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# Photon Physics and Plasma Research
# Photonics Applications and Web Engineering
# WILGA May 2012

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**ABSTRACT**

This paper is the third part (out of five) of the research survey of WILGA Symposium work, May 2012 Edition, concerned with Photon Physics and Plasma Research. It presents a digest of chosen technical work results shown by young researchers from different technical universities from this country during the Jubilee XXXth SPIE-IEEE Wilga 2012, May Edition, symposium on Photonics and Web Engineering. Topical tracks of the symposium embraced, among others, nanomaterials and nanotechnologies for photonics, sensory and nonlinear optical fibers, object oriented design of hardware, photonic metrology, optoelectronics and photonics applications, photonics-electronics co-design, optoelectronic and electronic systems for astronomy and high energy physics experiments, JET tokamak and pi-of-the sky experiments development. The symposium is an annual summary in the development of numerable Ph.D. theses carried out in this country in the area of advanced electronic and photonic systems. It is also a great occasion for SPIE, IEEE, OSA and PSP students to meet together in a large group spanning the whole country with guests from this part of Europe. A digest of Wilga references is presented [1-270]. Wilga Sessions on HEP experiments were organized under the umbrella of the EU FP7 Project EuCARD – European Coordination for Accelerator Research and Development.

Keywords: nanomaterials, optical fibers, optoelectronics, photonics, measurement systems, astronomy, high energy physics experiments

## 1. INTRODUCTION

XXXth Jubilee Symposium of young scientists WILGA 2012 on Photonics and Web Engineering has gathered over 250 participants. There were presented over 200 papers – mainly concerning the realized Ph.D. theses and participation in research projects relevant to the topical area of the meeting. There were also presented a few plenary papers introducing the audience into new research areas of photonics and electronics. The symposium is organized under the auspices of the SPIE – The International Society for Optical Engineering, IEEE (Poland Section and Region 8), Photonics Society of Poland, KEiT PAN, PKOpto SEP and WEiTI PW. The symposium is organized annually by young researchers from the PERG/ELHEP Laboratory of ISE PW with cooperation of SPIE and IEEE Student Branches. Media patronage over the symposium is extended by Elektronika monthly technical magazine, Symposium proceedings are published by Elektronika, IJET – Int. Journal of Electronics and Telecommunications KEiT PAN and Proceedings SPIE. Wilga Symposium is topically associated with the cyclic research meetings on optical fibers and their applications organized in Bialowieza (prof.J.Dorosz, Bialystok Uni. Technology) and Krasnobrod, now Naleczow, (UMCS Univ., and Lublin Univ. Technology, prof.W.Wojcik) every 18 months. Below, there are discussed some presentations from the main of the most interesting sessions or topical tracks of WILGA 2012 Symposium, May Edition. This part 3/5 debates the sessions on Photon Physics and Plasma Research.

## 2. TOPICAL TRACKS OF THE JUBILEE XXXTH WILGA MAY 2012

The topical session and tracks of WILGA 2012 were as follows: nanotechnologies and nanomaterials for optoelectronics and photonics, optical fibers for sensors and all-photonic devices for sensors, active optical fibers, sensors and sensory networks, object oriented design of optoelectronic and photonic hardware, photonics applications, advanced bioelectronics and bioinformatics, co-design of hybrid photonic – electronic systems, computational intelligence in optoelectronics and robotics, development in the wide-angle astronomic observations of the whole sky – pi-of-the-sky project, processing and imaging of multimedia data streams, machine vision, vehicles – quadrocopter and Mars rover, analog transmission systems in noisy conditions with digital reverse transmission channel, optoelectronic and photonic metrology, reconfigurable measurement systems, high performance – low-jitter low-latency transmission systems – White Rabbit, thermonuclear fusion experiments – JET and ITER, research results update from HEP experiments – TOTEM and CMS/LHC in CERN. A number of Wilga sessions concerned applications aspects of photonic and electronic circuits and systems, including in this advanced applications which combine hardware and software. A separate session track was organized by SPIE, IEEE, OSA and PSP - Photonics Society of Poland students for the new students beginning their adventure with the science of photonics and electronics.

## 3. PHOTON PHYSICS
## FREE ELECTRON LASERS AND SYNCHROTRON LIGHT SOURCES

Photon physics concerns the research of the properties of a photon as a boson, their mutual interactions, like gamma-gamma interactions, study of photon structure, virtual photons and interaction with matter at micro and macro scales, photon gas. Matter creation is a process inverse to particle annihilation, analogy to time reversal. Two mass less photons can be converted into two massive particles, like electron-positron pair, because of momentum conservation law. Energy conservation law prompts that the photons must be at least 1.022MeV (it is equivalent to the temperature of $10^{10}$ K), which is soft gamma ray, to create an $e^+$-$e^-$ pair. Creation of proton and antiproton pair requires 1,88GeV which is hard gamma ray (it is equivalent to $10^{13}$K). QUP – quark gluon plasma is created at the energy over 175MeV, or temperature $2*10^{12}$K. Matter creation events and two photon effects take place in ultra-relativistic charged particle accelerator colliders. In these events, the beam of photons is radiated in very narrow cone (the flux is big) along the direction of motion of original particle. Production of baryonic matter out of photon gas requires high photon density and temperature. Above the threshold temperature the bosons and fermions inter-convert freely.

## 4. POLFEL LASER

POLFEL LASER. Polish Free Electron Laser (4$^{th}$ generation light source) is planned in NCBJ Swierk (O.Choluj-Dziewiecka). It will provide coherent EM radiation from a few nm (soft X-rays) to a few hundred nm (THz). The laser is scheduled to work in CW and pulsed regimes. The shortest soft X-ray pulses will be in the fs range. The shortest THz pulses will be in the range of ps. Peak power is around 1GW in the whole range of frequency spectrum. The machine is able to switch to high average power operation in the entire wavelength range. In the latter mode of operation it will be one of the most powerful sources of coherent radiation in this region. The final design predicts the following parameters for POLFEL: source – VUV-FEL, electron beam energy – >800MeV, accelerating field frequency – 1.3 GHz, modes of operation – pulsed and CW, repetition rate – 100 Hz, RF gun – superconducting via photoemission for a photocathode; radiation wavelength <10 nm, peak power – 0,2 GW, pulse energy > 10μJ, pulse width < 10 fs, average power >10W, total length of linac around 300 m. Polfel, typically to other FELs will consist of the following basic infrastructural parts: electron injector, electron accelerator, undulator, optical beam lines and experimental stations. The machine will be build in two stages, The first one is scaled down to one quarter of the above parameters. The linear accelerator of Polfel will be built using TESLA technology, which was used in the linac of FLASH and is currently used in the construction of the European X-ray FEL. TESLA technology is also planned to be used in the future lepton collider for particle physics like the ILC project (International Linear Collider). Polfel undulators will enable generation of light with different states of polarization – linear and circular. Transport of the laser beam is predicted to nuclear reactor Maria for common experiments involving laser and neutron irradiations. Polfes is expected to be open for transnational access programs within the UE collaboration and financing.

Polfel will complement the capabilities of conventional lasers by extending the available generated spectrum. Polfel will provide crosswise and longitudinal coherence light, which is impossible for the synchrotron (3$^{rd}$ generation light source). Polfel will provide higher intensity by several orders of magnitude and pulse duration three orders of magnitude shorter. Polfel will enable the development of fundamental and technological research , in this region, in physics, chemistry, biology, material engineering etc. These experiments to be effective seek for bigger coherence of light (transverse and longitudinal) and shorter light pulses to avoid excessive heating and to make the reactions more adiabatic and bigger intensities to enable deeper effects. Predicted experiments for Polfel will include, but will not be limited to the resarch on: photon physics, properties of light and its interaction with matter, including the highly excited states of matter investigated now in plasma physics and astrophysics; molecular dynamics and transient states in excitations and chemical reactions; the structure of large biological molecules and systems of new organic semiconductor and magnetic materials; surface modification by irradiation, determination of the spectral signatures of materials in different wavelength ranges.

Superconducting RF electron Gun for high average power. FEL Superconducting electron gun for CW operation of superconducting linacs is under design by a collaboration consisting of TJNAF, NCNR, HZB, HZR and DESY

(R.Nietubyc, NCNR, Swierk). The purpose is to build a gun suitable for building of tunable CW free electron laser (high average power FEL) based on superconducting Nb cavities linear accelerator. The work stemmed from plasma physics laboratory and European FP6 project CARE – Coordinated Accelerator Research in Europe. Now the first e-gun is available with lead photocathode. Lat year progress include: e-gun tests in HOBICAT (horizontal bi-cavity test facility), application of new cavity with plug in and inclined back wall, design of new lead deposition system, emittance studies of the new design. The new design use Pb as a superconducting emitter, in a form of lead thin film spot for photocathode (400 nm thickness). Pb is deposited in UHV arc vacuum system with droplets filtering and adhesion optimization. Ions emission is from a small explosive spot. This spot is a local explosion decompression and ejection of neutrals and ions. High ions fraction enables a coupling to electrons and driving with the H field. The deposited Pb spot was annealed with a laser beam for better quantum efficiency QE=$3.3*10^{-3}$. Pb is a superconductor of the first type with the following parameters: critical field $H_c$=80 mT, critical temperature $T_c$=7,2 K, work function $W_e$=3,95 eV, quantum efficiency $10^{-5}$ – $10^{-2}$ in the range of photon energies 4 eV – 7 eV. Fully superconducting injector avoids normal conducting materials in the cavity, keeps simplicity similar to Nb back wall gun, leads to reasonable quantum efficiencies QE. To facilitate transport of samples between the laboratories the cavity was drilled and provided with a plug. Only the plug was coated with Pb spot. Baseline tests for cavity with and without a plug give the same results for the field maximum of around 53-54 MV/m. With Pb coated plug DESY II lab demonstrated reasonable finesse of $Q_o>4*10^{-9}$ up to 33 MV/m. With the tests at BESSY the experience is accumulated with the photocathode and with the LLRF cold tuner. Back wall symmetrical inclination of $8^o$ gives improvement in the slice emittance. The aim are the following parameters of the SC injector: 1nC and 1 μm*rad at 50 Hz; QE>$2*10^{-3}$ at 213 nm and QE>$2*10^{-5}$ at 258 nm; $E_{peak}$>60 $MVm^{-1}$ at $Q_o>10^{10}$ with Pb spot.

