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Realization of CARE and EuCARD Projects in ISE-WUT Accelerator and FEL Research, Development and Applications in Europe

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There are described coordinating actions of the accelerator science in Europe in 2003-2009. The actions embrace basic science, as well as development and applications. The accelerator research was not coordinated in Europe at a global scale but was rather concentrated in a few centers owning large infrastructure. These centers include: CERN, DESY, GSI, INFN, LAL, PSI etc. Such coordinating actions enable a lot of positive processes including new possibilities for research centers in this country. It is much easier for them to extend, deepen or even start from the beginning their activities in the field of the accelerator technology. This field includes also free electron lasers. There are described two European framework projects CARE and EuCARD on accelerator technology, their extent and the participation of the Institute of Electronic Systems ISE WUT in them.

Keywords: Accelerator science, accelerator technology, synchrotron, free electron laser, elementary particles, electronic and photonic systems, European framework programs

1. INTRODUCTION

The Accelerator Technology is one of these research branches, which involves design, construction, commissioning and then exploitation, during some confined time, a large or even immense, and very complicated technical infrastructure. This period, which is an effective lifetime of a large accelerator lasts around 20-25 years. It is possible, in the future, with the increased pace of development, that this period will shorten. On the other hand researchers tend to build even bigger and more complicated machines for more money, which will prevent this tendency. Smaller accelerators, of advanced construction, for technical and medical applications are built as a consequence, and parallel product, of intense research work on big accelerators. The size of research infrastructure is imposed by bigger requirements for energy and intensity of the accelerator beam. The biggest research accelerators, due to very high costs of construction and exploitation, are only a few and are almost only built as a result of wide international cooperation. The technologies created for the biggest accelerators, including mechanics, chemistry, electronics, photonics, material engineering, etc. are transferred very fast to the industry, including power engineering, nuclear, geology and mining, medicine, safety, environment engineering, etc. To gain a direct source access to these technologies, it is necessary for the research teams from this country to participate in large research experiments including: accelerators, nuclear, power, photonics, laser, cosmic, astronomic, etc. It is also necessary to build, around such large experiments in the country, local industrial and technical consortia. A question appears now, if this participation is sufficient, which is hard to answer. This participation might be much greater, reflecting the potential of the local research community.

After several years of wider participation of the local research and technical communities from this country in the European Framework Research Programs (FP), particular research teams have gathered critical experience, allowing for deeper and more essential reflections. Some research groups from this country participated in FP5, most of them started in FP6, quite a few continue in FP7 [1]. The participation of domestic teams was and is now so numerous, that an administrative infrastructure was built to facilitate the cooperation. The infrastructure consists of a national central office for the EU FP [2], regional information offices [3] and open community, non-governmental organizations. One of such useful associations is National Committee of EU FP Coordinators – KRAB [4]. The bylaws and mission of KRAB assumes realization of the flowing tasks: exchange of experiences from project realizations, promotion of good practices for professional conduct of projects, promotion of participation in FP teams from Poland, cooperation with governmental and local community administrations, recommendation of changes in the research law to facilitate the participation in the European Projects, education, organization of conferences on European Programs. KRAB defines the most important problems to be solved, as follows: big difficulties to obtain an European Project for a lot of research teams from Poland, big disproportions between salaries of the project participants in Europe and in this country, lack of stable law solutions for realized projects, lack of professional managerial staff supporting project realization in Poland. The aggregated participation of Poland in the realization of EU FPs, together with Operational Programs (POIG, POKL and POIiS) funded by the EU, is so massive that fast changes, breaking large inertial resistance on all levels – governmental and beneficiaries, are unavoidable.

Participation in large EU FP, and such are the integrated infrastructure projects concerning the accelerator technology, requires fulfillment of a few, sometimes quite difficult for universities, conditions: presence of a national research team in a sufficiently massive topical consortium which generates particular project, proposing an attractive research offer for infrastructure development (this infrastructure is very frequently outside this country) and declaration of own either financial or in-kind share. The offer has to be attractive for the consortium and for the owner of the infrastructure. In some cases, this declared share may be as high as 2/3 of the value of proposed work package or task ad typically is around 1/2. The necessity to declare such high own financial share prevents a lot of national teams to participate in big infrastructural undertaking, despite the support by directed national co-financing grants. The EU FP projects are now realized in the FC – full costs accounting frames. Previously, within the FP6, the accounting was AC – additional costs. This requires from the domestic universities to maintain complicated multilevel bookkeeping documentation, for which they are hardly prepared. Fulfilling of these requirements burdens not only the administration of the university but also the research leader of the project. It is evident, that some research leaders, who are prepared to undertake the effort, avoid it assuming the lack of appropriate support from the side of administration services of the institution.

