Plasma acceleration at Lund University

Olle Lundh

Department of Physics, Lund University, Sweden

New Synchrotron Radiation researches and accelerators in Italy and Sweden

Uppsala, 14-15 September 2023

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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.

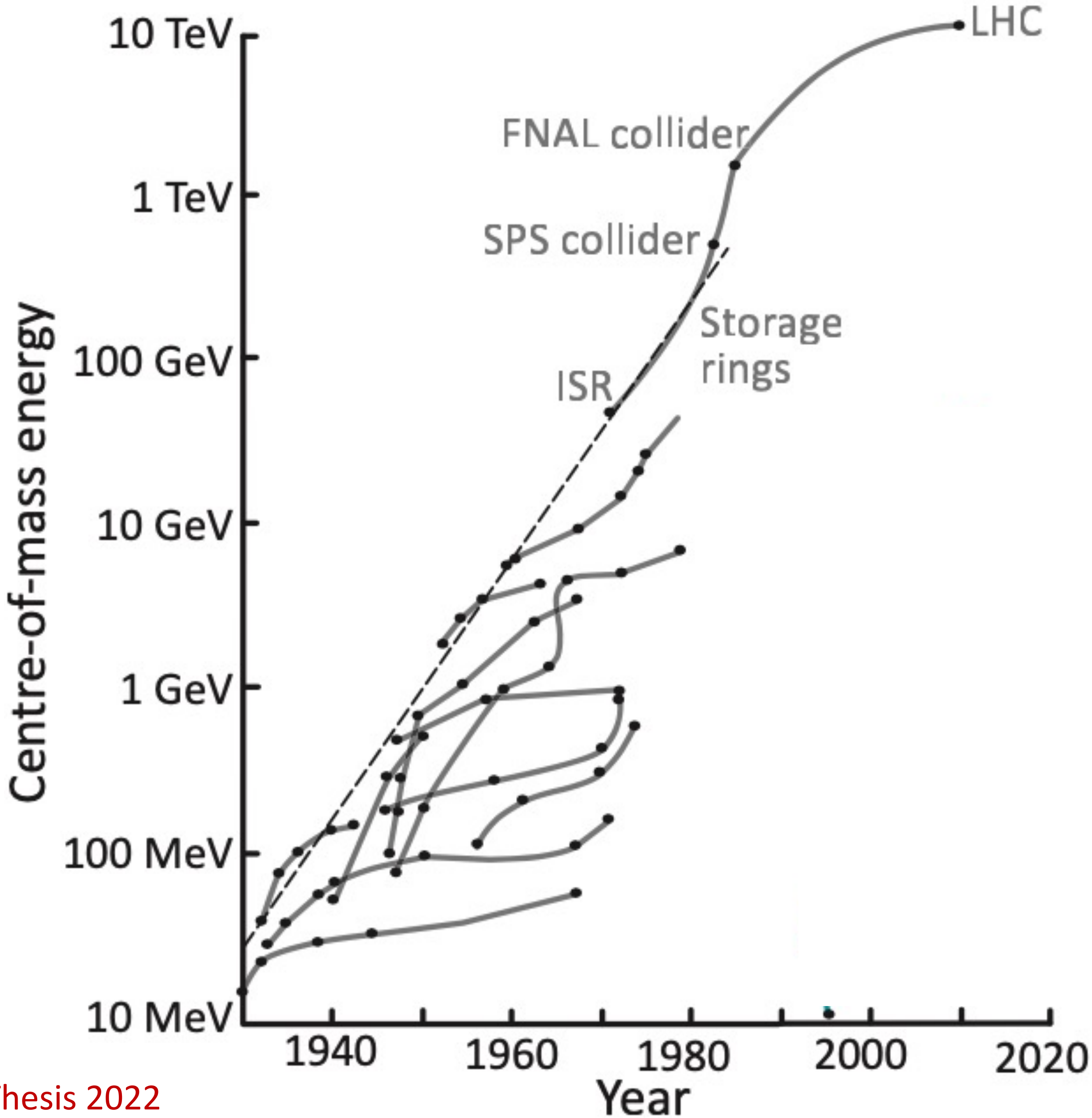
Industry

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

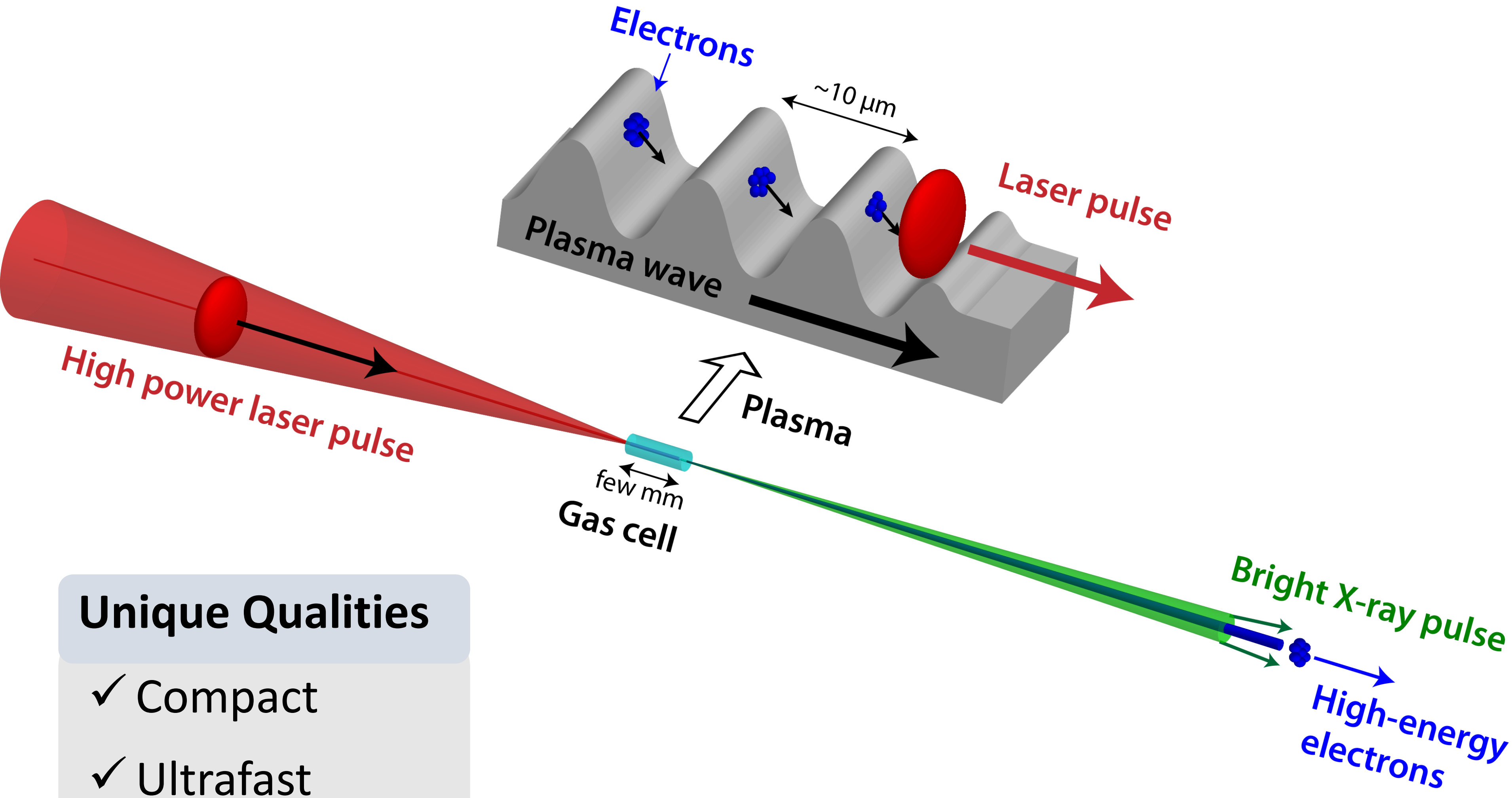
Particle accelerators play an important role in ensuring security, including cargo inspection and materials characterization.

Development of particle acceleration



K Svendsen, PhD Thesis 2022

Laser-plasma acceleration and X-ray generation

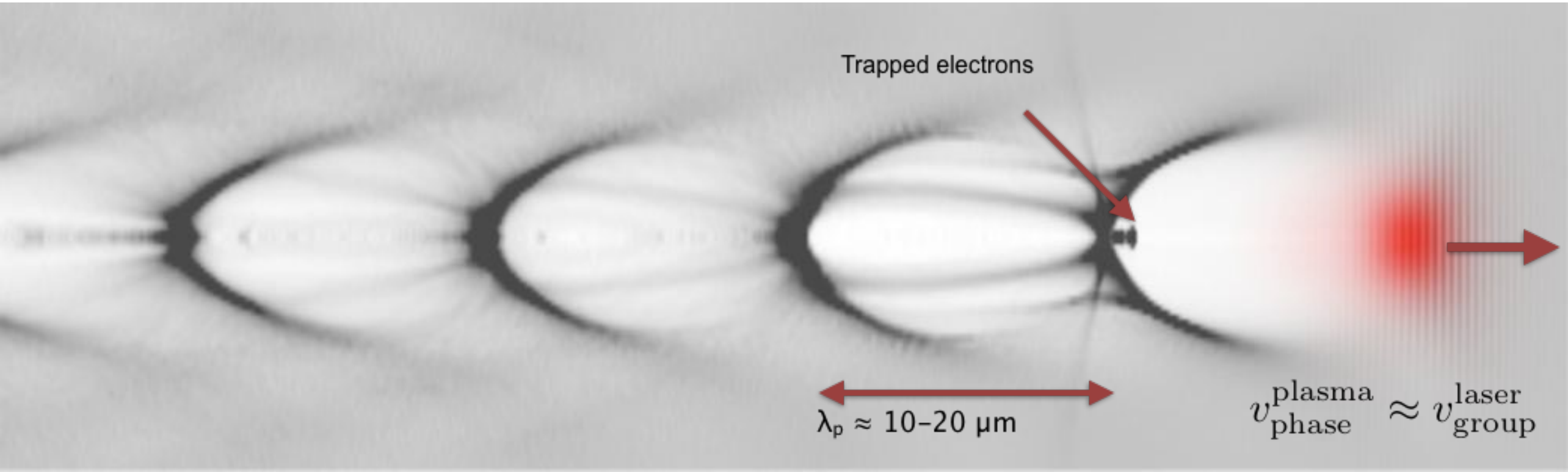


Unique Qualities

- ✓ Compact
- ✓ Ultrafast
- ✓ Tunable

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

Laser wakefield accelerator



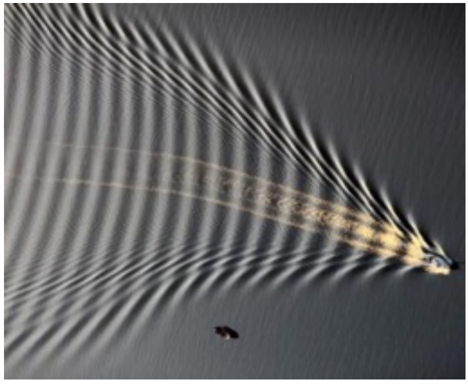
Intense laser pulse drives a plasma wave

Electrons 'surf' the plasma wave

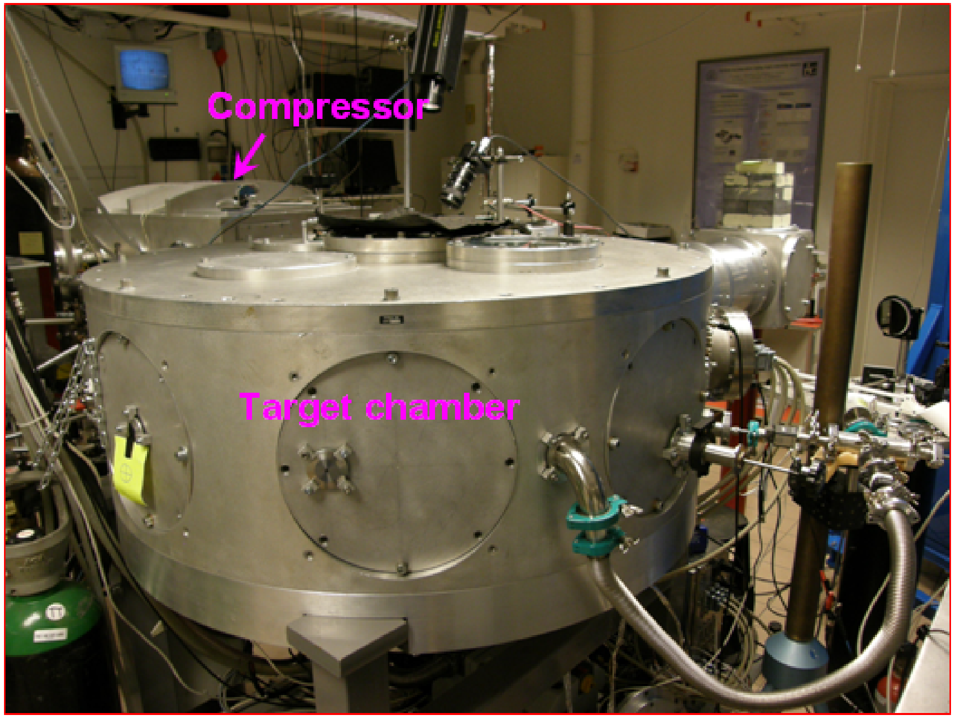
Accelerated electron pulse has duration of few fs

