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Trends in detector R&D

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Detectors are they eyes with which we observe the physics and explore new phenomena. The development of more performing detectors is essential for future physics discoveries and requires appropriate attention, funding, and recognition. In this paper the current trends in High Energy Physics detector research and development are reviewed. Since the topic is broader than the available space, figures are not included in the paper, but can be found in the references, whose main sources are the recent instrumentation conferences [1 – 6].

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1. Introduction

Experimental physics discoveries rely on the use of complex and sophisticated detector systems, which are the eyes through which new phenomena can be observed. Many technological challenges must be faced to construct and operate detectors for the next generation experiments, requiring an intense and diverse detector research and development program. As for all R&D processes, the outcome is often neither certain nor immediate, implying that many roads must be traveled with sufficient lead time. The great scientific success of LHC and of many other experimental programs is strongly linked to the amazing detector technology developments that form the basis of the experimental apparata. The three frontiers in particle physics research identified by global HEP strategic planning panels call for very different R&D directions[7].

At the energy frontier, the LHC high luminosity run[8] requires detector performances such as granularity in tracking devices to less than $50\,\mu$m; vertex detectors that can withstand fluxes of the order of $10^{16}\,\mathrm{n/cm^2}$; trigger and DAQ systems that can keep up with luminosity of $10^{35}\mathrm{cm^2 s^{-1}}$. At a high energy lepton collider, on the other hand, a $4\,\mu$m point precision in tracking and a hadronic jet energy resolution of $30\%/\sqrt{E(\mathrm{GeV})}$ will be required.

At the intensity frontier, the challenges will be to find low-cost photodetectors for a 300 kton water detector; to develop a robust and operable 20 ton Ar(Xe) TPC detector; to develop picosecond level time-of-flight techniques for rare decay tagging.

At the cosmic frontier, significant advances will require the reduction of background in Dark Matter (DM) detection down to 1 nuclear recoil/ton/yr; the development of different detection techniques for DM searches; the expansion of the depth of observation in the galaxy to probe Dark Energy.

In the forthcoming phase of particle physics, novel detector concepts and timely development of more performant systems will play a major role in supporting and enabling frontier research [9].

2. Tracking and Vertexing

2.1 Solid state (silicon) detectors

Silicon detectors provide the most precise tracking device a modern experiment can use. Granularity, speed, and material specifications are dictated by a number of requirements derived form physics: tracking resolution, separation of pile-up events, heavy flavor identification through secondary vertices, two-track separation in jets, low material budget to reduce multiple scattering. Accelerator conditions, event and background rates, radiation levels, determine the necessary readout speed and radiation hardness of the devices [9].

Since the late seventies, silicon strip detectors have set the standard for spatial resolution and have been engineered in increasingly large and complex detector systems reaching the a total surface of more than $100\,\mathrm{m}^2$ [10]. For today's strip and pixel detectors in large systems, with a granularity extending down to $50-100\,\mu$m, the readout electronics is typically fabricated in a commercial CMOS process, and directly connected to the sensors via wire- or bump-bonding. This hybrid interconnected structure tends to increase the complexity, cost, and material of the system and practically limits the attainable granularity.

A large effort is ongoing to develop alternative technologies, either by fabricating the sensor and the readout onto the same substrate (monolithic approach), or by employing beyond state-of-the-art interconnection technologies, such as 3D vertical integration, through-silicon-vias, or micro bump-bonding, which, while retaining the advantages of separate and optimized fabrication processes for sensor and electronics, would allow fine pitch interconnect of multiple chips. Future systems are expected to have granularities in the $25 \div 50\,\mu$m region or better, and a thickness of the order of $0.1 \div 0.2\% X_0$ per detection layer.

For hadron collider applications the sensor radiation hardness plays a central role, with expected fluxes in the range $1 \div 10 \cdot 10^{14} \mathrm{n_{eq} cm^{-2}}$ for larger radius strip detectors and $10 \div 200 \cdot 10^{14} \mathrm{n_{eq} cm^{-2}}$ for smaller radius pixels. Standard planar devices realized with n-in-p technology show a manageable loss in charge collection efficiency (“only” a factor 5 at the highest fluences) and provide a viable solution, also because of the higher collection speed of electrons compared to holes [11]. Alternative, very attractive, solutions are explored by abandoning the planar paradigm with 3D silicon sensors, where through-silicon doped columns provide lateral collection electrodes that improve both speed and efficiency in charge collection, resulting in an increased radiation tolerance [12].

