

Response of very fast decay phosphors in image intensifier tubes for CCD readout devices

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ABSTRACT

High repetition rate intensified cameras having interframe times in the μs range are needed for flow analysis measurements such as Particle Imaging Velocimetry (PIV) or Molecular Tagging Velocimetry (MTV). For these applications, the lower efficiency, fast decay P46 and P47 phosphors must then be used instead of the higher efficiency P20 and P43 phosphors. Previous literature provides only the time-resolved phosphor response. For very short interframe time imaging applications, a significant fraction of the previous frame's intensity can appear as a "ghost image" in the trailing frame. Fast phosphors minimize this energy transfer into a second frame. Previous data show a dependence of decay time on exposure time for the P46. The P47 has been reported to decay a factor of 3 to 30 faster than the P46. The transferred total intensity as a function of the shutter repetition rate is measured for these two fast phosphors. They are compared with data published in previous papers. Neither phosphor under investigation behaves fully in accordance with these prior characterizations.

Keywords: image intensifier, phosphor decay, flow analysis, P46 phosphor, P47 phosphor

1. INTRODUCTION

Intensified CCD cameras are now featuring more flexible timing modes with numerous new uses arising. One feature of special interest is the ability to provide high repetition rate (i.e. $> 50/60$ Hz) double exposures. This is particularly true for applications like Particle Imaging Velocimetry (PIV), Molecular Tagging Velocimetry (MTV), and Fluorescence Analysis. In liquid flow applications repetition rates up to the 1 kHz [1ms] regime are sufficient. Gaseous and plasma flows often reach supersonic conditions. They require repetition rates even down to the submicrosecond time scale. For such methods the time behavior of the image intensifier's output phosphor is of critical importance. Lack of reliable data on the time behavior triggered the work described in this paper.

Presently, there are mainly two classes of phosphors in use. The first class is represented by the somewhat higher efficiency P20 and P43 phosphors, which have the disadvantage of a long decay time. The P46 and P47 phosphors are widely-used members of the second class, that is the "fast" or "very fast" phosphors. This class of phosphors lacks a factor of 2 to 3 in output brightness for the same level of electronic excitation. Response of the slow phosphors was reported on in an earlier paper¹. This paper deals with the experimental setup and the results for the fast phosphors.

2. EXPERIMENTAL SETUP

All measurements were performed with our 4 Quik E camera and real time video spectroscopy package 4 Spec. The camera is a system that has all timing and power supply units for control of the intensifier included. The internal lens coupling of the intensifier to the CCD allows for a fast exchange of the intensifiers, keeping all other components identical. The camera's internal timing generator is flexible enough to perform all measurements without the need of an external timing control unit. The P46 data were obtained with two intensifiers from Proxitronic. For the P47 measurements only one intensifier from Proxitronic was tested. A yellow super bright LED provided constant illumination. It was focused directly onto the camera's photocathode for a spot size of one-half the diameter of the intensifier. With this setup very short photocathode gate times could be used, thus having a quasi-instantaneous excitation of the phosphor under investigation. This setup has the advantage of replicating a very typical application case of such cameras. A schematic diagram of the experimental setup is shown in Figure 1.

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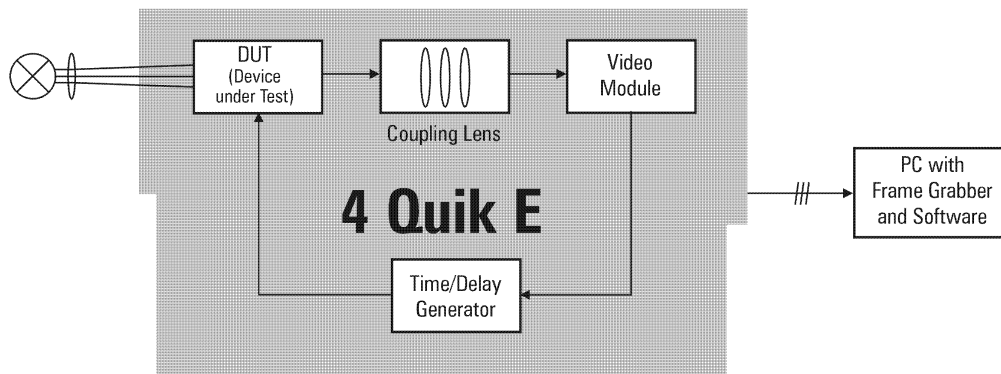


Figure 1: Experimental Setup

For readout of the phosphor intensity, a video unit with an interline transfer CCD chip is integrated. This type of CCD architecture uses optically sensitive columns to accumulate electrons induced by light during an integration period that is determined by the time in between consecutive readout pulses. In less than 100 ns this resulting charge is shifted from the open integration section to the opaque readout transfer registers. To determine the total brightness of unwanted ghost images the camera's exposure and frame grabber's digitizing were synchronized in such way that an increasing time was inserted in between turn-on of the photocathode and the chip readout.

