Headlamp with optimized light distribution for huge caves

Developed and handcrafted in a small batch for Landesverein für Höhlenkunde in Oberösterreich, Zweigverein Hallstatt Obertraun

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A. General

Ten samples of this helmet lamp were handcrafted for the internal use in the caving club. Since they are not offered on the market, they need no CE sign and are not damned to comply with any standard.

This lamp was developed to demonstrate the possibility of effectively improved light distribution especially for huge caves. All commercially produced headlamps on the market show suboptimal light distribution – even the most expensive models! Most of them provide a much too narrow beam pattern, or enlighten areas the bearer never can see. Additionally the development took care to avoid a point-shaped light source area – most commercially offered headlamps are glaring in case you look into the face of a caver.

Figure 1 – Lamp switched off

The headlamp provides three independent light sources:

- On the lower side of the front panel there is the *wide beam* light, which is declined downwards by about 20° mechanically (causing problems handcrafting the casing). It produces a diffuse beam with half width of ±45° (FWHM 90°); even at ±55° the luminous intensity is still above 15% of the maximum.
- On left upper side (front view) resides the *medium beam* light with half width of ±14° (FWHM 28°). Also this beam is nearly edge free. This light source is driven by a led with four dies. Thus the beam pattern can be modified electrically.
- On left upper side (front view) is a *narrow beam* light. In contrast to the other lights this thrower produces a sharp edge to suppress spill outside of its 15° FWHM.

position of switch	destination / name	light sources in use		
		wide beam	*medium beam*	*narrow beam*
0	off			
1	*pause light*	X		
2	*walking light low*	X	X	
3	*walking light high*	X	X	
4	*shaft spot*			X
5	*hall light*		X	

The headlamp can be supplied by four to six Alkaline AA cells or by rechargeable batteries in the range 3,5 to 9V. By means of a coding resistor inside the connector of the accumulator the overdischarge protection of the headlamp can be adjusted to the threshold voltage of the accumulator.

Note: **The three-pole connector of the accumulator should provide an appropriate coding resistor to activate the overdischarge protection of the headlamp.** (see below)

The casing of the headlamp is relatively small sized (85 x 56 x 24 mm). The lid on the back side of the headlamp is aluminium and acts as heat sink and as mounting plane. The weight of the headlamp including a stable polyurethane cable of 1 m and the three-pole connector is 240 g only.

The casing is a standard rectangular ABS box thermally warped for the declined *wide beam* light. ABS doesn't conduct heat effectively; thus the lamp is cooled by the aluminium lid on the back side only. To limit size and weight we provided no cooling fins. The price for that is, that switch positions 1 to 3 (*pause light* and both *walking lights*) can be used for infinite time only. Positions 4 (*shaft light*) and 5 (*hall light*) are for short term use only because of heat problems.

Note: ***Shaft spot* and *hall light* only can be used temporarily!**
During *shaft spot* (pos. 4) the power dissipation is up to 4,5 W and dring *hall light* (pos. 5) it is up to 11 W. When the aluminium lid on the back side of the lamp reaches 43 ±1°C[1], *shaft spot* and *hall light* will be deactivated automatically and will be reactivated when the lid has cooled down by about 1° again. The *medium beam* part of the *walking light* is not affected by this temperature control. The duration you can use shaft light and hall light depends upon the temperature of the lid when you switch these lights on (see temperature diagram in chapter G). The time needed to recover the function also depends upon the previous history and the ambient temperature (some seconds to some minutes).

The headlamp is splash proof and can be cleaned under running water. It contains about 1g silica-gel desiccant to absorb capillary leak from switch and supply cable. The lamp is not waterproof and cannot be used for diving.

Note: **The headlamp shall not be used for diving!**
Regularly the headlamp should be stored for long time periods at a dry place to allow the capillary leakage (axis of the rotary switch and cable / connector) to dry out.

The headlamp is controlled by a rotary switch with six positions which are explained in detail in the following chapters.

[1] The automatic temperature protection was defective at first delivery of six devices causing damage to circuitry and leds, because the threshold was set to about 65°C.

