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

TWG Meeting: November 18, 2010

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Research Sponsor: DOE Vehicle Technologies Program

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

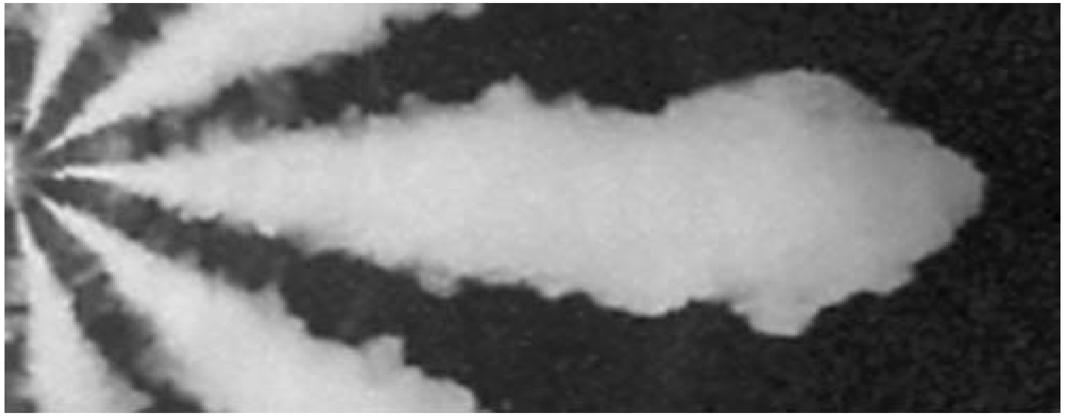
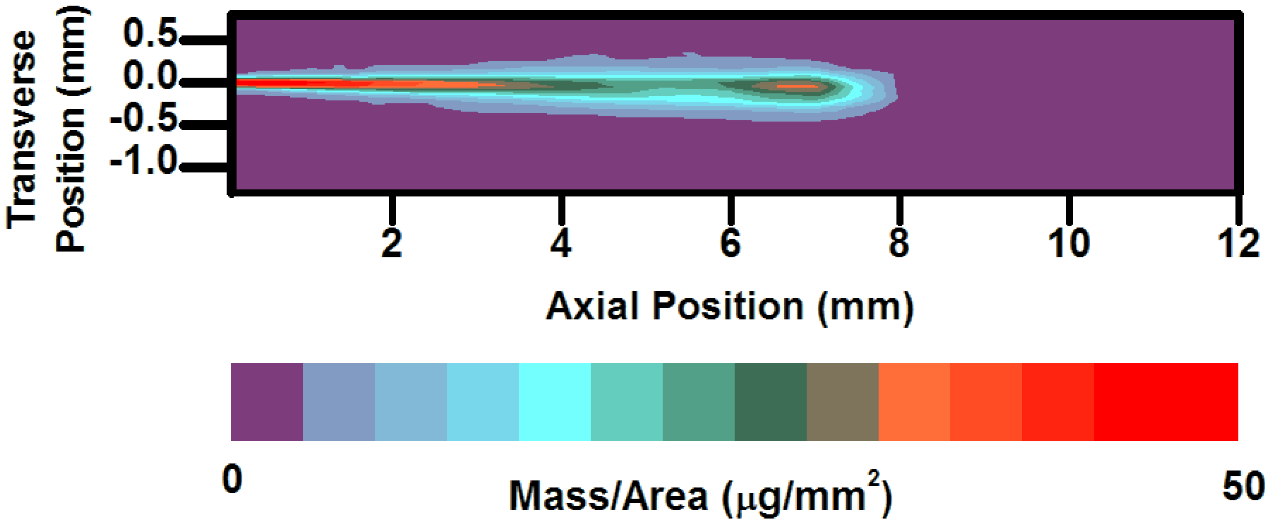


Image courtesy of EMD, Essam El-Hannouny (ES)



Radiography "Image"

- Quantitative measurement of the fuel distribution
- Stringent test for spray models

