FRAUNHOFER-INSTITUT FÜR ZUVERLÄSSIGKEIT UND MIKROINTEGRATION IZM

REPORT- TECHNICAL FEASABILITY ANALYSIS FOR THE IDENTIFICATION OF TYPES OF LAMPS IN RECYCLING STREAMS

TECHNICAL FEASIBILITY ANALYSIS

FOR THE IDENTIFICATION OF TYPES OF LAMPS IN RECYCLING STREAMS

Dr. Janis Winzer
Dr. Rafael Jordan
Dr. Mathilde Billaud
from
Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration IZM
Gustav-Meyer-Allee 25 | 13355 Berlin | Germany

Dr. Adrian Mahlkow
from
Optrotransmitter Umweltschutz Technologie (OUT) e.V.
Köpenicker Straße 325, Haus 201 | 12555 Berlin | Germany

Content

1 Management Summary

This report presents a technical feasibility study on the technology assessment for the separation of collected End-of-Life (EoL) lamps, more specifically the technical possibilities for separating conventional gas discharge lamps (GDLs) from conventional light-emitting diode (LED) lamps.

The project consisted of first a theoretical phase in which technological possibilities for sorting methods were explored and described. Based on this potential analysis, followed the testing phase, concentrating on static and dynamic testing with three promising sorting technologies. Ultimately however, only two methods, the blue light and electromagnetic induction tests, were considered promising and carried out in detail.

Test results:

The correct detection of non-broken GDLs totaled 100 percent in the electromagnetic alternating field. Broken GDLs cannot light up in the electromagnetic alternating field, since the gas has escaped, which is needed to generate the light in combination with the mercury. The tests with the electromagnetic coil have also shown that the large chip area of the LED filament lamps can light up due to induction, this should be excluded by employing filters in the Hg and Ar ranges.

The correct detection of LED lamps amounted to 60-90 percent with blue light. The recognition value can be increased by aligning the lamps so that they can be lit directly and with sensitive optical sensors which requires further testing. Since a few GDLs also showed a reaction to the blue light, these exceptions would have to be sorted out manually or via image recognition. The use of filters for certain spectral lines would not be suitable here, since the LEDs and GDLs that light up while being exposed to blue light do not show any difference in emitted wavelengths.

2 Motivation for the project

The framework for treatment of EoL lamps in Europe is defined by the WEEE Directive (Directive 2002/96/EC). New technologies for generating light are changing the composition of types of lamps in households, as well as in other areas of application, and thus ultimately of electronic waste in Europe. In particular, the increasing sale of LED lamps in recent years is slowly changing the composition of waste streams in collection group 3: lamps. The rate of gas discharge lamps (GDLs) will decrease in the future, while the proportion of LED lamps will rise. LEDs, as opposed to GDLs, do not contain any mercury. For GDLs, representing the vast majority of the current waste stream, the actual treatment technology for all lamps is designed to remove the mercury from the remaining waste fraction in order to achieve de-pollution, while LEDs consisting of other material and components which are considered as an impurity. As LED lamps do not contain mercury, they are feasible to undergo a different treatment process than the GDLs.

3 Sum up of the potential analysis

In the potential analysis (phase 1 of the project), various technologies were considered, regarding their suitability for separating GDLs from LED lamps. The open, unbiased search in phase 1 was largely carried out theoretically, while first tests were performed exploratively.
The potential analysis showed that in particular the classical sorting technologies for electronic waste, such as magnetic separation, eddy-current process, triboelectric process, sieve classification or wind sifting, are not appropriate for the task of separating GDLs from LED lamps in an undestroyed state. With most technologies, the lamps are crushed under controlled conditions in order to capture the mercury and the fluorescent powder before the remainder are separated in various output fractions. These technologies apply to GDLs only, while LEDs are bound for other preferable treatment applications. That is why a sorting step for GDLs and LEDs shall be established before the lamps are processed to the appropriate treatment application.

According to the research in the first project phase, we determined only three technologies, which can handle the sorted goods without destroying them:

1. The electromagnetic induction / charge.
2. Treatment with high energy blue light.
3. Technologies based on X-ray. (However, due to the high complexity, expensive sourcing and maintenance costs and health & safety risks regarding radiation protection, x-ray tests were not conducted in the feasibility study.)

Technology	Distinguishing criterion	Distinguishability	Result first quick tests	Evaluation	Conclusion
Magnetic processes					
Magnetic separation	ferromagnetic materials	Small proportion; available in both types	So far, theoretical consideration, derived from project knowledge, no experiments performed	shatter-prone	not suitable
Eddy-current process	electrostatic charge for separation into metallic vs. non-metallic	metallic vs. non-metallic	So far, theoretical consideration, derived from project knowledge, no experiments performed	several stages; error-prone	not suitable
Triboelectric process	electrostatic charge for the separation of carbon-based materials	charge-reactive vs. Non-boot reactive	So far, theoretical consideration, derived from project knowledge, no experiments performed	unsuitable for separation in non-destructive way	not suitable
Sieve classification	Size separation by sieve classes	The screen size makes the selection	So far, theoretical consideration, derived from project knowledge, no experiments performed	unsuitable for separation in non-destructive way	not suitable

Windsifting	Weight separation	gravity separation	So far, theoretical consideration, derived from project knowledge, no experiments performed	unsuitable for separation in non-destructive way	not suitable
		Sensor-based optical sorting			
Near-infrared spectroscopy (NIS)	Shortwave infrared light	Molecular vibration measurement	So far, pure theoretical consideration, derived from learned knowledge, no experiments performed	unsuitable for separation in non-destructive way	not suitable
Grayscale separator	Facets of grayscale of different materials	A grayscale separator sorts out light or dark parts	So far, theoretical consideration, derived from project knowledge, no experiments performed	unsuitable for separation in non-destructive way	not suitable
Color separator	Color differences of different materials	A color separator allows the separation i.g. different colored plastic parts	So far, theoretical consideration, derived from project knowledge, no experiments performed	unsuitable for separation in non-destructive way	not suitable
X-ray sorting techniques	The visualization of the inner fractions of GDL and LED		So far, theoretical consideration, derived from project knowledge, no experiments performed	High reliability; Expected too expensive (0.5 million)	Experiments would be possible with the TU Berlin and another Fraunhofer institute, which are active in the field of dual-energy XRay research.
		Fluorescence technologies			
	Fluorescent lamps, in particular, the excitation spectra between phosphors in LEDs and GDL differ significantly	**Phosphorus compounds in LEDs and GDLs shine differently**			
Excitation of the phosphor with blue light (light emission wavelength ~ 460 nm)	Different excitation and emission levels	Assumption: in the blue light only the LEDs light up, since the energy of 460 nm is not enough to light up the GDL phosphors	not yet the desired expectations	promising. Due to a very simple structure, processes for separation could take place with the aid of filters	further experiments required

Excitation of the phosphor with UV-C light (light emission wavelength 280 - 100 nm)	Different excitation and emission levels	Assumption: UV-C light is supplied from the outside of the lamp and illuminates the converter	The desired expectations were not met since there were lamp glasses which let UV-C light out, but not in	Due to the large number of different types of glass, the technology does not achieve a high success rate. Some glass types work well, but others do not	not suitable
Electromagnetic charge	High voltage illumination of converters	Assumption: the electromagnetic rays excite the converter so that they illuminate	first positive "quick tests"	promising	further experiments required
Electromagnetic induction (alternating field)	Different excitation and emission levels	Assumption: the specific radio waves excite the converter so that they illuminate	no "quick tests" yet	promising	further experiments required

4 Prototype concept

4.1 Technology assessment

The objective of the prototype concept in phase 2 was to accurately detect GDLs and LED lamps. Inasmuch as GDL are mercury vapor lamps, this gas inside the glass bulb should be excited by the electromagnetic induction and thus glow, which could be utilized as a signal for selection. This technology can be economically integrated into existing treatment processes and is robust enough to survive the daily routine in a recycling plant.

4.2 Identification of suitable technologies

As described in Chapter 3 and examined in phase 1 of the project, the focus of the investigation was on experiments with electromagnetic induction and irradiation with high-energy blue light.

4.2.1 Development of a mechanical structure

In a first step, the necessary measurement parameters must be determined for the development. Here we have set up a test stand with the following properties:

- Test setup with Tesla generator and power generator in the frequency range 1 kHz to 1 MHz
- Investigation of different GDLs (especially CFL)
- Determination of generally suitable excitation bands
- Spectroscopic determination of the optical response of intact GDL
- Determination of power consumption and ELM noise level

In order to be able to build the electromagnetic coil, tests were first conducted with a Tesla generator (Fig. 1), where we chose a universal model, which can be found in science centers and technology museums. A homogeneous field around the test objects can be achieved with a Helmholtz array or a linear coil. A high-voltage wire (Ernst & Engbring) is used on a lathe to wind a coil with a core diameter of 300 mm and a number of turns of 1200 / m on at least 400 mm, which creates a homogeneous field inside. The wire ends of this winding, which is almost 500 m long, are fixated with adhesive tape.

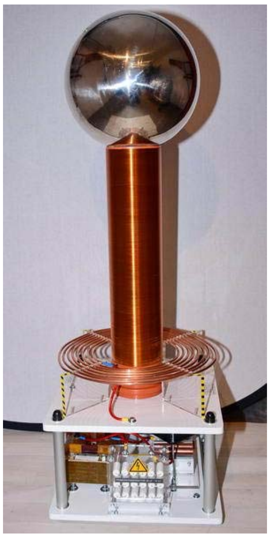


Figure 1: Tesla-Generator

These investigations are necessary because although GDLs are based on mercury, the excitation sought here should be carried out in a cold state, i.e., without thermally vaporized mercury. For a normal starting process of the lamps, some types are mixed with noble gases such as argon or xenon, which ignite when switched on, thus supporting a discharge that heats the mercury and after a few minutes the full partial pressure of the mercury is present, and the maximum light output is emitted. For a successful selection procedure, it must be ensured that the characteristic lines of the mercury discharge can be measured even after a few milliseconds. If this is not the case, lines of argon must be identified, which can always be excited. Therefore, this test setup for spectral characterization is as close as possible to the final solution.

The mechanical setup for demonstrating the potential of this method is then extended by a conveyor belt which includes a coil with larger core diameter (Fig. 2). Due to this larger diameter, the power consumption of the AF amplifier must be increased accordingly, and the inductance of the coil must be doubled. This can be achieved by winding a double layer of coil wire onto a glass body with a larger diameter of 500 mm and a length of 600 mm, which then has a total length of almost 2 km. The significantly higher ohmic resistance of this wire must be compensated by balancing out the excitation frequency to the resonance frequency of the overall structure. Simulation results have shown that a frequency band in the range 1.2-1.8 GHz can be expected. The design of the conveyor belt by this excitation field was based on a model that contains only aluminum and the rubber belt in the interaction area, while all electronic components and the motor are located clearly outside the interaction area.

Figure 2: Conveyor belt to lead the samples through the coil

4.2.2 Measurement of typical GDLs for the design of the optical sensor

To define an acceptable working range for an optical sensor, different compact fluorescent lamps were spectrally measured (Fig. 3). In accordance with the later task, an attempt was made to record the spectrum as soon as possible after switching on the lamps. These spectra show an astonishing variability with respect to the used dye, although the visual impression and also the measured color temperature in the range of 5200-6000 K showed little difference.

