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CMS NOTE 2000/054

The Compact Muon Solenoid Experiment

CMS Note

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September 29, 2000

The performance of prototype Vacuum Phototriodes in the first full sized Supercrystal array for the ECAL Endcaps

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Abstract

The performance of prototype Vacuum Phototriodes is presented from the first full sized Supercrystal array for the CMS ECAL Endcaps. The array was exposed to high energy electrons in H4 and tested in magnetic fields of up to 3 T in H2, in the CERN North area, in July and August 1999. The mean VPT electron yield, normalised to a naked crystal light yield of 8 photoelectrons/MeV into an HPMT, was found to be 25 electrons/ MeV at 3 T for devices from Research Institute Electron, 35 electrons/MeV for devices from Hamamatsu and 18/23 electrons/MeV from Electron Tubes.

1: Introduction

The first full sized prototype 5x5 Supercrystal (SC) array for the CMS ECAL Endcap detectors was constructed in 1999. The array was exposed to high energy electrons at CERN in H4 and tested in magnetic fields up to 3 T in H2. The SC is shown schematically in Fig. 1. It comprised 25 La doped lead tungstate crystals, each read out with a prototype Vacuum Phototriode (VPT) of one inch outer diameter. The VPTs were from three manufacturers : Hamamatsu (Japan), Research Institute Electron (Russia) and Electron Tubes (UK). A photograph of a prototype VPT is shown in Fig. 2.

The EE crystals in the array were polished on all sides. The crystal edges were ground to form chamfers with radii of ~ 0.5 - 1 mm. The crystals were located in the pockets of a 5x5 carbon fibre alveolar support unit. There were no special internal reflective liners on the long sides of the pockets. At the front face of each crystal was a layer of reflective Tyvek. At the back face of each crystal was an aluminium insert which surrounded the VPT.

The tests were carried out to quantify the performance of the VPTs at B = 0 and 3 T and to extrapolate to the performance expected in the 4 T field of CMS.

2: Detector operation

The VPT and crystal pairings are shown in Appendix 1. A schematic view of a VPT is shown in Fig. 3. The photocathode, **K**, is a semitransparent coating of caesium-antimony on the inner surface of the front window. **A** is an anode which consists of a very fine metallic mesh with a transparency to electrons of typically 50 %. **D1** is a solid metal dynode, coated with the same material as the photocathode.

The number of devices in the SC from each manufacturer and their anode mesh sizes were :

- 8 Hamamatsu VPTs with 2000 lines per inch (lpi) anode meshes
- 1 Hamamatsu VPT with a dished dynode and a 2000 lpi mesh
- 5 RIE VPTs with 2540 lpi
- 1 RIE VPT with 2000 lpi
- 6 ET VPTs with 1500 lpi
- 4 ET VPTs with 1000 lpi

Each VPT was operated with its photocathode at ground, the anode at +800 V and the dynode at +600 V. The external cylindrical surface of the VPT was connected to ground with a metallic sheath.

The anode signal was read out through a decoupling capacitor to a discrete component ‘Stephenson’ charge preamplifier **[1]** with single ended drive. This was connected to a ground isolating 51 ohm input impedance ‘paddle card’ in the H4 control room ~ 80 m away. The paddle card was connected to a charge integrating LeCroy 1881 ADC operated with a 200 nsec integration gate.

The H4 control room was used for the data taken at both the H4 test beam and at the H2 magnet.

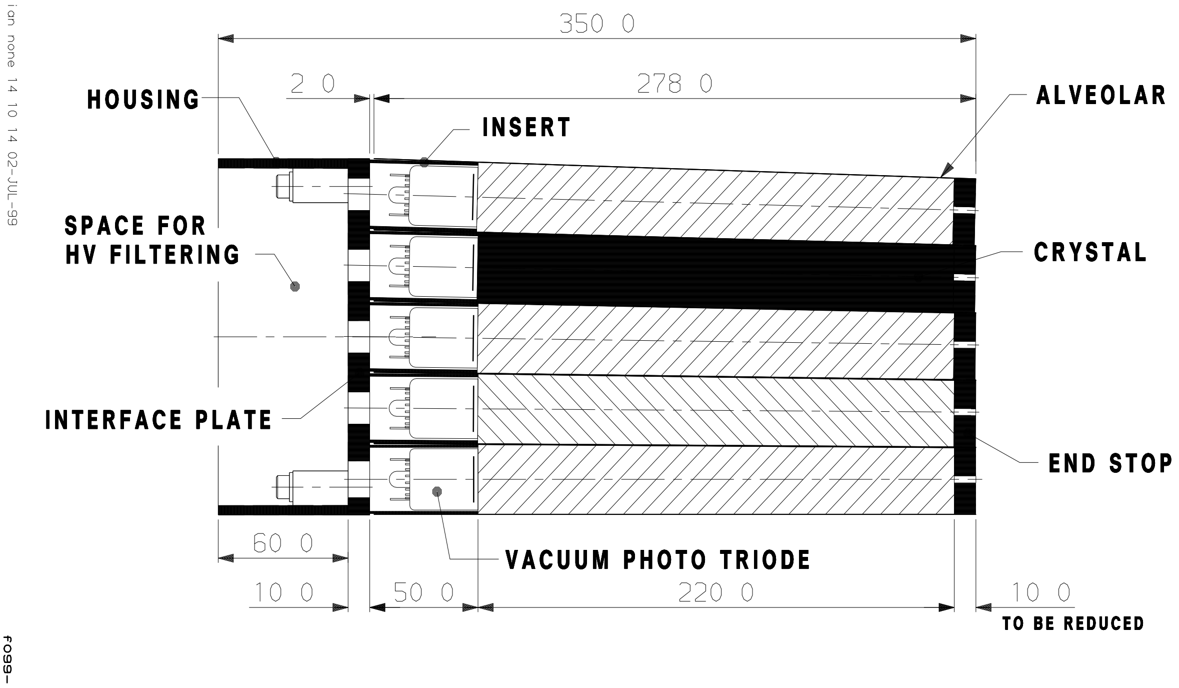

Figure 1.

A schematic view of a Supercrystal

Figure 2.