The camera is set up and programmed to operate fully synchronous with the video cycle. The gate timing is thus firmly integrated into the video timing sequence. The internal time/delay generator is programmed for a delay/exposure sequence that results in an 80 ms time in between two consecutive phosphor excitations. After this time there is no residual intensity left from the previous event. This shorter interval as compared to measurements with the slow phosphors¹ was chosen for increased timing accuracy. The frame grabber is triggered for the 1st or 4th field of the sequence, thus digitizing only the field images transferred with the 1st and 2nd readout pulse, or the 4th and 5th/1st respectively.

As long as the excitation pulse (EP) occurs fully after the 1st readout pulse (RP), all light is integrated during the 2nd field. With the EP taking place immediately before the 1st RP, we get only decayed intensity into the field that is transferred with the 1st RP.

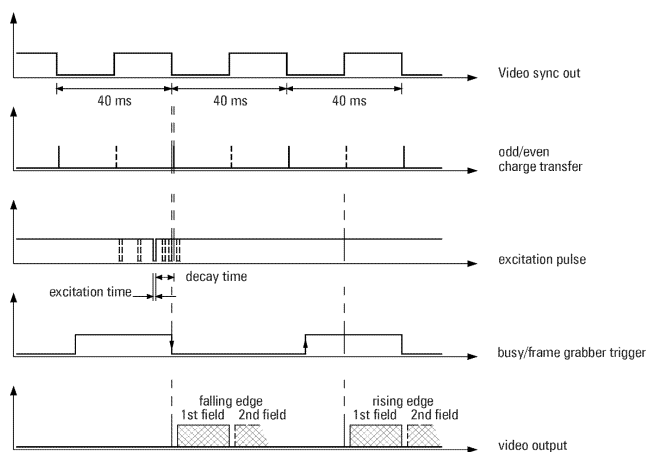


Figure 2: Timing diagram

Continuously shifting the excitation pulse to earlier times results in the integrated decay time behavior of the phosphor under test (DUT). This video signal is then digitized and is summed in real time into one exposure for 100 video frames. A spot of

10 lines in height by 50 pixels width is then binned into one relative intensity value for a given delay time. With this method one gets the sum of 50.000 single measurements for any single data point. This results in a S/N improvement of roughly a factor of 200.

In order to have a longer integration time available (40 ms) we used a CCIR video camera instead of the EIA with its 33.3 ms interframe time. The charge readout occurs every 20 ms, alternately on all odd and all even lines of the video image. This results in a total of 40 ms integration time for the subsequent odd and even fields. All light falling onto the chip during that 40 ms is integrated. In this way we measure the time-integrated intensity of the phosphor screen. It is the actual output of all such cameras and also the cause of the so-called “ghost images”. These ghost images are “missing” in the intensity of the digitized output of the “original image”. The output image’s intensity is lowered by the same amount if the integration time is too short. The literature of the intensifier’s manufacturers gives the output intensity as an instantaneous function of time. This results from the intensity being measured with a PIN diode or photomultiplier. This is much harder to interpret for a long decay time on low magnitude. It also has a higher noise due to the short integration time of these sensors. It finally results in seemingly too fast decay times.

3. DISCUSSION OF RESULTS

3.1. P46 Phosphor

The P46 phosphors under test were fairly consistent with the typically reported 90% - 10% decay times of around 100 to 300 ns. Their long time “faint decay” was identical for all exposure times and basically the same for the two samples under investigation. Figure 3 shows their behavior up to 10 ms after the beginning of the excitation pulse. Only for sample 2 the curve was shifted for 10 ns.