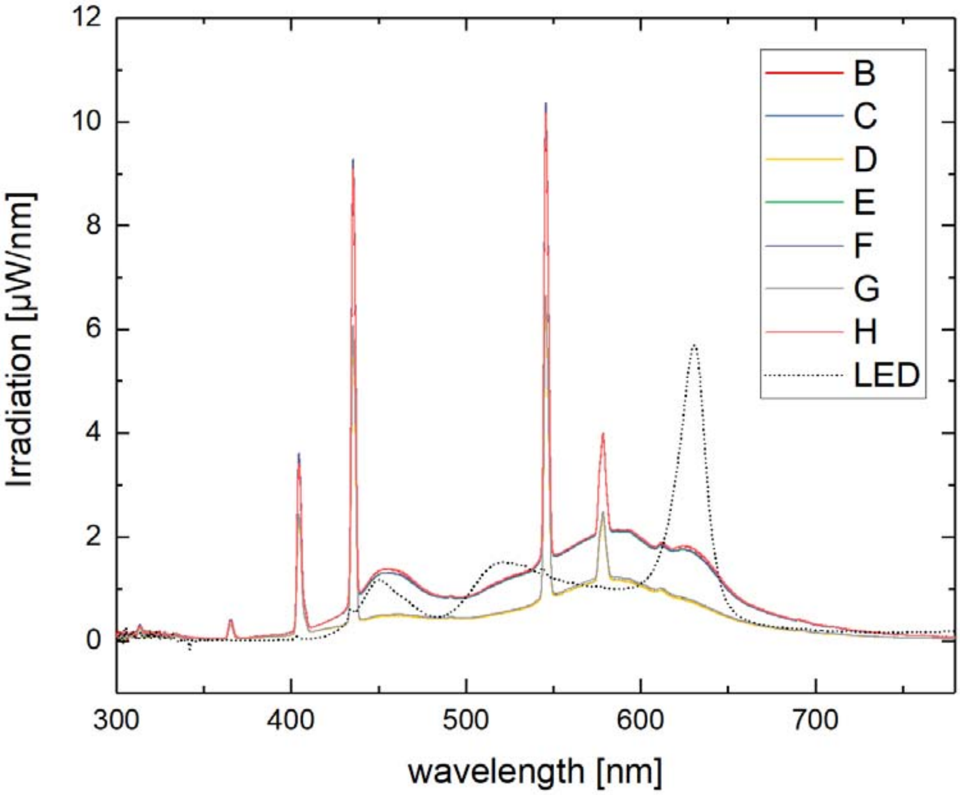


Figure 3: Spectral curves of different GDLs from two different manufacturers

The recording of spectra in fixed time intervals showed the expected shift of the intensity distribution and the width of the mercury lines. The typical LED spectrum of a white LED displays a strong excitation peak at 463 nm and a broad fluorescence around 580 nm, while the spectral line around 405 nm (the so-called h-line) is not the strongest line but unique (Fig. 4). The comparison with the typical spectra of LEDs (dashed line) is based on the fact that when excited in a high-frequency field, it cannot be completely excluded that simple LED retrofits may also show a slight fluorescence. For this reason, an optical sensor for later selection should be matched to an optical signature of the GDL that is as unique as possible. With high-resolution spectral measurements in the region of the h-line, the double line of the mercury could also be resolved here. However, these spectral lines are somewhat pressure-widened. These measurements could only be performed in a thermally stable state after about 15 minutes since each individual measurement requires at least 6 minutes integration time. The spectral position of the line is identical for all measured types. It is an excellent way to distinguish functioning GDLs from other lamps. This is also shown by the comparison of the following measurement on GDLs with an LED illuminant.

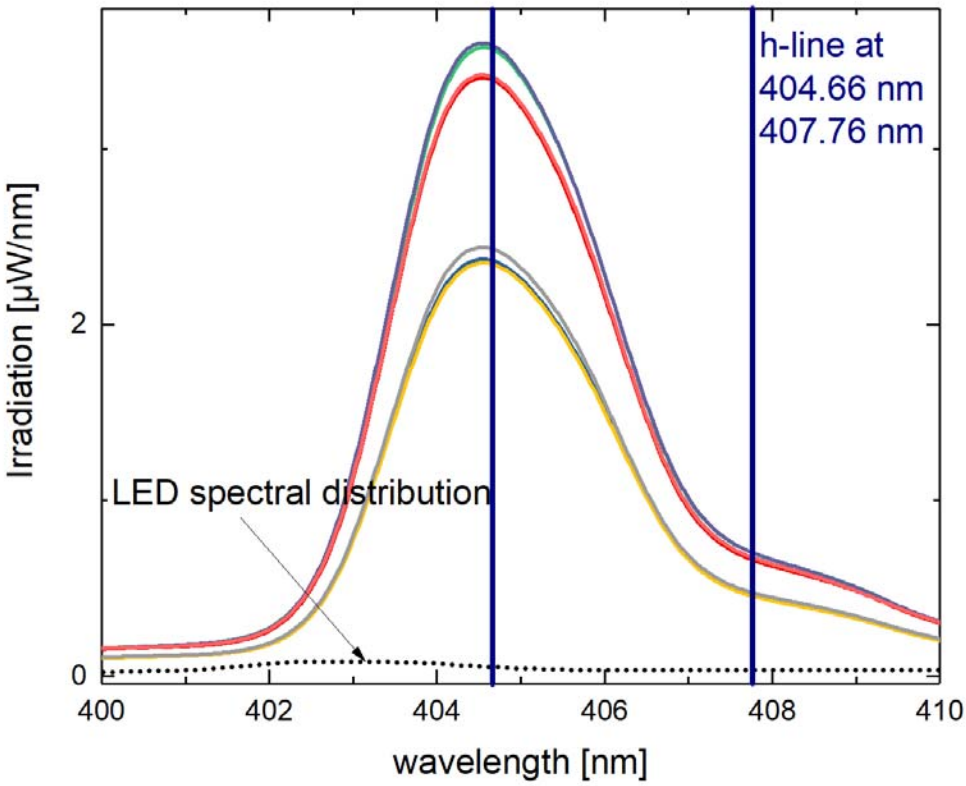


Figure 4: High-resolution spectral measurement on GDL and LED in the h-line region

As mentioned above, a line spectrum of argon required for igniting the GDL was recorded in parallel. Noble gas-discharge lamps are used for spectral calibration and exist on the market only in low pressure version. GDLs can contain the noble gases argon and partly also krypton, but the exact composition of the gas filling is of course a trade secret of the manufacturers. The characteristic glow of the different gases is shown in Fig. 5.

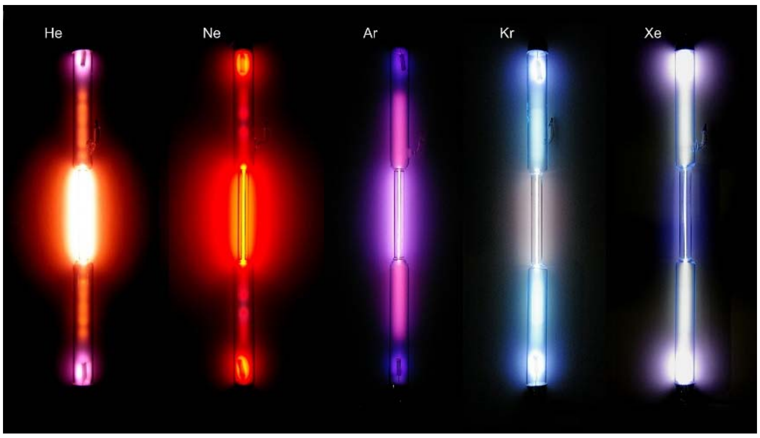


Figure 5: Noble gas-discharge lamps in operation

Argon emits numerous lines in the detectable spectral range between 350 nm and 950 nm, which are also immediately visible when igniting a discharge. The gas partial pressure of argon is constant in the GDLs. If the spectral lines of the mercury are not clear enough when the GDL is in the interaction zone, a new range must be selected based on the spectral lines of the two gases in the 350 to 950 nm range. The following figure 6 shows the lines of the optically active transitions with relevant relative intensities. The numerous argon lines are shown in violet and the mercury lines in black. A range around 360 nm shows very dominant lines for both gases, but it can be expected that the absorption of the glass bulb of the GDL prevents emission to the outside. In the visible spectral range, the lines may be overlaid by the broad emission of a converter dye of the GDL or by white LEDs, thus excluding the range of 380 to 750nm. The next detection window is around 790 to 810 nm, where both gases show clear lines, while the white LED does not show any emission.

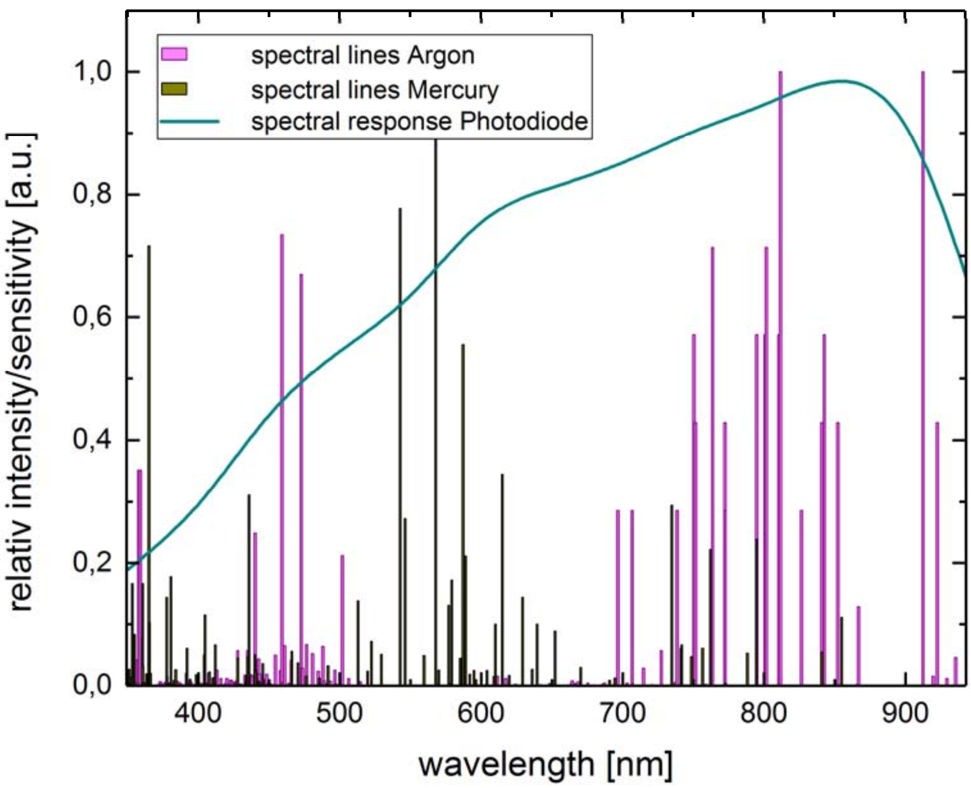


Figure 6: Spectral lines of mercury (black) and argon (violet)

The sensitivity of silicon photodiodes is also very good in this area, so that a sensitive and fast-reacting sensor can be built. In the figure above, the spectral sensitivity (Sensitivity curve of a photodiode) is shown as a turquoise line. A reception range around 800 nm is almost at the maximum sensitivity. Further restrictions result from the necessity to use optical band-pass filters to separate the ambient light from the line emission occurring during excitation. In order to enable a fast implementation, standard filters will be used here. In fig. 7 two potential filters are shown with their respective curves. In the UV range a very suitable filter exists only for the Hg line around 402 nm. For IR, a slightly wider filter with a predefined spectral half-width of 32 nm around 795 nm can be used to pass lines of mercury and argon. The design of the sensor is proposed in such a way that different filters can be used depending on the results of the preliminary tests and in a first realization stage both spectral channels are provided.

