Development of Applications for Laser Wakefield Acceleration

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Extreme Light Infrastructure Summer School

ELI ALPS Facility, Szeged, Hungary

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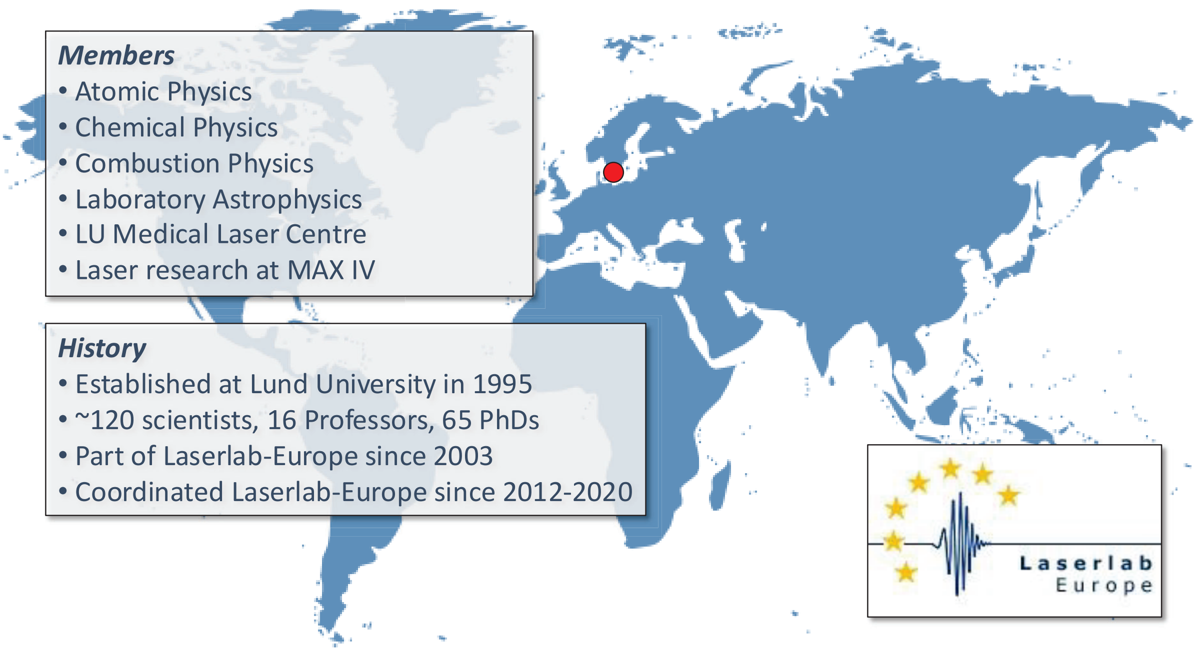
Lasers and accelerators in Lund
Lund University / Lund Laser Centre
High-power lasers
MAX IV Laboratory
3 GeV electron synchrotron
European Spallation Source
2 GeV proton linac

Lund Laser Centre

LLC
LUND LASER CENTRE

An organisation for laser, optics and spectroscopy research



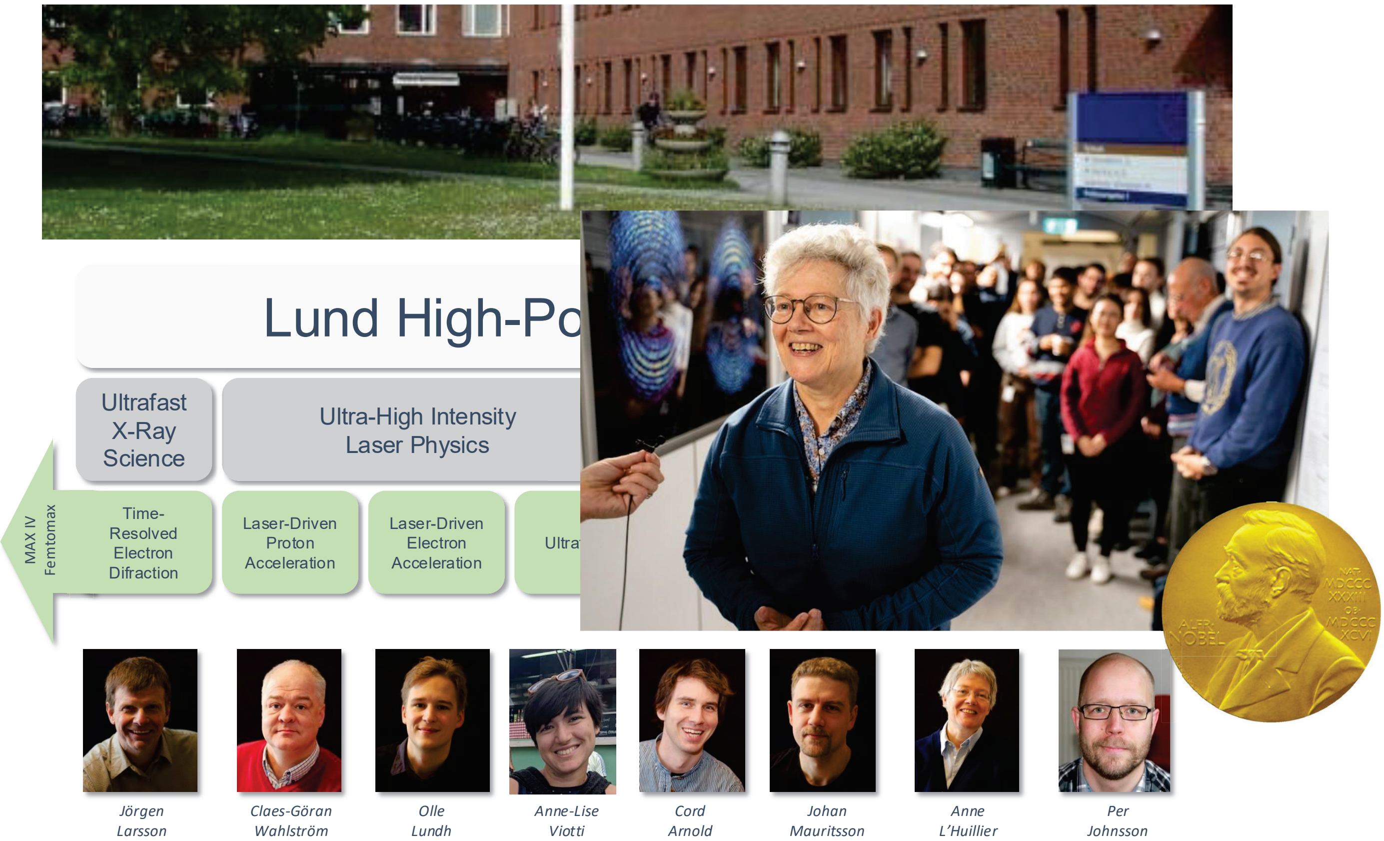
Members

- Atomic Physics
- Chemical Physics
- Combustion Physics
- Laboratory Astrophysics
- LU Medical Laser Centre
- Laser research at MAX IV

History

- Established at Lund University in 1995
- ~120 scientists, 16 Professors, 65 PhDs
- Part of Laserlab-Europe since 2003
- Coordinated Laserlab-Europe since 2012-2020

Laserlab
Europe



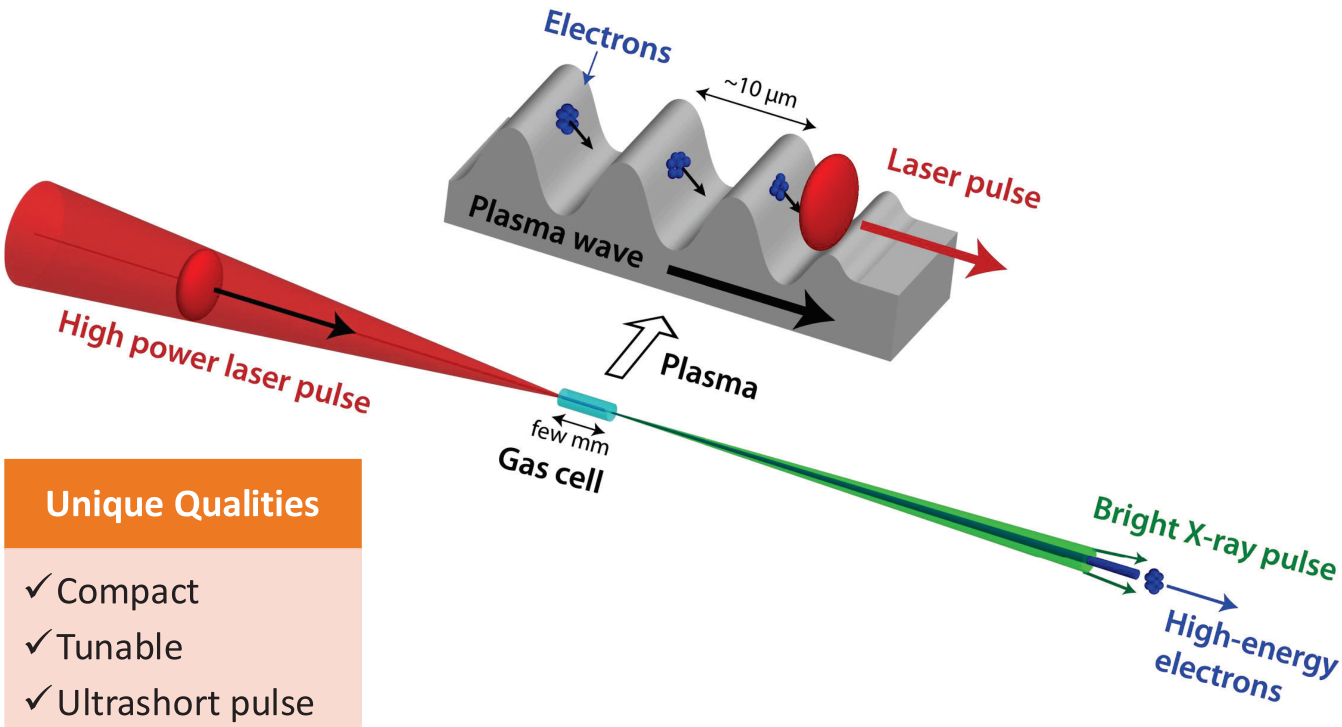
Lund High-Po
Ultrafast X-Ray Science
Ultra-High Intensity Laser Physics
MAX IV Femtomax
Time-Resolved Electron Difraction
Laser-Driven Proton Acceleration
Laser-Driven Electron Acceleration
Ultra
Jörgen Larsson
Claes-Göran Wahlström
Olle Lundh
Anne-Lise Viotti
Cord Arnold
Johan Mauritsson
Anne L'Huillier
Per Johnsson
ALFR. NOBEL

Lasers at the Lund High Power Facility

High repetition rate OPCPA	850 nm	200 kHz	15 µJ	6 fs
High repetition rate SWIR	2 µm	200 kHz	15 µJ	15 fs
Ytterbium laser	1 µm	10 KHz	700 µJ	200 fs
Titanium sapphire laser	800 nm	3 kHz	5 mJ	20 fs
High energy OPCPA	800 nm	100 Hz	50 mJ	9 fs
		10 Hz	250 mJ	9 fs
Titanium sapphire laser (retired)	*800 nm*	*5 Hz*	*1.2 J*	*30 fs*

OPCPA: Optical parametric chirped pulse amplification
SWIR: Short wave infrared

Laser-plasma acceleration and X-ray generation



Unique Qualities

- ✓ Compact
- ✓ Tunable
- ✓ Ultrashort pulse

O Lundh *et al*, Nature Physics **7**, 219–222 (2011)
J B Svensson *et al*, Nature Physics **17**, 639–645 (2021)

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.

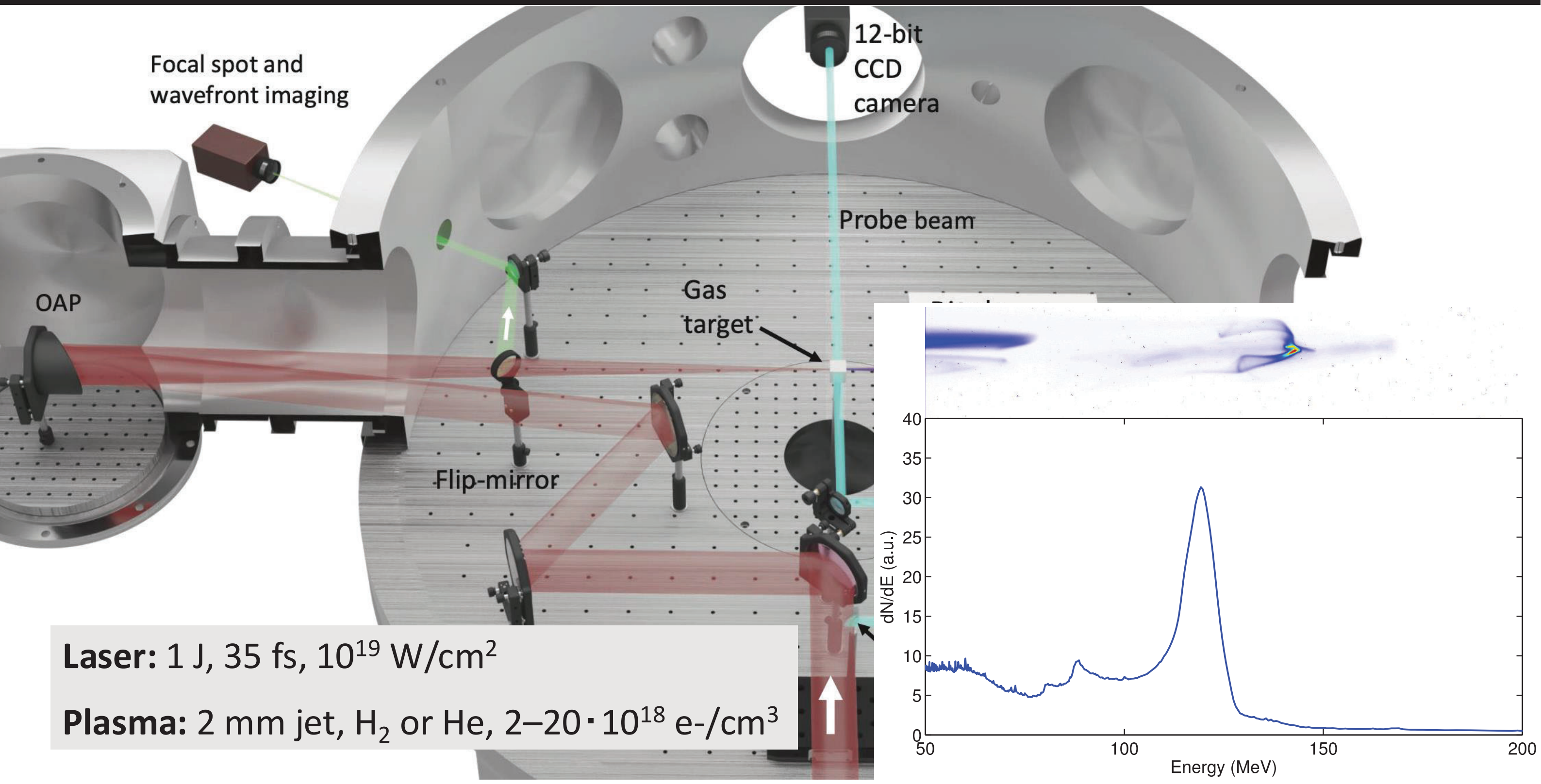
Industry

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.

