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RELIABILITY ISSUES IN ELEMENTARY PARTICLE PHYSICS EXPERIMENTS

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***Abstract* – We discuss the main reliability issues in present and future electronics equipment in elementary particle physics experiments. Aspects related to presence of high magnetic fields, ionizing and non-ionizing radiation and their effects on active electronics devices are briefly reviewed. Moreover, we also describe the constraints on the design issues due to the long lifetime of the experiments and to the reduced accessibility to the system, which is possible only during well-defined scheduled downtime periods.**

I. INTRODUCTION

Elementary particle physics experiments can be thought as complex measuring instruments. Thanks to them we can measure the properties of elementary particles (as their mass or lifetime) and of their interactions. The LHC (Large Hadron Collider) [1] - the most powerful proton-proton collider every built – is successfully operating at CERN since 2009 and has reached a center-of-mass energy of 13 TeV. ATLAS [2] and CMS [3] are two multi-purpose experiments built to exploit the LHC collisions. These are the two biggest experiments of this kind ever built and are the two experiments that in 2012 announced the discovery of the Higgs boson [4][5].

II. STRUCTURE OF A PARTICLE PHYSICS EXPERIMENT

The most interesting elementary particles have a very short lifetime (e.g., the Higgs boson has a lifetime of 10^{-22} s), and they decay as soon as they are produced in the collisions. So they cannot be observed directly but only through the stable particles (such as photons, electrons, muons and pions) produced in their decay. An experiment like ATLAS or CMS consists of a series of layers of detectors placed around the collision point to measure momentum, energy and direction of the particles. Usually the detectors are arranged in a barrel region with a cylindrical geometry around the beam axis and two endcap regions, with disk geometry, at both ends of the barrel region, to complete as much as possible the angular coverage of the detector. In ATLAS (see Fig. 1), for example, the innermost layers consist of silicon detectors

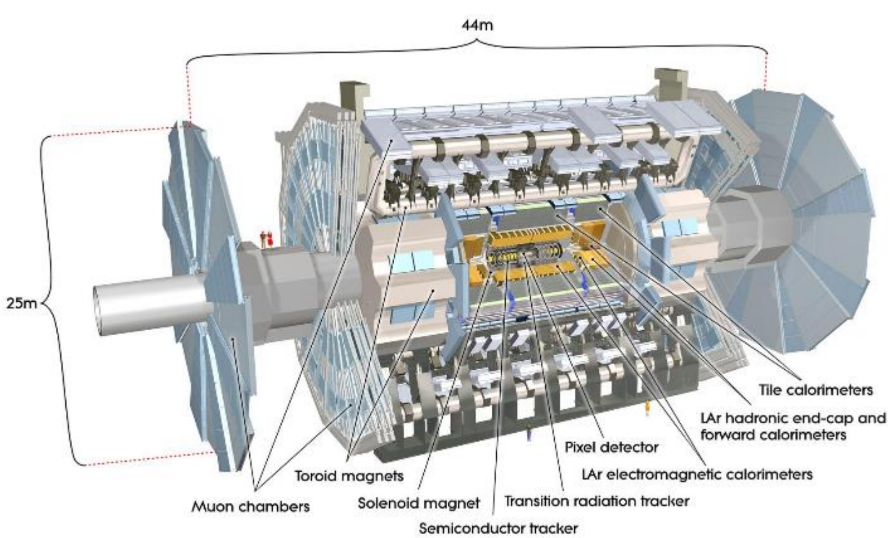

Fig. 1. Pictorial view of the ATLAS detector and of its subsystems.