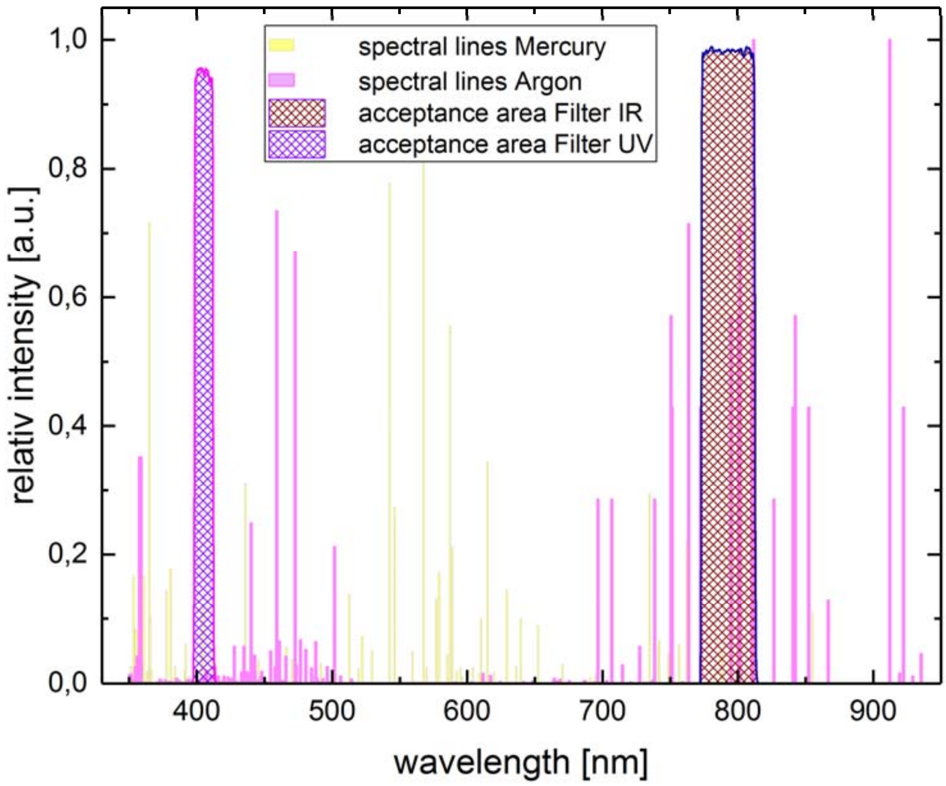


Figure 7: Optical bandpass filters with spectral lines of Ar and Hg

4.2.3 Conception of an optical sensor

To reliably detect the optical response of GDLs in the material flow, a robust optical design is important (Fig. 8). Therefore, a sensor is recommended which is located behind a solid and replaceable cover glass. In order to be able to quickly detect the different spectral lines and distinguish them from other background signals, a two-channel design was also designed.

For a mechanically robust design, the outer area consists of a stainless-steel pipe with DN25 external thread, that will be screwed in within the later detection area. The sensitive electronics are located inside another stainless-steel protection tube with the corresponding shielding made of copper braiding.

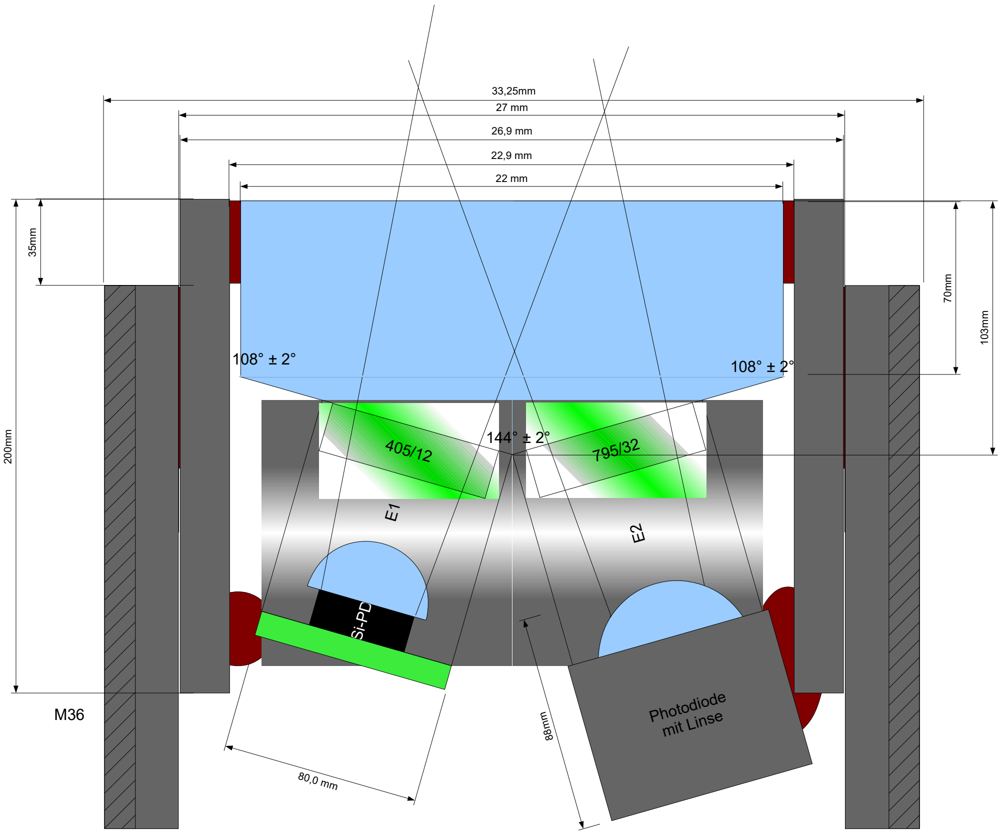


Figure 8: Mechanical concept of an optical sensor head

5 Assessment of the process with strength-weakness analysis

The treatment process for GDLs takes special organizational and technical precautions to ensure the removal of mercury and specifically pays attention to occupational health, safety, and environmental risks under consumption of additional resources like energy or filtration adsorbents. This effort can be saved on LEDs, which do not contain any mercury.

Furthermore, the different composition of GDLs and LEDs requires different treatment technologies generating different output fractions. LEDs even create the risk of down times or damages to the recycling plants for GDLs.

Finally, WEEE legislation and EN standardization obliges treatment operators to ensure that E-waste, containing hazardous substances like mercury, is undergoing a state-of-the-art de-pollution technology.

After all the accurate sorting of GDLs and LEDs is highly required before the dispatch to any further treatment technology. This represents the main strength of the proposed process.

A further strength of the process poses the selection into completely intact on the one hand and only slightly damaged (cracks in the glass or in the built-in base) GDLs on the other hand, which would not be optically recognizable. Once the mercury has volatilized from the GDL on its way to the recycling center, the GDL will not ignite and no gas-discharge will glow. For this purpose, a limit value must be defined in experiments.

Another advantage of the process is its selectivity of mercury itself. A gas-discharge lamp always shows the characteristic spectral lines so that highly selective optical filters without temperature compensation can be used. These lines are also in the visible spectral range of low-cost sensitive optical detectors.

Additionally, the process is based on a technology which only detects intact GDL. With a decreasing rate of GDLs, i.e., an observable dominance and displacement by mercury-free LED lamps, the process will ensure that no contamination by individual GDLs occurs.

A major weak point poses the targeted removal from the material flow, without damaging the GDLs. Here, experimentally suitable procedures such as magnets, compressed air centrifuges, flaps or manual selection should be investigated.

From an economic perspective another weakness lies in the fact that the share of GDLs within the waste stream will decrease over the following decades but the search effort will remain. Given the high potential of destruction to the environment and its living beings, it will be necessary to search for GDL and the mercury contained in the waste stream for the upcoming decades.

6 Experimental results

6.1 Selection of the EoL lamp samples for testing

Before presenting a detailed result analysis, a basic statement concerning the examined samples: The objective of the sample selection was not a statistical representativity by quantity, but the coverage of different lamp types, which may occur in the waste stream. We were focusing a lamp types which might create a challenge for technical detection. Except for four pieces no special attention was paid to broken lamps, when sampling at the plant, although cracked, broken, or destroyed lamps represent a substantial share in the waste stream of any European country. Nevertheless, breakage is obviously easy to simulate in the laboratory, if needed for testing purposes. Additionally, lamps out of scope of the WEEE legislation (e.g., medical applications or automotive) were not selected for the tests.

The samples for the technical trials were provided by one of the five German lamp treatment sites. The focus of research was EoL lamps from collection group 3 (ElektroG) or according to WEEE Category 5: Lighting Equipment. During a visit on October 23, 2018, a total of 110 EoL lamp samples were taken from the treatment plant and used for all tests. The EoL lamps are predominantly retrofit lamps with a screw base (E27 or E14) or a plug base and were all less than 60 centimeter in length. The selection of the 110 lamp samples was based on the following criteria:

- Selection of easily visible Compact Fluorescent Lamp (CFL)

- Selection of easily visible Light-Emitting Diode (LED)

- A selection of additional types of GDLs apart from the types of CFL

- Selection of GDLs and LEDs with a confusingly similar form/shape.

- Selection of some special lamps

- Selection of some incandescent lamps

- One fuse as a common contaminant

The selected lamps derived from the EoL lamp collection in Germany. Nevertheless, it can be presumed that the sample selection would have been very similar (by variety, but not by quantity) in any other European countries. The sample selection was sent to the Eucolight members by photo documentation before the tests. Eucolight members were invited to send further EoL lamps in case certain EoL lamp types were missing. Additional EoL lamps were not dispatched, which also suggests that the types of lamps that are sold in European countries are very similar.

6.2 Results with electromagnetic induction (alternating field)

The selected samples were evaluated according to the experimental setup described in chapter 4. The individual results for each sample can be found in the Appendix.

6.2.1 GDLs

As expected, all undamaged GDLs and HQLs containing mercury, were excited by the electromagnetic induction and thus lit up. Depending on the type of GDL, their illumination varied in intensity. However, a strong flare could always be seen with the naked eye and detected by the measuring device.
All GDLs with broken glass tubes did not show a reaction, which confirmed the predicted assumption.

