PMTs of the test beam telescope at TB21

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Abstract

During the summer students program at DESY, I worked on the PMTs of the test beam telescope DATURA and the new telescope DURANTA. The goal was to find reasons for broken or not working PMTs at DATURA. Therefore measurements at the TB21 were done, to find the best control voltages for the PMTs of DATURA, by which the PMTs should be prevented from damage. In addition to that a test setup for PMTs without attached scintillators was designed and first measurements were done. The test setup tries to test only the PMT modules free of other influences. Thus hopefully seeing differences from PMT modules before and after working at the test beam telescope. Besides this it is generally helpful for testing PMTs without attached scintillator. In a last measurement the rate vs. momentum behavior of TB21 was analyzed and compared with older measurements.

Contents

1 Introduction

To build todays huge and precise particle detectors it takes a long time of research and development. Especially testing, at as possible realistic conditions, is a very important step in developing detectors. Therefore a collaboration at DESY of people from the CMS and from the ATLAS group, which I belong to, build up test facilities for detector tests. One of these test facilities is the area of test beam 21 (TB21) which is located at the DESY II storage ring. The DESY II storage ring is an electron accelerator. These electrons can be used to produce a strong photon beam, which can produce an electron beam. This electron beam can reach energies from 1-6 GeV and is used as an particle beam to test detectors. As an reference detector, the so called 'test beam telescope' is permanently installed at the TB21 area. The test beam telescope is basically a very precise tracking tool for the electron beam. In the middle of the telescope the users can place their test device. The test beam area and its telescope can actually be used by everyone, more informations can be found on the official web page [1].
During my summer students journey my main task was to inspect photomultiplier tubes (PMTs) which are used as trigger devices at the test beam telescope detector. In the recent past some of the PMTs showed an unexpected behavior or completely due to unknown reasons. By building a test procedure for 'raw' PMTs[1], testing them in their normal working mode at the telescope and looking on the details, I tried to find indications.

2 The test beam at TB21 and it's beam telescope DATURA

The test beam area TB21 is located in building 27 at the DESY site, a detailed plan of the area [2] and a map of the campus [3] can be useful.
In figure 1 a schematic of the beam creation is shown. At DESY II electrons with a energy of 6 to 7 GeV are stored, during the measurements the energy was all the time 6 GeV. Inside the beam line there are three carbon fiber targets, one for each beam (test beam 21, 22 and 24). In a four step process the electrons are first emit photons by Bremsstrahlung when they hit the 25 μm carbon fiber target [4]. In a second step the photons are converted into electron positron pairs by pair production. The converter plate for the here presented measurements is a 3 mm Cu plate, but it can also be chosen aluminum as a converter plate. A full list [5] is online available. By a magnet(3) the electron/positron trajectories are bended to a wide fan. Only a small energy window of the fan can pass the collimator(4). The bending of the trajectories is given by $r = p/B \cdot e$, with r the bending radius, p the momentum of e^+/e^-, B the field strength of the magnet(3) and $e = \pm e$ the charge of the particles. By varying the magnet current the magnetic field can be varied from 0 T to 0.9 T which is equal to a test beam energy form 0 GeV to 6 GeV.

To track the test beam one can use the test beam telescope DATURA. In figure 2a one can see a sketch and a picture of the telescope. Let's first focus on

[1]'Raw' PMTs means PMTs without an attached scintillator.

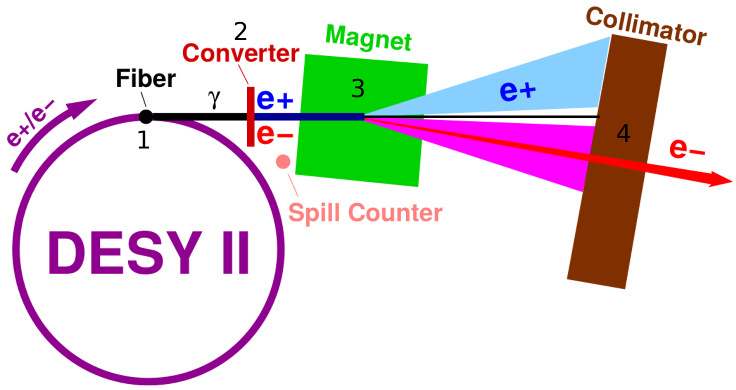
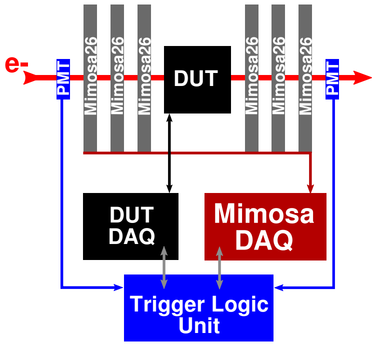


Figure 1: schematic of the beam generation at DESY II [6]

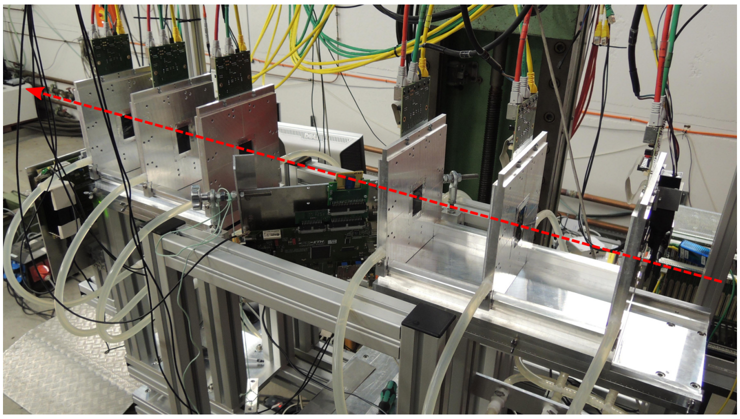
the sketch. The beam telescope starts with an incoming e^--beam[2], which hits first the scintillators of the two PMTs in front of the telescope. If every thing works, both of them detect a light signal from the scintillators and send two signals to the trigger logic unit (TLU). The same happens at two PMTs behind the telescope '*after*' the electrons passed the whole telescope setup. Because of beam energies form 1 GeV to 6 GeV and a telescope length of less than 2 m, '*after*' means after a few nanoseconds, so almost at the same moment. Therefore a coincidence signal of all four PMTs is used as a trigger signal. Now it is most probable that a particle has passed the telescope, as it is shown in the sketch. It is also probable that this particle was one of your beam electrons. With such a four coincidence the TLU produces a so called trigger signal. By an incoming trigger the TLU starts to accept the incoming measured data of the Mimosa detectors and of the device under test (DUT) if integrated. It takes some time to read out and save all the data of these sensors. So the TLU doesn't accept new triggers during the readout/ save time because the electronics are not build to read and write data in parallel. When all data is saved a so called 'hand shake' signal is send back from where the data is saved (PC) to the TLU. When the hand shake signal arrives the TLU, it is ready to accept the next coincidence of all PMTs to produce a next trigger signal for upcoming data taking.

