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A Large Scintillating Screen for the LHC Dump Line

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The 7 TeV proton beam from the LHC ring is ejected through a long transfer line to beam dump blocks, approximately 100m downstream of the ejection septa, a series of dilution kicker magnets provide a sweeping deflection spreading the extracted beam over a 40 cm diameter area on the face of the beam dump cores. During normal operation, the quality of each dump event must be recorded and verified. The so-called “Post-Mortem” dataset will include information from the beam dumping system (logic signals, kicker pulses…) as well as from the beam diagnostics along the extraction lines. For this purpose, profile monitors in front of the dump blocks must be permanently available during machine operation. With more than 10^{14} protons stored in LHC, the energy deposited in the screen becomes an issue and thermalresistant materials have to be considered.

In this paper, the design of this quite unusual device is presented. The different technical options considered for the choice of the screen material are discussed first. The complete layout of the installation is then described with a special emphasis on the mechanical design, the screen assembly and the choice of the radiation-hard camera used to observe the screen.

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INTRODUCTION

The LHC beam dumping system [1] is designed to make a fast extraction of the circulating beams from each ring of the collider with minimal losses. The particles are then transported to an external dump blocks, which are located in caverns at the end of a 650 m long vacuum line. A system of horizontal and vertical dilution kickers in these lines will be used to sweep the beams in an "e" shaped form on the surface of the dump, as an undiluted full energy and intensity beam can damage the dump block. For the case of a normal beam dump, the 2808 proton bunches are swept over a path length of about 110cm at the entrance window of the dump. The beta-functions at this location are about 4.6 km in each plane, such that the beam spot is circular, with σ of 6.0mm at 450GeV and 1.5mm at 7TeV.

The trace produced by the dilution kickers (see Figure 1) must be monitored using an imaging system, named the BTVDD (Beam TV Dump Detector). As part of the post-mortem analysis, the corresponding image would be stored and checked to ensure that the dilution system functioned correctly for each beam dump. High resolution for this device is not critical since accurate knowledge of the beam size is not important. A precision on the beam position and size around 1-2 mm r.m.s. is required with a reproducibility of about 0.5 mm.

For high energy particles, beam imaging systems are usually relying on the use of Optical Transition Radiation (OTR) screens [2] or on luminescent screens.

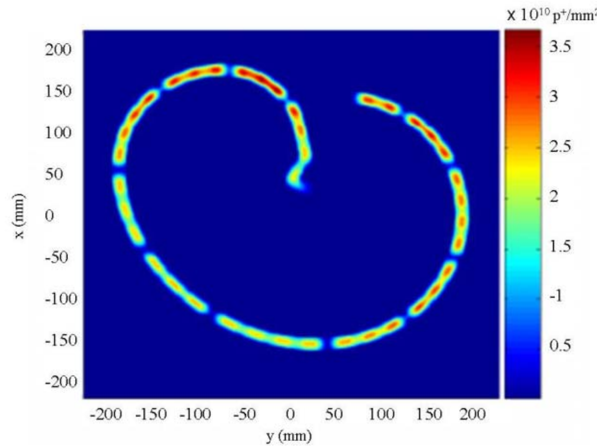

Figure 1: Protons density on the screen for a nominal sweep and 450GeV protons

Optical Transition Radiators provide a very reliable source with a total number of photons per proton in the wavelength range [λ_a, λ_b] given by:

$$N_{OTR} = \frac{2\alpha R}{\pi}\left[\left(\beta + \frac{1}{\beta}\right)\cdot \ln\left(\frac{1+\beta}{1-\beta}\right) - 2\right]\ln\left(\frac{\lambda_b}{\lambda_a}\right)$$

with α the fine structure constant, β the proton velocity, γ the relativistic factor and R the optical reflectivity of the screen. Moreover the OTR photons are emitted in a $1/\gamma$ aperture cone centred on the specular reflection of the beam trajectory with respect to the perpendicular of the screen surface. In consequence, only a small part of the OTR would be recuperated from particles away from the central axis. In addition, thermal resistant radiators, like carbon, have low reflectivity (27%), limiting by the same amount the light intensity produced.

Several decades of research on ceramic phosphors at CERN [3] and at other laboratories has led to the almost exclusive use of doped alumina ceramic screens, i.e., Al_2O_3:Cr^{3+}, for accelerator beam observation. Alumina (type AF995 [4]) is doped with 0.5% chrome sesquioxide and at room temperature two principal lines of luminescence at 692.9 and 694.3 nm are generated with a decay time of 3.4ms [5]. These screens are also compatible with ultrahigh vacuum systems, they exhibit good response linearity, and their radiation resistance is high. For example, in tests made at CERN, screens have withstood integrated relativistic proton fluxes of up to 10^{20} protons/cm^2.

