Laser Plasma Accelerators for Radiotherapy and Tomography

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EuroNNAc Special Topics Workshop

Isola d'Elba, Italy

18-24 September 2022

Lund Laser Centre

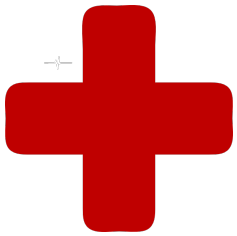
WALLENBERG ACADEMY FELLOWS

LUND UNIVERSITY

Why particle accelerators matter

Discovery Science

Particle accelerators are essential tools of discovery for particle and nuclear physics and for sciences that use x-rays and neutrons.



Medicine

Tens of millions of patients receive accelerator-based diagnoses and therapy each year in hospitals and clinics around the world.

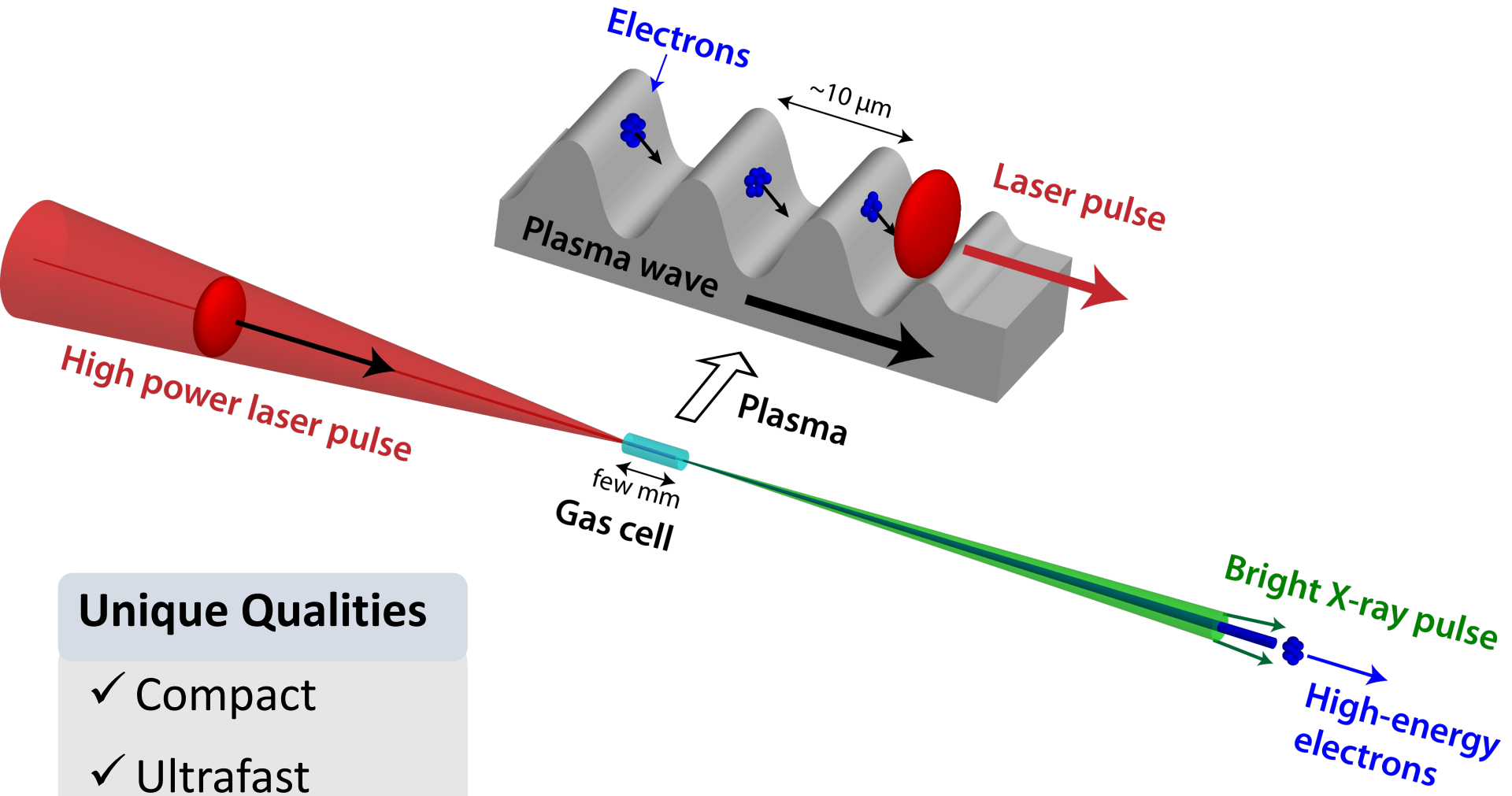
Industry

Worldwide, hundreds of industrial processes use particle accelerators – from the manufacturing of computer chips to the cross-linking of plastic for shrink wrap and beyond.

Security

Particle accelerators play an important role in ensuring security, including cargo inspection and materials characterization.

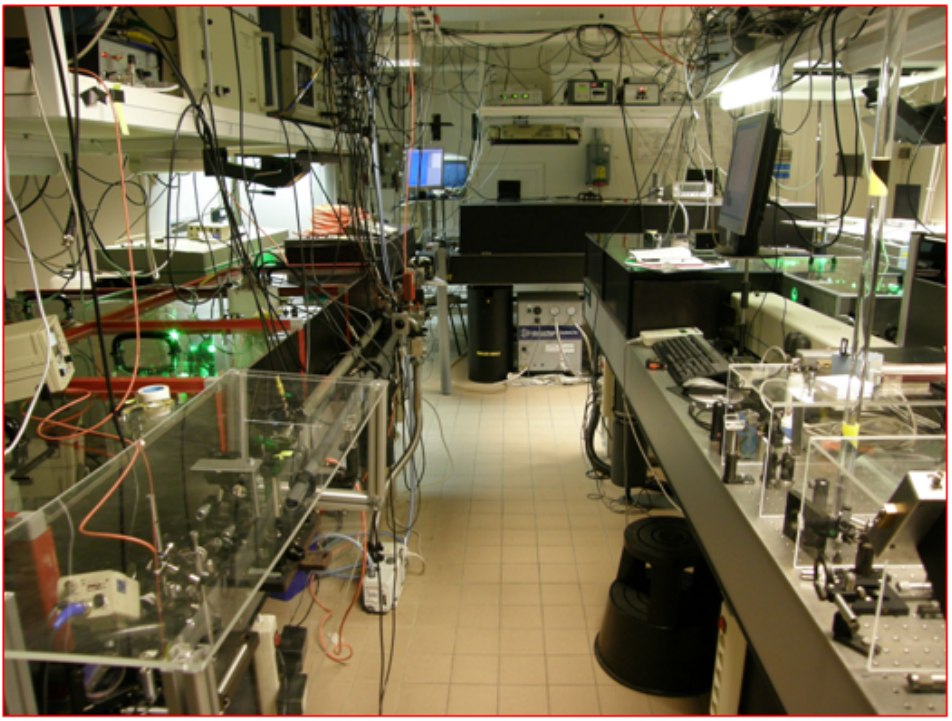
Laser-plasma acceleration and X-ray generation

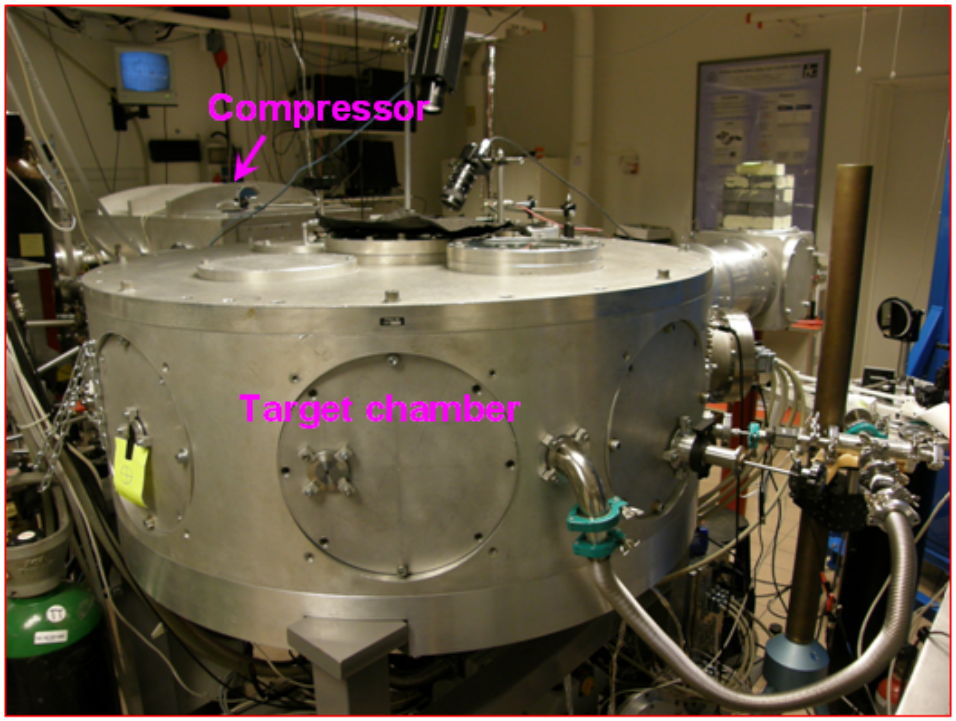


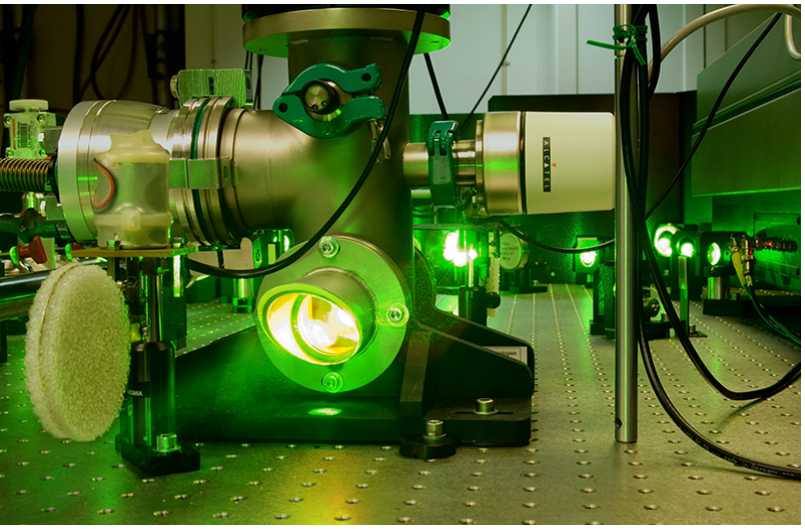
Unique Qualities

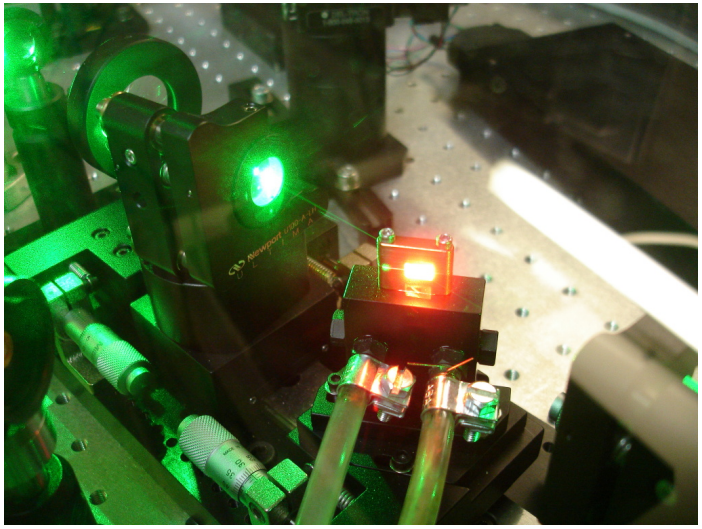
- ✓ Compact
- ✓ Ultrafast
- ✓ Tunable

Lund Multi-Terawatt Laser



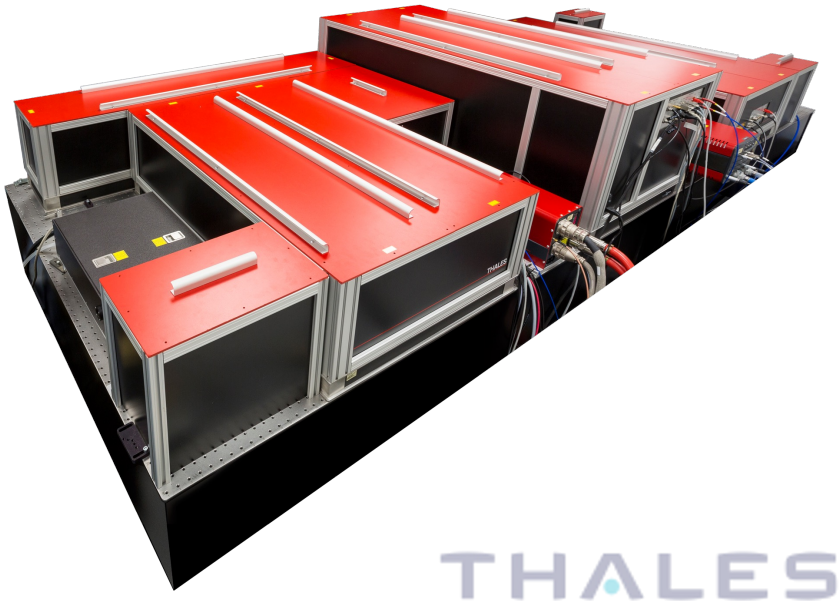




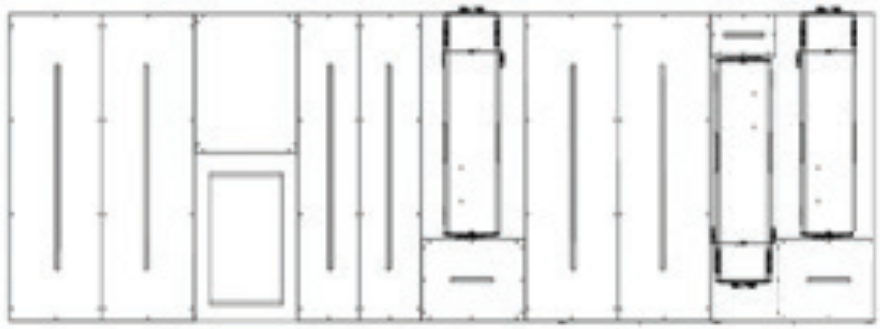


Ti:Sapphire
CPA laser
1 J
30 fs
10 Hz
10^{19} W/cm^2

Commercial TW laser



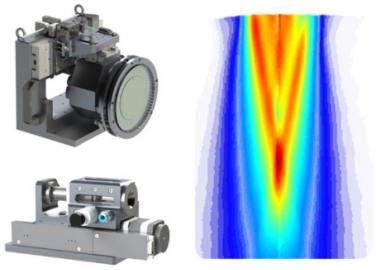
THALES



QUARK 45 layout example without compressor(*)
Table size: 1.5 x 4.2 m² (4.9 x 13.8 ft²)

Beamline technol.

TARGETRY SYSTEMS



Innovative gas and solid targets to experiment in laser-plasma interaction physics

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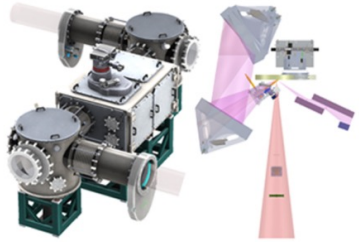
BEAMLINE ENGINEERING



Design & integration of beamlines systems up to multi PW laser intensity

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SourceLAB
Laser Plasma Technologies

PARTICLE SOURCES

Non Destructive Testing Plug & Play sources of particles for research and industry

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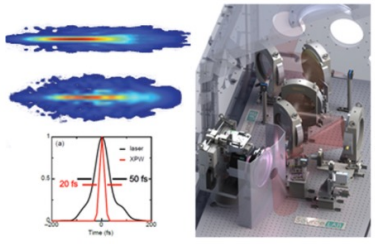
LASER BEAM SHAPING



Contrast-cleaning, post-compression, characterization for lasers up to multi-PW

.

