The First Professional-Grade EMCCD Camera

ProEM™

PERFORMANCE

PRECISION

PEACE OF MIND

Princeton Instruments

Welcome to Princeton

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

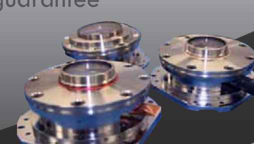
PI-MAX is the first ICCD camera to have a built-in delay generator for precise timing synchronization

2002

World's first scientific-grade microscopy EMCCD camera

2003

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



Instruments!

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

ProEM™

At last…
a professional-grade
EMCCD camera!

Features & Benefits

Princeton Instruments, a pioneer in low-light-level imaging technology, has been at the forefront of EMCCD technology for the better part of this 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.

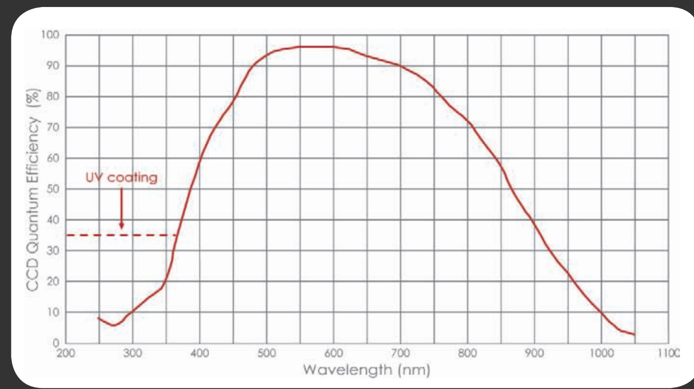
In the following pages, we shall examine how the ProEM camera addresses the most critical requirements of today's low-light, high-speed imaging applications.

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

ProEM Configuration

The ProEM camera is available in 512x512 (512B) and 1024x1024 (1024B) formats. The 512B format is ideal for high-frame-rate applications, whereas the 1024B format offers a wide field of view. The ProEM comes with everything needed to capture low-light images right out of the box!

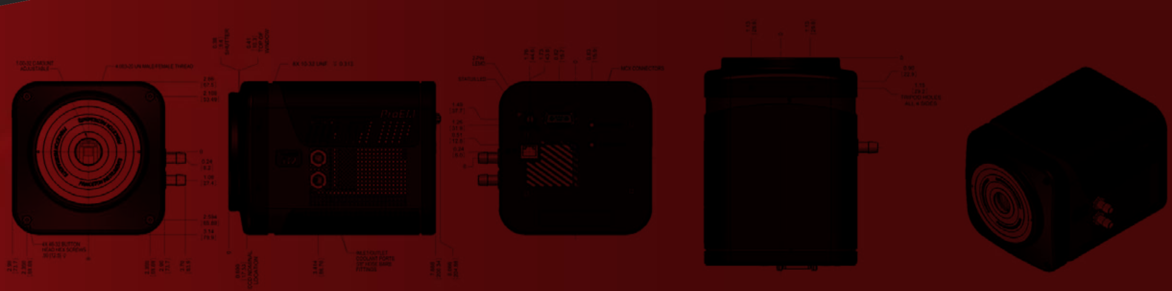
- Camera head with adjustable C-mount
- Integrated mechanical shutter
- Built-in precision light source
- Tripod mount
- GigE cable
- GigE adapter card (for computers that do not have Intel Gigabit Ethernet ports)
- Power supply



Model	Pixel format	Active area (mm x mm)	Pixel size (µm²)	Max. cooling†	Peak QE	Typ. read noise	Frame rate††
ProEM:512B	512x512	8.2x8.2	16	-80°C	95%	<1 e- rms (EM mode); 3 e- rms (traditional CCD mode @ 100kHz)	>33fps
ProEM:1024B	1024x1024	13.3x13.3	13	-65°C	95%	<1 e- rms (EM mode); 3 e- rms (traditional CCD mode @ 100kHz)	>8.5fps

†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

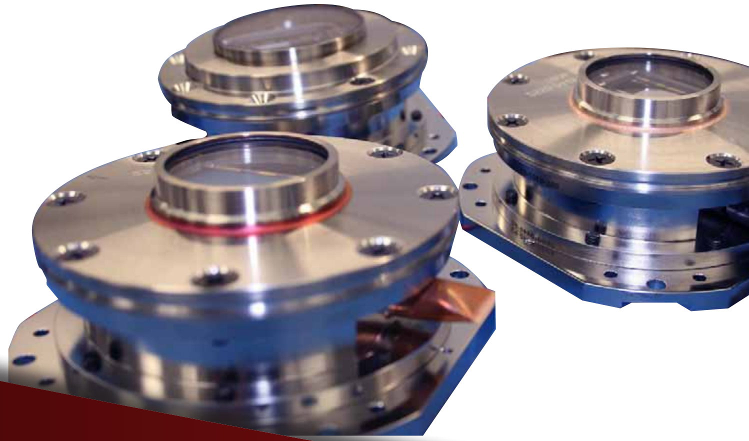
Note: Princeton Instruments also offers EMCCD cameras with 1Kx1K and 128x128 formats. Please contact us for more details.