A comparison between a carbon OTR screen and chromium doped alumina is presented in Table 1. From these values the use of OTR would be limited to the observation of well centered beams with relatively small sizes. The photon yield mentioned for alumina is expressed in photon per MeV of deposited energy. The number of photons generated is much greater than from an OTR screen, but since luminescence is isotropic, only a small fraction can be recuperated by the optical system. For high energy particles, alumina has shown sensitivities starting for 10^7-10^8 protons [6] when observed with a normal CCD camera. Even if the melting point for alumina is 2000°C, one should not use it with temperature higher than 1650°C.

Table 1: OTR and luminescent screen parameters

Screen	OTR Carbon	$Al_2O_3:Cr^{3+}$
Density (g/cm^3)	1.7	3.96
Specific heat (J/gK)	0.7-2.4	1.09
Melting point (°C)	3527	2000
Light directivity	0.07mrad	isotropic
Photons yield	10^{-2} (ph/p$^+$)	10^4 (ph/MeV)

The use of a thermal resistant luminescent alumina screen was considered for the BTVDD a few years ago in a preliminary study [7].

THERMAL ANALYSIS

Failures of the dilution kickers will result in higher particle densities which may damage the screen. The most dangerous are the total failure of all the dilution kickers in one plane, e.g. Fig. 2, or a total dilution failure, in which the full beam impacts in the center of the screen in a small spot.

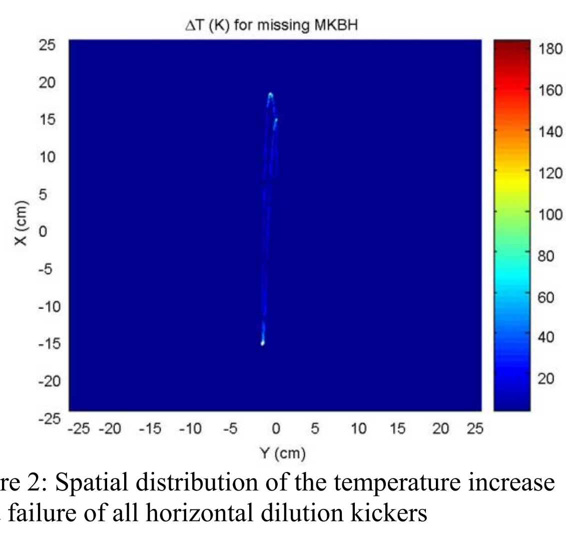

Figure 2: Spatial distribution of the temperature increase for a failure of all horizontal dilution kickers

Simulations have been performed using the Monte-Carlo code Fluka [8] in order to evaluate the energy deposition inside the screen. From these values, the local temperature increase of the screen has been calculated for the various load cases, which are reported in Table 2. The rates of the different failure modes expected per year [9] are indicated as well.

Carbon would survive any beam conditions and the temperature increase for alumina would be close to the acceptable limit for the case of a total failure. The energy deposition for 450GeV and 7TeV protons only differs by a few % but since the beam size is 4 times smaller for the highest beam energy, the maximum temperature increase will drop down by a factor 16 for 450GeV protons.

Table 2: Maximum temperature increase for different load cases for 7TeV protons together with expected occurrence rate

Load case	ΔTp (°C)		Rate (y^{-1})
	Carbon	$Al_2O_3:Cr^{3+}$	
One bunch	1	1.6	-
Nominal	15	22	400
No MKBH	116	191	0.008
No MKBV	166	241	0.005
No MKB	891	1150	4.2×10^{-5}

TECHNICAL CONSIDERATIONS

To observe the full dilution, the screen has to cover an area of 60cm in diameter, which is quite unusual in accelerators. Due to some limitations in the fabrication process of the ceramic, it was not possible to produce a screen in one piece. The screen is therefore made of 4 quadrants, which are machined in a way such that a 5cm diameter central area is left open to avoid damage in the case of non diluted beam (see Figure 3).

The central part of the screen is covered by a 5cm large, 35cm long, rectangular screen. Two options are envisaged for the choice of this second screen. During the commissioning period, either a single bunch or a reduced beam charge is used and AF995 Alumina is required because of its high photon yield. However, as previously mentioned, this screen will not stand a total dilution failure, so this would be replaced by an OTR carbon foil capable of surviving the highest charge densities. The observation angle and the screen tilt angle are chosen so that these two options can be implemented just by changing the central part of the screen.