(with pixel or microstrip geometry), and are followed by a drift tube detector with transition radiation detector capability. These detectors are placed in a large solenoidal magnet about 2.5 m in diameter and 5.8 m in length, which produces a magnetic field of 2 T. Charged particles ionize the detector materials, creating an electrical signal that can be detected. Signals detected in various layers allows to reconstruct the trajectory of the particle. Moreover, the magnetic field bends the trajectories of the tracks and makes it possible to measure their charge and momentum. Outside these tracking detectors we find calorimeters which measure the energy and directions of electrons, photons and jets of hadrons, through total absorption in the detector material. Outside the calorimeters we find separate trigger and high-precision tracking muon chambers. Muons are deflected by a system of three large air-core toroids (one barrel and two end-cap systems) each consisting of eight superconducting coils. The barrel (endcap) toroid provides a toroidal magnetic field of approximately 0.5 (1) T in the barrel (endcap) muon detector region.

Overall ATLAS has a length of 44 m, a diameter of 25 m and a weight of 7000 t. In total it has around 100.000.000 readout channels. The detector occupies almost entirely a 53m×35m×30m (L×H×W) cavern located 92 m below ground which communicate with the surface by two vertical access shafts, each wide 13 m and 18 m.

III. MAIN ISSUES

Several issues affect the operation of a particle detector.

A. Radiation Damage

Radiation damage to the detector and to the associated electronics can have different origins. The particles created in the proton-proton interactions represents a background of ionization radiation. There is also a Non Ionizing Energy Loss (NIEL) contribution from collisions between these particles and the detector or support structure material. The ionizing dose is expressed in Gray ("Gy") or "rad" (1 Gy = 100 rad) while the NIEL is usually expressed as the fluence of particles causing a damage equivalent to that of 1 MeV neutrons traversing 1 cm^2 of a sensor's surface. Radiation effects on the electronics can be due to the so-called Total Integrated Dose (TID) or on Single Events Upsets (SEU) (or SED, Single Event Damage). In the first case the degradation or complete failure of one component is due to the slow accumulation of radiation damage over long periods of time during which the experiment is running. At the end of the so-called Phase 2 (see Sec. III.C), at a radius of 40 mm from the beam line (the radius of the planned innermost pixel layer) the projected radiation dose is ~10^{16} n_{eq}/cm^2 and ~10 MGy. The ionizing dose decreases with distance from the beamline and is eg about ~0.3 kGy at the radius of the Lar calorimeter electronics. The NIEL has a more complex distribution that depends on the material position in the experiment and is about 10^{13} n_{eq}/cm^2 at again the position of the Lar calorimeter electronics taken as an example. All the detector material and related electronics installed in the experiment have to be validated to resist at the expected dose in their position, including some safety factors which account for uncertainties in the projected dose values or in the type of electronics (COTS, COTS from unknown multiple lots, ASICs,…). If a component cannot sustain the expected dose, its replacement has to be foreseen during the experiment lifetime in one of the planned down time periods (see Sec. III.C). The most affected detectors are the ones closer to the beam line. Silicon sensors undergo substantial radiation damage which causes an increase of effective doping concentration, leakage current and effective carrier trapping probability. The associated read-out electronics can be damaged by the passage of ionizing radiation in the silicon oxide on semiconductor devices that causes the built up of trapped charge in the oxide layers of the semiconductor. SEU can affect the logical circuitry of the devices. To study these effects specific R&D projects have been started at CERN for both sensors [6] and readout [7]. Another field were a common strategy between CERN and its experiments has been started, has been the development of radiation hard bi-directional optical links for use at the HL-LHC for the transport of data, timing and control signals between the experiments and the off-detector electronics. The data links should resist at the radiation doses reported above, with 5-10 (2.5-5) Gbps data rates in the upstream (downstream) direction, small footprint and high channel count. The development includes the optical components (optical components, lasers and PINs) and a high speed serializer/deserializer chipset. [8]

