Outline of the Lecture

• Early Applications of Planar Laser-Induced Fluorescence (PLIF)

• Modern Array Detectors
Planar Laser-Induced Fluorescence (PLIF)

Advantages

- 2-D (or in a couple of cases 3-D) information acquired on single laser shot
- Gradient and spatial structure information can be obtained, especially important in turbulent flames
- Data can be acquired very rapidly

Disadvantages

- Quantitative planar LIF is reacting flows is difficult or impossible to achieve due to the collisional quenching - not such a big problem in non-reacting flows
- Spectral information difficult or impossible to acquire for 2-D imaging
Types of Array Detectors Used in Early (1980-1995) PLIF Experiments

Vidicon
- Two-dimensional array of p-n junctions
- Electrosatic intensifier produces photoelectrons that bombard phosphor, illuminate p-n junctions
- Array is read out by a scanning electron beam
- Lag (image persistence), image distortion due to intensifier, and cross-talk between pixels are main problems with vidicon

Self-Scanned Photodiode Array
- Two-dimensional array of p-n junctions
- Typically fiber-optically coupled with microchannel plate (MCP) intensifier
- Photodiodes are read out by connection to external circuit, re-charging current required is the signal level
- Main disadvantage: high read noise (hundreds to thousands of electrons)
PLIF Measurements: Early 1980’s

Stanford PLIF system.

SRI and Stanford race to acquire first PLIF images from flames.

PLIF Measurements: Early 1980’s


Fig. 2. (a) Photograph of flat flame burner. (b) Digital picture of OH concentration in a laminar, premixed CH₄/air flame above the flat flame burner. OH levels are shown in increments of 200 ppm. The maximum OH concentration is ~1200 ppm. Each pixel indicates the level of fluorescence from a volume 0.5- × 0.9- × 0.3-mm in size.

Fig. 3. (a) Photograph of a turbulent, premixed CH₄/air flame. (b) Digital picture of OH concentration in the flame. Each pixel represents the level of fluorescence from a 0.4- × 0.4- × 0.2-mm region of the flame.

SRI PLIF system.

SRI and Stanford race to acquire first PLIF images from flames.

Fig. 1. Pictorial schematic of the experimental setup. A cylindrical lens forms the laser beam into a sheet of radiation, which passes through the conically shaped Bunsen burner flame. Laser-induced fluorescence in OH is excited in the plane where the laser cuts across the flame and is imaged onto the face of a vidicon tube. The tube output is stored digitally or displayed pictorially on an oscilloscope.
PLIF Measurements: Early 1980’s

SRI PLIF system.

Fig. 3. Plot of the results from a single laser shot. The overall frame corresponds to a 3.5-cm square, as noted directly on the x axis; the y axis is stretched and skewed for clarity by the plotting routine. In each track the intensity is summed over a 1.75-mm vertical dimension, and the horizontal direction contains 100 points of 0.35-mm extension each. Background has been subtracted, but this plot is not corrected for the laser-intensity distribution across the sheet.

PLIF Measurements: Early 1980's

Fig. 1. Schematic of the fan-induced combustion tunnel with movable test section.

PLIF Measurements: Early 1980’s


Fig. 3. Selection of images showing the OH concentration field in each of the three flames at each of the three locations investigated.
PLIF Measurements: Early 1980’s

FIG. 1 Laser fluorescence imaging experiment in a constant volume combustion chamber.

PLIF Measurements: Early 1980’s


FIG. 2 Schlieren photographs of methane-air flame propagating in CVCC at different time delays after ignition.
PLIF Measurements: Early 1980’s

PLIF Measurements: Early 1980’s

FIG. 5 (a) Single laser pulse OH concentration measurements as a function of radial distance from ignition source at a time delay of 12 ms.

FIG. 5 (b) Average OH concentration measurement as a function of radial distance from ignition source at a time delay of 12 ms. Dash lines are standard deviation limits of shot noise. Solid line is laminar-flame model result.

Modern Array Detectors – The CCD Array

Charge-Coupled Device (CCD) Array

- CCD is a charge transfer device, read out by shifting charge from each pixel on the array to a serial register
- Charge transfer efficiencies are \(~ 0.99999\)
- Can have very low read noise (2-6 electrons), unintensified operation is possible and in most cases preferable
- CCD cameras were developed for astronomical imaging applications, they have very low dark noise, typically negligible for combustion imaging experiments
- Can also be used for spectroscopic measurements, binned array detectors at spectrometer exit slit
Modern Array Detectors – The CCD Array


Front-illuminated versus back-illuminated CCD arrays.