Several groups have been trying to integrate on the same substrate both the radiation sensor and some element of the readout electronics, in order to reduce noise, interconnections, material [13]. In CMOS Monolithic Active Pixel Systems (MAPS) commercial CMOS processes are used, developing specially designed input stages that can cope with the very small charge deposited in the low resistivity CMOS substrate (of the order of $1000\,e^-$) [14]. With some foundries it has been possible to introduce process modifications, such as adding an extra well implantation, to reduce the undesired coupling between sensor elements and active electronics parts[15]. In the Silicon-On-Insulator devices development, instead, a fully depleted high-resistivity substrate is employed for the sensor, while readout electronics is fabricated in low resistivity silicon separated by and oxide layer. In the very sophisticated and complex DEPFET process, deep doping areas are used as the charge collecting backgate of a FET device that provides in-situ signal amplification [16]. All these devices, although in many cases successfully developed and used in experimental applications, tend to have limited readout speed, and the attempts to integrate faster digital electronics on the same substrate of the sensor have led for the most part to undesirable cross talk and induction effects, which are very hard to predict and control.

The semiconductor industry is pushing to increase the integration density by employing vertical integration technologies, where multiple chips can be stacked together and interconnected using through-silicon-vias. The possibility of employing this technology for sensor fabrication is at the forefront of solid state detector developments, opening the possibility of fabricating sensor, amplifier, digital processor in separate, optimized processes, and then stacking them together after reducing the single chip thickness to $10\,\mu$m or less. Besides the advantage of improving the performance of traditional detectors, this vertical integration technologies can also be used to design smart detectors [17], in which multiple hits are combined locally, possibly measuring track segments instead of single points, and providing crucial information to resolve the trigger and event overlap problems at high luminosity LHC [18].

As the sensors become thinner and more complex, and with more local intelligence, the material budget of the support structure, of the cooling system, and of the signal and power distribution become of paramount importance, with sophisticated engineering techniques and advanced materials routinely employed for the system design. As an example, carbon fiber or silicon micro-channel cooling with single or dual phase coolant is playing and increasingly important role in the design of low-mass systems [19].

The production processes used in semiconductor industry tend to be very expensive, and they are sustainable only because of the extremely large consumer electronics market. The detector developments, on the other hand, look at very small production scales, making them unaffordable unless a coordinated action is put in place across several groups and nations. Multi-project wafers and simultaneous submission of many different design are customarily used to share the run costs, while world-wide coordination of activities is increasingly essential.

2.2 Gas detectors

Gaseous detectors are the workhorse of tracking systems: being low mass and relatively inexpensive, they can be used to cover large areas and have provided the backbone of charged particle reconstruction and momentum measurement for most experiments, with the notable exception of the very high rate LHC detectors, mostly because of the superior rate capability and radiation hardness of solid state sensors. Although the area of a single gas chamber has plateaued at a few square meters, for practical reasons, the total area produced has shown an increase of a factor 10 every five years with projections for the future keeping the same trend.

The community has mastered a profound and detailed understanding of charge production, transport, and multiplication properties in gaseous systems, allowing the development of a very diverse collection of gas detectors, with many directions being pursued to improve the performance in terms of space, time, and energy resolution, as well as rate capability, radiation hardness, and ageing properties.

Wire-based drift chambers represent the standard reference for large volume tracking systems, although Time Projection Chambers have superior momentum resolution and are the device of choice for lower rate environments such as the Linear Collider, drastically reducing the material budget [20].

The possibility of large internal charge amplification using elevated electric fields in small multiplication regions is a key advantage of gaseous devices, and many Micro Pattern Gas Detectors (MPGDs) ideas have been and are being developed, taking advantage also of the advances in semiconductor industry technology [21]. The basic concept of MPGDs is to employ μm-resolution lithography to obtain zones with very large electric fields where gas gains of several orders of magnitude can be obtained. Pioneering devices in this field are the Micro Strip Gas Chamber (MSGC) [22], mimicking the structure of a multi-wire proportional chamber with metal strips deposited on an insulating layer, the MicroMega, where the ionization and the multiplication regions are separated by a micro-mesh electrode, and the Gas Electron Multiplier (GEM) [23], where microscopic multiplication holes are lithographically etched in a metal-coated insulating foil. Variations and evolutions of these basic structures are under study by several groups.

