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Compact Muon Solenoid Decade Perspective and Local Implications

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***Abstract*—The Compact Muon Solenoid CMS is one of the major detectors of the LHC Large Hadron Collider accelerator. The second, a competitive brother, is Atlas. The accelerator complex in CERN was shut down for two years, after two years of exploitation, and will resume its work in 2015. During this break, called long shutdown LS1 a number of complex components, including electronics and photonics, will be intensely refurbished. Not only the LHC itself but also the booster components and detectors. In particular, the beam luminosity will be doubled, as well as the colliding beam energy. This means tenfold increase in the integrated luminosity over a year to 250fb$^{-1}/_{\mathrm{y}}$. Discovery potential will be increased. This potential will be used for subsequent two years, with essentially no breaks, till the LS2 in 2017. The paper presents an introduction to the research area of the LHC and chosen aspects of the CMS detector modernization. The Warsaw CMS Group is involved in CMS construction, commissioning, maintenance and refurbishment, in particular for algorithms and hardware of the muon trigger. The Group consists of members form the following local research institutions, academic and governmental: IFD-UW, NCBJ-Świerk and ISE-WEiTI-PW.**

***Keywords*—CMS, LHC, CERN, HEP, accelerators, particle detectors, high energy physics experiments, Higgs boson, electronics and photonics for HEP, Poland in LHC/CMS experiment, Compact Muon Solenoid**

I. INTRODUCTION

LONG awaited discovery of the Higgs boson, and subsequent 2013 Nobel Prize in Physics for Peter Higgs and Francois Englert (for theoretical prediction of the new field in 1964) again turned broader public attention to the high energy physics experiments leading to the discovery of new particles and mechanisms of yet unknown forces of nature. This discovery was done at a cost of building the whole LHC accelerator complex in CERN. This complex includes two main detectors, ATLAS and CMS. These two detectors were entirely built by their completely and intentionally separate collaborations, consisting of around 4000 physicists and engineers each. The ATLAS Collaboration included a group of well organized Polish researchers from Kraków (AGH, IFJ-PAN), while the CMS Collaboration included researchers from Warsaw. Co-discoverer of the Higgs boson, the CMS detector [1], [2], now being under intense upgrade process has a large impact not only in CERN but also globally and locally. In Poland, the Warsaw CMS Group is working on the upgrade of electronics, including hardware and software. The group is involved in the CMS since the very beginning, which was mid of nineties of the previous century. The paper digests the modernization aspects of the CMS, presented on a wider research and technical background, and its impact on research endeavors in global and local scales, emphasizing local activities. Research teams from Poland are increasingly widely involved in the European accelerator technology [3]–[14]. The Warsaw CMS Group is responsible, in particular, for the maintenance and development of the Muon Trigger. Wilga Symposium on Electronics for HEP Experiments summarizes annually the achievements of young researchers involved in these subjects [15], including the LHC, CMS, ATLAS and other accelerator infrastructure now under construction in Europe. The paper was presented during the Wilga 2013 meeting and was published in Polish in Elektronika [16]. The Polish CMS and ATLAS teams are co-authors of the Higgs seminal discovery papers [17]–[20].

II. OUTSIDE THE STANDARD MODEL?

LHC accelerator [21] and its main detectors Atlas and CMS, full of photonics and electronics, are now the major laboratories searching for new physics. After two years of intense exploitation, ended with the Higgs boson discovery [19] a two year period will follow (Long Shutdown 1 – LS1) devoted to the intense modernization of this large machine. Modernized LHC will continue the search of new elementary particles, super-symmetric particles, new dimensions, components of dark matter, essence of dark energy, etc., but with doubled luminosity of the level, initially $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the collision mass center, and next upgraded to $5 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and 14 TeV collision energy. A question appears what have these exceptional, unique, exotic and fundamental searches of new physics outside the SM in common with the standard process of development of photonics, electronics, microwaves, resonant superconducting microwave cavities of ultimate finesse, telecommunications, advanced control systems ICT, and generally information sciences [22]–[32].