Figure 9-31  Illumination orientation: (a) front illumination and (b) back illumination.
Light sensitivity of the CCD array is the result of the creation of electron-hole pairs in the silicon substrate material.

FIGURE 1. Incident photons strike doped silicon surface of CCD array, and charge accumulates in potential wells (top). Phase switching controls the readout process (bottom).
Modern Array Detectors – The CCD Array

FIGURE 2. Sequential charge transfer between wells in a CCD array enables the electronic (charge) image to be read out in the detection process.

Modern Array Detectors - BICCD

Andor's DU440 CCD is designed to offer the best performance characteristics over a wide range of spectroscopy applications. The 2048 x 512 array camera is ideally suited to rapid, multi-channel, low-light applications including fluorescence and Raman spectroscopy, where high resolution is important. The system boasts negligible dark current with thermoelectric cooling down to -90°C.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Active Pixels</th>
<th>Pixel Size (µm)</th>
<th>Pixel Well Depth (e-, typical)</th>
<th>Linearity (% maximum)</th>
<th>Dummy Pixels**</th>
<th>Image Area (mm)</th>
<th>Register Well Depth (e-, typical)**</th>
<th>Gain (e-/count @ 18.2, 16, 32 µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2048 x 512</td>
<td>13.5</td>
<td>80,000</td>
<td>1</td>
<td>50, 50, 0, 0</td>
<td>27.6 x 6.9</td>
<td>600,000</td>
<td>2, 1.4, 0.7</td>
</tr>
<tr>
<td>Noise</td>
<td>System Readout Noise (e+)**</td>
<td>Typical</td>
<td>Maximum:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>31kHz pixel readout rate</td>
<td>3</td>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1MHz pixel readout rate</td>
<td>10</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Quantum Efficiency

Andor Back-Illuminated, Thermo-electrically Cooled CCD Array

![Quantum Efficiency for CCD's at -90°C](image)

Peak Quantum Efficiency at room temperature [-90°C] (%)**

<table>
<thead>
<tr>
<th>CCD Type</th>
<th>Minimum</th>
<th>Typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>FI</td>
<td>@ 700 nm</td>
<td>40</td>
</tr>
<tr>
<td>BU</td>
<td>@ 400 nm</td>
<td>80</td>
</tr>
<tr>
<td>BV</td>
<td>@ 550 nm</td>
<td>85</td>
</tr>
</tbody>
</table>

[46] [82] [94]
Quantum Efficiency for CCD’s at -90°C

<table>
<thead>
<tr>
<th>CCD Type</th>
<th>Minimum</th>
<th>Typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>FI</td>
<td>@ 700 nm</td>
<td>40</td>
</tr>
<tr>
<td>BU</td>
<td>@ 400 nm</td>
<td>80</td>
</tr>
<tr>
<td>BV</td>
<td>@ 550 nm</td>
<td>85</td>
</tr>
</tbody>
</table>
Modern Array Detectors - BICCD

- **Features & Benefits**
  - Peak QE of 95%
  - High detector sensitivity
  - Min operating temp of ~90°C with TE cooling
  - Negligible dark current without the nuisance or safety concerns associated with LN₂
  - Guaranteed hermetic vacuum seal
  - Ultimate reliability and sustained lifetime performance characteristics
  - Front- or back-illuminated design
  - Offers the best price/performance options
  - 13.5 x 13.5µm pixel size
  - Optimised pixel size for dynamic range and high resolution
  - Andor-MCD Software
  - Friendly Windows user interface offers system integration, automation and advanced data manipulation facilities

- **Dark Current**
  - Plot showing dark current vs. temperature
  - Max spectra per sec: 90 spectra/sec
  - Full Vertical Binning: 50 row sub-image

- **Temperature (°C)**
  - Auxiliary Cooling Connector
    - Air-cooled:
      - Ambient air @ 20°C: -65 to -75
    - Water-cooled:
      - @ 10°C, 0.75 l/min: -80 to -90

- **Operating & Storage Conditions**
  - Operating temperature: 0°C to 30°C ambient
  - Relative humidity: < 70% (non-condensing)
  - Storage temperature: -25°C to 55°C

