Advanced Research in Diesel Fuel Sprays Using X-rays From The Advanced Photon Source

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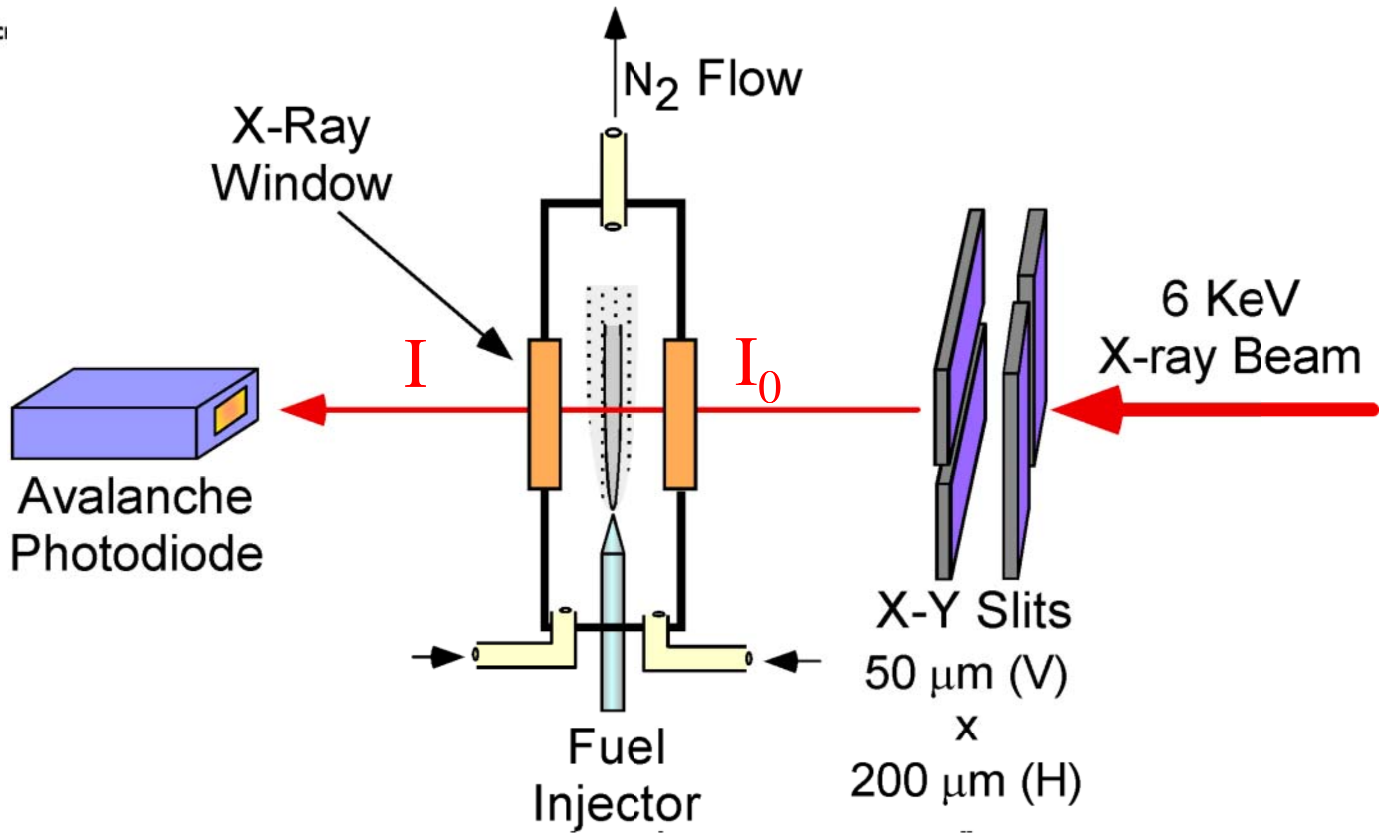
Project Motivation

- **Goal: Understand the mechanisms of spray atomization**
  - In-Nozzle effects - cavitation, nozzle structure
  - Aerodynamic effects - air entrainment, stripping, coalescence
  - Relative magnitudes unknown
  - Difficult to develop accurate spray models
- **Accurate modeling is important for emissions**
  - Engine testing is time-consuming, expensive
  - Modeling supplements real-world tests
- **Current spray models assume an initial fuel distribution**
  - Initial conditions uncertain
  - Little quantitative data exists in near-nozzle region
  - Visible light techniques limited by scattering
  - Lack of existing data, lack of reliable models
- **X-Ray technique**
  - Scattering is negligible
  - Quantitative measurement of fuel, even near the nozzle
  - Provide data necessary for accurate models
  - Unique diagnostic tool

Schematic of X-Ray Setup

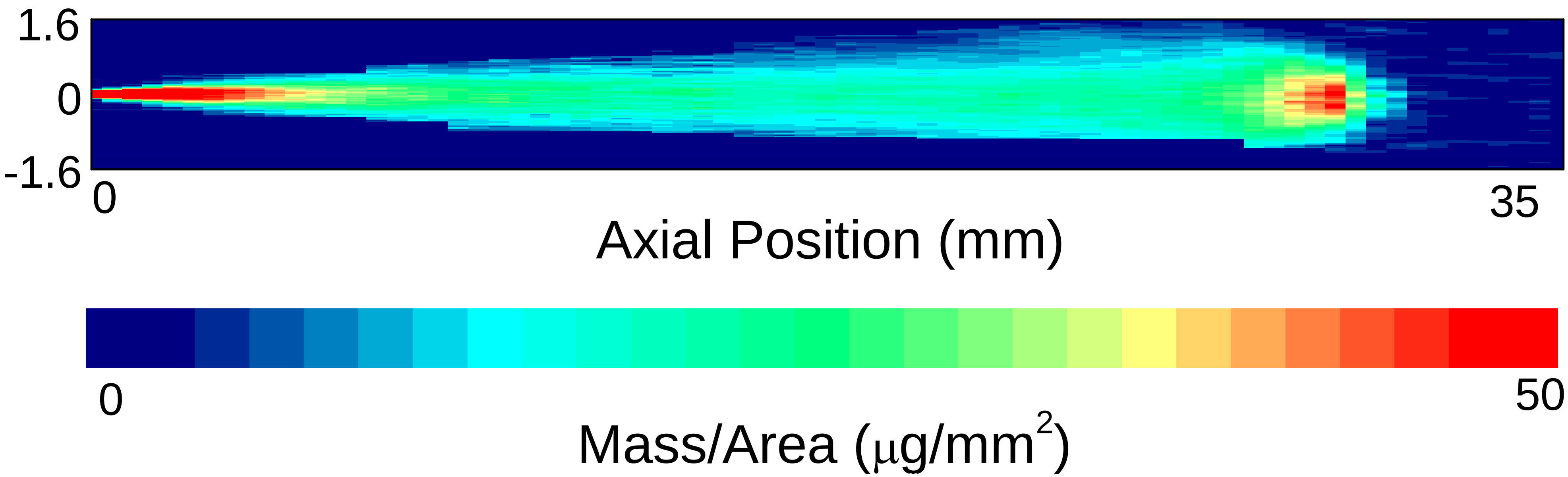


Direct relation between x-ray intensity and fuel mass

$$I/I_0 = \exp\left(-\mu_M M\right)$$

I_0	Incident x-ray intensity
I	Measured x-ray intensity
μ_M	Fuel absorption constant
M	Mass of fuel in x-ray beam

