www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

jet INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2016, VOL. 62, NO. 1, PP. 97-104
Manuscript received December 20, 2015; revised March, 2016. DOI: 10.1515/eletel-2016-0013

Enhanced European Coordination of Accelerator Research and Development – EuCARD^2 – Global and Local Impact

Ryszard S. Romaniuk

***Abstract*—Wide scale, European, infrastructural research projects on accelerator science and technology are under realization since 2003. CARE project was realized during the period 2003/4-2008, and next EuCARD during 2009-2013. Now during 2014-2017 there is successfully continued EuCARD^2 – Enhanced European Coordination of Accelerator R&D. European accelerator R&D community prepares next continuation of the EuCARD inside the Horizon 2020. The paper presents the work developments of EuCARD. Several institutions from Poland are participating in EuCARD: NCNR in Świerk, IChTJ, technical Universites in Łódź, Wrocław and Warsaw. Realization of the project during the last 12 years gave numerable and valuable results combined with essential modernization of the European research infrastructures. From the point of view of domestic interests, where we do not have large research infrastructures, the considerable benefits are associated with the participation of young researchers from Poland – engineers and physicists, in building of the top research infrastructures. Due to such participation, high technologies are developed in several centres in the country. The EuCARD project organizes annual meetings summarizing periodically the R&D advances. The EuCARD AM2015 was held in Barcelona in April.**

***Keywords*—accelerator science and technology, laser technology, electronic systems, European infrastructural projects, FEL, HEP**

I. Introduction

THE European advanced infrastructure research projects in the field of accelerator technology are being implemented since 2003. During the period 2003-2008 it was realized under the name of CARE and then as TIARA and EuCARD in 2009-2013. EuCARD^2 [eucard2.web.cern.ch/] continues the efforts of these predecessors with successes during the period 2014-1017. The European accelerator research Community prepares its further continuation within the framework of H2020. Diligent realization for more than a decade now of a topically homogeneous and perfectly focused infrastructure project, in the pan-European scale, has positively integrated and very much strengthened the European accelerator research and technology communities over the continent. The article presents a progress of implementation of the European FP7 Project – EuCARD^2 – Advanced European Coordination of Accelerator Research and Development [1] and its impact in global and local scales. The project organizes annual conferences summarizing the research and technology achievements. EuCARD^2 2015 spring meeting was held in Barcelona. The impact of uninterruptedly continued for 12 years now the European accelerator infrastructure projects is immense, not to be overestimated, and is discussed in detail throughout this paper. Local impact on the accelerator research community in Poland is emphasized [2-7].

R.S. Romaniuk is with Institute of Electronic Systems, Warsaw University of Technology, (e-mail: R.Romaniuk@ise.pw.edu.pl).

The paper is a consecutive part in the cycle of articles describing hi-tech instrumentation development for large-scale research infrastructure from the area of high energy physics, elementary particles, astroparticles, space, nuclear, high temperature plasma diagnostics, fusion energy, high energy high power optical lasers, FEL lasers, fifth generation light sources, superconductivity, accelerators, compactness and energy efficiency in future machines, environmental footprint of large infrastructures, combined actions of high fields, new directions of research, etc. [8-12]. This part describes the EuCARD^2 project, current work developments, and their impact in Europe and Poland. The description bases on materials of periodic coordination meetings of the project, contractual reports and intranet/Internet resources.

