Radiation Hardness of Trigger Electronics

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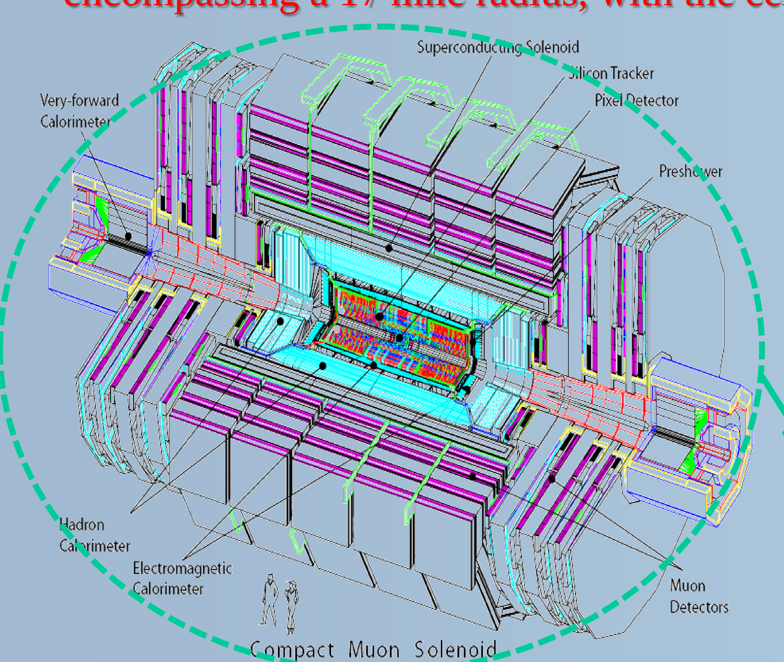
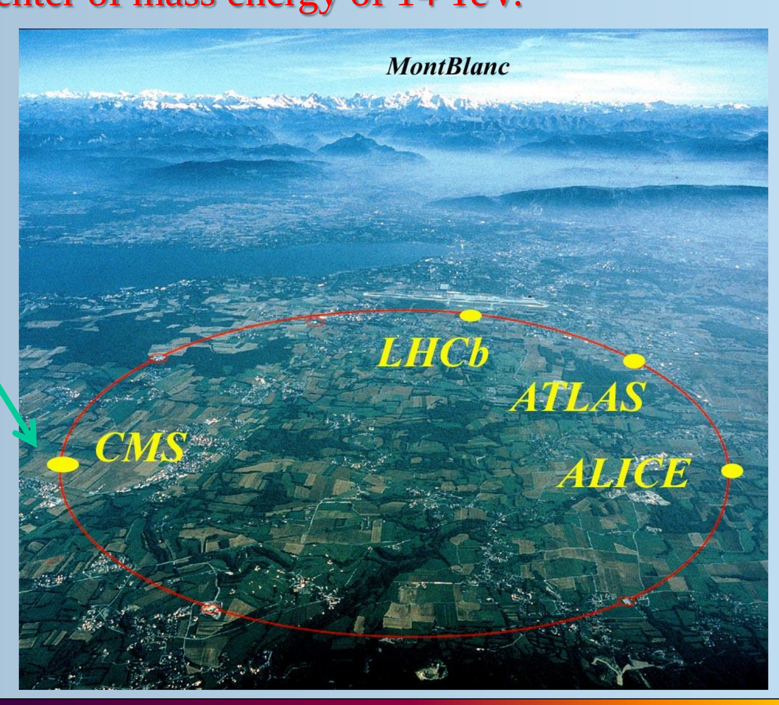
THE STANDARD MODEL OF PARTICLE PHYSICS

The Standard Model (SM) of Particle Physics has been a major success in describing the hierarchy of fundamental particles comprising visible matter in the Universe and their interactions, providing an important insight into the evolution of the Universe. Despite its many successes, our understanding of the elementary particles is incomplete, e.g. the SM cannot explain the hierarchy of particle masses, origin of dark matter or incorporate gravity in the same way as other known forces. Furthermore, one of the critical parts of the SM, the Higgs boson responsible for giving particles their masses, has not yet been observed experimentally, prompting further studies.