Requirements for Time-Resolved Spray Radiography

Aspects of Sprays

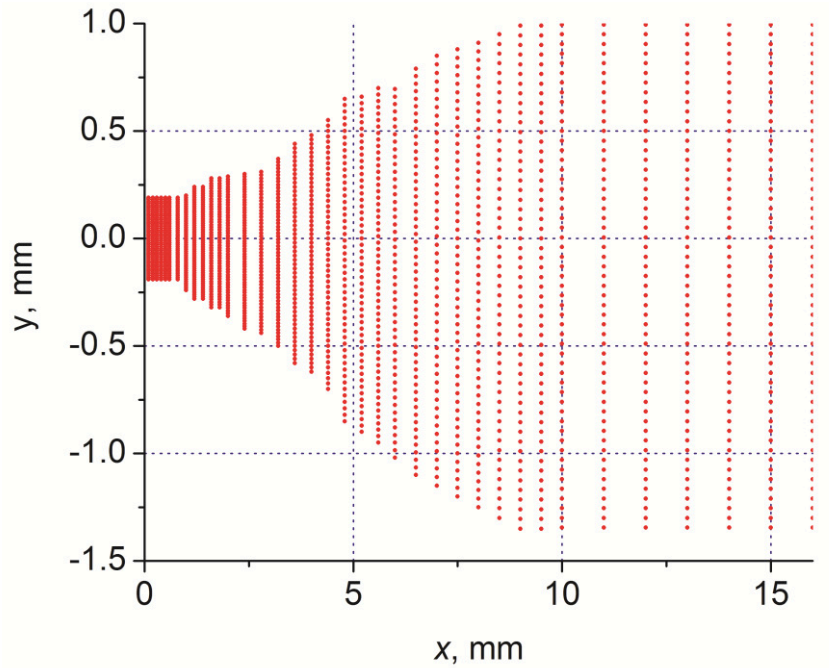
- Standard diesel injection nozzle hole: 100-150 μm diameter
- Fuel is a hydrocarbon
- Required time resolution < 5 μs
- Pressurized chamber needed to simulate gas environment experienced in an engine
- S/N of at least 30:1 in data once processed into mass/area
- Need simple conversion of flux to mass/area

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



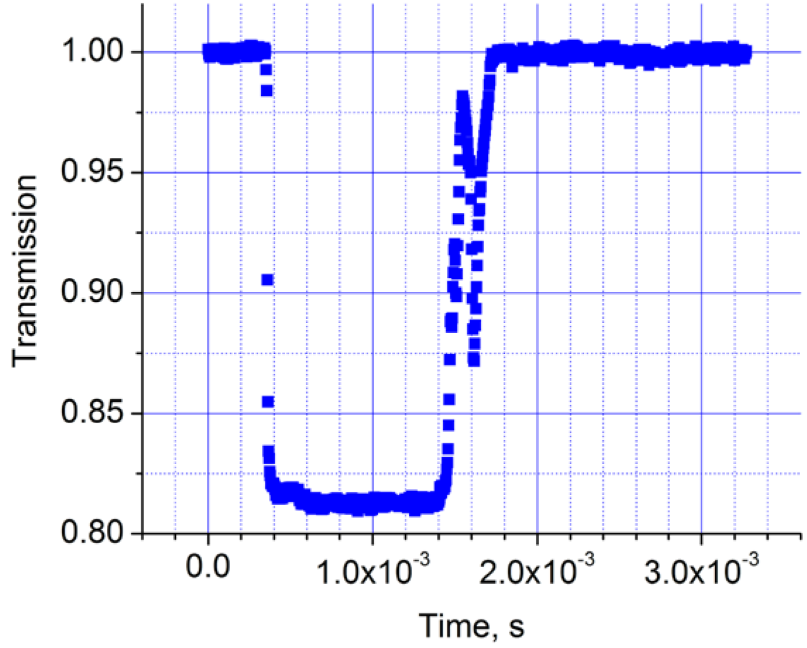
Typical Spray Radiography Raster Pattern

