X-ray Tomography and 3D CFD Simulation of Fuel Mass Distribution in a GDI Spray

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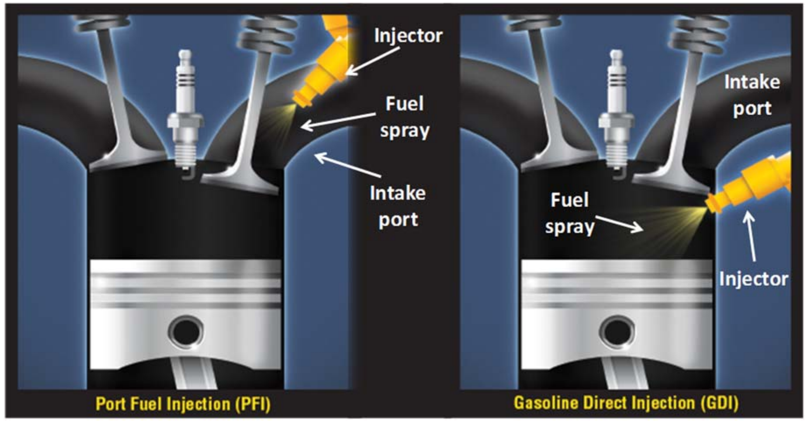
INTRODUCTION

New Spark Ignition engines promise higher combustion efficiency and exhaust emission reduction

How to reduce fuel consumption and CO_2 emission?

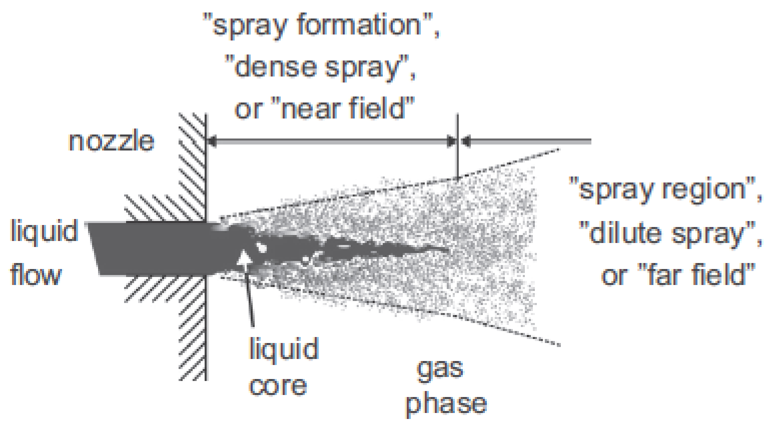
Through stratified lean combustion (up to 25% less consumption)



Controlling the charge formation by mans of injection

INTRODUCTION

How a high pressure spray works?



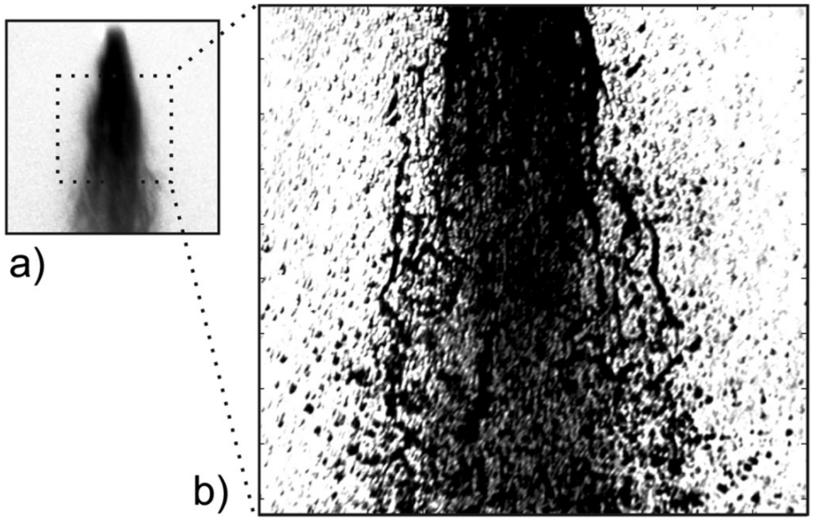
Sketch of the spray regions *

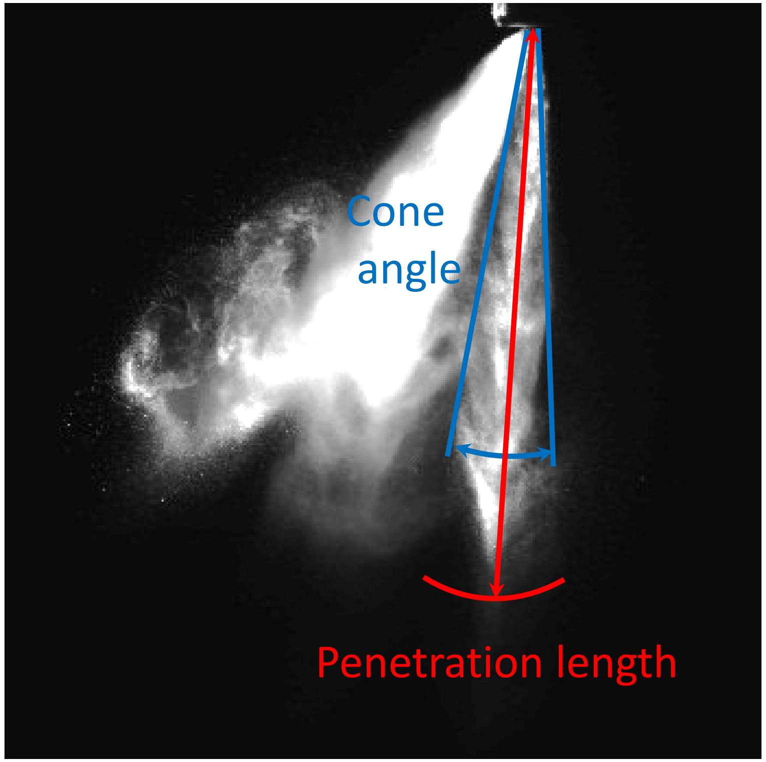
M. Linne, Imaging in the optically dense regions of a spray: a review of developing techniques, Progress in Energy and Combustion Science, 2013, 39: 403-440.

Several optical techniques have been applied for characterizing the fuel spray development and air-fuel interaction.

INTRODUCTION

main jet geometric parameters: tip penetration, cone angle

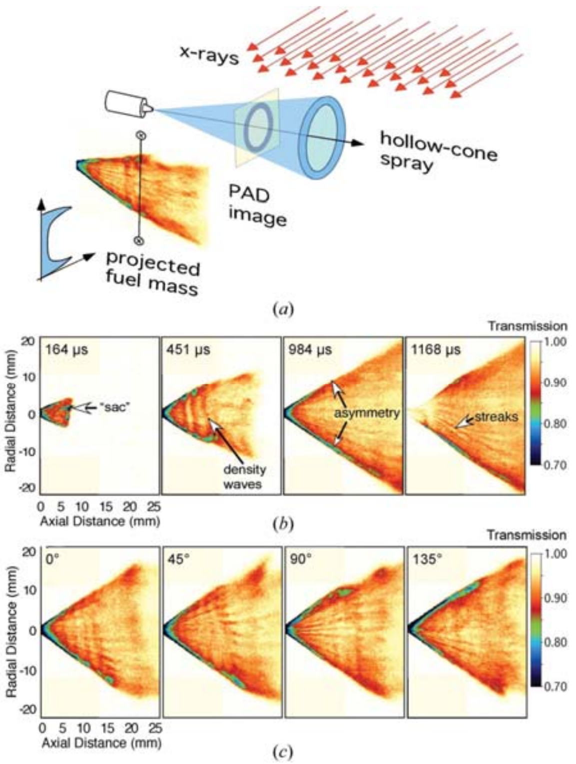




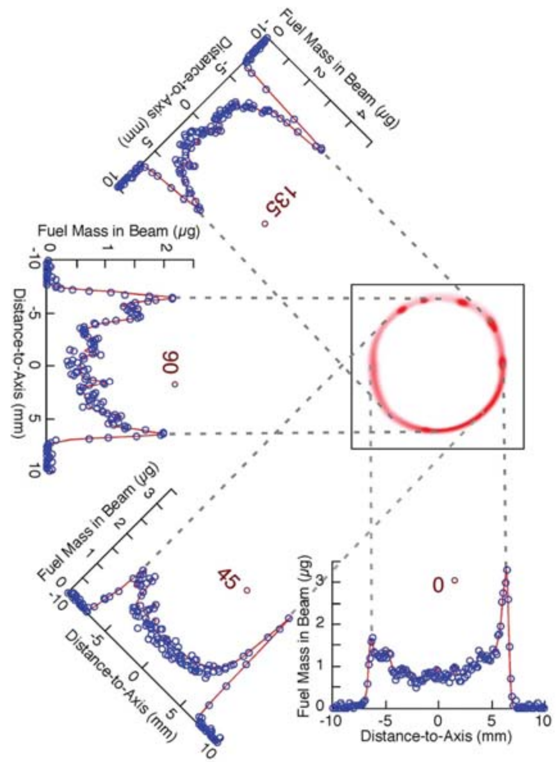
measurements about the internal structure of the spray results quite complicated, especially in the dense region close the nozzle

INTRODUCTION

Techniques based on X-radiation have been applied to estimate the fuel distribution into high-density regions of fuel sprays.



X-radiography of hollow-cone direct injection fuel spray



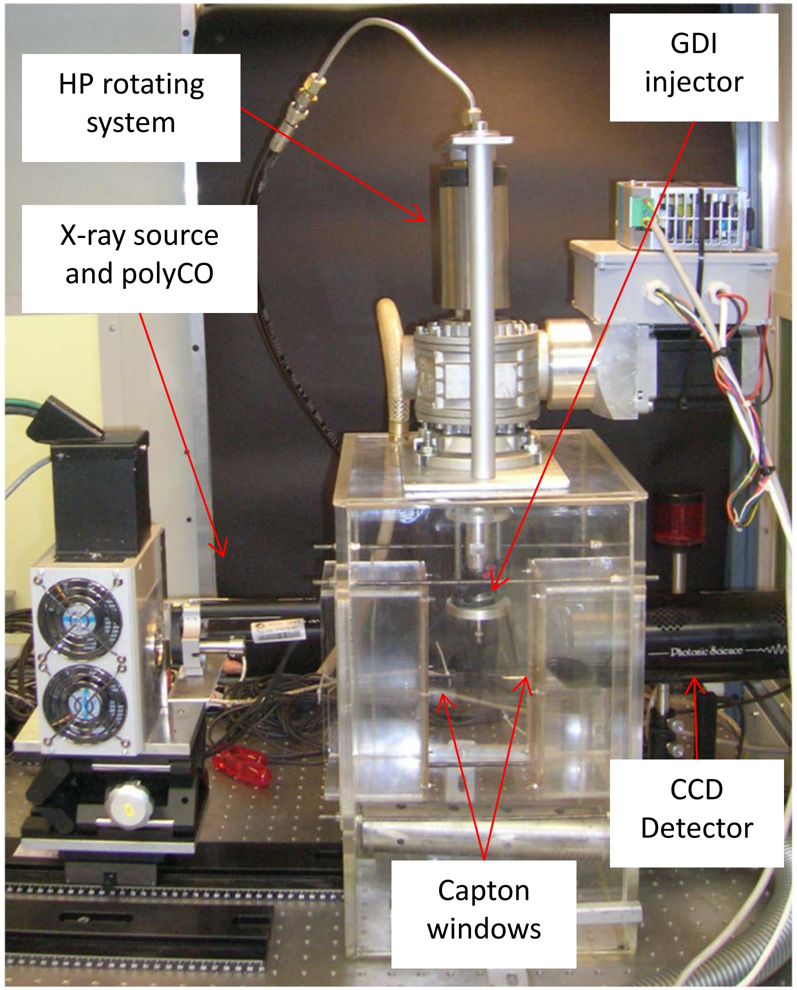
Computed fuel mass distribution by fitting the experimental data with mass reconstruction models

Wang, J., X-ray vision of fuel sprays, Journal of synchrotron radiation, 12: 197-207 (2005).

