PI-MAX® 4

ICCD Cameras

The Ultimate in Precision & Intelligence

Intensified CCD Cameras

TELEDYNE
PRINCETON INSTRUMENTS
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Introducing the New PI-MAX® 4

The PI-MAX® 4 is the culmination of years of research and development by Princeton Instruments to create an intensified CCD (ICCD) camera that not only meets, but anticipates, users' continually evolving requirements for sensitivity, speed, and control in time-resolved imaging and spectroscopy applications. The PI-MAX4 offers precision gating capabilities to <500 picoseconds, the ability to perform frequency domain measurements utilizing RF modulation, and unsurpassed control of all experiments via Princeton Instruments' intelligent LightField® software.

Readout of the PI-MAX4 ranges from video rates to thousands of frames per second in order to capture dynamics, while a sustained gating repetition rate of 1 MHz (2x better than most research-grade ICCD cameras available on the market today) allows the camera to keep up with the ever increasing repetition rates of pulsed and modulated lasers.

Before our engineers could begin designing the next generation of Princeton Instruments ICCD cameras, one deceptively simple question had to be answered: "How can we improve upon something already considered the industry's gold standard?"

For guidance, we decided to turn to the people who stood to benefit the most from our furthering of ICCD camera performance. Thus, we solicited plenty of input from our customers. After all, researchers worldwide who strive to break new ground via cutting-edge, time-resolved, optical diagnostic techniques rely on Princeton Instruments PI-MAX ICCD cameras every day. Our instrumentation helps them understand fundamental mechanisms and solve difficult problems in life and physical sciences, enabling research that ranges from improving internal combustion engine efficiency to uncovering new drug-cell interactions.

If you are embarking on new research or trying to elevate your current research to the next level, we invite you to take a look at how the PI-MAX4 can help.

An Impressive Lineage

• PI-MAX4

2012 New ICCD cameras offer picosecond gating capabilities, RF modulation capabilities, and complete control via LightField software

~1978	1990	1997	1998	2000	2005	2007	2009
First intensified photodiode array	First scientific-grade gated ICCD camera for imaging and spectroscopy	I-PentaMAX camera: revolutionized low-light-level, single-molecule fluorescence applications	PI-MAX: the first ICCD camera to have a built-in delay generator for precise timing	MCP gating: combined fast gating with the high QE of slow-gate Gen II intensifiers; ideal for PLIF imaging in combustion	PI-MAX2: readout speed 5x faster than original PI-MAX, plus unique Double Image Feature (DIF)	UNIGEN II: exclusive Gen III intensifier with UV-to-red sensitivity	PI-MAX3: fully integrated ICCD camera provided the best combination of frame rate, gating, and low-noise capabilities available

Key Features & Benefits

Ultimate in Precision

Video and higher frame rates:

Camera achieves near-video frame rates (even at full 1k x 1k resolution); thousands of spectra per second can be acquired while in spectroscopy mode; provides ability to capture a gated image or spectrum for every pulse of a high-repetition-rate laser.

SuperHV:

More powerful, built-in, high-voltage gating technology precisely turns on and off Gen II and Gen III image intensifiers in response to programmed delays and widths; standard implementation capable of achieving sustained 1 MHz repetition rate; optional implementation delivers picosecond gating capabilities with sustained 100 kHz repetition rate.

PIPs (Princeton Instruments Picosecond) gating technology:

Without sacrificing the quantum efficiency of a standard Gen II or Gen III image intensifier, new PIPs technology allows image capture with precision gating to <500 psec.

DIF (Double Image Feature):

Optional feature quickly transfers a full-resolution image under the interline CCD array's mask in the PI-MAX4:1024i, enabling the camera to take a second frame in as little as 450 nsec (limit imposed by P46 or P47 phosphor decay times).

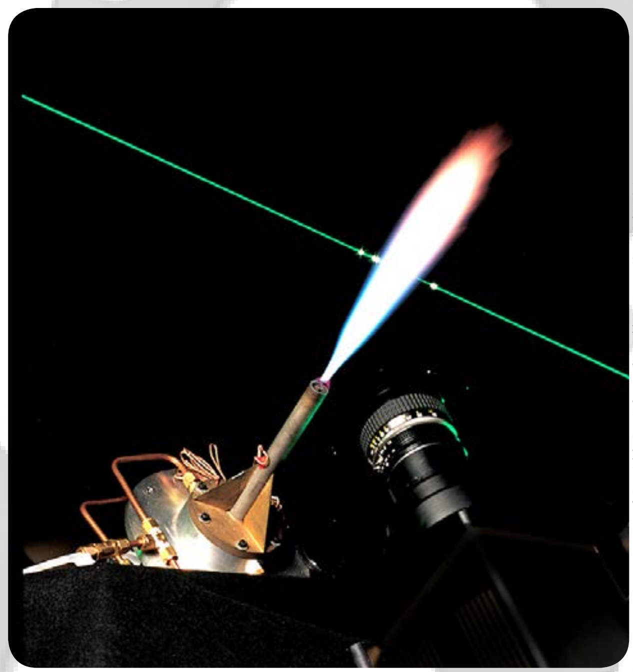


Image courtesy of Drs. Adela Ben-Yakar and Ronald K. Hanson (Stanford HTGL).

PRECISION

Ultimate in Intelligence

SuperSynchro: New timing-generator technology precisely controls intensifier gating; allows gate widths and delays to be set for 10 psec resolution with <35 psec jitter; offers wide variety of options to synchronize camera with external trigger sources such as pulsed lasers.

SyncMaster: Allows the camera to output two continuously running pulse trains (user-set frequency) to trigger pulsed lasers without interruption; reduces lab clutter by eliminating the need for an external timing generator; provides the lowest possible jitter.

LightField software: 64-bit data acquisition software platform has been designed “from the ground up” for scientific imaging and spectroscopy; provides complete control of PI-MAX4 cameras via easy-to-use tools that facilitate experimental setup, data acquisition, and post processing.

INTELLIGENCE

PINS (Princeton Instruments Noise Suppression) technology: Next-generation electronics ensure the best combination of CCD readout speed and the lowest possible noise levels in an ICCD camera; offers near-video frame rates at full 1k x 1k resolution with 16-bit digitization.

Gigabit Ethernet (GigE): High-bandwidth (125 MB/sec or 1000 Mbps) data interface affords real-time image transmission; supports remote operation from more than 50 meters away.

Photocathode cooling: Reduces equivalent background intensity (which can impose limitations on ultra-low-light or photon-counting applications) by cooling the photocathode directly via a dry nitrogen source.

Mounting: Camera mounts easily to C-mount lenses, F-mount lenses, and leading spectrographs such as the Acton Series and IsoPlane from Princeton Instruments.

PI-MAX4

Anatomy of the PI-MAX4 ICCD Camera

1 **DIF (optional)**
Double Image Feature allows capture of two full-resolution images separated by as little as 450 nsec; ideal for particle imaging velocimetry

2 **SuperHV**
Built-in high-voltage circuitry positioned close to intensifier for the lowest propagation delays and highest repetition

3 Easily mounts to C-mount lenses, F-mount lenses, and leading spectrographs such as the advanced Acton Series from Princeton Instruments

4 **PINS**
Princeton Instruments Noise Suppression technology for high-speed, low-noise CCD readout

5 **PIPs**
Princeton Instruments Picosecond gating technology available for Gen II and Gen III filmless intensifiers

6 **Gate Monitor**
Know when the intensifier is gated on/off for precise timing

Gen II and Gen III filmless intensifiers fiber-coupled to CCDs for the highest light throughput

Ultimate in Precision, Ultimate in Intelligence

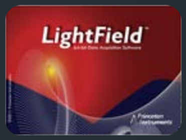
7 **SuperSynchro**
Built-in timing generator for fully programmable gate delays/widths; auxiliary outputs

8 **GigE**
The latest Gigabit Ethernet data interface; operate the camera more than 50 m away from the host computer

9 **Liquid-assist cooling (optional)**
Further reduction of CCD dark current

10 **TTL outputs with adjustable delays**
Synchronize lasers and other instrumentation in the experiment

11 **SyncMaster**
Continuously running, variable pulse trains to trigger lasers for the lowest jitter



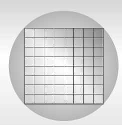
Powered by LightField®

PI-MAX4 Camera Configurations

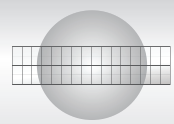
The PI-MAX4 is currently offered with two CCD sensors...

	1024i	1024x256
CCD type	Kodak KAI:1003 (interline)	e2v CCD30-11 (full frame)
CCD format	1024x1024	1024x253
CCD pixel size	12.8 µm x 12.8 µm	26 µm x 26 µm
Imaging area	13.1 mm x 13.1 mm (18 mm dia.)	18 mm x 6.6 mm or 25 mm x 6.6 mm
Intensifier size	18 mm	18 mm or 25 mm
Intensifier type	Gen II or Gen III filmless	Gen II or Gen III filmless
Phosphor type*	P43, P46, or P47	P43, P46, or P47
Double Image Feature (DIF)	Yes	No

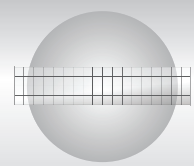
**Contact Princeton Instruments for P46 and P47 phosphor availability.*



Imaging
1024i with 18 mm intensifier

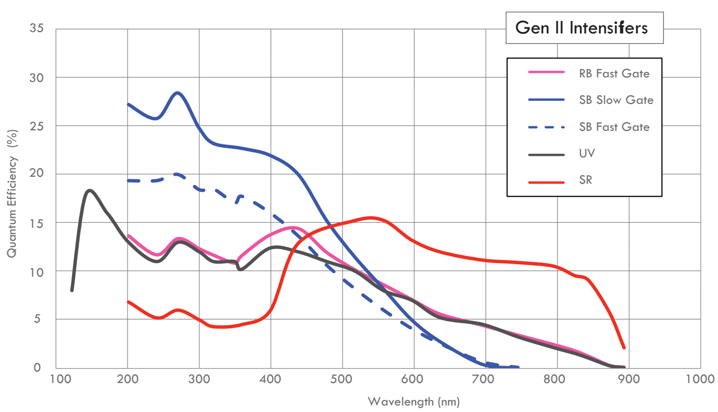


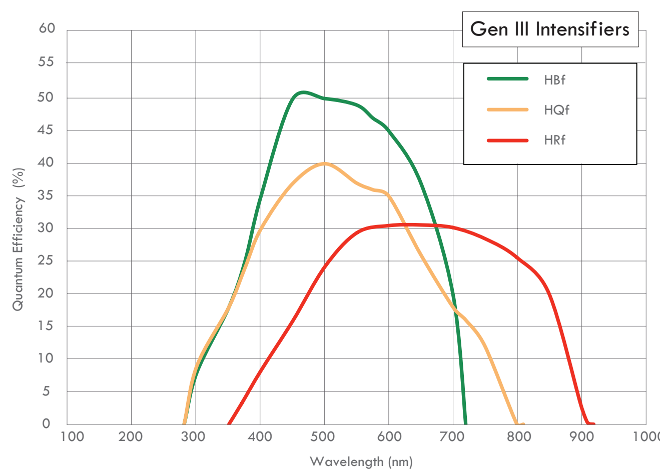
Spectroscopy
1024x256 with 18 mm intensifier

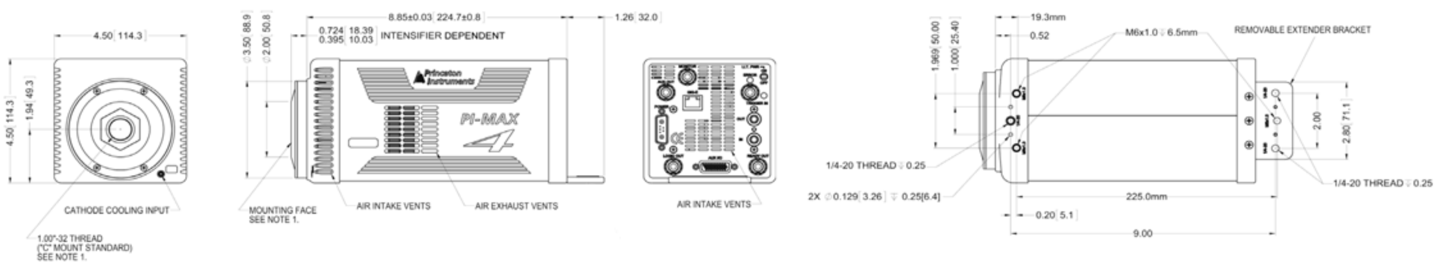


Spectroscopy
1024x256 with 25 mm intensifier

Quantum efficiency curves for selected Gen II and Gen III filmless intensifiers:







What's in the box?

Your PI-MAX4 is ready to tackle demanding gated imaging and spectroscopy applications – as soon as it arrives. We configure the camera with your choice of mount, CCD, and intensifier, and then put it through the most rigorous testing protocols available to ensure the highest performance possible.

INCLUDED:

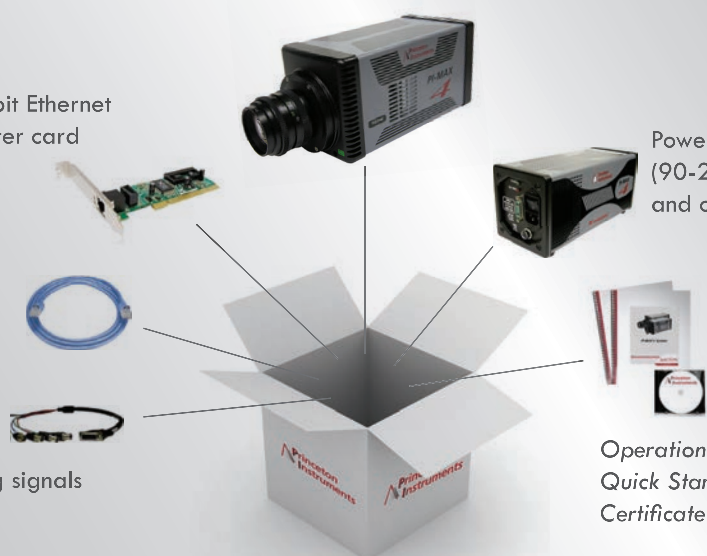
Camera (C-mount, F-mount, or spectroscopy mount)

Gigabit Ethernet adapter card

Power supply (90-264 V AC) and cable

Gigabit Ethernet cable (Cat 5e/6)

DB26-to-BNC splitter cable to access timing signals



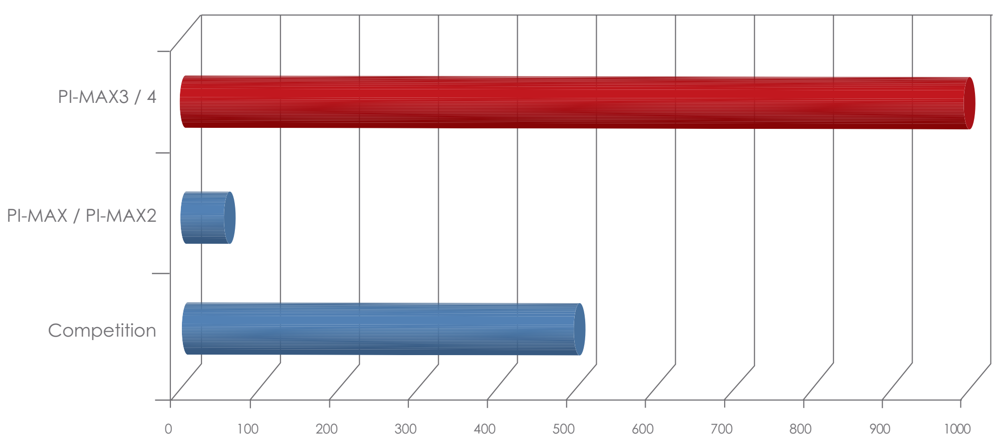
Operation Manual
Quick Start Guide
Certificate of Performance

OPTIONS:

Princeton Instruments LightField software
Princeton Instruments WinView / WinSpec software
Princeton Instruments PICAM / PVCAM® SDK
SITK LabVIEW™ (National Instruments) drivers

ICCD camera performance tailor-made to suit your toughest requirements!

Ultimate in Precision | SuperHV



...the spatial resolution of the intensifier is proportional to the square root of the gate voltage between the photocathode and the MCP

1 MHz Repetition Rate

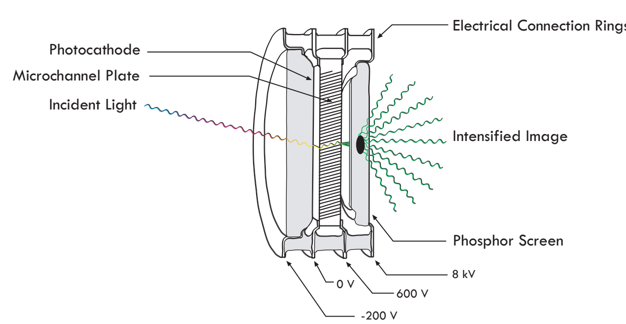
One of the key benefits of using ICCD cameras for time-resolved measurements is their gating ability, that is, their ability to open and close at the precise time necessary to capture a phenomenon of interest. They can freeze the action. For example, in fluorescence lifetime imaging measurements, the camera is synchronized by gating the ICCD at incremental delays after the excitation source, allowing the lifetime of the species to be measured from the *intensity vs. time profile*.

The SuperHV high-voltage gating employed in the PI-MAX4 is a real breakthrough in ICCD gating technology. It offers a 1 MHz repetition rate, which represents a full 2x increase from previous-generation ICCD cameras. Researchers can now make use of every excitation light pulse from high-repetition-rate lasers up to 1 MHz. To improve signal-to-noise ratio, multiple gate pulses can be accumulated on the CCD before readout. Photodegradation of samples is reduced by minimizing total experiment time.

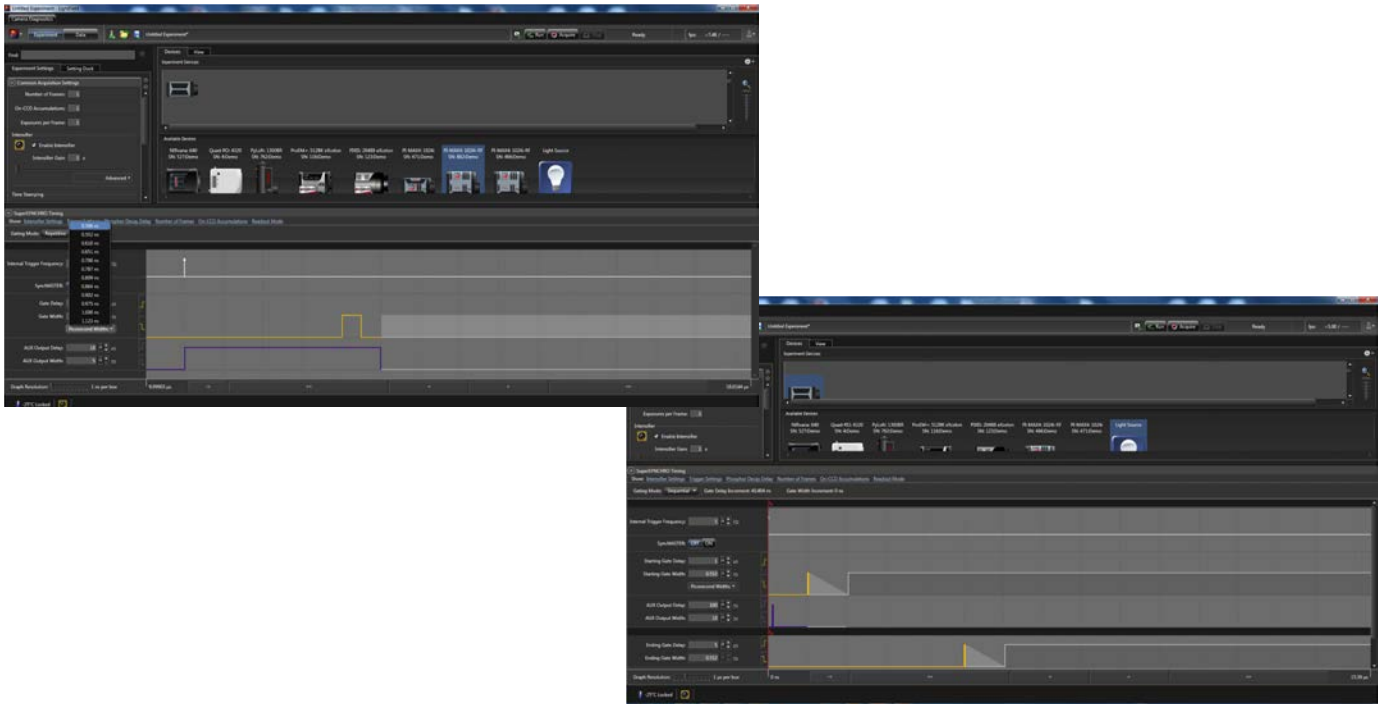
PRECISION

Although competitive ICCD cameras may claim faster repetition rates, they employ drastically reduced gate voltages to increase their rates. The PI-MAX4, on the other hand, takes no such shortcuts. It uses the full gate voltage to produce crisp images.

