necessary for the CLIC accelerator infrastructure. The energy efficiency of all types of large infrastructures is significantly improved by energy recovery and recirculation.

Laser technologies in LASPLA particle acceleration are considered as one of the very promising development trends and the potential construction of new types of accelerator infrastructures. In December 2020, the European Consortium EuPRAXIA, focusing research on laser and plasma acceleration methods, expanded the list of members to 40. From Poland, the members of the consortium are: NCBJ, PW, PŁ, IFPiLM and WAT. In plasma technologies, it is necessary to significantly improve the dynamics of the beam, which is related to the stability of the dynamically generated plasma channel, the synchronization and interaction of particle and laser beams, and the adaptation of appropriate types of high-power lasers [5]. A breakthrough in the design of high-intensity laser systems resulted in the practical use of the CPA chirp pulse amplification technique. Such laser systems will be the basis for the construction of acceleration infrastructures operating in the field of relativistic and ultra-relativistic optics and in the future approaching the Schwinger limit. Simulations of the development of high-power laser technology indicate the possibility of exceeding this limit and using laser technology to study the area of non-linear quantum electrodynamics. In any case, currently the limitation of the development of laser-plasma acceleration techniques is the insufficient development of adequate laser sources and the costs of their further development.

Another development path of laser technology are ultra-short pulses - femtosecond and in the future attosecond. Usable parameters are average power, pulse duration, repetition frequency, and pulse energy. In the research area, such lasers are necessary for synchronization, the implementation of pump-probe experiments, and the study of ultrafast phenomena. At the same time, femtosecond lasers are increasingly used in industry. Industrial applications require fs lasers with the following parameters: average power of the order of kW, pulse duration of 100 fs, repetition frequency of GHz, pulse energy from several to several hundred μJ. In acceleration applications, we talk about fs lasers with different parameters: average power kW, time 10 fs, energy 1-100 J, peak power 100 TW. ELI Beamlines [12], which is a member of the EUPRAXIA consortium, is working in this direction on the development of the powerful enough Ti:Sa source.

Plasma-laser acceleration requires high power lasers, high average power and ultra-short pulses. Currently, the technology of Ti:Sa lasers pumped with DPSSL laser diodes is used. The aim of the EuPRAXIA project is to construct a pilot demonstrator at an industrial technical level. Work is being carried out on the stability of such a system in the space, time and spectral domains as well as increasing the pulse repetition frequency. Current assessments estimate a decade of research needed to build an energy-efficient multi-kW demonstrator of such a LASPLA-class accelerator. The downside of the Ti:Sa technology is the indirect pumping architecture for both flash and DPSSL. Obtaining higher energy efficiencies is possible only in the case of direct pumping, e.g. in the systems of an appropriate matrix with the active ion Yb. Research is being conducted on an amplification medium that allows direct ultra-wideband amplification of DCPA chirps, has a good structure without quantum defects and can be pumped directly with laser diodes. The future configuration of such sources in the form of multi-fiber architectures is being developed in the XCAN project [27].

One of the groups of materials tested for laser-plasma technologies are laser-grade ceramics. In such materials, features unavailable in single-crystalline materials are sought, such as the structure of large components, any geometric shaping, gradient doping optimized to thermal properties, better homogeneity of the active dopant distribution in nano-crystallite grains, etc. Materials such as YAG, LuAG, Lu2O3, Sc2O3 are being researched, and classical dopants of Nd, Yb, Er, Tm, etc. Potential research applications of laser-plasma technologies are the compact plasma-laser X-ray FEL, the TeV collider for HEP experiments, the construction of effective sources for inertial fusion, and in the future sources for research of the phases of QGP strongly interacting matter, etc.

Many potential specialized functional applications are blocked by the size and energy efficiency of currently available devices. Many socially and industrially beneficial applications of accelerators would need miniature sources, such as could potentially be offered by laser-plasma techniques in the future. A very large group of such applications is envisaged for biomedicine. In industrial and security areas, applications of X-ray and particle beams, including neutron radiation, are mentioned, such as X-ray imaging with high time resolution, flaw detection of metallic objects, X-ray CT imaging, in battery production, in the aerospace industry, phase-contrast imaging, multi-energy scanning for security systems, disinfection of materials, etc.

The use of accelerators in health care currently requires the construction of large infrastructures, including a specialized large gantry. It is necessary to search for new technologies reducing the size of devices and improving their energy efficiency [6]. Laser-plasma acceleration is one of the ways to minimize the size of accelerator devices for medical applications, as well as eliminate the gantry scanner. The compact biomedical X-ray imaging device uses a kilowatt pulsed laser beam, a helium cell, and a thin Al foil to produce an X-ray beam. The image of a biological sample is detected by an X-ray camera through a beryllium window.

Another biomedical application of laser-plasma sources is radiotherapy. It is possible to achieve very high dose densities in short pulses and in very confined spaces. This is a future radiotherapy technique referred to as FLASH VHEE - pulsed therapy with very high energy electrons. Very high dose density protects healthy tissues. The currently operating radiotherapeutic linacs are not able to deliver pulses with the parameters required for VHEE, i.e. in the order of several kGy/min.