Electron beam stabilization in free electron laser

The free electron laser to shine a stable and coherent beam requires an electron beam of very high quality. A research on digital feedback system for direct electron beam parameters stabilization is carried on by the LLRF team of the NCBJ, Swierk (J.Szewinski) in cooperation with DESY. Classical LLRF feedback system stabilizes only the amplitude and phase of the high power RF field. More stable RF field does not directly cause the beam to be more stable above some stability threshold. Higher gain value in the feedback loop amplifies the noise, which degrades the beam. Beam stability in terms of dE/E [%] i.e. energy dispersion, as a function of feedback loop gain, has an optimal value for gain coefficients around 10 – 20. The basis of energy feedback of the electron bunch is similar to the action done by a prism in optics. Dipole magnets act as prisms. Energy dispersion of electrons in a single bunch is changed to their different path lengths. Red electrons (less energetic) are lagging behind the blue electrons due to dispersion. The bunch compressor equalizes the delays by delaying blue ones and speeding the red ones. The bunch has much bigger quality after the compressor to give better photon beam in the undulator. Arrival time of electron bunch and its length is measured by Bunch Arrival Time Monitor BAM. BAM is a photonic device where amplitude of laser pulses generated by the reference synchronization system (MLO) is modulated in electo optic modulator EOM by the arrival time of the travelling bunch. The amplitude of the bunch which arrives in due time is the same as the amplitude of the unmodulated laser pulses, due to zero-crossing. The signal from photo diode is sampled using two ADCs, with clock signal shifted in phase. Bunch compression is measured by the pyro-electric detector PYRO. PYRO is located after the bunch compressor and the bunch comes through it. Amplitude of generated electric pulse is proportional to the compression rate of the bunch. The system was installed at FLASH laser.

LLRF system for POLFEL laser

POLFEL accelerator, to be built at the NCBJ in Swierk, is expected to have the following parameters, which are important for the LLRF (low level RF distributed control and measurement system): operation modes are either CW or long pulses t>100ms; superconducting electron source; superconducting 1,3GHz accelerating structures of 4GLS or TESLA type criomodules; IOT – inductive output tube as an RF amplifier. Digital LLRF feedback system is predicted with I-Q field detection. Due to difficulties in field phase measurements, better results can be achieved by detection of In-phase and Quadrature components of the cavity signal. The I-=Q may be detected digitally. Sampling with frequency four times higher than the IF (intermediate frequency – after down-conversion) gives the I and Q values directly. Analog RF modulation is simple, there are ready to use vector modulator integrated circuits, with mixer and phase shifters in a single chip. In a digital RF modulation one DAC per channel is saved. However, RF analog part is more complex with needed band pass filters. Two control systems are options: GDR – generator driven resonator and SEL – self excited loop. GDR features are: frequency is fixed, better for pulsed operation if the detuning is small, fast predictable rise time, better to perform vector sum control. SEL features are: tracks the resonant frequency, better for CW operation, start up may be slow, better for single cavity control. The choice for POLFEL is (J.Szewinski, NCBJ, Swierk): feedback loop – digital feedback based on vector sum with P and I gains; field detection – digital I-Q demodulation; analog RF modulation; control method – SEL with cavity detuning compensation, optional GDR mode. The hardware for POLFEL LLRF may base on the proven SIMCON VME technology. The control environment would be EPICS.

## 5. SOLARIS SYNCHROTRON

SOLARIS SYNCHROTRON. Jagiellonian University in Krakow is building synchrotron based national light source (P.Tracz, UJ, Krakow, National Synchrotron Radiation Centre). Diagram of the source is presented in fig. It consists of linear injector (e-gun and liniac workin at 3GHz frequency), storage ring and beam lines. The first beam line U1 is predicted for soft X-ray spectroscopy. The photon energy range is 200eV – 1,5 keV. Radiation source is undulator. The used experimental techniques are: PES – photoelectron emission spectroscopy, XAS – X-ray absorption spectroscopy, and RIXS – resonant inelastic X-ray scattering.

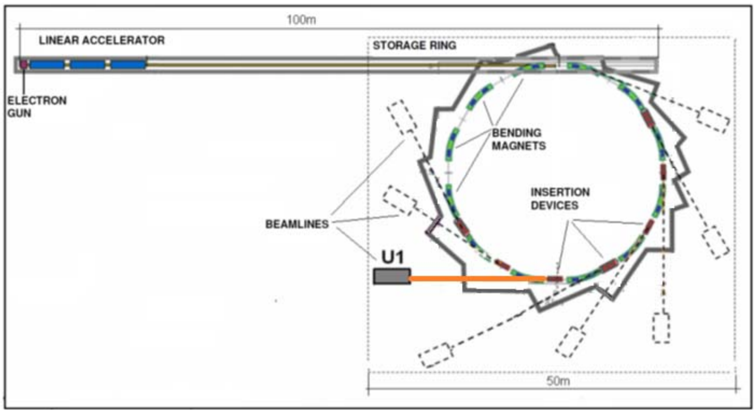


Fig. 1. Schematic view of the Solaris Synchrotron in Krakow.

The storage ring parameters are: 1,5 GeV energy, 500 mA current, circumference 96m, horizontal emittance around 6 nm rad, coupling 1%, overall lifetime 13h. Compact lattice in the storage ring consists of 12 double bend achromats (DBA) cells, 12*3,5 m long straight sections, out of which 10 are for insertion devices. The magnets have combined functions for compact optics and include gradient dipoles and quads with integrated sixtupole.

Solaris synchrotron uses Tango Distributed Control Environment (P.Goryl, UJ, Krakow). Tango is for integration of equipment; providing, collecting and presenting data; logging data for future reference; accessing hardware in a standard way; managing the control system; configuring fast control loops like setting parameters and setpoints. Tango is not suitable to do fast feedback and is not real time by itself. Tango uses tools: Jive – device configuration, Astor – system deploymenyt and management, Pogo – code generation, Sardana – scanning and macro running, JDraw – rapid GUI development, Taurus Library, ATK, and other. TANGO kernel contains API and TCP/IP CORBA and is an interface between configuration, GUI application, archive and devices. Tango is used by many synchrotron labs: ALBA. DESY, SOLEIL, ELETTRA, MAX-Lab, FN HML FRM II, and ESRF.

## 6. THERMONUCLEAR TECHNOLOGY AND PLASMA RESEARCH

Ultimately hot plasma is researched, also using photonic methods, for a few different purposes, including: properties of distinct state of matter, space and astronomical object entity, constituent of solar atmosphere, an environment of thermonuclear fusion. The latter area is combined with the trials to build a thermonuclear power plant in the future. Depending on the financing, such a plant may be built during the next five decades or so. The way to a thermonuclear plant utility leads via the research on the development of energy efficient tokamaks and stellarators.