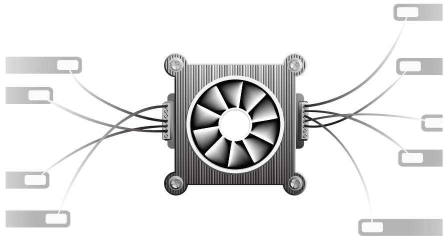
Performance | Cooling

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.

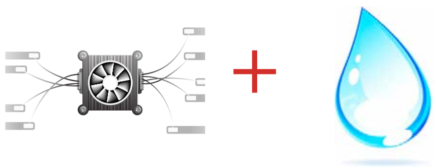


Options: The ProEM delivers the highest cooling performance, no matter which option is selected.



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.



Air+Water: The combined use of air and water 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.

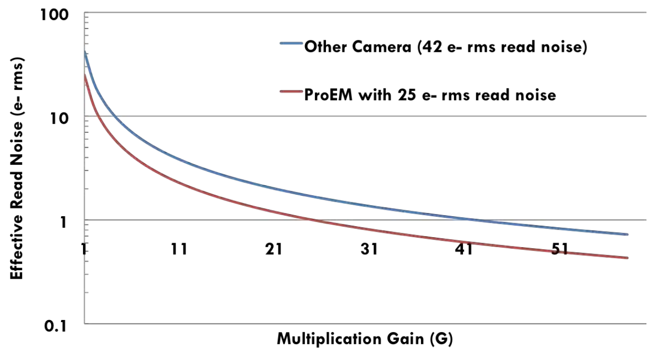
Performance | Low Noise

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.

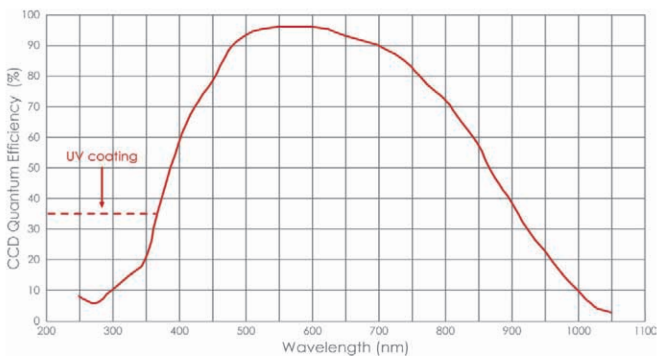
PINS technology also includes proprietary methods for lowering clock-induced charge, an unwanted noise source in EM applications requiring single-photon detection. This charge is reduced to 0.005 e-/p/frame via careful optimization of clock timing and voltage levels on every ProEM camera.

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.



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 100kHz slow-scan readout to provide the best possible read noise for steady-state applications.

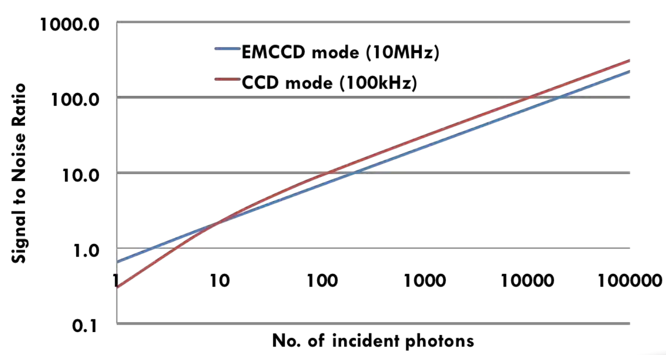
Performance | Speed

Video rates and higher: The ProEM offers readout rates that exceed video, even at full resolution (512x512). 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 at millions of frames 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.

Custom chip: The ProEM supports advanced readout via "custom chip", a mode in which the active number of pixels can be redefined on-the-fly, thus reducing readout time by 2x to 3x and providing sub-frame readout.

Variable vertical transfer time: The vertical transfer time, which determines the amount of smear, can be set through software control (300nsec 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.