Intensifiers operate on the principle of proximity focus. Photoelectrons generated at the photocathode are accelerated towards the MCP input by applying a forward bias voltage (aka *gate voltage*). If sufficient voltage is not used, the photoelectrons will either diffuse or not reach the MCP at all, resulting in loss of spatial resolution and/or loss of signal. In fact, the spatial resolution of the intensifier is proportional to the square root of the gate voltage between the photocathode and the MCP.



Ultimate in Precision | PIPs Option



New "Princeton Instruments Picosecond" Gating Technology

With the introduction of our picosecond gating (PIPs) technology, Princeton Instruments is revolutionizing time-resolved research applications such as fluorescence lifetime imaging microscopy yet again! As the first fiberoptically coupled ICCD camera to offer this type of advanced technology, the new PI-MAX4 is able to deliver the highest precision and sensitivity available.

PIPs technology is utilized to gate standard fast-gate tubes even faster (<500 psec) without sacrificing their high quantum efficiency (QE). This is achieved by designing and implementing innovative, high-performance electronics, similar to our renowned MCP gating technology in which the microchannel plate's high voltage is gated quickly to deliver high QE with traditionally slow-gate tubes. Princeton Instruments does not restrict our new technology to one or two types of intensifiers; we use PIPs to gate all fast-gate Gen II and Gen III tubes at the picosecond timescale.

As shown in the screen captures above, users are given several discrete, system-specific options when picosecond gating is purchased for the PI-MAX4 and then selected within Princeton Instruments LightField software.

The options presented via LightField are based on the measurements taken with the system's intensifier to deliver precise gate widths. These discrete picosecond gate width values are specific to the intensifier utilized in a particular system and are programmed in the detector so that the intelligent LightField software knows exactly which gate widths can be delivered.

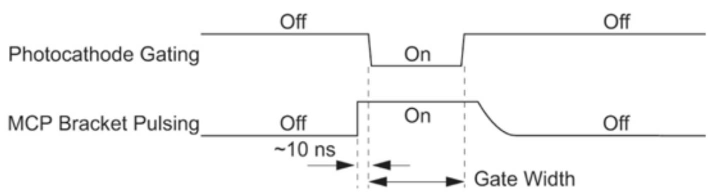
PRECISION

Ultimate in Precision | MCP Bracket Pulsing for Gen II Intensifiers

Raising the Bar… Even in the UV

The typical on/off ratio of intensifiers is 10^7:1. In the UV region, however, energetic photons can penetrate the photocathode and create electrons directly at the input of the MCP that then undergo the usual amplification process even when the photocathode is gated off. This reduces the on/off ratio to as low as 10^4:1. To alleviate this problem, Princeton Instruments pioneered *MCP Bracket Pulsing* in first-generation PI-MAX cameras by turning the MCP on and off along with the usual photocathode gating.

MCP Bracket Pulsing in the PI-MAX4 has been improved significantly. Now the MCP gates on synchronously with the photocathode, so there is no compromise in signal quality. As a result, there is no pre-pulse or head-start pulse required for MCP Bracket Pulsing in the PI-MAX4. In addition, the insertion delay is kept as low as possible even with MCP Bracket Pulsing turned on (providing an improvement of as much as 10 nsec over competitive designs).



Ultimate in Precision | Frame Rate

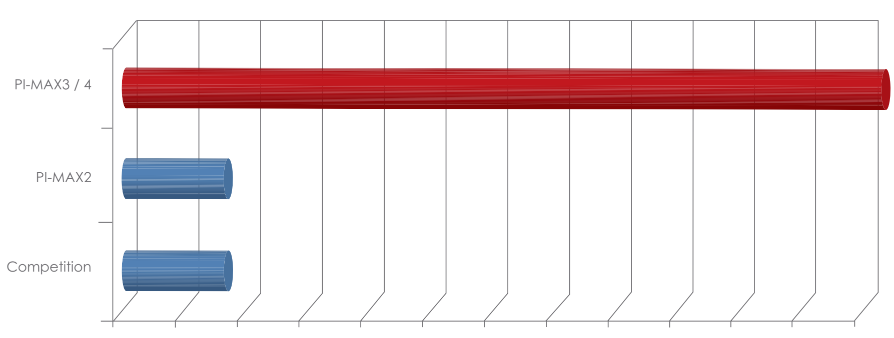
Video and Higher Frame Rates

While repetition rate refers to the intensifier on/off cycle frequency, frame rate refers to the CCD pixel readout rate. Once the image is captured on the CCD, it is important to read the frame quickly and start the next acquisition cycle.

The PI-MAX4 is capable of reading out a full 1k x 1k resolution image in as little as 38 msec (an effective frame rate of 26 fps). By comparison, slow-frame-rate ICCD cameras can take more than a full second to read out a frame at the same resolution. The new camera can offer even higher frame rates with reduced resolution and/or the use of binning. For spectroscopy applications, the PI-MAX4 can produce thousands of spectra per second when employing a rectangular CCD.

High-energy, Q-switched lasers (e.g., Nd:YAG) can now operate at very high repetition rates, from 10 Hz to more than 1 kHz. With the PI-MAX4, it is possible to produce a frame for every pulse from such laser systems.

Frame Rate (fps) @ Full 1k x 1k Resolution



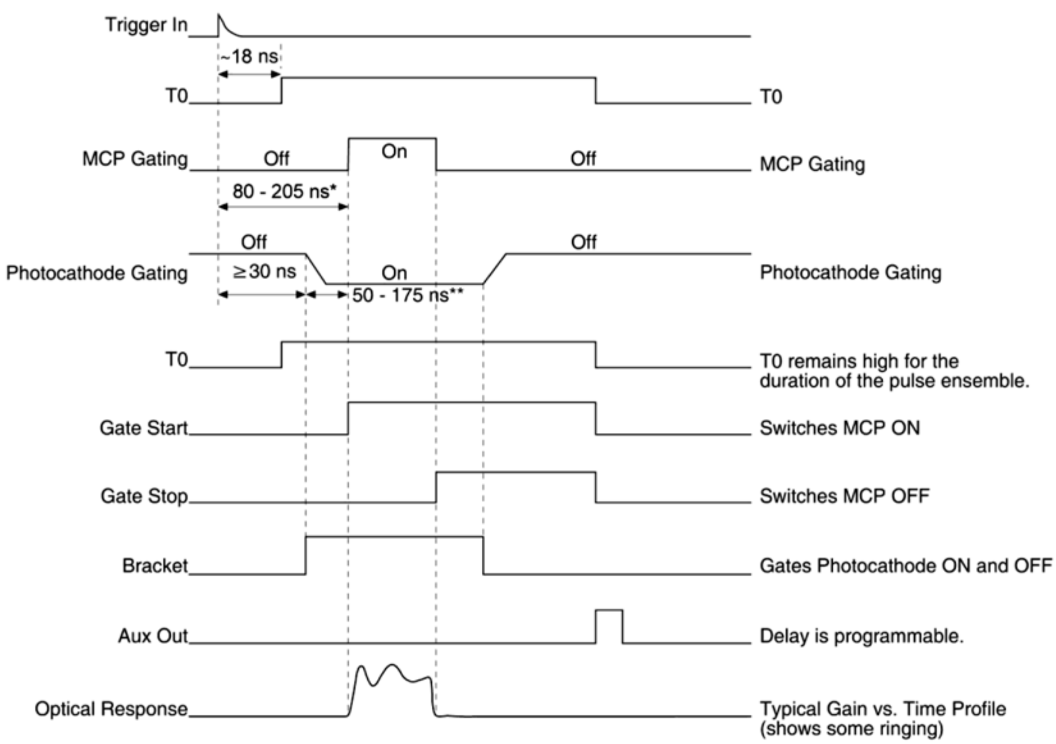
PRECISION

Ultimate in Precision | MCP Gating

Quick… but with High QE

The ability to gate the MCP on and off gives rise to an additional technique, known as MCP gating, which addresses the need to have the same QE as that of slow-gate tubes, but with shorter gate widths.

Princeton Instruments' special high-voltage electronics gate the MCP faster in order to allow standard slow-gate tubes (usually capable of gating at only ~100 nsec) to gate at ~9 nsec while preserving their high QE. This is an excellent solution for Gen II super-blue intensifiers, which offer ~30% QE in the blue region, yet are capable of <9 nsec gate speed.



* T_d+T_{pk} typical. Depends on individual image intensifier

** Depends on individual image intensifier

PRECISION

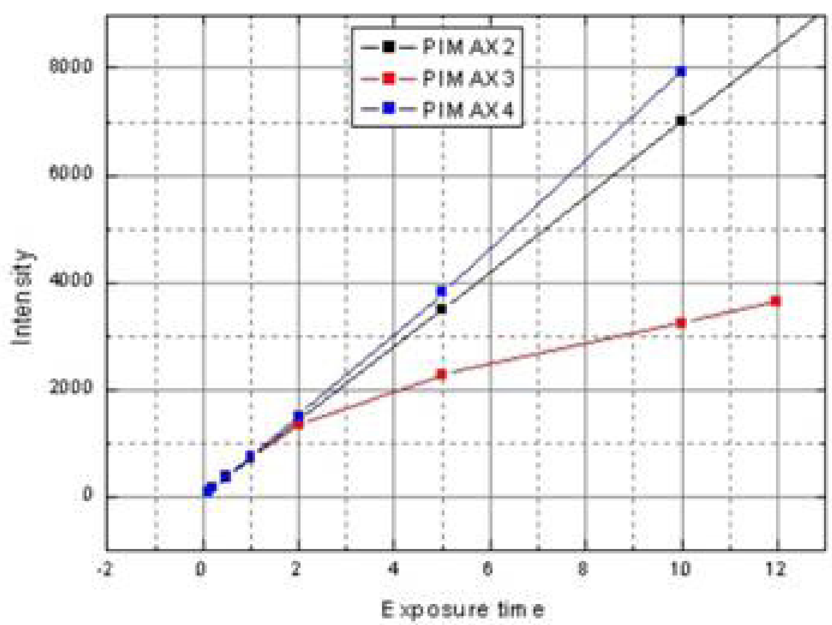
Ultimate in Precision | Linearity

Compare with Confidence

One of the most important specifications associated with any camera designed for scientific research is its linearity. The linearity of the detector enables researchers to confidently compare results from sample to sample (i.e., ratio between changes in experimental parameters) and within samples (i.e., ratio of contrasts). This specification is even more critical for scientific ICCD cameras because researchers must consider the linearity of two components, the image intensifier and the CCD, when controlling the intensifier gain. Care must be exercised by the user to set this gain so that neither the CCD nor the intensifier saturates in the intensity range of the experiment.

When it comes to camera precision, Princeton Instruments has never compromised. To provide the highest possible sensitivity, we have designed the PI-MAX4 without any window in front of the image intensifier as well as improved our high-voltage power supply (SuperHV) to provide higher intensifier gain, if desired by the user. The new camera's optical design has also been improved so as to reduce losses between the intensifier and the CCD. This better fiberoptic coupling allows us to utilize lower voltage across the MCP to improve gain performance (thus leading to better camera sensitivity and linearity). The PI-MAX4 also uses the best available scientific-grade CCDs in a system that already has extremely low noise and the best linearity available.

By carefully selecting every single component and painstakingly packaging each of them in a camera that does not require any external electronics boxes except a power supply, Princeton Instruments has ensured that the new PI-MAX4 surpasses the performance of all other scientific ICCD cameras on the market. The benefits of the PI-MAX4 design are readily apparent in the new camera system's superb linearity.



Ultimate in Precision | GigE

Operate Remotely and Easily

Another PI-MAX4 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 PI-MAX4 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 combustion or plasma studies in which the camera must be kept at a safe distance from host computers.

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 10GigE standard

Brief comparison of major data interface technologies...

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

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

GigE Vision is a registered trademark of the Automated Imaging Association (AIA).
Camera Link is a registered trademark of the Automated Imaging Association (AIA).
FireWire is a trademark of Apple Computer, Inc., registered in the U.S. and other countries.

PRECISION

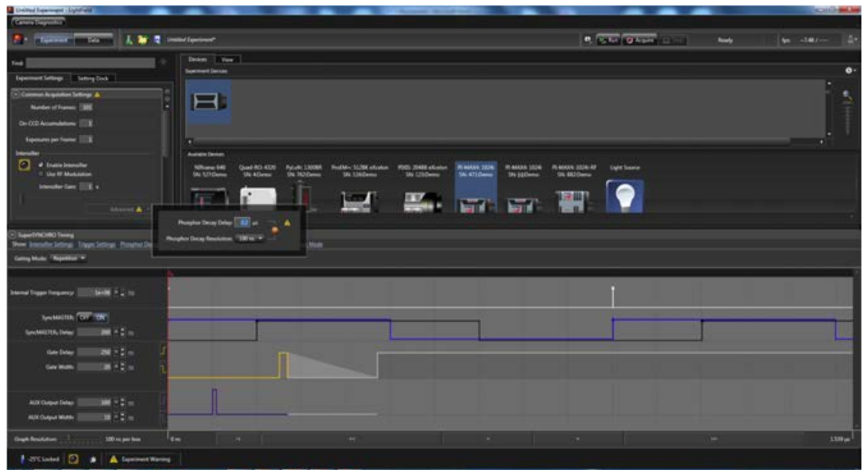
Ultimate in Intelligence | Timing

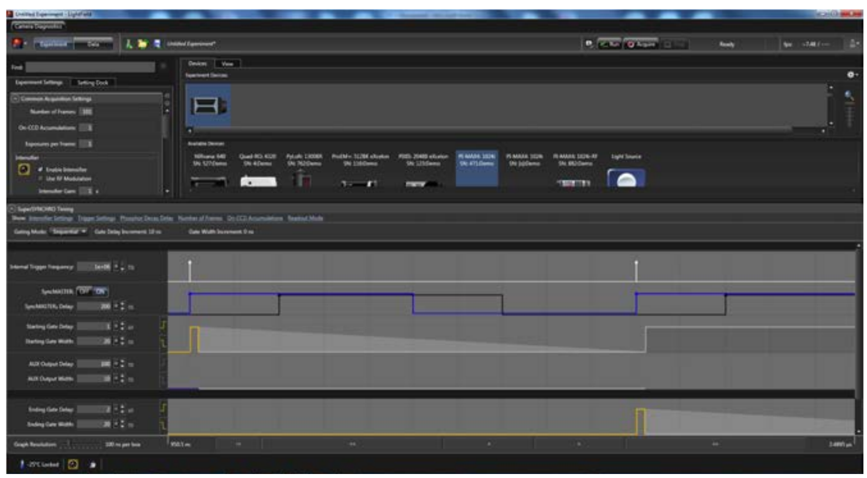
SuperSynchro

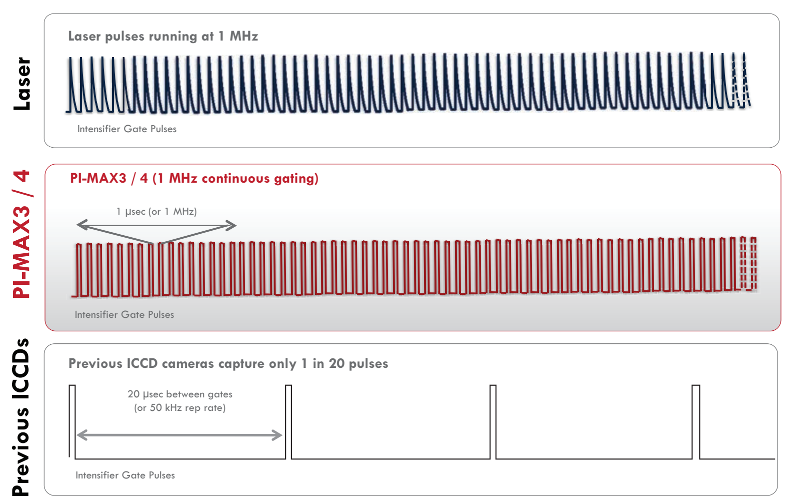
Built into the PI-MAX4 camera, the SuperSynchro timing generator makes setting up complex time-resolved imaging experiments easy. For example, SuperSynchro can store a sequence of gate delays and widths and execute them quickly to generate *time vs. intensity* data with just a few clicks of a mouse. It features several innovations, such as SyncMaster pulse output.

SuperSynchro advantages include:

- Complete and easy software control of gate width and delay sequences
- Closed coupled design for the lowest insertion delay (<27 nsec)
- On-board memory to store complex gate sequences and execute without delay
- 10 psec resolution and 35 psec rms jitter
- Configurable External Sync to accommodate a wide variety of trigger types
- Two SyncMaster continuous pulse trains to trigger pulsed lasers without interruption, or to trigger Q-switched flashlamp lasers or double-pulse lasers separately





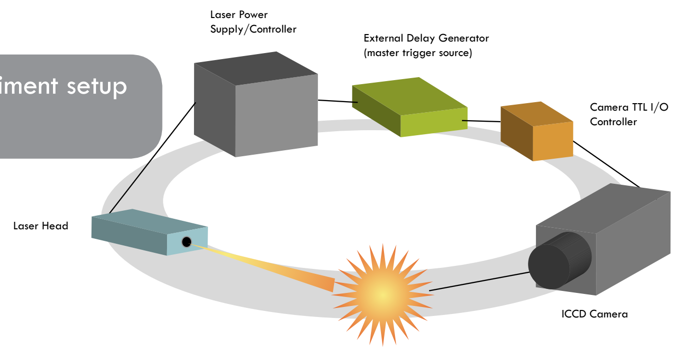


Ultimate in Intelligence | Space

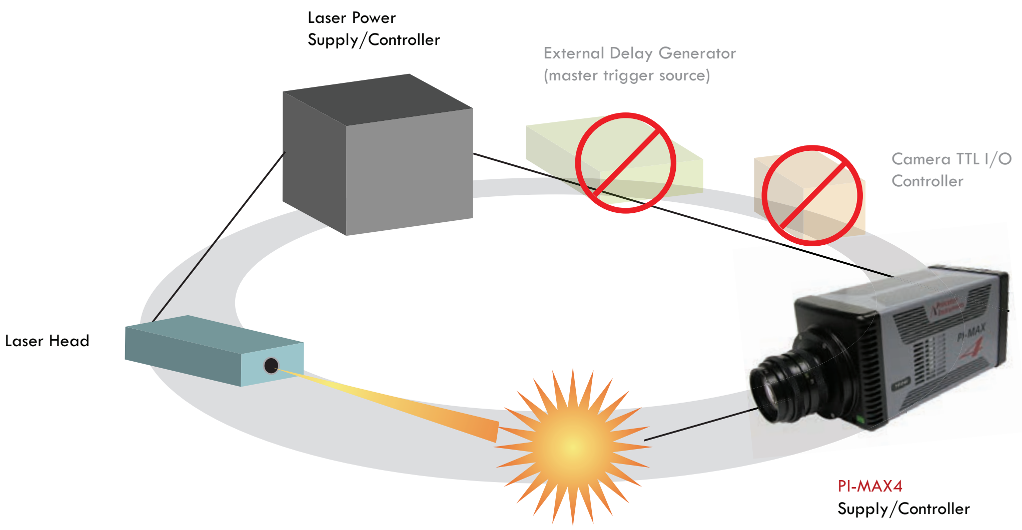
SyncMaster Keeps It Simple

Running out of space? Many research labs that conduct time-resolved measurements have an overabundance of delay generators and trigger sources to synchronize lasers and cameras. SyncMaster, a novel feature of the PI-MAX4, will help reduce this clutter by allowing the camera to output two continuously running pulse trains (user-set frequency) to trigger lasers externally. Because the camera's programmable gate widths and delays are generated from the same master clock, the resultant jitter is the lowest possible (typically determined by the laser jitter).

Time-resolved experiment setup **without** SyncMaster



Time-resolved experiment setup **with** SyncMaster



INTELLIGENCE

Ultimate in Intelligence | Control

INTELLIGENCE

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. LightField provides comprehensive control of PI-MAX4 cameras via easy-to-use tools that help streamline experimental setup, data acquisition, and post processing.

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

Drag and Drop Devices

Yes, simply drag and drop to create your experiment configuration. For spectroscopy, control the light path by directly clicking the mirrors!

A Virtual Oscilloscope

A special dashboard appears whenever a compatible PI-MAX4 ICCD camera is connected. Take complete control of gate delays, widths, and trigger input/output signals!

Gray Is Great

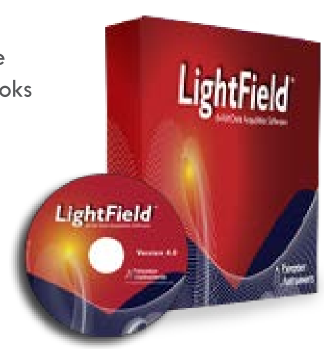
LightField's muted gray background minimizes interference with light-sensitive experiments. If complete darkness is required, LightField can simply turn off monitors during acquisition.

The Best Bar

View the status of hardware and acquisition settings at a glance!

