Microsecond Time-Resolved Radiography at 7-BM Beamline: Spray Diagnostics

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Alan Kastengren
Center for Transportation Research, Argonne National Laboratory

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Motivation for Fuel Spray Measurements

- Desire to reduce use of non-renewable petroleum fuels
  - Environment: transportation petroleum use creates 1.8 billion tons of CO$_2$ per year*
  - Economic considerations
- Two main strategies for IC engine combustion
  - Spark ignition gasoline engines: clean, but inefficient
  - Diesel engines: efficient, but dirty
- Improving engine combustion depends on a better understanding and control of fuel-air mixture preparation: sprays
- Optical diagnostics are often used to study sprays, but multiple scattering makes quantitative measurements difficult
- X-ray techniques have significant advantages for spray applications
  - Good penetration through phase boundaries
  - Quantitative data
  - Focuses on core of spray, where most of the mass resides
X-Ray Diagnostics Reveal the True Structure of Sprays

Visible Light Image

Quantitative measurement of the fuel distribution
Stringent test for spray models

Radiography “Image”

Image courtesy of EMD, Essam El-Hannouny (ES)
Requirements for Time-Resolved Spray Radiography

**Aspects of Sprays**

- Standard diesel injection nozzle hole: 100-150 µm diameter
- Fuel is a hydrocarbon
- Required time resolution < 5 µs
- Pressurized chamber needed to simulate gas environment experienced in an engine
- $S/N$ of at least 30:1 in data once processed into mass/area
- Need simple conversion of flux to mass/area

**Beamline Requirements**

- Tight focusing for good spatial resolution (< 10 µm spatial resolution)
- Low absorption (0.4/mm): even with contrast agent (2/mm), max absorption ~ 20-40%
- Need fast detector
- Relatively long (200-300 mm) working distance
- Limits usable photon energy
- $S/N > 150$ in x-ray flux measurement. When combined with time resolution, need high flux to reduce photon shot noise
- Relatively monochromatic beam needed
Flux Requirements and Experimental Setup

- Spray event lasts ~ 1 ms, fastest features last a few µs
- Spray is contained in a spray chamber filled with high pressure gas; 90% of flux can be lost in windows and chamber gas
- Not enough photons to do 2-D imaging
  - At $10^{10}$ ph/s, 5 µs = 50,000 photons
  - PAD measurements have been performed in the past
- Instead, measure one point at a time
  - Raster scan over 1000-2000 points
  - Spray is quite repeatable (µs) from event to event
  - 32-128 events/point to improve S/N
Mechanics of Radiography

- Dominant interaction of x-rays with matter is absorption, not scattering.
- Radiography: directly relate x-ray transmission to mass/area in beam:

\[ \tau = e^{-\mu M} \]

\[ M = -\frac{\ln(\tau)}{\mu} \]
Spray Distribution, 110 µm Diameter Nozzle
700 bar Rail Pressure, 1200 µs Duration
Focus BM fan onto a relatively small spot with upstream optics
  - Collimating mirror, sagittal focusing Si mono, vertical focusing mirror
  - Geometry precludes small focus spot sizes

Use slits to define a smaller beam

Problems with this approach
  - Beam size at spray not terribly well defined due to beam divergence
  - Little room to improve the flux
  - Longer working distances give a bigger beam
Multilayer Monochromator to Increase Flux

- While a monochromatic beam is desirable for radiography measurements, high spectral purity isn’t needed.
- Use a multilayer monochromator to increase flux at the expense of energy resolution:
  - W/B₄C multilayers, d = 2.4 nm, 100 layers
  - 1.4% ΔE/E

- Advantages:
  - Much higher flux than crystal mono
  - Virtually no harmonics due to multilayer design
  - Flexibility to change properties by changing multilayer coating

- Disadvantages:
  - Low Bragg angles (1.86° at 8 keV)
    - Long monochromator tank, and crystals must be held on separate stages
    - Sagittal focusing becomes far more challenging
  - Different d spacing on crystals causes mono beam to be tilted slightly
Multilayer Monochromator to Increase Flux

Beamline Flux at z = 36 m

Monochromator Energy Resolution at Three Photon Energies
7-BM Experimental Setup

- Spray event lasts ~ 1 ms, fastest features last a few µs
- Spray is quite repeatable (µs) from event to event, so we can measure one point at a time
- Raster scan over 1000-2000 points
- 32-128 events/point
IDT K-B Focusing Mirrors

- Focusing optics are a pair of K-B focusing mirrors from IDT
- Mirror specs:
  - 300 mm long for each mirror, 260 mm optical surface length
  - Coating: 50 nm Rh over 10 nm Cr
  - Design working distance 250 mm from end of mirror box
  - Designed mirror angle 5 mrad
- Mechanics
  - Motions for upstream position, downstream position, and two bending moments
  - Repeatability of motions around 1 µm
- Commissioned July-August 2010
- Identical mirrors will soon be installed in 7-ID-D
## Theoretical Mirror Performance