A prototype VPT

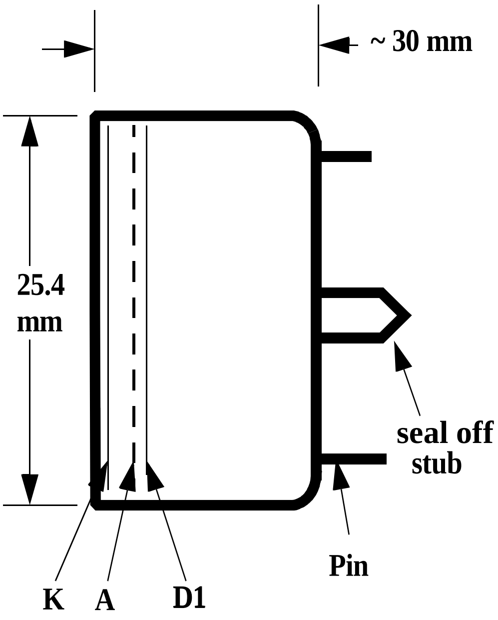

Figure 3.

A schematic view of a VPT
K indicates the photocathode, **A** the anode and **D1** the solid metal dynode. **K, A,** and **D1** are each separated by 1.5 - 3 mm.

The preamps were sited ~ 50 cm from the VPTs (the probable distance for the final CMS configuration). The input capacitance to the preamp was estimated to be ~ 40 pF, coming mainly from the 50 cm signal cable. The VPTs were estimated to have a capacitance of ~ 2 pF.

The array was operated with two independant LED light monitoring systems at the start of H4 running. One system provided fibre optic monitoring to all crystals from the front, the other to all crystals from the rear. This enabled photostatistics to be compared from each end of the crystal. The front fibres were removed for the joint running with the prototype preshower at H4 and from this point, and for the subsequent tests at field in H2, only the rear fibres were available for monitoring.

The ADC calibration, in MeV deposited, was taken from the 50 GeV electron runs 28367-28391. The calibration used gives a signal peak at the beam energy when the energy is reconstructed in a 3x3 array of crystals.

3: Characteristics of the VPTs in the 5x5 array

The characteristics of the VPTs used in the array were extensively measured at Brunel University **[2]** before assembly. The DC current gain (the ratio of the DC current drawn from the anode to the DC current drawn from the photocathode under illumination from a constant current green LED) was measured for each device. The relative photocathode response was also measured for each tube by measuring the photocurrent, in nA, under constant illumination from a blue LED.

Fig. 4 and Fig. 5 show the DC current gain and photocathode response for the three sets of VPTs used in the 5x5 matrix, as measured at Brunel at B=0T. The Hamamatsu and R.I.E gains are similar with a mean of ~8. The ET gains are lower with means of 4.8/7.0, for 1500/1000 lpi respectively. The mean photocathode response (arb units) for Hamamatsu is 12.1, whereas for RIE and ET it is 9.7 and 8.7/9.8 respectively. The spreads are lowest for the Hamamatsu tubes with 12% for the gain and with an impressively low 4% for the photocathode response.

The combined gain and photocathode response, for B=0T, is shown in Fig. 6. This quality factor is highest for Hamamatsu with a mean of 94 (arb. units). The mean for RIE is 77 and for ET 42.7/64. Is is interesting that the ET 1000 lpi are consistently better than the 1500 lpi.

4: Light yield for the crystals in the 5x5 array

The light yield for each crystal was measured at CERN in the Crystal Laboratory, bldg 27 **[3]**. The crystals were measured naked, without a reflector wrapping, using a hybrid photomultiplier (HPMT) and a Co^{60} gamma source. The crystals were placed on top of the HPMT with an optical grease for contact. A few crystals were also measured with Tyvek wrapping. In this report the measurements for naked crystals have been used.

Fig. 7 shows the crystal light yields measured at CERN with an HPMT, using naked crystals, sorted according to the type of VPT coupled to the crystal. The Hamamatsu VPTs are coupled to crystals with a mean light yield of 8.3 photo-electrons/MeV whereas for RIE and ET the means are 7.7 and 7.3/7.5 respectively. Fig. 8 shows the overall naked light yield distribution for the crystals used in the 5x5 array. The distribution has a mean of 7.8 photo-electrons/MeV and a spread of 15.7%.

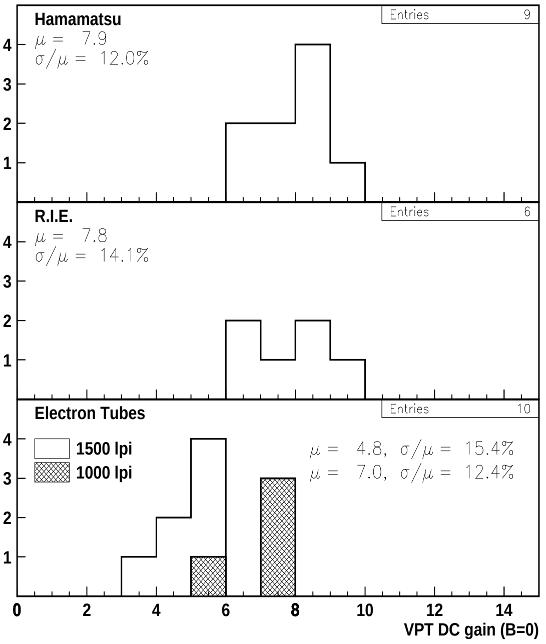

Figure 4.

VPT DC Gain measured at Brunel, B= 0 T

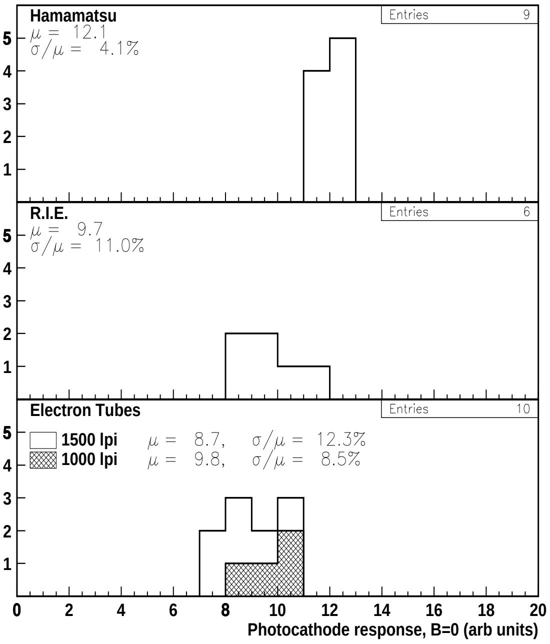

Figure 5.