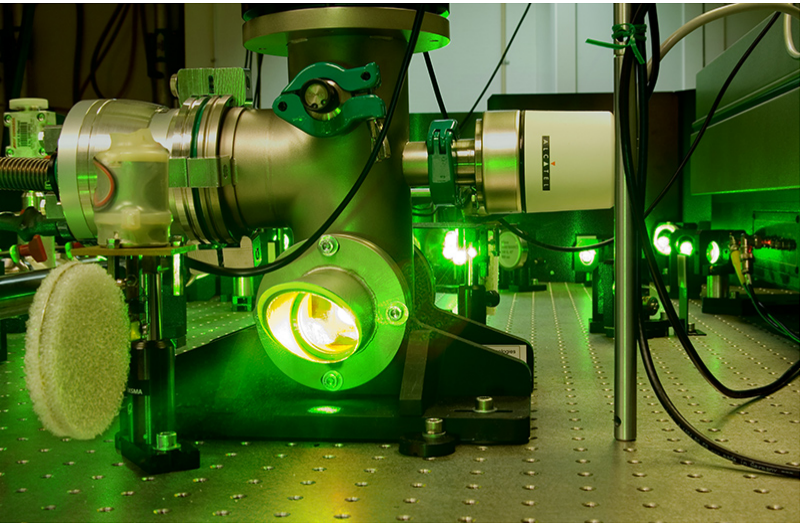
Henrik did the simulation

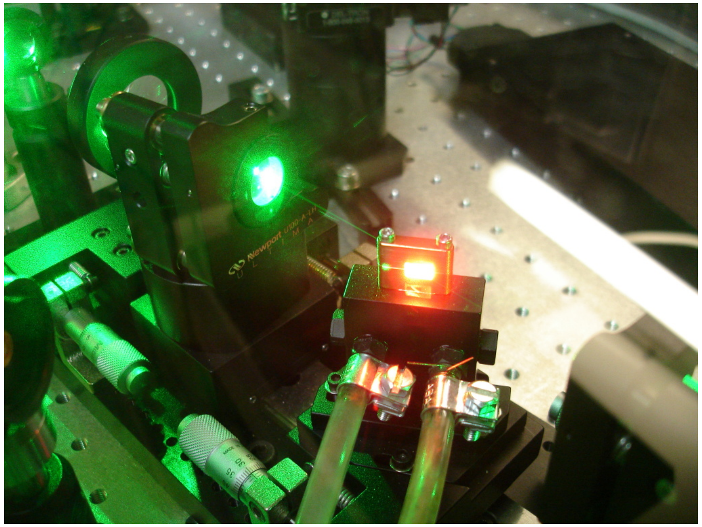
Wave in wake of boat



Lund Multi-Terawatt Laser

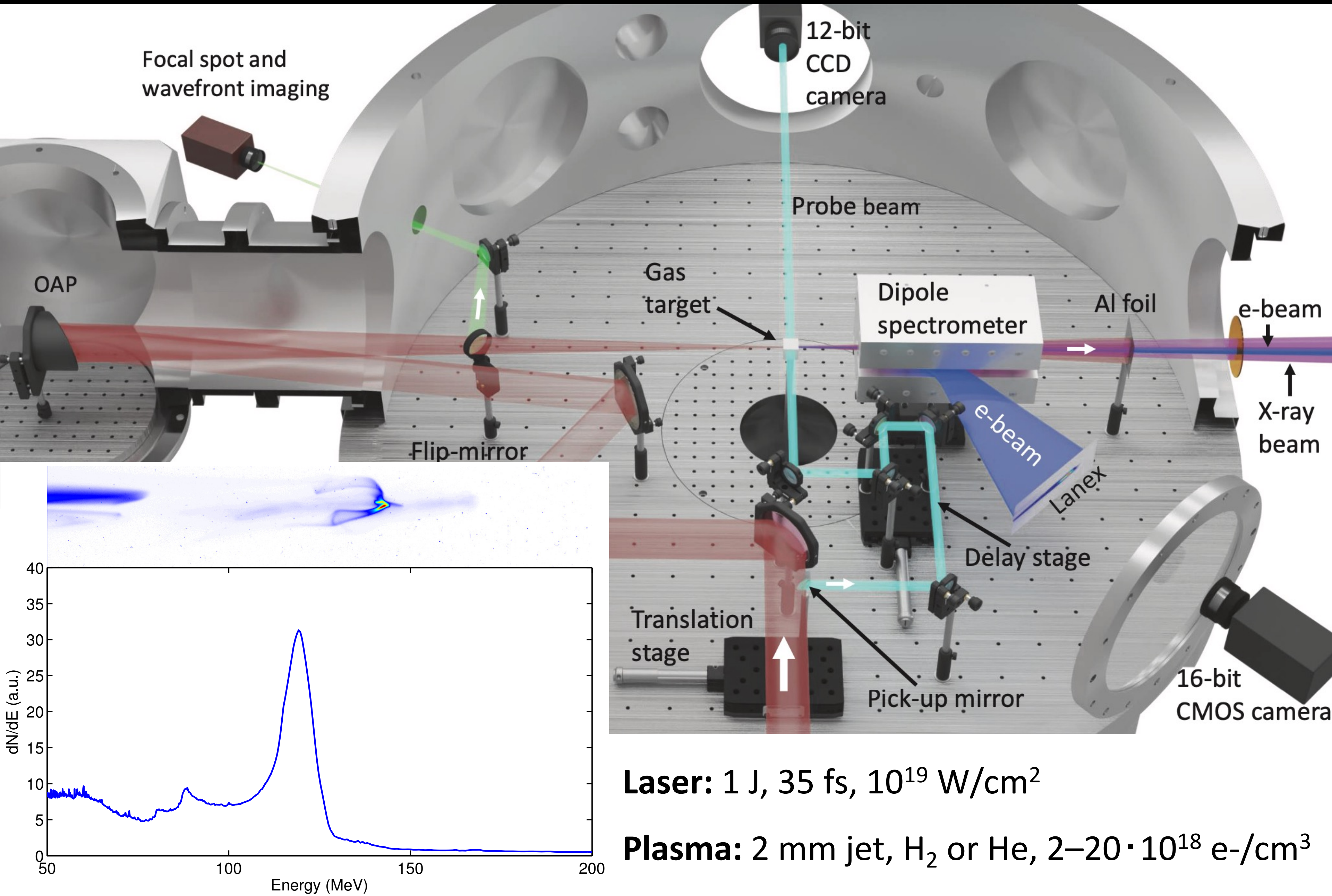






Ti:Sapphire
CPA laser
1 J
30 fs
10 Hz
10^{19} W/cm^2

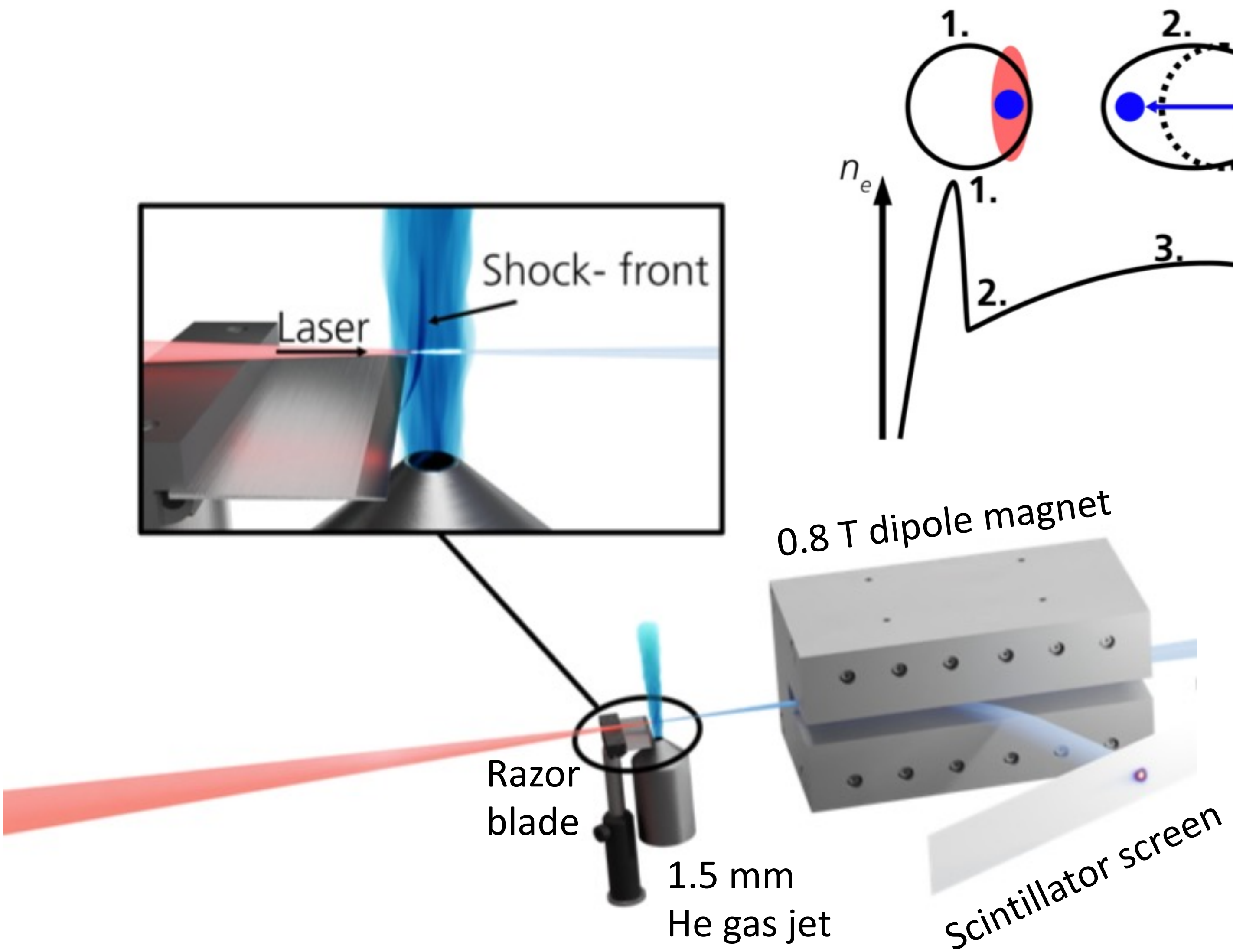
Typical experiment



Laser: 1 J, 35 fs, 10^{19} W/cm^2

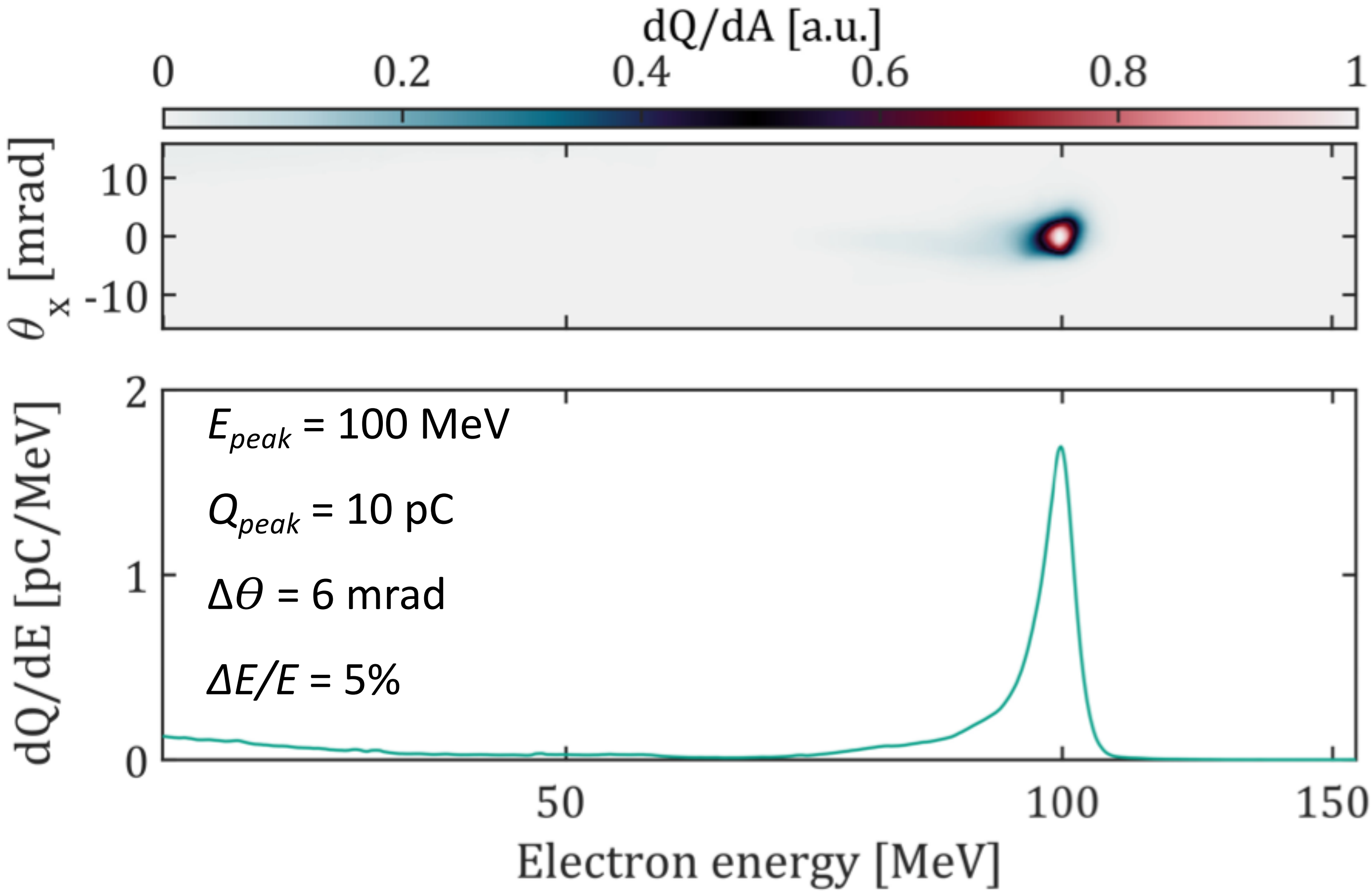
Plasma: 2 mm jet, H_2 or He, 2–20 $\cdot$ 10^{18} e-/cm^3

Setup for shock-front injection

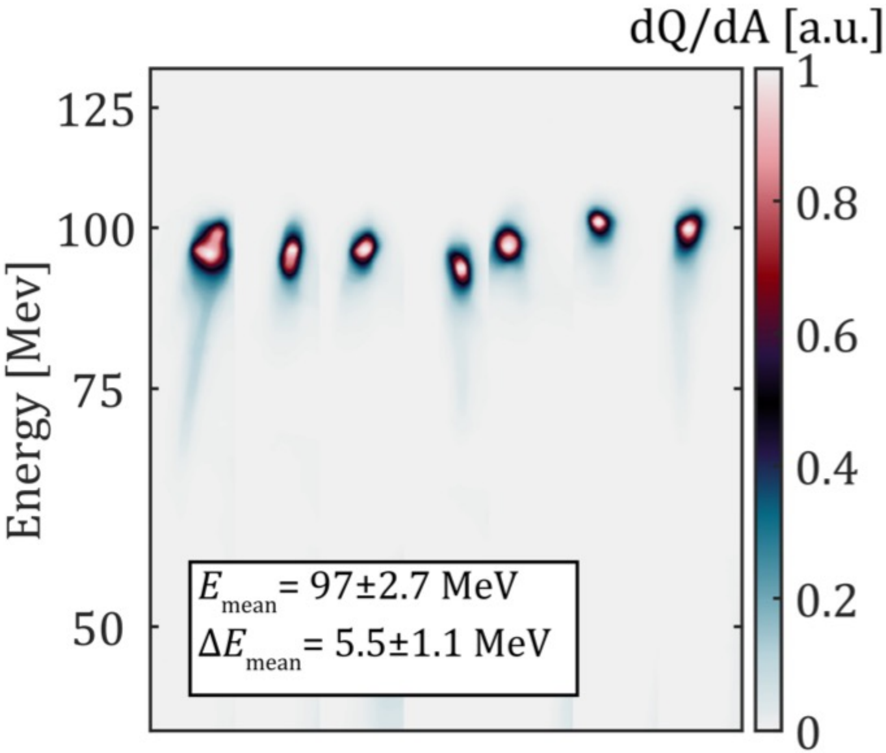


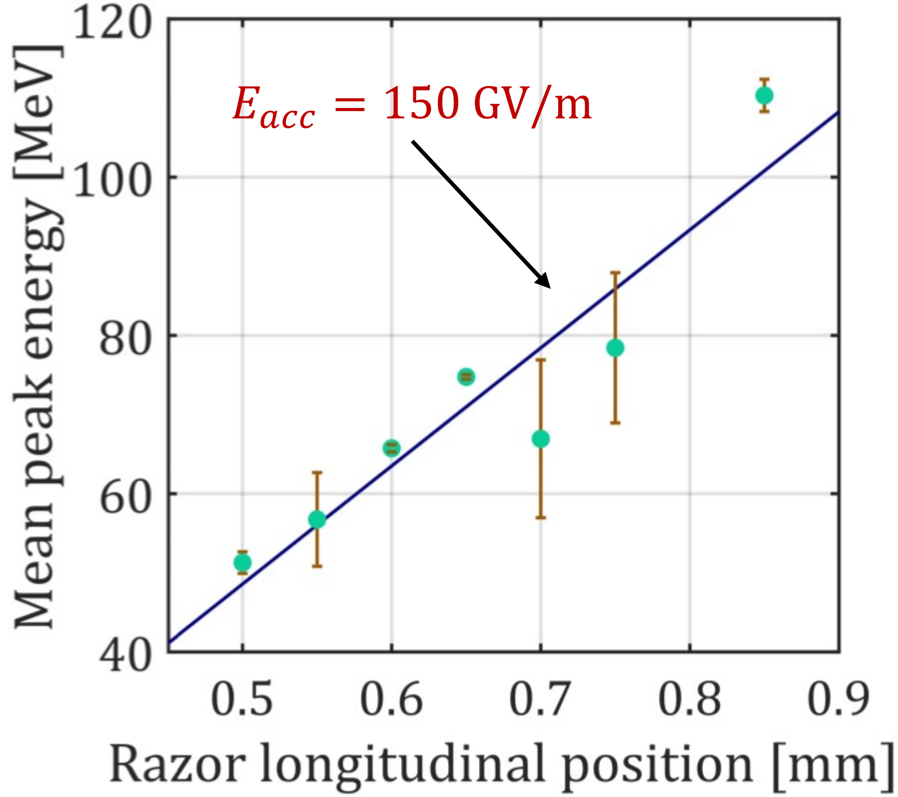
Cornelia did this experiment

Beam quality



Tunability and stability





Applications of laser-plasma acceleration

High Energy Electrons for Radiotherapy

X-rays for Imaging and Tomography

Prospects for plasma acceleration at MAX IV

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Laserlab Europe
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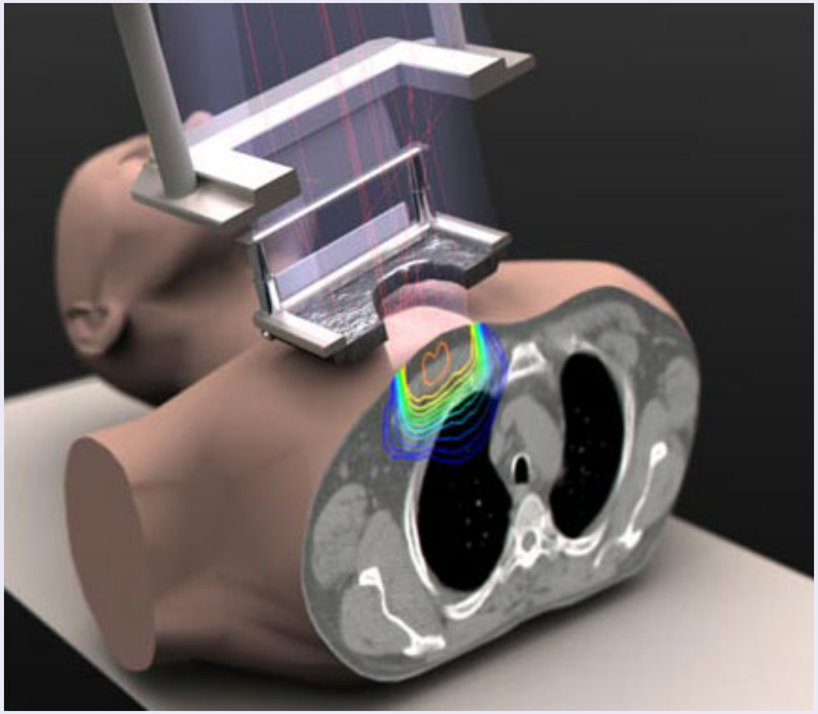
erc
Knut och Alice Wallenbergs Stiftelse
VETENSKAPSRÅDET
THE SWEDISH RESEARCH COUNCIL

Low energy electron radiotherapy

Clinical oncology machine

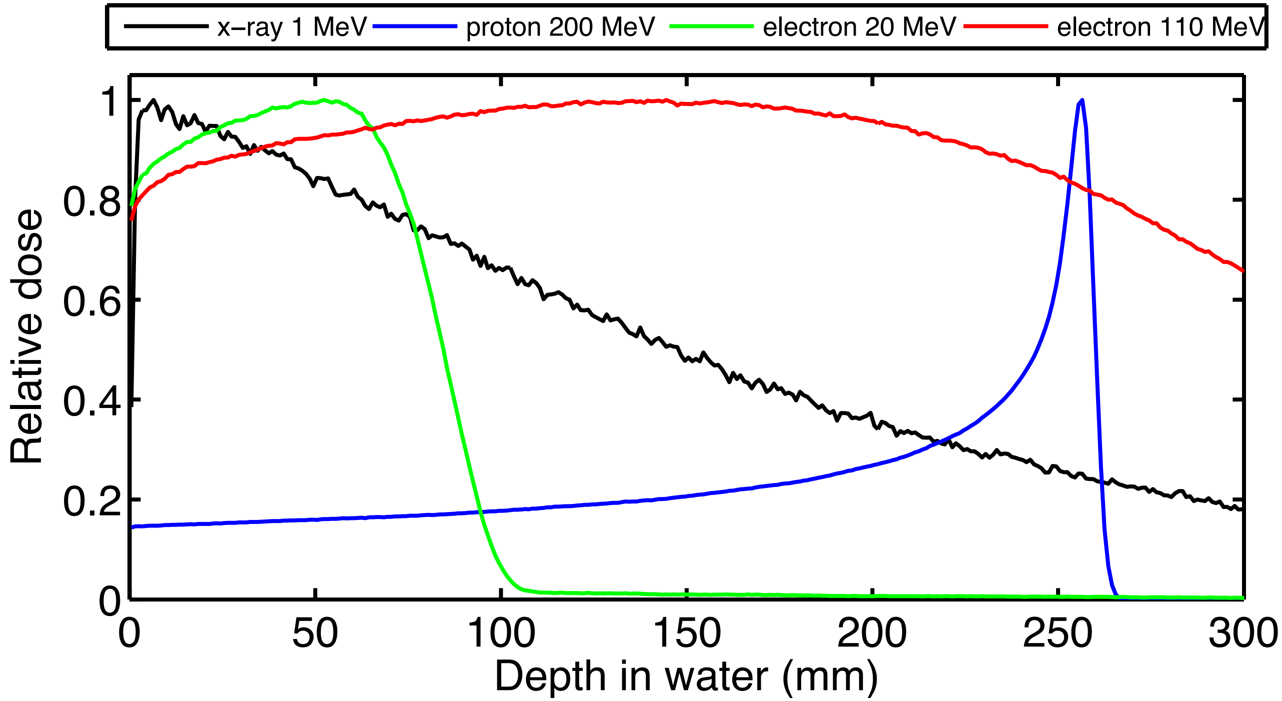
- 5-20 MeV electron beam
- X-rays by bremsstrahlung

Direct electron irradiation



- Electrons have limited range
- Underlying structures spared

Dose deposition for different particles



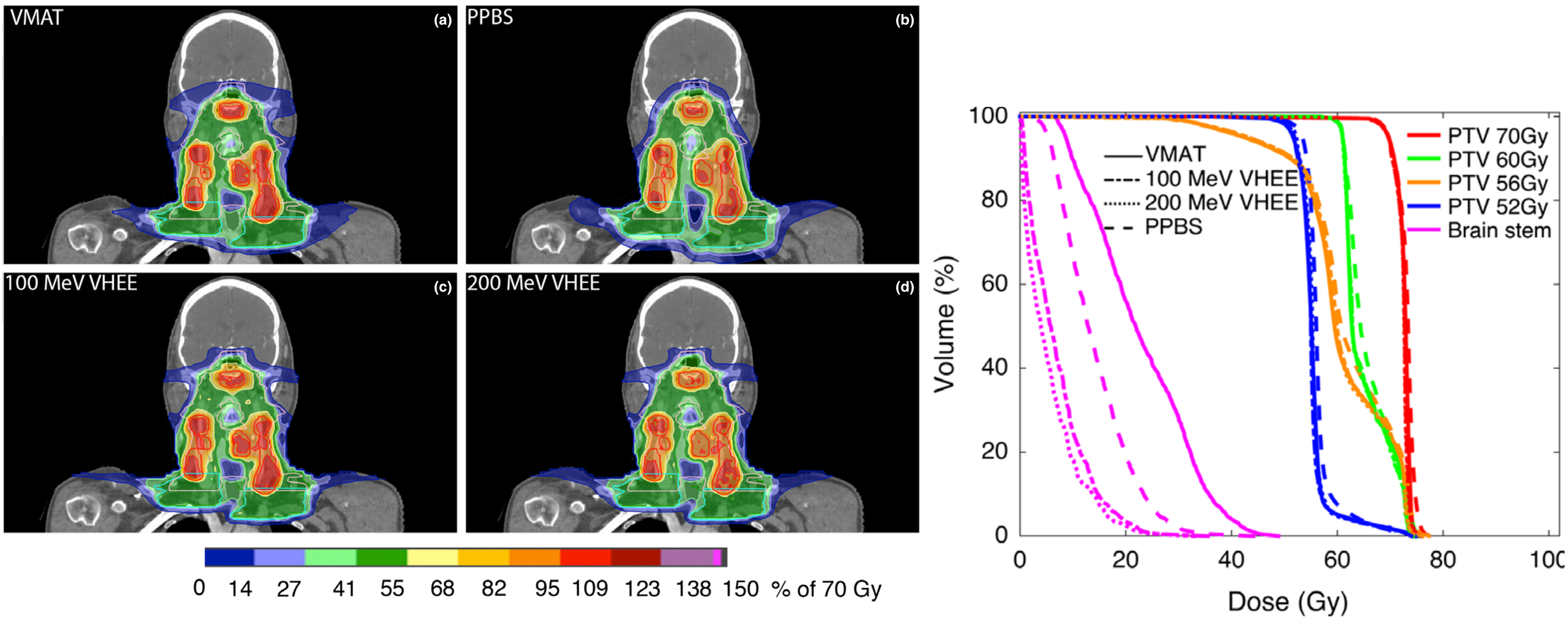
Low energy electrons < 20 MeV widely used for superficial tumours

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)

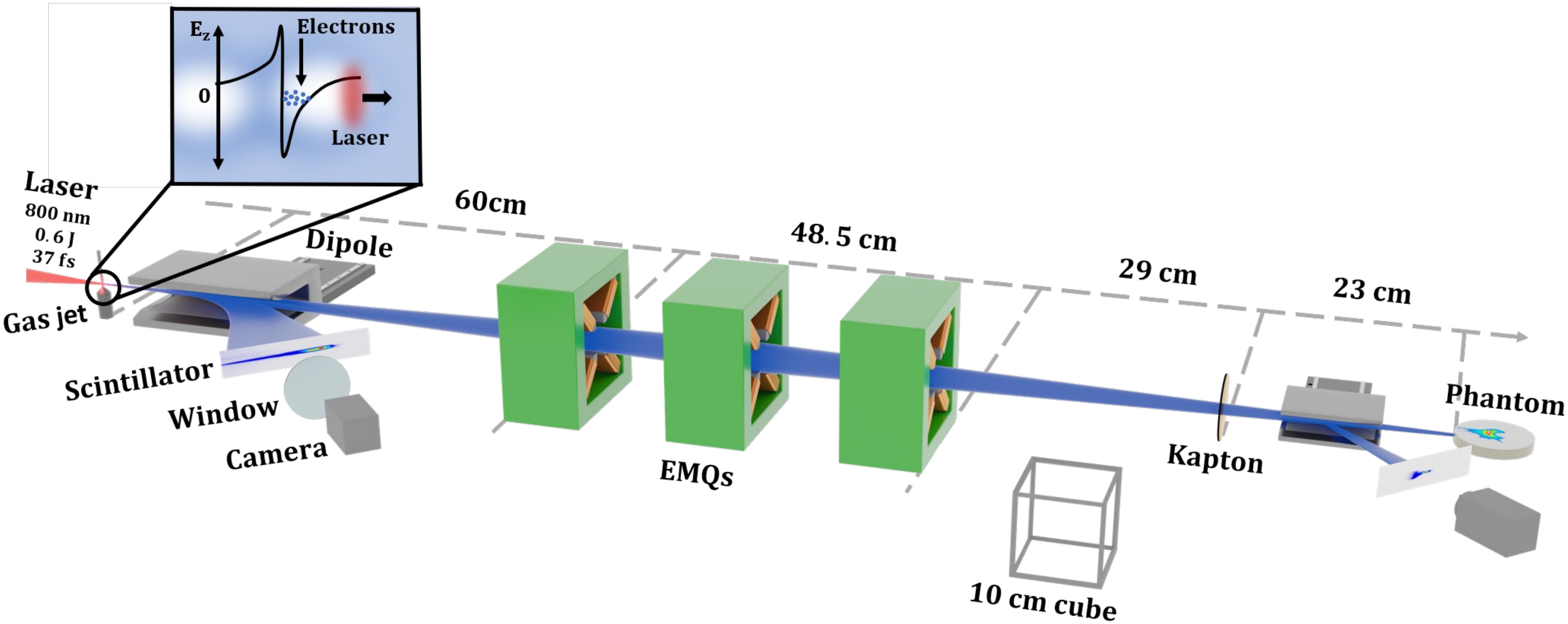


Compared to X rays (IMRT, VMAT), high-energy electrons (100-200 MeV) can give

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

Can plasma accelerators provide such beams?