B. Position 0: "off"

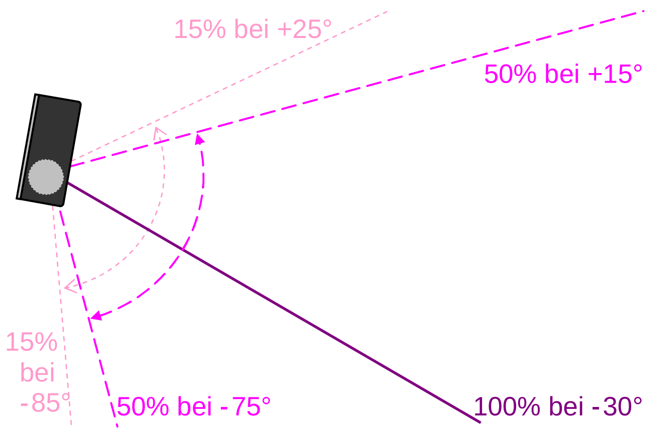
In position 0 (stop counterclockwise) the lamp is switched off in the sense of: no light is burning, as shown in fig. 1. The rotary switch does not disconnect the lamp from the battery, it does only give the control signal for the electronics. Thus also when switched off the electronic circuitry is powered.

Note: **During transport and storage the battery shall be disconnected!** The headlamp even draws a low level current when switched off (pos. 0). The off current is much below 1 mA, so the battery can remain connected during the whole cave expedition, even during sleeping at night. But it shall be disconnected during storage at home, especially when the accumulator was not recharged after the tour immediately.

C. Position 1: "*pause light*"

Figure 2 – *pause light*

In pos. 1 the *wide beam* light is activated solely and driven in a very low level. This setting is designed for pauses but suited for scrawling and in bivouac too. The led is used at about 0,1 W only and the supply current at 4,8 V (4 cells NiMH) is 22 mA only. Supplied at 7,4V (2 cells LiIon) the current is about 15 mA. Even with Alkaline batteries *pause light* would burn for more than a hundred hours.



The light distribution shown in fig. 3 is representative for caver standing upright holding his head in a normal position. Naturally the declination depends upon the mounting of the lamp on the helmet and upon the orientation of the head.

Fig. 3 – Light distribution of *pause light*

D. Positions 2 and 3: *"walking light"*

In positions 2 and 3 two lights are activated simuntaneously: *wide beam* and *medium beam*. Both positions differ by the levels driving the individual lights.

Figure 4 – *walking light*

The combination of *wide beam* and *medium beam* is the main feature of this headlamp. This combination enlightens all objects covered in the field of vision of the barer and avoids wasting light into those directions, the barer cannot see. The luminous pattern is asymmetric in the vertical plane, guarantees enough light immediately in front of the feet of the barer without the need of tilting its head and at the same time concentrates some additional light to the horizon to enlighten the objects far a way.

D.1 Distribution of light

The light distribution shown in figure 5 is representative for a caver walking upright holding his head in a normal position. Naturally the declination depends upon the mounting of the lamp on the helmet and upon the orientation of the head and additionally upon the preferences of the bearer how to adjust his light.

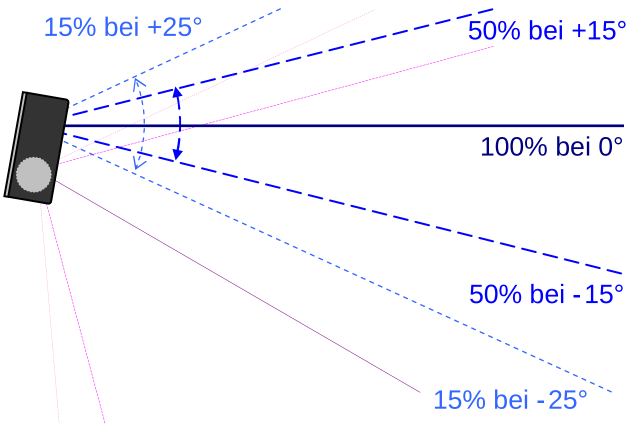


Figure 5 – Distribution of *walking light*

Because only one die out of four of the led is used for *medium beam* during *walking light*, the *medium beam* 'squints' about 10° upwards with respect to the front panel of the casing.