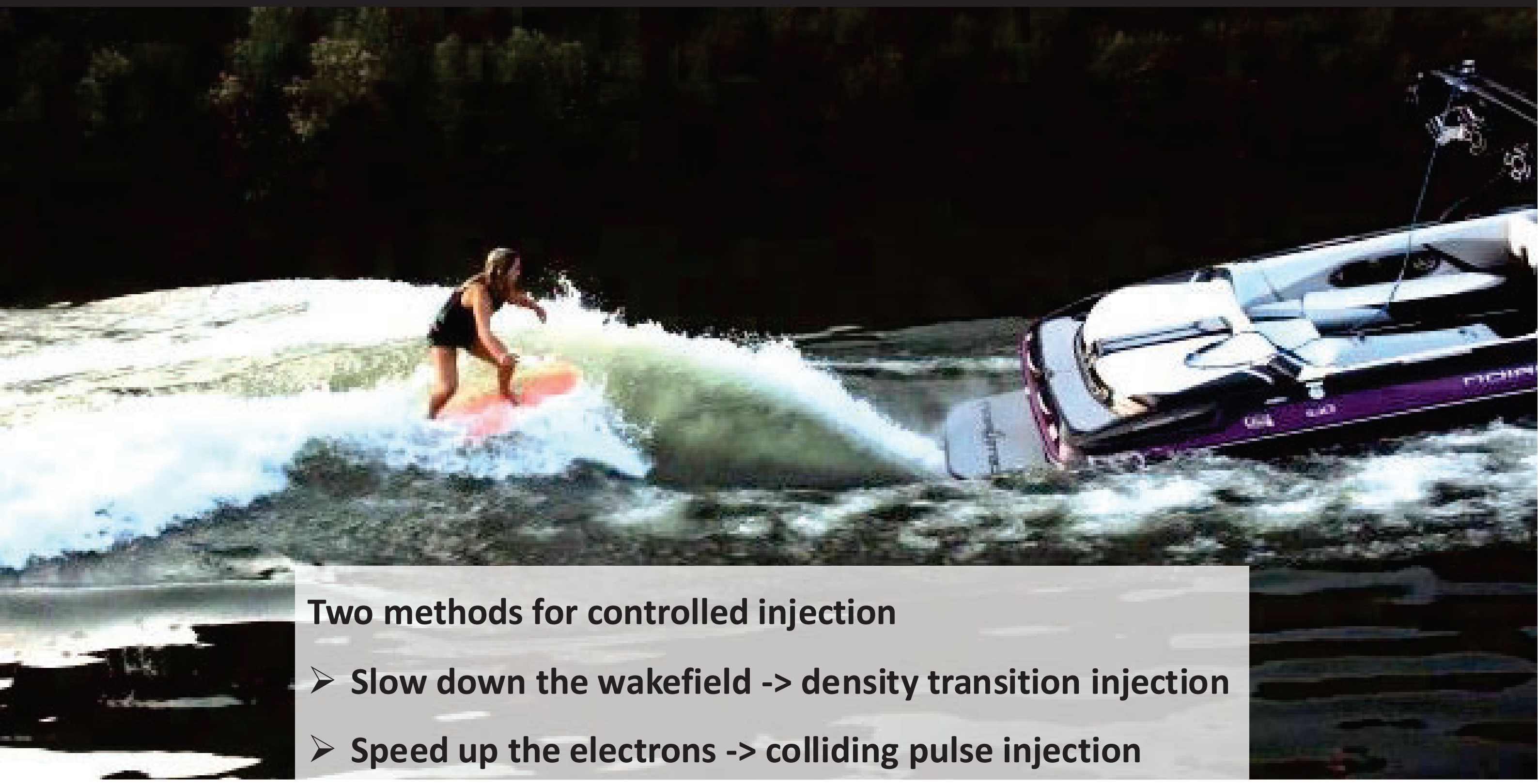
Security

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

Typical experiment



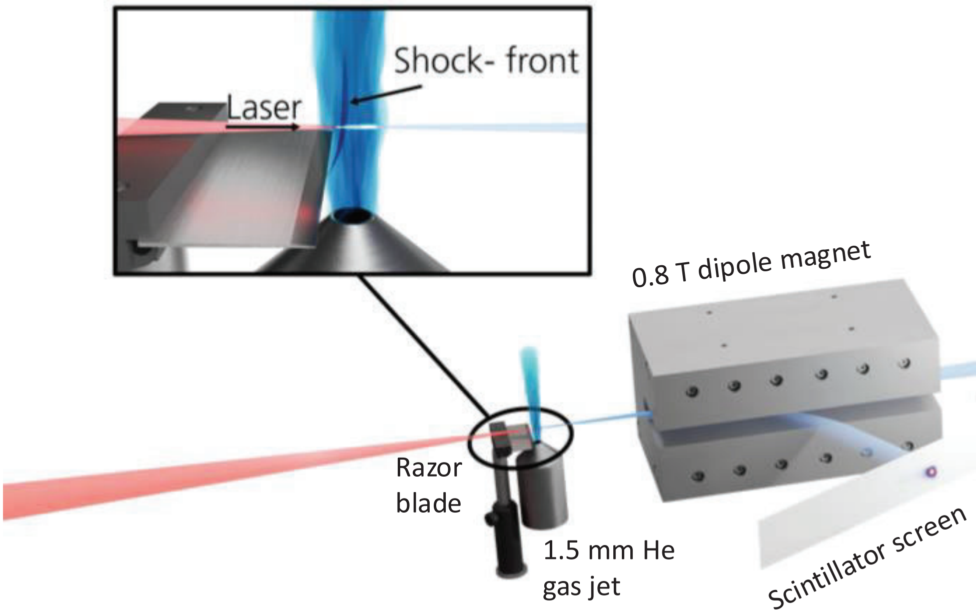
Surfing the wake wave

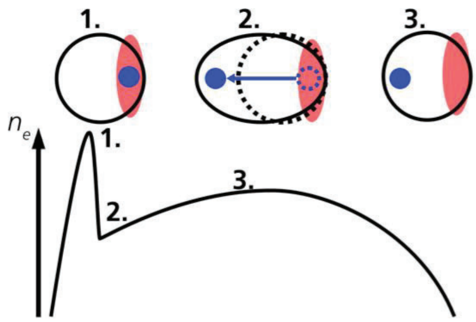


Two methods for controlled injection

- ➢ **Slow down the wakefield -> density transition injection**
- ➢ **Speed up the electrons -> colliding pulse injection**

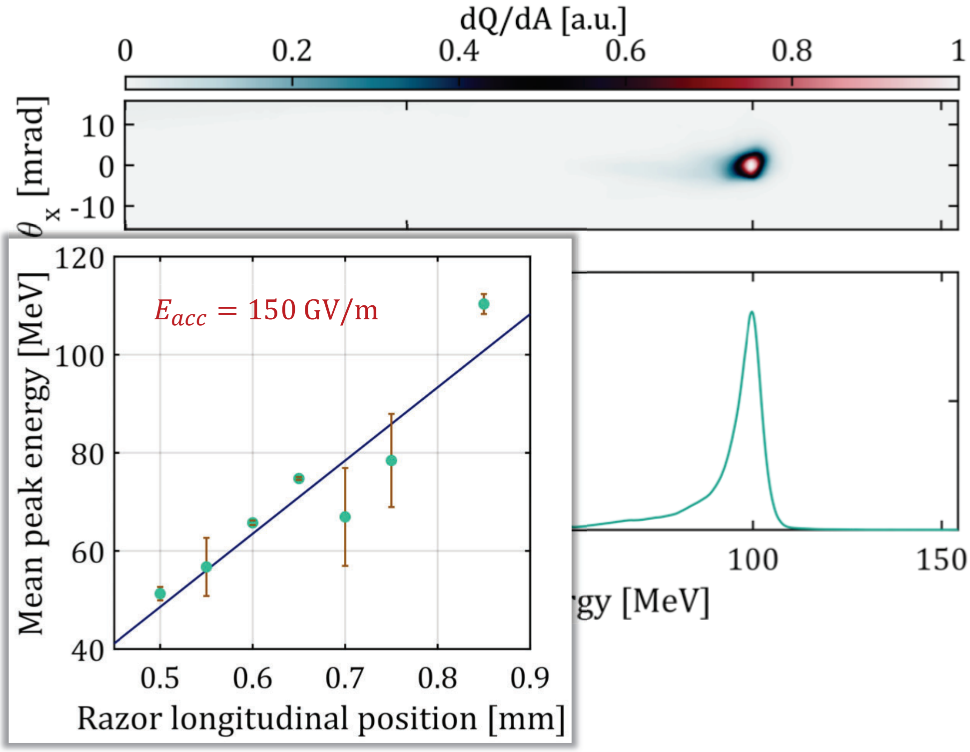
Setup for shock-front injection



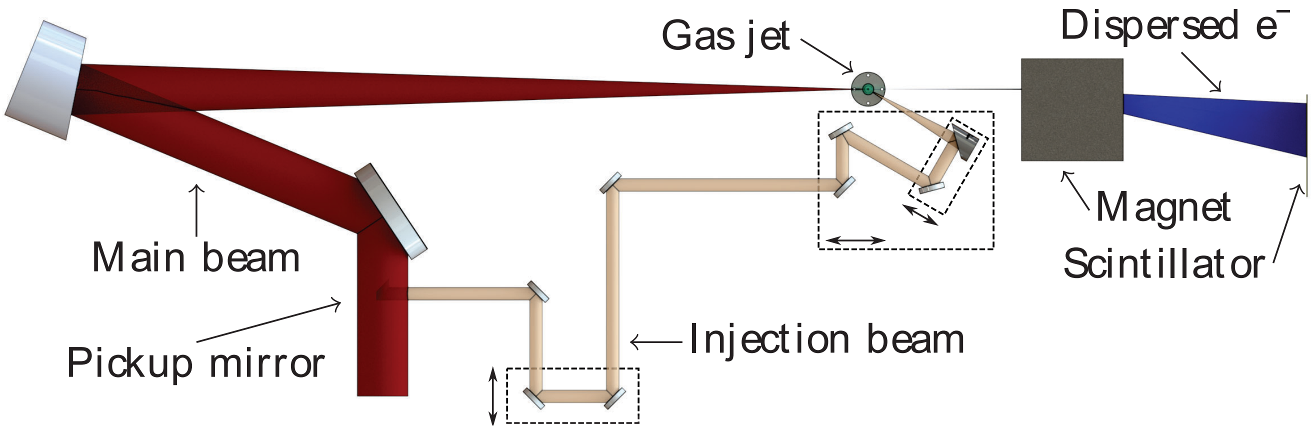


Cornelia did this experiment

Beam quality and tunability



Setup for colliding pulse injection



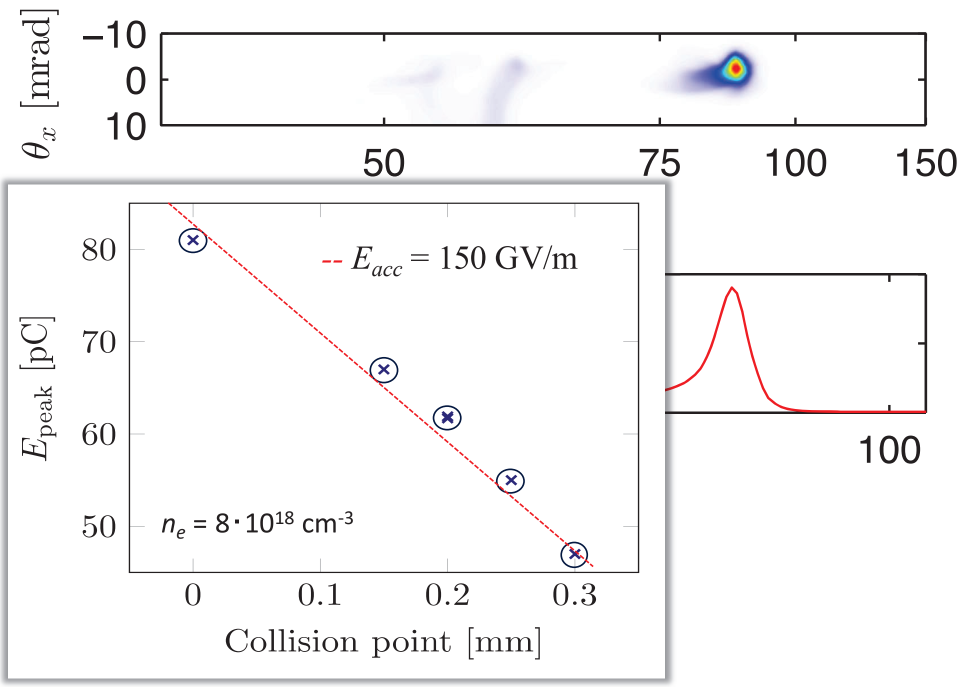
Pump laser: 500 mJ, 40 fs, 3×10^{18} W/cm^2

