ProEM® +

Performance | Precision | Peace of Mind

The professional-grade EMCCD cameras for imaging and spectroscopy.

Re-imagined for Even Greater Performance and Flexibility

Princeton Instruments

Welcome to Princeton Instruments

Our Team

At Princeton Instruments, we transform cutting-edge technology and application knowledge into instrumentation that redefines the way in which people think about high-performance imaging. Every day we speak with researchers representing a myriad of disciplines and listen carefully to what they need to expand the boundaries of science. This commitment to innovation has informed the development of many industry-leading Princeton Instruments products through the years, including an EMCCD camera that provides single-photon counting capability and blazing-fast frame rates, an ultradeep sensor cooling package based on state-of-the-art vacuum technology, and scientific-grade InGaAs detectors for near-infrared imaging.

For more than a quarter century, such innovations have helped researchers understand challenges more fully and find intelligent, remarkable solutions. Thanks to their creative use of our products, Princeton Instruments has become the most recognized name in high-performance imaging today.

1995

World's first scientific-grade gated ICCD camera

1997

I-PentaMAX ICCD camera revolutionizes low-light-level, single-molecule fluorescence applications

1998

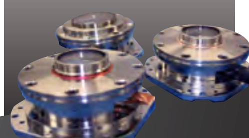
PI-MAX® is the first ICCD camera to have a built-in delay generator for precise timing synchronization

2002

World's first scientific-grade microscopy EMCCD camera

2003

XP cooling technology is the only cooling technology to offer a lifetime vacuum guarantee



2004

PIXIS CCD camera line offers ultradeep cooling and low noise with USB 2.0 interface

2005

PhotonMAX EMCCD camera becomes ultimate research camera, offers lifetime vacuum technology

OMA V is world's first scientific-grade 2D InGaAs camera for low-light NIR detection

2007

PIXIS:1024BR is world's first scientific-grade deep-depletion CCD camera for near-infrared imaging

2009

ProEM® professional-grade EMCCD camera line offers Gigabit Ethernet (GigE) interface

2010

eXcelon® CCD and EMCCD technology provides reduced etaloning and broad UV-NIR sensitivity

Exclusive 512BK EMCCD features on-chip mask for ultrafast kinetics

LightField® is industry's first 64-bit acquisition software "designed from the ground up"

2012

eXcelon 3

...CCD and EMCCD sensitivity *redefined*

eXcelon3 technology for even better performance

ProEM+ for greater flexibility, >10,000 fps, and improved stability and quantification

NEW

The ProEM+ platform now provides even better performance via:

- eXcelon3 sensor technology
- Ultra-high-speed readout modes
- LightField 64-bit software

ProEM® +

Now the world's first professional-grade EMCCD camera is even better!

*

The ProEM+ is the culmination of Princeton Instruments' years of experience and expertise in low-light-capture technology informed by feedback from researchers worldwide.

Features & Benefits

Princeton Instruments, a pioneer in low-light-level imaging technology, has been at the forefront of EMCCD technology for more than a decade. The Princeton Instruments ProEM+ camera is the culmination of years of working with leading researchers and skillfully implementing our own ultra-low-noise electronics, deep cooling, and EMCCD expertise.

When we started the ProEM project, our goal was simple. We wanted to provide the best EMCCD camera available for researchers seeking to understand the universe, whether they are observing distant stars through a telescope or looking at single molecules through a microscope. Our strategy for achieving this goal was threefold. We knew that we must surpass the performance, precision, and peace of mind afforded by any existent EMCCD camera.

In the following pages, we shall examine how the ProEM+ camera addresses the most critical requirements of today's low-light, high-speed imaging applications.

Newest Innovations

eXcelon CCD and eXcelon3 EMCCD technology provides reduced etaloning and broad UV-NIR sensitivity

Exclusive 512BK EMCCD features on-chip mask for ultrafast kinetics

LightField is industry's first 64-bit acquisition software "designed from the ground up"

The 2012 incarnation of the ProEM+ platform offers researchers several remarkable new innovations, including eXcelon3 sensor technology for reduced etaloning and broad UV-NIR sensitivity, our own custom 512BK EMCCD for ultrafast kinetics, and 64-bit data acquisition via Princeton Instruments' leading-edge LightField software.

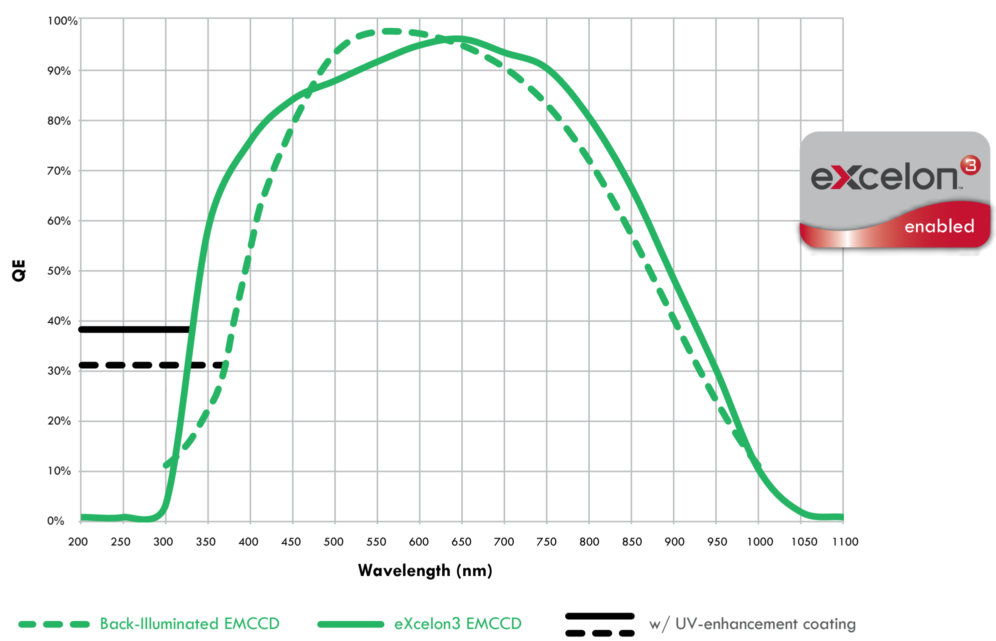
ProEM+ Configuration

ProEM+ cameras are ideal both for imaging and spectroscopy applications. For imaging, 512 x 512 and 1024 x 1024 formats are available, as is a special kinetics EMCCD with a 512 x 412 format. For spectroscopy, 1600 x 200, 1600 x 400, and 512 x 2 formats are offered.

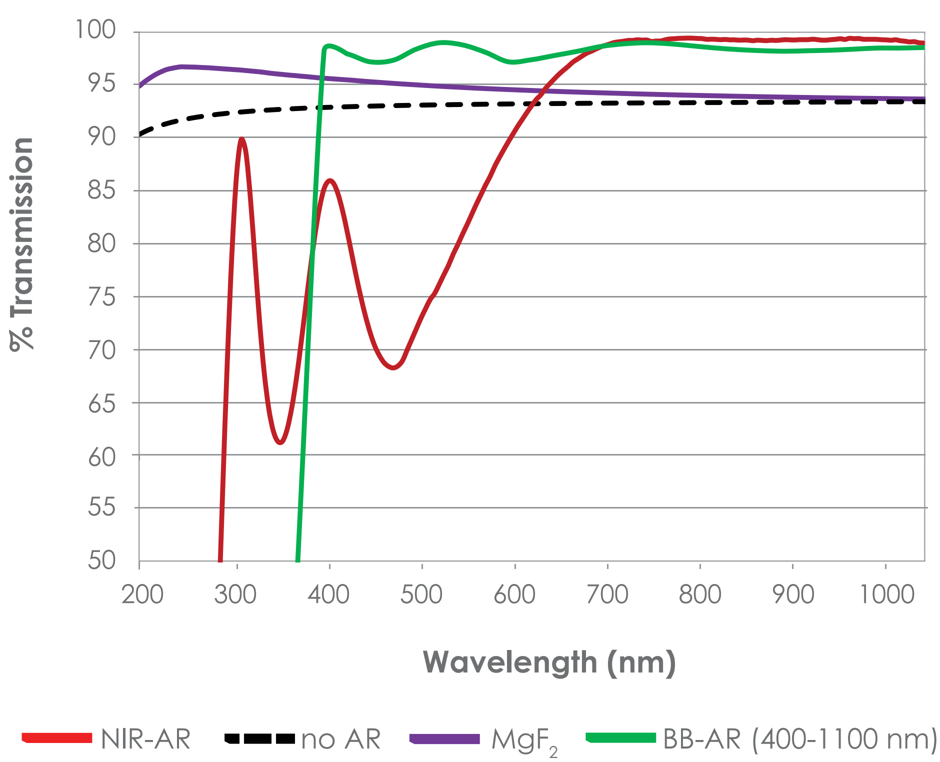
- Camera head with adjustable C-mount
- Integrated mechanical shutter
- Built-in precision light source
- Tripod mount
- GigE cable
- GigE adapter card (for computers that do not have Intel® Gigabit Ethernet ports)
- Power supply

ProEM+ MODELS*	PIXEL FORMATS	ACTIVE AREA (mm X mm)	PIXEL SIZE (µm)	MAX. COOLING†	PEAK QE	TYP. READ NOISE	FRAME RATE††
512B 512B eXcelon3 	512 x 512	8.2 x 8.2	16	<-90°C	95%	<1 e- rms (EM mode) 3 e- rms (traditional CCD mode @ 100 kHz)	>34 fps
512BK 512BK eXcelon 	512 x 2 512 x 410 (adjustable)	8.2 x .032 8.2 x 5.6	16	<-90°C	95%	<1 e- rms (EM mode) 3 e- rms (traditional CCD mode @ 100 kHz)	>1,000,000 spectra / sec >40 fps
1024B 1024B eXcelon3 	1024 x 1024	9 x 9	13	<-75°C	95%	<1 e- rms (EM mode) 3 e- rms (traditional CCD mode @ 100 kHz)	>8.5 fps
NEW 1600^2 eXcelon3 	1600 x 200	25.6 x 3.2 (optically centered)	16	-75°C	95%	<1 e- rms (EM mode) 4 e- rms (traditional CCD mode @ 100 kHz)	>4000 spectra / sec (single row)
NEW 1600^4 eXcelon3 	1600 x 400	25.6 x 6.4 (optically centered)	16	-75°C	95%	<1 e- rms (EM mode) 4 e- rms (traditional CCD mode @ 100 kHz)	>4000 spectra / sec (single row)

*Princeton Instruments also offers EMCCD cameras with 128 x 128 (e2v CCD60, 24 µm pixels) formats.
†Max. cooling is specified at +20°C ambient temperature and is regulated to within ±0.05°C.
††Frame rate can be increased via binning and/or ROI.



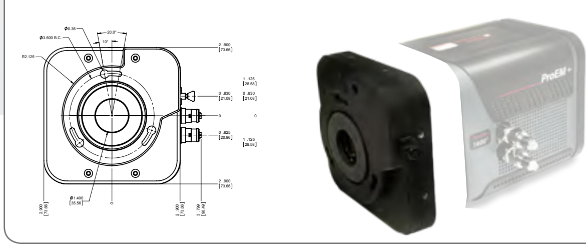
Typical QE shown at +25°C



NEW

ProEM® + 1600

New spectroscopy flange nose



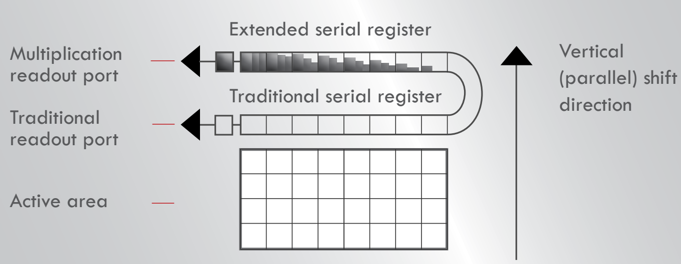
Spectroscopy EMCCD Cameras

The ProEM+ 1600^2 and 1600^4 are the most advanced spectroscopy EMCCD cameras on the market. The 1600 x 200 and 1600 x 400 format sensors, which feature Princeton Instruments' exclusive eXcelon3 technology, provide the lowest etaloning in the NIR as well as enhanced QE in the blue and red regions of the spectrum.

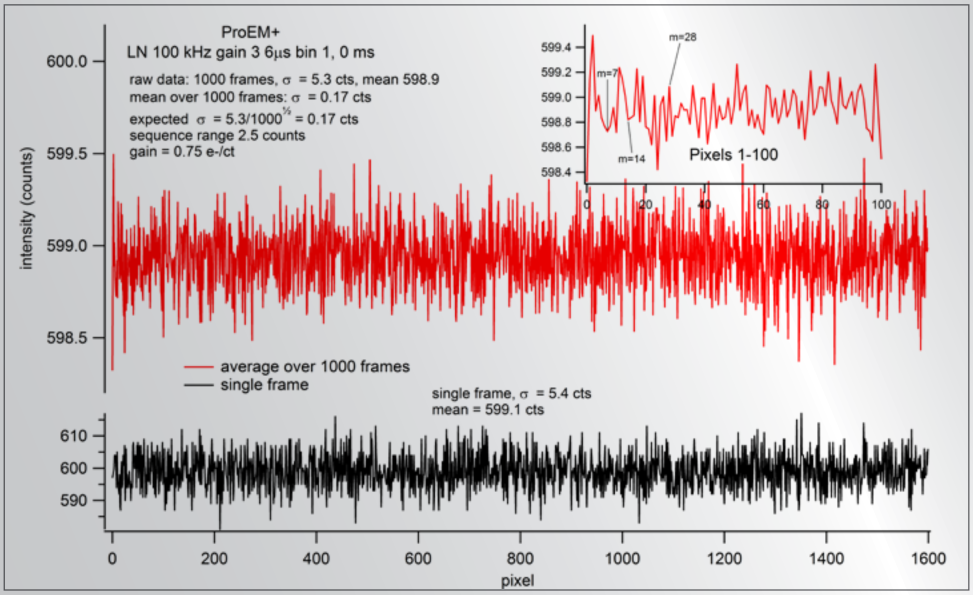
These cameras not only feature a high-speed "electron multiplying" (EM) mode to capture fast kinetics, but also a "normal CCD" mode with very low read noise for precision photometry. ProEM+ 1600^2 and 1600^4 cameras are deep cooled (using either air or liquid) and their all-metal, hermetic vacuum seals are warranteed for life – the only such guarantee in the industry.

