

PERFORMANCE OF THE ARC DETECTORS OF LHC HIGH POWER RF SYSTEM

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Abstract

During operation, the LHC high power RF equipment, such as klystrons, circulators, waveguides and couplers have to be protected from damage caused by electromagnetic discharges. Once ignited these arcs grow over the full height of the waveguide and travel towards the RF source. The burning plasma can cause serious damage to the metal surfaces or ferrite materials.

The LHC arc detector system is based on the optical detection of the discharge through small apertures in the waveguide walls. The light is guided by means of an optical fibre from the viewing port to a photo diode.

Experience shows that some of the currently used optical fibres suffer from x-ray induced opacity. The sensors are also exposed to the radiation produced by secondary showers coming from the high intensity beams which, if not treated properly, can cause frequent spurious trips.

In the second half of the paper we present a number of improvements to the design, measurements with optical parameters from real arcs and a fibre-less version of the detector with redundant detectors for critical environments.

INTRODUCTION

In the operation of high power RF systems, occasionally electromagnetic discharges occur in the power distribution system. Once ignited these arcs grow over the full height of the affected waveguide and travel towards the RF source. The burning plasma can cause serious damage to the metal surfaces or ferrite materials. Therefore, RF equipment such as klystrons, circulators, waveguides and couplers has to be protected.

Although the protection system merely consists of a detector for the light emitted by the arc in order to rapidly shut down of the RF source (or the beam) [1], the design and operation in the environment of a particle accelerator poses a number of challenges such as radiation hardness, redundancy, availability and reliability.

THE LHC WAVEGUIDE ARC DETECTOR

The design of the current LHC arc detector is based on optical detection of the discharge through small apertures in the waveguide walls. Direct or scattered light impinging on the viewing port is guided by an optical fibre to a photo diode [2]. The amplified signals from two diodes are fed to an arc detector logic box where the signals are compared with a threshold value which triggers an RF interlock. Every detector is equipped with a test lamp allowing for remote verification of the system (Figure 1). The two individual signals can be processed using AND or OR logic to obtain an interlock.

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The specifications for the LHC arc detector were based on the successful arc detection system used in LEP [3]: Detection of arcs with a minimum illuminance of 2 lx and maximum delay of 2 μ s. The LHC design took advantage of the recuperated LEP optical fibres featuring an inner diameter of 4 mm cut to pieces of 70 cm length.

Measurements on the actual LHC arc detectors showed a reliable detection of an illuminance of few lux (typ. 5 to 10) in few microseconds (typ. 1 to 5). The transmission of the interlock signal to the control system cutting the RF introduces another delay of a few microseconds.

In LHC there are total 160 arc detectors, each RF line is equipped by 10 arc detectors installed in the critical locations in the waveguide system (straight waveguide sections, circulator, ferrite load, cavity ceramic window). The view fields of several detectors overlap allowing for the detection of arcs before they travel along the waveguide and potentially damage sensitive equipment like ferrite circulators or a high power RF loads.

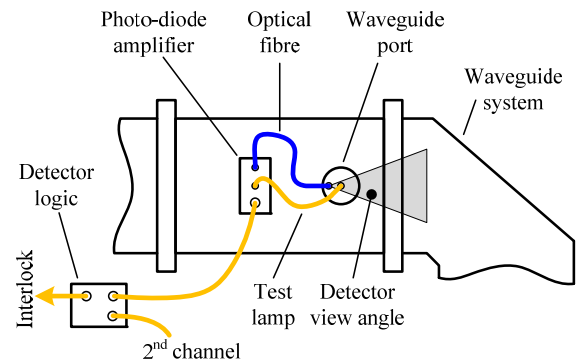


Figure 1: Current LHC arc detector design.

EXPERIENCE FROM LHC OPERATION

Shortly after the LHC RF system was commissioned, the high sensitivity and short reaction time paid off when the detectors started to trip regularly just above the circulator in one of the RF lines. After careful inspection it was found that the detector was seeing continuous micro arcing on a poorly manufactured waveguide flange leaving a small gap along the waveguide. No trips were observed after the flange was re-machined. Thanks to the fast and reliable arc detector system no RF power equipment was damaged due to arcing in the waveguide since the LHC start up in 2008.

Experience has also shown that optical fibres installed close to the LHC cavities suffer from x-ray induced degradation to the opacity, which renders the detector blind over time. Therefore, all fibres have to be frequently checked and replaced. However, the procurement of new radiation hardened fibres is difficult and costly due to the

specific design. Furthermore, some of the sensors are exposed to the radiation produced by the secondary cascade coming from the high intensity beams and their interactions with the residual gas, the latter not foreseen in the original design specification.