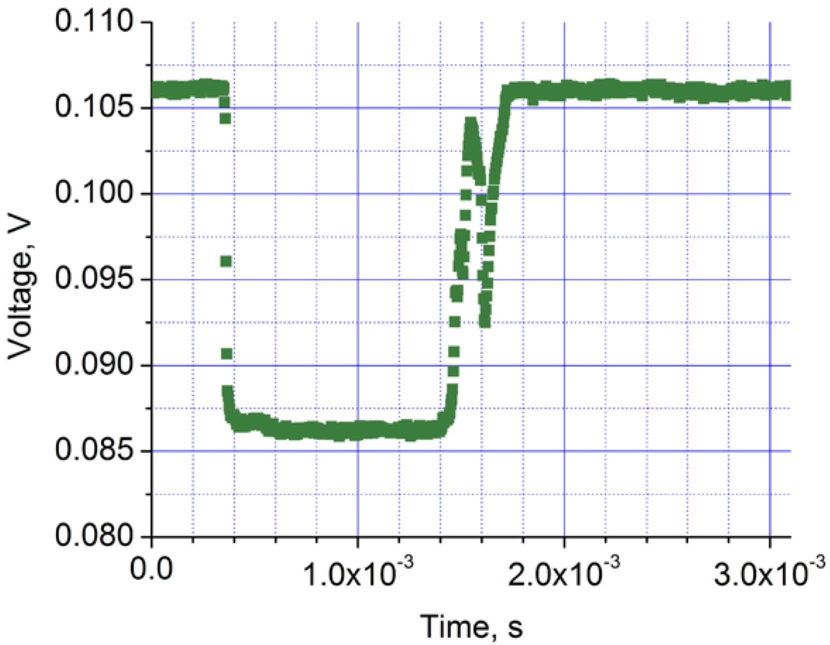
Mechanics of Radiography

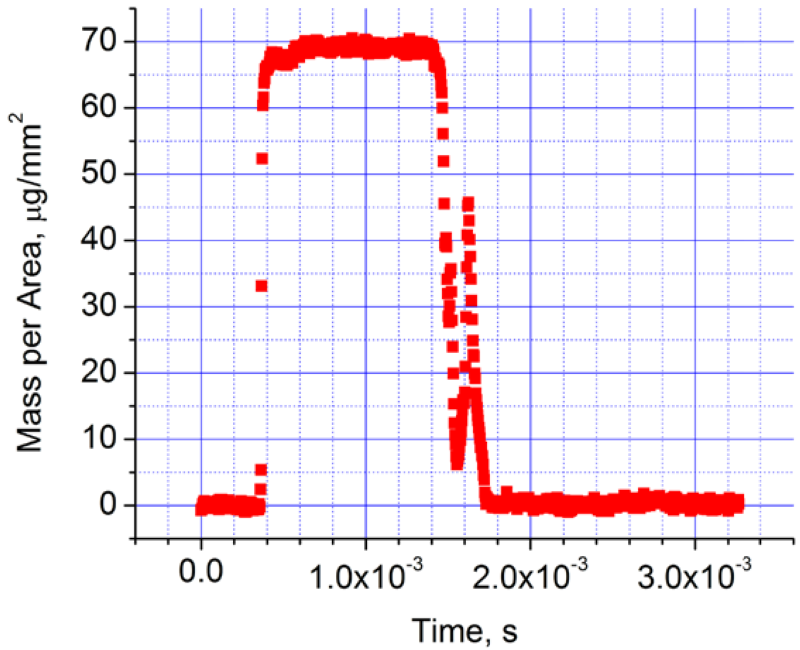
- Dominant interaction of x-rays with matter is absorption, not scattering
- Radiography: directly relate x-ray transmission to mass/area in beam:

$$\tau = e^{-\mu M}$$

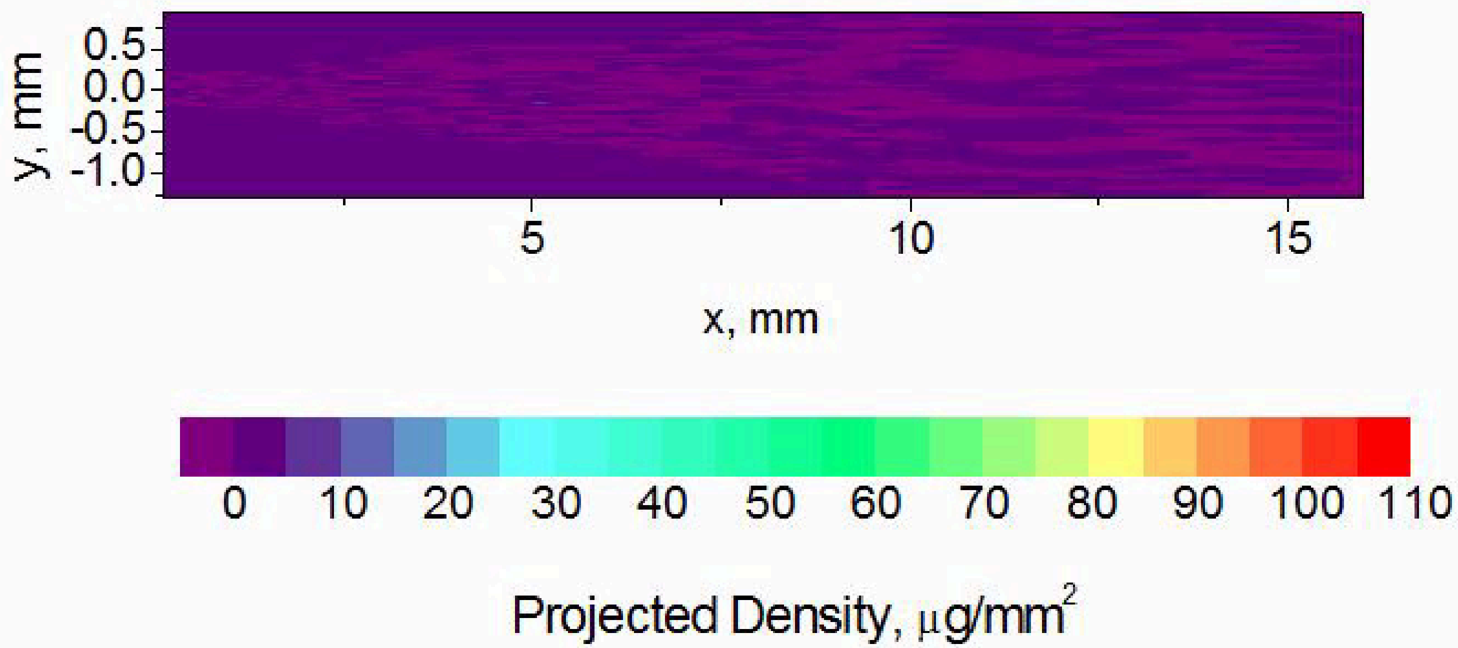
$$M = -\frac{\ln(\tau)}{\mu}$$



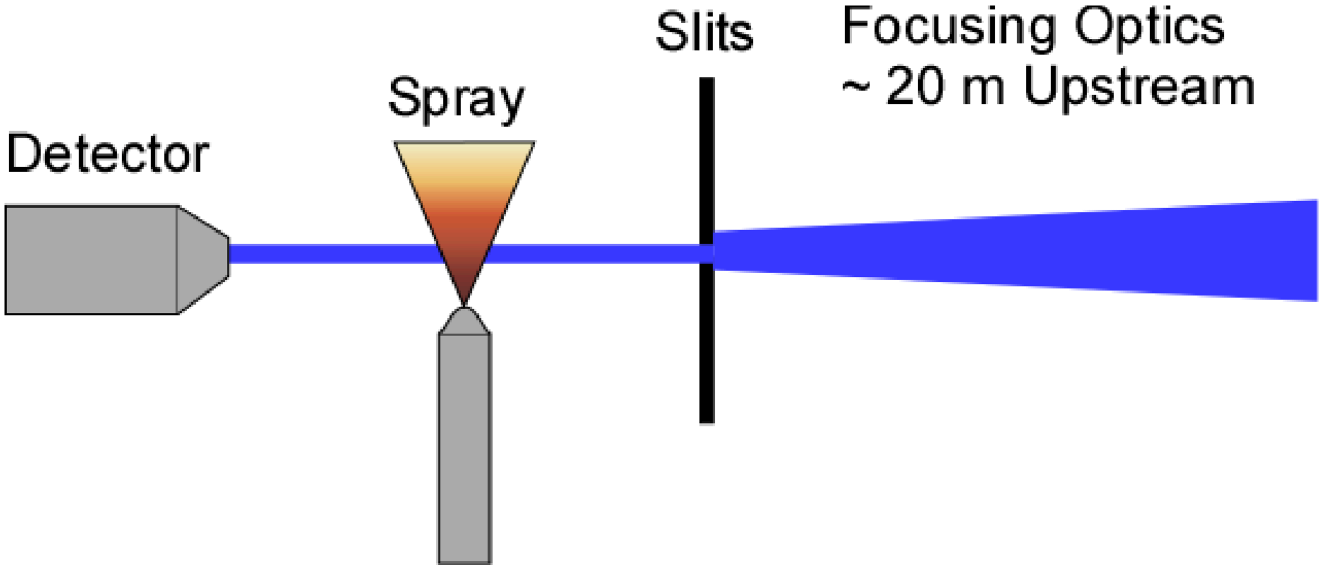




Spray Distribution, 110 μm Diameter Nozzle
700 bar Rail Pressure, 1200 μs Duration