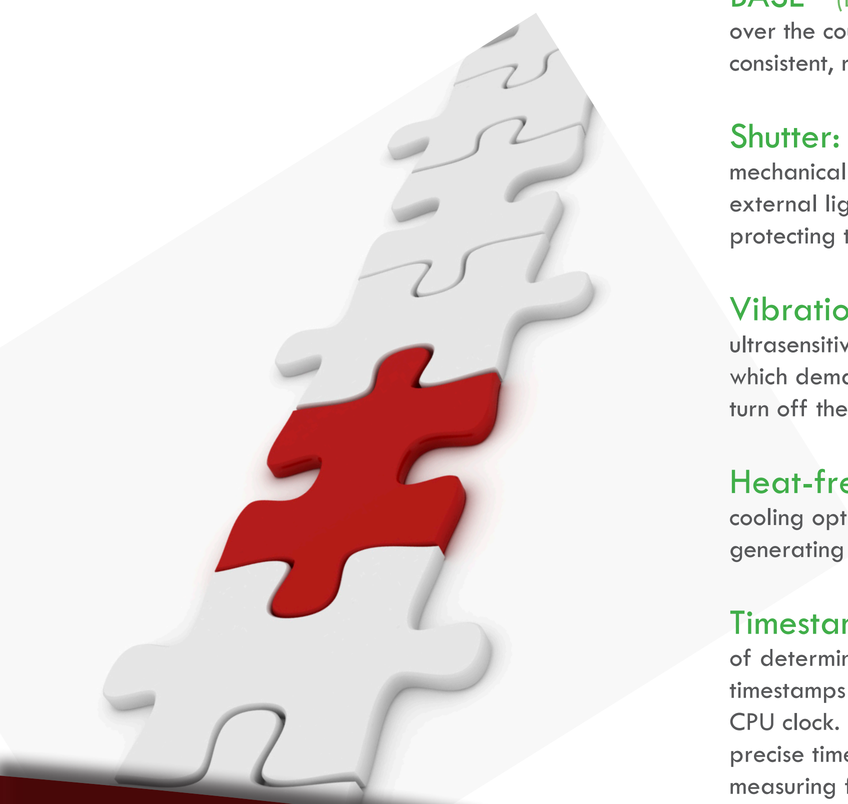
BASE™ (Bias Active Stability Engine): Whether acquiring images over the course of hours or days, BASE allows researchers to achieve a consistent, repeatable reference bias.

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.

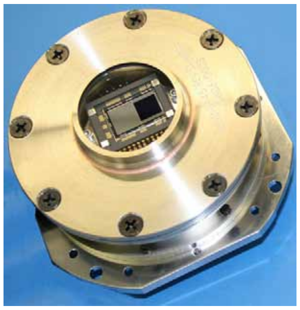
Timestamp: Princeton Instruments has taken the guesswork out of determining when an image was actually captured. Traditionally, timestamps have been done on the host computer using a low-precision CPU clock. In contrast, the ProEM stamps the frame data with a highly precise timestamp (microsecond resolution).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



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

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.



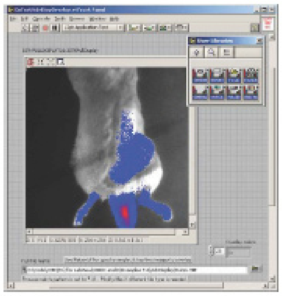
Anti-aging: EM gain can degrade over time, especially when large gain is used under high-light-level conditions. The ProEM utilizes many anti-aging measures, including clock-voltage optimization. Deep cooling allows the camera's high-voltage clocks to be operated well below their maximum ratings while 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 50m 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.

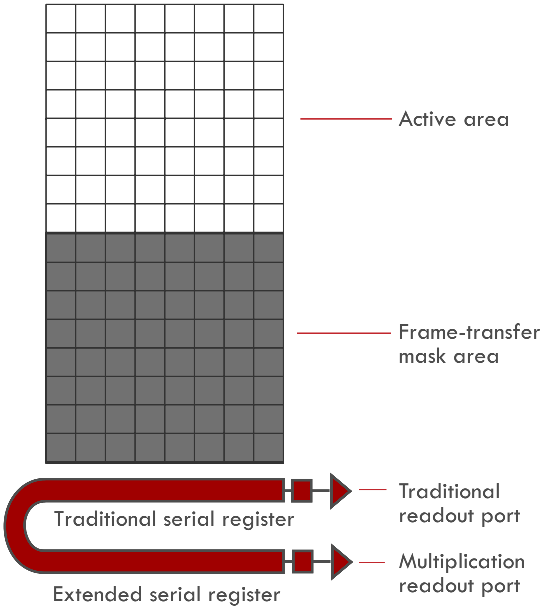


Free SDK: A free software development kit (SDK) is included, complete with helpful examples, so that ProEM users can write their own acquisition programs.

