Technical Note

emICCD: The Ultimate in Scientific ICCD Technology

Single-Photon Detection Capability
and <500 psec Time Resolution

Introduction

With the rapid expansion of research in areas such as nanotechnology, quantum computing, and combustion, the development of higher-performance time-gated cameras is becoming a necessity. This technical note describes the latest breakthrough in scientific intensified CCD (ICCD) technology: the world's first **emICCD**.

Princeton Instruments' new **emICCD** technology combines the benefits of an intensifier and an electron-multiplying CCD (EMCCD) in order to deliver single-photon detection capability and <500 psec time resolution.* This innovative technology, available exclusively in the renowned Princeton Instruments PI-MAX®4 camera platform (see Figure 1), is ideal for a broad range of applications, including fluorescence lifetime imaging microscopy (FLIM), combustion, planar laser-induced fluorescence (PLIF), photon counting, and time-resolved imaging and spectroscopy.

Figure 1. *The new Princeton Instruments PI-MAX4:512EM is the first scientific camera on the market to utilize revolutionary* ***emICCD*** *technology.*

Current Technologies: ICCDs and EMCCDs

In ICCD cameras, ultra-low-light detection is achieved by high amplification of incoming photons by an intensifier (see Figure 2). Time resolution is possible due to the fact that the intensifier can be switched on and off (gated) in very short intervals.

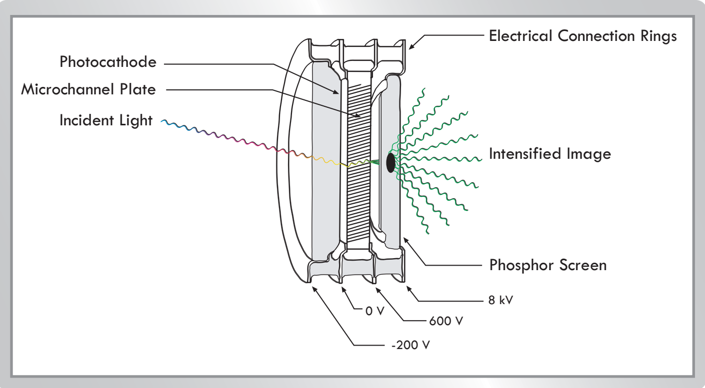

Figure 2. *Cross-section view of an image intensifier tube utilized in a Princeton Instruments ICCD camera.*

The intensifier consists of a photocathode, a microchannel plate (MCP), and a phosphor screen. A fraction (the quantum efficiency, or QE) of the photons incident on the photocathode is converted into electrons. Single photoelectrons are converted into clouds of electrons by the MCP, which acts as a distributed electron multiplier. The electrons released from the MCP then strike the fluorescent screen (phosphor) and cause it to emit far more photons than were incident on the photocathode.

In the traditional ICCD configuration, the voltage between the photocathode and the input of the MCP is used to switch the intensifier on and off. If the photocathode is electrically biased more positively than the MCP, electrons will not enter the MCP and the intensifier is gated off. If the photocathode is negatively biased, electrons will be accelerated toward the MCP and the intensifier is turned on.

Traditional EMCCD technology, meanwhile, does not use an external intensifier. An EMCCD enables multiplication of charge (i.e., electrons) collected in each pixel of the detector's active array. Secondary electrons are then generated via an impact-ionization process that is initiated and sustained when higher-than-typical clock voltages (up to 50 V) are applied to a special extended portion of the EMCCD's serial register (see Figure 3).