II. Direct and Indirect Impact of EuCARD/EuCARD^2 in Poland

The project involves several small research teams from Poland: NCBJ, IChTJ, Technical Universities of Łódź, Wrocław and Warsaw. Especially profitable is participation of small young research teams from Polish universities. The project has already led to many important results related to the essential modernization of the European research infrastructure in the field of accelerator technology. From the point of view of the accelerator research community in Poland, which unfortunately does not own a very large, European scale and discovery class research infrastructure, the benefits of participation in large international endeavours always have been large and are even more relevant today. These benefits relate mainly to participation in the construction of research infrastructures of many young scholars, physicists and engineers from Poland, from such areas like applied physics, photonics, radiation, power, electronics, IT, electrical, chemical, mechanical, mechatronic engineering and many more. Through the participation in the project of gifted and active young people, there are developed certain sectors of high technology in Poland. An Editorial Series on Accelerator Science and Technology published in collaboration between CERN and Warsaw University of Technology is associated with the continued cycle of infrastructure projects CARE, EuCARD, TIARA, and EuCARD^2 [wydawnictwopw.pl]. Large experiments of the discovery class, which were covered by the paper series devoted to the participation of young Polish researchers there, have a number of common outstanding features: are of large infrastructural scale, unfortunately all of them are localized outside our country, are decisively designed as discovery class instruments, and there is a substantial Polish participation in them. There were described chosen key research infrastructures and experiments like: lasers – LCLS, FLASH, EXFEL, POLFEL, accelerators – TESLA, LHC, ILC, detectors – CBM, CMS, TOTEM, tokamaks – JET, ITER, integrated infrastructures – MYRRHA, etc. with special emphasis on participation and active research input of young researchers from the Institute of Electronic Systems of WUT and other universities from Poland. Dedicated topical sessions devoted to these projects and large research infrastructures are organized annually during the WILGA Symposium on Advanced Photonic and Electronic Systems for High Energy Physics Experiments [wilga.ise.pw.edu.pl]. The meeting gathers a few hundred young scientists and Ph.D. students from Poland and neighbouring countries. Early participation in leading, large, discovery class experiments is something exceptional for very young researchers just starting their scientific career. It is a unique chance of own, personal, accelerated scientific and technical development. EuCARD^2 is no exception from this rule. More than enables such possibility to young researchers. EuCARD and EuCARD^2 supported and developed research infrastructure is under construction and modernization in several European accelerator laboratories like GSI and FAIR in Darmstadt, RAL near Oxford, DESY in Hamburg, CERN in Geneva, ESS/MAxLab in Lund, etc. Experiments in these institutions search for new elementary particles beyond the SM, precisely measure matter properties in extremal conditions, develop new directions in high energy and high intensity laser technology, research phases and critical points in the quark-gluon plasma and strongly interacting matter, try to measure properties of quark matter in different areas of existence, etc. PERG/ELHEP Laboratory in the Institute of Electronic Systems at WUT [ise.pw.edu.pl] is researching hardware and software systems for such experiments as: JET in Culham, WEST for ITER in Cadarache, CBM/FAIR in Darmstadt, FLASH and EXFEL in DESY/Hamburg, ESS in Lund, and other. EuCARD series of projects is a part of more general pan-European endeavour concerning massive modernization of old and building of new accelerator and related research infrastructure of discovery class. A few experiments supported by EuCARD is now during modernization or building new infrastructure. EuCARD specifically supports strongly the weaker or lacking links in the key experiments like: ultimately high field magnets, new generation of measurements control and diagnostics electronics, new triggers for new physics, new accelerating technologies, new materials, etc. Exploitation of some of these supported experiments under construction should begin during a decade and should last for the next two-three decades. This is a typical time scale for large, unique experiments of discovery class. Financial scale is billions of Euro, in which 10% is for hardware, ICT, software and instrumentation. Part of these costs, a value of millions of Euro, and this situation concerns a number of experiments, is shared by the participating countries, including Poland, as in-kind contribution. Intellectual input from Poland embraces also the work of numerable young researchers, especially on modelling and simulations, data bases, MTCA electronics, TRIDAQ electronics, LLRF systems, crio-systems, etc. The major fields of activity of EuCARD and EuCARD^2 projects were described elsewhere [1,2], including their local impact on innovative R&D, now we concentrate on the latest achievements and their impact on wider communities.

III. Areas of Activity of the Enhanced European Coordination of Accelerator Research and Development - EuCARD^2

The project promotes and coordinates research efforts at the European level concerning the development of next generation particle accelerators. It gathers more than 300 participants from 40 European institutions - universities, research centers and industry. It creates an interface to other national and international research projects in this field of science and technology. Disseminates and promotes the attractive research results. It organizes workshops. Identifies areas of potential interest to the industry, calling them "Catalysts for Innovation". Networking activities are aimed at transfer of technology to society, particularly in the areas of accelerators applications in medicine, like production of medical isotopes and new medical materials, and in industry, for example in the accelerator processing of nuclear waste. EuCARD is preparing a strategic document for the public and policy makers on the role of technology accelerator in Europe. Future accelerators and synchrotron light sources with low emittance will work with extreme beams. There is designed an accelerator ring of the next-generation for electron - positron, and proton – proton collisions, located at CERN, with a length of approx. 100 km, the construction of which could begin in approximately 30 years. EuCARD, while pointing to these future efforts, does not forget practical applications of accelerators.

In a sense, the EuCARD^2 project is aimed partly also to research the missing pieces of such futuristic projects. These partly or completely missing components are: large aperture magnets of ultra-strong magnetic fields – 20T or more, new concepts for high field accelerator cavities, femtometer scale stabilization of bunch crossing interaction points, bunch size reduction and charge density increase to unprecedented levels, construction of booster accelerator based on plasma-laser wakefield interaction, below femtosecond time scale synchronization, intelligent control systems and diagnostics, new generation of data acquisition systems, new solutions for detectors of ultimate time and space resolution, etc. The project networking activities are focused on working with young scholars. New accelerator techniques are aimed at laser and plasma interaction and synchronization of the bunched electron and pulsed photon beams. In this area there is prepared a research project within the H2020. AWAKE demonstrator is being built in CERN combining laser and plasma techniques and showing the proton acceleration in the excited plasma field. Future magnets are increasingly frequently using high-temperature superconducting materials - HTS. There are tested high power, high current density, superconducting cables. There are developed new technologies and techniques for making superconducting microwave cavities of ultimate finesse. There are optimized manufacturing costs of accelerating cavities, couplers and other components of the accelerator line. In the area of the RF technology there are works on effective metal photocathodes, beam monitors, monitors of excited plasma fields using electro-optical modulators, new solutions for input stages of electronic detectors.