The barer naturally does not sense two different beams but sees the resulting superposition: The illumination increases continuously from the floor immediately in front of his feet to the horizon. The strength of this effect naturally depends upon the power ratio of *wide beam* and *medium beam*.

D.2 Position 2: *walking light low*

The led of the *wide beam* is supplied with about 0,37 W and the upmost die of the *medium beam* gets 0,09 W additionally. At 4,8 V the supply current of the lamp is about 100 mA and at 7,4 V about 70 mA.

A set of four AA batteries maintains *walking light low* for more than 24 hours. Nevertheless this light is even brighter than a carbide lamp.

The dissipation is lower than 0,6 W and the long term temperature rise with respect to ambient air is limited to less than 5°K.

More than 80% of the light output comes from wide beam source, the power of wide beam light is about four times as high as the power of medium beam. But on the other hand the *medium beam* optic provides a higher spatial gain (about 4 Cd/lm) than the *wide beam* optic (about 1 Cd/lm), thus the luminous intensity of both partial lights is comparable (meaning the increase in illumination intensity of superposition in the horizontal direction is about two times).

This means that the effect of enlightening the horizon is very moderate. This is suitable for small dimensioned parts of caves, were it is not necessary to see father than about 10 m.

D.3 Position 2: *walking light high*

The led of *wide beam* is supplied with 0,83 W and one die of four from the led of *medium beam* is supplied with 0,47 W. At 4,8 V the lamp draws about 290 mA and at 7,4 V about 190 mA.

A set of four AA cells lasts about 8 hours with *walking light* high. This light is much brighter than any carbide lamp and especially enlightens objects in the background much better.

The dissipation is lower than 1,5 W and the long term temperature rise of aluminium lid with respect to ambient air is limited to less than 13°K.

About 64% of the overall light output is produced by the *wide beam,* thus the light output of the medium beam is about half value of wide beam. Because the spatial gain of the *medium beam* optic is about four times higher than that of *wide beam*, the luminous intensity of *medium beam* is about two times higher and results a maximum intensity in the horizontal direction which is about three times higher than outside of the *medium beam*.

With *walking light high* the enlightening of the horizontal direction is much stronger than with *walking light low*. This is suitable for large dimensioned parts of caves, were it is necessary to see much farer than 10 m. The wide beam needs no such high step of increase since the floor isn't much farer from your lamp even in very huge halls!

E. Position 3: *"shaft spot"*

Figure 6 – *shaft spot*

The led of narrow beam uses 2.8 W at 4,8 V and the lamp draws about 670 mA. At 7,4 V the led uses 3,7 W and the lamp draws about 590 mA.

The dissipation of the headlamp is up to 3,2 W when used with four NiMH cells and up to 4,4 W with two cells LiIon. Without temperature management this may lead to a long term temperature of the aluminium lid of about 29° (NiMH) or even 39° (LiIon) above ambient air.

Using NiMH in alpine caves may need a very long time to reach the threshold temperature of 42° to 44°C. With LiIon the threshold can be reached in 5 to 15 minutes depending upon the start temperature.

Note: **After automatic temperature shut down during *shaft spot* it will get totally dark.** But nevertheless *walking light* and *pause light* work normally.

The *narrow beam* exits the front panel of the casing perpendicularly. So it is comfortable to use it without further adjustment to take a look into a long horizontal tunnel or into a deep pit. Due to limitations of the human neck it will be necessary to tilt the headlamp upwards for taking a look into a high smokestack in the ceiling.

F. Position 5: "*Hall light*"

All four dies of the led of *medium beam* are used for *hall light*. At 4,8 V these use about 7,2 W and the lamp draws about 1,7 A. At 7,4 V the led uses about 9 W and the lamp draws about 1,4 A.

Figure 7 – *hall light*

The lamp dissipates about 8,2 W when used with four cells NiMH and about 10,5 W with two cells LiIon. Without temperature management this would lead to a long term temperature of the aluminium lid of about 80° (NiMH) or even 100° (LiIon) above ambient air.