Original Strategy: 1-BM

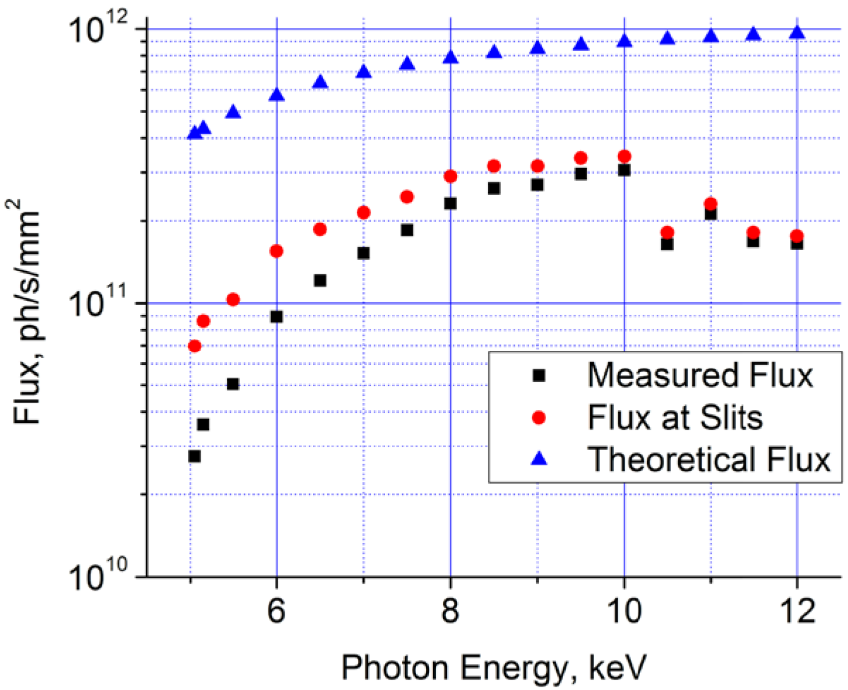


- Focus BM fan onto a relatively small spot with upstream optics
  - Collimating mirror, sagittal focusing Si mono, vertical focusing mirror
  - Geometry precludes small focus spot sizes
- Use slits to define a smaller beam
- Problems with this approach
  - Beam size at spray not terribly well defined due to beam divergence
  - Little room to improve the flux
  - Longer working distances give a bigger beam

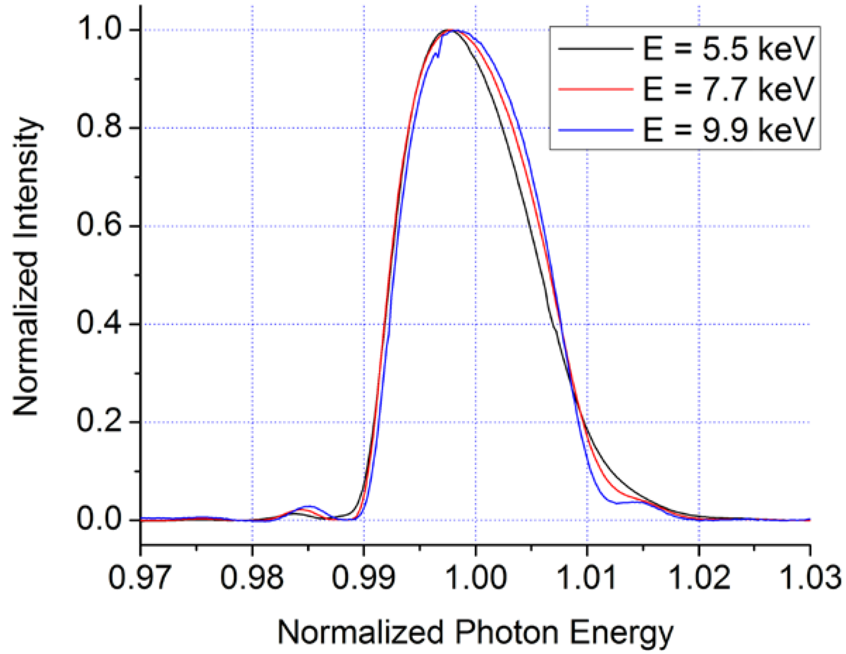
Multilayer Monochromator to Increase Flux

- 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/B_4C 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