- Gigabit Ethernet (GigE) interface that allows remote operation over a single cable without the need for custom frame grabbers
- Back-illuminated EMCCD with eXcelon3 technology
- Electron multiplication (EM) gain to amplify weak signals above the read noise floor
- Advanced pixel bias correction
- Versatile ADC… low noise: 100 kHz and 1 MHz; electron multiplying: 1, 4, and 8 MHz
- Maximum spectral rate >4000 frames per second
- Faster, quieter, and more sensitive performance than any other spectroscopy EMCCDs

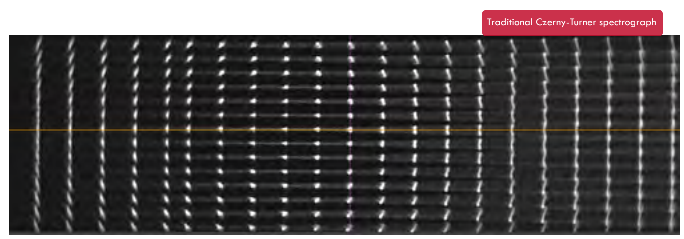
Spectroscopy EMCCD block diagram



Extremely flat bias at 100 kHz (bin 1 row)



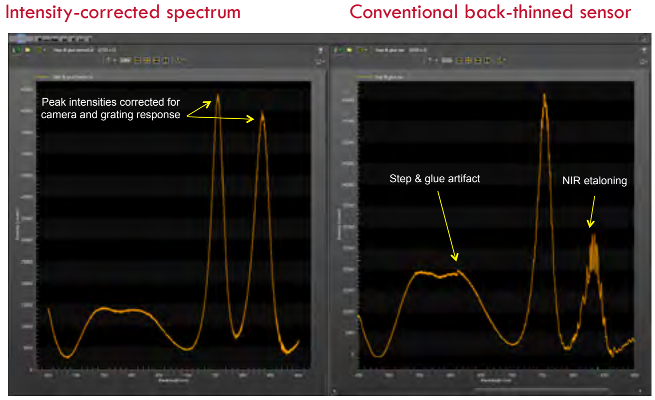
High-speed multifiber spectra with the Princeton Instruments IsoPlane™



IntelliCal™ Intensity Calibration

Princeton Instruments LightField software, with its exclusive Intensity Calibration routine, removes residual etaloning…

Intensity-corrected spectrum | Conventional back-thinned sensor



Applications include scanning confocal spectroscopy, hyperspectral imaging, single-molecule spectroscopy, and high-speed mapping.

ProEM+ Options

Readout modes:

All ProEM+ cameras support frame-transfer, full-frame, and kinetics readout modes. A special optional readout mode called “spectra-kinetics” is also available that allows ultrafast spectral acquisition via novel under-the-mask binning. See the section on kinetics for additional information.

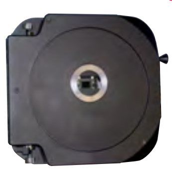
Mounts:

C-mount (standard): Allows easy mounting to C-mount lenses and microscopes. Provides fine focus adjustment.

C-to-F mount adapter: Allows attachment of F-mount lenses (Nikon®) to the camera.

Canon® mount: Allows easy mounting to Canon lenses or telescopes. Provides fine focus adjustment.

Kinetics adjustable-window adapter:



Princeton Instruments’ unique kinetics adapter allows precision adjustment of window size in order to eliminate shadow; window size can be adjusted to within one row. This adapter, which is standard on the 512BK model, also has a manual shutter for use when internally calibrating the EMCCD gain.

Liquid circulator:

CoolCUBE II: Compact liquid circulator designed to deliver optimum flow to the camera.

Vacuum window anti-reflection (AR) coatings:

Custom vacuum window coatings increase photon transmission by 6% to 8% in the wavelength of interest. ProEM+ cameras offer double-sided MgF_2, NIR-AR, and BB-AR coatings for increased photon throughput.

CCD coating:

Unichrome: Extends the detector’s response into the deep UV region.

NEW

Spectrometer adapters:

Spectroscopy flange nose allows easy mounting to Acton Series and IsoPlane spectrographs.

ProEM+ Software Options

NEW

LightField software

Princeton Instruments LightField is a new 64-bit data acquisition software platform that runs under Microsoft® Windows® 7 and has been designed for scientific imaging and spectroscopy (see LightField section on page 18).

PICAM/PVCAM®

Princeton Instruments PICAM (64 bits) / PVCAM (32 bits) is a custom, ANSI C library that is used to create the camera control and data acquisition interface.

LabVIEW™ SITK

This scientific imaging tool kit (SITK) provides prewritten virtual instrument (VI) modules to quickly integrate camera functions into a larger experimental setup using National Instruments LabVIEW.

SDK (Windows & Linux®)

A free software development kit (SDK) is included, complete with helpful examples, so that ProEM+ users can write their own acquisition programs.

WinSpec / WinView

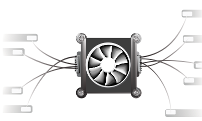
Princeton Instruments WinSpec and WinView each offer scientists a complete, off-the-shelf package that includes real-time data acquisition, display, post-acquisition processing, data manipulation, and archiving capabilities.

Performance | Cooling

Options: The ProEM+ delivers the highest cooling performance, no matter which option is selected.

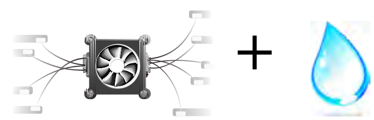
All-metal seals: Good vacuum is critical to achieving deep cooling and, subsequently, low dark noise. Traditional epoxy-based seals degrade over time and compromise vacuum performance due to outgassing. In contrast, Princeton Instruments' proprietary all-metal seal design provides the highest level of vacuum performance, year after year. Even the vacuum window, the only optical surface in the optical path, is brazed (fused at the molecular level) to the vacuum chamber.

Permanent vacuum guarantee: The ProEM+ comes with our lifetime vacuum guarantee, backed by our advanced technology and thousands of hard-working cameras in the field. It is the only guarantee of its kind in the industry.



Air only: The most convenient… just connect the camera and go. The camera is cooled using a built-in, low-noise fan.

Liquid only: In vibration-sensitive applications such as microscopy, moving parts like internal fans can create problems. In astronomy, air turbulence around the telescope optics can cause defocusing. The liquid-only cooling method eliminates heat and vibration while achieving exceptional cooling performance. This approach is better than temporarily turning off the fan, which compromises cooling stability over long periods of time. Princeton Instruments designed the compact CoolCUBE II (optional) to easily provide liquid circulation in a lab environment.



Air+Liquid: The combined use of air and liquid provides a perfect choice for applications that require the deepest cooling and the lowest dark noise. Cold liquid circulation and a built-in fan further enhance ProEM+ cooling performance.

* Optional CoolCUBE II: The compact CoolCUBE II liquid circulator provides an easy way to dissipate heat when operating the camera in vibration-sensitive environments.

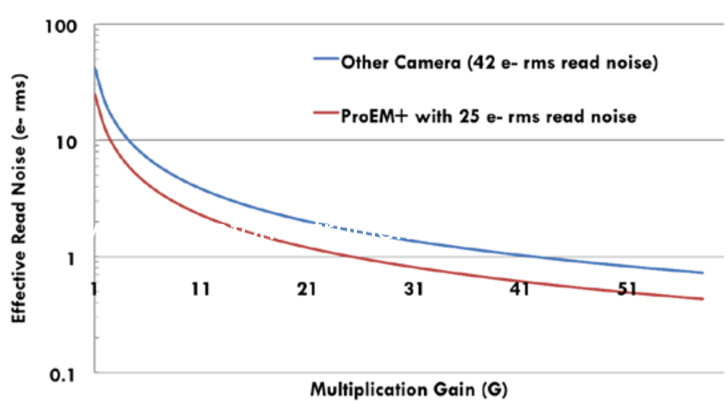
Performance | Low Noise

PINS (Princeton Instruments Noise Suppression) technology: Princeton Instruments engineers have designed the ProEM+ camera's advanced electronics to attain the lowest possible noise levels. In EM mode, the ProEM+ delivers the lowest starting noise of any camera on the market, a solid advantage considering that only a small amount of EM gain is required to achieve <1 e- rms effective read noise.

The camera's traditional readout port, meanwhile, delivers an unparalleled 3 e- rms read noise. Whether utilized for fast or slow applications, the ProEM+ delivers the lowest noise levels ever.

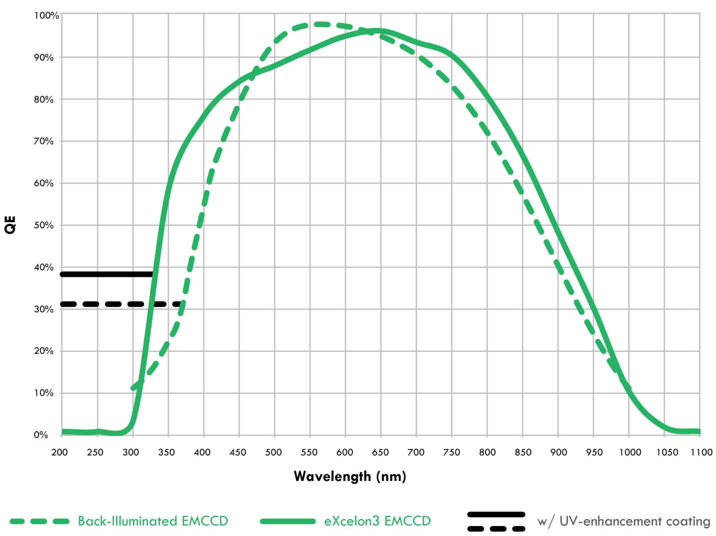
PINS technology also includes proprietary methods for lowering clock-induced charge, an unwanted noise source in EM applications requiring single-photon detection. This charge is reduced to 0.005 e-/p/frame via careful optimization of clock timing and voltage levels on every ProEM+ camera.

True 16 bits: The ProEM+ provides 16 bits of precision computing. With its exceptionally low read noise and linear full well, the camera can capture both dim and bright objects in a single frame.



Performance | Sensitivity

Back-illuminated sensor: The ProEM+ features a back-illuminated EMCCD that delivers greater than 90% quantum efficiency. The double-sided, anti-reflective-coated vacuum window is the only optical surface between incoming photons and the highly sensitive EMCCD surface. For enhanced sensitivity in the ultraviolet (UV) region, a proprietary Unichrome coating is available.



Typical QE shown at +25°C

NEW

Back-illuminated eXcelon3 sensor: Developed by Princeton Instruments, eXcelon3 EMCCD technology delivers excellent photon-detection capabilities across a wide spectrum (200 to 1100 nm) and is particularly beneficial for applications requiring enhanced sensitivity in the blue and NIR regions. Proprietary eXcelon3 back-illuminated sensors greatly reduce etaloning, the problematic appearance of fringes due to constructive and destructive interference in a device's back-thinned silicon when imaging in the NIR (750 to 1100 nm). For a comprehensive discussion, please refer to the eXcelon3 technology primer.

EM gain: EM gain enables researchers to observe fast processes that emit only a few photons. It effectively reduces the system read noise to below 1 e- rms, allowing single-photon detection.

Traditional CCD mode: While the ProEM+ camera's EM mode is ideal for low-light, high-speed imaging applications, the traditional readout amplifier (i.e., the non-EM amplifier) is preferred for slow-scan applications. By reading out slowly, the ProEM+ delivers unprecedented performance even in traditional CCD mode for applications such as astronomical imaging that require minutes to hours of exposures. The ProEM+ is equipped with 100 kHz slow-scan readout to provide the best possible read noise for steady-state applications.

Delivers excellent photon-detection capabilities across a wide spectrum!

Performance | Speed

Video rates and higher: The ProEM+ offers readout rates that exceed video, even at full resolution (512 x 512). If hundreds of frames per second are needed, a combination of binning and region of interest (ROI) can be used. All data is sent to the host computer via the latest Gigabit Ethernet (GigE) interface, a first for a scientific EMCCD camera. In another first, the ProEM+ features a hardware-generated precision timestamp. Researchers can now not only capture images at high frame rates, but know precisely when the images were captured.

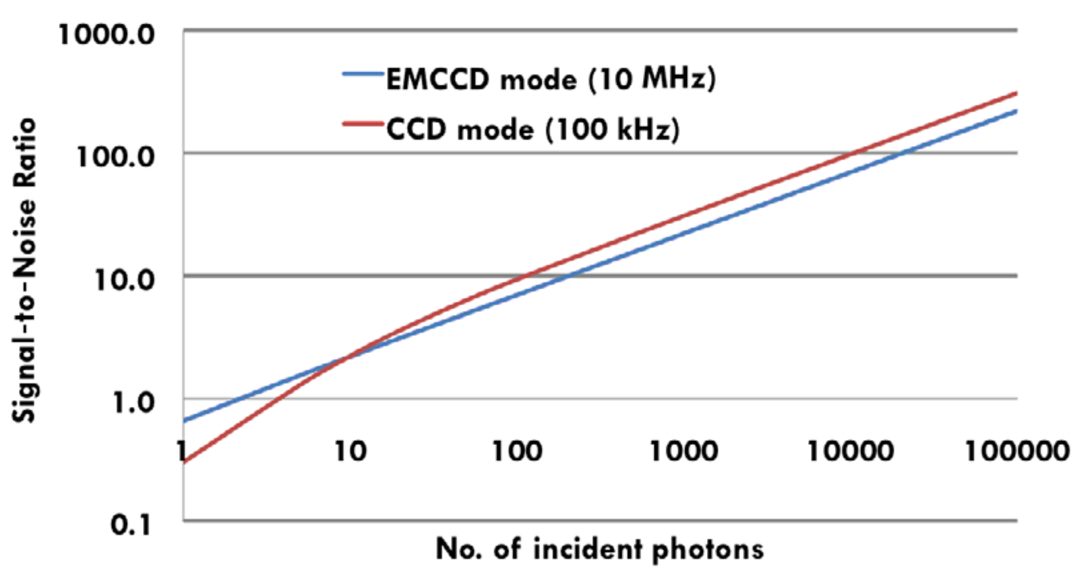
Kinetics mode: To capture a process with microsecond time resolution or millions of spectra per second, the ProEM+ fully supports kinetics, a special Princeton Instruments readout mode. With kinetics mode, temporal resolution can be increased by illuminating a small portion of the sensor and then capturing and shifting a series of sub-frames in microseconds.

NEW **512BK sensor:** Designed with a precision on-chip mask, the 512BK EMCCD allows illumination of exactly two rows and delivers burst frame rates in excess of 1 million spectra per second. In addition, external blades provide a "variable kinetic mask" for increased sensitivity.

NEW **Spectra-kinetics mode:** Our new spectra-kinetics option provides higher sensitivity (via binning) than our standard kinetics mode and is ideal for capturing longer-duration events. Use of spectra-kinetics allows the ProEM+ camera to acquire the full masked height's worth of spectra irrespective of the height of the "illuminated" rows — all while delivering the same temporal resolution as standard kinetics.

High-speed mode: The ProEM+ supports advanced readout via "custom chip", a mode in which the active number of pixels can be redefined on-the-fly. The mode allows the camera to achieve >10,000 fps with reduced ROI and binning. It is useful for single-shot experiments requiring μs resolution.

Variable vertical transfer time: The vertical transfer time, which determines the amount of smear, can be set through software control (450 ns and up).