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

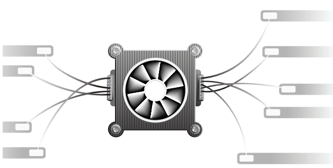


Visit our website for a 45-day trial.

www.princetoninstruments.com/products/software/LightField.aspx

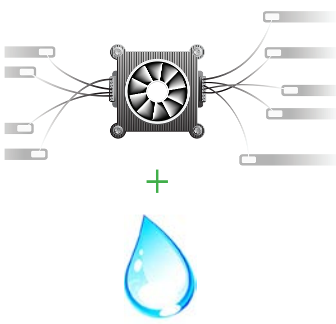
Ultimate in Intelligence | Cooling

The PI-MAX4 has a built-in thermoelectric cooler (TEC) to reduce the CCD temperature. An internal fan dissipates the heat load for reliable operation, while the addition of an external liquid circulator allows the user to further reduce dark current for improved signal-to-noise ratio.



-20 to -25°C

Air only: The most convenient cooling – just connect the camera and go! The built-in, low-noise fan does all the work.



-30 to -35°C

Air+Liquid: When your application requires maximum cooling and the lowest dark noise, the addition of an external liquid circulator used with the built-in fan results in even better cooling and reduced dark current.

Photocathode cooling: While CCD dark current may be negligible in short gating experiments, additional background noise exists in intensifiers. Equivalent background intensity (EBI) refers to thermally generated random events from the photocathode that can impose limitations on ultra-low-light or photon-counting applications. The only way to reduce EBI is to cool the photocathode directly and uniformly. Every PI-MAX4 has this capability – simply connect a dry nitrogen source to the camera and begin cooling.

Most gated, time-resolved experiments involve nanoseconds-to-microseconds exposure times. At these exposure levels, the signal-to-noise ratio of the frame is not influenced by CCD dark current or intensifier EBI. However, for experiments involving extremely low light at single-photon levels or when accumulating multiple gate pulses in order to improve signal-to-noise ratio, EBI can be a serious hindrance. A cooled photocathode has EBI levels as much as 20x lower than a room-temperature photocathode.

More about EBI

The EBI of an intensifier is akin to the dark charge of a CCD. The photocathode, due to thermal excitation, releases electrons even when it is in the dark. These unwanted electrons are amplified in a manner similar to photon-generated electrons and appear as bright spots in an image. EBI is specified as lumens/cm^2 or, more conveniently, as electrons/pixel/sec.

INTELLIGENCE

Ultimate in Intelligence | Sensitivity

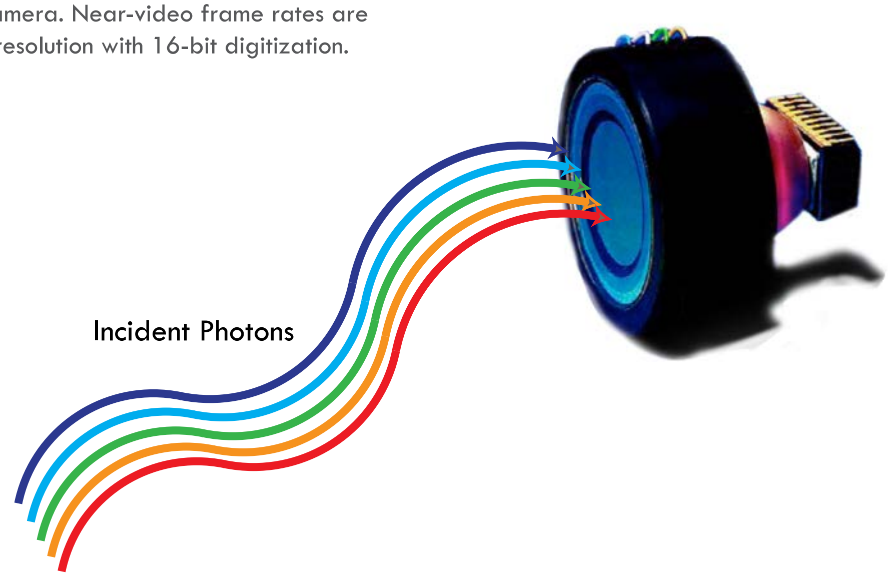
See the Light

Intensifier: Choose from a variety of Gen II or Gen III filmless intensifiers for the highest sensitivity from the deep UV to the NIR. All PI-MAX4 cameras use a windowless design for maximum light throughput.

Fiber coupling: At the heart of every PI-MAX4 is a scientific-grade CCD coupled to an intensifier. Fiber coupling, which offers greater than 6x the throughput between intensifier output and CCD as compared to the best lens-coupled configuration, results in the intensifier being operated at a much lower MCP gain.

PINS (Princeton Instruments Noise Suppression) technology: The engineers at Princeton Instruments have designed the PI-MAX4 with next-generation electronics, ensuring that it offers the best combination of CCD readout speed and the lowest possible noise levels in an ICCD camera. Near-video frame rates are provided at full 1k x 1k resolution with 16-bit digitization.

All PI-MAX4 cameras use a windowless design...



INTELLIGENCE

Ultimate in Intelligence | Flexibility

Gigabit Ethernet: For the first time, a scientific-grade ICCD camera is being offered with a Gigabit Ethernet (GigE) interface, allowing operation of the camera from a workstation from more than 50 m (150 ft) away – a critical requirement when the camera needs to be positioned in a remote or hazardous environment. For applications that require an even greater distance (up to several kilometers), the PI-MAX4 can be used with a fiberoptic converter.

LabVIEW (National Instruments): Need to integrate your PI-MAX4 into a larger experiment? Use LabVIEW VIs (virtual instruments) for easy access to the camera's many powerful features.

Free SDK: Occasionally, researchers need to modify acquisition software to meet the demands of a particular application. Princeton Instruments includes a free software development kit (SDK) with each PI-MAX4, complete with examples, to allow you to make any necessary edits right away so that you can get started on your research.

Ultimate in Intelligence | Mounting

Stay Focused

Change C-mounts, F-mounts, and spectroscopy mounts on your PI-MAX4 quickly and easily and still stay focused. Our factory-calibrated mounts* are designed for precision camera focusing, no matter what the gated application. Furthermore, the PI-MAX4 is easier than ever to mount on your optical table (metric and English-standard mounting holes on the camera offer ultimate convenience).

* Each PI-MAX4 camera system includes a single C-mount, F-mount, or spectroscopy mount. Additional mounts may be purchased from Princeton Instruments.

Maintenance-Free Operation

How do years of worry-free operation sound? The PI-MAX4 has fully integrated electronics and expertly sealed chambers, making your new camera virtually maintenance-free for years to come.

Unsurpassed Quality

Every Princeton Instruments product is designed, engineered, and manufactured with more than 50 solid years of scientific imaging and spectroscopy expertise to back it up. For five decades, researchers worldwide have depended on our instrumentation to provide the quality, reliability, and consistency their applications require.

PI-MAX4 cameras are manufactured in state-of-the-art facilities utilizing the latest manufacturing methods.

Worldwide Support

As a widely recognized and respected name in the scientific community, Princeton Instruments employs an extensive global network of representatives. These seasoned professionals gladly offer their application expertise and knowledge of low-light, gated ICCD camera technology to assist you in choosing the right solution for your most demanding research.

Online ICCD Resources

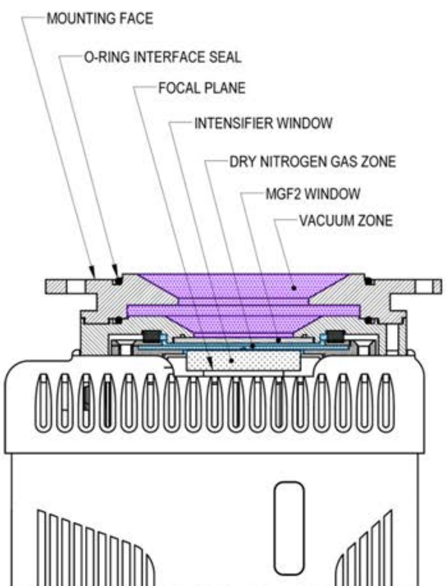
Need to learn the basics about how intensifiers work? Want to know how to select the right ICCD camera for your application? Perhaps you'd like clarification concerning the differences between fiber and lens coupling. Or maybe you're looking for reference papers published by researchers from leading labs.

Princeton Instruments has amassed a compendium of technical and application notes relating to ICCD cameras and time-resolved imaging and spectroscopy applications. Visit our website for the most current information.

www.PI-MAX4.com

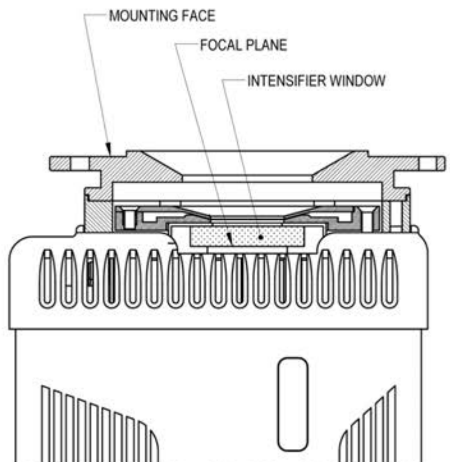
Spectrometer Interface

wavelength range: 120 nm – 1100 nm



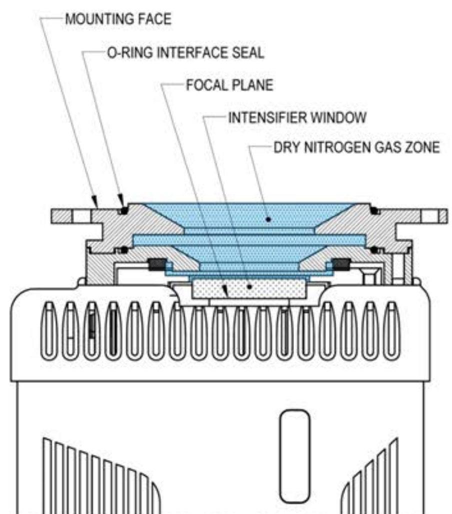
Vacuum Configuration

For the ultimate in detection down to ~120 nm, the camera must be sealed properly against a vacuum spectrograph. To meet this experimental requirement, Princeton Instruments offers a special vacuum-UV spec mount.



Standard Configuration

PI-MAX4:1024x256 and PI-MAX4:1024i cameras are supplied with a standard spec mount that can interface with Princeton Instruments IsoPlane™ and Acton Series spectrometers, popular high-precision instruments designed to facilitate detection from 350 nm to 1100 nm.



Nitrogen-Backfilled Configuration

When research demands detection below 350 nm but above 180 nm, a spec mount with a specially designed adapter capable of sealing the camera against Acton VM Series spectrometers is needed. Note that these advanced spectrometers are filled with dry nitrogen to eliminate the absorption of wavelengths between 180 nm and ~350 nm.

PI-MAX4:1024i-RF Camera

Widefield FLIM Measurements

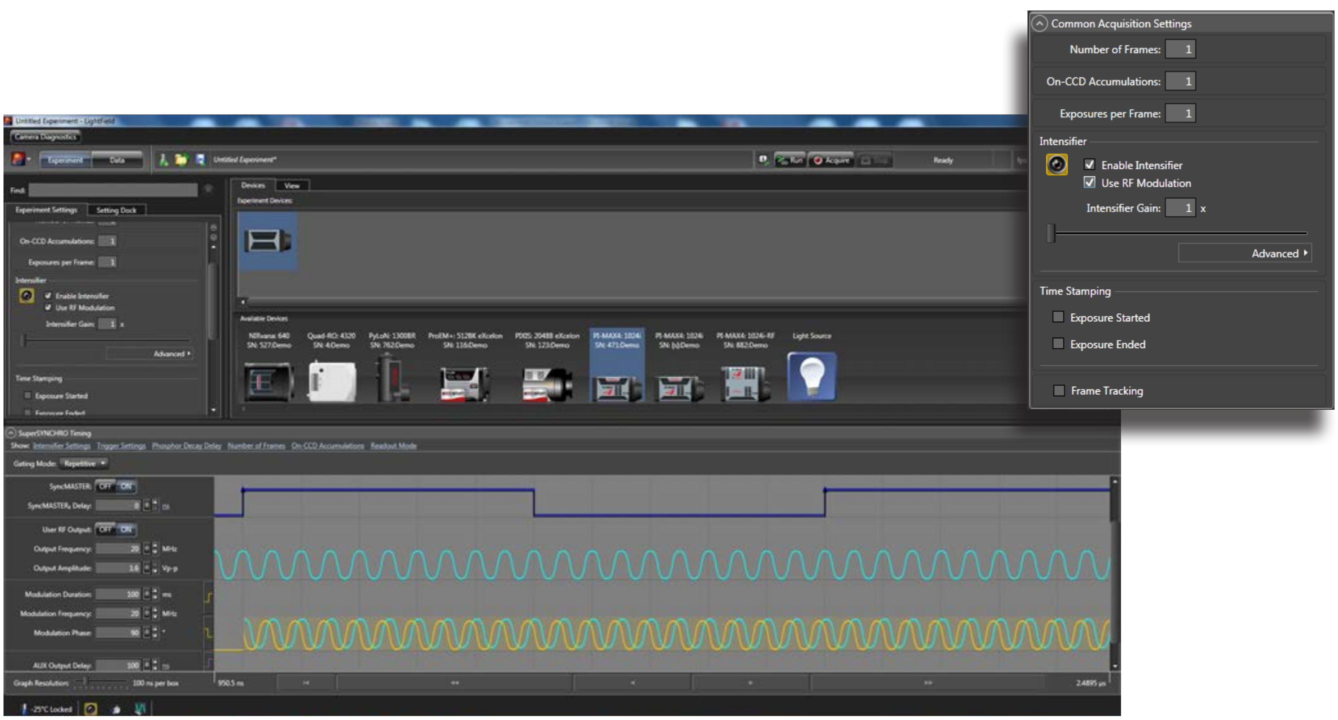
In addition to the PI-MAX4:1024i and PI-MAX4:1024x256, which both offer exclusive PIPs technology for gating to <500 psec, Princeton Instruments is pleased to introduce the PI-MAX4:1024i-RF, a next-generation camera that allows researchers to acquire frequency domain measurements for fluorescence lifetime studies utilizing minimal external equipment.

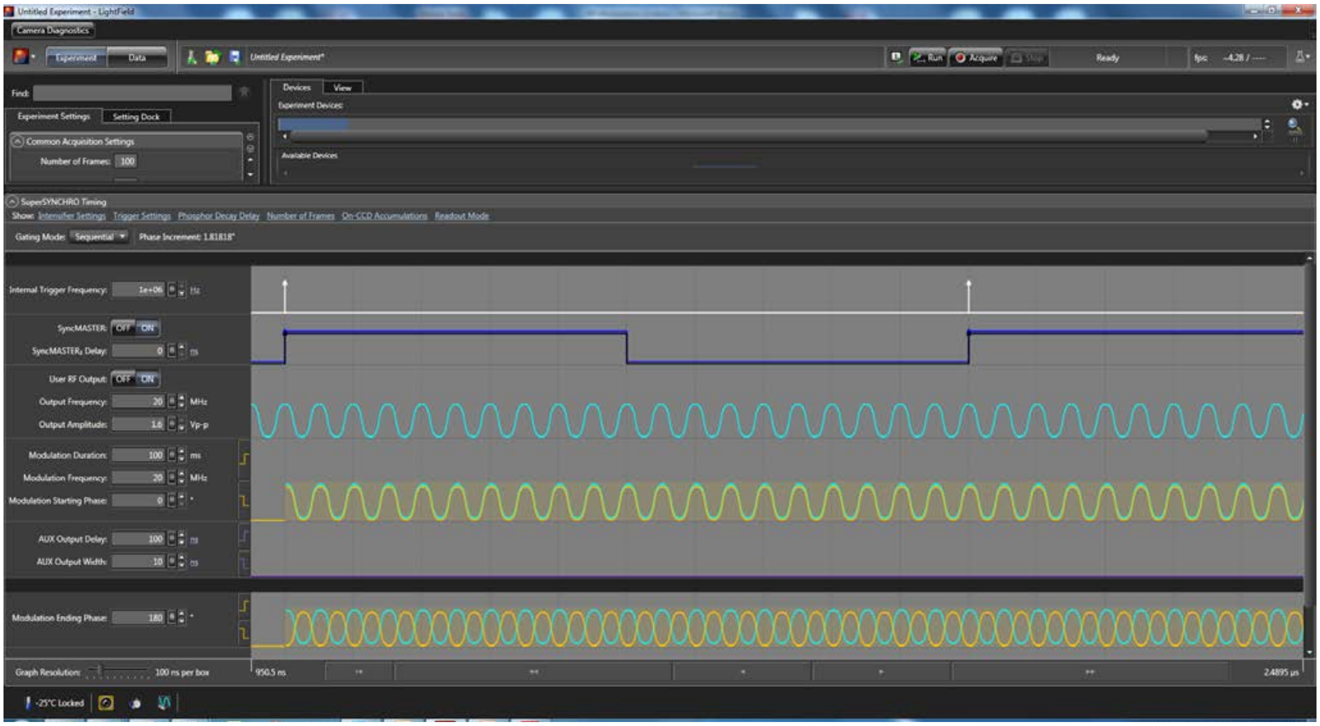
By modulating the gain of a Gen III filmless intensifier at a radio frequency (RF) rate, this special camera operates as a 2D lock-in amplifier. Each pixel acts as an individual phase-sensitive (lock-in) detector. The PI-MAX4:1024i-RF is ideal for advanced imaging techniques such as fluorescence lifetime imaging microscopy (FLIM) and fluorescence resonance energy transfer (FRET).

The new camera features two independent built-in direct digital synthesizers. One generates the RF to modulate the intensifier, whereas the other provides a user-controlled RF signal that can be employed to modulate the illumination so as to perform RF phase-sensitive detection. Minimal additional equipment will vary depending on the preferred light source. Typically, such equipment includes a light modulator (e.g., Mach-Zehnder, Kerr cell, Pockels cell) as well as an RF power amplifier to drive the modulator. The RF amplifier that drives the intensifier is built into the camera.

An intelligent LightField GUI lets researchers select frequency, control phase sweep range and granularity, and set user RF output p-p voltage levels. The system's built-in RF modulator provides full control of all intensifier gain parameters, ensuring highly precise measurements. An integrated frequency generator means there is no need for an additional, expensive external frequency generator. Furthermore, the built-in SuperHV high-voltage power supply / pulser eliminates the requirement for an external high-voltage supply.

The PI-MAX4:1024i-RF can also be utilized for work that involves time domain gating, as this system retains the impressive ICCD performance provided by our non-modulated PI-MAX4 cameras (with the exception of picosecond and MCP gating).





The PI-MAX4:1024i-RF is one of the most advanced ICCD cameras in the world!

RF Modulator Specifications

Modulation frequency	1 MHz – 200 MHz (in 1 MHz increments)
Phase modulation	static phase: 0° – 359° (in 1° increments); programmed sweeps (can cover >360°)
User RF output voltage	0.1 – 1.6 Vp-p (in 0.01 V increments)

Outputs

User RF OUT
programmable continuous frequency output to synchronize external devices with PI-MAX4

MON RF OUT
an approximate indicator of the RF applied to the photocathode

PI-MAX4 “RF”

Anatomy of the PI-MAX4:1024i-RF Camera

for frequency domain imaging applications

1 DIF (optional)
Double Image Feature allows capture of two full-resolution images separated by as little as 450 nsec; ideal for particle imaging velocimetry

2 SuperHV
Built-in high-voltage circuitry positioned close to intensifier for the lowest propagation delays and highest repetition

3
Easily mounts to C-mount lenses, F-mount lenses, and leading spectrographs such as the advanced Acton Series from Princeton Instruments

4 PINS
Princeton Instruments Noise Suppression technology for high-speed, low-noise CCD readout

5 RF Modulation
By modulating the gain of an intensifier at a radio frequency (RF) rate, this camera operates as a 2D lock-in amplifier

6 Gate Monitor
Know when the intensifier is gated on/off for precise timing

Utilizes Gen III filmless intensifiers fiber-coupled to CCDs for the highest light throughput

Ultimate in Precision, Ultimate in Intelligence

7 **SuperSynchro**
Built-in timing generator for fully programmable gate delays/widths; auxiliary outputs

8 **GigE**
The latest Gigabit Ethernet data interface; operate the camera more than 50 m away from the host computer

9 **Liquid-assist cooling (optional)**
Further reduction of CCD dark current

10 **TTL outputs with adjustable delays**
Synchronize lasers and other instrumentation in the experiment

11 **SyncMaster**
Continuously running, variable pulse trains to trigger lasers for the lowest jitter

Powered by LightField®

An Interview with Ray Simpson: The Man behind PI-MAX®4

Ray, you've been with Princeton Instruments for a long time. When did you join?

RS: I started in the very beginning, when we were a small operation. I designed the original IRY and the ST-100 controller, as well as the FG-100, our first gate generator. Together, they formed the first Princeton Instruments intensified, gated system. [Ed. note: The "R" found in the product name "IRY" honors Ray's invaluable contribution to the project.]

Princeton Instruments has had a long history of building scientific-grade intensified cameras. Can you take us through a few of the milestones?