6.2.2 Incandescent lamps and foreign objects

As anticipated, the incandescent lamps, fuses and all interfering substances did not light up since the electromagnetic induction field cannot interact with these types of lamps.

6.2.3 LEDs

The results for LED lamps were not as straightforward since some of the LED-chips (Die) faintly lit up in the electromagnetic field which could also be seen with the bare eye. The difference to GDLs was only apparent when employing an optic sensor which can detect the wavelength of the emitted light. For mercury contained in GDLs this spectrum ranges from 400 to 410 nm.

6.3 Results with blue light

6.3.1 LEDs

When using energy-rich blue light the majority of LED samples lit up, as blue light excites the converter matrix on the LED chips (Die). The light is visible to the human eye and detectable with optic sensors. However, out of the 31 LED lamps 12 samples did not show the expected reaction by remaining dark. Those lamps all possessed a milky or white, glass or plastic bulb, that inhibited the detection of fluorescence. Moreover, two LEDs only showed very faint illumination, as these two samples possessed a very small converter behind a long lens, which was difficult to detect.
We hypothesise that both these problems could be solved by employing a more sensitive sensor. Nevertheless, this method requires further testing.

6.3.2 Incandescent lamps and foreign objects

Most incandescent lamps, fuses and all interfering substances did not light up, as the blue light cannot interact with any substances. However, three halogen lamps (DUT 43, 44 & 104) showed bright fluorescence, which could be ascribed to the glass covering, for example Borosilicate glasses react strongly to blue light, while Mangan content in the glass shows an orange illumination. Yet, as halogen lamps do not contain mercury, it is inconsequential whether these are sorted into the mass of LEDs which will be recycled without the mercury distillation step.

6.3.3 GDLs

Almost all GDLs did not light up, however, the first exception were GDLs designed for warm light, more specifically CFLs with a YAG:Ce converter which can be excited and faintly shine when exposed to blue light. This type of light bulb can be recognised by its brightly yellow toned glass tube (for reference see DUT 95 in the appendix included in this document). Additionally, two more CFLs (DUT 40 & 108) also showed a reaction to the blue light, likely due to the used dye. All these exceptions would have to be sorted out manually or via image recognition.
Image recognition was a process which was deemed unsuitable in the potential analysis due to the similarity in color and shape of the light bulbs of LEDs and GDLs. However, for distinctive lamps such as DUT 95, it could assist in solving the problems with GDLs reacting to blue light. Nevertheless, the functionality of image recognition has not been tested in the study because of project limitations and its utility will have to be examined in future experiments.

6.4 Results in the test with the start of electromagnetic induction

In the following, the test process will be described when starting with electromagnetic induction as the initial selection mechanism.
During the first step, all GDLs with undamaged glass tubes will light up and will thus be recognised as a GDLs. Some LED packages will light up as well (em+) and would have to be detected with optic sensors and wavelength filters as they do not show interaction in the mercury (Hg) wavelength spectrum. This process is depicted in fig. 8, while fig. 9 shows the same process, but with a hypothetical future LED lamp share of 60% of the collected EoL lamps. Highlighted in black boxes are the groups which are made up of a single lamp type.

This leaves GDLs with broken glass tubes, the portion of LED lamps that do not light up (em-), most incandescent lamps (bl-), all other types of lamps, as well all interfering substances such as fuses.
In the second step for this mass, blue light would be deployed as a selection tool, exciting all converter matrixes on the LED chips (Die) and thus illuminating them. Moreover, some GDLs will also light up (bl+), hence these would have to be picked out with an image recognition method or by hand. The small number of halogen lamps which also react positively to the blue light (bl+) are inconsequential, as they do not require a mercury

distillation step.

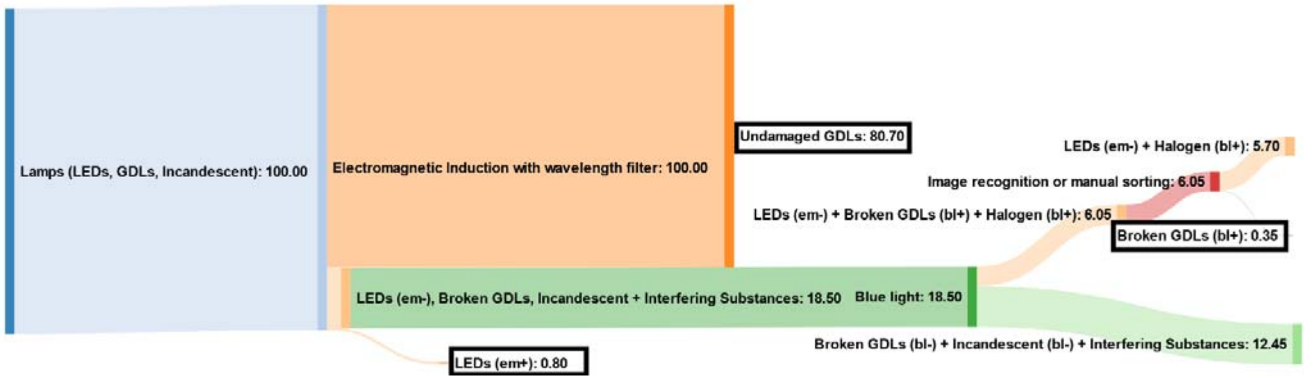


Figure 8: Sankey diagram for testing starting with electromagnetic induction including wavelength filter

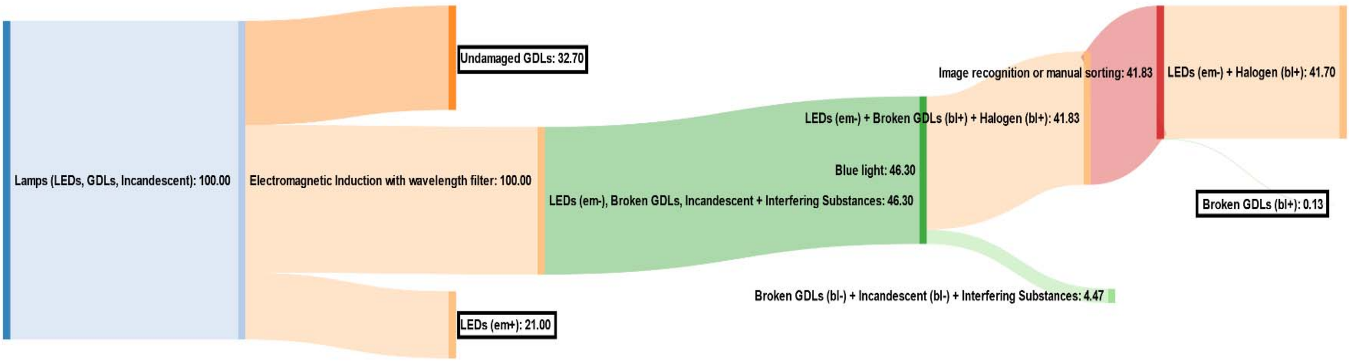


Figure 9: Sankey diagram for future scenario starting with electromagnetic induction including wavelength filter

If it is not possible to put a wavelength filter into practice, the unsorted mass of undamaged GDLs and small percentage of LEDs would have to be subjected to a second blue light filter (Blue light b) with a sensitive sensor which winnows out the LEDs, and a small number of halogen lamps (bl+), as depicted in fig. 10, while fig. 11 shows the same process, but with an LED lamp share of 60%.

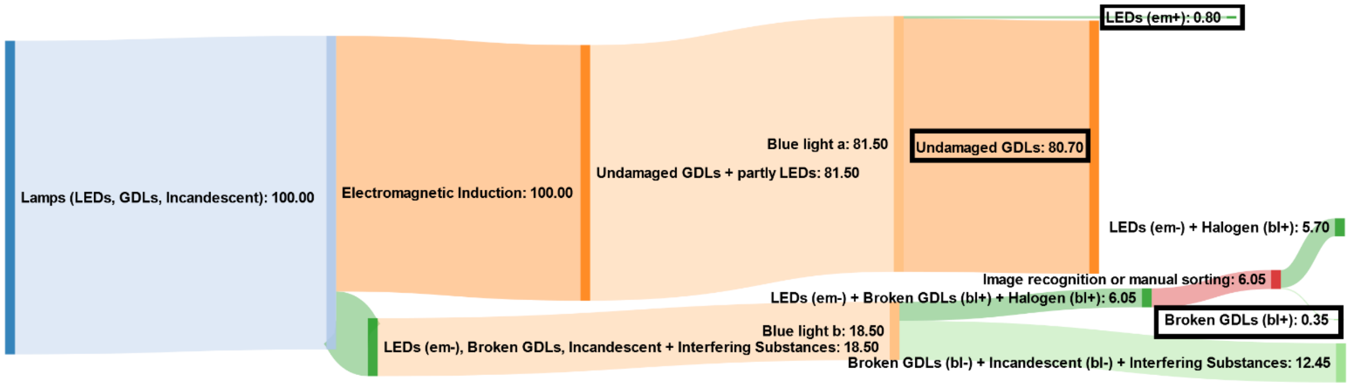


Figure 10: Sankey diagram for testing starting with electromagnetic induction including blue light twice

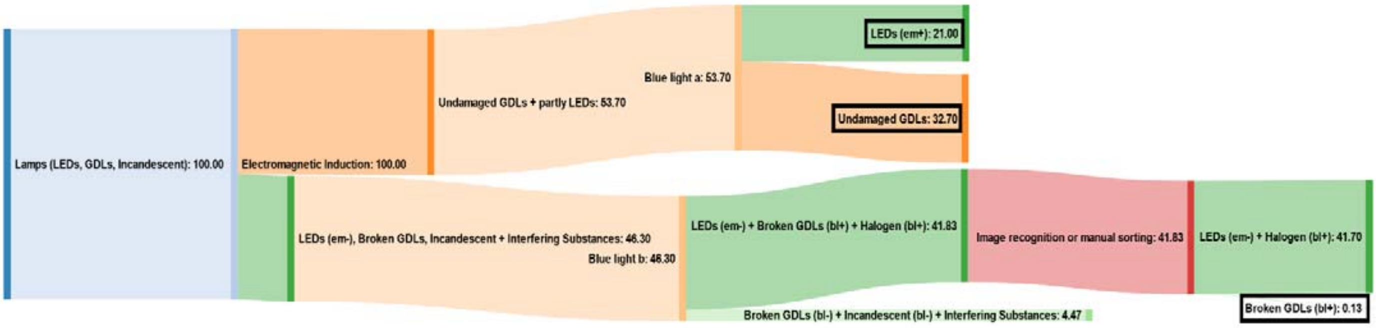


Figure 11: Sankey diagram for future scenario starting with electromagnetic induction including blue light twice

The number of LED lamps that light up in the electromagnetic induction alternating field was extrapolated from the samples that showed these characteristics in the testing. Out of 31 LED lamps, 11 showed faint illumination, yielding 35.5%. In the same way, the number for GDLs which positively react to blue light was calculated: 3 lamps out of 110 samples translates to 2.7%. However, as the samples were specifically picked for their unusual appearance and structure, the realistic percentage of CFLs with YAG:Ce converter and other GDLs that illuminate under blue light will likely amount to much lower numbers.