Acceleration techniques in biomedicine include the following groups of applications: low and high VHEE electrons for therapy, protons and ions for therapy, radioisotopes for imaging and therapy, neutrons for therapeutic technique BNCT - localized neutron capture by Boron ^{10}B isotope, photons for imaging and X-ray therapy. The most common application is an electron liniac with a tungsten target producing an X-beam with an energy of 11-18 MeV integrated with a rotating gantry. There are about 14,000 such working devices in the world. The development of these popular devices goes towards: cost reduction, imaging-guided precision therapy, selection of optimal therapeutic tactics to protect healthy tissues, a new type of impulse work with a higher dose density, such as FLASH and VHEE in the future.

In the case of proton and ion radiotherapy with the most popular source in the form of a synchrocyclotron, the development is going towards precise control of the location of the Bragg peak of the maximum ion energy deposit. There are about 110 such devices in the world, including 30 in Europe. The design problem in the classical solutions of hadron radiotherapy is the rotating gantry. Alternative LIGHT solutions (linac for image guided hadron therapy) are being tested - where the synchrocyclotron is replaced by a compact electron linac with a system of modulators and klystrons. In the case of carbon and other ion therapy, the synchrotron has larger dimensions, but it is necessary to resign from the rotary gantry by using several treatment rooms with stationary but differently located beams. Carbon ions with an energy of 100-430 MeV, used for therapy, are much more difficult to bend their beams compared to therapeutic protons with an energy of 60-250 MeV. New carbon ion therapy infrastructures are starting to use superconducting magnets to reduce size, weight, cost and increase energy efficiency.

Another direction in the development of radiotherapy techniques is VHEE with a pulsed electron beam of 50-200 MeV energy. The source is a compact high-gradient warm copper or superconducting liniac. The electron pulse interacts similarly to the photon pulse in terms of the energy deposit profile. It does not have a Bragg peak, but it can be shaped in a wide range, directed, focused, is easy to curve, can be formed into a multi-beam form adapted to the area of influence. There are currently several such devices in the world, e.g. at CERN, in Berlin, LOA, SLAC, Argonne, INFN, etc.

The use of accelerators in the environment and industry is related to their ability to modify and produce new materials, new products, and carry out new chemical reactions. The application criteria are costs and other economic aspects, the possibility of easy integration into the production line, as well as security aspects. Low-energy electron accelerators are most commonly used in industry. The type of application is defined by the way the electron beam interacts with matter. Such functional types of interaction can be divided into three groups: scattering on electron shells and on atomic nuclei, continuous energy transfer, and secondary phenomena. Many effects are associated with these groups of interactions, such as: statistics of electronic paths in the material, limited penetration depth, diffusion phenomena; inhomogeneous energy transfer, energy transfer dependent on electron energy and material density; ionization and activation of the material, generation of secondary electrons, and generation of X-rays, and others.

Impacts can be divided into two main groups – thermal and non-thermal. Thermal interactions require a well-focused beam with a high power density of 10^6 -10^9 W/cm^2, low-energy 20-150 keV and vacuum processes that change the material due to heating effects. Non-thermal interactions require the use of a diffuse beam with a low power density below 10^4 W/cm^2 and atmospheric processes that change the properties of the material by radiation chemistry [7]. Thermal applications involve heating the material to a liquid or vapour state. The melting of the material allows it to be purified. The evaporation of the material enables coating with a thin layer by the PVD method. PVD coating is used in photovoltaics, solar thermal technologies, the construction of electrodes in batteries, etc. Thermal applications include joining and welding of materials, as well as surface processing and modification. Non-thermal applications include, synthesis, conversion and cleaning of gases, NOx reduction, cleaning of ballast water and fertilizers, sterilization, disinfection, deactivation, e.g. in wastewater, medical, pharmaceutical, food products, packaging, etc.

In the pharmaceutical industry, accelerator devices are used to inactivate viruses, bacteria and parasites in the production of vaccines. In agriculture, it is used for seed disinfection. In the processing of rubbers and plastics as well as ceramic fibers, the electron beam is used to cross-link the material, such as: varnish curing, lithography, lamination, fiber drawing, etc.

The directions of development of industrial applications are related to the search for methods of cost effectiveness of equipment and its operation. Methods of cost reduction are related to the use of the lowest possible energy of the electron beam necessary for the application. Low beam energy requires less device shielding, cheaper and smaller high-voltage sources, and easier methods to implement the required safety protections. The stability and lifetime of exit windows is related to the industrial applications of electron accelerators, and in this area research is being conducted on new material and construction solutions. New, more resistant window solutions allow the use of electron currents with higher density.

I.FAST is an example of a very well-prepared project application, approved for implementation by EC with the highest marks under the FP Horizon 2020 as Innovation Pilot. The I.FAST project is being implemented in 2021-2025 and has beneficiaries from Poland. The project, in accordance with the EC guidelines, is a kind of a door, an essential civilization gate, between the world of science and technology developments at the top research frontiers, and the world of innovation, that is being opened wider and wider, in the extremely demanding field of accelerator science and technology.

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