Beam shaping using EMQ magnets



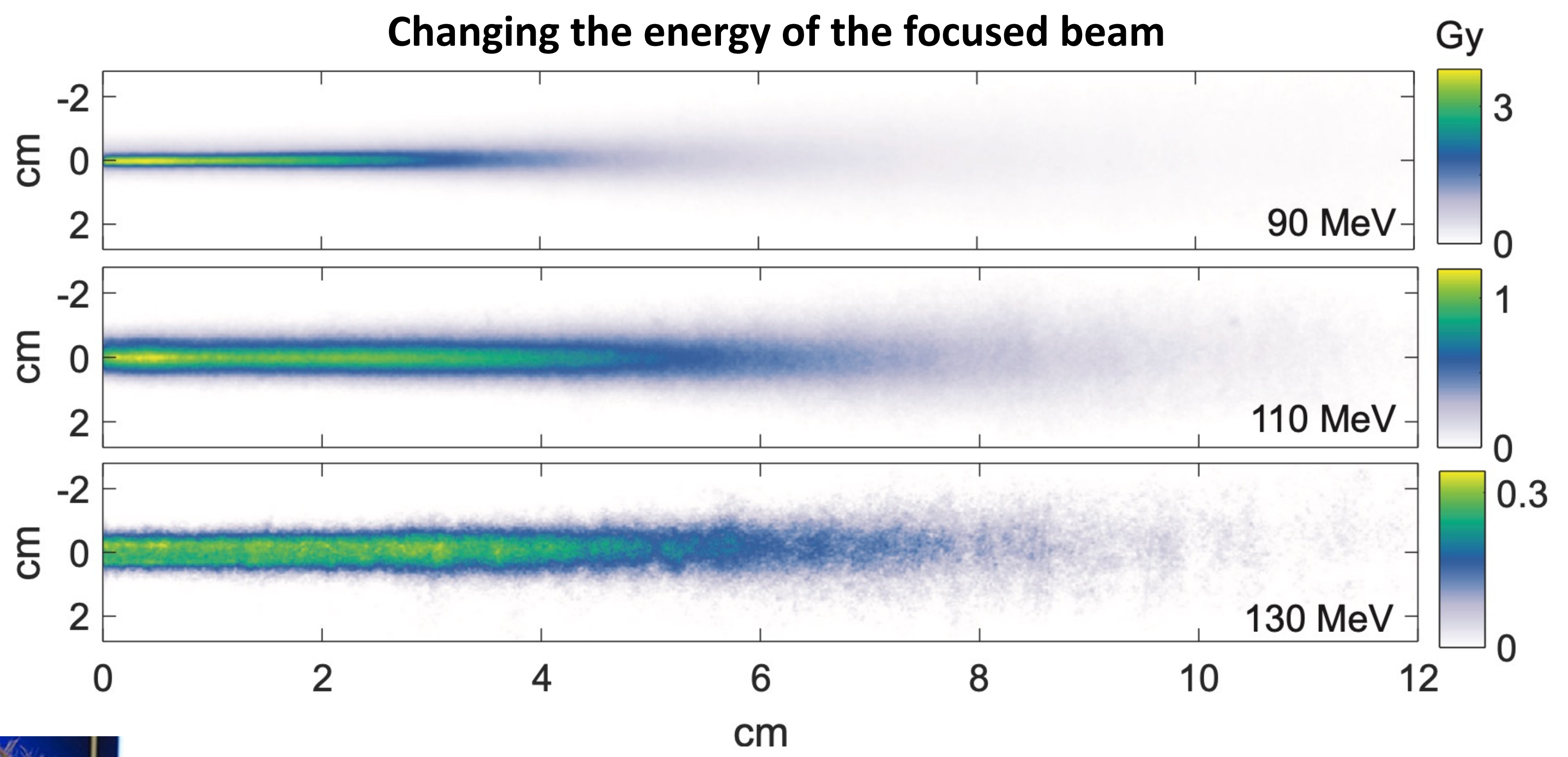
Focusing the beam at depth

✓ Mitigates lateral spread

✓ Gives more uniform dose

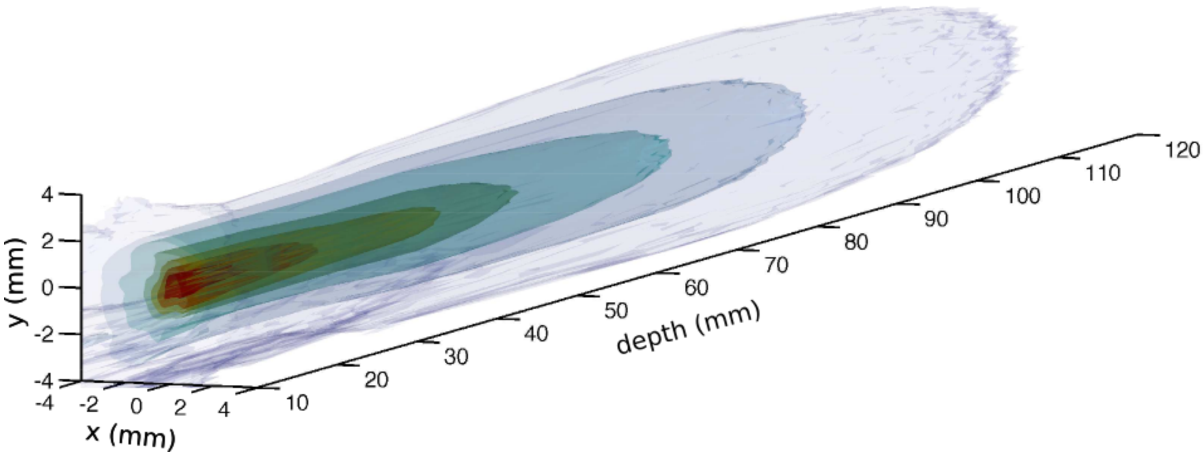
Jonas designed the beamline

Dose deposition by focused beams



Kristoffer did the measurements

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

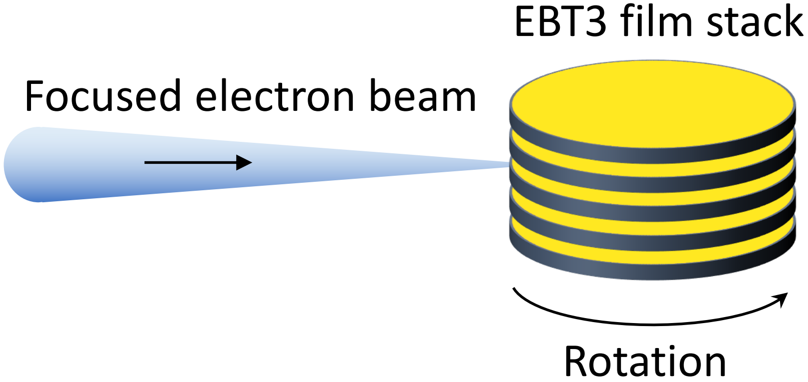
200 shots (20 s): 2 Gy over 20x20 mm^2

Reasonable numbers

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

Multiple irradiation angles

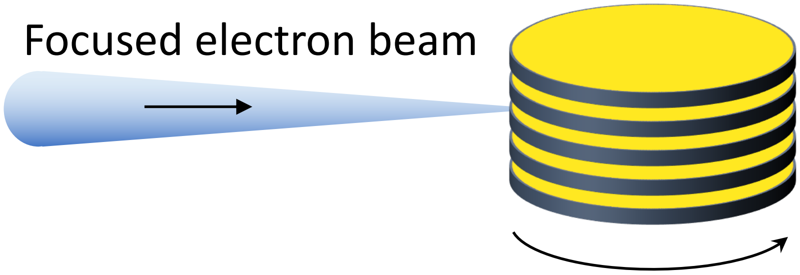
Phantom stack



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

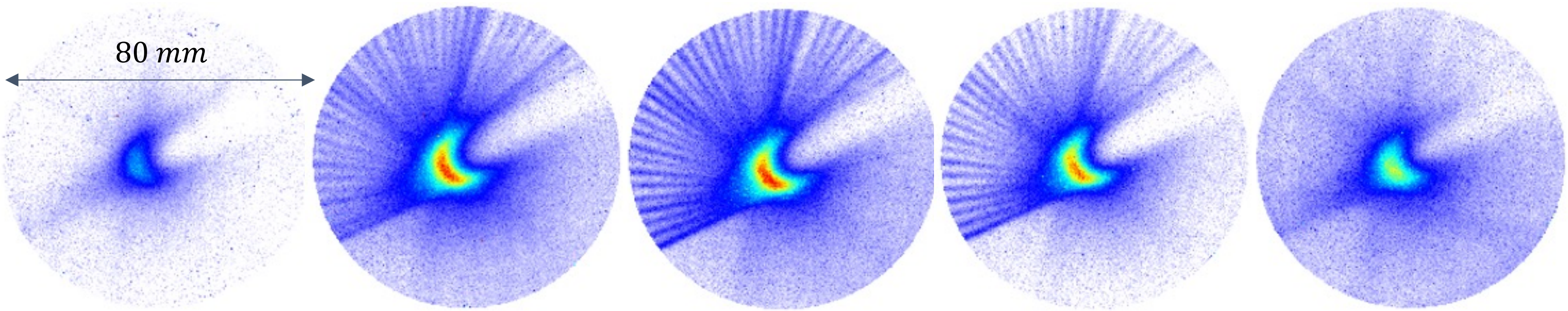
Multiple irradiation angles

Phantom stack



Measurement – concave volume

36 angles, 10 pulses/angle

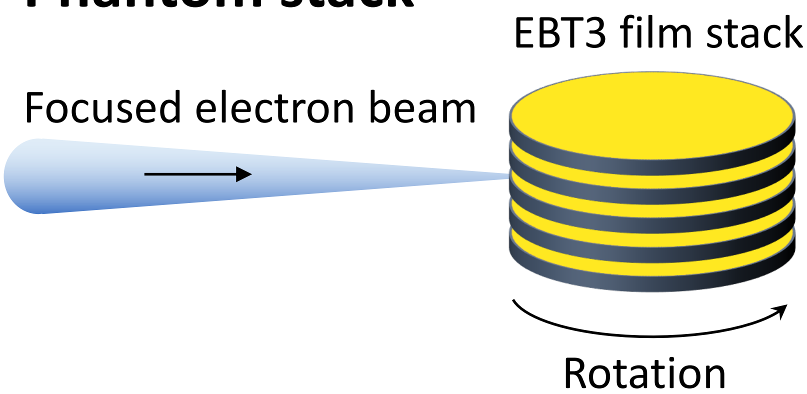


Layers at different heights from beam center

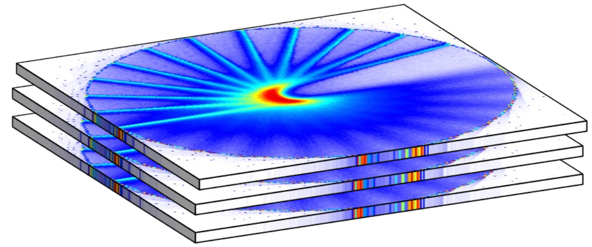
K. Svendsen *et al*, Sci Reports **11**, 5844 (2021)

Multiple irradiation angles

Phantom stack



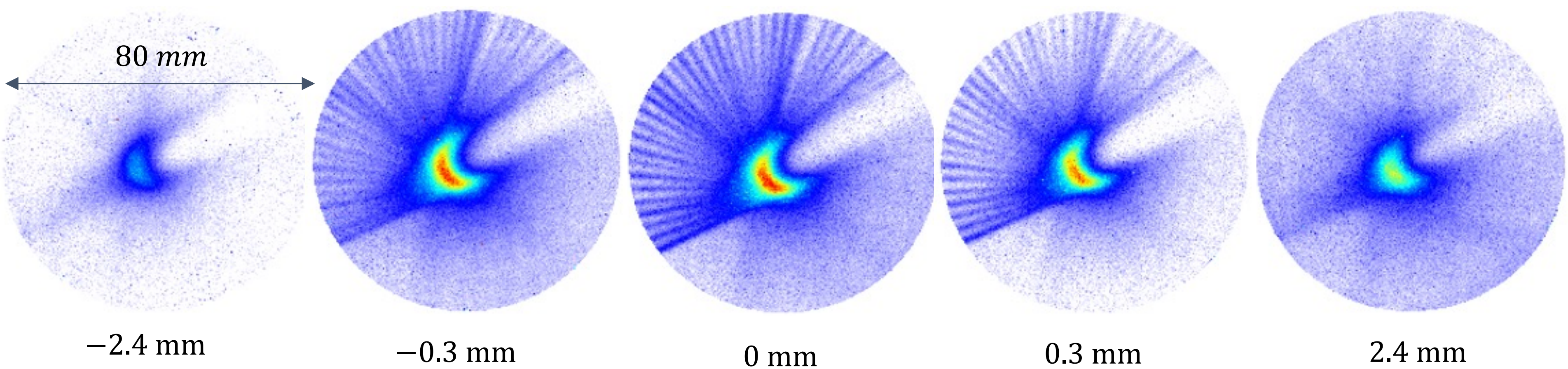
Simulation



Simulation using Fluka

Measurement – concave volume

36 angles, 10 pulses/angle

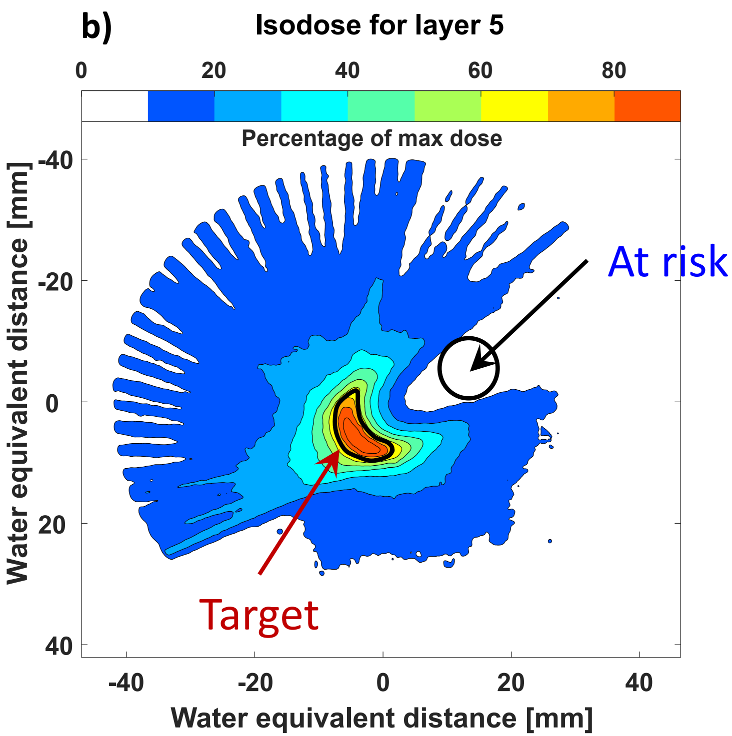


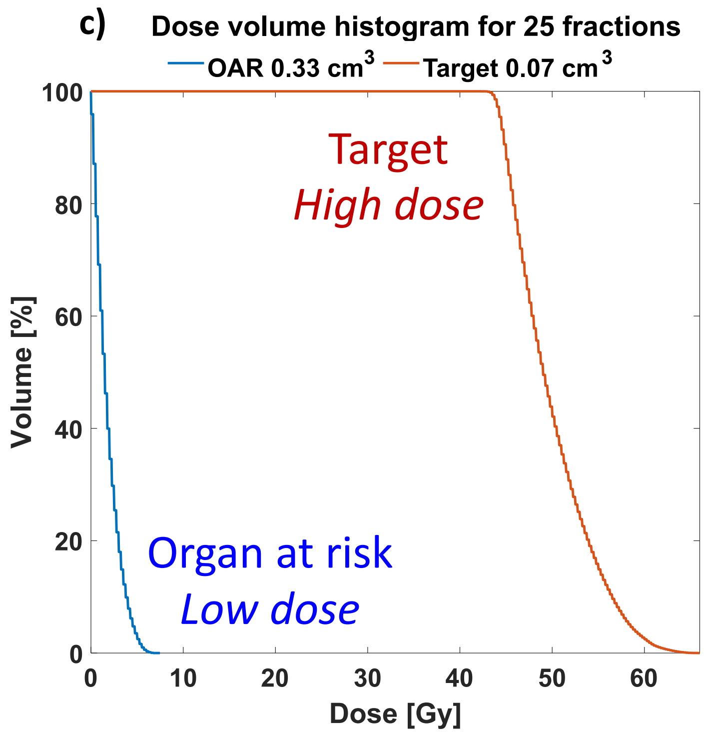
Layers at different heights from beam center

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)

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)

Kristoffer Petersson, *Oxford Univ*

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
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erc
Knut och Alice Wallenbergs Stiftelse
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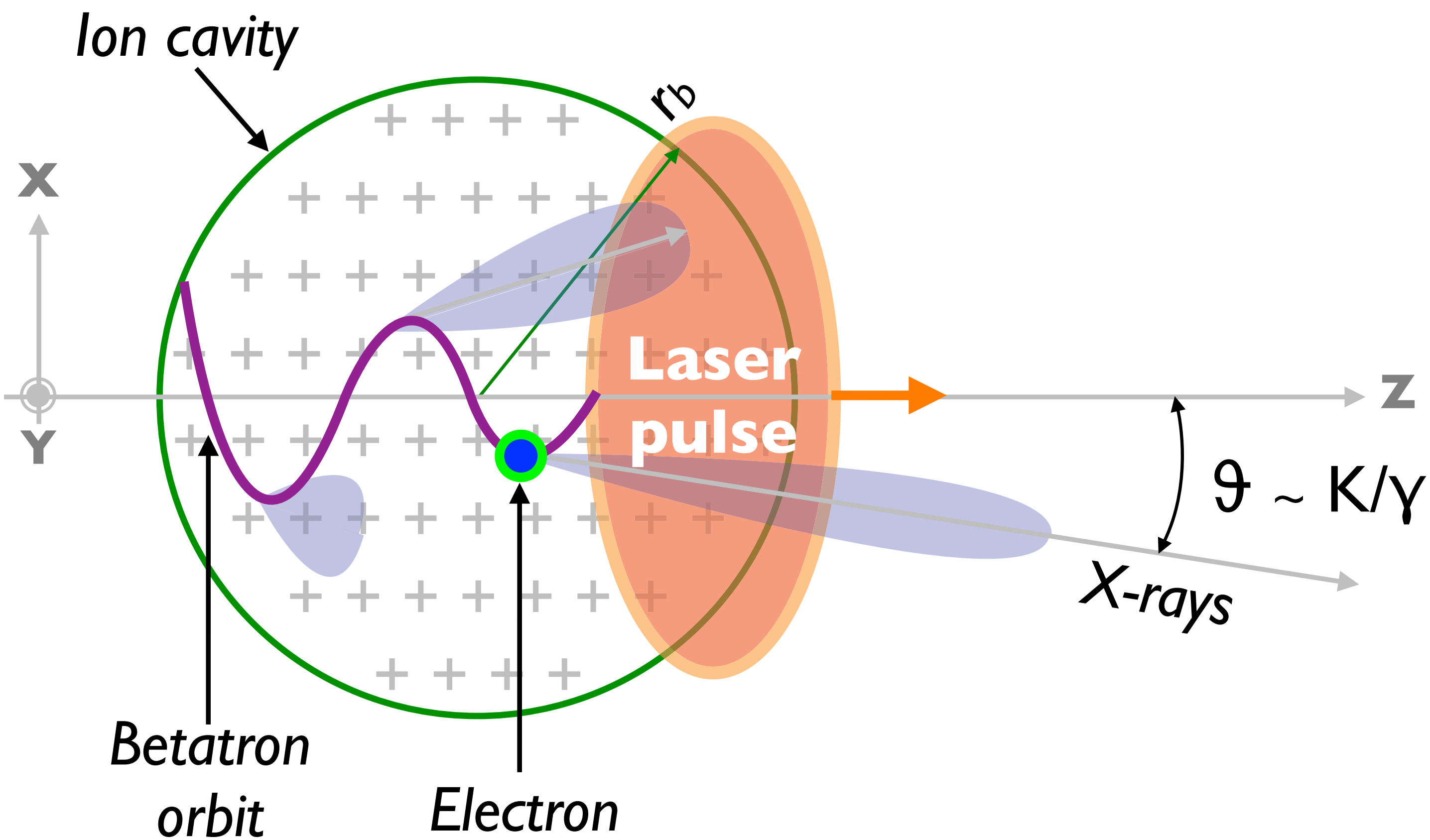
THE SWEDISH RESEARCH COUNCIL

Betatron X-ray source



S Corde *et al*, Rev Mod Phys 85, 1 (2013)