The realization of the beam telescope looks like in figure2b. The Mimosa26 detectors are inside the six aluminum jigs and are located behind the black taped area. Each consists out of 576x1152 pixels of 18.4 μm pitch, so the total detector area is 13,7 mm x 21,5 mm [9]. By using the data of all six detectors one can reach a resolution of roughly 2 μm at the device under test (DUT), which is located in the middle of the six Mimosa planes. Therefore the Mimosa detectors are read out row by row all columns in parallel, which takes about 115 μs. The aluminum jigs are kept on a constant temperature by water pipes which goes through the plates to have constant noise level. On top of the aluminum plates the read out electronic is fixed and cables lead the signals to the data acquisition (DAQ). In front of the first Mimosa aluminum plate two of the four PMTs and their scintillators are installed. The red dashed line illustrates the test beam.

[2]The test beam can be an e^+/e^- beam. For simplicity i will speak always about an e^- beam



(a)
sketch of the DATURA test beam telescope[7]



(b)
DATURA at the TB21 area[8].

Figure 2: DATURA=**D**ESY **A**dvanced **T**elescope **U**sing **R**eadout **A**cceleration, a sketch of the telescope and the telescope in reality at TB21

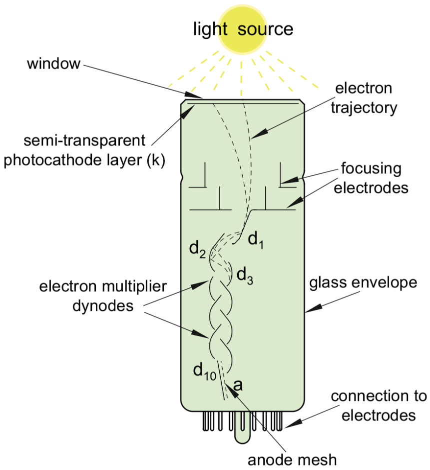
3 Photomultiplier tubes & scintillators

3.1 Photomultiplier tubes (PMTs)

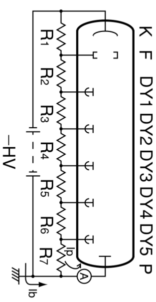
Let us first discuss the general operating mode of a PMT, you can find more informations in[10]. Afterwards we have a look on the special structure of a metal package PMT[11], as the H11902 series of Hamamatsu, which will be used for the new telescope DURANTA. The general principle of a PMT can be divided in two basic steps. First the conversion of a photon to an electron by the photoelectric effect in the photocathode layer and second the amplification of the electron by a chain of dynodes. Therefore the electron is focused and accelerated to the first dynode by a electrostatic potential. Because of the acceleration the electron has enough energy to create a few secondary electrons during hitting the first dynode. The secondary electrons are accelerated to the second dynode and produce again more electrons. The form and the number of dynodes and the potential between the dynodes, affects the amplification of incident electrons on the first dynode to the number of electrons on the last dynode, which is the collection anode. The ratio between incident and final electrons is defined as the gain:

$$\text{gain} = \frac{\text{incident } e^{-} \text{ at the first dynode}}{\text{number of } e^{-} \text{at the anode}} \tag{1}$$

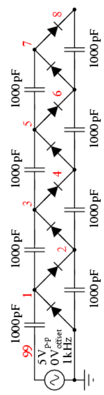
Also the energy of the incident photon influences the gain. An user controls the gain by setting the electrostatic potential between the dynodes The ratio of the potential between the dynodes is normally given by a voltage divider network, shown in figure 3b. In such a network the high voltage (HV) drops over a chain of resistors, the resistors set the fraction of the HV for each dynode. The HV for this network is today supplied by a internal high voltage AC-DC-converter to make the handling of PMTs safer and easier. Internally, there is also a DC-AC-converter 3c, from which the hight of the AC amplitude can be controlled by an external control voltage. According to this, the external control voltage the HV and so the gain of the PMT is controlled. One has to keep in mind that the gain typical reaches high values of about 10^5 and if one wants to compare measurements the gain should be stable. This means the control voltage and the DC-AC and high voltage AC-DC-converter should be stable. As a rule of thumb:
"If the output stability of a photomultiplier tube should be maintained within one percent, the power supply stability must be held within 0.1 percent"[10, p. 24]
So, the control voltage should be much more stable than 0.1 percent. As a last step one should amplify the signal of the PMT, to measure signals.



(a) The general operating principle of a photomultiplier tube[10, p. 2]



(b) schematic voltage divider for a PMT[11, fig. 5-2,(1)]

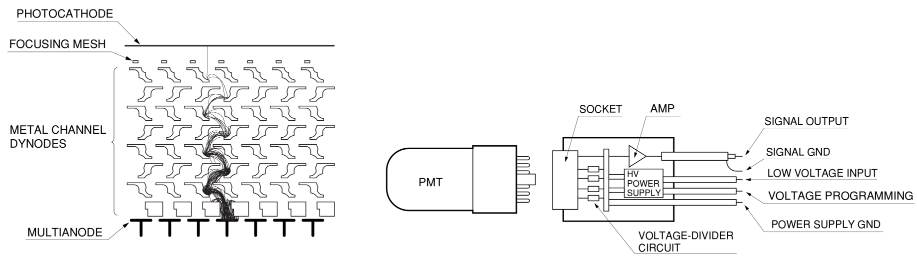


(c) schematic high voltage AC-DC-converter[12]

Figure 3: General principles of a PMT module

Let's have a look on todays PMTs. During the time PMT modules shrink to smaller and smaller devices (see fig.4). In addition they become more stable against magnetic fields and other external influences. But the basic idea is still the same, photon to electron conversion and amplified electrons by a 'dynode chain'. The main difference are the dynodes and the internal electric devices. An example are metal package PMTs, which are the PMT type of the current beamtelescopes at DESY. Such a PMT has metal channel dynodes, which are shown in figure 5a. The metal channel dynodes are very thin and close together, which makes the multiplication stable and fast. The initial photomultiplier tube is nowadays only a small part of the whole 'PMT case'(fig.5b). In the case, typically some or all of these three electronic devices are installed: A voltage divider (D), which is perfectly adjusted to the PMT geometry, and material, which is connected by a socket, and a stable, precise and by a control voltage programmable high voltage power supply (P). This results in a safe handling and gives the ability to control the gain precisely. And as a last element, a low noise current to voltage amplifier (A), which is directly connected to the PMT anode to reduce external noise. Depending on what you need you can order D-, DA-, DP- or DAP-type PMTs. Thus, you can get and easily install a PMT with clear signals out of a small box which works, assumed the PMT is treated well, for decades of years.