Injection laser: 40 mJ, 40 fs, 1×10^{18} W/cm^2

Hansson *et al*, NIMA 829, 99-103 (2016)

Martin did the experiment

Beam quality and tunability



E_{peak} = 86 MeV

Q_{peak} = 2 pC

$\Delta\theta$ = 4 mrad

$\Delta E/E$ = 3.5%

Hansson *et al*, NIMA 829, 99-103 (2016)

Outline

Controlled injection and acceleration

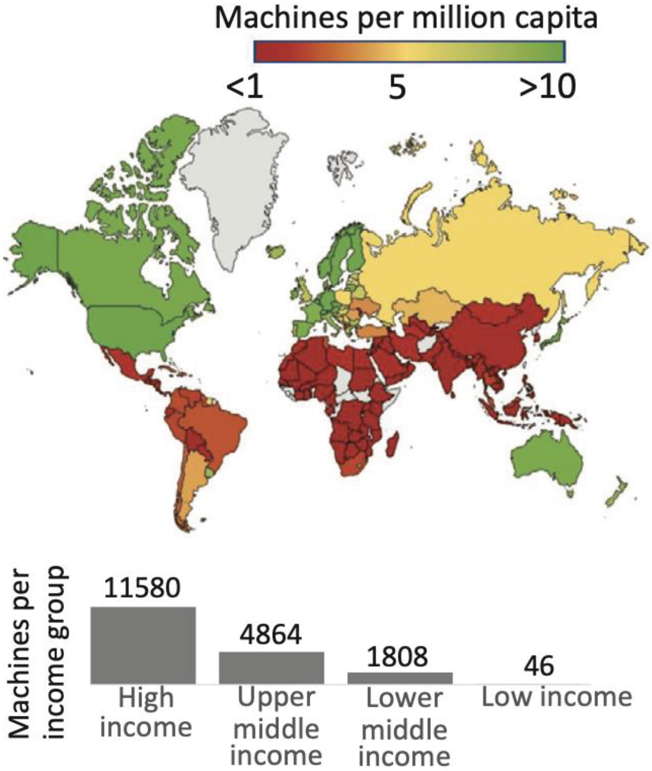
High energy electrons for radiotherapy

X-rays for (time-resolved) tomography

Hard X-rays for radiography

Towards laser-based FELs

Number of radiotherapy machines per million citizens

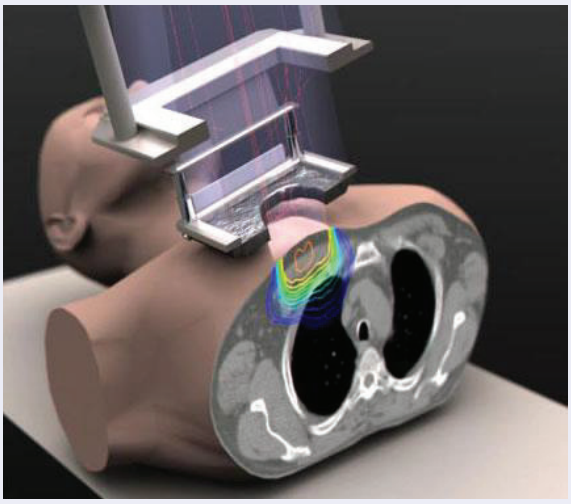


Low energy electron radiotherapy

Clinical oncology machine

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

Direct electron irradiation



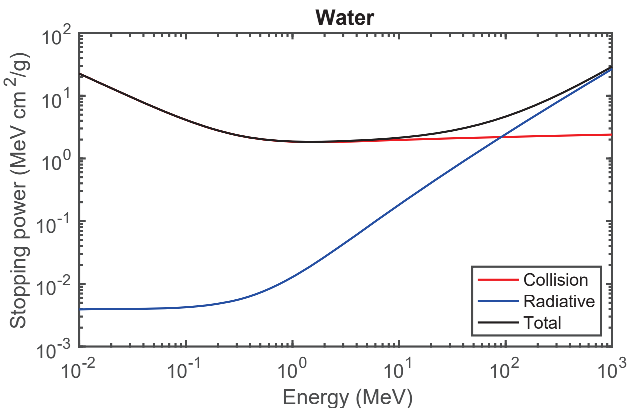
- Electrons have limited range
- Underlying structures spared

Stopping power and dose

Low energy electrons primarily lose energy through **collisions** which leads to **ionization** and **excitation**. Contributes to the dose **near the track**.

High-energy electrons primarily lose energy by **radiation (bremsstrahlung).** Energy spent is **carried away** from the track by photons.

The stopping power is the mean rate of energy loss $S(x) = -\frac{dE}{dx}$



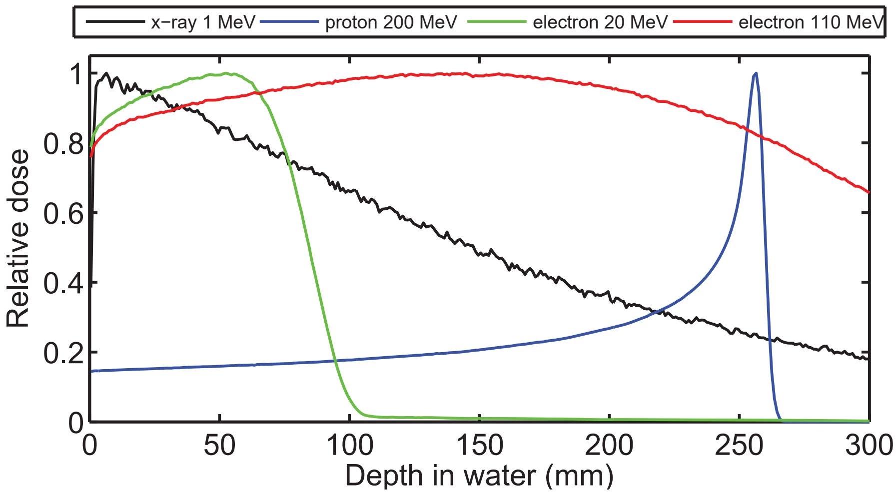
Locally deposited dose is

$$D(x) = \Phi \frac{S_{col}(x)}{\rho}$$

where Φ is particle flux density

Databases ESTAR and PSTAR calculate stopping-power for electrons and protons fr many materials
https://www.nist.gov/pml/stopping-power-range-tables-electrons-protons-and-helium-ions

Dose deposition for different particles



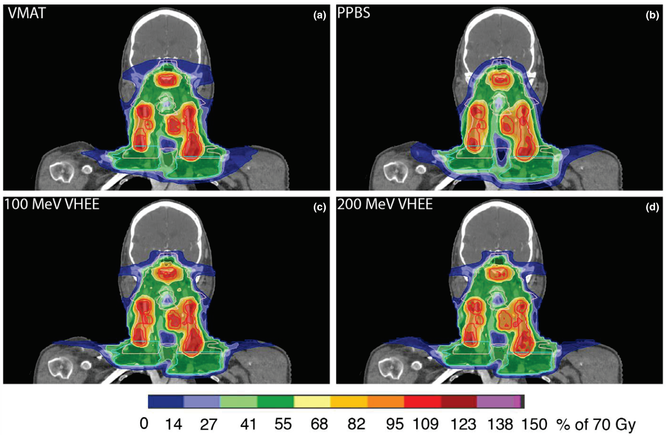
Low energy electrons < 20 MeV widely used for superficial tumours

High energy electrons > 100 MeV not yet available in hospitals

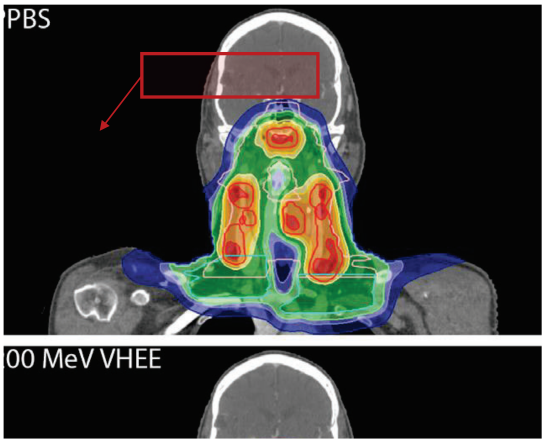
Can high-energy electrons be useful for radiotherapy?

Potential advantage of high energy electrons

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



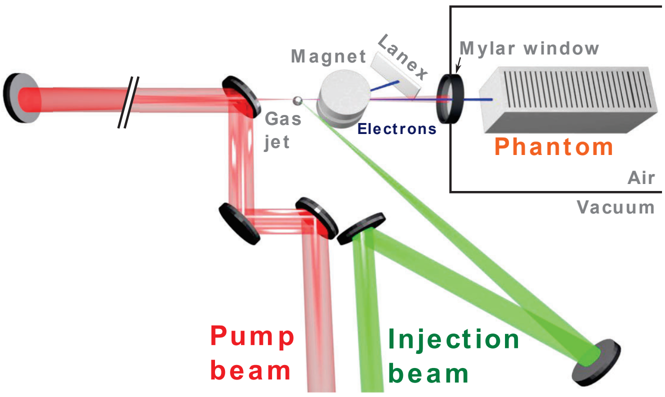
VHEE Very High Energy Electrons



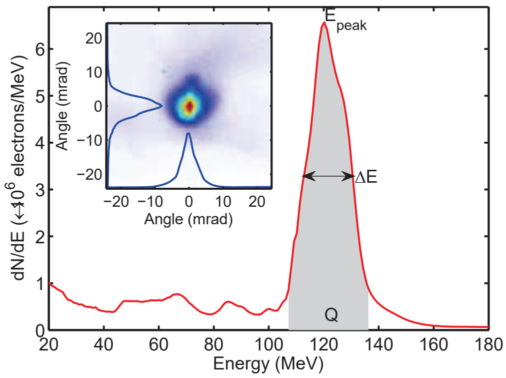
Compared to X rays (IMRT, VMAT), high-energy electrons (100-200 MeV) can give

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

Experimental setup



Electron beam: 120 MeV

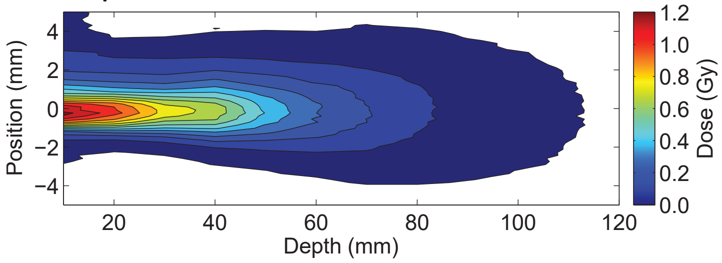


Blocks of polystyrene (10 mm) + Fuji film detectors (40x40 mm^2)

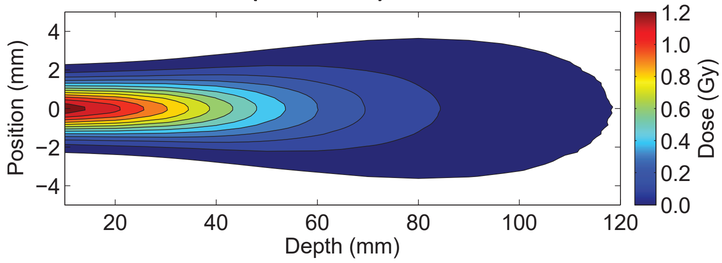
Lundh *et al*, Medical Phys. 39, 3501-3508 (2012)

Measured and simulated dose

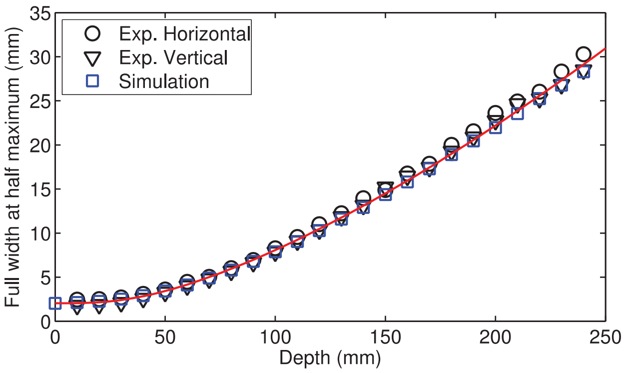
Experiment



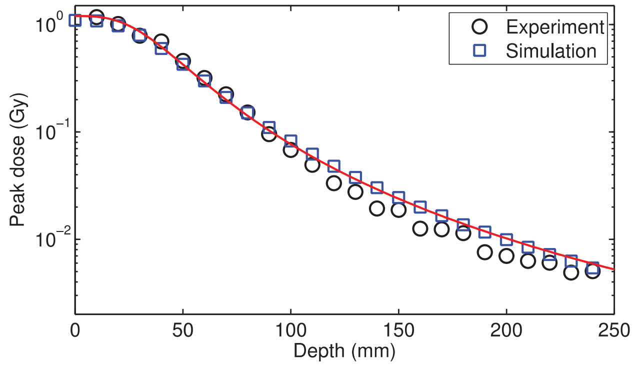
Simulation (Geant4)



Beam size

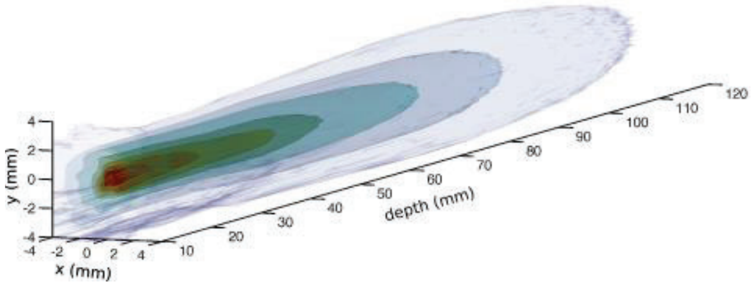


Peak dose



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

Laser-accelerated VHEE's for radiotherapy?



