

REVIEW ARTICLE

UHP lamp systems for projection applications

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Abstract

Projection systems have found widespread use in conference rooms and other professional applications during the last decade and are now entering the home TV market at a considerable pace. Projectors as small as about one litre are able to deliver several thousand screen lumens and are, with a system efficacy of over 10 lm W^{-1} , the most efficient display systems realized today. Short arc lamps are a key component for projection systems of the highest efficiency for small-size projection displays.

The introduction of the ultra high performance (UHP) lamp system by Philips in 1995 can be identified as one of the key enablers of the commercial success of projection systems. The UHP lamp concept features outstanding arc luminance, a well suited spectrum, long life and excellent lumen maintenance. For the first time it combines a very high pressure mercury discharge lamp with extremely short and stable arc gap with a regenerative chemical cycle keeping the discharge walls free from blackening, leading to lifetimes of over 10 000 h.

Since the introduction of the UHP lamp system, many important new technology improvements have been realized: burner designs for higher lamp power, advanced ignition systems, miniaturized electronic drivers and innovative reflector concepts. These achievements enabled the impressive increase of projector light output, a remarkable reduction in projector size and even higher optical efficiency in projection systems during the last years.

In this paper the concept of the UHP lamp system is described, followed by a discussion of the technological evolution the UHP lamp has undergone so far. Last, but not least, the important improvements of the UHP lamp system including the electronic driver and the reflector are discussed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Large screen projection systems became increasingly popular during the last decade. The business developed rapidly and growth is expected to continue to be high, as shown in figure 1. Looking back, the introduction of the ultra high performance (UHP) lamp concept by Philips in 1995 [1–4] was a significant technological breakthrough for the projection market and can be identified as one of the key enablers of the commercial

success of projection systems. Following its launch, the UHP lamp system has been improved with a fast innovation rate [5, 8–10, 12, 14, 19, 20, 22–24]. UHP lamps today are the standard for most commercially available front and rear projectors and have replaced the previously used metal halide lamps.

About ten years ago, the performance of liquid crystal display (LCD) projectors was rather poor: a 46 litre size, 21 kg projector delivered just 400 screen lumens with VGA

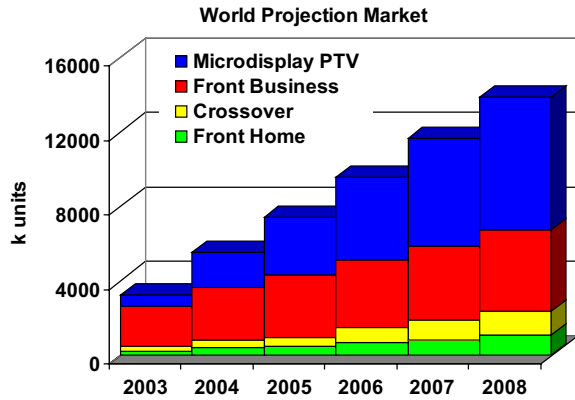


Figure 1. World projection market according to Techno Systems Research.



Figure 2. Ultra-portable projector with UHP lamp (InFocus).



Figure 3. Rear projection TV with UHP lamp (RCA).

resolution. Today, projectors of one-tenth that size can create high-quality XGA pictures with more than 3000 screen lumens brightness with a single UHP 200 W lamp. On the other end of the product spectrum, ultra-portable projectors (see figure 2) of 1 kg weight and less than 1 litre volume enable a bright XGA presentation with more than 1000 screen lumens.

Front projectors—now commonly called ‘beamers’—have found their place in almost each meeting room during the last ten years. In the last few years also, rear projection TV sets (see figure 3) have become important in the market and sales are growing rapidly.

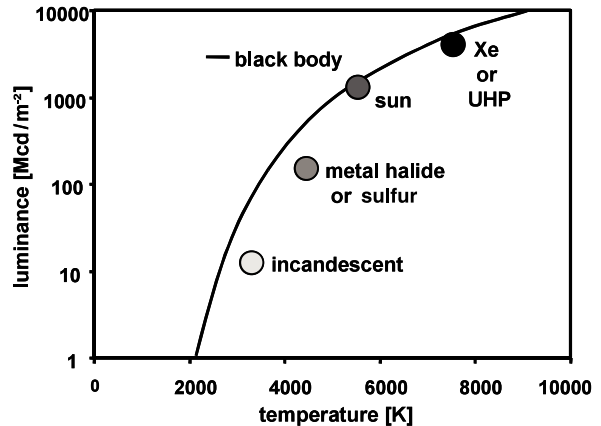


Figure 4. Luminance of light sources compared with the black body radiator luminance.

Short arc lamps are a key component for projection systems for achieving the highest efficiency for small projection display sizes. Projection is a very demanding application for the lamp. The light source should be point-like, provide extremely high brightness, high total light flux and a white spectrum. Besides, high demands on lamp efficiency and lifetime have to be fulfilled.

Further progress in both displays and optics increases the optical demands to be fulfilled by the light source. The innovation speed therefore depends on the availability of improved light sources with smaller size and even shorter arc length.

2. The concept of the UHP lamp

2.1. A pure mercury discharge for highest luminance

For highly efficient projection systems the arc luminance should be as high as possible. With today’s small display sizes, an average luminance of above 1 Gcd m⁻² is needed. The maximum luminance $L(T)$ that can be reached in thermal equilibrium is physically linked to the discharge temperature by the well-known Planck’s law:

$$L(T) = k \cdot \int V(\lambda) \cdot \frac{2hc^2}{\lambda^5} \cdot \frac{1}{e^{hc/kT\lambda} - 1} d\lambda. \quad (1)$$

Here, k is the Boltzmann constant, λ is the wavelength of emitted light, $V(\lambda)$ is the wavelength sensitivity curve of the human eye, h is the Planck constant, c the speed of light and T the radiator temperature.

Metal halide additives that are used in many lamp types for improving the colour properties of the lamp spectrum mostly reduce the arc temperature owing to their comparably low ionization potential. This leads to a lower luminance of the arc and hence does not make metal halide lamps ideal for projection. A high luminance (see figure 4) can only be reached by rare gas and pure mercury discharges, as used in the UHP lamp. A pure mercury discharge, however, is superior to rare gas discharges in luminous efficiency while reaching the same luminance.

The UHP lamp follows this approach and contains only mercury as radiating species. UHP lamps typically reach an average arc luminance well above 1 Gcd m⁻² and are, in that respect, an ideal light source for projection applications.

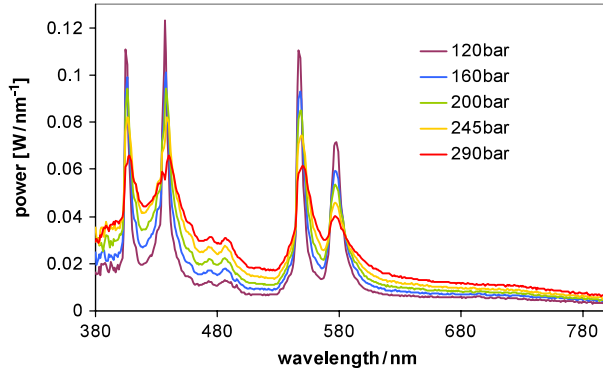


Figure 5. UHP Spectra for different mercury pressure, an arc gap of 1 mm measured at 120 W and through an aperture representing an optical system etendue of $E = 10 \text{ mm}^2 \text{ ster}$. This figure is best viewed in colour in the online edition. The 120 bar curve is the highest in the peaks and the lowest between peaks; the 290 bar curve is the lowest in the peaks and the highest between the peaks.

2.2. High pressure for continuous spectrum

For an efficient projection system the spectral properties of the light source are at least of the same importance as the lamp luminance. Filters are typically used for colour matching and for rebalancing white. With an UHP lamp, the efficiency of this colour matching and rebalancing is typically 25% for a single-panel, sequential colour device and 70% for a three-panel projector. In any case, light is lost by this filtering. To reduce these losses the lamp should exhibit an even distribution of the spectral contributions between red, green and blue.

Figure 5 shows spectra for various lamp pressures measured through an aperture (for details see section 2.7) representing the usable light in a typical optical system of a modern projector. It can be clearly seen that for mercury pressures above 200 bar more light is emitted in the continuum radiation than in the atomic spectral lines. Especially, the important red light contribution above 600 nm strongly depends on the lamp pressure. The more even distribution of the emitted light over the wavelength range is directly related to a higher colour balancing and therefore to the projector efficiency. For good colour balancing in projection systems it is essential to realize ultra high lamp pressures.

2.3. Regenerative cycle for long life

The lifetime of UHP lamps can exceed 10 000 h by far. This is realized for the first time in a commercial HID lamp by a so-called regenerative chemical transport cycle using a halogen filling [1].

As principally known from halogen incandescent lamps, in the presence of halogen and oxygen (O_2 level fixed by the tungsten oxide temperature) evaporated tungsten material can be transformed near the relatively cold discharge vessel wall into stable ternary tungsten compounds, e.g. WO_2X_2 ($\text{X} = \text{halogen}$), see figure 6.

In the hotter regions close to the lamp electrodes the oxy-halide molecules are decomposed. By these chemical transport processes, tungsten atoms are brought back to the lamp electrodes in a regenerative manner. This cycle prevents, or at least considerably reduces, wall blackening caused by the evaporation of tungsten from the electrodes.

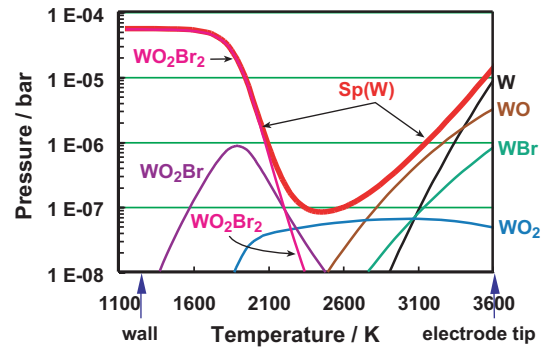


Figure 6. Principle of regenerative cycle: typical gas phase composition of a UHP lamp as a function of temperature. Sp(W) is the sum of saturation pressures of all tungsten containing species.