Figure 4: PMTs through the ages



(a)
metal channel dynodes and electron ways[11, fig. 9-2]

(b)
modern DAP-setup PMT with divider, amplifier and HV power supply[11, fig. 3-8]

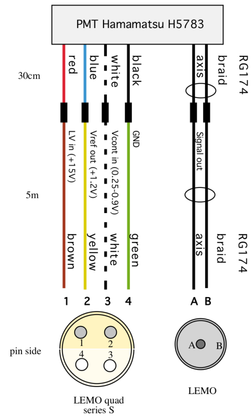
Figure 5: Principles of modern PMT modules with their support electronics

3.2 Hamamatsu H11901-110

Our purpose is to install the H11901-110 PMTs from Hamamatsu at the new telescope DURANTA. For a test beam telescope, the PMTs don't need to fulfill highest requirements, because they are 'only' used for a sufficient trigger signal. Basically, one has to choose a 'matching pair', of a 'fast' scintillator and PMT.

'Matching pair' means here, matching the sensitive wavelength of the PMT which is mainly given by the material of the PMT window and the material of the photocathode to the scintillator or vise versa. The H11901-110 is a metal package DP-type PMT, which gives fast signals in a wide spectral range from 230 nm to 700 nm. It needs a DC input voltage from +11.5 V to 15.5 V, which is converted to a HV and adjusted by a control voltage from 0 V to 1.1 V.The peak sensitivity is at 400 nm, the maximal output signal current is 100 μA. Other specifications are available at [13].

(a)



(b)

Figure 6: Wiring of the PMT. Same wiring for the old and new PMTs.

3.3 Scintillator BC408

For DATURA and the new test beam telescope DURANTA the scintillator material BC408[14, 15, 16] is used. It's a plastic scintillator with a maximum emission at 425 nm and can be used to detect charged particles or high energetic gamma rays. Its density is $\rho = 1.032\,\mathrm{g/cm^3}$ and it has a refractiv index of $n = 1.58$. For our applications we have scintillators with an effective area of 2 cm x 1 cm and a thickness of 0.3 cm. To get a idea of what happens in the scintillators, how many photons they produce and how much they influence the beam path by multiple scattering, I do some estimations in the following.
First let's have a short look to the processes in a plastic scintillator. A incident ionizing particle, which is traveling through the material of the scintillator, loses energy by ionization and excitation of the surrounding material. The energy loss due to this processes for heavy incident particles like protons or even heavier particles is well described by the Bethe-Bloch formula. For electrons one has to be careful, because they don't require all the assumptions which leads to the Bethe-Bloch formula. Therefore one has to add correction terms to this formula, but for our raw estimate, the results from the normal formula should be sufficient. Let's come back to the scintillation process. The excitations in the material decay fast by emitting UV-radiation. Because normal scintillator materials are opaque for UV-radiation, one has to add special molecules which shift the wavelength from UV-radiation to visible light. The visible light can easy propagate trough the material and is leaded by light guides to the window

of the photomultiplier.
For our estimate, we just calculate the energy loss by the Bethe-Bloch formula and ignore the process of wavelength shifting and other processes, by which the deposited energy can decay without producing scintillation light. By assuming this, we result inA.1:

$$\text{energy loss in MeV} \cdot \text{cm}^2/\text{g}: \qquad dE/dx \approx -3.5 \tag{2}$$

$$\#\text{photons of } 425\,\text{nm } 1/\text{cm}^2: \qquad \#\gamma \approx 3.72 \cdot 10^5 \tag{3}$$

One can also calculate the multiple scattering in the scintillator using the Molière theory, but for that, the radiation length of BC408 has to be known.

4 Functionality tests in the Lab

Because it is not clear, why the PMTs of the test beam telescope sometimes don't work in the right manner, or completely fail, one of my tasks was to build up a functionality test for the PMTs. An important requirement was to build a test for PMTs without an attached scintillator. The first idea behind this is, to test new PMTs without the influence of an attached scintillator, so that one gets the raw PMT behavior, between input and output data, which can be tested later and should come to the same results. A second advantage is that one can make two different tests, with a radioactive source and attached scintillator and with a light source without a scintillator. Indirectly one can test in this way the scintillator and its connection to the PMT. As a third motivation, it was just a test to get familiar with PMTs and their behavior and get a better understanding. Because of problems in the creation of a reasonable light source, the functionality test were done in parallel to the tests at the TB21.

4.1 Maximum light input for the H11901-110 PMT

A first task was to estimate the amount of light, which can be handled by a PMT, without damaging or even destroying the PMTs. As the main constrain the maximal output signal current of $100\,\mu$A was used [13]. As a light source we used a simple LED with a dominant wavelength in the region of our scintillator emittance and PMT sensitive wavelength. We choose a LED, because they are easy to handle, quickly available, stable running and last but not least cheap. A problem was that we were not sure if the LED can handle the short and weak pulses, which are needed for the PMTs. Our LED is the L-934MBC, Round series blue from Kingbright, with 80 mcd, $\theta = 20°$ viewing angle and a dominant wavelength of 455 nm. More informations in the data sheet [17]. From this we can calculate (used values[13, 17]):
For the PMT the typical anode luminous sensitivity is 210 A/lm, the luminous intensity of the LED is 80 mcd @ 20 mA$\gtrsim$3.8 V at $\theta = 20°$. By this we can calculate the total luminous flux of the LED.

$$\text{solid angle of LED:} \qquad \Omega = 2\pi(1 - \cos(\theta/2)) \approx 0.095\,\text{sr} \tag{4}$$

$$\text{luminous flux of LED:} \qquad 80\,\text{mcd} \cdot 0.095\,\text{sr} \approx 0.0076\,\text{lm} = 7.6\,\text{mlm} \tag{5}$$

Out of this the PMT output current for a constant shining LED@20 mA can be calculated.

$$\text{PMT output current:} \qquad 7.6\,\text{mlm} \cdot 210\,\text{A/lm} \approx 1.6\,\text{A} \tag{6}$$

So for a constant shining LED the output current is as expected much to high. Therefore the idea is to make short pulses with a proper frequency to get an average current of the required $100\,\mu$A. During the light pulse, the output current can exceed the maximum. We only have to guarantee that the average current (DC) is below the maximum. We set the light pulse length to 40 ns which is in the region of scintillation light pulses. This results in a maximum frequency of:

$$1.6\,\text{A} \cdot 40\,\text{ns} \cdot \text{f[Hz]} \stackrel{!}{=} 100\,\mu\text{A} \tag{7}$$

$$\text{f} = 1562.5\,\text{Hz} \tag{8}$$

4.2 Puls generation with the NE555 chip and the LEMO solution

So, the aim is to build a LED with 40 ns pulses @ 1.5 kHz. To be safe, in the further part it is the aim to build the LED@∼400 Hz. For tests in the future I tried to build a blinking circuit in which one can vary the frequency. To build such a circuit I used an NE555 timer chip[18, 19] and soldered the astable operation mode figure7b. The values for the frequency, high times and low times of the circuit are given by simple formulas.

