# Radiation tolerant digital quench detectors for LHC

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## Quench detection algorithms in digital quench detectors

**General**

A quench of a superconducting magnet is usually detected by the voltage drop over the resistive zone of the quenching magnet. This voltage drop is measured by measuring the total magnet voltage.

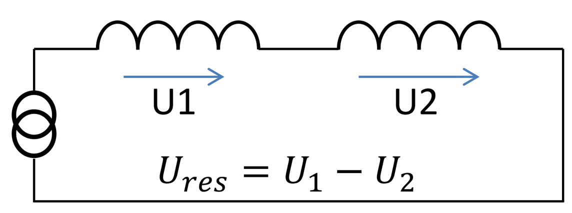
Since the superconducting magnets are inductors, changing currents will cause an inductive voltage:

$$U_{mag} = L * \frac{dI}{dt}$$

One of the main tasks of a quench detection system is the compensation of these inductive voltages as they might be a magnitude higher than the resistive voltage threshold.

**4-6kA magnets**

A very effective reliable and simple method is the "virtual bridge". Two coils of a magnet are compared with each other. If the inductance is identical the following equation applies to detect a quench.

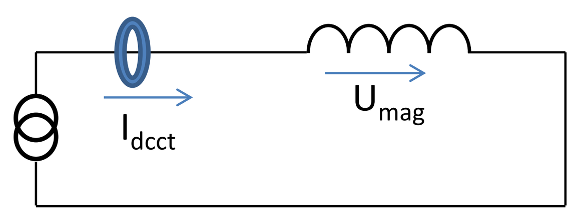



$$U_{res} = U_1 - U_2$$

In many magnet designs it is very unlikely that both coils used for comparison will quench at the same time. Therefore, this simple, yet very effective algorithm can be used. Symmetric quenches (both coils quench at the same time) can be detected by the total voltage.

**600A circuit protection**

Some of LHC's superconducting magnets require more sophisticated algorithms due to the lack of a "middle tap". Given the current and the inductance the inductive voltage can be calculated numerically by the quench detector



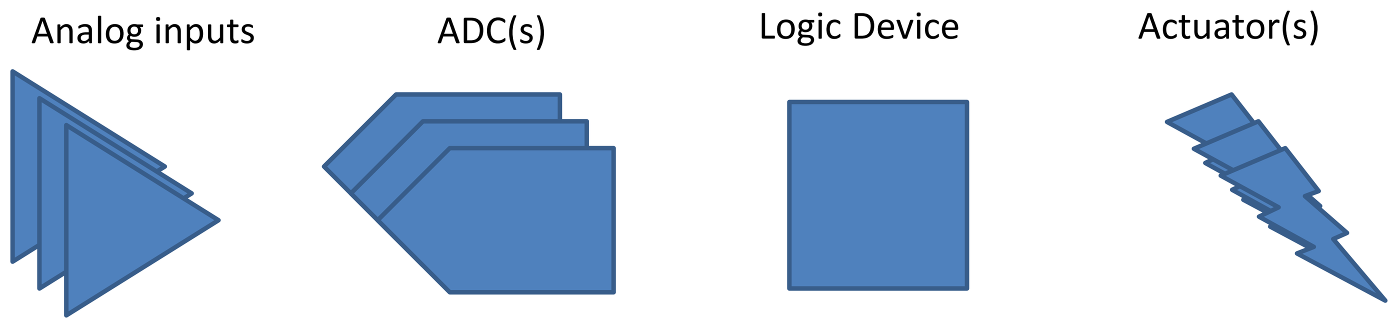

$$U_{res} = U_{mag} + L(i) * \frac{di}{dt}$$

Due to the numerical derivation these detectors need sophisticated filtering to avoid spurious trips. A radiation tolerant quench detector for the 600A magnets will use this technique.