What if we are someday able to build an effective communications system using no photons but neutrinos (the second most abundant particles in our universe, after photons). A clumsy prototype of such a digital system has already been demonstrated by FermiLab in March 2012. These were trials with the NuMi experiment (Neutrino Beam in the Main Injector). In order to generate a pulsed beam of neutrinos of high intensity, there were transmitted several tens of pulses, each consisting of 10^{13} neutrinos, separated each from the other by a few seconds. Neutrino beam crossed 250 m of solid underground rock. The beam was directed towards a 200 tones Minerva detector, spaced from the generator of 1 km. The detector sensitivity was around 10^{-13}, thus, from each pulse 0,8 neutrino was detected on the average. Transmission

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rate was around 0.1 bps with the error rate less than 1% [33]. Not very encouraging beginnings? Searches of neutrino communications are associated with applications in completely not or yet hardly accessible places for the classical EM communications, like communication with submarines – especially with deeply submerged ones, space communications, direct communication with space stations and lunar bases located on the reverse side of the Moon, communication with remote space shadowed objects. There are built large neutrino transmission lines, of the length spanning from several hundred km to several thousand km, and neutrino detectors. Such experiments with short or long base are called neutrino factories. The aim is not yet telecom, but measurement and gathering knowledge on these weekly interacting with matter and still elusive particles. Neutrinos are only subject to subnuclear week interactions and gravitation. They are leptons and fermions of half spin, have no charge, and very small mass. In a sense, they are similar to chargeless electrons. Neutrinos exist in a few flavors (which are quantum changes). There are built large neutrino detectors, called neutrino telescopes, such as IceCube [34] on the Southern Pole. The aim is to measure neutrino cosmic radiation of TeV energy and localization of the sources, but also indirect measurements of dark matter and additional dimensions and microscopic dark holes, also reading encoded messages in the abundant cosmic streams of neutrinos.

Existence of dark matter (DM) and estimates of their quantity stems from the research of global gravitational interactions in the cosmologic scale. The gravitational impact is felt by the baryonic (visible) and non-baryonic (non-visible) matter. Now, the prevailing research consensus assumes, that the dark matter consists of an unknown sub-atomic, non-baryonic particle. Search for this particle, using various methods (neutrinos, astroparticles, etc.) is one of important research directions of particle physics. Widely accepted theoretical candidate, which is hunted for, is a weakly interacting massive particle – WIMP, thought to be a component of the cold DM (CDM). WIMPs interact only via weak forces and gravitation. The theory of warm DM (WDM) assumes that the component is a massive neutrino. The global quantity of the DM is estimated from the discrepancy between the observed gravitational effects and quantity of bright visible matter. This number is now 84% of the whole matter in the Universe, and 23% of the whole energy density of the Universe. Dark energy DE makes around 73% of the Universe, and atoms make only around 4%. Dark energy is a hypothetical form of energy of the global density around 10^{-29}g/cm^3 permeating homogeneously the whole space. Its effect is observable only globally in the form of accelerated expansion of the Universe. Two models of DE are: cosmological constant and quintessence. Of 4% of baryonic matter, 3,6% is intergalactic gas, and only 0,4% are stars. It is expected that LHC, via the search of new elementary particles may explain some of these questions, not from the cosmological side but from the accelerator side. These open questions embrace, for example: asymmetry in the Universe between matter and antimatter, existence of heavy super-symmetric particles, existence of additional dimensions, presence of WIMPs, neutrino nature, etc.