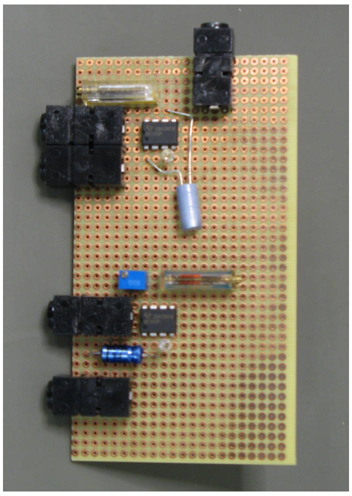
$$\text{frequency } f\text{[Hz]:} \qquad f = \frac{1.44}{(R_1 + 2 \cdot R_2) \cdot C} \tag{9}$$

$$\text{high time } ht\text{[s]:} \qquad ht = 0.69 \cdot (R_1 + R_2) \cdot C \tag{10}$$

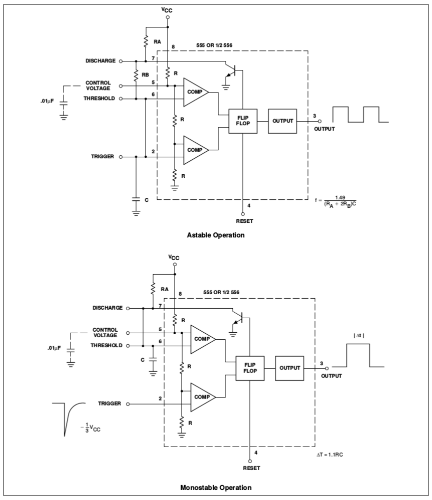
$$\text{low time } lt\text{[s]:} \qquad lt = 0.69 \cdot R_2 \cdot C \tag{11}$$

It's obvious that $ht > lt$ holds always, so one should use lt for the short pulses and ht for the rest period of the LED, given by the frequency. Because it was not obvious how long the rise time of the LED is and we were not able to find values in the data sheets, we first tried to make longer pulses and observe the behavior of the LED. This I get the values: $C = 10\,\mu\text{F}, \quad R_1 = 70k\Omega, \quad R_2 = 20\Omega$. This should give us $lt \approx 13.8$ ms and $ht \approx 483$ ms, so a frequency of about $f \approx 2$ Hz. First we set these values, because we want to see if the circuit works and then change the resistors to better values: The resistor R_1 was a 100 kΩ potentiometer and the resistor R_2 a 50Ω potentiometer. The circuit worked in the expected manner and by changing the potentiometer R_2 down to $\sim 2\Omega$ we get pulses of about $12\,\mu$s which was observed on a oscilloscope. So the LED managed pulses of μs. In a next step the monostable operation mode [18] was build. In this circuit, one can trigger the frequency by an external trigger signal and gets pulses of the length $\Delta t = 1.1 \cdot R \cdot C$. a capacity $C = 1\,\mu$F and a potentiometer from 1Ω to 50 Ω was chosen. Theoretically one gets pulses of 55-1.1 μs but if the pulses gets shorter the NE555 chip is to slow and the circuit doesn't work any more.

Poorly, this wasn't described in the data sheet [18] which we used first. If one has a detailed look in [19] it's clear that the chip can not handle pulses in a nanosecond range. It turned out that therefore a newer timing integrated circuit, like the ICM7555 [20], would be a much better choice. With the ICM7555 one can in principle build now the same circuits as for the NE555 and should get the required conditions.
But to save time and get a real flexible pulse and frequency behavior of the LED, we decided to connect the LED directly to the pulse generator. With an 47 Ω resistor in series to match the impedance, the LED was directly soldered to a LEMO cable and this was connected to the pulse generator. At the beginning this easy solution was unfavored, because with one 'wrong click' at the pulse generator, the LED can turn into a too strong shining mode and destroy a direct connected PMT immediately. If one keeps in mind that such a PMT costs 500-600 €, it's clear that one should be careful with this running mode. But it turns out that this solution was a good one, which achieves pulses down to 2 ns, which is the restriction of the pulse generator.



(a) First try to make a 'blinking' LED. Monostable (upper part) and astable operation (lower part).



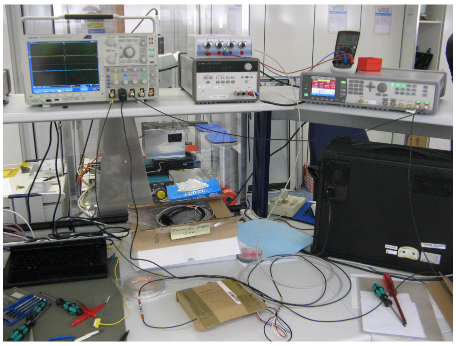
(b) Circuit diagramm of the NE555 in an astable and monostable mode[18, p. 351].

Figure 7: Soldering a circuit using the NE555 for a blinking LED

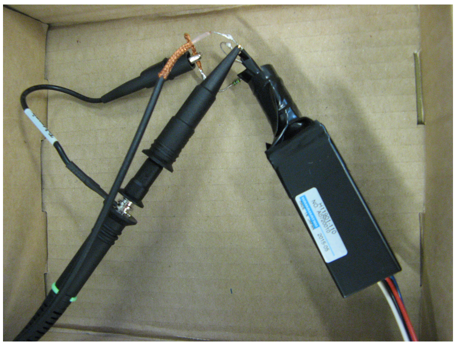
To answer the question, how the LED handles fast pulses, the voltage drop at the PMT was measured. The forward voltage was set to 4 V, but even with less then 4 V one can see a light in the LED, with voltages down to ∼ 3 V. At pulse pulse width of about 40 ns, the voltage at the LED rises above the 3 V for only a fraction of 40 ns due to the intrinsic rise time of the LED. However in principle, the LED should shine. After we made ourself familiar with the behavior of the LED on different pulses, we were ready to attach the PMT.

4.3 The PMT test setup

To attach the LED to the PMT a housing for the LED was designed and produced by a 3d printer. The housing has to be lightproof and would fix the LED at the right position in front of the PMT, so that the whole window is illuminated. A PMT window with $\varnothing = 8\,\text{mm}$ and a LED viewing angle of $\theta = 20°$, results in : $d = 4\,\text{mm}/\tan(\theta/2) \approx 22.69\,\text{mm}$ for the distance d(PMT window to LED). In figure 8 one can see the final test station and the electronic setup. Before starting the LED, a dark count measurement was done (see fig. 9a) to make sure that the test station is total lightproof. Then the LED was smoothly turned on from 1 V to 3 V at 40 ns pulse length and a frequency of 5 Hz. The whole procedure can be found in the lab book at page 20-21 and page 24. The result of the first testing is shown in figure9b. All the measurements with an oscilloscope were done with the Digital Phosphor Oscilloscope DPO 4104B from Tektronix.