The research teams from Poland are participating in a number of scientific and technical projects concerning construction and/or development of the accelerator or nuclear infrastructure in Europe (like E-XFEL, FAIR, ITER). These programs are coordinated on several levels by governmental agencies of the biggest European countries, by non-governmental organizations, also by the European Commission. The main coordinator on the European level in this topical area is ESGARD [5] – European Steering Group for Accelerator R&D. The first project realized within FP6 was CARE [6-8], which run during the period 2004-2008. A continuator of this project is EuCARD [9-12] European Coordination of Accelerator R&D, scheduled within FP7 for the period of 2009-2013. All European accelerator infrastructures participate in the project as well as many other institutions like universities having accelerator research groups, including Warsaw University of Technology. The area of activities of a team from ISE WUT in CARE and EuCARD is SRF – superconducting radio frequency [13-14]. The teams and persons from ISE WUT participate also in different related projects concerning accelerators, astro-particle physics, elementary particles realized previously like ZEUS/HERA and realized now like ALBA, CMS/LHC, SPS, FLASH, E-XFEL, ILC, PITZ, CBM, Chandrayaan satellite, Pi-of-the-Sky, etc. The people involved directly in technical work are mainly M.Sc. and Ph.D. students, which work under the supervision of university faculties.

2. APPLICATIONS OF ACCELERATOR TECHNOLOGY

The current possibilities of broad applications of accelerator technology are a direct consequence of large research projects and experiments in Europe like: TESLA, HERA, LHC, CLIC and worldwide like: ILC, CEBAF, SLAC, SNS, KEK, carried out from a few decades, and resulting in essential achievements in fundamental and technical areas. Chosen European centers of accelerator infrastructure are gathered in table 1. The research in HEP concentrates today in a few main directions: recreation of the initial conditions during the BB – big bang; search for very rare events; observations of the universe; gathering of immense data sets enabling reliable statistical analyses. Four types of large, complex and costly accelerator infrastructures are required to realize these aims. These embrace: accelerators of big energies and big intensities of the beams; accelerator detectors; management and gigantic data processing systems (zetta-byte data sets 10^{21}); large auxiliary infrastructure, for example underground. The development of each kind of these infrastructures translates nearly immediately to industrial applications, from which the whole society may profit. These applications include: medicine, safe nuclear power utilities, new materials, information technologies, Internet, and in the future: making the Moon and the Mars our home, and other space technologies.

Table 1

European accelerator infrastructures (chosen objects)

Laboratory	Accelerator	Description
ALBA Barcelona	ALBA	Synchrotron light source
BESSY Berlin	BESSY	Synchrotron light source
CCLRC – RAL Didcot	ISIS, MICE	Accelerator complex: muons and neutrons
CERN Geneve	LHC Detectors CLIC, SLHC	Proton accelerator complex, Neutrino beam, Ion accelerator, Two beam electron linac, SRF laboratory
DESY Hamburg	FLASH, PITZ, E-XFEL, TESLA	Superconducting electron linac, Electron injectors, FEL, Synchrotron,
FZ Rossendorf	ELBE	Linear electron accelerator
GSI Darmstadt	SIS, ESR, FAIR, UNICAL	Accelerator complex for heavy ions, Beam tests laboratory
INFN Frascati	SPARC DAFNE	FEL, Synchrotron source
LAL IN2P3 Orsay	PHIL	Electron injector, European synchrotron