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.

Signal-to-noise ratio (SNR)

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

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

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

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.

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

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

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

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.

EMCCD, ICCD, or CCD?

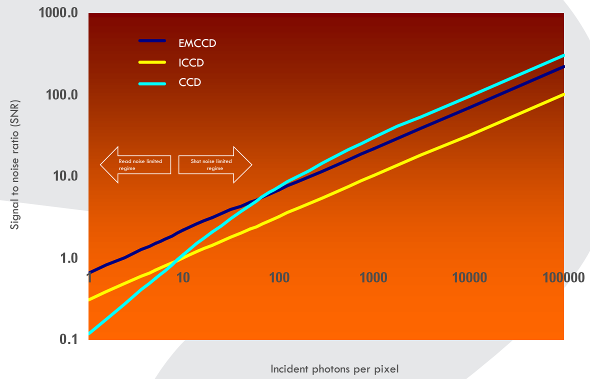
Choosing the right camera technology…

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 – 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*



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

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

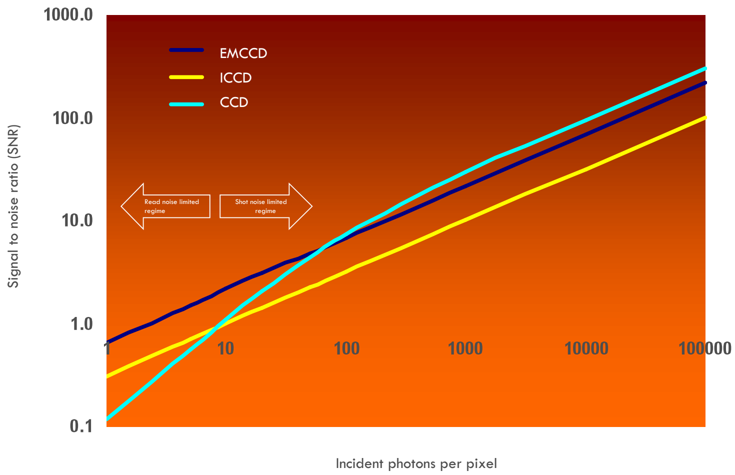
Gating refers to a camera's ability to take extremely short exposures, ranging from a few hundred picoseconds to microseconds. By controlling the forward bias voltage, ICCD intensifier tubes can be turned on or off with a high degree of precision. In addition, the on/off ratio of intensifiers, which 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

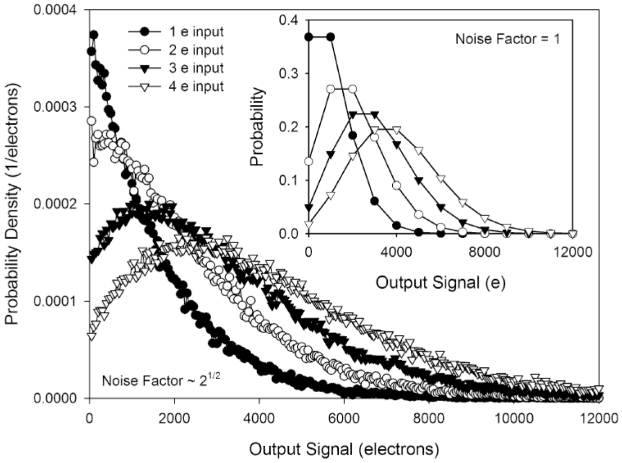
While the biggest advantage of EMCCD cameras is seen when used in applications that require low-light capture at high frame rates, more versatile EMCCD cameras such as the ProEM offer both high-speed EM and slow-speed traditional CCD modes of operation. For example, the ProEM is specially equipped with a 100kHz traditional CCD mode of operation to deliver read noise as low as 3 e- rms and high signal-to-noise ratio. Since 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.