EXPERIMENTAL SET-UP 1/2

A Cu Kα X-ray source at ~ 8.0 keV coupled with a polycapillary halflens focuses the radiation on a selected spray region .
A CCD detector for X-radiation collects the emerging signal

A 6-hole GDI injector is coupled to the high pressure pump by a specially designed rotating device able to work up to 50 MPa with an angular step $\Delta\theta = 1°$



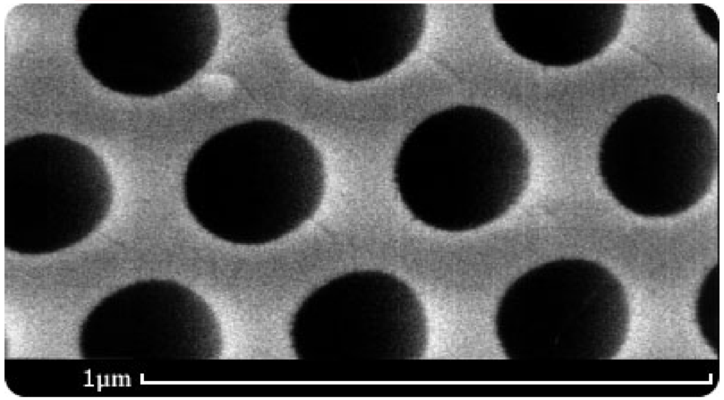
EXPERIMENTAL SET-UP 2/2

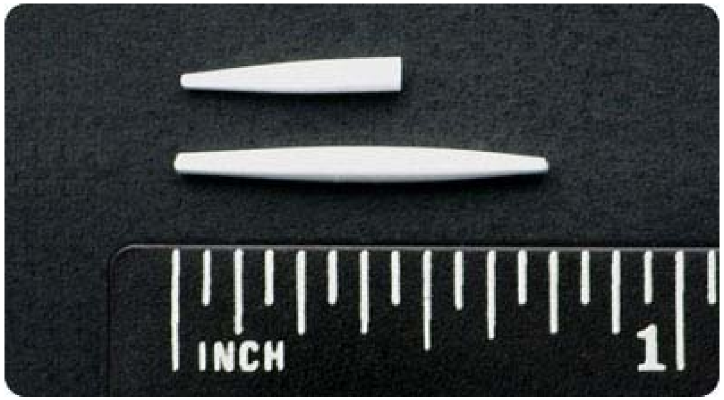
Polycapillary Lens

POLYCAPILLARY SEMI-LENS	
beam diameter	~4 mm
residual divergence	1.4 mrad
channel mean diameter	~ 5 µm

The polycapillary lens total efficiency is about 60%, at selected energies.

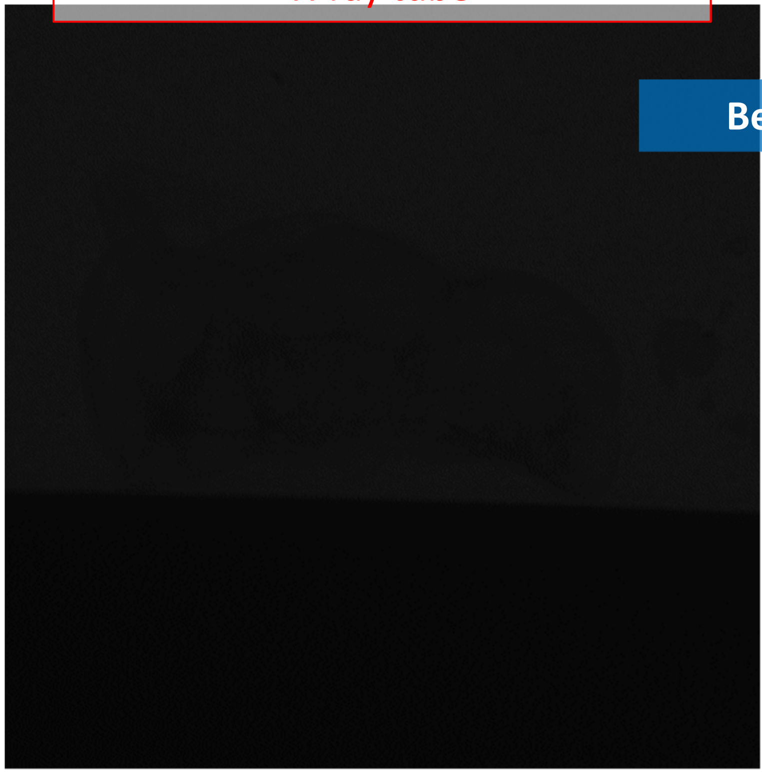
Polycapillary cross-section

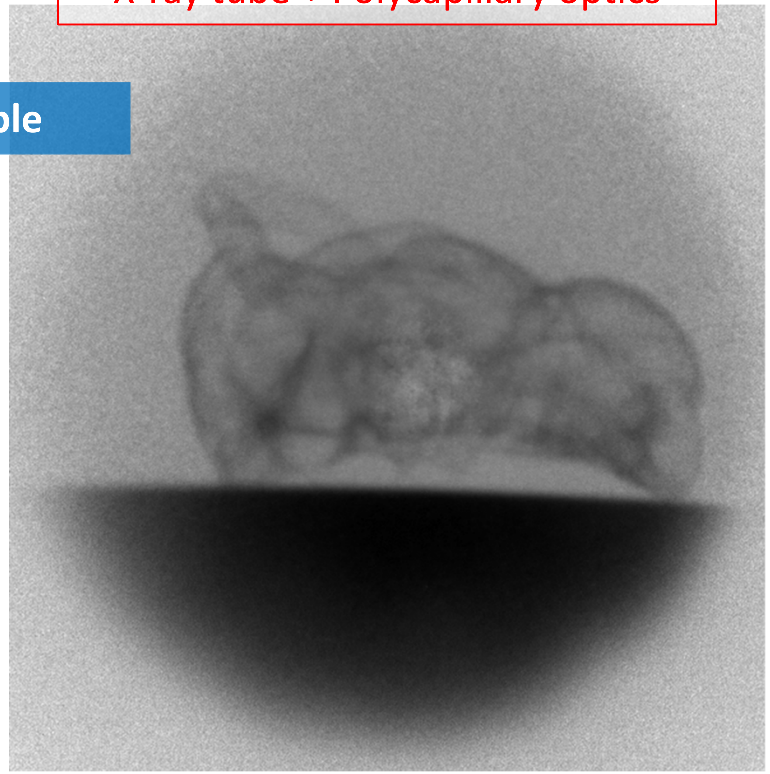




EXPERIMENTAL SET-UP 2/2

Polycapillary Lens

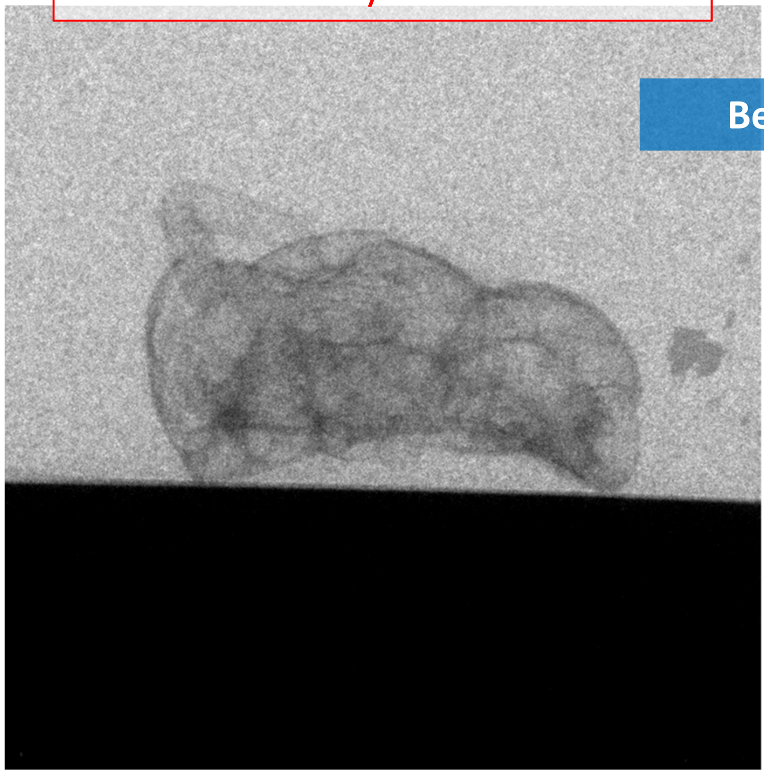




EXPERIMENTAL SET-UP 2/2

Polycapillary Lens

X-ray tube



Bee Head Sample

X-ray tube + Polycapillary optics

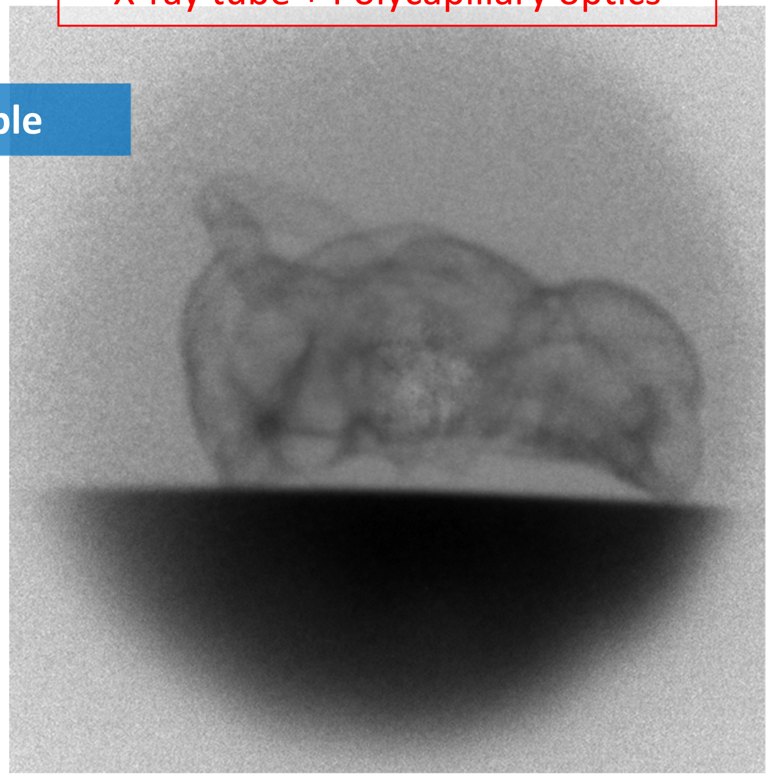
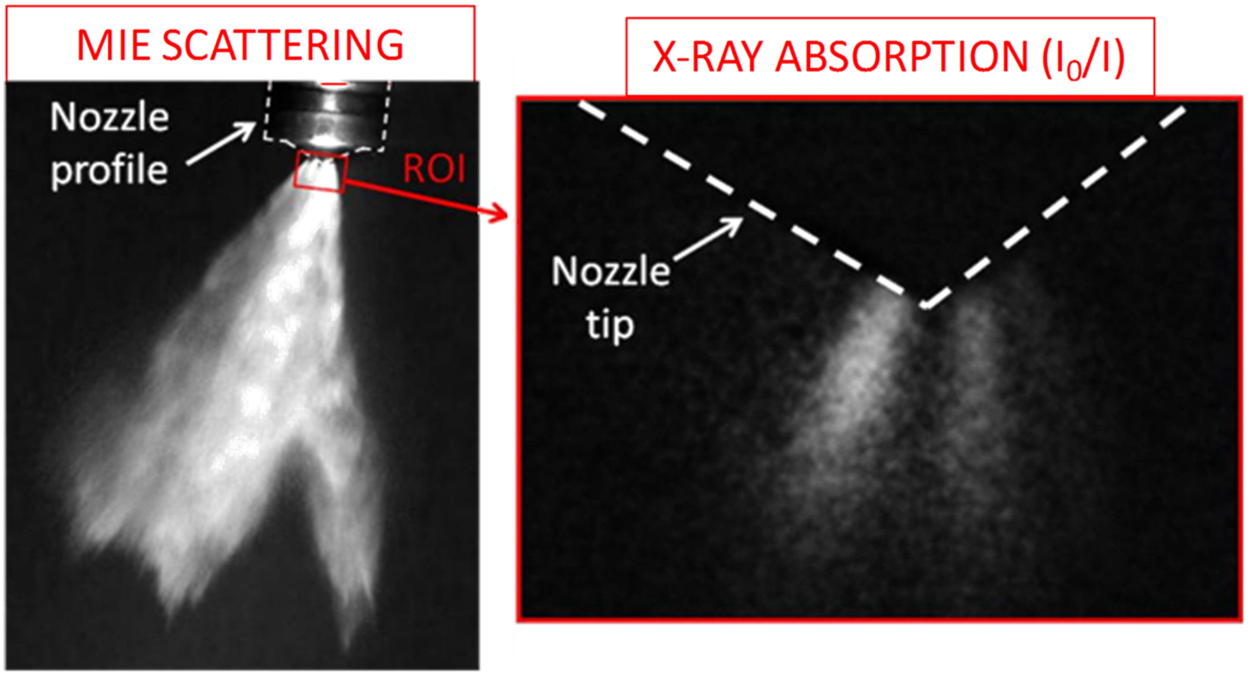
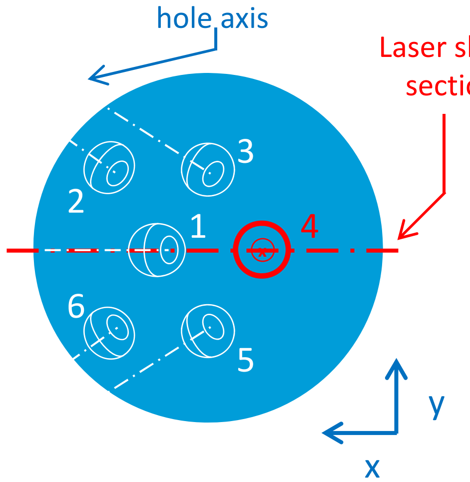