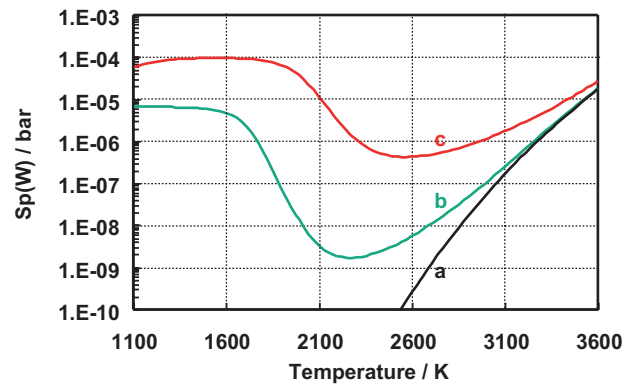


Figure 7. Schematic view of the summed tungsten pressure Sp(W) as a function of temperature for different bromine levels (curves a, b, c are explained in the text).

The direction and magnitude of tungsten transport strongly depend on the effective vapour pressure of tungsten, i.e. on the sum of saturation pressures of all tungsten-containing species for a given halogen and oxygen concentration. Figure 7 shows the summed tungsten pressure Sp(W) as a function of temperature for three bromine levels:

- Without or with insufficient bromine, Sp(W) at the wall will remain at an extremely low level ($< 10^{-20}$ bar); thus only material transports from hot to cold sites will occur causing massive blackening with no chance of tungsten recovery from the wall.
- With sufficient bromine (in the order of 10^{-4} bar), Sp(W) at the wall will exceed Sp(W) at hotter sites of the electrode enabling chemical transport of tungsten from cold to hot sites (i.e. from wall towards electrodes).
- With excess of bromine, the chemical cycle will still work, but at enhanced transport rates. Especially at the electrode feed-through with temperatures around 1800 K, chemical attack of the electrode rod can occur (see figure 8) which will lead to early lamp failure. This effect is strongly enhanced if larger amounts of gaseous impurities (H_2 , H_2O , CO , CO_2) are present (for details see discussion in [6]).

The fruit of all these efforts is lamps with exceptionally long lifetimes and good maintenance, as shown in figure 9. The integral lumens remain nearly constant for more than 10 000 h

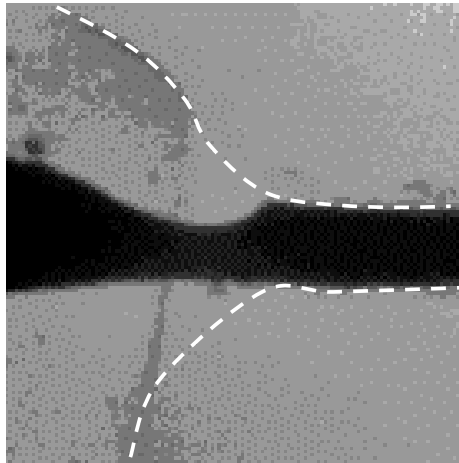


Figure 8. X ray of the electrode rod with chemical attack by too much bromine. The inner bulb contour is indicated by the white dashed lines.

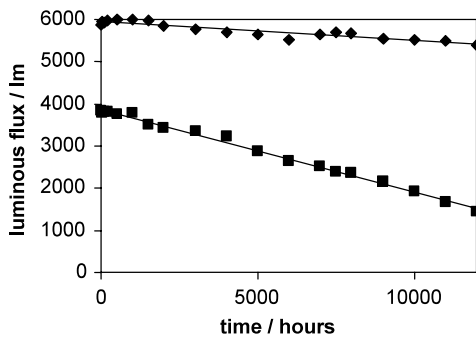


Figure 9. Light output versus burning time of an UHP 100 W lamp, 1 mm arc gap, operated in a hot environment of 250°C. (◆) integrated luminous flux, (■) luminous flux collected in a typical projector system.

owing to the halogen transport cycle. A breakdown of the chemical cycle, however, would lead to strong blackening, resulting in an overheating of the bulb and a very fast end of life. The collected lumens drop over life under the present experimental conditions. This is a consequence of electrode burn back and whitening of the bulb.

In the past years, the continuous demand for ever higher brightness was satisfied by increasing lamp powers. The higher power loads lead to a decrease in the lifetime of these lamps to about 2000 h, which is a good compromise for professional applications. For the consumer market (cf figure 1), a longer lamp life becomes a key requirement again. We also see a trend where the size of micro-display projection TV (MD-PTV) is shifting towards screen diagonals >50 inches. This asks for a combination of longest life and high brightness and challenges the design of new UHP lamp generations.

2.4. Burner models

The design of higher power UHP lamps—while keeping the arc short—is guided by advanced lamp models [7, 21], which include the plasma, the plasma–electrode interaction and the thermal balance of the lamp envelope. This allows for a proper design of lamps operating close to the limits of the bulb and electrode materials.

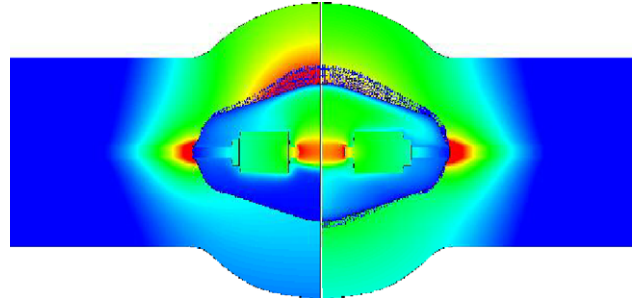


Figure 10. Temperature of plasma and quartz bulb, calculated with (right) an without (left) inclusion of radiative transfer. Please note that the same colour coding is used for the space inside the lamp and for the bulb, but the real temperature scale is largely different.

The performance of UHP lamps is determined largely by the temperatures on the inside of the burner. The Hg pressure inside the lamp has to be higher than 200 bar to allow for good colour quality and high efficiency. This requires bulb temperatures above 1190 K at the coldest spot inside the lamp. At the same time the hottest parts of the quartz envelope have to stay cold enough (<1400 K) to resist the high pressure without deformation and to stay clear without any recrystallization. A sophisticated burner design is necessary to keep the temperature differences within these limits.

Especially for a long life product, the temperature differences should be as small as possible. Owing to the strong convective energy transport in the lamp plasma, the temperature at the upper wall is considerably higher than that at the lower wall.

Because the crucial temperatures on the inside cannot be measured directly, a thermal model is required for lamp design. A model of the lamp plasma is needed to predict the distribution of the thermal flux that heats the wall. The plasma model has to include heat transport owing to thermal conduction, convection and radiative transfer.

The calculation of radiative transfer requires an enormous numerical effort, but is inevitable, because its neglect leads to wrong temperature profiles of the plasma and the [21, 27], as is shown in figure 10. The left-hand side shows the result of a model calculation without radiative transfer, while the right-hand side is based on a model including radiative transfer. As can be clearly seen, radiative transfer leads to a reduction of the top–bottom asymmetry introduced by convection. Both the plasma temperature distribution and the bulb temperature distribution show much smaller deviations between top and bottom when radiative transfer is included in the plasma model. In figure 11 the comparison with a spectroscopic measurement of the plasma temperature demonstrates the quality of the model.

2.5. Electrical properties

The burning voltage of a UHP lamp can be described by

$$U_{\text{lamp}} = U_{\text{elec}} + U_{\text{arc}} = U_{\text{elec}} + a \cdot ed \cdot p_{\text{Hg}}, \quad (2)$$

where U_{elec} is the voltage drop at the electrodes, i.e. the sum of cathode and anode fall voltages, ed the electrode distance or arc gap, p_{Hg} the pressure and a is a constant. The higher

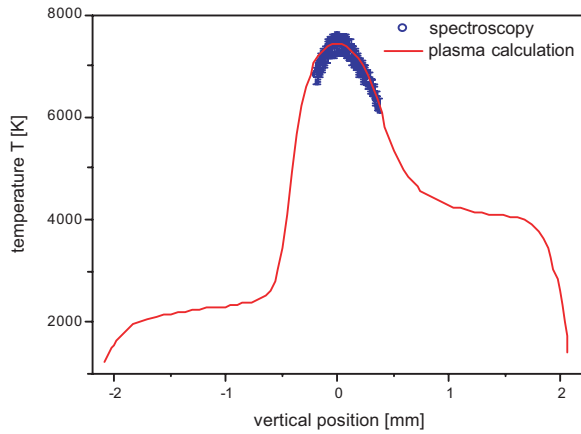


Figure 11. Plasma temperature as a function of vertical coordinates in the mid-plane as measured by plasma spectroscopy and calculated for a 120 W UHP burner.

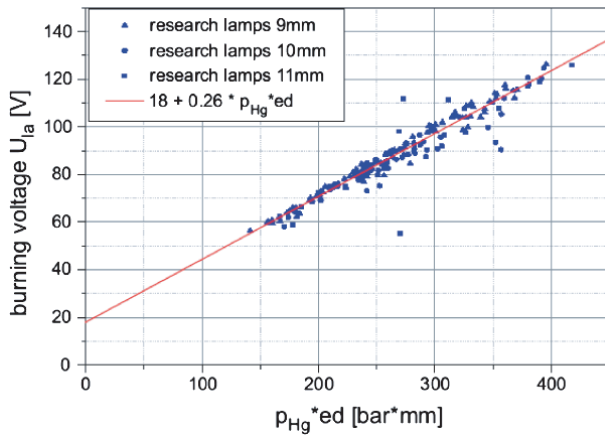


Figure 12. Burning voltage of UHP lamps as a function of the product of mercury pressure and electrode distance.

the burning voltage, the smaller is the relative contribution of the electrode losses, and a higher lamp efficacy will result. However, with decreasing arc length, the voltage drop over the arc is reduced and, relative to the total input power, the electrode losses become more important.