VPT photocathode response measured at Brunel, B = 0 T

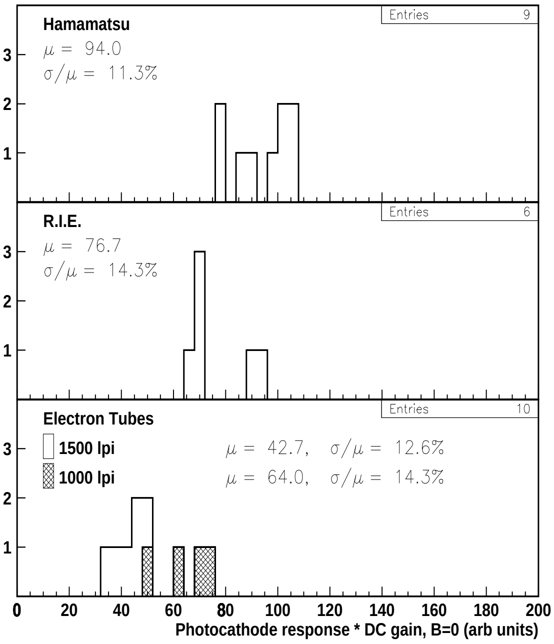

Figure 6.

VPT photocathode response times DC Gain from measurements at Brunel, B= 0 T

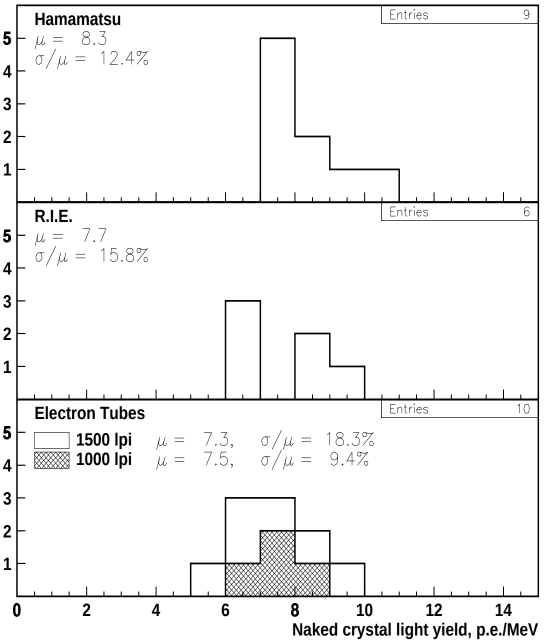

Figure 7.

Naked crystal light yield, in p.e./MeV, measured with an HPMT at CERN, for the crystals in the array, sorted according to attached VPT type.

The naked light yield measurements correspond to a wrapped light yield of 10-11 p.e./MeV (see Appendix 2). The Endcap crystal light yield is therefore consistent with the mean light yield for wrapped barrel crystals of 10.3 p.e./MeV.

5: Combined response of crystals and VPTs

A calculated quality factor, of VPT DC current gain times photocathode response times crystal light yield, using the measurements at B=0 at Brunel and at CERN, is shown in Fig. 9. There is a factor of two between the best set, Hamamatsu, with a mean of 783 (arb. units) and ET with only 340/480 with RIE midway at 620.

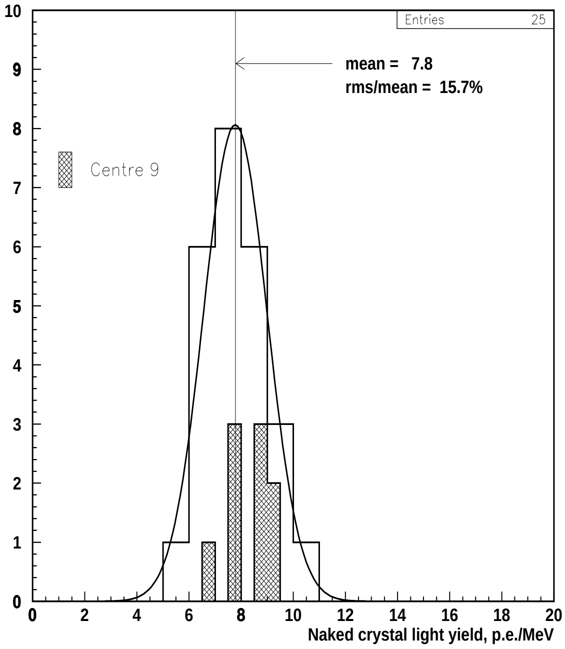

Figure 8.

Naked crystal light yield in p.e./MeV, measured with an HPMT, for the crystals used in the array.

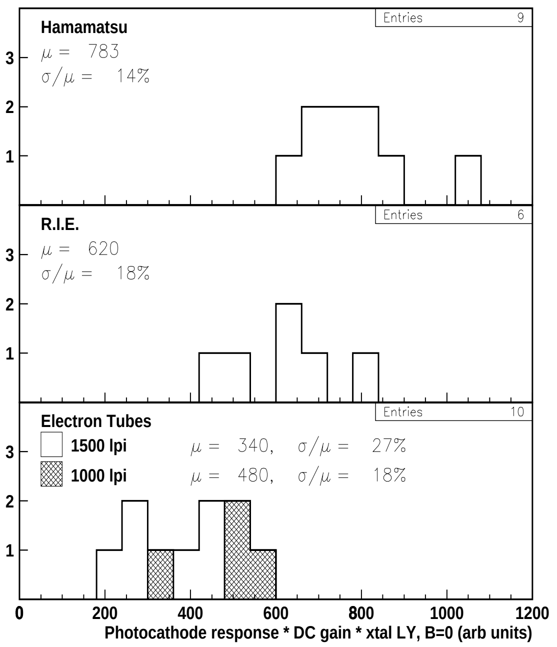

Figure 9.

Crystal/VPT quality factor (photocathode response * DC gain * crystal light yield) according to VPT type

Fig. 10 shows the quality factor plotted against the ADC signal for a deposited energy of 50 GeV, at H4 (B=0T). There is a good degree of correlation between the quality factor of the crystal/VPT combination and the ADC signal.

Fig. 11. shows the ratio of the measured signal to the quality factor. The width of the distribution is only 8.5%. The quality factor is therefore a reasonable predictor for the final output of the combined crystal/VPT system. It could be used at a number of stages during the build of the EE : to cross check channels during Dee calibration or during operation in CMS. In particular, if not all Dees are calibrated at H4, the quality factor could provide initial calibration constants at the 10% level or better.