LARGE HADRON COLLIDER – LHC

Conditions of the early Universe can be reproduced with particle colliders, where there is an abundance of all kinds of particles. These machines accelerate "everyday" particles to relativistic speeds before colliding them at high energies allowing for the production of heavy particles, e.g. the Higgs boson, which will quickly decay into lighter particles. To detect the production of a new particle, experimental detectors are built around the collision point . Detectors identify and retrace the decay products of a collision in order to fully reconstruct the interaction. Currently the Large Hadron Collider (LHC) accelerator in Europe is the world's largest particle accelerator, encompassing a 17 mile radius, with the center of mass energy of 14 TeV.

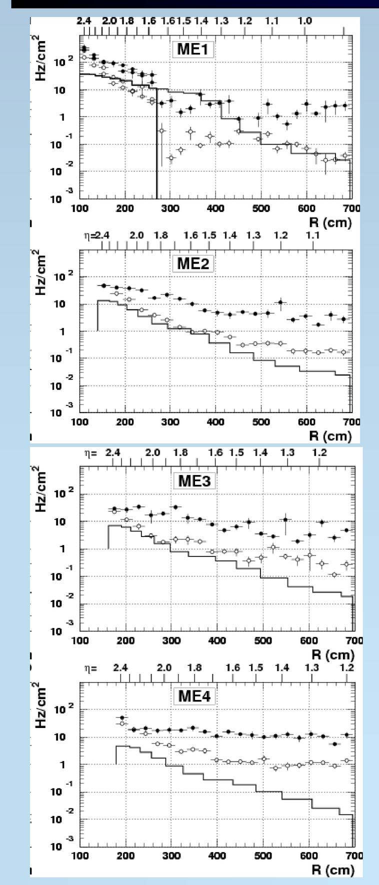




COMPACT MUON SOLENOID – CMS

Identification of stable and semi-stable particles is performed using particle detectors, which are designed to measure properties of particles as they pass through the detector and interact with its material. The Compact Muon Solenoid (CMS) is one of the two flagship detectors at the LHC. In addition to many components designed to identify different particles, CMS utilizes state of the art fast electronics-based data acquisition and triggering systems to select interesting events. Of particular relevance to this study is the CMS Endcap Muon system (including the detector , readout and triggering electronics) designed to reconstruct and identify muons in the LHC collisions. Muons are heavier cousins of electrons and are expected to be among the decay products of the Higgs boson.

RADIATION SIMULATION AND NEUTRON FLUX RATES



Test Data Report (TDR) Simulation Data

Some of the CMS trigger electronics components have to be mounted on the detector in order to maximize the efficiency, which causes them to be exposed to high levels of radiation. The main challenge in terms of radiation effects is posed by neutrons due to their long lifetimes and significant potential for damaging electronics. The major radiation damage seen by electronics are Single Event Upsets (SEUs) and accumulated degradation of silicon components. SEUs are caused by hard neutrons, or high energy radiation, and are a non-permanent corruption of data. An accumulated displacement of silicon crystals occurs when the electronics are exposed to soft neutrons, or low energy radiation.

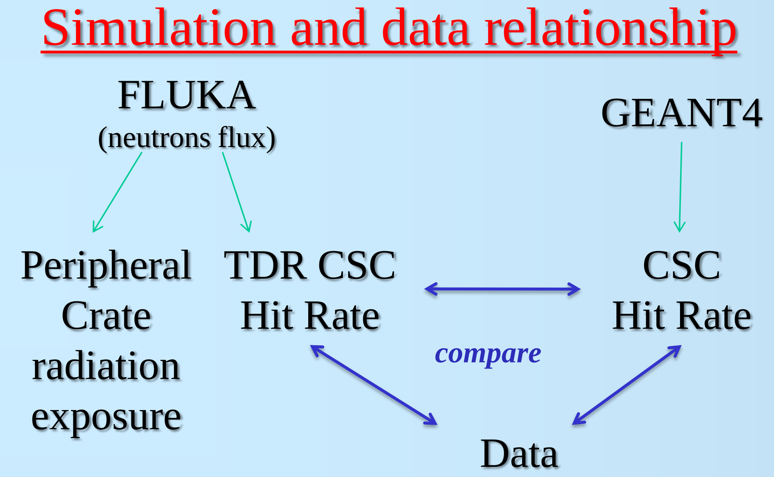
To determine minimal requirements for electronics, one first needs to establish the expected neutron rates. While several simulation-based predictions are available, the reliability of those predictions has long been questioned. A recent measurement of neutron-induced hits in the CMS muon chambers(the flux of neutron-induced hits per layer of CSC chamber) provides an opportunity to check the neutron simulation tools.