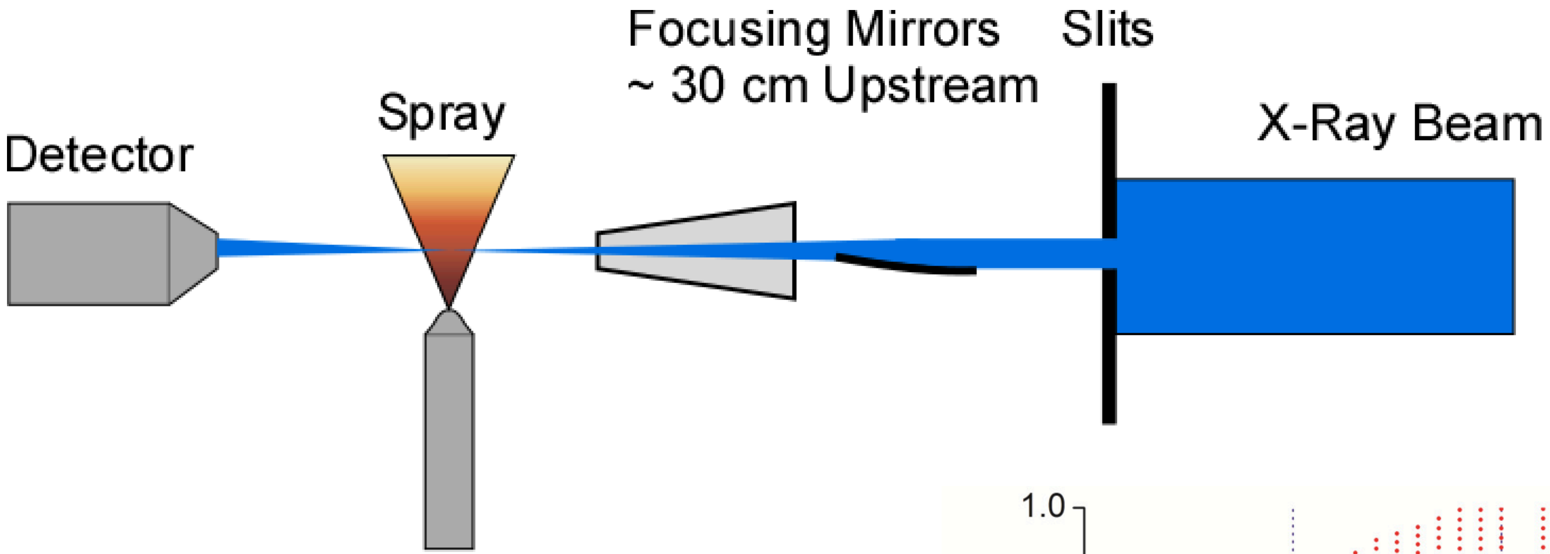


Beamline Flux at z = 36 m



Monochromator Energy Resolution at Three Photon Energies

7-BM Experimental Setup



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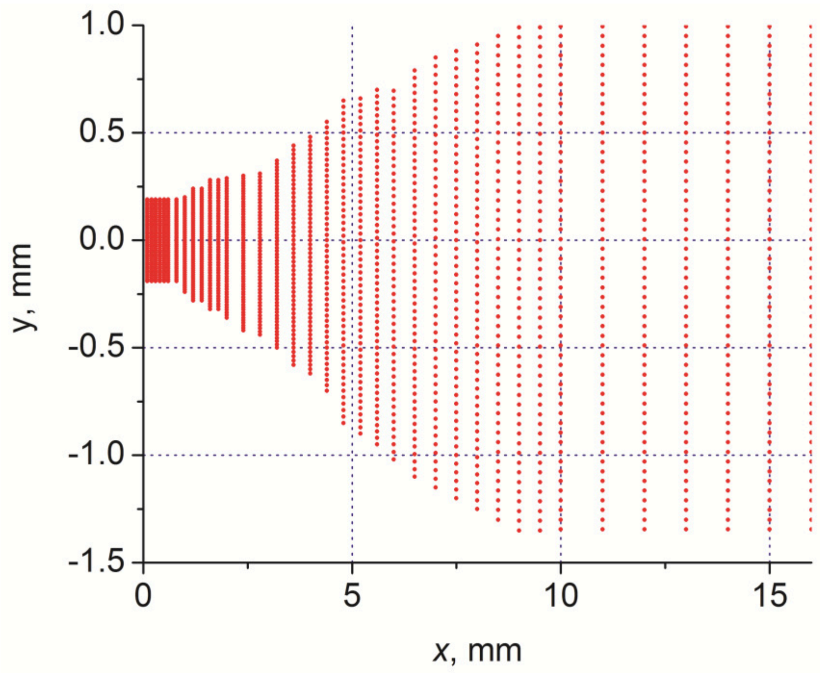
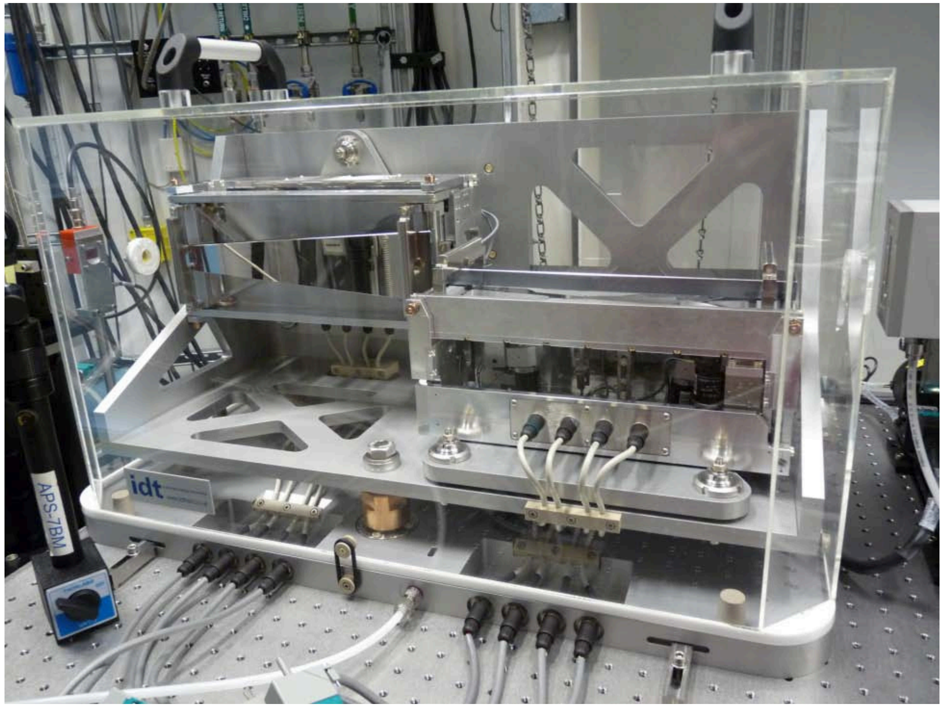