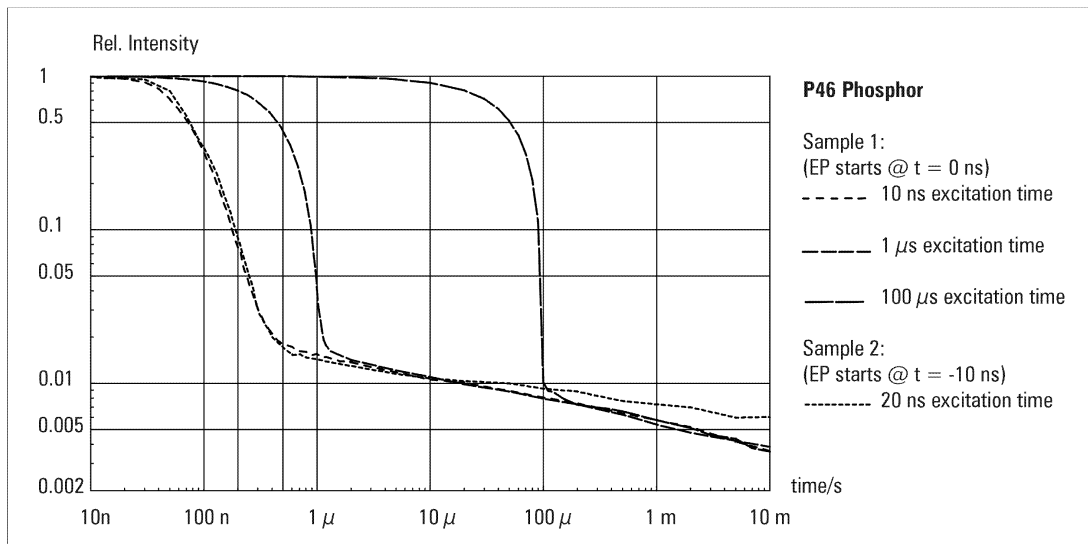


Figure 3: P46 Phosphor decay of two intensifiers after various excitation times

All 4 curves are normalized to the full intensity with the complete output signal integrated into one field. The 10 ns, 1 μs, and 100 μs excitation time decay curves all converge into one identical long time decay curve.

This may be unexpected at first but is simply caused by the fact that each output of a differentially short time has the same decay characteristics. As the output is normalized for identical total integrated intensity, the sum of the differentials leads into the same decay after the cessation of the excitation pulse.

In Figure 3 two distinct regimes of the decay time can be identified. There is a fast portion down to the 3% range within 200 ns, followed by a very slow tail. The fast part of the decay after a 10 ns excitation is not a straight line in this log-log plot because of its exponential behavior.

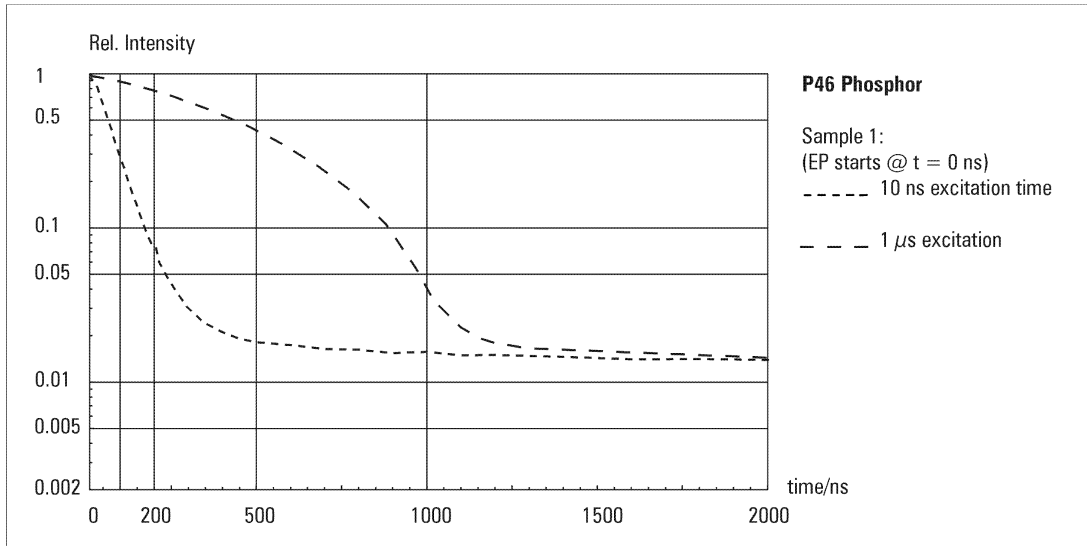


Figure 4: Fast exponential section of the P46 phosphor decay.

Figure 4 shows the exponential decay of the P46 phosphor for two different excitations times. From the 10 ns data, its characteristic time constant can be approximated to be 150 ns from the 10 ns data. The 1 μ s excitation curve can not be used to determine the decay time constant because during its 1 μ s active time intensity is continuously added, both from earlier differential excitation portions and the ongoing excitation which itself is only 1% of the 10 ns intensity. This also leads to a seemingly slower decay for longer excitation times if the data are normalized to one at the end of the excitation pulse. This likely explains the time dependencies observed elsewhere.