IMAGE ACQUISITION 1/2

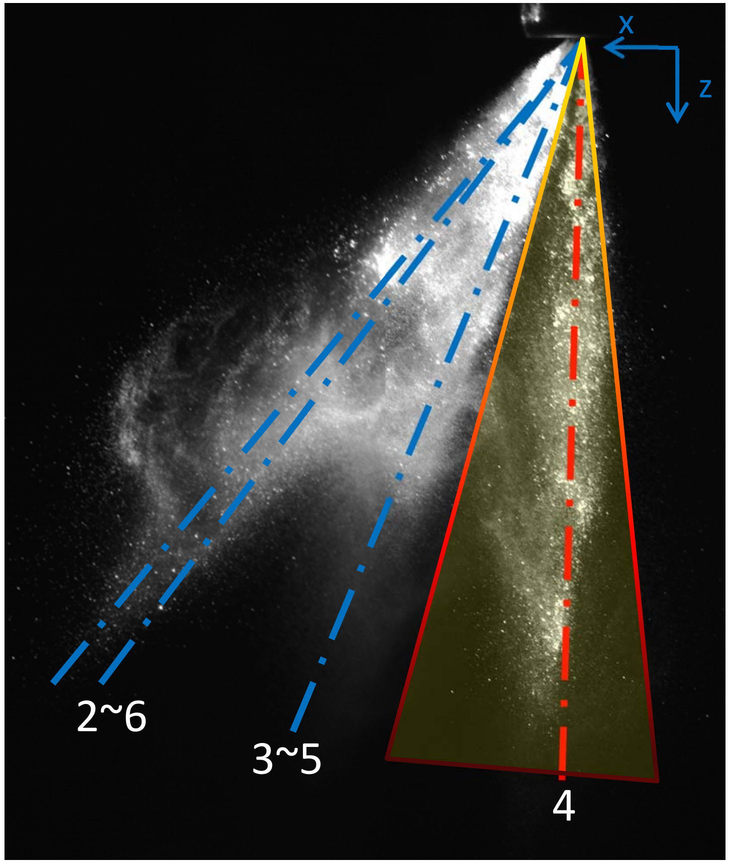


Field of View

IMAGE ACQUISITION 2/2

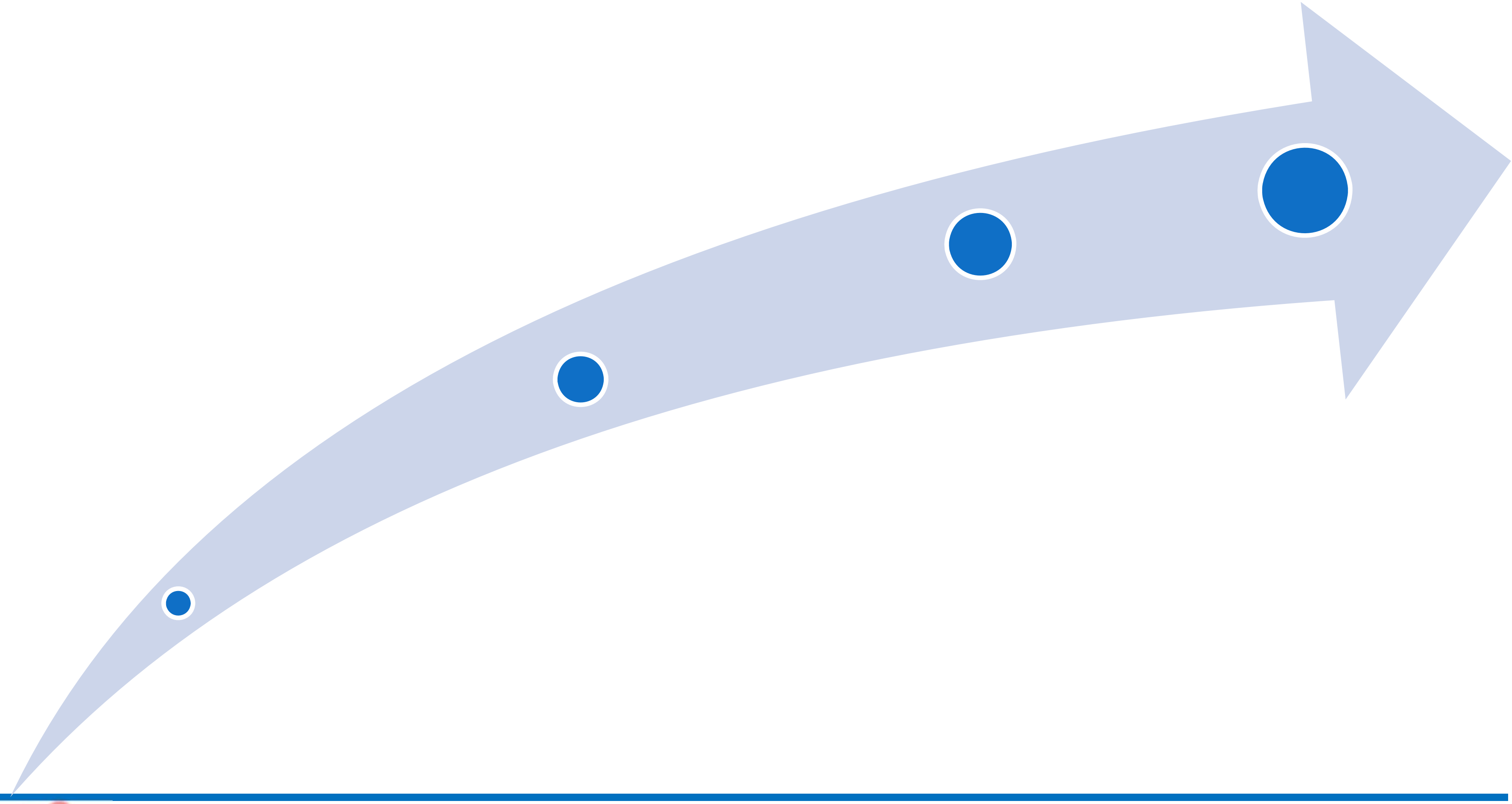


Hole	xz [°]	yz [°]
1	54.8	0.0
2	49.9	-27.7
3	21.8	-11.6
4	3.1	0.0
5	21.8	11.6
6	49.9	27.7



The jets don't have any symmetry. The jet 4 has just a little inclination respect to nozzle axis and it is confined always in the beam spot.

TOMOGRAPHY – BASE CONCEPT



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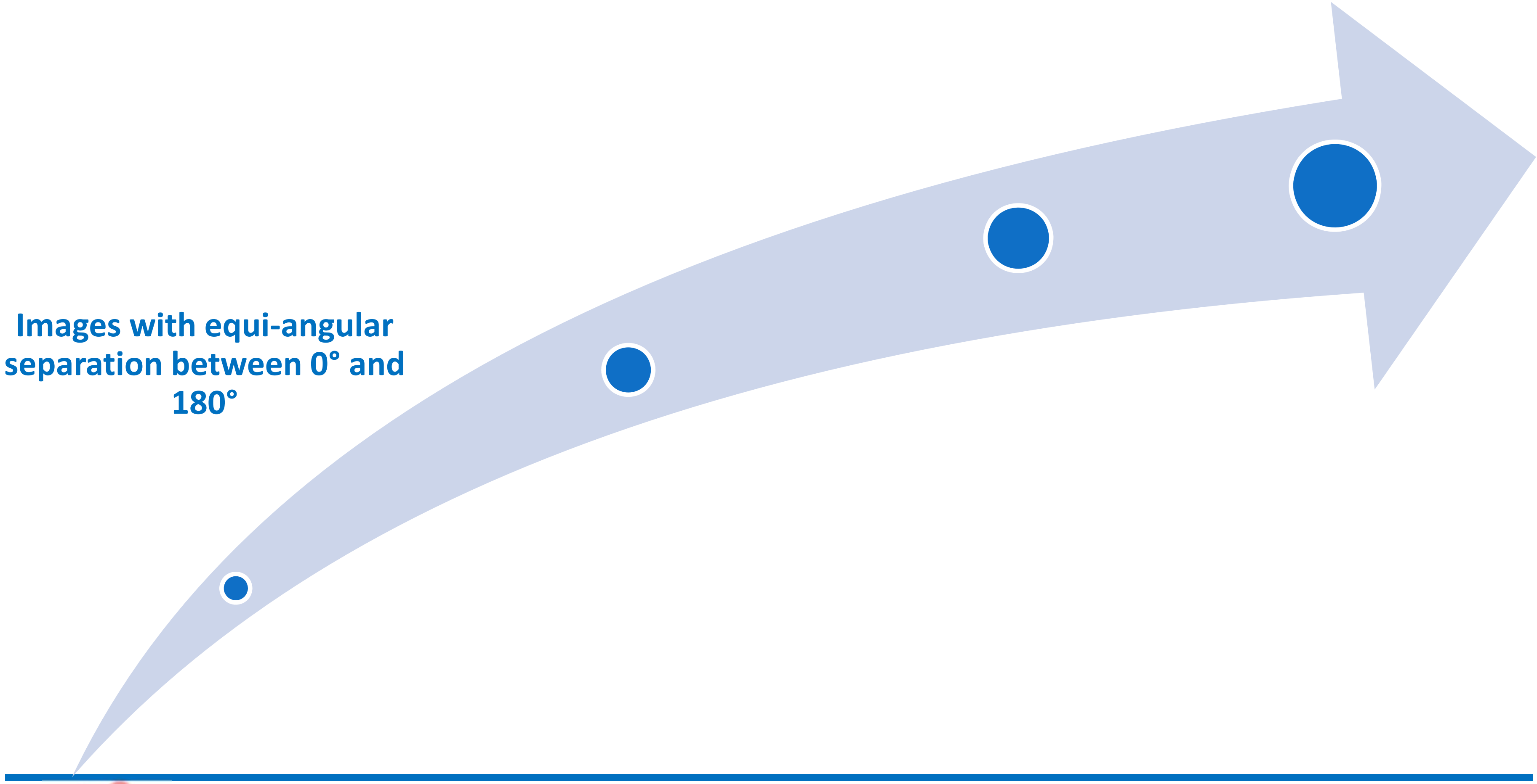