Before the total beam current in the LHC reached half its nominal value, only the total RF voltage interlock was connected to the beam dump. A tripped RF line was simply restarted by the operator without affecting the circulating beam. However, above this level, the beam induced voltage/power in the tripped cavity could cause damage to the RF power equipment [4]. Therefore the sum of all RF interlocks was connected to the beam interlock chain triggering a beam dump [5]. This makes the system vulnerable to spurious trips from the arc detectors.

Figure 2 shows the detector signals from a spurious radiation induced trip. Now that the LHC is operating with more than 300 bunches (as of summer 2010), the two arc detectors that are exposed to the radiation (looking at the cavity coupler window) were connected in an AND configuration triggering only for signals overlapping within a 10 ms window.

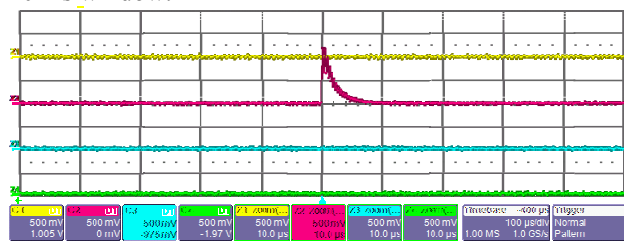


Figure 2: Signals of two cavity window detectors showing a radiation induced pulse. Horizontal scale 10 μs/div.

The further increase of the beam intensity (~900 bunches) in spring 2011 required the removal of the coincidence window for the exposed detectors (true AND) and the installation of 5 μs lowpass filter. Otherwise, the arc detectors would trip and dump the beam every few minutes, due to the secondary particle flux coming from the beam-gas interactions. Putting two channels out of the two available in coincidence improves the immunity to spurious trips, but it compromises redundancy if one of the systems fails.

In order to increase the reliability, also the arc detectors located in the klystron gallery (UX45) were ruggedized by installing 15 μs lowpass filters. No spurious arc detector trips have been detected since.

A set of new, off-the-shelf telecom optical fibres were installed onto each accelerating module in the LHC tunnel to observe the long-time effect of radiation on the fibre integrity and optical parameters.

ALTERNATIVE DESIGN

Following the experience gained from the LHC, an alternative arc detector design has been proposed. A series of measurements have been conducted on a full scale RF system in order to re-qualify the inherited arc detector specifications (2 lx, 2 μs), especially for the units exposed to radiation.

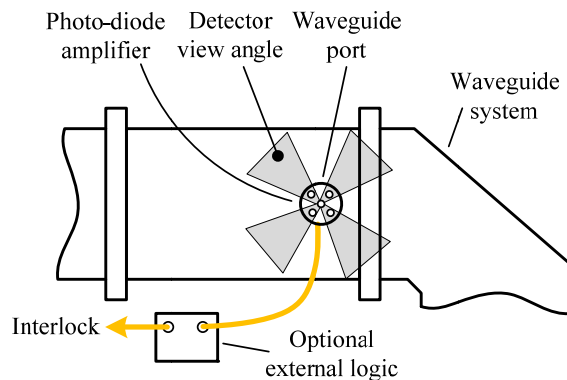


Figure 3: Fibre-less arc detector integration.

The new compact design features four redundant sensors. The whole detector is located in a single housing that is installed directly to the waveguide port (Figure 3). The large area photodiodes look directly into the waveguide via four inclined shielding holes eliminating the need for the optical fibres formerly used, which increases the viewing angle to almost 360° (Figure 4).

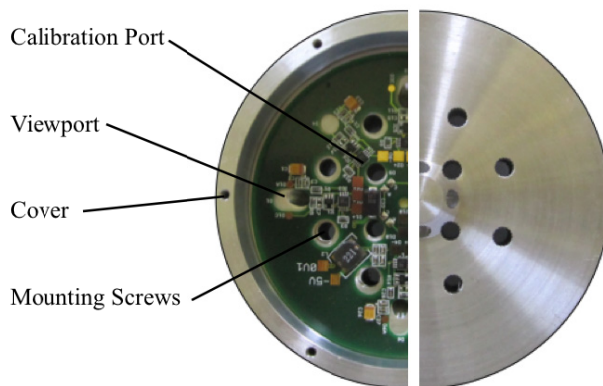


Figure 4: Fibre-less arc detector sensor. Top view (left) and the waveguide interface (right).

Additionally two “blind” photo diodes are installed in the detector body to help distinguish spurious signals that originate from the high-energy showers from the signals generated by a real arc.

By utilising four independent sensors the level of sophistication in the detection logic can be increased to provide higher overall system reliability and a reduction in the number of spurious trips, while maintaining the sensitivity and the fast reaction time.