The optical system consists of a set of optical density filters for the control of the light intensity and a camera located at a distance of 1.2m from the screen. The required magnification of 0.015 is obtained by a fused silica 12.5mm focal length camera lens. Compared to the design done in [7] with a set of 4 lenses, the present design provides a much better optical spatial resolution, with lower aberrations. The simplicity of the system, avoiding any precise optical alignment makes it easily and rapidly maintainable.

The spatial resolution of ceramic screen is limited by the combination of three characteristics [10]: finite thickness of the screen, limited opacity of the screen material, and light scattering inside the screen. The beam creates a line of light emitter points inside the screen. The light coming from these points is not strongly attenuated, while it is scattered before it reaches the screen surface.

As a consequence, a blurring of the spot on the screen occurs and degrades the spatial resolution. In order to minimize this effect the screen should be as thin as possible, and the angle between the screen and the beam trajectory should be close to 90^{o}. For mechanical reasons a 3mm thick screen is preferred and 80^{o} tilt angle screen is chosen. The observation angle is then set to 20^{o}. The resolution of the screen would be better than 1mm.

The radiation dose received by the camera has been estimated using Fluka and corresponds to 270krad for a year of nominal operation. The simulations are done for 7TeV protons and only consider the shower corresponding to the beam hitting the screen. In reality, the radiation dose would be higher because of beam losses and interactions between protons and rest gas atoms upstream of the BTVDD. A radiation resistant camera was selected (SIRA APS250) and tested [11], it will withstand up to 10Mrad. It should be noted that possibly due to the lower fill factor of the sensors, these radiation resistant Charge Injection Detector (CID) cameras present a factor 10 less sensitivity compared to a normal CCD camera.

OVERALL SYSTEM

The overall system is described in Figure 3. The 2m long 60cm diameter vacuum chamber is directly welded to the beam tube at both ends. It is installed at a distance of 30m upstream of the vacuum window [12]. Even if the tunnel is large, the beam line is installed to one side in order to leave most of the place free for transport vehicles. The 4 quadrants screen support is mounted on a vertical flange and due to its weight needs some dedicated equipment to be manipulated securely. The central screen support is on the 6cm diameter flange which can be quickly connected. This is an important feature of the design to ensure an easy and quick maintenance since the central part of the screen is the most likely to be often damaged and replaced.

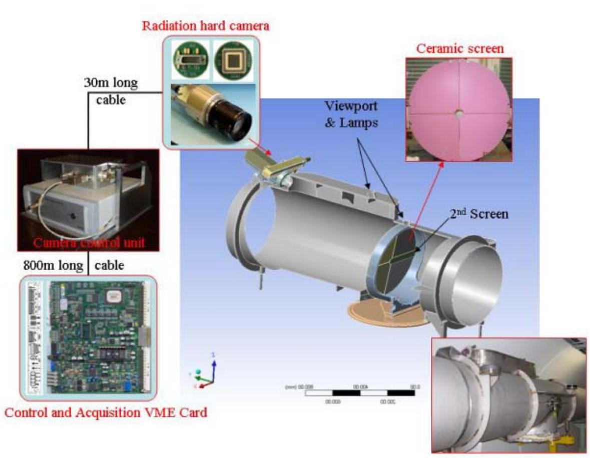

Figure 3: Overview of the BTVDD imaging system

The camera is composed of two parts, a radiation resistant sensor and its control unit which is more sensitive to radiation damage. Therefore the control unit is installed 25m upstream of the BTVDD tank and surrounded by iron and concrete blocks for shielding. The control of the camera, the control of two lamps used for calibration and the control of the filter wheel are done using a CERN standard VME card [13], which is located in a technical gallery at a distance of 800m from the BTVDD. This card is also equipped with a frame grabber for image acquisition. The trigger signal (1µs, 12V), provided by the firing system of the extraction kicker, is interfaced via a dedicated PCB to match the TTL trigger required by the frame grabber.

The choice of the optical density filter must be set automatically in accordance with the total beam charge circulating in the machine.

CONCLUSIONS AND PERSPECTIVES

The design and the construction of the large imaging screen for the LHC dump line have been done. It relies on the use of high sensitivity and thermal resistant chromium doped alumina. Fluka simulations have been performed to estimate energy deposition in screen and the corresponding temperature increase for the different beam dumping scenarios. The overall system has been designed to guarantee a simple maintenance and to survive in high radiation zone.

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