Outline

High Energy Electrons for Radiotherapy

X-rays for Tomography of Transient Sprays

Stiftelsen för Strategisk Forskning

Knut och Alice Wallenbergs Stiftelse

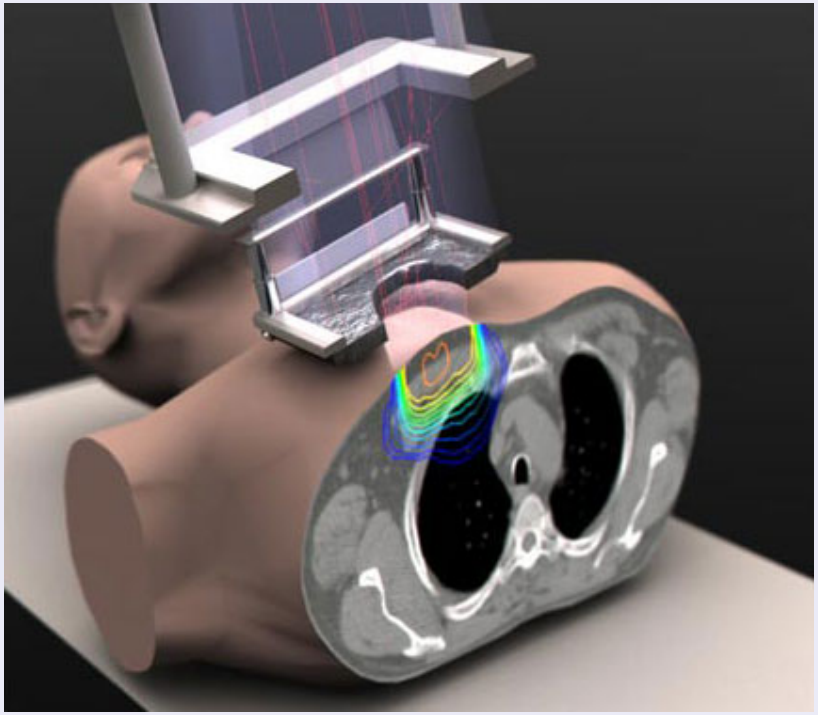
VETENSKAPSRÅDET
THE SWEDISH RESEARCH COUNCIL

Low energy electron radiotherapy

Clinical oncology machine

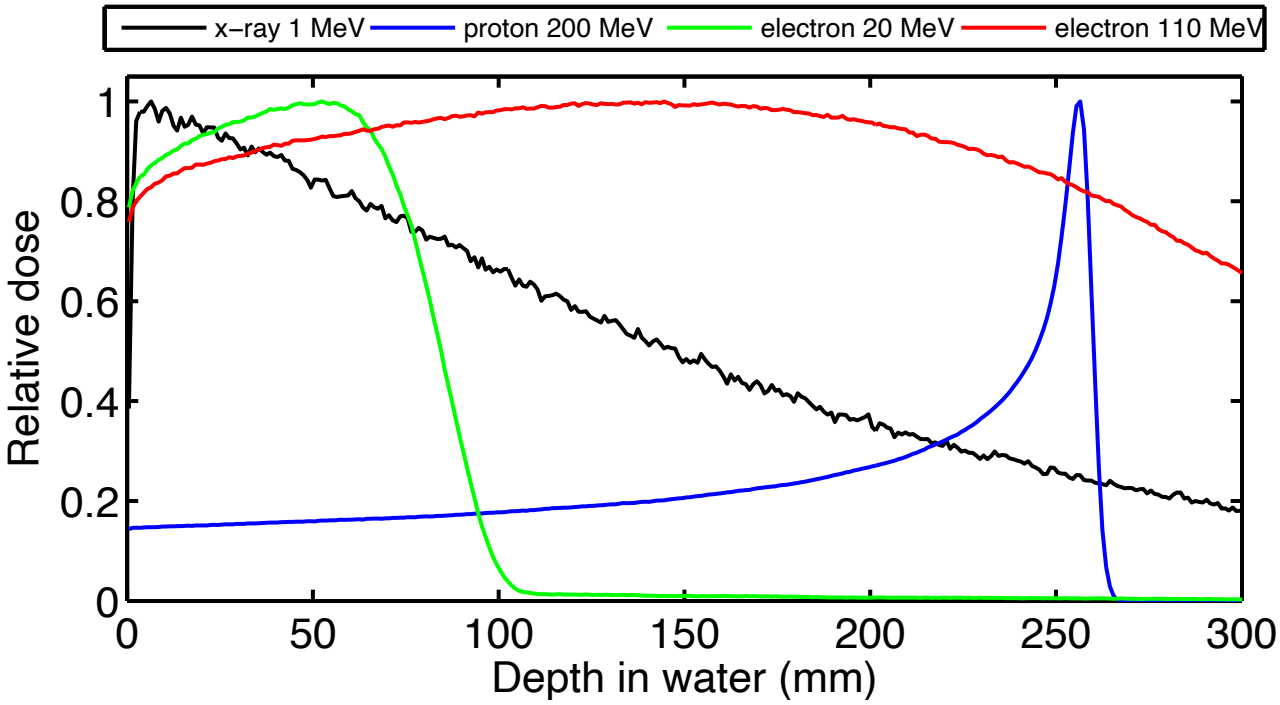
- 5-20 MeV electron beam
- X-rays by bremsstrahlung

Direct electron irradiation



- Electrons have limited range
- Underlying structures spared

Dose deposition for different particles



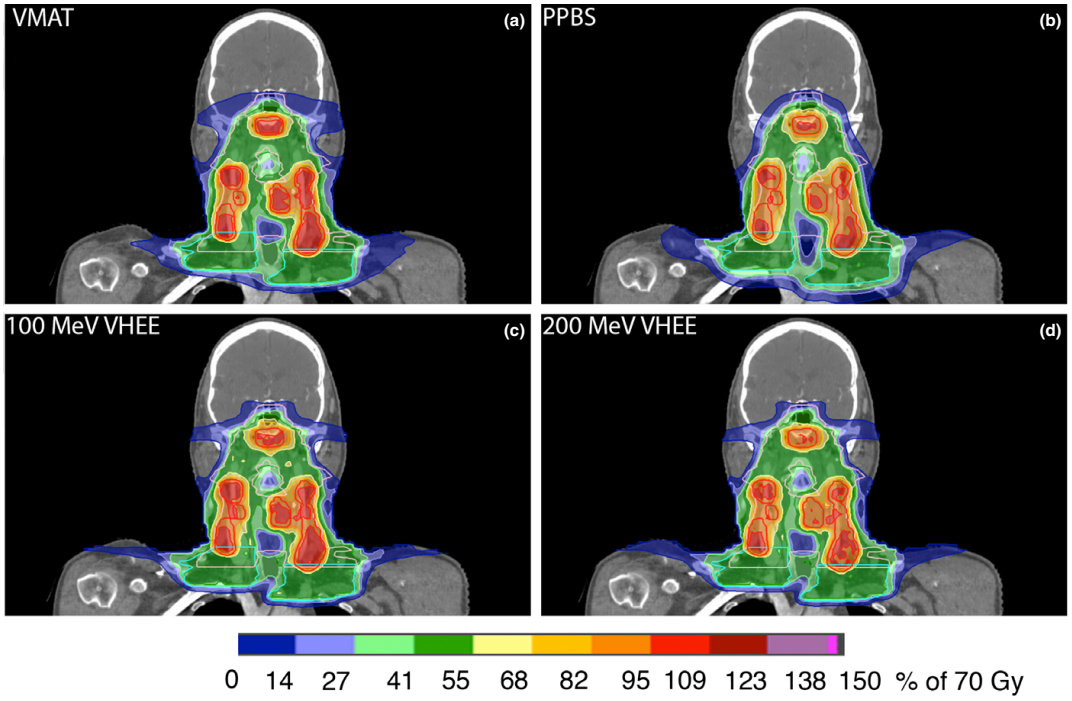
Low energy electrons < 20 MeV widely used for superficial tumours

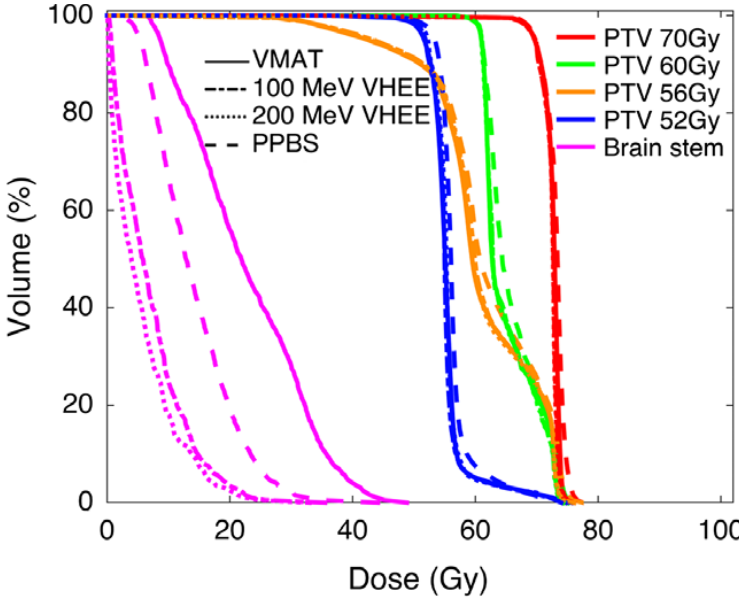
High energy electrons > 100 MeV not yet available in hospitals

Can high-energy electrons be useful for radiotherapy?

Potential advantage of high energy electrons

Schüler *et al*, Med. Phys. **44**, 2544-2555 (2017)

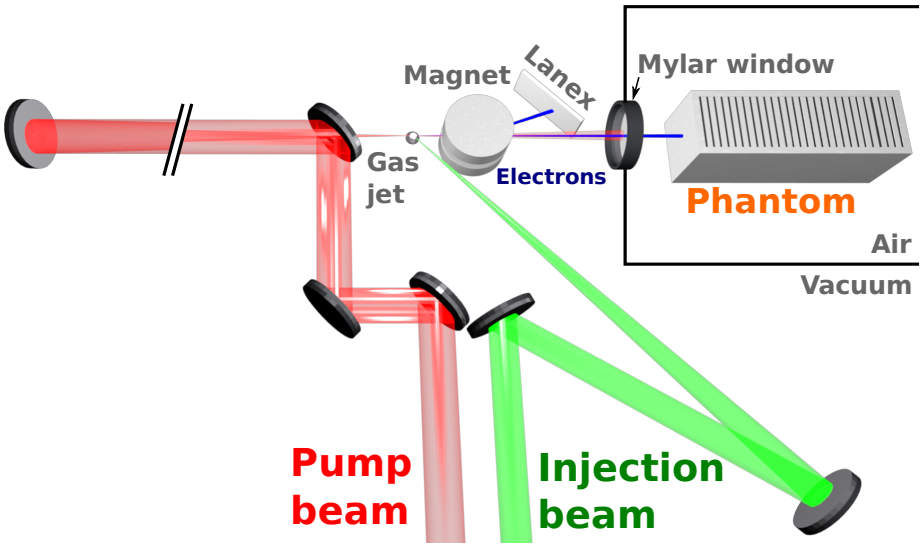




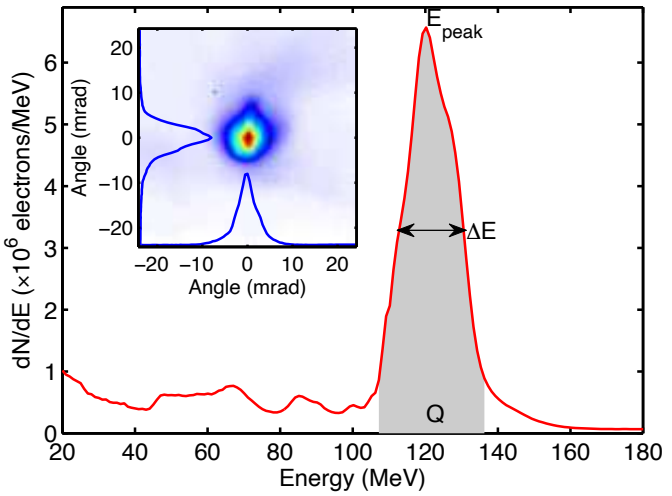
Compared to X rays (IMRT, VMAT), high-energy electrons (100-200 MeV) can give

- Similar coverage of the target volume
- Better sparing of critical structures and organs at risk

Experimental setup

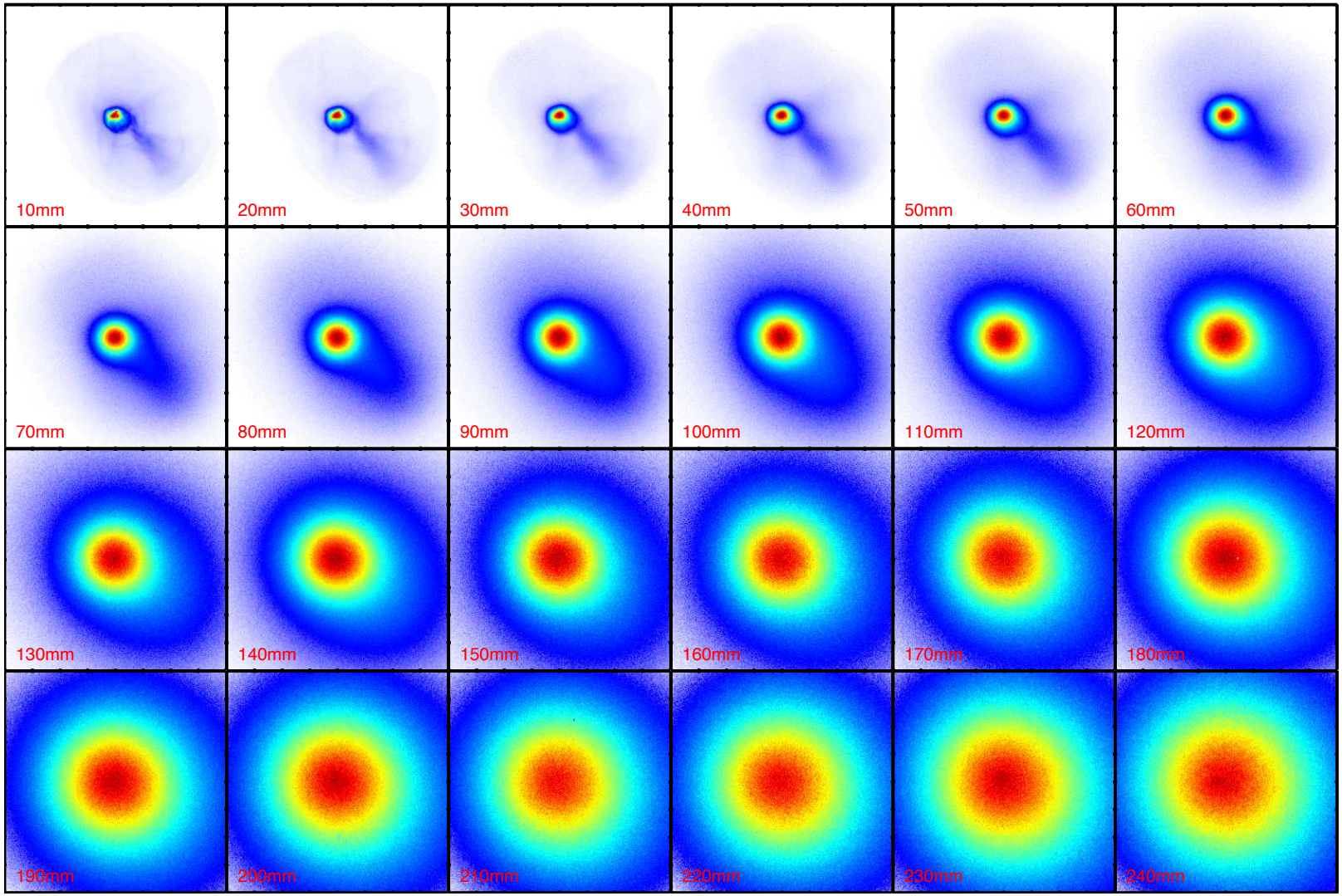


Electron beam: 120 MeV; 30 pC



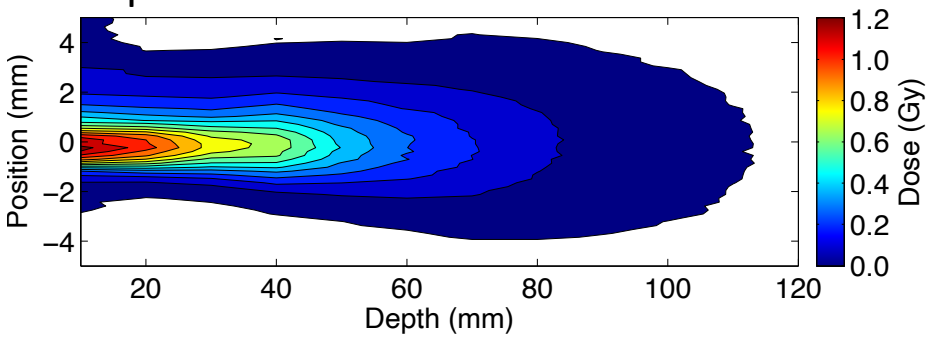
Blocks of polystyrene (10 mm) + Fuji film detectors (40x40 mm^2)