Precision

OptiCAL: EM calibration has finally gone optical. A precision light source built into every ProEM+ camera is used to generate a linearized EM gain map on-demand. EM gain is also user-controlled in absolute steps via software. In other words, what you see is what you get.

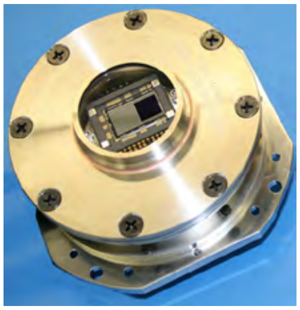
BASE (Bias Active Stability Engine): Whether acquiring images over the course of hours or days, BASE allows researchers to achieve a consistent, repeatable reference bias.

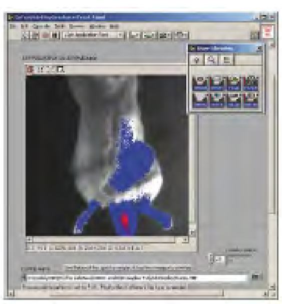
Shutter: While a frame-transfer architecture does not require a mechanical shutter for normal operation, it is highly useful for blocking external light when acquiring reference background images and for protecting the sensor from dust when not in use.

Vibration-free operation: The ProEM+ has been designed for ultrasensitive experiment setups, such as microscopy and ion imaging, which demand that no vibrations be introduced into the system. Simply turn off the fan permanently and use liquid-only cooling instead.

Heat-free operation: Another benefit of the ProEM+ liquid-only cooling option is that heat is carried away from the camera without generating air turbulence around sensitive optics, such as telescopes.

Timestamp: Princeton Instruments has taken the guesswork out of determining when an image was actually captured. Traditionally, timestamps have been done on the host computer using a low-precision CPU clock. In contrast, the ProEM+ stamps the frame data with a highly precise timestamp (microsecond resolution). This feature is essential for measuring fast kinetics over time. The timestamp feature is easily accessible in the newest LightField 64-bit acquisition software.





Peace of Mind

Permanent vacuum guarantee: The ProEM+ comes with our lifetime vacuum guarantee, backed by our advanced technology and thousands of hard-working cameras in the field. It is the only guarantee of its kind in the industry.

Anti-aging: EM gain can degrade over time, especially when large gain is used under high-light-level conditions. The ProEM+ utilizes many anti-aging measures, including clock-voltage optimization. Deep cooling allows the camera's high-voltage clocks to be operated well below their maximum ratings while still achieving greater than 1000x EM gain.

Worldwide support: With years of experience and expertise, Princeton Instruments representatives are ready to assist our camera users worldwide!

Flexibility

Ethernet®: For the first time, a scientific EMCCD camera is being offered with a Gigabit Ethernet (GigE) interface. Using this interface, researchers can operate the ProEM+ from up to 50 m away. A fiberoptic interface option allows camera operation from up to several kilometers away.

LabVIEW: LabVIEW (National Instruments) can be used to integrate the ProEM+ into larger imaging experiments and to easily access camera features.

Free SDK: A free software development kit (SDK) is included, complete with helpful examples, so that ProEM+ users can write their own acquisition programs.

NEW

For the first time, a scientific-grade EMCCD camera is being offered with a Gigabit Ethernet (GigE) interface.

NEW

LightField 64-bit Software

...for optimum ProEM+ performance

Princeton Instruments LightField is a new 64-bit data acquisition software platform that runs under Microsoft Windows 7 and has been designed for scientific imaging and spectroscopy. LightField provides comprehensive control of Princeton Instruments ProEM+ cameras via easy-to-use tools that help streamline experimental setup, data acquisition, and post processing. It is especially useful for ultrafast kinetics and spectroscopy applications.

LightField is an excellent solution for multi-user facilities. The platform remembers each user's hardware and software configurations and tailors its own features accordingly, displaying all relevant tools via an intuitive graphical user interface.

LightField offers patent-pending IntelliCal for accurate spectrum calibration in both the wavelength and intensity spaces!

INTUITION
Build a hardware configuration...

POWER
Set up complex acquisitions in a single window...

CONTROL
Customize your environment...

SEARCH
File Information window...

LightField®

Salient features:

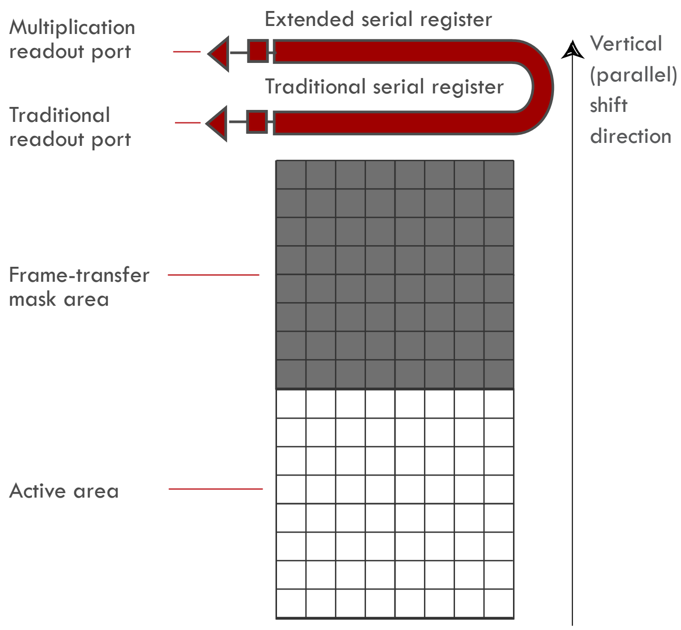
- Cutting- edge user interface
- Built for latest generation of multi-core 64-bit processors
- Progressive disclosure; contextual menus ensure that only relevant options appear
- Hard drive streaming; stream thousands of images and gigabytes of data to hard drive
- All experimental parameters saved to data file headers; no more searching old notebooks for data acquisition settings
- Precise hardware-generated timestamping for time-resolved studies
- Automatic light saturation warning with pseudocolor

Visit our website for a 45-day trial.

EMCCD (electron-multiplying CCD)

A technology primer

ProEM+ cameras use electron-multiplying gain technology to amplify the signal (photoelectrons) in each pixel. This technology allows ultra-low-light levels to be detected without the need for external intensifiers.



The ProEM+ offers dual amplifiers that make the camera a versatile solution for applications requiring long integration as well as for dynamic studies.

The special multiplication takes place in the extended serial register through a process called impact ionization. The key is to amplify the electrons before they reach the output amplifier and subsequent electronics. This will effectively boost the signal above the read noise of the system. The main benefit of the technology, therefore, is a far better signal-to-noise ratio for signals below the read noise.

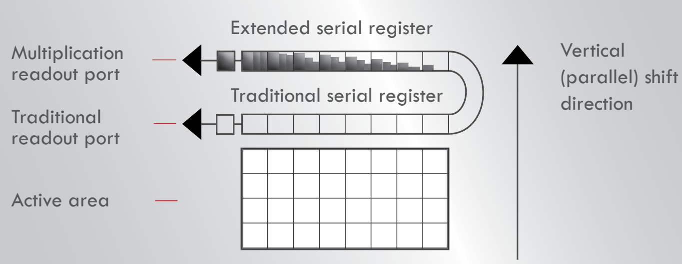
The gain factor achieved by impact ionization can be greater than 1000x. In fact, the actual gain factor is a complex function of the voltage applied, the temperature of the device, and the number of stages in the extended serial register. At constant voltage and temperature, it is given by

$$G = (1+p)^N$$

where G is the total gain, p is the probability of secondary electron generation in each transfer (pixel) in the serial register, and N is the number of stages.

The probability of multiplication in each stage is quite small, in the range of 1% to 1.5%; however, due to a large number of stages (>500), the total multiplication gain can be quite high.

Spectroscopy EMCCD block diagram



The gain factor achieved by impact ionization can be greater than 1000x.

Signal-to-noise ratio (SNR)

SNR

The signal-to-noise ratio of an EMCCD is given by

$$SNR = \frac{S \times QE}{\sqrt{[(S \times QE \times F^2) + D \times F^2 + (\sigma_R/G)^2]}}$$

From the above equation, in a low-light-level application where system read noise (σ_R) is the limitation, EMCCDs effectively reduce the system read noise to below 1 e- rms by applying an appropriate amount of multiplication gain (G). However, the introduction of an additional noise term, called excess noise factor (F), means that the resulting signal-to-noise ratio will be reduced by that amount.

EMCCDs effectively reduce the system read noise to below 1 e- rms.

In contrast, the SNR for traditional CCD cameras is given by

$$SNR = \frac{S \times QE}{\sqrt{[(S \times QE) + D + \sigma_R^2]}}$$

Notice the lack of excess noise in standard CCDs, which allows better signal-to-noise ratio in shot-noise-limited or high-light-level conditions.

S = number of incident photons
QE = quantum efficiency at a given wavelength
D = dark current (e-/pixel/sec)
σ_R = read noise of the entire detector system, including readout electronics
F = excess noise factor
G = multiplication or amplification gain

eXcelon 3

Next-generation, performance-enhancing EMCCD technology

A primer on eXcelon® 3 technology

Exclusively from Princeton Instruments!		
Technology	**Sensor type**	**Architecture**
eXcelon3	Back-illuminated EMCCD	Custom thinned
eXcelon	Back-illuminated CCD	Thinned or deep depletion

Introduction

Since their invention in 1969, charge-coupled devices (CCDs) have been used to detect the faint light from items as nearby as cells under a microscope to those as far away as stellar objects at the edge of the known universe. Over the past four decades, low-light CCD cameras have facilitated some of the biggest breakthroughs in both the life sciences and the physical sciences. Salient features that have contributed to the remarkable track record of these detectors include greater than 90% peak quantum efficiency (QE), very low read noise of 2 e- rms or less, 100% fill factor, and excellent charge-transfer efficiency.

About twelve years ago, a variant of CCDs known as electron-multiplying CCDs (EMCCDs) was developed. In addition to the features noted above, EMCCDs are able to achieve sub-electron read noise at high frame rates, allowing single-photon detection. Thus, CCD and EMCCD cameras are commonly the instruments of choice for scientific applications ranging from steady-state astronomical imaging to dynamic single-molecule imaging, and from widefield imaging to spectroscopy.

This paper provides a basic overview of the advantages and disadvantages of EMCCDs and introduces a new sensor technology, eXcelon3, that mitigates some of their inherent limitations. ***Those who are mainly interested in learning about a novel way to obtain enhanced low-light CCD (i.e., non-EMCCD) performance can refer to the Princeton Instruments technical note on eXcelon technology.***

Primer contents:

1. Types of EMCCDs
2. Advantages and disadvantages
3. New eXcelon3 technology for EMCCDs
4. Comparison: eXcelon3 vs. less-advanced EMCCD designs
5. Ways to further improve sensitivity
6. Conclusions
7. Appendix A: Etaloning in the NIR
8. Appendix B: Effect of cooling on QE

Types of EMCCDs

In a traditional front-illuminated EMCCD, light passes through the polysilicon gates that define a charge well at each pixel (see Figure 1). While the gates transmit a number of the incident photons to the EMCCD's photoconversion layer, they also reflect and absorb a fraction of photons, thereby preventing some light from reaching the pixel's photosensitive region. As a result, front-illuminated devices typically offer only about 50% QE (i.e., the fraction of incident photons contributing to the signal).

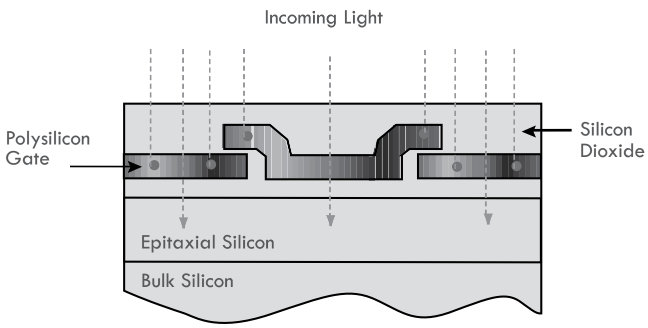


Figure 1. Cross-section of a traditional front-illuminated EMCCD. Light passes through the polysilicon gates in order to reach the device's photoconversion layer.

To improve QE, devices can be uniformly thinned via acid-etching techniques to attain approximately 10 to 15 µm thickness so that an image can be focused directly onto the photosensitive area of the EMCCD (i.e., the depletion region), where there is no gate structure. Compared to front-illuminated EMCCDs, these thinned back-illuminated devices have a higher QE (>90%) across the visible spectrum. (See Figure 2.)

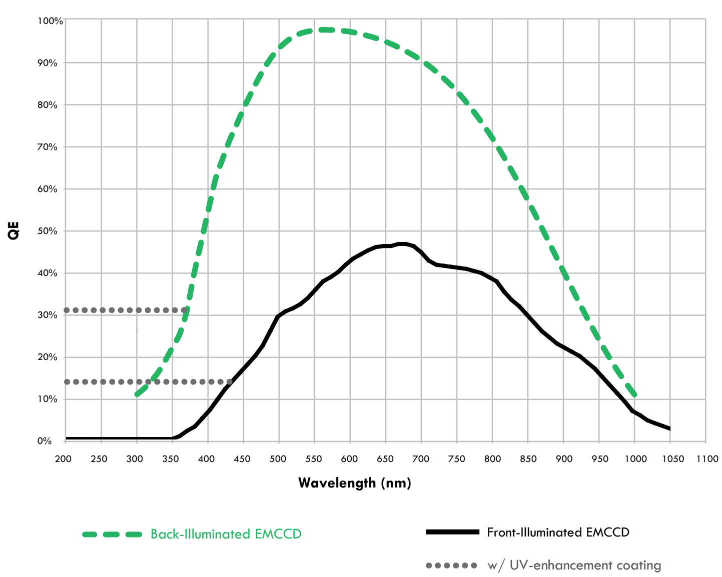


Figure 2. Typical QE of traditional front-illuminated EMCCDs and standard thinned back-illuminated EMCCDs. Dotted lines on the left represent QE in UV region with UV-enhancement coating.

All EMCCDs employ on-chip amplification of photoelectrons to boost signals above the read noise of the sensor (see Figure 3). As a result, EMCCD cameras can achieve sub-electron read noise even at video rates or higher. Not surprisingly, these cameras have become very popular for a variety of ultra-low-light, high-frame-rate applications, including time-resolved astronomy and single-molecule fluorescence imaging (see Figure 4).