B. Magnetic Field

The presence of magnetic field up to 2 T (4T in the CMS experiment), poses some constraints on the choice of the commercial devices (COTS) and on the design of custom circuits. This issues are particularly severe for power supplies (mainframes and point-of-load devices) where core coil inductances and transformers are often present. The request to operate in such fields together with the request to be radiation resistance (see previous section) has led to some custom developments for the LHC experiments. For example, a few years ago CERN started an R&D which has led to the production of the DCDC converters of the FEAST family [9]. These are rad-tolerant (positive and negative) DCDC converter modules built around a buck converter, low emitted (conducted and radiated) noise, ASIC switching at 1.8 MHz and using a custom toroidal air-core inductor. The device has an input voltage of 5 to 12 V, continuous 4A load capability and can operate in magnetic fields in excess of 4 Tesla, and up to more than 200 Mrad total ionizing dose and an integrated

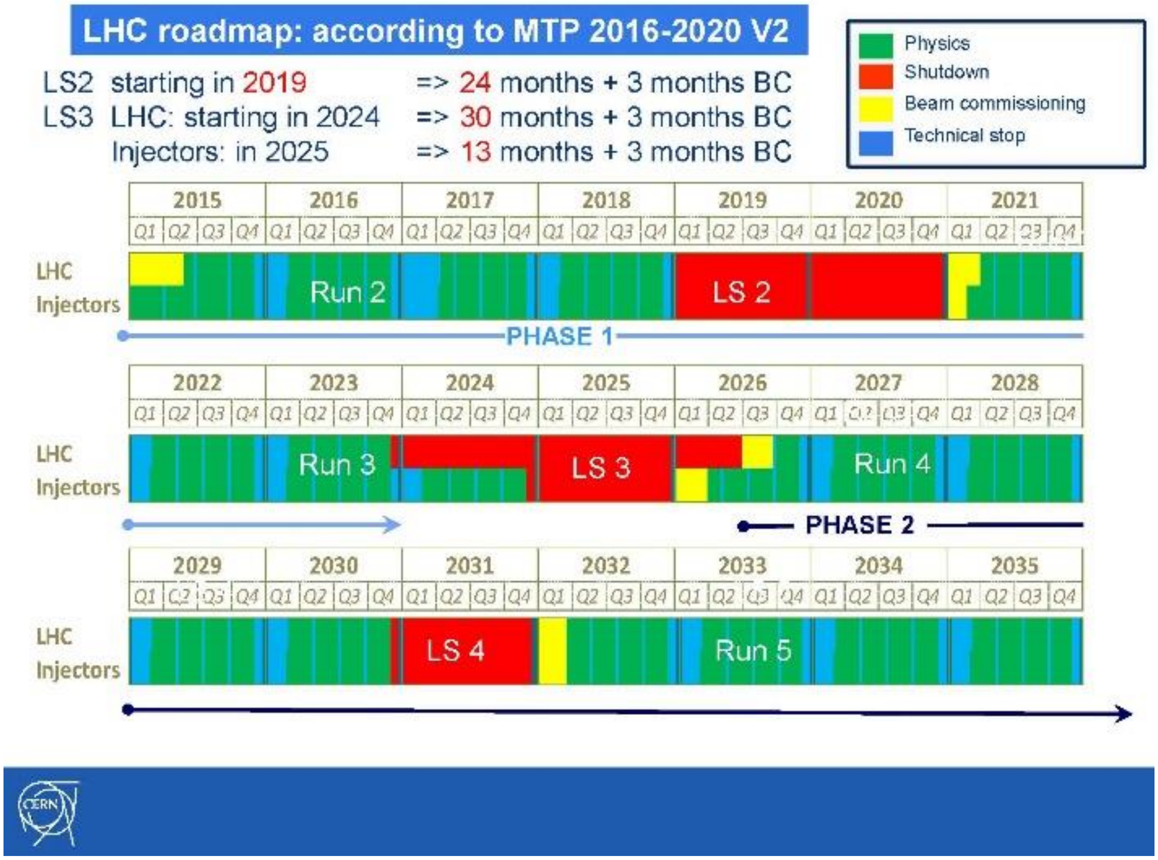

Fig. 2. Outline LHC schedule up to 2035 [25].

particle fluence of $5x10^{14}$ n_{eq}/cm^2. More details on the selection of DCDC converters and mainframes for high-energy physics experiments and results of measurements of electrical propertis, behavior in magnetic field, thermal dissipation and radiation tolerance can be found in [10]-[24].