- **Computer Requirements**
  - Minimum:
    - Windows 95/98: 100MHz Pentium + 64MB RAM
    - Windows NT2000: 100MHz Pentium + 128MB RAM
  - Recommended:
    - 300MHz Pentium (or better) + 256MB RAM
  - Also:
    - PCI-compatible computer
    - PCI slot must have bus master capability
    - Additional auxiliary internal power connector
    - 32MB free hard disk

- **Power Requirements**
  - (for kHz [MHz] operation)
  - No Auxiliary Cooling Connector
  - Auxiliary Cooling Connector
  - No cooling slot
    - 2.4A [3A]
    - 0A [0A]
  - TE cooler on slot
    - 1.5A [1.5A]
    - 2.2A [2.2A]
  - Total
    - 3.9A [4.5A]
    - 4.6A [5.2A]

(Power drawn from +5V power supply; Optional external power supply (PS150) plugs into the mains)
Modern Array Detectors - BICCD

Andor Back-Illuminated, Thermo-electrically Cooled CCD Array

Dark Current

Temperature (°C)

NOTE - Dark current for both FI and BI sensors
Modern Array Detectors - BICCD

Andor Back-Illuminated, Thermo-electrically Cooled CCD Array

Note: There are two mounting holes (1/4-20UNC), one located on the top of the CCD head and one on the bottom. They are positioned centrally at a distance of 24mm from the front of the front face.

Required Cable Clearance at back:

<table>
<thead>
<tr>
<th>Exit connector type</th>
<th>Clearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>140 mm</td>
</tr>
<tr>
<td>45° angle</td>
<td>50 mm</td>
</tr>
<tr>
<td>90° angle</td>
<td>40 mm</td>
</tr>
</tbody>
</table>

Weight: 2 Kg [4 lb 8 oz]
Modern Array Detectors- BICCD

Chip manufacturers may include a number of pixels or elements that are neither active nor part of the shift register. Andor refers to these pixels as dummy pixels and represents them in a 4-part notation \((W,X,Y,Z)\), where:

- \(W\) = dummy pixels to the right of the shift register (non-amplifier end)
- \(X\) = dummy pixels to the left of the shift register (amplifier end)
- \(Y\) = dummy pixels at the top of the image area
- \(Z\) = dummy pixels between the shift register and the image area.

\(A\) = position of output amplifier

It should be noted that the elements can be made up of either pixels, rows or columns.
The diagram shows what is seen when looking at the front of the CCD.

1. The register well depth that is actually accessible by the CCD system is dependant on the gain setting.
2. Linearity is measured from a plot of Counts vs. Signal over the 16 bit dynamic range. Linearity is expressed as a percentage deviation from a straight line fit. This value is not measured on individual systems.
3. System Readout noise is for the entire system. It is a combination of CCD readout noise and A/D noise. Measurement is for Single Pixel readout with the CCD at a temperature of -50°C and minimum exposure time under dark conditions.
4. Quantum efficiency of the CCD sensor is measured by the CCD Manufacturer.
5. The graph shows typical dark current level as a function of temperature for front-illuminated (FI) and back-illuminated (BI) CCDs. Systems are specified in terms of minimum dark current achievable rather than absolute temperature. The dark current measurement is averaged over the CCD area excluding any regions of blemishes.
6. The max spectra/sec for spectroscopy CCDs is the maximum speed at which the device can acquire spectra in a standard system. It assumes a 1MHz digitization rate, internal trigger mode and full vertical binning. Also given is the rate for a 50 row high sub-image (crop mode) on a CCD in a standard system. Note that faster rates may be achieved by operating the CCD in Fast Kinetics mode.
7. These power requirements are the maximum load that will be drawn from the computer for the camera head and controller card combined.
8. Specifications subject to change.
Modern Array Detectors - EMCCD

Andor Back-Illuminated, Thermo-electrically Cooled, Electron Multiplying CCD Array (Ixon DV887)
Modern Array Detectors- EMCCD

- Noise & EMCCD Gain

Andor Back-Illuminated, Thermo-electrically Cooled, Electron Multiplying CCD Array (Ixon DV887)
Modern Array Detectors- EMCCD