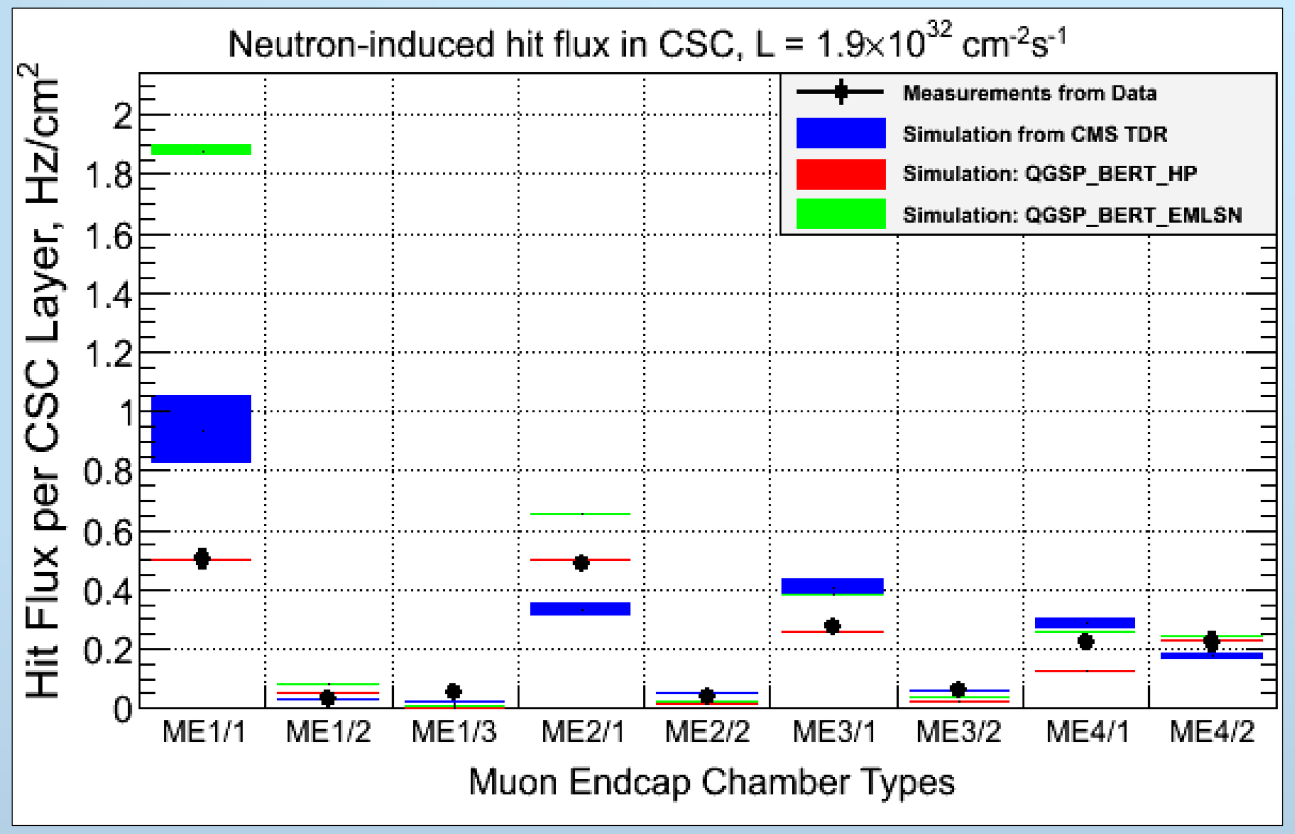
COMPARISON OF SIMULATIONS AND DATA MEASUREMENTS