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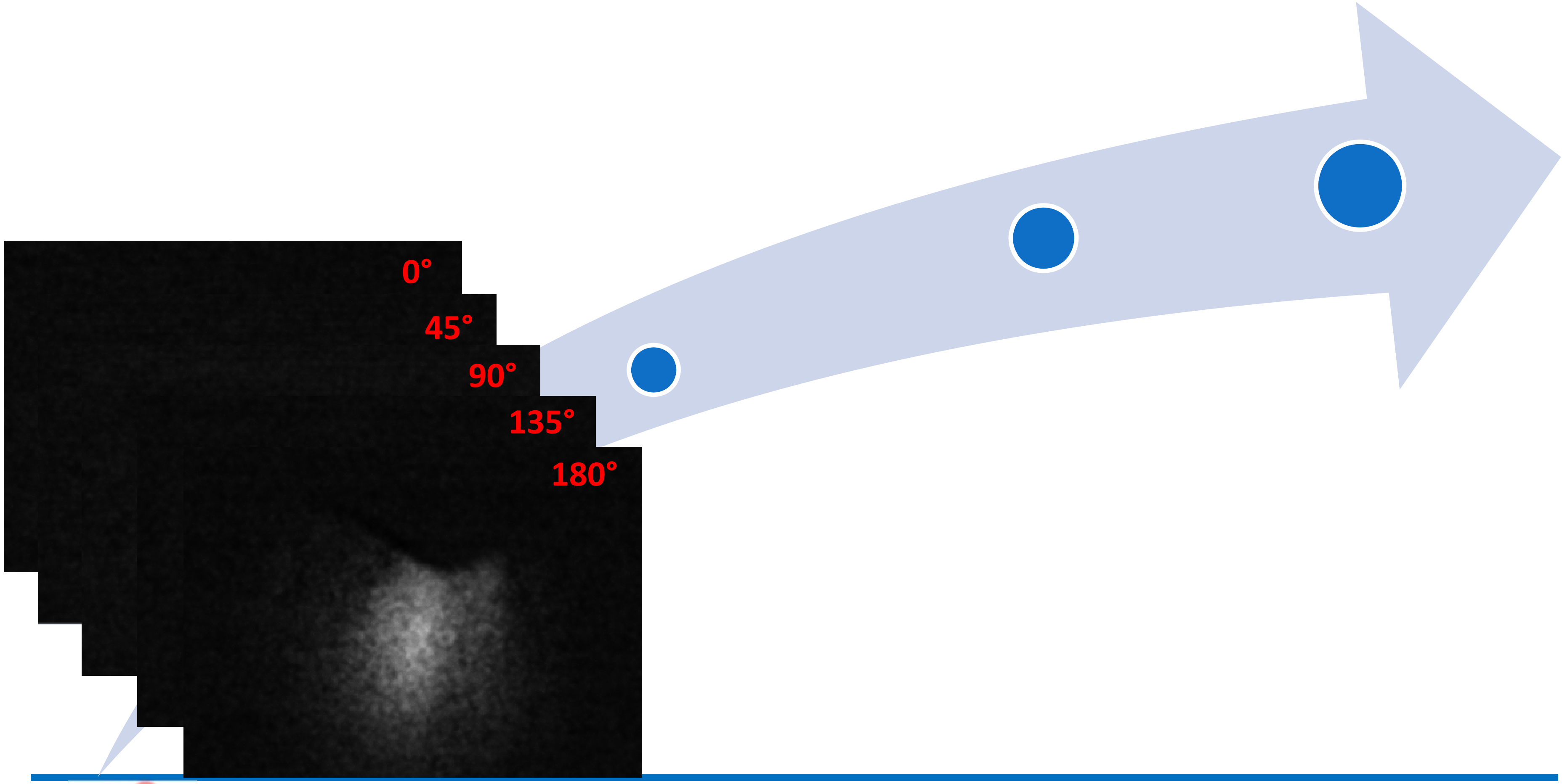
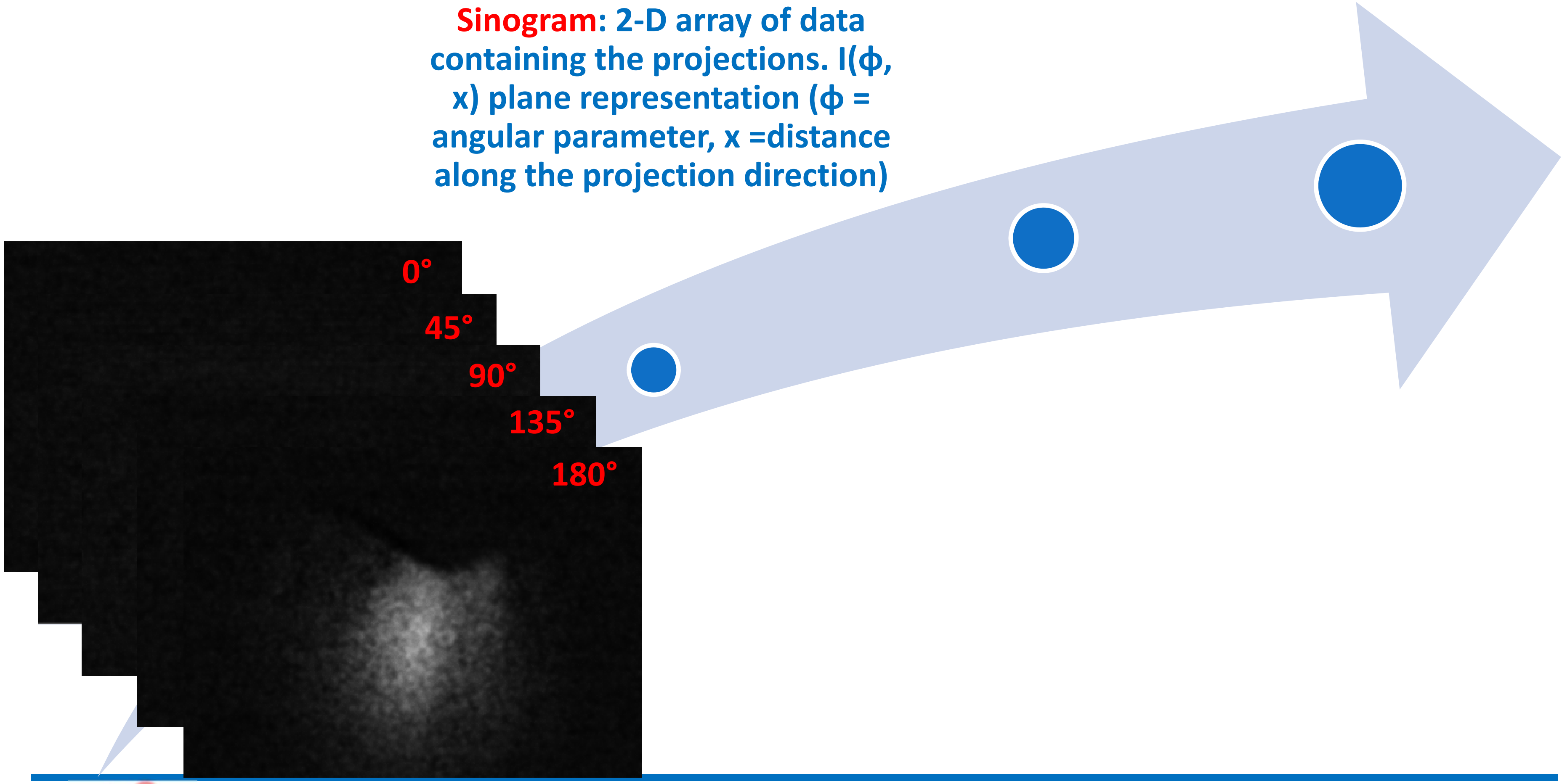


TOMOGRAPHY – BASE CONCEPT

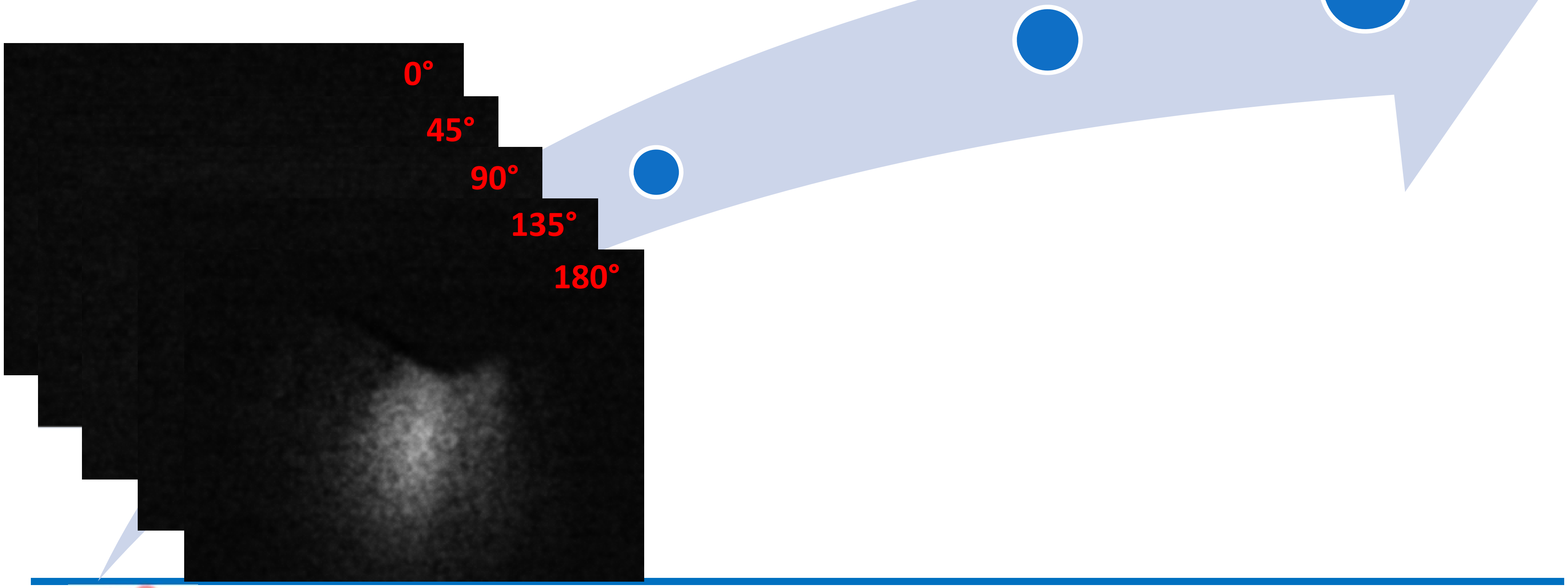
Sinogram: 2-D array of data containing the projections. I(ϕ, x) plane representation (ϕ = angular parameter, x =distance along the projection direction)



TOMOGRAPHY – BASE CONCEPT

Sinogram: 2-D array of data containing the projections. I(ϕ, x) plane representation (ϕ = angular parameter, x =distance along the projection direction)

Slices: planar reconstruction, I(x,y)