RS: The first system was an intensified photodiode array for spectroscopy [the IRY system]. It had 14-bit dynamic range and performed well for the time. As scientific-grade CCDs became available, the company's focus shifted in that direction. Our early ICCD cameras were based on Thomson and EEV [now e2v] CCDs. Soon there were a myriad of combinations, some general purpose and some with more specialized capabilities. EEV introduced some large-area CCDs, which we coupled to 25 mm intensifiers to provide really state-of-the-art ICCD cameras. These cameras were good performers even by modern standards, but had some limitations and user inconveniences, such as large controller size and the need for multiple boxes [controller, gate generator, head]. Also, the original gate generator had all-analog controls. It was replaced by the PG-200, which had similar performance, but with digital control – which helped improve user convenience and allowed more automated experiment control.

How did the ICCD cameras evolve for scientific imaging and spectroscopy?

RS: The original ICCD cameras were effective, but required dry gas purge to avoid condensation on the cooled CCD. Competitors used noncooled CCDs; however, for high-performance scientific work, cooling is really needed. The PI-MAX was developed to provide improved performance and ease of use. The nose was sealed, so no gas purge was needed. Newer, more compact, high-voltage supplies were used and the pulse repetition rate was increased to 50 kHz sustained. It was a very popular combination and has been in production for 15 years.

Can you summarize the PI-MAX4 camera?

RS: The PI-MAX4 is a new design, internally and externally, and it extends the capabilities of the PI-MAX family. No separate controller is needed, but it's smaller than its predecessor. It can sustain a 1 MHz gating repetition rate and is designed to allow us to add more functionality. The sealed chamber includes the CCD, but there is no extra window over the intensifier, so stray light is reduced. Readout rate is greatly increased for time-resolved studies. Trigger response time is much quicker because there aren't any external cables between timing and gating circuits. The host interface is Gigabit Ethernet, so it allows wide data bandwidth and remote operation from a long distance.

What are some of the target applications for the PI-MAX4?

RS: This new camera's key features are engineered to support all of today's most challenging time-resolved applications, from combustion to nanotechnology. As I stated previously, the PI-MAX4 is a ground-up design that takes advantage of the latest in low-noise electronics and advanced intensifiers. You can see

This new camera's key features are engineered to support all of today's most challenging time-resolved applications, from combustion to nanotechnology.

many improvements in performance… close to 26 full frames per second at full 1 megapixel resolution, a 1 MHz sustained gating repetition rate, and a SuperSynchro timing generator with low propagating delays. Not only does it have better all-around performance, a lot of the innovations really enhance the usefulness of the camera. A case in point is the SyncMaster output that lets the camera act as a true master to optimize synchronization.

How does the PI-MAX4 achieve a 2x faster gating repetition rate over previous/competing models?

RS: The higher repetition rate is a combination of using the newest component technology and smart thermal management with custom heat sinks designed in-house. The economically achievable power density in switch-mode power supply designs has advanced remarkably in the past dozen years, allowing us to fit a high-power 200 V supply in a small corner of the backplane board. The gate generator driver stages use RF transistors designed for [microwave] cellular base stations; these didn't exist back when the original PI-MAX was developed. This lets us provide full 200 V gating pulses up to a 1 MHz repetition rate, allowing full resolution and gain.

Can you elaborate on SyncMaster?

RS: SyncMaster is a great convenience to researchers using pulsed lasers that are more stable when kept pulsing at a steady rate. SyncMaster derives its output from the same master oscillator that operates the timing generator, so jitter is minimized. SyncMaster remains active even when the camera is not capturing data, so the laser operation is never disturbed.

Princeton Instruments first designed bracket pulsing to improve on/off ratio in the UV range. Is it available in the PI-MAX4?

RS: Yes, it's available on PI-MAX4 models that use Gen II intensifiers, which can benefit from this technique. Its response time has been improved from the old version and the propagation delay in bracket mode is kept to a minimum.

What are the challenges you had to overcome while designing picosecond gating and MCP gating in the compact PI-MAX4 package?

RS: The challenges associated with these two types of gating are quite different. In the case of 500 psec gating, it is a question of generating such a short pulse and transferring it to the intensifier with minimal loss of fidelity. Fortunately, very high speed FETs have become available, mostly as a spin-off of the advances in cellular radio and radar technology, so it is possible to generate the required short pulses. The use of controlled impedance flexible transmission lines allowed us to get the gate to the intensifier. For MCP gating, issues include generation of a pulse of 800 to 900 V, with pulse width <10 nsec… and again getting it to the intensifier. In addition, the MCP capacitance is quite high, so the peak currents are also high [I= CdV/dt]. This leads to high peak power dissipation in the gate driver, and therefore the repetition rate in this mode is limited. Furthermore, there is a tendency for the capacitance to interact with the transmission line and cause overshoot and other gate pulse aberrations. We adjust the damping on each camera for optimum operation.

What are the technical differences between MCP Bracket Pulsing and true MCP gating?

RS: MCP Bracket Pulsing was pioneered by Princeton Instruments and is used to enhance the on/off ratio in Gen II intensifiers in the UV portion of the spectrum. The MCP bracket gate has to have a fast opening to ensure the bracket is fully open when the main photocathode gate occurs, but a fast closing time is not required. The circuitry to do this has to fit in along with the main photocathode gate generator, so it needs to be compact. True MCP gating was also pioneered by Princeton Instruments. It allows the gating of slow-gate intensifiers [which have approximately twice the QE of fast-gate intensifiers] at <10 nsec gate width. The slow photocathode increases the insertion delay, but otherwise gating acts very similarly to a fast-gate tube [within the minimum gate-width limitation].

With the availability of EMCCDs, what do you think about the future role of ICCD cameras for low-light imaging and spectroscopy?

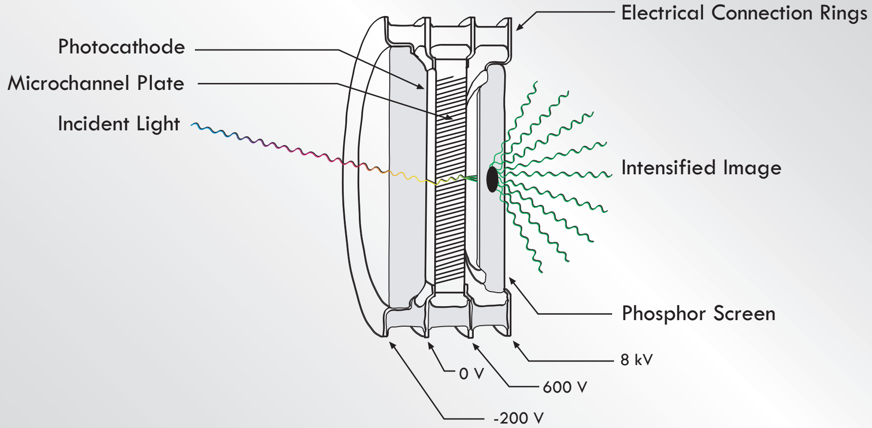
RS: EMCCDs are a great innovation… Princeton Instruments offers the best of this technology, too. However, only ICCD cameras provide gating over the picoseconds-to-microseconds range. ICCD cameras can also be operated with RF modulation in order to act as a 2D imaging lock-in amplifier. [This capability is available in the PI-MAX4:1024i-RF camera.]

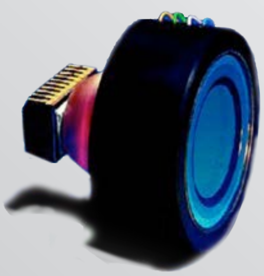
What's next for the PI-MAX4?

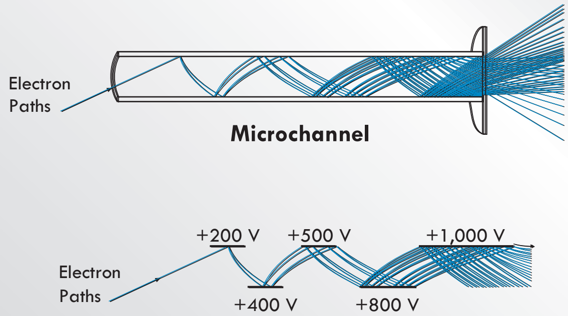
RS: Obviously, I can't reveal all of our new product plans, but if one looks at PI-MAX evolution thus far as a guide, one would predict more CCD choices and other enhancements from Princeton Instruments.

Technical Notes

The following technical notes offer an introduction to ICCD technology and performance parameters.







Introduction to Image Intensifiers for Scientific Imaging

Introduction

An image intensifier is a vacuum tube device, generally 18-40 mm in diameter. The intensifier (see Figure 1) comprises a photocathode input, which is a coating of multi-alkali or semiconductor layers on the inside of the input window, and a phosphor screen, which is a fluorescing phosphor coating on the inside of the output window. Also included are either simple grid-shaped electrodes (i.e., early intensifier technology) to accelerate electrons through the tube or, in later intensifiers, a complex electron-multiplying microchannel plate (MCP) (Figure 2).

A portion of the incident photons striking the photocathode causes electrons to be released via the photoelectric effect. These electrons are then accelerated and multiplied to the phosphor screen, where they strike the output phosphor coating and cause it to release light. This released light consists of many photons for every incident light photon striking the photocathode surface.

The development of image intensifiers has been primarily motivated by use in the military for night vision. Various types of imagers have been optimized for use in the near infrared (NIR), the main form of night illumination in battle environments. This military influence has led to the adoption of their official convention in the naming of the types of image intensifiers. These types are referred to as generations (Gen) and currently consist of (in order of technology development) Gen I, Gen II, Gen III, and Gen III filmless. Distinctions among the intensifier generations are discussed in the appendix.

The incorporation of image intensifiers into high-performance charge-coupled-device (CCD) cameras has produced intensified CCD (ICCD) systems for imaging and spectroscopy that possess high sensitivity in ultra-low-light conditions and allow temporal resolution, as high as 500 psec, to capture extremely short phenomena. These ICCD systems are widely used for such state-of-the-art applications as laser-induced fluorescence (LIF), laser-induced breakdown spectroscopy (LIBS), combustion research, plasma studies, and nondestructive testing (NDT).

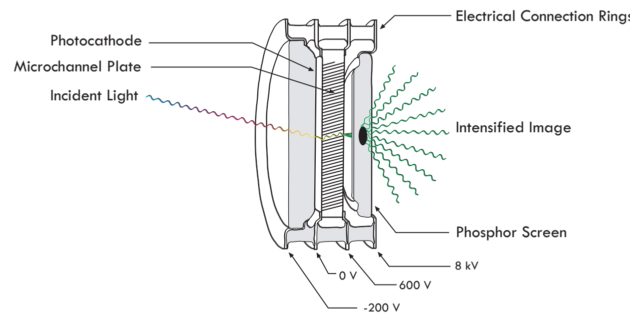


Figure 1. Components of an image intensifier tube.

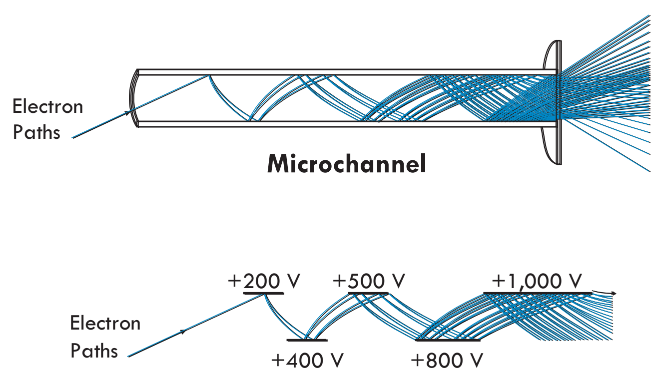


Figure 2. Schematic drawing of an MCP channel (top), which acts analogously to a photomultiplier (bottom).

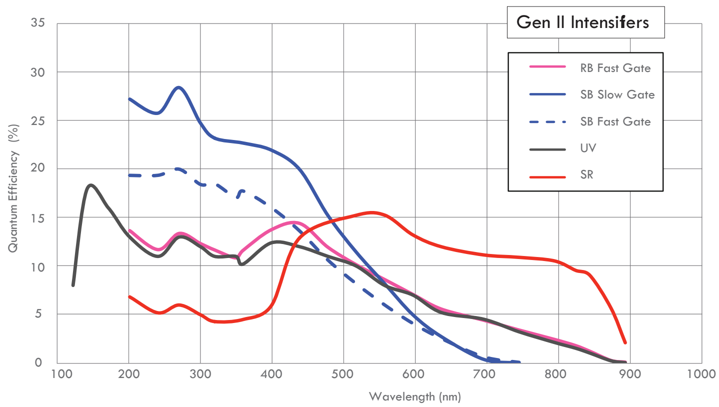


Figure 3. Comparison of Gen II RB (red-blue balanced response), SR (super-red), SB (super-blue), and UV photocathodes.

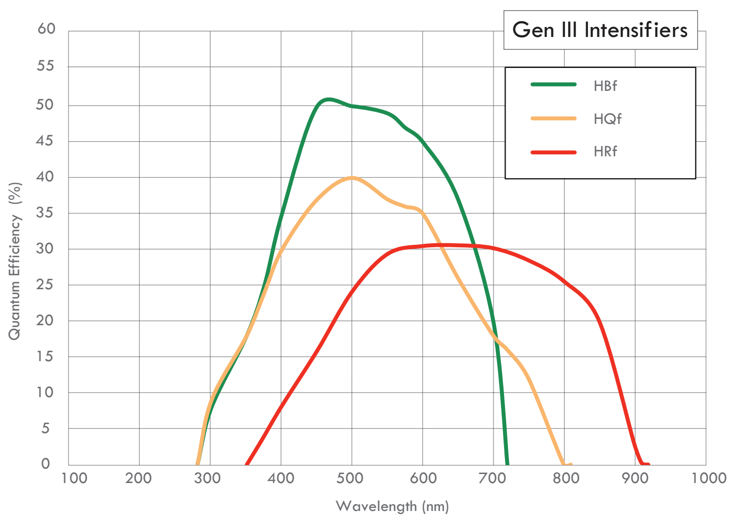


Figure 4. The latest Gen III filmless HRf, HQf, and HBf GaAsP photocathodes provide the highest QE in the visible region.

Components of an Image Intensifier Photocathode

The photocathode is the first major component in an image intensifier. Coatings on the photocathode convert a portion of the incident light photons into electrons. Photons that are not captured by the photocathode are lost from the final signal produced by the intensifier. Therefore, quantum efficiency (QE), defined as the percentage of incident photons converted to electronic charge, is very important for intensifiers.

Early intensifiers used multi-alkali coatings consisting of compounds with fair photoconversion performance in the visible (VIS) and ultraviolet (UV) regions, but relatively limited response at NIR wavelengths. These coatings were generally analogs of sodium, potassium, antimony, cesium, or silver. Gallium arsenide (GaAs) is a more recent semi-conductor, low-bandgap coating with high QE in the VIS and NIR regions. In contrast to military needs for intensifiers with higher NIR sensitivity, scientific ICCD usage usually focuses on the blue/green region of the spectrum. This has led to the development of photocathode coatings for ICCD use with QE improvements in the blue/green region. For example, Princeton Instruments (PI), the leading manufacturer of high-performance ICCD camera systems, offers Gen II red-blue balanced response, super-blue, super-red, and UV photocathodes (Figure 3).

Subsequent Gen III intensifiers were based on GaAs photocathodes and required the use of ion barriers to prevent ion feedback and to prolong lifetime.

The latest Gen III filmless intensifiers, as the name suggests, are produced without the ion barrier or film, and achieve the highest possible QE in the visible region (Figure 4).

EBI

A component of the noise in an intensifier comes from thermally generated electrons from the photocathode and is known as equivalent background illumination (EBI). These electrons are indistinguishable from those generated by light photons and therefore contaminate the image signal. In advanced ICCD cameras, EBI can be reduced by cooling the image intensifier and is usually negligible in gated applications.

MCP

The MCP is the second and most sophisticated component of an image intensifier. It is a slightly conductive glass substrate (approximately 2 cm in diameter and 0.5 mm thick) with millions of parallel traversing channels containing a secondary electron emitter (e.g., cesium iodide, copper iodide) on their inner walls. Early MCPs generally had channels 10-12 μm in diameter, arranged in a hexagonal pattern with 12-15 μm, center-to-center spacing. More recent MCPs have been developed with 6 μm channels, leading to enhanced image spatial resolution (>64 line-pairs/mm).

Electrons generated by the photocathode are driven through the channels by a constant field from a voltage (600 V) applied to the MCP. A portion of the electrons passing through strikes the walls, causing the formation of more electrons. Multiple collisions continue, with a single entering electron producing many thousands of electrons that finally exit the plate (Figure 2). To provide electrical contact for all the channels, the MCP input web surface is generally coated with nichrome, which also has a low secondary electron emission coefficient. Because of this latter characteristic, electrons missing the channels and striking the input surface (which comprises up to 55% of the MCP) create secondary electrons, some of which are then pulled into nearby channels by electrostatic forces. This allows recovery of some of the electronic charge that would otherwise be lost by electrons missing channel openings. In essence, each MCP channel acts analogously to a standard photomultiplier device.

Phosphor Screen

The third major component of an image intensifier is the phosphor screen. Electrons exiting the MCP are accelerated by a constant voltage (5-8 kV) and strike the screen, where they are converted back into light photons for detection by the CCD. Phosphor screens usually emit green light and are made of rare-earth oxides or halides (e.g., gadolinium, lanthanum, yttrium), with decay times of a few hundred nanoseconds to a few milliseconds. Figure 5 shows some typical phosphor emission spectra at various wavelengths. Table 1 shows fluorescence decay times of a variety of phosphors commonly used in ICCDs. When applications require high frame rates (>300 Hz) or frames to be captured with short interframe times (e.g., Double Image Feature, or DIF), a faster phosphor such as P46 is required. Otherwise, for most applications P43 is a suitable phosphor as it provides the highest emission and closely matches the peak sensitivity of the CCD.

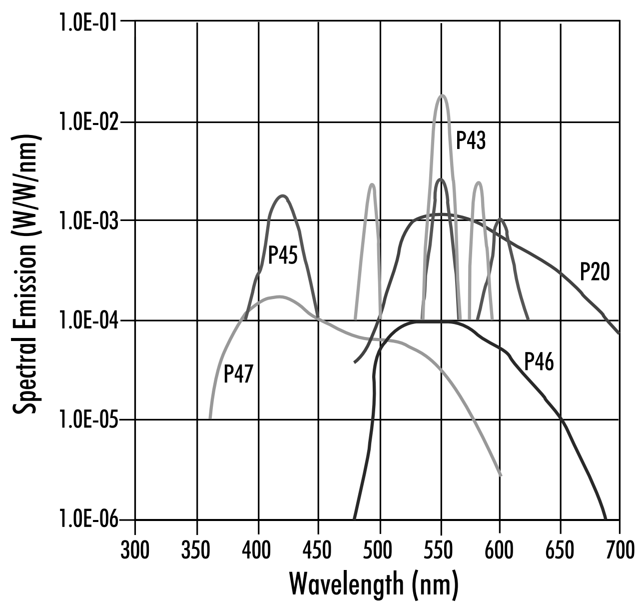


Figure 5. Emission spectra of intensifier phosphor screen coatings.
P20 = Y_2O_2S:Eu
P43 = Gd_2O_2S:Tb
P45 = Y_2O_2S:Tb
P46 = $Y_3Al_5O_{12}$:Ce
P47 = Y_2SiO_5:Ce

Phosphor Decay	Time Down to 1%
P20	60 msec
P43	3 msec
P46	2 µsec
P47	0.4 µsec

Table 1. Fluorescence decay times of phosphors.

Coupling of Image Intensifiers to CCDs

The intensifier in an ICCD camera can be coupled to the CCD either with a lens or a fiberoptic bundle (Figure 6). Lens coupling offers the advantage of flexibility: (1) the intensifier can be removed and the camera used as a standard CCD imager, and (2) an intensifier can be added cost effectively to an existing CCD camera. Disadvantages of lens coupling include lower light throughput (5-10%), shorter lifespan of tubes due to higher gain operation, and increased stray light in the camera system.

Coupling via fiberoptics offers better light throughput (~60%) between intensifier and CCD than lens-coupled configurations. Fiberoptic-coupled ICCD cameras are capable of sensitivities approaching single-photoelectron detection and have a much better signal-to-noise ratio (SNR) than lens-coupled devices. Disadvantages are that the fiberoptic coupling is permanent and the detector must be operated in a dry, non-vacuum, inert environment. Advanced ICCD cameras, such as those produced by Princeton Instruments, incorporate such operating conditions in a sealed, maintenance-free package. For more information, see the Princeton Instruments technical note "Comparison of Lens-Coupled and Fiberoptic-Coupled ICCD Cameras".

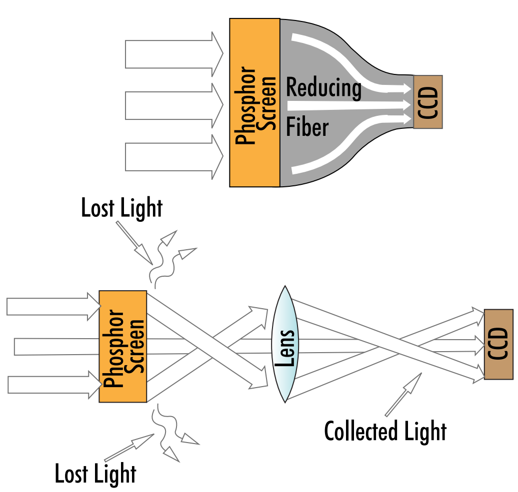


Figure 6. Comparison of fiberoptic-coupled (top) and lens-coupled (bottom) ICCD cameras.

