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From light to color:
how design choices make the difference

Why this white paper?

Selecting the right high-brightness projector is becoming increasingly complex for our customers. The emergence of laser light sources and the availability of multiple imager technologies (3-chip DLP™, 1-chip DLP™, LCD, LCoS) for high-brightness projection have significantly increased the number of options customers can choose from.

From a manufacturer's point of view, laser-illumination gives a range of new possibilities in the development of better projectors, but the right design choices need to be made.

The differences between these options, however, are substantial in terms of image quality, efficiency, reliability and many other dimensions. This whitepaper clarifies these differences and answers the questions our customers ask:

- Does laser light reproduce and display better colors and images than Xenon or UHP™ lamps?
- Does DLP™ technology remain the best solution for high-brightness applications?
- Do 1-chip DLP™ projectors match the state-of-the-art image quality of 3-chip DLP™ projectors?

What makes a great image?

Regardless of the application – watching movies, delivering a corporate presentation, enjoying a dark ride, using a simulator – viewers want to be "wowed" by the high-quality image on their screens. A high-quality projected image depends on 5 parameters.

Content resolution: higher resolutions convey more details embedded in the image and higher perceivable quality. 4K screen resolutions have become the standard and hence projection technology should be able to display 4K images. *Read more about our 4K UHD solution on our website.*

Colors: The performance of an optical projection system should to a high extend be judged by the colors it reproduces. High-quality colors ensure the projected image matches the native, intended image, and makes it come alive. Reproducing colors is an art, and too often entire illumination types or imager technologies are unfairly criticized or praised for its colors. *In this whitepaper, we will explain what drives great colors, using various light sources and imaging technologies.*

Brightness / Contrast: the more ambient light, the more brightness you need to create and project a high-contrast image. Especially with laser, brightness can be increased at the expense of color quality. *More on that in section 4.*

Internal image processing: in many high performance applications, images get scaled, warped and blended before they hit the screen. No image artefacts should be added during processing to preserve native image quality. *Read more about our "Pulse" electronics on our website www.barco.com.*

Lenses and screens: The lens, screen, mirrors, windows, ambient lighting and reflections can determine whether your image details can be displayed at their optimum level. For example, a grainy, perforated or colored screen is not the best material to show high resolution details. *This is out of the scope of this whitepaper.*

All 5 parameters need to be top notch in order to display the highest quality images possible. In this whitepaper we will mainly focus on color and the link with brightness.

What are great colors and how are colors represented?

Key messages:

- The purer your red, green and blue the bigger your color gamut and the more colors the projector can reproduce accurately.
- Perceived color saturation is more important than theoretical color-to-white ratios or color brightness levels. The eye captures the image, but it's our brain that 'sees' it.

Colors can be seen by living beings and every species has its own way of seeing colors, depending on the structure of their eyes. Humans can see millions of colors when colored light is focused onto the retina of the eye. That light is exciting sensors on the retina: the rods and the cones. Have you ever wondered why you can only see in black and white when the environment becomes dark? The rods only detect light and dark, **the cones detect color.** The rods are more sensitive than the cones, so you start losing colors when it becomes dark.

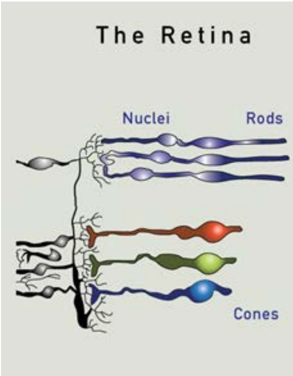


Figure 1 The human eye has cones and rods[1]

[1] Picture courtesy of University of Virginia, source: http://faculty.virginia.edu/ASTR3130/lectures/humaneye/humaneye.html

There are three different types of cones to see color and every type detects a different color: red, green or blue. To see color differences, you need to excite the three different types of cones and they all have a different spectral sensitivity. See the graph in figure 2.