Treatment plan

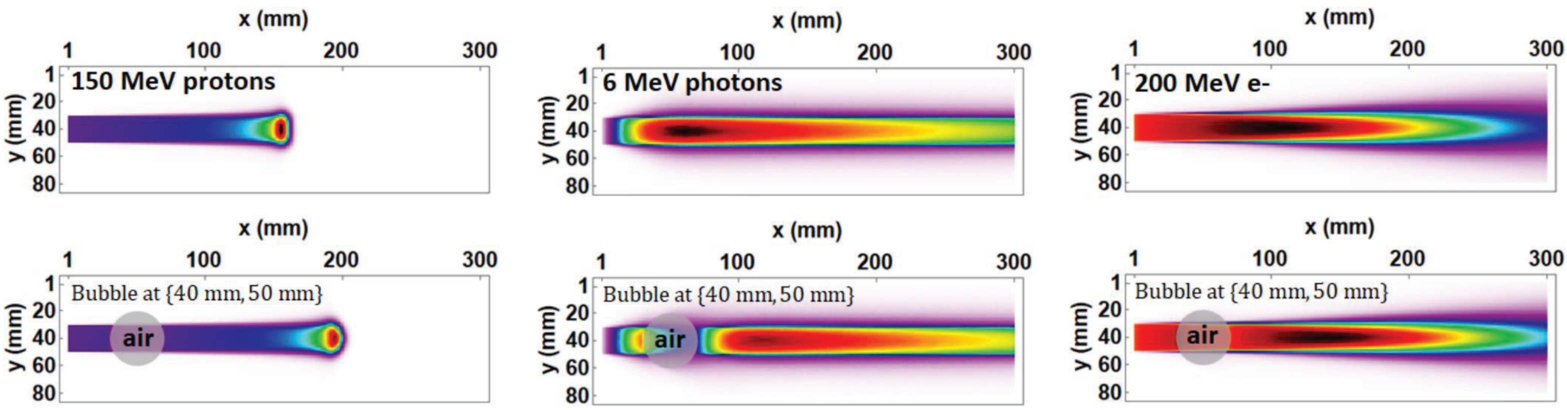
Total treatment dosage: 20-80 Gy
Fractional daily dosage: 2 Gy/day

Laser-plasma beam

1 Gy/shot over 2x2 mm^2
200 shots (20 s): 2 Gy over 20x20 mm^2
Reasonable numbers

Impact of inhomogeneities

- Inhomogeneities (air bubbles, bone, etc.) can negatively impact the dose delivered compared to the dose plan.
- This simulation study shows that the dose deposition by high-energy electrons is less sensitive to inhomogeneities when compared to protons and x-rays. This effect is also confirmed by dose measurements.

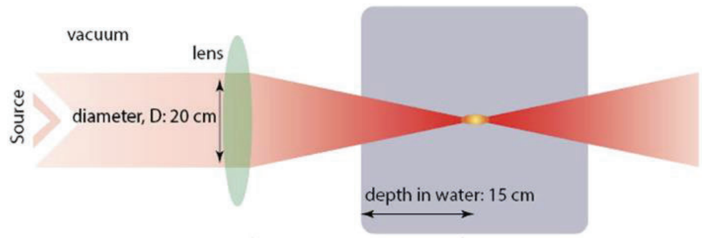


A. Lagzda, Ph.D. Thesis, 2019

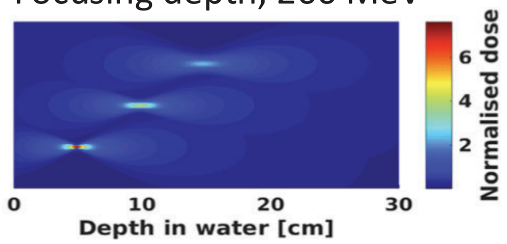
Focused electron beams

Contrary to X-rays, electrons can be magnetically focused to increase the dose at depth.

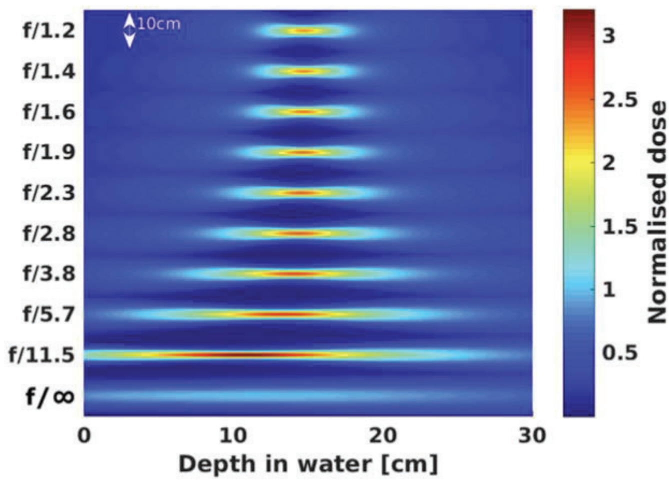
In this simulation study, the influence of the focusing geometry and focusing depth is explored.



Focusing depth, 200 MeV



Focusing geometry, 200 MeV

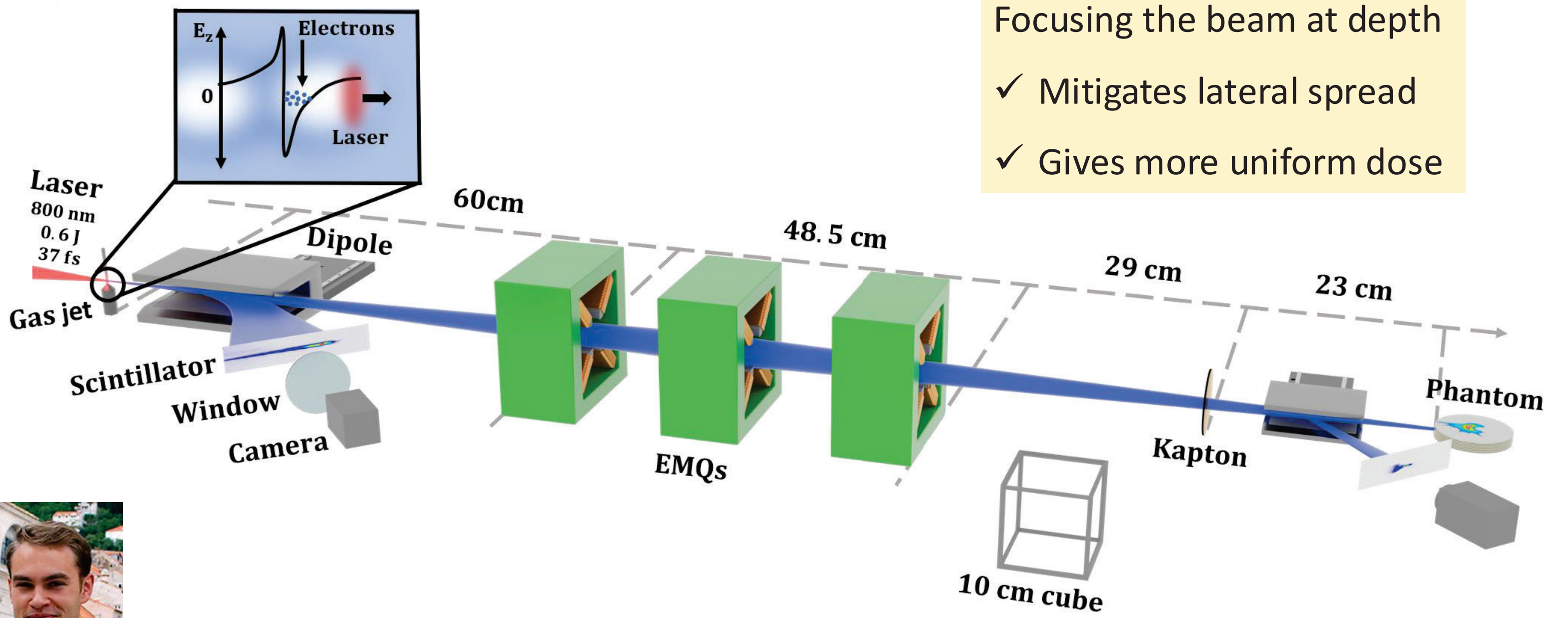


K. Kokurewicz *et al.*, Sci Rep **9**, 10837 (2019)

Beam shaping using EMQ magnets

Focusing the beam at depth

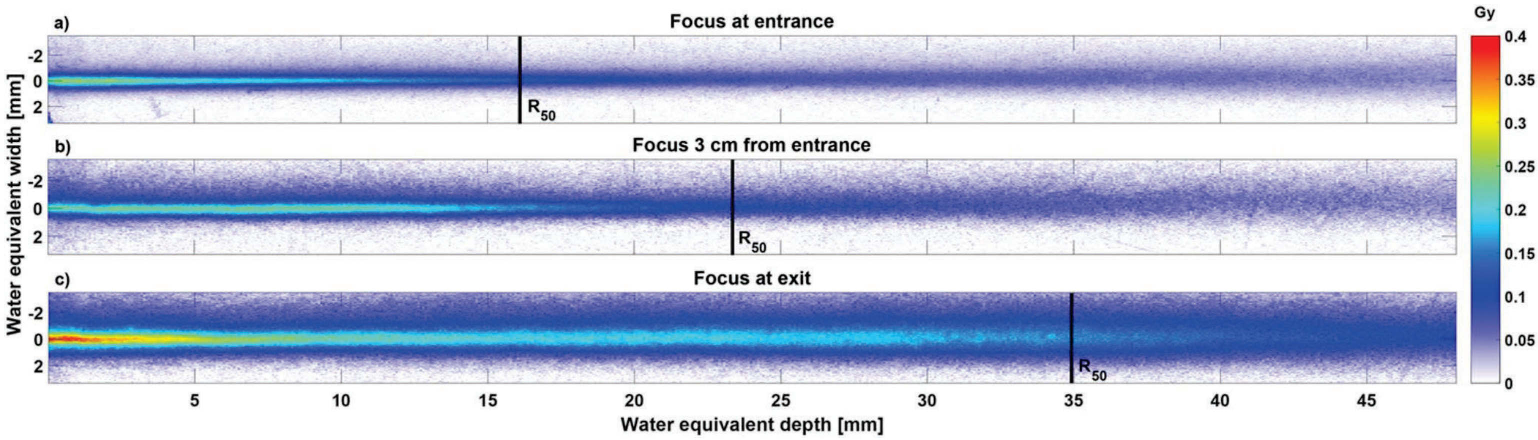
- ✓ Mitigates lateral spread
- ✓ Gives more uniform dose



Jonas designed the beamline

Dose deposition by focused electrons beams

Changing focal plane changes the dose distribution

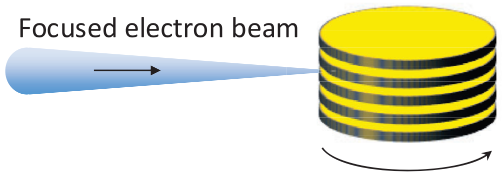


Kristoffer did the measurements

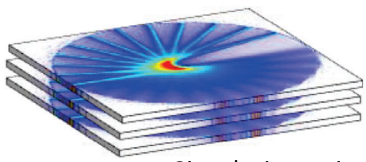
LUND UNIVERSITY

Multiple irradiation angles

Phantom stack

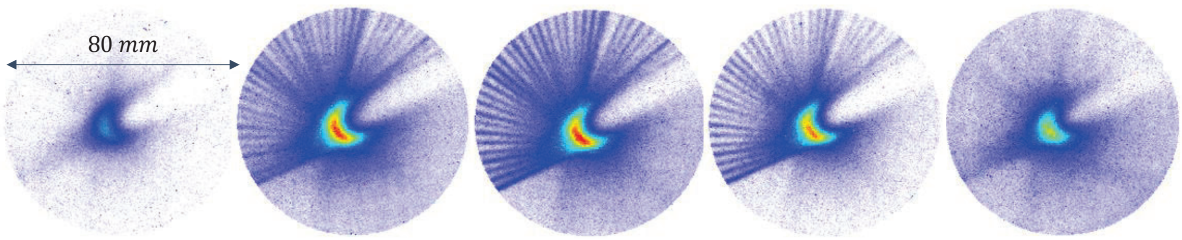


Simulation



Measurement – concave volume

36 angles, 10 pulses/angle

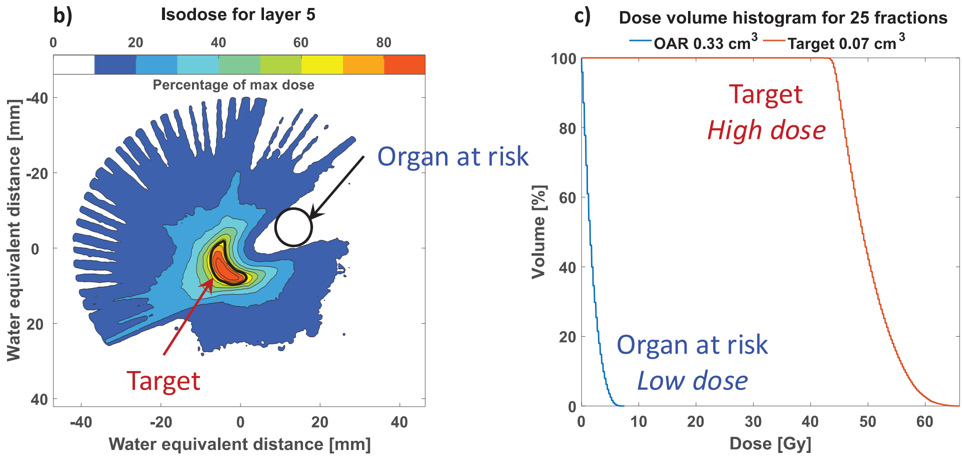


Layers at different heights from beam center

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

Towards stereotactic radiotherapy

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

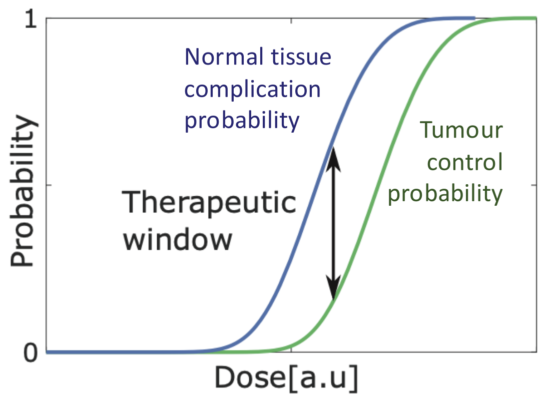


K. Svendsen *et al*, Sci Reports **11**, 5844 (2021)

The therapeutic window

The therapeutic window in radiotherapy refers to the delicate **balance** between the **dose required to effectively treat** a cancerous tumor and the **dose that can cause harm** to normal, healthy cells in the surrounding tissue.

