Photodetector R&D proposal

Introduction

Current CERN planning foresees a programme of upgrades to the LHC machine to achieve 'Super LHC' (SLHC). It is anticipated that these will result in an increase in the luminosity delivered to CMS over the lifetime of the experiment by almost an order of magnitude compared to the value assumed in the original design.

It is clear that a number of CMS sub-systems will need upgrading or replacing if the experiment is to benefit fully from the increased physics reach offered by the LHC luminosity upgrade. A very important, but particularly challenging, requirement will be to maintain adequate performance in the Endcap electromagnetic calorimeter (ECAL) through the SLHC era.

Beam tests have demonstrated that the lead tungstate crystals currently deployed in the ECAL Endcaps will be degraded to an unacceptable degree by the radiation dose and neutron fluence expected at SLHC. Work is already in hand to address this problem.

The other potentially limiting component of the crystal calorimeter is the photodetector.

Photodetectors for the CMS ECAL must be fast, radiation hard and operate in a 4 T magnetic field. Furthermore, they must have a very low sensitivity to shower particles leaking from the back face of the crystal (the 'nuclear counter effect'). The Avalanche Photodiodes (APDs) developed for the Barrel ECAL subsystem will continue to meet these criteria through the SLHC era. However, the higher radiation levels in the Endcaps already precluded the use of APDs for this subsystem for LHC and resulted in the selection of vacuum phototriodes (VPTs).

Even so, the VPTs currently in use (FEU188 from RIE) will suffer some loss in performance at LHC and would not survive SLHC operation. There are two aspects of the FEU188 tubes that make them unsuitable for use at SLHC. One is the susceptibility of the front window to radiation induced darkening. This limitation could be overcome in a replacement device, in a reasonably straightforward way, by using fused silica or a more radiation resistant glass for the window material. The other problem, which is more intractable, is a loss in photocathode efficiency. The deterioration depends on the integrated charge delivered by the photocathode and is caused by ion bombardment and by loss of caesium through evaporation. It is inherent to semi-transparent photo-cathodes of this type which typically have charge lifetimes of less than 1 C.

There have been a number of interesting recent developments in solid state and hybrid photo-detectors, but at present it appears unlikely that such devices could achieve the degree of radiation hardness required for the Endcap ECAL of CMS.

Proposed development

Reflective photo-cathodes deposited on metal substrates can be made extremely robust, and for this reason they are generating considerable interest in the context of photo-injectors for electron free lasers. For example, work at BNL has shown that a CsK_2Sb photocathode deposited on Mo, Cu or stainless steel (SS) can deliver in excess of 100 C with no loss in performance [1]. This goes an order of magnitude beyond the requirement of a CMS photo-detector for SLC.

Another potential advantage of using photocathode materials in a reflective mode is that much higher quantum efficiencies can be achieved than with the equivalent semi-transparent configuration. Unfortunately, high quantum efficiency and long lifetime tend to be mutually conflicting properties in photocathode optimisation. Nevertheless, the photocathodes produced at BNL have quantum efficiencies which are sufficiently high to be of interest in photodetector applications (of order 3% at 532 nm and 10% at 355 nm).

The reason that reflective photocathodes have hitherto found only limited use in photodetectors is that for most applications, devices with internal gain are required and this is more easily achieved in devices with head-on photocathodes.

In the endcaps of CMS the Lorentz boost ensures that the average energy of particles from hard collisions is high, resulting in large signals in the calorimeters. Thus the product of crystal light yield and photodetector anode sensitivity is less of an issue in achieving the necessary signal to noise performance. Furthermore, the very high count rates in the forward region at SLHC will mean that the noise floor is set by pile-up. Thus given a crystal with adequate light yield, it is not essential for the photodetector to have internal gain for this application.

The proposal is therefore to develop and demonstrate a new generation of vacuum photodiodes with good quantum efficiency and extremely high radiation resistance, incorporating a reflective photocathode. The principle features of the design are shown in figure 1.