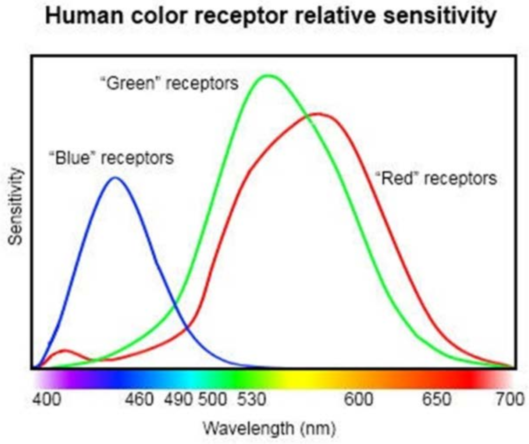


Figure 2 Color sensitivity graph[2]

A projector needs to provide a red, green and blue image to our eyes and with these three "primary" colors, the viewer can see all the colors possible to be represented by these RGB Primaries. The spectrum (spectral power density) of each color, and the absolute intensities of the different colored images will determine the color the eyes will see.

To represent all the colors a human eye can see, the Commission International de l'Eclairage (CIE) created in 1931 the CIE 1931 color space. As not all humans see the same colors in the same way, this standard has been made for the standard, or "average" viewer, so it is based on statistical measurements of multiple viewers' responses. There are more color spaces defined and all have their specific benefits, but as most people know the CIE 1931 color space, we will use this one.

[2] Picture courtesy of Obsessive Coffee Disorder: http://obsessive-coffee-disorder.com/human-visual-system/

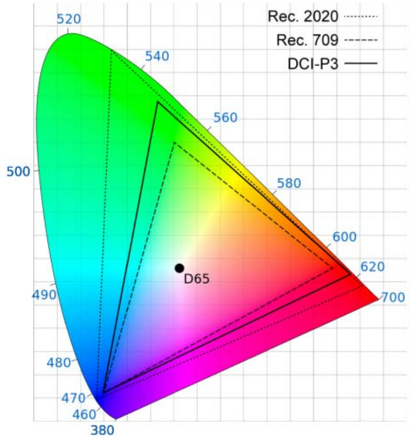


Figure 3 CIE 1931 2° Chromaticity Diagram[3]

This chromaticity diagram shows all colors a human can see. On the outer edge, the dominant (spectral) wavelengths are displayed, called the hue. The more you go toward the center, the less pure a color is; it's becoming less **saturated**. In the center, you have a white color, which is then the combination of all other colors. As an example, the D65 white light represents the average midday light in Western Europe / Northern Europe. The Rec. 709 or ITU-R BT.709 is the standard format for High Definition Television color primaries and is widely adopted in the industry.

Projectors need three primaries to display a variety of colors. When these three primaries are mapped onto the chromaticity diagram, all colors within the resulting triangle can be displayed. Outside the triangle the colors can't be represented by the projector. That triangle that describes what colors can be displayed by the projector is called the **color gamut of the projector**.

Figure 4 Hue and saturation of colors[4]

[3] Picture courtesy of AV Forums, source: https://www.avforums.com/article/what-is-wide-colour-gamut-wcg.12811
[4] Picture courtesy of De Montfort University, source: https://wiki.our.dmu.ac.uk/w/index.php/Colour_theory

The CIE 1931 diagram represents only the color gamut, not the brightness the projector is capable of for each color. When a projector displays a white image, this is a combination of a red, green and blue image. The brightness of white is higher than that of a separate color, but this information can't be found on the chromaticity diagram.

Therefore, we need separate parameters like **brightness** and **color-to-white ratio** to indicate how bright an image is. To know the brightness of a projector, you need to measure the intensity of the white image. The color-to-white ratio is then the percentage of red, green and blue in that white image.