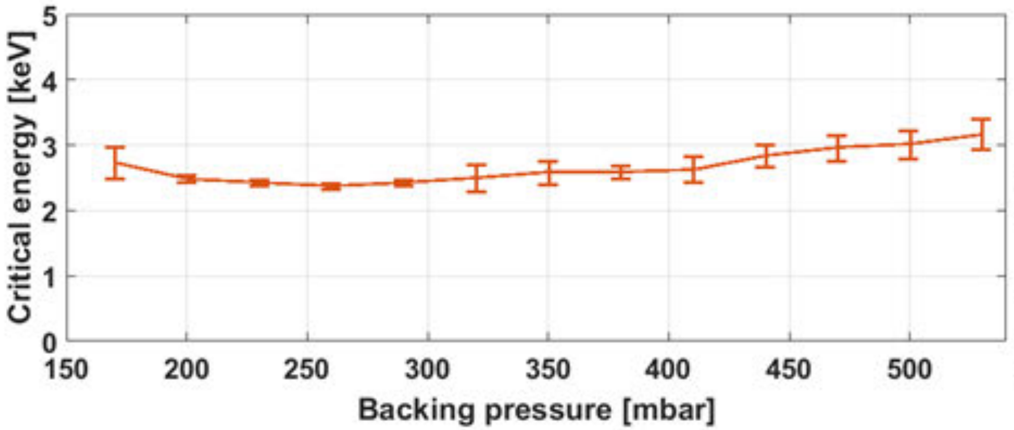
X-ray spectrum

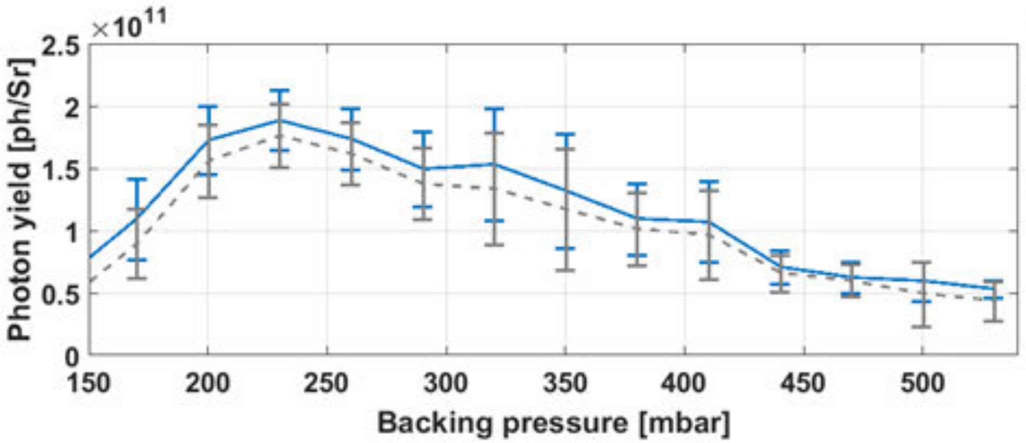
Critical energy: 2-3 keV

Flux: 1-2 · 10^{11} photons/sr

Divergence: 30 × 40 mrad

~4 · 10^{8} photons

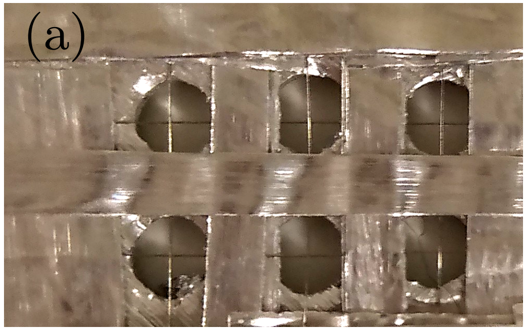




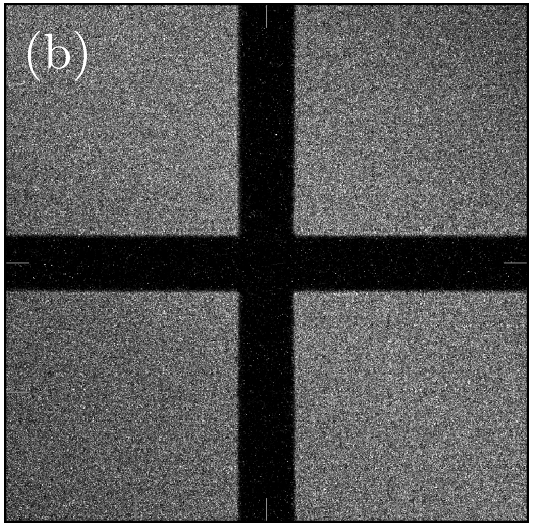
Isabel did the analysis

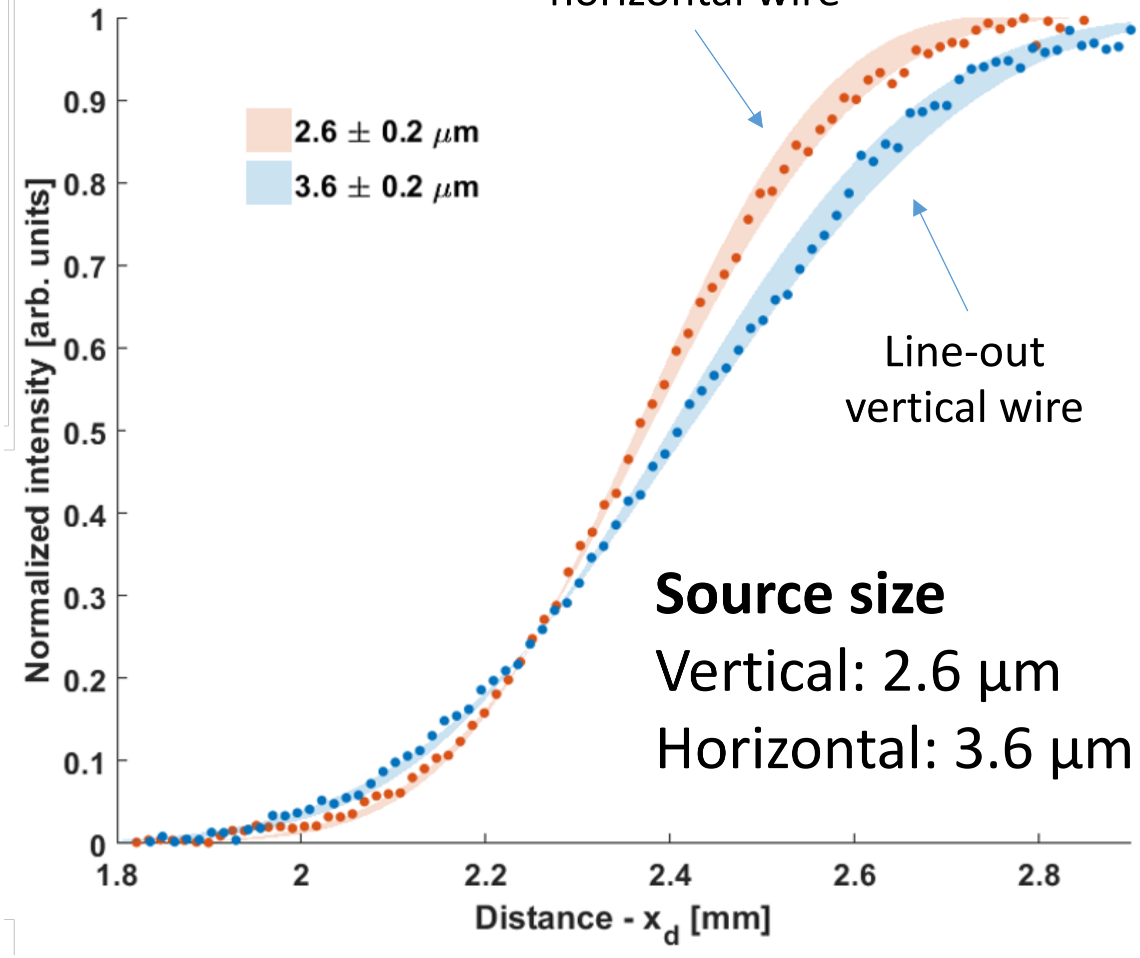
X-ray source size

25 µm tungsten wires



Wire shadow on CCD



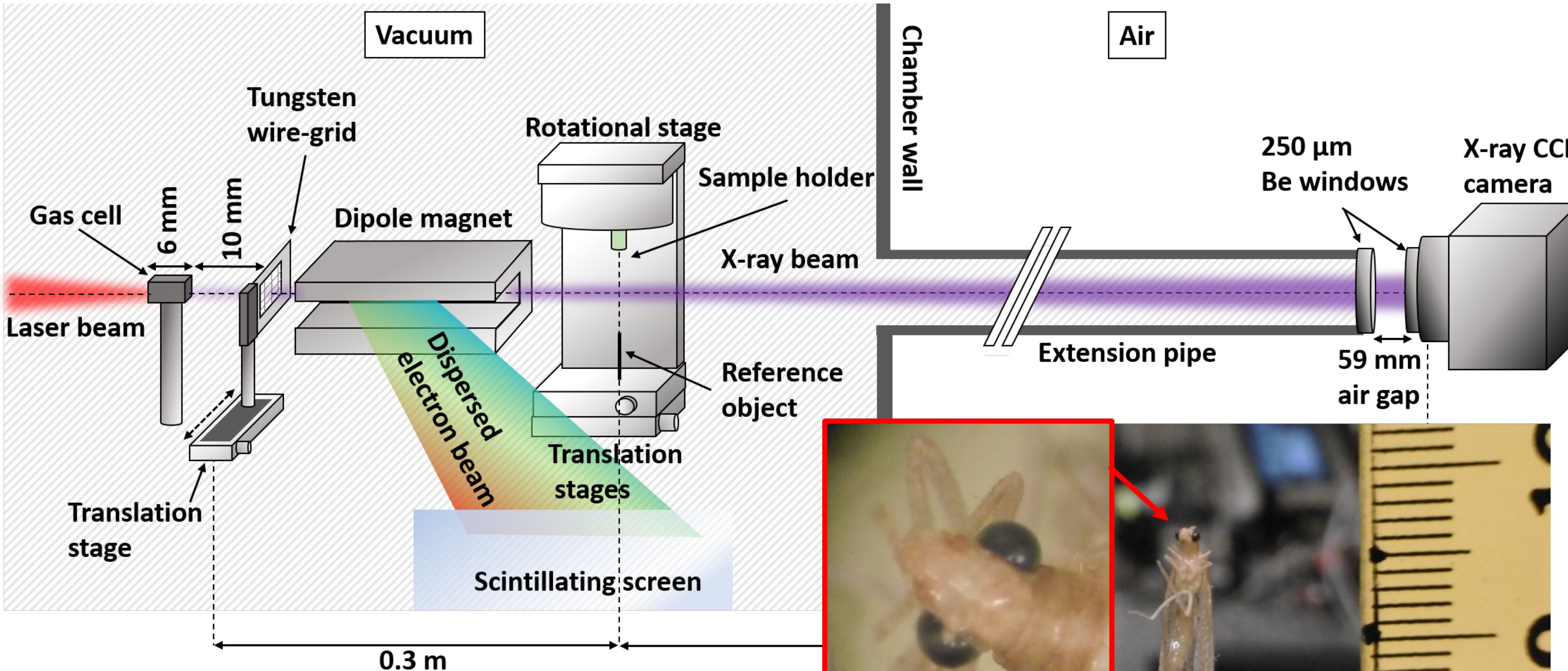


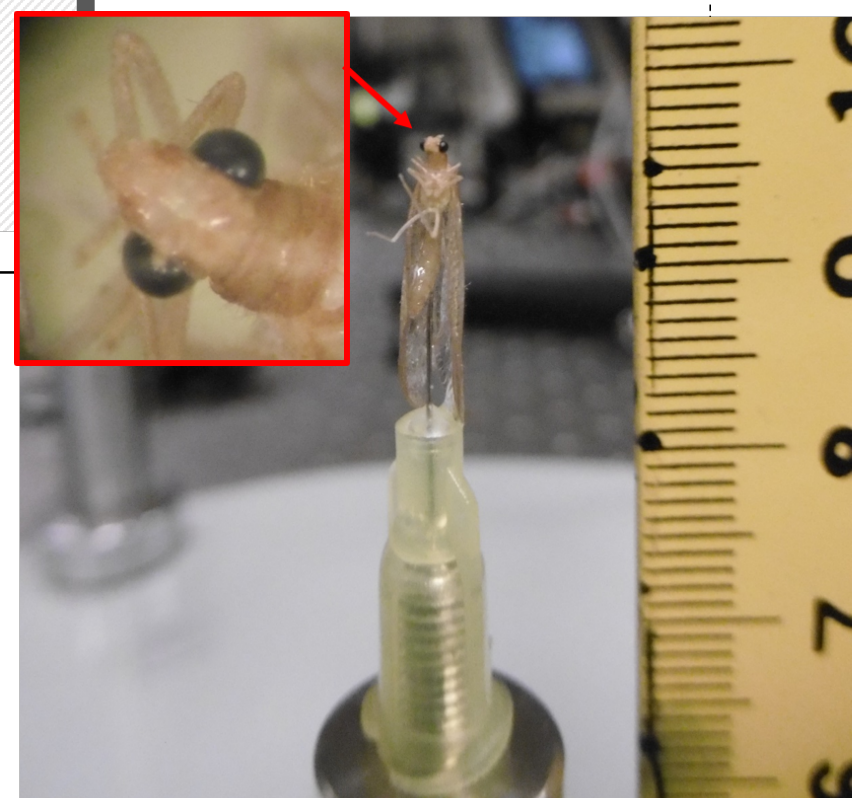
Source size

Vertical: 2.6 µm

Horizontal: 3.6 µm

Setup for phase-contrast imaging

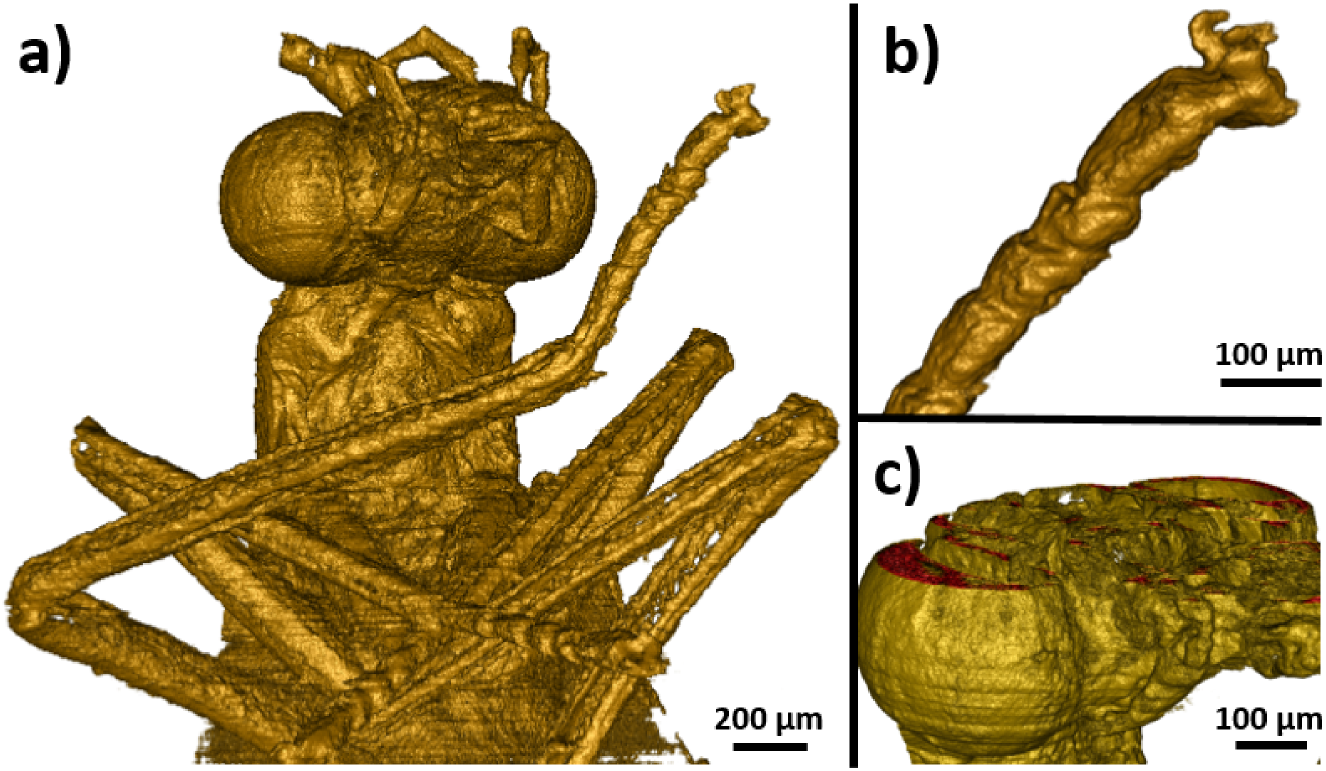




Kristoffer did the experiment

Phase-contrast tomography

3D rendering



10 µm structures can be resolved in tomogram

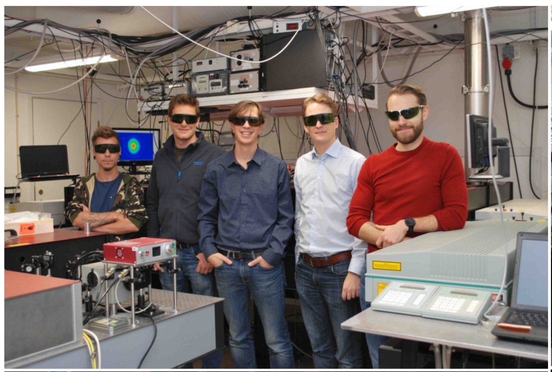
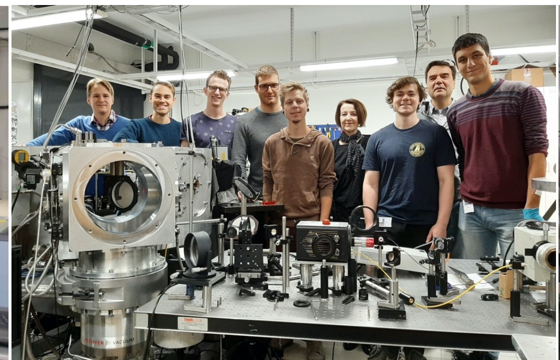
K. Svendsen *et al*, Optics Express **26**, 33930 (2018)

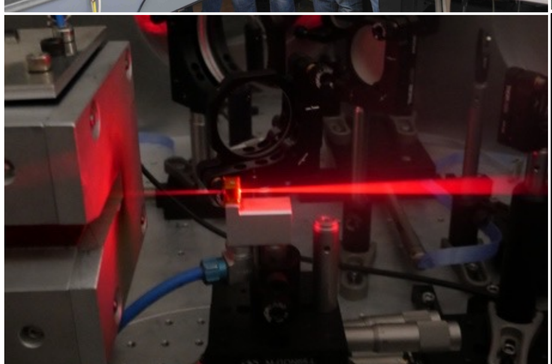
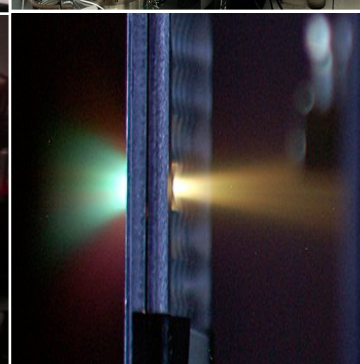
Lund University Laser Acceleration Laboratory

LUNDS UNIVERSITET

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

Short title	Leader	Institute	Country	Hours	Completed
Multistage plasma accelerator	V. Tomkus	FTMC Vilnius	Lithuania	135	Feb 2019
Testing plasma souce for EuPRAXIA	M. Streeter	Imperial College	UK	244	Dec 2019
Spray imaging by laser driven x-rays	L. Zigan	Erlangen FAU	Germany	138	Mar 2020
Optimizing acceleration by AI/ML	F. Filippi	ENEA Frascati	Italy	271	Dec 2021

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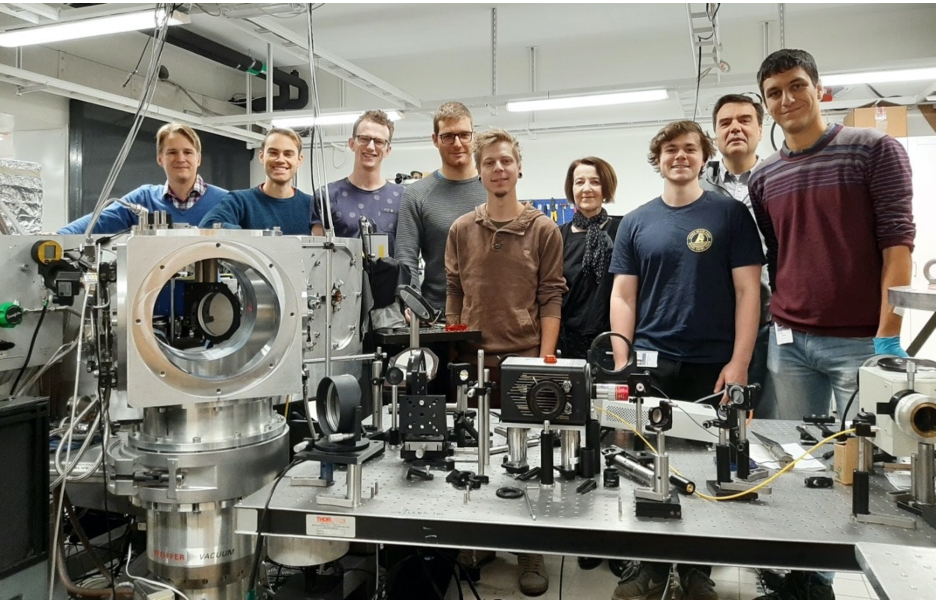


Testing plasma accelerator source for EuPRAXIA

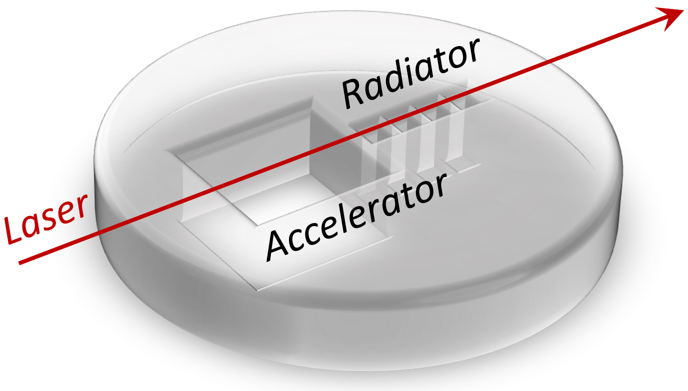
4 weeks access, 10 visiting users, 10 participating institutes, 5 countries