X-Ray Image Reconstruction



- Image is built from measurements at over 1500 different positions
- Image represents line-of-sight mass distribution

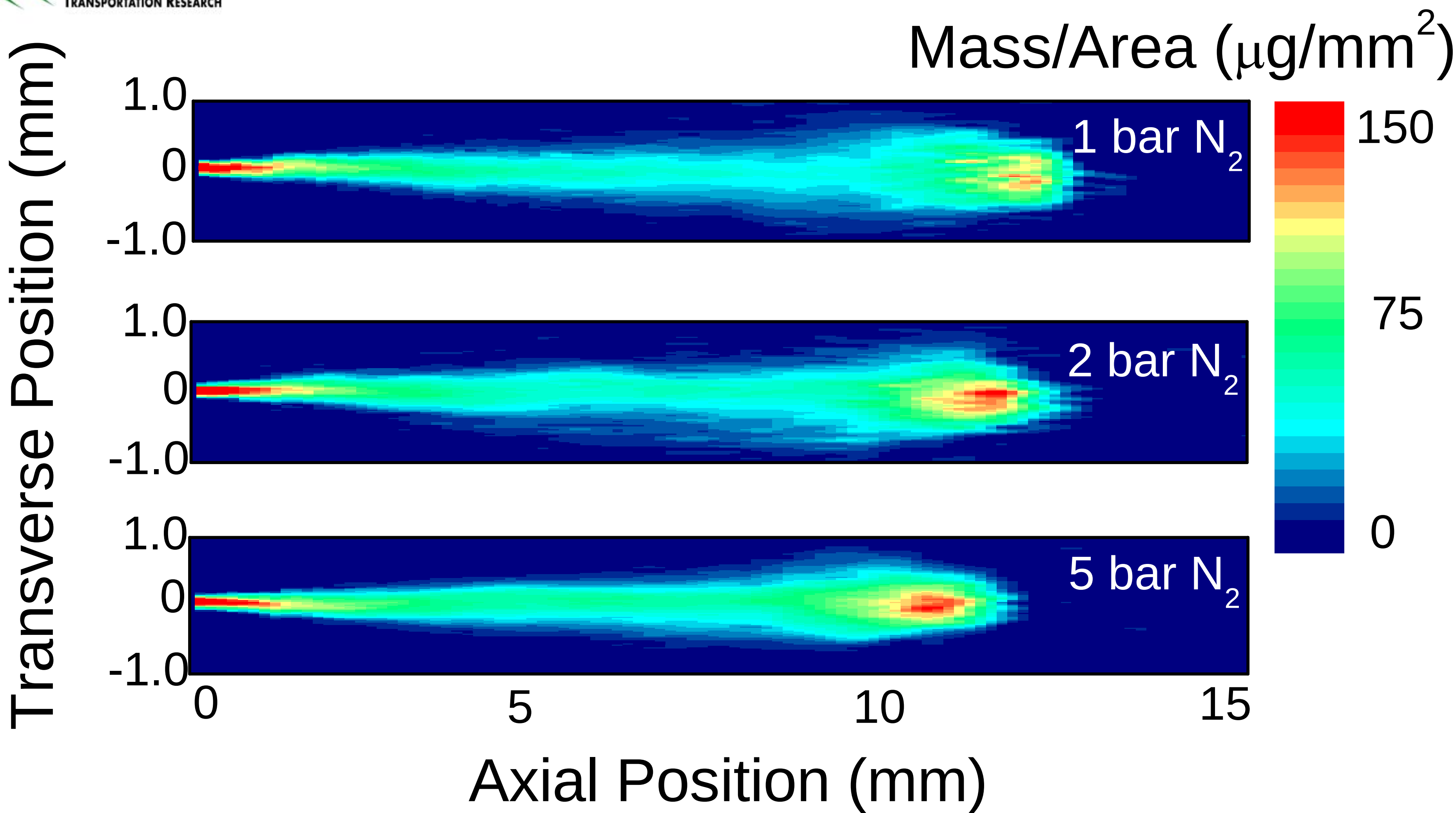
Injection Pressure = 500 bar
Ambient Pressure = 1 bar N_2
200 μs after SOI