In all cases, removal of back-flowing ions is a major issue for operation at high rate, with sophisticated electrical structures devised to keep them under control. Chemical addictives to base noble gas mixture are also essential to control the ageing properties and reduce photon feedback. MPGDs, possibly directly coupled to custom high density readout electronics integrated circuits on one side, and to a photocathode on the other side, with space resolution of few tens on μm and sensitivity to either charged particles or photons, or both, are becoming increasingly crucial in many detection systems such as the TPC, to readout the large gas volume; or particle identification and calorimetric systems, to detect the photons produced in Cherenkov radiators or scintillating crystals.

3. Particle Identification and Photon Detection

Particle identification plays an essential role in detector design, because of its power to select signal events and separate the wheat from the chaff even in the presence of severe background. While π/μ separation relies primarily on penetration depth techniques, e/π, π/K, and K/p identification requires a velocity measurement, which rests experimentally on three legs with different ranges of momentum sensitivity: dE/dx, time-of-flight (TOF), Cherenkov and transition radiation, ordered from low to high momentum. Often these techniques need to be combined to provide optimal performance, as, for example, in the ALICE detector, that uses all of these techniques to provide complete and redundant particle ID over the full momentum range [24].

The community has developed an admirable workmanship in the design and construction of radiators as well as of the light transport system, with many different options: gas, solid, liquid, aerogel, at low or high temperature. Since the PID system is usually confined between the tracking and the calorimetry system, with severe constraints both on the geometry and on the amount of material, many clever techniques have been developed, especially in experiments where heavy flavour particles play central roles in the physics program.

It has been demonstrated in Babar that a suitably polished quartz bar can be used as both a radiator and a minimally-distorting light guide allowing the placement of the light detection system outside of the active volume. Evolutions of this technique are being developed for the “Focusing DIRC" proposed in SuperB [25], the “Time Of Propagation" (TOP) counter in Belle-II [26], in which both the position and arrival time of Cherenkov light is measured with high accuracy (40 ps), and for the “Time Of internally Reflected Cherenkov light detector" (TORCH), a proposed (15 ps) TOF system for LHC-b [27].

To reduce material, lower index of refraction radiators are used for the higher momentum region, although the lower photon yields must be compensated for using for instance very sensitive photo-detectors and optical focusing systems, such as spherical mirrors, or devising clever arrangements of radiator material, as employed in the focusing aerogel system [28]. In this system, slabs of aerogel with different indices of refraction are stacked in such a way that photons emitted at slightly different positions with slightly different angles end up in the same location of the photon detector, giving a higher photon yield without the blurring effect of a thicker radiator.

3.1 Photon detector

Photon detector are essential components in many particle identification (and calorimetry) systems. The most relevant performance requirements are: high gain in magnetic field ($> 5 \cdot 10^5$); good time resolution ($\ll 100\,\text{ps}$); fine granularity, long lifetime; very high detection efficiency (often down to single photon); high rate capability (several MHz/cm^2). Evolution of the traditional

PhotoMultiplier Tube (PMT) technology, such as the Multi-Anode PMT (MaPMT) and the Multi-Channel-Plate PMT (MCP-PMT) can meet many of these challenges, but tend to be expensive and usable only for relatively small areas. For large area application a combination of a scintillating crystal such as CsI and a micro-pattern gas detector can be cost effective, as long as time resolution is not an issue [29].

Various R&D efforts are ongoing to enlarge the area of the multichannel plate system. A particularly promising one is the Large Area Picosecond Photodetector (LAPPD), employing dual MCP foils obtained by atomic layer deposition on inexpensive glass substrates, showing picosecond level time resolution on large areas and a modular design usable to cover large surfaces at a fraction of the cost of other systems [30].