One of the most important areas of network operation of EuCARD^2, in accordance with the EU guidelines, is the transfer of innovation for public use, which is a far broader process than just a simple offer of new technology to industry. This type of action is called for short "innovation catalysis". EuCARD^2 is developing a number of innovative technologies, methods of operation, collaboration, management, focused on advanced research and development of infrastructure. However, after some additional analysis and adaptation, many of these innovations can be almost directly applied to practical solutions. Industry easily adapts such solutions like new materials with excellent thermal and mechanical properties. It is much more difficult to adapt immediately solutions that are still ahead of their application time, and which require the client to learn new technologies and convince him/her to their usage. Some parts of this difficult process was unintentionally shifted to industry. The unprepared industry treated these tasks as significant additional risk of undertaking too innovative production and the case often limped to a standstill. EuCARD^2 decided to undertake, inside the framework of innovation catalysis, a broader action on the social platform concerning the popularization of scientific-technical issues, seemingly "too innovative". The results are very encouraging. With great contemporary scientific initiatives of a global nature, and the industry friendly character of EuCARD^2 is just like this, an efficient and multi-level, very active social interaction seems to be absolutely necessary.

EuCAN is a network of coordination of the European activities in the field of accelerator technology, which operates inside the EuCARD^2. EuCARD/EuCAN undertakes various social initiatives, cultural, educational, managerial, and industrial. The activities include identification of potential areas of innovation and application of accelerators, and ideas investigated by the project. EuCARD^2, within broader and integrated initiatives of CERN, is participating in large industrial fairs, presenting actively its achievements. It is also organizing own local workshops for the industry, emphasizing direct needs of cooperation with the manufacturers of advanced materials, components and systems. It strives for the presence of industry at the events organized by the project. The organized workshops in the area of accelerator technology under the title "Universities meet with research laboratories" are intended to recognize the issue of cooperation in the field of education, promotion of accelerator research at universities, making maps of accelerator research in Europe in higher education, departmental laboratories and organizing industrial, systematic and continuous training courses on accelerators. Education in the field of accelerator technology, in comparison with other perhaps more stabilized fields of physics and technology in Europe shows that continuous training is based on a kind of self - organization of particular research community. Efforts in this area are undertaken by various local initiatives, major research laboratories, universities, and associations like the Accelerators Group of the European Physical Society. For students the potential attractiveness of this subject is probably in its interdisciplinary character, and proximity of theory and experiment. The accelerator institutes in Poland, including NCBJ, IFJ-PAN, IChTJ, IFPiLM organize similar targeted events like schools, open days, science festivals, popular seminars, industry days, etc. aimed at outreach and dissemination, but also cooperation with industry.

IV. Energy Efficiency of Large Accelerator Complexes and Research Infrastructures

Increase in the size of accelerator research complexes and the associated increase in energy consumption forces the system designers to work on energy usage efficiency. If the designers do not change the energy technology for the planned next large circular accelerator, it would have needed electric power at the multiple GW level. Big research infrastructure projects require serious and wide social and political acceptance. Such acceptance is associated with energy consumption, environmental impact, potentially arduous impact of infrastructure, pollution, costs, etc. "Energy Efficiency" it is an action network in EuCARD^2 project aimed at developing a wider, European consensus in this area. The works are conducted towards the development of technologies and methodologies for energy management in large infrastructure accelerator complexes with a view to their potential, future use also in other relevant industrial complexes. Recovered and/or not consumed energy resources in a specific large research or industrial infrastructure become a global network, virtual source of additional energy. This source of energy can, with proper organization of the system, return it effectively to the network for other users. An analysis was done of the total energy balance of the 12 largest European energy-consuming research infrastructures. The combined annual usage is at the level of more than 2TWh (in this number 50% is for CERN), thus there is a serious reason to fight for, using complex energy consumption modelling and optimization techniques. The issue of energy efficiency in energy-intensive large accelerator research complexes includes the following topics:

- Energy recovery from cold factories and from the particle beam, possibly also from the high field magnets,
- Increasing the efficiency of generation of high-power RF, optimization of RF control and diagnostics,
- Short-term accumulation of energy,
- Virtual power plant management,
- Superconducting beam transfer channels of a very low (close to zero) energy consumption.