Three simulation predictions available to compare:

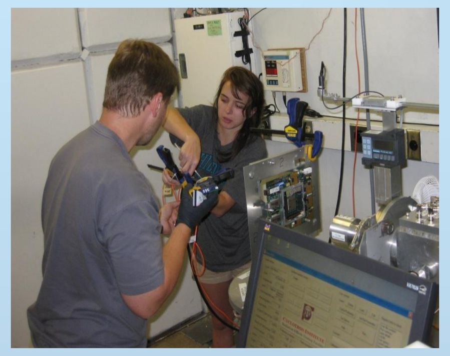
- CMS Technical Design Report (2000) –based on FLUKA simulation program
- GEANT4 package + QGSP_BERT_HP "physics table" (older, no recent data included in the fits, but well validated parameterization)
- GEANT4 package + QGSP_BERT_EMLSN "physics table" (newer, faster, with more recent neutron interactions data, but less validated)

Simulation and data relationship

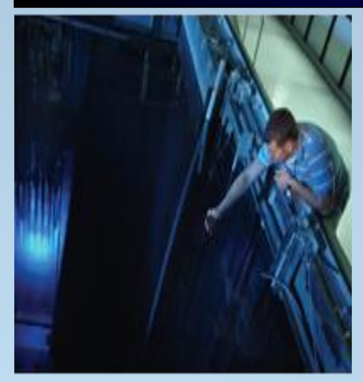


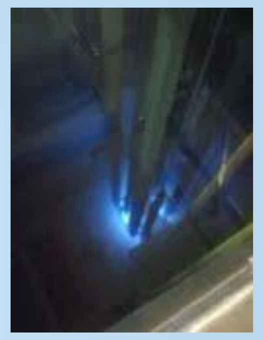


For the most part, the data agrees with the simulation results within an acceptable range. The simulations give a reasonable representation of the actual exposure rates in the CMS cavern.