In the area of fundamental research, the accelerator technology infrastructure is used to find answers to the following questions concerning the energy: are there any other laws of physics?, what is dark energy?, are there additional dimensions?, do all the forces originate from a single one?, and questions concerning the elementary particles: why there are so many elementary particles?, what is dark mass and how it can be generated?, what is the nature of neutrinos?, and also questions concerning the universe: how it started into being?, what has happened to the antimatter? The research accelerators for HEP are developing into bigger energies, bigger intensities and smaller dimensions of the beam. The further development of accelerator technology requires access to test facilities: accelerated beams, high field magnets and superconductive resonant cavities of the highest quality. The development of the biggest accelerators for HEP gave birth to a number of other research accelerator families for new generation of light sources of the highest intensities [15-16], muon and neutron sources, neutrino beams [17], and then medical accelerators for cancer therapy, as well as industrial ones for ion implantation, material engineering, welding and cutting with an electron beam, radioisotope production, ion transmutation, nondestructive testing and safety. Certain accelerator devices of appropriate power are used additionally for transmutation processes of nuclear power reactor waste. Table 2 gathers an arbitrary estimate concerning the worldwide, industrial accelerator markets in 2009.

Table 2

Industrial market for accelerators (predictions for 2009) in [pcs.] and [M∈]

Application	Number of working systems [pcs.]	Numer of systems sold in the last year [pcs.]	Total value of trade [M∈]	Range of price for a single system [M∈]
Medical therapy	> 10 000	> 600	> 2000	2,0 – 5,0
Ion implantation	> 12 000	500	> 1500	1,0 – 3,0
Cutting and welding with electron beam	> 5 000	> 100	> 200	0,5 – 2,5
Irradiators with e and X	> 2 000	> 100	> 150	0,2 – 5,0
Radiosotope production and PET	> 650	> 50	> 100	1,0 – 3,0
Nondestructive testing and safety systems	> 1 000	> 200	> 100	0,3 – 2,0
Ion beams analysis and AMS	> 250	> 30	> 30	0,4 – 1,5
Neutron generators	> 1 100	> 50	> 30	0,1 – 3,0
Isotope transmurtation, transmutation of nuclear reactor waste (nuclear power stations)	> 100			Similar to the production of radioisotopes
FEL	single			v.high
Other	> 1 000			Relat.small
Together (plus other industrial applications)	> 35 000	> 2 000	> 5 000	0,1 – 5,0
Research: Accelerator Energy Recovery; Accelerator I-FEL;	single			Very high Plasma –laser accelerators

3. EUROPEAN ACCELERATOR PEOJECTS: CARE AND EuCARD

Project CARE embraced the following, so called, Joint Research Activities JRA: SRF [13] – superconducting radio frequency, PHIN [18] – photon injectors, HIPPI [19] – proton injectors, NED [20] – high field magnets from Nb_3Sn, and research networks: ELAN [21] – European electron linear accelerators, BENE [22] – beams for neutrino experiments, HHH [23] – hadron beams of high energies and high intensities. As a result of CARE realization, a large development step was obtained in the following areas: quality of superconducting RF cavities for ultimately high fields – fig.1, control and tuning of cavities, diagnostics and control of the beams, parameters of couples and high field magnets, injector construction, surface preparation and quality improvement of accelerator materials, etc. The pioneering project CARE initiated and cooperated with a series of other European undertakings and common activities in accelerator technology, like: EuroTeV [24], EuroLEAP [25], EURISOL [26], CLIC [27], SLHC-PP [28].

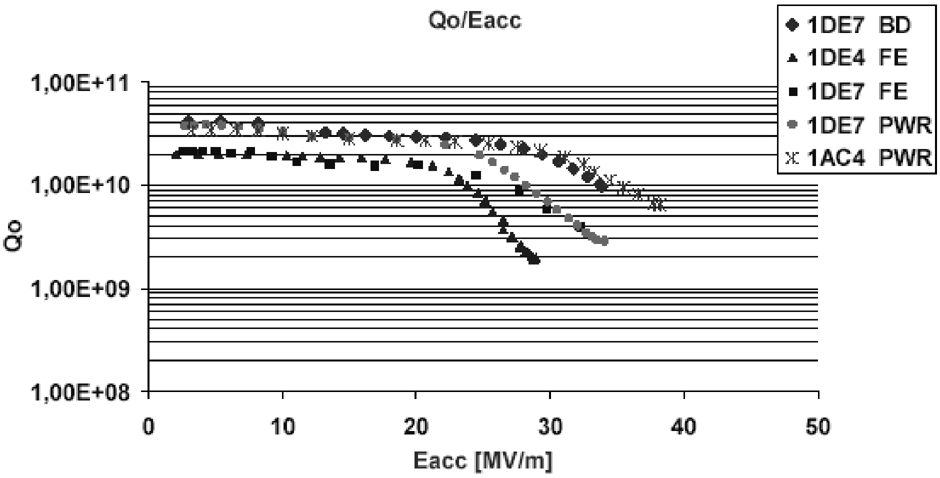

Fig. 1. Unloaded Q characteristics for single-cell superconducting niobium resonant cavities, of TESLA type, for f=1,3GHz. Surface processing: quasi-single crystal surface (large grain), electro polishing, dry-ice cleaning, [6]