In any case the temperature threshold will be reached after a short time (in the range of 2 to 6 minutes)

Note: **After automatic temperature shut down during *hall light* it will not get totally dark.** Only three of four dies of the led will shut down and *walking light* as well as *pause light* will work normally. Switching back to *walking light* you will experience intermediately total darkness because narrow beam is deactivated completely!

The *medium beam* exits the front panel of the casing perpendicularly. So it is comfortable to use it without further adjustment to take a look into a huge hall only in case of standing at an elevated position. Due to limitations of the human neck it will be necessary to tilt the headlamp upwards for taking a look into a high hall.

G Temperature management

The temperature sensor resides on the inner surface of the aluminium lid near the heat sink of the led of medium beam. The threshold is set to 43 ±1°C. Reactivation starts at 1° below this.

During *pause light* and *walking light* the threshold never will be reached. Even with *walking light high* the dissipation is less than 1,5 W at any time.

The drivers feed an increased current to the led of the *narrow beam* and to the three dies of the *medium beam* when the supply voltage is higher. This means that *shaft spot* and *hall light* are brighter with LiIon batteries than with NiMH. Therefore the temperature rise is faster using LiIon batteries. The time needed to reach temperature threshold depends additionally from the temperature at the starting time.

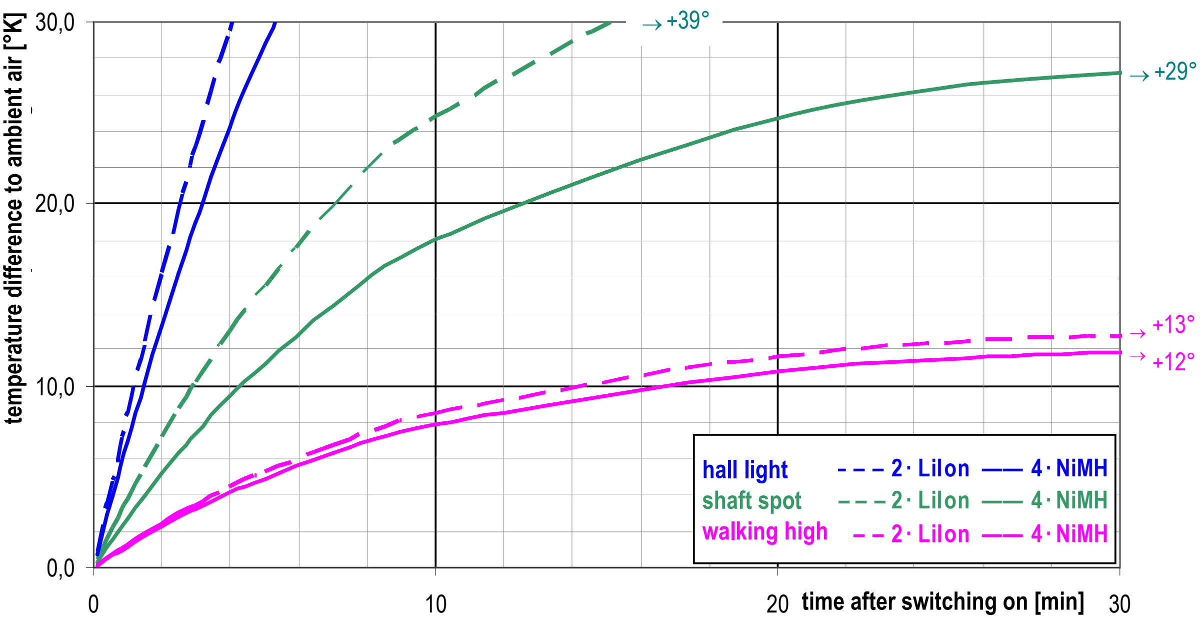


Figure 8 – temperature rise of aluminium lid relative to ambient air temperature

<u>Example</u>
Let's assume the ambient air in front of the helmet is 15°C. An unused lamp thus would have a temperature reserve of 27 to 29°K. If you switch on hall light at first you will get full *hall light* for about 5 minutes (NiMH) or for 3½ minutes (LiIon). If the lamp was used before with walking light high for long time, than you start with heating even at about 28°C and the time temperature shutdown decreases to about 3½ minutes (NiMH) or 2½ minutes (LiIon).