Research carried out in the LHC accelerator complex are amazingly closely combined also with the cosmology and theories of the Universe fate. The discovered Higgs particle is an expression of the Higgs field, about which we do not know exactly if it is constant or changing, obviously in sufficiently long time scale. If the Higgs field changes, then the Universe may undergo a phase change sometime in the future. In any case, the mass of Higgs particle is combined with quark masses. Depending on these masses, the Universe is stable or not stable. Current calculations, taking into account the fundamental particles mass coordinates: Higgs boson mass vs. the top quark mass (the most massive one and which is not subject to hadronization), shows that our Universe is in a metastable area, and in the future may undergo a large ripping, and disappearance of atoms. This is a general background, in which the immense machines like the LHC, Atlas and CMS are modernized.

III. LHC MODERNIZATION

LHC accelerator is the largest single complex of research machines and instruments ever built by human beings. During this decade, there are predicted large modifications of the machine. There are many aims of the modernization. One of them is to increase the annually accumulated integrated luminosity IL, to the level ten times bigger than now, or up to over IL>250 fb^{-1}/y. A project HL-LHC or LHC of High Luminosity is co-financed by the EU FP7. Modernization will require exchange of the current basic large dipole magnets of the field 8 T for larger field magnets of 13 T. This also means very probably a change of technology of the used superconductors in the magnets from NbTi to Nb_3Sn. Further increase in the magnetic field intensity requires applications of inserts made of high temperature superconductors (HTS) at the cost of aperture diminishing. Exchange of high power, long distance transmission lines is required from copper warm to cold superconducting ones. The required transmission length is around 300 m and goes from the surface, via shafts down to the caverns and the tunnel. Cold lines will have near zero energy dissipation. Cables will carry 150 kA DC current per a single line. The cables are made of superconductor MgB_2, of critical temperature 25 K. This material is considerably cheaper than any HTS materials of critical temperatures in the range of 40-50 K.

The cavities near the interaction point need exchange for much more precise ones and performing designed rotation of the field, in order to increase beam luminosity just exactly in the interaction point. These are crab-cavities of several innovative designs. Quality of the vacuum has to be improved in the HL-LHC machine along with the dynamics of the cryogenic system and safety and reliability of the machine.

It is necessary to apply new solutions and materials for particle beam collimators. Increased luminosity of the beam requires much more precision in its guidance, and in the collision point the dimensional precision is sub-nm. Before the new components are manufactured, they must be modeled and simulated for different work conditions, parameters and materials. Essentially, without the SRF technology embracing resonant cavities [8]–[10], [27]–[30], powering cables, an magnets, it is impossible to speak of modern accelerating technologies. These components require precision control and diagnostics by means of photonic and electronic measurement and control systems, automation systems, data distribution, triggering, and acquisition [11], [31], [32]. Each change of the design of superconducting element, as simple as high power of signal cable, or magnet armature, is seemingly easy, but requires apart of detailed calculations and design, also a thorough simulations, but also a specialized workshop where many costly investigations and destructive tests have to be done. Such workshops are equipped in specialist, usually unique apparatus.

Around the LHC modernization [21], there are prepared and financed narrow topical projects and research collaborations concerning particular fragments of the machine in research and commissioning aspects like: EuCARD – European Coordination of Accelerator R&D, HiLumi, LHC LARP (American research project for LHC), TIARA (Test Infrastructure and Accelerator Research Area) preparatory phase project to build and integrate large European accelerator infrastructures – project particularly targeted for industry and practical applications of accelerators in medicine and other ones. The scale of each of these projects is tens of MEuro, and around LHC there is a number of such projects.