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

Major differences between dark current and clock-induced charge

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 512x512 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

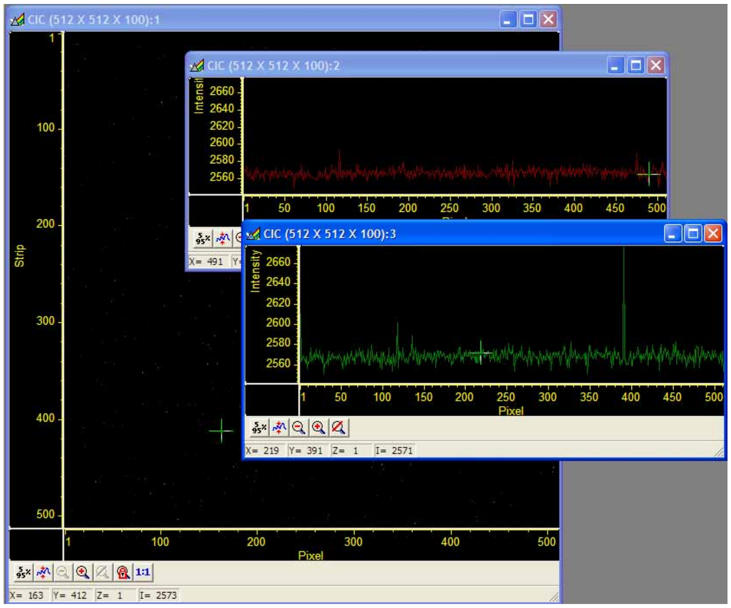


Image taken at 1000x EM gain to show clock-induced charge. With careful clock shaping and optimization, the CIC is reduced to 0.005 e-/pixel/frame.

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
10MHz (EM mode)	50 e- rms	<1 e- rms
5MHz (EM mode)	25 e- rms	<1 e- rms
5MHz (traditional CCD mode)	12 e- rms	not applicable
1MHz (traditional CCD mode)	7 e- rms	not applicable
100kHz (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 @ 100kHz) 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.

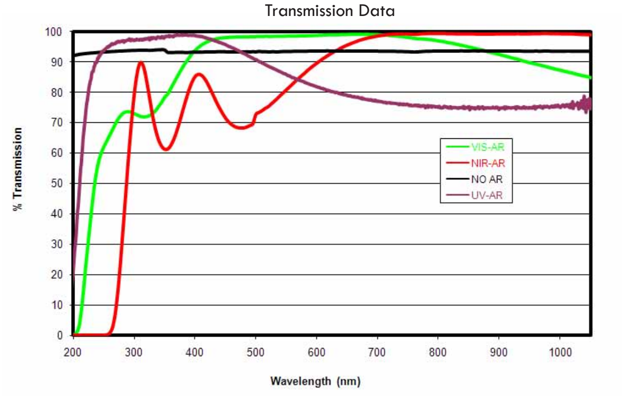
Anti-reflective coatings and single-window design

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 3.5% to 4% transmission loss, or a total loss of 7% 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 coatings on the window in the optical path, which reduces total losses to below 1% and sometimes even to 0.5%.

All Princeton Instruments cameras, including the ProEM, are designed with a single window made of high-grade fused silica/quartz 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 single- or multi-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.

Vacuum window
Transmission Data



Princeton Instruments offers a choice of multi-layer VIS-AR, UV-AR, and NIR-AR coating options on the vacuum window. For broadband applications, a choice of $MgFl_2$ or broadband AR coatings is available upon request.

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.

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

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.

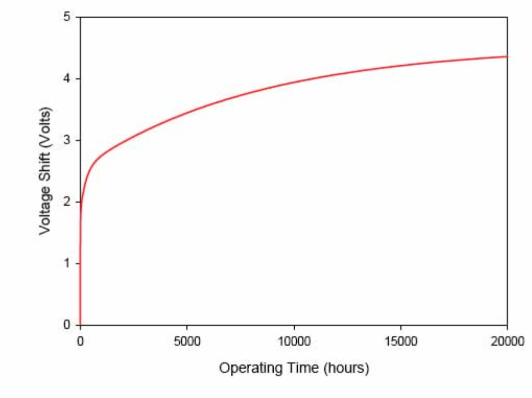
All-metal vacuum seals are superior to traditional epoxy-based seals that may degrade over time.

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.

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.

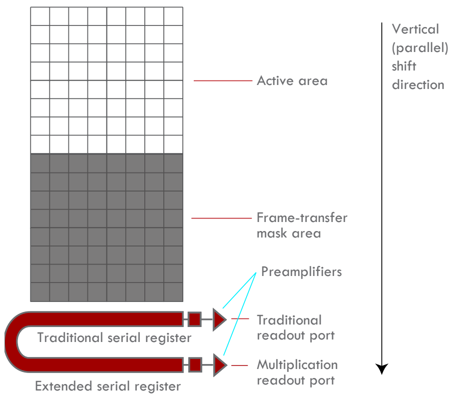
This section details some of the advanced speed-related features of the ProEM.