The new infrastructures can design cold plants, from the beginning, in an optimum way in terms of really needed heat input levels, and allowing the recovery of heat energy. In the existing infrastructures, operated for a long time, the optimization is generally combined with a significant investment that can be returned only after a long period of time, often exceeding the duration of their life span. In modern accelerators with very high beam power, the main problem is the conversion efficiency of electricity from the network into the beam. This problem concerns in particular today a large infrastructure of the ESS just under construction in Lund, but also the newly designed infrastructures - ILC, CLIC, LHeC, FCC, etc. Conventional solutions of large RF power sources do not meet the requirements of future research infrastructures of the biggest scale. The current research on powerful sources are focused on: increasing the efficiency of klystron, optimization of multi-beam sources, research on IOT (inductive output tube) with solid state drivers, increasing the stability of the magnetrons, tetrodes and solid state amplifiers - SSA of big power. Modifications of high power klystrons to obtain the efficiency of more than 90% go into the adiabatic bunching of the beam (generation of core oscillations, periodic change in the velocity distribution of electrons counteracting the dissipation of bunches by the space-charge forces) as it passes through the klystron and the use of multi-slit cavities. Both techniques of klystrons modifications may be combined. The first requires the use of a greater number of cavities in klystron, the second reduces the length of klystron. Multi-beam IOT source currently reach the efficiency of 70% for the CW power level of 1 MW. Compared to the klystron the IOT is not achieving the best performance under the saturation conditions resulting in that they still have differential amplification capability and can be used to control the signal amplitude inside the feedback loop. High power solid state amplifiers, have efficiency in the range of 70 - 80% for the frequency 70 - 400 MHz. Lower level of generated output RF power by single units requires cascading of multiple elements. In addition, the intelligent monitoring, control and diagnostics system prevents unplanned downtime of the complex accelerator infrastructure. In a complex system, there are supervised hundreds of parameters - electrical, thermal, mechanical, physical and chemical, with varied dependencies and relationship between them. The diagnostics follows on-line these values and the relationships (direct and cross-), responding if needed by changing the work conditions of the machine. The aim of optimization is to increase the availability of the accelerator beam and provide more safety.

Optimizing of the energy system takes into account the continuous availability of electrical power and heat, and the consequences of interruptions in the availability of the beam, and reliable high power RF sources. Increasing the efficiency of high power RF sources is associated with a reduction in the reliability. It is necessary to keep a balance between the efficiency and reliability. Unavailability of the beam caused by downtime or damage to the source, is a reason for the lack of measurement data at that time, while simultaneously there are acting all the time very energy-intensive cold factories, which cannot be easily switched off. As a result, the energy efficiency of the entire system infrastructure decreases. Accelerator infrastructure requires the presence and availability of energy stores of different capacities and different time scale. The concept and the cost of such magazines are different depending on the application. The diversity of energy users, in terms of time, location, quantity, density, etc., enables the design of a large infrastructure as a virtual energy source. Electron optics, distributed over large distances electron and particle beams focusing magnets require significant amounts of energy. High-energy beam transport requires the use of quadrupole magnets with high magnetic field. Work is underway on new quadrupole lens solution containing no iron in the core structure, with winding of low resistance and inductance. Low inductance and resistance enables fast action of these pulsed magnets to effectively reduce the average consumption and power dissipation in comparison with the conventional CW magnets. When working with high-power pulses of power supply it is necessary to take into account the transient phenomena in the supply cabling and connectors. Energy efficiency of a pulse power source working with a magnet can be optimized if the system is running in a resonant loop, synchronized properly with the accelerator clock. Pulse magnets introduce significant errors in the pulse and integrated magnetic fields. The development of energy-efficient magnets include comparison of the following technologies of various types of magnets: permanent - small field, the field errors, radiation resistance; superconducting - low-energy, costly; classical electromagnetic - the dominant solution, optimized in terms of size and cost, and working conditions. Global energy efficacy of the whole accelerator complex embraces also such issues as energy receptors standardization in terms of construction and energy consumption characteristics, physical exchange between laboratories of high energy devices like large dipoles of high field intensity, cold factories, etc. Such wider scale standardization lowers the cost of infrastructure building and maintenance.

V. Applications of Accelerators in Research, Technology, Industry and Medicine

The activities are focused on the use of accelerators by society, mainly in medicine and industry. These activities use the results obtained in the previous accelerator research project TIARA. There are considered such areas as energy, nuclear industry, production of isotopes, medicine, safety, research in the area of HEP, photonics, light sources, general industry, semiconductor industry, materials engineering, materials testing, cryogenic industry, applied superconductivity, aerospace, space exploration, gas turbines, etc. There are organized industrial workshops, which used to gather dozens of partners interested in cooperation with the project and the extension of the range of accelerator technology, for example in the field of new materials. The workshops include: construction of new solutions of compact gantry devices for medical hadron therapy, medical and industrial applications of neutron beams, energy production using accelerators, transmutation of radioactive materials, efficient production of medical radionuclides, as well as construction of other facilities where a particle accelerator is a source of energy. The project has just prepared a strategic document "Applications of particle accelerators in Europe." The document has a general strategic character but moves also economic, social and political issues. The broad subject of accelerators application includes: low-energy accelerators to 20 MeV, proton and ion accelerators in the medium energy range 10 MeV - 1 GeV, proton and ion accelerators for high-power beam, and accelerator targets for beams of extreme energy and/or power density. An important direction of research is not only to determine the potential applications of accelerators, but the exact identification of the limits of current technology and explore opportunities for using modified or completely different technology, which may be related to a fundamental change in the direction of the research, using new materials or using other physical phenomena. Around the identified new research directions there are created research and technology consortia, whose job is to prepare promising, and profitable to the society, subject applications to the European program H2020.

