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SOLENOIDAL DETECTOR NOTES

CRYOGENIC ISSUES FOR SOLID-STATE PHOTOMULTIPLIER OPERATION

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Abstract

A tracking system for the SSC employing some 10^6 scintillating fibers has been proposed. This system is made possible by the recently developed solid-state photomultiplier, a multichannel device that is extremely small and can detect single photons. However, since the device must be operated near 7°K, a cryogenics system is required. This paper presents a simple conceptual environment for the cold region, and estimates the resulting heat loads.

Introduction

The solid-state photomultiplier, developed by Rockwell International Science Center, may revolutionize photon detection in high-energy physics. Capable of detecting single photons, a multichannel array can have individual sensitive areas a fraction of a millimeter on a side.[1] A version called the visible light photon counter (VLPC) currently being optimized for high-energy-physics applications will have a quantum efficiency of 80% and a gain of 5×10^4. Based on this technology, the Solenoid Detector Collaboration has proposed, as one option, a tracking system employing some 10^6 scintillating fibers each of which is read out by a VLPC channel.[2]

Along with its promise, the VLPC presents challenges. Foremost, to keep noise to a reasonable level, the device must be maintained near 7°K. For a large system, several liquid-helium-temperature cryostats are required, each involving the penetration of thousands of entering fibers and exiting signal leads. Also, cold preamps located near the VLPCs are desirable.

This paper presents a simple conceptual environment for the cold VLPC volume and estimates the heat loads presented to the liquid-helium cryogenics. The estimates can form the basis for an initial design of the cryosystem.

Conceptual Design

A conceptual design for the cold volume is shown in Fig. 1. Wave-guide fibers enter a vacuum region and are thermally grounded at liquid nitrogen temperature (77°K). They continue through a second vacuum region into the 7°K volume and are coupled to 96-channel VLPC arrays. The VLPC output signals pass through a vacuum region to preamps operating at 77°K. Finally, amplified signals emerge into a room temperature environment.

The fibers have a 750-μm-dia. polystyrene core and a thin acrylic cladding, and extend 5 cm between the 77°K and 7°K regions. The VLPC outputs are sent on 15-cm-long ribbon cables made of 2-mil-dia. SS304 wires spaced at 25 mils and embedded in 10-mil-thick Teflon. A similar two-conductor cable 10 cm long supplies a 7V bias to each photodetector array.

Heat Load Estimates

These per-channel estimates consider only heat in the 7°K VLPC region. Neither heat transferred to the liquid nitrogen nor static cryostat heat loads are considered here.

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Conduction

Neglecting heat losses through their sides, the steady-state rate of conductive heat transfer through the fibers and electrical cables is determined by $P_c = -k(T)A\ dT/dx$, where A is the cross-sectional area and k(T) is the thermal conductivity at temperature T. Integration over a length L gives $P_c = AK/L$, where K is the integral of k(T) dT between 7°K and 77°K.

if 3% of the 300°K radiation was trapped and propagated without loss, the heat load would be 2.7×10^{-4} W. However, although the infrared absorption spectrum of polystyrene is complicated, little transmission is expected over the distances involved.

VLPC Heat

Electron multiplication in a VLPC produces heat. As a worst case, consider scintil-

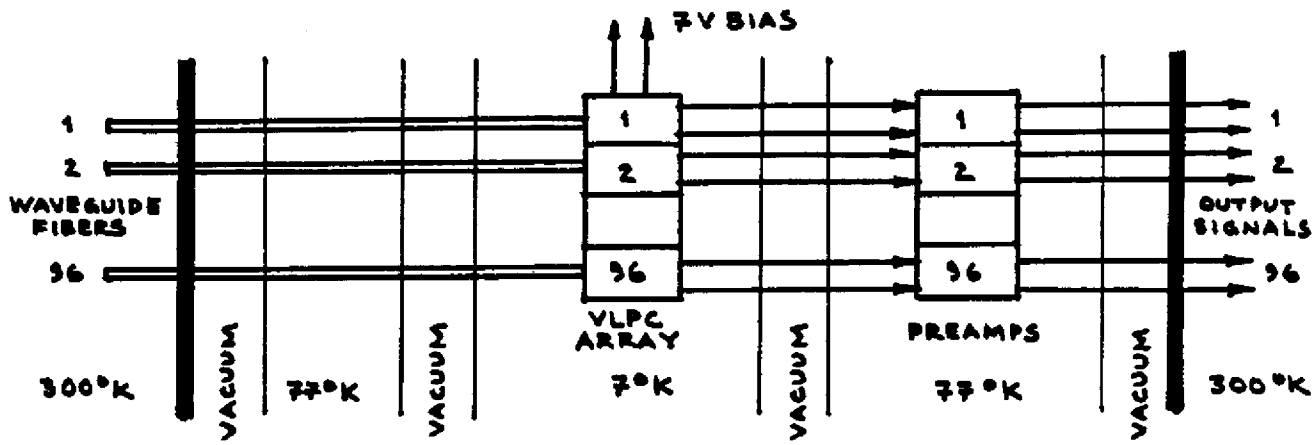

Figure 1. Schematic diagram of the cryostat system.

The values of K used were calculated using data from Ref. [3]. For a polystyrene fiber, where $K = 2.34\times10^{-2}$ W/cm, there follows $P_c = 2.1\times10^{-5}$ W. For the signal and d.c. bias cables, the contribution from the wires (K = 3.14 W/cm for SS304) is 8.6×10^{-6} W and that from the Teflon (K = 0.13 W/cm) is 2.8×10^{-5} W. The average cable rate is then 3.7×10^{-5} W per channel.