Image Intensifier Gating

Temporal resolution in an ICCD is made possible by switching the intensifier on and off (gating) very rapidly. If the photocathode is biased more positively than the MCP, electrons will not enter the MCP and the intensifier is gated off. If the photocathode is negatively biased, electrons will be accelerated into the MCP and the intensifier is gated on. Typical Gen II fast-gate intensifiers have minimum optical gate widths (FWHM = full width at half-maximum) of ~2 nsec. (Note: PI offers select Gen II intensifiers with <500 psec gate speeds.) For slow-gate devices, optical FWHM is 50-200 nsec.

To overcome the high resistance of the photocathode material, a nickel (Ni) underlayer is deposited on the photocathode to lower this resistance and enable fast gating. However, the Ni layer can produce effective QE reduction of as much as 40%. Slow-gate intensifiers have neither a Ni layer nor its effects on QE.

The latest Gen III filmless intensifiers offer similar gating performance to Gen II, yet the highest QE.

The on/off gating ratio of the intensifier is a direct measure of the quality of gating, with a high ratio being necessary to eliminate background and accurately reproduce the transient image. This parameter is defined as the ratio of light output when the intensifier is *on* to the output when the intensifier is *off*. In the VIS region of the spectrum, gating ratios of 10^7:1 are possible with standard intensifiers. In the UV region, ratios of only 10^4:1 were traditionally the best that could be attained due to energetic UV photons striking the MCP input surface and releasing secondary electrons. However, ratios as high as 10^7:1 in UV wavelengths can now be achieved with advanced gating technologies such as Princeton Instruments MCP Bracket Pulsing. Other novel gating techniques include MCP gating, where gating is carried out across the MCP instead of the photocathode. With MCP gating, it is possible to achieve gate widths of 9 nsec or less without sacrificing the QE of a slow-gate tube. New PIPs (Princeton Instruments Picosecond) gating technology improves fast-gate rates to <500 psec. For more information, see the Princeton Instruments technical note on "ICCD Gating".

Conclusions

The development of image intensifiers has been driven primarily by the needs of large military markets; these needs are frequently not the same as those in scientific arenas. With careful selection and proprietary photocathode development, scientific camera manufacturers such as Princeton Instruments can tailor performance to meet the needs of the research community for high sensitivity and gate speed.

Princeton Instruments offers the state-of-the-art PI-MAX®4 line of scientific ICCD cameras with a wide selection of Gen II and Gen III filmless intensifiers. These systems offer lens or fiberoptic coupling, as well as a full array of advanced features such as a built-in SuperSynchro timing generator to deliver the highest performance and flexibility available for time-resolved studies.

APPENDIX

Gen I Intensifiers

Developed in the early 1960s, Gen I intensifiers employed electrostatic focusing and electron acceleration to achieve signal gains up to 150. Gen I intensifiers could detect images under ambient light intensity as low as .01 lux (roughly equivalent to the light intensity under a full moon at night). Problems included image distortion, short-lived components, and the large size of the devices. Gen I intensifiers are now obsolete.

Gen II and Super-Gen II Intensifiers

These are the most commonly used image intensifiers in ICCD cameras. Introduced in the late 1960s and early 1970s, these intensifiers incorporated MCPs. Substantially improved gain (up to 20,000) is accomplished by accelerating electrons as well as by multiplying electrons in the MCP channels. Gen II intensifiers are only two-thirds as efficient as Gen I devices due to the loss of electrons striking the MCP input surface (discussed above) and to the lack of multiplying effects of those electrons passing through channels without striking interior walls. The Gen II devices have high resolution, are small, and produce no image distortion. Gen II intensifiers can detect images under ambient light intensity as low as .001 lux (roughly equivalent to the light intensity under a quarter moon at night).

Super-Gen II image intensifiers are Gen II devices that employ novel photocathodes with extended spectral range or high QE in a particular wavelength range. For the military, this generally involves response curves shifted in the red direction, which may reduce blue/green performance. For scientific ICCD applications, on the other hand, improved blue/green performance is usually the goal, with NIR QE sometimes being an additional advantage.

Gen III and Gen III Filmless Intensifiers

Gen III image intensifiers are Gen II technology with GaAs added as the photocathode coating. GaAs is extremely photosensitive in the NIR region above 800 nm, but is relatively poor in the blue/green region. Gen III intensifiers utilize high-resolution MCP plates (6 µm diameter channels) and ion-barrier films.

Gen III intensifiers are 2-3 orders of magnitude more sensitive to ambient light than Gen II intensifiers. Gen III devices can detect images under ambient light intensity as low as .00001 lux (roughly equivalent to the light intensity under a heavily overcast sky at night with the moon and all but a few stars completely obscured). Recently, Gen III devices have been further improved with the introduction of higher-resolution tubes (>72 lp/mm).

The latest Gen III intensifiers are produced without an ion barrier and use GaAsP and GaAs photocathodes. These intensifiers currently offer the best combination of QE (50% peak) and gating speed.

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ICCD Gating

Introduction

In recent years, rapid developments in the field of intensifier technology coupled with advancements in CCD technology have allowed ICCD cameras to be used in spectroscopy and imaging applications involving transient phenomena at ultra-low-light levels. Detection and time resolution of low light are two unique strengths of ICCDs. Low-light detection is achieved by high amplification of incoming photons by the intensifier, whereas time resolution is possible due to the fact that the intensifier can be switched on and off (gated) in very short intervals. The use of PIPs (Princeton Instruments Picosecond) technology enables gating to <500 psec.

Principle of Operation

The construction of an image intensifier tube is shown in Figure 1. The intensifier consists of a photocathode, a microchannel plate, and a phosphor screen. A fraction (called the quantum efficiency, or QE) of the photons incident on the photocathode is converted into electrons. Single photoelectrons are converted into clouds of electrons by the microchannel plate (MCP), which acts as a distributed electron multiplier. The electrons released from the MCP then strike the fluorescent screen (phosphor) and cause it to emit far more light than was incident on the photocathode. In the traditional configuration, the voltage between the photocathode and the input of the MCP is used to switch the intensifier on and off. If the photocathode is electrically biased more positively than the MCP, electrons will not enter the MCP and the intensifier is gated off. If the photocathode is negatively biased, electrons will be accelerated toward the MCP and the intensifier is turned on.

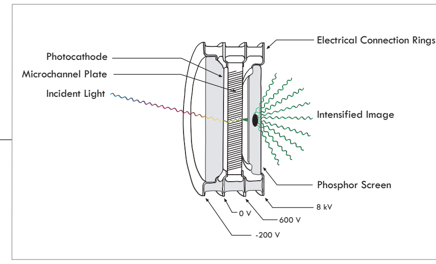

Figure 1. Cross-section of an image intensifier tube.

Gating Speed

Photocathode material is deposited on the inside face of the front window of the intensifier. Electrically, this can be represented as a resistor-capacitor network. Due to its high resistance (thereby high RC constant) photocathode material in a generation II (Gen II) intensifier by itself does not allow fast gating. To overcome this limitation, in Gen II intensifiers, a nickel underlayer is deposited on the front window, which lowers the resistance and allows fast gating. With the Ni layer, Gen II intensifiers can be gated down to 2 nsec (<500 psec on select tubes). But, due to the Ni layer, the sensitivity (QE) of the system is lowered. Intensifier manufacturers' data indicate that the reduction in QE can be as much as 40%. Slow intensifier tubes, on the other hand, do not have this Ni layer and thus have no QE loss. They can, however, have minimum gate widths up to 50 nsec or more.

In addition to fast gating performance (<500 psec), the latest Gen III filmless HRf intensifier offers the highest QE available in the NIR.

A summary of gating performance of various intensifiers is provided in Table 1.

Intensifier Type (PI Model)	Photocathode Material	Minimum Gate Width Optical FWHM	Gating Voltage (Typical)	Notes
Gen II - Slow Gate (SB)	Bi- and multi-alkali	50-200 nsec (<9 nsec with MCP gating)	200 V	MCP gating allows faster gating
Gen II - Fast Gate (RB, SB, SR)	Bi- and multi-alkali	<500 psec - 2 nsec	200 V	Select fast-gate tubes can offer <500 psec SR intensifier offers QE from UV to NIR
Gen III filmless (HQf, HBf, HRf)	GaAsP, GaAs	<500 psec - 2 nsec	200 V	Select tubes can offer <500 psec HRf intensifier offers QE from ~360 nm to >900 nm

Table 1. Comparison of gating performance of different intensifiers.

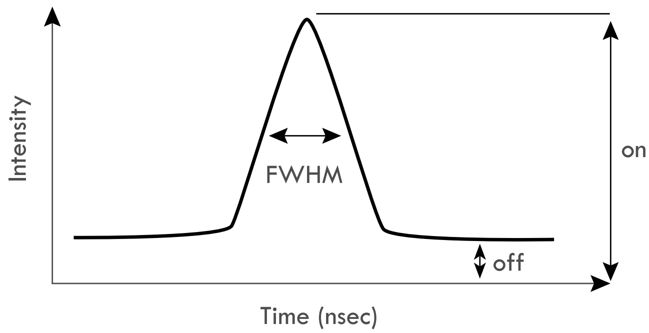

Figure 2. Optical FWHM and on/off ratio are important parameters to specify an intensifier's gating performance.

Gating performance of an ICCD is measured in terms of the minimum width and on/off ratio. The minimum width of gating is specified by the optical full width at half maximum (FWHM). In all scientific-grade ICCD cameras, such as the PI-MAX®4, optical full width at half maximum is measured by sweeping a very short pulsed laser across the gate opening in the time domain. On/off ratio, the ratio of light output when the intensifier is electrically turned on and off, is a direct measure of the quality of the gating (see Figure 2). A high on/off ratio is necessary to eliminate the background and to faithfully reproduce the transient phenomenon. In the visible region, an on/off ratio of 10^7:1 is typically achieved. In the UV region, the on/off ratio is typically much poorer (10^4:1). However, with a gating technique called MCP Bracket Pulsing, on/off ratios in the UV region can be improved dramatically (10^7:1).

MCP Bracket Pulsing

As explained earlier, only a fraction of incident photons is absorbed by the photocathode. The rest then pass through it and strike the input side of the MCP. This leakage is not damaging in the visible region because photons do not have sufficient energy to generate electrons at the face of the MCP. At UV wavelengths though, photons are energetic enough to occasionally release a photoelectron from the MCP. Once into the MCP, undesired photoelectrons are multiplied into charge clouds, which in turn generate photons from the phosphor. This effect reduces the on/off ratio in the traditional configuration (where the MCP is continuously on) to approximately 10^4:1.

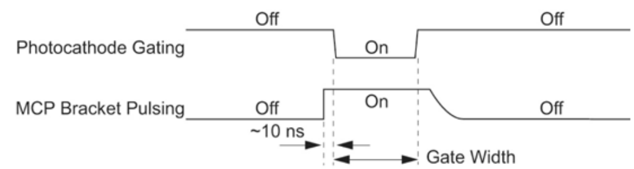

Figure 3. MCP Bracket Pulsing in the PI-MAX4.

To alleviate this problem, Princeton Instruments pioneered MCP Bracket Pulsing in first-generation PI-MAX cameras by turning the MCP on and off along with the usual photocathode gating. MCP Bracket Pulsing in the PI-MAX4 has been improved significantly. Now the MCP gates on synchronously with the photocathode, so there is no compromise in signal quality. As a result, there is no pre-pulse or head-start pulse required for MCP Bracket Pulsing in the PI-MAX4 (see Figure 3).

MCP Gating

The ability to gate the MCP on and off gives rise to an additional technique, known as MCP gating, which addresses the need to have the same QE as that of slow-gate tubes, but with shorter gate widths. The lower resistance of the two sides of the MCP allows the MCP to be gated more quickly than a slow-gate photocathode (see Figure 4). This technique gives gate widths of <9 nsec (better than Gen II slow-gate tubes), but provides the higher QE of Gen II slow-gate tubes. This is an excellent solution for Gen II super-blue intensifiers, which offer ~30% QE in the blue region, yet are capable of <9 nsec gate speed.

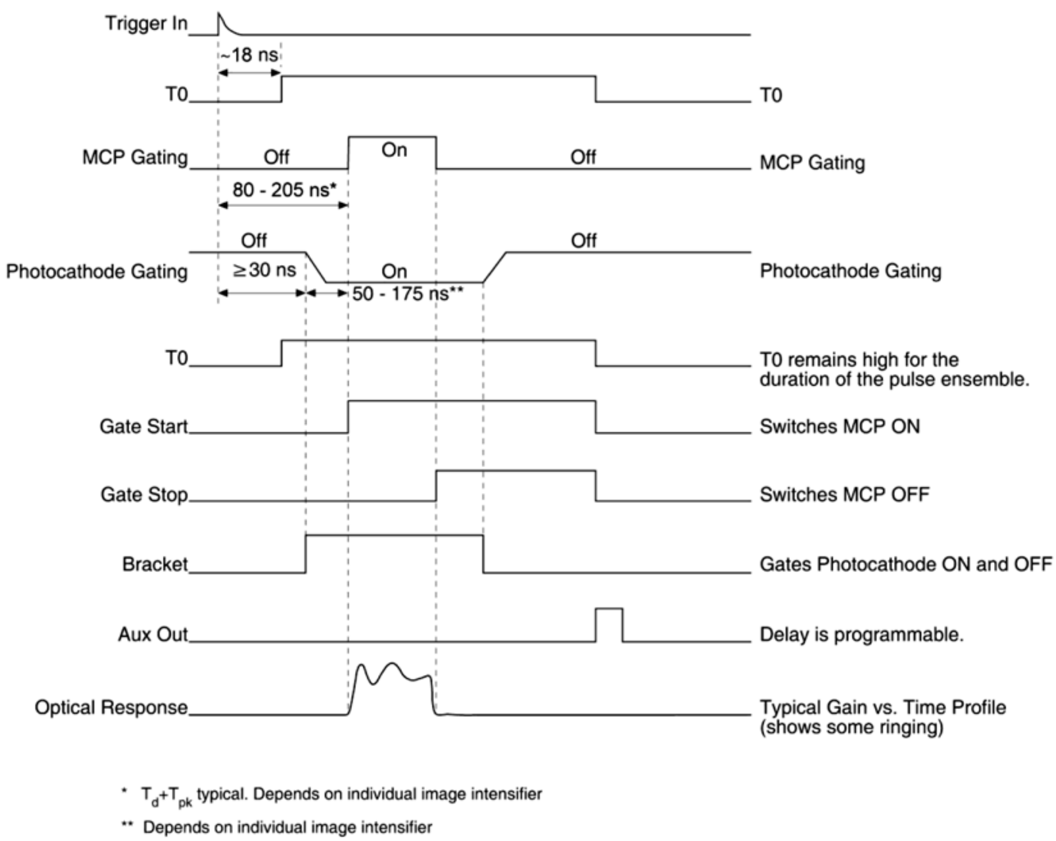

Figure 4. MCP gating in the PI-MAX4.

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Comparison of Lens-Coupled and Fiberoptic-Coupled ICCD Cameras

Introduction

Many intensified CCD (ICCD) camera users are interested in the relative merits and demerits of lens-coupled and fiberoptic-coupled ICCDs (see Figure 1). This technical note compares a variety of features of these high-performance cameras, concentrating primarily on camera sensitivity and signal-to-noise ratio (SNR) performance.

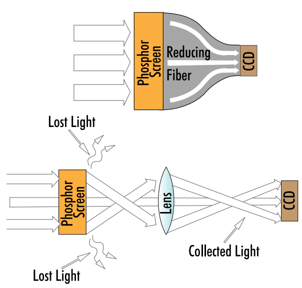

Figure 1. Comparison of fiberoptic-coupled (top) and lens-coupled (bottom) ICCD cameras.

Sensitivity and SNR performance are often confused in discussions of ICCD cameras, especially in advertising literature. This is unfortunate and sometimes misleading to potential users. The reason for the confusion is that over most of their dynamic range, the SNRs of both lens-coupled and fiberoptic-coupled ICCDs are determined primarily by photon statistics. This fact makes it tempting for vendors with only lens-coupled ICCDs to claim that there is no difference between lens-coupled and fiberoptic-coupled ICCDs, or even that it is somehow beneficial (in SNR terms) to use a lens system with low throughput. However, sensitivity is not the same as SNR at very low light levels (i.e., under 100 photons per pixel).

At very low light levels, sensitivity is more closely related to gain. Basically, it is the ability to determine whether or not a photon has been emitted from the photocathode within a pixel in a frame. To consider sensitivity, we must therefore consider the probability of detection and the probability of false detection (a false alarm). A false alarm occurs whenever the CCD readout noise exceeds the false-alarm decision threshold. Random emission from the photocathode (i.e., equivalent background illumination or EBI) is another false-alarm source from the user's perspective. However, EBI is not considered a false alarm in the optical sense because an EBI primary electron is still an electron that should be detected. EBI can be reduced by cooling the intensifier and is normally negligible in gated applications. CCD cameras generally have between 250,000 and 1,000,000 pixels. Thus, to have a tolerably low probability of false alarm in an entire frame, the probability of a false alarm per pixel must be extremely small. Assuming the readout noise to be Gaussian, the false-alarm decision threshold must be many times the standard deviation of the readout noise. On the other hand, the pulse height distribution of the image intensifier is approximately exponential (see Figure 2), which means that some of the photoelectrons give rise to a relatively small light pulse.

Figure 3 shows the probability of detection for two values of probability (0.1 and 0.01) of false alarm per frame for a 512x512-pixel CCD camera in a system with the effective CCD readout noise (including support electronics and A/D noise) set to 1 A/D unit. While the setting of an acceptable false-alarm rate and probability of detection depends heavily on the experimental conditions, performance that is much worse than 90% detection probability and 10% probability of false alarm per frame is hard to justify as true detection. Figure 3 clearly demonstrates that to attain this level of performance, an average gain of about 50 A/D units per photoelectron is required. Even with current intensifier technology, this level of gain is impossible to obtain with a reasonable image-intensifier life span in a lens-coupled system using a single-stage intensifier. Furthermore, minimum-decay-time phosphors composed of rare-earth materials are often necessary to obtain excellent linearity. Unfortunately, these phosphors are four to ten times less efficient than standard coatings and produce even smaller signals in the CCD. While the superior coupling efficiency of the fiberoptic-coupled ICCD can still maintain good sensitivity, the lens-coupled ICCD is further strained under such circumstances.

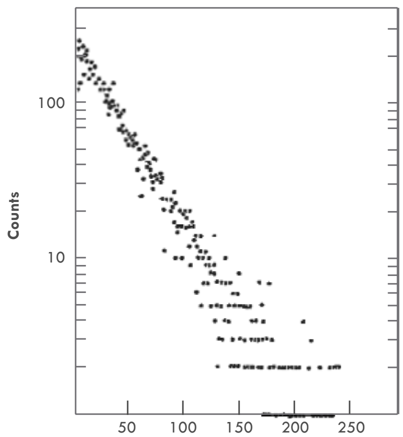

Figure 2. Pulse amplitude distribution from a straight-channel MCP. Counts are shown as a function of channel number.

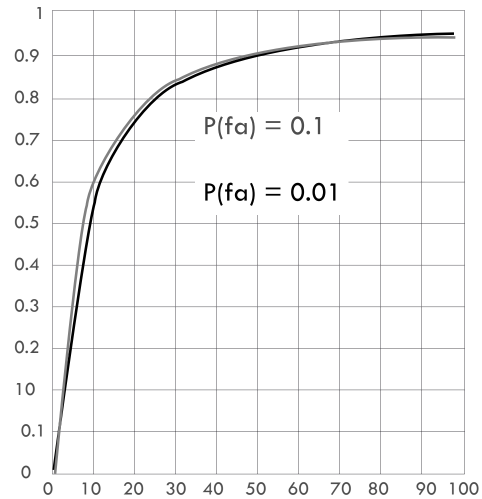

Figure 3. Probability of detection.

Lens-Coupled ICCD Advantages and Disadvantages

One of the most notable conveniences of lens-coupled ICCDs is the ability to use the camera as both an ICCD and a CCD by removing the intensifier. The lens-coupled system has the significant advantage that when the intensifier and lens are removed, the underlying CCD camera is a full-performance CCD detector. The lens-coupled ICCD also represents a cost-effective way to add gating capability to an existing CCD camera if ultimate sensitivity is not required.

Potential ICCD camera users should be wary of statements by manufacturers that a single photoelectron will produce 100,000 photons from the phosphor. This value, which is often used to justify the use of inefficient lens coupling, is too high by almost one order of magnitude even for the most efficient (but not linear) P20 phosphors. The value is exaggerated even for fast phosphors.

In addition, the lower light throughput of lens coupling (relative to fiberoptic coupling), typically 5-10%, is claimed by some manufacturers to be an advantage at medium light levels on the grounds that it results in fewer A/D units per photoelectron. This is said to make the camera able to withstand more photons per pixel before saturating. Since the SNR is presumably photon-noise-limited at medium light levels, it is claimed that higher SNRs can therefore be achieved. While there is some truth to this argument, especially in cases where intensifier gating is used, Princeton Instruments cameras provide better alternatives.