Low energy accelerators are used for the production of neutrons from the beams of protons and deuterons. Such modern neutron source should soon replace the classic and not very convenient reactor sources. Neutron beams are used in the following areas: energy – radiative aging and destruction of materials; measurements of characteristics of nuclear waste; industry - neutron activation analysis; medicine – BNCT therapy with boron capture and production of radioisotopes; and security - monitoring of critical areas. The aim of the research is to develop a compact, reliable accelerator based neutron factories, of high beam currents, and resignation from the previous generation of nuclear reactor based neutron sources. With the usage of compact accelerator neutron sources, a substantial growth and expansion of applications of BNCT is expected. Availability of relatively low-cost, compact neutron sources may cause a revolution in the industrial applications.

Accelerators of low-energy electron beam are used to enhance the properties of materials, for polymerization, joining materials, sterilization, material activation in technological processes, removal of sulphur and nitrogen oxides from flue gases, modify chemical reactions, and the like. Similarly to the neutron sources, the industry is expecting the availability of relatively low-cost, reliable, and above all compact, high-current electron beam sources.

Research area of the energy production includes a number of applications of accelerators of various particle beams and low energy but high intensity. Material tests are related to the premature aging and destructive action of radiation. Direct accelerator based or accelerator assisted generation of energy includes such research as inertial confinement of heavy ions in fusers, the use of neutral ion beams for heating the plasma, etc. These applications require beams of extremely high currents, even hundreds of kA.

Proton and ion accelerators of medium energy work in medical equipment. Compact solutions of such accelerators, integrated with small beam scanners (gantry) work in numerous applications for cancer therapy with charged particles, mostly protons and light ions like carbon. This is due to a significant therapeutic advantage of this method over the gamma radiation. Therapeutic C ion beam requires today accelerators and scanners of quite a considerable size. Miniaturization of such machines is a key issue determining their further development in medical applications. Reducing the size of the beam spots is related to the use of superconducting magnets. Another option is the use of permanent magnets in miniature scanners of FFAG type (fixed field alternating gradient).

Efficient production of medical radioisotopes requires compact and medium energy accelerators. The most popular medical radioisotope 99mTc is produced in nuclear reactors from 99Mo. The isotope can be manufactured using a nuclear reactor. A cheaper and more efficient alternative is the direct production of Tc radioisotope using an accelerator technology. A compact accelerator, relatively inexpensive and placed directly inside the hospital environment is a sought-after target solution. Research is ongoing on technical solutions of such accelerators coupled with other specialist equipment, therapeutic, but also chemical, biological and clinical laboratory equipment.

Specialized systems which are powered by accelerators require large, high energy machines. Such systems include, for example: transmutations of nuclear waste; co-supply of safer than uranium, sub-critical nuclear reactors with thorium fuel; production of neutron beams by spallation method, and production of muon beams. During the transmutation of nuclear waste the highly radioactive actinides bombarded with high-energy neutrons are subject to decay for light ions with short half-life, or stable light ions. The aim of transmutation (in the European project MYRRHA) is shorter half-life of the waste, at least by a factor of 10^3, and their reduction in volume by a factor of 10^2. The purpose of the construction of hybrid thorium reactors with an extra accelerator generated neutron powering beam is to give up the uranium technology. Additional neutron beam power supply is due to the lower neutron activity of thorium than uranium, which is insufficient for self-sustaining nuclear reaction. Requirements for the powering accelerator are: continuous work, 1-2 GeV beam energy, beam power 4-10 MW, target for neutron production, accurate parameter control of the accelerator. The purpose of the production of muon beams is their application to the muon-catalysed fusion, where there are produced muon atoms of deuterium and tritium, hundreds of times smaller than the classic atoms, which essentially facilitates the fusion. Another use of muon beams, at best from the compact source, in contrast to cosmic muons, is scanning of goods and detection of nuclear waste.

Accelerator production of various types of particles is using different, dedicated targets. Targets are an important component of accelerator systems and often constitute a restriction on the efficiency of their operations. This applies to production of neutrons, radioisotopes, muons, etc. Research is conducted into the next generation of optimized accelerator targets, but also associated issues like cooling of targets, target material fatigue, thermal cycles, target construction, materials, etc. Targets are important elements in the compact accelerator based muon and radioisotope factories.

VI. Development of Linear and Circular Research Accelerators of High Energy and Intensity

The progress of high energy accelerator technique is marked by increasing luminosity, energy, beam power, beam intensity and polarization control. This progress will require, in the future construction of new colliders operating in the energy range of 100 TeV, superconducting accelerator rings and lines of today inaccessible quality parameters, as well as unattainable beam control, including the polarization. Today, some scenarios are analysed, on the cutting edge of technology, or bravely but consciously exceeding these limits, concerning the future colliders for high-energy physics. There is considered the future and direction of modernization of existing infrastructures such as KEKB, CERN and others. CERN teams have developed quite precise designs for multi-stage upgrade of the LHC accelerator complex up to 2040. There was launched a new study on the future circular collider for electrons and protons - FCC and TLEP of the length in the range of 80-100 km. In China, a similar project is analysed called CepC/SppS. The energy front will be represented then, very probably, by the future muon colliders. FCC is designed as the next stage for HEP experiments after the LHC era, if the plasma wakefield accelerators will not achieve the power and energy frontier. Potential progress in the construction of large infrastructure depends on progress in the key elements of the infrastructure such as the ability to operate with stable, low emittance, extreme beams of high energy and intensity, precise control of beam polarization and its orbital position in the accelerator ring, the use of new high field intensity magnet, the use of ultra-precision magnets corrections, sub-femtometre stabilization for the point of interaction, new collimation materials, and new solutions to the RF and SRF electronics, including the use of sophisticated next generation high-speed measurement systems, control, precision feedbacks and diagnostics.