The slow time constant of the P46 phosphor shows a low intensity “long tail” decay, with a “power law” characteristic as reported earlier only for the P20 phosphor². This is indicated by the straight line in the log-log plot of Figure 3. It can be written in the form of:

$$B(t) = B_0(t/T)^{-n}$$

where $B(t)$ is the remaining brightness t seconds after cessation of the excitation; n has a value of ~ -0.15 and T is of the order of 6×10^{-19} s. The long decay time at very low intensity levels is a straight line for all excitation times.

Its flat progress makes it difficult to resolve exactly the 1% decay time. For both our samples, the 1% decay time falls in the 20 to 50 μ s range. This is roughly a factor of 2 faster than what Proxitronic reports⁴, and a factor of 10 to 100 slower than what the DEP^{3,5} data show.

We did not find any decay dependence on excitation time as has been reported by Flynt⁶ and as is also indicated in the DEP brochures⁵. On the contrary, our measurements show that the P46 decay time is totally independent of exposure time and signal amplitude. This feature allows numerical image correction from artifacts of the previous exposure.

The ghost image of the first exposure is at 10% if the second exposure is taken 190 ns after the first one. After 10 μ s the remaining ghost is only 1.04%. With this decay time information available, image correction mathematics can be performed and the ghost image be subtracted from the second exposure. Therefore even intra-exposure delay times of 200 ns and shorter can be used. If e.g. a second exposure is taken 300 ns after the first one, a ghost image of $\sim 2.8\%$ of the correct values of the first image would be visible in the second image. The intensities of the first one could be corrected to their true values which are a factor of 1.029 ($= 1/[1 - 0.028]$) higher than the digitized results. The ghost image which is a factor of 0.027 ($= 0.028/[1 - 0.028]$) times the first digitized image, can be subtracted from the second one. With such small values, this correction may not be necessary for many applications.

These calculations must be applied to every single pixel of the images. This functionality is already included into our 4Spec software package.

3.2. P47 Phosphor

The P47 is typically recommended as “the fastest” phosphor available in MCP intensifiers. It is specified with a 10% decay time of 100 ns from Proxitronic⁴. DEP⁵ specifies 60 to 120 ns, being a weak function of exposure time. The specified time for 1% remaining intensity is 2.9 μ s from Proxitronic⁴ and 400 ns in a publication of Bosch from DEP³, or exposure time dependent 100 ns to 3 μ s specified from DEP in their data sheet⁵.

For our tests we obtained a tube from Proxitronic with a blue phosphor that was nominally a P47 phosphor. The denomination of this tube is dubious because our experimental decay results deviate significantly from any given specifications.

We did not check any exposure time dependencies with this tube, firstly because we did not find any of the reported behavior even for the P46 and secondly, only DEP reports finding such effects, although weak, for the P47.

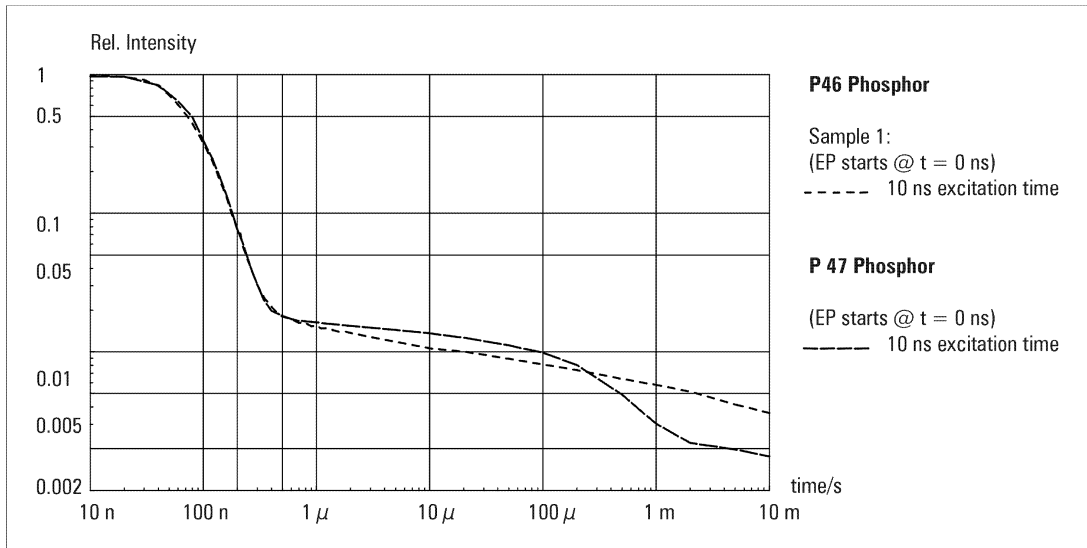


Figure 5: Decay of P47 and P46 phosphors with “long tail”.