Increasing the therapeutic window improves the treatment



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 might be needed for studies of the FLASH effect (high dose (many Gy) in short time (~100 ms))

Seminal paper

V Favaudon *et al., "Ultrahigh dose-rate FLASH irradiation increases the differential response between normal and tumor tissue in mice"*, Science Transl. Med. **6** (2014)

Review articles

M Kim *et al*, IEEE Transactions on Radiation and Plasma Medical Sciences **6** (2021)

Hughes and Parsons, Int. J. Molecular Sciences **5** (2020)

Kristoffer Petersson, *Oxford Univ*

Outline

Controlled injection and acceleration

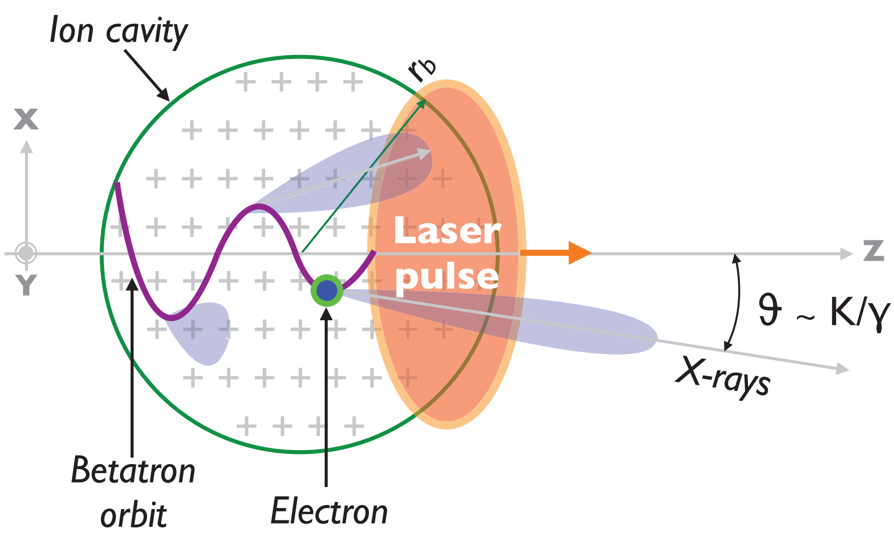
High energy electrons for radiotherapy

X-rays for (time-resolved) tomography

Hard X-rays for radiography

Towards laser-based FELs

Betatron X-ray source

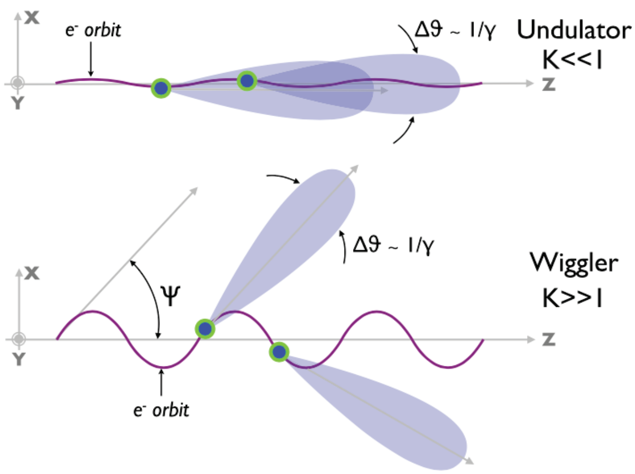


Review article
S Corde *et al*, *"Femtosecond x rays from laser-plasma accelerators",* Rev Mod Phys **85**, (2013)

Undulator and wiggler regimes

$\psi \ll \Delta\theta$

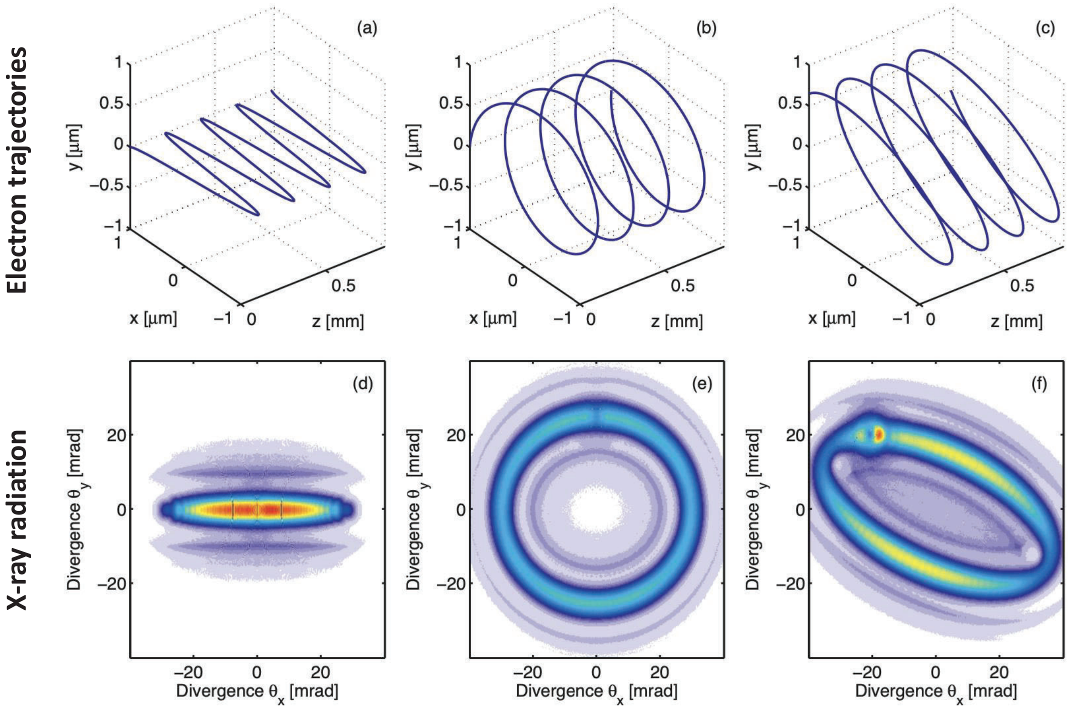
$\psi \gg \Delta\theta$



ψ	Maximum angle of the electron velocity vector
$\Delta\theta = 1/\gamma$	Opening angle of the radiation cone
$K = \gamma\psi$	Dimensionless parameter separating the regimes

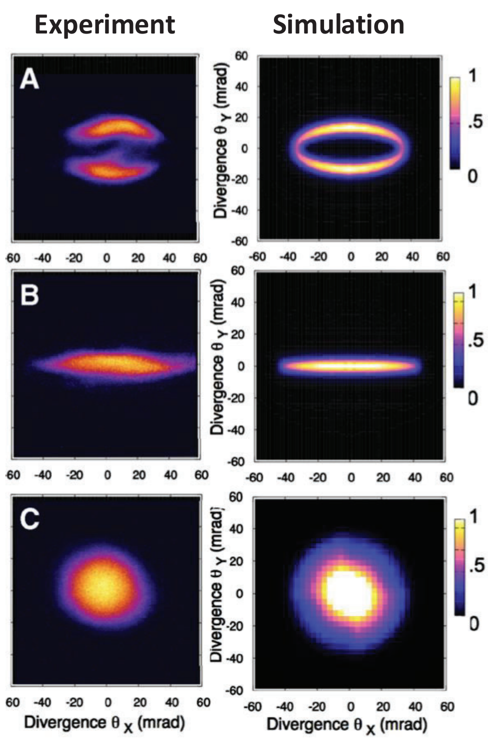
S Corde *et al*, Rev Mod Phys **85**, (2013)

Electron trajectories shapes the radiation



G Genoud, PhD Thesis, 2011

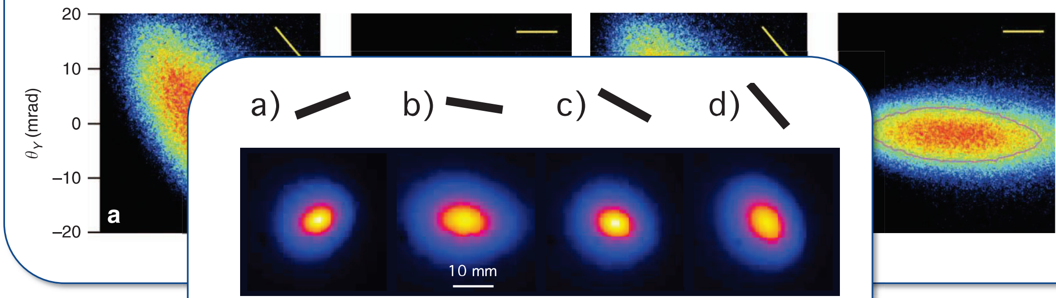
Electron trajectories shapes the radiation



K Ta Phuoc *et al*, Phys Rev Lett **97**, 225002, 2006

Tunable X-ray polarization

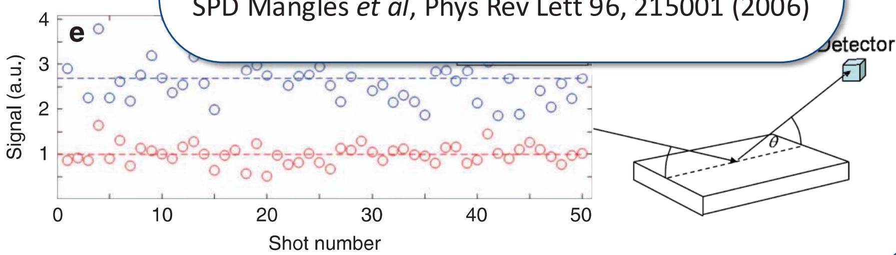
Elliptical X-ray beams rotate with laser polarization



Elliptical electron beams rotate with laser polarization

SPD Mangles *et al*, Phys Rev Lett 96, 215001 (2006)

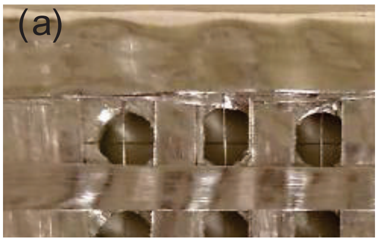
X-ray ... on



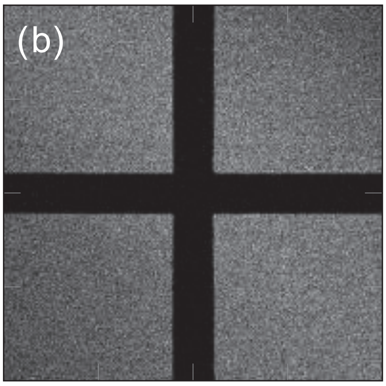
A Döpp *et al*, Light: Science and Application 6, e17086 (2017)

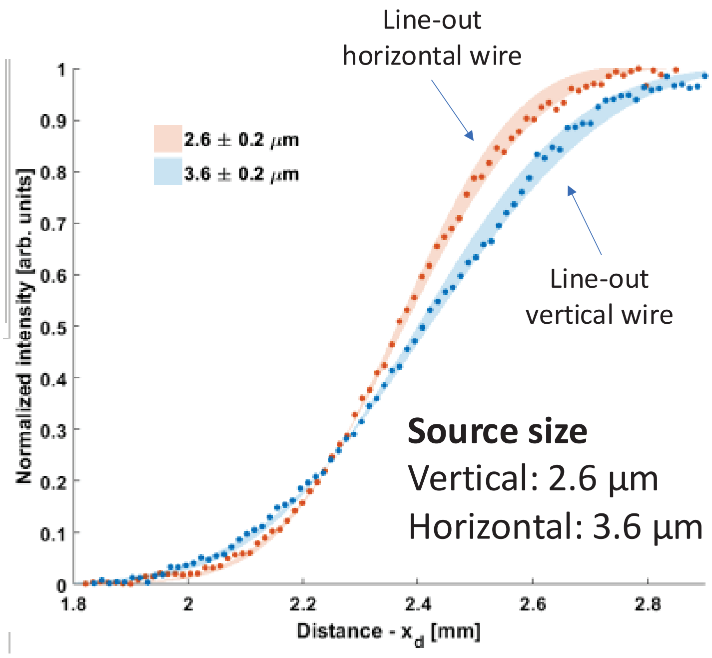
X-ray source size

25 µm tungsten wires



Wire shadow on CCD





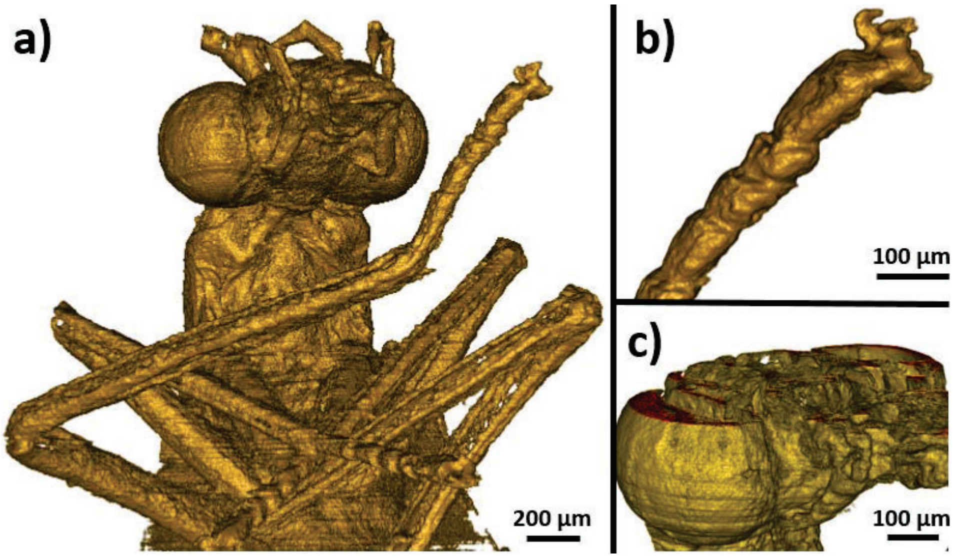
Source size

Vertical: 2.6 µm

Horizontal: 3.6 µm

Phase-contrast tomography

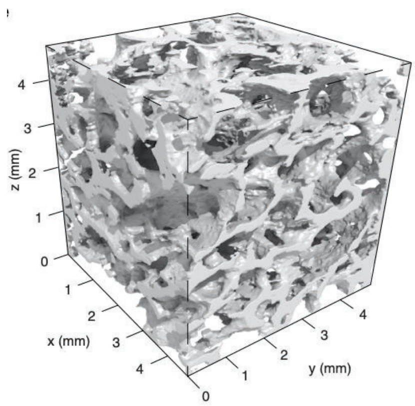
3D rendering



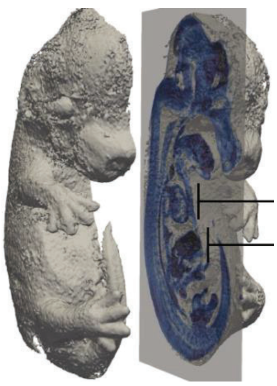
10 µm structures can be resolved in tomogram