Extreme beams of future particle accelerators. Other issues related to extreme beams in the designed, built or currently upgraded accelerator infrastructures include: optimizing of magnets for extreme beam dynamics; construction of extreme proton liniacs in terms of the European Spallation Source - ESS; spin polarization of leptons; crab cavities and Tera-Z factory; accelerator impedance; electron multipacting prevention, crown phenomena, electron clouds and passive intermodulation in accelerator; beam waveguiding in crystals; infrastructure upgrades options for - SuperKEKB, HL-LHC, LHeC, integration of electron-hadronic collider in LCC; and the construction of future Higgs boson factories. A tenfold increase is planned for the beams luminosity at the bunch collision interaction point, using resonant skew crab cavities. Further development of the colliders will require continuous increase of luminosity and extreme, femtometre stabilization for the point of interaction. Work is continuing on the concept of obtaining a substantial increase in luminosity and power density at the point of interaction using the idea of crystalline collider – CC.

Accelerator rings of high-quality and low emittance. Development techniques of accelerator rings of low emittance (transverse beam scattering) now refers to the constructed, upgraded and planned European synchrotron light sources of the third and fourth generation. Modernization of the light sources is required by both the industry and the academia communities using electron/positron colliders. The key issue is extreme beam instability in the rings of new generation. Currently, this issue concerns the new beams propagating in the constructed and modernized accelerators: new injector complex for the LHC, FAIR accelerator complex, ISIS and PSI-HIPA. One of the tested solution is the use of fixed field and variable gradient magnet technology - FFAG. The dynamics of particle beams in modernized and new accelerators requires new solutions for the magnets. High-quality extreme beams require precise analytical determination of the area of their stability in the magnet aperture, determination of dynamic aperture, determination of conditions of beam resonance stability in the accelerating ring, beam resonance trapping in four-dimensional phase space (orbit with standing wave), noise reduction, beam distortion phenomena, avalanche multiplication of electrons, multipacting in the accelerator line, reduce of effects associated with the space charge, beam and field instabilities, accelerator impedance, and collective phenomenon, research on non-coherent effects caused by beam resonances due to errors in nonlinear magnetic fields.

Polarization of particle beam. Beam polarization was only partially used till now to determine the properties of the particles and their acceleration process. Extreme beams require precise research on polarization effects. Polarization has here a larger and much broader meaning. Recording of the polarization phenomena adds a number of valuable observational data as compared to non-polarization experiments. The differences between two such experiments show: keeping or not keeping the state of polarization; observation of the potential differences between particles and antiparticles; different behaviour of leptons and hadrons, etc. Research on polarization phenomena include both polarimetry with great accuracy in the low-energy electron scattering experiments, as well as the dynamics of depolarization of the beam in the accumulation rings of high energy, also the phenomena during collisions of polarized electron and ion beams. Fundamental questions about the polarization are: what are the most effective benchmarks to measure the polarization in the present experiments, whether it is worthwhile to study the polarization of antiproton, which is the research potential associated with the precise control of the spin in accumulation rings, and if the spin control should be included in future infrastructure solutions for accelerator?

Future magnets. Magnets for future accelerators technology include several classes of devices. For the high energy experiments there are needed massive superconducting device class-20T and 10kA currents. The new class includes 5T-HTS devices, autonomous dipoles and inserts to large aperture magnets boosting the field. Future magnets and power cables for them base on materials from the family of high-temperature superconductors. The tested materials and parameters are HTS (BSCCO, YBCO-GBCO-REBCO), HTS cable designs (tapes and wires), ways of winding of superconducting wires, optimization of cable constructions, parameters of the cable including the maximum allowable current density (critical current for the overall cross section of the conductor in the cable), the effect of pressure and forces on the high field magnets, impregnates, isolation, fatigue phenomena due to cyclic temperature changes and induced stresses. There are designed and tested new designs of magnets class 20T and 5T HTS. Projects are developed for magnets with YBCO tape suitable for 5kA and 20T. New designs include HTS materials properties and optimize the distribution of stress forces at significant values of the magnetic field.