The LHC accelerator complex will be exploited at least during the next two decades. This period was divided roughly to two nearly equal phases, till 2020 and beyond. Towards the end of first phase, the luminosity is expected to be doubled than the original design value from the 2010., i.e. to the value $2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$. The first phase will see two long shutdowns LS1 and LS2. The LS1 has just started and will last till January 2015. The accelerator worked with the collision energy of 8 GeV, just before starting the LS1. After LS1, the expected collision energy is to reach 14 GeV. During the LS1 there are exchanged some dipole magnets, and fist of all, the connectors between superconducting cables and copper cables. Some subdetectors will be exchanged in the CMS. During the LS2, the pixel detectors and triggers will be exchanged. The Microstrip Tracker will be used by the whole first period. The terms and durations of LSx periods are determined now only with some accuracy. LS1 which runs now is determined precisely. Discovery of a new particle may cause necessary prolongation of the machine and the whole complex exploitation period, due to the need to gather necessary amount of data for off line analyses. On the other hand, excessive radiation destruction of the sub assemblies and electronics may cause additional technological shutdown. This sort of time uncertainty has to be calculated into the exploitation periods and machine modernization.

After the year 2020, the whole machine will be subject to serious modernizing, during long technological break LS3, which will last very probably for three years. Possibly, the integrated annual luminosity will be increased ten fold in comparison with the first phase. The CMS will exchange tracker detector and trigger, and data acquisition system. After the year 2030(35) the LHC seems to be replaced totally by a new machine. If it is going to remain in the same tunnel, then quite large radius of curvature, at the length of 26 km, for such large beam energies, will require magnets of the field over 20 T. Such strong magnets of big dimensions do not exist now, though, there are intense research works going on these solutions. HTS inserts magnets of several T are combined with 13 T large dipoles of enlarged apertures. Inserts make the aperture smaller. The high field magnet technology is different, taking into account cryo-cooling, from the methods applied today.

IV. CMS MODERNIZATION

The CMS detector [35], [36] has to be modernized along with the LHC, in order to fully exploit the detector and accelerator abilities. LHC gives certain abilities for its detectors which must be fully used. The LSx periods have to be efficiently used for rebuilding of some and chosen critical components to be replaced or repaired. During the experiment runs the detector is completely unavailable. The components to be changed are the ones which are narrow throat in measurements, data acquisition, particle detection, etc., or were broken during the exploitation. The detector has to follow the ever increasing beam brilliance offered by the accelerator. There are modernized all parts of the detector: muon detectors, hadron calorimeters, pixel detector, tridaq systems, beam monitoring, brilliance measurement. Space coordinates in the detector are expressed by the rapidity and pseudorapidity.

A superconducting compact solenoid is the backbone of CMS. It is 13 m in length, 6 m in diameter and the internal field is 4 T. High bending power of particle trajectories equal to 12 T*m provides good space resolution of measurements of their movement. The return field, on the outside of solenoid, is sufficiently large to saturate iron plates, of 1,5 m in thickness, building the magnet yoke, interlaced with sensors and used to reconstruct muon trajectories. The section tracing muon paths consist of aluminum drift tubes DT in the barrel region, and cathode strip chambers CSC in the cap regions. Measurement systems supplement the Resistive Plate Chambers RPC. The solenoid interior is filled with the internal tracker and calorimetric systems. Tracker length is 6 m, diameter 2,5 m and consists of 10 layers of silicon microstrip detectors. Tracker provides sufficient granularity and precision of temporal and spatial measurements, for large number of particles and their paths, called multiplicity, generated by proton bunch crossing. Strong magnetic field of the solenoid and long curved paths of particles provide also good resolution of momenta. In the barrel region, there are additionally three layers of pixel detectors. The barrels are closed from both sides by lids, covers, called caps, also equipped in detectors which cover their all surface. Vertex detector is a device located closest to the collision vertex. Detectors in the caps facilitate identification of the secondary vertexes.

Electromagnetic calorimeter ECAL is built from scintillating crystals PbWO2 cooperating with silicon avalanche photodiodes in the barrel and with vacuum photo-triodes in the caps. The Veto system (for neutral pi mesons) is installed before the ECAL caps. Electromagnetic calorimeter is surrounded by hadron calorimeter HCAL. The HCAL uses polymer scintillators with optical fibers collecting light and doing frequency shift from the UV to the visible and IR. Optical fibers are coupled to hybrid photodiodes which are ruggedized to work in strong EM fields. The next supplementing calorimeters are: HO, HF, CASTOR and ZDC. The HF, made of optical fibers and photomultipliers, is a detector of Cerenkov radiation. It measures the transverse energy of the collision.