K. Svendsen *et al*, Optics Express **26**, 33930 (2018)

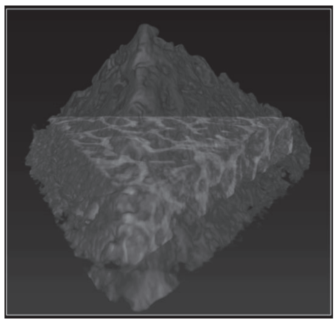
Tomography for medical purposes



Tomographic reconstruction of trabecular bone sample
J M Cole *et al*, Sci Rep **5** (2015)



High-resolution μCT of a mouse embryo
J M Cole *et al*, PNAS **115** (2018)



Quick micro-tomography
A Döpp *et al*, Optica **5** (2018)

Outline

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High energy electrons for radiotherapy

X-rays for (time-resolved) tomography

Hard X-rays for radiography

Towards laser-based FELs

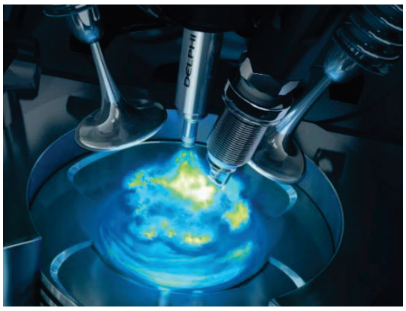
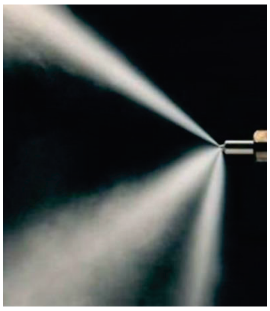
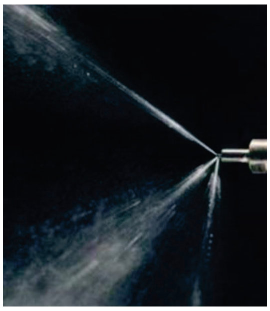
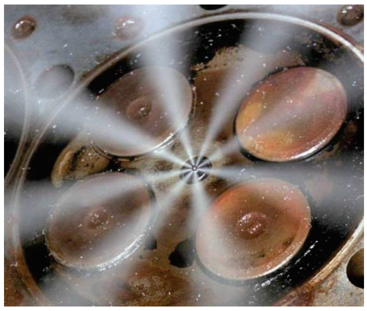
Spray applications

Medical Applications: Inhalation and skin treatment

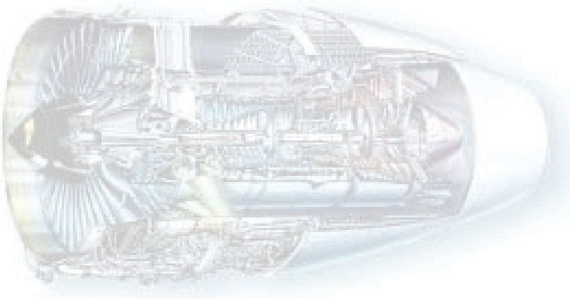
Industrial Applications: Spray drying / painting / cutting / *etc*

Spray applications

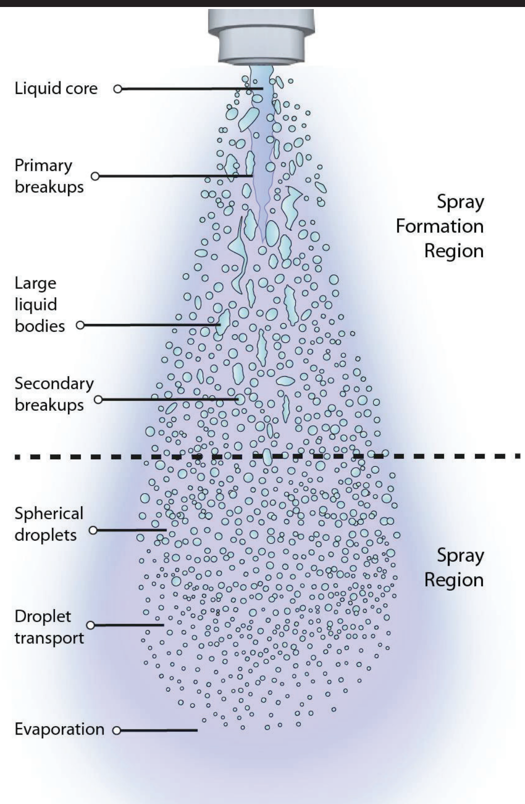
Internal Combustion Engines Applications: Diesel and GDI sprays

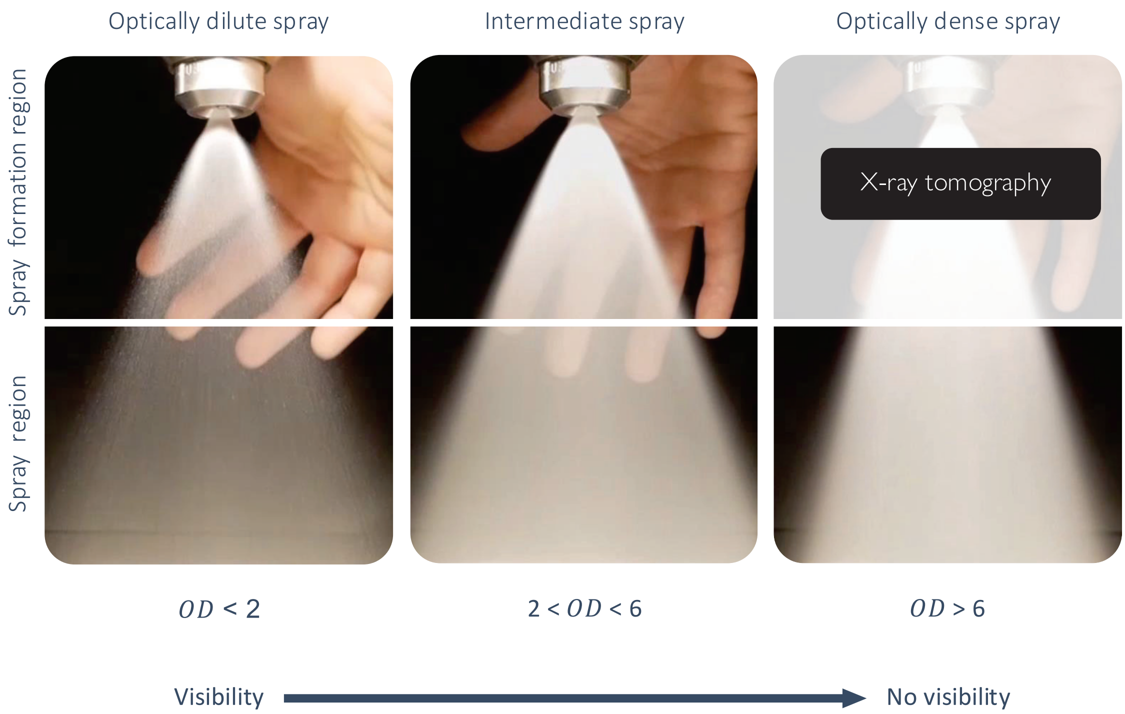
Gas Turbines Applications: Aero Engines



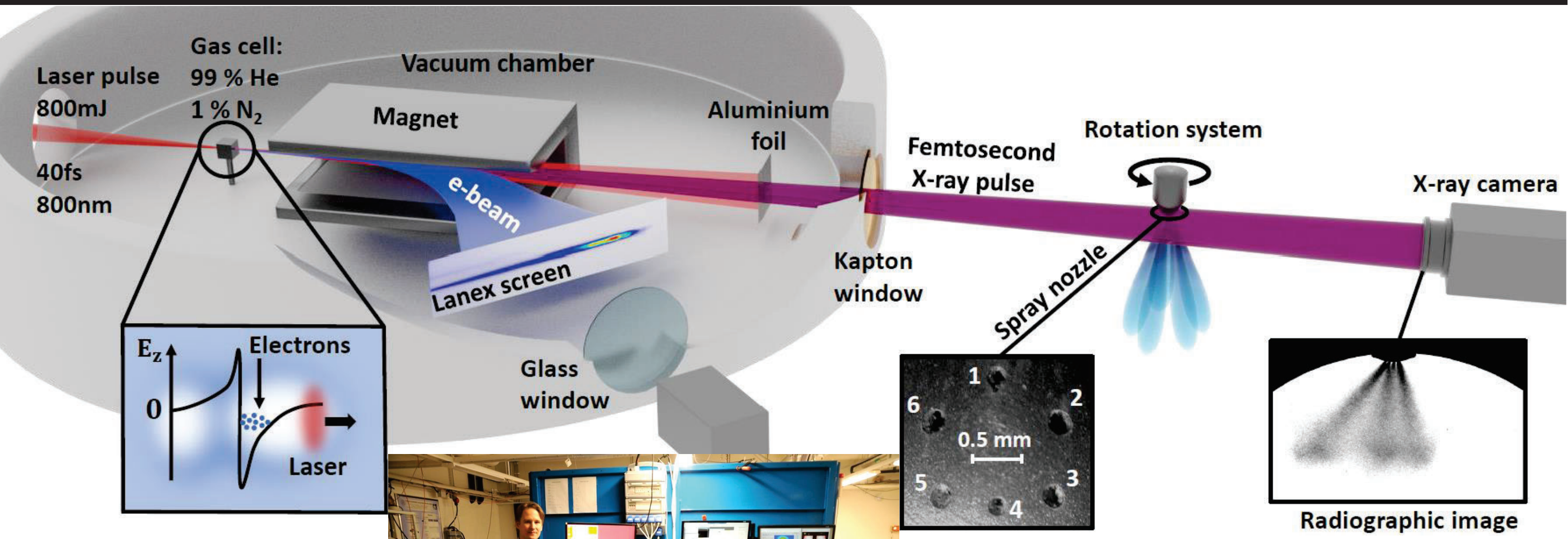
Physics of spray formation

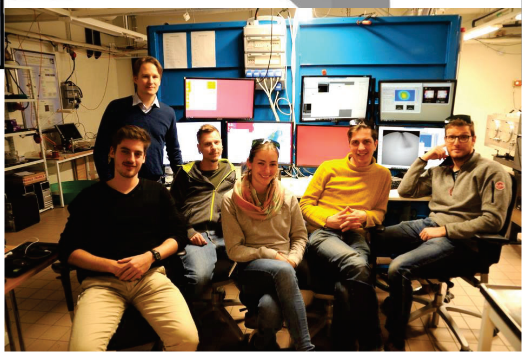


Multiple scattering limits visibility



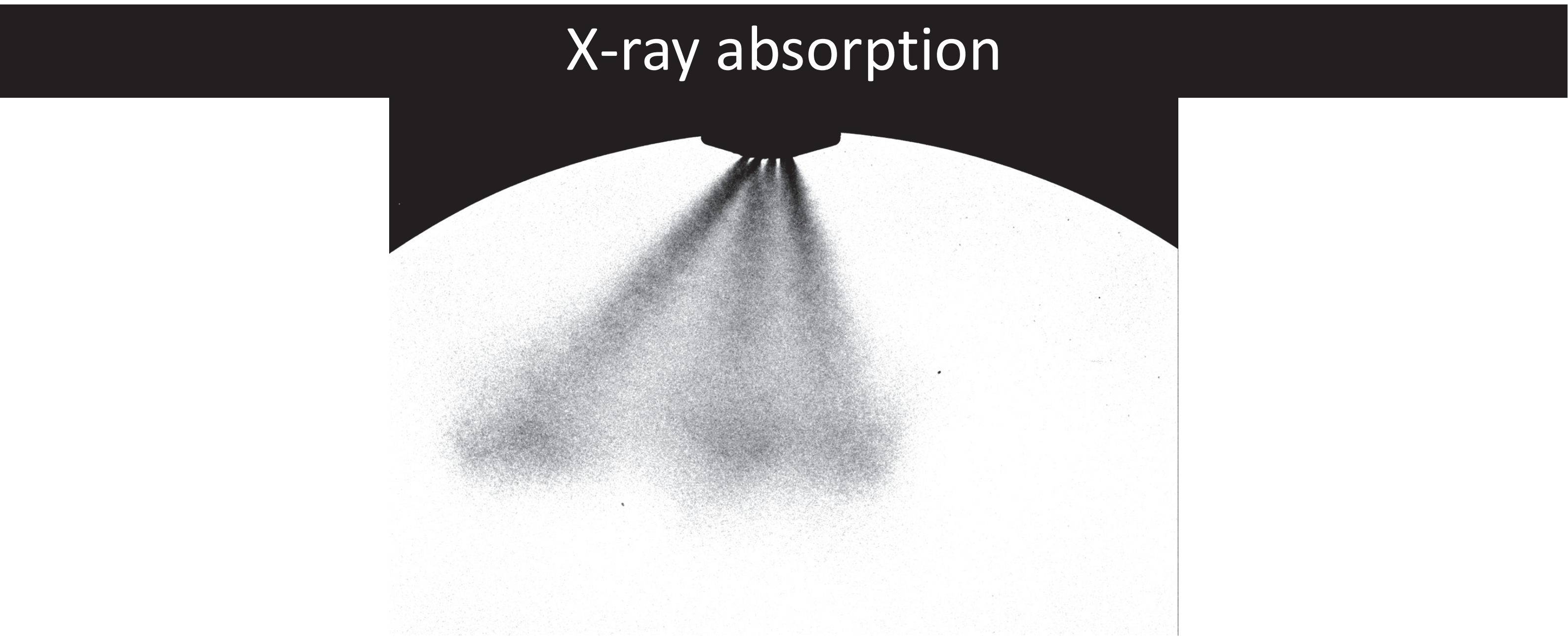
Spray imaging combining laser-driven X-rays and laser-induced fluorescence