IDT K-B Focusing Mirrors

- 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

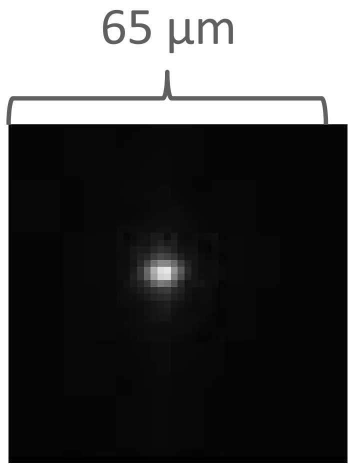
	Vertical	Horizontal	
Source sigma	28.5	86	µm
Mirror Length	0.3	0.3	m
Working Distance	0.28		m
f1	36.3	36.62	m
f2	0.75	0.43	m
Flat Slope Error	0.63	1	µrad
Total Slope Error	0.632	1.027	µrad
Ideal FWHM	1.384	2.373	µm
FWHM	2.621	3.153	µm
Mirror Angle	5	5	mrad
Intercepted Beam	1.3	1.3	mm
Ideal Flux at 8 keV	1.5×10^{12}		ph/s

Measured Mirror Performance

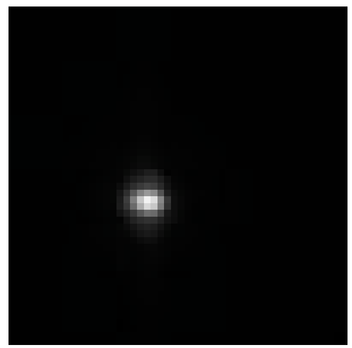
- Best focus spot achieved: 4 (V) x 5 (H) µm FHWM
  - Not far from expected beam size
  - Determined with imaging on a Ce:YAG, so this may overestimate beam size
- Mirror reflectivities at 8 keV: 88% V focusing mirror, 87% H focusing mirror, 76% combined
- Flux at mirror exit: 1.5 x 10^{11} ph/s at 8 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



Before



After

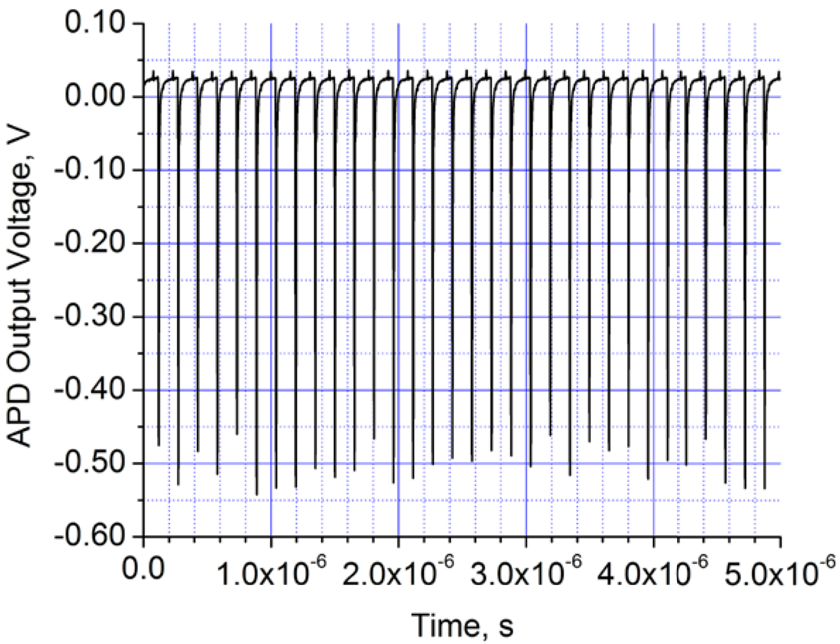
Detectors for Time-Resolved Radiography: PIN Diode vs. APD