Modular construction of the CMS detector facilitates its exploitation, repairs and modernization. The unity, not to be dismantled, is only the superconducting solenoid and the central yoke. All the rest is movable, may be shifted and opened. Pixel detector is overlaid on the beryllium pipe with the beam in two halves. The majority of calorimeters is demountable after shifting the caps and opening of the vacuum container. The most precise description of the CMS detector is published in the CMS manual, published in the CERN CDS open library [1].

Triggering of data from the CMS is done by multilevel system localized in an underground control room, close to but outside the experiment cavern. Measurement signals are transmitted by optical fibers from the front end electronics co-working with calorimeter and muon detectors, to the Global Trigger of the First Level GLT. The GLT obtains data concerning all events with the frequency of 40 MHz, and reduces them to the level of 100 kHz, with the latency below 4 microseconds. High Level Trigger HLT works on a computer cluster and reduces them to precise reconstruction of particular complete events. Initial reconstruction done by HLT is to choose only the most interesting events, at a rate 300 events per second.

The time schedule of work on the modernization of CMS is precisely described in the document Proposal for Technical Development of CMS [22] and is as follows: LS1 – years 2013-2014: exchange of cable connectors in LHC in order to enable work of the whole complex at 14 GeV; improvement of the beam collimation to enable work with bigger luminosity, 2014-2016: thorough investigations of the machine work at 14 TeV and at modest levels of luminosity; 2017 – LS2: improvement of collimation for bigger luminosity; preparation of the LHC for skew crab-cavities; inclusion of the new Linac 4 to the injector complex; increase of the PS Booster energy to reduce beam emittance; 2018-2020: 14 TeV with maximum luminosity and modernized detectors. After ending of the first phase, there will follow a long period of machine development LS3. The aim of work in phase two (2020-2030) is obtaining of much bigger luminosity up to 5×10^{34}, and annual integrated luminosity of 300fb^{-1}/y.

The machine will change its name to SLHC or HL-LHC. It is predicted that during the period two, the integrated luminosity for the decade of machine exploitation will reach 3000 fb^{-1}. The detectors for this phase have to be essentially rebuilt, including in this the particle tracking system. The detectors have to be ruggedized to much bigger level of ionizing radiation, and be able to register much bigger number of particle and radiation products from the interactions (multiplicity). Listed time schedules and data are flexible and may change together with the development of technology and LHC management decisions. Apart from long shutdowns LSx, there are planned short technical shutdowns, lasting for a few months each and associated with the machine maintenance. There are planned 220 working days for the machine per annum, with physical data acquisition.

Proton bunches are collided in the detector. Nominally every 25 ns, but till now every 50 ns. Each bunch contains over 10^{11} protons. For the luminosity of 10^{34} cm^{-2}s^{-1}, it is necessary that 3000 bunches are circulating in LHC accelerator of 26 km in length. During the bunch crossing there are now 20 proton collisions observed on the average. At the end of phase 1, the number of collisions via accumulation will increase to approximately 40, with increased number of protons in the bunch. Most of these proton interactions are soft or peripheral, not leading to creation of dense states of energy and mass, below the level of weak interactions. Only very rarely are taking place hard collisions with strong interactions between quarks. Weak interactions leave low transverse energy deposits in calorimeters, but strong interactions leave large deposits. This effect is the basis of discrimination. The aim of the CMS trigger is identification and writing/saving such events for further off-line analysis. The detector has to possess strong and pertinent discrimination mechanisms between soft and hard collisions, what is difficult in the conditions of accumulation and overlapping, or when many events take place at the same time, or nearly the same time.