Collimator materials. There are tested new beam collimator materials designed to protect the accelerator structures, to direct the beam in the right direction and to absorb the stray radiation. The materials are resistant to the energy deposit of high density. The group of investigated materials include copper-diamond composites - CuCD, and molybdenum - carbon - graphite - MoGr. The materials have a small coefficient of thermal expansion over a wide temperature range 20-2000^{o}C and very high coefficient of thermal conductivity, of the order of 800 W/mK at room temperature. These materials arouse considerable interest in the industry.

Innovative RF and SRF technologies. The aim of research in the area of RF/SRF is to increase the acceleration field gradient in the resonant microwave cavities, and to reduce the beam emittance, as well as the optimization of efficient cooperation between hot and cold accelerating techniques. Acceleration of high quality beam requires very precise diagnosis and control of beam position in the cavity and excited parasitic fields. The development of diagnostic techniques inevitably goes in the direction of monitoring a much larger number of the acceleration process parameters, accelerator itself and auxiliary technical infrastructure. There are developed new techniques for deposition of superconducting monocrystalline thin films of high quality (Nb_3Sn) onto the Cu cavities, to lower the costs. The technology used was PEALD plasma deposition of atomic layers. These techniques were used for the production of prototype accelerating cavities, and the test for the construction of production lines. Tests are carried out on the TESLA type single-cell cavities with resonance frequency of 1.3 GHz. The cavities with superconducting thin films were characterized and compared with volume cavities. A quadrupole cavity was developed for advanced deposition tests of thin niobium films. There are formed thin multilayer structures having a lower resistance than the volume niobium. Other ongoing work in this area includes: new methods of increased efficiency of klystron beam bunching, warm cavities of ultra-high-gradient, implementation of electro - optical modulators for RF signal acquisition and transport, a new solution of electronics for diagnostics of high order modes - HOM, simulations and stability studies on eight-cavity chain shaping the bunches, resonant accelerator cavities for the triple frequency of 3.9 GHz, search for mono-pole modes for this frequency, characterization (quantum efficiency and energy spectrum of electron emission) and RF tests of photocathodes optimized for high average current and high pulse current in the superconducting and warm injectors, and research on new materials for photocathodes.

VII. New Accelerators and New Acceleration Techniques

There are intensively tested acceleration techniques based on beam induced wakefields in plasma. A proposal to build the infrastructure of the European test plasma - accelerator within the H2020 was submitted. The works relate to electron beams of high brightness generated using laser - plasma accelerators. Femtosecond and femtometre time – space synchronization between the pump laser pulses and injected bunches of the relativistic electron beam is the key issue. Laboratory work on fs synchronization is carried out in several centres, equipped with superconducting electron liniacs and relevant high power Ti-sapphire lasers, like in ELBE and FLASH infrastructures. Protons are also accelerated in the plasma wakefields, in the AWAKE experiment. There are developed and characterized single and multi-stream, supersonic He gas targets, with a precisely controlled and well located, fast changeable, micrometer size, local plasma density gradient, created by the shock wave. Exact characterization of fast changeable micro-gradient in plasma is performed using double angle interferometric tomography - LOA, LLC. There are conducted experiments at CERN SPS with beam self-modulation in plasma excited by seeding laser. These types of experiments with electron beam micro-waveguiding and acceleration (and in the future with muon and proton beams) in the plasma are conducted in several laboratories interested in building future compact but powerful plasma wakefield accelerators.

There are examined limitations of future superconducting liniacs of extreme energies and intensities and beam brilliances. An extreme beam of significant dynamics, carrying large energy requires new, ultra-fast methods of control and feedback, redundant and rapid diagnostic methods (including the accelerative phenomena of higher order), different in the transverse and longitudinal directions. Ultra-fast method of longitudinal feedback separate for the electron beam and photon beam are tested in the superconducting electron liniac and FEL laser, which is the FLASH in DESY. Ultra-precise time-space synchronization (fs-fm, μrad angular jitter) is required between high power femtosecond laser pulses exciting GeV wakefields in plasma, and injected to periodic wakefield relativistic electrom beam bunches. Such experiments are tested using superconducting ELBE liniac and Ti:Sa laser Draco in HZDR laboratory. Both beams are focused and overlap at the point of interaction. As a result of the interaction, through Thomson backward scattering, there are generated intense, ultra-short hard X-ray pulses. Stable generation of X-ray pulses provides a proof of high quality synchronization between electron and photon beams. It is a step on the way to study periodic phenomena in the plasma wakefield which could lead to the generation of coherent synchrotron light and effective plasma acceleration of bunched electrons.

In many laboratories there are examined: formation of capillary channels in plasma, stable nonlinear self-focusing of injected relativistic electron bunches in plasma, evolution of the laser pulse and electron bunch in the plasma channel, plasma response to accelerating action, relative strength of the excitation interaction process between all participants electron-plasma-wakefield-photon. There are tested methods of excitation of a significant gradient in the plasma - gas interface, with usage of ionizing boundary, laser pulse preceding proton bunch, abruptly ending long proton pulse, to increase the intensity of the field induced in the plasma. Modulation of the long proton pulse occurs with a period of laser-induced plasma wave. The aim is to obtain plasma channels having stable and constant periodic characteristics of induced wakefield at long length.