**Symmetric quench detection**

A sophisticated comparison algorithm is used for the symmetric quench detection system which is part of LHC's nQPS system. As the initial QPS system compares the two apertures of a single magnet, a simultaneous quench might not be detected. Therefore the voltages of four consecutive magnets are compared. This method requires additional logic and adaptive filters to perform well in operation.

## General architecture




Analog front end, attenuate/amplify/level shift signal to fit ADC requirements. AALP included

Analog to digital conversion. Resolution 16..24 bit.
Key component in design.

Logic device. Performs quench detection algorithm:
- Filtering
- Inductive compensation
- quench detection

Includes interface to local crate controller

Actuator reacts when quench is detected
Usually current loops are cut. Different implementations with relay (slow)
PhotoMOS (fast)

## Digital logic devices vs. Ionizing radiation

The function of the logic device (micro controller, DSP, FPGA) can be strongly affected by the presence of ionizing radiation. Among others, the most dominant effect in digital logic is the single event upset (SEU) where a single particle alters the content of a register or memory cell.


Digital signal processor


Micro controller


FLASH FPGA

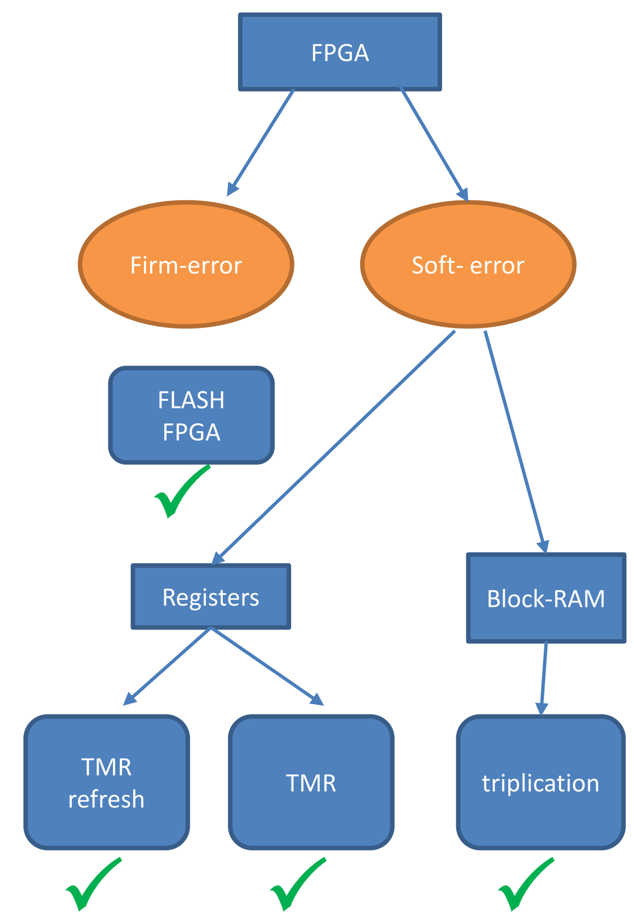
LHCs QPS system uses three different families of logic devices for its digital quench detectors. While DSPs are used for non rad-tol applications, certain micro controllers proved to work well in low dose environments. Flash based FPGAs are the core component of all new rad-tolerant quench detectors.

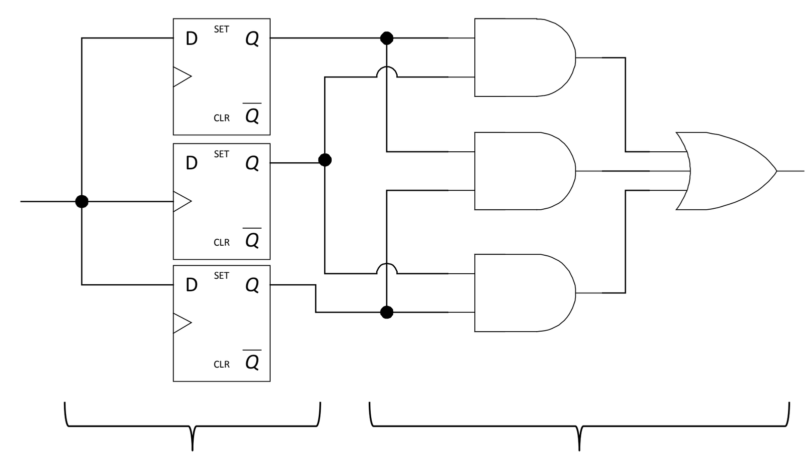
While todays standard FPGAs store their configuration in SEU sensitive SRAM cells, FLASH based FPGAs store their configuration in FLASH cells which do not show SEU sensitivities. With a SEU-hard configuration, the memories and registers of the FPGA are still subject to SEUs. Techniques like triple modular redundancy (TMR) can mitigate the effects of a single event upset. A widely used FLASH FPGA is the Microsemi™ ProAsic3™ family.