C. Accessibility

Fig. 2 shows the expected LHC schedule for the next years and up to 2035. Although the exact dates are likely to change in the next years, the global time pattern is not expected to change. LHC alternates data-taking periods (called RUN1, RUN2…) to other periods in which the machine is stopped for maintenance or upgrades, the so-called "Long Shutdowns" (LS1, LS2). The LHC Phase 1 extends up to the start of LS3. At that point a substantial upgrade of the LHC machine will lead to the high luminosity runs of Phase 2 (HL-LHC). The machine also stops for shorter "Technical Stops" (TS) during data taking periods and at the end/beginning of each year, for the so-called "Year-End Technical Stops (YETS)".

Access to the detectors for maintenance or upgrade is carried on in the shadow of these machine stops. Brief (~hours) access to the experimental area during running are possible when the LHC stops for some problems and are limited to quick module swapping or fixing for the electronics that is easily accessible (like some electronics racks located on the cavern walls). Longer intervention is possible during the TS and the YETS while substantial detector upgrades are only possible during the LS.

IV. CONTROL AND MONITORING

Successful operation of the detector requires that it can be safely brought into its operational state and then constantly monitored. This is the task of the Detector Control System (DCS) [26] that additionally archives the operational parameters and signals any abnormal behavior allowing for automated or operator-assisted recovery procedure. For each of the various subdetectors of which ATLAS is composed, the monitored quantities include high voltage, low voltage power supplies (and their currents), temperature of detectors and of the electronics, pressure of detector and cooling gases, etc...