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

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.

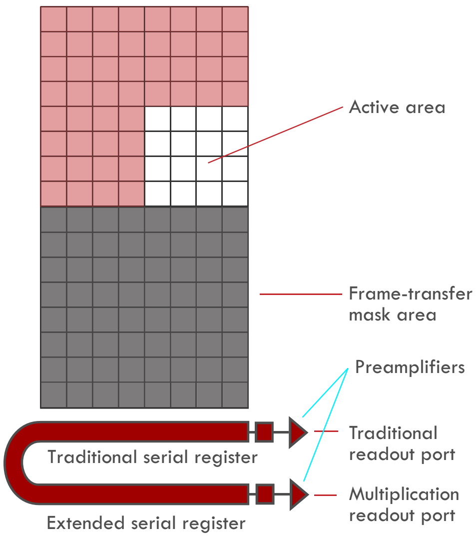


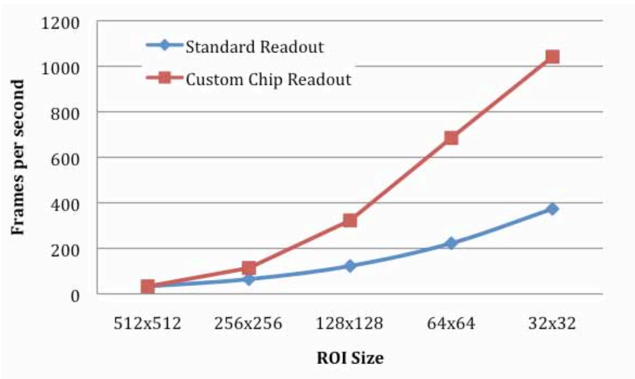
Custom chip mode

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 512x512 format sensor, using the ROI method to read out 128x128 pixels would take 8.2msec, or a frame rate of 122fps (1/0.0082). Using the custom chip feature, the readout time for the same region would drop to 3.1msec, which is equivalent to a frame rate of 323fps.

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





(a) Custom chip mode offers the highest frame rate possible by redefining the active array size. It is important to ensure that no light falls outside the active area. (b) Comparison of frame rates that can be achieved at various ROI sizes using standard readout and custom chip readout. Data acquired with the ProEM:512B.

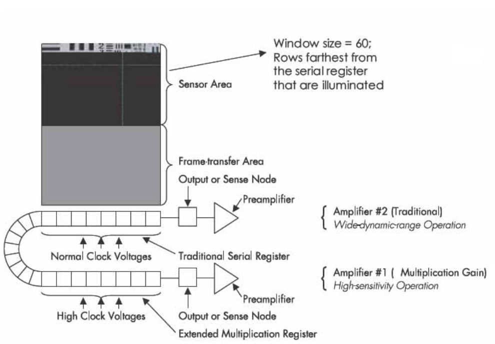
Kinetics

...take advantage of advanced readout modes

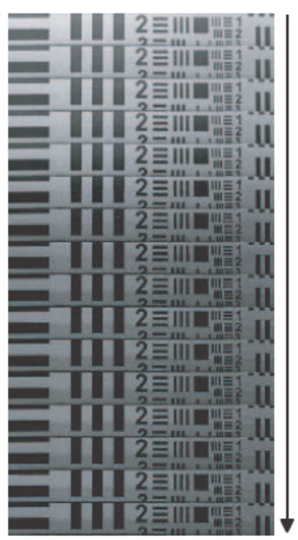
Kinetics refers to a special readout mode in which a portion of the EMCCD is illuminated while the rest of the array is used as a temporary storage area. At the end of the exposure-shift sequence, the entire EMCCD is read out to provide a series of sub-frames (kinetic frames) separated in time. In order 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.



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.



*(b) 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".*

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 50m 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