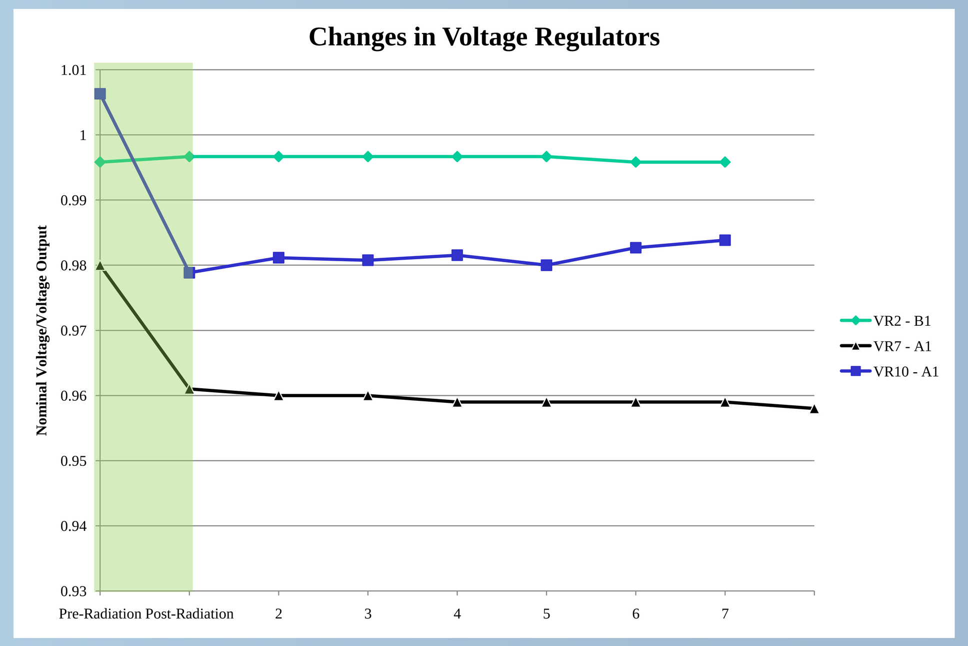


EVALUATION OF ELECTRONICS TOLERANCE TO SOFT NEUTRON RADIATION





We can determine the radiation hardness of several proposed electronic components by soft neutron exposure or irradiation from low energy neutrons. These tests were done at the Nuclear Science Center (NSC) nuclear reactor. The first exposure of neutrons was the equivalent to the total radiation seen by CMS over its lifetime, or ten years of radiation in CMS. The second exposure is soon to follow and will be the equivalent of the next fifteen years worth of radiation to be seen by CMS. The survivability of voltage regulators based on pre and post irradiation data indicates that some circuits will definitely fail, some circuits demonstrate partial recovery due to annealing, and some circuits will continue to work even after being exposed to high levels of irradiation. We found several circuits that meet the requirements for the robust operation of CMS.



CHANGES IN VOLTAGE REGULATORS:

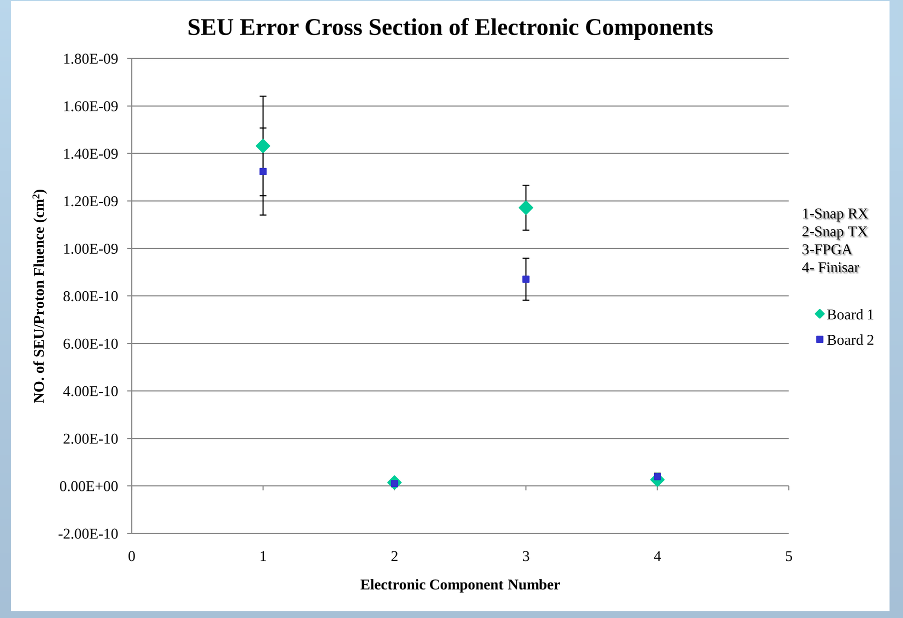
VR2 – voltage remains constant both before and after radiation

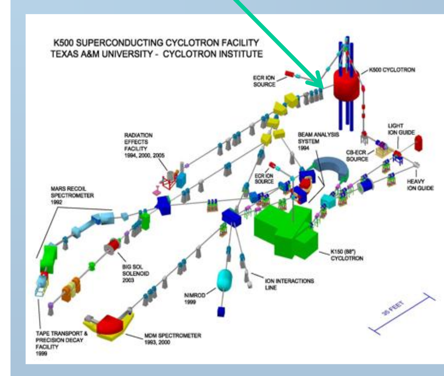
VR7 – voltage drops, seeing no improvement, the chip has serious degradation after radiation

VR10 – voltage drops, but as time increases, voltage also increases; this process is called annealing

EVALUATION OF ELECTRONICS TOLERANCE TO HARD NEUTRON RADIATION

Hard neutron exposure is also required when determining radiation hardness of electronics. In our study, we used a 55 MeV proton beam from the K500 Cyclotron to mimic hard neutron exposure. The K500 Cyclotron uses an ionized hydrogen (proton) beam and observes energies ranging from 8 MeV to 70 MeV. Due to a protons positive charge, the beam can be steered and focused using magnets. In this fashion, we are able to focus and expose each TMB component for approximately 90 minutes, which is the equivalent of one year of radiation exposure seen by CMS. The TMB runs a variety of tests designed to detect SEUs in any of its main components (FPGA, PROM, optical receivers and transmitters, translator chips, optical fibers etc.) during the exposure.