Measurement Conditions

Common rail diesel, mini-sac nozzle, single hole

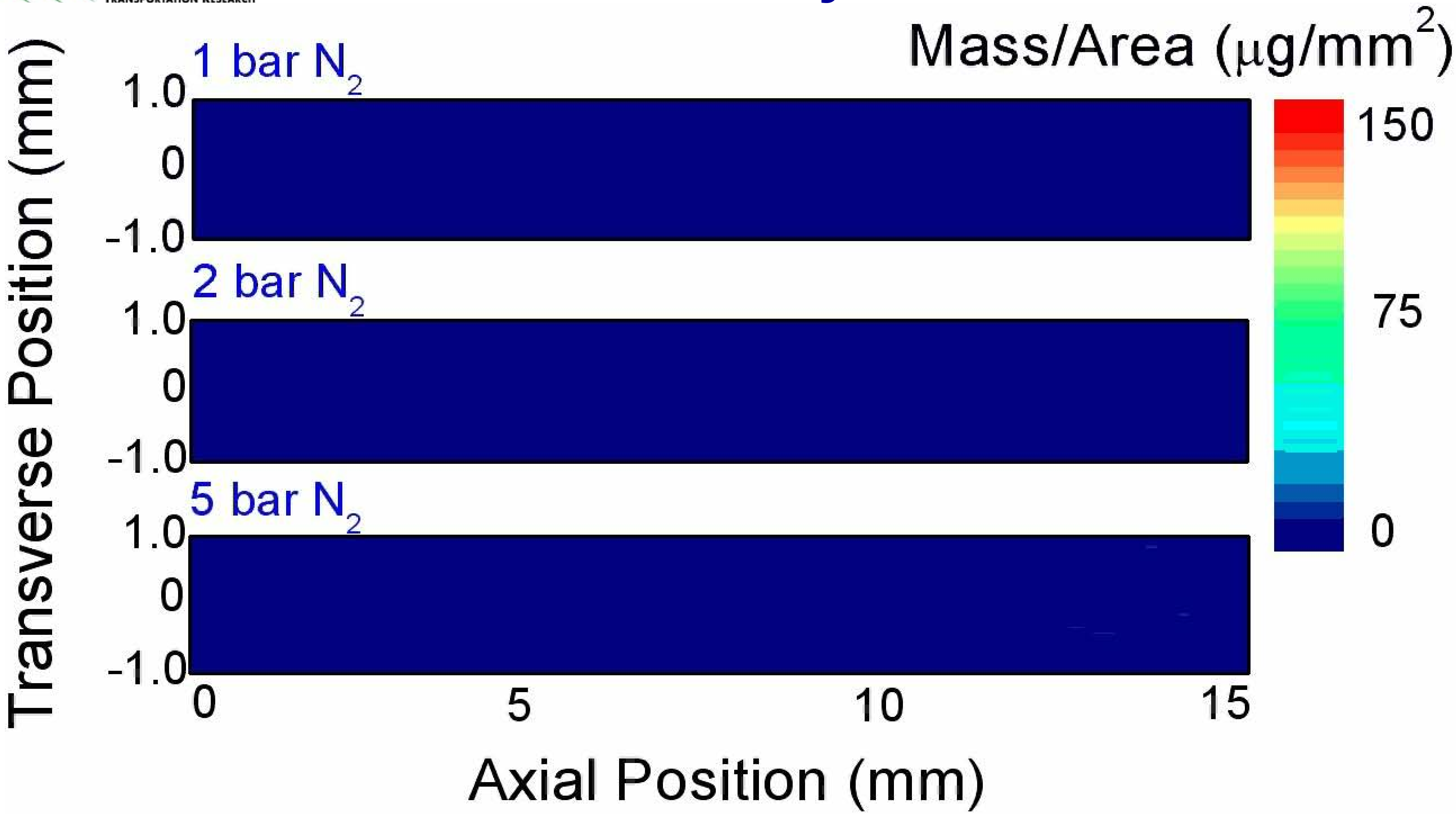
➢Orifice diameter	180 μm
➢Fuel pressure	500 bar
➢Pulse duration	400 μs
➢Spray chamber gas	N_2 @ 1-10 bar, 25 °C
➢Fuel Additive	Ce compound, 10%
➢Data Averaging	50-150 sprays

Sprays Under Different Ambient Pressures



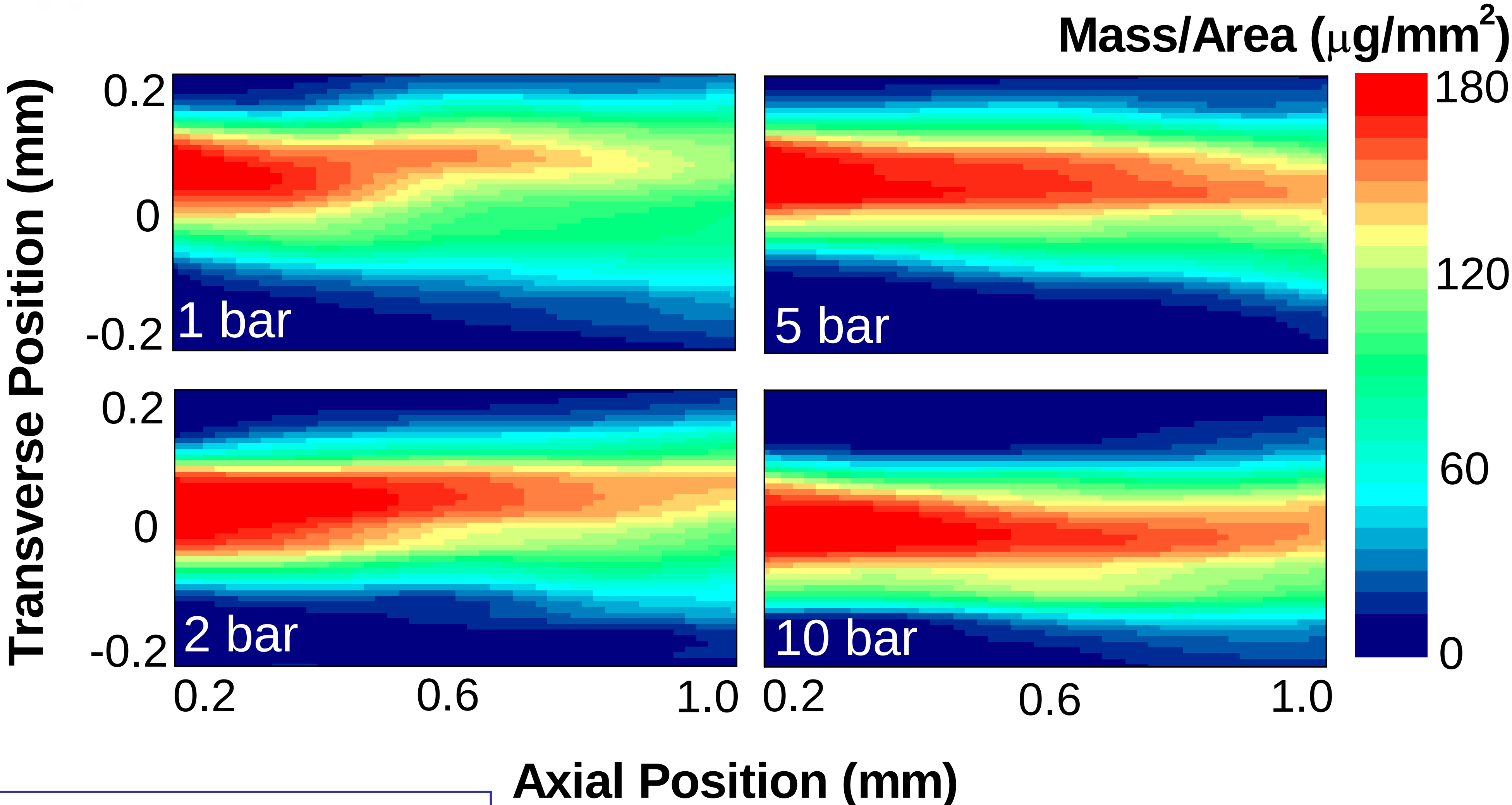
Injection Pressure = 500 bar
135 μs after SOI