The number for halogen lamps that showed a reaction under blue light, was extrapolated as well: 3 out of 110 samples yields 2.7%.

The general numeric structure of the waste stream of the test investigations, is based assumptions, which aim to reflect the actual mix in the EoL waste stream and deferred to information from sampling campaigns in Germany and Austria. That information illustrated that the share of breakage, the structure of collection, degree of consolidation, system of receptacles etc. all broadly differ by country. Additionally, the share of LEDs is volatile and will face a strong increase within the coming years.

Nevertheless, the structure of the waste stream should not make a difference for the suitability of the detection technology applied to the sorting process.

6.5 Results in the test with the start of blue light

Starting the filter process with blue light including a sensitive optical sensor would detect 60-90% LED lamps, as well as broken and undamaged GDLs with YAG:Ce converter and other types of GDLs with excitable dye. Additionally, a few halogen lamps would also illuminate while the rest would not light up. The large range of 60-90% results from the fact that the position of the end-of-life lamp on the conveyor belt is of great importance.

Following, the electromagnetic induction method would be applied to the mass that lit up in the blue light step beforehand. Now all undamaged GDLs with YAG:Ce converter and other types of intact GDLs with excitable dye would illuminate, whereas the broken GDL samples would still have to be sorted manually or with image recognition to separate the GDLs from the LEDs as depicted in fig. 12. Figure 13 again shows the same process, but with a hypothetical future LED share of 60% of the collected EoL lamps.

The fraction of GDLs, Incandescent and interfering substances would pass through the mercury distillation step. However, the estimated percentage of incandescent and interfering substances is small (~2.4%) in relation to the GDLs bound for de-pollution.

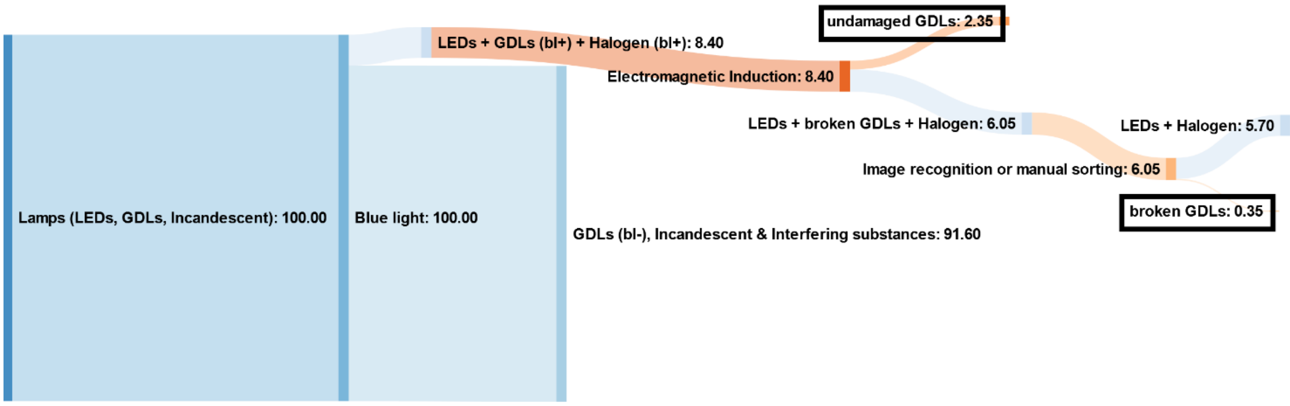


Figure 12: Sankey diagram for testing starting with blue light with electromagnetic induction as second step

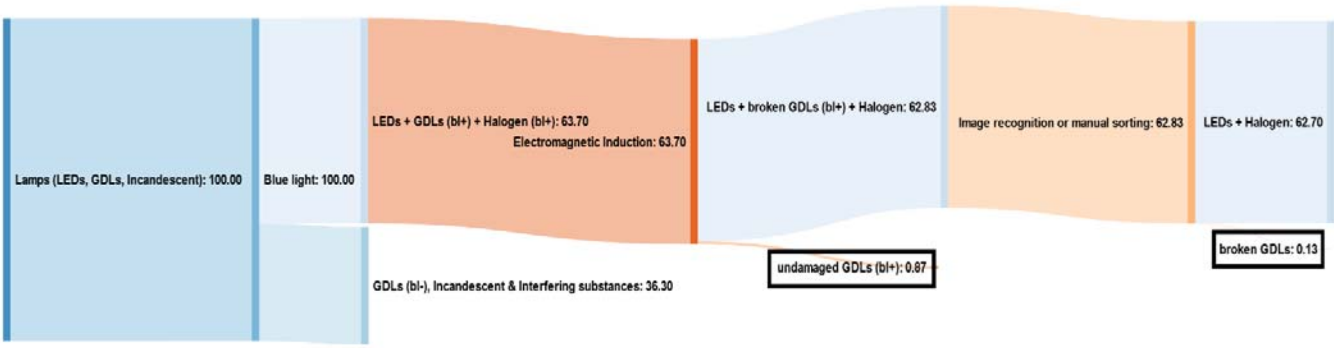


Figure 13: Sankey diagram for future scenario with blue light with electromagnetic induction as second step

Alternatively, the image recognition or manual sorting process could already be applied after the blue light filter method to avoid a second elaborate filter process by electromagnetic induction. It is assumable that manual sorting would be a minor effort as the mass that will have to be examined is already quite small see fig. 14, while fig. 15 shows the same process, but with a hypothetical future LED share of 60% of the collected EoL lamps.

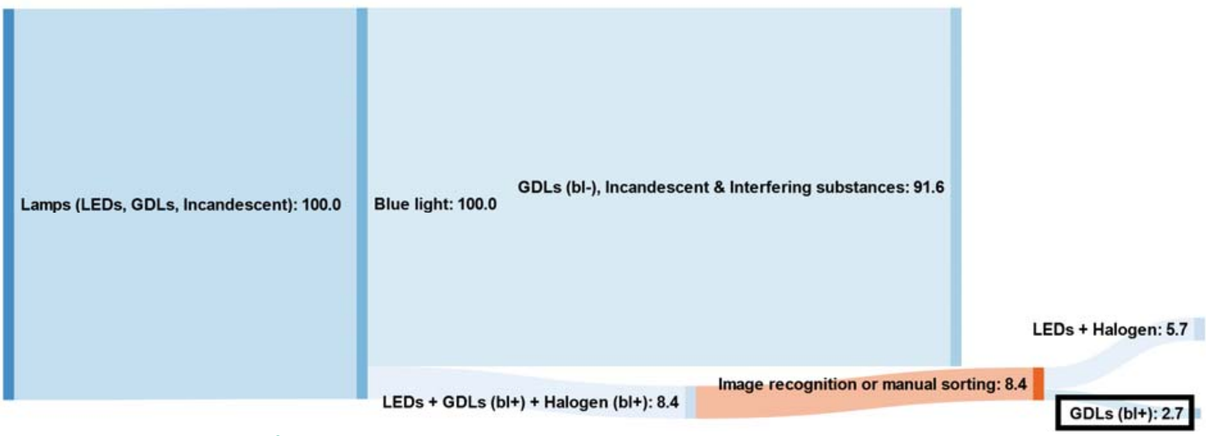


Figure 14: Sankey diagram for testing starting with blue light with only manual sorting as second step

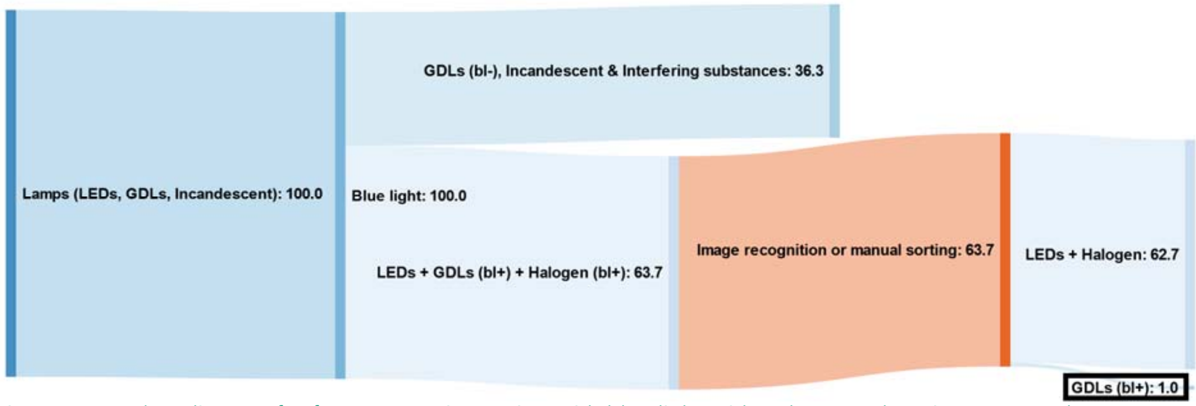


Figure 15: Sankey diagram for future scenario starting with blue light with only manual sorting as second step

6.7 Detection and process speed

An important aspect for the implementation of the two technologies is the process speed. The process speed depends on the type of installation within the existing recycling system. It is important that not every recycling machine is equal and works as the ones in other plants. However, some steps are performed similarly by all machines and give indications for the process speed to be achieved. For the detection process itself, it can be noted that all sensory work can be done in the range of microseconds, which is many times faster than pneumatic or mechanical work to separate a detected sample. Therefore, a process time calculation of the electromagnetic and blue light excitation does not happen, which leaves us with the consideration of the pneumatic and mechanical processes in the overall process.

Mechanical outward transfer (Ejection):

A low cost solution for the separation process would be by a switching flap. A suitable switching flap is usually operated at 6 bar pressure and the speed is variable. The temporal calculation of a switching flap as shown in the picture 1 would be as follows

Adopted drop height = 20 cm (15cm + 5 cm safety), ergo t = root (2h / g) = 0.2 s

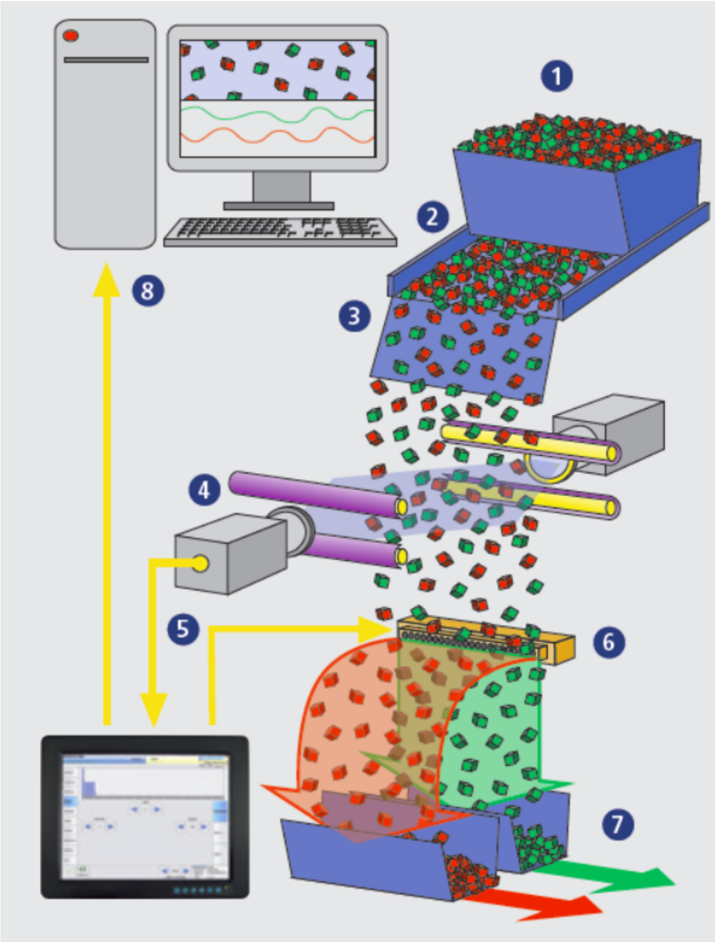
Conveyor belt speed 15 cm / 0.2s = 75 cm / s. Result 5 EoL lamps per second, or 430,000 pieces per day.