Solid state photon detector represent a cost effective alternative to PMTs, and are in addition insensitive to magnetic field. The main families of such detectors are: photodiodes with no internal amplification; linear avalanche photodiodes (APD); silicon photomultipliers (SiPM), formed by a large array of very small avalanche photodiodes operated in Geiger mode and reaching a gain of 10^5. Extensive effort is ongoing to optimize both the individual devices and the system design to improve the performance: increase gain, reduce dark count rate, improve radiation hardness. It would not be surprising if in the future solid state devices almost completely replace PMTs, much in the same way as transistor have replaced vacuum tubes and LED screens CRTs.

4. Calorimetry

The energy measurement is an central element in modern detector design, providing essential physics tools such as photon and π^0 reconstruction, electron identification, jet and energy flow measurement.

Homogeneous crystals offer the best possible energy resolution for electromagnetic showers; many different variations, such as NaI, CsI, PWO, LYSO, have been developed over the course of the years, also because they have many applications outside basic research, among which positron emission tomography imaging systems and homeland security [31]. Light yield, radiation length, decay time, and radiation hardness vary enormously among the different materials and are extremely sensitive not only to voluntarily introduced dopants, such as Tallium in CsI, but also to any undesired impurity that might be present in the high temperature crystal growth plants, making the reliable fabrication of crystals with stable characteristics quite difficult and expensive.

LYSO is the king of crystal, with large light yield, fast response, and very good radiation hardness, making it the material of choice for low energy high rate systems. Energy resolution of a few percent at 100 MeV has been demonstrated [32]. In spite of all the efforts to reduce the industrial cost of LYSO, it remains prohibitively expensive for most large scale applications. The cheaper crystals with fast response, such as pure CsI and PWO, have very low light output, making the development of appropriate photosensors a challenge, especially for low energy applications. Since both cost and space resolution considerations limit the crystal size to about the Molière radius, the mechanical structure plays an important role in the resolution of the overall system and sophisticated designs based on composite materials have been realized for large scale systems.

In sampling calorimeters, which are the only practical solution for higher energy ranges and for hadronic calorimetry, an absorber material (W,Fe,Pb) triggers the shower development, while interleaved active layers (scintillator, gas or solid state detectors) provide a charged multiplicity measurement. They tend to have poorer linearity compared to homogeneous systems and different response to the electromagnetic and hadronic components of the shower; several techniques have been explored to improve their performance.

Imaging calorimeters, such as CALICE, take advantage of technological developments allowing cost and size reduction in solid state and gas detectors to decrease the sampling readout granularity at the expense of a large increase in readout channels, from the half million of today's systems to $10^7 \div 10^8$ foreseen for ILC [33]. The Particle Flow Algorithm, following individual particles in the shower, can correct for nonlinearities and e/h response differences, and has demonstrated a factor 3-4 improvement in resolution compared to standard techniques. Quite obviously high granularity can make the system prohibitively expensive, and efforts are ongoing to engineer and industrialize the fabrication of the sensor and readout electronics and their insertion into the absorber material, typically tungsten [34].

To overcome the energy resolution limitations caused by $e/h \neq 1$, compensating hadron calorimeters exploit a clever selection and arrangement of absorbing material, for instance by using uranium. A very promising different approach has been explored by the DREAM project, based on the independent measurement of scintillation and Cherenkov light in showers. Since the latter is mostly produced by the electromagnetic component, event-by-event e/h corrections can be applied, significantly improving resolution. The principle has been successfully tested on copper fiber calorimeters, but it can be in principle also applied to homogeneous crystals, as long as one can distinguish the two components, for instance exploiting their different time structure or wavelength [35].

The possibility of obtaining the best of the two worlds is investigated in sampling calorimeters with scintillating crystal like LYSO as active layer and "shashlik" readout, obtained with wavelength shifting fibers traversing the crystal tiles through holes along the depth of the calorimeter. The crystal layers, by s measuring the residual energy of the lower energy particles in the shower, provide significantly better resolution than scintillator readout.