JET, a precursor of ITER. JET – Joint European Torus, realized as a tokamak,  is an experiment which is expected to expand into ITER and then into thermonuclear energy utility. A lot of photonics and electronics equipment is realized around this experiment with the participation of teams from IFPiLM (Institute of Plasma Physics and Laser Microfusion in Warsaw, EURATOM), in cooperation with NCBJ Świerk, WU and WUT Universities. JET is realized inside the EFDA (European Fusion Development Agreement). JET wall materials are beryllium and tungsten. It features the in-vessel toroidal magnetic field up to 4T. The circular plasma current is over 3MA. The D-shape plasma current is around 5MW. Lifetime of the plasma is 20-60s. Auxiliary heating comes from NBI – up to 34 MW and ion cyclotron resonance heating up to 10 MW. A typical tokamak plasma consists mainly of electrons and deuterons together with a small concentration of impurities. These impurities come mainly from interaction between the plasma and the vessel wall. Once impurities enter the plasma they become highly ionized and radiate energy thus cooling the plasma. The radiation can be lost by Bremsstrahlung and characteristic x-ray radiation. The major JET tokamak chamber is densely surrounded by diagnostics. Our team works on KX1 X-ray crystal diagnostic spectrometer. The larger is the spectrometer the better is the energy resolution $\lambda/d\lambda=(R/dx)\tan\theta$. The spectrometer is opearated in so-called Johann geometry with the Rowland circle radius of about 12m giving an excellent resolution $\lambda/d\lambda=2x10^4$. The plasma rotation velocity is around 10km/s. The soft X-ray photons (2 – 12 keV, which is the measurement range) are reflected by a germanium crystal (of 220 cut and of crystalline constant 4Å) cylindrically bent with a radius of curvature of around 25m. The line of sight of the X-ray crystal spectrometer diagnostic is full cross section of the plasma channel. The main task addressed by the high resolution X-ray diagnostic (KX1) is probing the 100 million degree core of the JET plasma. The system is looking for the contamination of the plasma by tungsten (and Ni) released from the newly installed ITER-like wall. The high-resolution X-ray crystal spectrometer is expected to measure: impurity concentration, ion temperature and toroidal rotation velocity (rotation frequency 25 – 110 krad/s). The measurements are based on the $Ni^{+26}$ resonance line at around 7.81keV, $W^{+46}$ line at 2.4keV, and continuum radiation. Once tungsten erodes from surfaces and penetrates the high temperature plasma a plentitude of tungsten charge states may be produced across the confined plasma profile. For JET plsma conditions, the expected charge-state distribution spread around Ni-like $W^{+46}$ in the hot core, requiring sophisticated and specialized detection and analysis systems for line identification (from $W^{+44}$ to $W^{+50}$). In order to measure the tungsten impurity concentration in the new ITER-like JET configuration, the upgraded spectrometer will operate with an additional quartz crystal (of cut 1011 and crystal constant 2d=6,7Å) mounted in 2009 and sharing the same 266mm diameter beamline. The quartz crystals are used for the reflection of low energy X-ray photons emitted by $W^{+46}$ at 2,4 keV. The higher energy range of the $W^{+46}$ spectra can be measured by means of the Si crystal which has been provided together with a new quartz crystal and can be curved and installed at a later time. The measurements are based on Bragg spectroscopy: $n\lambda=2d\sin\theta$, $E=hc/n\lambda$, for the n-th order of reflection and $SiO_2$ crystal. E(n=1)=[2,3; 2,5] keV; E(n=2)=[4,6; 5,0] kev; E(n=3)=[6,9; 7,5] keV. With usual positive sensitive detectors it is not possible to distinguish between different orders of reflection. Position sensitive detectors with energy resolution allow us to distinguish between different orders of reflection. By application of the distinguishing procedures the measurement system provides: more data; pure X-ray spectra for $W^{+46}$; more precise information on tungsten contamination, ion temperature and rotation velocity of the JET plasma; Z effective information from continuum; ITER-relevant diagnostic system.

Gas Electron Multiplier GEM plasma detector system

The plasma diagnostic system researched by a team from IFPILM (IPPLM), UW and WUT, uses GEM (gas electron multiplier) detectors. They have to be precisely calibrated. The particular structure of choice is T-GEM (triple GEM) of optimal voltage and space distribution. The size of gas detector is $100x200mm^2$. Hole sizes are 70µm, whiel hole separation is 140µm. The filling gas is: Ar70%+$CO_2$30% flowing at a rate around 30ml/min. T-GEM structure with charge gain consists of transparent cathode and a window permeable for hν photons, three layers of GEM and conducting pixelized or stripped anode. The measurement is energy and position resolved. The tested windows for soft x-ray photons were: 12µm mylar with 0,2µm Al, or 5µm W, 12µm Ni. Detectio efficiency was measured for various windows. A GEM detector is the first module of the measurement chain for X-ray detection of tokamak plasma. The space charges which are collected on the strip plane generate current anode signals for 256 channels. Multichannel system should be calibrated to uniform all channel characteristics. The succession of signal generation in a GEM is: photon conversion to electron, avalanche multiplication of charge, drift and diffusion of electron via the induction gap, discharge and generation of the anode signal. GEM detectors are calibrated using signal from $Fe^{55}$. The electronics is calibrated for all 256 channels to equalize the individual channel amplification. Calibration charge type includes cluster and strip. Calibration parameter type includes gain charge and mean charge. A general assumption for calibration procedure is as follows: for regular charge distribution a parameter value for each channel is equal to the mean value for each channel. Thus, the calibration coefficient is equal to the inverse of normalized parameter. Fast electronics based on FPGA circuits is used for energy estimation and creation of real time histograms.

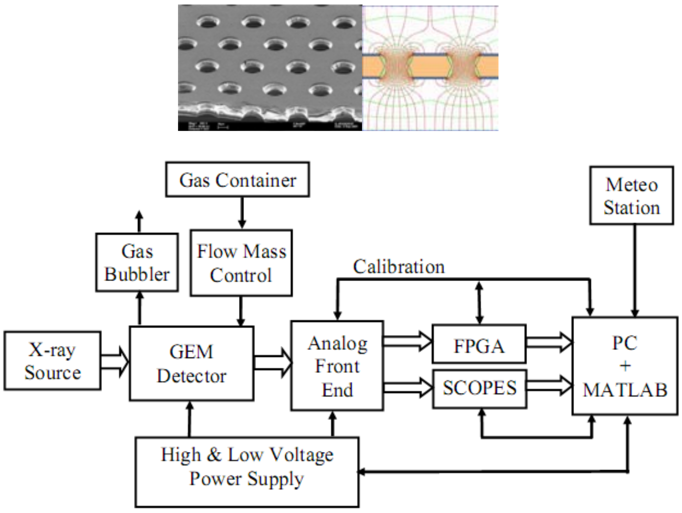


Fig.2. GEM structure, experimental set-up for characterization of T-GEM detectors of soft X-rays (IPPLM Euratom)

Plasma Focus PF-1000 experiment
A new generation of data acquisition system for the plasma fusion experiment PF-1000 is under preparation. The experiment is located at the Institute of Plasma Physics and Laser Microfusion in Warsaw. The plasma focus device is a compact powerful pulsed source of intense radiation including neutrons, X-rays, optical and particle beams. The radiated spectrum depends on the temperature and the used sample material. The amount of stored energy in the discharge capacitors exciting the device is over 1MJ. The experiment is a convenient local test bed for some measurement, diagnostics, procedures and hardware designed finally for implementation at the European JET and ITER experiments. PF-1000 is used to diagnose plasma dynamics and stability for future prototypes of specific high temperature plasma reactors. Plasma focus device consists of anode and cathode separated by an insulator. The hermetic chamber is filled with deuterium under pressure optimized for particular experiment. The collector is a part of the power supply for PF – which are high power capacitor banks. The plasma creation event is triggered by a laser pigtailed with an optical fiber. Now, the experiment features a number of old analog diagnostic solutions, over 10 of them, which are successively replaced by modern FPGA-DSP-CPU and photonics sensing and transmission based multichannel systems.

## 7. OPEN HARDWARE REPOSITORY

A topical track on photonic Internet consisted of papers on photonic LANs, trunk optical lines of ultimate throughput, new optical non-blocking codes, developments in all-optical architectures. One of the concepts, not yet fully confirmed, is application of organic photonics to build the framework of the variety of access networks to the terabit photonic transport network. Micro-structured plastic optical fibers - mPOF are under intense studies, also in this country. They are cheap and are user scalable, even in singlemode version.

Open hardware repositories are increasingly frequently supported by large research organizations financed from public funds. The process is similar to the analogous actions undertaken in the area of publications of the research results. Contemporary electronics and photonics contains now more IP intellectual property than ever before. And this effort to generate this IP is financed publically. One of the current development trends in the photonic and electronic functional systems for research and/or industrial applications relies on very low cost application tailored solutions, making the hardware virtual and enabling All designs in open hardware repositories. This may change considerably the approach to photonics and electronics design, usage and marketing. This situation may be compared to the situation on the open publishing market, where some big and influential i.e. leading research institutions make the results of their work open access rather than publishing them in high-rank closed archival journals. The designs from the open access repositories may be used by manufacturers freely and after fabrication marketed of their own. An absolute leader in this approach is CERN, but there are more and more followers. Here we present a few open access hardware designs origination in the PERG/ELHEP and other associated Research Groups. The designs are destined for HEP experiments, photon physics research, astronomical and space equipment, plasma research, biomedical engineering applications, etc (dr W.Zabolotny, dr G.Kasprowicz).

Features of open access hardware

Most FPGA based systems, especially these used for data acquisition functions use a bus (typically VME bus, but more modern ones use ATCA bus) to provide access to internal registers. The VME or similar solutions require to use expensive components like VME crates, VME controller, etc. If we need to debug the VME board more thoroughly, with a scope, we need yet another VME extended board, which still does no allow easy access to the vertically positioned board. A question arises: can we do it simpler? The design goals are to do it simpler and cheaper. Low cost interface is very convenient, which could be easily connected to the development machine, which usually is a laptop. Such solution may also be used in the final system. The outside PC is connected with the embedded PC. This solution provides easy development of FPGA based system via the JTAG access for configuration and debugging. It gives also a convenient possibility to work with the board alone, completely without the crate. A typical development machine should contain several basic and universal interfaces and make them available for the system design purposes.