UHP lamps show a clear linear dependence of the burning voltage on the mercury pressure p_{Hg} [26]. This is shown in figure 12 for three different types of burners designed for different lamp powers, the larger burners being used for higher power. All the lamps used here were research samples, where a large variation in electrode distance and pressure was possible.

From figure 12 the electrode fall voltage $U_c = 18 \text{ V}$ and the slope $a = 0.26 \text{ V mm}^{-1} \text{ bar}^{-1}$ can be determined. With these two parameters, the electrical efficiency of UHP lamps can be written as:

$$\varepsilon_{\text{el}} = \frac{P_{\text{arc}}}{P_{\text{lamp}}} = \frac{U_{\text{arc}}}{U_{\text{arc}} + U_c} = \left[1 + \frac{69.2}{p_{\text{Hg}} \cdot ed} \right]^{-1}, \quad (3)$$

where p_{Hg} is in bar and ed in millimetres. As an example, for a UHP lamp with $p_{\text{Hg}} = 200 \text{ bar}$ and $ed = 1 \text{ mm}$, the electrical efficiency is $\varepsilon_{\text{el}} = 0.74$.

The burners from the lamps shown in figure 12 were measured in an integrating sphere. From the total emitted light

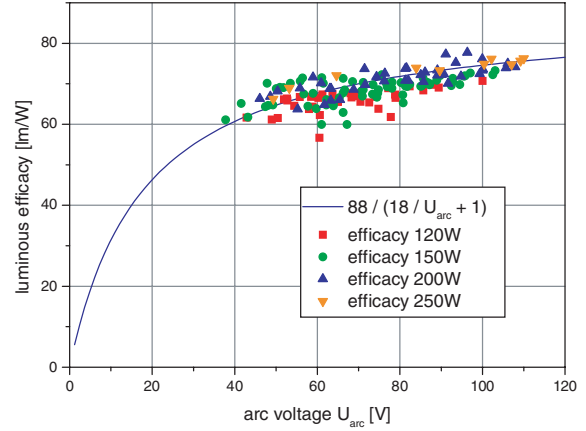


Figure 13. Luminous efficacy of UHP lamps as a function of arc voltage for research lamps operated at lamp powers between 120 and 250 W. The solid line is calculated from equation (3).

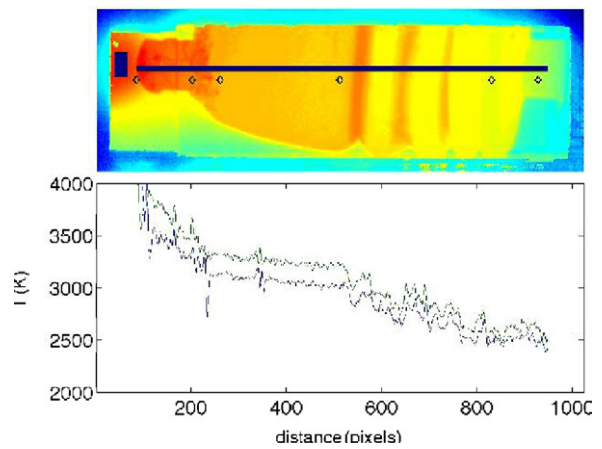


Figure 14. Measured temperature along a UHP electrode (250 W, 1.3 mm), at full operation (green) and dimmed operation (200 W, blue).

flux we could then determine the radiation efficacy of the arc plasma, using equation (3). The result is shown in figure 13.

The straight line is fitted to the experimental results with the plasma efficacy $\eta_{\text{plasma}} = 88 \text{ lm W}^{-1}$ as a fit parameter. The plasma efficacy is slightly dependent on the power on which the lamp was operated: for higher powers, it is slightly higher than for the same burners operated at lower powers.

2.6. Electrode design

A long-life lamp requires electrodes with a very stable shape: the electrode tip should not recede (burn-back) or move laterally, owing to evaporation and transport of tungsten. These phenomena depend mainly on the temperature of the electrode [24,27]. Therefore, long-life electrode design aims at controlling electrode temperature. The optimum temperature distribution features a moderately hot electrode body (for little burn-back but sufficient cooling by radiation) and a hot tip (for a stable arc attachment).

More detailed criteria can be deduced from systematic life tests of lamps with known electrode temperatures, flanked by model simulations [24]. Figure 14 shows the

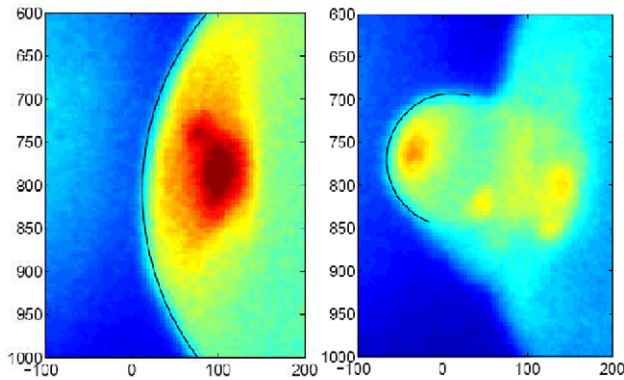


Figure 15. Two different front geometries (false coloured intensity image, dimensions in micrometres), leading to different heat loads of 15.9 W (left), 13.2 W (right).

measured electrode temperature in a 250 W UHP lamp. The cylindrical tip is partly molten (>3685 K), and the radiator body temperature is about 3200 K at the massive part down to 2500 K at the coil.

Given a target electrode temperature, one must also be able to predict the temperature expected for various design alternatives. Here, the most difficult part is to predict accurately how much power P_{in} the electrode will receive from the plasma and where the heat load will be localized. Under UHP conditions, P_{in} is particularly high (≥ 10 W A⁻¹ of lamp current), and the underlying plasma–electrode interaction is less well understood than in other discharges. Therefore, we have determined P_{in} from the measured electrode temperature for a variety of conditions.

For example, apart from depending on current, P_{in} is found to be a function of the shape of the electrode front. In figure 15, electrode temperature and heat load have been measured for one electrode at a current of 1.6 A, before (left) and after (right) the growth of a tip on the electrode front (the growth is favoured by the Philips pulse current scheme discussed in section 2.8). In the former case, $P_{in} = 16$ W, while $P_{in} = 13$ W for the latter—the sharper front reduces P_{in} . This effect must be taken into account to predict electrode temperature and to assess design alternatives. Also, the shape dependence helps to estimate where the heat load hits the electrode.

To summarize, knowing the magnitude and distribution of P_{in} , we can predict the electrode temperatures for different designs and select the one with the maximum expected electrode stability and lifetime.

2.7. Optical system performance

The optical requirements of a projection system can be translated back to a requirement for the lamp via the etendue formalism [5, 9, 11, 18]. Etendue, sometimes called optical invariant, is a quantity describing the ability of an optical system to conduct light. In any optical system, the etendue can be at best conserved but never decreased. Etendue at any location in the optical train is defined as the product of the beam cross-sectional area at that location and the solid angle spanned by all rays passing through that cross-sectional area.

In a properly designed projection system the display is limiting light throughput by its size and acceptance angle. The etendue of the projection system is then given by the product

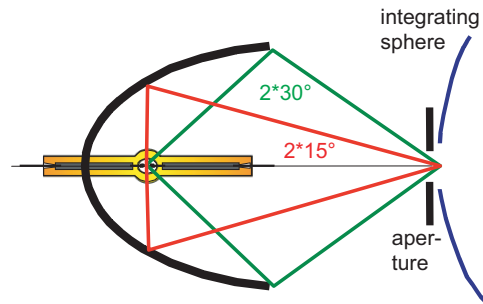


Figure 16. Measurement set-up to measure collected light flux versus etendue with a variable aperture in front of an integrating sphere. With decreasing aperture diameter (smaller etendue), the 30° rays would be cut off, because they were then falling outside the collection etendue.

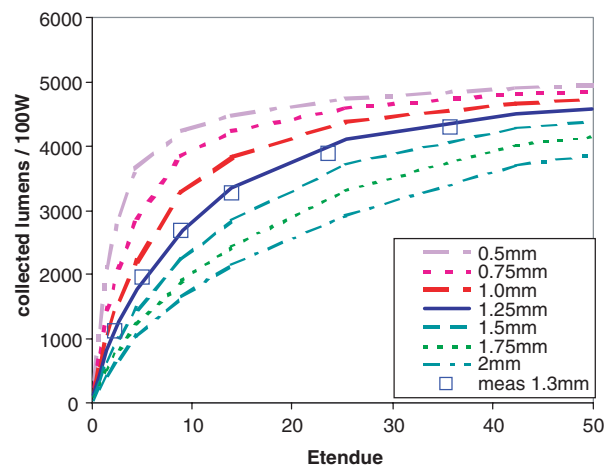


Figure 17. Simulation of collected luminous flux (in lumen) as a function of optical system etendue (measured in mm² ster) for several arc lengths and a measurement for a 1.3 mm arc.

of the display area and the solid angle defined by the possible transmission angles through the display.

Because the etendue is at best conserved throughout any optical system, only light from the lamp within the etendue of the display system can be used. The light collection for a given source inside a certain etendue can be measured, e.g. through apertures of variable diameter [11], or simulated [18]. A simple measurement set-up is shown in figure 16.

To predict the performance of future UHP lamps, figure 17 shows the results of ray tracing simulations, with the simplified assumption that the light-technical data scale with the electrode gap. Nevertheless, the simulated numbers agree quite well with measurements for the electrode distance of 1.3 mm also shown in the figure.

Clearly, a short arc is very important especially for low etendue projection systems, i.e. systems with small display size. Current projector designs use displays as small as 0.5 inch, the system etendue is typically about 5–25 mm² ster.