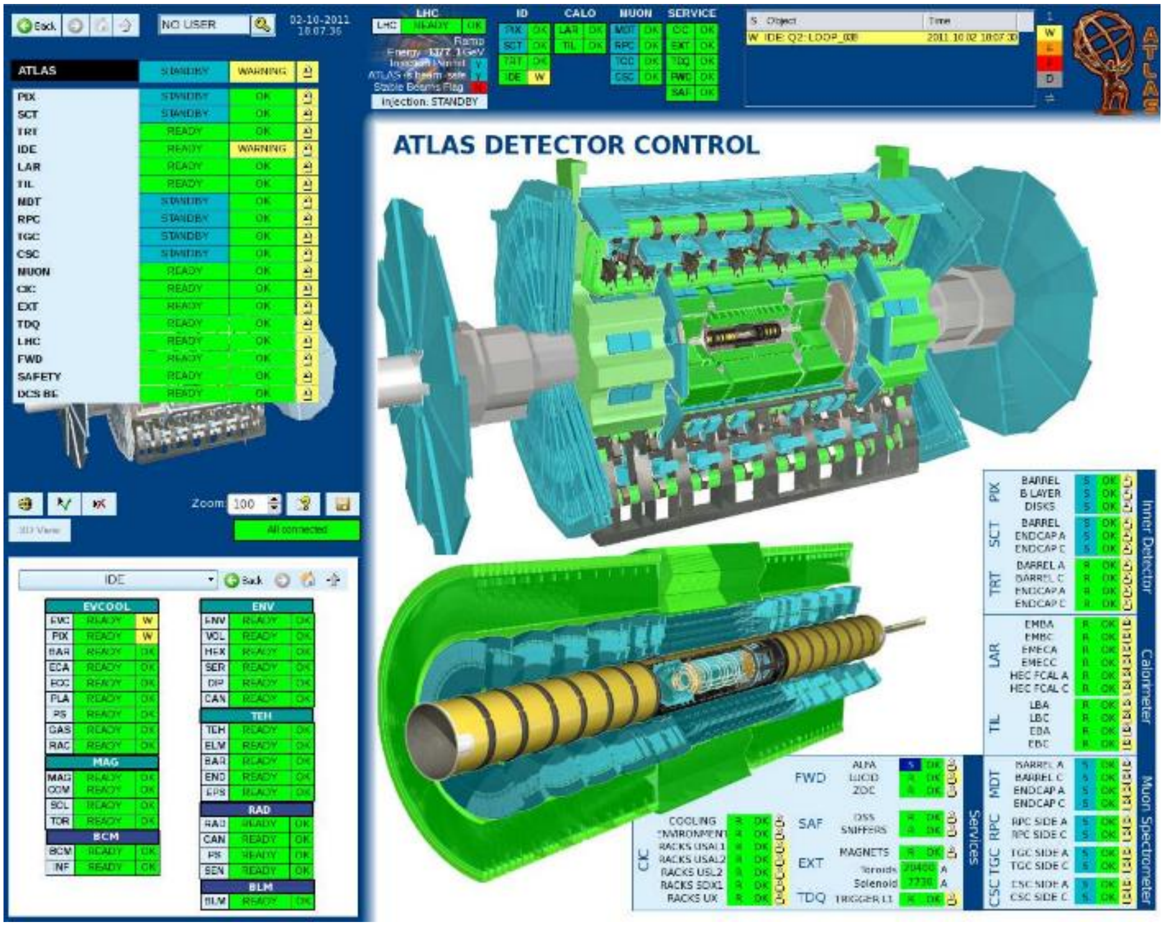

Fig. 3. Finite State Machine showing the status of the ATLAS detector during data taking. The detector is in STAND-BY mode, as it is usually during LHC ramp up.

The front-end part of the DCS includes all the I/O devices used to capture the analog or digital measurements and tunnel them to the back-end for saving and displaying. It consists of devices embedded in commercial units (like some of the power supplies used in ATLAS) and of custom devices called Embedded Local Monitoring Board (ELMB). These are I/O devices which provide a certain number of digital and analog channels, include a microcontroller, a firmware that can be remotely reprogrammed and can also embed custom designs. The communication of these devices, and of most of the other commercial devices in use, is based on the CAN fieldbus and the CANopen protocol.

The DCS back-end is implemented on commercial, rack-mounted server machines running the SCADA software SIMATIC WinCC [27] as main framework. This framework provides scalability, platform independence, interface to relational databases (Oracle) and a built-in alarm mechanism. Moreover, individual control systems (eg the atlas subdetectors) can be connected via LAN to form a “distributed system”.

The front end is interfaced to WinCC (apart for a few exceptions handled differently) using the OPC standard. The OPC server is provided by the commercial unit manufacturer or, as for the ELMB, custom-developed. For platform independence (the OPC standard is limited to MS Windows) and additional features, a migration towards OPC UA (Unified Architecture) is on-going.

The back end is mapped into a hierarchy of Finite State Machine (FSM) elements. A fixed state model is applied to reflect the detector condition, i.e. if the detector is ready for data taking, is turned off or is in some transient or compromised state. The actual state of each logical block of the FSM is determined by the states of the associated lower level objects (children) via state rules. In this scheme state changes are propagated upwards and “actions” can be defined for each state and propagate downwards in the hierarchy to allow for the operation of the complete detector (or part of it) by means of topmost levels.

Overall the ATLAS DCS is run on about one hundred stations and is based on the event driven processing of more than 10.000.000 data elements.

V. CONCLUSIONS

Elementary particles physics experiments pose severe constrains on the electronics instrumentations to be used in the experimental area due to the harsh environment: high radiation doses, magnetic field, scarce accessibility to the system during long data-taking periods. We discussed in detail the design challenges faced and how they have been addressed for the current detectors. Perspective for the future HL-LHC runs, where most of these problems will be amplified, were also addressed.

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