<table>
<thead>
<tr>
<th>Max Frames per sec</th>
<th>Array size</th>
<th>512 x 512 (full frame)</th>
<th>256 x 256</th>
<th>128 x 128</th>
<th>512 H x 100 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1x1</td>
<td>32</td>
<td>60</td>
<td>106</td>
<td>128</td>
<td></td>
</tr>
<tr>
<td>2x1</td>
<td>57</td>
<td>102</td>
<td>167</td>
<td>196</td>
<td></td>
</tr>
<tr>
<td>2x2</td>
<td>57</td>
<td>102</td>
<td>167</td>
<td>196</td>
<td></td>
</tr>
<tr>
<td>4x1</td>
<td>93</td>
<td>156</td>
<td>238</td>
<td>263</td>
<td></td>
</tr>
<tr>
<td>4x4</td>
<td>93</td>
<td>156</td>
<td>238</td>
<td>263</td>
<td></td>
</tr>
</tbody>
</table>

Full Frame Rate

<table>
<thead>
<tr>
<th>Readout Rate / MHz</th>
<th>No. frames per sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
</tr>
</tbody>
</table>

Power Requirements

- 0.6A @ +12V
- 0.3A @ -12V
- 3.0A @ +5V

Operating & Storage Conditions

- Operating Temperature: 0°C to 30°C ambient
- Relative Humidity: < 70% (non-condensing)
- Storage Temperature: -25°C to 55°C

Computer Requirements

- To handle data transfer rates of 10MHz readout over extended kinetic series, a powerful computer is recommended, e.g:
  - 2.4 GHz Pentium (or better)
  - 1GB RAM
  - Minimum of 10,000rpm hard drive, RAID 0 15,000rpm preferred for extended kinetic series
- Also:
  - PCI-compatible computer
  - PCI slot must have bus master capability
  - Available auxiliary internal power connector
  - 32 Mbytes free hard disc

Andor Back-Illuminated, Thermo-electrically Cooled, Electron Multiplying CCD Array (Ixon DV887)
Andor Back-Illuminated, Thermo-electrically Cooled, Electron Multiplying CCD Array (Ixon DV887)
Modern Array Detectors – CMOS Arrays

Complementary Metal Oxide Semiconductor (CMOS) Arrays

- CMOS arrays have a very different architecture.
- Each pixel element has imbedded transistors so the analog-to-digital conversion is performed at the pixel element.
- The pixel elements of the CMOS camera are addressed in parallel, and the output from the chip itself is digital as compared to the analog signal output of the CCD chip.
- CMOS cameras have very high framing rates because pixels are addressed in parallel.
- Response nonuniformity is a significant issue because each pixel is addressed individually, response is not nearly as uniform as for a CCD.
- CMOS cameras are less sensitive than CCD camera, transistor structure absorbs light, pixel element itself has lower quantum efficiency.
CCD is a charge transfer device, on CMOS device charge is converted to voltage at each pixel.

Figure 3. CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node; CMOS imagers convert charge to voltage inside each pixel.

Figure 4. CMOS imagers can be fabricated with more “camera” functionality on-chip. This offers advantages in size and convenience, although it is difficult to optimize both imaging and processing functions on the same device.
Scientific Complementary Metal Oxide Semiconductor (sCMOS) Arrays

- sCMOS arrays were introduced in 2009
- A microlens array is used to improve the pixel fill factor, resulting in increased quantum efficiency
- A dual set of amplifiers and analog-to-digital converters is used for each pixel, the gain settings are different to maximize the dynamic range of the array.
- Framing rates are not as high as for typical CMOS arrays, but still quite high compared to low-read-noise CCD arrays
- Read noise and dark noise comparable to cooled CCD arrays
Performance highlights of the first sCMOS technology sensor include:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor format</td>
<td>5.5 megapixels 2560 (h) x 2160 (v)</td>
</tr>
<tr>
<td>Read noise</td>
<td>&lt; 2 e⁻ rms @ 30 frames/s; &lt; 3 e⁻ rms @ 100 frames/s</td>
</tr>
<tr>
<td>Maximum frame rate</td>
<td>100 frames/s</td>
</tr>
<tr>
<td>Pixel size</td>
<td>6.5 μm</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>16,000:1 @ 30 frames/sec</td>
</tr>
<tr>
<td>QEmax</td>
<td>60%</td>
</tr>
<tr>
<td>Read out modes (User selectable)</td>
<td>Rolling and Global Shutter</td>
</tr>
</tbody>
</table>

sCMOS
Scientific CMOS Technology
A High-Performance Imaging Breakthrough
Modern Array Detectors – SNR Calculations