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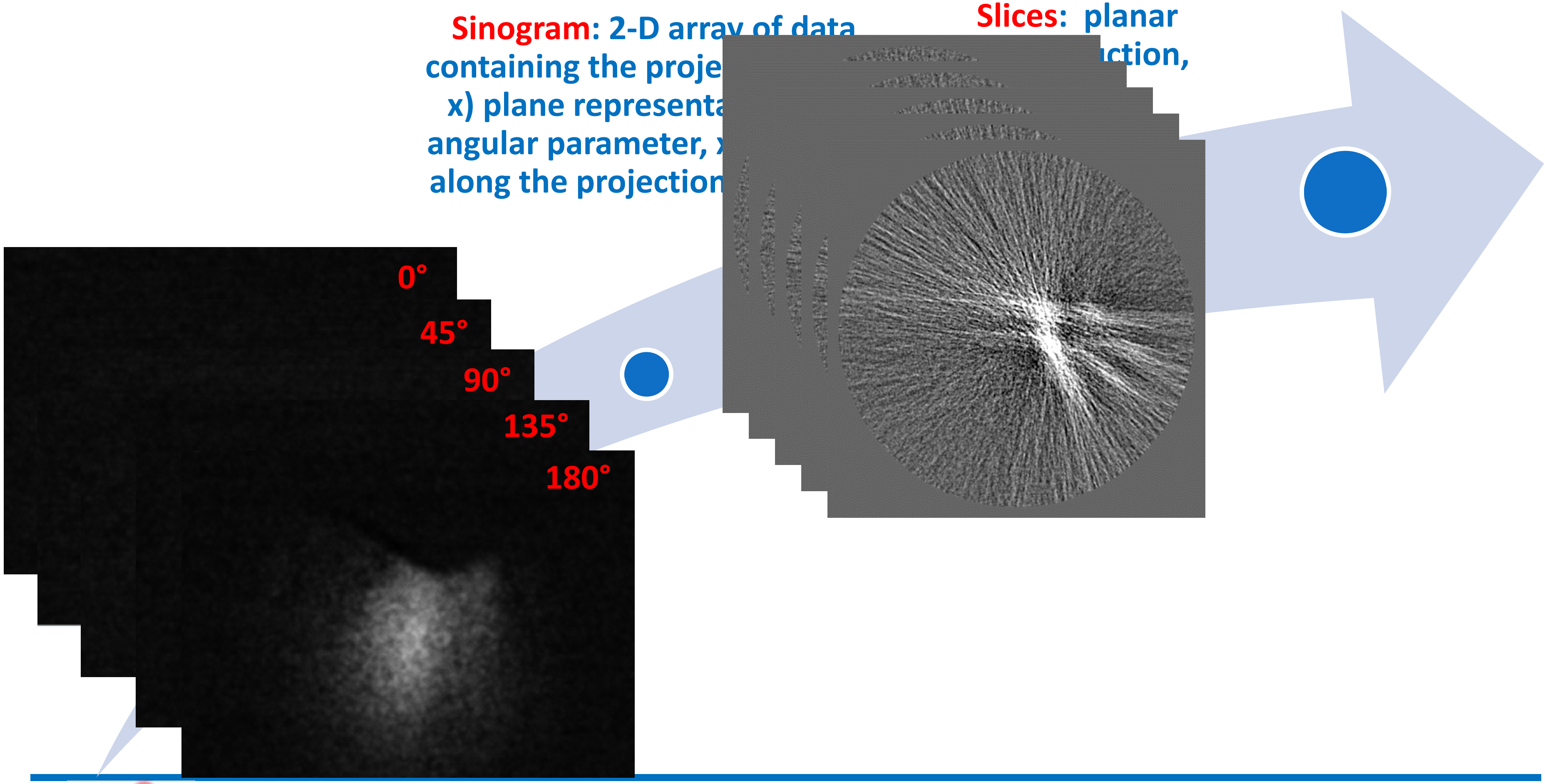

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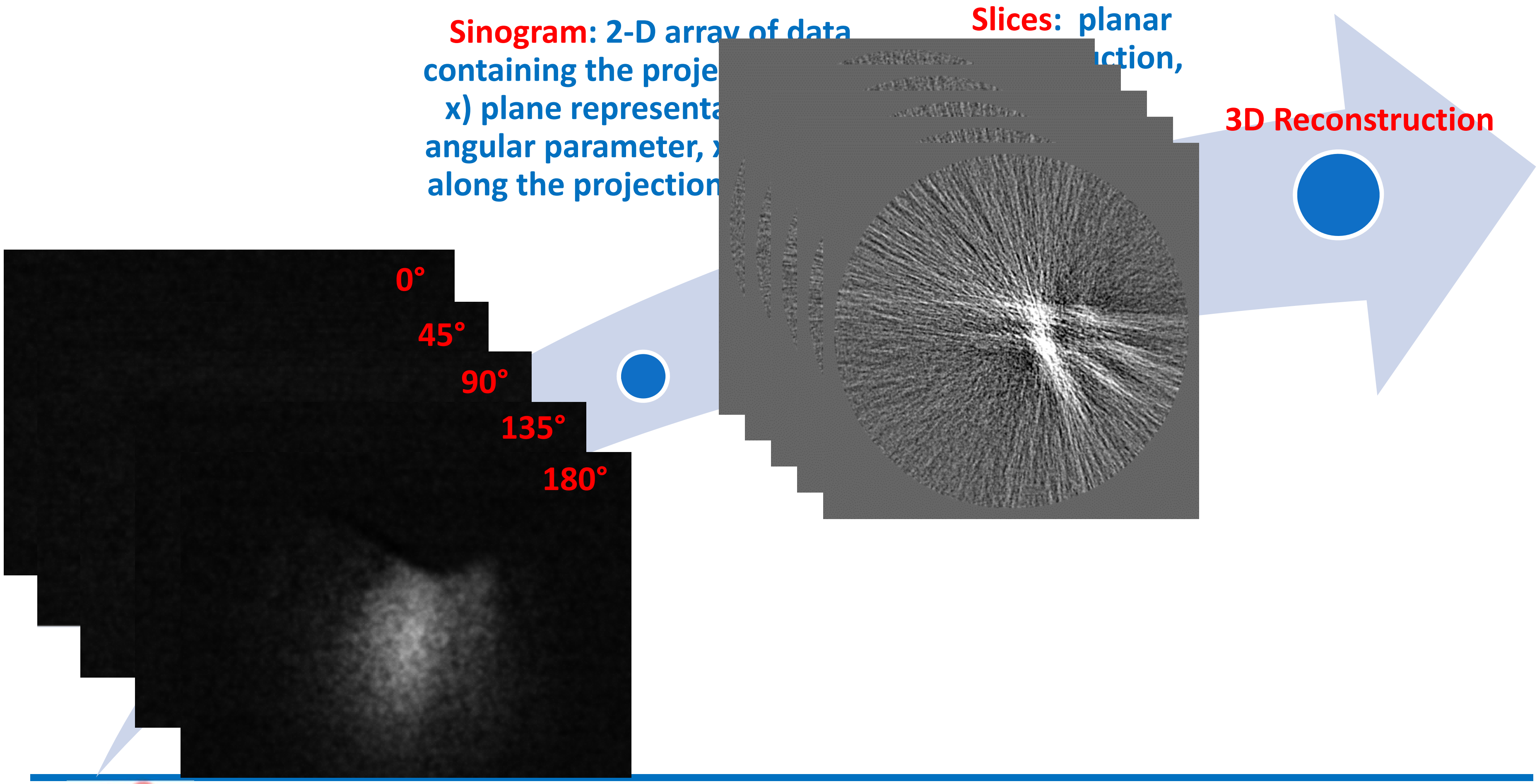

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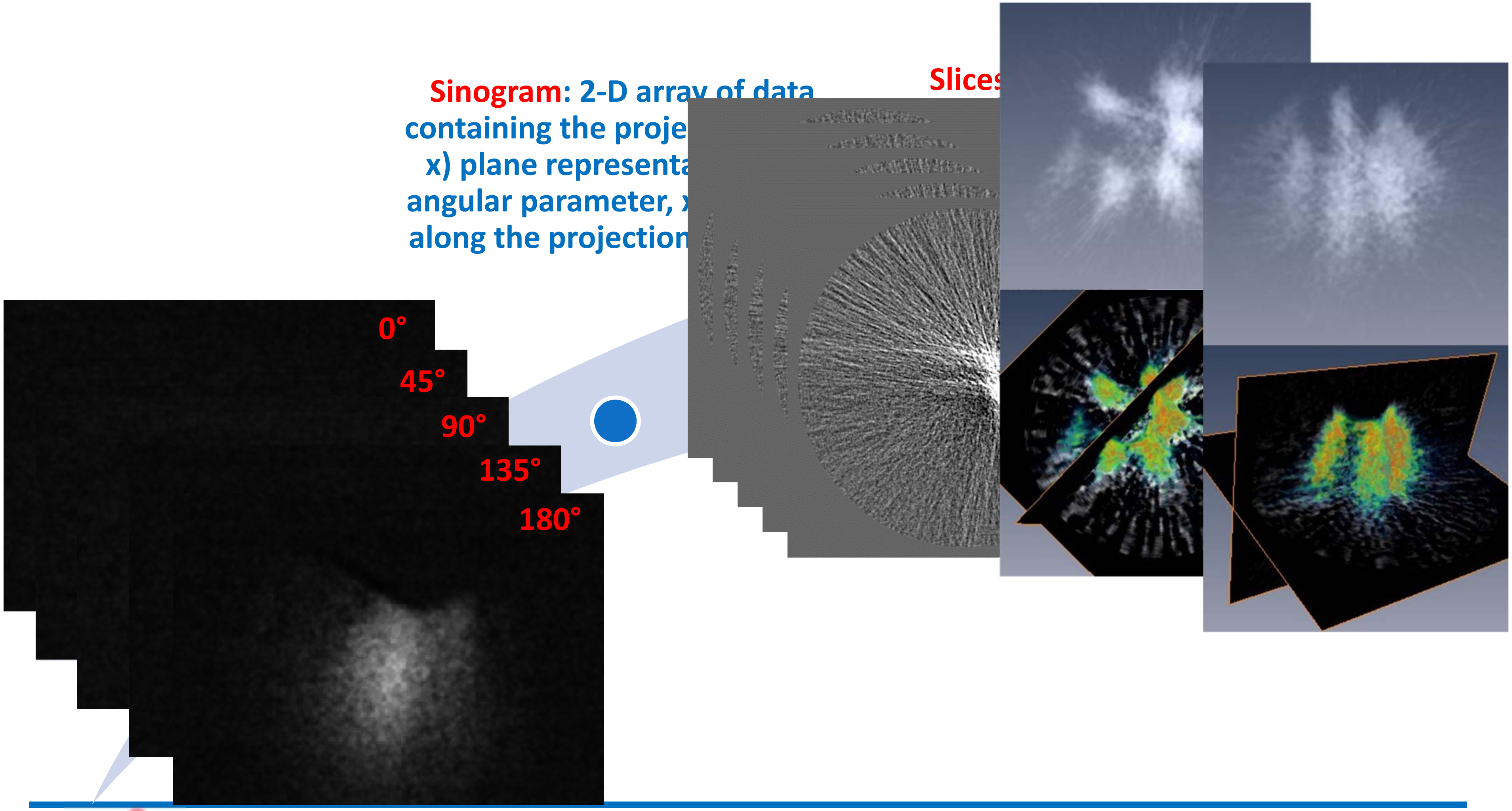