Picture: 1 Ejection with switching flap (source: Schuma)

Pneumatic outward transfer (Ejection):

If you exhale with compressed air, the whole process will be increased by about a factor of 10 and more. When blowing out the EoL lamps, a parabolic slide has to be used to avoid the breakage of the lamps. A machine, selected here for clarification, creates 250t/h rocks.

Considering the lighter EoL lamps about 25-50 t/h would be realistic, which results in 250,000-500,000 lamps in an hour.



Functionality

1. Feed material
2. Distribution and transport
3. Acceleration and separation
4. Scanning of the material curtain using various detection systems
5. Image analysis via state-of-the-art parallel process technology
6. Separation through highly accurate compressed air pulses
7. Discharge of the separated product flows
8. Remote system monitoring

Picture: 2: Ejection with pneumatic / compressed air pulses (source: Allgaier)

Both calculations give an idea of the challenges and limitations during detection and ejection. It is obvious that both detection technologies, electromagnetic and blue lights, are not time-critical. Both technologies work many times faster than the process ejection. Diverse manufacturers and various machines are available for the ejection. The speed is also influenced by the way the lamps are presented in the assembly line: piece by piece and one behind the other or next to each other. The detection, processing and ejection system could work with both.

6.8 Feedback regarding the results from recycling plant operators

In order to receive feedback from the real life of recycling end-of-life lamps, the project results obtained from the test implementation were discussed with four operators of recycling plants for end-of-life lamps in Germany. The research team first presented the test results to the audience, afterwards the results were discussed with all participants. In addition, written statements could be submitted within one week.

In principle, the recycling plant operators were very interested in the results and brought up relevant aspects orally or in writing. They were all open to new technologies, which as a result improve the quality of the end-of-life lamp recycling. In particular, the purity of the different material flows such as glass, metal and plastic is of particular interest in order to find buyers for these materials again on the market.

The following are the aspects that were brought up by the recycling plant operators:

- The priority aim of sorting is to obtain fractions that are completely mercury-free in addition to the fractions containing mercury. For this reason, technologies that make it possible to collect a fraction with mercury are generally very welcome.
- The four recycling plant operators agreed that the increasing amount of end-of-life LED lamps in the material flows raise the relevance of the separation of LED and GDL. Currently, the proportion of end-of-life LED lamps coming back is still very low, but the proportion of end-of-life LED will rise continuously in the coming years. With an increase in the end-of-life LED share, there is an interest in recognizing and removing LEDs from the other end-of-life lamp fractions. Today, the priority lies within the detection of the few LEDs in the large amount of GDLs. In the future, the priority would be to identify a few end-of-life GDL in the large amount of other end-of-life lamps.
- The recycling plant operators made it clear that today's problems are much more related to the very large number of special lamps in the end-of-life lamp collection. The LED lamps are relevant, but currently not a priority when considering the recycling challenges. LED lamps are also not of high priority in the recycling challenges because the LED lamps do not contain any explicit problem content such as mercury. LED lamps are currently disappearing as a rather insignificant fraction in the mass of other end-of-life lamps. With regard to their composition, they are troublesome, if at all, due to the high plastic content.
- The previously mentioned large number of special lamps makes the recycling plant operators doubt whether it is ultimately a machine in which various detection technologies work, or trained personnel that achieve better results in sorting. *Note from the contractor:* The project itself did not aim to show a direct comparison between personnel and machines.
- In the discussion it became obvious that the recycling machines/lines and their modes of operation differ in some parts. Therefore, the recycling plant operators explicitly asked about the possibility to integrate the blue light und electromagnetic technologies into the existing recycling machines/lines. The interest in integration into existing recycling systems was significantly higher than the willingness to buy an additional system and having a completely separate process flow.
- From today's point of view, with the percentage compositions of end-of-life lamps today, it seems to make the most sense for the recycling plant operator to search for the LEDs with blue light and then to focus on the GDL with the electromagnetic alternating field. A changing composition of the lamps collection group could reverse the order of the processes in the future.
- The recognition of the DUT 95 sample, with its very clearly recognizable yellow phosphor, was discussed as a challenge. How many similar lamps of this type are

currently being recycled could not be conclusively determined. However, according to initial estimations there will be very few lamps.

- The fact that some halogen lamps light up in the electromagnetic field was classified as uncritical with regard to the quality and purity of the collection and sorting process. Halogen lamps do not contain harmful substances such as mercury and therefore do not cause much concern if they are incorrectly detected.
- The recycling plant operators were not yet sure about treatment requirements or laws for handling the end-of-life LED. The exact form is still unclear for the recycling plant operators, but they expect official orders on how to deal with the increasing share of LED lamps in the recycling process in the future.

7 Cost estimation

The following cost estimation for a prototype is based on the small demonstrator built for the study. The cost estimation includes the required components and a calculated time for the assembly. Additional components may be required during the production of the prototype. The real project costs can only be determined after consulting a mechanical engineering company.

Description	Piece	Cost per piece [€]	Total cost [€]
Optical sensor	4	280,00	1.120,00
Conveyor belt (optional, depending on the application)	1	2.500,00	2.500,00
Tesla coil	4	800,00	3.200,00
LW (long wave) amplifier	1	260,00	260,00
Shielding	1	450,00	450,00
Machine	1	12.000,00	12.000,00
Machine design	1	8.000,00	8.000,00
Flap system	4	600,00	2.400,00
PLC (programmable logic controller, in German speicherprogrammierbare Steuerung SPS)	1	3.200,00	3.200,00
Programming	1	8.500,00	8.500,00
			41.630,00

8 Risk Assessment

8.1 General assessment

Both the test setup and the planned equipment work with a Tesla-like coil. Since no Tesla generator, but a defined alternating voltage generator is used for the excitation, there is no risk of unknown multiple electromagnetic waves, where the effects would be difficult to estimate due to a lack of knowledge of the frequency and energy components.
The defined alternating voltage generator, here 185 kHz with 40 W power supply, generates electromagnetic waves of approximately 1.62 km. A resonant absorption in the human body can thus be excluded.
For the much less effective absorption outside the resonance, the next legally relevant limit value would be that of microwaves at a wavelength of 0.12 km with an upper limit of 5 mW / cm^3. Following an estimate of the energy density of the structure is outlined:

- A highly assumed construction efficiency of 60% would result in an electromagnetic power of 25 W
- the volume of the coil is 46,000 cm^3
- The power density in the coil is therefore 0.54 W / cm^3

This line density is ~ 1/10 of the permissible power for microwave radiation. The machine that will be deployed will work with higher powers, but since the volume also increases, the power density remains similar. The power density, which was determined in the preliminary test, is rather a target variable for the machine that can be used, since in addition to occupational safety, material and operational efficiency are also criteria.
Regardless of the power density estimate, it is urgently recommended to have an EMC check carried out during mechanical engineering, since the interaction with active medical implants can be diverse and possibly risky. This check is not associated with high costs and any risks can be eliminated by simple means such as metal grids, diverting processes of the material flow or shutdown mechanisms.

8.2 Electromagnetic compatibility with the environment (EMC)

Contrary to what the title suggests, the EMC is largely about people themselves. Doses that directly harm people are not to be expected with our constructions (rather in the area of transmitters, etc.). But far below this energy level, active implants can already sense these fields. If the interference immunity of the implant is exceeded, data transmission can be interrupted, and the implant can be inhibited. Not only well-known cardiac pacemakers (~ 100,000 implantations per year) should be considered, but also other active implants such as defibrillators, cochlear implants, neurostimulators, insulin pumps, retinal stimulators and more (Figure 16). Special attention should also be paid to the various operating modes of these implants, which may be changed in the interference field and might then lead to failure in critical situations.

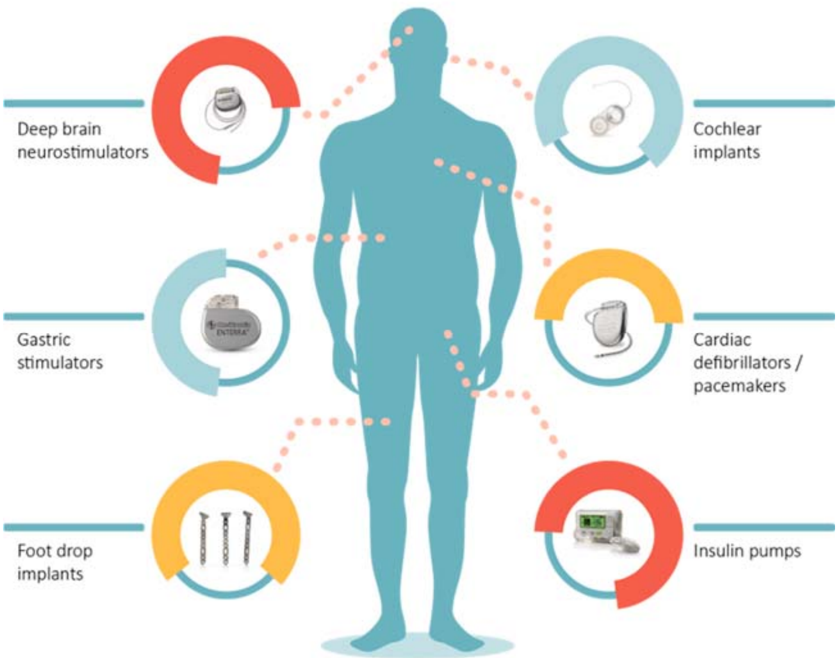


Figure 16: Various active implants (Source: Global Implantable Medical Devices Market Insights, Forecast to 2025)

The Tesla coil used for the sorting machine, which can build up voltages in the range of 100 kV due to the superposition of frequencies and this at a frequency of a few 10 kHz, cannot cause direct harm to people through the field (rather a possible electrostatic discharge should be considered here). Therefore, an influence on passive implants (force, heating by inductive coupling) is unlikely.
However, the safety of active implants should be ensured. There are specific permissible values from the implant manufacturer or general permissible values from the DIN VDE 0848-3-1 standard, which should generally be adhered to in order to be on the safe side.
Due to the large number of implants, however, it is advisable to carry out relevant considerations (measurements, calculations, estimates) for the affected person in order to avoid excessive safety measures. With "normal" pacemakers, for example, it is sufficient to only examine the thorax area (but in all its possible positions).