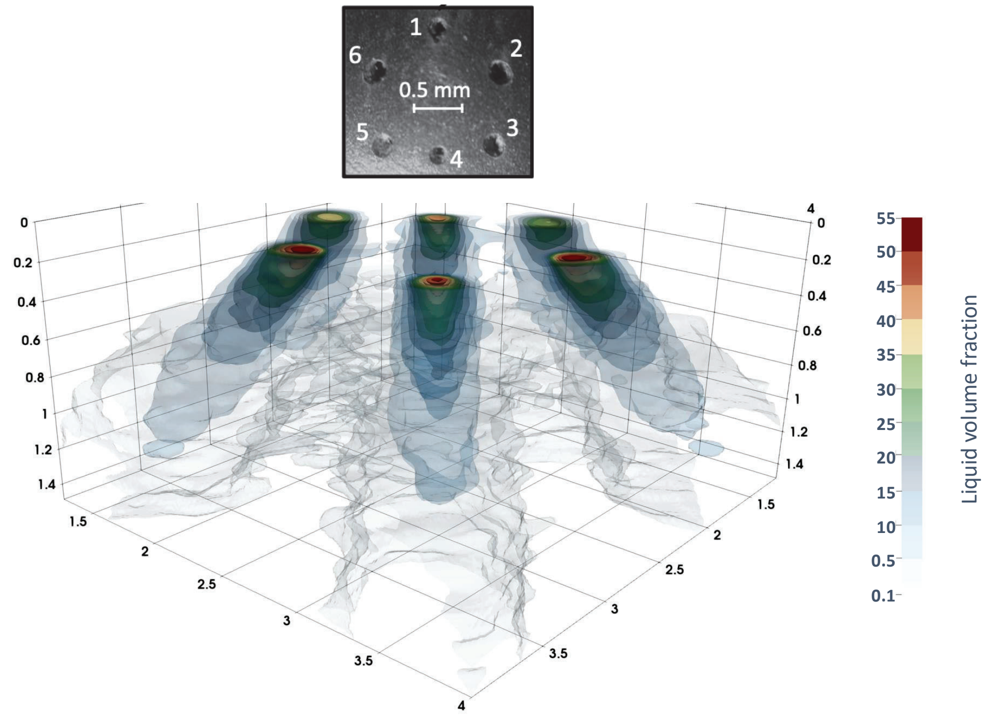
3 weeks access

5 users from Univ Erlangen FAU (Germany)

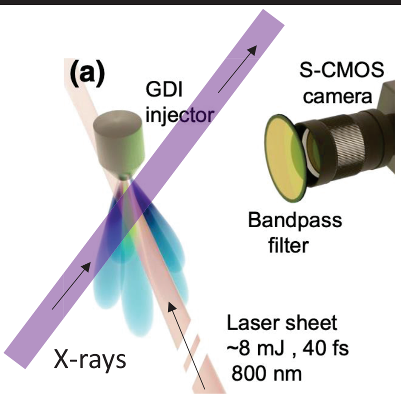


0°

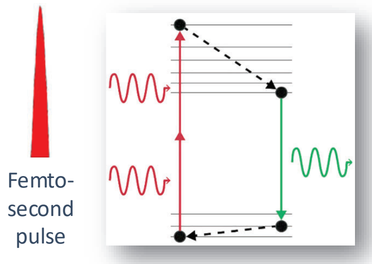
Transient spray tomography



Combining X-rays and 2-photon Fluorescence

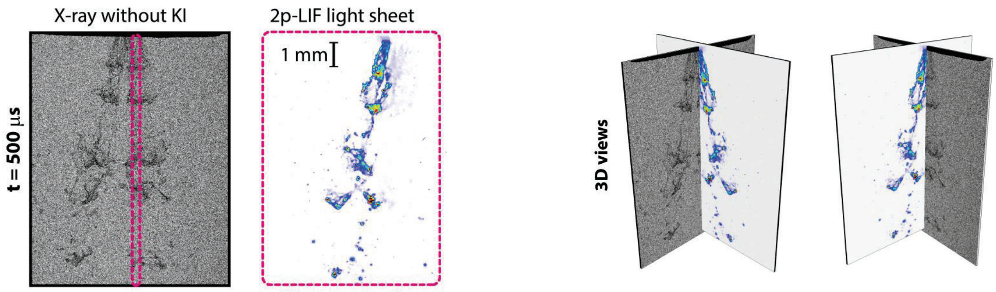


2-photon LIF in sheet mitigates scattering



Edouard Berrocal develops the technique

Simultaneous recordings

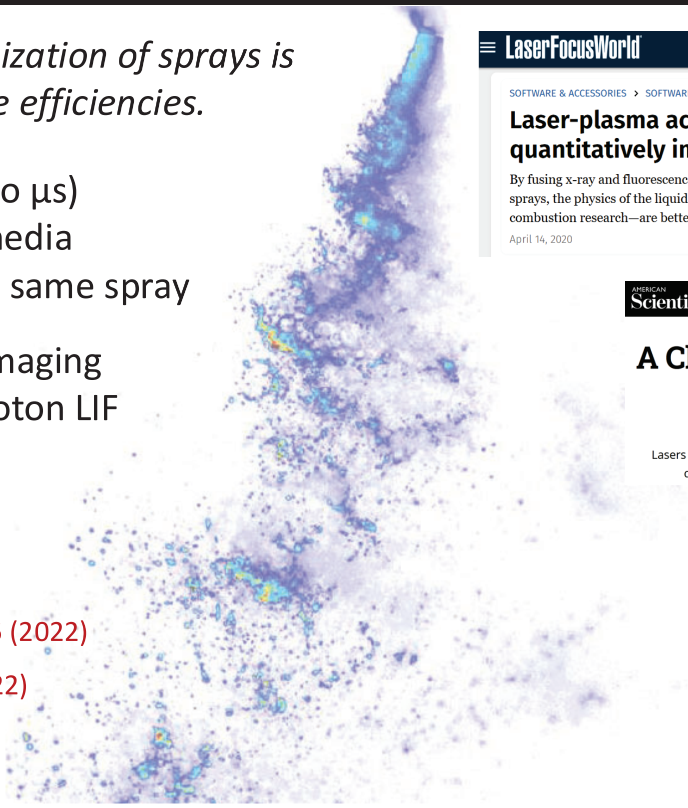


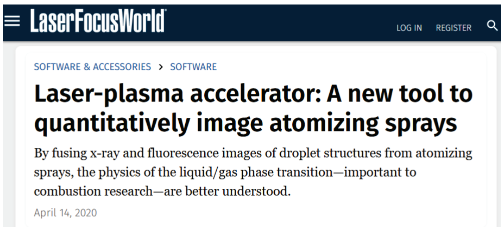
Seeing into sprays

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





LaserFocusWorld

SOFTWARE & ACCESSORIES > SOFTWARE

Laser-plasma accelerator: A new tool to quantitatively image atomizing sprays

By fusing x-ray and fluorescence images of droplet structures from atomizing sprays, the physics of the liquid/gas phase transition—important to combustion research—are better understood.

April 14, 2020

American Scientist

A Clear View of Cloudy Sprays

BY CHARLES Q. CHOI

Lasers and x-rays combined can capture quick-changing droplets as they break apart and evaporate.

E. Löfquist *et al,* in preparation

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)

Outline

Controlled injection and acceleration

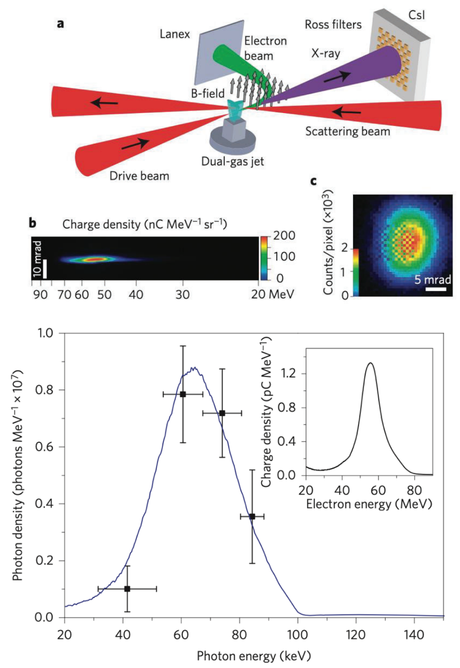
High energy electrons for radiotherapy

X-rays for (time-resolved) tomography

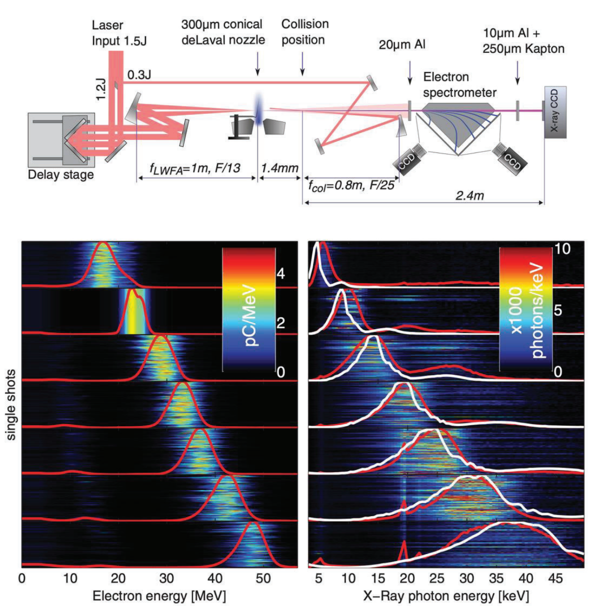
Hard X-rays for radiography

Towards laser-based FELs

Hard X-rays from Compton scattering

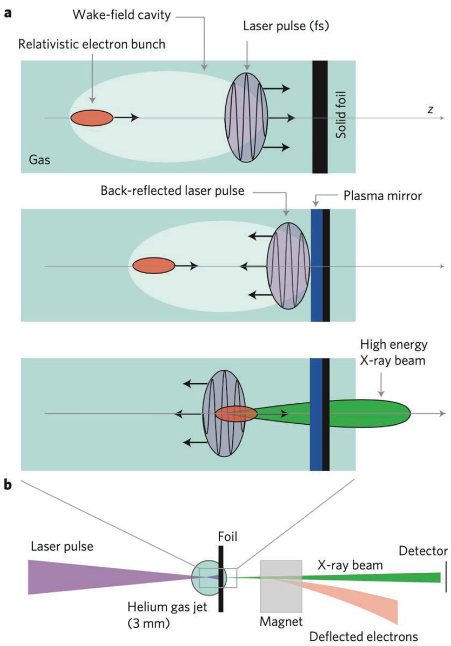


N D Powers *et al*, Nature Photonics **8**, 28–31 (2014)

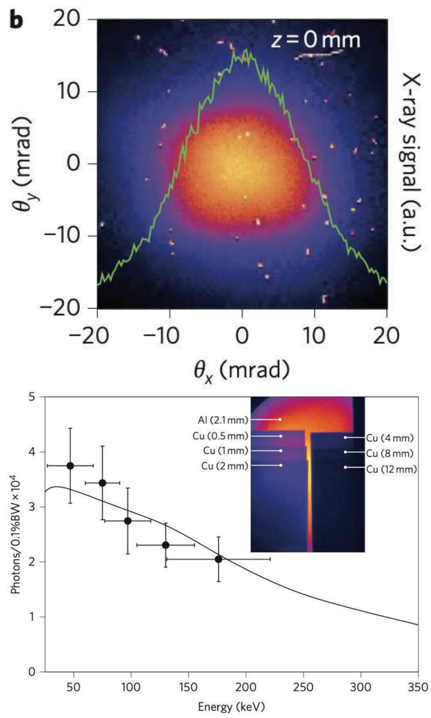


K Khrennikov *et al*, PRL 114, 195003 (2015)

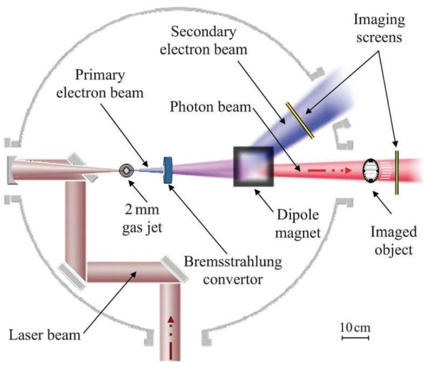
Compton scattering using only one laser beam