Animation of X-Ray Measurements



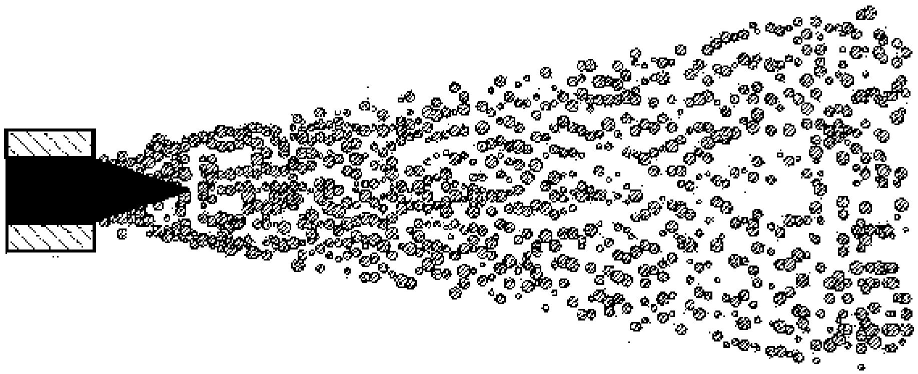
Injection Pressure = 500 bar

Near-Nozzle Mass Distributions

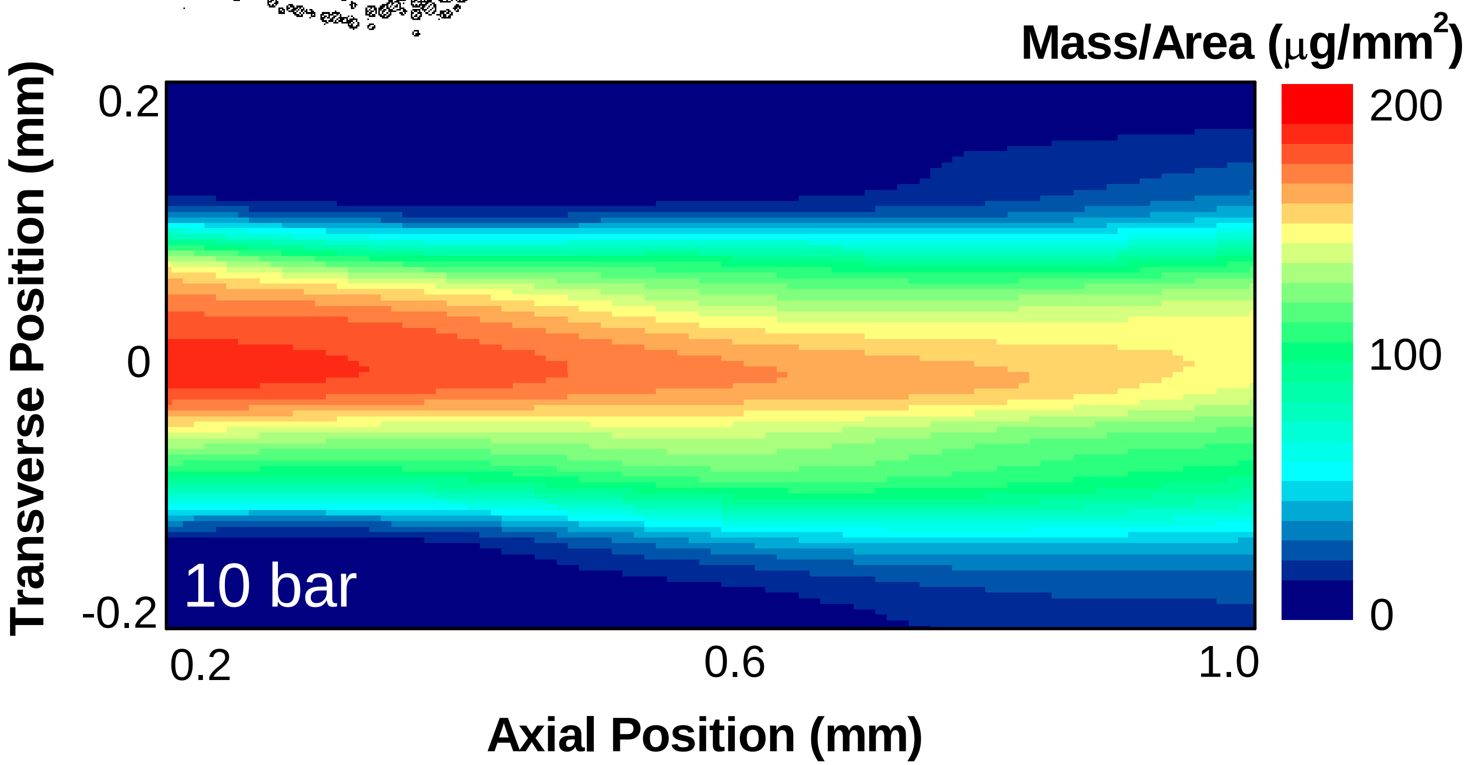


Injection Pressure = 500 bar
280 μs after SOI

Near-Nozzle Spray Structure



Smallwood and Gülder
Atomization and Sprays **10**, 2000.



Future Work

- **Continue Analysis of Current Data**
  - Effects of ambient and injection pressure on atomization
- **Collaborations with modeling groups**
  - Develop new models of spray structure
- **Measurements at Higher Ambient Pressure**
  - Recent measurements at 10 bar.
  - Plans to measure up to 25 bar in 2004
- **Measurements at High Pressure, Temperature**
  - “Diesel-Like” conditions
  - Rapid Compression Machine for x-ray measurements