2.8. Stable arc

It is well known that the lamp electrodes of all short arc lamps (UHP, Xenon, Metal Halide) change their shape after some ten or hundred hours of operation. The electrodes have to

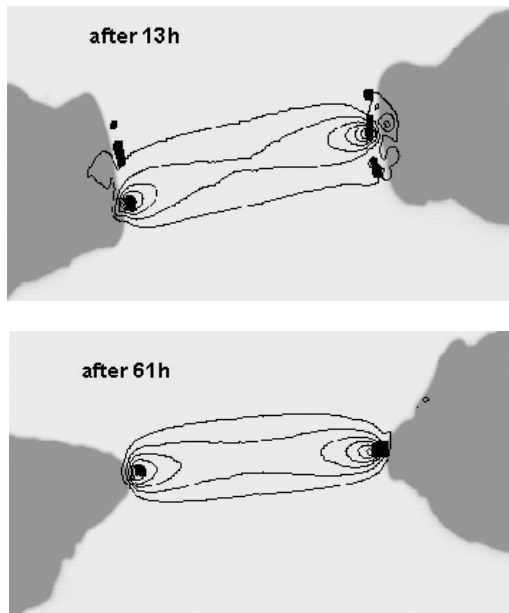


Figure 18. Electrode shape (grey) of the same lamp after 13 and 61 h of burning. The contours and black dots indicate the arc positions as described in the text.

deliver a high current into a very small discharge volume of below 1 mm^3 in the case of the UHP arc. The stability of these electrodes in direct contact with a 7000 K hot plasma is one of the challenges for a short arc lamp with long life.

In the UHP lamp the electrodes are operated at temperatures close to the melting point of tungsten (above 3500 K). No matter which perfect electrode shape is used initially, a rough electrode front surface develops after some burning time. The arc plasma will change its attachment point on this surface frequently. The stability of arc attachment depends on the actual microstructure of the electrode front and varies, therefore, in frequency and amplitude during lamp life. Such a moving arc affects the light distribution on the display and therefore causes disturbing brightness variations on the screen [10, 12].

UHP lamps were observed during their total burning time with a CCD camera set-up. The position of the arc and the two hot spots in front of the electrodes are recorded every few seconds. A detailed photo of the arc and electrodes is stored every hour. This experiment allows the tracking of any arc movements directly and correlating them with the status of the electrode surface.

Figure 18 shows typical pictures of the electrodes after some ten hours, burning time, taken from the same lamp. The shape of the electrodes is shown as grey areas while the black contours indicate the brightness distribution of the arc at the same time. The varying positions of arc hot spots were recorded throughout the last hour of burning before taking the pictures and are indicated by black dots at the electrode front.

After 13 h, the arc has attached on a lot of different positions distributed over the flat front part of the electrode. After some further burning hours, the electrode surface has changed to the more pointed shape shown in the second photo. The arc position is much more stable at this time. However, this situation will not last for long but will return to the previous one later on.

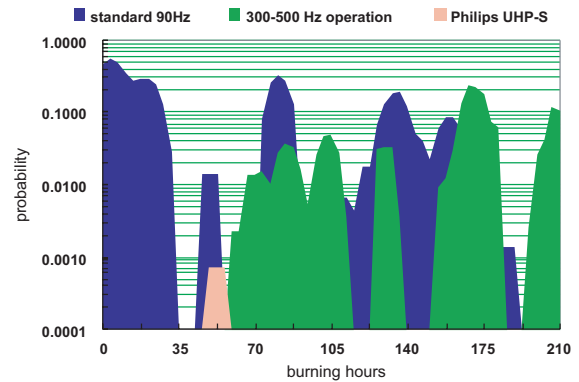


Figure 19. Probability of arc jumps of more than $100 \mu\text{m}$ during lamp life for different operation modes. The red area indicates the Philips proprietary UHP-S™ operation mode. With the other operation modes, long periods of very unstable operation will occur. The photos in figure 18 have been taken at 13 and 61 h burning time for this lamp at 90 Hz operation.

The recordings of the arc attachment position shown before can be used to calculate a ‘jump width’, where the probability $P(\mu)$ of a jump width μ is defined as the relative number of measurements showing a jump width of at least μ . A typical development of arc jump probability during lamp life is shown in figure 19 for different operation modes. With the standard 90 or 300–500 Hz square wave current operation, the arc jump activity varies between relatively quiet periods and probabilities up to 30% for jumps $>100 \mu\text{m}$, depending on the constant change of the electrode surface. Quiet periods are always correlated with a pointed front surface, while arc jumping indicates a flat structure. The operation mode related to the red area shown in figure 19 will be discussed later in this section.

As experiments with large numbers of lamps have proved, any lamp will show arc attachment instabilities in an unpredictable way during several hundred hours, no matter whether it is more or less stable at the beginning of lamp life.

Using special electrode shapes like a pointed shape does not work in practice for short arc lamps. During the lamp’s lifetime, the large electrode surface modifications will change any initial electrode surface into a rough and sometimes flat structure. A lamp design which allows stable arc attachment only for the first 10–100 h is no solution for projection applications.

For a proper optical design of the projection system the arc jump widths have to be known. A cumulative distribution of the probability of arc jumps is shown in figure 20. The figure indicates that in the standard situation, jumps of up to $100 \mu\text{m}$ occur in 13% of the burning time. Jumps of above $300 \mu\text{m}$ do not occur.

The moving arc affects the light distribution on the display and therefore causes brightness variations on the screen. With typical jump frequencies of 0.01–10 Hz they attract the attention of the observer. Even with a uniform illumination, fluctuations of the total screen brightness may be the consequence of arc instabilities. It is nearly impossible to define a general threshold above which brightness variations are perceived as disturbing. We experienced visual (and therefore disturbing) effects for brightness variations above 1% at any place of the screen.

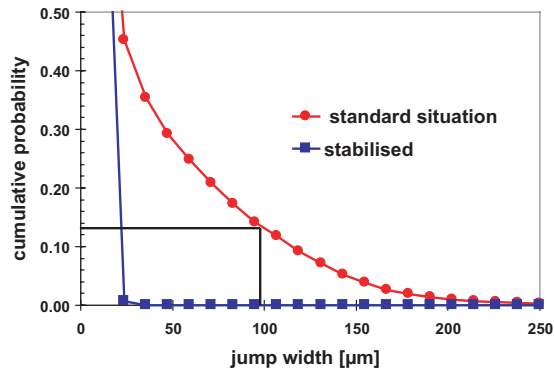


Figure 20. Cumulative arc jump distribution in standard and UHP-S™ operation mode.

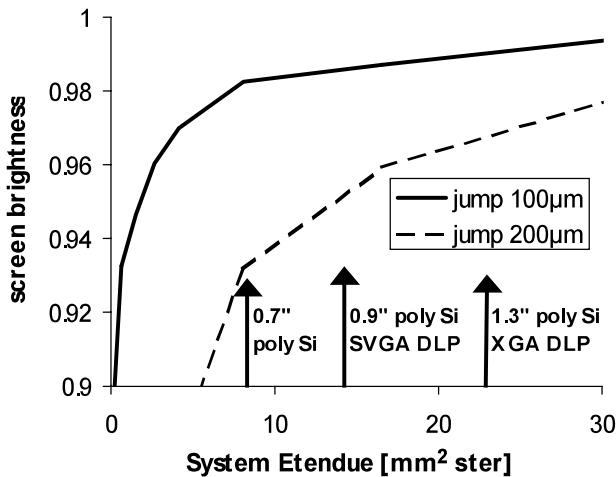


Figure 21. Simulation of the effect on total screen brightness of an arc jump of 100 μm . The arrows indicate etendue values of typical LCD and DLP based display systems with diagonal size given in inches.

The arc attachment instabilities occur with all kinds of short arc lamps at most times in life. Sophisticated electrode designs only help for the first hours in life and are therefore no solution. To avoid complaints in the market, all set makers use some kind of optical integration to suppress the visibility of arc jumping. The general working principle of optical integrators is to split the beam of light from the lamp into a large number of sub-beams which are superimposed on the display. Any fluctuations from beam to beam are averaged out.

Two types of integrators are most common: lens array integrators [15], mostly used in combination with LCDs and rod integrators [16] normally used with DLP™ displays ('Digital Light Projection', trademark of Texas Instruments. DLP displays are arrays of small micro mirrors which can be tilted for image generation).

Optical integration has been a good measure against the visibility of arc jumping for the past years. For display sizes smaller than 1 inch, however, even if the integration still preserves a good homogeneity, arc instabilities become visible again as a fluctuation of total image brightness [10]. Figure 21 shows the simulated effect on screen brightness in the case of a typical arc jump width of 100 and 200 μm (cf figure 20).

Hence, the feasibility of optical integration becomes limited for small etendue, i.e. small displays. An

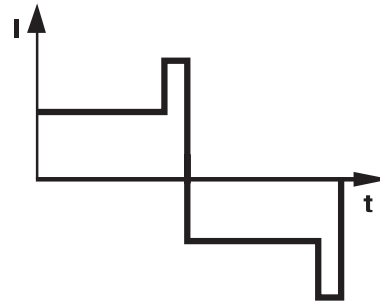


Figure 22. Relative lamp current versus time which guarantees a stable arc attachment.

alternative solution, preferably at the source itself, is urgently needed.

The physics of the arc attachment modes in high pressure arc lamps is a very complex problem and no general theoretical model is available so far. Detailed investigations, however, led to a way to stabilize the lamp arc directly without reducing the overall performance of the lamp.

The stabilization of the arc during the total lifetime is based on an electronic drive scheme and was invented by Philips in the mid-90s. It was realized in the UHP-S™ electronic driver using a specially designed lamp current [2], shown schematically in figure 22.

The solution is closely related to the interaction of driving mode and arc attachment. Contrary to the standard 'block' form current shape, the application of the special current form with extra current pulses at the end of each half-wave (see figure 22) results in a perfectly stable arc attachment on the electrode over the whole lifetime [10]. The arc position is fixed and the disturbing effects of a moving arc are successfully avoided.

Figure 19 shows the probability of arc jumping with the standard block form current and the new current form for arc stabilization. Any instability is suppressed by more than a factor of 1000 and no disturbing visual effects remain. The cumulative probability shown in figure 20 indicates that the stabilization suppresses all arc jump widths down to our measuring accuracy of 20 μm .