The accumulation effect is much stronger in the conditions of increased luminosity, over the nominal value. This issue is a strong motivation for detector modernization. The accumulation/overlapping may originate from the same bunch crossing, or from the adjacent bunch crossings – predeceasing and next one. In such cases, the data from current bunch crossing is polluted with data from neighboring bunch crossings. This stems from the very small time period between bunch crossings which is only 25 ns. Data pollution may be avoided by enlarging of the detector segmentation, lowering its reaction time, or doing much complex signal analysis disentangling signals overlapping in time. The CMS modernization takes into account all of these possible methods to improve the data quality. Other sources of data accumulation may be particles themselves. Some of these particles, unknown yet, may be very slow or weakly interacting, scattered many times in the detector and leaving energy deposit in active element during the readout window.

Considerable increase in the beam luminosity over the current nominal value, and this is the condition sine qua non of further development of the whole experiment, leads to much worst work conditions of the CMS trigger, and to degradation of information quality about the collisions. The trigger of the first level works with incomplete information about the collision, and at bigger luminosity the data start to overlap from teen or a few tens of interactions. The modernization of muon and hadron calorimetric systems leads to keeping the data processing ability by the first level trigger, via providing it with more data of much higher quality. The HLT does not meet such issue, because its decision is calculated on a computer farm. Accumulation effect may also introduce errors to the data analysis off-line. The interactions are distributed on the length of a few cm along the collision region, in parallel to both beams. Resolution of the tracker along the axis is less than 1 mm. Usually, the tracker links without errors the charged particle tracks from individual and well separated interaction vertexes. In extreme conditions, the tracker efficiency is lowered. The calorimeters do not possess precise directional resolution and are not able to combine neutral particles, which look like energy deposits, with correct interaction vertexes. This may lead to data overlapping from various interactions during a single beam crossing.

Ionizing radiation causes gradual destruction of a detector. This results in the increase of noise level, decrease in the signal response, degradation of resolution and efficiency. The detector under strong radiation may generate false signals as the right ones, which considerably degrades the measurement data quality. This is one of the reasons of the necessity to understand deeply all effects combined with detector degradation under the influence of ionizing radiation. The detector has to work properly up to the maximal value of the TID parameter (total ionizing dose). The modernization takes into account the works on new solutions of sensors, either hardened to ionizing radiation or tolerant for ionizing radiation. The same problem concerns the front end photonics/electronics of the readout channels, directly cooperating with the sensors and usually positioned together, thus, very close to the beam. The current design of CMS considered radiation compromise of the components close to the beam and assumed their minimal destruction during the first exploitation period of the spectrometer's detector. The situation changes, when the beam luminosity is considerably increased, initially two fold, and next even five fold. These changes of the radiation levels jeopardize the components close to the beam, over ten times. The CMS modernization project for components close to the beam has to be completely different from the current one. Before the phase 2, there will be exchanged all the most compromised by the ionizing radiation components like: internal layer of the forward hadron calorimeter HF and internal layer of the pixel detector in the barrel. The latter is positioned only 4 cm from the colliding beams.

There exists a number of radiation sources influencing measurements of the processes in the interaction points. Majority of these sources may be removed by topological or temporal methods. However, it is necessary to understand them correctly. The beam halo is created by particles migrating from the beam and colliding with the pipe, collimators, and in effect generating scattered muons. These muons may be detected as noise in the muon detectors. Next source is beam interaction with the molecules of the residual gas inside the vacuum pipe of the beam. Products of such collision reach detector directly after being produced or indirectly by producing secondary cascades of particles and photons. The next factor is cosmic radiation, which constantly traverses the detector. The cosmic radiation may also hit exactly during the trigger and may be superimposed on the event and be recorded as a part of this event during the bunch crossing. This may happen, especially when the path is close to the just analyzed vertex. Such a case is determined as cosmic mimicry. The next factor is residual radiation, which is generated by radio-nuclides excited in the accelerator components by ionizing radiation. The decay products excited signals in some detectors.