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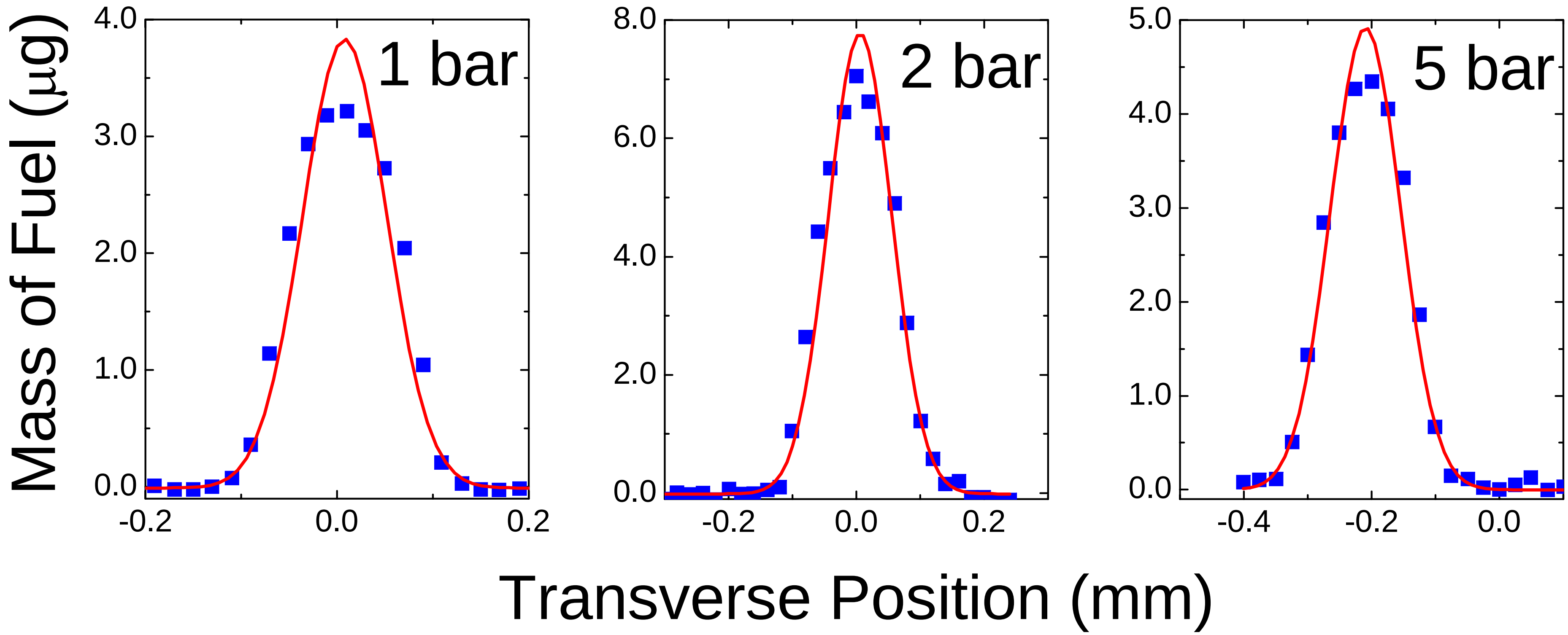
Challenges of X-Ray Measurements

- **Fuels inherently have low absorption**
  - Low energy (long wavelength) x-rays
  - Metal fuel additive
  - Average results from multiple sprays
- **Combustion engines operate at high pressure**
  - Pressurized gases attenuate x-rays
  - X-ray windows must support pressure without attenuation

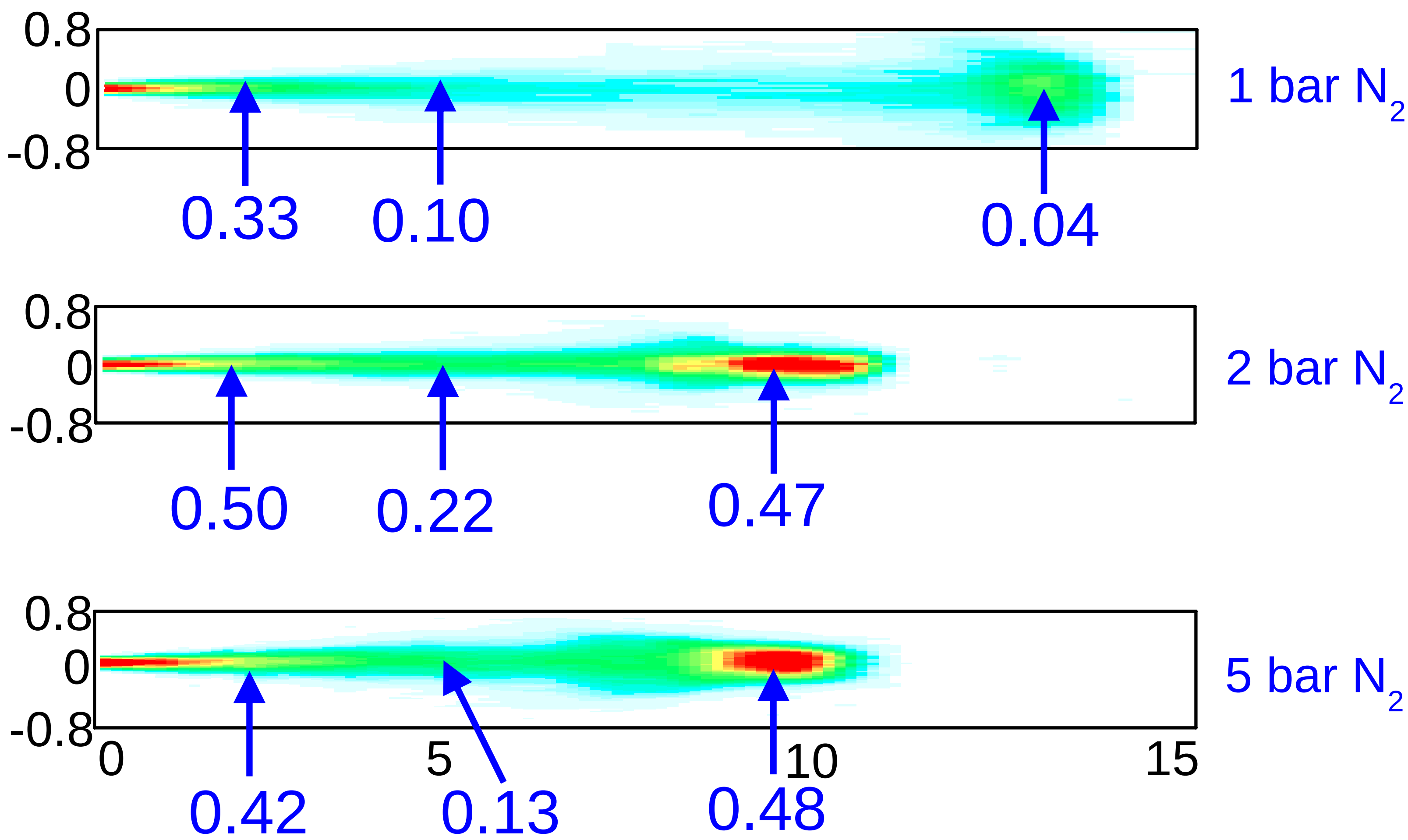
X-ray transmission through 50 mm N_2 at 6 keV		
	1 bar	0.90
	2 bar	0.81
	5 bar	0.60
	10 bar	0.37