Measured dose profiles

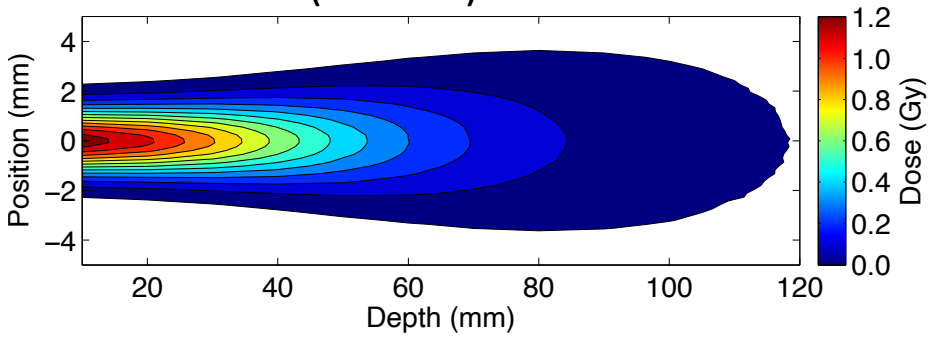


Comparison to simulation

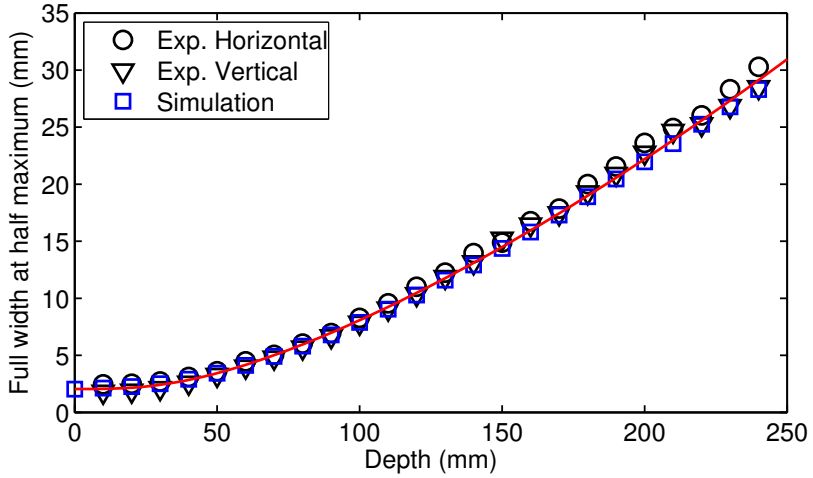
Experiment



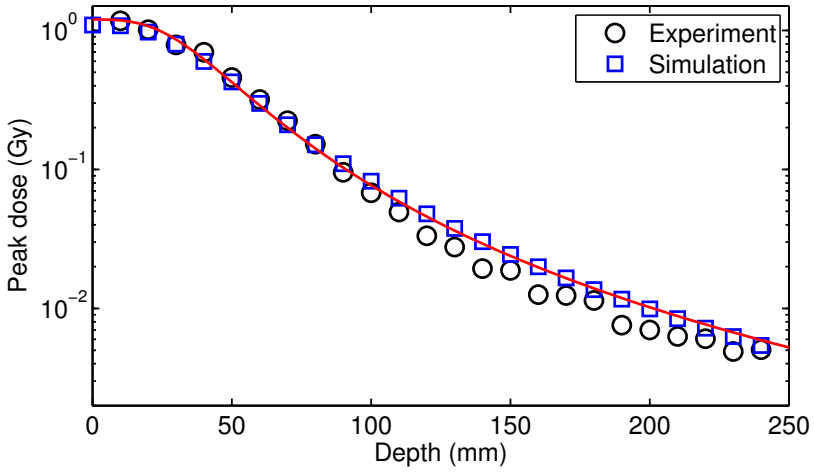
Simulation (Geant4)



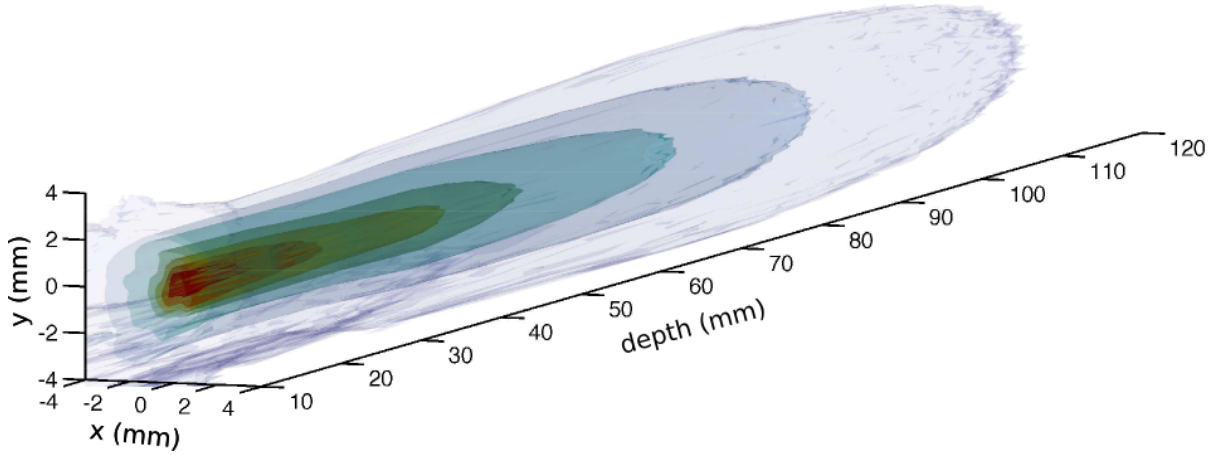
Beam size



Peak dose



Laser-accelerated VHEE's for radiotherapy?