By operating at higher light throughput (low f-number lens coupling or fiberoptic coupling), the opportunity exists to extend the life span of the intensifier by reducing the gain of the multichannel plate (MCP) with lower operating voltage. Operation at lower gain provides better linearity and far greater intensifier life span. By reducing the intensifier gain, the required output charge per photoelectron from the MCP is reduced, which in turn prevents any gain reduction due to local discharge of the MCP. It has been incorrectly argued that operating at higher gain increases the MCP standing current and therefore the linearity. The fallacy here is that the gain and the output charge requirement increase exponentially with the MCP voltage, but the standing current only increases linearly.

Lens coupling increases the stray light of the camera system, reducing the intrinsic dynamic range. This is especially important in systems that must detect small features in the presence of large backgrounds, such as emission from high-temperature plasmas or laser-induced fluorescence (LIF) in combustion analysis. Operation of lens-coupled ICCDs at very high gain results in a significantly reduced intensifier life span.

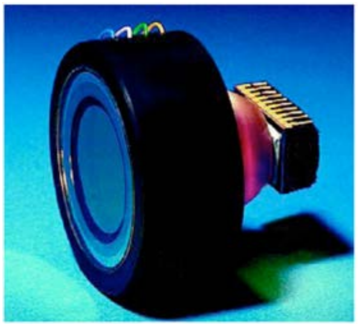

Figure 4. An intensifier coupled to a CCD via a fiberoptic offers the highest possible sensitivity in low-light-level applications.

Fiberoptic-Coupled ICCDs

The integrated fiberoptic-coupled ICCD is the highest-performance ICCD available. Fiberoptic coupling provides the highest coupling efficiency, as high as 60%, between intensifier and CCD (Figure 4). As discussed above, single-photoelectron detection is possible with this ICCD. When sufficient light is available, the MCP voltage (and gain) can be reduced to allow higher dynamic range and greatly extended intensifier life span. Furthermore, the effective noise associated with the electron-multiplication process in the MCP is increased at higher voltages. The integrated fiberoptic-coupled ICCD does not operate at these high voltages even when set to 50-100 counts per photoelectron, so this ICCD provides better output SNR for a given signal than a lens-coupled ICCD.

Princeton Instruments is the leader in the manufacture of high-performance CCD and ICCD cameras. The integrated fiberoptic-coupled ICCD is very difficult to design and produce as it requires optimum performance from various parameters that are naturally in conflict. These parameters include clean driving signals to the CCD, low-level signals from the CCD, efficient cooling and thermostating, high-voltage wiring, intensifier cooling mechanics, and thermal insulation requirements.

In fiberoptic-coupled ICCD cameras, the CCD and intensifier cannot be under vacuum. Therefore, these detectors must have a dry, inert environment to prevent condensation. In the case of PI-MAX®4 cameras, the head is sealed with dry nitrogen for maintenance-free operation. Whenever the CCD is cooled, water or air is used to dissipate the heat generated by the thermoelectric cooler.

While CCD dark current may be negligible in short gating experiments, additional background noise exists in intensifiers. The only way to reduce EBI is to cool the photocathode directly and uniformly. Every PI-MAX4 has this capability; users need only connect a dry nitrogen source to the camera and begin cooling. A cooled photocathode has EBI levels as much as 20x lower than a room-temperature photocathode.

Conclusions

It is important to understand the differences between lens-coupled and fiberoptic-coupled ICCDs. Though lens coupling offers the flexibility to retrofit the intensifier to an existing CCD camera, the superior performance of integrated fiberoptic coupling outweighs that advantage. One of several distinct advantages of fiberoptic-coupled ICCDs is their ability to deliver the highest sensitivity at low light levels while still offering a long life span for expensive intensifier tubes.

Princeton Instruments provides the world's finest fiberoptic-coupled ICCD cameras with a wide selection of intensifiers (Gen II and Gen III filmless). By utilizing intensifier tubes with the best QE in the wavelength of interest, the highest practicable sensitivity is ensured. Integrated high-voltage pulser design and the industry's most advanced programmable timing generator (SuperSynchro) provide seamless operation and superior gating performance. The full line of Princeton Instruments fiberoptic-coupled ICCD cameras is being widely used throughout the world in imaging and spectroscopy applications such as LIF, combustion research, laser-induced breakdown spectroscopy (LIBS), plasma studies, and nondestructive testing (NDT).

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Selecting the Right ICCD Camera

The latest advances in intensified CCD camera technology

This technical note is intended to help researchers select the best intensified CCD (ICCD) camera for their specific low-light, time-resolved imaging and spectroscopy applications. It briefly describes the benefits and tradeoffs involved with various system components, including intensifier type, CCD resolution, and frame rate. For more detailed information on intensifiers and gated ICCD technology, please refer to the Princeton Instruments (PI) technical notes "Introduction to Image Intensifiers for Scientific Imaging", "ICCD Gating", and "Comparison of Lens-Coupled and Fiberoptic-Coupled ICCD Cameras".

Introduction

A typical high-performance ICCD camera consists of an intensifier tube coupled via a fiberoptic taper or a faceplate to a CCD (Figure 1). Camera electronics consist of both high-voltage gating and timing controls for the intensifier, as well as low-noise CCD readout circuitry.

Though primarily used for military night vision applications, intensifier tubes possess several notable features, such as ultra-low-light sensitivity and picosecond shuttering (gating), that make them ideal for scientific time-resolved imaging and spectroscopy applications. With continuous improvements in sensitivity and gate speeds, intensifier tubes are helping researchers gain better insight into physical, chemical, and biological processes.

Intensifier: Performance Parameters

In order to match ICCD system performance to the requirements of the experiment, one should pay careful attention to the selection of the intensifier tube. This choice is primarily based upon:

a) Quantum efficiency (QE) of the photocathode
b) Gate speed

Quantum efficiency refers to the fraction of incoming photons absorbed by the photocathode at a specific wavelength. This is an important parameter as it ultimately determines the sensitivity of the entire detection system. Based upon the different photocathode materials used, intensifier tubes are typically grouped into Gen II (generation II) or Gen III filmless. The QE curves for some of these intensifiers are shown in Figure 2.

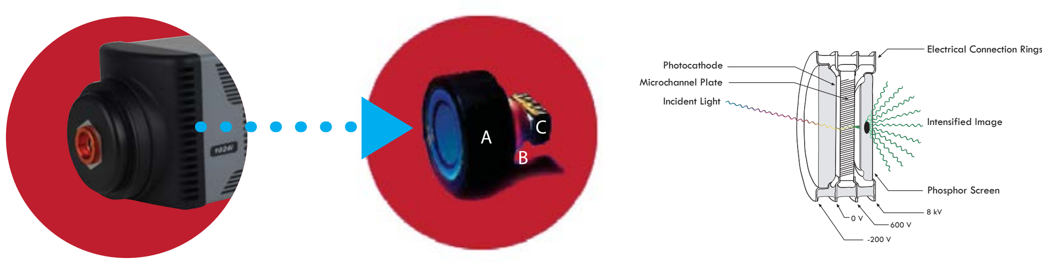

Figure 1: High-performance ICCD cameras use a fiberoptic taper/faceplate (B) to couple the intensifier (A) to the CCD (C). Also shown is the cross-section of a Gen II intensifier.

From the quantum efficiency graphs in Figure 2, it is clear that:

a) For applications involving the UV-to-blue region of the spectrum, Gen II intensifier tubes (UV and super-blue, SB) offer the best sensitivity. Notice the tradeoff between the gating speed and the quantum efficiency. However, as described later, it is possible to minimize this compromise with intelligent gating schemes.

b) For the blue-to-visible and visible-to-NIR regions, the latest Gen III filmless intensifiers (GaAsP) offer the best sensitivity.

Gate speed is the time required to optically turn on and off a given intensifier. It is specified as the optical FWHM (full width at half maximum). Gen II fast-gate and Gen III filmless intensifiers are capable of picosecond gate widths.

Gen II Intensifiers

Gen II intensifiers use bi- or multi-alkali photocathodes (Table 1) and are capable of broad wavelength coverage. They can also be selected to give the highest sensitivity over a specific wavelength range. For example, SB-style intensifiers can offer >25% QE at around the 300 nm region; a UV-sensitive intensifier with a MgF_2 input window offers the best sensitivity for deep-UV measurements; SR-style intensifiers offer the highest QE available for the NIR region.

Typical slow-gate Gen II intensifiers are only capable of 50 nsec to 200 nsec gate speeds. In contrast, fast-gate Gen II tubes have a metal underlayer (to reduce electrical resistance) and can be gated down to picoseconds. The drawback of these tubes is the reduced QE caused by the metal underlayer. In order to reduce the compromise between gating speed and QE, Princeton Instruments has developed MCP gating and PIPs (Princeton Instruments Picosecond) technologies.

"Gen II intensifiers are ideal for applications such as combustion (OH-PLIF), where high sensitivity in the UV-to-blue region and fast gate speeds are important."

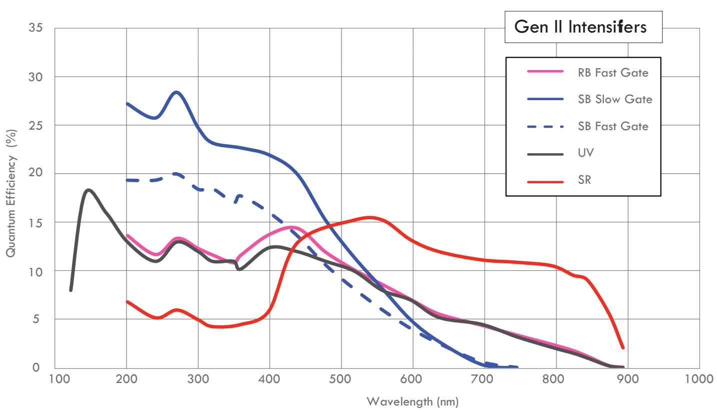

Figure 2a. Comparison of Gen II RB (red-blue balanced response), SB (super-blue), SR (super-red), and UV photocathodes.

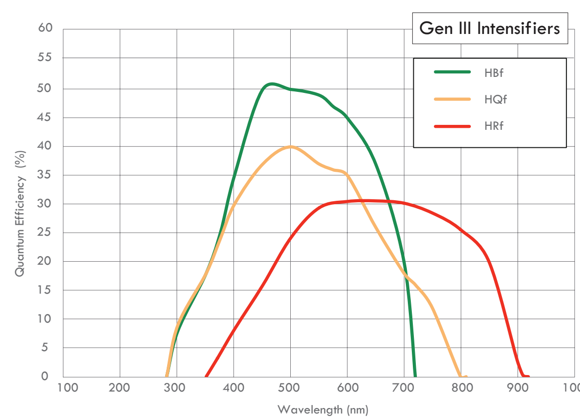

Figure 2b. The latest Gen III filmless HQf, HRf, and HBf GaAsP photocathodes provide the highest QE in the visible region.

Parameter/Specification	Gen II Intensifiers	Gen III Filmless Intensifiers	
Photocathode	Bi- or multi-alkali	GaAsP	GaAsP
Peak QE	>25% (SB)	>50% (HBf)	~30% (HRf)
Ideal wavelength range	UV to NIR	Blue to visible	Visible to NIR
Gating voltage	~200 V	~200 V	~200 V
Gate speeds*	~2 nsec	~2 nsec	~2 nsec
Cost	+	+++	+++

Table 1: Performance comparison of various intensifiers.

*picosecond gate speeds are possible

Gen III Filmless Intensifiers

Early Gen III intensifiers used GaAs photocathodes and required an ion barrier film to prevent ion feedback and to prolong lifetime. More recently, intensifier manufacturers developed a new class of Gen III intensifiers using GaAsP and GaAs photocathodes. These intensifiers eliminate the ion barrier film yet achieve reliability similar to filmed Gen III intensifiers. The technology behind these intensifiers remains a trade secret, but the advantages to the scientific community are clear (e.g., higher sensitivity and faster gate speeds).

In addition to offering the highest possible sensitivity in the visible region (<780 nm), Gen III filmless intensifiers are capable of fast (picosecond) gating similar to Gen II intensifiers. This performance combination makes them the ideal choice for many time-resolved applications that operate in the visible region of the spectrum.

"Gen III filmless intensifiers feature fast gating as well as >50% QE, offering the best combination of sensitivity in the visible region (<780 nm) and gate speed."

Gating

[For more detailed information, see the Princeton Instruments technical note "ICCD Gating".]

The fast shuttering or gating capability of intensifiers allows capture of transient phenomena such as fluorescence or luminescence immediately following the excitation of a sample. Gating is also used to effectively eliminate ambient light. Typically, gating is performed by switching the voltage between the photocathode and the MCP. High-performance ICCD cameras such as the PI-MAX®4 use optimum gating voltages in order to achieve effective gating and high spatial resolution.

As mentioned earlier, fast-gate Gen II intensifiers are capable of picosecond gate speeds, whereas slow-gate intensifiers are capable of 50 nsec to 200 nsec. However, by gating the voltage across the MCP (instead of photocathode-MCP voltage), it is possible to achieve <9 nsec gate speeds on slow-gate intensifiers. This has proved very beneficial for applications such as OH-PLIF that require high sensitivity in the blue region (SB intensifiers) with fast gate times. Gen III filmless intensifiers are capable of ~2 nsec gate speed as they require only ~200 V (similar to Gen II intensifiers). New PIPs (Princeton Instruments Picosecond) technology enables gating to <500 psec for select Gen II and Gen III filmless intensifiers, with no loss in QE.

Advanced ICCD cameras such as the PI-MAX4 are capable of a sustained 1 MHz repetition rate while using full gating voltage. It is important to note that a lower gating voltage (often used by other manufacturers to achieve a similar repetition rate specification) results in lower signal and loss of spatial resolution.

For ultra-high-frame-rate applications (>300 Hz), it is also important to consider P46 and P47 phosphors with faster decay times (<2 µsec) as opposed to P43, which has 2-3 msec decay times. A P46 or P47 phosphor is especially important for applications requiring DIF mode operation. In this mode, two full frames can be captured with µsec resolution. Advanced ICCD cameras such as the PI-MAX4 offer DIF capabilities coupled with powerful gating for ultra-high-frame-rate gated applications.

CCD Performance

Though the performance of the intensifier tube plays an important role in overall ICCD camera system performance, the choice of an appropriate CCD cannot be overlooked.

In time-resolved applications, it is often important to minimize the effects of photobleaching of the samples under study. This requires that data be captured using a minimal number of excitation pulses. For example, typical pulsed Nd:YAG lasers operate at around 10 Hz, so it is often necessary for an ICCD camera to capture a frame every 100 msec. This requirement is met by the availability of higher readout rates to achieve >26 full frames per second (1k x 1k-pixel resolution). See Figure 3.

Newer interline CCDs, such as those utilized in PI-MAX4:1024i cameras, offer a unique capability that allows the capture of two distinct frames in as little as 450 nsec or less – ideal for time-resolved flow measurement applications. A P46 or P47 phosphor must be selected to avoid cross-talk between images.

Furthermore, the dynamic range and linearity of an ICCD camera is often determined by a combination of MCP saturation and CCD full well. Empirical data show that it is possible to achieve >15 bits of true dynamic range in transient as well as CW applications.

Ease of Use

Apart from providing the highest performance, scientific-grade ICCD cameras should be easy to use. For example, PI-MAX4 cameras from Princeton Instruments are offered with a built-in timing generator (SuperSynchro), a Gigabit Ethernet (GigE) data interface for remote operation, and complete software support including LabVIEW (National Instruments) drivers.

Summary

A scientific-grade ICCD camera should be able to satisfy an often conflicting set of requirements to achieve optimum performance for a given application. Gen III filmless intensifiers and enhancements to older-generation intensifiers allow researchers to design new time-resolved experiments with greater performance and ease.

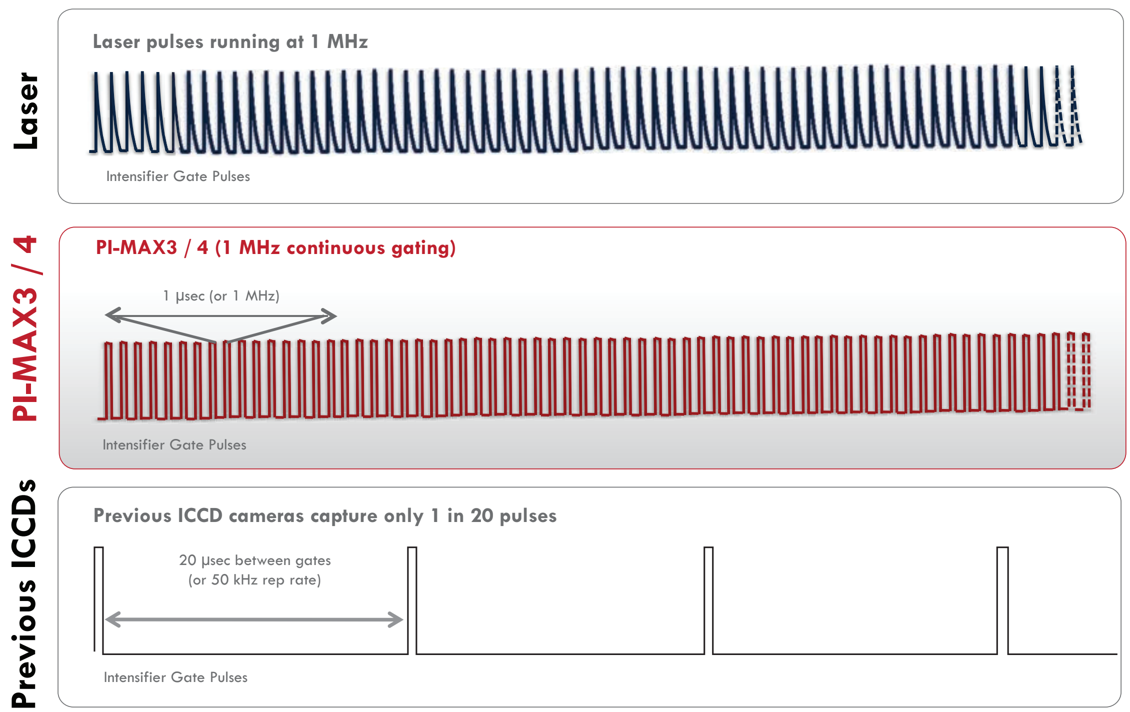

Figure 3: A higher sustained repetition rate (like that of the PI-MAX4) facilitates more efficient use of excitation light sources such as pulsed lasers operating at higher repetition rates.

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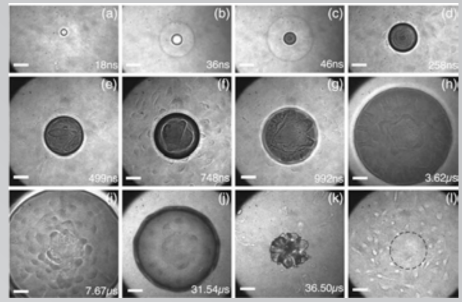
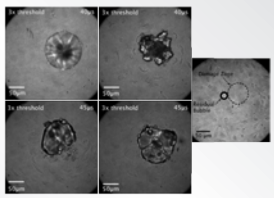
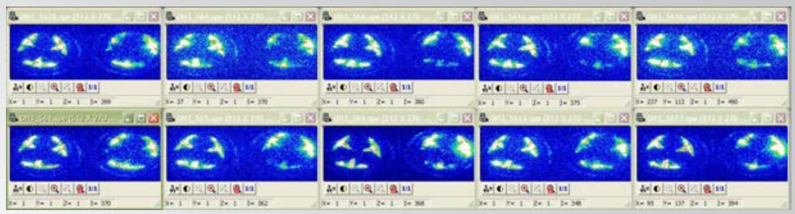
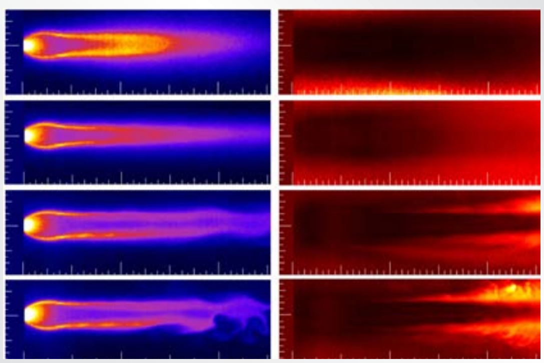
Application Notes

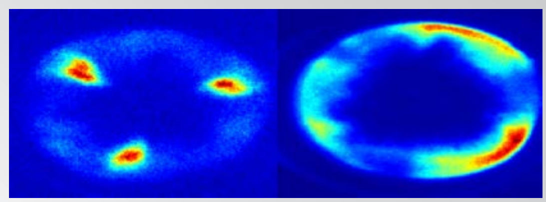


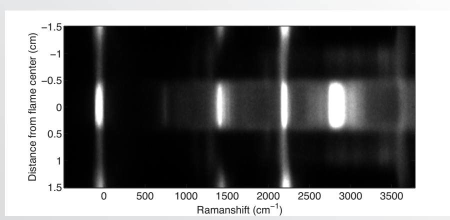
The following application notes provide a glimpse into the usage of Princeton Instruments ICCD cameras for applications ranging from combustion studies to nano-research. These applications involve various time-resolved imaging and spectroscopy diagnostic techniques.