Near-Nozzle Mass Distributions



200 μm from nozzle
Injection Pressure = 500 bar
115 μs after SOI

Maximum Volume Fraction



Injection Pressure = 500 bar
115 μs after SOI

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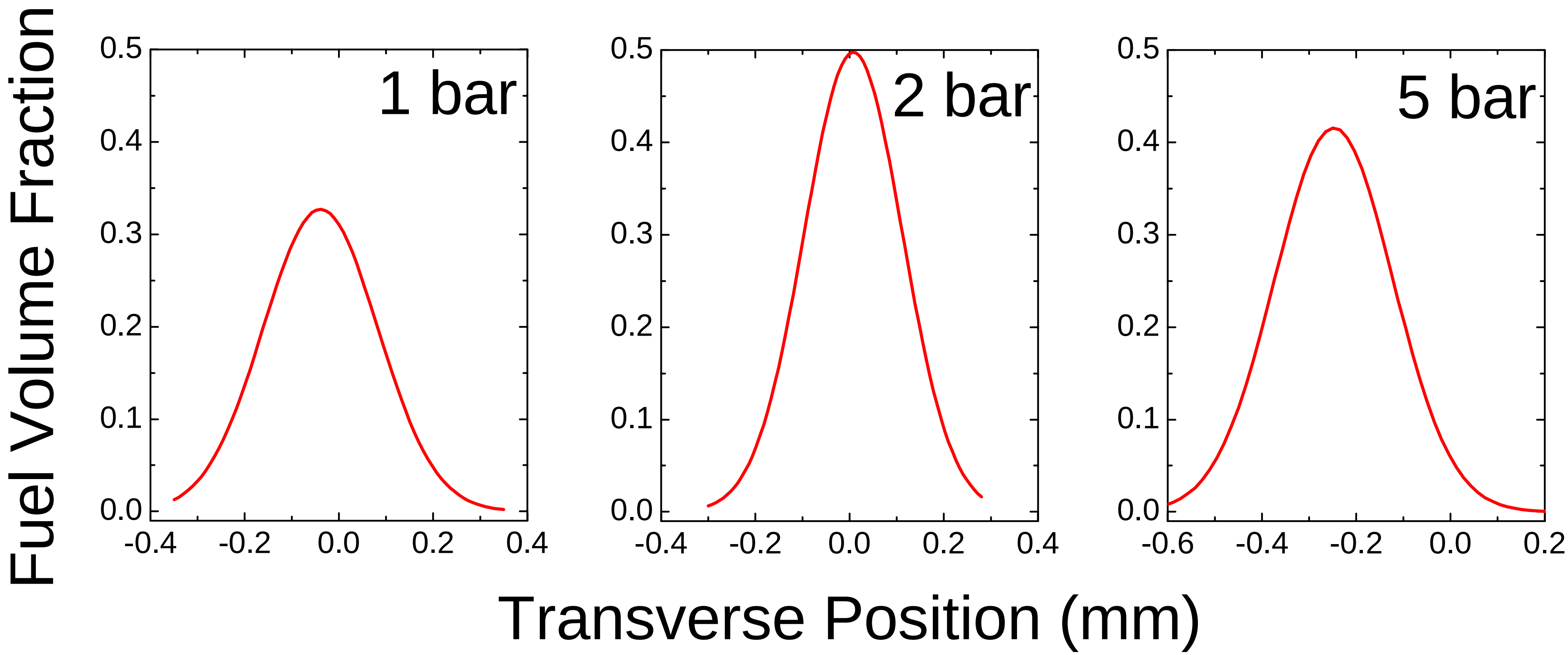
Spray is Atomized 2 mm From Nozzle