Project EuCARD [9] embraces the following joint research activities (JRA): HFM – high field magnets, ColMat – collimators and materials, NCL – warm linear accelerators, SRF – superconducting RF technology, ANAC – new conceptions in accelerators, and research networks (NA) and transnational access (TA) to accelerator infrastructure: NEU2012 [29] – European neutrino network, AccNet – European accelerator network, HiRadMat – research access to proton and ion beams in SPS CERN, and MICE [30] – research access to muon and neutron beams in RAL [31]. The accelerator network (and neutrino network) and a good organization of facilitated, transnational access to the beams are a sort of a backbone of the EuCARD project. Without a considerably extended access to the existing beams for wider research community, international, European and domestic, it is impossible to justify the realization of such expensive projects like EuCARD. Are we going to use this facilitated access?

4. ISW WUT PARTICIPATION IN CARE AND EuCARD PROJECTS

The participation of research teams from ISW WUT concerned a realization of a few tasks including: design, construction, testing, application and commissioning of advanced electronic and photonic systems for accelerator technology, in close co-operation with the DESY – a host of this infrastructure. The other coworkers in this effort were domestic institutions: IPJ-Świerk, Łódź Uni. of Technology, Wrocław Uni. of Technology, Institute of Experimental Physics, Warsaw University, and Institute of Nuclear Physics, Kraków.

There were carried out the following tasks: modelling and measurements of electronics and photonics degradation mechanisms in VLSI chip based systems, in particular memory modules and FPGA circuits, all working in high ionizing radiation fields. A laboratory set-up was constructed for testing of the kinds of errors appearing commonly under the influence of highly energetic EM radiation and corpuscular beams, in a system managed by an FPGA chip. There were tested mitigation methods based on introduction to the system hardware redundancy and algorithmic redundancy. Adverse environment in an accelerator channel includes: highly energetic electromagnetic radiation and secondary, relatively low corpuscular radiation, like neutrons. The biggest sensitivity to the neutron radiation show SRAM memories and FET transistors. A remotely controlled monitoring system for radiation level was mounted in FLASH tunnel. The system was oriented towards checking the influence of radiation on the FPGA based circuit. The system was integrated with DOOCS which enabled on-line analysis including radiation measurements, watching the effect of accumulation of radiation energy deposits and harmful changes in electronics with power of dose. There were also carried out numerous measurements of radiation hardness of electronics in the Linac 2 in DESY.

Noise phenomena were investigated in a frequency down converter with the intermediate frequency IF=250kHz, used in analog-digital control feedback loop for superconducting resonant Tesla cavity. The measurements showed the noise level of around two orders of magnitude larger than calculated from the specification of the key components used for building of the device. The reasons were identified as external noise sources and errors in the down converter design. The electromagnetic environment of down converter work is highly noisy via the presence in the vicinity the high power supplies, klystrons, modulators, waveguides, cabling, digital electronics, etc. A classification of noise sources was done taking into account their influence on the analog electronics. A new solution of low-noise down converter was proposed, with the IF=81MHz. The linearity of the device was measured for the new IF on the level of 10^{-3}. The quality requirements for vector sum control of many resonant cavities were estimated. Integration of the down converter was considered in a form of a single chip.

A few models of multilayer system PCBs were designed and manufactured. They work in motherboard-daughterboard configuration and contain 8 channels of ADC, four channels of DAC, FPGA and DSP chips and a few channels of gigabit optical links. The noise level of working digital system was measured and equal to 1 – 4 mV rms. This noise level of the first solution of PCB was not satisfactory. It was lowered in the next PCB designs. Control programming for the PCBs was designed and implemented. It consisted of software layer and firmware layer. The system was tested in different conditions of laboratory work, and then during exploitation conditions accessible in the accelerator infrastructure. In particular, remote tests of electronic equipment, software and algorithms were done in level Chechia thermostat test stand and in multicavity (containing a single criomodule without a RG gun) MTS test hall.