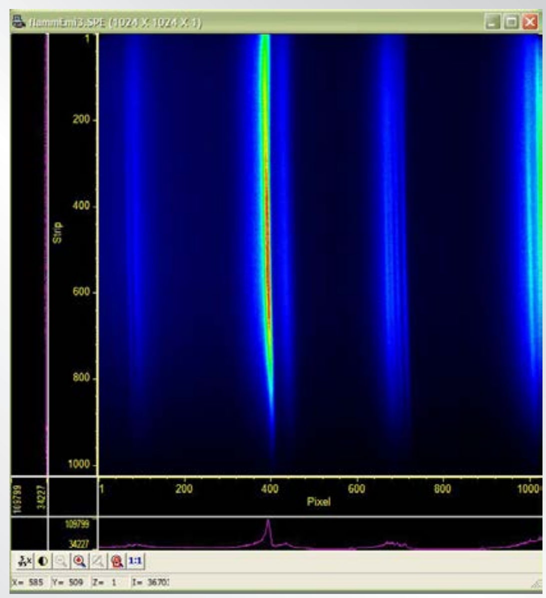












Images courtesy of Paul Danehy (NASA Langley Research Center); Lund University, Sweden; and Kaustubh R. Rau, Pedro A. Quinto-Su, Amy N. Hellman, and Vasan Venugopalan (Laser Microbeam and Medical Program, Beckman Laser Institute, University of California, Irvine) from *Biophysical Journal,* vol. 91, July 2006, 317-329.

Intensified CCD Imaging and Spectroscopy Unravel the Mysteries of Carbon Nanotube Formation

Carbon nanotubes are hollow, cylindrical tubes formed by single layers of carbon atoms. They can be one atom layer thick (single-wall nanotube, or SWNT) or multiple layers thick (MWNT) with additional graphene layers forming concentrically aligned cylinders (see Figure 1).

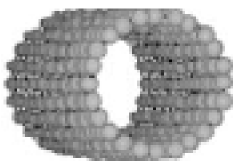


Figure 1: An SWNT showing conjoined hexagonal rings of carbon (as in a graphite sheet) rolled into a tube. The tubes can be produced open-ended or end-capped by manipulation of physical and chemical conditions.

SWNTs are formed by laser vaporization, dc-arc vaporization, chemical vapor deposition, or gas disproportionation in the presence of metal catalyst nanoparticles in background gases. Recently, SWNTs were formed by annealing C60 and Ni films in vacuum. SWNTs are another allotrope of solid carbon, joining the family of graphite, diamond, and solid fullerenes. They are the latest discovery in the field of carbon nanomolecules that began in the 1980s with the discovery of "Buckyballs", symmetrical carbon-atom spheres (named Buckminsterfullerenes) that resemble soccer balls. Like other carbon allotropes, the distinct characteristics of SWNTs are conveyed by the propensity of carbon atoms to bond to one another and form the ubiquitous planar hexagonal rings, as in graphite or the benzene molecule.

Potential Applications for Nanotubes

SWNTs have extremely high length-to-diameter ratios. Their diameters are approximately 1-2 nm, with known lengths up to 1 mm. Although their diameter is only 1/10,000 of a human hair, SWNTs have been estimated to be 10 times lighter and 1000 times stronger than a steel rod of the same size. They can also have metallic characteristics with unique electrical properties.

SWNTs can associate into linear bundles or ropes, which suggests that they might serve some revolutionary structural and electronic uses, including:

- Nanoelectronics — carbon-based nanotransistors; replacement for silicon as components become nanosized; nanogenerators and machines
- Nanoshielding — protection of enclosed materials (e.g., metals and drug molecules) from outside influences such as oxidation
- Hydrogen containers — safe storage of hydrogen for use as a fuel
- Lubrication — solid lubricants for use in place of petroleum products
- Structural materials — ultrastrong, ultralight building materials
- Tethers — super tethers for energy or momentum transfer in space or between earth and space

Investigation of Nanotube Formation

For nanotubes to be fabricated into useful products, their formation will have to be clearly understood and the dynamics will have to be modifiable and controllable. However, understanding of nanotube synthesis is in its infancy and controlled nanotube production has yet to be realized. Drs. David Geohegan (www.ornl.gov/~odg) and Alexander Puretzky and their colleagues at Oak Ridge National Laboratory (ORNL) use laser ablation, as well as laser-induced luminescence (LIL), incandescence, and scattering measurements, to study the dynamics of nanotube formation. In their experiments, a small amount of material (~10^{16} carbon atoms plus ~10^{14} metal catalyst atoms [Ni and Co] from a 1-inch composite target) is vaporized by a laser pulse (Nd:YAG, 8 nsec FWHM) in inert gas in a small tube furnace (see Figure 2). Under the proper conditions, a portion of the vaporized material self-assembles to form SWNTs. Experimental conditions are varied, and the resulting images and spectroscopic measurements have provided some of the most detailed data ever on the formation dynamics of SWNTs. The ORNL investigators use a Princeton Instruments PI-MAX® intensified CCD (ICCD) camera system for imaging and spectroscopy. The high sensitivity and intensifier's fast gating make this the ideal system for their experiments, as does the dual imaging and spectroscopy capability of the PI-MAX camera.

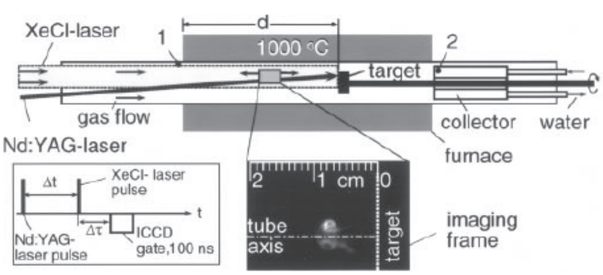


Figure 2: A schematic of the ORNL laser-vaporization setup. A 2-inch-diameter quartz tube and 1000°C furnace were used. Beam geometries and imaging area are shown. The black dots and numbers indicate the collection points of ablated material: 1 = upstream, 2 = collector. The C/Ni/Co target was placed at different distances, d, from the front of the furnace.

Dynamics of SWNT Formation

In the ORNL experiments, nanotubes were synthesized under variable laser repetition rates, flow conditions, target positions, and numbers of shots on the target. Resulting product deposits were analyzed by brightfield TEM (transmission electron microscopy) and correlated with the transport dynamics observed during the run by either time-resolved imaging or spectroscopy. Figure 3 shows typical bundles (~10 µm in length) of SWNTs and residue material from the collector (formed from only a single laser shot) when the laser was placed 21 cm from the target and operated at 0.016 Hz. To investigate nanotube growth, the C/Ni/Co plume was examined at different times after laser vaporization ranging from 20 nsec to 3 sec.

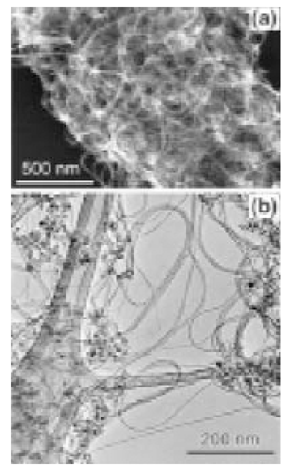


Figure 3. A TEM image of raw soot from the collector (point #2) with d = 21 cm. There is a high proportion (~90%) of SWNT bundles, along with metal nanoparticles (black dots) and some amorphous carbon.

Figure 4 shows ICCD images of the nascent plasma emission from the plume at times up to 200 µs both at 1000°C and room temperature. The images demonstrate oscillations and self-focusing effects during the early plume dynamics at each of the temperatures.

Laser-induced incandescence images also recorded plume dynamics during SWNT synthesis at times after ablation (see Figure 5). At 1000°C, the leading edge of the plume propagates with velocities ranging from 10^3 cm/sec (early on) to 6 cm/sec (at later times). After 2 sec, the plume stops moving upstream and the plane of the vortex ring tilts toward the tube axis.

The plume is then dragged by the gas flow back to the collector at a flow velocity of 0.6 cm/sec, where nanotubes and residual material deposit on the cool collector surface by thermophoresis. At room temperature, the plume propagates slower in the axial direction and the motion of material in the plume is extremely turbulent.

Rayleigh-scattering images were used to estimate the onset of plume condensation into nanoparticles after KrF-laser ablation at room temperature. These measurements yielded an estimate of 150 µs for the onset time. The images also revealed that despite the turbulent expansion of the plume, the ablated material remained confined to a relatively small volume within thin sheets of multiple vortices.

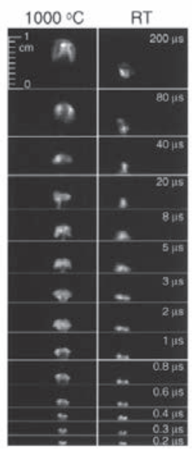


Figure 4. ICCD images of plumes at 1000°C and room temperature at various times after laser vaporization.

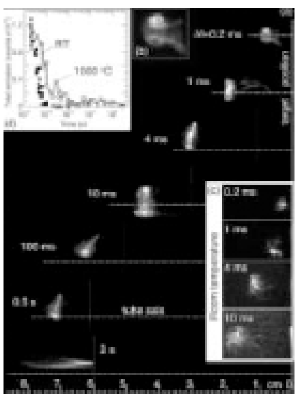


Figure 5. (a) = LIL images of plume dynamics. The Nd:YAG laser vaporized the target (right edge of figure) at 1000°C in 500-Torr argon (flowing to the right at 100 sccm). Each image is a different ablation event (100 nsec gate width, opened Δt = 100 nsec after the XeCl-laser pulse). (b) = Enlarged view (2x) of the plume at 0.2 msec showing vortex ring. (c) = LIL images at room temperature in 500-Torr argon. (d) = Integrated total emission from LIL images acquired at the indicated times at 1000°C and room temperature.

OES (optical emission spectroscopy) and LIL spectra were obtained at 1000°C and room temperature. Figure 6 shows summary spectra from room-temperature experiments. These data indicated that at early times in the plume expansion close to the target while the plasma is very hot, the plume species are primarily electronically excited. This emission from excited states dominates any laser-induced luminescence from the ground states. As the plasma expands, cools, and recombines, the ground states become populated, and LIL-emission emerges and competes with the nascent plasma emission. Finally, the nascent plasma emission completely disappears, leaving only LIL from ground states. Disappearance of plasma emission presumably signals the onset of nanoparticle formation.

Once sharp spectral features were identified in a set of spectroscopic data, optical filters were used with ICCD imaging to selectively picture different constituents of the plume (spectroscopic imaging). For example, the 320-380 nm spectral region was imaged at 1000°C to observe the groundstate atomic Co in the plume. Figure 7 shows results of these experiments. The data were consistent with sequential condensation of carbon and cobalt into clusters. This clustering presumably initiates nanotube formation; nanotubes subsequently grow in a vortex ring from a feedstock of mixed nanoparticles during seconds of time.

To check this conclusion and estimate SWNT growth rate, experiments were performed with the target placed closer to the front furnace edge (d = 12.5 cm). The plume motion seen in Figure 8 is similar to that observed previously, though at times >100 msec the plume propagation changed such that the plane of the ring vortex tilted relative to the tube axis. The ring also elongated along this axis because of the flow gradients in the quartz tube. At 0.5 to 0.7 sec, the plume exited the furnace in this orientation to deposit on the upper surface of the tube. The inset in Figure 8 is a TEM image of this deposit showing a collection of aggregated carbon and metal catalyst nanoparticles and thin SWNT bundles only ~100 nm in length. Therefore, the time spent by the plume in the hot zone (~0.5 sec) was not sufficient to convert all of the carbon into nanotubes. Based on results like these, the ORNL scientists estimated that the average SWNT growth rate at 1000°C was ~1 to 5 µm/sec.

Conclusions

The elegant work of Drs. Geohegan and Puretzky and their associates has yielded the following important information about the dynamics of SWNT formation:

- Long SWNTs (i.e., ~10 µm) can be created from a very small amount of material with a single laser shot, at repetition rates as low as 0.016 Hz.
- The average growth rate is ~1 to 5 µm/sec at 1000°C with laser vaporization.
- The ablation plume initially consists of atomic and molecular species, with no evidence of hot, molten particulates.
- Condensation of carbon occurs within 0.2 msec of ablation, with Co condensing much later (i.e., 1.5 to 2 msec).

- After this time, nanotubes grow within a plume vortex ring in a ~1 cm^3 volume during seconds after laser ablation.

- Nanotubes grow during such long times (for all times after a few msec) from the condensed phase conversion of the carbon clusters and nanoparticles by the metal catalyst nanoparticles.

The latter result was confirmed by recent *ex situ* annealing experiments in which deposits were collected from the laser-oven after limiting the nanotube-oven with *in situ* diagnostics.

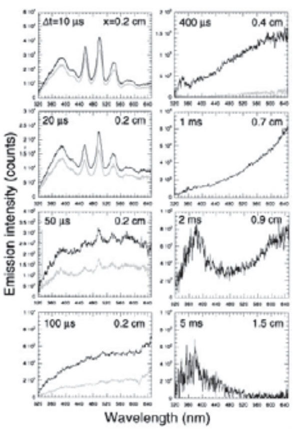


Figure 6. Plasma emission (light curves) and LIL (black curves) spectra measured at room temperature at different times (Δt) after the laser pulse and at different distances (x) from the target.

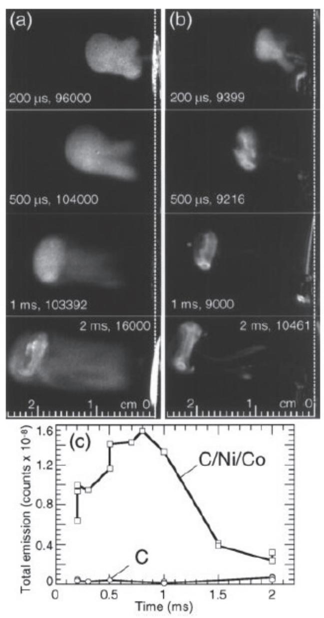


Figure 7. Selective imaging in the 320-380 nm spectral range at 1000°C in 500-Torr argon (100 nsec gate width, Δt = 0, peak image intensities listed). (a) = Groundstate Co in the plume during SWNT synthesis. (b) = Carbon species in the same region. (c) = Total emission intensities from sets of images as in (a) and (b) comparing the Co emission temporal history with that of carbon species in the same spectral region.

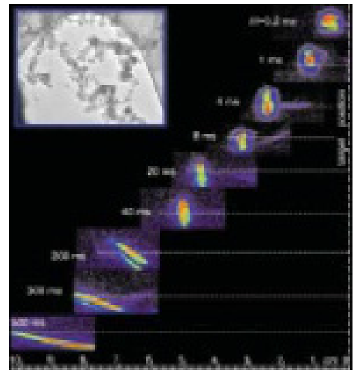


Figure 8. (a) = LIL images of the C/Ni/Co plume during synthesis of SWNTs with controlled growth times of ~0.5 sec. (b) = TEM of deposit collected from point #1 showing short (~100 nm) SWNTs in the early stages of growth.

Technology Update

The PI-MAX intensified CCD camera mentioned in this application note is the predecessor of the PI-MAX4. The PI-MAX4 ICCD camera offers readout ranging from video rates to thousands of frames per second for capturing dynamics, while a sustained gating repetition rate of 1 MHz (2x better than most research-grade ICCD cameras available on the market today) allows the camera to keep up with the ever increasing repetition rates of lasers. This state-of-the-art ICCD camera is also equipped with SuperSynchro and SuperHV technologies, which provide ultimate gating control in an easy-to-use configuration. Picosecond gating capabilities, RF modulation capabilities, and complete experimental control via Princeton Instruments LightField® software are offered as well. The PI-MAX4 sets performance benchmarks for fluorescence lifetime imaging measurements (FLIM), laser-induced breakdown spectroscopy (LIBS), pulsed Raman spectroscopy, nanotechnology, plasma diagnostics, and more.

References:

1. A.A. Puretzky, D.B. Geohegan, X. Fan, and S.J. Pennycock. *In situ* imaging and spectroscopy of single-wall carbon nanotube synthesis by laser vaporization. *Appl. Phys. Lett.* 76: 182-184, 2000.

2. A.A. Puretzky, D.B. Geohegan, X. Fan, and S.J. Pennycock. Dynamics of single-wall carbon nanotube synthesis by laser vaporization. *Appl. Phys.* A, 70: 153-160, 2000.

Figure 1 courtesy of Dr. Riichiro Saito, University of Electrocommunications (Tokyo, Japan) in collaboration with Prof. Mildred S. Dresselhaus, MIT (Cambridge, MA).

Figures 2 - 8 courtesy of Drs. David Geohegan and Alexander Puretzky, Oak Ridge National Laboratory (Oak Ridge, TN).

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Using Planar Laser-Induced Fluorescence To Study Plasma Turbulence

The successful development and optimization of fusion power sources will depend largely upon learning more about plasma turbulence and its relation to transport. Gaining a greater knowledge of plasma-edge turbulence is key, as the transport of particles near the plasma's edge has a profound effect on global plasma confinement. It is in this region that the boundary values for plasma temperature and density are established, values from which internal gradients are subsequently determined. Unfortunately, theories often fail to predict transport under turbulent conditions. Researchers have now begun to utilize high-performance intensified CCD (ICCD) cameras for innovative studies designed to evaluate the potential of using planar laser-induced fluorescence (PLIF), an optical diagnostic technique, for the experimental visualization of plasma-edge turbulence. It is hoped that data acquired via PLIF imaging will lead to improved turbulence-transport models. This note discusses the recent work of Fred M. Levinton (Nova Photonics, Inc., Princeton, NJ) and Fedor Trintchouk (Princeton Plasma Physics Laboratory, Princeton, NJ).

Tokamak and PLIF Basics

One of the most promising (and successful) confinement fusion concepts today, the tokamak is a toroidally shaped magnetic field produced by a set of poloidally constructed electromagnets. As a rule, tokamak experiments use deuterium and tritium isotopes of hydrogen since this combination requires the lowest possible fusion temperatures. A current of up to several million amperes flows through the plasma, which is heated in short pulses by high-energy particle beams or radio-frequency waves to maintain temperatures in excess of one hundred million degrees centigrade. Ohmic heating and magnetic compression also help achieve the temperatures necessary for fusion.

Large temperature and density gradients near the edge of the plasma contribute to transport greater than that predicted by standard, non-turbulent theories. As Levinton and Trintchouk note in their January 2001 paper entitled "Visualization of plasma turbulence with laser-induced fluorescence" (*Review of Scientific Instruments,* vol. 72, #1, 898-905), although various numerical simulations and diagnostic techniques address turbulence-driven transport, the picture is still far from complete. The relation between turbulence and transport needs to be understood more fully in order to improve global plasma confinement and ultimately better the performance of fusion devices.

Levinton and Trintchouk have chosen to evaluate the potential use of planar laser-induced fluorescence to investigate plasma-edge turbulence. PLIF is a technique in which a laser source is tuned to the absorption line of an atomic or molecular species present in a given plasma. The tunable laser source is then utilized to create a sheet of light that traverses the field, exciting fluorescence via a resonant energy-level-transition process. A series of two-dimensional images is acquired by an ICCD camera. Unlike other diagnostic techniques used to examine plasma turbulence, PLIF provides high-resolution images of the phenomena occurring throughout an entire plane of interest.

Experiment Setup

The Princeton Plasma Physics Laboratory (http://www.pppl.gov) is a collaborative national center for fusion energy and plasma physics research managed by Princeton University for the U.S. Department of Energy. As described in their paper, Levinton and Trintchouk are using the lab's magnetic nozzle experiment (MNX) helicon plasma source to test and evaluate the PLIF concept. With a magnetic field of 1.5-3.5 kG, the MNX can run steady-state in a working gas of argon, krypton, or xenon.

The setup also utilizes a Boswell-type double saddle antenna (length = 10 cm; diameter = 4.5 cm) constructed from 0.125” copper tubing, which is wrapped on the outside of a Pyrex tube. The antenna and tube are air-cooled to under 100°C. A radio frequency (rf) power amplifier is operated at 0.3-1.0 kW at a frequency of 27 MHz, while a matching circuit comprising capacitors in series and parallel with the antenna is encased in an rf-shielded box next to the antenna. The resultant plasma column (length = 1.7 m; diameter = 2 cm) has a density of 5×10^{17} to 1×10^{20} m^{-3}. Electron temperature is ~5 eV and ion temperature is ~0.5 eV.

Since turbulence is usually far longer in scale parallel to the magnetic field than perpendicular to it, a laser sheet beam that allows light to be viewed parallel to the field direction is used. This enables imaging perpendicular to the magnetic field and integration along the sight-line without resolution loss. As Figure 1 shows, the laser propagation direction is perpendicular to the plasma column and magnetic field direction. A reentrant mirror situated in the vacuum vessel reflects the light towards the ICCD camera, a Princeton Instruments PI-MAX®, providing an axial view of the plasma.