A proposed detection algorithm introduces a voting logic on a running sum for each detector. The interlock is issued if:

- light is detected on 4 out of 4 channels for time τ_4 OR
 - light is detected on 3 out of 4 channels for time τ_3 OR
 - light is detected on 2 out of 4 channels for time τ_2 OR
 - light is detected on 1 out of 4 channels for time τ_1 ,
- where $\tau_4 < \tau_3 < \tau_2 < \tau_1$. Precise values of the time constants still need to be defined. As a rough estimate τ_4 will be in the order of 10 μs while τ_1 will be about 10 times longer. This allows an interlock to be issued rapidly when an intense arc is detected while being sensitive enough to

detect smaller, less violent arcs in the exposed areas, which currently cause many radiation induced spurious trips. If needed in the future, the false interlocks triggered by gamma showers could be masked by the signal from the blind sensors.

The detector electronics has been designed such that the sensor and the logic part can be physically separated and hence only the detector part needs to be qualified for use in a radioactive environment.

TEST RESULTS

The new arc detector prototype has been tested with the LHC klystron test stand, which has been equipped with a spark gap located in the maximum electric field in front of a waveguide short circuit. The discharge intensity can be varied by means of the distance between the two rods (Figure 5). The spark gap is equipped with two attenuating viewing ports allowing to adjust the two rods and to observe the arcing (Figure 6).

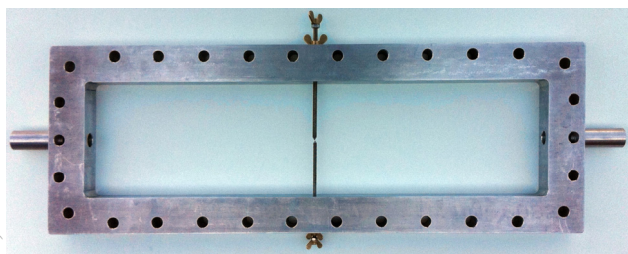


Figure 5: Spark gap with two viewing ports.

Figure 7 shows detector signals measured with a real waveguide arc. The RF power level was set to 100 kW (1/3 of the nominal power), the RF pulse length was 1 ms. The yellow channel has the best view on the arc and it saturates 10 μ s after the arc ignition. It is followed by the blue and green channels 20 μ s later.

The analysis of a number of collected events allowed us to estimate time constants for the detection algorithm: $\tau_4 = 10 \mu$ s (all channels trigger), $\tau_3 = 20 \mu$ s (3 of 4 channels trigger), $\tau_2 = 40 \mu$ s (2 of 4 channels trigger), $\tau_1 = 100 \mu$ s (single channel triggers).

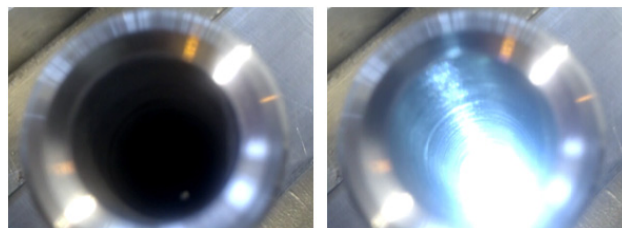


Figure 6: Arc filmed through the spark gap viewing port.

CONCLUSIONS

A total of 160 installed arc detectors in the LHC RF system play an important role in the protection of the power equipment. A number of observed trips originated from real arcs allowed us to diagnose local problems in the waveguide system. In order to minimize the number

of false trips it has been necessary to improve performance of the waveguide arc detectors.

A prototype of a new fibre-less detector with four redundant sensors and a more advanced detection algorithm has been successfully tested with real arcs. Additional sensors provide a better viewing angle and therefore improve the sensitivity of the whole system. At the same time, multiple detection channels allow the controller to distinguish between radiation induced spurious pulses and signals generated by real arcs.

In fall of 2011 the system will undergo a series of radiation tests in the new SPS irradiation area (H4IRRAD) which exactly reproduces the LHC radiation field [6]. When qualified, the most exposed LHC arc detectors will be gradually replaced by the new model in order to increase the system reliability.

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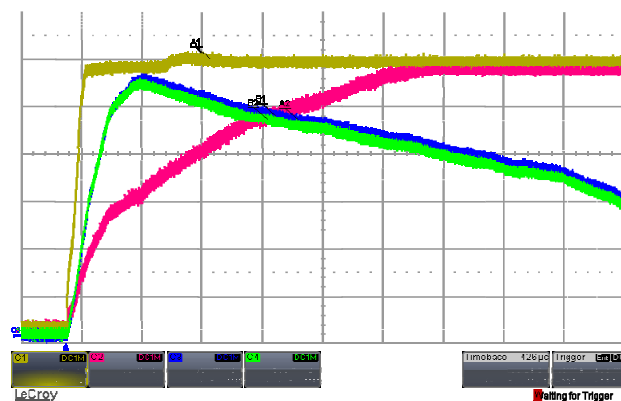


Figure 7: Analogue signals of the four photodiode amplifiers capturing a provoked arc.

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