<u>Note:</u> The automatic temperature protection was defective at first delivery of six devices causing damage to circuitry and leds, because the threshold was set to about 65°C. This allowed to use the powerful modes for much longer time – but unfortunately the drivers using integrated circuit C310 were blown thereby 〉:-(
The actual setting is very conservative. The disadvantage of this safe setting is that the powerful lights (shaft spot and hall light) are deactivated continuously in case the lamp is used in mode walking light high and the ambient air at the helmet is above 30°C. Pause light and working light are not affected by temperature.

H Overdischarge protection

The headlamp needs an electric power supply (plus and minus), but uses three-pole cable and connector. The third wire allows setting the threshold voltage by an external resistor. This resistor should reside in the connector of the battery, because each type of battery needs a different threshold voltage.

- Primaries accept to be discharged until completely empty – they are garbage afterwards anyhow.
- Rechargeable batteries will suffer when overdischarged. Especially LiIon batteries will be damaged if discharged below a certain voltage and may explode if recharged again. But NiMH batteries also suffer from overdischarge and need protection, otherwise they will reach end of life after only a few cycles.

The electronics inside the headlamp measures the supply voltages with a resistive divider, where one resistor is missing and needs to be added externally. This setting resistor should connect the third wire to plus pole.

When the supply voltage reaches or falls below the threshold voltage, *medium beam* or *narrow beam* (which ever is used) will start blinking. The *wide beam* is not affected, so it is possible to continue using the headlamp in case of emergency (at the price of overdischarging the battery).

Note: **When the supply voltage reaches or falls below the threshold voltage, *medium beam* or *narrow beam* (which ever is used) starts to blink.**

If blinking occurs during *hall light* it may be possible to use *walking light* still for hours, because the current required for *hall light* is much higher than for *walking light*.

When blinking occurs during *walking light* the battery should be replaced as soon as possible.

During *pause light* blinking never occurs: This can be used in case of emergency but it may shorten the cyckle life of the battery or even damage it.

Note: **In case you have changed the battery and nevertheless the *wide beam* works only (neither *medium beam* nor *narrow beam* are blinking), than you may have got a totally dead battery pack. If either *medium beam* nor *narrow beam* are blinking, than the 'fresh' battery pack seems to be empty but still not totally dead.**

There are three cases to be distinguished:

1. No *shaft spot*; weak *hall light* only; hot lid → overtemperature: wait!
2. *Wide beam* only and cold lid → battery totally empty: change immediately!!
3. Something is blinking → battery empty: change as soon as possible...

The resistor in the battery connector should have the following value:

battery system	*number of cells in series*	*nominal voltage*	*shut down voltage*	*resistor R_X (1%)*	*voltage per cell*[(1)]
Li Ion ($LiCoO_2$)	2	7.4 V	6.2 V	324 k	3.10 V
Ni MH	4	4.8 V	3.6 V	107 k	0.90 V
Ni MH	5	6.0 V	4.8 V	210 k	0.96 V
Ni MH	6	7.2 V	6.0 V	309 k	1.00 V
Ni MH	7	8.4 V	7.2 V	422 k	1,03 V
Alkaline / $LiFeS_2$	4 to 6	6 to 9 V	none	short circuit	none

(1) These cell voltages are valid for ideally balanced battery packs only. Under real life conditions the packs may be unbalanced. In the worst case the threshold guarantees, that no NiMH cell will be reversed charged, even if all the other cells of the pack still have 1,2 V each. For LiIon batteries the threshold guarantees that no cell is discharged below 2,5V even if the other one holds still 3,7V.

For all other voltages use the equation: $R_X = 100\,k\Omega \cdot V / 1.176\,V - 200\,k\Omega$

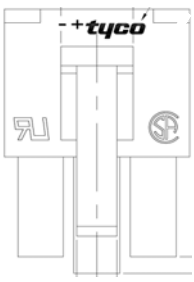
I Pin configuration of the supply connector

In case no fixed connection to a fix mounted battery case at the rear of the helmet is used, the supply cable is fitted with a three-pole connector of 4,2 mm PE-series from Tyco/AMP.