3D RECONSTRUCTION

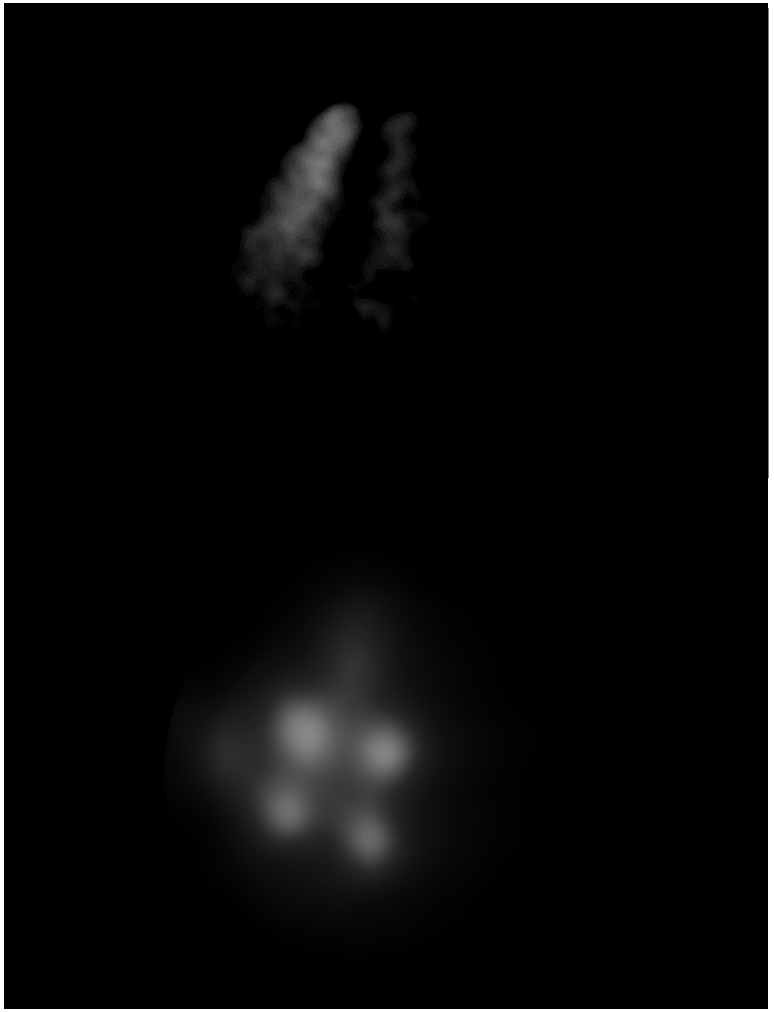
The absorption is linked to the sample local density ρ by the well known Lambert Beer law :

$$I/I_0 = e^{-\mu_l \rho l}$$

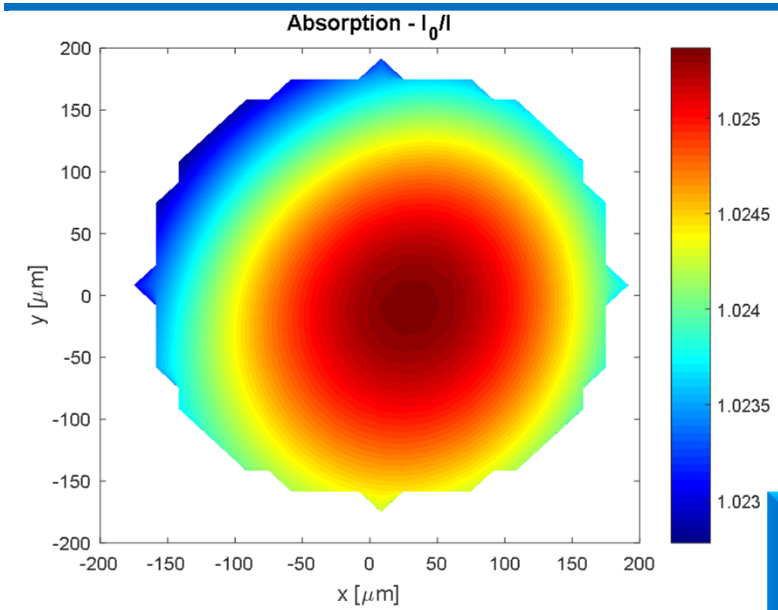
where μ_l is the linear absorption coefficient and l is the crossed spray length. The previous equation can also be written as:

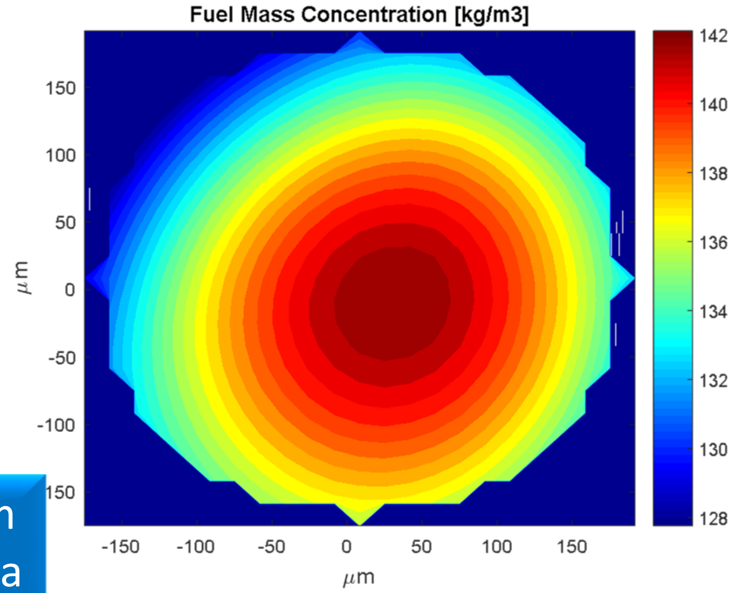
$$I/I_0 = e^{-\mu_M M}$$

where μ_M is the mass absorption coefficient. Considering the single cross section, M represents the fuel mass m related to the spray cross section area A.



CROSS SECTION MEASUREMENTS





$\Delta h = 500\ \mu m$
$P_{inj} = 10$ MPa
$T_{inj} = 4$ ms
$T_{acq} = 3$ms

Absorption
I_0/I

Fuel Mass Concentration
m_{fuel}/V_{voxel}

3D CFD CHARACTERIZATION OF THE SPRAY EVOLUTION

3D CFD spray description through *Discrete Droplet Method (DDM):* solving the trajectory, momentum, heat and mass transfer ordinary differential equations of single droplets, each being a member of a group of identical non-interacting droplets termed a "*parcel*", tracked through a Lagrangian approach.

AVL FIRE®

Numerical sub-models for spray description:

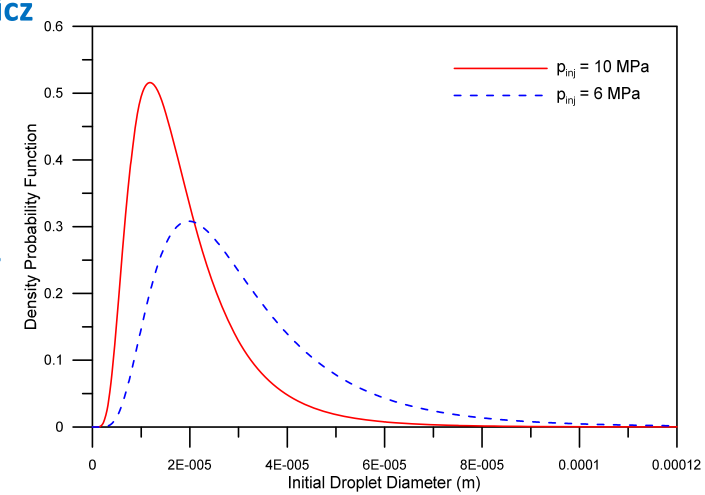
- the droplet-gas momentum exchange: **Schiller - Neumann**
- turbulent dispersion: **O' Rourke**
- evaporation of droplets: **Dukowicz**
- break-up: **Huh Gosman**
- droplet collision: **Nordin**

Initial size of droplets at the nozzle exit section is considered variable according to a probabilistic **log-normal distribution***:

Expected value $D_{th} = \frac{2\pi\tau_f\lambda}{\rho_g u_{rel}^2}$

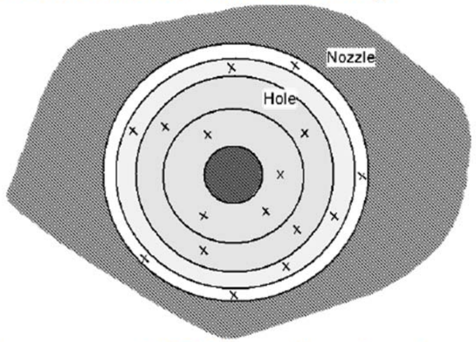
+

Variance σ



The number of parcels introduced per nozzle hole per time step is set as the product of three variables:

- **NSIZES:** Number of different particle sizes introduced per time step and ring;
- **NINTRO:** number of radial parcel release locations on each hole;
- **NCIRCD:** number of circular parcel release locations on each ring.

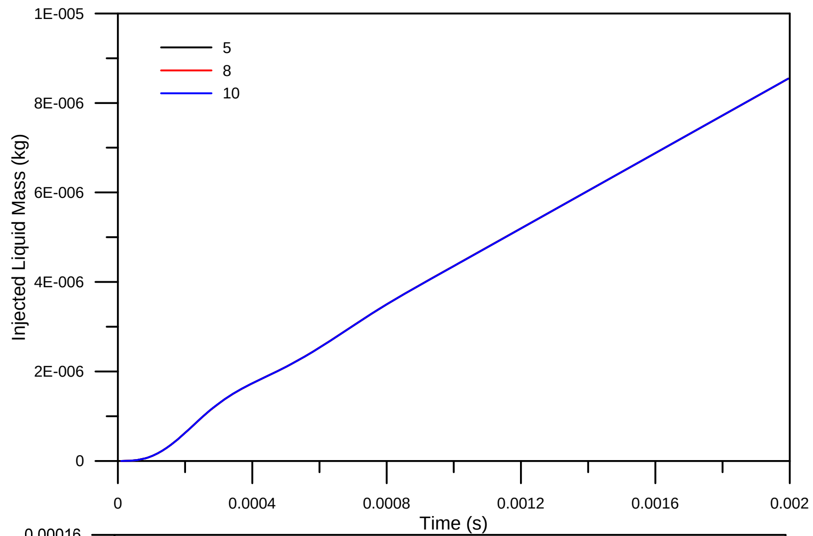


The choice of the **distribution variance** and the tuning of the **Huh Gosman model constant** is performed by means of an automatic optimization procedure* with respect to the experimental penetration length.