Treatment plan

Total treatment dosage: 20-80 Gy

Fractional daily dosage: 2 Gy/day

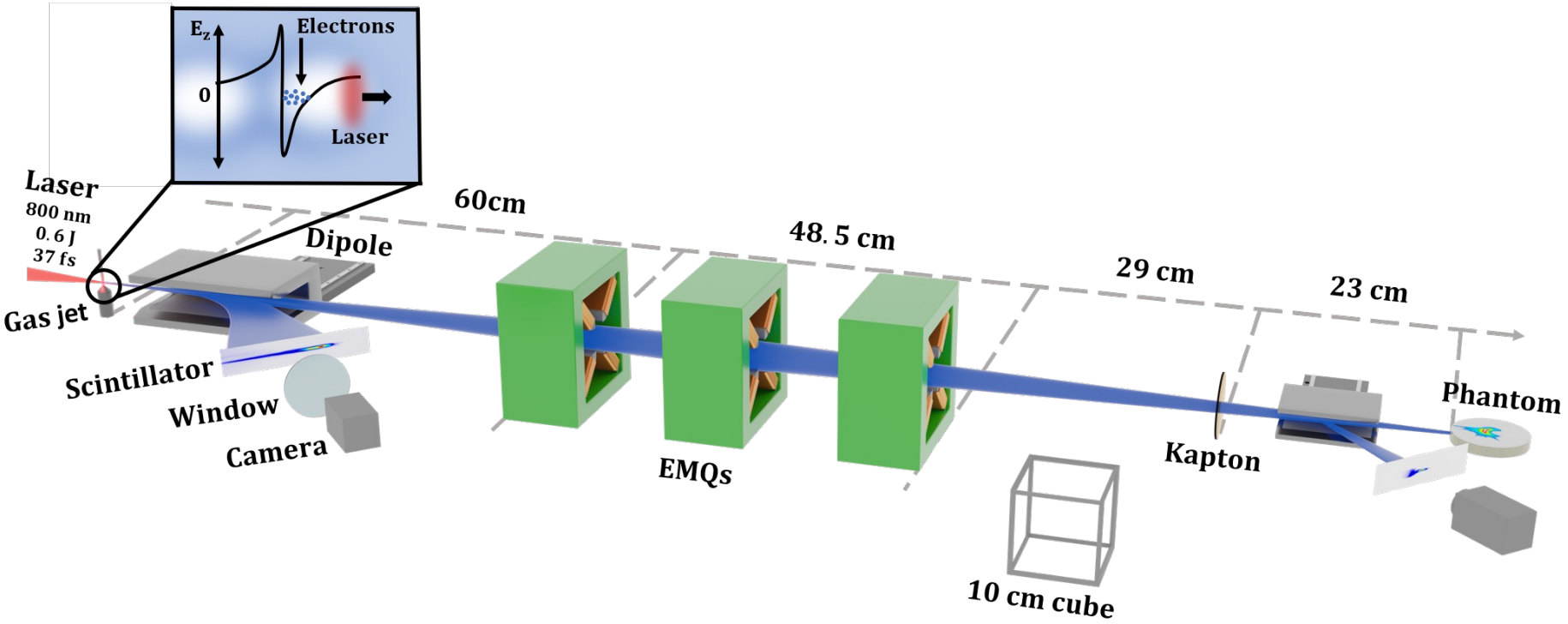
Laser-plasma beam

1 Gy/shot over 2x2 mm^2

200 shots (20 s): 2 Gy over 20x20 mm^2

Reasonable numbers

Beam shaping using EMQ magnets



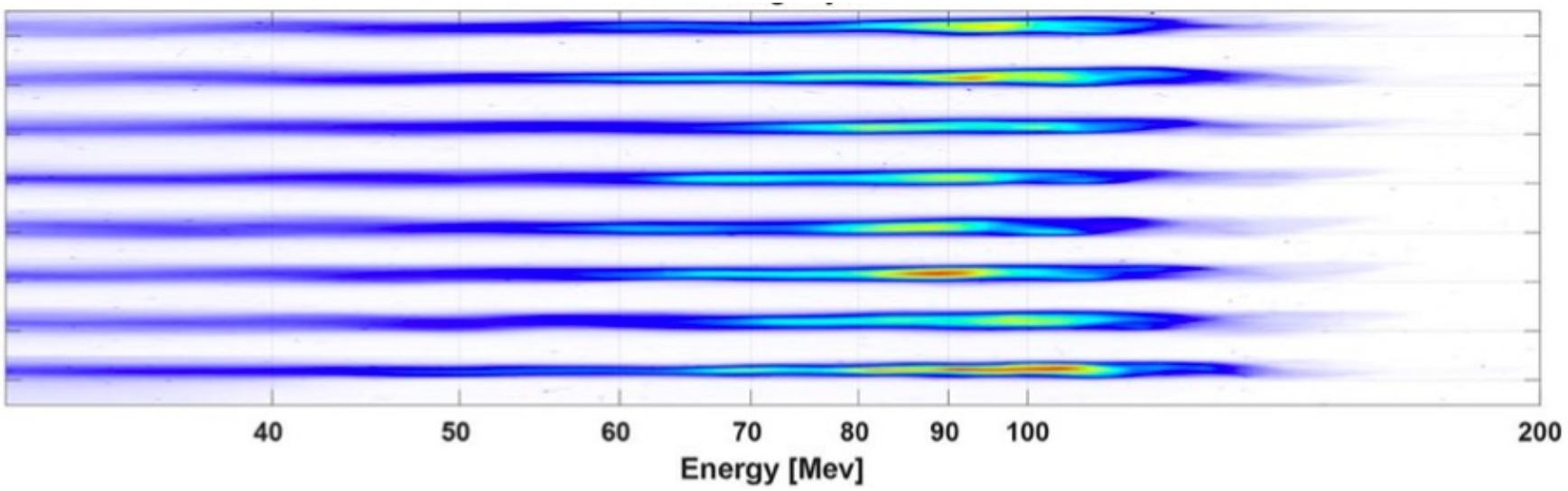
Focusing the beam at depth

- ✓ Mitigates lateral spread
- ✓ Gives more uniform dose

Energy spectrum

Consecutive measurements

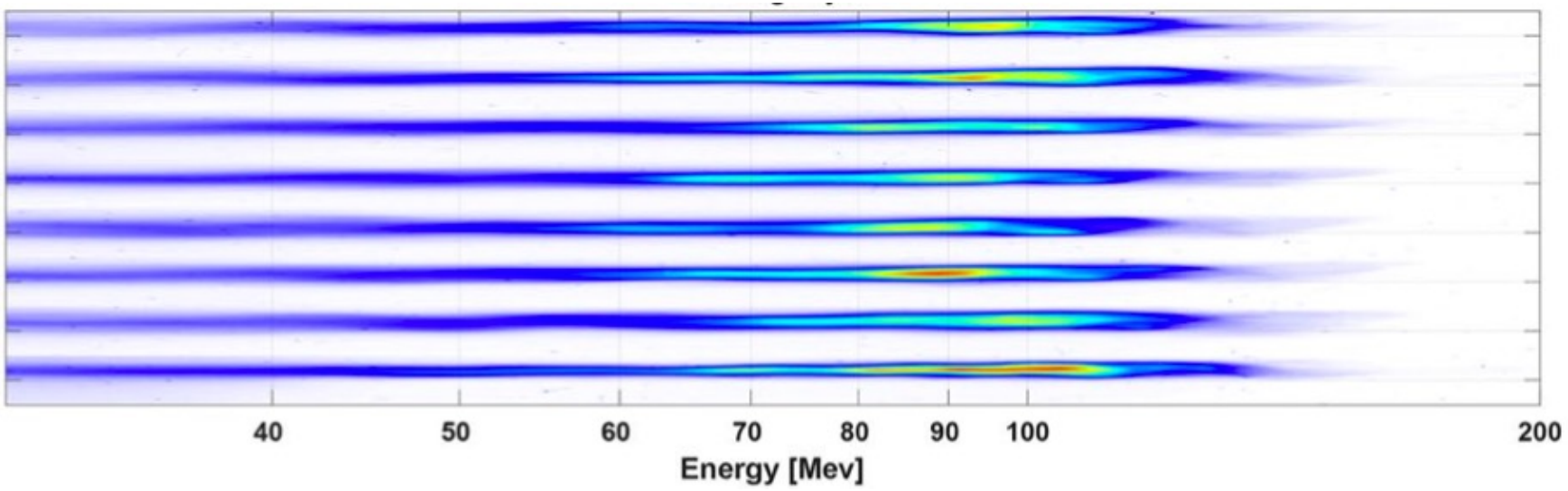
Before EMQ magnets



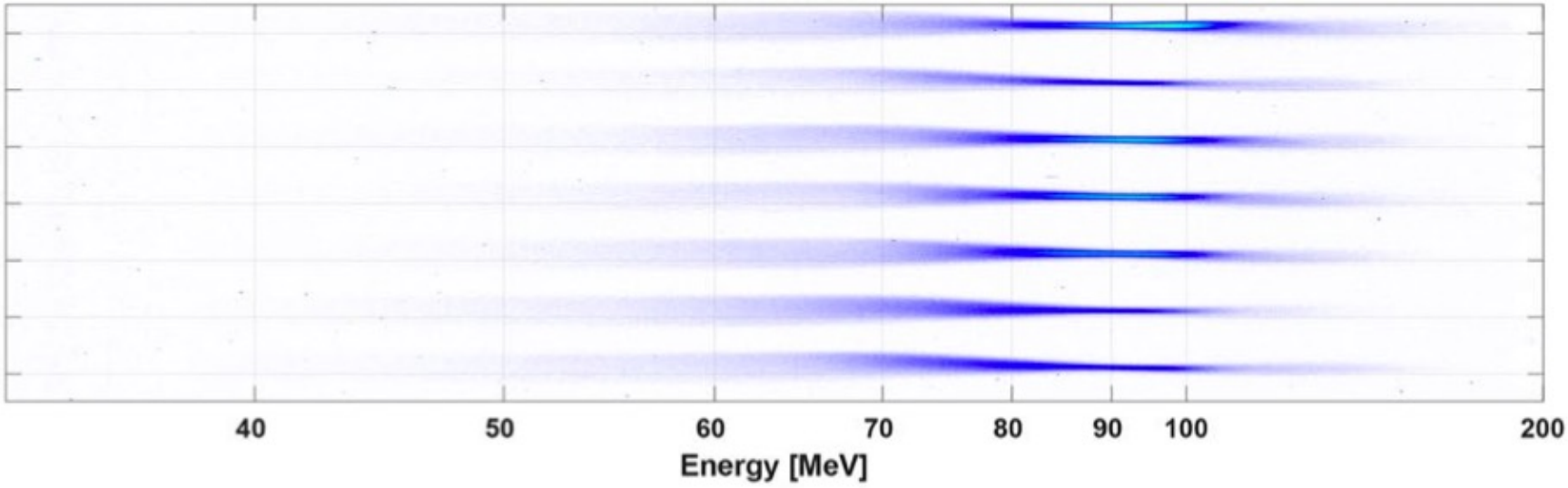
Energy spectrum

Consecutive measurements

Before EMQ magnets

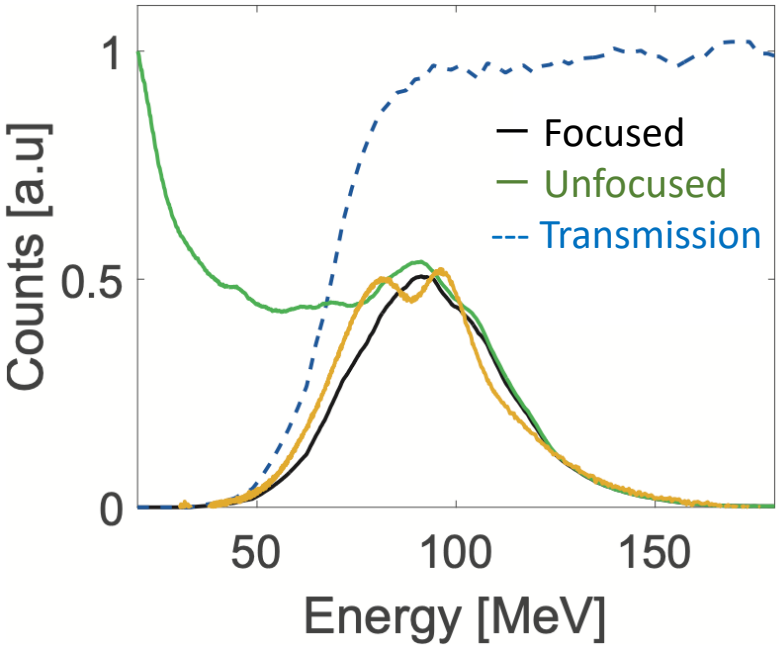


After EMQ magnets

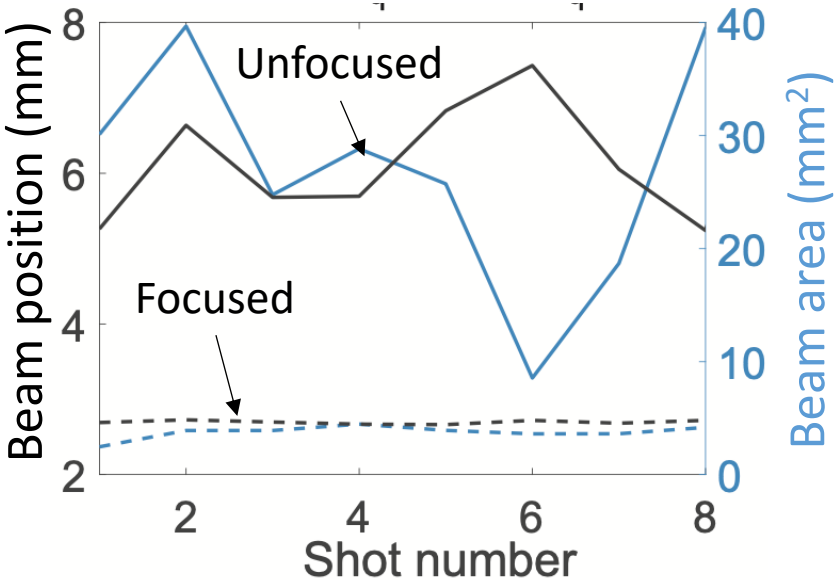


Beam control

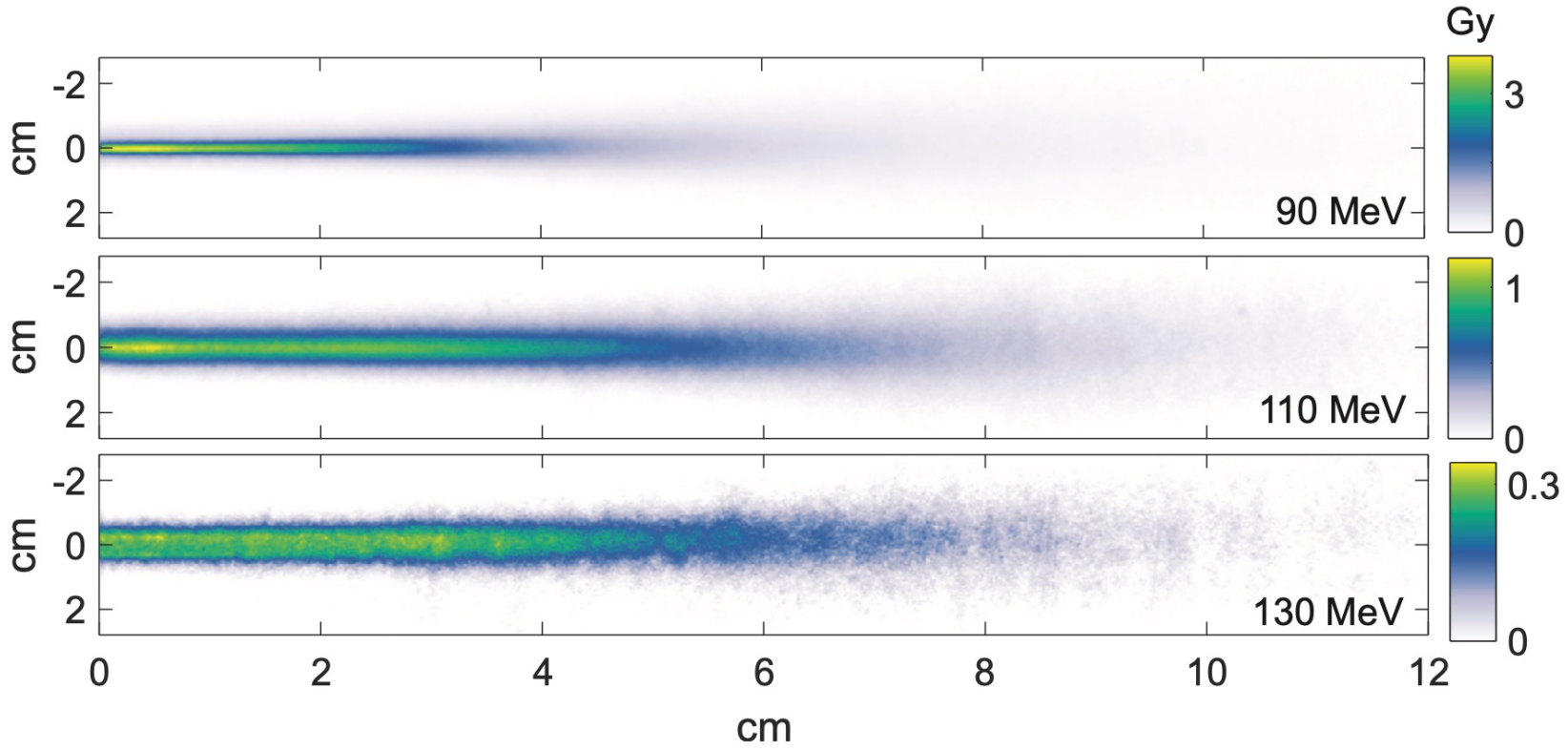
Spectral filtering



Pointing stabilization

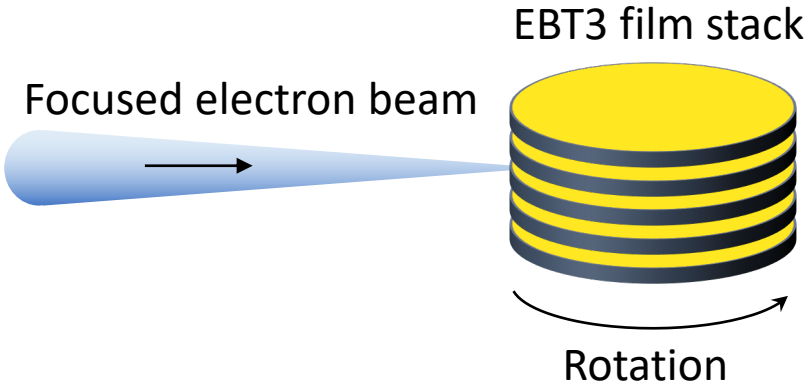


Dose deposition by focused beams



Multiple irradiation angles

Phantom stack



Multiple irradiation angles

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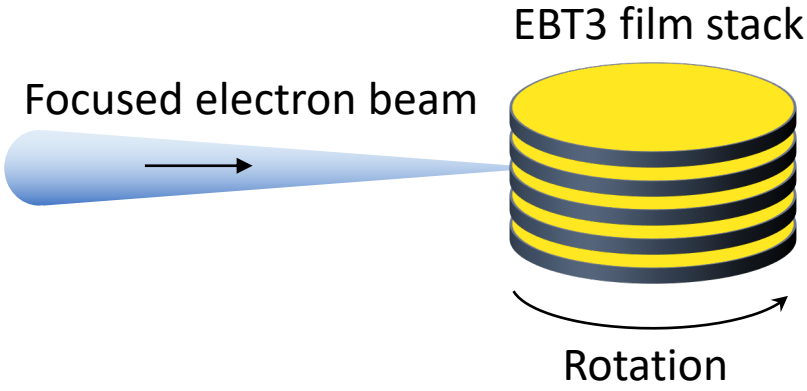
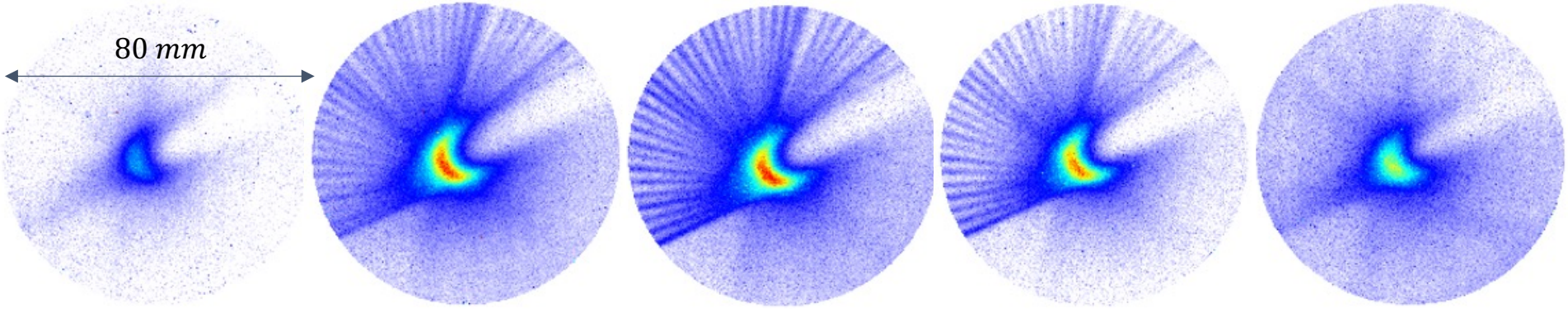


Measurement – concave volume

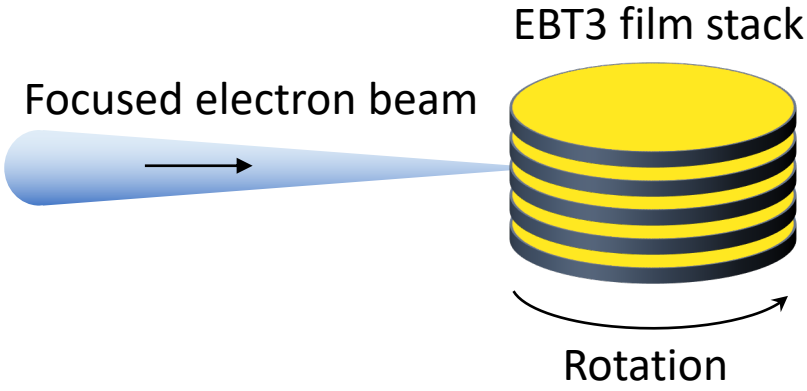
36 angles, 10 pulses/angle



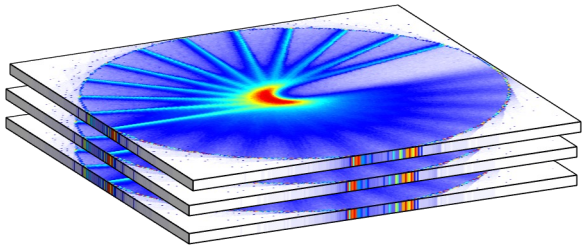
Layers at different heights from beam center

Multiple irradiation angles

Phantom stack



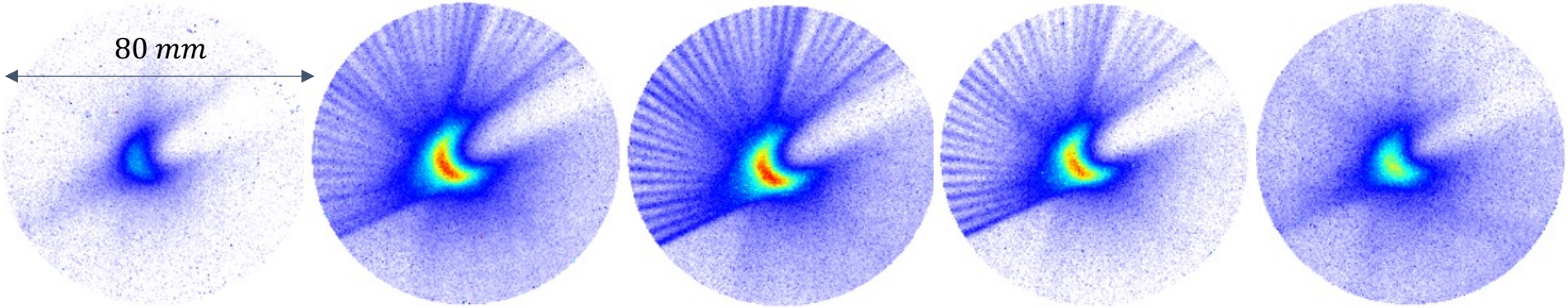
Simulation



Simulation using Fluka

Measurement – concave volume

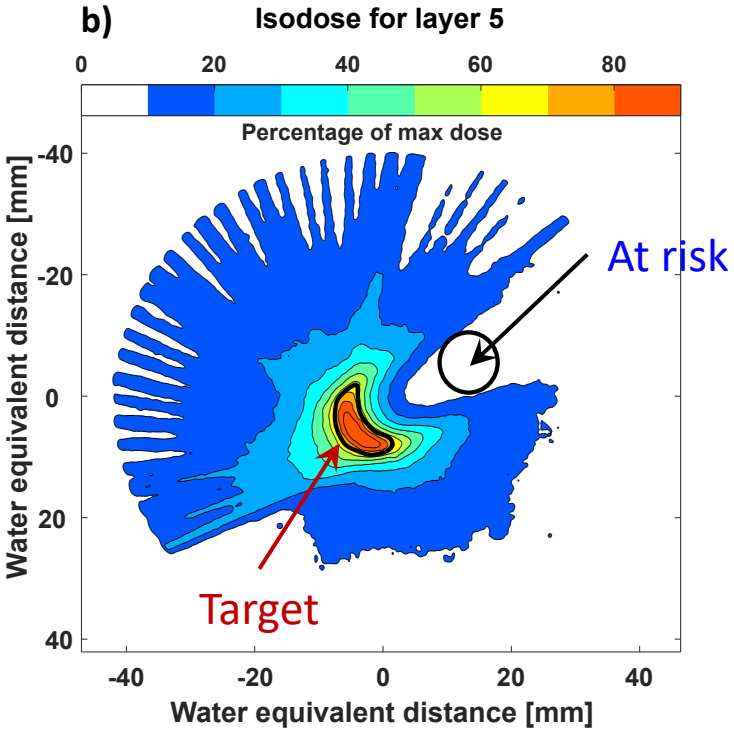
36 angles, 10 pulses/angle

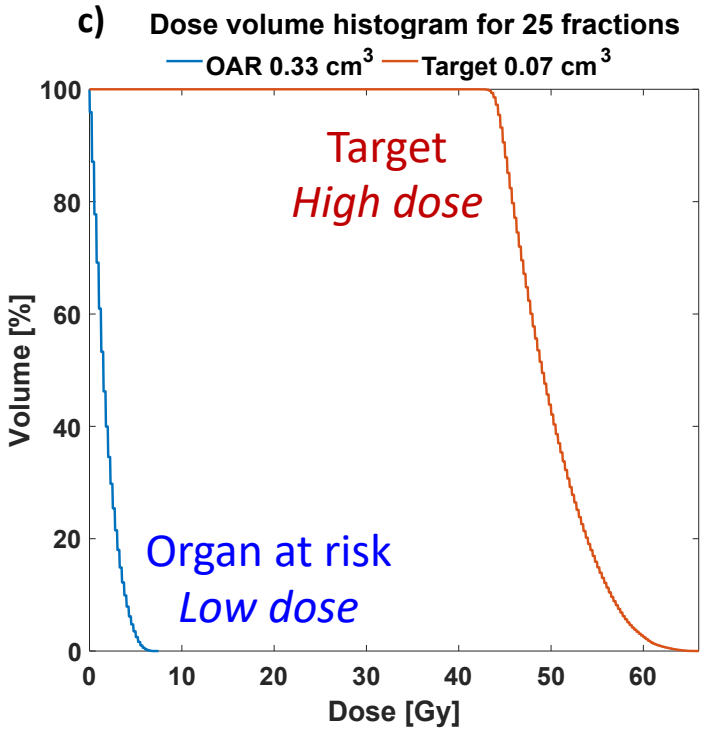


Layers at different heights from beam center

Towards stereotactic radiotherapy

Purpose of stereotactic radiotherapy is very precise delivery of the dose to the target volume