Male housing mounted on the cable of the head lamp, equipped with three female jacks

(top view, clamp visible)
side of cable from headlamp

yellow/green blue brown

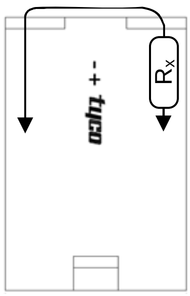


1 2 3
(plug side)

Female housing mounted on the cable of the battery, equipped with three male pins and the resistor.

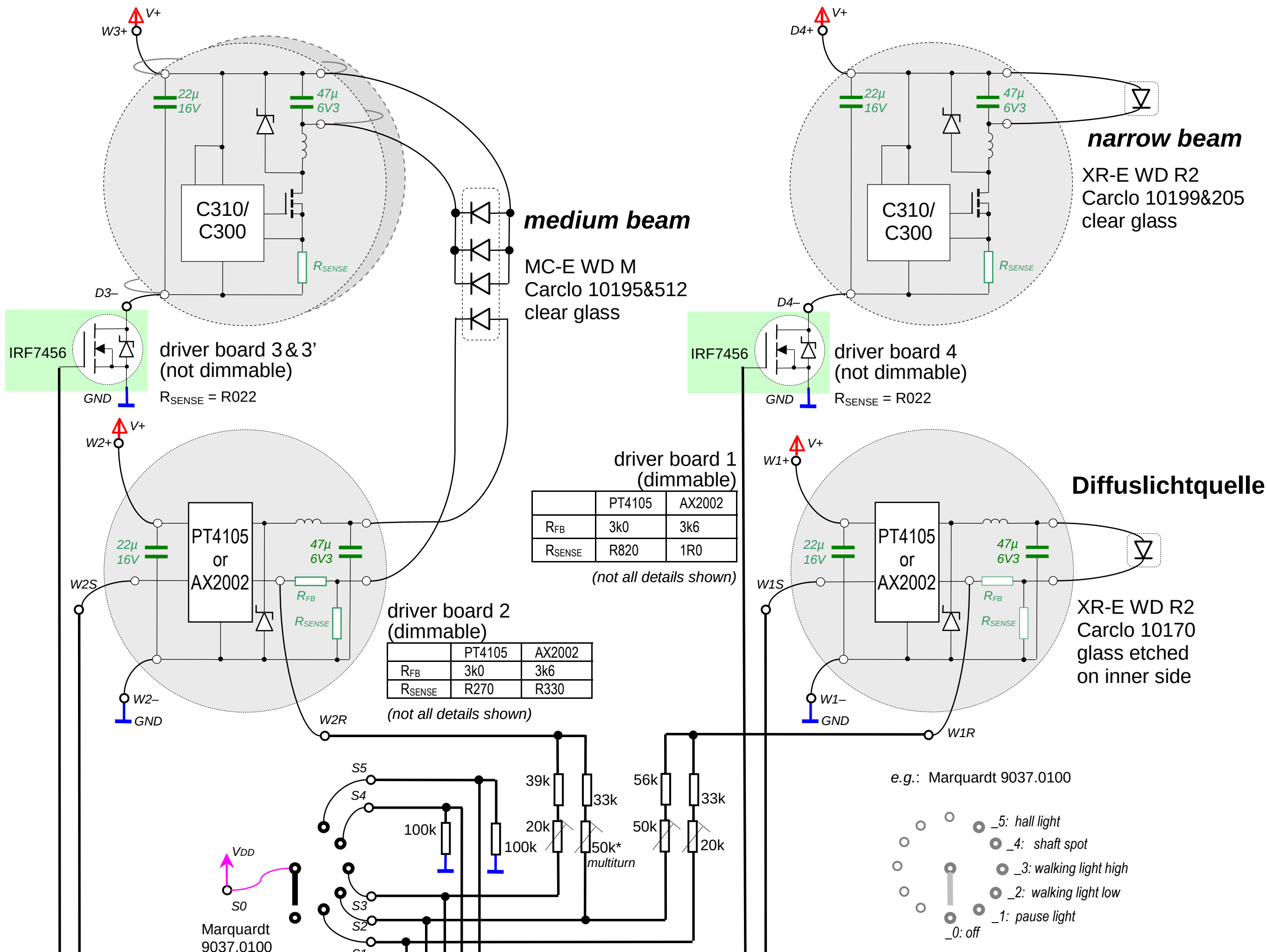
(top view, hook visible)
side of cable from battery