The large effect on the arc caused by the small pulse on the lamp current shows the close relation between lamp and electronics and the importance of a combined lamp and electronics development. The relation to the display system has to be addressed too: synchronization of the pulse current with the display frame frequency is implemented in the electronics. For all projection systems, it is, therefore, possible to use the extra light boost caused by the extra current.

Because of its clear advantage with respect to picture stability over the whole lamp life, all other properties of the lamp being as good as before, the new current form has been implemented in the Philips UHP-S™ system which has been used for most projectors since the end of 1999. With this unique lamp and electronics combination new projector designs are possible with the optical integration reduced to the level that is necessary for uniform screen illumination.

3. Evolution of the UHP lamp

3.1. Increased power

One clear trend in the projection market is towards larger screens and brighter displays. This leads to a demand for higher brightness from the lamps, which can be achieved in a straightforward way by an increase in lamp power. In figure 23 the increase in screen lumens from a projector and the lumen output of UHP lamps is plotted. It becomes clear that increased lumen output of the lamp has been the driving force behind the performance increase of projectors over the last few years.

The first UHP lamp, introduced in 1995, had a lamp power of 100 W, whereas nowadays 300 W UHP lamps are available. An increase in the lamp power goes along with an increase in the luminous efficacy. Whereas the efficacy of the 100 W lamp is 60 lm W^{-1} , the 250 W burner reaches an efficacy of 67.5 lm W^{-1} . Therefore, the lumen output from these burners is even more than proportional to the lamp power. The different burners of these lamps can be seen in figure 24.

3.2. Limits of power increase

A further increase of lamp power, although desired, is becoming more and more difficult. The burner design is approaching the material limits: the temperature at the inner top of the burner must not exceed a certain limit in order to avoid recrystallization of the quartz. At the same time the temperature at the coldest spot anywhere in the burner must always be high enough so that all the mercury within the burner can evaporate and the desired high pressure is reached. For a proper thermal lamp design, extensive computer simulations

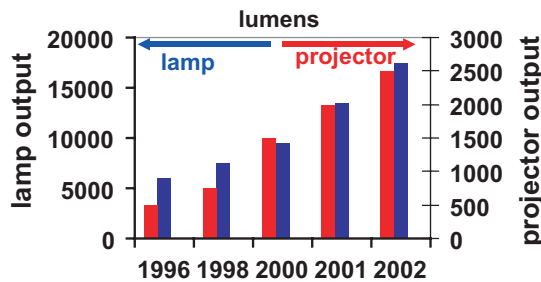


Figure 23. Light output increase of UHP lamps and projectors since the introduction of the UHP lamps in 1996. Left bars: projector output; right bars: total lamp output.

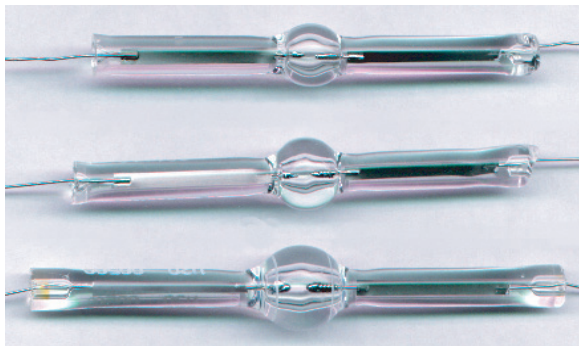


Figure 24. The burner size increases with the lamp power. Shown are 100, 150 and 250 W UHP burners (from top to bottom).

are necessary, see section 2.4. The realized lifetimes of high power lamps so far do not reach the outstanding long life of the lower power types. Since the lamp is the main heat source in a projector, an increased lamp power also leads to an increased cooling effort and requires additional measures to keep the noise level from the projector fan low.

3.3. Projector demands and efficiency

In the preceding sections, the trend towards higher power UHP lamps has been described. Now another trend will be covered: the trend towards more efficient UHP lamps with better colour rendering.

The total efficiency of a projector is the product of the efficiencies ε corresponding to the various functional subunits:

$$\Phi_{\text{screen}} = \varepsilon_{\text{coll}} \cdot \varepsilon_{\text{RGB}} \cdot \varepsilon_{\text{disp}} \cdot \varepsilon_{\text{lenses}} \cdot \Phi_{\text{lamp}}, \quad (4)$$

where, $\varepsilon_{\text{coll}}$ is the collection of light into the system etendue, ε_{RGB} the colour matching and rebalancing white (explained later in the text), $\varepsilon_{\text{disp}}$ the display transmission incl. polarization and $\varepsilon_{\text{lenses}}$ is the in line transmission of lens optics.

The display transmission $\varepsilon_{\text{disp}}$ is given by the properties of the LCD or DLP display used, with efficiencies of the order of 40% (LCD) to 60% (DLP). The transmission of the optics $\varepsilon_{\text{lenses}}$ is usually quite high (80–90%). Both factors $\varepsilon_{\text{disp}}$ and $\varepsilon_{\text{lenses}}$ are usually not influenced by the design of the UHP lamp.

The collection of light into the system etendue has already been discussed shortly in section 2.7. Besides a proper lamp reflector design, arc length and lamp pressure have an influence on collection efficiency $\varepsilon_{\text{coll}}$ and colour efficiency ε_{RGB} . This will be described in the following two sections.

3.4. Arc length

The optical requirements of the display can be translated back to lamp arc length and luminance via the etendue formalism [17]. The light collection inside a given etendue E can be simulated or measured, e.g. through apertures with a variable diameter as described earlier in figure 16. A heuristic description allows one to calculate the collection efficiency $\varepsilon_{\text{coll}}$ into a required etendue E (in $\text{mm}^2 \text{ ster}$) and for an arc gap ed (in millimetres), [12, 18, 19]:

$$\varepsilon_{\text{coll}} = \arctan \left(\frac{E}{3.8ed^2 + 0.9ed + 0.8} \right). \quad (5)$$

This formula is based on an optical lamp model, including a detailed description of bulb distortions, reflections on the electrode surface and electrode shadowing. It has been verified using lamps with arc gaps in the range 1.0–1.5 mm, see figure 25 and [18].

For arc gaps below 1.0 mm the purely optical simulation clearly deviates from the measurements. This is due to electrical losses at the electrodes. A part of the electrical power is lost close to the electrodes—in the so-called electrode fall—and is dissipated as electrode heating, as has already been discussed in section 2.5.

With decreasing arc length, the voltage drop over the arc is reduced and, relative to the total input power, the electrode losses become more important. The optical efficiency

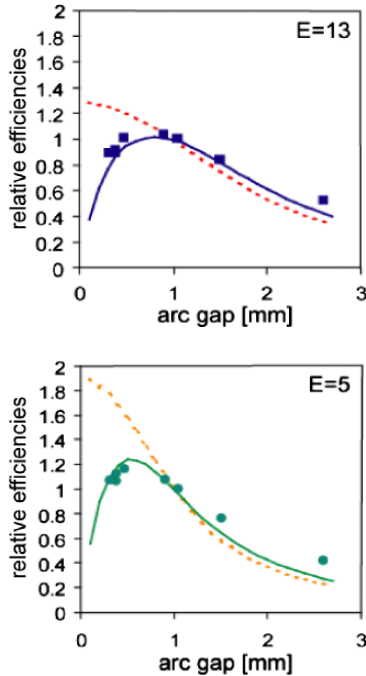


Figure 25. Relative efficiency of UHP lamps as a function of arc gap length in an $E = 13 \text{ mm}^2$ ster (top) and $E = 5 \text{ mm}^2$ ster (bottom) projection optics. Measurements (●, ■), model based on optical simulation alone (---), and improved simulation taking into account the variation of lamp efficacy with arc gap (—).

improvement calculated by equation (5) has therefore to be multiplied by the efficacy penalty given by equation (3), to give a more realistic prediction of the performance of lamps with ultra short arcs.

For lamps with arc lengths below 1.0 mm, the simulations including the lamp efficacy in figure 25 show a much better agreement with the measured data. The most important consequence is that there exists an optimum arc length for a given etendue rather than an ever-increasing benefit from shorter arcs.

The requirements for a shorter arc as well as for higher power have a severe impact on lamp performance. They increase the load on electrodes and bulbs and therefore lead to a compromise in lifetime of the lamp. In addition, significant progress in manufacturing technology has to be achieved. For modern projection lamps, designed close to the material limits, simple scaling laws no longer apply.

Unlike the UHP lamp, most other projection lamps are limited to arc lengths above 1.5 mm and therefore require much higher power than 300 W to illuminate a standard 0.7 inch display. Most of the light is wasted then, because of poor collection efficiency.

The UHP technology enables arc gaps as small as 1.0 mm with good lifetimes. This reduces the power consumption to a mere 150 W and is a good choice with respect to feasibility. In our research laboratories the outstanding luminance advantage of the short arc has been proved with experimental UHP lamps with arc length as short as 0.3 mm [19], as shown in figure 26.

The key task for the development of real-life products will be to deal with lamp design and electrode stability issues. Future developments towards shorter arcs will further increase the system performance for smaller and smaller displays.

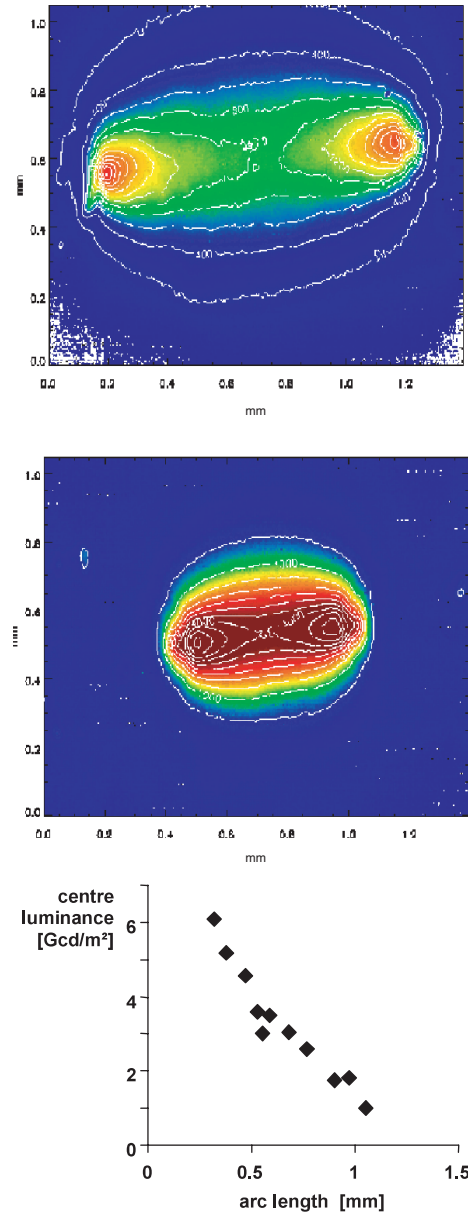


Figure 26. Research results: ultra short arc UHP luminance at 1.0 mm arc length (top), 0.5 mm arc length (mid) and dependence of centre luminance on arc length (bottom).