K. Svendsen *et al*, Sci Reports **11**, 5844 (2021)

O. Lundh *et al*, Med Phys **39**, 3501 (2012)

Perspectives for FLASH therapy

FLASH therapy is the delivery of very high dose rates (>40 Gy/s)

FLASH effect provides better sparing of healthy tissue

not yet completely understood

Femtosecond electron bunches from LWFA

- Allow radiobiological studies at ultra-high dose rates
- High repetition rate is also needed for the delivering high total dose (several Gy) in very short time (~100 ms)

M. Kim *et al*, IEEE TRPMS **6**, 252-262 (2021)

O. Rigaud *et al*, Cell Death & Disease **1**, e73 (2010)

Outline

High Energy Electrons for Radiotherapy

X-rays for Tomography of Transient Sprays

Stiftelsen för Strategisk Forskning

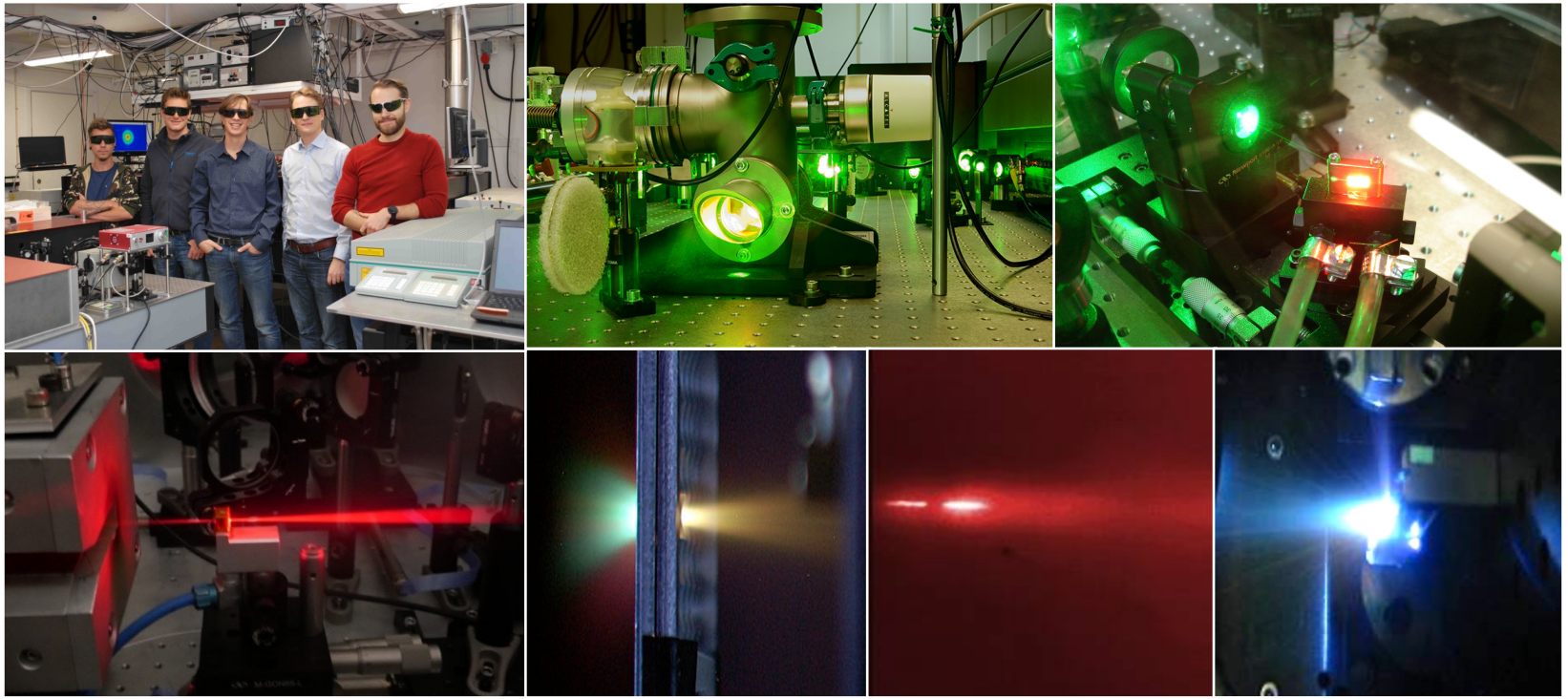
VETENSKAPSRÅDET
THE SWEDISH RESEARCH COUNCIL

Lund University Laser Acceleration Laboratory

LUNDS UNIVERSITET

Transnational Access to Plasma Accelerated beams of Electrons and X-rays

Short title	Leader	Institute	Country	Units	Completed
Multistage plasma accelerator	V. Tomkus	FTMC Vilnius	Lithuania	135	2019.02.22
Testing plasma souce for EuPRAXIA	M. Streeter	Imperial College	UK	244	2019.12.16
Spray imaging by laser driven x-rays	L. Zigan	Erlangen FAU	Germany	138	2020.03.13
Optimizing acceleration by AI/ML	F. Filippi	ENEA Frascati	Italy	251	2021.12.10



ARIES

Spray applications

Medical Applications: Inhalation and skin treatment




Industrial Applications: Spray drying / painting / cutting / *etc*

Spray applications

Medical Applications: Inhalation and skin treatment

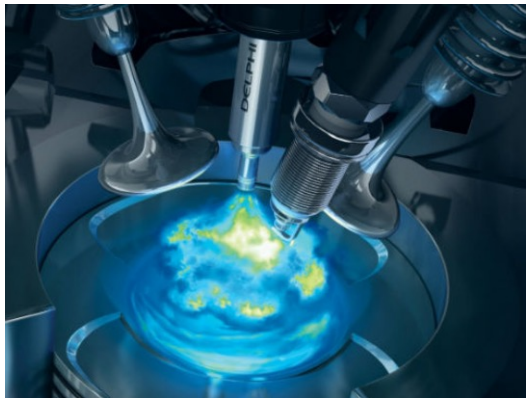


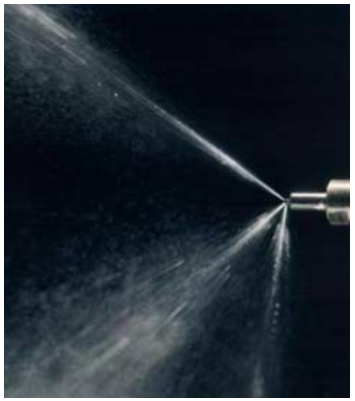
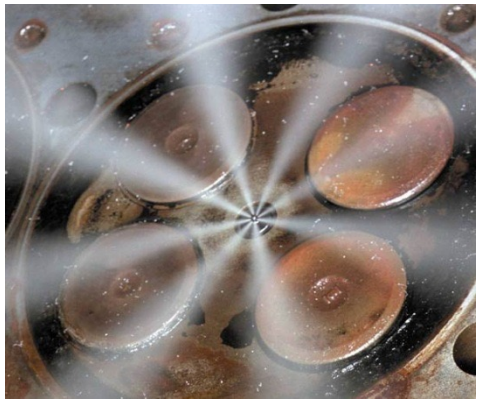

Industrial Applications: Spray drying / painting / cutting / *etc*



Spray applications

Internal Combustion Engines Applications: Diesel and GDI sprays

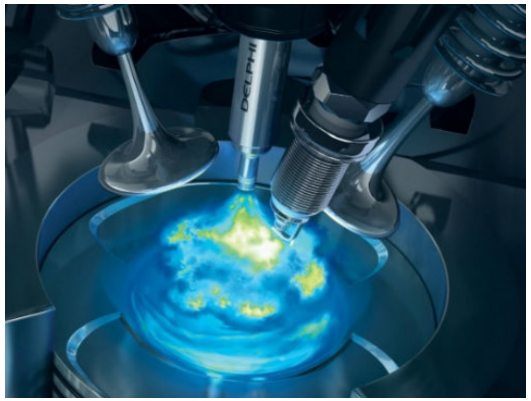


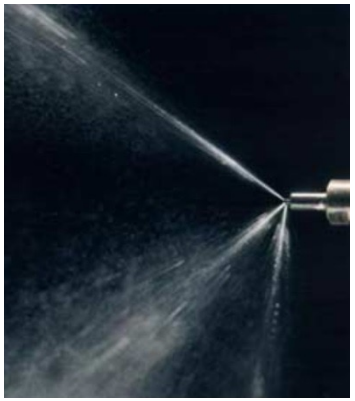
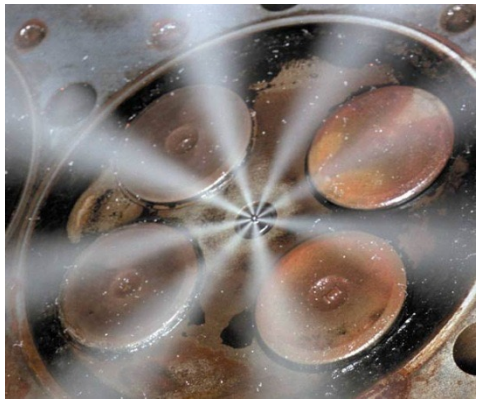