## Radiation tolerance

### SEU in FPGA

Using the ProAsic3 virtually eliminates the risk of having firm-errors due to single events. The corruption of SRAM memories and registers are called "soft error". These are handled by either standard TMR, special TMR refresh logic which protects registers without periodic refresh, or manual triplication of block ram structures.



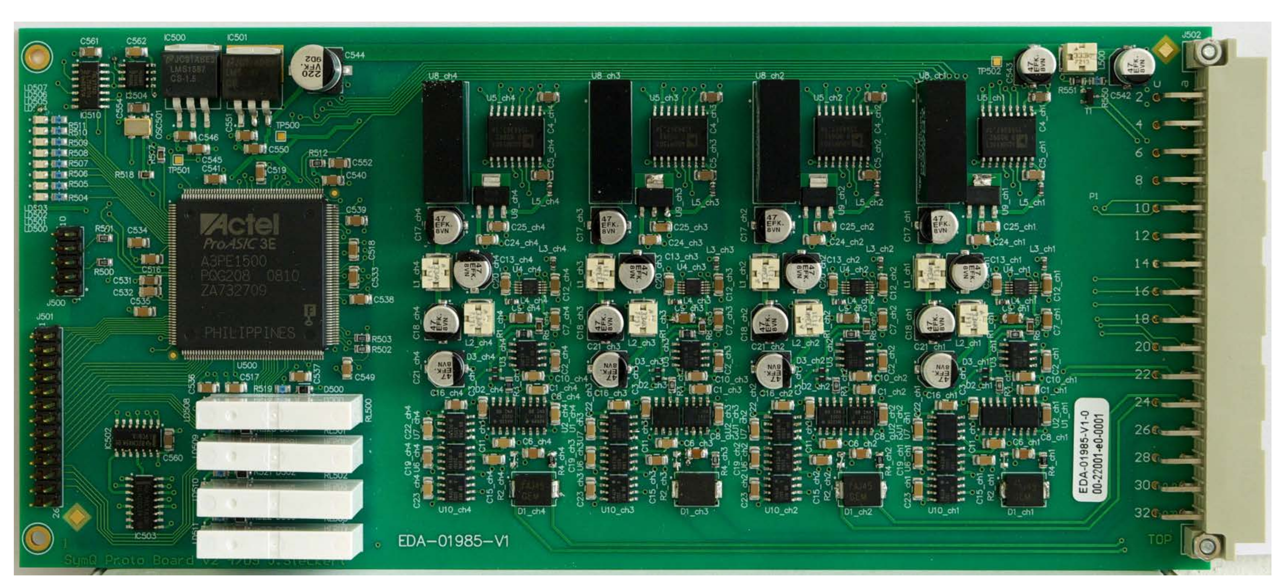

### Radiation to other components

Since most of the areas with QPS electronics receive only low doses of ionizing radiation, the electronic is designed using tested commercial parts. All critical components of the rad-tol quench detectors had been tested in radiation. The focus of radiation testing is on known critical parts. Especially the ADC is vital since the detector fails to work with a damaged/broken ADC. Digital slew-rate limiters or median filters are used to avoid triggers due to single corrupted samples.