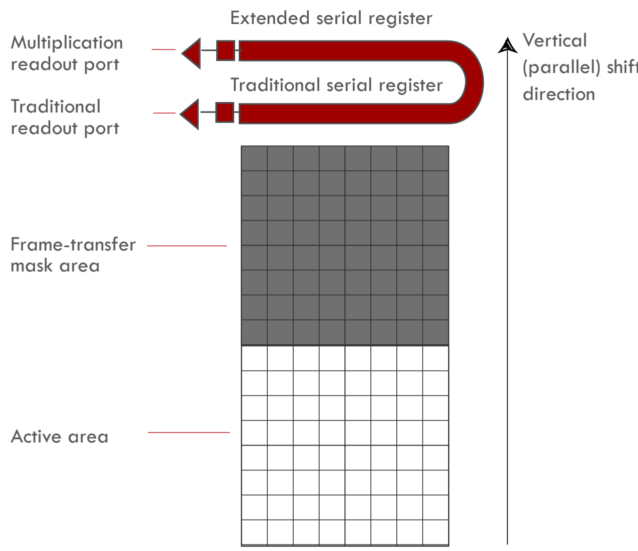


Figure 3. EMCCDs amplify electrons in an extended serial register through a process called impact ionization before they reach the output amplifier and subsequent electronics. The main benefit of the technology, therefore, is a far better signal-to-noise ratio for signals below the read noise.

EMCCD cameras can achieve sub-electron read noise even at video rates or higher.

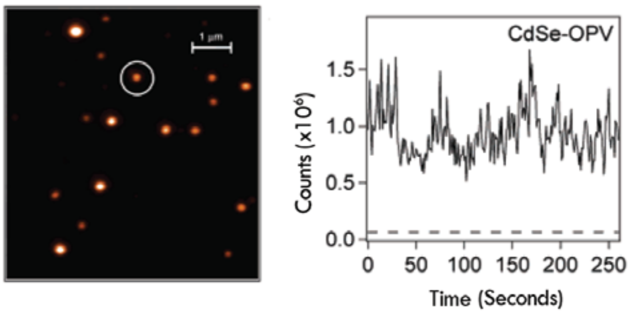


Figure 4. Single-particle fluorescence image acquired using an EMCCD camera (left) with fluorescence time trace (right) of the circled nanostructure.[1]

Due to material processing and manufacturing complexities, EMCCDs are unable to realize deep-depletion technology (which allows longer-wavelength photons to interact within the photosensitive area of the EMCCD as opposed to merely penetrating it) commercially at this time. Unfortunately, for applications requiring NIR sensitivity and low etaloning (see Appendix A), this imposes significant limitations. Front-illuminated EMCCDs, for instance, offer etalon-free imaging, but have 2x to 3x lower sensitivity than their back-illuminated counterparts. Conversely, back-illuminated EMCCDs suffer from etaloning in the NIR, though they have higher QE in this region.

Advantages and disadvantages

Table 1 briefly summarizes the main advantages and disadvantages of the aforementioned technologies in relation to low-light imaging and spectroscopy applications. Overall, front-illuminated EMCCDs are relatively inexpensive, but provide lower sensitivity (refer to Figure 2). In the NIR, they have 2x to 3x lower QE than back-illuminated EMCCDs. It is worth noting, however, that front-illuminated EMCCDs may be preferable for certain high-light-level NIR applications, as they do not suffer from etaloning.

Technology	Sensitivity range* (nm)	Peak QE wavelength (nm)	Peak QE**	Etaloning reduction/fringe suppression in NIR	Dark current
Front-illuminated EMCCDs	200 to 1100	700	47%	Excellent	1x
Standard back-illuminated EMCCDs	<200 to 1100	550	97%	Poor	1x (with AIMO)
NEW eXcelon3 back-illuminated EMCCDs	<200 to 1100	650	95%	Very good	1x

*Sensitivity range with special UV coating that extends UV sensitivity
**Typical data at +25°C

Table 1. Main advantages and disadvantages of various sensor technologies.

New eXcelon3 technology for EMCCDs

Until now, researchers whose applications require low-light broadband photon detection had but one choice when utilizing an EMCCD camera, that is, standard thinned back-illuminated technology. Although such EMCCD cameras are capable of delivering extremely high sensitivity, their performance is nonetheless compromised to a certain extent by the limitations described in the preceding section. Recently, Princeton Instruments developed EMCCDs (and associated cameras) that minimize and even eliminate some of these hindrances.

While the precise details regarding this new technology are beyond the scope of this primer and cannot be revealed for intellectual property reasons, the benefits of eXcelon3 can be explained via comparative measurements.

New eXcelon3 sensors are based on a custom back-illuminated architecture and provide three significant advantages over other EMCCD technologies:

- **Best possible QE and fringe suppression**
- **As much as 70% reduction in etaloning (i.e., peak-to-peak fringe amplitudes)**
- **Outstanding QE improvement — up to 3x increase in the UV and 1.3x increase in the NIR**

First, consider the sensitivity of eXcelon3 technology. Figure 5 shows that eXcelon3 back-illuminated EMCCDs provide higher sensitivity below 475 nm and above 625 nm than standard thinned back-illuminated EMCCDs. The small drop in the green region can generally be tolerated, especially taking into account the other benefits that this technology offers. For the broadest wavelength sensitivity, the new sensors are also available with UV-enhancement coatings. The relative gain in QE using eXcelon3 technology is plotted in Figure 6.

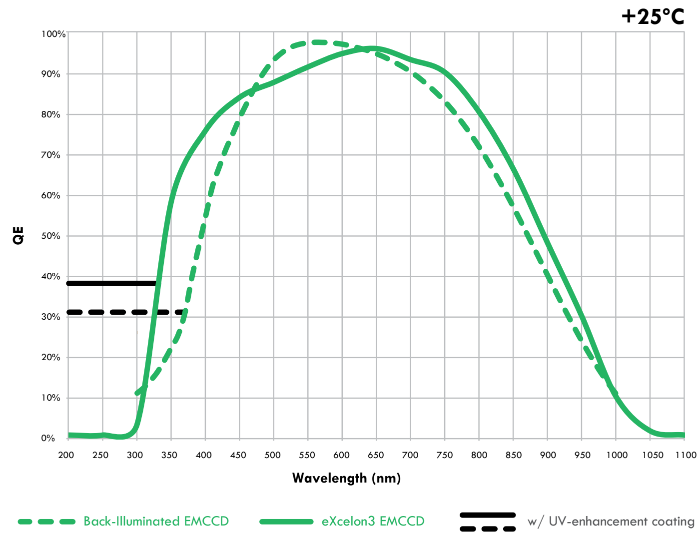


Figure 5. Typical QE of eXcelon3 back-illuminated EMCCDs and standard thinned back-illuminated EMCCDs. Solid/dashed black lines on the left represent enhanced QE in UV region with optional UV-enhancement coatings.*

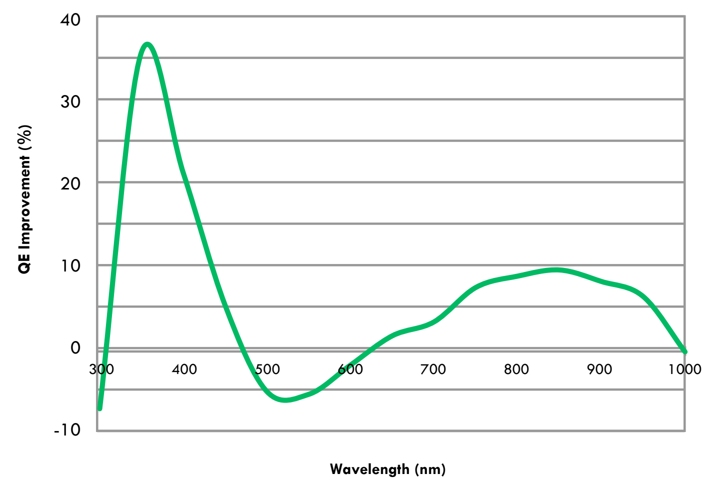


Figure 6. The improvement in QE provided by eXcelon3 back-illuminated EMCCDs relative to standard thinned back-illuminated EMCCDs.

Until now, researchers whose applications require low-light broadband photon detection had but one choice when utilizing an EMCCD camera.

Another key eXcelon3 advantage is the new technology's lower etaloning in the NIR. Figure 7 presents a series of images showing the etaloning performance of cameras utilizing standard thinned back-illuminated EMCCDs and eXcelon3 back-illuminated EMCCDs.

Finally, eXcelon3 technology has similar dark current to the AIMO (Advanced Inverted Mode Operation) utilized by standard thinned back-illuminated EMCCDs. This is 100x lower than that of the NIMO (Non-Inverted Mode Operation) employed by back-illuminated deep-depletion CCDs. Low dark current is an important consideration, especially in spectroscopy, where signal is integrated over many minutes and binned over several rows.

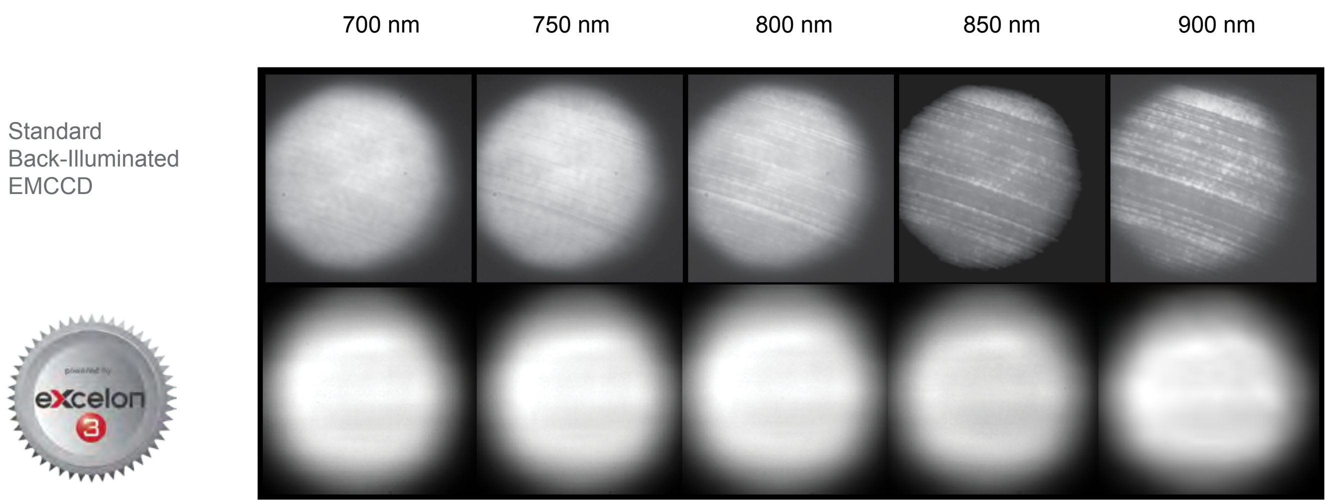


Figure 7. Etaloning in the NIR for standard thinned back-illuminated EMCCD cameras and eXcelon3 back-illuminated EMCCD cameras.

Another key eXcelon3 advantage is the new technology's lower etaloning in the NIR.

**Data shown for imaging-format eXcelon3 EMCCDs. Similar improvements are seen for spectroscopy-format eXcelon EMCCDs. Refer to www.princetoninstruments.com/products/excelon for details.*

eXcelon3 is a breakthrough technology that provides the best EMCCD performance available on the market!

Comparison: eXcelon3 vs. less advanced EMCCD designs

Princeton Instruments' exclusive eXcelon3 EMCCD technology is the result of years of dedicated R&D. This custom technology represents an intelligent and comprehensive approach to EMCCD performance improvement. From the time Princeton Instruments first introduced its original eXcelon technology to the market, however, several other manufacturers have touted their own design enhancements, claiming to provide similar improved performance. In truth, their relatively simplistic approaches (e.g., mere utilization of AR coatings) provide camera users with only modest gains. Princeton Instruments' eXcelon3, on the other hand, is a true breakthrough technology that delivers readily appreciable benefits. Figures 8 and 9, for instance, show that eXcelon3-enabled cameras offer far less etaloning than cameras that rely on less-sophisticated EMCCD designs.

Both figures compare etaloning performance at the critical NIR wavelengths from 700 to 900 nm. A broadband light source coupled to a monochromator acts as an illuminator. The data presented is a series of images taken at 1 nm increments that shows the onset of etaloning around 700 nm in the less-advanced designs. From the data, it can also be appreciated that due to the spatial and temporal variation of etaloning, it is very difficult to correct for this phenomenon during post-processing. In contrast, Princeton Instruments ProEM+ cameras with eXcelon3 significantly reduce etaloning throughout the NIR region.

Figure 8. Improvement in etaloning of eXcelon3 back-illuminated EMCCDs (right) over less-sophisticated back-illuminated EMCCD designs (left). To watch this video online, please visit www.princetoninstruments.com/products/excelon.

Figure 9. Reduction in etaloning provided by eXcelon3 back-illuminated EMCCDs (right) compared to less-sophisticated back-illuminated EMCCD designs (left). Cross-sectional data of magnified images from Figure 8 at various wavelengths. To watch this video online, please visit www.princetoninstruments.com/products/excelon.

Ways to further improve sensitivity

While sensor technology is an important determiner of camera system sensitivity and signal-to-noise ratio in a given experiment, factors such as optical window throughput are also important.

To maximize light throughput, Princeton Instruments uses a highly advanced single-window vacuum design (see Figure 10). This means the vacuum window is the only optical surface encountered by incident photons before they reach the EMCCD detection surface. Although the design is the best available, each uncoated optical surface of the vacuum window can still have 3 to 4% transmission loss, or a total loss of 6 to 8%. For light-starved imaging applications, this loss can result in a significant reduction of signal-to noise ratio. Moreover, any light reflected inside the system can lead to glare and fringing, especially when used with coherent illumination. The solution is to apply anti-reflective (AR) coatings on the window in the optical path, which reduces total losses to below 1% and sometimes even to less than 0.5%. For applications utilizing extremely coherent light sources, a wedge window may also be required to eliminate glare and fringing.

Figure 10. A single vacuum window with optimized anti-reflective coating ensures maximum light throughput. Furthermore, a brazed metal-to-glass interface provides long-term vacuum seal integrity, as opposed to the degradation associated with traditional epoxy.

Princeton Instruments cameras are designed with a single window made of high-grade fused silica/quartz/ MgF_2 that acts as a vacuum viewport. Any shipping-protection windows on the EMCCD are removed prior to installing it in the vacuum chamber. The vacuum window,

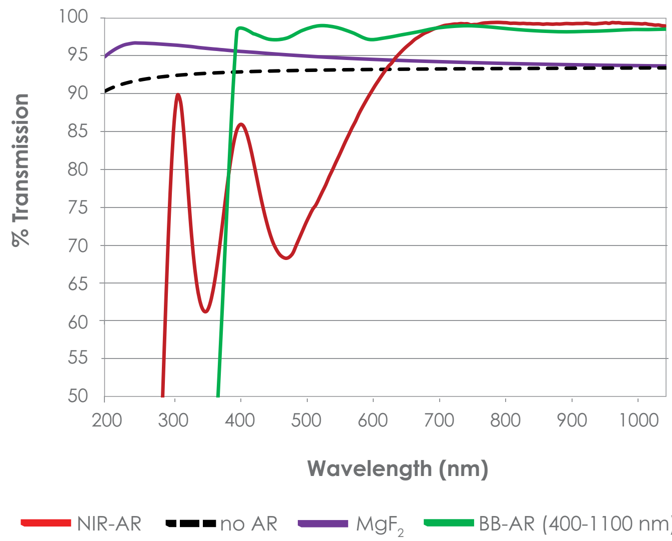


Figure 11. Princeton Instruments offers a choice of multiple-layer coating options on the vacuum window.

which is brazed (a high-temperature fusion process at the molecular level) to the vacuum chamber, can be customized with single- or multiple-layer AR coatings to match the wavelength of interest (see Figure 11). It should be noted that AR coatings typically provide the best performance when they are tuned for a narrow wavelength range. Since they may have poorer transmission outside their optimum wavelength range, care must be taken before choosing an AR coating.