From Phil Paul, AIAA-91-2315 (similar analysis in Seitzman and Hanson [AIAA Journal, 513-519 (1993)]), the signal-to-noise ratio for a single pixel on an array detector with a multichannel plate (MCP) intensifier is given by

$$SNR = \frac{N_p \eta_{pc} G_{e,mcp}}{\sqrt{N_p \eta_{pc} G_{e,mcp} (G_{e,mcp} \kappa + 1) + \left(\frac{N_x}{G_{e,phos}}\right)^2}}$$

where $N_p$ is the number of photons incident on the pixel,

$\eta_{pc}$ is the quantum efficiency of the MCP photocathode or the semiconductor material,

$G_{e,mcp}$ is the electron gain of the MCP,

$\kappa$ is a noise factor associated with the MCP intensification (decreases with increasing gain),

$G_{e,phos}$ is the conversion efficiency of electrons at the output of the MCP to electrons in the array pixel,

and $N_x$ is the sum of noise electrons due to the read process, dark noise, charge transfer inefficiency, etc.
Modern Array Detectors – MCP Intensifier

- $G_{e,mcp}$
- $G_{e,phos}$
- $G_{e/e}$
- $A$ (DN's / e)

$N_{pp}$

$\eta_{pc}$

$\eta_{ad}$

$N_x$

$M$

phosphor minilier

array

Modern Array Detectors – MCP Intensifier

![Graph showing the relationship between detector performance and voltage applied to the MCP (Multielectrode Channel Plate). The graph plots \( D_s(V_{\text{mcp}}) \) and \( \kappa(V_{\text{mcp}}) \) as functions of \( V_{\text{mcp}} \). The lines represent Camera A and Camera B, showing the performance difference at various voltages.]
Modern Array Detectors – SNR Calculations

For detection on an unintensified CCD,

\[ G_{e,\text{mcp}} = 1, \quad \kappa = 0, \quad G_{e,\text{phos}} = 1 \]

\[ \Rightarrow \quad \text{SNR} = \frac{N_p \eta_{pc}}{\sqrt{N_p \eta_{pc} + N_x^2}} \]

For detection of high light levels with an intensified CCD,

\[ N_p \eta_{pc} G_{e,\text{mcp}} \left( G_{e,\text{mcp}} \kappa + 1 \right) \gg N_x^2, \quad G_{e,\text{mcp}} \kappa \gg 1 \]

\[ \Rightarrow \quad \text{SNR} = \sqrt{\frac{N_p \eta_{pc}}{\kappa}} \]
Modern Array Detectors – Dynamic Range

For the unintensified CCD, dynamic range under ideal conditions,

\[ DR = \frac{\text{Number of Electrons in CCD Potential Well}}{\text{Read Noise Electrons}} \approx 100,000 \]

For an array detector with MCP intensifier, DR is reduced greatly, (Reference Phil Paul, AIAA-91-2315)

\[ DR = \frac{N_{e,\text{sat}}}{N_{e,\text{SNR}=1}} \]

\[ N_{e,\text{sat}} = N_{mp} \frac{S\left(G_{e,mcp}\right)}{G_{e,mcp}} \]

\[ S\left(G_{e,mcp}\right) \text{ determined expt for given MCP} \]

\[ N_{e} = \# \text{ electrons at output face of MCP} \]
Typically, can get about $10^4$ electrons per microchannel at full gain of $10^3$, $N_{mp} = 3-4$ microchannels per pixel.
Can show that for SNR = 1,

$$N_{e, SNR=1} = \left( N_p \eta_{pc} G_{e,mcp} \right)_{e, SNR=1}$$

$$= \frac{1}{2} \left( G_{e,mcp} \kappa + 1 + \sqrt{ \left( G_{e,mcp} \kappa + 1 \right)^2 + 4 \left( \frac{N_x}{G_{e,phos}} \right)^2 } \right)$$

$$= \frac{1}{2} \left( G_{e,mcp} \kappa + \sqrt{ \left( G_{e,mcp} \kappa \right)^2 + 4 \left( \frac{N_x}{G_{e,phos}} \right)^2 } \right)$$