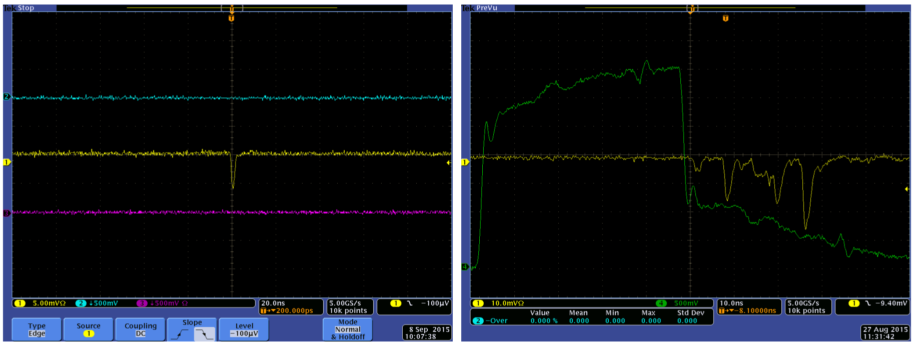
(a) Whole setup for the PMT test station. On the top: left the oscilloscope, middle the power supply for the PMT, right the pulse generator& multimeter for the control voltage.
Bottom: paper box of 8b.



(b) PMT test setup, the LED in its lightproof housing attached to the PMT and a test probe to view the voltage drop across the LED+47 *Omega* resistor. The LED is powered via a LEMO cable from a pulse generator.

Figure 8: Setup of the PMT test setup with a 'blinking' LED.

As one can see the the PMT signal is noisy and doesn't looks as expected. It is assumed that the PMT signal is a signal of many photons which are emitted in a short random series. This test indicates that the PMT is working, but it seems impossible to analyze the signal easily to get a quantitative measurement of the PMT behavior. To get less photons, or in the best case single photons we tried to make shorter pulses. But by make shorter pulses one also reduce the pulse height at the PMT, because this element slows down the rise and fall of the pulse. Therefore the pulse height of the pulse generator was increased, but by doing this we could not achieve the hoped results. In a next step it was tried to start from a higher base line (low to $\sim 2\,\text{V}$) to achieve faster rising pulses at the LED. You can see the results in figure 10. As one can see the pulse is slightly above 3 V but no light is emitted by the LED. By triggering on the PMT signal, one gets many PMT signals(see fig. 10) in the low region of 2.2 V, where the LED should not emit light. The signals in this region are of different pulse heights and it seems that the height distribution follows an exponential

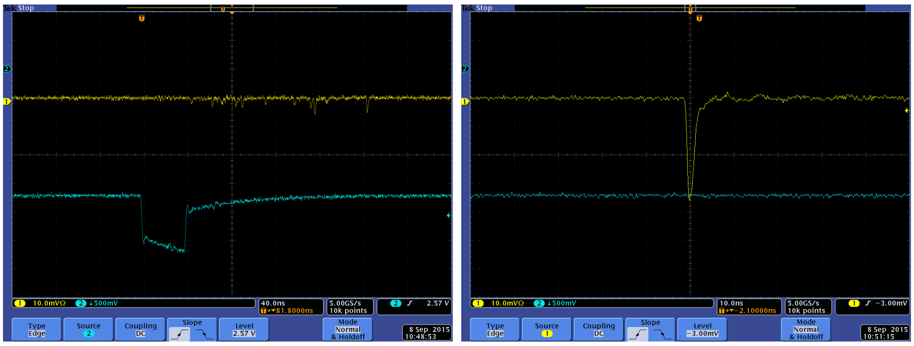


(a) Dark count measurement of the PMT with attached test station. Control voltage is 651 mV, signals with <1 Hz

(b) PMT signal with pulsed LED. Channel 1 is the PMT signal and channel 4 the voltage drop at the LED+47 Ω resistor.

Figure 9: Measurements with the PMT test station

decay[3]. As a conclusion it might be spontaneous emission of the LED which we can observe with the PMT.
By rising the lower voltage of the pulse generator one attach nearly a DC voltage to the LED, because the high pulses are 40 ns long at frequency of 5 Hz. Now more symmetric signals were observed, which strength the idea of spontaneous emission. In total, the symmetric, gaussian pulse shape, the theory that one observes spontaneous emission and the low height of the signals leads to the idea that we observe single photons. However further studies would be needed to confirm this.



(a) PMT signals at the pulses of the pulse generator. High signal of -3.4 V, low signal of -2.2 V. It seems like the pulse don't generates photons in the LED.

(b) Spontaneous emission of the LED@2.2 V. This signals occurred with a high random frequency $\mathcal{O}(10\,\text{Hz})$ by eye, and random distributed pulse heights.

Figure 10: Spontaneous emission of the LED. Channel 1 PMT signal, channel 2 voltage drop at the LED+47 Ω resistor.

[3]To proof this a histogram of the pulse heights was plotted on the oscilloscope. Whatever threshold we used for the trigger one can see after a time a exponential decay in the distribution. For higher thresholds one has to measure longer. Sadly the oscilloscope has no option to get the data of the histogram to analyze the distribution on a pc.

4.4 Results from the PMT test station

The LEMO solution of the blinking LED is a flexible test station and brings unexpected results. To make a quantitative measurement of the PMT behavior one has to do more investigations on this topic. In our measurements, we observed that a short pulsing of the LED doesn't lead to clear PMT signals. It seems that a far better running mode for the LED is a low DC current at about 2.2 V. It seems to us that in such a mode the LED emits spontaneous single photons of different energies. By a higher DC current one can get a higher rate of spontaneous emissions. For the LEMO solution one has to keep in mind that by 'one wrong click' on the pulse generator the PMT can be destroyed. Therefore in the first part we tried to solder a circuit for a 'blinking' LED. It is summarized, that too short pulses don't lead to a good PMT signal and that also the NE555 chip is much to slow for such pulses. For further investigations one can use the ICM7555 chip, capacitors of $\mathcal{O}(1\,\text{nF})$ and resistors of $\mathcal{O}(1\,\Omega)$ or below. Accordingly it should be possible to reach the required short pulse length. However one should think about, if a 'blinking' LED makes at all sense for further tests or if one should focus on the DC mode.