Conclusions

Developed by Princeton Instruments, new eXcelon3 EMCCD technology provides higher sensitivity (over a broad wavelength range) as well as lower etaloning than standard thinned back-illuminated EMCCDs. For most imaging and spectroscopy applications in which standard thinned back-illuminated EMCCDs are commonly utilized, such as single-molecule fluorescence, FRET, luminescence, kinetics, BEC imaging, Raman spectroscopy, and astronomy, eXcelon3 now offers researchers superior performance (see Figure 12).

Acknowledgment

[1] N.I. Hammer, K.T. Early, K. Sill, M.Y. Odoi, T. Emrick, and M.D. Barnes, "Coverage-mediated suppression of blinking in solid state quantum dot conjugated organic composite nanostructures," Journal of Physical Chemistry B, 110, 14167, (2006). Copyright © 2006 American Chemical Society.

Choosing the Right Camera

Figure 12. Technology and application summary. Next-generation eXcelon3 technology is available in Princeton Instruments EMCCD cameras. Novel eXcelon technology from Princeton Instruments is available for select back-illuminated CCD cameras with thinned and deep-depletion sensor architectures.

Appendix A: Etaloning in the NIR

Standard thinned back-illuminated EMCCDs are solid-state imaging devices that have been etched to 10 to 15 µm thickness in order to collect light through the back surface. As a result of this modification, no light is lost via absorption and reflection by the polysilicon gate structure; these EMCCDs have more than twice the QE of their front-illuminated counterparts. An unfortunate side effect of this process is that the devices become semi-transparent in the NIR. Reflections between the parallel front and back surfaces of these EMCCDs cause them to act as partial etalons. This etalon-like behavior leads to unwanted fringes of constructive and destructive interference, which artificially modulate a spectrum. The extent of modulation can be significant (more than 20%) and the spectral spacing of fringes (typically 5 nm) is close enough to make them troublesome for almost all NIR spectroscopy.

An etalon is a thin, flat transparent optical element with two highly reflective surfaces that form a resonant optical cavity. Only wavelengths that fit an exact integer number of times between the surfaces can be sustained in this cavity. Because of this property, etalons can be used as comb filters, passing just a series of uniformly spaced wavelengths. In an imperfect etalon, the reflectance of the surfaces becomes less than 100% and the spectral characteristics soften from a spiky comb to a smooth set of fringes. Absorption between the surfaces also worsens the quality of the resonant cavity, which is measured by cavity finesse (see Figures A-1, A-2, and A-3).

Thus, the three factors that determine the shape and character of an etalon are d, the distance between the two surfaces; λ, the wavelength of the light; and **Q**, the finesse of the cavity, as shown in the following equation (where ***I*** is intensity):

$$I = \frac{I_{max}}{1+(2Q/\pi)^2\sin^2(2\pi d/\lambda)}$$

(Equation adapted from B. Saleh and M. Teich, Fundamentals of Photonics, John Wiley & Sons, New York, 1991)

At NIR wavelengths, the silicon of which EMCCDs are made becomes increasingly transparent, causing the QE to decline in the red. The back surface, where light enters an EMCCD in the back-illuminated configuration, is typically AR coated. These coatings are not perfect, however, and their effectiveness varies by wavelength. Most EMCCD back-surface AR coatings are not optimized for the NIR.

For example, the reflection from the back surface of an EMCCD that is optimized for ultraviolet (UV) response is worse in the NIR than that from an EMCCD whose AR coating is optimized for longer wavelengths.

Once light has passed through the body of an EMCCD and is about to reach the polysilicon electrodes, it encounters a sandwich of layers that generally includes silicon dioxide (refractive index 1.5). This sizeable discontinuity from the refractive index of silicon (which is 4) produces a large

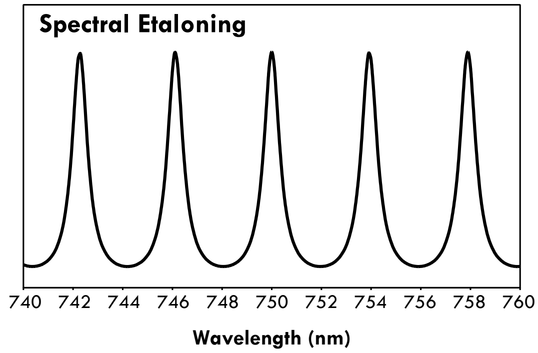


Figure A-1. Example of spectral etaloning showing the variation in intensity (vertical axis) with wavelength.

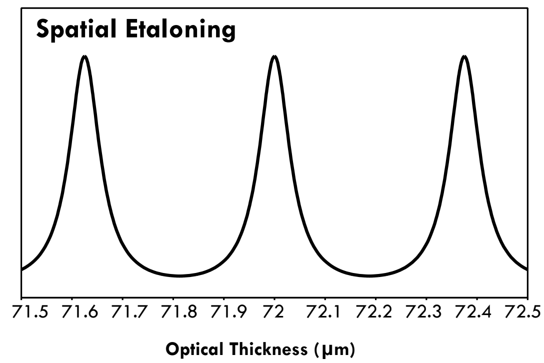


Figure A-2. Example of spatial etaloning showing the variation in intensity (vertical axis) with thickness.

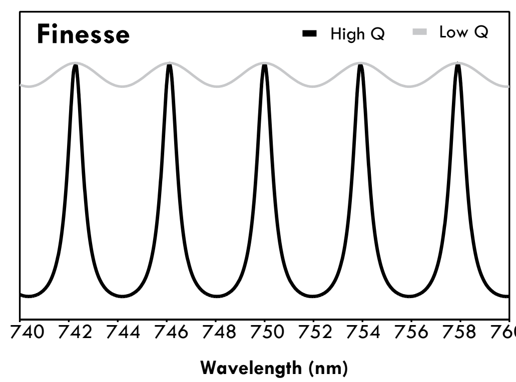


Figure A-3. Example of etaloning showing the effects of finesse (Q) on the quality of the etalon.

reflection back into the EMCCD. At wavelengths where silicon is transparent enough that light can traverse the thickness of the EMCCD several times, light bounces back and forth between the two surfaces. This increases the effective path length in the silicon (enhancing the QE) and also sets up a standing wave pattern. Amplitude is lost at both reflective surfaces and by absorption in the body of the silicon. However, at longer wavelengths, sufficient amplitude survives to cause significant constructive or destructive interference.

While silicon is usually thought of as opaque, it must be remembered that a standard back-illuminated EMCCD is typically only 10 to 15 µm thick (less than a thousandth of an inch). A layer this thin can transmit a significant fraction of NIR light. For example, a back-illuminated EMCCD that is 15 µm thick (mechanically) would have the effective optical thickness of about 60 µm (since the refractive index of silicon in this wavelength range is 4). Thus, the roundtrip optical path length between the surfaces is approximately 120 µm. At 750 nm, this would be 160 wavelengths. Therefore, there would be constructive interference at 750 nm. This pattern of interference would continue to repeat with intervals of about 5 nm.

In addition to the spectral source of etaloning, in a thinned EMCCD there can also be spatial etaloning. The spatial pattern arises from the incidence of monochromatic light on an etalon whose thickness is not perfectly constant. A small variation in thickness can change the local properties from constructive to destructive interference. The change required is only a half-wavelength in the roundtrip path length. Since the index of silicon is 4, the change in EMCCD mechanical thickness required to produce this optical effect is only about 1/16 of a wavelength, or 0.05 µm at a wavelength of 800 nm. This effect can actually be used to visualize how uniform the thickness of an EMCCD is. If an EMCCD had perfectly uniform thickness, the modulation due to spatial etaloning at a given wavelength would disappear. All pixels would have the same degree of constructive or destructive interference at a given wavelength.

In most imaging applications with standard thinned back-illuminated EMCCDs, spatial etaloning is not evident because the applications are at shorter wavelengths, where the silicon absorption damps out the etalon effect. In addition, many applications use light that is spectrally broad enough to span (and average out) several etalon-fringe cycles. The latter requires only a spectral bandwidth of a few nanometers. In a spectrometer, by comparison, the light on any one column of pixels is very narrow spectrally, typically less than 0.1 nm. Thus, this spectral bandwidth is much less than the period of etalon cycles (~5 nm). As a result, spatial etaloning is quite evident when viewing an image of a uniform spectrum (e.g., tungsten bulb) in the NIR (see Figure A-4).

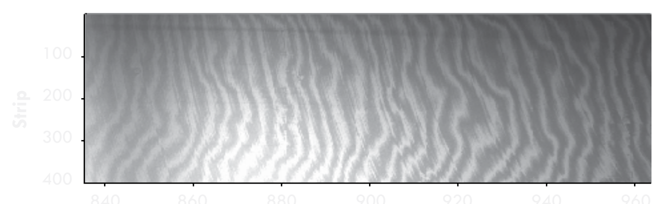


Figure A-4. Image from a back-illuminated CCD camera showing combined spectroscopic and spatial etaloning.

Spectroscopic etaloning is related to, but different from, spatial etaloning. It derives from the fact that in a spectrometer the wavelength of light varies across the EMCCD. Thus, even if a back-illuminated EMCCD was available with absolutely uniform thickness, it would still show fringes due to this etalon effect. The fringes in this case are due to the variation of the wavelength, not the thickness. As a result, when a spectrum is dispersed across a back-illuminated EMCCD, the characteristic comb pattern will be superimposed on the normal response.

Appendix B: Effect of cooling on QE

In addition to the sensor technology type and factors such as optical window throughput, cooling the detector has an effect on QE. Typically, cooling decreases long-wavelength coverage due to a change in electron mobility and effective path lengths. Figure B-1 presents a theoretical estimate of QE as various sensors are cooled.

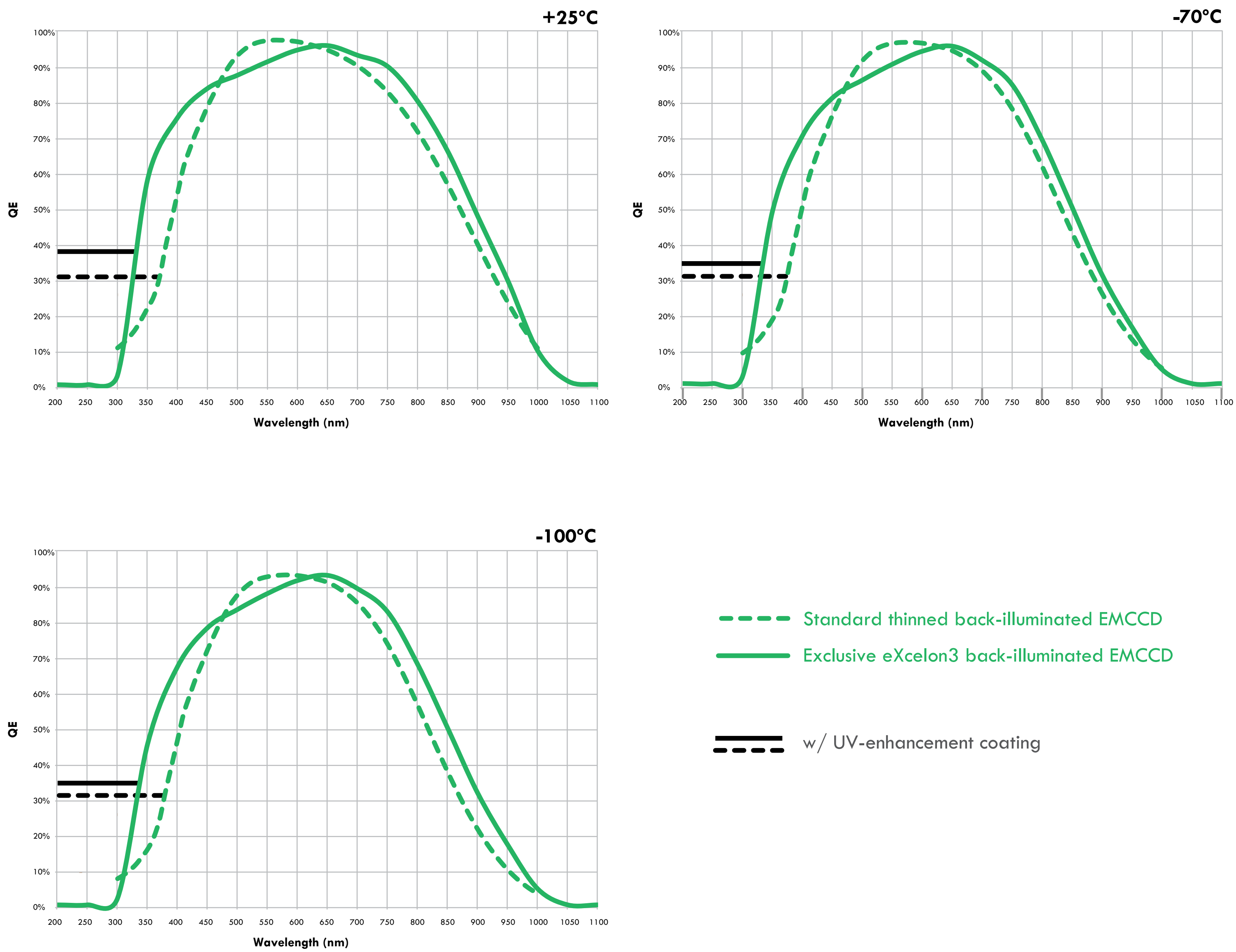


Figure B-1. QE for various types of back-illuminated EMCCDs at +25°C, -70°C, and -100°C. Solid/dashed black lines on the left represent QE in UV region with optional UV-enhancement coatings.

EMCCD, ICCD, or CCD?

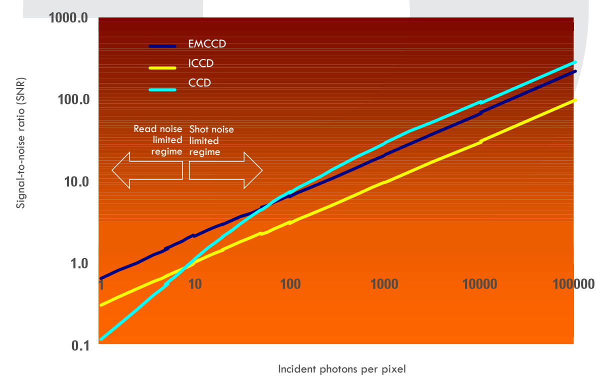
Choosing the right camera technology…

One of the most frequently asked questions when selecting a detector is which technology should be used for low-light-level applications. Princeton Instruments works with all major low-light detector technologies to date, including standard CCDs, intensified CCDs, and electron-multiplying CCDs. As a result, we are in a unique position to recommend the right detector technology to suit a given application. Although all current state-of-the-art detectors are capable of detecting very low light levels, specific demands such as frame rates, exposure times, and fields of view dictate eventual choice.