3.5. Improved spectrum

Increasing the lamp pressure is a way of compensating for the efficacy loss predicted in equation (3) for shorter arc gaps. The pressure has a similar effect as the arc gap, i.e. only the product $p \cdot ed$ appears in the formula. This efficiency increase is another advantage of high mercury pressures, besides the improved spectrum shown in figure 5.

In figure 27, the lamp efficiency of UHP lamps is shown as a function of mercury pressure [25]. The squares indicate the measured increase in efficiency with increasing lamp pressure. These measurements are in good agreement with the prediction of the simple model presented in section 3.4.

In addition, in figure 27 the colour balancing efficiency ϵ_{RGB} is plotted normalized to the 200 bar lamp value. This factor takes into account that in a projector, the white light

from the lamp has to be split into three primary colours R, G, B, defined by the television norm and these three primary colours have to be rebalanced to yield saturated RGB-colours at a specific colour temperature of e.g. 8000 K.

The requirement of well-saturated RGB colours limits the parts of the spectrum which can be used, e.g. yellowish light cannot be used for red or for green and has to be wasted (typically a 15% light loss). The sum of all three colour channels has to yield white light again. Depending on the lamp spectrum and the desired white point (in most cases 8000 K) this causes again a typical 20% light loss, i.e. the colour efficiency ε_{RGB} is typically 65%. The calculated colour efficiencies for all lamps measured in figure 27 are plotted as open circles and show an increasing colour efficiency of around 15% per 100 bar. This increase is the result of an improved colour balancing owing to the higher pressure of the lamp.

Figure 28 shows spectra of a 120 W UHP lamp with 200 bar pressure and an arc gap of 1.0 mm and a 200 W UHP lamp with 300 bar pressure and an arc gap of 0.8 mm. While the colour efficiency of the first lamp is 66%, the 300 bar lamp reaches 83%, i.e. 25% more light on the screen owing to better colour balancing efficiency ε_{RGB} alone. In addition, of course,

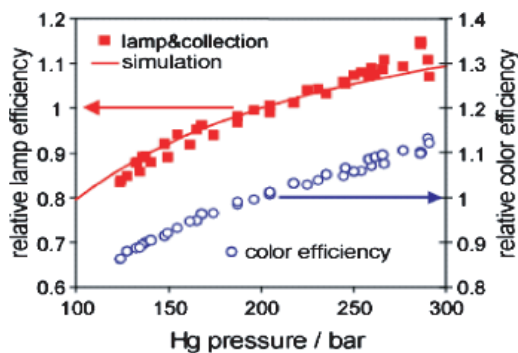


Figure 27. Measurements of lamp efficiency (■) and calculated colour balancing efficiency ε_{RGB} (○) for a 120 W 1.0 mm UHP lamp collected into $E = 10 \text{ mm}^2$ ster, normalized relative to the efficiency at 200 bar lamp pressure. The solid line is calculated from the simple model of section 3.4.

the 200 W lamp can deliver a lot more light by its higher power and shorter arc.

It has to be noted that the latter lamp already shows a perfect balance between the red and the green part of the spectrum. A further increase in pressure would give no additional colour benefit. Besides the pressure, the spectrum also depends on the power density (lamp power per arc length). It is easier to realize the perfect spectrum at higher power densities.

In figure 29 the measured spectra of different experimental lamps with various electrode gaps have been evaluated to deduce the dependence of the colour efficiency ε_{RGB} on the lamp power per arc length for a constant pressure of 220 bar. A lamp of, e.g. 200 W at 1 mm arc gap exhibits nearly the same colour efficiency as a lamp with 0.5 mm arc gap operated at 100 W. The spectrum cannot be driven to be perfect: there is a saturation of colour efficiency at about 0.82.

It should be noted that only etendue limited measurements through an aperture—as indicated in figure 16—can represent the usable light in projection systems. A standard integral spectral measurement with the lamp in an integrating sphere would collect light not only from the arc but also from the glowing hot electrodes, leading to increased red spectral contributions. This effect would lead to unrealistic predictions of spectral performance especially for lamps with a relatively long arc in combination with low-etendue projection systems which can utilize the light of a very short arc only.

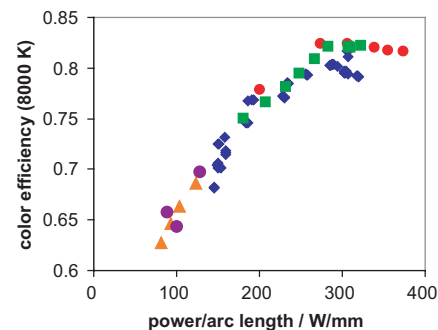


Figure 29. Measured dependence of the colour efficiency on the lamp power per arc length for a constant pressure of 220 bar.

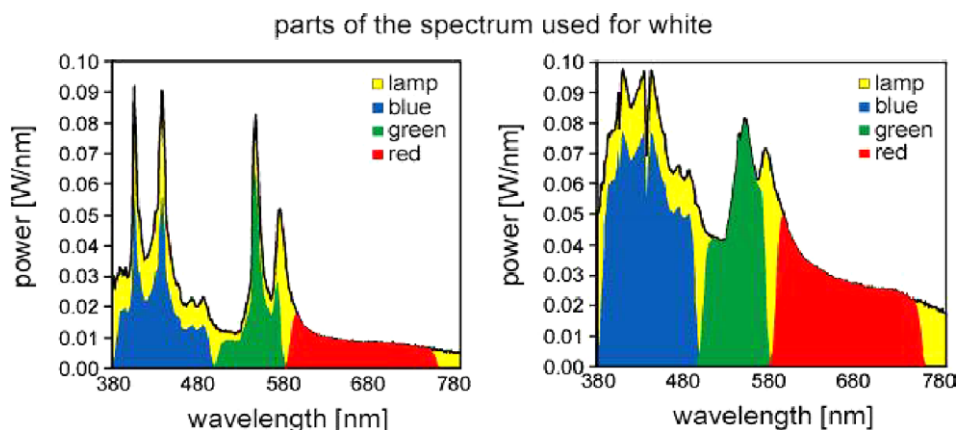


Figure 28. Spectra for a 120 W UHP lamp with 200 bar, 1.0 mm (left) and a 200 W UHP lamp with 300 bar, 0.8 mm (right) and the parts of the spectrum after spectral filtering (a typical projector filter set is assumed here) used to create the RGB colour gamut. Both spectra have been measured at $E = 10 \text{ mm}^2$ ster collection. (This figure is best viewed in colour in the online edition. The three areas of darker shading, from short to long wavelength, are the blue, green and red parts of the spectrum.)

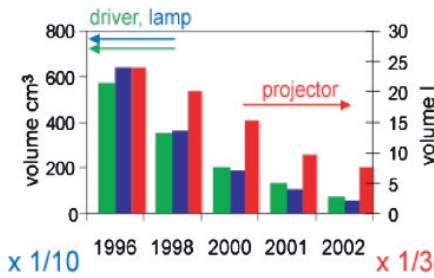


Figure 30. Volume reduction of projectors (right bars) since the introduction of the UHP lamp. Lamps (middle bars) and drivers (left bars) contribute more than proportionally to this development.

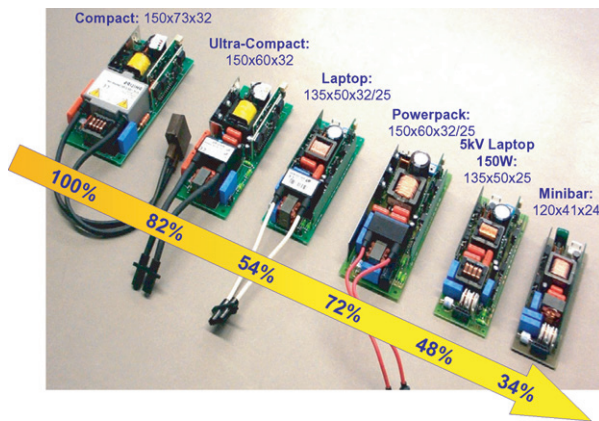


Figure 31. Size reduction of the Philips UHP driver over the years.

4. Evolution of the UHP lamp system

4.1. Miniaturization

Another trend in the field of digital data projection is the drastic reduction in projector size seen since the introduction of the UHP lamp. From figure 30 one can see that the lamp and driver volume has shrunk to 1/10 of its original size since 1996. In the same time frame, the volume of an average projector has reduced to one-third. Therefore, the reduction of lamp and driver size contributed very significantly to projector miniaturization. Nowadays, projectors as small as a litre with a weight of less than 1 kg are available.

In this paper the different means of achieving this impressive size reduction will be reviewed. These are through the use of smaller reflectors, an integrated reflector approach and also a concept that allows for smaller lamp drivers via a reduction in the ignition voltage.

4.2. Electronic driver

During the last years significant miniaturization of the power supply subsystem has been accomplished. As shown in figures 30 and 31, a size reduction by a factor of 10 for the driver has been reached since 1996.

The ‘microbar’ lamp driver from Philips shown in figure 32 has a size of only $80 \times 42 \times 22 \text{ mm}^3$ and therefore a total volume of 74 cm^3 . The weight is only 80 g. It is controlled by a microprocessor and can communicate with the projector electronics.