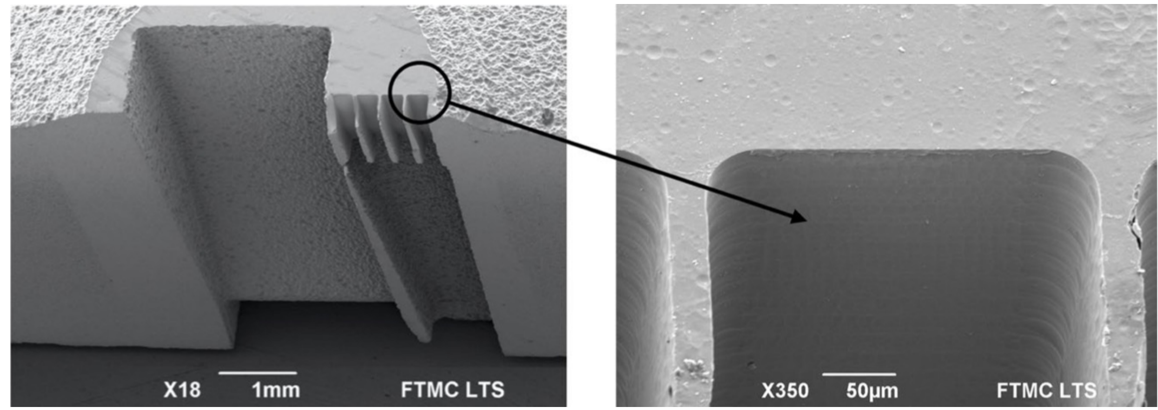
Imperial College (UK), University of York (UK), Oxford University (UK), CLF (UK)
CNRS (FR), U Paris-Saclay (FR), CEA-Saclay (FR), INFN (IT), IST (PT), Lund University (SE)

L. Dickson *et al.*, Phys. Rev. AB **25**, 101301 (2023)
F. Filippi *et al.*, JINST **18**, C05013 (2023)

Lund University Laser Acceleration Laboratory

Micromachined multi-stage gas nozzle





Recent TNA project (Jan-Feb 2019):

Multistage plasma accelerator

3 weeks access, 5 users from Center for Physical Sciences and Technology, Vilnius, Lithuania

V. Tomkus *et al.*, Scientific Reports **10**, 16807 (2020)

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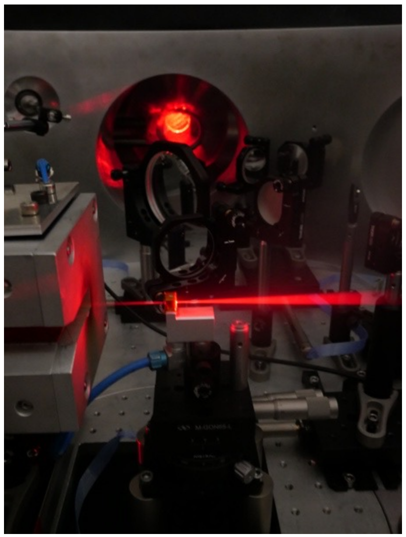
Lund University Laser Acceleration Laboratory

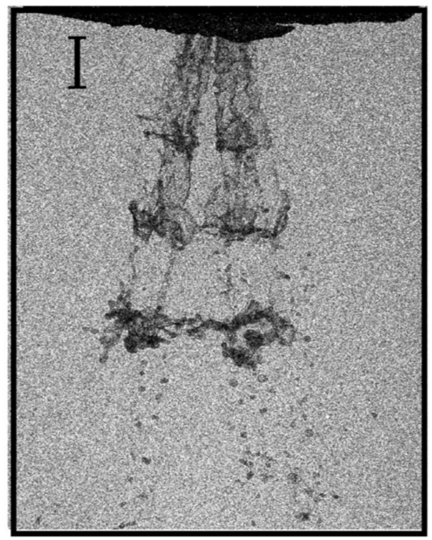
Understanding the breakup and atomization of fuel sprays is essential for improving e.g. engine efficiencies.

LWFA X-ray source

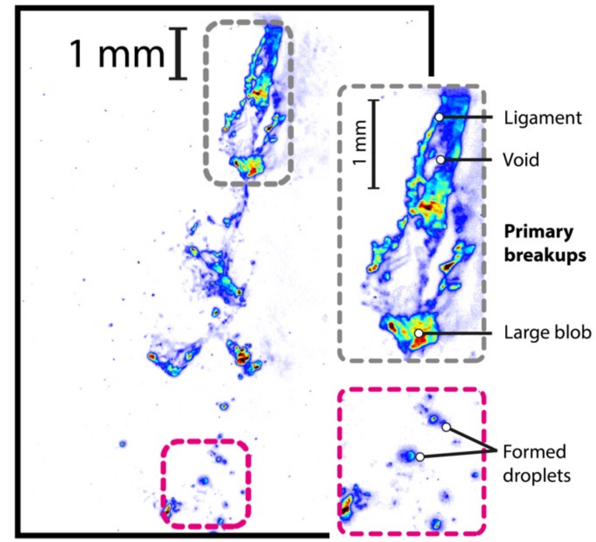


Fuel injection spray

LWFA X-ray image



Laser-induced flourescence



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

3 weeks access, 5 users from Univ Erlangen FAU (Germany)

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

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

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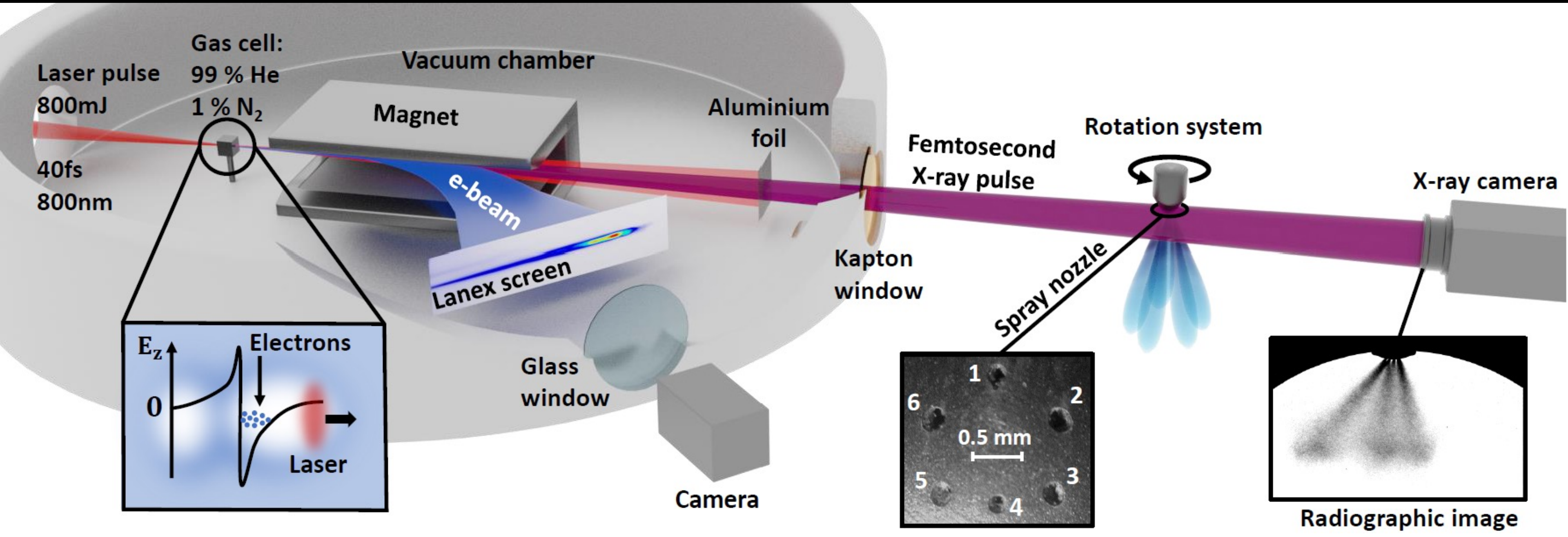
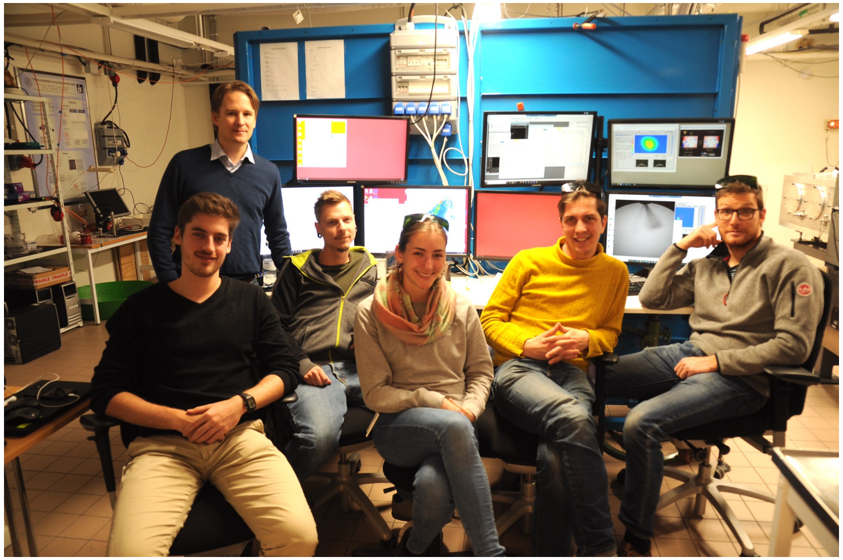
Experimental setup