	EMCCD	ICCD	CCD
Excess noise factor	1.4	2.0 to 3.0	1
Spurious noise	yes, but negligible	no	no
Susceptible to damage due to bright lights	low	high	none
Min. exposure	milliseconds*	sub-nanoseconds	milliseconds*
Gating	no	yes	no

**EMCCDs and CCDs can be operated in kinetics mode with μsec exposure times in a greatly reduced region of interest.*

The ProEM+ offers dual amplifiers for traditional CCD as well as EMCCD operation.



Signal-to-noise ratio

Typically, EMCCDs and ICCDs, which use internal amplification or gain mechanisms, are preferred for kinetic studies when a short-lived phenomenon needs to be temporally resolved. In this case, the available photons per exposure are limited and the frame rate (consequently read noise) is high. The internal gain of EMCCDs and ICCDs effectively reduces the read noise of the detector, allowing the detection of very faint objects. However, the amplification process also creates additional noise, specified by excess noise factor, that limits the achievable signal-to-noise ratio. For applications requiring detection of very low light (below read noise levels) and frame rates of hundreds of frames per second, this is a compromise that must be acknowledged.

The preceding plot provides a comparison of the signal-to-noise ratio at various incident photon counts achievable with the three technologies. It can be seen that when the signal is below the read noise (in the read-noise-limited regime) EMCCDs offer the highest sensitivity thanks to their low excess noise factor compared to ICCDs. As the light level increases, or as the system becomes shot-noise-limited, EMCCDs (and ICCDs) offer lower signal-to-noise ratios compared to standard CCDs. Some EMCCDs, such as those used in the ProEM+, offer dual amplifiers to enable standard CCD as well as EMCCD operation. Therefore, when imaging under high-light-level conditions or performing steady-state imaging, the ProEM+ camera can be operated as a standard CCD camera.

Susceptibility to damage

All optical detectors, including CCD, EMCCD, and ICCD cameras, must be protected from intense light sources such as lasers and other radiation sources.

ICCDs are especially susceptible to damage if they are accidentally exposed to bright light sources. EMCCDs and CCDs, on the other hand, are less susceptible to such damage. A note of caution regarding the operation of EMCCD cameras – it is known that the attainable level of multiplication gain is reduced with repeated use under bright lights and at high EM gain levels.

Although advanced EMCCD cameras such as the ProEM+ do have built-in anti-aging protection and/or automatic recalibration, care must be taken not to use excessive EM gain when the incident light level is high. Note that this is different from the catastrophic failure of intensifier tubes that can occur in the presence of bright lights.

Gating

Gating refers to a camera's ability to take extremely short exposures, ranging from a few hundred picoseconds to microseconds. By controlling the forward bias voltage, ICCD intensifier tubes can be turned on or off with a high degree of precision. In addition, the on/off ratio of intensifiers, which quantifies the degree of shuttering effectiveness, can be as high as 10^7:1. As a result, ICCD cameras provide impressive gating capabilities. When applications require capturing time slices of a short-lived and/or repeated phenomenon, ICCDs are a good choice. For other low-light applications that do not require gating, EMCCDs are a better choice due to their lower noise factor and higher spatial resolution.

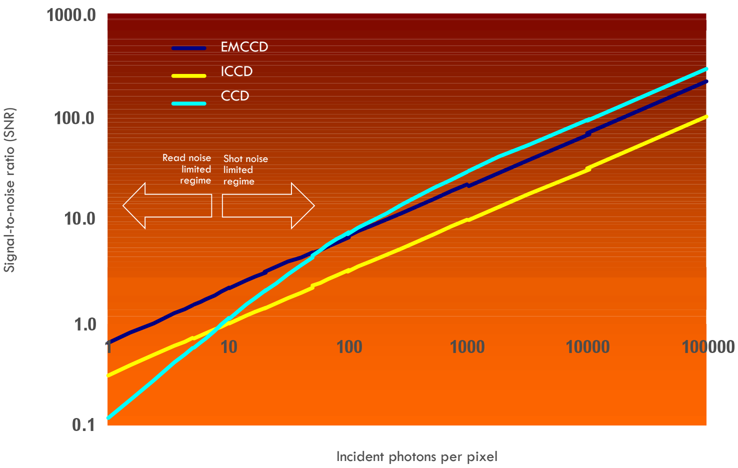
Slow-scan applications

While the biggest advantage of EMCCD cameras is seen when used in applications that require low-light capture at high frame rates, more versatile EMCCD cameras such as the ProEM+ offer both high-speed EM and slow-speed traditional CCD modes of operation. For example, the ProEM+ is specially equipped with a 100 kHz traditional CCD mode of operation to deliver read noise as low as 3 e- rms and high signal-to-noise ratio. Since the traditional CCD mode does not suffer from excess noise factor, it provides the best achievable signal-to-noise ratio for photon flux above the read noise limit.

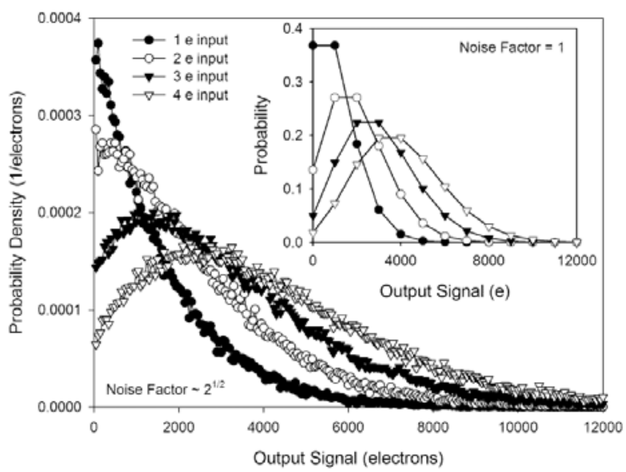
EMCCDs are a better choice due to their lower noise factor and higher spatial resolution.

What is the application's light level?

Single photon to a few photons… capturing them all



Signal-to-noise ratio (SNR) vs. incident photons: a comparison between back-illuminated EMCCD, ICCD, and CCD detectors.



Simulated output signal distribution for a range of mean input signal levels (zero dark signal). Input follows a Poisson distribution. The signal passes through 536 multiplication stages providing a total mean gain of 1000. Inset shows the probability versus output assuming a noise factor of unity. Data courtesy of e2v technologies.

A proper understanding of the operating characteristics of EMCCDs allows users to optimize performance for different applications. Essentially, the available light levels can be divided into the following categories:

- Shot-noise-limited regime (high light)
- Read-noise-limited regime (low light)
- Single-photon detection (extremely low light)

In the shot-noise-limited regime, the signal-to-noise ratio of the system is limited by the photon shot noise itself. Here, a standard CCD or an EMCCD (with no gain applied) offers superior signal-to-noise ratio. With EMCCD cameras that provide dual amplifiers, such as the ProEM+, a traditional readout port can also be used.

When fast processes need to be studied, such as single-molecule dynamics, there is neither sufficient light nor time to accumulate enough photons. In this scenario, the experiment is said to be read-noise-limited. Here, EMCCDs are operated with just enough gain to overcome the system read noise and effectively achieve sub-electron read noise (<1 e- rms). Using "just enough" gain is important, as it reduces long-term aging effects associated with EMCCDs and maximizes the dynamic range so that bright objects do not saturate.

As photon flux continues to decrease, EMCCDs can be operated in photon-counting mode. In this mode, the detector is operated with >1000x EM gain and a threshold scheme is used to count the photon "hits". Several researchers are currently working on photon-counting schemes using EMCCDs. Potential applications range from astronomy to quantum optics. Photon arrival rates, pulse height distribution of output signal, and spurious or clock-induced charge are some of the factors that need to be kept in mind when trying to use these cameras in photon-counting applications.

What is clock-induced charge?

...and how to keep it low

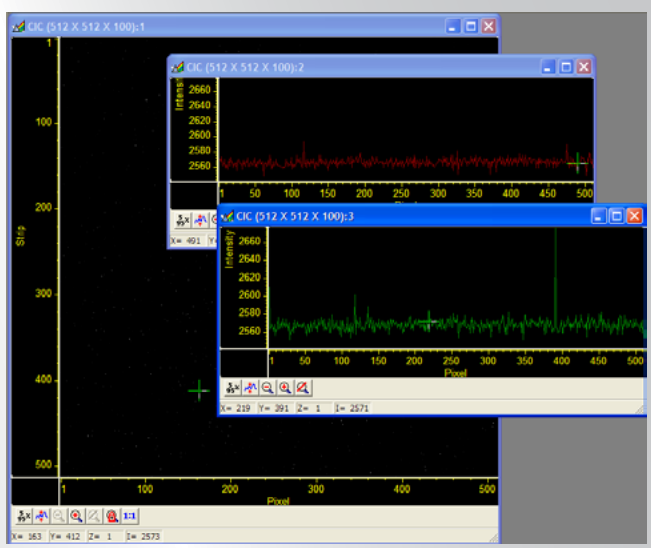
Clock-induced charge (CIC) is a noise source that must be taken into account when operating EMCCDs at single-photon levels. As charge is shifted from pixel to pixel during readout, a random electron may be generated in the pixel purely due to clock transitions. Once an electron is generated in the pixel, it undergoes the same multiplication process as a photon-induced electron. Since this noise is generated during readout, it is independent of exposure time. Empirical tests show that CIC is only weakly dependent on the temperature of the sensor. Dark current, meanwhile, is a function of exposure time and is dependent on temperature.

	CIC	Dark current
Source of noise	electronic	thermal
Function of exposure time	no	yes
Temperature dependent	no (or weakly)	yes
Units of measure	e-/pixel/frame	e-/pixel/second

The presence of CIC creates an error in photon estimation. The state-of-the-art ProEM+ minimizes spurious charge by optimizing clock voltages and timing edges, down to 0.005 e-/pixel/frame. In other words, when a 512 x 512 image is captured under dark conditions at 1000x EM gain, the probability is that a total of 1310 spurious electrons are generated over the entire imaging area. The ProEM+ achieves this extremely low level of CIC via precise control of several factors, including:

- Keeping parallel clock voltages low while retaining optimal charge transfer efficiency and full well
- Increasing the vertical shift rate
- The careful shaping of clock transitions to remove sharp edges

Image taken at 1000x EM gain to show clock-induced charge. With careful clock shaping and optimization, the CIC is reduced to 0.005 e-/pixel/frame.



Princeton Instruments Noise Suppression (PINS)

...exclusive camera technology for a broad range of applications

With the launch of the ProEM+, Princeton Instruments unveiled the most advanced readout electronics in a scientific camera to date. The culmination of decades of experience designing low-noise cameras, the ProEM+ delivers the lowest noise of any EMCCD camera on the market. In order to achieve hitherto unattainable performance, our engineers utilized cutting-edge electronics that a casual user might not appreciate at first glance. For example, the signal chain is kept pristine by keeping all switching power supplies isolated from the ProEM+ camera's most sensitive, low-level signal circuitry. Furthermore, to achieve the best noise performance and linearity possible, independent signal chains have been created for the camera's EM and traditional CCD operation modes.

Readout speed	Read noise	Read noise with EM gain applied
10 MHz (EM mode)	50 e- rms	<1 e- rms
5 MHz (EM mode)	25 e- rms	<1 e- rms
5 MHz (traditional CCD mode)	12 e- rms	not applicable
1 MHz (traditional CCD mode)	7 e- rms	not applicable
100 kHz (traditional CCD mode)	3 e- rms	not applicable

Typical ProEM+ read noise performance at various speeds of operation.

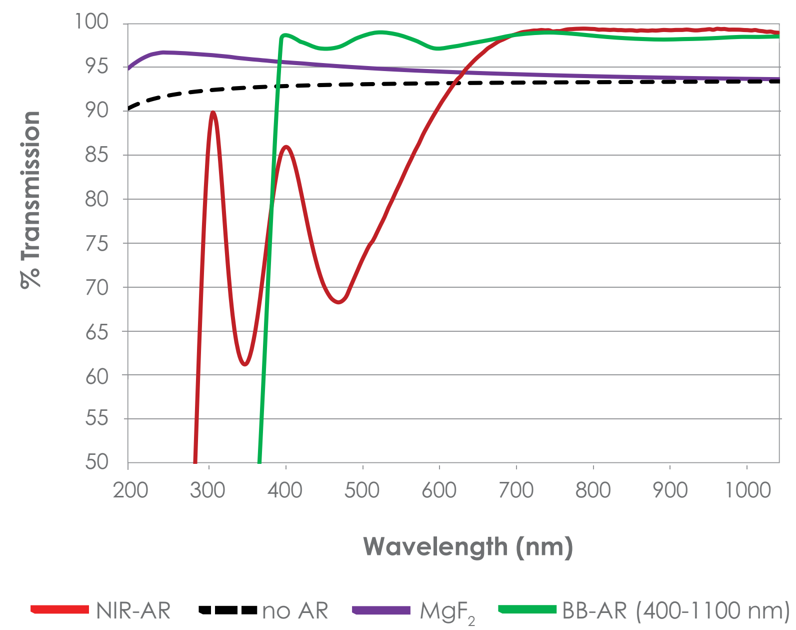
Read noise in EM mode can be effectively reduced to below 1 e- rms in the ProEM+. This low starting read noise can pay long-term dividends, as using smaller EM gain levels extends the life of the device and preserves dynamic range by preventing saturation of brighter objects in the image. When operated in traditional CCD mode, extremely low (3 e- rms @ 100 kHz) read noise translates to no-compromise ProEM+ performance equal to that of any standard slow-scan CCD camera. This combination of superb noise performance both in EM and traditional CCD operation modes is possible only with the ProEM+.

ProEM+'s superb noise performance in EM and traditional CCD modes is unrivaled in the industry.

Anti-reflective coatings
and single-window design

Don't lose a photon…

To maximize light throughput, the ProEM+ uses a highly advanced single-window vacuum design. This means the vacuum window is the only optical surface encountered by incident photons before they reach the EMCCD detection surface. Although the design is the best available, each uncoated optical surface of the vacuum window can still have 3% to 4% transmission loss, or a total loss of 6% to 8%. For light-starved applications, this loss can result in a significant reduction of signal-to-noise ratio. Moreover, any light reflected inside the system can lead to glare and fringing, especially when used with coherent illumination. The solution is to apply anti-reflective coatings on the window in the optical path, which reduces total losses to below 1% and sometimes even to 0.5%.



Princeton Instruments offers a choice of multiple-layer coating options on the vacuum window.