Gas Turbines Applications: Aero Engines

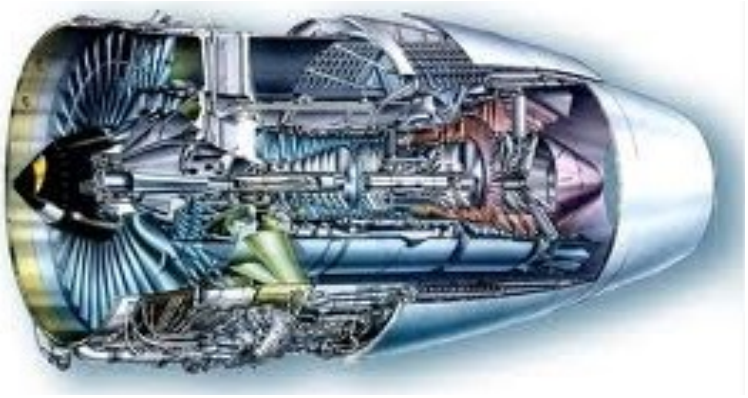
Spray applications

Internal Combustion Engines Applications: Diesel and GDI sprays

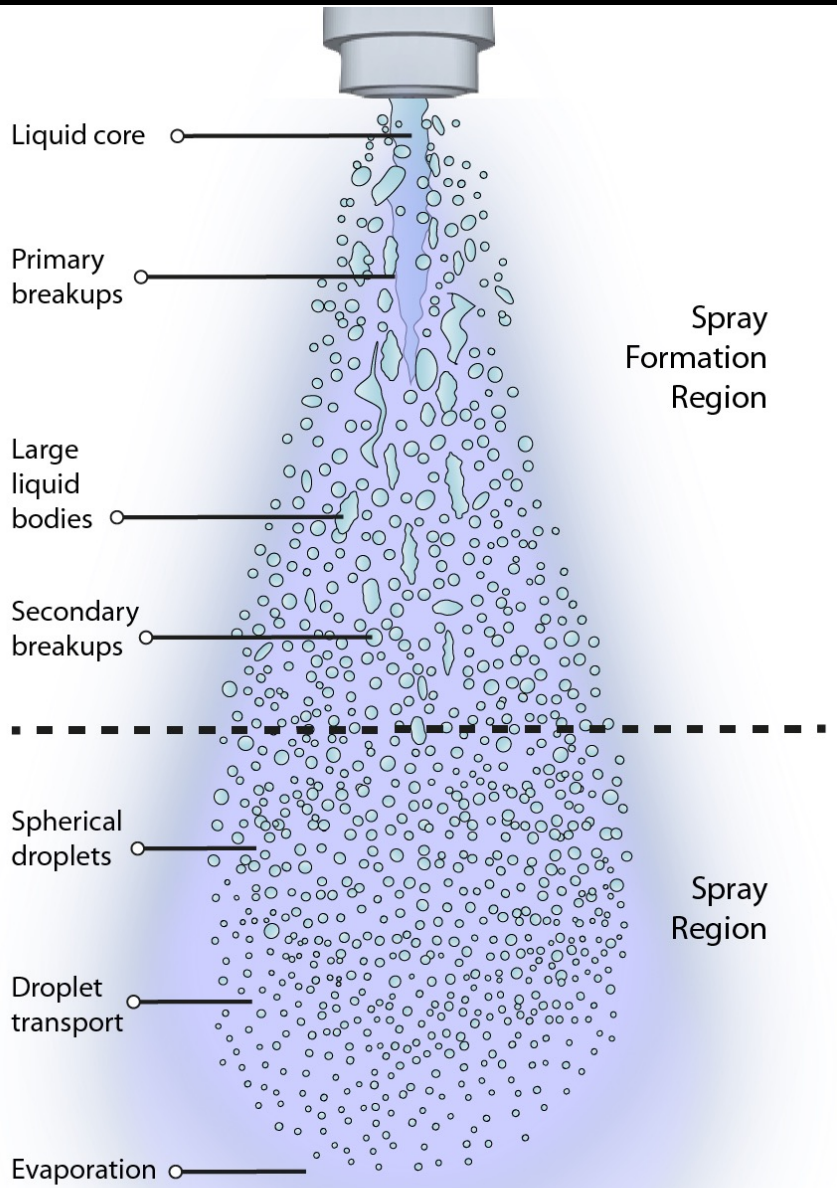


Gas Turbines Applications: Aero Engines



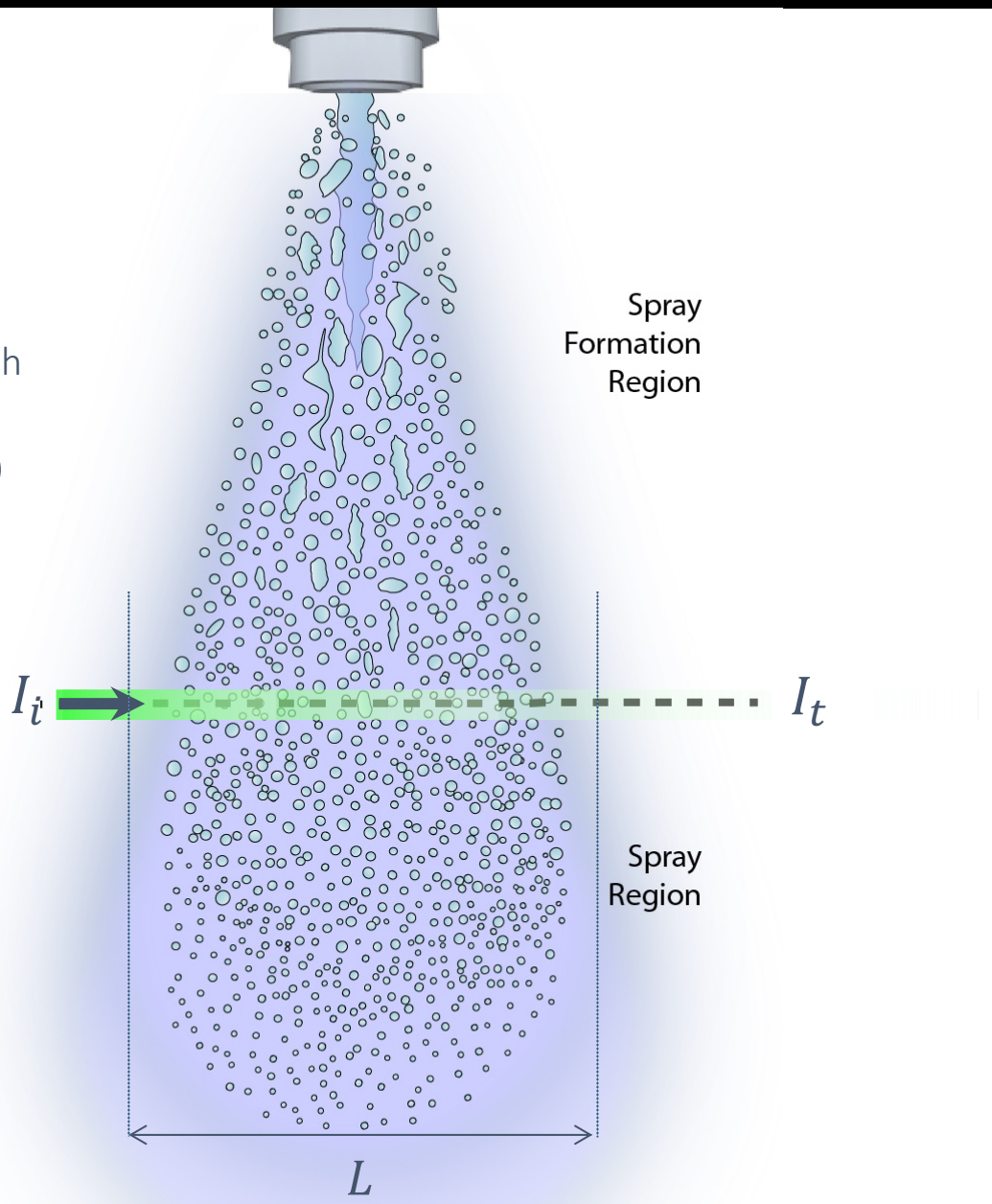
Atomizing sprays



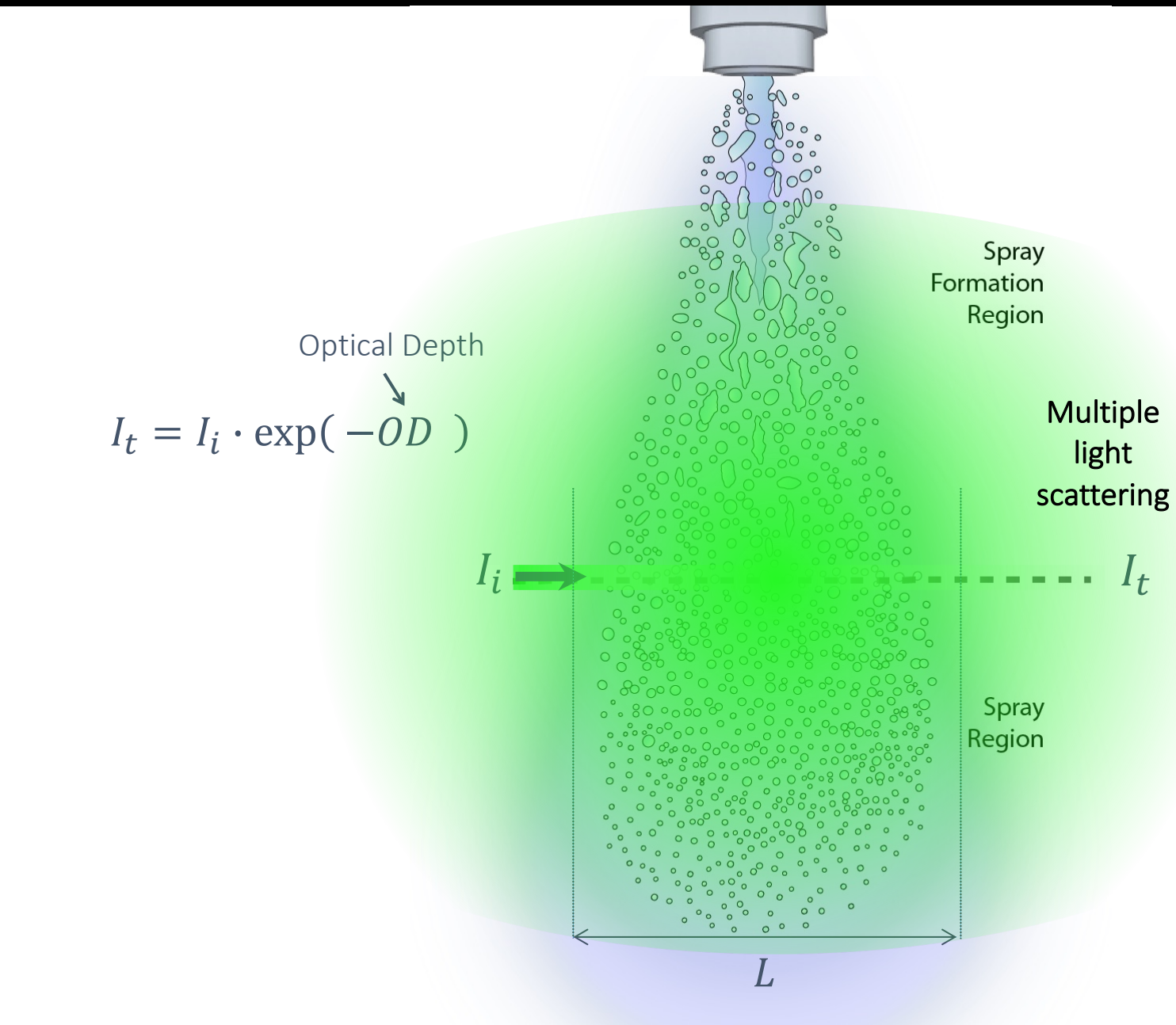
Atomizing sprays

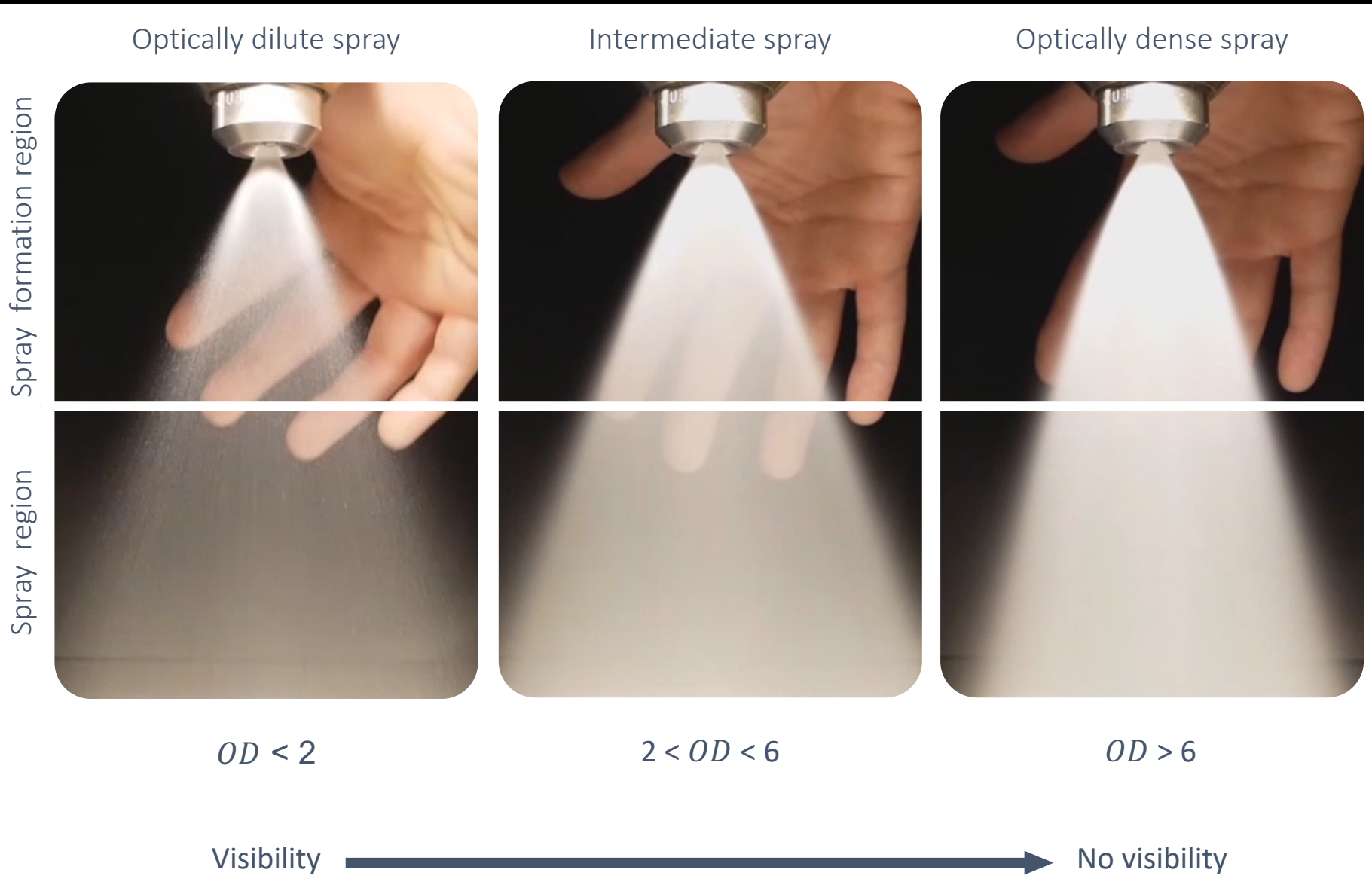
Optical Depth

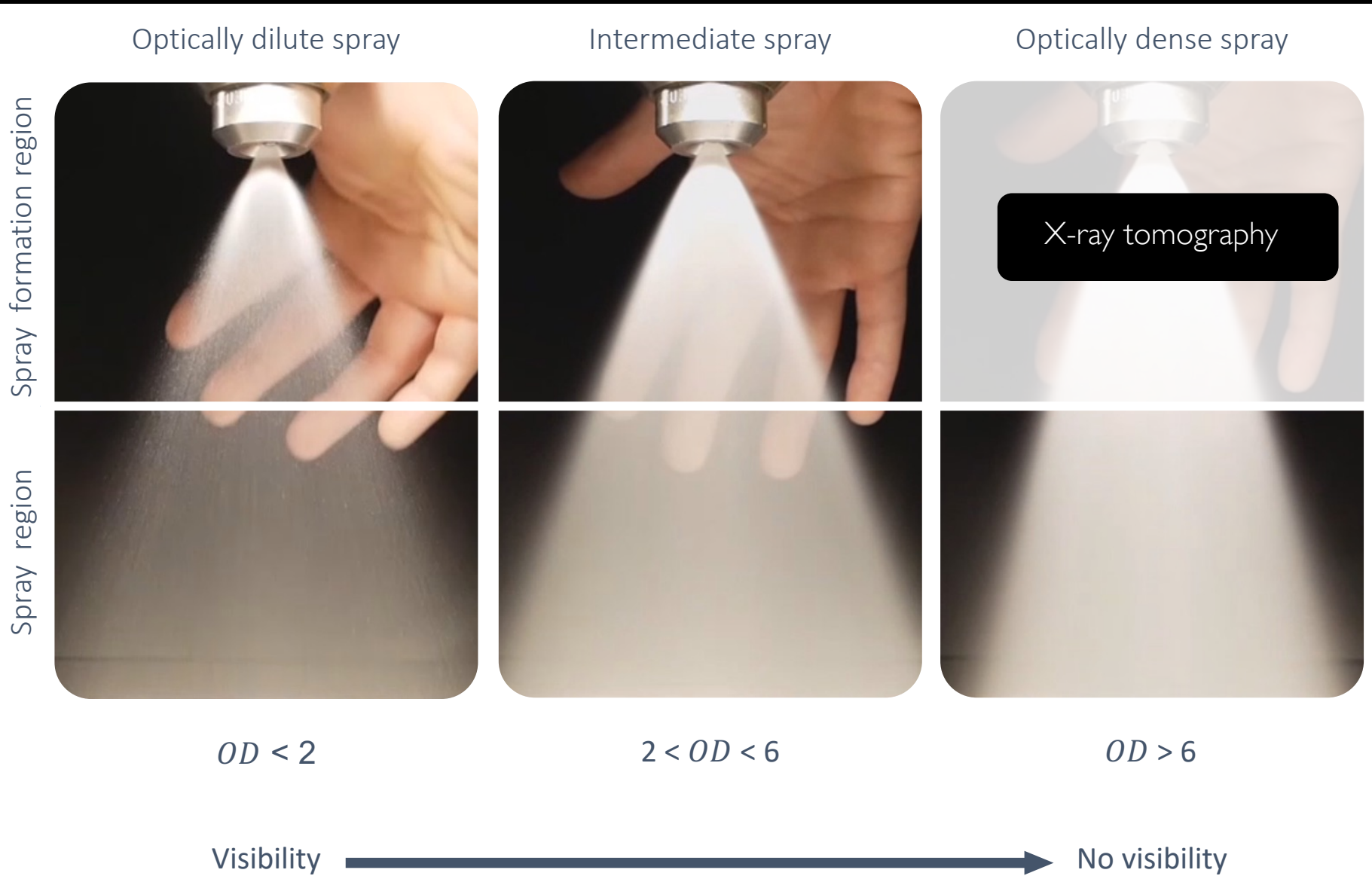
$$I_t = I_i \cdot \exp(-OD)$$



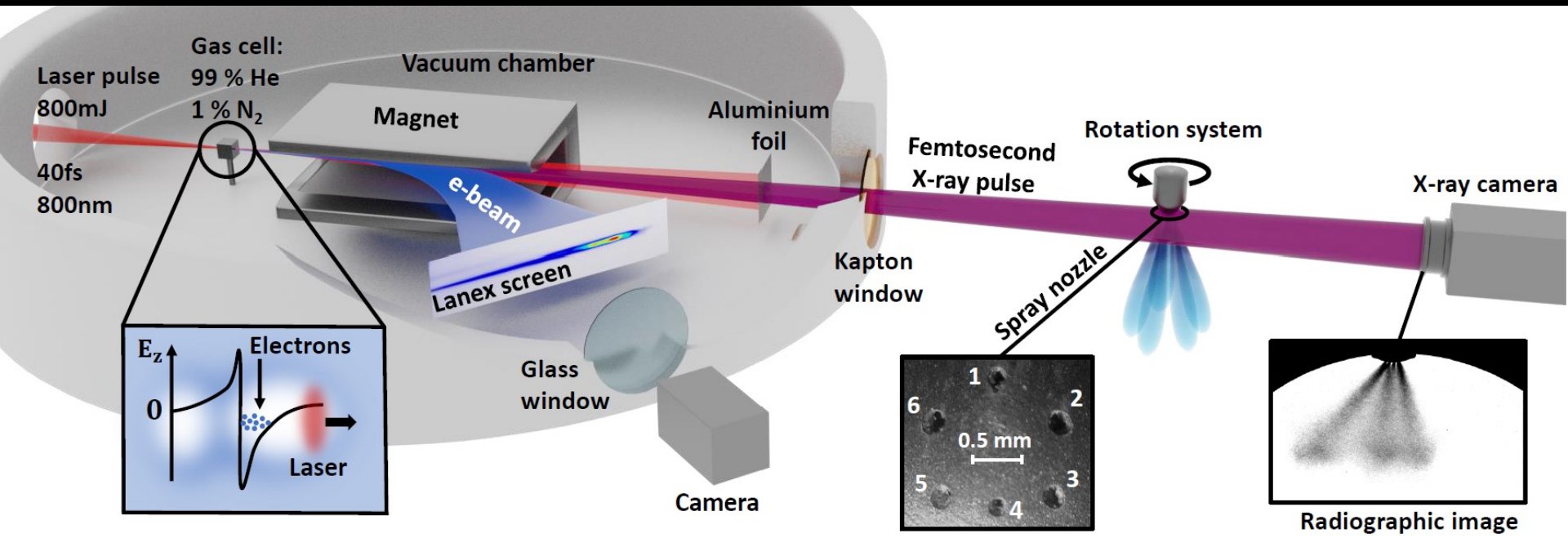
Atomizing sprays

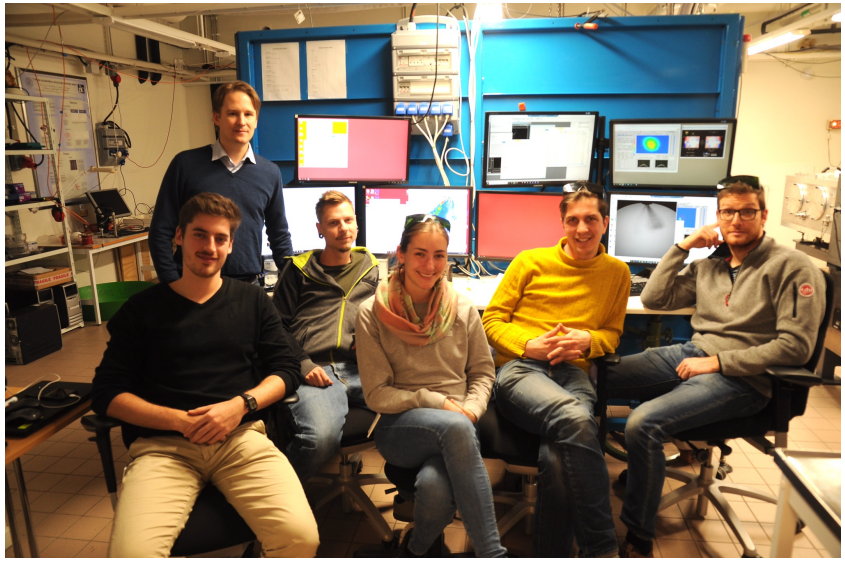



Optically dilute spray
Intermediate spray
Optically dense spray
Spray formation region
Spray region
$OD < 2$
$2 < OD < 6$
$OD > 6$
Visibility
No visibility