Ion Selection

Many factors must be considered when selecting an appropriate ion for PLIF measurements, including the laser’s ability to attain the pump wavelength, the power needed for saturation, and the intensity of the fluorescence signal. Performing the PLIF at saturation is important, as doing so ensures the maximum signal (and optimal signal-to-noise ratio). Furthermore, when operating at saturation, small fluctuations in laser power cause very little change in the fluorescence signal. Thus, the chance of mistaking any spatial variations from the laser power intensity for density variations in the plasma is practically eliminated. Through both numerical and experimental means, Levinton and Trintchouk have identified several three-level schemes for Ar II, Kr II, and Xe II that provide the desired transitions within the visible wavelength range. (In a three-level scheme, the laser is tuned to one wavelength and the fluorescence is observed at another. An interference filter makes it easy to distinguish between stray light and the fluorescence signal.)

To test these ions, a tunable Alexandrite laser capable of providing the ~104 W required for saturation is used. The pulse width of the laser is approximately 80 nsec with a repetition rate of 10 Hz. The Alexandrite laser is a flashlamp-pumped, Q-switched oscillator stage that is tunable from 700-800 nm at its fundamental wavelength and from 350-400 nm with second harmonic generation. The intermediate range from 400-700 nm is covered by tuning the laser with a specially configured Raman converter. A Princeton Instruments VersArray CCD camera (with a 512x512-pixel array) is utilized to provide feedback during the precision tuning procedure.

After testing several ion schemes using an avalanche photodiode (APD) detector, an Ar II transition with a pump wavelength at 378.6 nm and fluorescence at 488.0 nm was deemed the most advantageous for the experiment. While each of the schemes tested produced a fluorescence signal significantly higher than the level of background light, the aforementioned Ar II scheme yielded a signal about 10x as great as the background.

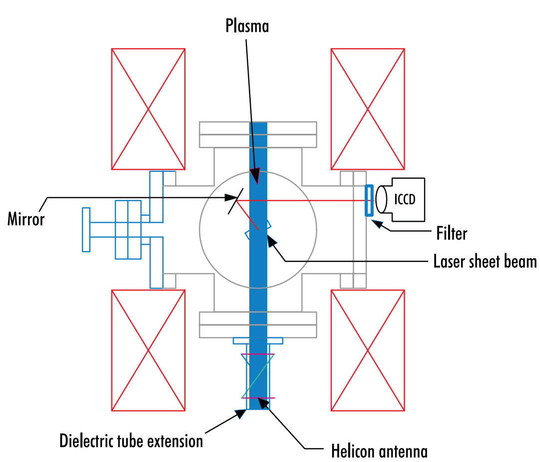


Figure 1: The diagram shows the laser and collection optics on the MNX plasma source, while the image is a view from the Princeton Instruments PI-MAX intensified CCD camera.

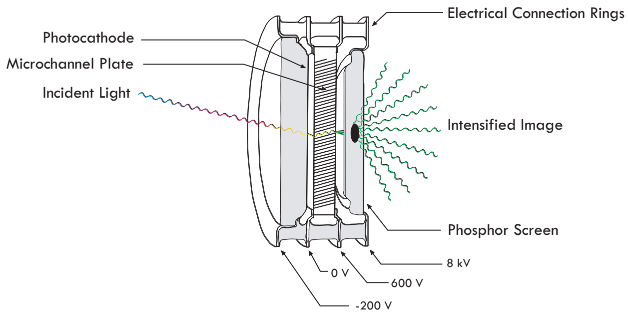


Figure 2. Components of an image intensifier. For a discussion of image intensifiers, refer to the Princeton Instruments technical note "Introduction to Image Intensifiers for Scientific Imaging".

The detection system that collects the fluorescence signal is, of course, a critical component of the PLIF experiment. The Princeton Instruments PI-MAX camera utilized by Levinton and Trintchouk is a high-performance instrument that features an image intensifier (see Figure 2) coupled to a thermoelectrically cooled CCD. Light is collected by a 58 mm f/1.2 lens, imaged onto the image intensifier, and transmitted via a tapered fiberoptic bundle to a 512x512-pixel front-illuminated detector.

Levinton and Trintchouk cite a number of reasons for using the PI-MAX camera in their work. First and foremost, the low-noise detection system can be gated. A gating ratio of 10^7:1 as well as a gate width of about 100 nsec for a laser pulse width of 80 nsec allow the PI-MAX to effectively minimize the leakage of plasma background light onto the CCD. The high gating ratio is needed because the CCD's readout time per frame is between 0.1 and 1 sec (depending on frame size) and the pixels are able to integrate light as the detector is being read out. Gating the intensifier prevents the CCD from detecting too much background signal.

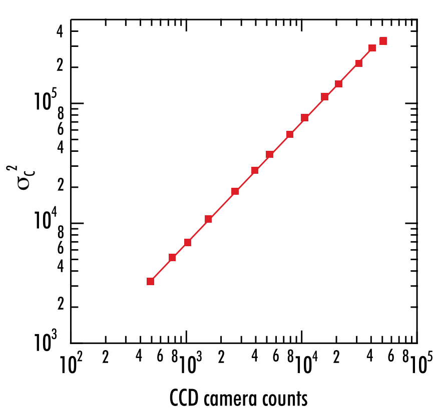


Figure 3. Data acquired by Levinton and Trintchouk illustrates the outstanding linearity provided by the PI-MAX system.

Levinton and Trintchouk observe that the detection system provides linear response through virtually the entire CCD readout range (see Figure 3). The camera is also capable of remote operation via a fiberoptic interface, which is useful (and often required) when working in high-current / high-magnetic-field environments.

In addition, the spatial resolution provided by the PI-MAX camera is also important to the PLIF experiment. Taking into account the lens, the image intensifier's 18 mm photocathode, the fiberoptic taper's reduction factor of 1.27, and the CCD's 19x19 µm pixels, the optical system magnification is a factor of 1/8.49 onto the detector. This figure yields a corresponding spatial resolution of 0.161 mm/pixel in the plasma, which translates to 0.8 mm when using 5x5 pixel-binning.

Figure 4 shows the results of imaging the PLIF emission. Each view represents an average of 20 frames of the same data. Large-scale structures are studied by subtracting individual frames from the 20-frame average to identify deviations (see Figure 5). Small-scale turbulence, meanwhile, is investigated by calculating standard deviations and performing two-dimensional Fourier transforms using data from sub-regions of similar pairs of images.

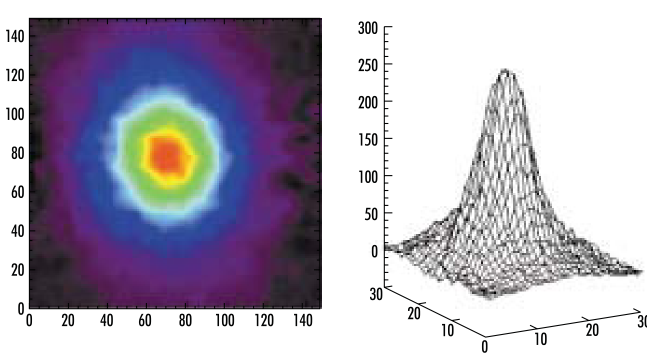


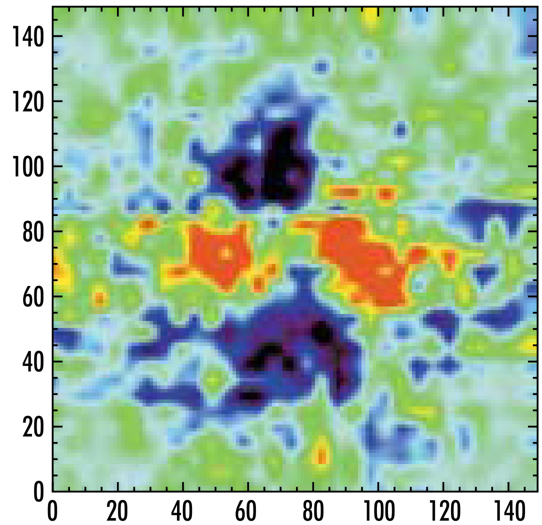
Figure 4. This PLIF emission data, a 20-frame average, corresponds to 23.3 mm along each dimension and clearly displays increasing density towards the center of the plasma.

According to Levinton and Trintchouk, PLIF imaging holds substantial promise in this area of research. Their work demonstrates that the technique can successfully measure structures and turbulence in a plasma with unprecedented temporal and spatial resolution. Future efforts will include testing the method on other devices using argon seeding to provide the ions required for PLIF. It is suggested that since passive edge measurements of visible emissions have already been utilized to observe plasma structures, an argon gas puff could eventually be used to seed the edge region of a fusion plasma.

Technology Update

The PI-MAX intensified CCD camera mentioned in this application note is the predecessor of the PI-MAX4. The PI-MAX4 ICCD camera offers readout ranging from video rates to thousands of frames per second for capturing dynamics, while a sustained gating repetition rate of 1 MHz (2x better than most research-grade ICCD cameras available on the market today) allows the camera to keep up with the ever increasing repetition rates of lasers. This state-of-the-art ICCD camera is also equipped with SuperSynchro and SuperHV technologies, which provide ultimate gating control in an easy-to-use configuration. Picosecond gating capabilities, RF modulation capabilities, and complete experimental control via Princeton Instruments LightField® software are offered as well. The PI-MAX4 sets performance benchmarks for fluorescence lifetime imaging measurements (FLIM), laser-induced breakdown spectroscopy (LIBS), pulsed Raman spectroscopy, nanotechnology, plasma diagnostics, and more.

Figures 1, 3, 4, and 5 courtesy of Fred M. Levinton (Nova Photonics, Inc.) and Fedor Trintchouk (Princeton Plasma Physics Laboratory).



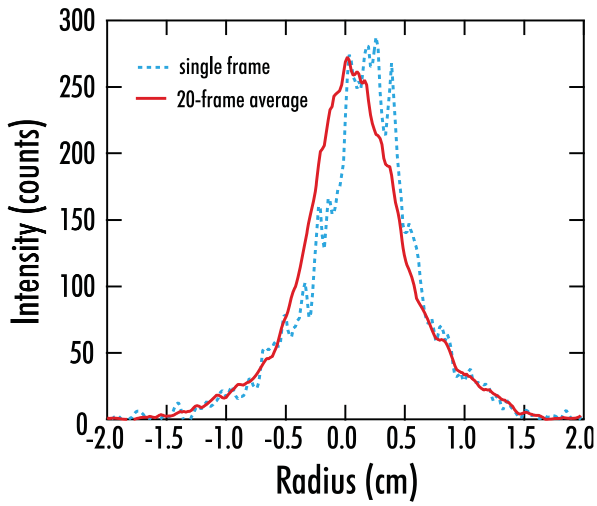


Figure 5. Comparing the intensity profiles of an averaged image and a single frame provides information about large-scale structures (20-frame image shown).

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Planar Laser-Induced Fluorescence Imaging of OH Radicals (OH-PLIF) in Hypervelocity Combustion with an Intensified CCD System

The utility of future hypersonic air-breathing propulsion systems will depend on the efficient injection, mixing, and combustion processes in the high-speed combustion chamber. For scramjet engines, for example, these processes have to be optimized for flight speeds in excess of Mach 8. Most combustion research to date has focused on speeds much lower than this. Due to the large enthalpies associated with high-Mach flight, only impulse facilities are capable of providing the required total temperature and hypervelocity to adequately replicate the combustor environment. Expansion tubes and reflected shock tunnels are two such impulse environments where hypervelocity testing can be conducted. Expansion tubes have the advantage of less dissociated chemical species being formed, as well as more accurate simulation of combustion chemistry, including ignition delay and reaction times. However, the test times possible in expansion tubes are shorter than those of reflected shock tunnels.

Stanford Expansion Tube Facility

The hypervelocity combustion studies of Drs. Adela Ben-Yakar and Ronald K. Hanson (http://navier.stanford.edu/hanson) are conducted at the Stanford expansion tube facility of the High Temperature Gasdynamics Laboratory (HTGL). This facility is one of the few that can provide a wide range of total-enthalpy conditions, including 4 to 6 mJ/kg-air to replicate Mach 10 to Mach 13 conditions. The expansion tube is 12 m in length with an inner diameter of 89 mm. It consists of three sections: driver, driven, and expansion. The driver section is filled with pressurized helium gas and is separated by a double diaphragm from the lower pressure-driven section, which is filled with the test gas. A run is initiated by bursting the diaphragms to form a shock wave that propagates into the test gas, producing intermediate velocity with increased pressure and temperatures. The shocked test gas is then accelerated by an area expansion process into the expansion section, with both a higher stagnation enthalpy and a higher effective reservoir pressure than the shock tube flow from which it originated. A schematic of this setup is shown in Figure 1.

The experiments performed by Ben-Yakar in the expansion tube used simultaneous Schlieren imaging and planar laser-induced fluorescence of OH radicals (OH-PLIF), formed by auto-ignition of a hydrogen jet, to obtain information on the location of the shock waves and the region of combustion during hypervelocity. Application of these two nonintrusive techniques permits unique and crucial visualization of the

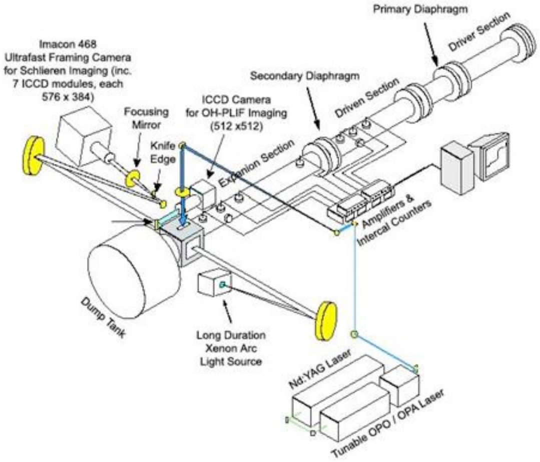

Figure 1: Schematic of the Stanford expansion tube facility used in these experiments.

behavior of complex reacting supersonic fuel flowfields. The OH-fluorescence intensity can be associated with the OH mole fraction. At the combustion pressures obtained in this work, the fluorescence signal can be modeled briefly as:

$$S_f \propto \chi_{OH}\left[\frac{f_{J''}}{T^{1/2}}\right]$$

where X_{OH} is the OH mole fraction and fJ'' is the Boltzmann fraction of OH molecules in the absorbing state.

In this particular absorption transition — the Q1(7) transition of the $A^2\Sigma^+ \leftarrow X^2\Pi$ (1,0) band of OH, located at 283.31 nm — the effect of temperature plays only a small part in signal interpretation for regions containing OH. Fluorescence intensity, meanwhile, can be used as a direct indicator of OH mole fraction.

Experiment Setup

The Stanford HTGL investigators employ a Princeton Instruments PI-MAX® intensified CCD (ICCD) camera system for the OH-PLIF experiment. This system is ideally suited for the application because of its high QE in the lower-wavelength region (200-500 nm) and fast gating. The system's nanosecond intensifier gating speeds and efficient on/off gating ratio of 10^7:1 permit weak OH-fluorescence images to be distinguished from the strong background of the combustion flame.

The frequency-doubled output of a dye laser pumped by a pulsed Nd:YAG laser creates the required laser sheet. For OH-PLIF transitions near 283 nm, Rhodamine 590 dye is used with pulse energies of about 8 mJ. At the viewing section, the laser sheet is approximately 0.5 mm thick and 3 cm wide. The fluorescence signal is collected through the same exit window as that of the Schlieren system. A 5 cm diameter dichroic mirror is mounted at 45 degrees to the optical axis perpendicular to the exit window to separate the signals. The dichroic, which is designed for >99% reflectivity between 300 and 320 nm, is transparent to the Schlieren beam. The OH-fluorescence, however, is reflected and collected by the PI-MAX camera.

Experiment Results

Figure 2 shows simultaneous side-view OH-PLIF and Schlieren images of hydrogen injection into a supersonic crossflow at Mach 10 conditions. The OH-PLIF image displays the regions containing OH molecules. The evolution of the reaction zone is in good agreement with the jet position seen with Schlieren imaging. A significant and uniform level of OH in the recirculation area confined by the separation wave upstream of the injector is apparent. A thin filament along the outer edge of the plume attached to the recirculation-zone ignition region follows. Further downstream, a decrease in OH-fluorescence is visible as the mixture expands around the jet flowfield. This decrease could be due to lower local-mixture temperature or poor mixing of air with the hydrogen of the jet.

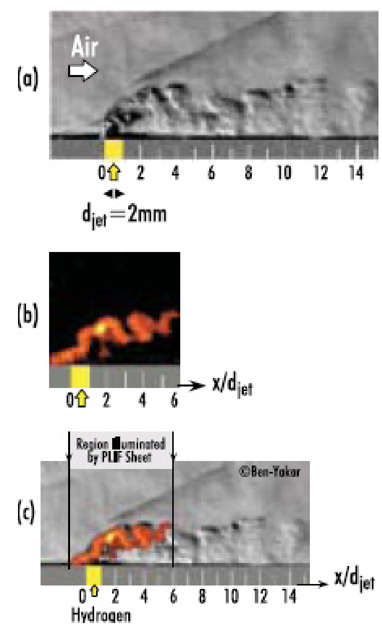

Figure 2: Simultaneous OH-PLIF and Schlieren images of hydrogen injected into a supersonic crossflow. Freestream conditions: air; burner entry Mach number = 3.46; temperature = 1300 K; pressure = 0.32 atm; velocity = 2420 m/sec (Mach 10); jet-to-freestream flux ratio = 1.4.

a) Schlieren image

b) OH-PLIF image showing ignition and combustion regions of the jet in crossflow at high enthalpy

c) OH-PLIF and Schlieren images overlaid

Horizontally illuminated OH-PLIF images are then obtained (see Figure 3). These images show OH fluorescence around the jet, while the center of the plume has no OH formation. The results are consistent with those seen in Figure 2, showing that the OH concentration at the outer edge of the jet decreases as the jet moves downstream.

OH-PLIF imaging experiments at Mach 13 conditions show similar combustion characteristics as those at Mach 10. The pulsating nature of the upstream recirculation region can also be seen in Mach 13 conditions (see Figure 4).

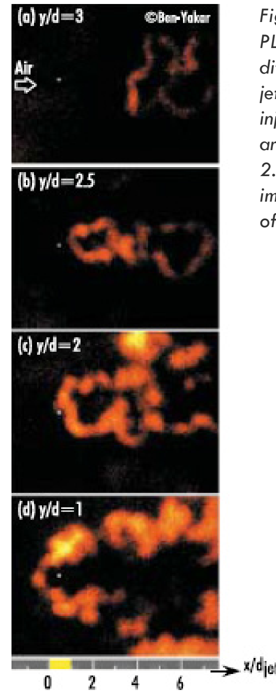

Figure 3: Top-view OH-PLIF images obtained at different heights (y/d = jet diameters) above the injection plate. Conditions are the same as in Figure 2. The white dots on the images indicate the center of the jet exit.

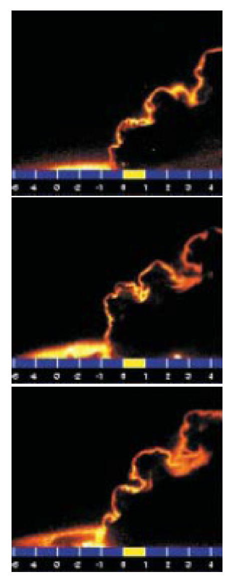

Figure 4: Three instantaneous sequential side-view OH-PLIF images at Mach 13 conditions. Conditions: pure oxygen; burner entry Mach number = 4.7; temperature = 1300 K; pressure = 0.05 atm; velocity = 3300 m/sec (Mach 13).

PLIF images courtesy of Drs. Adela Ben-Yakar and Ronald K. Hanson (Stanford HTGL).

Conclusions

The Stanford HTGL scientists have been able to successfully generate high total-enthalpy flows simulating Mach 10 and Mach 13 conditions. The overlaid OH-PLIF and Schlieren images indicate the flame-holding capability of the hydrogen jet in air crossflow at different jet-to-freestream momentum flux ratios. The OH-PLIF images, obtained with an ICCD camera system, permit visualization of combustion that shows OH-fluorescence at the recirculation region upstream from the jet and along the outer edge of the jet plume. These results and the techniques used to acquire them will contribute greatly to the successful development of future hypersonic air-breathing propulsion systems.

Technology Update

The PI-MAX intensified CCD camera mentioned in this application note is the predecessor of the PI-MAX4. The PI-MAX4 ICCD camera offers readout ranging from video rates to thousands of frames per second for capturing dynamics, while a sustained gating repetition rate of 1 MHz (2x better than most research-grade ICCD cameras available on the market today) allows the camera to keep up with the ever increasing repetition rates of lasers. This state-of-the-art ICCD camera is also equipped with SuperSynchro and SuperHV technologies, which provide ultimate gating control in an easy-to-use configuration. Picosecond gating capabilities, RF modulation capabilities, and complete experimental control via Princeton Instruments LightField® software are offered as well. The PI-MAX4 sets performance benchmarks for fluorescence lifetime imaging measurements (FLIM), laser-induced breakdown spectroscopy (LIBS), pulsed Raman spectroscopy, nanotechnology, plasma diagnostics, and more.

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