All Princeton Instruments cameras, including the ProEM+, are designed with a single window made of high-grade fused silica/quartz/MgF_2 that acts as a vacuum viewport. Any shipping-protection windows on the EMCCD are removed prior to installing it in the vacuum chamber. The vacuum window can be customized with multiple-layer AR coatings to match the wavelength of interest. Customers should note that AR coatings typically provide the best performance when they are tuned for a narrow wavelength range. Since they may have poorer transmission outside their optimum wavelength range, care must be taken before choosing an AR coating. Princeton Instruments representatives can help users select the most appropriate AR coating for their application needs. For use with coherent light sources such as lasers, Princeton Instruments also provides AR-coated wedge window options.

A single vacuum window with optimized anti-reflective coating ensures maximum light throughput. Furthermore, a brazed metal-to-glass interface provides long-term vacuum seal integrity, as opposed to the degradation associated with traditional epoxy.

Cooling and vacuum

Princeton Instruments' exclusive lifetime guarantee…

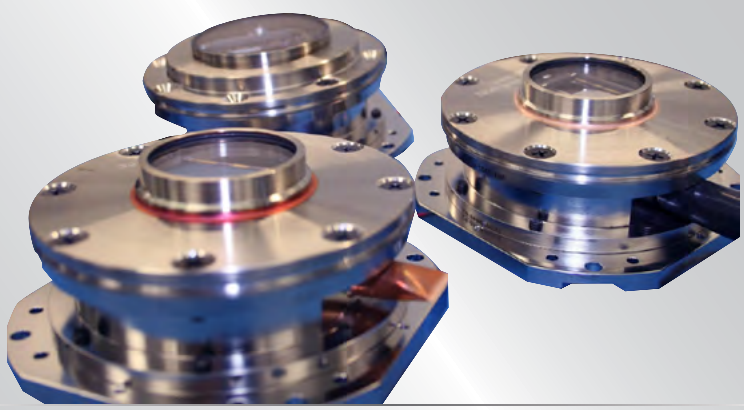
While methods for cooling scientific cameras represent a relatively mature area of technology, Princeton Instruments is nonetheless the only company in the world able to offer a lifetime guarantee on its cooling. This guarantee is not a hollow claim. It is backed by many years spent perfecting vacuum designs and associated manufacturing processes.

The cool essentials

The cooling technology utilized in the ProEM+ uses a hermetically sealed vacuum chamber with all-metal seals. A single vacuum window is brazed to the housing to produce a perfect seal year after year. This design contrasts the traditional, epoxied seals used by most camera manufacturers that lead to degradation and vacuum leaks. The contents of the vacuum chamber are minimized to reduce and eliminate outgassing that can occur over time. The entire vacuum assembly is baked and vacuum-processed for more than five days and continuously checked prior to being tested inside a camera.

Princeton Instruments is the only scientific imaging company that guarantees both cooling temperature and dark current for the lifetime of the camera. It is important to note that ProEM+ cooling is achieved without additional power supplies.

Princeton Instruments is the only scientific imaging company that guarantees both cooling temperature and dark current for the lifetime of the camera.



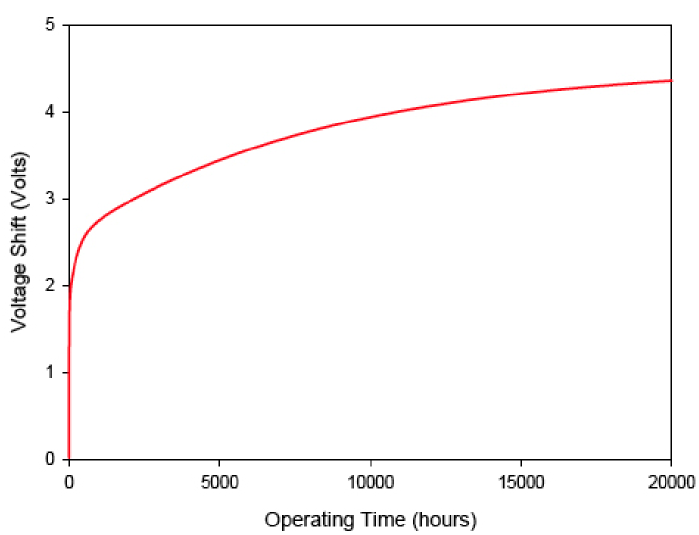
All-metal vacuum seals are superior to traditional epoxy-based seals that may degrade over time.

Aging in EMCCDs

…and countering it

Multiplication gain diminishes over time, especially when an EMCCD is used in high-light-level conditions and at high gain levels. While definitive data is not yet available on the cause of aging and the factors affecting it, empirical data shows that aging is a strong function of the amount of signal passing through the multiplication register. It is typically quantified by the amount of voltage increase required to maintain the original level of multiplication gain.

Note that the data presented here depicts the results of an extreme test not typically encountered in low-light-level applications. In normal situations, little or no EM gain is needed to achieve the optimum signal-to-noise ratio. All ProEM+ cameras are calibrated to provide a maximum of ~1000x EM gain. The EM gain levels beyond 100x are only useful for detecting single photons.



An example of EMCCD aging when the device is operated at the maximum 1000x gain for a prolonged period and at a high level of output. The voltage shift represents the amount of increase required for the high-voltage clocks to maintain 1000x multiplication gain.
Data courtesy of e2v technologies.

Princeton Instruments has taken several measures to counter the effect of aging in the ProEM+. These steps include setting the EM gain to unity when the EM gain is not being used, as well as running the high-voltage clocks lower than their maximum rated levels. The latter is possible because at the cold temperatures at which the camera operates, 1000x can be achieved using lower levels on the high-voltage clocks. Furthermore, the camera's auto-calibration procedure can compensate for any gain reduction by increasing the clock voltages by just a few volts.

Despite the anti-aging measures built into the ProEM+, some general precautions are helpful in further countering the effect of aging:

- Use the minimum required EM gain for a given light level. For example, only ~50x gain is needed to achieve <1 e- rms read noise. Once <1 e- rms effective read noise is achieved, there will be no further improvement in signal-to-noise ratio for most applications.
- Turn down the EM gain to 1x when used with bright light sources.
- Use maximum gain only when there is a need to amplify single-photon events above the background for the purpose of thresholding.

Princeton Instruments has taken several measures to counter the effect of aging in the ProEM+.

When speed is everything

…maximizing the frame rate

One of the biggest advantages that EMCCDs bring to scientific imaging is the ability to deliver very high frame rates while maintaining extremely low read noise (<1 e- rms).

The ProEM+ provides high-speed, low-noise performance with the flexibility to handle any challenging application. The camera's unique modes of operation increase the frame rate beyond the EMCCD's normal limits.

This section details some of the advanced speed-related features of the ProEM+.

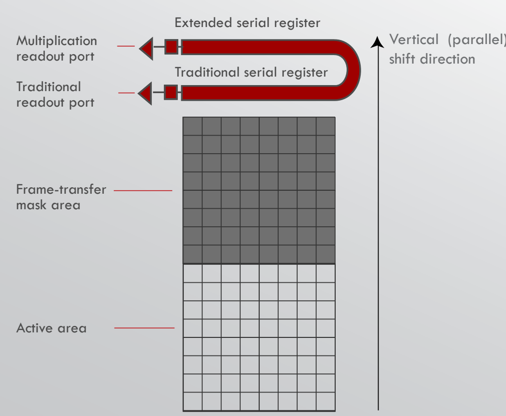
Feature	Benefit
Frame-transfer EMCCD	100% duty cycle imaging, expose the next frame while the current frame is being read out
Fast vertical shift time	Reduce vertical smearing, minimize exposure time
Variable vertical shift time	Optimize EMCCD operation for slow-speed or high-speed applications
Custom chip mode	Achieve the highest frame rate possible by effectively redefining the EMCCD size
NEW Kinetics and spectra-kinetics modes	Achieve burst spectra rates up to 1 million frames per second

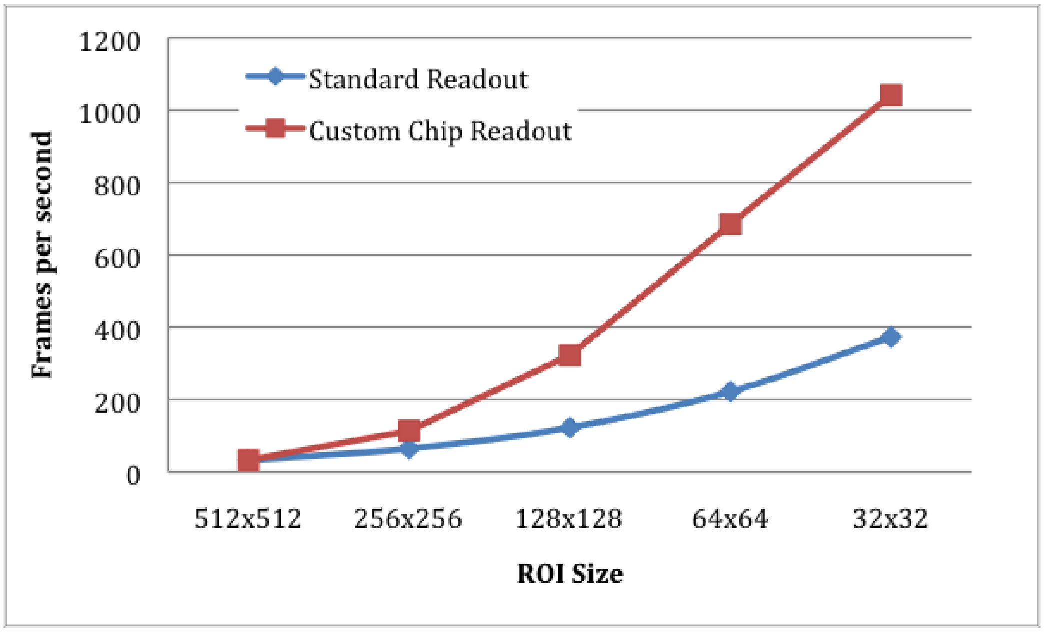
Fast/variable vertical shift time

Vertical shift refers to the movement of charge (electrons) captured in a pixel into the serial register. The highest rate at which the electrons can be transferred is limited by many factors, including the EMCCD's capacitance. Note that increasing the vertical shift time has an effect on the charge transfer efficiency (CTE) of the EMCCD.

Poor CTE is apparent when circular objects, such as single molecules, appear elongated. Careful re-optimization of multiple clock voltages on the EMCCD is required to restore CTE when the vertical transfer rate is increased.

By employing completely independent voltages optimized for each vertical shift speed, the ProEM+ not only preserves CTE but maximizes overall camera performance.





Custom chip mode

The ProEM+, like many other Princeton Instruments cameras, supports custom chip mode. This innovative feature allows users to redefine the size of the EMCCD's active area via software. Unlike setting a smaller region of interest (ROI), which also involves reading out fewer pixels, custom chip mode does not incur overhead from discarding or skipping the rest of the rows.

In custom chip mode, all pixels outside the current active area are ignored, thereby saving time spent to shift. However, when using custom chip mode, users must ensure that no light falls outside the currently set active area, as illustrated in the following example. For a 512 x 512 format sensor, using the ROI method to read out 128 x 128 pixels would take 8.2 ms, or a frame rate of 122 fps (1/0.0082). Using the custom chip feature, the readout time for the same region would drop to 3.1 ms, which is equivalent to a frame rate of 323 fps.

The graph above compares the ProEM+:512B camera's expected frame rates using standard ROI readout and custom chip readout.

This innovative feature allows users to redefine the size of the EMCCD's active area via software.

Kinetics

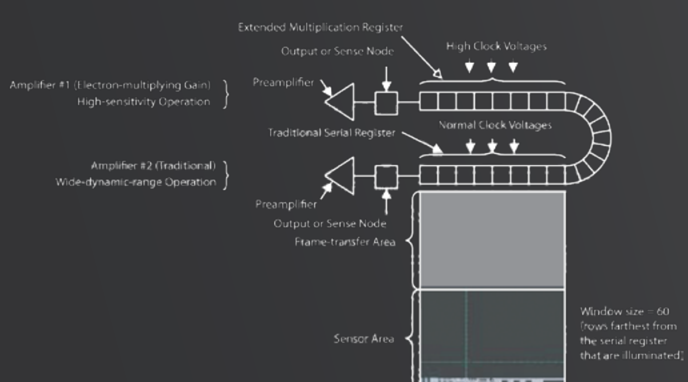
...take advantage of advanced readout modes

Kinetics refers to a special readout mode in which a portion of the EMCCD is illuminated while the rest of the array is used as a temporary storage area. At the end of the exposure-shift sequence, the entire EMCCD is read out to provide a series of sub-frames (kinetic frames) separated in time. In order to support this special mode of operation, it is essential that the camera architecture be flexible and offer special access to underlying EMCCD clocking functions. The ProEM+, like many Princeton Instruments cameras, supports this type of burst readout mode for microsecond time resolution. The kinetics feature is particularly attractive to Bose-Einstein condensate (BEC) researchers, as well as those interested in capturing transient events at the microsecond timescale.

Though the frame rate can be increased by using a smaller subregion and/or binning, in most scientific-grade cameras the rate is still limited to temporal resolutions on the order of milliseconds to seconds. Kinetics readout allows a burst of sub-frames to be captured with microsecond resolution, albeit using a much smaller field of view. This is accomplished by shifting each sub-frame exposure under the mask before reading it out. Since there is no overhead of readout time between each exposure, higher temporal resolution is achieved. At the end of the exposure-shift series, the entire frame can be read out at a slower readout speed. Since the exposure time for each sub-frame is typically on the order of a few microseconds, the available number of photons per exposure tends to be low. When the light level is well below the read noise, EM gain can be used to improve signal-to-noise ratio.

In kinetics mode, a portion of the EMCCD image is optically masked in order to minimize the crosstalk between sub-frames. In imaging applications, this can typically be accomplished by placing a knife edge or optical mask in the collimated beam path. In spectroscopy, this is best achieved by limiting the height of the entrance slit of the spectrograph. In most applications, the ability to mask as few rows as possible sets the ultimate limit on the temporal resolution.

*Data acquired shows multiple sub-frames separated in time by only a few μsec. Temporal resolution is given by "number of rows in the sub-frame * vertical shift rate + exp. time".*



In this example, kinetics operation is illustrated using the frame-transfer EMCCD featured in the ProEM+ camera. A partially illuminated image of a target is overlaid on the EMCCD diagram for illustration. The illuminated area is the farthest from the serial register.

NEW

Spectra-kinetics mode

In standard kinetics mode, binning is performed in the serial register. This limits the total event time that can be captured, even for spectroscopy applications. By binning under an external "variable kinetic mask", however, Princeton Instruments' exclusive new spectra-kinetics option is able to capture longer-duration events and provide higher sensitivity than standard kinetics mode.

Use of spectra-kinetics allows the ProEM+ camera to acquire the full masked height's worth of spectra regardless of the height of the "illuminated" rows — all while delivering the same temporal resolution as standard kinetics.