K Ta Phuoc *et al*, Nature Photonics **6**, 308–311 (2012)

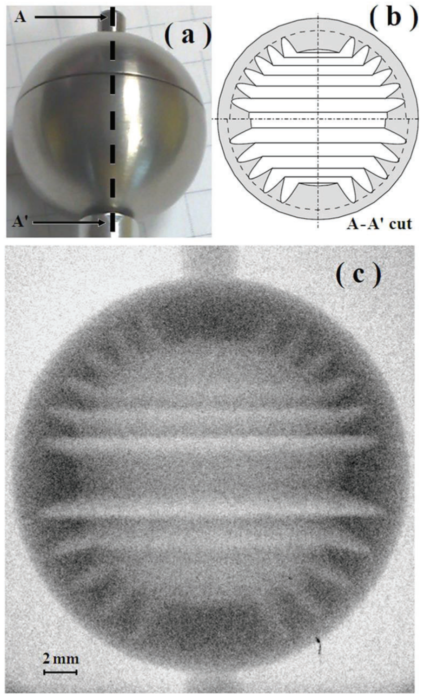


Gamma ray source for radiography



- Laser: 30 TW, 30 fs laser
- Electrons: 100 MeV, 70 pC
- 1 mm tantalum Bremsstrahlung converter
- Image plate detector
- Copper foil enhances gamma detection (converts gamma-rays to low-E electrons)

A Ben-Ismail *et al*, Appl. Phys. Lett. **98**, 264101 (2011)



Radiograph of a dense hollow sphere
(20 mm diameter tungsten)

Outline

Controlled injection and acceleration

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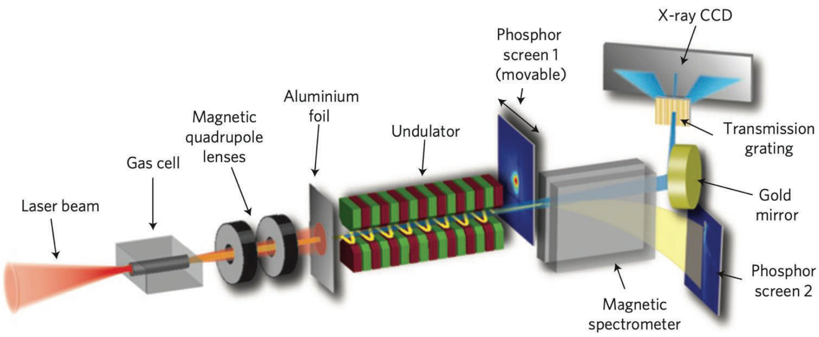
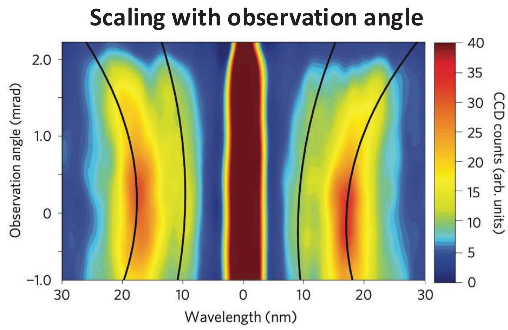
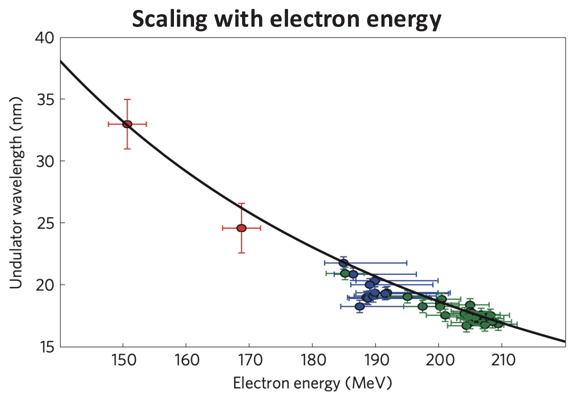
Laser-driven soft-X-ray undulator source





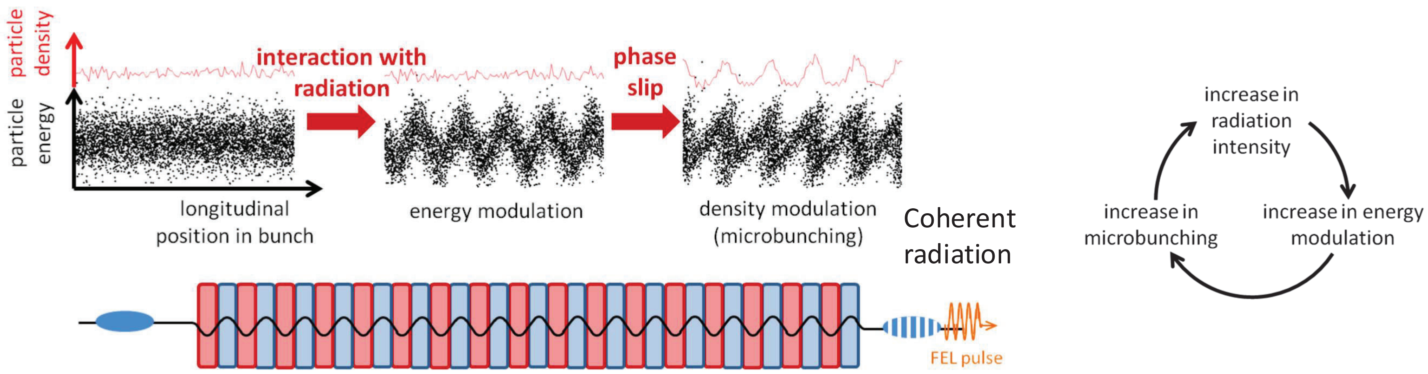
$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\Theta^2\right)$$



M Fuchs *et al,* Nature Physics **5**, 826–829 (2009)

Coherent radiation from an undulator

Electrons in a bunch passing through an undulator can interact with the radiation produced by other electrons within the bunch so that "microbunches" start to develop, which gives an exponential increase in the radiation intensity with distance along the undulator.

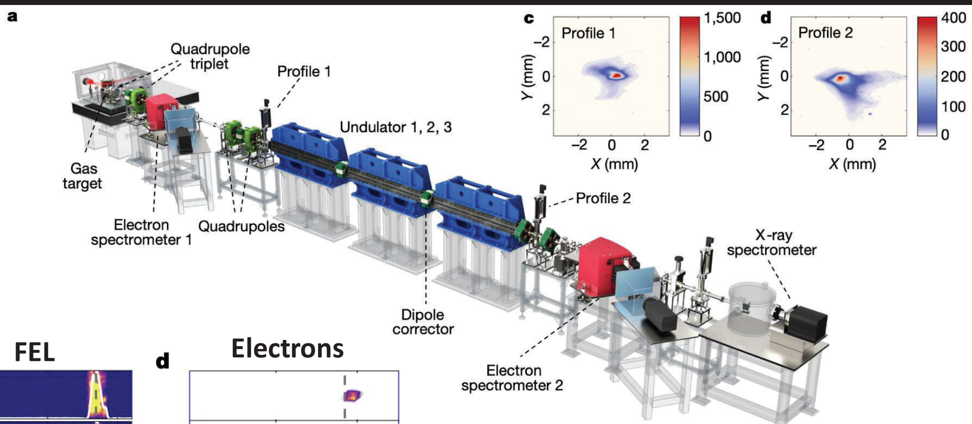


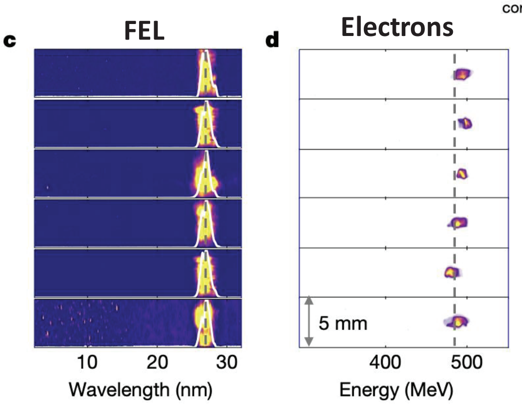
Achieving gain require exceptional electron beams with **simultaneously**

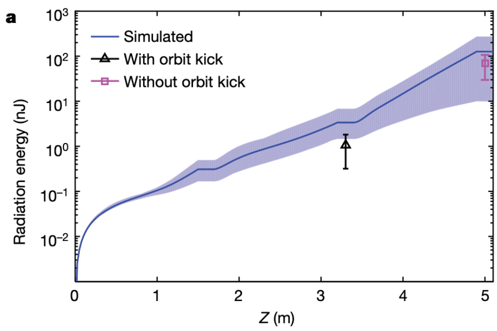
- ✓ High peak current (kA)
- ✓ Low normalized emittance (<1 mm mrad)
- ✓ Low energy spread (<1%)

Slide: A Wolski, CAS 2012

Laser-driven Free Electron Laser

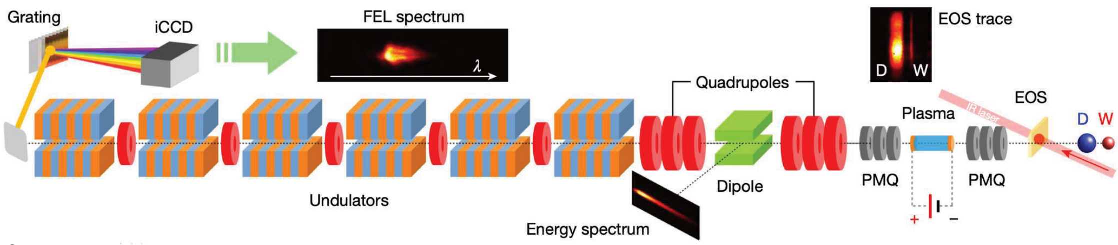


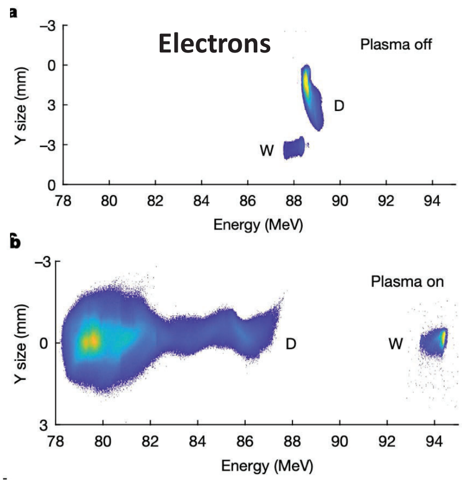


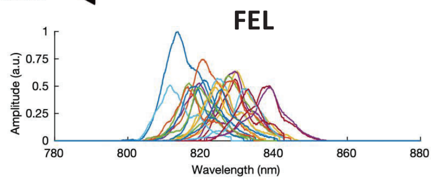


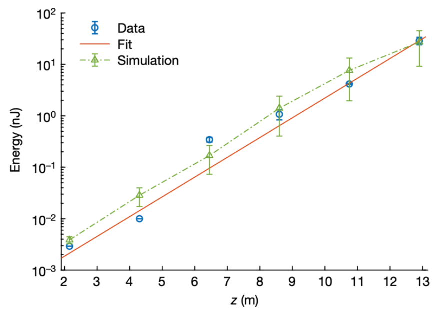
W Wang *et al*, Nature **595**, 516–520 (2021)

Beam-driven FEL



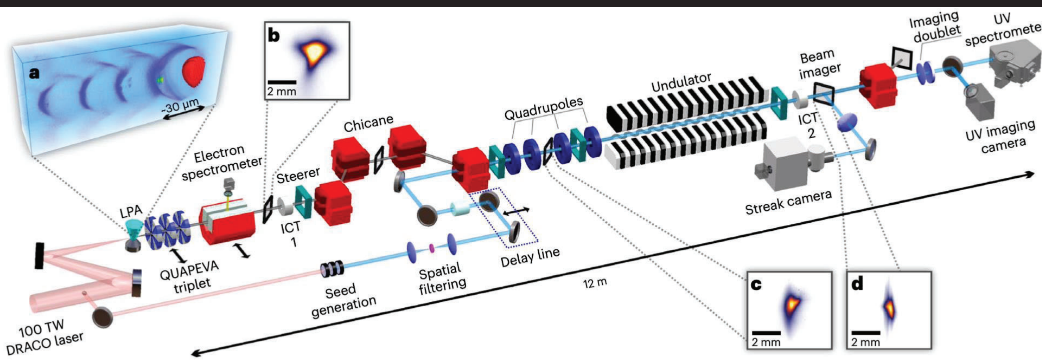


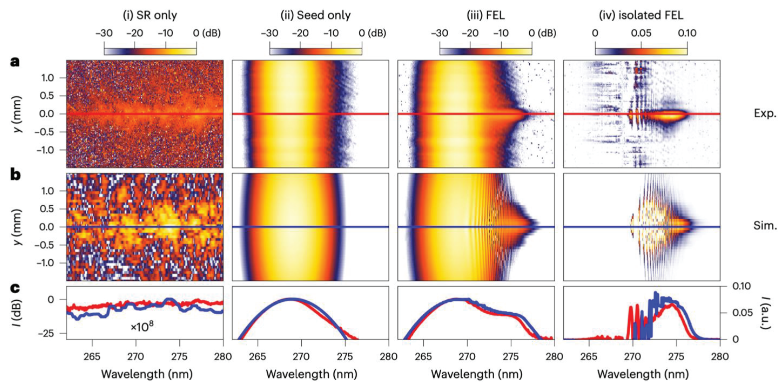




R Pompili *et al*, Nature **605**, 659–662 (2022)

Seeded FEL





M Labat *et al*, Nature Photonics **17**, 150–156 (2023)

Conclusion

High-power lasers essential for plasma acceleration are available commercially from multiple providers.

Plasma accelerators come in **compact setups**, making them ideal for space-constrained **industrial or hospital settings**.

Now is **the ideal moment for YOU** to pinpoint key areas with significant **impact on science and society**.