Common platform – Ethernet, Linux, FPGA

The Ethernet is usually needed to connect to the local network/Internet. Use of typical TCP/IP protocols would require significant resources in the interface, but the use of nonstandard protocols may cause software compatibility issues. The PCIe interface is available in ExpressCard slot. Only one board may be connected. The usage of hardware PCIe bridge in the interface is necessary, and only short cables may be used. The advantage of using the USB is that multiple boards may be connected via a hub, the cables are cheap and it seems to be the optimal solution. How to connect an arbitrary development board to the USB? In the case of direct connection – a PHY chip is required, where a relatively complicated software support is needed for USB compatibility includig enumeration. A connection via USB bridge is significantly cheaper with the most popular USB bridges like Cypress, FX2LP, FTDI. The functionalities which are offered by FTDI FT2232H, including multiple operating modes, are: USB to FIFO transfer data rate practically up to 8MB/s, single channel synchronous FIFO mode for transfers practically up to 30MB/s, CPU style FIFO interface mode simplifies CPU interface design, Dual multi-protocol synchronous serial engine (MPSSE) is used to simplify synchronous serial protocol design like USB to JTAG, I2C, SPI or bit-bang. The following selection of modes in FT2232H is available: local bus emulation (the slowest solution), parallel FIFO mode (the fastest solution, however single channel), asynchronous FIFO where the second channel may be used as JTAG, ChipScope, Impact. System architecture is as follows: USB, FT2232H, channels A and B, FPGA (and JTAG access), local bus and fast JTAG. Commands and data are transferred through FIFO, therefore encapsulation technique is used. Interfacing with the development machine includes several ways: directly from the Python scripts, using the module of pyusb; from the C code using the library libusb; from Matlab scripts via TCP/IP connection using the server implemented in C with libusb. The described interface was successfully used in development of control and readout system for GEM detector for KX1 detector in JET experiment. In the final system, the interface is connected to the USB port of embedded PC and is used to provide slow control, diagnostic, configuration functionalities supporting the main PCIe based data transmission channel. Now the solution works as a low price efficient way to control the local bus in the FPGA based systems. Usage of synchronous FIFO improves the transmission parameters of the interface at a cost of slow JTAG channel. Then, ChipScope may be used for debugging. Usage of USB 3 bridge is expected to improve all system parameters.

Hardware – software co design

Hardware – software co-design paradigm is one of the issues of contemporary functional systems. Now the advanced photonic and electronic systems integrate heavily hardware and software layers. Hardware and software are configurable. Combination of hardware and software layers requires proper communication between them. Prototyping of a new photonic and/or electronic system requires significant redesign stages. Multiple repetitions of the redesign stages are costly and time consuming unless the hardware and software are not widely configurable. Software components of the system, including device drivers, user space application, etc, may be developed in parallel as soon as hardware specification is ready. Such approach may expose some problems related to the hardware design. These issues appear during attempts to write the code, when a skilful programmer detects obvious inefficiencies. Thus, a full testing of the system is not possible until the hardware is ready. At the early stage of development it may be useful to verify functionality of the design using Virtual Hardware (VH). VH environment is used to develop ne software, like emulators and simulators, including mobile phones. Typical simulators emulate standard platforms. Description of digital hardware in HDL, including Verilog or VHDL, makes the hardware simulable. Efficient simulators for this purpose include: Modelsim, GHDL, Icarus Verilog. It is inefficient to emulate the whole VHDL model of the system (including CPU, program, data memory). An interesting solution is a behavioral, optimized for simulation, model of the whole PC system (or only a CPU). Such a model may be run in the hardware simulator. Thus, the task is software co-simulation with hardware simulators. An effective approach, for simple programs, is when the tested software communicates with the simulated hardware, a if it were with the real one. The methods include: simulated bus controller allows Python programs to access local bus in FPGA; simulated UART allows the simulated hardware to exchange data with Linux pseudoterminal pts device, etc. Another method bases on software simulator emulating PC system and hardware simulator emulating real hardware, which is called HW/SE cosimulation, where precise time synchronization is required for both systems. Two way system response is possible. Hardware responds to requests from software simulator. Hardware simulation is then run for time periods between interaction with hardware. Hardware also reacts to external stimuli and generates asynchronous events like interrupts for the PC simulated with software simulator. Time synchronization in the universal case requires full integration of the HW simulator kernel with the SW simulator. The HW and SW simulators should be tightly coupled like in QUEMU System C by GreenSocs. Another solution is OVP (open virtual platform). QUEMU is a simulator enabling additions of own HW, like x86 32 and 64bit, ARM, PPC, MIPS and other ones. QUEMU was used successfully for development of software part of the GEM readout system, for testing of USB based communication and of network data distribution. Some models of own HW were implemented including: high speed ADC, AES256 cryptographic accelerator, experimental network adapter supporting BM DMA and SG buffers. VH may be a tool allowing to decrease gravely time and cost of HW SW co-development. However, no ideal solution as yet exist. Appropriate tool must be carefully chosen for particular application. QUEMU may be a good solution if the HW can be described in C. API is sparsely documented and often changing.

Industrial standards and FMC carrier based systems
A number of various hardware designs and hardware – software co-designs are under preparation to be available in the open hardware repository (PERG/ELHEP Research Group at ISE PW). These include: Low cost FMC carrier board with embedded ARM processor and fast optical I/O, Linux running module on Power PC embedded processor with FPGA interface, Multichannel pico-ammeter FMC module, group repository environment, combustion engine parameters recorder, universal image acquisition system on FPGA, acceleration artificial intelligence algorithms with reconfigurable computers, handheld distributed measurement system, multichannel digital oscilloscope for universal measuring platform. A number of these design use FMC carrier with ARM processor and Linux OS.

The main idea is to build an open source platform basing on FMC standard, for computing and measurement applications. The existing competing platforms are as follows and have some drawbacks:
- CPCI and VME – they have unpredictable latency and low bandwidth;
- uTCA, ATCA – high cost, expensive controller, complicated packet based interfaces, good for computing data and communication, not really suitable for low latency data processing and fast control systems;

On the other hand the FMC standard (ANSI for FPGA Mezzanine card) maximizes data throughput, minimizes latency, reduces FPGA design complexity, minimizes system costs, reduces system overheads. FMC standard supports VME, VPX, VPX REDI, CompactPCI Express. Cooperates with ATCA, AMC, PCI and PCI carriers, PXI and PXI express carriers. A family of high speed connectors for IO mezzanine modules are available. It supports up to 10Gb/s transmission, and single ended and differential signaling up to 2Gb/s. Has numerous IOs available. The electrical connectivity of the IO mezzanine module is provided by high speed connector which supports a wide range of signaling standards, supports system configurability of IO functionality, provided FPGA intimacy. The mechanical properties of the IO mezzanine module are: minimal size, scalable from low end to high performance applications, has conduction and ruggedized support. The following questions are addressed during the design (G.Kasprowicz, PERG Group, ISE PW). How to enable low latency data transfer between FMC modules, what is critical for DSP based on correlation. How to obtain low cost, which is essential for multichannel systems. How to obtain high speed serial transfer capability. How to obtain simplicity of parallel IO modules. How to obtain non-limited scalability. And finally, how to obtain it all in a single design.

Parameters of the FMC carrier. FMC carrier was designed featuring: 36xFMC sockets, PCIe Gen@ (5Gb/s), low jitter clock distribution network, White Rabbit IEEE 1588 enabled, standard main board with 4X86 cores, maximum 46

FPGA chips. The specific FMC carrier features are: modularity, up to 18 modules in 2U 19" case, not defined logical interface, just 38 bidir LVDS lines, up to 24Gb/s; any type of interface is possible to implement; star type connection, deterministic behavior; latencies may be as low as a few ns; low cost measurement modules; they may be even passive; central processing unit with storage; PCIe Gen II 5Gb/s non blocking switch; centralized low jitter clock management; centralized FPGA configuration; I2C, SPI, JTAG management interfaces; intelligent module detection; dedicated FMC sockets for DSP accelerators or 10Gbit/s connection; embedded strong multi-core x86 with Linux. Recently developed FMS modules embraced, for example, 4 x 125 Mhz oscilloscope featuring 16 x ADC + SDRAM + FPGA; quad time to digital converter and fine delay lines, featuring 8 core DSP + FPGA. The computing and DSP power of FMC system is: 10XFPGA 23k slices, 147k logic cells, 180DSP slices, maximum 500MHz each + 16x SDRAM 1Gb; plus 34xFPGA each of FMC; two dedicated FMC slots for 8 core FP DSP, 2GbEth ports' 21 port PCIe switch connecting FPGAs, FMCs and Power PC. The FMC carrier – ITX main board features: ASUS 2 core x86, FPU and network accelerator; PCIe 2x4 lane GEN2 switch, 1xGb Thernet interface, USB local bus converter FPC' Mini-ITX format. The exemplary applications of the FMC system include:

- 256 channel, 100MS/s data acquisition system each with online processing for HEP with aggregated 256Gb/s of the on line data processing throughput;
- 2048 channel slow speed DAQ;
- Low power computing platform – 16 modules equipped with 8 quad core ARM processors running at 1GHz; up to 1TIPS of peak computing power available in PC-size box, with 4k Euro budget, consuming 150W of supply power;
- 16 ADC modules plus 16 quad DSP modules for advanced radar applications;

The new hardware solution of the system features: is based on recent large Kintex 7 FPGA circuits, what results in less chips onboard, less connectivity problems and resources used for communication; 6 carrier slots; up to 12 HPC dual with FMCs addressing the clock issues; 4U case with improved cooling; fully symmetrical architecture with no dedicated controller FPGA; each carrier may perform controller function; backplane with PCIe switch and cross-point 48 channel switch up to 5Gb/s; use of standard ITX PC board; USB and small FPGA for JTAG and slow control; optimized for HEP applications like: LLRF system for accelerators and free electron lasers, in particle detectors and BPM – beam position measurements. The project is fully opened and done in cooperation with the Brazilian LNLS laboratory.