BGI-GUV-I-5111 provides a flow chart to advise which path is the most practicable (Figure 17).

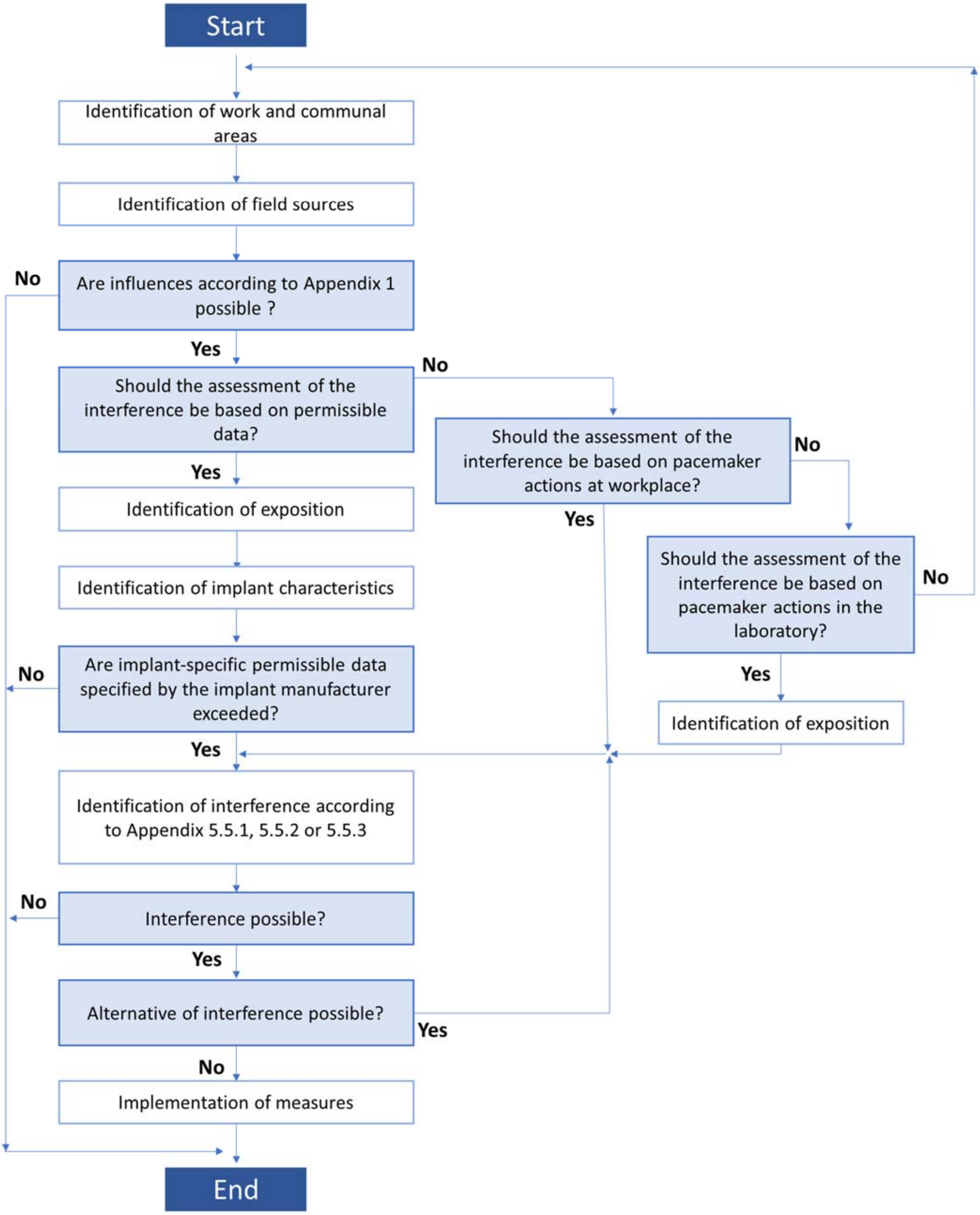


Figure 17: Flowchart of the procedure for assessing whether implanted cardiac pacemaker devices can be influenced from the BGI-GUV-I-5111

Once it is decided how the environment will be safeguarded, the electromagnetic effects can be determined using measuring devices in accordance with DIN VDE 0848-1 and DIN EN 50 413. The measurement as well as the determination of the applicable permissible value should be left to a specialist, as these depend on the electric and magnetic field, the voltage, and, if necessary, also the transient.
If the permissible values are exceeded, various measures can be taken. Inherently, these are:

- Adjustment of the operating conditions of the emitter
- Shielding the emitter
- Physical limitation of the approach area
- Temporary (work-related) or to be reset (unintentional) shutdown when approaching
- More details can be found in DIN EN 50 527-1 " „Verfahren zur Beurteilung der Exposition von Arbeitnehmern mit aktiven implantierbaren medizinischen Geräten (AIMD) gegenüber elektromagnetischen Feldern“ (2017-12) = Procedure for assessing the exposure of workers with active implantable medical devices (AIMD) to electromagnetic fields

9 Conclusion

First, a few statements regarding occupational safety: A resonant absorption of electromagnetic waves in the human body can be excluded and the radiation density will be approximately 1/10 of the allowed microwave radiation. Nevertheless, it is urgently recommended and prescribed in the product development process to have an EMC check carried out during mechanical engineering, since the interaction with active medical implants can be diverse and possibly risky. This check is not associated with high costs and any risks can be eliminated by simple means while special attention should also be paid to the various operating modes of these implants, which may be changed in the interference field and might then lead to failure in critical situations. Due to the large number of implants, it is advisable to carry out relevant considerations (measurements, calculations, estimations) for the affected person in order to avoid excessive safety measures.

Summary of the sorting tests: The evaluation of the tests shows a promising result. However, a perfect result, defined by using one technological approach, one conveyer belt run, and a 100 percent hit rate, cannot be achieved, due to the large number of different types of lamps. Furthermore, the limits of detection of the end-of-life lamps are very narrow.
The detection of non-broken GDL works very well due to the electromagnetic induction technology in the alternating field. In combination with filters in the Hg range and Ar range (focusing on spectral lines Hg range and Ar range, see Figure 7), intact GDLs can be recognized 100 percent correctly (it should be noted that the statements on accurate recognition are always based on the 110 selected lamp samples for the tests - see attachment in the annex). The detection increases in difficulty as soon as the glass bulbs of the GDLs are broken, since then the gas escapes, which is needed to generate the light in combination with the mercury. If converters are used in the GDLs that do not light up with high-energy blue light, the GDLs can be separated from the LEDs in this way. However, particularly if YAG: Ce converters are used, as with DUT 95, the lamp lights up and would be recognized as an LED, even though it is a broken GDL. The use of filters for certain spectral lines would not be successful here, since the LEDs and GDLs are based on YAG: Ce converters and do not show any difference when they light up. In cases such as the DUT 95 with a partially broken glass bulb, the only thing that helps is a visual inspection by a person or a programmed image recognition, which would immediately recognize the DUT 95 lamp as a GDL.
The tests with the electromagnetic coil have also shown that the large chip area of the LED filament lamps can light up due to induction, which we did not expect before the tests. On the one hand, an incorrect assignment of an LED to the group of GDLs would not be as harmful as the other way round; on the other hand, this should be excluded by the filters in the Hg and Ar ranges.

The tests with the blue light showed good results. Many LEDs are triggered by the blue light and light up. Depending on the mixture of the converter mass, and there are many different mixtures for the converters on the market, the lighting differs in intensity. To receive better results the LED should also be lit directly. For real operation, it is therefore advisable to align the lamps in order to increase the successful recognition from 60-90%. This could be done, for example, by magnetic alignment on the metallic screw base. If the illumination is very low, it can only be recognized by an optical sensor, but not by the human eye.

The feasibility study shows good results that are very promising. However, the large number of different types of end-of-life lamps may cause errors in the detection process. Only the production of a prototype and its operation within a recycling plant in Europe will provide certainty.

10 Appendix

10.1 Demonstrator Pictures

Figure 18: Prototype of conveyor belt with device under test

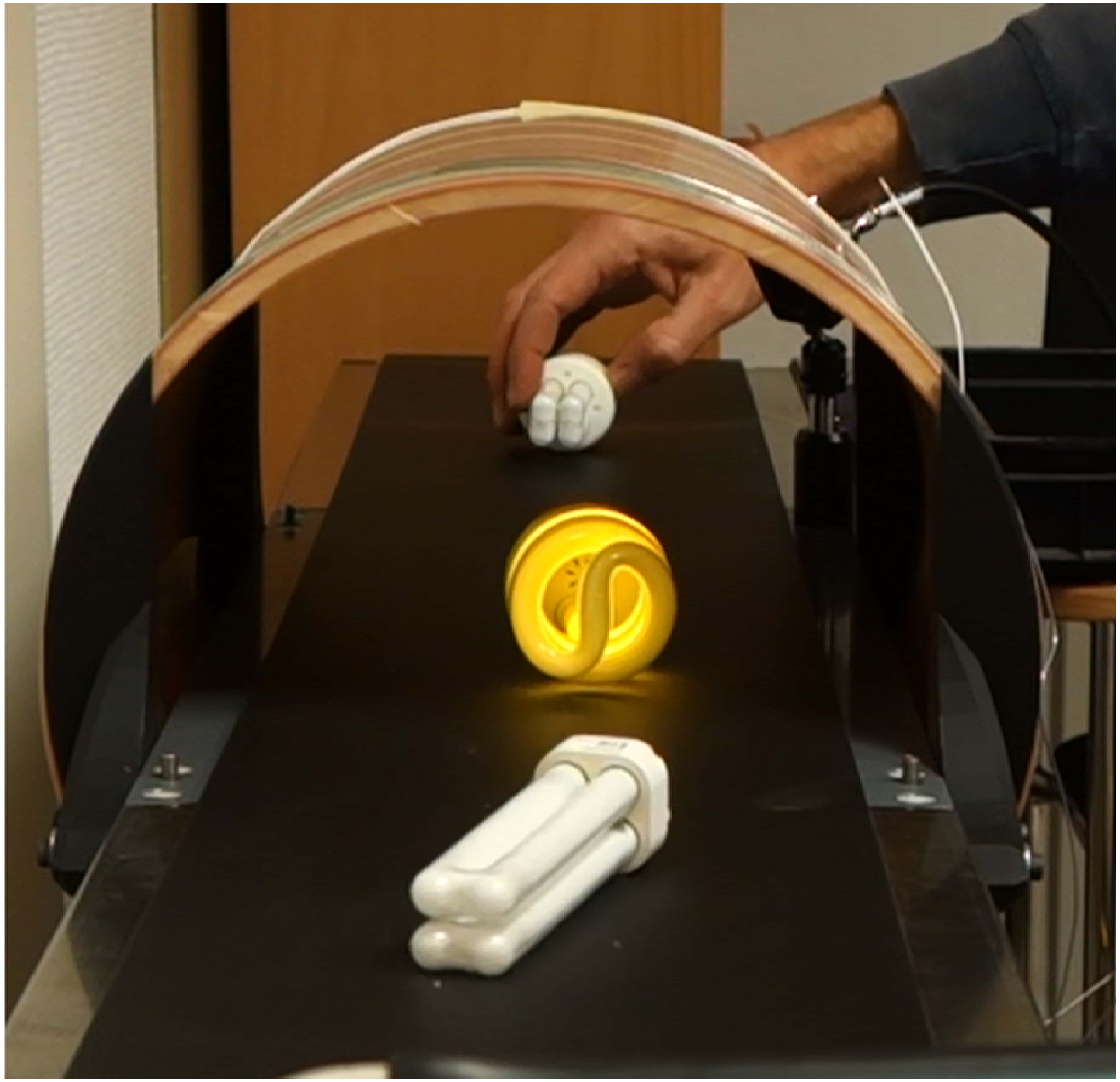


Figure 19: Prototype of conveyor belt with devices under test, partly showing fluorescence