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

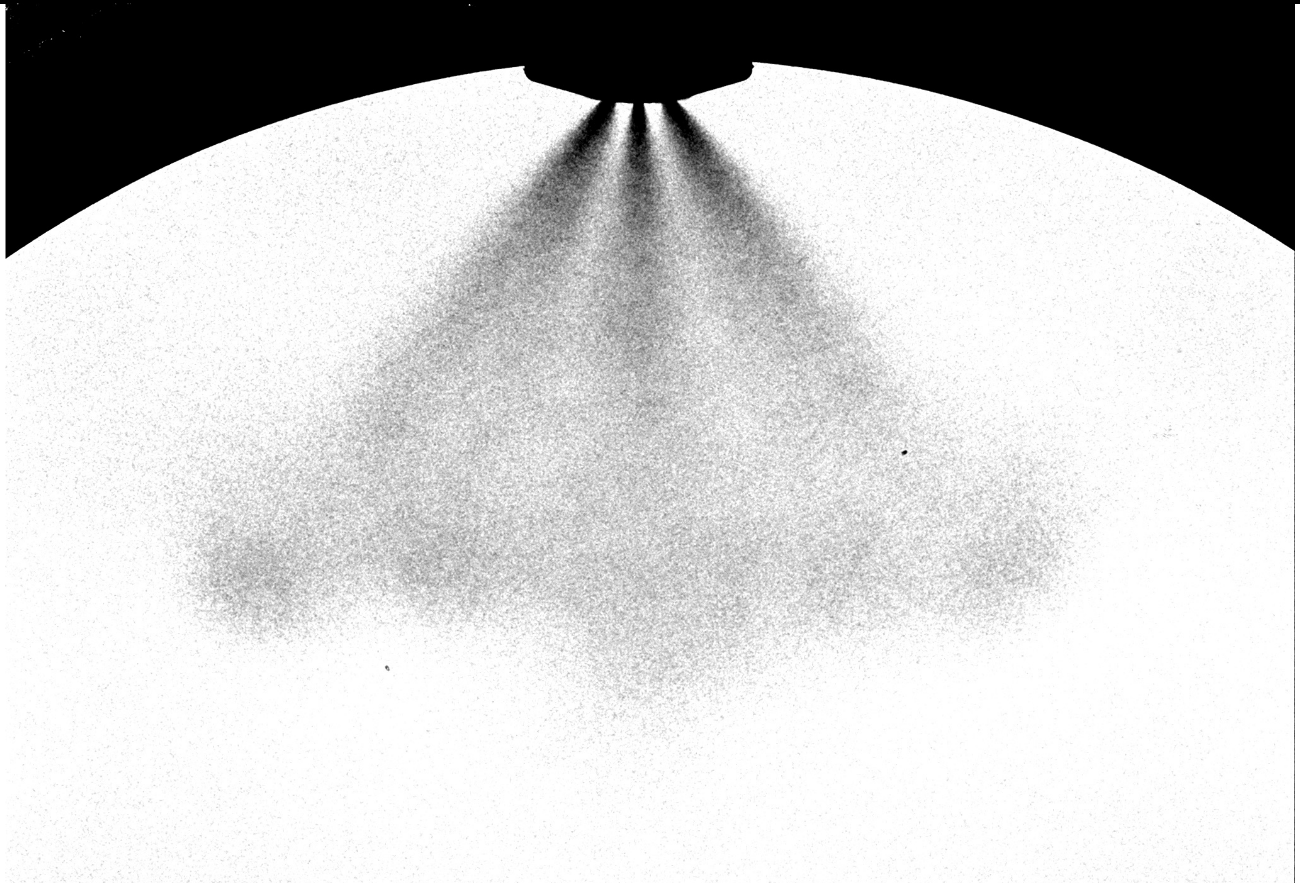
X-ray absorption

0°

X-ray absorption

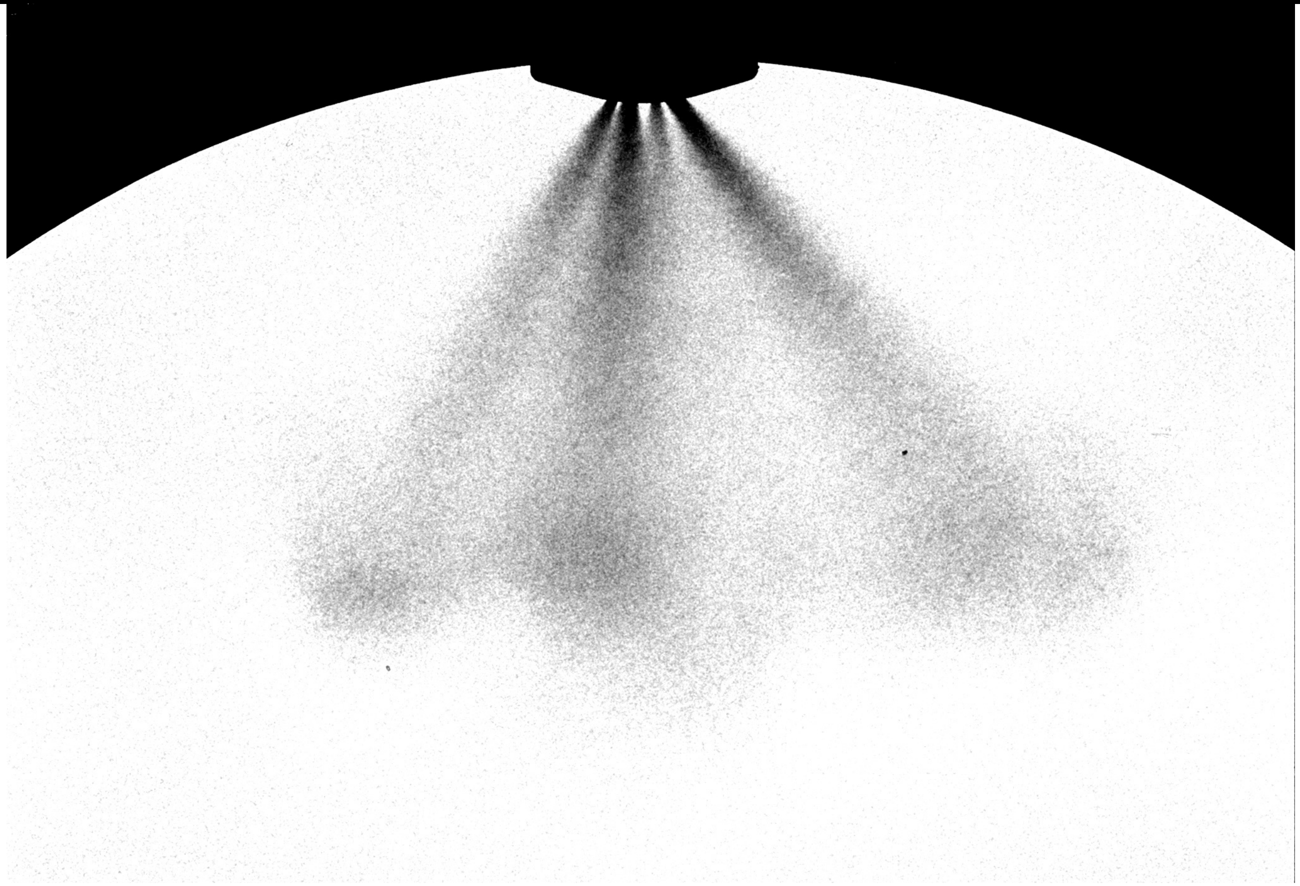
20°

X-ray absorption



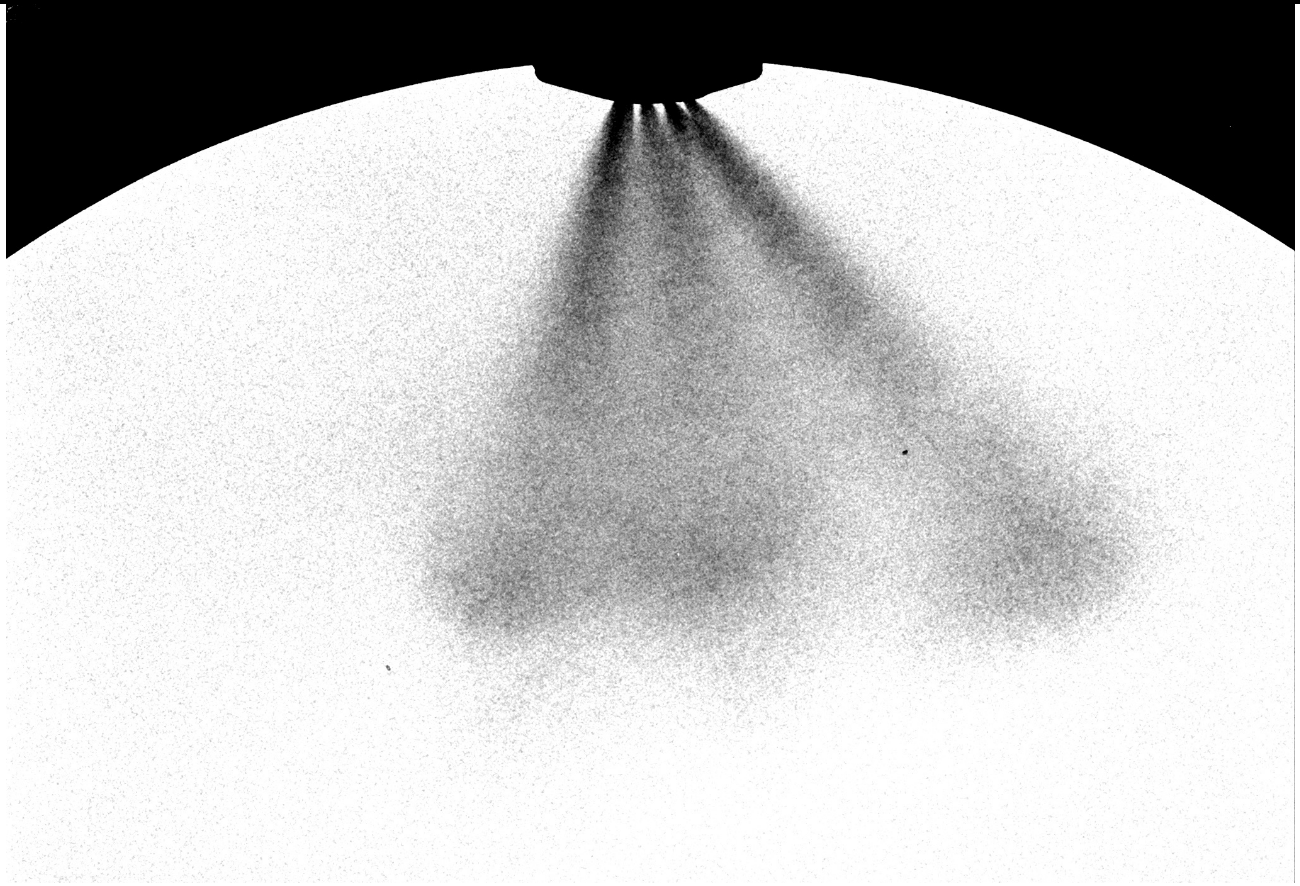
40°

X-ray absorption



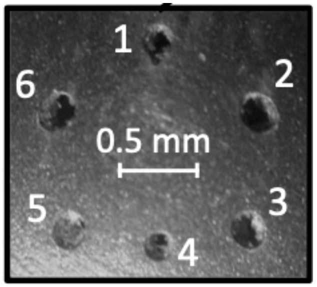
60°

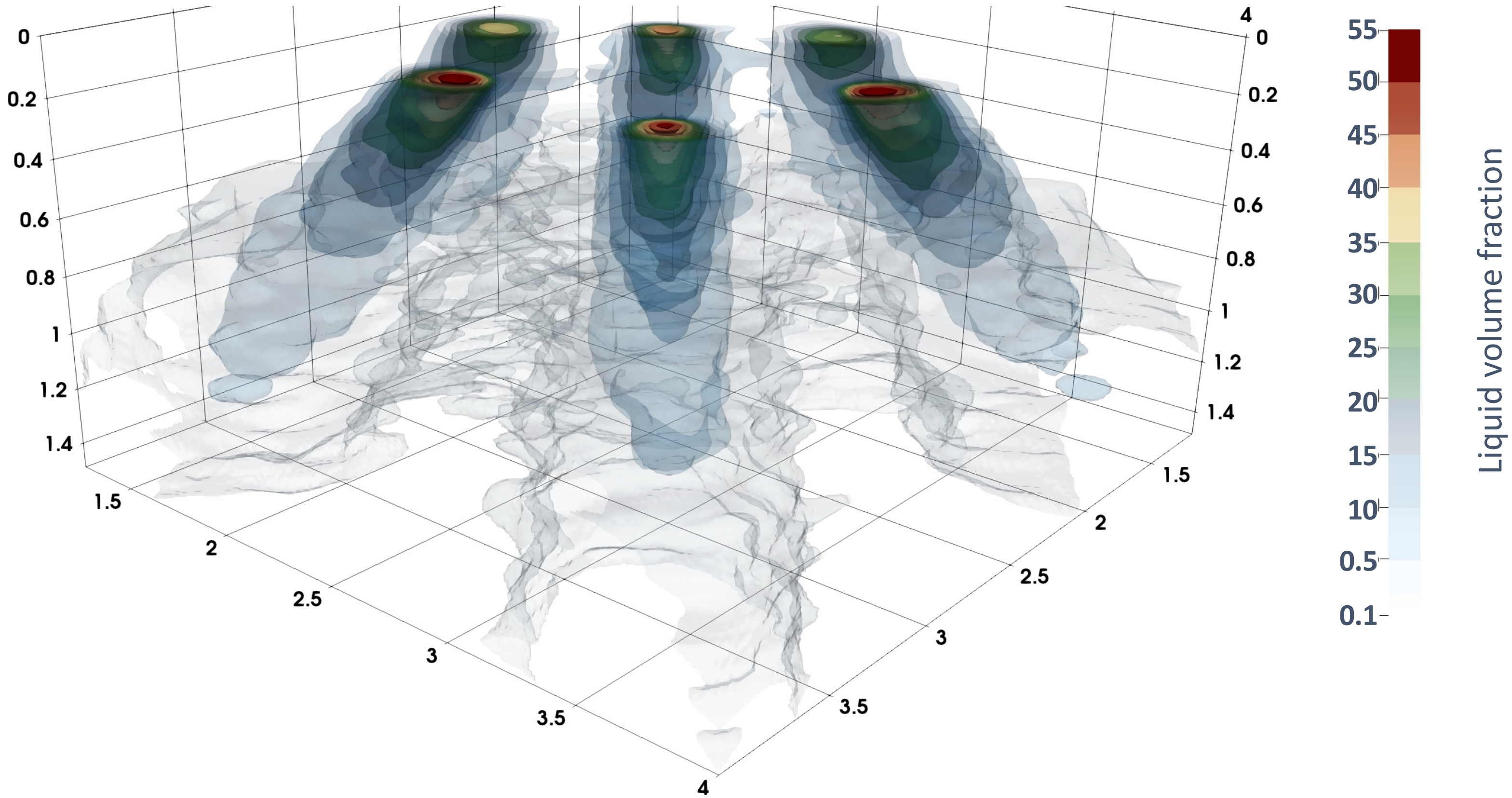
X-ray absorption



80°

Transient spray tomography



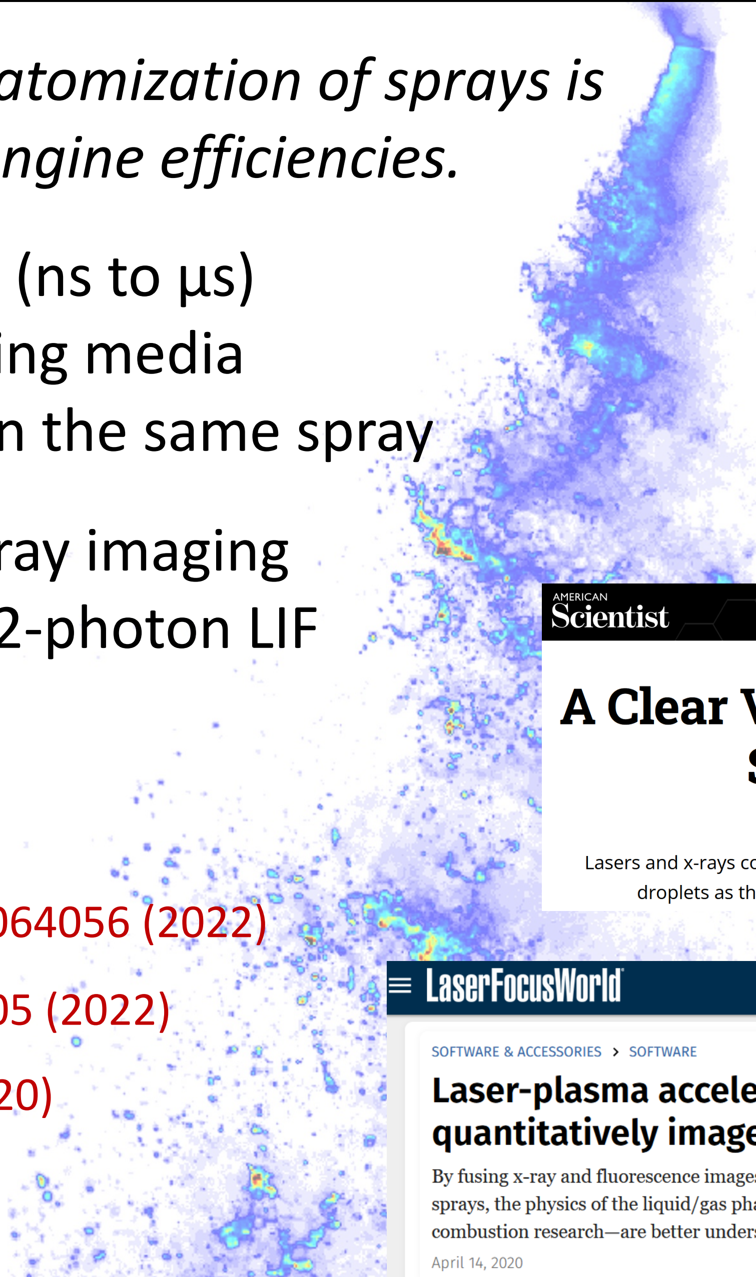


Conclusion

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

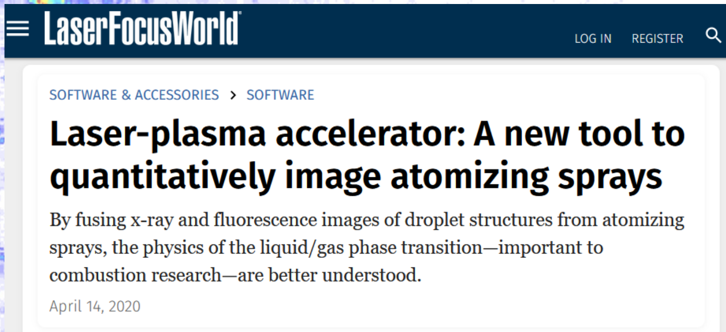



AMERICAN Scientist

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.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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.

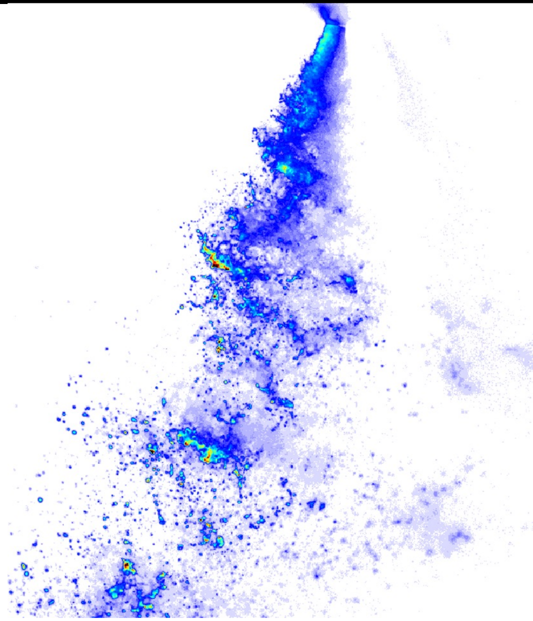
April 14, 2020

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)

Summary



Laser plasma particle accelerators

✓ Compact – Ultrafast – Tunable

High energy electron dosimetry

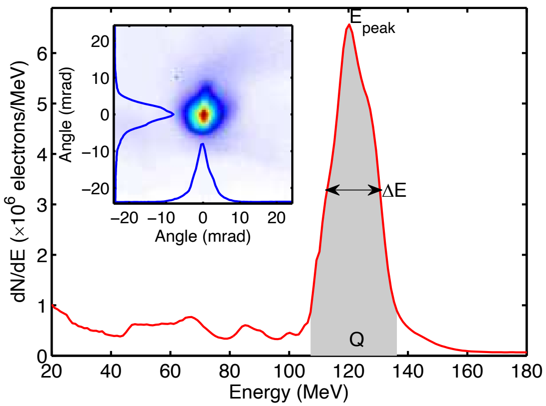
✓ High dose – Ultrahigh dose rate

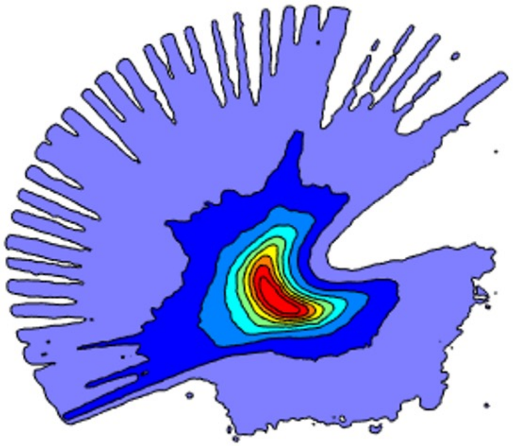
✓ Focused pencil beam

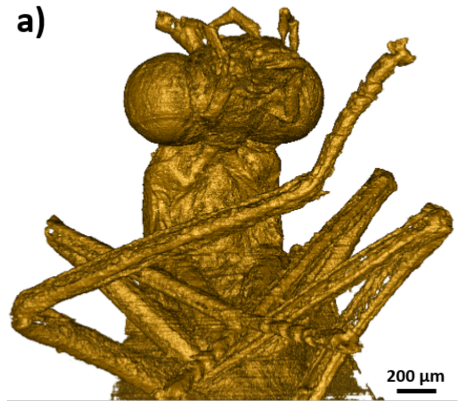
X-rays for imaging and tomography

✓ Phase-contrast imaging of low-absorbing samples

✓ Combining X-rays and fluorescence imaging of sprays







Applications of laser-plasma acceleration

High Energy Electrons for Radiotherapy

X-rays for Imaging and Tomography

Prospects for plasma acceleration at MAX IV

STIFTELSEN för STRATEGISK FORSKNING

Laserlab Europe

ARIES

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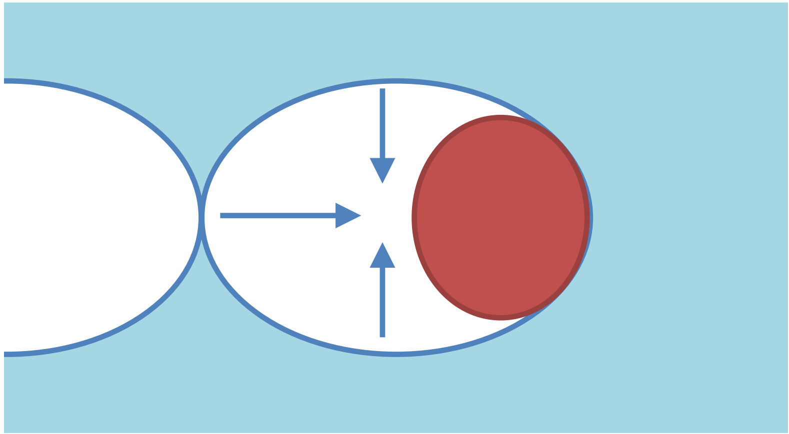
Knut och Alice Wallenbergs Stiftelse

VETENSKAPSRÅDET
THE SWEDISH RESEARCH COUNCIL

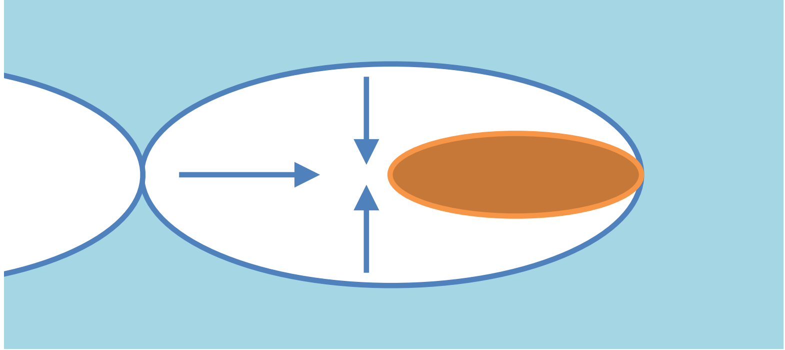
Particle acceleration in a plasma



LWFA

Wakefield driven by laser pulse

+ Lasers are compact and available
+ Internal injection schemes well developed
- External injection (synchronisation) difficult
- Dephasing limits energy in one stage

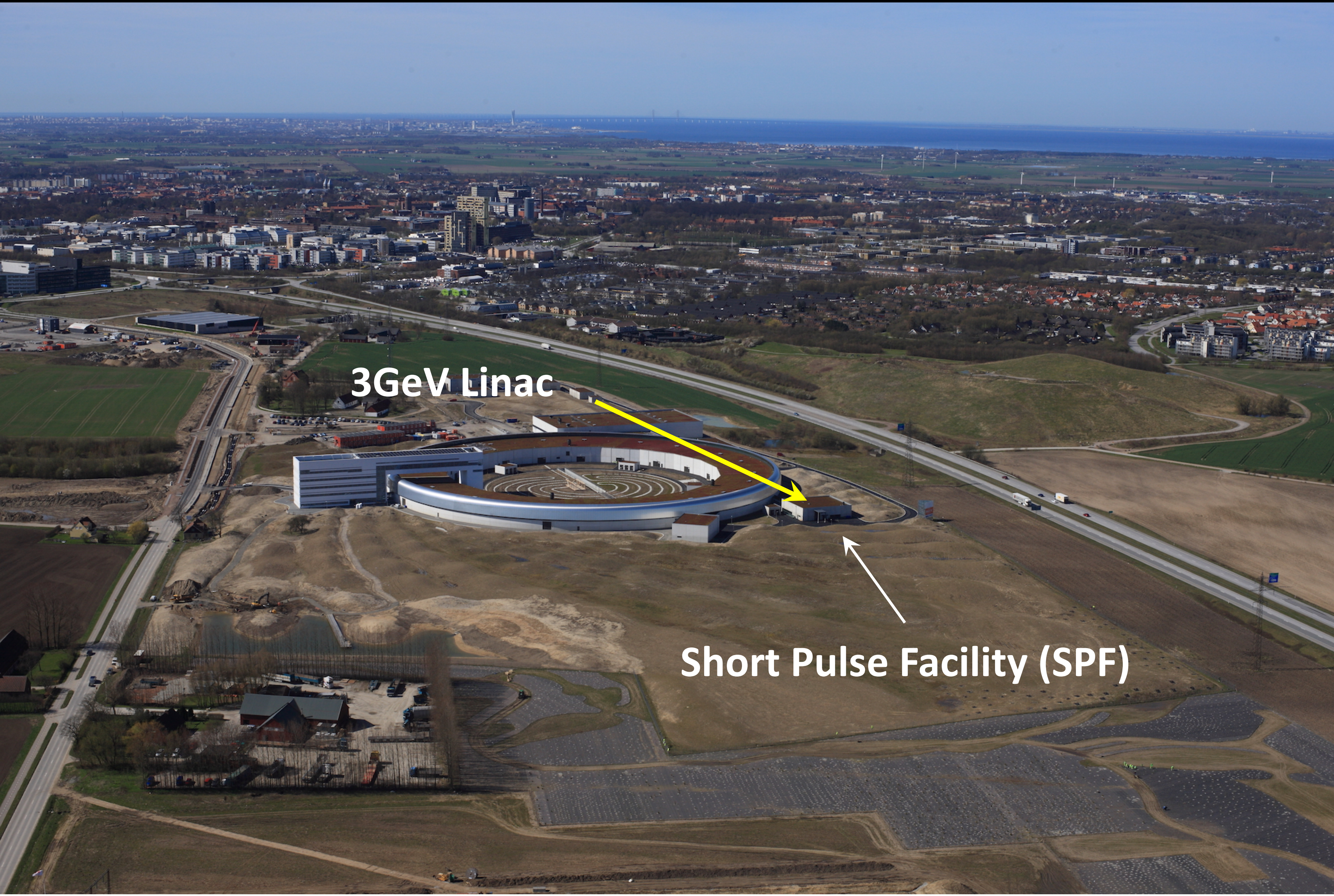


PWFA

Wakefield driven by particle beam

+ No dephasing, energy gain limited by depletion
+ External injection (synchronisation) “easier”
- Needs large particle accelerator