Real time Embedded Systems for DAQ. A research work on real-time performance of Linux based embedded system is realized by a team in the Institute of Aviation in Warsaw (R.Rybaniec). The aim of the work are cheap airborne applications. It is to be noted however, that Linux is not inherently a real time system. Real time operation systems, software environments or isolated programs, algorithms and procedures must guarantee a deterministic response within very strict time constraints. There is also a number of terms around this notion like soft-real-time, near-real-time and finally hard-real-time (or real-real-time). In the soft-real time system, after crossing the deadline, usefulness of the system response is degraded but still may be of attention. In the hard-real-time, missing deadline means full system failure, with no exception. Real time means fully deterministic, synchronous. Parameters of real-time systems are latency and jitter. Latency is time period between an event occurring in the system and end of processing of this event by this system. Jitter is a variation in periodic timing in the system. Jitter should be as small as possible in the real time systems as it introduces uncertainty. Linux is popularly used in embedded systems. Embedded systems are popularly used in construction of real time systems. Linux is used in embedded systems because: is a versatile, thoroughly checked, and very good application base, is popular and used by large community also professional, is characterized by out of the box operation, free of charge and open source with ease of configuration. Linux in not a real time system, even not a near real time. It is a general purpose OS sharing resources in a "fair" manner, optimizing resources for maximal throughput and maximum average performance. Maximum, but set, latency is never guaranteed. It is a typical best effort type system. But, using special methods like nano-kernel approach and real time shells, it may be turned to near real time. There are a lot of purposes to do this. Such an open source near real time OS may service demanding data acquisition systems for airborne applications like for gyrocrafts. Such systems base on cheap PCBs containing ARM processors and cooperating with numerable RF and photonic teledetection sensors. Linux Xenomai uses nano-kernel approach ith domain concepts, kernel is low priority domain and fully preemptive. Improved preemptiveness of Linux Preempt_RT kernel relies on that the preemption is active in kernel mode and also critical section are preemptive. IRQ service routines are threading with preemption in ISR with priorities. Both Xenomai and Preempt_RT approaches significantly improve real-time performance of Linux. Xenomai shows better performance while in Preempt_RT less changes are needed. Xenomai enabled kernel proves to work well in data acquisition system (SPI 400 Hz).

Open hardware projects

The projects listed below are currently under realization in the PERG/ELHEP ISE WUT Research Group. Most of the results are intended to be available in the open hardware repository.

- Implementation of PCI Express bus communication for FPGA based data acquisition systems: communications core is based on mixed Verilog/VHDL; Linux OS and device drivers;
- Multisensor, low-cost measurement LAN for use in personal cars, cooperation with temperature, humidity, vibration and acceleration low power sensors;
- Local positioning system for use inside buildings, to replace lot of RFID readers and solve the screening effect for GPS, based on White Rabbit, low-cost realized on Fpga, method based on triangulation and trilateration;
- Mobile measurement system based on a smart cell phone (iOS and Android) with capacity to read numerable distributed sensors located at the user promontories, and with user friendly integrated and interactive display;
- Measuring system for hybrid power plants including combination of various generators: wind and solar;
- Detection system for car driver physical status including: closed eyes, movements, some physiological parameters, tracking drivers face, anti sleep alarms, lane departure;
- Artistic design table controller using display screen modules, organization of the array of touch display screens;
- Mult-sensor ultimately low-power point with energy harvesting;
- Control system for omni-directional mobile robot – wheeled and quadrocopter;
- Real time omnidirectional camera with parallax mitigation techniques and image alignment and stitching;
- Interactive whiteboard with laser pointer and CMOS camera, standalone device;

Multichannel ultrasonic/photonic data acquisition system;

## 8. PHOTONICS AND ELECTRONICS APPLICATIONS

A number of session concerning the applications of photonic and electronic circuits and systems included work on particular engineering and technical solutions for various fields like: car industry, airborne industry, robotics, management of the road traffic, remote control methods for utility systems via the Internet, audio and video techniques, biomedicine, safety techniques, home appliances. A group of work concerned the development of a mobile platform for a universal robot equipped with advanced devices like cameras, grippers, Other group concerned the development of distributed measurement networks for minimum energy service of the network of self configuring environmental sensors. These sensors are expected to use a lot of energy harvesting.

## 9. CONCLUSIONS AND WILGA 2013

The WILGA May 2012 meeting was a fruitful event gathering young researchers from the fields of photonics and electronics systems. The 2013 Symposia on Photonics and Internet Engineering will be held on 24-27 January 2013 at WEiTI PW building in Warsaw and on 27.05 – 02.06 2013 in Wilga Resort by PW. The organizers warmly invite young researchers to present their work. The WILGA Symposium web page is under the address: http://wilga.ise.pw.edu.pl.

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## REFERENCES

WILGA Symposium has produced more than 2500 articles, out of which over 1000 were published in Proc.SPIE. Several hundred of them are associated with the research activities of the PERG/ELHEP Research Group at ISE WUT. The Group is an initiator and major organizer of the WILGA Symposia. The paper was prepared using the invited and contributed presentations debated during Wilga 2012 May Edition. Some fragments of the text were quoted from these presentations and from session discussions.

[1] R.Romaniuk, Manufacturing and characterization of ring-index optical fibers, Optica Applicata 31 (2), pp.425-444 (2001)

[2] R.Romaniuk, et al., Multicore single-mode soft-glass optical fibers, Optica Applicata 29 (1), pp.15-49 (1999)

[3] J.Dorosz, R.Romaniuk, Fiber Optics Department of Biaglass Co. twenty years of research activities, Optica Applicata 28 (4), pp. 267-291 (1998)

[4] J.Dorosz, R.S.Romaniuk., Multicrucible technology of tailored optical fibres, Optica Applicata 28 (4), pp.293-322 (1998)

[5] R.Romaniuk, Tensile strength of tailored optical fibres, Opto-electronics Review 8 (2), pp.101-116 (2000)

[6] R.Romaniuk, Capillary optical fiber – design, fabrication, characterization and application, Bulletin of the Polish Academy of Sciences: Technical Sciences 56 (2), pp.87-102 (2008)

[7] R. Romaniuk, et al., Optical network and fpga/dsp based control system for free electon laser, Bulletin of the Polish Academy of Sciences: Technical Sciences 53 (2), pp.123-138 (2005)