The remarkable reduction in size has been achieved thanks to improved design and the consequent use of miniaturized

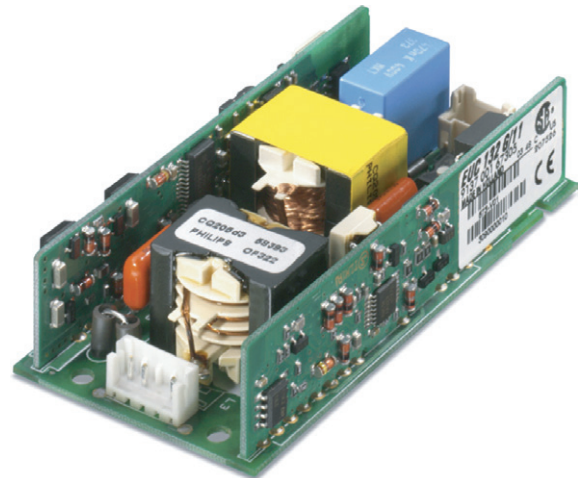


Figure 32. Photograph of the Philips microbar driver.

components. A reduction of the lamp ignition voltage down to 2.5 kV (cf the following section) enabled a further reduction in size of the ignition part of the driver. On the other hand, the time the user has to wait to re-ignite the hot lamp is extended to 90 s. Cooling the lamp after switch-off helps to reduce this time span.

4.3. Low voltage ignition system

In a modern, ultra-compact projector, the lamp system is the subsystem of highest power density and uses a significant amount of the total system volume. About one-third of a standard lamp driver size is used by the ignition module alone. A new system approach of a low voltage ignition system enables a breakthrough in compactness [12–14, 19].

Lamp ignition is a topic familiar to the lighting industry for years, but many phenomena are still not completely understood, and new concepts can lead to improvement.

To create a gas discharge, primary electrons are needed. After switching off a lamp, after some hours, all charge carriers will have been neutralized. Primary electrons can be produced by natural radioactivity, but in the small UHP bulb-volume it is very unlikely that this will happen right at the time the lamp ignites. So primary electrons have to be created via field emission at the electrodes. Owing to the electrode shape modifications during the lifetime of the lamp, one cannot rely on extremely high field enhancement factors from sharp micro structures, but has to apply 20 kV to the lamp for a safe ignition. During operation, the lamp current must pass the ignitor transformer, which consequently has to be designed quite large because of heat dissipation in the many coil turns required to create 20 kV.

Electrons can also be produced, via photo-emission, from the tungsten electrodes. Owing to the work function of tungsten, photons of energy $>4.54 \text{ eV}$ are needed, i.e. ultra-violet (UV) radiation with $\lambda < 270 \text{ nm}$. The required UV radiation can be produced by an ignition aid, which is often called a ‘UV enhancer’, and is basically a small discharge lamp of its own.

In a compact reflector system it is not easy to place a UV enhancer without some obscuration of light. A very elegant

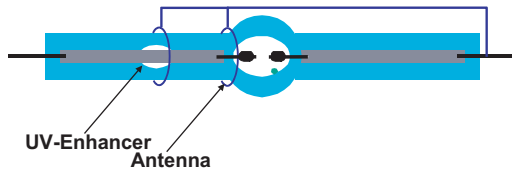


Figure 33. UHP burner with UV enhancer cavity in one of the seals. The additional antenna wires are connected to the opposite electrode.

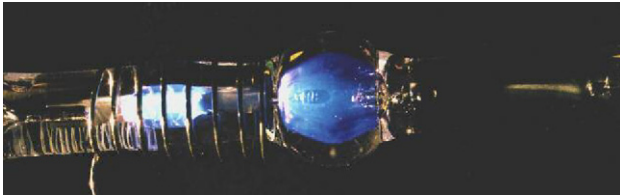


Figure 34. Initial discharge in the UV enhancer cavity (left part) and light conduction into the main burner cavity (middle of picture). The antenna wires are formed like a spiral here.

and simple solution, without any optical disturbance, is to incorporate the UV enhancer into the electrode seal of the UHP burner [13], cf figure 33. The seal is made in such a way that some millimetres in the middle are simply not closed, leaving a small cavity filled with an argon–mercury mixture, with the molybdenum foil going through it. An external wire (‘antenna’) creates an electrical field and a first ignition takes place inside this small cavity.

Thanks to the sharp edges of the foil, relatively low voltage is sufficient to extract electrons and create a breakdown within the UV enhancer. Subsequently, a capacitive discharge between the foil and the antenna produces UV light, which is conducted along the sealing by total internal reflection towards the main burner cavity, see figure 34. There the UV photons create electrons by photo-emission and a primary breakdown in the main cavity is induced. After this breakdown sequence, only a few hundred volts are required in the glow phase and below a hundred volts when the arc is established after less than a second. Even after days in total darkness, the lamp ignites reliably at voltages much below 5 kV.

The so-called ‘cold and dark ignition’ scenario discussed so far is only one limiting situation for lamp ignition. The other limit can be called the ‘hot ignition’ situation. After switching off a discharge lamp plenty of charges still exist. But at this time, owing to the high pressure, a very high voltage is required to create a breakthrough. While the burner cools down, the pressure decreases and the mercury will condense. The breakthrough voltage then decreases as well.

A metal wire close to the burner can modify the field distribution inside the burner and helps to lower the required restriking voltage. The field forming wire can be combined with the antenna around the UV enhancer, as indicated in figure 33.

In figure 35 measurements of the required ignition voltage over time after switch-off are shown for different ignition aids. With the application of the antenna wire, the lamp can be ignited with voltages as low as 5 kV, after 50 s, which is a clear improvement compared with the standard situation without ignition aids. The measurement in figure 35 has been done without any cooling. If the projector provides lamp cooling after switch-off, the re-ignition times can be reduced further.

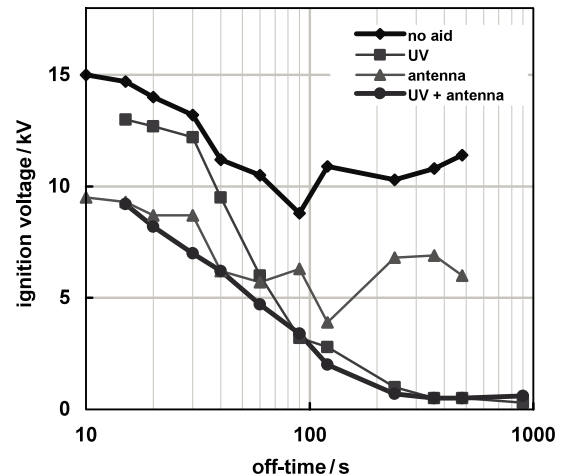


Figure 35. Measurement of the required ignition voltage with several ignition aid configurations. The ‘hot-restrike’ voltage of the burner without any ignition aid (◆) is lowered by a simple antenna (▲) while the UV enhancer (■) has a major effect for >50 s after switch-off. For the combination of antenna + UV enhancer (●), the lowest ignition voltages are sufficient at any time.

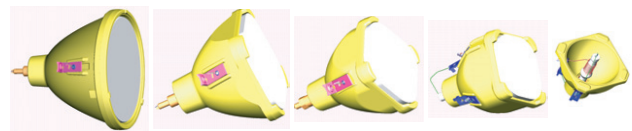


Figure 36. Miniaturization of reflector lamp size over the last few years. The left reflector is 95 mm in diameter while the right one is only $46 \times 46 \text{ mm}^2$.

Low ignition voltages are possible for off-times greater than some 30 s.

To summarize, the UV enhancer and antenna combination is an ideal solution for both the ‘hot’ and ‘cold & dark’ ignition scenarios and can significantly contribute to a miniaturization of the electronic driver, cf figure 32.

4.4. Reflector

UHP reflector design is a combined optimization with respect to thermal and optical considerations as well as to feasibility of the final glass parts. It takes into account details of the projection system, and, therefore, Philips offers a large variety of different reflector types [22]. Basically, parabolic reflector shapes are preferred in combination with lens array optical integrators, while elliptical reflectors are ideally suited for combination with rod-type integrators.

Figure 36 shows the size evolution of Philips UHP reflector lamps over the last few years. Several design considerations led to the reflector size reduction.

First of all, the UHP burner emits light into $\pm 45^\circ$ from the equator. The reflector has to cover as much as possible of this solid angle. Rays that do not hit the reflector are lost and generate heat in the system (red ray in figure 37).

Second, the collimating optics (condenser lens and parabolic reflector or elliptical reflector) should produce a cone of light that is matched to the display requirements. The illumination optics, e.g. the DMD displays is built to

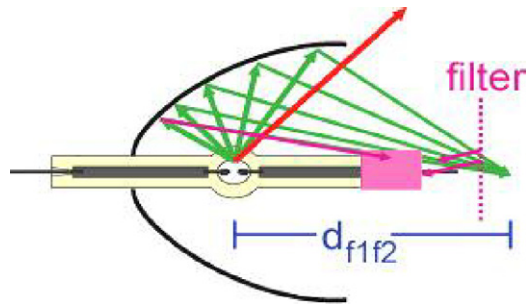


Figure 37. Design considerations for elliptical reflectors.

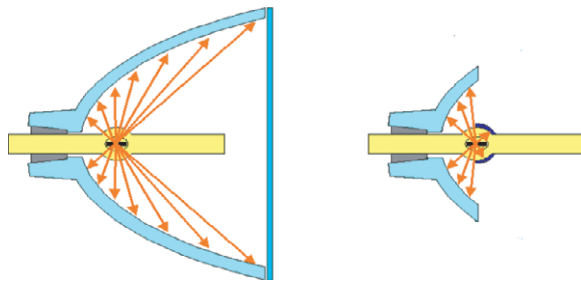


Figure 38. Size comparison of a standard reflector lamp and an integrated reflector lamp. A coating on one hemisphere of the burner reflects back the light normally emitted in this direction and allows for a dramatic size reduction.

handle light with an f -number $f = 1.0$, i.e. the light cone from the reflector is used inside a 30° half-opening angle.