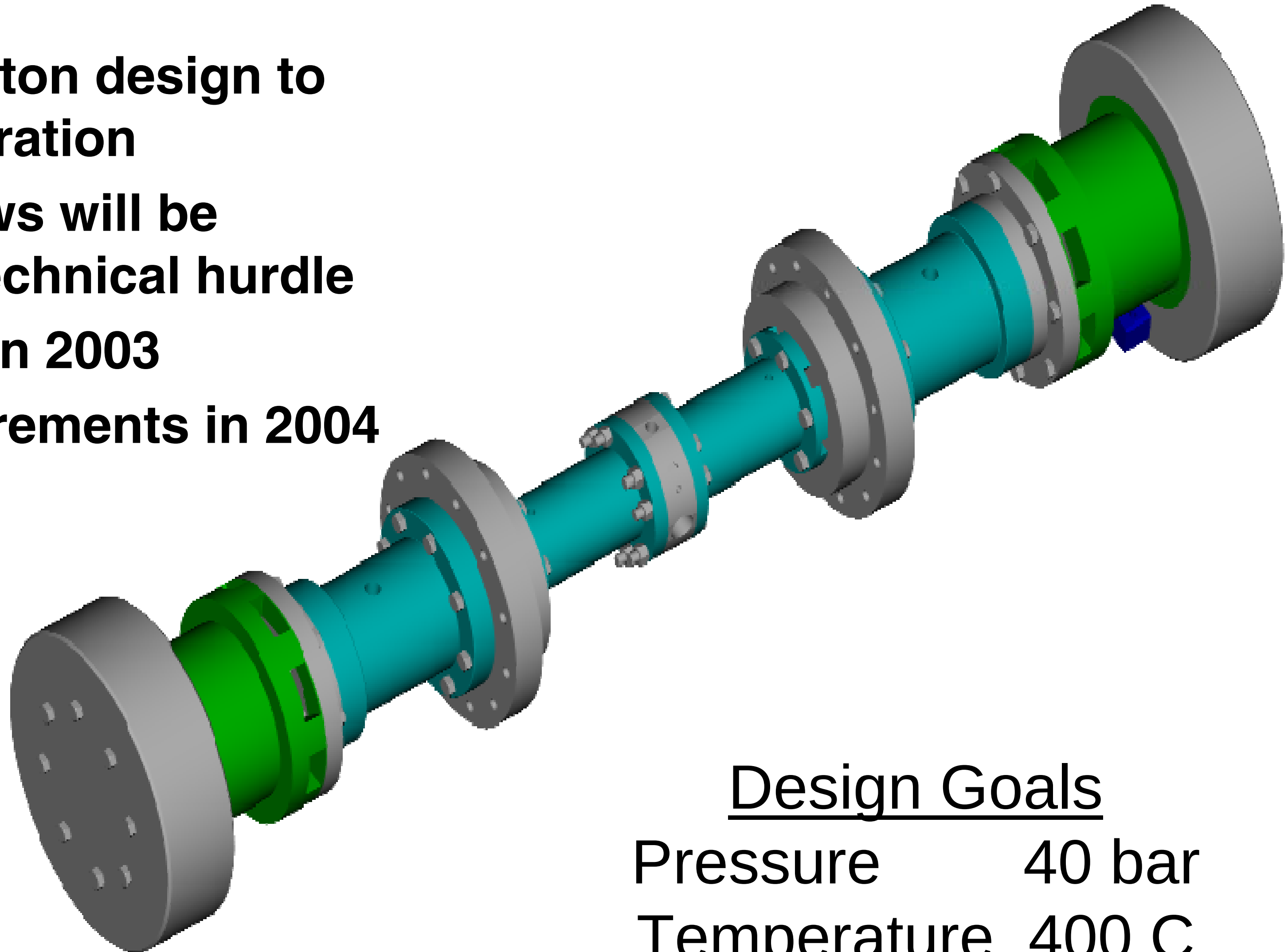


2 mm from nozzle
Injection Pressure = 500 bar
115 μs after SOI

Center for Transportation Research

Rapid Compression Machine for X-Ray Studies

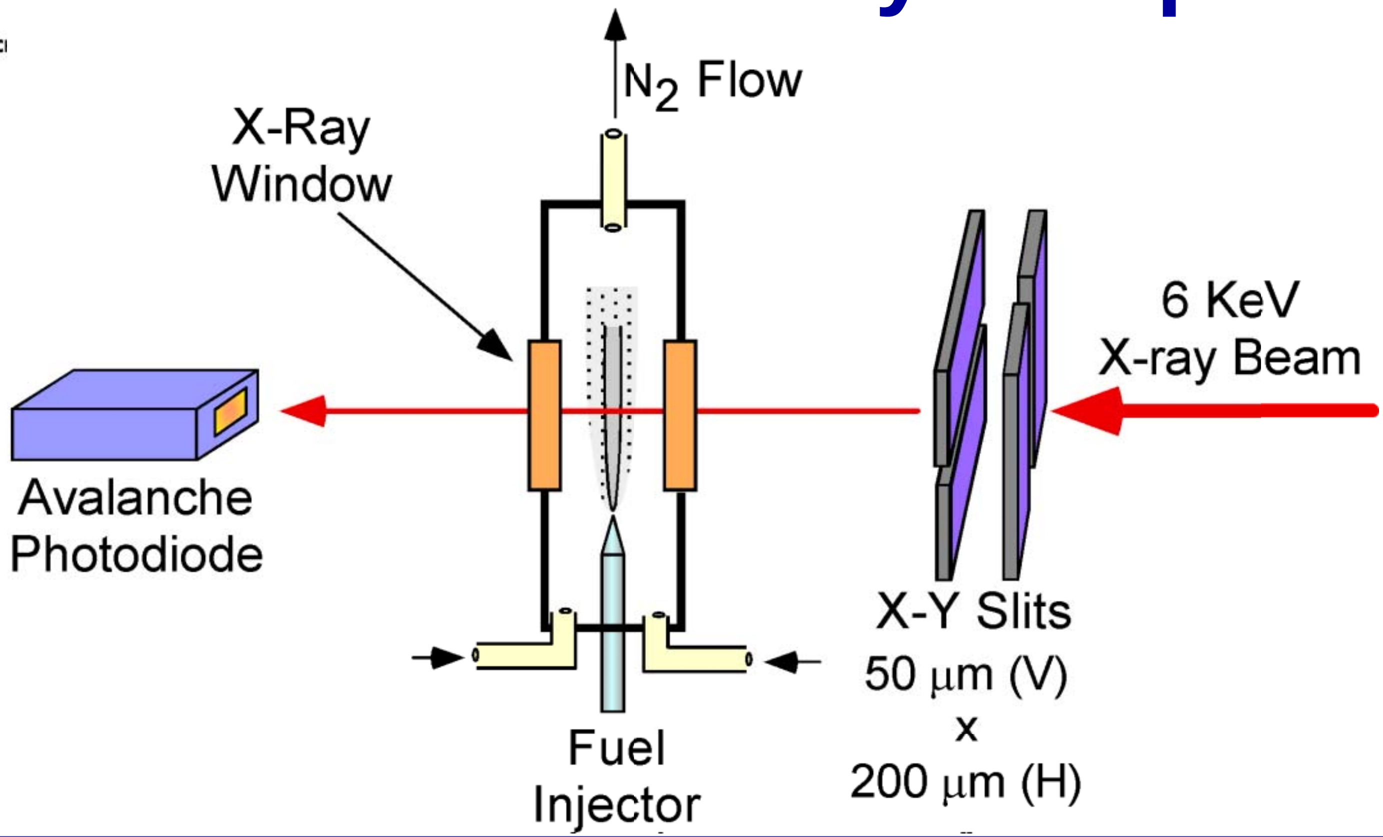
- **Opposed Piston design to minimize vibration**
- **X-ray windows will be significant technical hurdle**
- **Operational in 2003**
- **X-ray Measurements in 2004**



Design Goals

Pressure	40 bar
Temperature	400 C

Schematic of X-Ray Setup



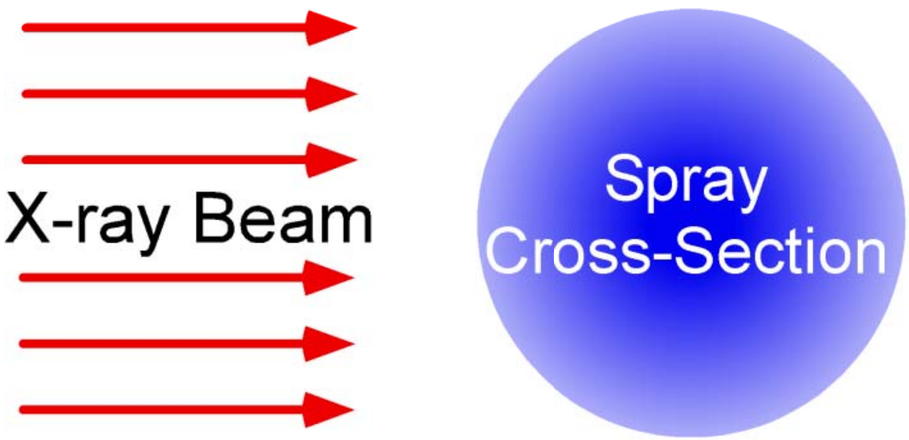
- **Injection chamber moves to probe different areas of spray**
  - Image is measured one pixel at a time
  - Each pixel obtained by averaging results from many sprays
  - Measure thousands of individual pixels
- **Fast detector, continuous measure of x-ray intensity**
  - Time-resolved measurement of fuel mass