5 Control voltage optimization at the test beam

As a second big test for the PMTs I did, were some measurements at the TB21 area, with the telescope DATURA. The aim was to find optimal control voltages for each PMT. As in chapter 3.1 described the control voltage adjust the high voltage power supply and the gain[4]. The optimum control voltage provides a sufficient gain for a sufficient signal height to get maximal trigger rates. Thus, a high control voltage would match. Secondly, a low control voltage should be chosen to prohibit damages during long-term operation. Therefore, a trade-off is searched. The plan is to use the test beam and to measure the rates of the PMTs for different control voltages. It is expect that for low control voltages the rate is very low, because the gain is too low and so one gets almost no signals. At higher values we hope to measure a steep rise because now the gain is for more and more light signals high enough to produce a PMT output. At even higher values we expect a plateau because one measures all the incoming light signals. By increasing the gain more, one only increases the amplitude of the PMT output signals, but not the rate. So at this values, only the probability for damage increases and due to the gain the possibility for more dark counts rises. The optimal value for the control voltage is therefore the edge of the plateau.

5.1 Set up the rate measurement

To measure the rate vs. the control voltage we lead the raw PMT signals with LEMO cables out of the test beam area into a nearby hut, because one can not stay in the test area during a measurement, because of too high radiation. In the hut we build up the electronics to measure the rate. In figure 11 one can see the

[4]In the telescope DATURA is the previous model of the described PMT installed. The H5783-None from Hamamatsu [21] has almost the same characteristics as the H11901-110, except the control voltage which can be set from 0-1.0 V instead of up to 1.1 V.

counting electronics. From the right side the four raw PMT signals 12a are put into the discriminator with a threshold of -40 mV. By this we can cut off most of the noise signals. The threshold is an approved limit, which is also used by the TLU of the telescope. We confirmed this by analyzing the PMT signals with the math mode of the oscilloscope. As a short test we plotted the values of the pulse minimum of each pulse over some seconds end ended up with histograms like in figure 12b[5] One can see the typical shape of the PMT signals with a width of about 20 ns and the characteristic shape of a steep fall and slow rise of the negative peak. As we expected the four signals are basically at the same time and one can see the ordering from the PMT 1 signal to the last signal of PMT 4[6]. In picture 12b one can see the typical Landau distribution of the peak heights of PMT 1, which is given by the energy loss fluctuations in the attached scintillator. Back to the discriminator. If a signal with a peak 'larger' than -40 mV is given to the discriminator, it sends a standard logic pulse to its output. This pulse is the input for the coincidence unit. Here one can, by pressing the white buttons, built a coincidence circuit of the desired PMTs. As soon as a coincidence of the desired channels is fulfilled a logic pulse is sent to the scaler. The scaler counts pulses in a given time, which results in a rate.

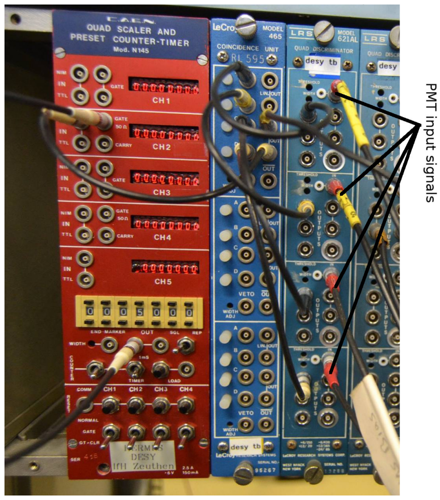


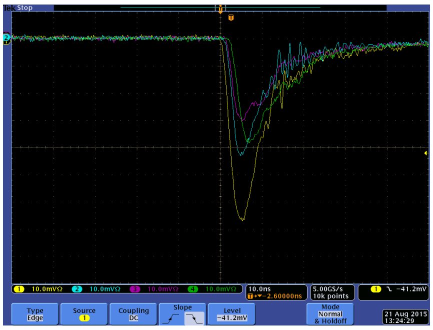
Figure 11: Setup to count the raw PMT signals in the hut of TB21. From left: scaler, coincidence unit and a discriminator.

5.2 Measuring rates vs. control voltage

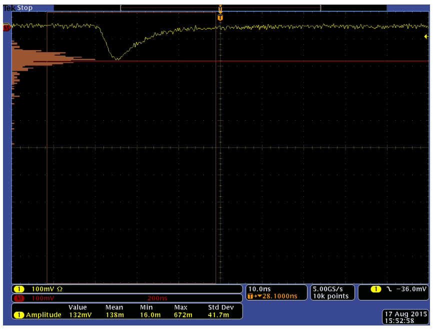
Using this setup(5.1), we measured the rate vs. control voltage. Before doing this, we had a short look on the test beam stability, which is mainly given by the beam stability of DESY II. As you can see in figure13 the beam in DESY II runs through cycles of low and high numbers of particles. The high rate is about 30 s long and the low rate about 10 s. The low rate comes from the extraction of particles out of the DESY II beam line into the PETRA III ring, which one can see in the yellow and orange part of the diagram. The most particles are in the light green region which stands for the particles in linear accelerator 23(L23) which is the preaccelerator of DESY II. To achieve valid data it was only measured in the high rate phases, because here the statistics for the rate measurements are higher. Because even this phases were fluctuating in time, the rate measurement for each control voltage was repeated at least six times. Each measurement was 10 s long. During the whole rate vs. control voltage measurements the test beam momentum/energy was fixed to 2 GeV,

[5] Sadly we lost accidentally some of the oscilloscope measurements from a USB flash device, so that we can not show here the noise peak or a better histogram of the amplitude distribution.

[6] We used four all the PMTs the same cable length($\pm \sim 10$ cm uncertainty) from the test area to the hut.



(a) Raw signal from all PMTs, trigger on channel 1.



(b) Histogram of the amplitude distribution of PMT 1 with a threshold of -36 mV, which cuts the noise peak.

Figure 12: Measurements of the raw PMT signals with the oscilloscope. Channel one belongs to PMT 1, which is the PMT which is hit first by the test beam. Same for channel 2, 3 and 4.

which corresponds to a magnet current of 74.93 A. It was done because there the highest rate was expected, based on a older measurement [22]. The PMT powering is provided by the EUDET TLU. The control voltage of each PMT can be set via a command line in 1 mV steps by: *./TLUControl -p1 800*[7], which is a stand alone program from the EUDAQ software framework.

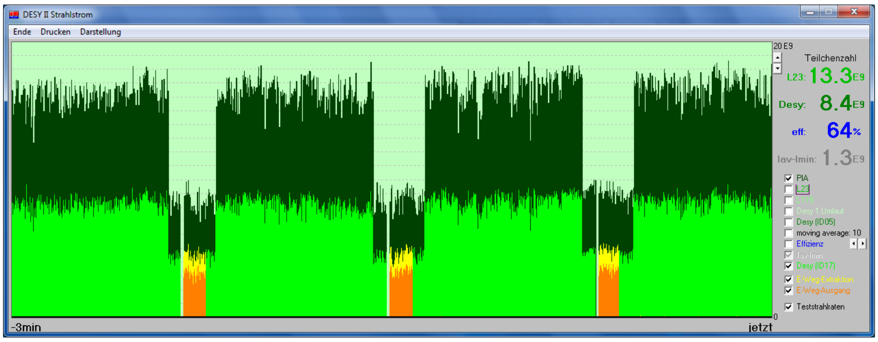


Figure 13: Stored particles in DESY II and number of particles in the acceleration chain before and after the DESY II ring. On the x-axis the time from 0 to -3 min and on the y-axis the number of particles times $20 \cdot 10^9$. In dark green the particles in DESY II.