Radiation

Visible photons, produced by hits on the scintillating sections of the fibers, have typical energies of 3.3×10^{-19} J. Because a maximum ionizing hit due to a neutron-induced recoil proton should produce about 2.6×10^{3} photons at the VLPC, the energy transfer is negligible.

Heat from infrared photons is difficult to calculate. Basically, each section of a fiber is in thermal equilibrium with black-body radiation of the corresponding temperature, and photons may be trapped and propagate. As an extreme case,

lation light from a 2.7-m-long fiber in the innermost tracker superlayer located 0.6m from the beam. A minimum-ionizing particle should produce about 10 photons at the VLPC, and a recoil proton-- from a hit by an albedo neutron -- will yield about 2.6×10^{3} photons. With the stated VLPC parameters, because the avalanche charge is collected in about 1 ns,[1] the corresponding signal currents are 6.4×10^{-6} A and 1.7×10^{-2} A.

A layer at 0.6m radius contains 5.0×10^{3} fibers. At SSC operation at $L = 10^{33}$ $cm^{-2}s^{-1}$, 1.6 interactions are expected per crossing, with each interaction producing some 150 charged particles. Doubling this value to include spiraling particles and conversion electrons, the probability that a fiber is hit by a minimum-ionizing particle is 9.6×10^{-2}/crossing. Assuming a 1-ns-wide VLPC current pulse, the 16 ns crossing period results in a duty factor of 1/16. These values yield a time-averaged signal current of 3.8×10^{-7} A/channel.

At the above **L**, the fluence of the neutron albedo in the tracking volume will be $0.5\times10^{12}/cm^2$ in one year,[4] producing an inner fiber hit rate of $3.2\times10^5\ s^{-1}$. The np elastic cross-section at 1 MeV, the peak of the neutron spectrum, is 6 barns. Thus, the probability that a neutron hit will produce scintillation via a recoil proton is 2.0×10^{-2}. These values result in a time-averaged signal current of 1.1×10^{-7} A/channel.

Because the quiescent current is 10^{-8} A,[1] the total average VLPC current is thus 5.0×10^{-7} A/channel which, with a bias potential of 7V, corresponds to 3.5×10^{-6} W of heat. At **L** = $10^{34}\ cm^{-2}s^{-1}$, both the interactions per crossing and the neutron fluence increase tenfold, and the heat rate is 3.4×10^{-5} W.

Joule Heating

Joule heating, $P_j = RI^2_{total}$, is produced in the output signal and bias cables. At 7°K, the resistance of a pair of output leads is 73Ω; that of the two conductor bias cable is 49Ω.

The output current is the sum of signals due to minimum-ionizing particles and neutrons. For estimation, assume the pulses to be 1 ns wide and have amplitudes and frequencies as described above. Because the two signals are uncorrelated, their cross terms vanish when the time average of I^2_{total} is calculated. At **L** = $10^{33}\ cm^{-2}s^{-1}$, this average is 1.1×10^{-9} A^2/channel, due principally to neutrons. The resulting joule heating is 8.1×10^{-8} W. At **L** = $10^{34}\ cm^{-2}s^{-1}$, this value increases to 8.8×10^{-7} W.

One bias cable supplies all 96 channels in a VLPC array. The current consists of pulses due to minimum-ionizing particles and neutrons superimposed on the quiescent current. The signal pulses are assumed to be as described above. Again, in calculating the time average of I^2_{total} their cross terms vanish; however, their cross terms with the quiescent current contribute. At **L** = $10^{33}\ cm^{-2}s^{-1}$, the per-channel value of the average of I^2_{total} is 1.1×10^{-7} A^2, due principally to neutrons. The corresponding joule heating is 5.4×10^{-6} W. This value increases tenfold at **L** = $10^{34}\ cm^{-2}s^{-1}$.

Conclusion

The individual heat loads estimated for the assumed configuration are summarized in Table 1, as are their sums. For a tracking system of some 10^8 fibers, the total load at a luminosity of $10^{34}\ cm^{-2}s^{-1}$ is about 150 W. This is quite manageable since, for comparison, one Fermilab superconducting ring magnet requires about 10 W of refrigeration.

Table 1. Summary of heat loads.

Mechanism	Head Load (W/channel) L=$10^{33}cm^{-2}s^{-1}$	L=$10^{34}cm^{-2}s^{-1}$
Conduction		
Fibers	2.1×10^{-5}	2.1×10^{-5}
Cables	3.7×10^{-5}	3.7×10^{-5}
Radiation		
Visible	negligible	
Infrared	negligible	
VLPC Heat	3.5×10^{-6}	3.4×10^{-5}
Joule Heating		
Signal Cable	8.1×10^{-8}	8.8×10^{-7}
Bias Cable	5.4×10^{-6}	5.4×10^{-5}
Total	7.0×10^{-6}	1.5×10^{-4}

References

[1] M.D. Petroff et al., "Detection of individual 0.4-28 μm wavelength photons via impurity-impact ionization in a solid-state photomultiplier", Appl. Phys. Lett. 51, 406-408, 1987; M.D. Petroff and M.G. Stapelbroek, "Photon-counting solid-state photomultiplier", IEEE Trans. Nucl. Sci. 36, 158-162 (1989).

[2] "Expression of Interest by the Solenoid Detector Collaboration", 24 May 1990, pp. 22-31, (unpublished).

[3] Y.S. Touloukian, R.W. Powell, C.Y. Ho, and P.G. Klemens, "Thermophysical Properties of Matter". New York: IFI/Plenum Press, Vol. 1, pp. 1160-1162; Vol. 2, pp. 963-969.

[4] Ref. [2], p. 19.