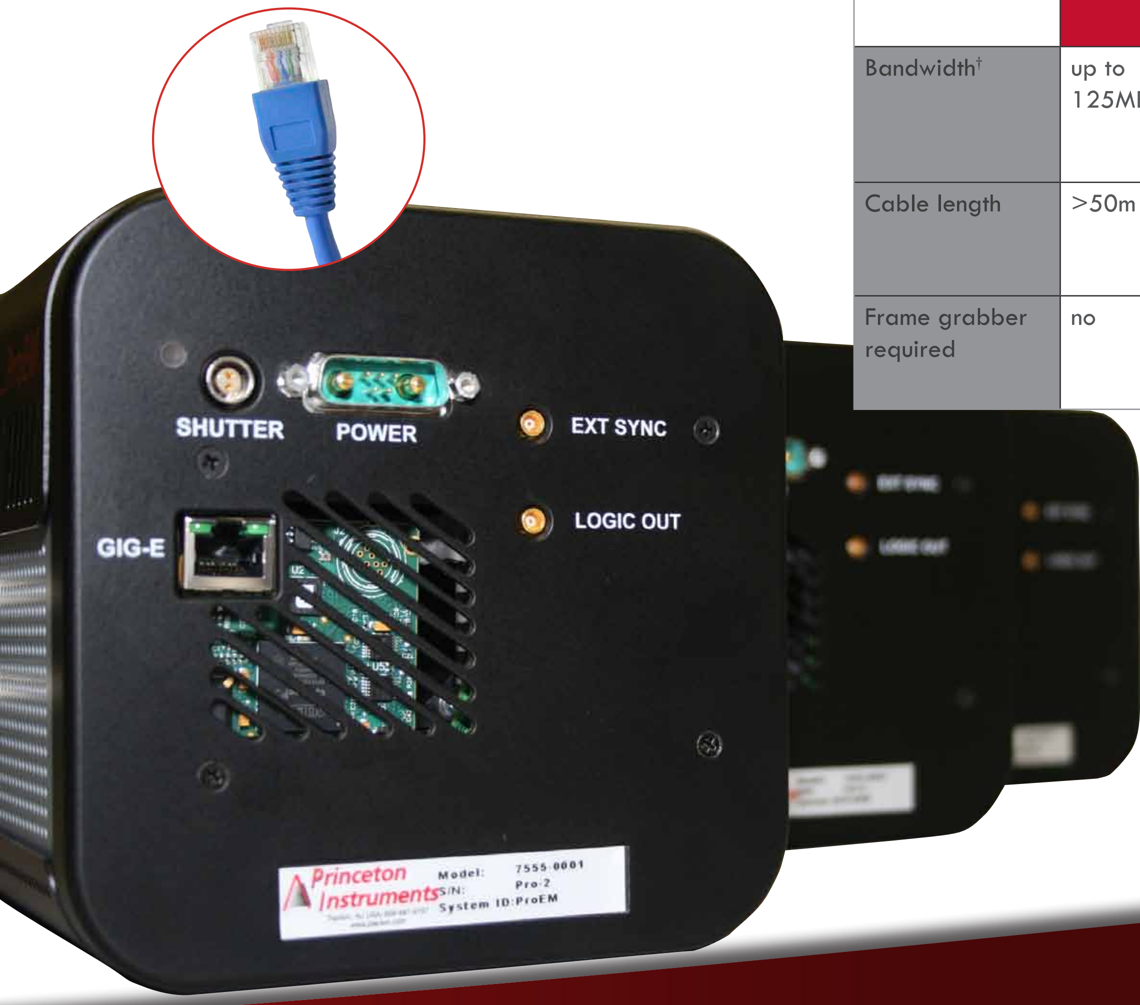
Data interface advantages:

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

Brief comparison of major data interface technologies...

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

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



No vibrations

...keep it quiet

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

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.

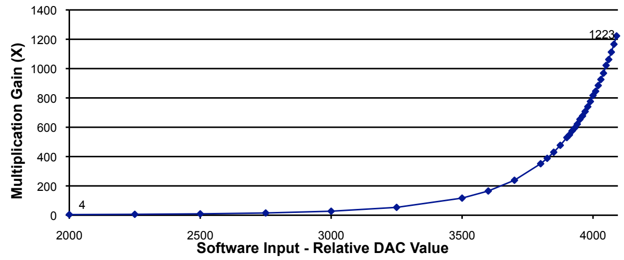
After holding extensive engineering discussions and listening to valuable customer input, Princeton Instruments has designed a novel heat-dissipation mechanism for the ProEM that performs equally well with either liquid circulation or standard airflow. The camera's fan can be completely turned off for 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.

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 figure below.

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.

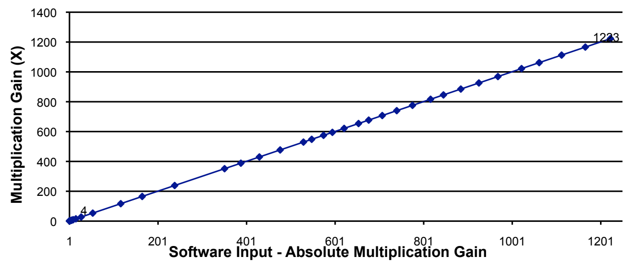


(a) EM gain vs. input DAC value, prior to gain calibration.