An important modernization factor is dead time reduction in CMS detector. It is time period when there is no activity of the detector despite the fact that the beam in LHC is available. Usually, during this period either the trigger, or data acquisition system, or one of sub-detector is down. The measure of efficient usage of detector is its integrated luminosity. The periods where there is no beam in LHC should be extremely efficiently used for maintaining of the highest possible detector efficiency and availability. In other cases, the reparations should be done efficiently and fast, because the beam time is very expensive. This means the necessity to keep an appropriate rich stock of spare parts and sub assemblies ready to be mounted in the machine, and the dynamic technical groups ready to intervene immediately, to exchange these broken parts, reset or reinstall the software. A part of such dead time reduction system is a distributed diagnostic network with intermediate data readout out of the whole system, in order to prevent breakdowns, localize them, undertake preventive actions which reduce potential outages. Also partial relocation of the electronics/photonics from the compromised places to safe places reduces the number of potential hardware breakdowns. The aim of these collective action to reduce outages is to go below the level of 5% [35].

Characteristic specificity of design of such large machines as LHC accelerator complex with its large detectors CMS and ATLAS is that it lasts well over a decade. Majority of the used technology in currently exploited CMS detector is, in many cases older than 10-15 years. Maintenance of detector and its efficient exploitation depends on the availability of these obsolete spare parts. Modernization relies on such an approach so as to enable exchange used parts for new technologies, which are in certain way compatible (dimension, rates, supplies, interfaces) with the rest of the system. In shorter time perspective, the modernization of the software is considered, but for the hardware 15 years old and older, it is not always possible. Reparations and hardware exchanges in CMS are facilitated by its modular construction.

Experiences gathered during long time construction, exploitation and modernization of the detector results in its deeper understanding and identification of problems not predicted during the original design. Sometimes this leads to the necessity of considerable changes in the detector, so as to increase its discovery potential. Changes of the exploitation parameters of accelerator and detector for more demanding pull behind changes in the hardware an control software. After the 2013-1014 modernization of the CMS, the system designers predict that the discovery potential of the whole accelerator complex, including the CMS, will increase considerably.

V. CMS in Poland

The Warsaw CMS Group, chaired by prof.J.Krolikowski of Warsaw University, Institute of Experimental Physics, with participation of engineers from NCBJ in Świerk, and Warsaw University of Technology, ISE, Faculty of Electronics and Information Technology, has participated since the mid nineties in the design of sub-detectors of the CMS spectrometer [1], [2], [22]–[24]. This Group was responsible for building and commissioning of the Muon Trigger, and its daily maintenance. Now, this Group actively takes part in CMS exploitation and modernization. Modernization includes also work on electronics replacements, new hardware ideas, new software architectures, new procedures, software, firmware, new triggers for potentially unknown particles, but at least partially of expected, and theoretically predicted, properties. During over two decades of work of this Group, more than twenty students have done their engineering theses on CMS related topics. A number of them were the Eng., M.Sc. and Ph.D. students of Warsaw University of Technology. The advantages of participation in the large LHC and CMS projects for the Polish accelerator and HEP electronics communities can not be overestimated. Such immense research infrastructure is unavailable in this country. As a direct result tens of young researchers from Poland got involved in cutting edge technologies and found their professional paths in numerable and leading European and world laboratories.

VI. CONCLUSIONS AND ACKNOWLEDGEMENTS

Particle accelerators, the immense and ultimately complex research ones, are the birthplace of many new technologies and ideas of practical accelerator applications. This concerns also increasingly complex applications of accelerator driven machines where takes place a close synergetic combination of such technologies as superconductivity, nanotechnology, metamaterials, accelerators, plasma, and lasers [37], [38]. Such examples include accelerator and/or laser driven plasma wakes, laser driven acceleration, table top miniature accelerators, etc.

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