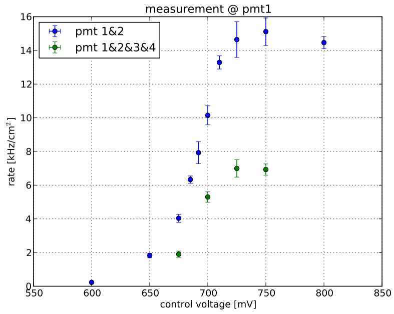
To be sure that we don't measure noise signals, which increases with the control voltage, one always has to measure PMT signals in coincidence. The control voltage of all PMTs is set to 800 mV by default by starting EUDAQ. Because not even one of the best control voltages for the PMTs was known, the following procedure for the coincidence setup was used. First only PMT 1 and PMT 2 were measured, to prevent a bad influence from PMT 3& 4. The control voltage of PMT 2 was fixed at 800 mV and the control voltage of PMT 1 was varied

[7]This is an example for setting PMT 1 on 800 mV. One can just add the other PMTs by -p'#number of PMT'+voltage in mV.

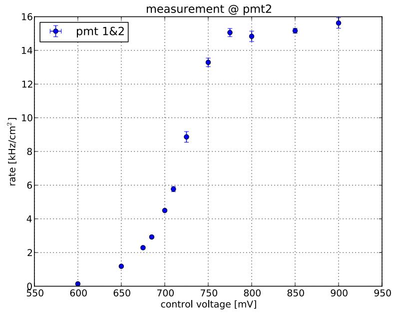
from 600 mV to 800 mV. Then the data from PMT 1 was rough analyzed to find it's best control voltage at 725 mV. Vice versa the control voltage of PMT 2 was varied and the coincidence of PMT 2& 1 was observed, but now PMT 1 was fixed to its best control voltage 725 mV. By analyzing the data of PMT 2 its best control voltage was set to 775 mV. Now it was measured PMT 3 in coincidence with PMT 1 @725 mV and PMT 2 @775 mV and the control voltage for PMT 3 was set to 800 mV. For PMT 4 the same was done in coincidence of PMT 1& 2& 3 @best control voltages and 750 mV turned out as the best control voltage for PMT 4. To be sure that by this procedure the control voltages of the first both PMTs were not set to wrong values a control measurement was done. Therefore, some of the important points of PMT 1 were measured again in a coincidence setup of all PMTs @ best control voltages. Again 725 mV turned out as the best control voltage (green data in 14a). The measurements are plotted in figure 14. The errors on the y-axis/ rate are given by the standard deviation of the mean rate of all measurements at a fixed control voltage. The error on the x-axis/ control voltage is set to 1 mV, the last digit of the control voltage adjustment. This could be an underestimated error, but with regard to the errors on the rate one can neglect most of the x-errors and even some bigger errors would not change much the results.
One interesting aspect of this measurement (fig. 14) is the strong shrinkage(up to a factor 2) of the rate with a coincidence of more PMTs. Especially if one has a coincidence of PMTs before and behind the telescope. Therefore one can compare the rate of figure 14b and figure 14c. It's not totally clear were so many particles of the beam get lost, but one also has to keep in mind were the test beam comes from and how it was created. Obviously, the beam is traveling over a long distance before it passes the beam telescope. The only optics which 'focus' the beam are collimators, so the beam has a shape and is neither perfectly parallel aligned nor focused on all elements in the beam telescope. Because of its high energy the beam is strongly forward directed, but this seems not to be enough to hold all the electrons inside the sensitive area of the telescope. Just keep in mind that a beam normally has a gaussian shape, with a beam waist and a beam divergence.
Smaller contributions to the loss of roughly around 50% of the beam are multiple scattering in all the elements, for what a small estimate should be done in chapter 3.3 and maybe a not perfect aligned telescope. The telescope was not aligned before the measurement, but with a short crosscheck, provided by the EUDAQ software, the old alignment was measured. Because the alignment was sufficient, it was not necessary to change the placement. In a later measurement15a the rate vs. momentum was measured and we get pretty much the same rates, so the telescope should be as good aligned as in the previous measurement15b. A last reason which I would mention here is the efficiency of the single PMTs which is at all times $eff < 1$. So if you build a 'AND' logic of PMTs which is the same as a coincidence, your over all efficiency eff_{all} behaves like:

$$\text{eff}_{\text{all}} = \prod_{\text{all PMTs}} eff_{PMT}$$

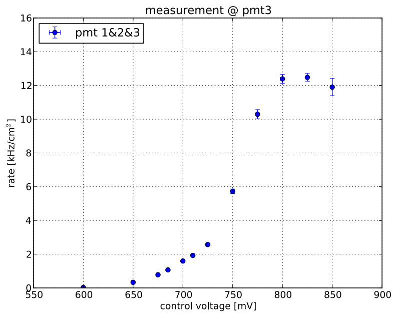
For a single efficiency of eff_{PMT}=99% your over all efficiency $\text{eff}_{\text{all}} = 0.99^4 \approx 96\%$, but for eff_{PMT}=95% you already end up with $\text{eff}_{\text{all}} \approx 81\%$. Determining the efficiency for a single PMT is not easy because they normally reach effi-



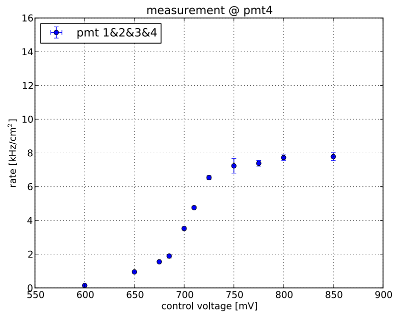
(a) first& fifth measurement



(b) second measurement



(c) third measurement



(d) fourth measurement

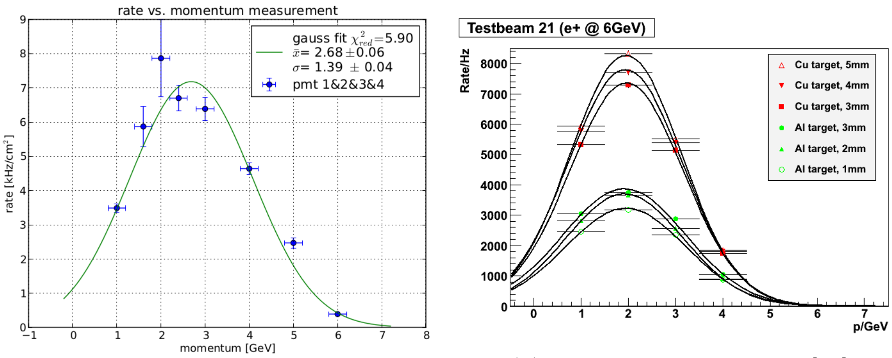
Figure 14: Measurement of rate vs. control voltage for all four PMTs @ a beam momentum of 2 GeV. In the legend the coincidence setup is shown by '&' and the numbers of the PMTs. PMT 1 and 2 are in front of the telescope(hit first by the beam), PMT 3 and 4 are the one behind. The rates were calculated to kHz per cm^2 of scintillator area perpendicular to the beam.

ciencies near to 1, so such measurements were not done. But due to this high efficiencies, it's obvious that this should be only a small effect.