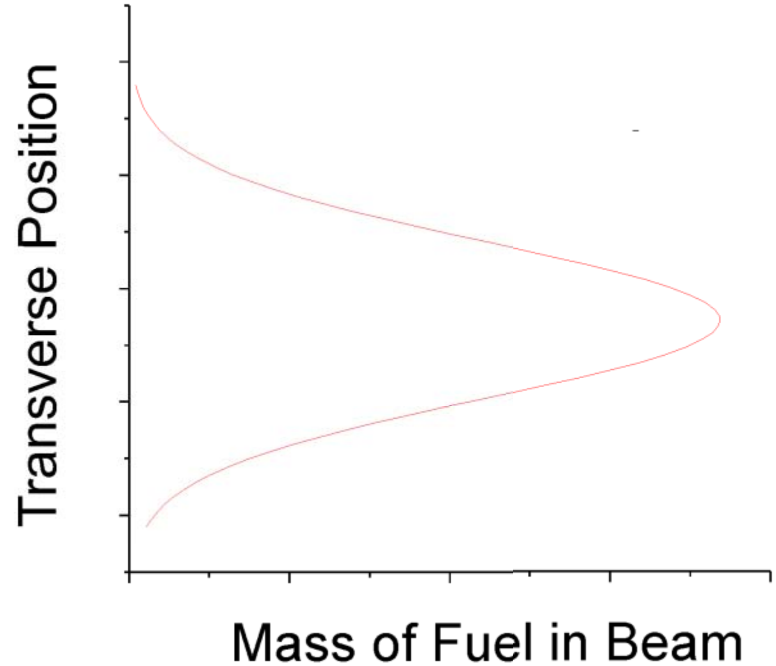
Advantages of X-Rays

- **Techniques utilizing visible light are limited near nozzle**
  - ⇨ Scattering from droplets is likely
  - ⇨ Multiple scattering prevents quantitative analysis
- **X-rays have low scattering probability**
  - ⇨ Multiple scattering negligible
  - ⇨ Absorption is most likely interaction
- **Quantitative measurements**
  - ⇨ Direct measurement of the mass of fuel
  - ⇨ Intense beam, fast detector permit time-resolved measurement

Modeling the Cross Section of the Spray

2-D Mass Distribution ⟷ 1-D Mass Projection



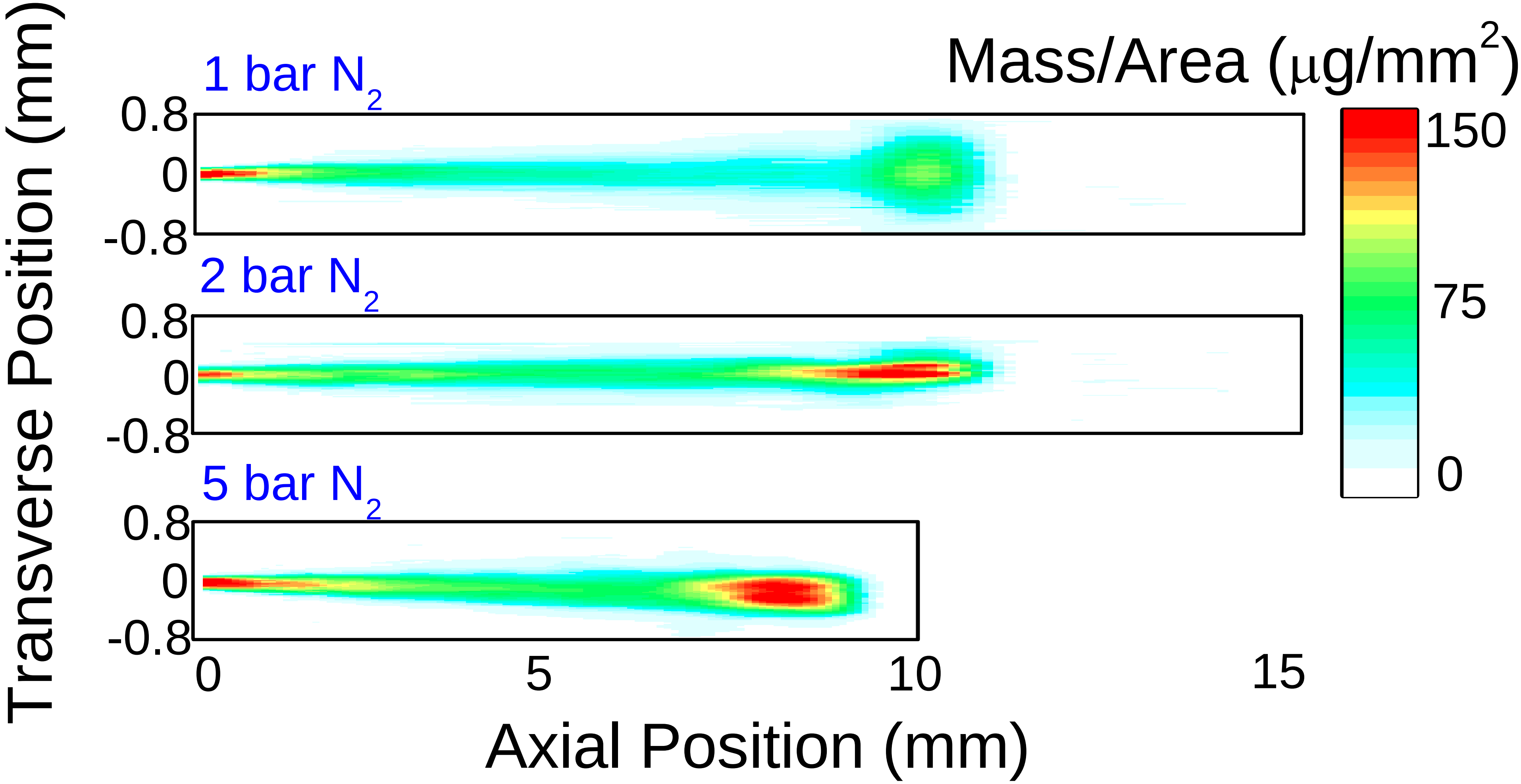


$$c(r,t) = \frac{M(r,t)}{A\sqrt{2\pi a_t}}$$

$$M(y,t) = M_0(t)\exp\left(-y^2/2a_t^2\right)$$

Volume Fraction = density / bulk fuel density

Comparison of Different Ambient Pressures



Injection Pressure = 1000 bar
45 μs after SOI