6: Normalised response of VPTs

The response of the system at H4 is dependant on the combined factors of VPT gain, photocathode response and crystal light yield.

In order to get a valid measure of the relative and absolute performance of the VPTs used in the 5x5 array, the data were normalised to a naked crystal light yield of 8 p.e./MeV, taking the rounded value of the mean, of 7.8 p.e./MeV, in Fig. 8. The normalised signal for an energy deposit of 50 GeV is shown in Fig. 12. The mean ADC signal from Hamamatsu VPTs is 1073

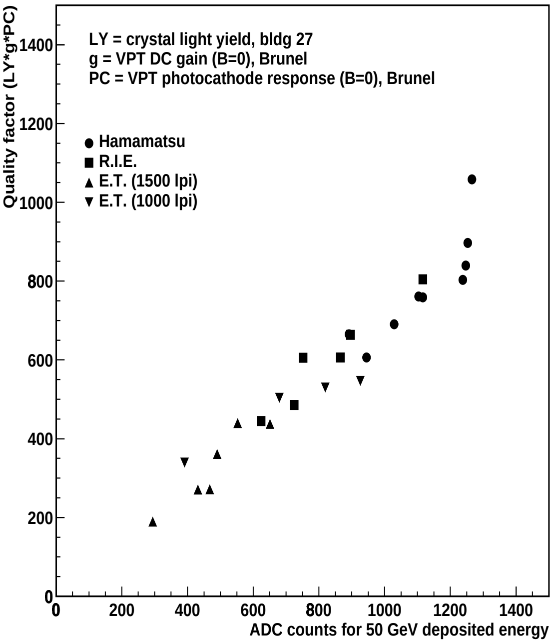

Figure 10.

Quality factor (VPT photocathode response * DC gain * crystal light yield) against the ADC signal for 50 GeV deposited energy.

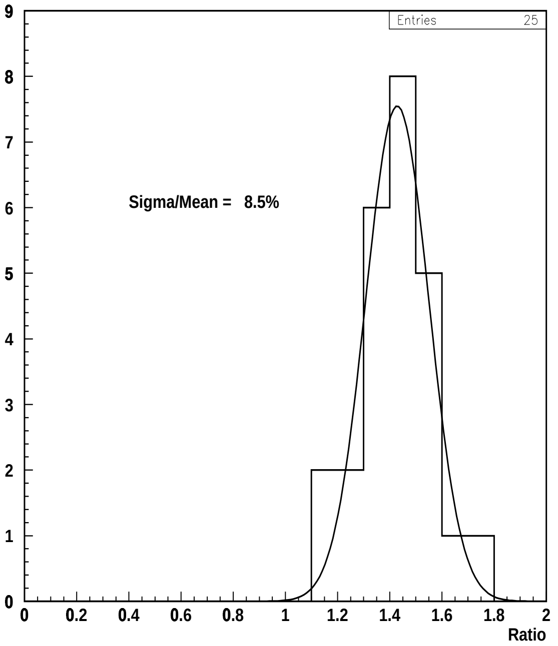

Figure 11.

Ratio of ADC signal at 50 GeV to the VPT/crystal quality factor

counts with a spread of 11%. For RIE the mean is 846 with a spread of 15% and for ET the means are 513/740 with spreads of 9/26 %.

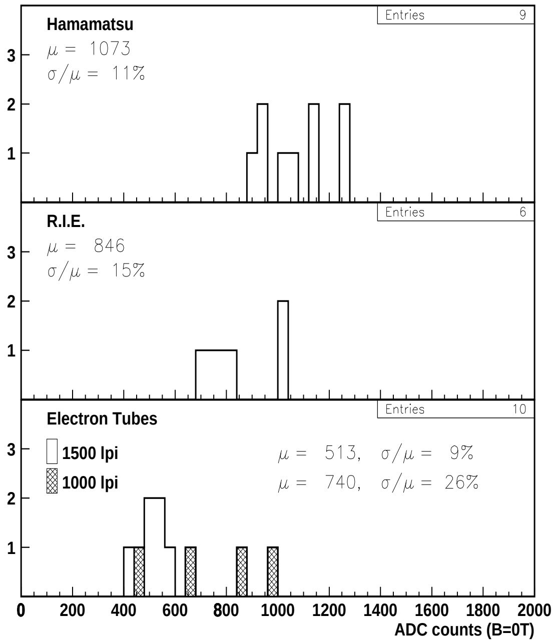

Figure 12.

ADC signal for 50 GeV deposited energy, normalised to a naked crystal light yield of 8 p.e./MeV, by VPT type.

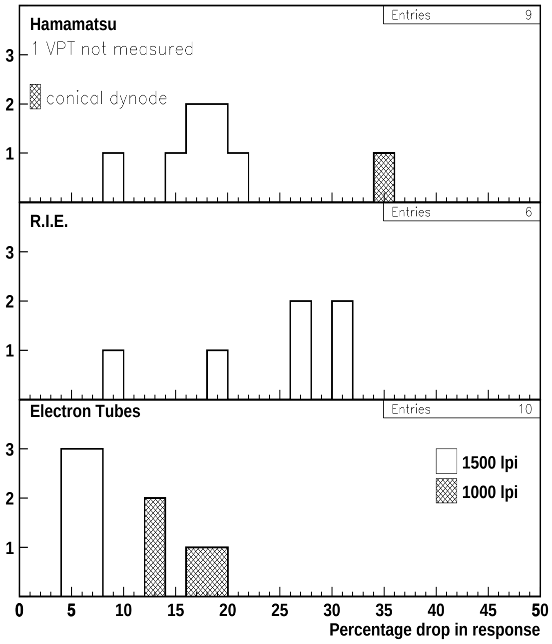

Figure 13.

VPT drop in response (%) at 3T with respect to 0 T, by VPT type. VPTs at 15^{o} to the field.

7: VPT performance at B=3T

The LED response of the VPTs was measured at H2 in magnetic fields from 0 to 3T. The VPTs were at an angle of 15 degrees to the magnetic field. This is representative of the average angle of VPTs to the field in CMS.

Fig. 13 shows the percentage drop in the LED signal between the 0T and 3T data. The Hamamatsu tubes drop by 10-20%, except for the dished, or conical dynode tube which dropped by 35%. The RIE tubes drop by 10-30%, and the ET tubes drop by (5-8)/(12-20) %, showing for the first time a superior aspect of the 1500 lpi over the 1000 lpi tubes.