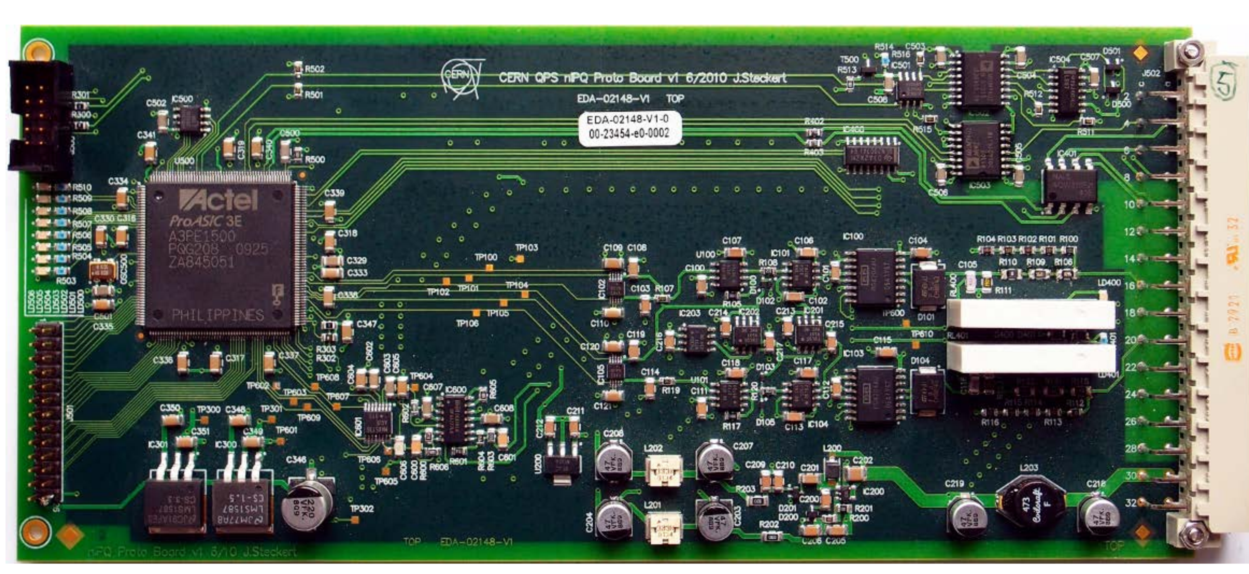
## Specifications of actual detectors

| | DQQDS | nDQQDI | nDQQDG |
|---|---|---|---|
| Type | quench detector, MB/MQ (SymQ) | quench detector, IPQ/IPD/IT | quench detector, 600A magnets |
| Channels | 4 | 2 | 2 |
| Input range | +/- 15V | +/- 10V | +/-10V, +/-5V |
| Resolution | 16bit | 16bit | 24bit |
| Sampling speed | 6.41kHz | 12.1kHz | 16kHz |
| Logic device | Actel A3PE1500 | Actel A3PE1500 | Actel A3PE3000 |
| Galvanic insulation | 2kV ch vs. ch vs. local bus | 2kV vs local bus | 2kV vs local bus |
| Rad tol measures | TMR + slew rate limit | TMR + TMR SRAM + slew rate limiter | TMR + glitch filter |
| Interlocks | Relay | PhotoMOS | PhotoMOS |
| Persistent memory | none | 512kBit flash | 512k + 2M flash |
| Number installed | 1632 since 2009 | 2 since 2012, (200 in LS1) | 0, (200 in LS1) |
| Location | LHC tunnel | RR underground area | RR underground area |

## Devices produced/installed in LHC



DQQDS, symmetric quench detection board. Part of the nQPS system for LHC's super conducting main dipoles and main quadrupoles. 1632 pieces are installed since 2009



nDQQDI, 200 pieces produced to provide and rad-tol upgrade the protection for LHC's individual powered magnets in the RR areas. One test installation since TS3 2012.

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