Optically dilute spray
Intermediate spray
Optically dense spray
Spray formation region
Spray region
X-ray tomography
$OD < 2$
$2 < OD < 6$
$OD > 6$
Visibility
No visibility

Experimental setup





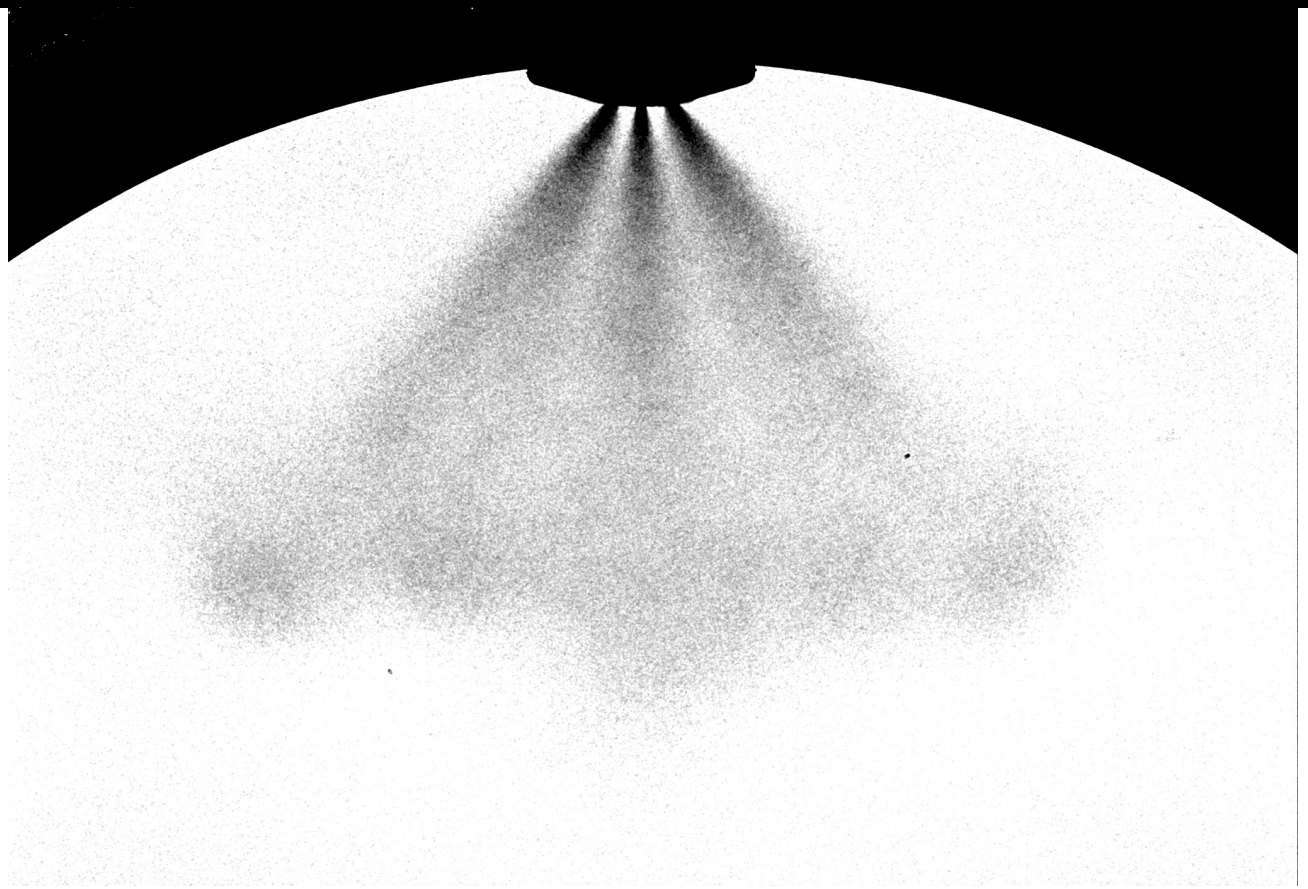
X-ray absorption

0°

X-ray absorption

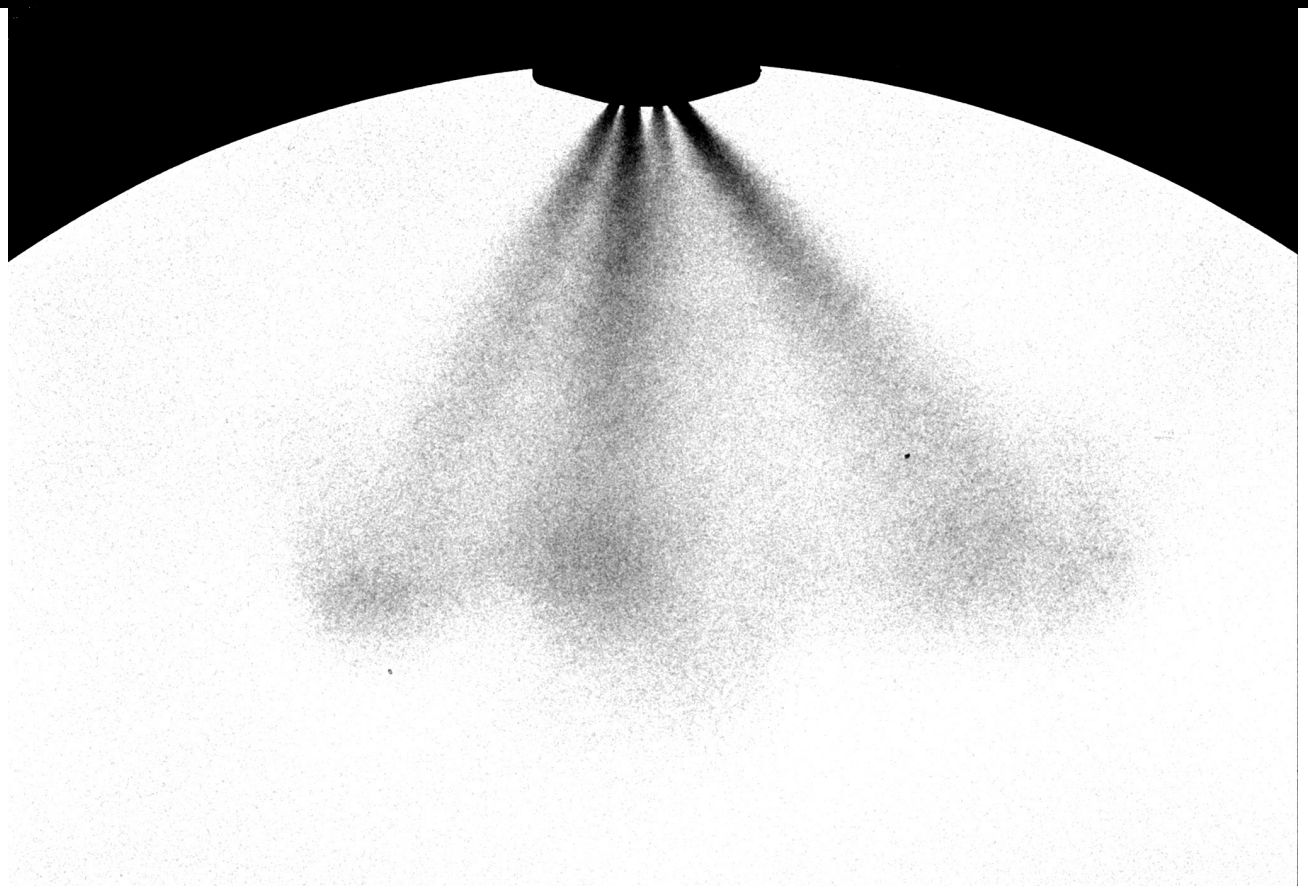
20°

X-ray absorption



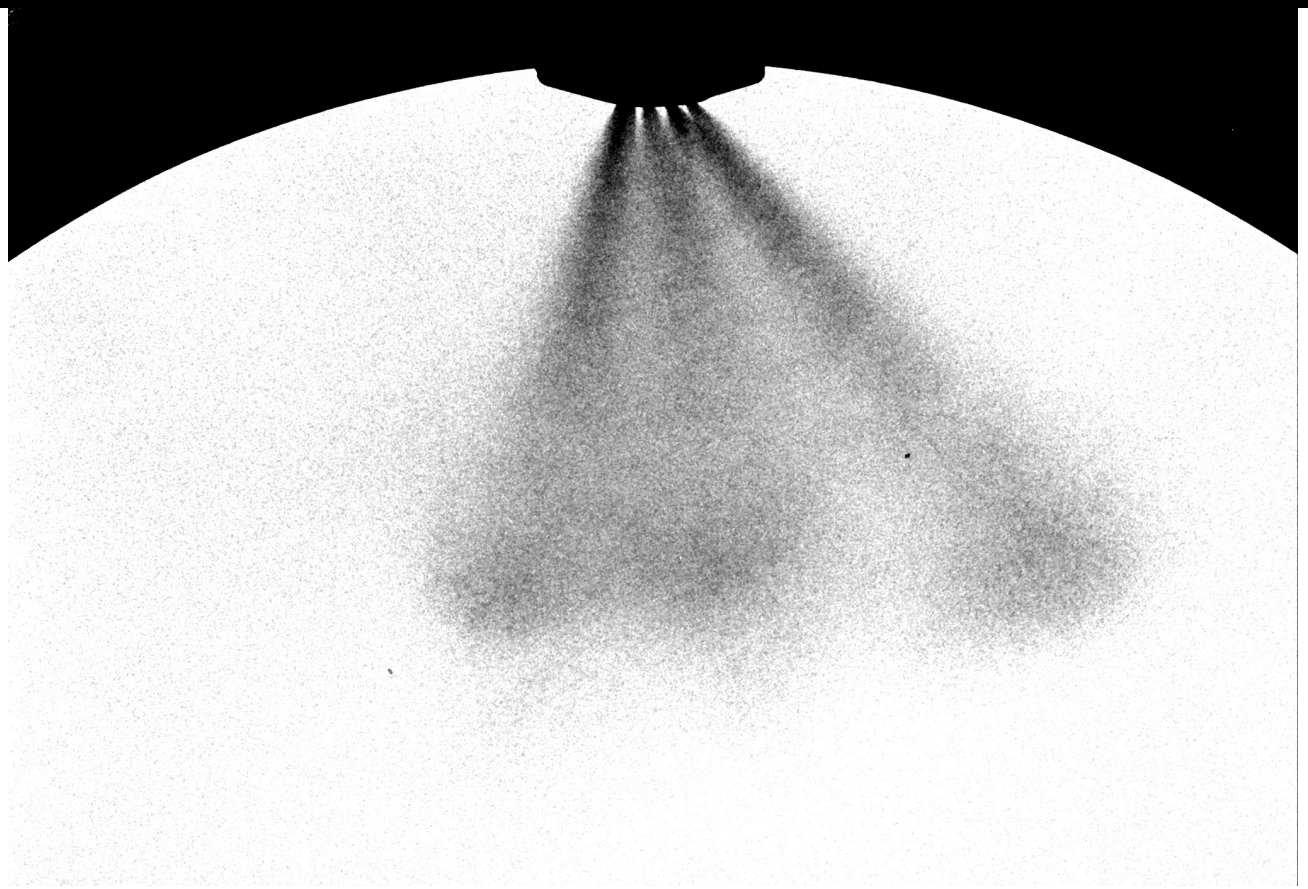
40°

X-ray absorption



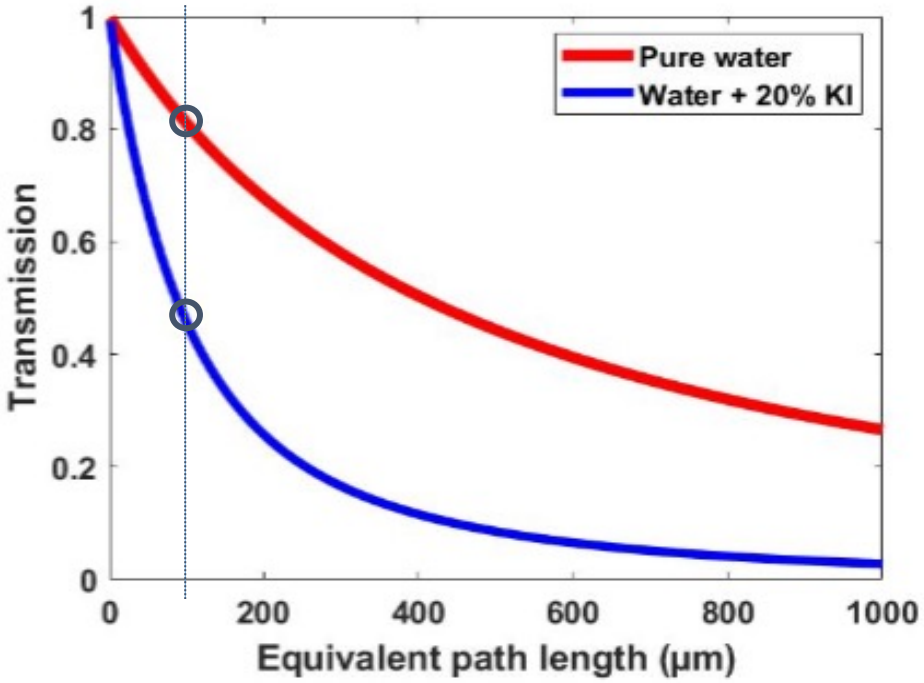
60°

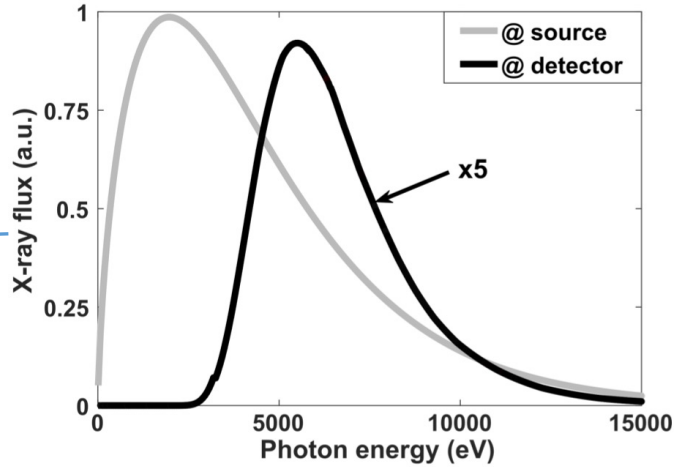
X-ray absorption



80°

Path length from absorption

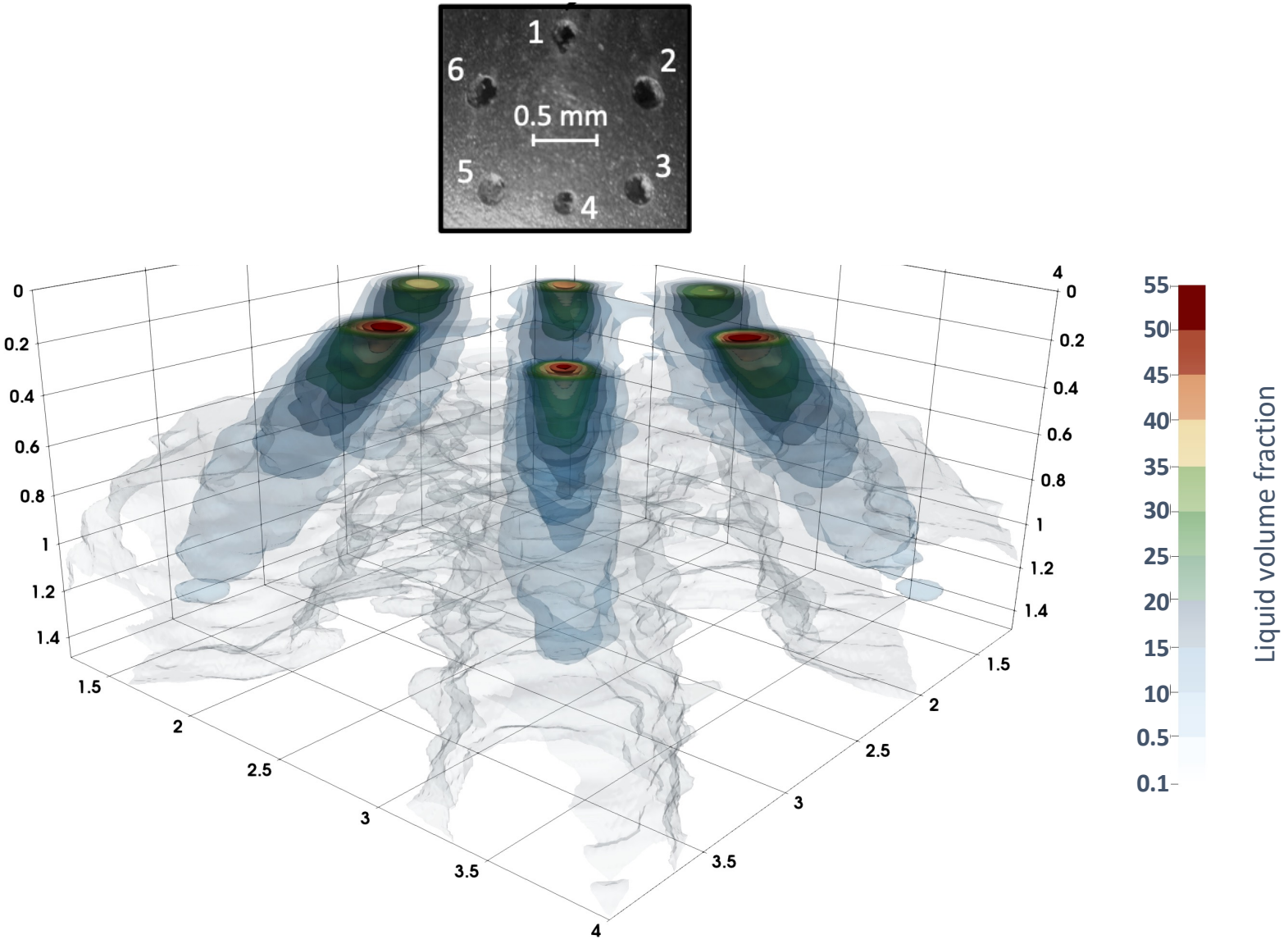




100 µm of water transmit 80% of the light

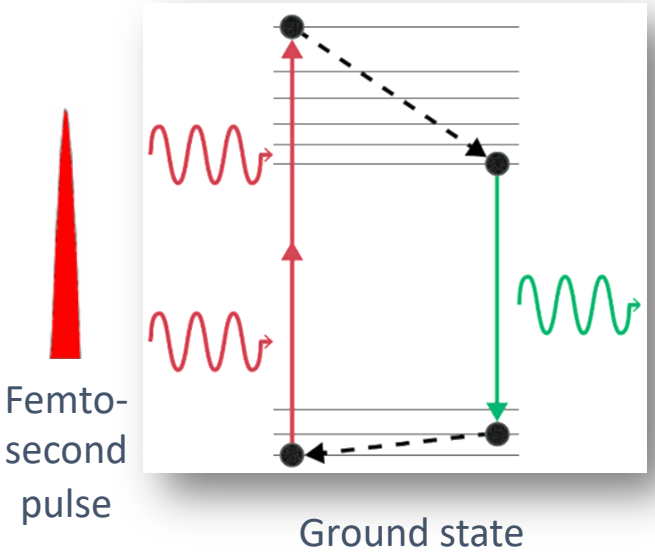
Adding 20% KI (potassium iodide), the transmission drops to 45%

Transient spray tomography

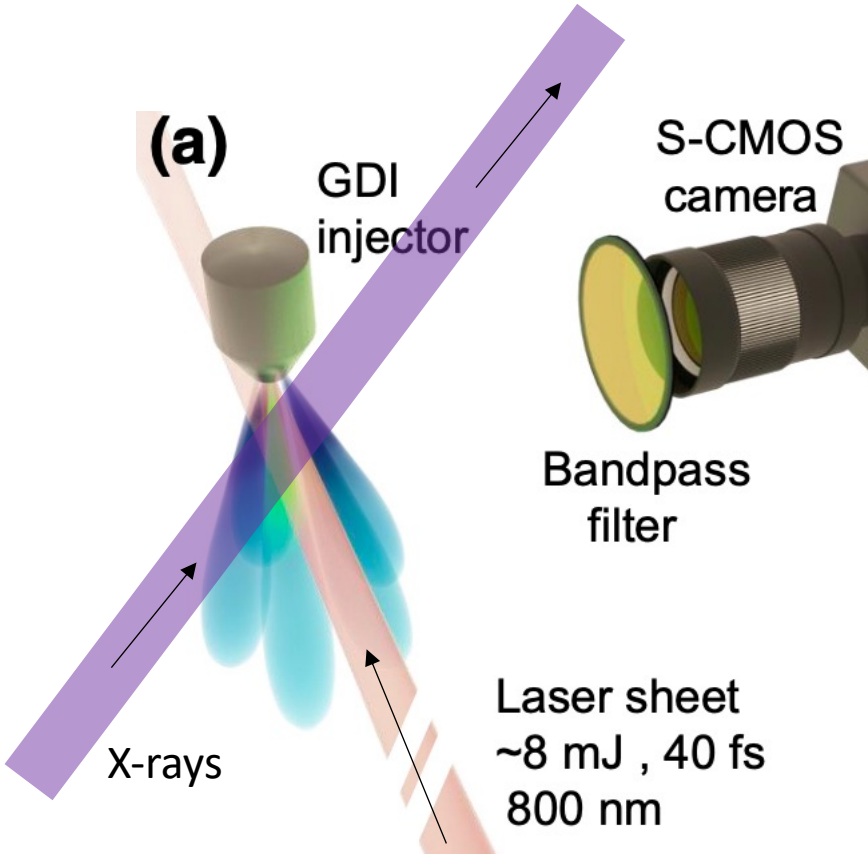


Combining X-rays and flourescence

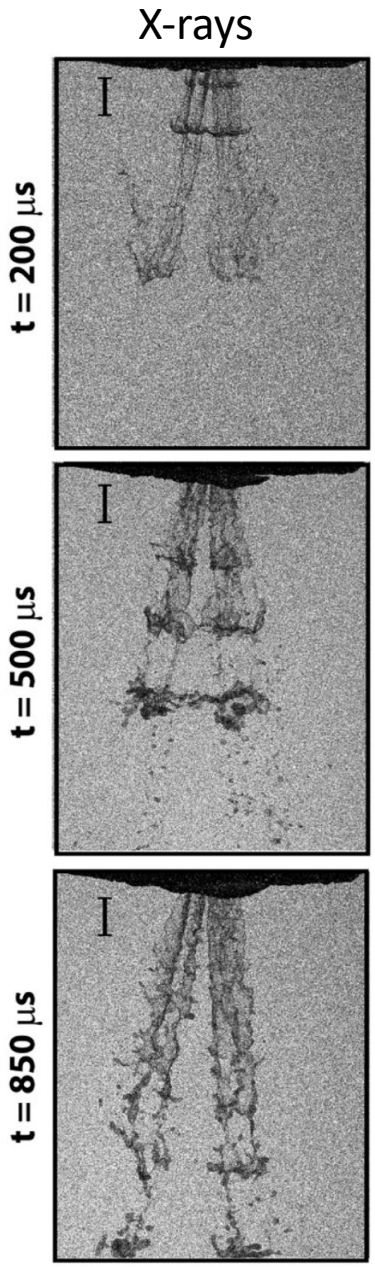
2-photon laser-induced flourescence



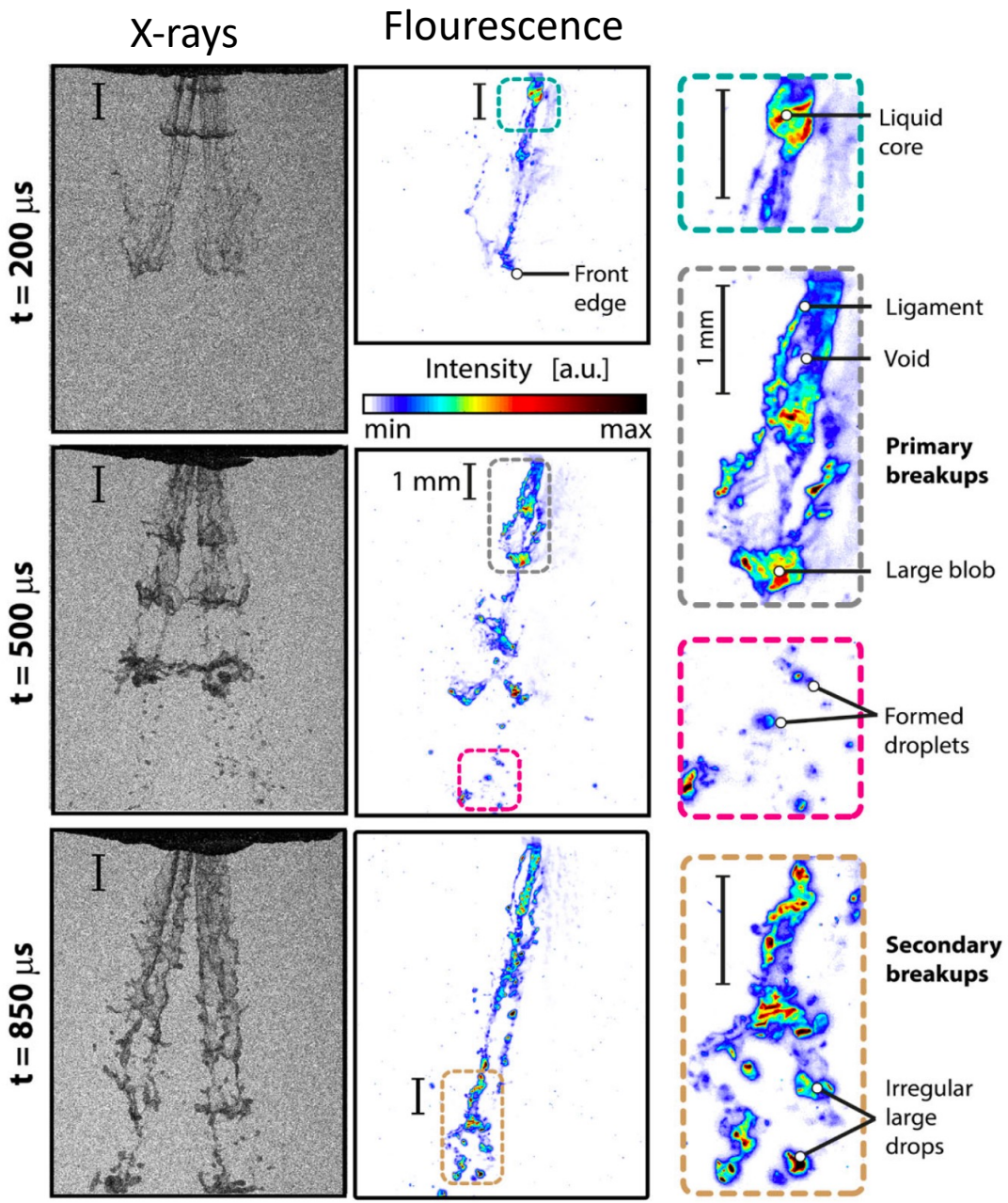