We talked about the receptors in the human eye, how colors are represented on the chromaticity diagram and how brightness can be measured. However, the measurements and mathematical representation is one thing, the eye plays an important role in seeing colors, but it is our brain that 'sees' the image, and therefore **perceived color saturation** is more important for color quality than measured color saturation.

The brain can influence the way we see images. Look at the below optical illusions.

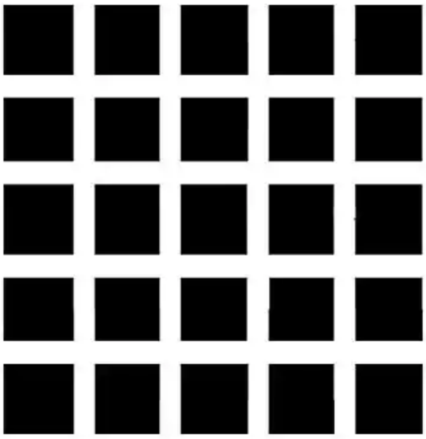


Figure 5 White lines or grey spots?
(Herman Grid illusion)[5]

[5] Picture courtesy of The Telegraph, source: http://www.telegraph.co.uk/news/newstopics/howaboutthat/3520448/Optical-Illusions-the-top-20.html?image=8

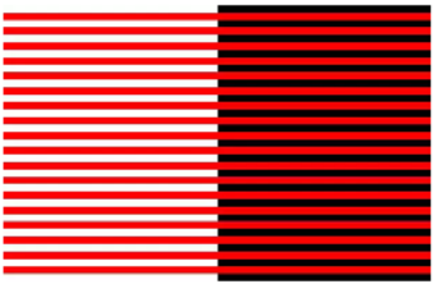


Figure 6 Red appears brighter when the background is dark (Bezold effect)[6]

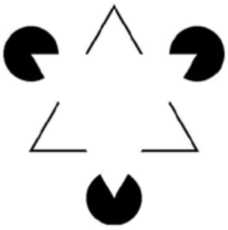


Figure 7 Kanizsa triangle: The white triangle is not drawn and it even looks brighter than the background[7]

When seeing colors, there is a well-documented effect, called the Helmholtz-Kohlrausch effect*, that tells us that a **more saturated color** is perceived as brighter. In Fig 8, all colors have the same luminance, but the more saturated colors are perceived as brighter.

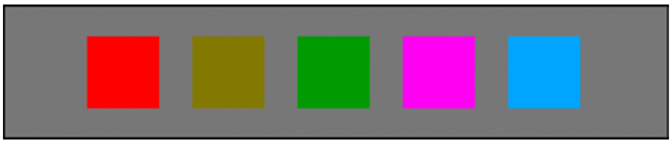


Figure 8 All colors have the same luminance, but some are perceived as brighter[8]

In conclusion, we can say that when looking at a projected image, not only are the measurable color gamut and each color's brightness important, but the perceived saturation of color is perhaps the most important driver of color quality. At Barco, we master the art of balancing colors and brightness in our projectors to optimally display the native image: crisp, colorful and bright.

[6] Picture courtesy of The Telegraph, source: http://www.telegraph.co.uk/news/newstopics/howaboutthat/3520448/Optical-Illusions-the-top-20.html?image=8
[7] Picture courtesy of The Telegraph, source: http://www.telegraph.co.uk/news/newstopics/howaboutthat/3520448/Optical-Illusions-the-top-20.html?image=8
[8] Picture courtesy of Wikipedia, source: https://en.wikipedia.org/wiki/Helmholtz%E2%80%93Kohlrausch_effect

Lamps vs laser: different illumination technologies

Key messages:

- A large color gamut is possible with all light sources, but not all are equally efficient in delivering great colors. Brightness needs to be sacrificed in some technologies.
- Xenon illumination has been the standard in the past for delivering great colors in high brightness applications. Now Laser Phosphor technology allows to match Xenon color performance at high.