Sub-femtosecond synchronization between the electron beam and the laser is required in plasma accelerators and pump-probe experiments using FEL laser (like FLASH) powered by superconducting liniac. The optical laser operates in a pulsed mode with a maximum pulse repetition frequency of 3 MHz. It is necessary to stabilize the compression process and the correction of fluctuation of transmission time of electron bunches by introducing modulation of magnetic energy before the bunch compressor. The role of the ultra-high-speed broadband actuator is done by the normally conductive cavity with a low latency loop feedback. Arrival time of bunches, and compression stability are monitored by the BAM and BCM detectors linked with feedback from the phase and amplitude actuators. Arrival time correction is performed at the beginning of the liniac by energy-dependent beam path of the magnetically compressed electron bunches.

New concepts of accelerators, in particular plasma-laser, arouse considerable interest in numerable research communities. The project EuCARD^2 established the European Network of New Concept Accelerators - EuroNNAc. The network organizes a series of meetings and workshops on Advanced Concepts of Acceleration EAAC - European Advanced Acceleration Concepts. The aim is to coordinate the activities on the laser-plasma accelerators in Europe, definition of a coherent research program, apply for research projects in this field in the framework of H2020 (EuPRAXIA, Hi-Flux, ELBA), determination of optimal areas of research, preparation of common standards of reference, construction of the European pilot infrastructure. Technical parameters of the infrastructure are initially determined: ultra-compact FEL 250 m, beam energy of 5 GeV, charge 1-10 pC, repetition rate of 10 Hz, maximum current 1-100 kA, bunch length of 10 fs, energy dissipation of 0.1%, normalized transverse emittance 10-1000 nm. The results of the EuPRAXIA project are designed to be used after 2020 to the further development of technologies of ultra-compact FEL laser of 10-100 m in length, ultra-compact medical accelerators, and compact linear plasma colliders, 3-5 km in length, to do research in the area of HEP.

The development of accelerator technology for research in the field of high energy physics stimulates technological advances in areas such as new solutions of electronics, sensors, RF and SRF techniques, crio-technologies, superconductivity, microwave cavities of extreme Q factor, electro-optical measurement methods of high-accuracy, laser technology, plasma technology, electron optics, atomic optics, new materials, accelerator miniaturization, and many others. Progress in the area of research, stimulate many new applications of accelerators in technology, industry and medicine.

Realization of such infrastructural projects like EuCARD^2, and its predecessors, are profitable not only directly to the owners of large accelerator infrastructures, but also to a number of smaller university based research teams, which participate via their young research representatives and fellows. Not remembering of this simple truth, and not inviting small university teams to participate, will self-confine the future projects and make them humble.

References

[1] R.S.Romaniuk, EuCARD^2 – 2015, Elektronika – konstrukcje, technologie, zastosowania, vol.56, no.10, str.65-71 (2015), doi:10.15199/13.2015.10.13

[2] R.S.Romaniuk, EuCARD^2: enhanced accelerator research and development in Europe, Proc.SPIE8903, art.no.89031Q (2013); doi:10.1117/12.2035218

[3] R.S.Romaniuk, Accelerators and society: succession of European infrastructural projects: CARE, EuCARD, TIARA, EuCARD^2, Proc.SPIE, art.no.890320 (2013), doi: 10.1117/12.2035376

[4] R.S.Romaniuk, Visions for the future of particle accelerators, Proc.SPIE, art.no.890324 (2013); doi:10.1117/12.2035418

[5] R.S.Romaniuk, Accelerator Science and Technology in Europe: EuCARD2012, International Journal of Electronics and Telecommunications, vol.58, no.4, pp.327-334 (2012),

[6] R.S.Romaniuk, Accelerator infrastructure in Europe: EuCARD2011, Proc. SPIE, art. no.800805 (2011), doi: 10.1117/12.905095

[7] R.S.Romaniuk, EuCARD2010: European coordination of accelerator research and development, Proc.SPIE, art.no.774509 (2010), doi:10.1117/12.876542

[8] R.S.Romaniuk, Compact Muon Solenoid decade perspective and local implications, International Journal of Electronics and Telecommunications, vol.60, no.1, pp.79-84 (2014), doi:10.2478/eletel-2014-0010

[9] R.S.Romaniuk, International Linear Collider global and local implications, International Journal of Electronics and Telecommunications, vol.60, no.2, pp.181-185 (2014), doi:10.2478/eletel-2014-0022

[10] R.S.Romaniuk, LCLS large laser infrastructure development and local implications, International Journal of Electronics and Telecommunications, vol.60, no.2, pp.187-192 (2014); doi:10.2478/eletel-2014-0023

[11] R.S.Romaniuk, European X-Ray Free Electron Laser – EXFEL – local implications, Proc.SPIE, art.no.890368 (2013), doi:10.1117/12.2035411

[12] R.S.Romaniuk, Fusion 2050 – European and Polish perspective, International Journal of Electronics and Telecommunications, vol.60, no.1, pp.85-91 (2014); doi:10.2478/eletel-2014-0011