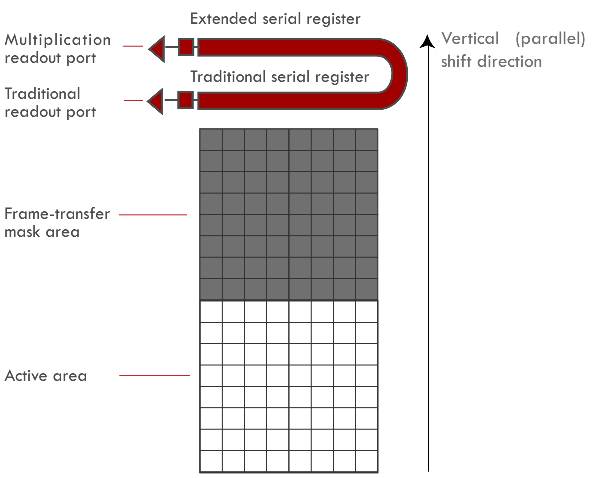

Figure 3. *Princeton Instruments cameras with EM gain utilize two output amplifiers: (1) an EM gain amplifier that enables the camera to be used for ultra-low-light, high-speed applications and (2) a standard amplifier for wide-dynamic-range applications. It is possible to adapt this technology to all current CCD architectures. This illustration depicts a frame-transfer device.*

The level of EM gain can be controlled by either increasing or decreasing the voltage; the gain is exponentially proportional to the voltage. Multiplying the signal above the read noise of the output amplifier enables ultra-low-light detection at high operation speeds. EM gain can exceed 1000x.

ICCD cameras and EMCCD cameras each have distinct performance advantages along with inherent limitations (see Table 1). Traditional intensified cameras, the workhorses of ultrashort, time-resolved applications, are limited by nonlinearity due to MCP saturation as well as by an inability to distinguish single photons. Alternatively, EMCCD cameras, which have become the main tools for ultra-low-light scientific applications, lack ultrashort (i.e., psec to µsec) gating capabilities.

	EMCCD	**ICCD**
Linearity	High	Medium to Low
Gating	No	Yes
Spurious Noise	Yes, but negligible	No
Minimum Exposure	Milliseconds	Subnanoseconds
Photon-Counting Capability	No	No
System Gain	Medium	Low

Table 1. *Performance comparison of traditional ICCD and EMCCD technologies.*

Breakthrough: *em*ICCD

For more than three decades, Princeton Instruments ICCD cameras have been the industry standard for time-resolved imaging and spectroscopy applications. The recently introduced PI-MAX4 camera series, for example, offers advanced capabilities* such as <500 psec gating and complete experiment control via Princeton Instruments' revolutionary LightField® software platform with an oscilloscope-like user interface.

Now, by combining ICCD and EMCCD technologies, Princeton Instruments has created unique ***em*ICCD** cameras that are free of the inherent limitations of the two constituent technologies (see Table 2). New ***em*ICCD** technology delivers the ultrashort, subnanosecond exposure times

	emICCD	EMCCD	ICCD	emICCD Notes
Linearity	High	High	Medium to Low	Optimized between two gains
Gating	Yes	No	Yes	
Spurious Noise	Yes, but lower than EMCCD	Yes, but negligible	No	Using lower EM gain
Minimum Exposure	Subnanoseconds	Milliseconds	Subnanoseconds	
Susceptibility to Bright Light	High	Low	High	
Photon-Counting Capability	Yes	No	No	
System Gain	High	Medium	Low	Two gains available

Table 2. *Performance comparison of* ***emICCD*** *technology, ICCD technology, and EMCCD technology.*

of ICCDs and the electron multiplication gain and high quantum efficiency of back-illuminated (optional) EMCCDs, allowing researchers in areas such as combustion, ultra-low-light chemiluminescence imaging, quantum optics, and time-resolved imaging and spectroscopy to design experiments hitherto not possible.

In an **emICCD** camera, either a back- or front-illuminated EMCCD is fiberoptically bonded to an intensifier with a Gen II (S20/S25) or Gen III (GaAs or GaAsP) photocathode for the highest light throughput. By intelligently utilizing both the intensifier (i.e., MCP) gain and the EMCCD gain, the detector provides a wider dynamic range than that of an intensifier alone. This wider dynamic range is very useful for quantitative measurements in comparing bright and dark scenes within a single image. The same camera can be operated at the highest system gain to detect single photons, overcoming the excess noise limitations of typical "gain" systems.

New **emICCD** cameras from Princeton Instruments also feature a built-in, fully calibrated, high-precision timing generator with 10 psec time resolution for external synchronization. These high-frame-rate (>30 fps) cameras can be operated via a Gigabit Ethernet (GigE) data interface.