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

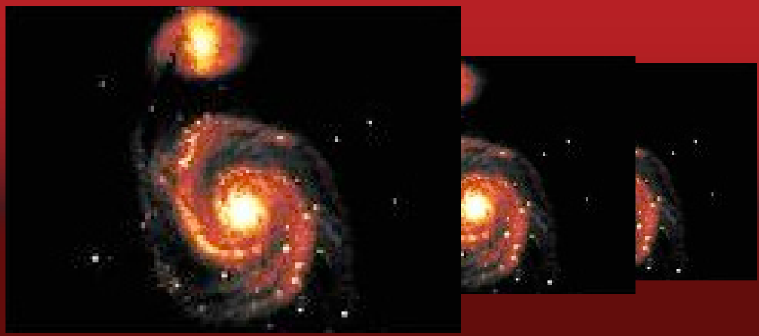


(b) After OptiCAL, a high-precision EM gain calibration method that allows EM gain to be controlled in linear, absolute steps.

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 astronomers, SMF researchers, and BEC physicists.

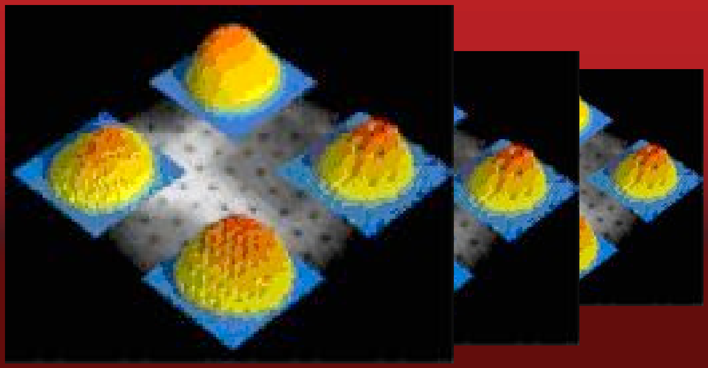
The camera's flexible architecture is optimized to achieve the best performance in every important category, including noise, linearity, and full well. Each readout mode is individually characterized; thus, the ProEM is the ideal low-light imaging and spectroscopy solution for a wide range of applications.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



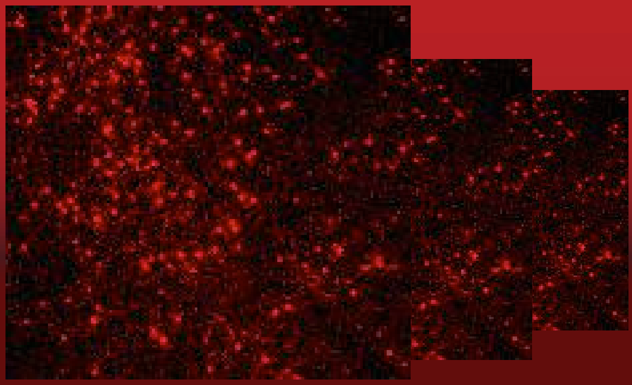
Astronomy

- 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 50m away via Gigabit Ethernet cable
- 100kHz, slow-speed channel for 3 e- rms read noise
- Accurate EM gain calibration using OptiCAL
- Very low clock-induced charge for photon-counting applications
- Multiple analog gain settings (e-/ADU) to suit low-light or high-light applications

Its advanced features are the result of years of discussions with astronomers, SMF researchers, and BEC physicists.



Images courtesy of Prof. Wolfgang Ketterle, MIT



Bose-Einstein condensate (BEC) imaging

- Kinetics readout for microsecond temporal resolution
- Video rates and up to hundreds of frames per second for high temporal resolution
- EM and traditional CCD modes of operation for high-speed and steady-state observations
- Ultra-low-noise design and back-illuminated EMCCD for very high sensitivity
- Single-vacuum-window (AR-coated) design for the best light throughput
- Liquid-only cooling for quiet, vibration-free operation
- Hardware-generated timestamp for accurate temporal reference

Single-molecule fluorescence (SMF) imaging

- Video rates and up to hundreds of frames per second for high temporal resolution
- Frame-transfer operation for 100% duty cycle imaging (simultaneous exposure and readout)
- EM and traditional CCD modes of operation for high-speed and steady-state observations
- 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
- Spectral and imaging capabilities for single-molecule imaging and spectroscopy
- Adjustable C-mount for precise mounting on microscopes
- Hardware-generated timestamp for accurate temporal reference

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