Climatic tests were designed and performed, as well as exploitation tests of optical fiber, stabilized frequency distribution system. The necessity to apply such a system stems from large dimensions of accelerator infrastructure, of the order of hundred m and even km. The control, measurement and safety electronics is distributed over distant locations around the engineering infrastructure. There were carried interferometric measurements with the usage of optical phase shifter. The methods to lower the phase noise of master oscillator were introduced. The necessary phase stability was initially below 1ps for the distance of a few km. Next this value was lowered to 100fs and 1ps for analysis time 100ms and 1000s respectively.

There were carried out works on accelerator control software including a single cavity and simultaneously multiple cavities control. The control algorithm based on mechano-electrical model of the cavity, written in MatLab. This algorithm was subject to optimization. The software was written for work and communication management of the system. User panels were prepared for operator communications. The user system bases on DOOCS – a virtual control environments used popularly in DESY. Other cavity control tests were performed with the usage of alternative solutions like EPISC and simply web browser.

An algorithm was designed and implemented based on object identification and a full closed feedback loop. Tests of remote control of cavities mounted in the MTS in DESY from the VME system mounted in ISE WUT were successfully done. A sub-system of auto-calibration was proposed during multichannel vector sum control. A module with eight cavities is controlled with closed feedback loop (FB). The FB is enhanced by the direct control feed forward (FF). The FPGA controller performs procedure in agreement with the data in the set point tables: Feed-Forward, Set-Point, Corrector-Unit. Nonlinearities and deterministic perturbations are compensated by FF table for open loop. The correction for closed loop (tuning) is performed by Complex Gain module in the Correction Block. The circuit contains also a module for klystron linearization. The amplification in the loop was around 300 during ACC1 control of FLASH accelerator. The adaptive control algorithm was applied for FB and FF work modes, according to process identification. The applied control method for a crio-module is useful for repeatable deterministic work conditions of the accelerator, what was confirmed experimentally. The following parameters of field stabilization in the cavity were obtained: relative amplitude stabilization - 10^{-4}, phase stabilization approx. 2 10^{-4} rad. New control algorithms were elaborated for superconducting cavities and for the RF gun. The algorithms use fully the extended hardware resources of the new, third generation of LLRF control system SIMCON. The control system for power generated by the RF gun the following stabilities was obtained during the first run: phase – better than 1°, amplitude – better than 1%. The control system of the RF gun can not measure the field value in the gun cavity. The SIMCON system, consisting of hardware and software, was used for the control and work stabilization of the RF gun in FLASH accelerator for FEL operation of SASE type. For a pulse of the length which is not bigger than 100µs, it is enough to use a common PI controller. Longer RF pulses, and repetitive sets of pulses require additionally the AFF control (adaptive feed forward). SIMCON system of the third generation was used to control a few versions of the RF gun. The control software for RF gun was written in VHDL and implemented in FPGA circuit of fit resources. A DOOCS server was prepared for the hardware-software control system. An improved stability of phase and amplitude was achieved. There were performed tests of superconducting linac control, via introduction of field gradient dispersion between different cavities. The measurement results show that, via fitting of the loaded Q and phase of the input signal at preset detuning of the cavities during the pulse, the gradient dispersion in cavities of the order of 5% may be tolerated. In a system with arbitrary programmable, nonstationary, changing during the high power RF pulse, detuning of an individual cavity, the gradient dispersion may be fully compensated. Then, each cavity works with its own maximum of the field gradient. The following conditions: available maximum power, range of loaded Q tuning in a cavity, phase of forward wave and cavity detuning, impose a boundary value for the gradient dispersion which is equal to ±20%. A few % of the average gradient value is lost due to mechanical resonances of the cavities.

The chosen architecture version of the individual loop in the LLRF control system has a large influence on the costs. Such a loop is replicated in the system hundred times. During the whole process of the LLRF system design there were considered all the time the possibilities to reduce the overall costs. There are a few ways to reduce the costs. The ultimate confinement for system cost reduction is considerable narrowing of the control system functionalities, which cannot be accepted by the machine operators. One of the cost reduction paths leads via the functional integration of the whole LLRF system circuitry. The frequency down-converters may be possibly integrated with the ADC circuits and with the initial data processing in the FPGA, where a value for a partial vector sum is calculated. Such an input (front-end) signal processing circuit form the cavity may be positioned close to the individual criomodules, as so called front-end RF patch panel. This circuit is then connected with the rest of the system by means of gigabit optical links. This architecture eliminates expensive connections with the usage of thermally stabilized RF cables of very high quality.