+battery -battery *(open)*

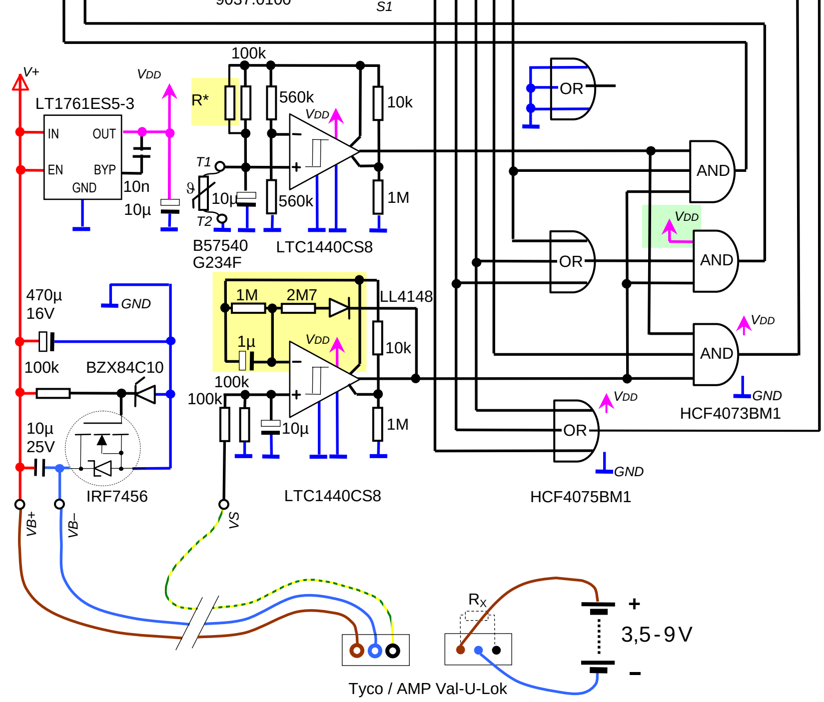


3 2 1
(plug side)

J Electronic circuitry of the headlamp



Led currents at 4,8V / 7,4V	wide beam	medium beam	narrow beam	supply power [W]
hall light		1400 / 2300 + 740		8,30 / 10,8
shaft spot			700..1150	3,2 / 4,4
walking light high	250	150		1,4 / 1,4
walking light low	120	30		0,5 / 0,5
pause light	30			0,1 / 0,1



R* was chosen individually to achieve 43 ±1°C threshold measured on the outer side of the lid.

chemistry	number of cells in series	nominal voltage	threshold voltage	resistor R_X ±1%	cell voltage
Li Ion Li Po	2	7.4 V	6.2 V	324k	3.10 V
Ni MH	4	4.8 V	3.6 V	107k	0.90 V
Ni MH	5	6.0 V	4.8 V	210k	0.96V
Ni MH	6	7.2 V	6.0 V	309k	1.00 V
Ni MH	7	8.4 V	7.2 V	422k	1.03 V
Alkali Mn $LiFeS_2$	4 bis 6	6 bis 9 V	NA	R00 gebrückt	NA

After production of smd motherboard some modifications were necessary to achieve satisfying behaviour.

Some modification were conducted with normal through hole parts (yellow marking) at the top side of the board. These modifications guarantee blinking even when the supply voltage is far below threshold voltage.

At the bottom side of the board two MOSFET were added (green) to guarantee enabling of the drivers using C300/C310.

Development team of the headlamp:

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