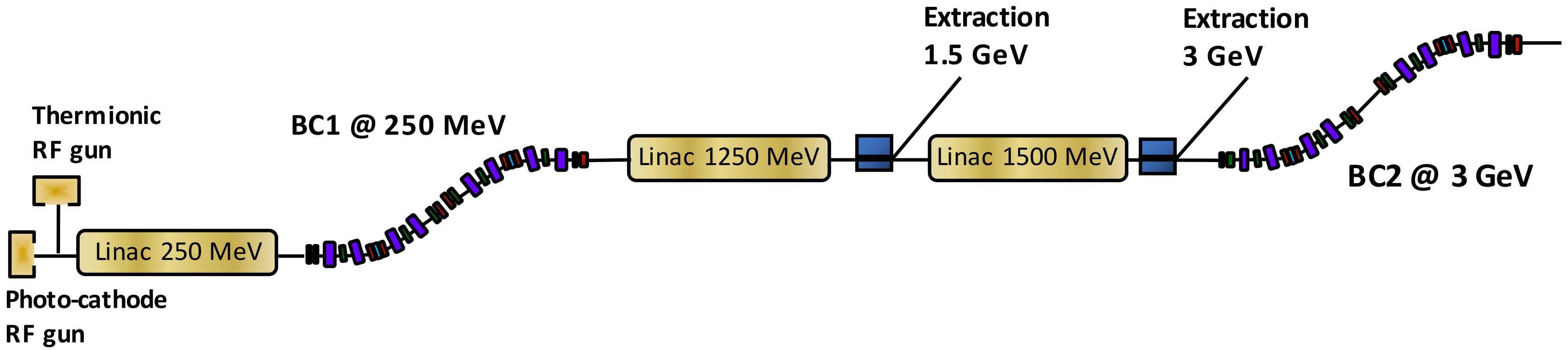
MAX IV Laboratory



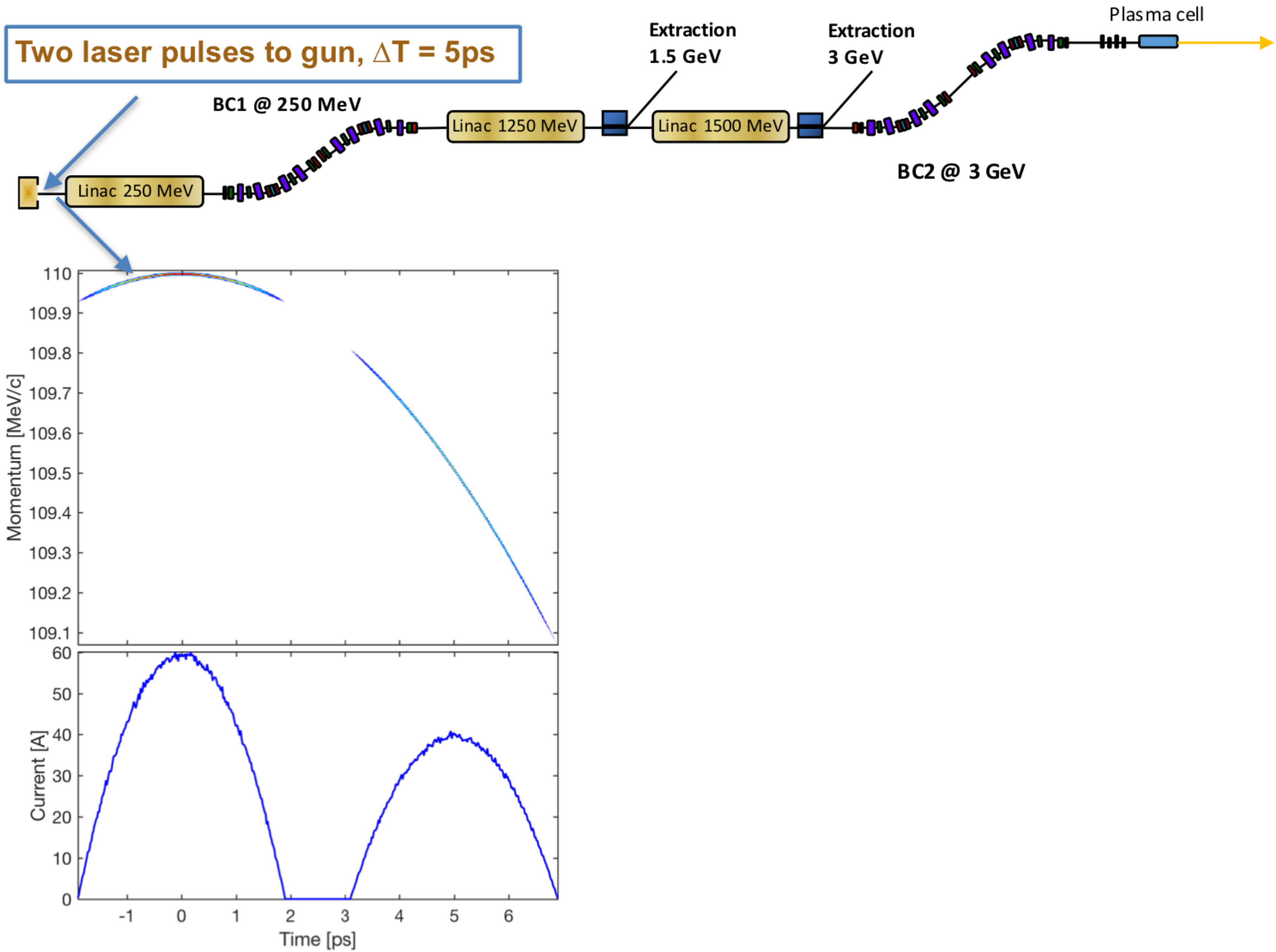
MAX IV Linear accelerator

Operation modes

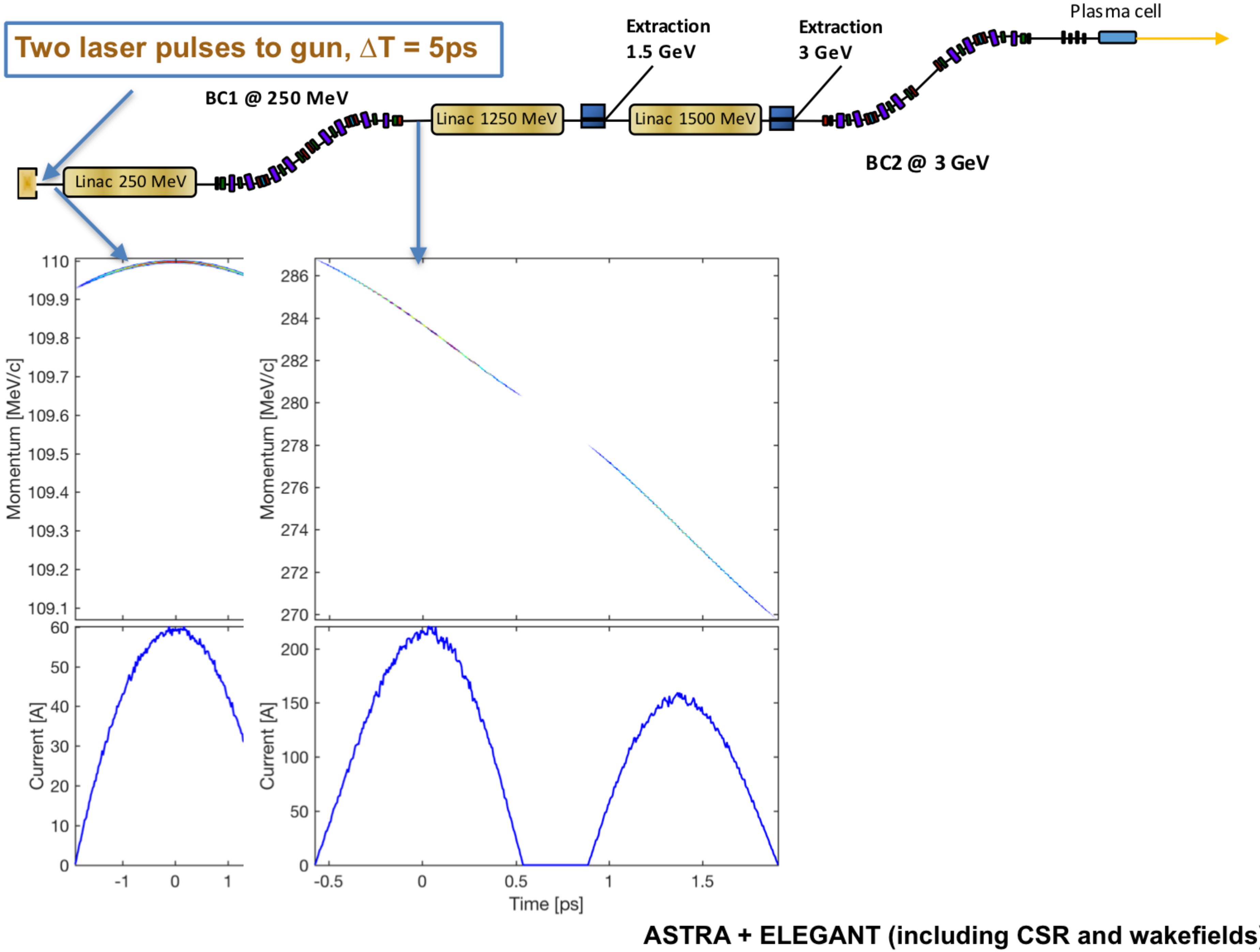
- Top-up injection for storage rings (~every 5-10 min)
- Driver for Short Pulse Facility (SPF, 100 Hz)



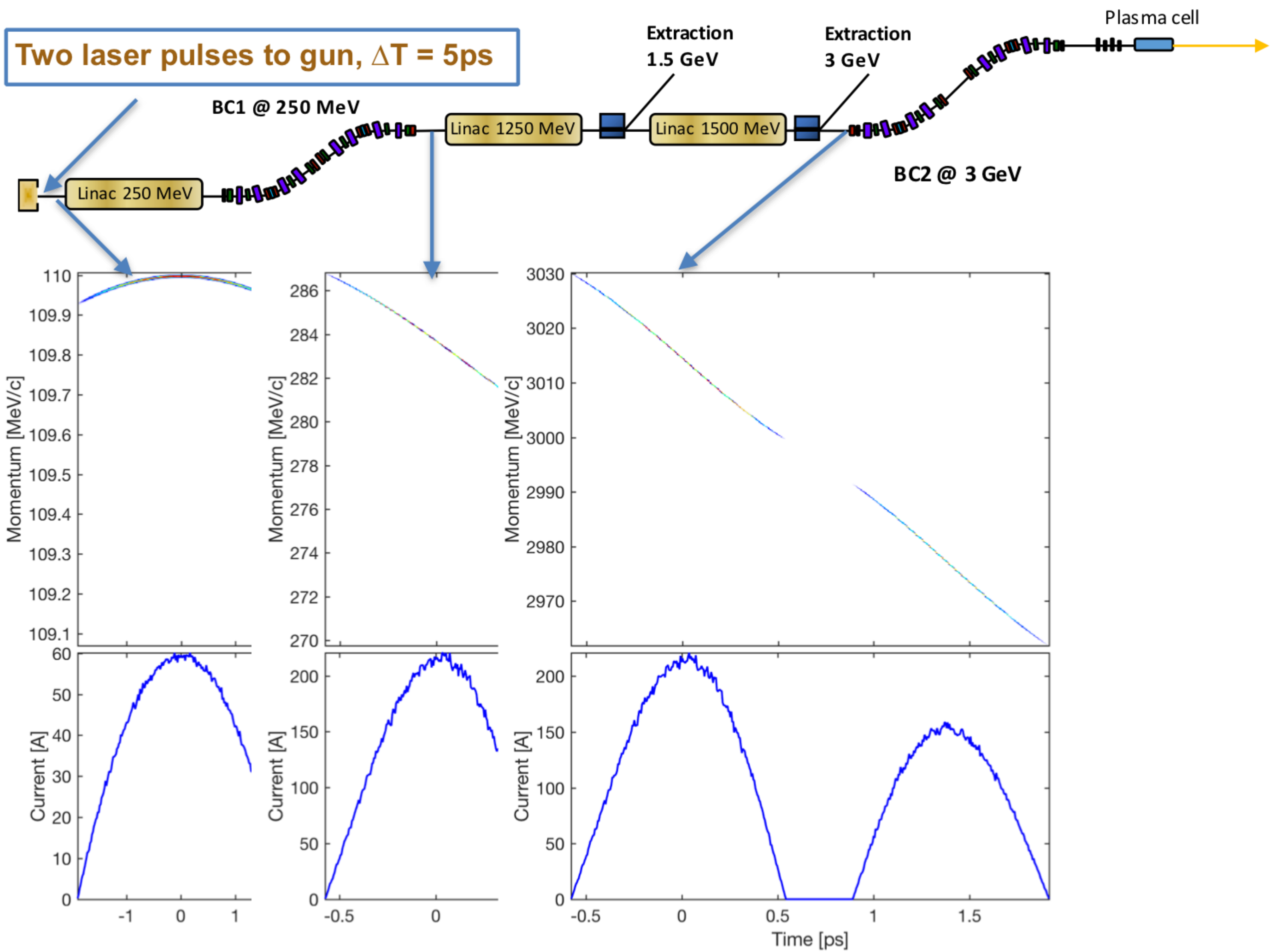
Energy	3 GeV
Charge	> 100 pC
Peak current	> 1 kA
Duration	< 100 fs
Emittance	< 1 mm mrad



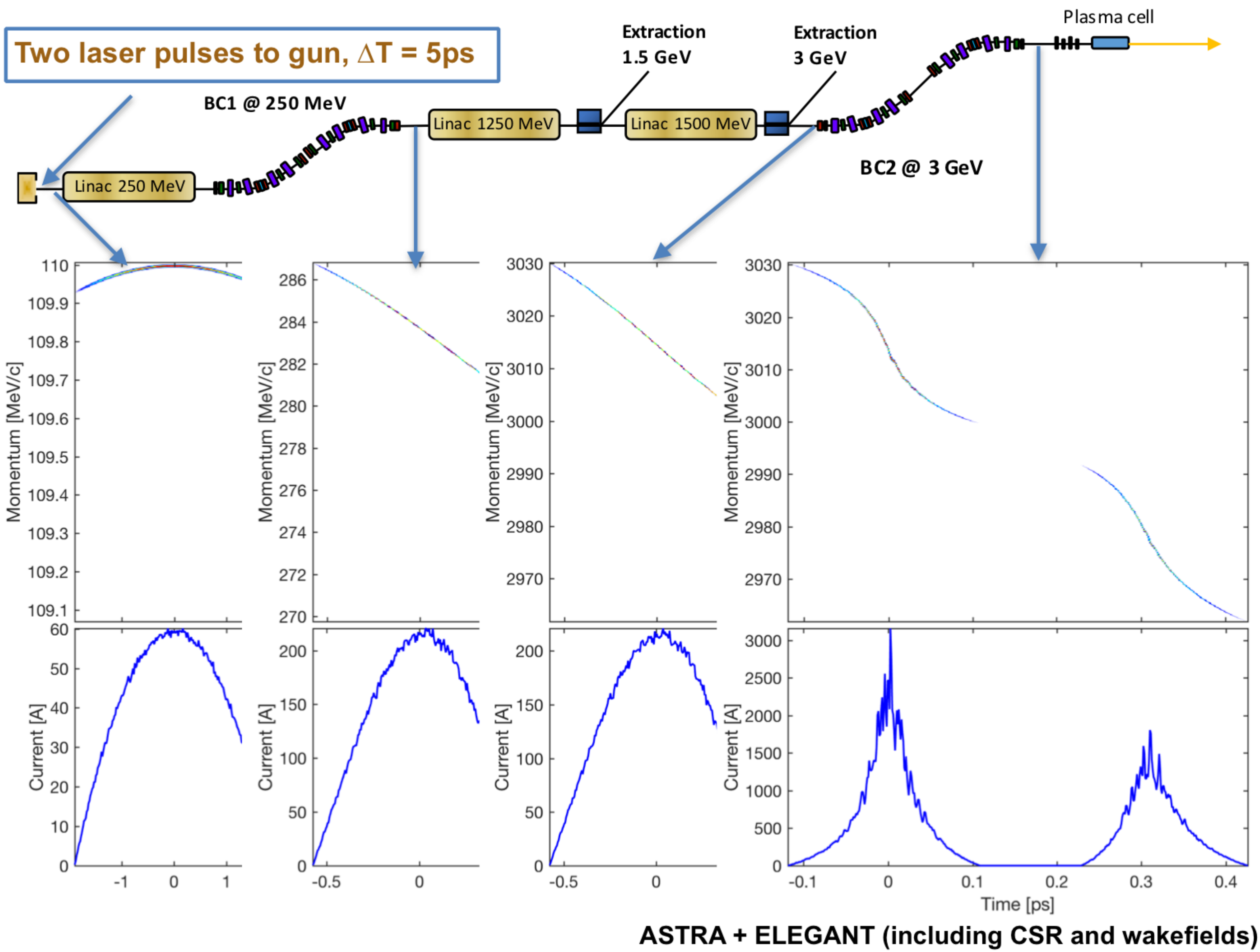
ASTRA + ELEGANT (including CSR and wakefields)



Two laser pulses to gun, ΔT = 5ps
BC1 @ 250 MeV
Linac 250 MeV
Linac 1250 MeV
Extraction 1.5 GeV
Linac 1500 MeV
Extraction 3 GeV
BC2 @ 3 GeV
Plasma cell
Momentum [MeV/c]
Current [A]
Time [ps]
ASTRA + ELEGANT (including CSR and wakefields)



ASTRA + ELEGANT (including CSR and wakefields)



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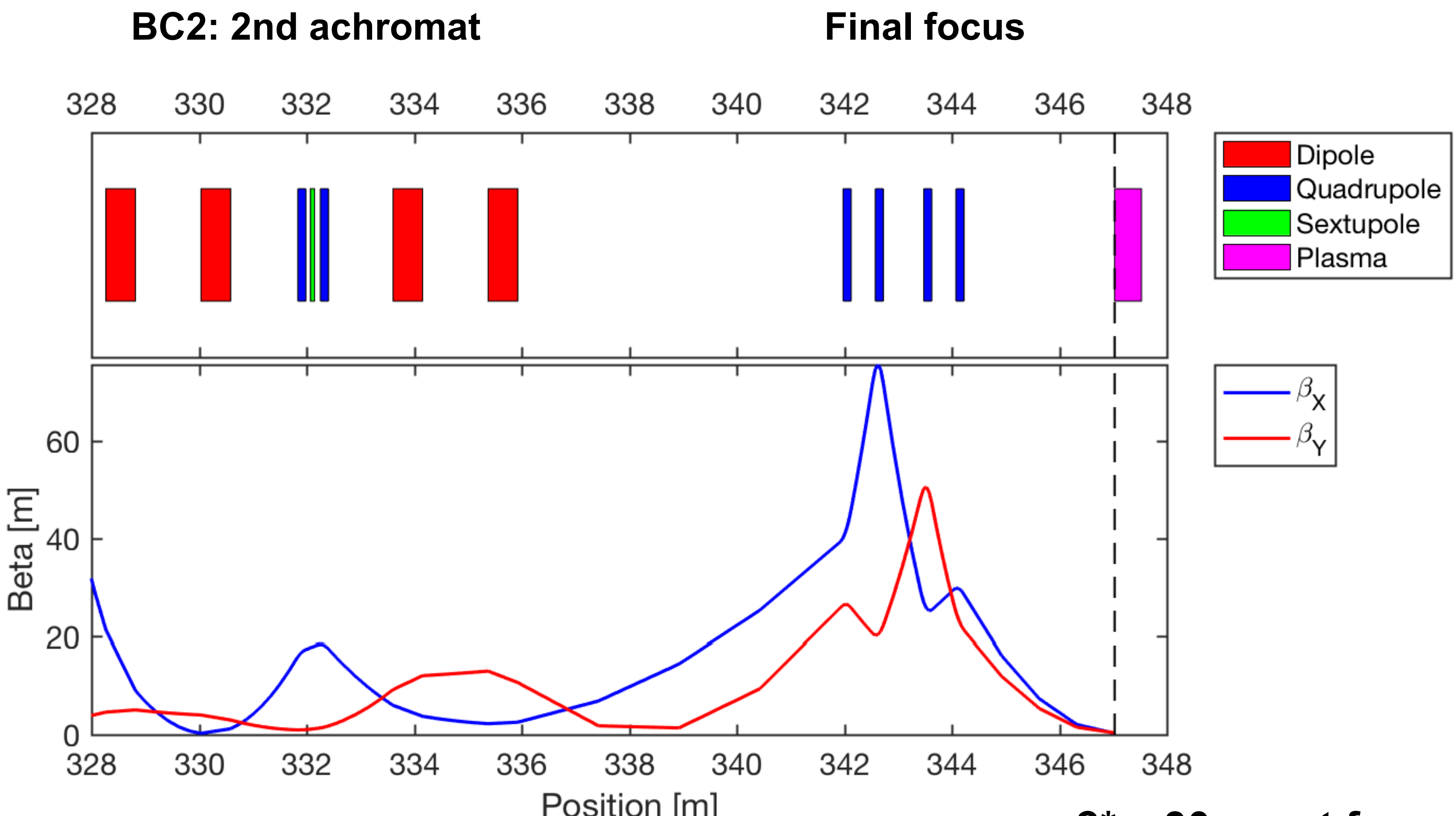
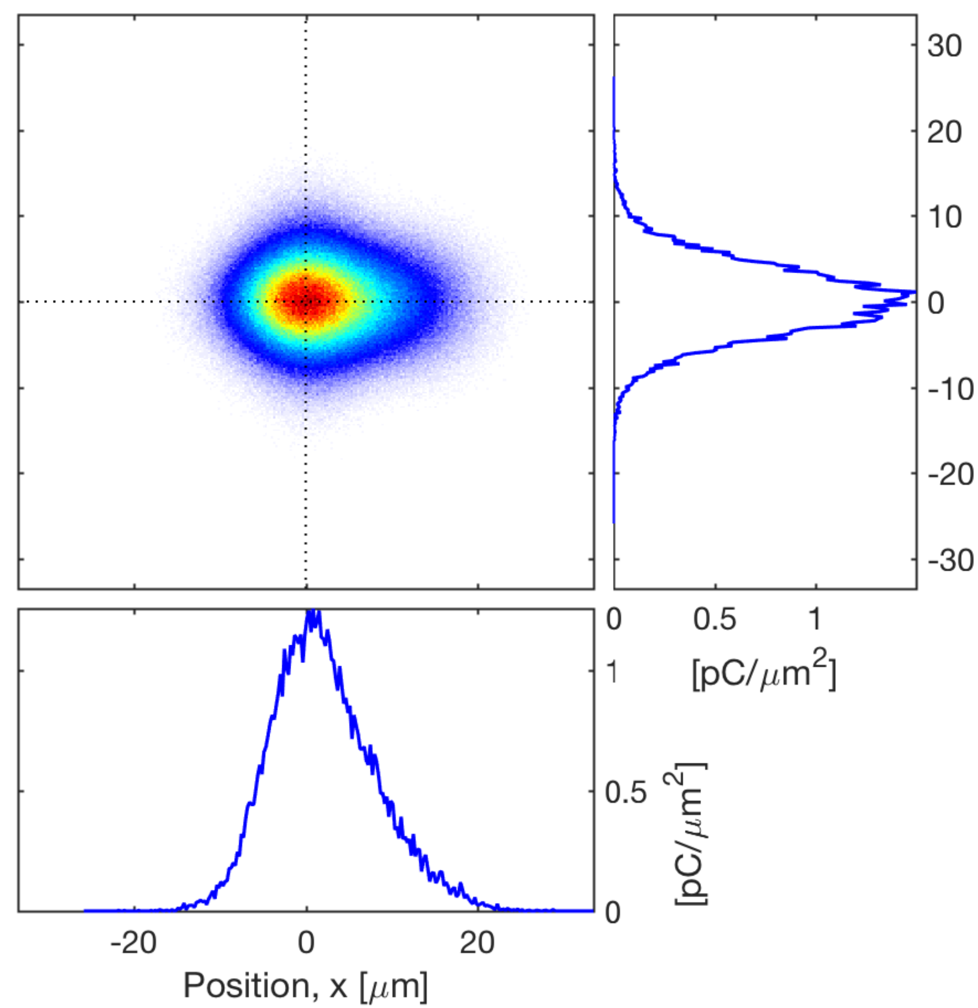
Linac 1500 MeV
Extraction
3 GeV
BC2 @ 3 GeV
Plasma cell
Momentum [MeV/c]
Current [A]
Time [ps]
ASTRA + ELEGANT (including CSR and wakefields)