8: VPT electron yield at 0T and 3T

In order to measure the VPT electron yield an ADC calibration was carried out by injecting a known charge into each preamplifier. This was done by applying a voltage, V_T, of 0.1 V (0.2 V on channel 2) across a 2.2 pF capacitor, C_T, as shown in Fig. 14. The normalised calibration corresponds to an input charge of 0.22 pC = $1.375.10^6$ electrons.

The injected charge was checked by measuring the output peak voltage from the preamplifiers with an oscilloscope connected in-line (through 1 M-ohm) to the output cable leading to the counting room, at the preamp box. Fig. 15 shows the peak voltages measured on the 25 channels. The mean is 100 mV.

The preamp response was also measured on the bench top, in the laboratory, after the preamps were dismounted from the array. Charge was injected into each preamp using a calibrated capacitor. The distribution is shown in Fig 15. The mean value is 104 mV, in close agreement with the test beam. The width is 3.6% in comparison to the test beam width of 9.3%.

The expected peak output voltage is given by :

$$V_{peak} = \frac{1}{2} \bullet \frac{C_T}{C_F} \bullet V_T \bullet \frac{1}{e} \bullet \frac{R_S}{R_I}$$

for a preamp with equal rise and fall times (in this case 27 nsec) **[4]**. The components are shown in Fig 14. Their values are given in Appendix 3. The expected peak voltage is 123 mV. The bench top measurements are within 16% of the expected voltage and the test beam measurements within 19% of the expected voltage.

The measured and expected voltage peaks can differ due to the tolerance on components and the preamplifier board layout. The latter can give rise to stray capacitance and finite strip impedances which change the response.

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Fig. 16 shows the electron yield per MeV, measured at H4 with B=0T, for the 25 channels of the array. The data have been normalised to a naked crystal light yield (HPMT) of 8 p.e./MeV. The Hamamatsu VPTs show the best electron yield with a mean of 42 electrons/MeV at B=0T, and a spread of 12%. The RIE mean is 33 and the ET means are 19/28 electrons per MeV.

Fig. 17 shows the electron yield/MeV, at 3T, after normalising to the drop in the LED signal measured in H2 (Fig. 13). The Hamamatsu yield drops to 35 electrons/MeV, RIE to 25 and ET to 18/23 electrons/MeV.

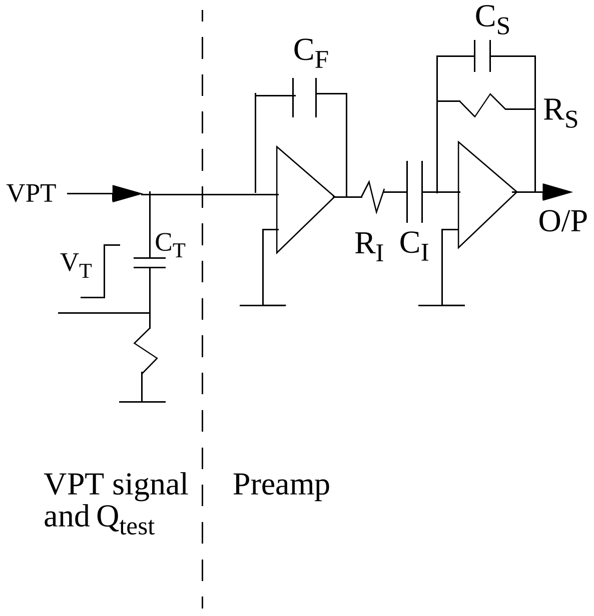

Figure 14.

Preamplifier details and arrangement

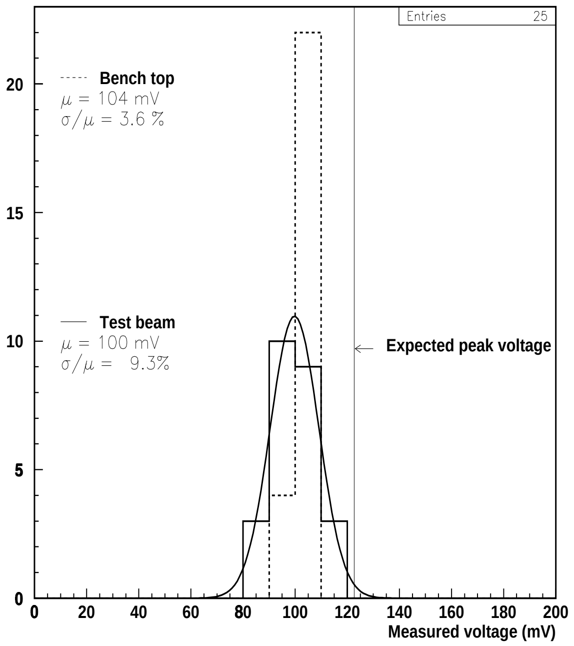

Figure 15.

The distribution of the peak voltage measured from the preamplifiers in comparison to expectation.

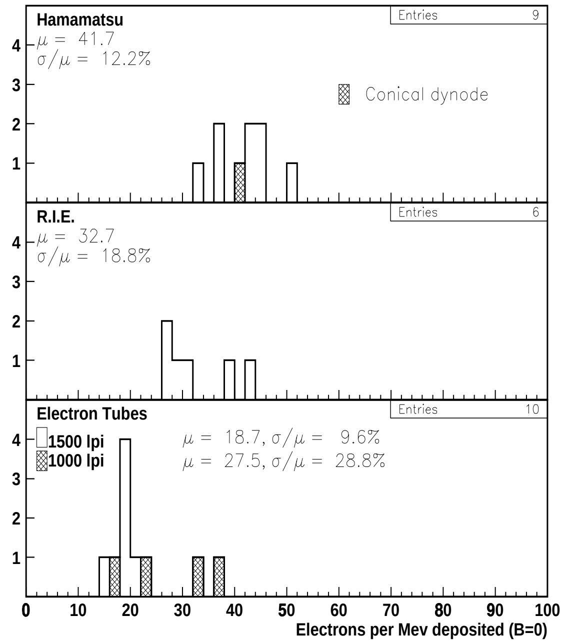

Figure 16.