In Figure 5 our results for the decay of this tube are shown. For comparison the decay of the P46 phosphor is shown in the same figure. There is no significant difference down to 2% during the first 500 ns. Then, at this low level, the P47 is slightly brighter than the P46 for the next 200 μs. Only thereafter the P47 decays faster than the P46. This may be explained by a series of exponential decays with different (at least 3) time constants.

The published speed advantage of the P47 over the P46 cannot be verified with the device that we had for testing. Nor does it lack the long decay tail that is usually associated only with the P46 phosphor.

3.3. Comparison of the two phosphor types under investigation

The electron to photon conversion efficiency of the (blue) P47 phosphor is specified⁴ with 212 photons per electron at 6kV acceleration, while efficiency is only 90 hv/e⁻ for the (green) P46. The higher brightness of the P47 phosphor is countered by the lower blue sensitivity of the CCD sensor. As a result the overall system’s response is the same when either a P46 or P47 phosphor is used. They are both roughly a factor of three less efficient than a system with a P43 phosphor at the same MCP gain voltage. The lower efficiency can be compensated for by a higher MCP voltage. It has not been investigated if this higher gain voltage leads to a significant increase in MCP gain noise. For typical low light applications the increase would be hidden by the input signal’s shot noise, in any case. This noise behavior explanation is supported by measurements done by Toedter⁷ et al. in a study of the performance of MCP cameras for spectroscopy applications.

The limiting spatial resolution was the same for all tubes that we analyzed.

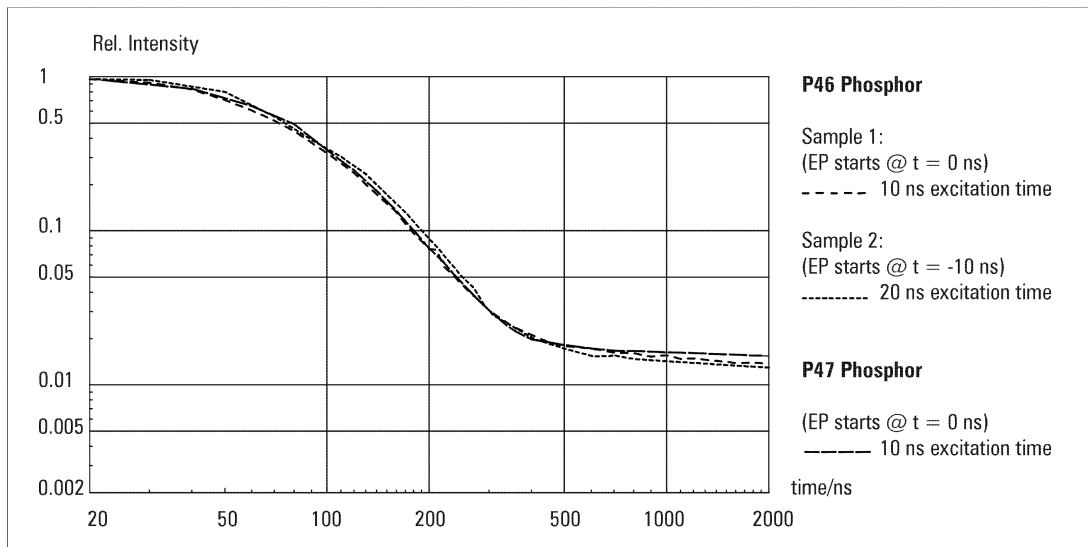


Figure 6: Fast decay section of three tubes under test

Figure 6 shows the fast decay section of the tubes that we tested. It can be seen that their decay is identical within the limits of the measurement accuracy during the first 2 microseconds.

There may be a suspicion that the identical decay of the two phosphors in Figure 6 is caused by a speed limitation of the measurement system. However, all previous data^{3,4,5,6} show a decay time that is exactly in the order of magnitude of our results. If there were a “real” difference between the two phosphors, it would show up as a variation in the convolution of the two decays with the time behavior of the sensor.

4. CONCLUSION

The P46 and P47 phosphors are both very fast decaying phosphor types. Appropriately normalized, their decay behavior is independent of both excitation time and intensity. Ghost images can be calculated from a set of double exposures. There appears to be no speed advantage for the P47 phosphor. With the better spectral matching in between the P46 phosphor and the typical CCD sensitivities, this phosphor type would be the material of choice. With the P43 being well-suited for double frame flow analysis experiments in liquid flows, the same can be claimed for the P46 phosphor tube when used with all kinds of very high speed gaseous flows.

5. REFERENCES

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