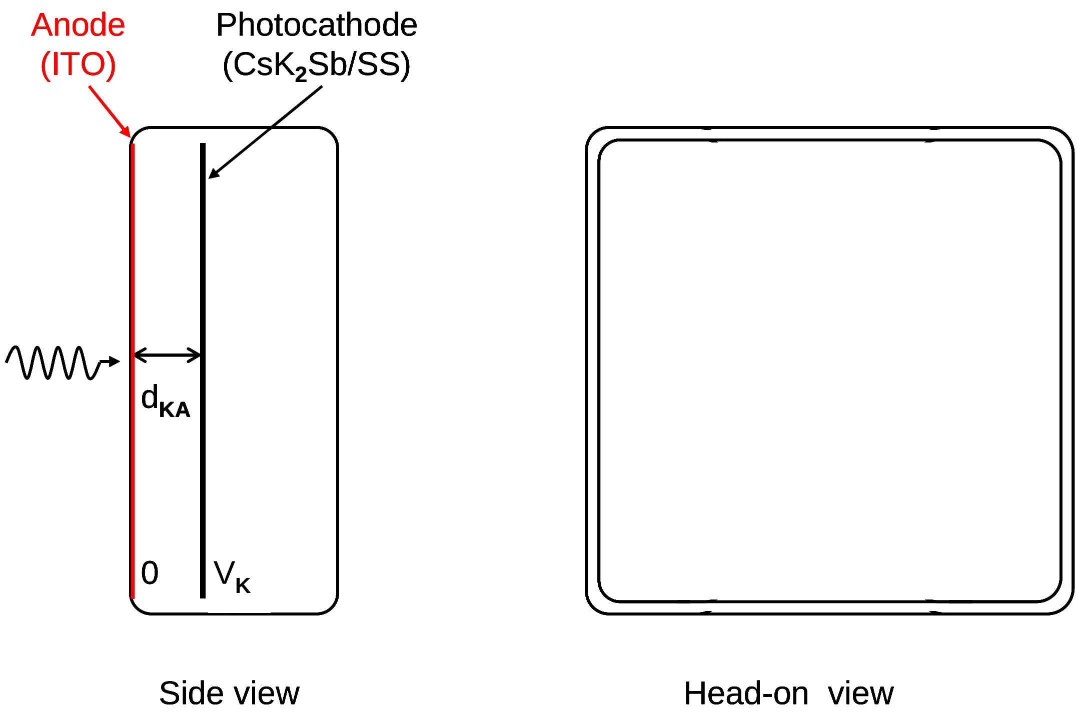

Figure 1. Schematic arrangement of the proposed photodiode electrode structure (not to to scale).

The entrance window (in direct contact with the scintillating crystal in the CMS application) is made of a cerium doped glass. Such glasses may have extremely high resistance to radiation-induced darkening and, compared to fused silica, are much more easily incorporated into the glass envelope of a vacuum photodetector. (The problem is to match the thermal expansion properties of the window glass with those of the glass at the rear of the detector, which is required to be compatible with metal-in-glass seals. Fused silica requires several intermediate types of glass to achieve this. Not only does this make the tube more expensive, but it also increases the overall length.)

The anode consists of a thin film of indium-tin-oxide (ITO) deposited on the inner surface of the front window. ITO is transparent to visible light, yet is an electrical conductor up to very high frequencies. It is often used as a substrate for large area semi-transparent photocathodes, to reduce the resistivity. The tube will operate with the anode at earth potential. Having the tube envelope at earth avoids problems of electrical insulation in the overall detector design (tight clearances may be used to minimise geometrical losses) and facilitates the coupling of the anode to the associated preamplifier.

The photocathode consists of a metal plate (stainless steel or copper) coated with a semiconductor photocathode. Semiconductor photocathodes with negative electron affinity can have very high quantum efficiencies. Caesium-implanted GaAsP is particularly good in this respect (and much cheaper when used as a reflective rather than transmissive photocathode) however it has a rather short charge lifetime. The best candidate for our application appears to be CsK_2Sb, although other possibilities (such as caesiated metal surfaces) will be investigated.

The cross section of the device shown in figure 1 is square. The choice of a square rather than a cylindrical geometry is to maximise the match to the back face of a crystal. It is estimated that a factor of almost two in coverage, compared to the FEU188 VPTs, might be obtained, thus offsetting to some extent the lack of internal gain. It may be noted that vacuum photodetectors with square cross section are commercially available

It is anticipated that the tube development will be done in close collaboration with one or more commercial phototube manufacturers. Furthermore, laboratories such as CERN and BNL have the capability to produce high quality photocathodes and it would be natural to take full advantage of their expertise in this part of the development.

Summary

The principle objectives are to:

- produce prototype devices
- investigate their properties (most notably quantum efficiency, radiation hardness and charge lifetime)
- demonstrate that, coupled to a suitable crystal, they can achieve the performance required for application in CMS at SLHC.

Applicability to other areas

Photodetectors are widely used in research, medical diagnostics, security systems and industrial applications such as oil well logging. However, few applications require the degree of radiation tolerance that motivates this project. On the other hand, if successful, the proposed photocathode development could find immediate application in photo-injectors and in photodetectors required to operate with high light levels.

References

1 Multi-alkali Photocathode Development at Brookhaven National Lab for Application in Superconducting Photoinjectors; Burrill, A et al., Contributed to PAC05, SLAC-PUB-11692