The VPT electron yield / MeV at B = 0 T, normalised to a naked crystal light yield of 8 p.e./MeV

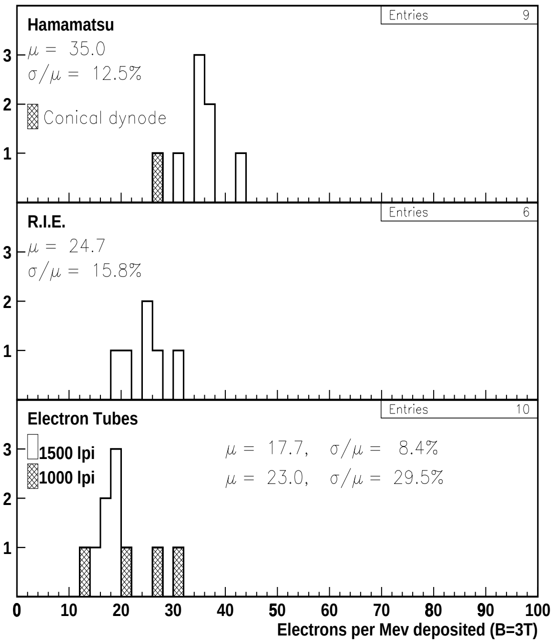

Figure 17.

The VPT electron yield / MeV, at B = 3 T, normalised to a naked crystal light yield of 8 p.e./MeV.

9: Electron yield expected at B = 0 T

The expected electron yield at B = 0 T has been calculated for a typical Hamamatsu VPT, in order to compare to the measured electron yield of 41.7 electrons/MeV in the previous section. The expected yield has been calculated from the following :

- the naked crystal light yield as measured in the lab with an HPMT
- the relative crystal optical matching factor between a VPT and an HPMT
- the relative VPT to HPMT quantum efficiency
- the VPT DC gain
- the Pulsed to DC VPT gain factor

The values used are listed in Table 1.

For this estimate a naked crystal light yield of 8 p.e./MeV has been assumed.

Table 1:

Crystal Light Yield (HPMT)	8 p.e./MeV
VPT to HPMT matching factor	0.63
VPT to HPMT quantum efficiency factor	0.9
VPT DC gain	7.9
VPT pulsed gain to DC gain factor	0.9 - 0.95
Expected Electron Yield	**32.2 - 34.0 e$^-$/MeV**
Measured Electron Yield	**41.7 e$^-$/MeV**

The VPT to HPMT optical matching factor was found by carrying out ray tracing simulations with the programme RAGE **[5]** which modelled the naked crystal with HPMT (which covered the entire back face of the crystal), and the VPT with crystal optical arrangement inside a supercrystal.

The VPT to HPMT matching factor was found to be 0.63 for VPTs with a 20 mm active diameter (this diameter is characteristic for the Hamamatsu devices). The matching factor is significantly larger than the 0.31 geometric factor between the VPT and HPMT because many of the photons which miss the VPT are reflected back around the crystal and have subsequent chances of detection.

The quantum efficiencies of the HPMT and the Hamamatsu VPT with a Caesium/Antimony photocathode are shown in Fig. 18 as a function of wavelength. Also shown is the lead tungstate emission spectrum. The relative quantum efficiency of the VPT to the HPMT, convoluted with the emission spectrum, is 0.9.

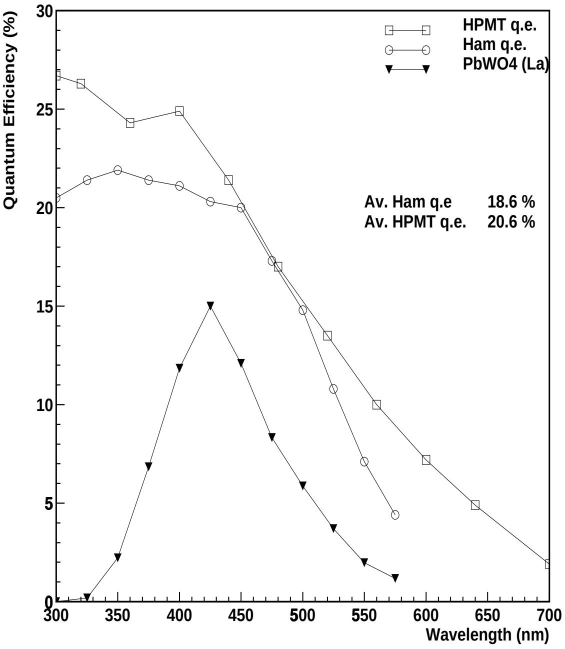

Figure 18.

The HPMT and VPT quantum efficiencies as a function of wavelength and the PbWO4 (La) emission spectrum.

The average Hamamatsu VPT DC gain is 7.9 (Fig. 4). The relative magnitude of the pulsed gain to the DC gain has been measured for a number of VPTs and is found to be 90 - 95 % of the DC gain **[6]**.

The resultant expected electron yield is 32.2 - 34.0 e^-/MeV, as shown in Table 1. This is in reasonable agreement with the measured Hamamatsu yield of 41.7 e^-/MeV as shown in Fig. 16.

10: Predicted noise at 0T and 3T

The preamplifier currently proposed for the EE is based on Harris bipolar technology. The electronic noise is expected to be ~ 3500 electrons **[7]**. Contributions to the noise arise partly from the input capacitance of the cable, from the VPT to the preamp, and from preamp design constraints for the dynamic range and pulse peaking time stability as a function of pulse size. A dynamic range of 16.5 pC, an input capacitance of 40 pF, and a shaping time of 40 nsec were used for the design of the preamp.

Fig. 19 shows the predicted noise in MeV at B = 0 T after normalising for a naked crystal light yield of 8 p.e./MeV (HPMT) and taking the values for the number of electrons per MeV from Fig. 16 for each of the VPT types.

The mean Hamamatsu noise is 84 MeV at B = 0 T. For RIE it is 110 MeV and for ET the mean values are 189/141 MeV. The spread is smallest for Hamamatsu at 14% and largest for the ET 1000 lpi at 32%.

The predicted noise at 3T is shown in Fig. 20. The noise was calculated from the reduced electron yield per MeV shown in Fig. 17. The mean Hamamatsu noise at 3T is 102 MeV. For RIE the mean noise is 145 MeV and for ET the means are 202/169 MeV. Again the spread is lowest for the Hamamatsu tubes at 13%. The noise target in CMS is 150 MeV.

The Hamamatsu and RIE tubes would meet the noise target for CMS. However at high luminosity LHC operation VPT burn-in losses (~10%), VPT faceplate darkening (~5%), and crystal light yield losses (~10%) will increase the noise figures by ~ 20-25%.