	Kinetics	**Spectra-kinetics**
Rows illuminated	Farthest away from the serial register	Closest to the frame-transfer mask
Time resolution	N*V.shift speed	N*V.shift speed
Number of kinetic frames	Total height/N (N = illuminated number of rows)	Frame-transfer mask height (independent of N)
Included as standard option	Yes	Standard for ProEM+:512BK Optional for ProEM+:512B and 1024B

	ProEM+:512B/BK		**ProEM+:1024B**	
Rows illuminated	Total number of kinetic frames (kinetics)	Total number of kinetic frames (spectra-kinetics)	Total number of kinetic frames (kinetics)	Total number of kinetic frames (spectra-kinetics)
32	32	538	64	1024
64	16	538	32	1024
128	8	538	16	1024
256	4	538	8	1024

NEW

ProEM+:512BK

…exclusive sensors designed for ultrafast kinetics

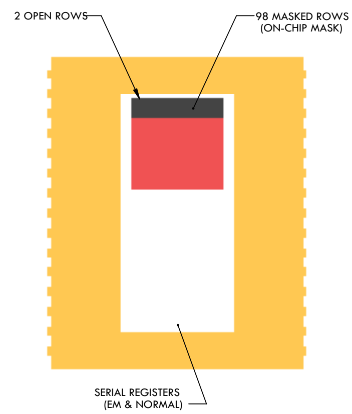
In the previous section on kinetics, it is shown that optically masking a portion of the sensor is essential to achieving fast temporal resolution. Although it is possible to achieve such performance using external slits and spectrographs to mask all but a few rows, it is extremely difficult and cumbersome to adjust the illumination with micrometer precision so that only one or two rows can be illuminated.

If this level of precision masking is achieved, however, then vertical shift speeds of 450 ns/row can enable burst frame rates exceeding 1 MHz. This capability is valuable in applications such as combustion research in which ultrafast kinetics allow researchers to understand and thereby improve critical mechanisms.

In response to customer feedback, Princeton Instruments has now designed an exclusive 512BK sensor based on the popular 512 x 512 back-illuminated EMCCD. The basic architecture of this new custom EMCCD is shown here. In addition to the standard frame-transfer mask, there is an additional mask of 512 x 98 rows that is deposited on the sensor utilizing the same precision lithography techniques used during sensor fabrication. As a result, the 512BK has two open rows (farthest from the serial register).

The ProEM+:512BK camera is the most versatile of all the models in the ProEM+ series. In addition to featuring the custom 512BK sensor, it also incorporates a custom front end with adjustable (external) blades that provide a "variable kinetic mask" for increased sensitivity.

EMCCD VIEW



Variable kinetic mask for increased sensitivity!

Go Giga

…operate remotely and easily

Another ProEM+ innovation is the use of a Gigabit Ethernet (or GigE) data interface to allow simple, reliable data transmission without the need for custom frame grabbers. This ubiquitous data interface is designed to be rugged enough to handle industrial data traffic. The key advantages of using GigE with the ProEM+ stem from the fact that the camera can be easily operated from more than 50 m away, which is not possible when custom frame grabbers are utilized. Remote operation is important for applications such as astronomy that require keeping any heat-generating sources (e.g., host computers) away from sensitive optics.

Princeton Instruments GigE

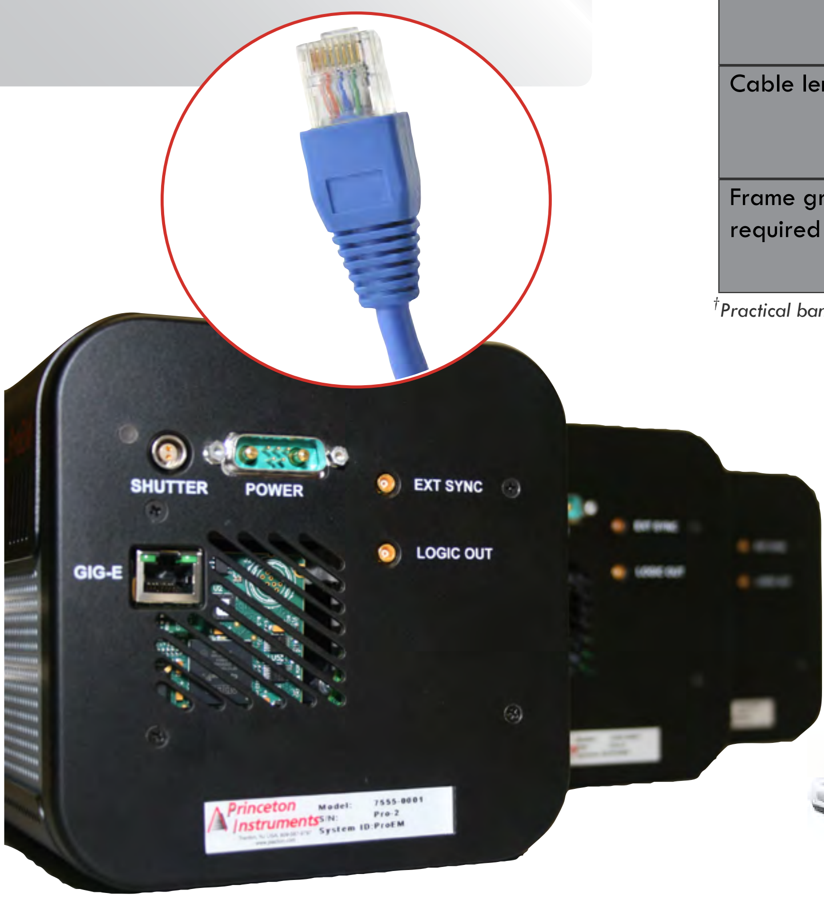
Data interface advantages:

- High bandwidth (125 MB/sec or 1000 Mbps) for real-time image transmission
- Remote operation from more than 50 m away
- Low-cost cables (CAT5e or CAT6) and standard connectors
- Scalable to future 10 GigE standard

Brief comparison of major data interface technologies...

	GigE	CameraLink	FireWire® (IEEE-1394a/b)
Bandwidth†	up to 125 MB/sec	over 680 MB/sec	up to 50 to 100 MB/sec
Cable length	>50 m	5 to 10 m	5 m
Frame grabber required	no	yes	no

†*Practical bandwidth is typically lower than theoretical maximum due to overhead.*



No vibrations

...keep it quiet

Researchers using sensitive instruments such as telescopes and atomic force microscopes take extreme care to minimize vibration in their setups. In some cases, they need to keep the ambient air around the optics stable and not generate any turbulent currents that might change the focus of the optics.

Cooled scientific cameras require the dissipation of heat to maintain cooling stability, one of the main criteria for EM gain stability. Heat dissipation is generally accomplished by using a fan to circulate air, sometimes aided by the circulation of liquid. An oft-heard solution to the vibration problem in the industry is to turn the camera's fan off temporarily during image acquisition. However, this is only a partial solution, as the fan cannot be turned off for sequences that last tens of seconds to minutes without compromising the camera's cooling stability.

Furthermore, for imaging setups in which hot air currents are problematic, the complete removal or disabling of the fan is the only way to prevent changes to sensitive optics.

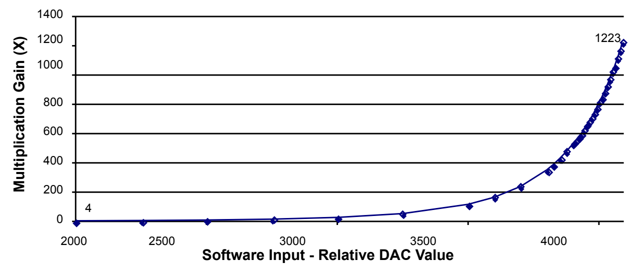
After holding extensive engineering discussions and listening to valuable customer input, Princeton Instruments has designed a novel heat-dissipation mechanism for the ProEM+ that performs equally well with either liquid circulation or standard airflow. The camera's fan can be completely turned off for a long period of time, or even permanently, without ill effect. In this way, the ProEM+ is able to eliminate vibration while still providing stable cooling performance via the use of liquid circulation only. If a given application is not sensitive to vibration, the fan can always be turned back on via software control.

The ProEM+ is able to eliminate vibration while still providing stable cooling performance.

EM gain calibration

...what you see is what you get

As noted elsewhere, EM gain is generated by applying a high-voltage clock pulse to accelerate electrons in the extended multiplication register. The gain is a complex exponential function of the high voltage, as shown in the first figure.



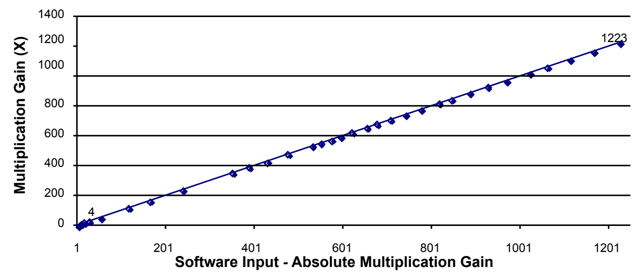
EM gain vs. input DAC value, prior to gain calibration.

Typically, the high voltage is mapped to a digital-to-analog converter (DAC) that is controlled via software. For example, a 12-bit DAC offers EM gain control in 4095 (2^{12}) steps, where 0 is mapped to 1x and 4095 is mapped to the maximum EM gain (typically ~1200x). In these cases, an offline calibration report provides the real EM gain corresponding to the DAC value.

OptiCAL

In the ProEM+ camera, an advanced, field-ready method known as OptiCAL utilizes a built-in, high-precision light source for easy, accurate EM gain calibration. The calibration map is directly loaded into the camera memory, giving users complete control over this function, in absolute terms. The use of a built-in light source offers several advantages:

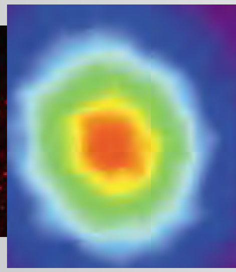
- EM gain calibration takes only a few minutes (rather than tens of minutes to hours using dark images)
- Better precision, as the technique utilizes actual light levels encountered in real-world experiments
- The calibration method is easy to use in the field
- No need for external, expensive light sources
- Repeatable calibration for many years



After OptiCAL, a high-precision EM gain calibration method that allows EM gain to be controlled in linear, absolute steps.

The calibration map is directly loaded into the camera memory.

Single-molecule imaging



Plasma imaging

Astronomy

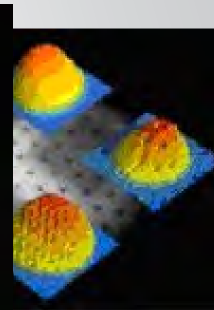
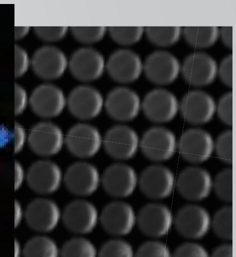


Image courtesy of Prof. Wolfgang Ketterle, MIT

Bose-Einstein condensate (BEC)



Multispectral imaging

Applications

The ProEM+ is designed to meet the demanding requirements of many low-light-level imaging applications. Its advanced features are the result of years of discussions with researchers in the field.

The camera's flexible architecture is optimized to achieve the best performance in every important category, including noise, linearity, and full well. Each readout mode is individually characterized; thus, the ProEM+ is the ideal low-light imaging and spectroscopy solution for a wide range of applications. The ProEM+ utilizes Princeton Instruments software to acquire, store, and process data quickly and efficiently.

Astronomy

- Deep cooling for extremely low dark current
- Maintenance-free, all-metal vacuum seals guaranteed for life
- Liquid-only cooling to minimize hot air currents and vibration around telescopes
- Single-vacuum-window (AR-coated) design for the best light throughput
- Remote operation from up to 50 m away via Gigabit Ethernet cable
- <1 e- rms in EM mode for single-photon detection capability
- 3 e- rms in non-EM mode (100 kHz) for steady-state imaging
- Custom chip mode for faster frame rates
- Accurate EM gain calibration (OptiCAL) and Bias Active Stability Engine (BASE) for quantitative imaging
- Very low clock-induced charge for photon-counting applications
- Multiple analog gain settings (e-/ADU) to suit low-light or high-light applications
- Hardware-generated timestamp for precise photometry
- SDK for custom programming
- NEW eXcelon3 EMCCD technology provides reduced etaloning and enhanced sensitivity in the blue and NIR regions

Multispectral imaging

- <1 e- rms in EM mode
- Custom chip mode for ultrahigh frame rates
- Rapid data collection using GigE data interface
- Hardware-generated timestamp for precise time-resolved measurements
- Flexible ROI / binning
- SDK for custom programming

Bose-Einstein condensate (BEC) imaging and ion imaging

- Custom chip and kinetics readout modes for ultrahigh frame rates
- <1 e- rms in EM mode for single-photon detection capability
- 3 e- rms in non-EM mode (100 kHz) for steady-state imaging
- Ultra-low-noise design and back-illuminated EMCCD for very high sensitivity
- Accurate EM gain calibration (OptiCAL) and Bias Active Stability Engine (BASE) for quantitative imaging
- Single-vacuum-window (AR-coated) design for the best light throughput
- Liquid-only cooling for quiet, vibration-free operation
- Hardware-generated timestamp for precise time-resolved measurements
- LabVIEW interface for custom experiments
- NEW eXcelon3 EMCCD technology provides reduced etaloning and enhanced sensitivity in the blue and NIR regions

Its advanced features are the result of years of discussions with researchers in the field.

Single-molecule imaging and spectroscopy

- Custom chip and kinetics readout modes for ultrahigh frame rates
- Frame-transfer operation for 100% duty cycle imaging (simultaneous exposure and readout)
- <1 e- rms in EM mode for single-photon detection capability and long EM life
- 3 e- rms in non-EM mode (100 kHz) for steady-state imaging
- Single-vacuum-window (AR-coated) design for the best light throughput
- Ultra-low-noise design and back-illuminated EMCCD for very high sensitivity
- Liquid-only cooling for quiet, vibration-free operation
- Accurate EM gain calibration (OptiCAL) and Bias Active Stability Engine (BASE) for quantitative imaging
- Adjustable C-mount for precise mounting on microscopes
- Hardware-generated timestamp for precise time-resolved measurements
- LabVIEW interface for custom experiments
- Direct-to-hard drive streaming (LightField)
- NEW eXcelon3 EMCCD technology provides reduced etaloning and enhanced sensitivity in the blue and NIR regions

Plasma imaging

- <1 e- rms in EM mode
- Custom chip, kinetics, and spectra-kinetics readout modes for ultrahigh frame rates
- Multiple spectra capture (ROI / binning)
- Hardware-generated timestamp for capturing kinetics
- Long data cable (>50 m) and GigE interface
- NEW eXcelon3 EMCCD technology provides reduced etaloning and enhanced sensitivity in the blue and NIR regions

Contact Princeton Instruments for additional application information and to learn more about our other products.

Princeton Instruments

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INDUSTRIAL GROUP
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X-RAY GROUP
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www.princetoninstruments.com | info@princetoninstruments.com
USA TOLL-FREE +1.877.474.2286 | USA +1.609.587.9797

RevA3