I want to add here one last comment to the measurements of figures 14c& 14d. Surprisingly the total beam rate brakes down form about 12 kHz to below 8 kHz, just by adding the fourth PMT in coincidence to the rest PMTs. As before discussed, there are many reasons why the beam rate decreases, but none of them can easily describe why the rate is so much lowered by adding PMT 4. The scintillator of PMT 4 is directly behind the one of PMT 3, so the beam shape and multiple scattering should not much influence the rate between a coincidence of two of them. To conclude, it's not obvious where one third of the beam is going in a distance below 1 cm. Therefore, one should do further investigations on PMT 4, or if this is not solving the problem once again on all PMTs.

5.3 Measurement of rate vs. momentum

As last measurement the rate versus the momentum of the particles was measured, which is set by the magnet current. Therefore, all PMTs in coincidence at their best control voltages were operated. The rate was measured in the high beam rate region, for each selected momentum at least five times by which each single measurement was 30 s long. The average rate and its standard deviation for each momentum were calculated. The deviation on the momentum was estimated to be 0.2 GeV based on a simulation in [23, p. 52 fig. 5.29]. This results in figure 15a. By comparison with 15b for the 3 mm Cu target, it's showing pretty much the same results and the deviations which are in the 1σ region are due to te low statistics. One important result is that we get the same rate @ 2 GeV as in the measurements before.



(a) Own measurements for 3 mm Cu

(b) Previous measurements [22]

Figure 15: Rate vs. momentum measurements by comparison.

5.4 Results from the test beam measurements

During the week-long measurements at the TB21 with DATURA, most of the time was used to prepare the measurements and to attend the DESY lecture program, which takes place each morning. Nevertheless with some straight forward measurements, it was possible to figure out for each photomultiplier its best control voltage. Because EUDAQ sets the control voltage of each PMT by default to 800 mV, I would recommend to set the control voltages to the new values in table 1 in future operations.

PMT	recommended control voltage	comments
1	725 mV	OK
2	775 mV	OK
3	800 mV	OK
4	750 mV	strange behavior[8]

Table 1: Recommended control voltages+comments based on5.2.

[8] There are more investigations on PMT 4 needed to understand the apparently huge beam loss between PMT 3 and PMT 4. See the discussion in the last part of5.2.

By measuring the beam rate vs. the beam momentum, previous measurements were confirmed and it confirms the current performance of the whole DESY II test beam facility.

6 Conclusions, further work and outlook

In conclusion, we find some first hints why the PMTs could brake. It is assumed that by setting the optimal control voltages for each PMT, the lifetime of the PMTs might be increased, but it can not be the only reason for the PMT breaking. A PMT test setup was developed but for quantitative results it needs further improvements. However, it seems to be interesting to improve the test setup and from the physical point of view get a better understanding of what is going on in a LED, which is short pulsed or powered by a too low voltage. In the next days I maybe can assist in building up the new test beam telescope DURANTA. Therefore, the scintillators has to be attached to the new PMTs and after this to be installed at the telescope.

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A Appendix

A.1 Energy loss in BC408

The values for BC408 which are used can be found in[14, 15, 16]. The used python code:

```
# calculation of energy loss of a ionizing particle by Bethe Bloch

import math as m;

print 'energy␣loss␣by␣ionisation␣with␣bethe␣bloch'

#######    INPUT    ########################################

me = 511*10**3      # eV; elektron mass

# absorber material
ZH = 1
AH = 1       # g/mol
nH = 5.23   # atoms per Volume

ZC = 6
AC = 12      # g/mol
nC = 4.74   # atoms per Volume

# incoming particle
M = me              # eV; mass off incomming particle
z = 1
E = 2*10**9         # eV; Energy of incoming particle
p = m.sqrt(E**2-me**2)
print 'p=', p*10**(-9), 'GeV'
#######    CALCULATIONS    ##################################

K = 0.307075 *10**6        #eV*cm^2/g ;unit for K/A, A=1, so a
     dimensionless

n = nH+nC
Z = nH/n*ZH + nC/n*ZC
A = nH/n*AH + nC/n*AC

beta = p/E
gamma = 1/m.sqrt(1-beta**2)

# print 'beta:', beta, ',', 'gamma', gamma, ',', '<Z>', Z, ',', '<A>', A


def bethebloch(beta, A, Z, M, me, z): #alles in eV; Formeln nach Herten
     Skript 03
        I = Z*(12+7/Z)           # in eV; Herten 03,14 Z<13
        Tmax = 2 *me *beta**2 *gamma**2 / (1+ (2*gamma*me)/M+(me/M)**2 )
        # print 'ionistaion energy', I, 'eV,', 'maximum energy transfer
             ', Tmax*10**(-9), 'GeV'
        dEdx = -K *z**2 *Z/A *1/(beta**2)*(1./2.* m.log(2*me*beta**2*
             gamma**2*Tmax / I**2)-beta**2)
        return dEdx

def photons(d = 0.3, rho = 1.032, photonenergy = 2.917):
        """␣calculation␣of␣number␣of␣photons␣from␣ionisation␣energy.␣
             Without␣any␣losses.
␣␣␣␣␣␣␣␣␣␣␣␣d␣=␣thickness␣of␣scinti␣in␣cm
␣␣␣␣␣␣␣␣␣␣␣␣rho␣=␣densiti␣of␣scinti␣in␣g/cm^3
␣␣␣␣␣␣␣␣␣␣␣␣photonenergy␣=␣scintillation␣light␣in␣eV␣(425nm)
␣␣␣␣␣␣␣␣"""
        depositedenergy = -d*bethebloch(beta, A, Z, M, me, z)*rho
        numberofphotons = depositedenergy/photonenergy
        return numberofphotons

print 'dE/dx=', bethebloch(beta, A, Z, M, me, z)*10**(-6), 'MeV*cm^2/g'
print '#photons=', photons()*10**(-5), '*10^5␣1/cm^2'
```