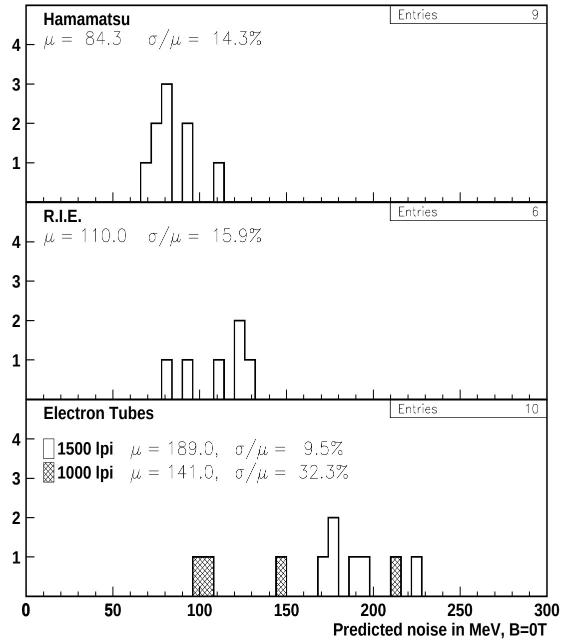

Figure 19.

Predicted noise term, in MeV, at B = 0 T for preamp noise of 3500 electrons and a naked crystal light yield of 8 p.e./MeV

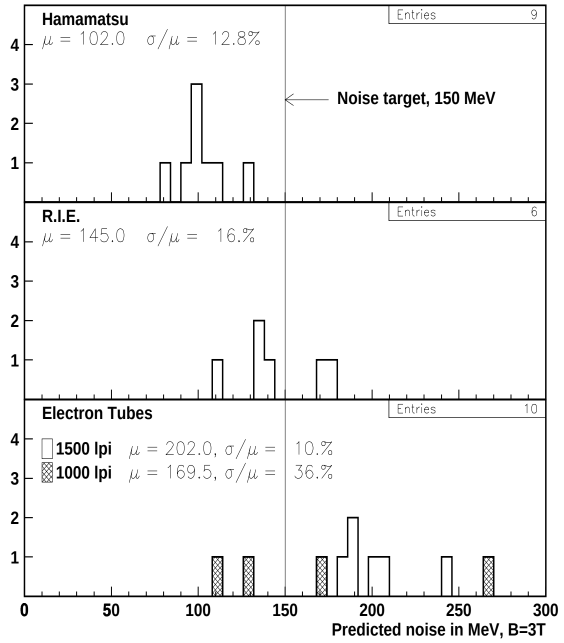

Figure 20.

Predicted noise term in MeV, at B = 3 T, for preamp noise of 3500 electrons and a naked crystal light yield of 8 p.e./MeV

11: Predicted output at 2 TeV, at 3T

The ECAL Endcaps are expected to perform linearly up to a value of 2 TeV of deposited energy in a single crystal (this may be increased to 3 TeV). The corresponding electronic dynamic range required from the Endcap preamplifiers is crucial for their design.

The predicted charge output from a VPT at B=3T for 2 TeV in a single crystal is shown in Fig. 21. The data from Fig. 17, for the number of electrons per MeV at B=3T, have been used.

The Hamamatsu VPTs have a mean predicted output of 11 pC, with a spead of 12%. The mean for RIE is 8 pC with a spread of 14% and for ET, 5.5/7.5 pC with spreads of 9/30%.

12: Predicted output at 4T

The data need to be extrapolated from 3 T to the 4 T operating field of CMS. The field scans in H2 indicate that the Hamamatsu tubes are largely unchanged in their response above 2T, as shown in Fig. 22. The predicted noise and pico-coulomb output shown at 3T are likely to be representative at 4T.

The RIE tubes show a complex behaviour with field from 0T to 3T, with both improving and degrading behaviour at the 10% per Tesla level. The response at 4 T is therefore likely to be within 10% of that measured at 3T.

The trend for the ET 1500 lpi tubes is relatively flat. However the 1000 lpi tubes show a fall in response above 2T by about 9% per Tesla. At 4T the output is likely to be about 10% lower than at 3T.

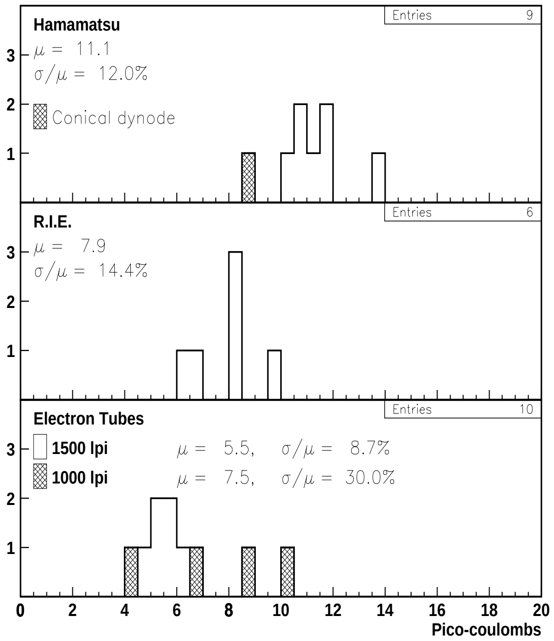

Figure 21.

The predicted charge output, in pico-coulombs,
for 2 TeV deposited energy, for B = 3 T
with the field at 15 degrees to the VPTs

It is interesting to note that, despite their lower output, the Electron Tube 1500 lpi devices show the closest correlation in behaviour as a function of magnetic field. This could be due to tighter tolerances on the mechanical dimensions or on better manufacturing reproducibility of the anode meshes.