5. Electronics, Trigger and DAQ

Even very performant sensors are deaf, dumb and blind without good readout electronics, trigger, and data acquisition systems, which have become an integral and essential part of any experiment design. Complexity and pervasiveness of electronics in modern detectors requires sophisticated electronic design and simulation tools as well as the ability to integrate the design all the way from ASIC to system integration, for instance through systematic use of a Hardware Description Languages such as VHDL. Distributing and sharing tools and knowledge across large engineering teams and multiple organization, as well as training the designers to the newest technologies and design techniques are major challenges. Since High Energy Physics production volumes are incredibly small compared to consumer electronics, access to the most advanced technologies is limited or too expensive; multi-project wafers and shared runs are the rule in the designer community and the very latest technology is often out of reach. For instance the HEP designers have currently access 65 nm CMOS technology, while the most advanced processor in the industry are already in 32 nm technology since already a few years.

Trigger/DAQ systems require increasingly large local intelligence and transmission bandwidth. This is obtained using fast and large Field Programmable Gate Arrays for information processing, organized in boards communicating on fast industrial buses, such as VME and more recently μTCA, then connected to computing farms through fast optical links running at 10 Gb/s. Large and fast network switches play an essential role in event building and processing, and allow for a greater portion of the trigger decision to be taken in software, with sophisticated algorithms.

On the other hand, in high rate hadronic experiments, the readout bandwidth can be easily saturated by uninteresting minimum bias events, thus losing good physics events, which no software trigger can recover. Local on-detector information processing is essential to provide sophisticated trigger primitives to be applied before data transmission. One of the most powerful tools is the associative memory based track trigger, where detector hit patterns are used for a fast extraction from a content addressable memory of approximate track parameters which can then be combined to trigger directly on heavy flavour secondary vertices. The system has shown its effectiveness in CDF and is currently proposed in different forms for LHC experiments [36].

Modern technologies allow the integration of significant intelligence at the sensor level and many different lines of development are being explored, like local hit clustering for strip and pixel detectors, local energy summing for calorimeters, local track segment finding.

6. Detectors for Neutrinos and Dark Matter

Detectors for Neutrinos and Dark Matter (DM) searches share similar technological challenges caused by the elusiveness of the particles they need to detect. For neutrinos the interaction is known, albeit small, whereas for dark matter we are definitely groping in the dark. In both cases extremely massive and very low background detectors are required.

6.1 Indirect DM Search

Indirect search experiments strive to detect standard particles generated in annihilation of unknown DM particles [37]. Ground based experiments require very large (km^2) arrays of detectors looking for radiation emitted by atmospheric showers initiated by cosmic rays that can originate from DM annihilation. The main components of this radiation are Cherenkov and fluorescence light emission but other frequency ranges are also possible, with devices developed to detect radio and microwave emission from atmospheric showers.

Satellite experiments, instead, can directly detect the products of DM annihilation, requiring thick detectors ($30X_0$) with percent level energy resolution, good angular resolution and good e/p separation. These experiments require tracking devices coupled to good calorimeters surrounded by veto devices, with very severe requirements on low power, low mass, and space operation compliance. The community has admirably developed the ability to build detectors that can be deployed and operated in space.

6.2 Direct searches

In direct searches one has to detect an unknown particle with an unknown, but certainly small, interaction. Many different approaches are possible for different DM candidates [38].

Axion detection is based on their interaction with strong electromagnetic fields. In particular they convert into microwave photons in an RF cavity threaded by a strong magnetic field. The ADMX experiment uses very sensitive superconducting Squids to measure the effect.

Weakly Interacting Massive Particles (WIMPs) detection, instead, requires sensitivity to different signals produced in their interaction with atomic nuclei: ionization charge; scintillation light; heat phonons. Ideally one would like simultaneous sensitivity to multiple signals, to reinforce the evidence of any discovery and reject background.

WIMP detectors require large mass and high purity, low energy ($< 100\,\mathrm{keV}$) nuclear recoil, and a low enough background to be able to measure 1 event/ton/year at a $10^{-47}\,\mathrm{cm}^2$ cross section. In order to be shielded from ordinary cosmic rays, experiments are installed in underground laboratories and surrounded by a background veto system, with the ability to measure residual background in situ.