It should be noted that there are ICCD cameras on the market that couple an intensifier to an EMCCD with a lens, as opposed to a fiberoptic bundle. Lens coupling, however, offers lower light throughput and suffers from increased stray light. Coupling via fiberoptics (see Figure 4) delivers 6x higher light throughput between the image intensifier and the detector than lens-coupled configurations. Fiberoptic bonding also provides a much better signal-to-noise ratio (SNR) than lens-coupled devices.

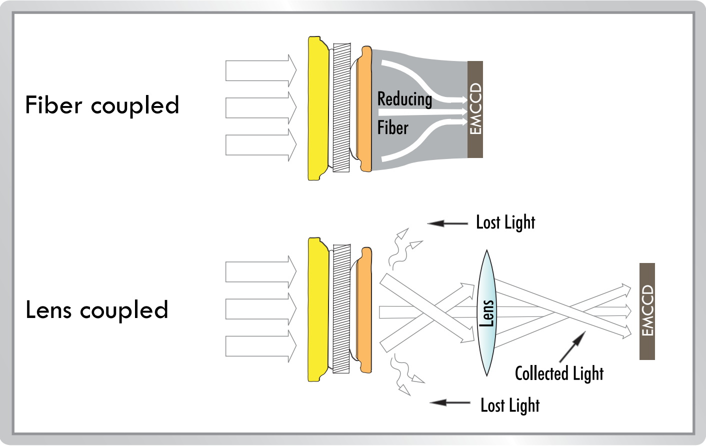

Figure 4. *The PI-MAX4:512EM utilizes fiberoptic coupling, which offers higher light throughput and a better signal-to-noise ratio than lens coupling.*

Precision: emICCD

Groundbreaking **emICCD** technology offers researchers an unprecedented combination of precision, true single-photon detection, intelligence, and speed. Its precision performance is evidenced by superior linearity.

The importance of high linearity is demonstrated in Figure 5, where different species from exhaust gas residue (CO, NO, C_2, OH, etc.) are studied under different conditions. To obtain accurate fluorescence values of traces, a background image has to be subtracted from each fluorescence image under the same conditions. By intelligently controlling the image intensifier gain and the EMCCD gain, better linearity is obtained from an **emICCD** camera than from a traditional ICCD camera, in which linearity is limited by the MCP.