Other potential methods to lower the LLRF system costs are: automation of control procedures in the widest extent by using of state machines and knowledge data base about the system; application of industrial standards for hardware and software; reduction of the number of separately transmitted signals; as deep system digitalization as possible; standardized signal multiplexing all over the system; design and testing of the system in own laboratory. One of the important system cost reduction options, with a clear look out to the future, is exchange of the now prevailing VME standard with the new one ATCA (or its version μTCA). ATCA system is now widely introduced in the telecommunications.

An important component in the design and testing process of the complex LLRF system is evaluation of its reliability. The reliability of an individual RF station was evaluated. This evaluation was extended to the whole LLRF system. The following assumptions were taken: MTBF for a single VME crate is around 10^5, the station consists of 10 crates, the system consists of a few tens of stations, a few crates in each station is critical for system performance, the system is redundant on the level of hardware and control method (algorithm), with the possibility to switch the work mode between closed loop and direct deterministic control. At these assumptions, it is estimated that a single LLRF system halt caused by either hardware or software breakdown appears less than one time during a year.

The third generation LLRF system SIMCON, ver.3 bases on double FPGA circuit (Fig.2.). One of FPGA chips fulfills logical functions while the other does system tasks (performs the control algorithm). The FPGA chips have inbuilt DSP blocks to facilitate fast floating point calculations. The VME 6U PCB has 10 wideband analog inputs 270MHz, ± 1V, fit to 50 Ω, 4 DAC channels, a few trigger I/O ports, reference clock input of the stability 0,3ps rms, static and dynamic memories, interfaces for optical gigalinks, and Ethernet input. The system was tested in Chechia horizontal thermostat and in the TTF accelerator. There were prepared cotrol algorithms in MatLab and DOOCS server for the SIMCON 3. VHDL firmware was written for SIMCON 3 PCB. The results of control and measurements of phase and amplitude for eight cavities of ACC1 criomodule of FLASH laser, obtained with the aid of SIMCON 3, were presented in fig.3. A separate board of optical gigabit signal concentrator for SIMCON system was designed, manufactured and tested. The board called SIMCON 4 has eight optical giga links and Flash memory card pocket for storing the configuration data. It enables the system to work stand alone. The data concentrator serves for data exchange between other SIMCON boards and VME controller. This board was tested as a candidate for a universal node of a distributed, multichannel control measurement version of the LLRF system.

The LLRF control system for accelerator is under further development. This development is now continued in the EuCARD project in the following directions: optimization of software and algorithms, modularization of the software for low-level LLA and high-level HLA parts, introduction of coupled FPGA-DSP processors, change to standardized, intelligent, telecom grade, system platform ATCA with the IPMS functionality.