Homogeneous pure crystals, such as CsI, NaI, Ge, Si and others, can be the basis for kg-scale detectors. As background reduction is a crucial element, ongoing developments try to improve the radiopurity of the produced crystals, the shielding design, and the energy resolution of the crystal. Some crystal experiments (such as DAMA/LIBRA, ANAIS) only detect one kind of signal (scintillation in NaI), while other experiments (such as CDMS, CRESST) have developed cryogenic techniques to simultaneously detect ionization and phonon signals. Many different approaches are being investigated, including, for instance, the use of fully equipped low noise Si CCDs for ionization charge detection (DAMIC), or combining neutrinoless double-beta decay searches with WIMP detection in ^{76}Ge (IGEX) or TeO_2 (CUORE). Current experiments typically use few tens of kg, and upgrades are planned to reach the few hundred of kg.

For larger detector masses (liquid) noble gas systems have been used and are the subject of intense developments. Hundreds of kg detectors have been realized and several experiments (LUX, Darkside, Xenon) are planned at the ton scale. In TPC-based detectors, both the scintillation (prompt) signal and the ionization (delayed) signal are readout, allowing for very powerful background discrimination. Careful studies of the details of the sensor medium response, for instance the nuclear recoil light yield as function of the drift electric field, are needed to properly calibrate the detector. Dual phase TPCs use the liquid phase for the WIMP conversion and an anode-separated gas phase for internal ionization charge multiplication. Micropattern technologies developed for tracking gas detectors (for instance the GridPix array [39]) can also be used to improve charge detection efficiency.

With a novel approach, the NEXT experiment plans to use a high pressure Xenon *gas* TPC, thus significantly reducing the fluctuations in energy partition between scintillation and ionization and improving energy resolution at the level of 1% at 662 keV [40]. The resulting improved background rejection capability can be put to use both for neutrinoless double-beta decay and WIMP searches.

7. Applications

Detectors originally developed for high energy physics experiments often find application in other fields, among which for instance medical imaging, cultural heritage preservation, and photon science, bringing additional benefits to the overall technological advancement of society.

Many digital imaging systems have been developed starting from the technology of radiation detectors for physics. One very recent development, also giving rise to an industrial spin-off, is the PIXIRAD detector, employing a large CdTe sensor coupled to a custom designed CMOS ASIC to provide chromatic photon counting for X-ray imaging [41]. This technique should improve contrast and resolution, and provide extra diagnostic tools.

Positron emission tomography (PET) is a powerful diagnostic tool whose core is the 511 keV photon detector; many improvements to the established PET technique are under study in the detector physicists community. For instance the possibility of measuring the interaction depth of the photon in the Axial PET development would provide better efficiency and space resolution, thus allowing a reduction in patient dose [42]. The impressive endoscopic PET development deploys a miniaturized multisensor head inside the patient to detect one of the photons, while also providing ultrasound imaging, reaching a $30\,\mu m$ resolution, crucial for diagnosing certain classes of tumors [43].

New challenges come from the field of photon science and in particular from high brilliance Free Electron Lasers which, besides allowing sophisticated experiments in atomic and molecular physics, provide a very powerful research platform for other fields, like biology, chemistry, material science. The extremely wide range of photon energies, from 0.1 eV to 10 keV, and the high dynamic range (10^4) require dedicated detector developments with different technologies, that can often operate synergetically with developments for HEP experiments. For instance high resolution, high speed, high bandwidth, radiation hardness are all common requirements that can benefit from the same basic technology development.

8. Conclusions and Outlook

If detectors are the tools with which we can perform physics research, they also provide numerous applications bringing general advancement to society. New technologies require a long time to mature, typically not less than 10 years, and often very large costs, calling for a general coordinated action in the field. In addition, the transition from the R&D phase, always pushing for an ever improving performance, to the production phase, where a usable and stable detector system is needed, is triggered by construction and data taking plans of the experiments, once again calling for a general coordinated action.

As a field we need to maintain and develop detector expertise. Today's detector marvels are not automatically reproducible by the next generation of scientists. It is clear that detector R&D programs need to receive adequate funding and support from agencies, but this may not be enough. Three essential elements need to be put in place to maintain the expertise: *training*, for instance organizing and stimulating participation in instrumentation schools and providing good instrumentation classes in standard courses; *experimenting*, encouraging young experimentalists to do hands-on detector work especially in smaller, shorter time scale experiments; *rewarding*, giving proper recognition of excellence in instrumentation development in careers at universities and research institutions.

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