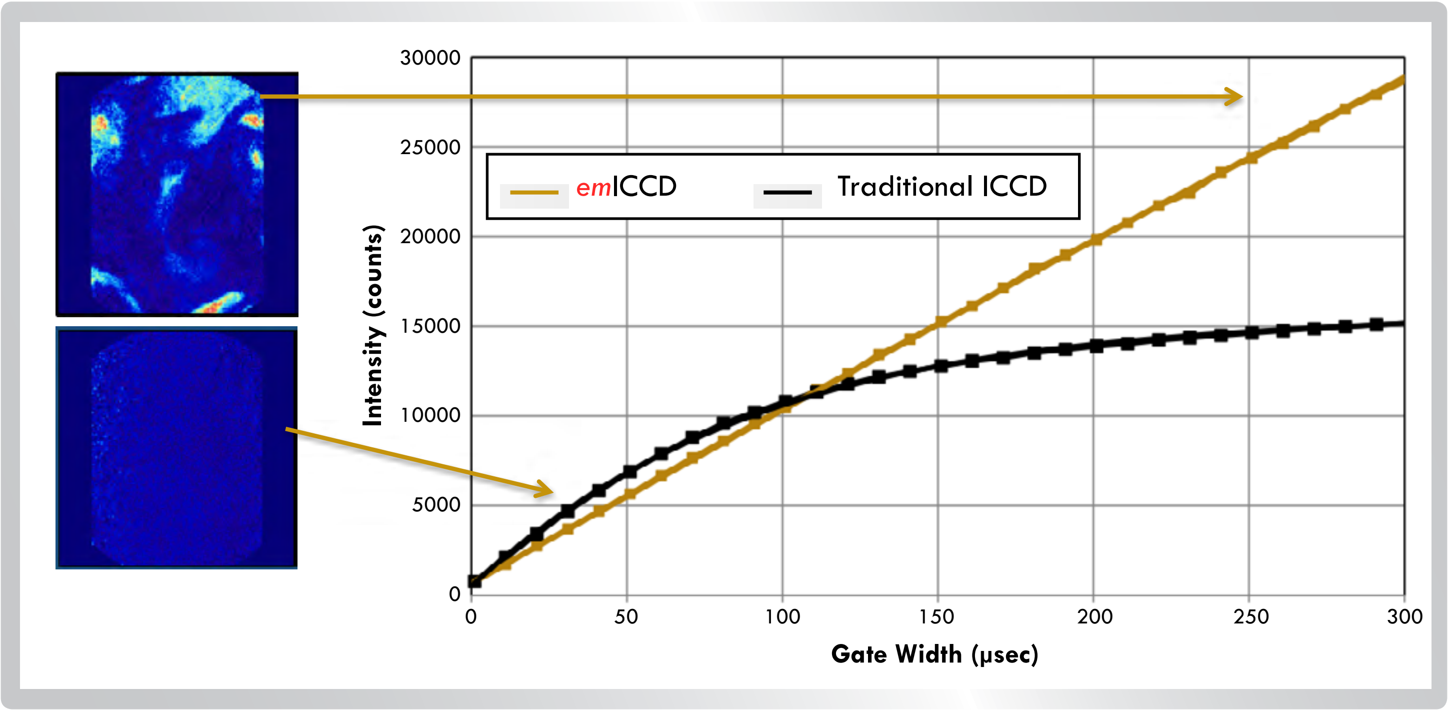

Figure 5. *Laser-induced fluorescence emission from residual exhaust gases in an internal combustion engine. Images courtesy of Prof. David Rothamer, University of Wisconsin-Madison.*

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True Single-Photon Detection: *em*ICCD

Higher sensitivity is another important advantage of **emICCD** technology. These new cameras utilize, for the first time, an EMCCD fiber-coupled to either a Gen II or Gen III intensifier and are capable of true single-photon detection.

The benefit of photon counting is readily apparent in Figure 6, where the accumulation of a large number of frames with thresholding yields a higher-contrast image (i.e., better signal-to-noise ratio) compared to an image captured using a traditional ICCD camera with high gain.

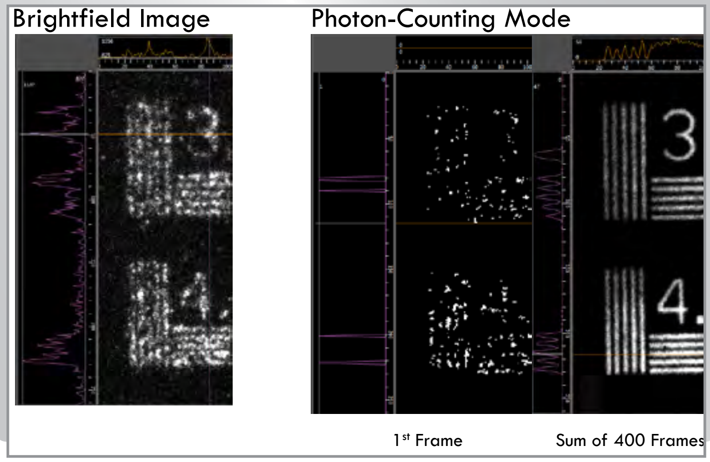

Figure 6. *Comparison of a traditional ICCD image to the 1st frame and to the accumulation of 400 frames of a photon-counting image.*