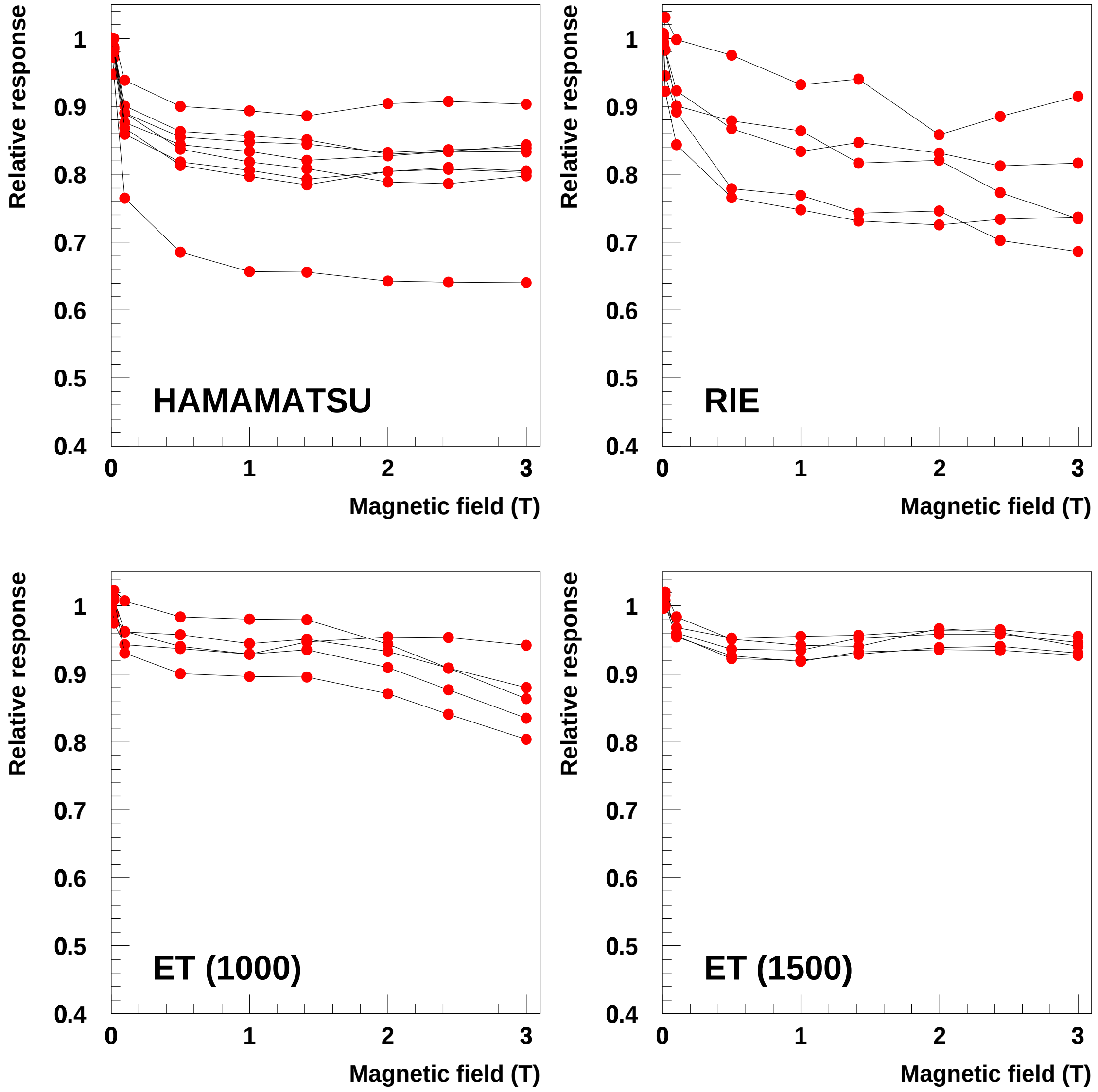

Figure 22.

VPT response as a function of magnetic field (current)
normalised to the response at B = 0 T. The VPTs were at 15^{o} to the magnetic field.

13: Conclusions

The RIE mean electron yield, measured at 3 T at 15 degrees to the field, is 25 electrons per MeV. The output for 2 TeV deposited in a single crystal is 8 pC, with a spread of 15%. These figures are currently the most important since RIE was awarded the contract to supply the pre-production series of 500 VPTs for the EE in April, 2000. The yield at 4 T is likely to be within 10% of the yield at 3 T.

Based on the RIE data, the noise per channel is predicted to be 145 MeV at 4T, for a naked crystal light yield of 8 p.e./MeV (HPMT, CERN) and an ECAL Endcap preamp with 3500 e^{-} noise. This is close to the design target of 150 MeV, but leaves little headroom.

The Hamamatsu yield is 35 electrons per MeV at 3 T, giving a noise term of only 100 MeV which is well within the 150 MeV target. The Electron Tube devices do not meet the noise target.

References

[1] ‘Stephenson’, RAL, discrete component preamplifier with a design shaping time of 27 nsec (33 nsec measured) and a maximum input level of 2.10^7 electrons.
[2] ‘Tests on 1999 Vacuum Phototriodes for the CMS ECAL Endcaps’, B Camanzi et. al., CMS Note 2000/010.
[3] ‘Initial Tests on First Full-size ECAL Endcap Crystals’, G Davies et. al., CMS Note 1999/022
[4] ‘Electronics for the physicist’, Cyril Delaney, p 63.
[5] ‘Simulation of the HPMT/VPT Light Collection Ratio’, D Britton, M Apollonio, E McLeod, CMS Note in preparation.
[6] D. Imrie, ‘A study of pulsed and DC VPT gain’, private communication.
[7] J-P Walder, private communication, 20 April 2000.

Appendix 1 : Crystal and VPT pairs as seen from the back of the array.

Crystal number
VPT make and number

2200 Ham 858	2194 RIE 41	2178 Ham 1029	2191 RIE 56	2198 Ham 1039
2175 ET 22	2195 RIE 33	2185 Ham 1037	2202 ET 37	2188 ET 32
2174 ET 23	2199 ET 31	2182 Ham 958	2179 ET 38	2183 Ham 957
2203 Ham 1033	2201 RIE 35	2184 Ham 967	2186 RIE 59	2187 RIE 36
2190 ET 33	2181 ET 40	2177 ET 24	2176 ET 20	2192 Ham 971

Appendix 2 : Crystal Light Yields

The reference light yield measurement for barrel crystals, in building 27 at CERN, is undertaken with Tyvek wrapping on 5 sides of the crystal with a grease joint to a photomultiplier (PM) tube fully covering the rear face of the crystal. HPMT measurements give the same results as those with the PM.

The light yield for unwrapped (naked) crystals is 30-40 % less, for polished crystals, and 50% less if depolished on one side. The naked polished Endcap crystal light yield of 8 p.e./MeV therefore corresponds to a reference light yield of 10.4-11.2 p.e./MeV which is consistent with the average light yield for barrel crystals of 10.3 p.e./MeV.

Appendix 3 : Preamplifier details

C_F = 2.2 pF, R_I = 150 ohms, C_I = 180 pF, R_S = 1000 ohms, C_S = 27 pF
Rise and fall times, $R_I*C_I = R_S*C_S$ = 27 nsec