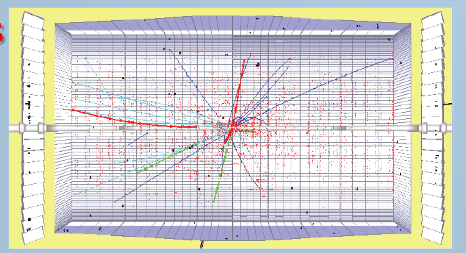
Based on preliminary observations of Cyclotron proton tests, after the beam upgrade at LHC we made the following preliminary observations about the new electronics:

- We will probably see about 3 errors every day on each fiber optic link to the TMB board.
- There might be a logic error in a TMB FPGA about every 5 minutes, but this can probably be mitigated somewhat. We will not know more until further study.
- The FPGA configuration PROM is not susceptible to logic upsets
- The level-shifting translator chips never have any logic upsets

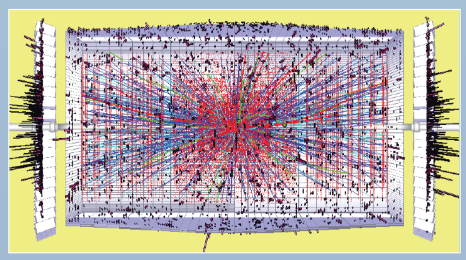
However, these are very preliminary estimates with large uncertainty at this time.

SYSTEM UPGRADE

In order to observe rare processes in a reasonable amount of time, the LHC beams will be further intensified leading to a five fold increase compared to the design LHC luminosity. With an average of 100 pp collisions every 25 ns (compared to 20 in the original design), the CMS detector and electronics will need an upgrade to maintain its performance in the environment with much higher particles rates and densities.

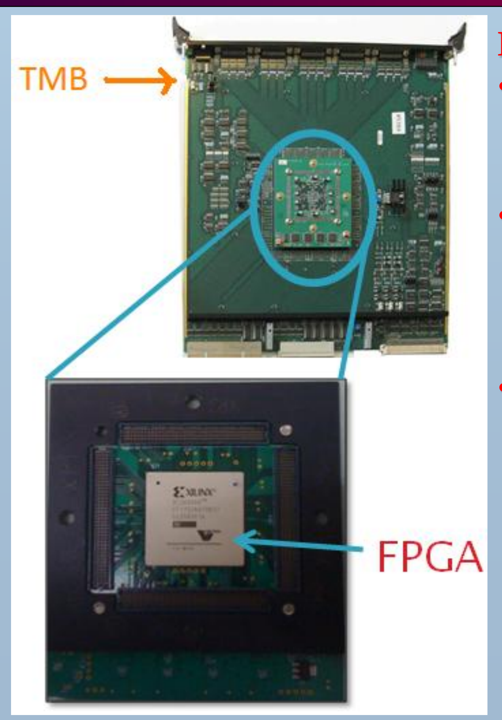


Collision reconstruction at current LHC intensity



Collision reconstruction at upgraded LHC intensity

With many electronics components mounted inside or on the detector, they cannot be accessed or replaced for months or even years. That sets high standards on the quality of electronics components and their ability to provide long term stable operation in the environment of high radiation levels.



Major Requirements for the Electronics and Tests Performed:

- *Operating Stability* – components are evaluated to guarantee consistency in main parameters
  - Voltage and current measurements over extended period of time
- *Temperature Regulation* – the expected operational stability at the temperature that the components will reach in operation
  - Measurement of surface temperatures of the silicon voltage regulators using the *Flir Extech i5* Thermal Imager
- *Radiation Hardness* – ability to sustain high intensity ionizing radiation and maintain operation after substantial accumulated exposure.
  - Irradiate electronics to evaluate its performance as a function of intensity and accumulated exposure expected at CMS
    - High energy (hard) neutrons lead to single event upsets
    - Low energy (soft) neutrons lead to high accumulated exposure

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