Technique developed by
Edouard Berrocal (Lund University)



Simultaneous recordings



Simultaneous recordings

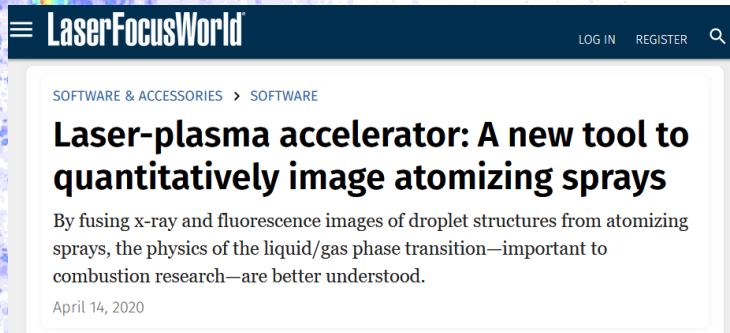


Summary

Understanding breakup and atomization of sprays is essential for improving e.g. engine efficiencies.

Challenges Fast dynamics (ns to µs)
Highly scattering media
Multiple jets in the same spray

Approach **Mass flow:** X-ray imaging
Atomization: 2-photon LIF



D. Guenot *et al*, Phys Rev Applied **17**, 064056 (2022)

H. Ulrich *et al*, Phys of Fluids **34**, 083305 (2022)

D. Guenot *et al*, Optica **7**, 131-134 (2020)

Thank you for the attention !

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Lars Zigan
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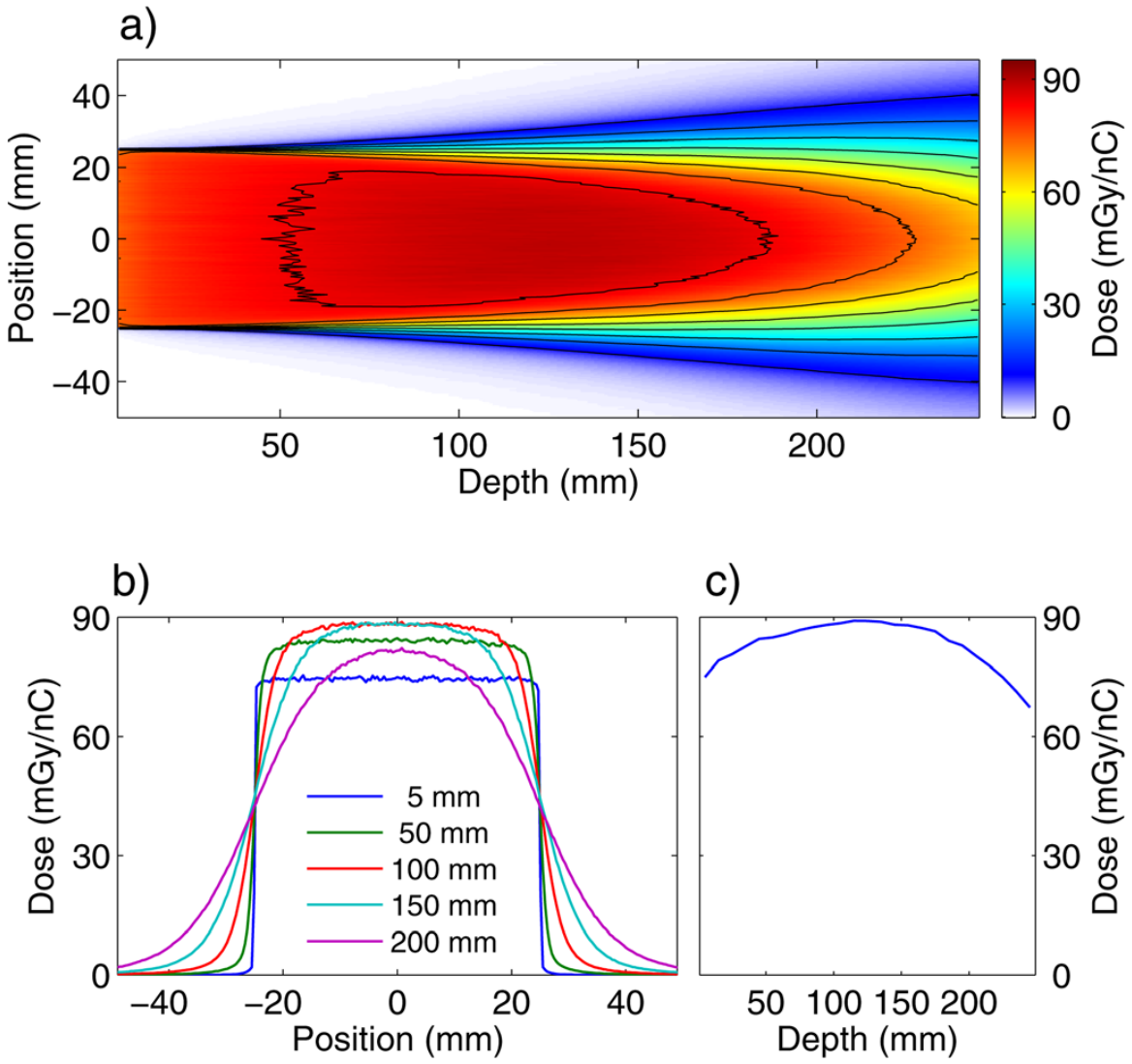
Knut and Alice Wallenberg Foundation

VETENSKAPSRÅDET
THE SWEDISH RESEARCH COUNCIL

Wide irradiation field (simulation)



Lundh *et al*, Medical Phys. 39, 3501-3508 (2012)