Explaining the different illumination technologies

Different illumination technologies will by design result in different color performance, as the color spectrum and efficiency of the light source varies. However, also within the same technology, different design choices made by manufacturers will influence the color performance of the projectors. We will look into 4 different illumination technologies and how they represent colors:

- *UHP™ type of lamps*: Small arc high pressure lamp with multiple gasses inside the bulb
- *Xenon lamps*: larger arc lamps with Xenon as the only filling gas
- *Laser phosphor technology*: only blue lasers are used. Red and Green colors are made by laser pumping a phosphor wheel
- *RGB laser technology*: Distinct Red, Green and Blue lasers

We will show that we can theoretically get a wide color gamut with any of the available technologies. The fact that different projectors have different color gamuts is because manufacturers make different design choices.

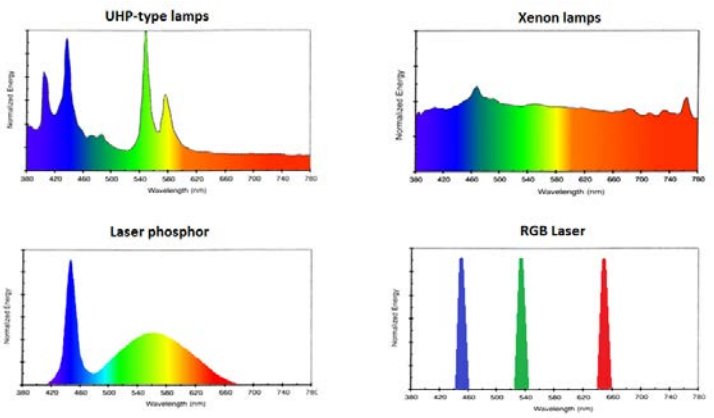


Figure 9 The spectra of the different illumination technologies

The produced spectra of the different technologies, as you can see in figure 9, look very different:

UHP-type lamps: The peaks in the UHP-type spectrum come from the mixture of different gas components in the light bulb and the buildup of the high pressure inside the bulb during the actual use. It doesn't contain much red, so the color point of the native white tends to be bluish. Due to the peaks, a small variation of the peak over time can have a big influence on the color of the projected image.

Xenon type lamps: The spectrum is more flat as Xenon is the only gas inside the bulb and this is the pure Xenon emission spectrum. There is much more red in the spectrum so the native white point is more red, a 'warmer' color point and as there are no peaks in the spectrum, the variations in color over time are not so big.

Laser + phosphor: The Blue laser in a laser phosphor projector has a relatively narrow emission peak in the blue. The rest of the spectrum is coming from the emission from the Blue laser-pumped or "excited" phosphor. The broadband emission of the phosphor contains green, yellow and red wavelengths. With appropriate filtering, a variety of color gamuts and whitepoints are possible. The resulting white color point can be more bluish or reddish. The laser wavelength is stable over time and the rest of the spectrum has no peaks, so color stability over time is assured.

RGB laser: The RGB light source has three or more peaks, depending on the number of wavelengths used in the light source. There could be multiple lasers with a slightly different wavelength for each color. The laser wavelengths are pure and are stable over time.

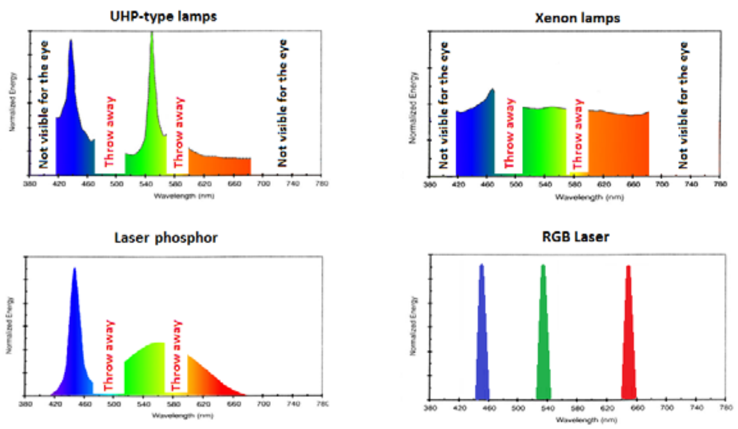


Figure 10 Optimized spectra filtering

As mentioned earlier, the projector requires to filter red, green and blue from the light source in order to reproduce any color in an image, and the purer red, green and blue the wider the color gamut will become (see section 3). There are two types of light that need to be filtered out:

- The non-visual UV and IR light to avoid damage of organic materials and overheating
- The mixed colors that can't be used in any primary color to achieve purer red, green and blue

The rods and cones from human eyes are sensitive to wavelengths from about 400nm to about 700nm. This wavelength band is called the visual spectrum. Ultra Violet light (UV), with wavelengths lower than 400nm and Infrared light (IR), with wavelength higher than 700nm can't be seen with the naked eye. Lamps however produce a lot of UV and IR light. Think about how hot an incandescent lamp is in your home. As UV and IR light can damage organic materials and end up as waste heat that must be removed from the projector and its chips, optics and sensitive electronics, they are filtered from the visual spectrum. Lamps also produce a lot of unused wavelengths (colors) that consume power and thus require extra cooling which also requires additional power.

Next to the light that the eye doesn't see, there is also a part of the spectrum that needs to be filtered out because it's a mixed color that can't be used in any primary color. For instance, the large yellow peak in the UHP-type of lamps needs to be removed. If you put it together with the red primary, the red becomes orange and if you put it in the green primary, the green becomes too yellow. For the same reason the cyan part between blue and green needs to be filtered out.

Manufacturers design choices

In theory, you can reach a very wide color gamut with any light source, as long as you throw away enough light to end up with only a narrow spectrum for red, green and blue. In this way it would act like an RGB spectrum. This is theory however, because at some point the brightness becomes unreasonably low for that light source.

As explained above, a lot of the light generated needs to be filtered out for different reasons. Filtering away light is something projector manufacturers want to avoid, because you pay on 3 fronts:

- It reduces the overall brightness of the projector
- The power consumption of the light source compared to the brightness is higher (watt/lumen), making the total cost of ownership less attractive for the customer
- The unused light increases the absorbed energy in the projector and hence increases the need for extra cooling, which further increases the cost and power consumption of the projector

Manufacturers need to make a trade-off between representing great colors – by throwing away light to achieve pure red, green and blue – and maximizing brightness. It's tempting for manufacturers to maximize brightness as it is the primary specification a projector is evaluated on, having a direct influence on the willingness-to-pay. Barco, global leader in large venue projection technology, finds it essential not to compromise on colors, and designs its projectors to deliver both exceptionally good saturated colors *and* a high brightness at the same time. This is what BarcoColor™ stands for.

RGB laser light sources are the exceptional choice where this trade-off is not necessary - all light, generated from pure R G B wavelengths, can be used, hence maximizing brightness. It comes, however, at a higher cost and larger projector size, which makes it today not viable for every market application.

Implications for the Strategy of Barco

Xenon illumination has been the standard for high brightness and great colors in large venue projection. Now, with laser phosphor illumination Barco is able to meet the color performance of Xenon– by making the right design choices as explained above – while bringing several benefits of solid state illumination:

- Longer lifetime and constant brightness over time
- Higher optical efficiency, as a lower share of the output spectrum is wasted as heat
- Flexible setup orientation
- No image flicker or sudden lamp failures (inherent redundancy)

Laser phosphor brings the benefits of solid state illumination in a cost-effective and compact way, required for the live events and large venue market applications. However, in other markets the customer requirements are different, and hence no single SSI technology is optimal. For instance, in Cinema, where the size of the projectors is significantly larger, Barco uses both the highest brightness RGB laser light sources and the most economical laser phosphor light sources.