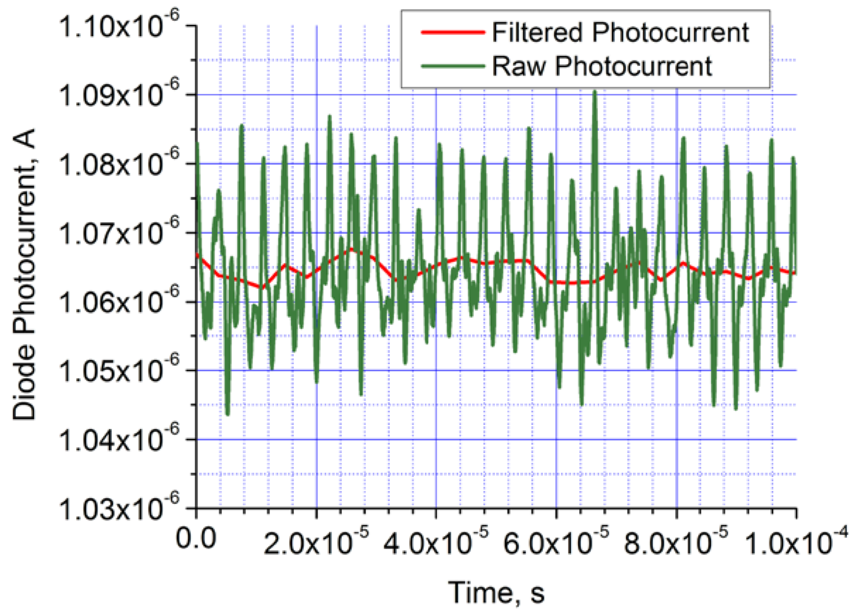
APD

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

PIN Diode

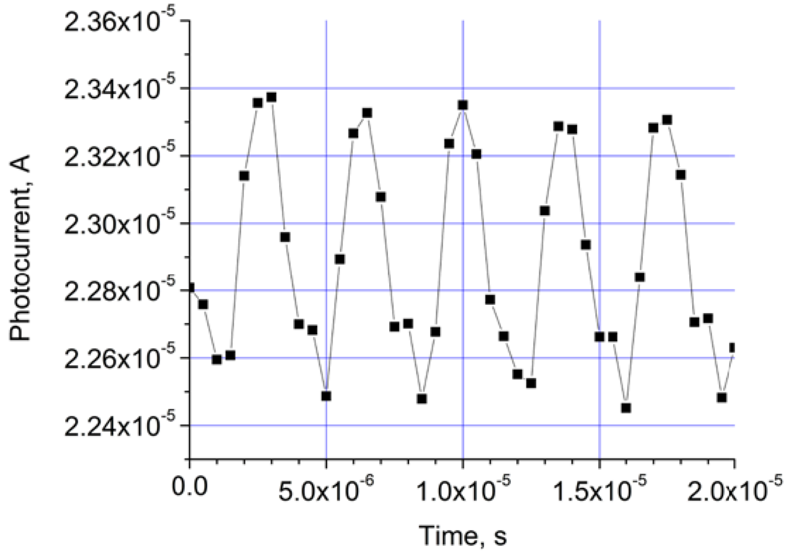
- Linear
- DC to several MHz
- Works in all fill patterns
- Can treat x-ray source as quasi-CW





Beam Intensity Varies Significantly at P0 Frequency

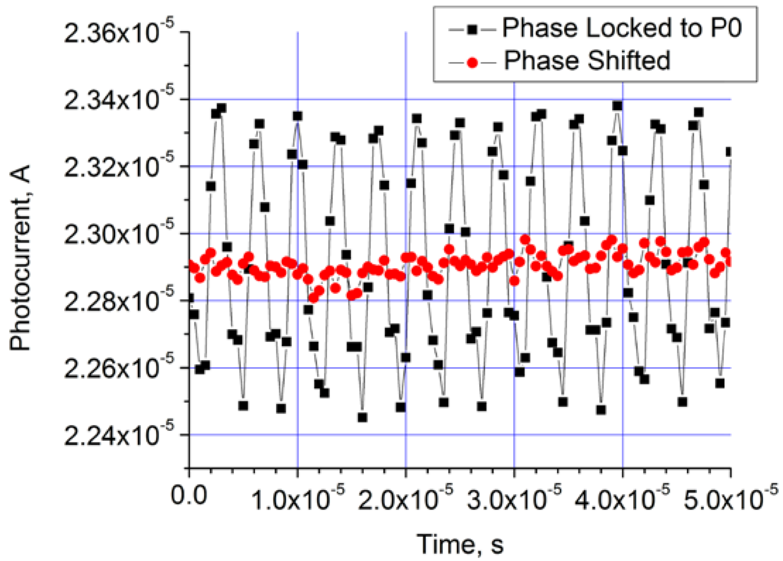
- Bandwidth required for spray measurements is 1 MHz or less
- Different bunches in the electron ring contain significantly different charge
  - A few %
  - Shows up as beam intensity variations at P0 and higher harmonics
  - Interferes with investigating fast changes in the spray
  - Changes slightly 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 (~ 3 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 μs / n for every trigger
- After averaging over n events, the bunch charge variations average out
- Greatly reduces intensity fluctations
  - 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

Acknowledgements

- Chris Powell (ES) and Jin Wang (XSD)
- Eric Dufresne, Dohn Arms, Dohn Walko
- Peter Eng