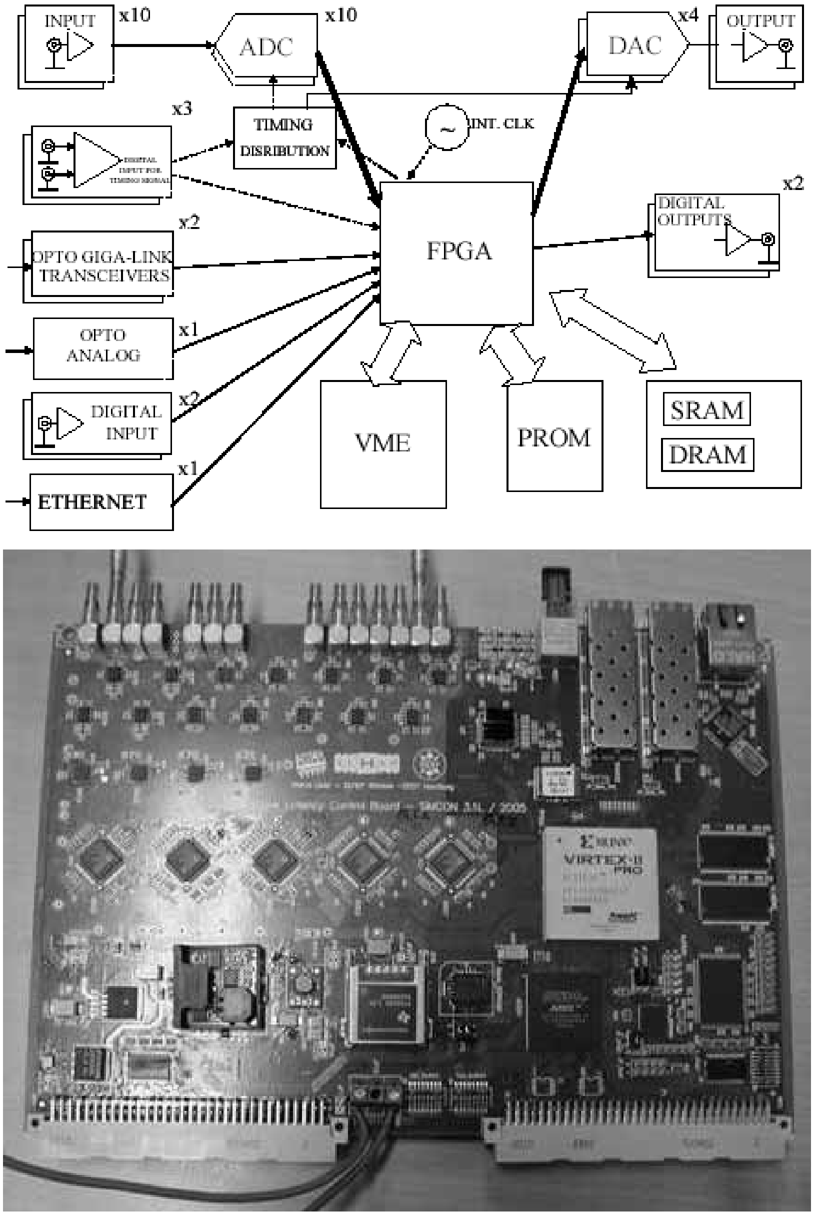

Fig. 2. SIMCON 3.1. PCB and its block diagram

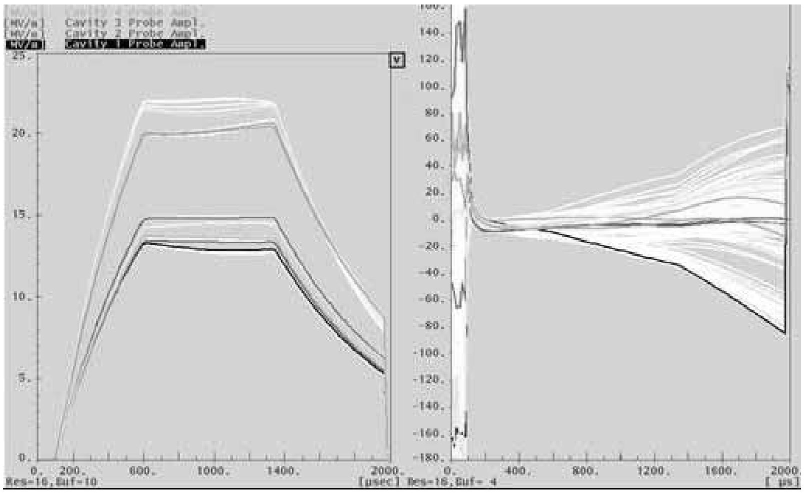

Fig. 3. Amplitude and phase of signals in eight cavities of ACC1 module of FLASH accelerator

5. ROLE AND EXPECTATIONS FOR EuCARD PROJECT

The EuCARD Project belongs to a group related to building a large, common European Research Infrastructure ERA. The expectations of the European Commission is that this infrastructure will be, in a positive sense, competitive against to other regions, especially Japan and USA. These ambitious assumptions are moderated by the current conditions of the world wide crisis. These economic conditions may influence the pace of realization of the biggest accelerator projects requiring the aggregation of financing from many various sources. Participation in such a big pan-European project like EuCARD is a large challenge and simultaneously is a chance for smaller research teams, especially from countries not possessing an own, large accelerator infrastructure. One of these chances is to overcome a critical threshold of building own infrastructure, leading directly to extension of industrial applications of new technologies.

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