Another design criterion for elliptical reflectors is the total length of the optical path. For compact projectors, where a major contribution is the distance between the first and the second focus $d_{f_1f_2}$ (see figure 37), this length should be minimized.

And finally, it should be ensured, that the burner is not unnecessarily heated by light that hits the front end of the burner. Both, light beams coming directly from the reflector and beams that are reflected back from filters or optics placed in the beam path, contribute to a heating of this already critical region of the burner (purple rays in figure 37).

4.5. Integrated reflector approach

Even smaller reflector sizes are made possible by an integrated reflector concept. By applying a dichroic coating on one hemisphere of a UHP burner (figure 38) the visible part of the spectrum is reflected while the major parts of UV and IR are transmitted. Because the outer shape of the UHP burner is a perfect sphere the light is reflected back through the arc towards the uncoated side of the burner. Light emission is therefore confined to one hemisphere and only these rays have to be collected by the reflector. The concept using this integrated backmirror (acronym ‘BAMI’ for ‘backmirror’) has been successfully introduced by Philips [22].

This design offers an additional advantage: the apparent brightness of the arc is increased, leading to better light collection for systems with high optical demands. By passing the light a second time through the source the collection efficiency is increased by 20–30%.

It is not an easy task to develop an integrated BAMI system as described before. The conditions on the UHP burner surface

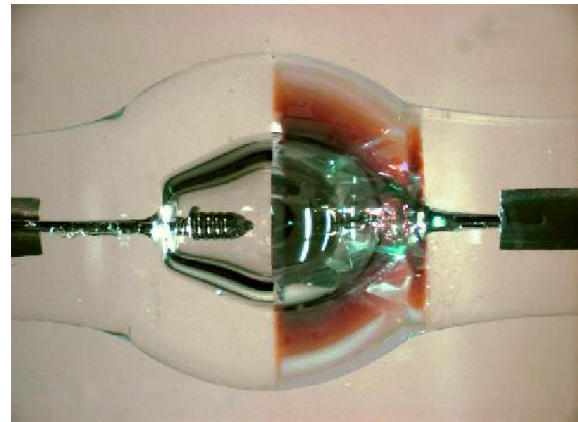


Figure 39. Photo of a UHP burner with a dichroic mirror coating on the right side.



Figure 40. Photo of the BAMI lamp. The back reflection principle allows for a reflector as small as $33 \times 33 \text{ mm}^2$. The antenna spiral for the low voltage ignition can be seen.

are quite extreme: temperatures reach up to 1000°C ; frequent lamp switching causes fast temperature cycles.

To reduce the reflection of IR and UV back to the critical burner interior the coating should be of the dichroic type, only reflecting the visible wavelengths. Furthermore, the thermal emission properties of a dichroic coating are similar to quartz, thus leaving the temperature balance of the burner more or less intact.

The special dichroic coating successfully developed by Philips (see figure 39) survives the extreme thermal conditions on the UHP burner without damage for thousands of hours. The first products described below have a guaranteed life of 2000 h.

With the integrated retro-reflector many advantages for the optical system of the projector can be gained. With the light output from the UHP lamp restricted to only one hemisphere, the reflector does not have to extend much beyond its focal point (see figures 38 and 40). Compared with a large reflector, in the case of the coated burners, both the aperture area of the reflector and the collection angle are smaller (see figure 16). The optical diameter that can be achieved with the BAMI concept may be as small as 30 mm.

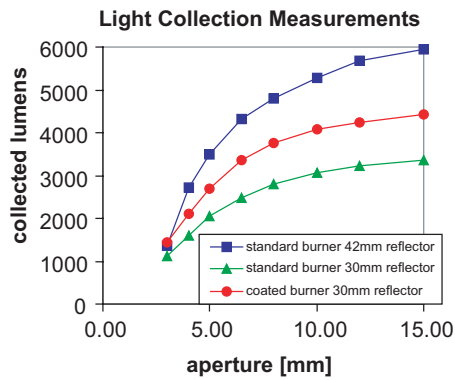


Figure 41. Measured collected light through an aperture for different reflector sizes.

A direct calculation of optical efficiency for different reflector sizes and for the BAMI concept would require a strict treatment within the etendue formalism [9], the etendue being defined in this case as the product of reflector aperture area and the collection solid angle. Optical efficiency can be measured in a simple way, however, with a set-up like in figure 16 by using varying aperture sizes. The results of these measurements for three configurations can be seen in figure 41.

With the smaller reflector, a large amount of the standard burner's light is lost in the front direction without hitting the reflector (compare curves with squares and triangles). With the coated UHP burners it is possible for the first time to reduce these losses significantly (compare curve with diamonds versus triangles) and to realize extremely compact reflectors with high optical efficiency. The coated burner offers more than 30% better collection in this 30 mm reflector.

Taking into account the angle under which light is collected, i.e. the etendue, the advantage of a coated burner becomes even clearer. The 30 mm sized reflectors used in the set-up are trimmed 42 mm elliptical Philips reflectors with half axes $a = 22.15$ mm and $b = 35$ mm. The 42 mm reflectors focus the light inside an angle of 30° , the 30 mm reflectors inside 15.8° .

The results of the aforementioned measurements taking into account the system etendue are shown in figure 42. The comparison of coated with uncoated burners in the 30 mm reflectors has already been discussed in the context of figure 41 (curves with diamonds and triangles). The comparison between the coated burner in a 30 mm reflector and the standard burner in the 42 mm reflector shows that for optical systems with high optical demands (etendue < 25) more light can be collected by the retro-reflection principle (curves with diamonds and squares). For larger etendue the quality of the light becomes less important than the quantity and the coated burner suffers from losses owing to the second passing of light through the arc.

For common projection systems with etendue of 5–15 $\text{mm}^2 \text{ster}$, the performance improvement has been measured to be 20–30%. At the same time the reflector size can be reduced and this can help to reduce the overall projector size.

Besides the optical advantages of the retro-reflection design in terms of miniaturization and better light collection discussed until now, there are also spectral improvements to be reached by focusing the light back through the arc. The

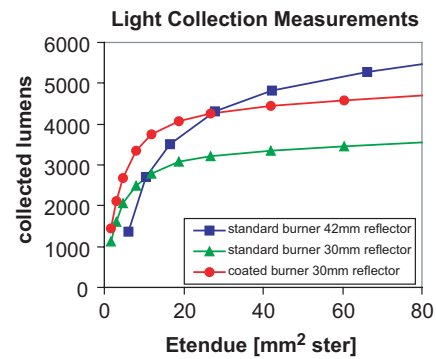


Figure 42. Measured collected lumens versus etendue. The measured data are the same as in figure 41, only the aperture size has been transformed into the corresponding etendue.

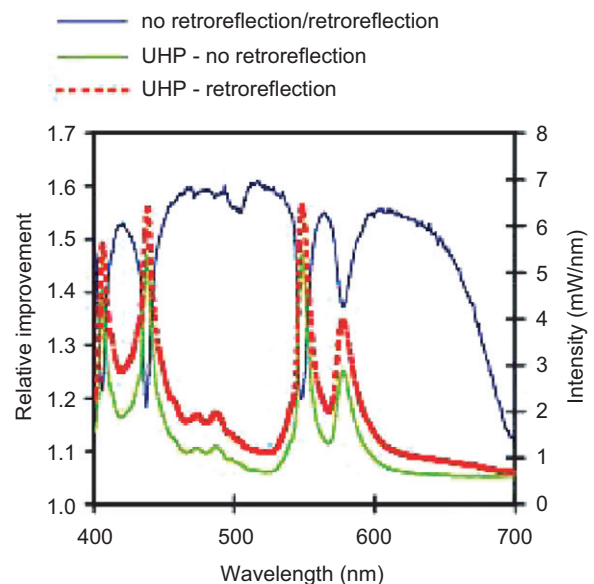


Figure 43. Measured spectra with (red dotted line) and without the retro-reflected arc (green line). Please note that these are not integral spectra. The drop towards long wavelengths is a property of the separate mirror used for this measurement. The blue line indicates the ratio of spectral intensity with and without retro-reflection (left axis).

plasma is still transparent at the radiation wavelengths outside the spectral lines. In the vicinity of strong atomic transitions, however, the radiation is reabsorbed by the plasma. The absorbed energy serves as an additional heating mechanism for the plasma and the energy is redistributed over the full wavelength range. Especially in the situation of a high-pressure discharge like the UHP lamp, the intense spectral lines at 404, 435 and 546 nm and in the UV region exhibit a strong absorption.

With a set-up using a UHP burner (without its standard reflector) and a separate spherical mirror, where the burner is positioned exactly in the centre point of the spherical reflector, it is possible to adjust the reflected light such that it is superposed to the original arc. The spectra of the UHP lamp with and without this retro-reflection are shown in figure 43. The green curve shows the spectrum from the burner without the additional retro-reflection, whereas the red curve is obtained by using the spherical mirror. The intensity in

the continuous parts of the spectrum is about 60% higher now (blue line) because of the additional light back-reflected by the spherical mirror through the burner walls and the arc. One can see from the ratio of the two spectra (blue curve) that a huge part of the retro-reflected light is absorbed in the atomic lines, whereas it adds to the continuum part of the spectrum. The combination of line and continuum transmissions accounts for an observed 70% transparency.

Note that a relatively strong continuum contribution especially in the red is highly desirable for projection applications because it allows for an increase in colour efficiency. Therefore, using the coated UHP lamps described here increases the system efficiency including colour balancing further.

5. Conclusions

The development of the UHP lamp was a unique catalyst for the breathtaking growth of the projector market during the last decade. Its outstanding brightness, well suited spectrum, long life and excellent lumen maintenance enabled the development of high-quality projection systems. The impressive increase of projector light output, the remarkable reduction of projector size and the higher efficiencies of projection systems during the last years have been made possible by important new technology developments of burner, ignition system, electronic driver and reflector implemented in the advanced UHP lamp systems.

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