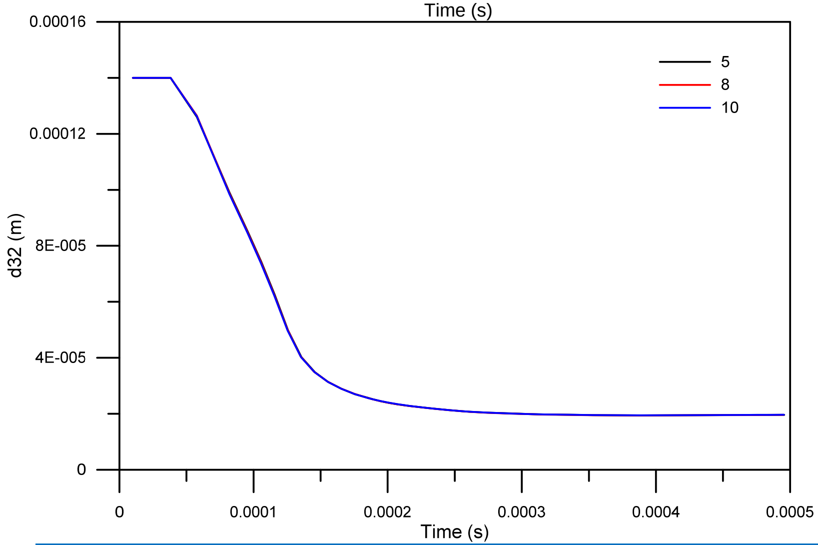
*M. Costa, L. Marchitto, S.S. Merola, U. Sorge, «*Study of mixture formation and early flame development in a research GDI (gasoline direct injection) engine through numerical simulation and UV-digital imaging*», Energy, 1-9, (2014)

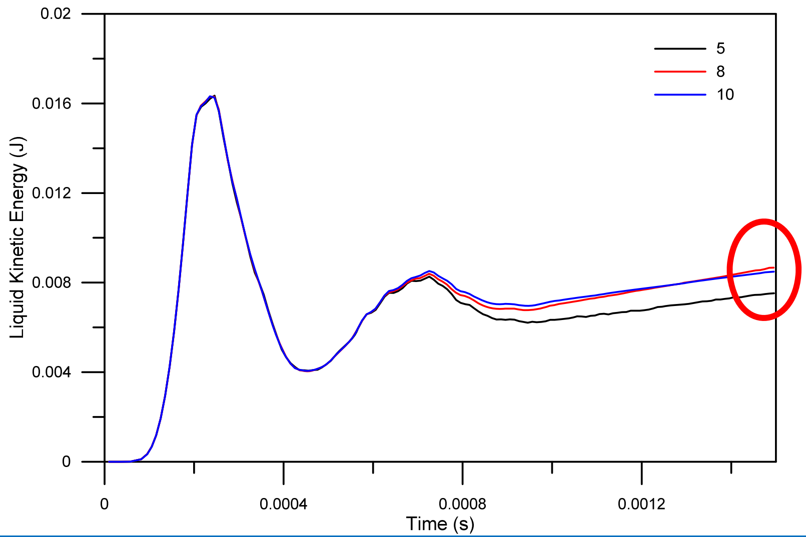
3D CFD CHARACTERIZATION OF THE SPRAY EVOLUTION

Sensitivity Analysis to the number of parcels introduced per nozzle hole per time step



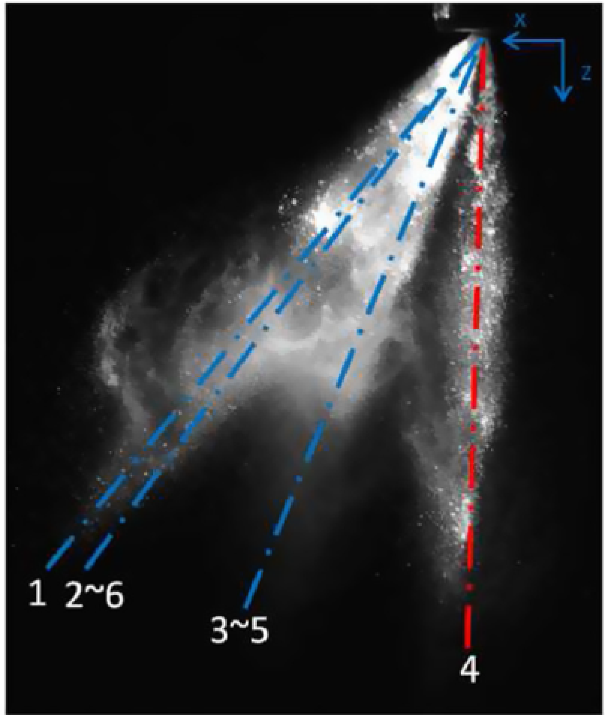
Operative Conditions	
Injection Pressure [MPa]	10
Fuel Temperature [K]	293
Vessel Pressure [Pa]	101325
Vessel Temperature [K]	298
Fuel Mass Injected [mg]	4,36 x hole
DOI [ms]	3,13
Hole Diameter [mm]	0,14





3D CFD SIMULATION OF THE HOLE N° 4 SPRAY EVOLUTION

3D CFD simulation of the injection process of the only n° 4 nozzle hole



Comparison between the measured and computed **liquid concentration** in a plane orthogonal to the n° 4 hole axis, at a distance from the nozzle tip equal to 250 µm and 500 µm

Operative Conditions	
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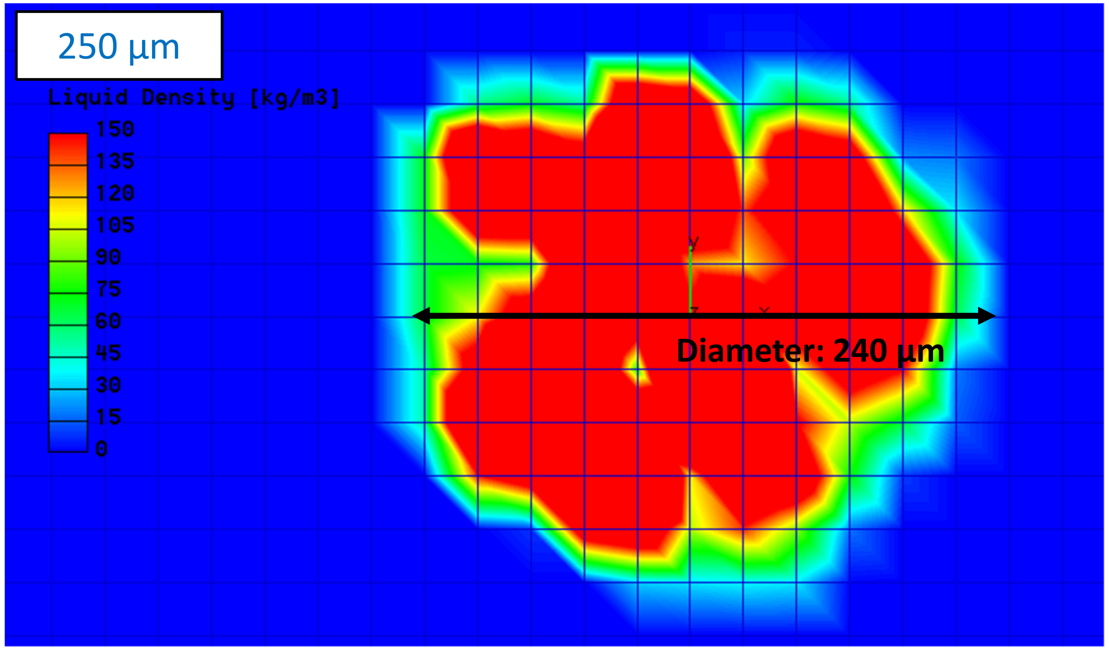

Cubic numerical grid: 1x1x10 mm

Computational cell dimensions: 20 µm

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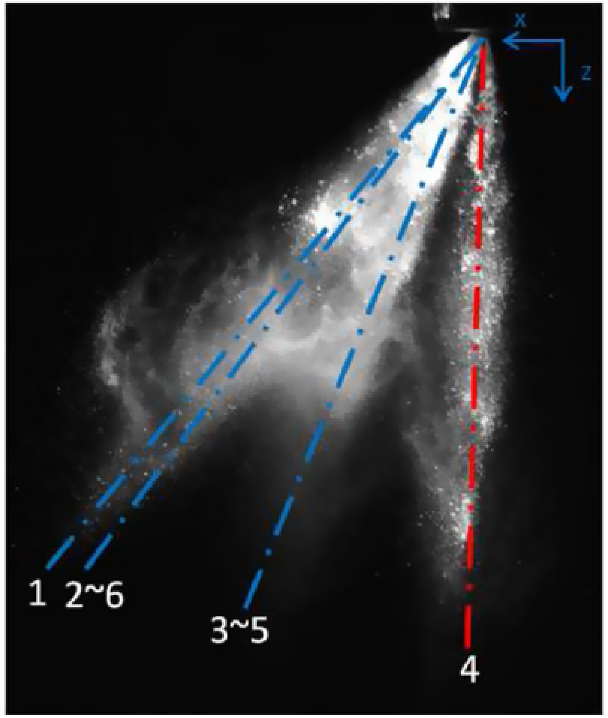

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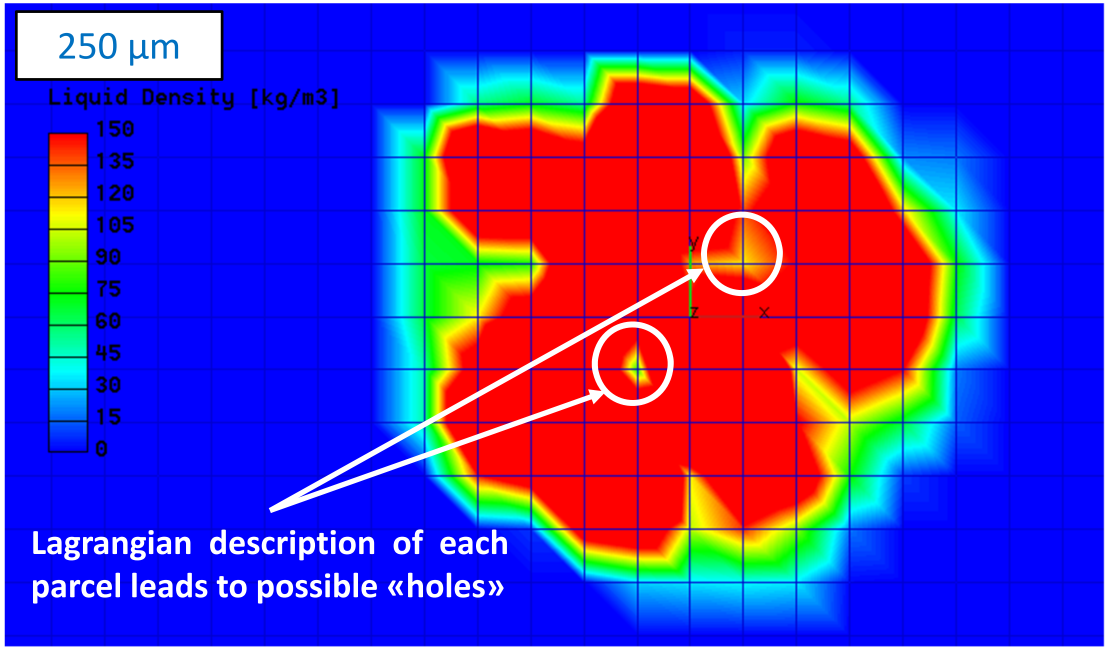