[8] A.Dybko, et al., Assessment of water quality based on multiparmeter fiber optic probe, Sensors and Actuators, B: Chemical, .51 (1-3), pp. 208-213 (1998)
[9] A.Dybko, et al., Efficient reagent immobilization procedure for ion-sensitive optomembranes, Sensors and Actuators, B: Chemical, 39 (1-3), pp.207-211 (1997)
[10] A.Dybko, et al., Applications of optical fibres in oxidation-reduction titrations, Sensors and Actuators, B: Chemical, 29 (1-3), pp.374-377 (1995)
[11] A.Dybko, et al., Polymer track membranes as a trap support for reagent in fiber optic sensors, Journal of Applied Polymer Sciences, 59 (4), pp.719-723 (1996)
[12] B.Mukherjee, et al., Application of low-cost Gallium Arsenide light-mitting-diodes as kerma dosemeter and fluence monitor for high-energy neutrons, Radiation Protection Dosimetry, 126 (1-4), pp.256-260 (2007)
[13] R.Romaniuk, et al., Metrological aspects of accelerator technology and high energy physics experiments, Measurement Science and Technology, 18 (8), art.no.E01 (2008)
[14] P.Fąfara, et al., FPGA-based implementation of a cavity field controller for FLASH and X-FEL, Measurement Science and Technology, 18 (8), pp.2365-2371 (2008)
[15] A.Burd, et al., Pi of the sky – all-sky, real-time search for fast optical transients, New Astronomy, 10 (5), pp.409-416 (2005)
[16] A.Burd, et al., ‘Pi of the sky’ – automated search for fast optical transients over the whole sky, Astronomische Nachrichten, 325 (6-8), p.674 (2004)
[17] W.Ackerman, et al., Operation of a free-electron laser from the extreme ultraviolet to the water window, Nature Photonics, 1 (6), pp.336-342 (2007)
[18] T.Czarski, et al., Superconducting cavity driving with fpga controller, Nuclear Instruments and Methods in Physics Research A, 568 (2), pp.854-862 (2006)
[19] T.Czarski, et al., TESLA cavity modeling and digital implementation in fpga technology for control system development, Nuclear Instruments and Methods in Physics Research A, 556 (2), pp.565-576 (2006)
[20] T.Czarski, et al., Cavity parameters identification for TESLA control system development, Nuclear Instruments and Methods in Physics Research A, 548 (3), pp.283-297 (2005)
[21] R.S.Romaniuk. Petabit photonic internet, Photonics Letters of Poland, 3 (2), pp.91-93 (2011)
[22] P.Obroślak, et al., Digital techniques for noise reduction in ccd detectors, Photonics Letters of Poland, 2 (3), pp.134-136 (2010)
[23] R.Romaniuk, Wilga photonics and web engineering 2010, Photonics Letters of Poland, 2 (2), pp.55-57 (2010)
[24] R.Romaniuk, Geometry design in refractive capillary optical fibers, Photonics Letters of Poland, 2 (2), pp.64-66 (2010)
[25] R.Romaniuk, Modal structure design in refractive capillary optical fibers, Photonics Letters of Poland, 2 (1), pp.22-24 (2010)
[26] R.Romaniuk, ‘The Photonics Letter of Poland’ A new peer-reviewed internet publication of the Photonics Society of Poland, Photonics Letters of Poland, 1 (1), pp.1-3 (2009)
[27] G.Kasprowicz, et al., CCD detectors for wide field optical astronomy, Photonics Letters of Poland, 1 (2), pp.82-84 (2009)
[28] R.Romaniuk, Wilga symposium on photonics applications, Photonic Letters of Poland, 1 (2), pp.46-48 (2009)
[29] R.Romaniuk, POLFEL – A free electron laser in Poland, Photonics Letters of Poland, 1 (3), pp.103-105 (2009)
[30] T.R.Wolinski, R.Romaniuk, Photonics Society of Poland established, Metrology and Measurement Systems 15 (2), pp.241-245 (2008)
[31] R.Romaniuk, Search for ultimate throughput in ultra-broadband photonic Internet, International Journal of Electronics and Telecommunications 57 (4), pp.523-528 (2011)
[32] R.Romaniuk, Photonics and web engineering 2011, International Journal of Electronics and Telecommunications 57 (3), pp.421-428 (2011)
[33] R.Romaniuk, Accelerator infrastructure in Europe EuCARD 2011, International Journal of Electronics and Telecommunications 57 (3), pp.413-419 (2011)
[34] J.Dorosz, R.Romaniuk, Development of optical fiber technology in Poland, International Journal of Electronics and Telecommunications 57 (2), pp.191-197 (2011)
[35] R.Romaniuk, Advanced photonic and electronic systems Wilga 2010, International Journal of Electronics and Telecommunications 56 (4), pp.479-484 (2010)
[36] R.Romaniuk, EuCARD 2010 accelerator technology in Europe, International Journal of Electronics and Telecommunications 56 (4), pp.485-488 (2010)
[37] W.Wojcik, R.Romaniuk, Development of optical fiber technology in Poland, International Journal of Electronics and Telecommunications 56 (1), pp.99-104 (2010)
[38] S.Chatrchyan, et al., The CMS experiment at the CERN LHC, Journal of Instrumentation, 3 (8), art.no S08004 (2008)
[39] S.Chatrchyan, et al., Commissioning of the CMS experiment and the cosmic run at four tesla, Journal of Instrumentation 5 (3), art.no.T03001 (2010)
[40] S.Chatrchyan, et al., Performance of the CMS Level-1 trigger during commissioning with cosmic ray muons and LHC beams, Journal of Instrumentation 5 (3), art.no.T03002 (2010)
[41] S.Chatrchyan, et al., Performance of the CMS drift-tube chamber local trigger with cosmic rays, Journal of Instrumentation 5 (3), art.no.T03003 (2010)
[42] S.Chatrchyan, et al., Fine synchronization of the CMS muon drift-tube local trigger using cosmic rays, Journal of Instrumentation 5 (3), art.no.T03004 (2010)
[43] S.Chatrchyan, et al., Commissioning of the CMS High-Level Trigger with cosmic muons, Journal of Instrumentation 5 (3), art.no.T03005 (2010)
[44] S.Chatrchyan, et al., CMS data processing workflows during an extended cosmic ray run, Journal of Instrumentation 5 (3), art.no.T03006 (2010)

[45] S.Chatrchyan, et al., Commissioning and performance of the CMS pixel tracker with cosmic ray muons, Journal of Instrumentation 5 (3), art.no.T03007 (2010)
[46] S.Chatrchyan, et al., Measurement of the muon stopping power in lead tungstate, Journal of Instrumentation 5 (3), art.no.P03007 (2010)
[47] S.Chatrchyan, et al., Comissioning and performance of the CMS silicon strip tracker with cosmic ray muons, Journal of Instrumentation 5 (3), art.no.T03008 (2010)
[48] S.Chatrchyan, et al., Alignment of the CMS silicon tracker during commissioning with cosmic rays, Journal of Instrumentation 5 (3), art.no.T03009 (2010)
[49] S.Chatrchyan, et al., Performance and operation of the CMS electromagnetic calorimeter, Journal of Instrumentation 5 (3), art.no.T03010 (2010)
[50] S.Chatrchyan, et al., Time reconstruction and performance of the CMS electromagnetic calorimeter, Journal of Instrumentation 5 (3), art.no.T03011 (2010)
[51] S.Chatrchyan, et al., Performance of the CMS hadron calorimeter with cosmic ray muons and LHC beam data, Journal of Instrumentation 5 (3), art.no.T03012 (2010)
[52] S.Chatrchyan, et al., Performance of CMS hadron calorimeter timing and synchronization using test beam, cosmic ray, and LHC beam data, Journal of Instrumentation 5 (3), art.no.T03013 (2010)
[53] S.Chatrchyan, et al., Identification and filtering of uncharacteristic noise in the CMS hadron calorimeter, Journal of Instrumentation 5 (3), art.no.T03014 (2010)
[54] S.Chatrchyan, et al., Performance of the CMS drift tube chambers with cosmic rays, Journal of Instrumentation 5 (3), art.no.T03015 (2010)
[55] S.Chatrchyan, et al., Calibration of the CMS drift tube chambers and measurement of the drift velocity with cosmic rays, Journal of Instrumentation 5 (3), art.no.T03016 (2010)
[56] S.Chatrchyan, et al., Performance study of the CMS barrel resistive plate chambers with cosmic rays, Journal of Instrumentation 5 (3), art.no.T03017 (2010)
[57] S.Chatrchyan, et al., Performance of the CMS cathode strip chambers with cosmic rays, Journal of Instrumentation 5 (3), art.no.T03018 (2010)
[58] S.Chatrchyan, et al., Aligning the CMS muon chambers with the muon alignment system during an extended cosmic ray run, Journal of Instrumentation 5 (3), art.no.T03019 (2010)
[59] S.Chatrchyan, et al., Alignment of the CMS muon system with cosmic-ray and beam-halo muons, Journal of Instrumentation 5 (3), art.no.T03020 (2010)
[60] S.Chatrchyan, et al., Precise mapping of the magnetic field in the CMS barrel yoke using cosmic rays, Journal of Instrumentation 5 (3), art.no.T03021(2010)
[61] S.Chatrchyan, et al., Performance of CMS muon reconstruction in cosmic-ray events, Journal of Instrumentation 5 (3), art.no.T03022 (2010)
[62] J.R.Just, et al., Highly parallel distributed computing system with optical interconnections, Microprocessing and Microprogramming, 27 (1-5), pp.489-493 (1989)
[63] R.S.Romaniuk, Multicore optical fibres, Revue Roumaine de Physique, 32 (1-2), pp.99-112 (1987)
[64] I.U.Romaniuk, R.Romaniuk, Light-conducting-fibre properties of retinal receptors, Klinika Oczna (Acta Ophthalmologica Polonica) 83 (1), pp.29-30 (1981)
[65] I.U.Romaniuk, R.Romaniuk, The use of light-conducting fibres in ophthalmological equipment, Klinika Oczna (Acta Ophthalmologica Polonica) 83 (1), pp.31-33 (1981)
[66] R.Romaniuk, Elektronika 23 (10-12), pp.8-14 (1982)
[67] R.Romaniuk, et al., Elektronika 24 (9), pp.18-22 (1983)
[68 J.Dorosz, et al., Elektronika 24 (1-2), pp.27-31 (1983)
[69] R.Romaniuk, Elektronika 24 (7-8), pp.47-50 (1983)
[70] R.Romaniuk, Elektronika 24 (4), pp.53-55 (1983)
[71] B.Darek, et al., Elektronika 24 (1-2), pp.53-55 (1983)
[72] R.Romaniuk, Elektronika 24 (6), pp.16-20 (1983)
[73] R.Romaniuk, et al., Elektronika 25 (9), pp.22-24 (1984)
[74] R.Romaniuk, Elektronika 25 (12), pp.11-15 (1984)
[75] R.S.Romaniuk, et al., Proc. SPIE 403, pp. 249-252 (1983)
[76] R.S.Romaniuk, et al., Proc. SPIE 404, pp. 96-101 (1983)
[77] R.S.Romaniuk, J,Dorosz, Proc.SPIE 514, pp.275-278 (1984)
[78] R.S.Romaniuk, Proc. SPIE, 566, pp. 62-63 (1985)
[79] R.S.Romaniuk, Proc. SPIE 566, pp. 276-283 (1985)
[80] R.S.Romaniuk, Proc. SPIE 566, pp. 340-347 (1985)
[81] R.S.Romaniuk, Proc. SPIE 576, pp. 105-109 (1985)
[82] R.S.Romaniuk, Proc. SPIE 585 pp. 260-265 (1985)
[83] R.S.Romaniuk, Proc. SPIE 658, pp. 70-76 (1986)
[84] M.Szustakowski, et al., Proc. SPIE 670, pp. 2-6 (1986)
[85] F.Szczot, et al., Proc. SPIE 670, pp. 172-176 (1986)
[86] R.S.Romaniuk, et al., Proc. SPIE 670, pp. 12-20 (1986)
[87] R.Romaniuk, et al., Proc. SPIE 704, pp. 144-151 (1986)
[88] R.Romaniuk, Proc. SPIE 713, pp. 28-35 (1986)