Comparing different imager technologies

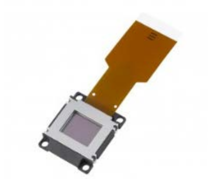
Key messages:
- All available imagers have their application-based strenghts and weaknesses.
- DLP™ technology is by design best suited for high-brightness applications.
- 1-chip DLP™ technology can match 3-chip DLP™ color quantity in a more cost effective way, when the right design choices are made

Different imager technologies

Three main imager technologies are currently dominating the projection market: DLP™ (Digital Light Processing), LCD (Liquid Crystal Display) and LCoS (Liquid Crystal on Silicon).

The DLP™ device is a reflective technology where every pixel is a mirror that reflects the light to the screen or into a "light dump" inside the projector. The mirror is very durable against high power densities and is therefore selected for the high brightness applications. Also the high switching speed of the mirrors allows to have high frequencies (e.g. 120 Hz) required for 3D applications. The markets where high brightness is needed and where the lifetime of the projector is crucial, this technology is omnipresent.

LCD technology uses organic liquid crystal materials and polarized input light to turn a pixel on or off. The light passes through the panel and is either blocked by a polarizer to create a black pixel or let through. This technology is less expensive and especially appropriate for lower brightness consumer markets.



LCoS technology is also using liquid crystal and polarized light to turn a pixel on or off, but the light is reflected off a metal backplane surface and this has the advantage that the pixels can be put closer together, creating a higher resolution. The fact that light enters and exits the device at the same side of the device can increase contrast. The high resolution and high contrast, yet with some brightness limitation (see 5.2), makes this technology ideal for Home Cinema applications.

Why Barco chooses DLP™ for high brightness applications

Barco chooses for DLP™ as the preferred technology for stable high-quality performance in high brightness applications.

In the projector industry, there is a long term trend toward brighter products. This was possible due to the incremental improvement steps in the lamp manufacturing industry but only to a point. With the rapid shift to laser illumination systems, it is now possible to take a big step up in brightness because the high spatial brightness of laser light sources enables much more light to pass through the optics and chips of a given size.

However, as the brightness increases, that is, the optical power, for the same panel size, the *thermal load becomes higher*. Cooling the imagers becomes the limiting factor and not all imager technologies provide the same thermal management options.

The DLP™ can withstand higher temperatures by design. DLP™ panels use mirrors, so the majority of the light is reflected and not absorbed. The reachable back side of the DLP™ panel can also be liquid cooled, further enhancing stability and lifetime.

LCD panels are transmissive, so all light needs to pass through the panel, and as a consequence can't be liquid cooled easily. The electronics to control each pixel are located in between the pixels and need to be protected against light with a black mask, or they will leak. This mask can be seen on the screen as large black gaps between the pixels (screen-door effect). A lot of light is absorbed as heat by the black mask and in the liquid crystal. The liquid crystal itself is organic, so the temperature must be kept low, or the material will degrade. In conclusion, it

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makes it much more difficult to keep the LCD in good shape over time:

- the temperature of the LCD's should be kept lower than the DLP™'s
- at the same time the absorption is higher in LCD's
- and it can't be cooled as efficient as DLP™'s

LCoS panels are also a reflective technology and the backside is accessible for liquid cooling. However, the liquid crystal material inside is organic and this puts a limitation to the heat load, especially over long periods of high illumination.

LCD and LCoS technology uses liquid crystal as the basic material. This is an organic material with large molecules that all need to rotate when an electrical field is applied to put the pixel on or off. The voltage to drive the pixels is analog and the slightest change in thickness of the liquid crystal layer causes a non-uniformity in color. Also the organic material that heats up will deteriorate over time, again adding to the non-uniformity. DLP™ uses metallic mirrors and a digital driving voltage, keeping the uniformity stable over time.