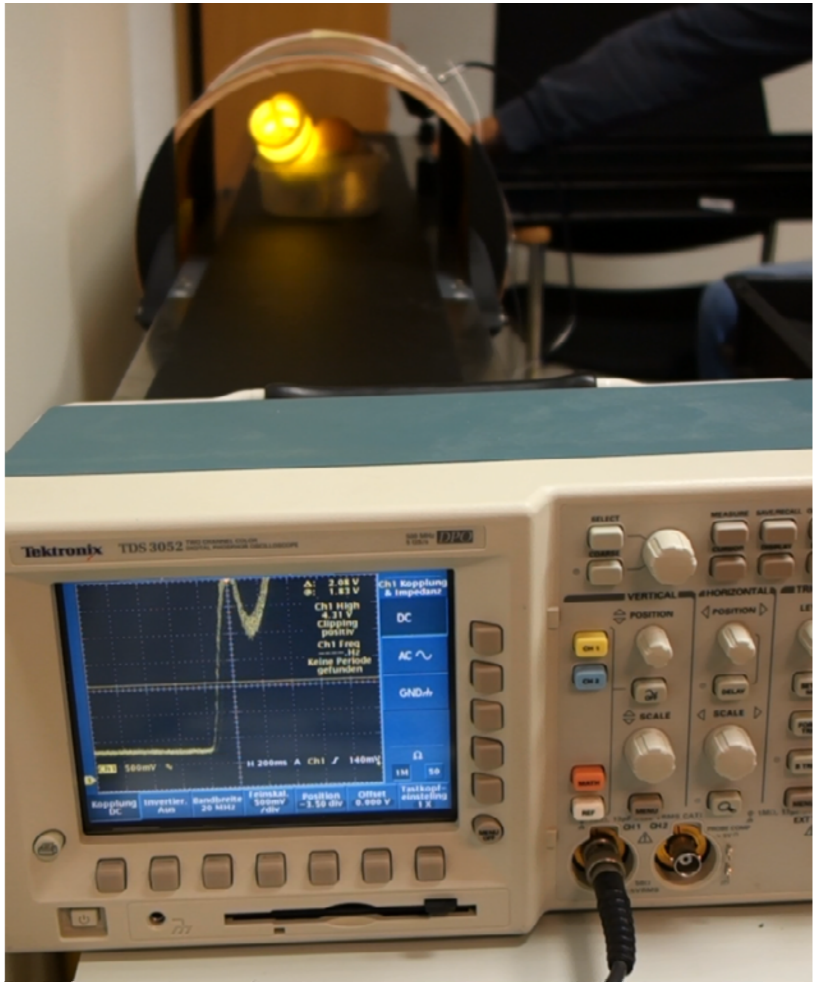


Figure 20: Light deflection at the oscilloscope

10.2 Samples for testing

DUT	Picture	Type	Confirmation as GDL in electromagnetic induction (alternating field) (yes/no)	Confirmation as LED in blue light illumination (yes/no)
1		LED	No No reaction to electromagnetic field.	No No reaction to blue light.
2		LED filament	Yes Lights up faintly even though it is not a GDL.	Yes LED filament lights up bright when exposed to blue light.
3		LED	No No reaction to electromagnetic field.	No No reaction to blue light.

4		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
5		LED	Yes Lights up faintly even though it is not a GDL.	No No reaction to blue light.
6		GDL tube	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

7		LED filament	Yes Lights up faintly even though it is not a GDL.	Yes LED filament lights up bright when exposed to blue light.
8		LED	No No reaction to electromagnetic field.	No No reaction to blue light.
9		LED	No No reaction to electromagnetic field.	No No reaction to blue light.

10		Incandescent	No No reaction to electromagnetic field.	No No reaction to blue light.
11		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
12		GDL tube	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

13		HQL	Yes Mercury lights up very brightly in the electromagnetic field.	No No reaction to blue light.
14		LED	Yes Lights up faintly even though it is not a GDL.	Yes LED packages lights up bright when exposed to blue light.
15		LED filament	Yes Lights up faintly even though it is not a GDL.	Yes LED filament lights up bright when exposed to blue light.

16		LED	No No reaction to electromagnetic field.	Yes LED packages lights up bright when exposed to blue light.
17		LED	Yes Lights up faintly even though it is not a GDL.	Yes LED packages lights up bright when exposed to blue light.
18		LED	No No reaction to electromagnetic field.	No No reaction to blue light.

19		HQL	Yes GDL lights up faintly in the electromagnetic field.	No No reaction to blue light.
20		LED	No No reaction to electromagnetic field.	Yes LED packages lights up bright when exposed to blue light.
21		LED	No No reaction to electromagnetic field.	Yes LED packages illuminate a little bit when exposed to blue light.
22		LED	Yes Lights up faintly even though it is not a GDL.	Yes LED packages lights up bright when exposed to blue light.

23		GDL tube	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
24		Incandescent	No No reaction to electromagnetic field.	No No reaction to blue light.
25		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
26		GDL tube	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

27		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
28		SOX (Sodium)	No No reaction to electromagnetic field.	No No reaction to blue light.

29		LED	No No reaction to electromagnetic field.	No No reaction to blue light.
30		Flashlamp (Xenon)	No No reaction to electromagnetic field.	No No reaction to blue light.
31		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

32		SOX (Sodium)	No No reaction to electromagnetic field.	No No reaction to blue light.
33		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
34		LED	No No reaction to electromagnetic field.	No No reaction to blue light.

35			GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
36			LED	No No reaction to electromagnetic field.	No No reaction to blue light.

37		HQL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
38		GDL tube	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
39		SOX (Sodium)	Yes Lights up faintly even though it is not a GDL.	No No reaction to blue light.

40		GDL	Yes GDL lights up very brightly in the electromagnetic field.	Yes GDL illuminate a little bit when exposed to blue light.
41		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

42		Halogen lamp	No No reaction to electromagnetic field.	No No reaction to blue light.
43		Halogen lamp	No No reaction to electromagnetic field.	Yes Halogen lamp lights up bright when exposed to blue light.

44		Halogen lamp	completely broken during transport	Yes Halogen lamp lights up bright when exposed to blue light.
45		SOX (Sodium)	No No reaction to electromagnetic field.	No No reaction to blue light.
46		LED	No No reaction to electromagnetic field.	Yes LED packages lights up bright when exposed to blue light.

47		LED	No No reaction to electromagnetic field.	Yes LED packages lights up bright when exposed to blue light.
48		Incandescent	No No reaction to electromagnetic field.	No No reaction to blue light.
49		LED	No No reaction to electromagnetic field.	No No reaction to blue light.
50		HQL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

51				LED	Yes Lights up faintly even though it is not a GDL.	No No reaction to blue light.
52				Incandescent	No No reaction to electromagnetic field.	No No reaction to blue light.

53		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
54		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
55		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

56		LED	No No reaction to electromagnetic field.	No No reaction to blue light.
57		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
58		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

59		Incandescent	No No reaction to electromagnetic field.	No No reaction to blue light.
60		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
61		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

62		Incandescent	No No reaction to electromagnetic field.	No No reaction to blue light.
63		Xenon	No No reaction to electromagnetic field.	No No reaction to blue light.
64		HQL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
65	Sample was deleted - damage too great to recognize type			
66		Halogen lamp	No No reaction to electromagnetic field.	No No reaction to blue light.

67		LED	No No reaction to electromagnetic field.	No No reaction to blue light.
68		Incandescent	No No reaction to electromagnetic field.	No No reaction to blue light.

69		GDL	Yes GDL lights up weakly bright in the electromagnetic field.	No No reaction to blue light.
70		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

71		LED	Yes Lights up faintly even though it is not a GDL.	Yes LED packages illuminate a little bit when exposed to blue light.
72		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

73		Halogen lamp	No No reaction to electromagnetic field.	No No reaction to blue light.
74		Halogen lamp	No No reaction to electromagnetic field.	No No reaction to blue light.
75		Halogen lamp	No No reaction to electromagnetic field.	No No reaction to blue light.

76		LED	No No reaction to electromagnetic field.	Yes LED packages lights up bright when exposed to blue light.
77		Incandescent	No No reaction to electromagnetic field.	No No reaction to blue light.
78		Halogen lamp	No No reaction to electromagnetic field.	No No reaction to blue light.

79		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
80		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
81		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

82			GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
83			GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

84		LED filament	No No reaction to electromagnetic field.	Yes LED filament lights up bright when exposed to blue light.
85		GDL	No No reaction to electromagnetic field. Glass bulb defective.	No No reaction to blue light.

86		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
87		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

88		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
89		Incandescent	Yes Lights up faintly even though it is not a GDL.	No No reaction to blue light.
90		LED	No No reaction to electromagnetic field.	Yes LED packages lights up bright when exposed to blue light.

91		Halogen lamp	No No reaction to electromagnetic field.	No No reaction to blue light.
92		LED	Yes Lights up faintly even though it is not a GDL.	Yes LED packages lights up bright when exposed to blue light.
93		LED	No No reaction to electromagnetic field.	No No reaction to blue light.

94			Incandescent	No No reaction to electromagnetic field.	No No reaction to blue light.
95			GDL	Yes GDL lights up very brightly in the electromagnetic field.	Yes GDL YAG:Ce Converter lights up brightly when exposed to blue light.
96			Fuse	No No reaction to electromagnetic field.	No No reaction to blue light.

97		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
98		Incandescent	No No reaction to electromagnetic field.	No No reaction to blue light.
99		LED	Yes Lights up faintly even though it is not a GDL.	Yes LED filament lights up bright when exposed to blue light.

100		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.
101		LED	No No reaction to electromagnetic field.	Yes LED packages lights up bright when exposed to blue light.
102		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

103			Halogen lamp	No No reaction to electromagnetic field.	No No reaction to blue light.
104			Halogen lamp	No No reaction to electromagnetic field.	Yes LED packages lights up bright when exposed to blue light.
105			Incandescent	No No reaction to electromagnetic field.	No No reaction to blue light.

106		Halogen lamp	No No reaction to electromagnetic field.	No No reaction to blue light.
107		GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.

108		GDL	Yes GDL lights up very brightly in the electromagnetic field.	Yes LED packages illuminate a little bit when exposed to blue light.
109		Halogen lamp	No No reaction to electromagnetic field.	No No reaction to blue light.

110			GDL	Yes GDL lights up very brightly in the electromagnetic field.	No No reaction to blue light.