[89] E.Marszalec, et al., Proc. SPIE 718, pp. 212-217 (1986)
[90] R.S.Romaniuk, et al., Proc. SPIE 721, pp. 119-126 (1986)
[91] R.S.Romaniuk, et al., Proc. SPIE 722, pp.117-124 (1986)
[92] R.S.Romaniuk, Proc. SPIE, 722, pp.125-132 (1986)
[93] R.S.Romaniuk, et al., Proc. SPIE 798, pp. 316-323 (1987)
[94] F.Szczot, et al., Proc. SPIE 842, pp. 174-183 (1987)
[95] F.Szczot, et al., Proc. SPIE 867, pp. 80-86 (1987)
[96] L.Kociszewski, et al., Proc. SPIE 867, pp. 122-129 (1987)
[97] L.Kociszewski, et al., Proc. SPIE 906, pp. 97-106 (1988)
[98] E.Marszalec, et al., Proc. SPIE 1003, pp. 300-310 (1988)
[99] F.Szczot, et al., Proc. SPIE 1010, pp.160-167 (1988)
[100] L.Kociszewski, et al., Proc. SPIE 1011, pp. 71-80 (1988)
[101] R.S.Romaniuk, et al., Proc. SPIE 1014, pp.120-129 (1988)
[102] R.S.Romaniuk, Proc. SPIE 1085, pp. 214-238 (1989)
[103] R.Romaniuk, et al., Proc. SPIE 1085, pp. 239-272 (1989)
[104] J.Dorosz, et al., Proc. SPIE 1085, pp.273-276 (1989)
[105] R.Romaniuk, et al., Proc. SPIE 1128, pp.25-37 (1989)
[106] L.Kociszewski, et al., Proc. SPIE 1128, pp. 90-102 (1989)
[107] M.Szustakowski, et al., Proc. SPIE 1169, pp. 50-62 (1989)
[108] J.Buźniak, et al., Proc. SPIE 1172, pp.174-183 (1989)
[109] R.Romaniuk, Proc. SPIE 1174, pp.332-357 (1989)
[110] R.Stępień, et al., Proc. SPIE 1177, pp.438-448 (1989)
[111] R.Romaniuk, et al., Proc. SPIE 1368, pp.73-84 (1990)
[112] A.Dybko, et al., Proc. SPIE 2085, pp.131-136 (1993)
[113] A.Dybko, et al., Proc. SPIE 2508, pp.351-357 (1995)
[114] A.Dybko, et al., Proc. SPIE 3189, pp.122-127 (1996)
[115] A.Dybko, et l., Proc. SPIE 3105, pp.361-366 (1997)
[116] J.Dorosz, et al., Proc. SPIE 3731, pp.9-31 (1998)
[117] J.Dorosz, et al., Proc. SPIE 3731, pp.32-58 (1998)
[118] J.Dorosz, et al., Proc. SPIE 3731, pp.59-71 (1998)
[119] J.Maciejewski, et al., Proc. SPIE 3731, pp.161-166 (1998)
[120] R.S.Romaniuk, et al., Proc. SPIE 3731, pp.224-245 (1998)
[121] R.S.Romaniuk, et al., Proc. SPIE 3731, pp.246-273 (1998)
[122] R.S.Romaniuk, et al., Proc. SPIE 3731, pp.274-295 (1998)
[123] R.S.Romaniuk, et al., Proc. SPIE 4887, pp.55-66 (2002)
[124] J.Dorosz, Romaniuk R.S., Proc. SPIE 5028, pp. xi-xii (2003)
[125] Romaniuk R.S., Proc. SPIE 5028, pp.1-18 (2003)
[126] Romaniuk R.S., Proc. SPIE 5028, pp.19-25 (2003)
[127] Romaniuk R.S. et al., Proc. SPIE 5064, pp.210-221 (2003)
[128] R.S.Romaniuk, Proc. SPIE 5125, pp.xiii-xxxiv (2003)
[129] Romaniuk R.S., Proc. SPIE 5125, pp.5-16 (2003)
[130] Romaniuk R.S., Proc. SPIE 5125, pp.17-31 (2003)
[131] Romaniuk R.S., et al., Proc. SPIE 5125, pp.38-58 (2003)
[132] Romaniuk R.S., Proc. SPIE 5125, pp.59-75 (2003)
[133] W.M.Zabołotny, et al., Proc. SPIE 5125, pp.112-118 (2003)
[134] K.T.Poźniak, et al., Proc. 5125, pp.124-139 (2003)
[135] K.T.Poźniak, et al., Proc. SPIE 5125, pp.155-164 (2003)
[136] T.Nakielski, et al., Proc. SPIE 5125, pp.175-181 (2003)
[137] T.Jeżyński, et al., Proc. SPIE 5125, pp.182-192 (2003)
[138] Z.Łuszczak, et al., Proc. SPIE 5125, pp.193-204 (2003)
[139] T.Czarski, et al., Proc. SPIE 5125, pp.205-213 (2003)
[140] T.Czarski, et al., Proc. SPIE 5125, pp.214-222 (2003)
[141] W.Zabolotny, et al., Proc. SPIE 5125, pp.223-230 (2003)
[142] G.Wrochna, et al., Proc. SPIE 5125, pp.359-363 (2003)
[143] W.L.Wolinski, Z.Jankiewicz, R.S.Romaniuk, Proc. SPIE 5229, pp.xi-xii (2003)
[144] W.L.Wolinski, Z.Jankiewicz, R.S.Romaniuk, Proc. SPIE 5230, pp.ix-x (2003)
[145] R.S.Romaniuk, Proc. SPIE 5484, pp.19-28 (2004)
[146] T.Czarski, et al., Proc. SPIE 5484, pp.69-87 (2004)
[147] T.Czarski, et al., Proc. SPIE 5484, pp.88-98 (2004)
[148] T.Czarski, et al., Proc. SPIE 5484, pp.99-110 (2004)
[149] T.Czarski, et al., Proc. SPIE 5484, pp.111-129 (2004)
[150] K.T.Poźniak, et al., Proc. SPIE 5484, pp.130-138 (2004)
[151] W.M.Zabołotny, et al., Proc. SPIE 5484, pp.139-147 (2004)

[152] P.Rutkowski, et al., Proc. SPIE 5484, pp.153-170 (2004)
[153] W.Zabołotny, et al., Proc. SPIE 5484, pp.171-179 (2004)
[154] K.T.Poźniak, et al., Proc. SPIE 5484, pp.208-216 (2004)
[155] K.T.Poźniak, et al., Proc. SPIE 5484, pp.217-222 (2004)
[156] M.Ćwiok, et al., Proc. SPIE 5484, pp.283-289 (2004)
[157] L. Mankiewicz, et al., Proc. SPIE 5484, pp.305-316 (2004)
[158] K.T.Poźniak, et al., Proc. SPIE 5484, pp.586-596 (2004)
[159] R.S.Romaniuk, et al., Proc. SPIE 5576, art. no 52, pp.299-309 (2004)
[160 R.S.Romaniuk, Proc. SPIE 5775, pp.xxi-xxvii (2005)
[161] K.T.Poźniak, et al., SPIE 5775, art. no 02, pp.9-21 (2005)
[162] P.Roszkowski, et al., Proc. SPIE 5775, art. no 03, pp.22-31 (2005)
[163] W.Koprek, et al., Proc. SPIE 5775, art. no 04, pp.32-43 (2005)
[164] P.Pucyk, et al., Proc. SPIE 5775, art. no 06, pp. 52-60 (2005)
[165] W.Giergusiewicz, et al., Proc. SPIE 5775, art. no 07, pp. 61-68 (2005)
[166] K.T.Pozniak, et al., Proc. SPIE 5775, art. no 08, pp. 69-77 (2005)
[167] D.Rybka, et al., Proc. SPIE 5775, art. no 09, pp.78-94 (2005)
[168] T.Filipek, et al., Proc. SPIE 5775, art. no 15, pp.139-149 (2005)
[169] W.Koprek, et al., Proc. SPIE 5775, art. no 74, pp.543-555 (2005)
[170] K.T.Pozniak, et al., Proc. SPIE 5775, art. no 75, pp.556-562 (2005)
[171] J.Szewinski, et al., Proc. SPIE 5948 I, art. no 59480H, pp.1-8 (2005)
[172 R.S.Romaniuk, Proc. SPIE 5948 I, pp.xvii-xxi (2005)
[173] T.Czarski, et al, Proc.SPIE 5948 I, art. no 59480E, pp.1-11 (2005)
[174] K.Olowski, et al., Proc. SPIE 5948 II, art. no 59481Y, pp.1-7 (2005)
[175] W.Koprek, et al., Proc.SPIE 5948 I, art. no 594817, pp.1-11 (2005)
[176] W.Giergusiewicz, et al., Proc.SPIE 5948 I, art no 59480D, pp.1-11 (2005)
[177] M.Kwiatkowski, et al., Proc. SPIE 5948 I, art. no 59480L, pp.1-6 (2005)
[178] D.Rybka, et al., Proc. SPIE 5948 I, art. no 59480J, pp.1-12 (2005)
[179] W.Giergusiewicz, et al., Proc. SPIE 5948 II, art no 59482C, pp.1-6 (2005)
[180] A.Burd, et al., Proc. SPIE 5948 II, art. no 59481H, pp.1-7 (2005)
[181] R.S.Romaniuk, Proc. SPIE 6159, pp.xxxi-xxxii (2006)
[182] K.T.Pozniak, et al., Proc. SPIE 6159, art. no 615902 (2006)
[183] K.T.Pozniak, et al., Proc. SPIE 6159, art. no 615903 (2006)
[184] K.T.Poźniak, et al., Proc. SPIE 6159, art. no 615904 (2006)
[185] W.Giergusiewicz, et al., Proc. SPIE 6159, art. no 615905 (2006)
[186] K.T.Poźniak, et al., Proc. SPIE, 6159, art. no 615906 (2006)
[187] K.T.Poźniak, et al., Proc. SPIE 6159, art. no 615907 (2006)
[188] K.T.Poźniak, et al., Proc. SPIE 6159, art no 615908 (2006)
[189] W.Koprek, et al., Proc. SPIE 6159, art no 61590A (2006)
[190] W.Koprek, et al., Proc. SPIE 6159, art. no 61590B (2006)
[191] P.Pucyk, et al., Proc. SPIE 6159, 2006, art. no 61590C (2006)
[192] P.Pucyk, et al., Proc. SPIE 6159, art. no 61590D (2006)
[193] W.Koprek, et al., Proc. SPIE 6159, art. no 61590E (2006)
[194] A.Burd, et al., Proc. SPIE 6159, art. no 61590H (2006)
[195] R.S.Romaniuk, J.Dorosz, Proc. SPIE 6347 I, art. no 634713 (2006)
[196] K.Perkuszewski, et al., Proc. SPIE 6347 I, art. no 634708 (2006)
[197] R.S.Romaniuk, J.Dorosz, Proc. SPIE 6347 I, art. no 634710 (2006)
[198] R.Pietrasik et al., Proc. SPIE 6347 I, art. no 634705 (2006)
[199] R.S.Romaniuk, J.Dorosz, Proc. SPIE 6347 I, art. no 634711 (2006)
[200] T.Czarski et al., Proc. SPIE 6347 I, art. no 634709 (2006)
[201] K.T.Pozniak et al., Proc. SPIE 6347 I, art. no 634704 (2006)
[202 R.Graczyk et al., Proc. SPIE 6347 I, art. no 634706 (2006)
[203] G.Kasprowicz et al., Proc. SPIE 6347 I, art. no 63470N (2006)
[204] R.S.Romaniuk, Proc. SPIE 6347 I, art. no 634712 (2006)
[205] W.Koprek, et l., Proc. SPIE 6347 I, art. no 634703 (2006)
[206] J.Szewinski et.al., Proc. SPIE 6347 I, art. no 63470B (2006)
[207] J.S.Zielinski et al., Proc. SPIE 6347 I, art. no 634707 (2006)
[208] R.S.Romaniuk, Proc. SPIE 6347 I, pp. xxix-xxxii (2006)
[209] R.S.Romaniuk, Proc. SPIE 6347 I, art. no 634714 (2006)
[210] R.S.Romaniuk, Proc. SPIE 6347 I, art. no 63470Z (2006)
[211] J.Zysik et al., Proc. SPIE 6347 II, art. no 63472W (2006)
[212] W.L.Wolinski, et al., Proc. SPIE 6598, pp.ix-xi (2007)
[213] R.Romaniuk, Proc. SPIE 6937, pp.xxix-xli (2007)
[214] G.Kasprowicz, et al., Proc. SPIE 6937, art. no 693709 (2007)