In LCD and LCoS technology, the large liquid crystal molecules need to rotate to put pixels on or off, limiting the switching time due to the reaction time and the physical movement of the molecules. This limited switching speed makes it not possible to use these imagers in a 1-chip setup, which is possible with DLP™ technology.

In the LCD technology, the black mask around the pixels is also the reason that it becomes difficult to go to higher resolutions with this type of imager, as the protective black mask still needs to be there. In the LCoS technology, the black mask is not there as this is a reflective technology, but as the pixels are closer together, the applied voltage for one pixel is influencing the neighboring pixel (fringe-field effect). The result is a pixel with lower intensity than intended and thus a lower spatial resolution than expected.

In addition to the durability against heat, the DLP™ does not change over time in color uniformity, the information transmitted by one pixel doesn't influence the neighboring pixel and it's easy to seal against dust; all good reasons to choose for DLP™ as the preferred technology for stable performance in high brightness applications.

1-chip DLP™ technology

In the DLP™ technology, the switching speed of the mirrors is so high – as opposed to LCD and LCoS - it can produce a colored image with only one imager, by projecting the primary colors *sequentially*. The RGB images of 1-chip DLP™ projectors follow each other so quickly that our eyes integrate the

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sequential images and we see a full-colored image. The different colored images are generated using a color wheel, which is synchronized with the DLP™ device. This technique has the extra advantage that there can't be a misalignment of the R, G and B pixels on the screen and it reduces the cost of the projector, without reducing the lifetime and the stability over time.

In the past, 1-chip DLP™ products were put on the market with an oversized 'white' segment in the color wheel. This led to a bright projector, but with low color-to-white ratios and color saturation. The end results were pale colors and a bad reputation for 1-chip DLP™ products.

However, as explained, it's all about design choices. For many years, Barco's 1-chip DLP™ lamp-based projectors have been successfully used in the most demanding simulator programs, as the color wheels are optimized for this application (e.g. F35).

The new laser phosphor-based Barco 1-chip DLP™ products (F-series) have made the color advantage of 3-chip DLP™ products become negligible, as was confirmed by several blind tests with Barco customers.

Figure 11 Barco F90 projector (1-chip DLP) matching 3-chip DLP color performance

Summary

Brightness and color are essential parameters to evaluate the quality of a projected image. Brightness is required to overcome the ambient light and achieve a high-contrast image. Perceived color saturation is the most important driver for color performance, more important than color-to-white ratios based on brightness.

In theory, several illumination technologies can reproduce great colors, but not all technologies are equally efficient in doing so. While Xenon has been the standard for large venue projection, now with Laser Phosphor (LP) it is possible to meet the same color standards, while reaping the benefits of solid state illumination: long lifetime, flexible orientation, no image flicker or lamp failures. Yet the right design choices need to be made.

Barco chooses for DLP™ as the preferred technology for stable high-quality performance in high brightness applications. The laser phosphor illumination in combination with the 1-chip DLP™ can display colors comparable with 3-chip DLP™ products.

About the author

Koen Van Belle is responsible for business projectors and is a member of the product management team of Barco's Entertainment division. In 2000, he started his Barco career as an Optical Engineer and developed the optics for various projectors in the fixed install market. He became R&D Manager in 2007 and managed global projects for different simulation products. Koen joined the product management team of the projection division in 2013. He holds a master's degree in science from the Vrije Universiteit Brussel (VUB) and is based in Belgium.

In case of questions or feedback on this paper, you can contact Koen via koen.vanbelle@barco.com.

Definitions and references

DLP™ = Digital Light Processing
LCD = Liquid Crystal Display
LCoS = Liquid Crystal on Silicon
UHP = Ultra High Performance

DCI colors = Color gamut according to the Digital Cinema Initiative, the organization that determined the specifications for the Digital Cinema market, see: http://www.dcimovies.com/specification/index.html

Rec. 2020 colors = Future target for the color gamut. See: https://en.wikipedia.org/wiki/Rec._2020

* Helmholtz-Kohlrausch effect:
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