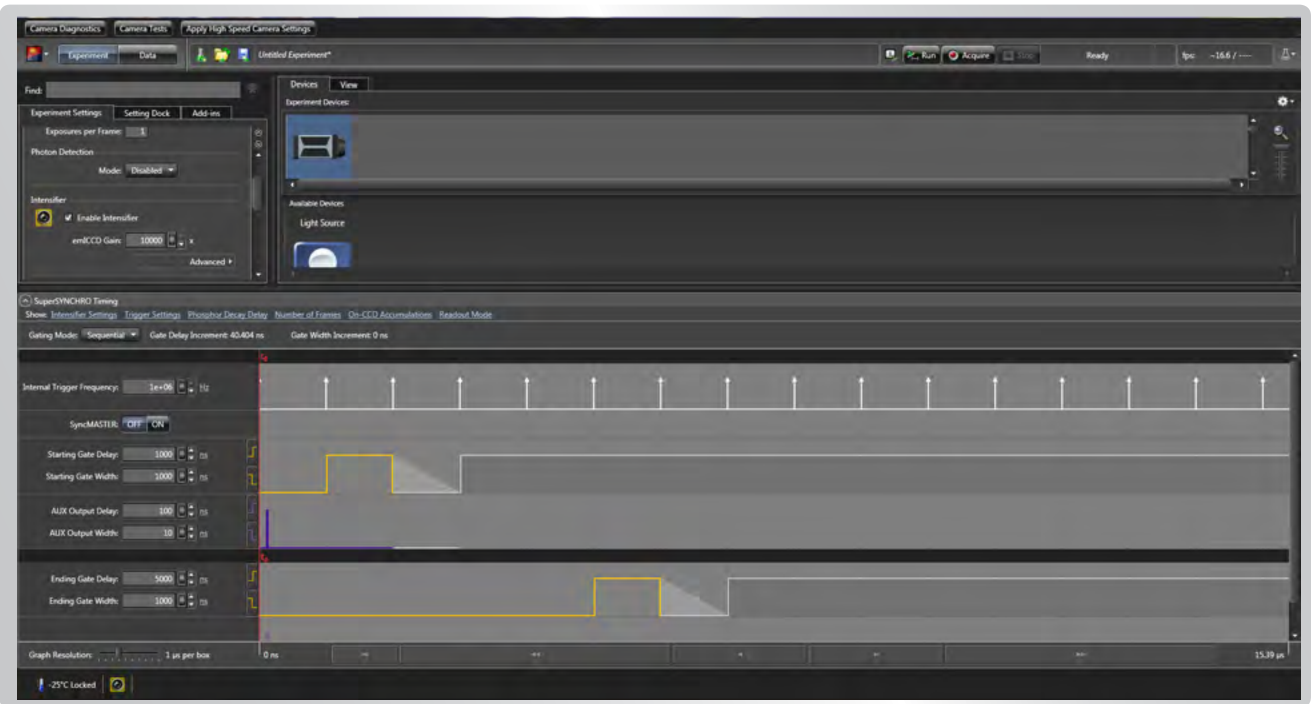

Figure 7. *An oscilloscope-like user interface enhances the utility of Princeton Instruments' **emICCD** cameras.*

Figure 8. *New Princeton Instruments PI-MAX4:512EM camera operating in kinetics mode with 512x20 pixel window, running at >800 fps. (If the movie does not start automatically, please click on the image.)*

Intelligence and Speed: *em*ICCD

Impressive intelligence is another hallmark of Princeton Instruments' new ***em*ICCD** cameras. Sophisticated yet intuitive LightField software* provides an oscilloscope-like user interface (see Figure 7) that allows dynamic control of gains, intensifier gate widths, and gate delays, while automatically keeping track of experiment setups, users, etc.

Using kinetics mode, these new cameras also offer sensational speed to capture ultrafast transient phenomena (see Figure 8).

Summary

The Princeton Instruments PI-MAX4:512EM,† the new benchmark for ICCD cameras, leverages the key advantages of both EMCCDs and ICCDs via fiberoptic coupling for the first time. Featuring ***em*ICCD** technology, these cameras deliver an unrivaled combination of precision, true single-photon detection, intelligence, and speed. They are perfectly suited for numerous time-resolved scientific imaging and spectroscopy applications.

The new cameras' superior linearity is a must in quantitative imaging (e.g., combustion), while their true single-photon detection capability ensures the high sensitivity needed for light-starved applications. An oscilloscope-like user interface even remembers complete experiment setups. In addition, thanks to their ability to acquire >8000 spectra/sec, these cameras can capture every pulse from next-generation lasers.

For more information about ***em*ICCD** technology, please visit **www.emICCD.com**.

*LightField software and <500 psec gating are available as PI-MAX4:512EM options.

†Please note that all PI-MAX4:512EM cameras (both front- and back-illuminated) require an end-user statement and licensing process for shipments outside the United States.

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