[215] M.Kwiatkowski, et al., Proc. SPIE 6937, art. no 69370A (2007)
[216] A. Brandt, et al., Proc. SPIE 6937, art. no 69370F (2007)
[217] T.Czarski, et al., Proc. SPIE 6937, art. no 69370H (2007)
[218] P.Strzałkowski, et al., Proc. SPIE 6937, art. no 69370I (2007)
[219] K.Lewandowski, et al., Proc. SPIE 6937, art. no 69370J (2007)
[220] L.Dymanowski, et al., Proc. SPIE 6937, art. no 69370K (2007)
[221] R.Graczyk, et al., Proc. SPIE 6937, art. no 69370M (2007)
[222] K.Bujnowski, et al., Proc. SPIE 6937, art. no 69370O (2007)
[223] K.Bujnowski, et al., Proc. SPIE 6937, art. no 69370P (2007)
[224] R.Romaniuk, Proc. SPIE 6937, art. no. 693716 (2007)
[225] R.Romaniuk, Proc. SPIE 6937, art. no 693717 (2007)
[226] J.Dorosz, et al., Proc. SPIE 7120, pp.xiii-xv (2008)
[227] M.Kwiatkowski, et al., Proc.SPIE 7124, art. no 71240F (2008)
[228] A.Kalicki, et al., Proc.SPIE 7124, art. no 712410 (2008)
[229] R.S.Romaniuk, Proc.SPIE 7124, art. no 71240D (2008)
[230] R.S.Romaniuk, Proc.SPIE 7502, art. no 750201, pp. xxiii-xxiv (2009)
[231] R.S.Romaniuk, Proc.SPIE 7502, art. no 750202 (2009)
[232] R.S.Romaniuk, Proc.SPIE 7502, art. no 750220 (2009)
[233] R.S.Romaniuk, Proc.SPIE 7502, art. no 75021Z (2009)
[234] R.S.Romaniuk, Proc. SPIE 7745, art. no 774501, pp. xiii-xviii, (2010)
[235] R.S.Romaniuk, Proc.SPIE 7745, art. no 774502 (2010)
[236] R.S.Romaniuk, Proc.SPIE 7745, art. no 774503 (2010)
[237] J.Modelski, et al., Proc.SPIE 7745, art. no 774504 (2010)
[238] J.Modelski, et al., Proc.SPIE 7745, art. no 774505 (2010)
[239] J.Modelski, et al., Proc.SPIE 7745, art. no 774506 (2010)
[240] J.Gajda, et al., Proc.SPIE 7745, art. no 774507 (2010)
[241] W.Wójcik, et al., Proc.SPIE 7745, art. no 774508 (2010)
[242] R.S.Romaniuk, Proc.SPIE 7745, art. no 774509 (2010)
[243] T.Janicki, et al., Proc.SPIE 7745, art. no 77451H (2010)
[244] A.Zagozdzinska, et al., Proc.SPIE 7745, art. no 77451I (2010)
[245] R.S.Romaniuk, Proc.SPIE 8008, art. no 800801, pp.xiii-xvii, (2011)
[246] R.S.Romaniuk, Proc.SPIE 8008, art. no 800802 (2011)
[247] R.S.Romaniuk, Proc.SPIE 8008, art. no 800805 (2011)
[248] R.S.Romaniuk, Proc.SPIE 8008, art. no 800806 (2011)
[249] R.S.Romaniuk, Proc.SPIE 8008, art. no 800807 (2011)
[250] R.S.Romaniuk, Proc.SPIE 8008, art. no 80080Q (2011)
[251] R.S.Romaniuk, Proc.SPIE 8008, art. no 80081X (2011)
[252] R.S.Romaniuk, Proc.SPIE 8008, art. no 80080Z (2011)
[253] R.S.Romaniuk, Proc.SPIE 8010, pp.ix-x (2011)
[254] J.Dorosz, et al., Proc.SPIE 8010, art. no.801002 (2011)
[255] R.S.Romaniuk, Proc.SPIE 8010, art. no 801003 (2011)
[256] R.S.Romaniuk, Proc.SPIE 8010, art. no 801004 (2011)
[257] R.S.Romaniuk, Proc.SPIE 8010, art. no 801005 (2011)
[258] B.Niton, et al., Proc.SPIE 8010, art. no 80100R (2011)
[259] B.Niton, et al., Proc.SPIE 8010, art. no 80100S (2011)
[260] B.Niton, et al., Proc.SPIE 8010, art. no 80100T (2011)
[261] R.S.Romaniuk, Wilga Photonics Applications and Web Engineering, January 2012, Proc. SPIE 8454, art no 845401 (2012)
[262] R.S.Romaniuk, Astronomy and Space Technologies, Photonics Applications and Web Engineering, Wilga May 2012, Proc. SPIE 8454, art 845402 (2012)
[263] R.S.Romaniuk, Accelerator Technology and High Energy Physics Experiments, Photonics Applications and Web Engineering, Wilga May 2012, Proc. SPIE 8454, art 845403 (2012)
[264] R.S.Romaniuk, Photon Physics and Plasma Research, Photonics Applications and Web Engineering, Wilga May 2012, Proc. SPIE 8454, art 845404 (2012)
[265] R.S.Romaniuk, Optoelectronic Devices, Sensors, Communication and Multimedia, Photonics Applications and Web Engineering, Wilga May 2012, Proc. SPIE 8454, art 845405 (2012)
[266] R.S.Romaniuk, Biomedical, Artificial Intelligence and DNA Computing, Photonics Applications and Web Engineering, Wilga May 2012, Proc. SPIE 8454, art 845406 (2012)
[267] R.S.Romaniuk, Accelerator Science and Technology in Europe – EuCARD 2012, Proc. SPIE 8454, art no. 845407 (2012)
[268] B.Niton, K.T.Pozniak, R.S.Romaniuk, A plug-in to eclipse for VHDL source codes: functionalities, Proc. SPIE 8454, art no 8454xx (2012)
[269] R.S.Romaniuk, Polish Debut, Photonics Spectra, vol.26, no.5, pp.10-12, May 1992
[270] R.S.Romaniuk, The photonics scene in the new Poland, Photonics Spectra, vol.26, no.4, pp.64-65, April 1992