<table>
<thead>
<tr>
<th></th>
<th>Vertical</th>
<th>Horizontal</th>
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<tbody>
<tr>
<td>Source sigma</td>
<td>28.5</td>
<td>86</td>
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<tr>
<td>Mirror Length</td>
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<td>0.3</td>
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<tr>
<td>Working Distance</td>
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<tr>
<td>f1</td>
<td>36.3</td>
<td>36.62</td>
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<tr>
<td>f2</td>
<td>0.75</td>
<td>0.43</td>
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<td>Flat Slope Error</td>
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<tr>
<td>Total Slope Error</td>
<td>0.632</td>
<td>1.027</td>
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<tr>
<td>Ideal FWHM</td>
<td>1.384</td>
<td>2.373</td>
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<tr>
<td>FWHM</td>
<td>2.621</td>
<td>3.153</td>
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<td>Mirror Angle</td>
<td>5</td>
<td>5</td>
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<tr>
<td>Intercepted Beam</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Ideal Flux at 8 keV</td>
<td>1.5 x 10^{12}</td>
<td></td>
</tr>
</tbody>
</table>
Measured Mirror Performance

- Best focus spot achieved: 4 (V) x 5 (H) µm FHWM
  - Not far from expected beam size
  - Determined with imaging on a Ce:YAG, so this may overestimate beam size
- Mirror reflectivities at 8 keV: 88% V focusing mirror, 87% H focusing mirror, 76% combined
- Flux at mirror exit: $1.5 \times 10^{11}$ ph/s at 8 keV
  - About 10% of ideal flux from bending magnet
  - Reasonable considering multilayer reflectivity, windows, mirror reflectivity
  - 8 x more flux than with 100 mm long K-B pair used previously
- Tested at 5 and 6 mrad angle: more intensity at 6 mrad, but reflectivities worse
- Tested at working distances from 200 – 450 mm
- Performed well at 7, 8, and 10 keV
- Room in mechanics to decrease working distance
  - Bend motion at 12 mm when focused, compared to limit of 19 mm
  - Requires different shape to mirror substrate
Price of Tight Focusing + Time Resolution: Need for Good Beam Stability

- With smaller beam from the new mirrors, we found that beam stability becomes increasingly important.
- Use a Prosilica camera, YAG:Ce screen, and 5x microscope to image beam motion at 150 Hz frame rate.
  - Exposure time < 1 ms, so it makes a reasonably high-speed diagnostic.
  - Vertical beam FWHM = 4-5 µm.
  - Vertical beam motion = 8 µm p-p.
- Lead to significant repairs of monochromator.
- Additional vibrations tied to a vacuum pump used to pump down flight tube.
- After improvements, motion is 2-3 µm.
Detectors for Time-Resolved Radiography: PIN Diode vs. APD

**APD**
- Nonlinear at high flux (> $10^9$ ph/s)
- Requires GHz sampling rates
- Will not work in 324 bunch mode

**PIN Diode**
- Linear
- DC to several MHz
- Works in all fill patterns
- Can treat x-ray source as quasi-CW
Beam Intensity Varies Significantly at P0 Frequency

- Bandwidth required for spray measurements is 1 MHz or less
- Different bunches in the electron ring contain significantly different charge
  - A few %
  - Shows up as beam intensity variations at P0 and higher harmonics
  - Interferes with investigating fast changes in the spray
  - Changes slightly with each top-up
- Workarounds
  - Measure fluctuation with an I0 monitor, but hard to get a good enough signal
  - Bin data every cycle: limits time resolution
  - Average away intensity fluctuations

Beam Intensity Fluctuations
11/11/2010: 324 Bunch
PIN Diode Filtered at 1 MHz
Phase Shifter: Strategy to Remove Bunch Charge Variations

- Average across \( n \) spray events to improve S/N (\( n=16, 32, 64 \))
- Synchronize DAQ to P0 (\( \sim 3 \text{ Hz} \))
- Phase shifting box built by the Detector Pool based on their generic digital concept
  - Small on-board computer that runs EPICS
  - FPGA to perform processing
- Adds a time delay of \( 3.68 \mu s / n \) for every trigger
- After averaging over \( n \) events, the bunch charge variations average out
- Greatly reduces intensity fluctuations
  - More flexibility in time resolution
  - Easier filtering of remaining fluctuations

Beam Intensity Fluctuations
11/11/2010: 324 Bunch
PIN Diode Filtered at 1 MHz
Summary

- Fuel spray measurements are an important component of DOE IC engine research
- 7-BM beamline optimized for time-resolved radiography measurements
- Multilayer monochromator for higher flux
- Large K-B focusing mirrors to achieve a small focus spot size with high flux
- PIN diode detector: linear at higher flux than APD in analog mode
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