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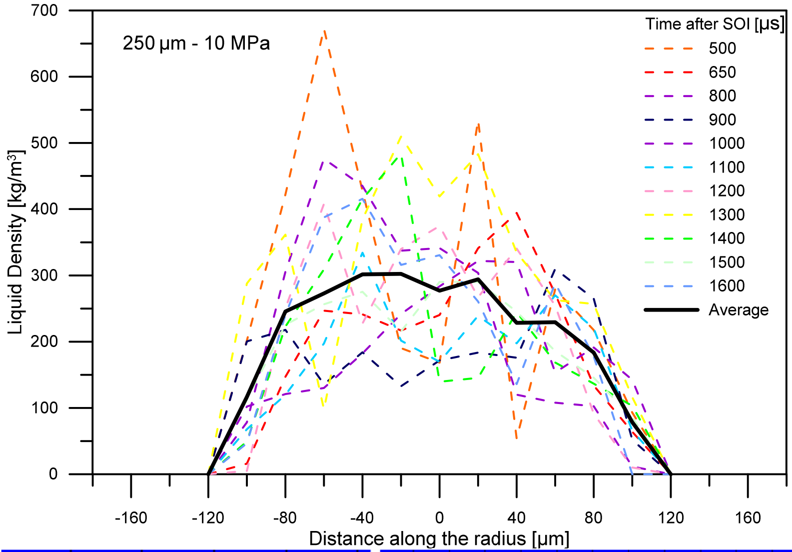
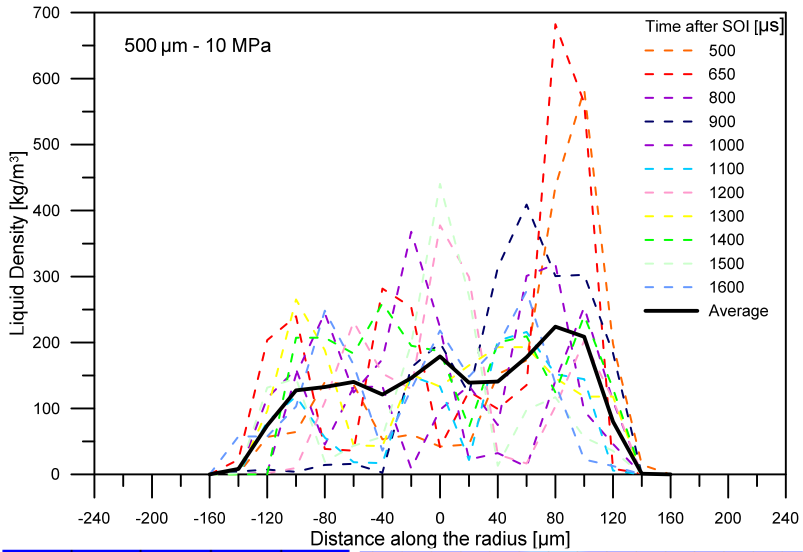
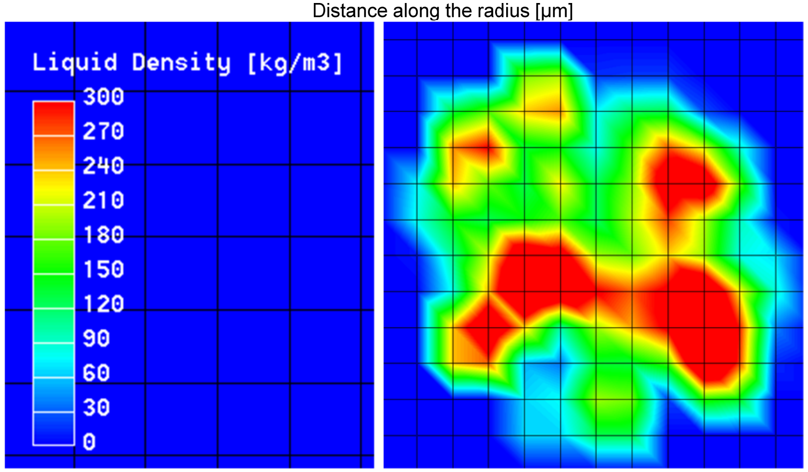
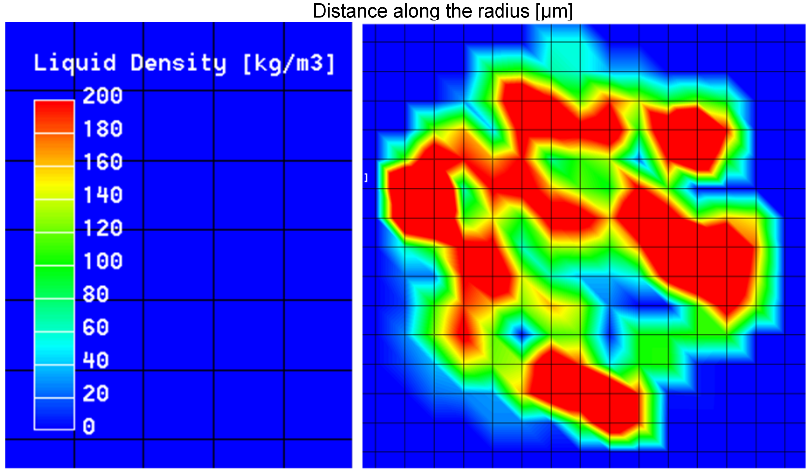




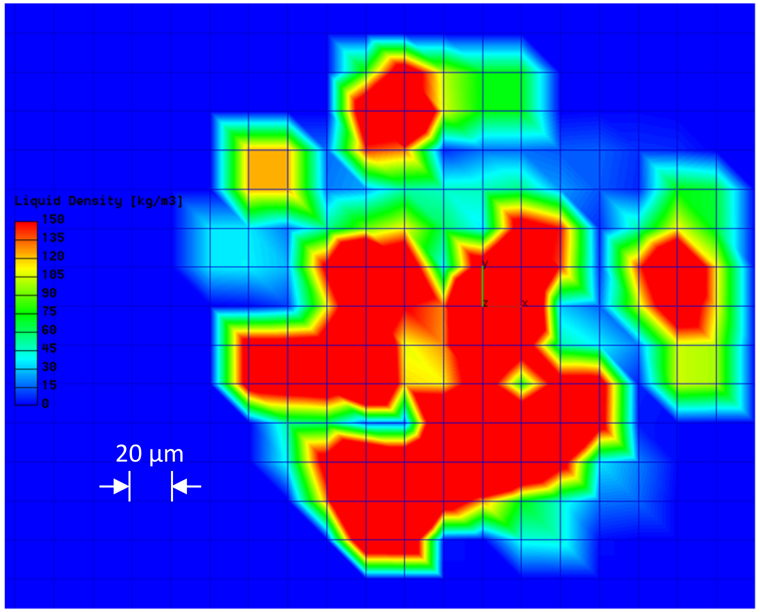


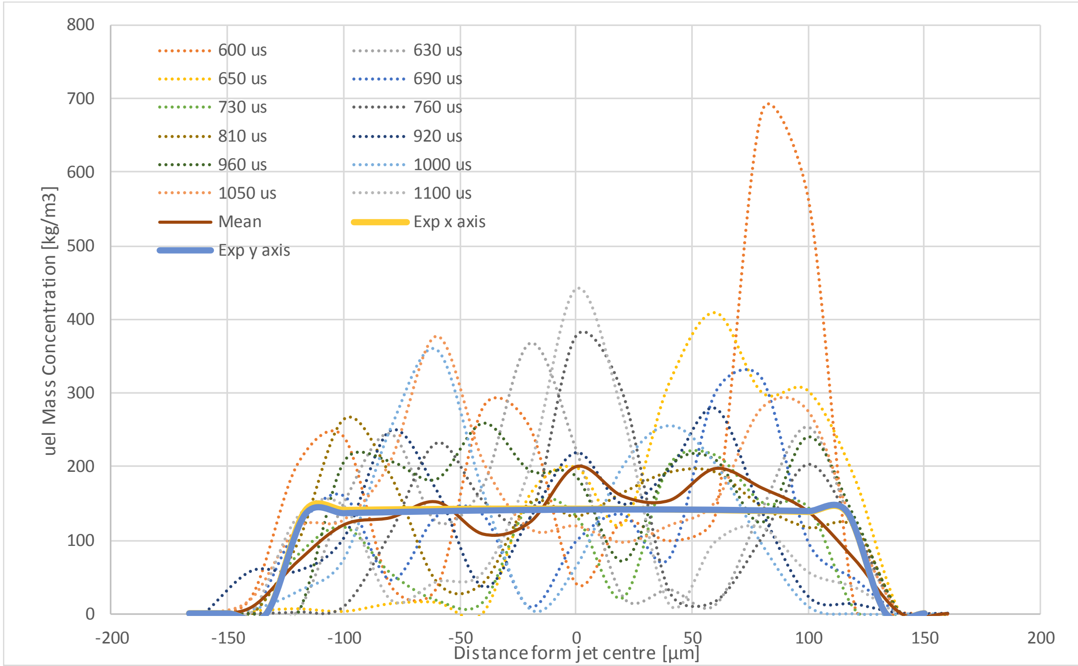


EXP./NUM. RESULTS COMPARISON

Mass Fraction

m_{air}/m_{fuel}





Δh=500 µm

P_{inj} =10 MPa

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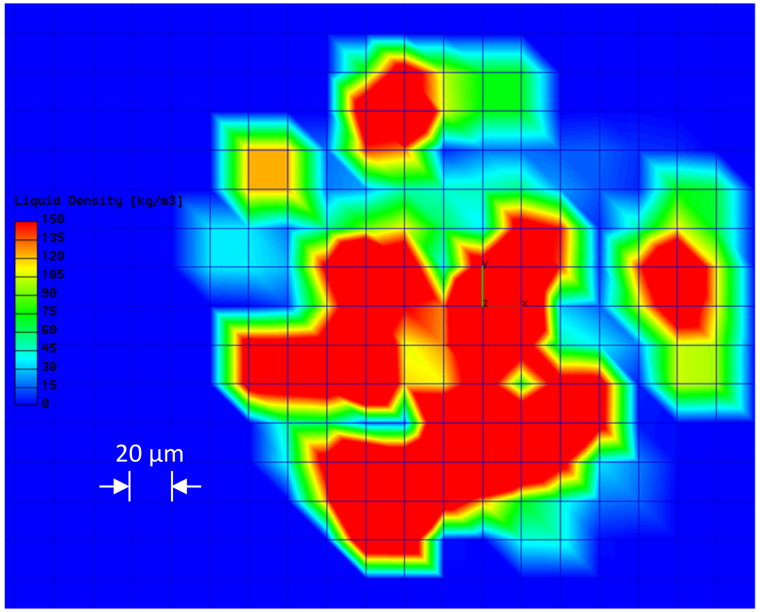

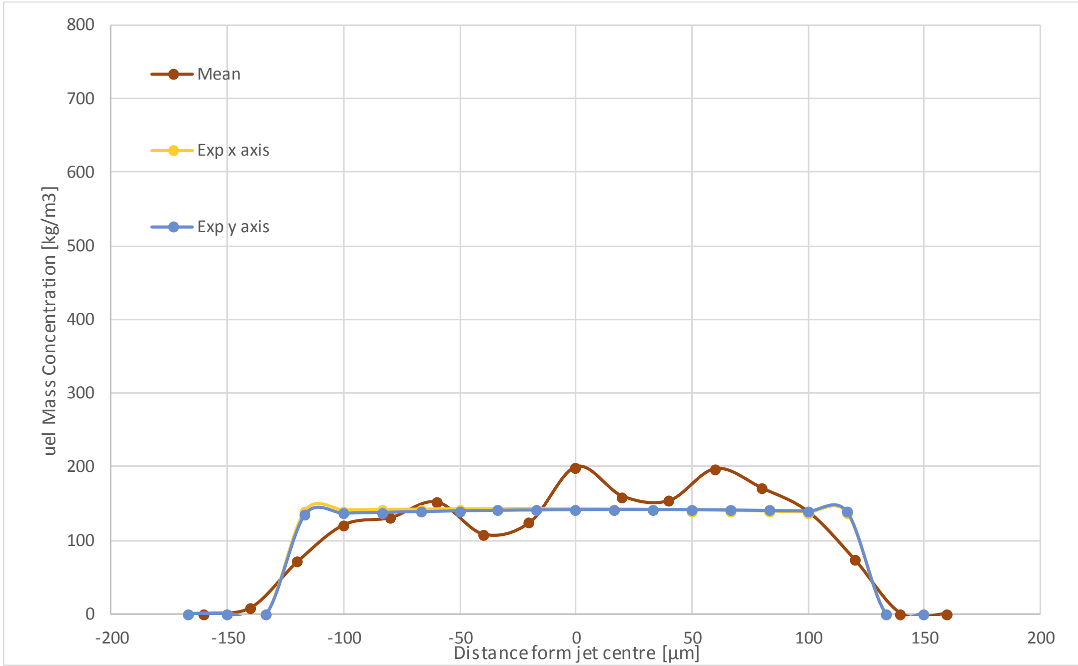

Δh=500 µm

P_{inj} =10 MPa

CONCLUSION

X-ray tomography has been applied to investigate the inner structure of a gasoline spray delivered by a 6-hole Gasoline Direct Injection system. The experimental set-up is based on a Cu Kα X-ray tube coupled with a polycapillary halflens, that allowed to obtain a high intensity quasi parallel beam (lens total efficiency ~60%).

The technique has provided a detailed reconstruction of the spray structure in the region close to the nozzle allowing quantitative 3D measurements of fuel mass and local air-fuel distribution

A 3D CFD model in the AVL FireTM environment, based on a Reynolds Averaged Navier-Stokes (RANS) approach was developed to reproduce the operative conditions.

The comparison demonstrates the accuracy of x-ray tomography desktop facility as a reliable diagnostic tool to get quantitative information about the local mass distribution and fuel flow.

THANK YOU FOR YOUR ATTENTION