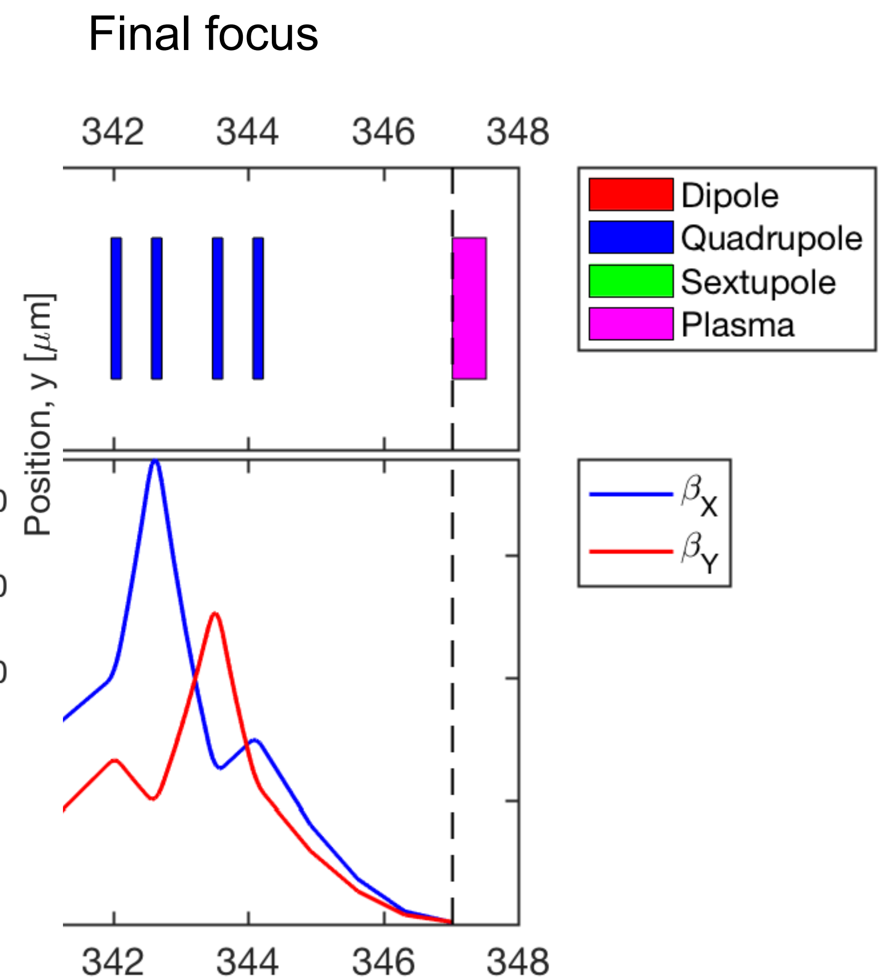
Preliminary focusing system



β* ≈ 30 cm at focus

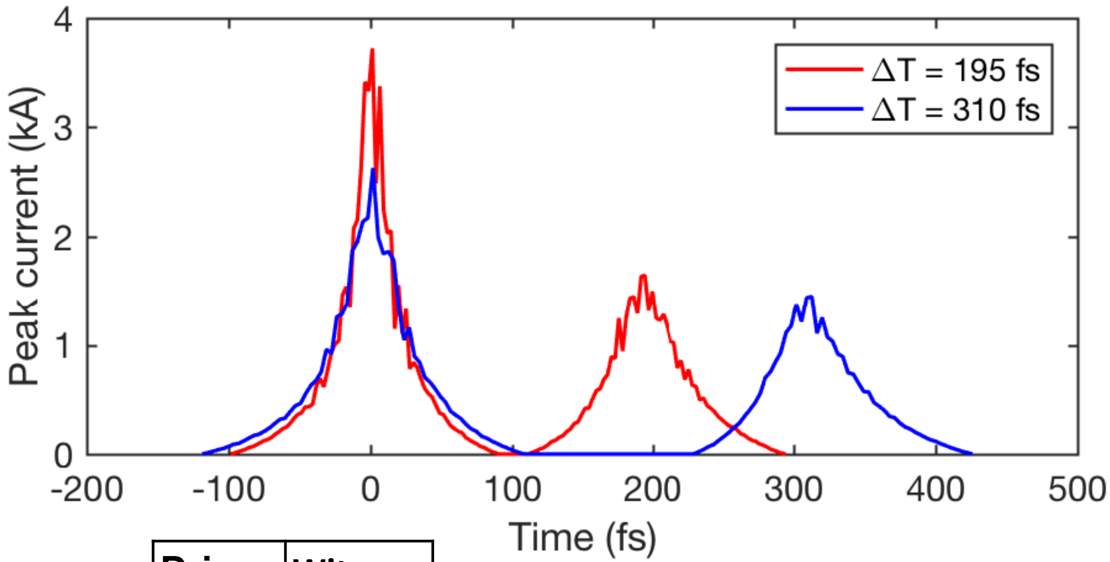
Preliminary focusing system





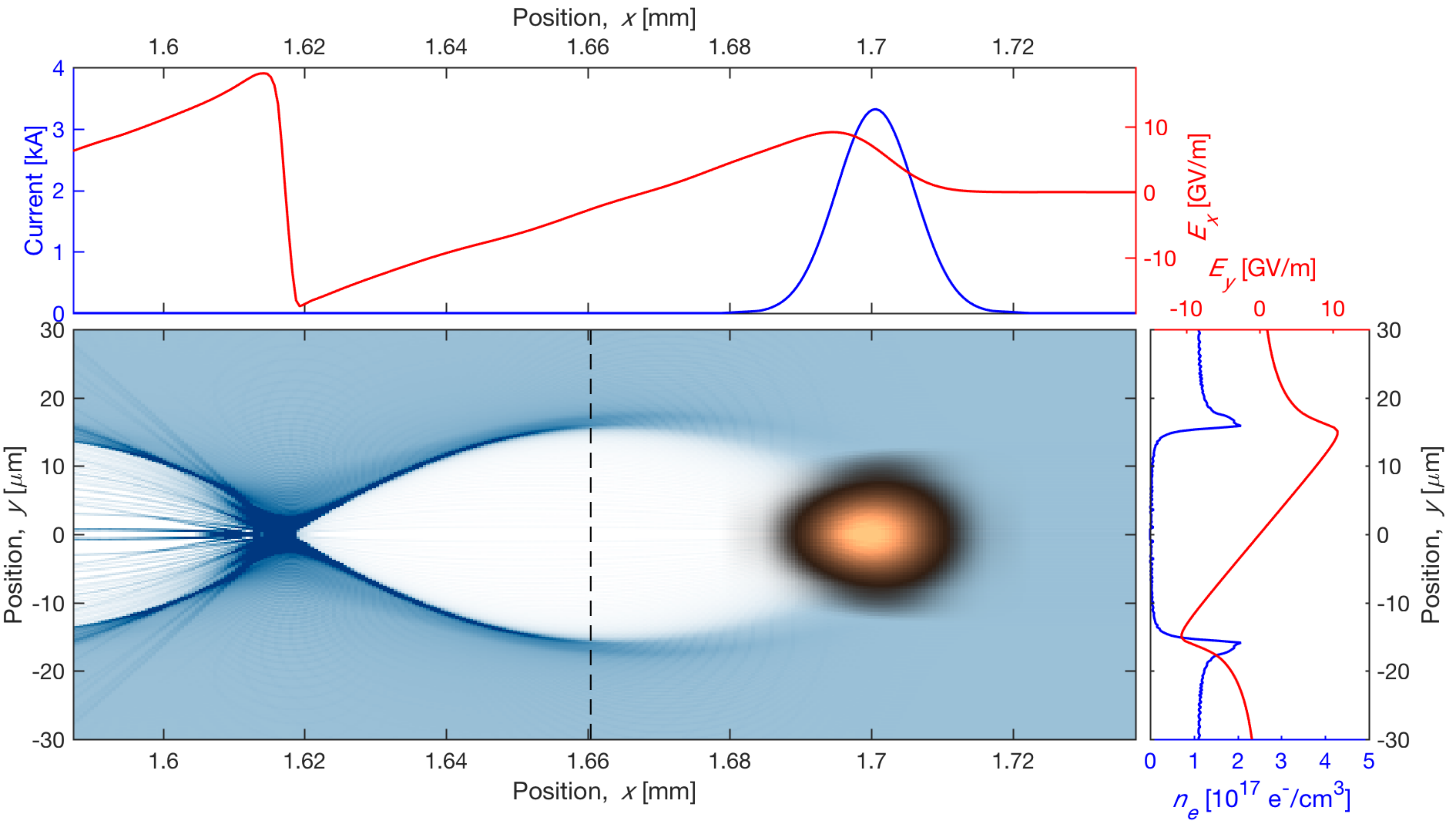
β* ≈ 30 cm at focus

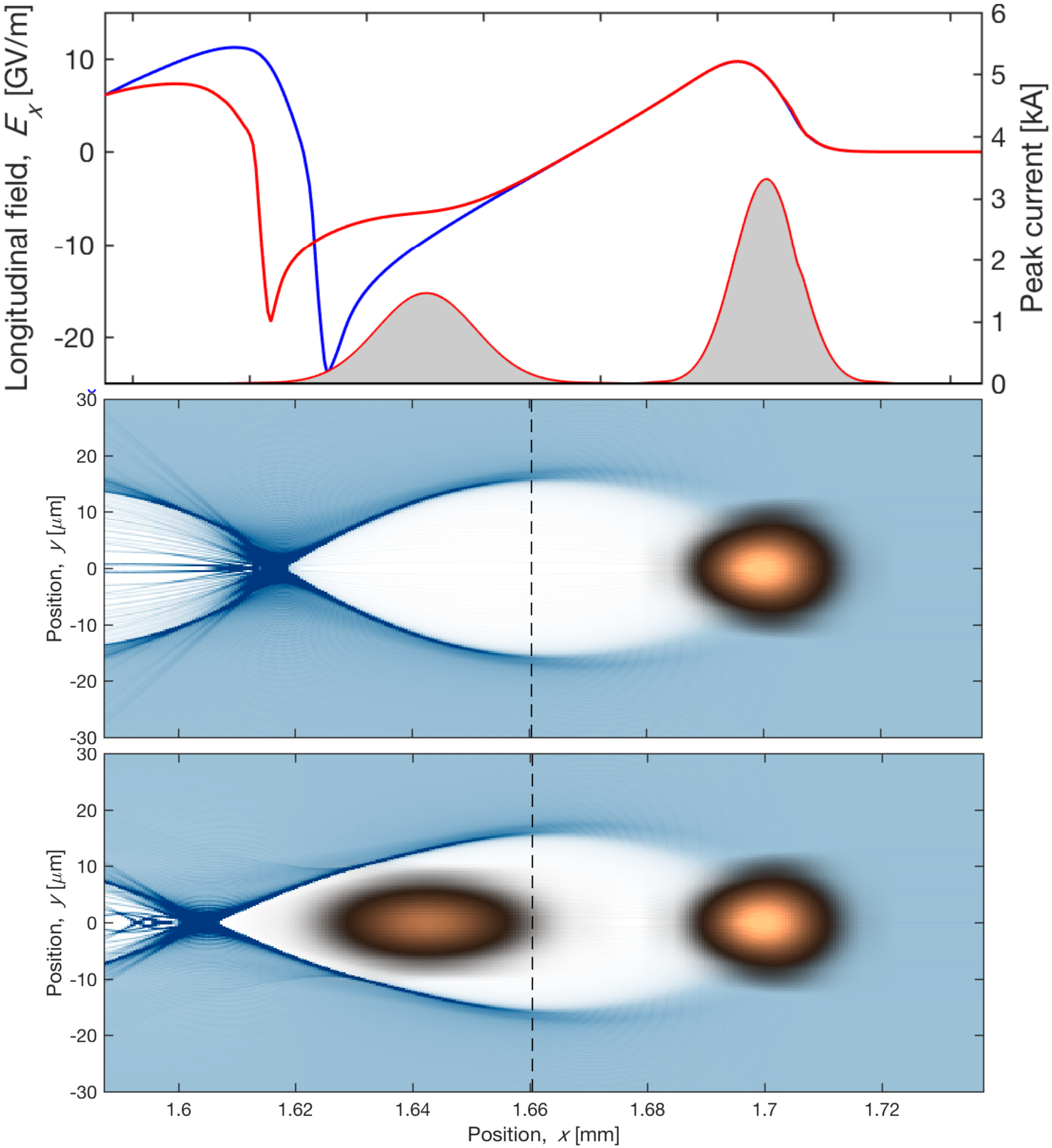
Adjustable beams



	Driver	Witness	
Delay		195	fs
Duration	31	55	fs
Peak current	3.3	1.5	kA
Peak density	6.0	2.6	10^{17} cm^{-3}
Charge (pC)	150	100	pC
Emittance hor.	0.51	0.40	mm mrad
Emittance, vert.	0.34	0.37	mm mrad
Width, hor.	15	9.3	μm
Width, vert.	8.6	9.4	μm
Energy spread	0.9	0.9	%

Single bunch





Plasma density chosen so both bunches are in the bubble

Driver bunch

3.3 kA

31 fs (FWHM)

10 µm (FWHM)

150 pC

$n_b = 6 \cdot 10^{17}$ cm^{-3}

Driver bunch

1.5 kA

55 fs (FWHM)

10 µm (FWHM)

100 pC

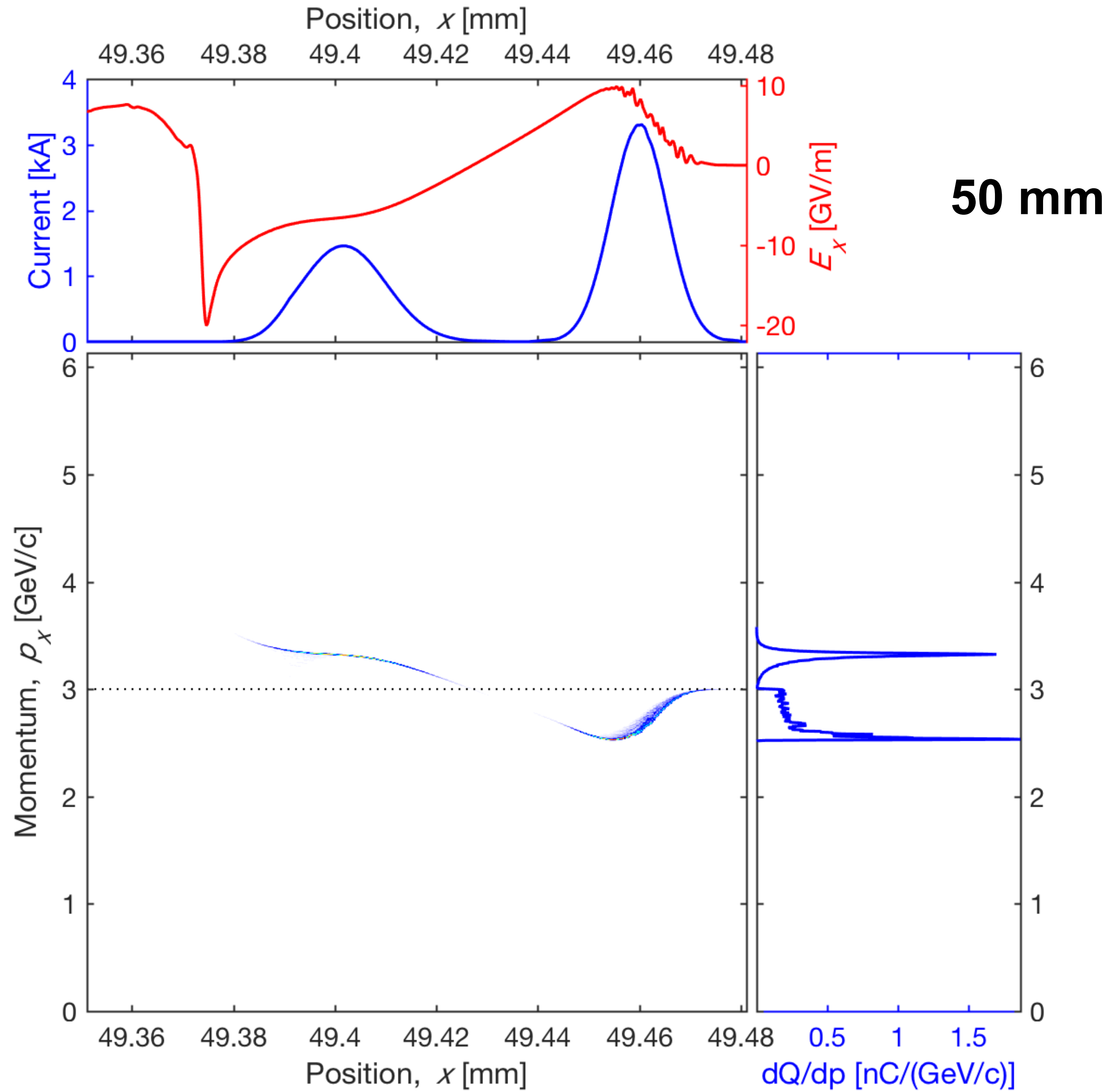
$n_b = 2.6 \cdot 10^{17}$ cm^{-3}

Plasma parameters

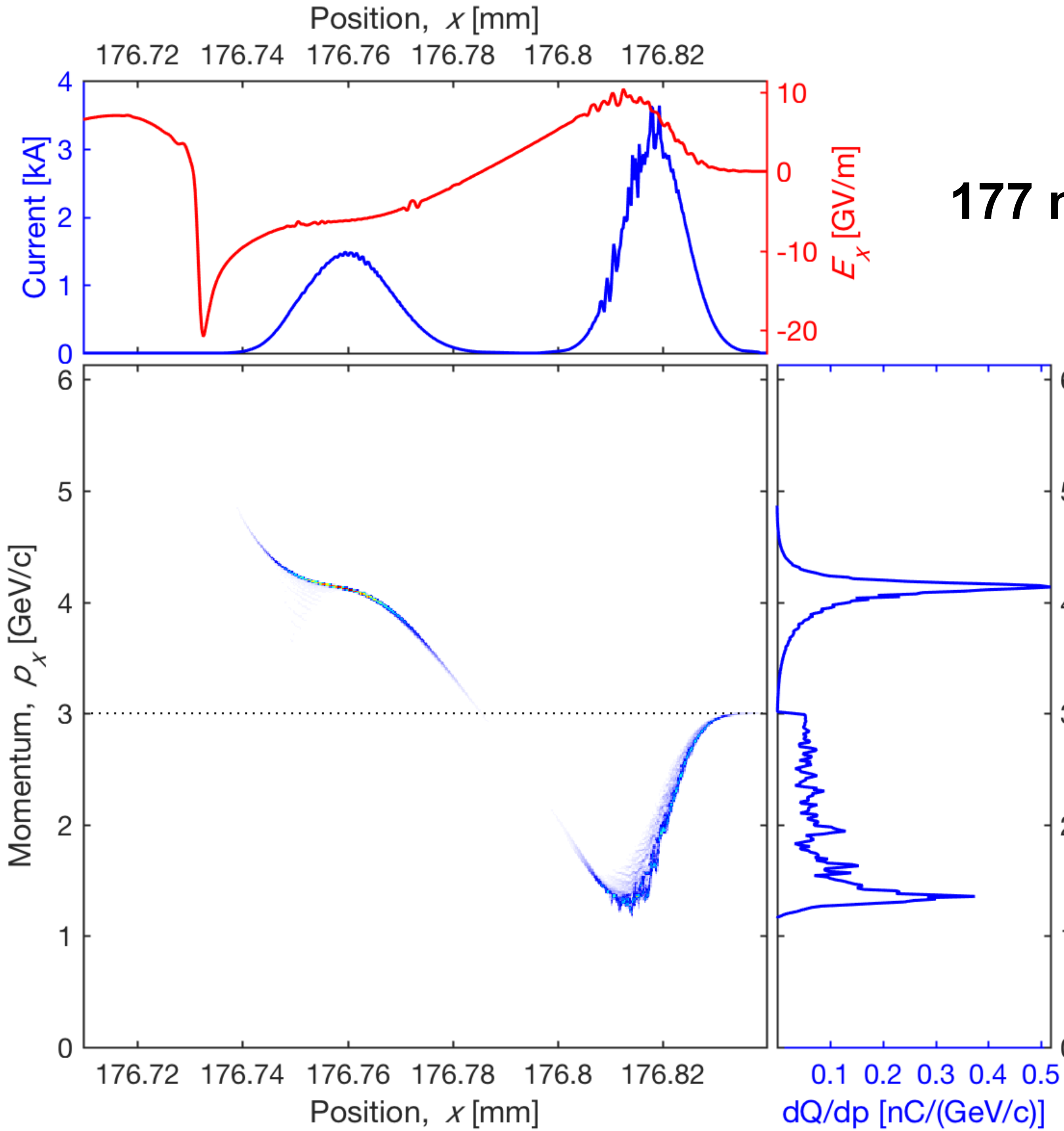
$L_{ramp} = 0.5$ mm

$n_e = 1.1 \cdot 10^{17}$ cm^{-3}

Simulation using CALDER-CIRC

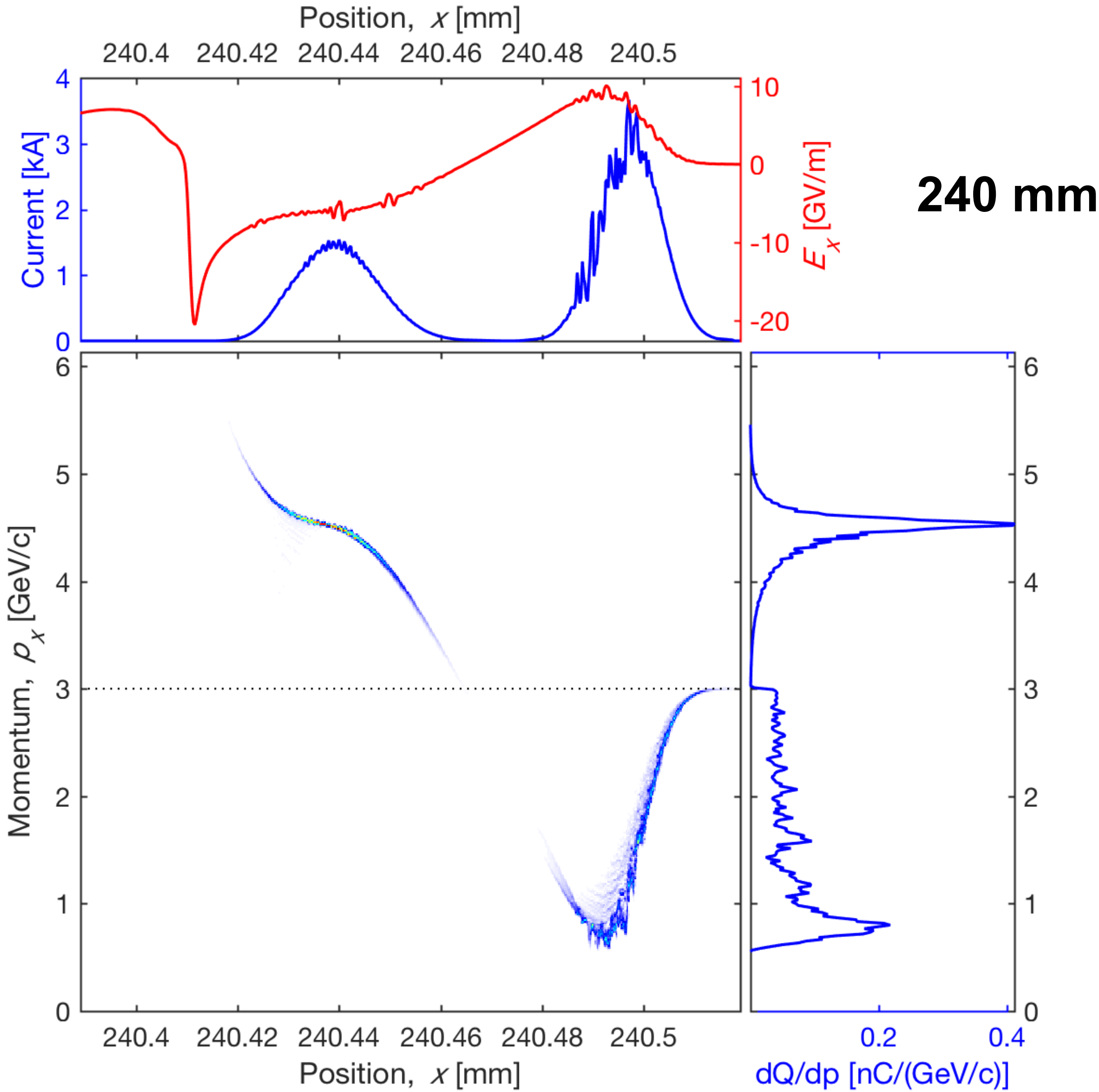


Position, x [mm]
49.36
49.38
49.4
49.42
49.44
49.46
49.48
Current [kA]
E_x [GV/m]
10
0
-10
-20
50 mm
Momentum, p_x [GeV/c]
dQ/dp [nC/(GeV/c)]
0.5
1
1.5

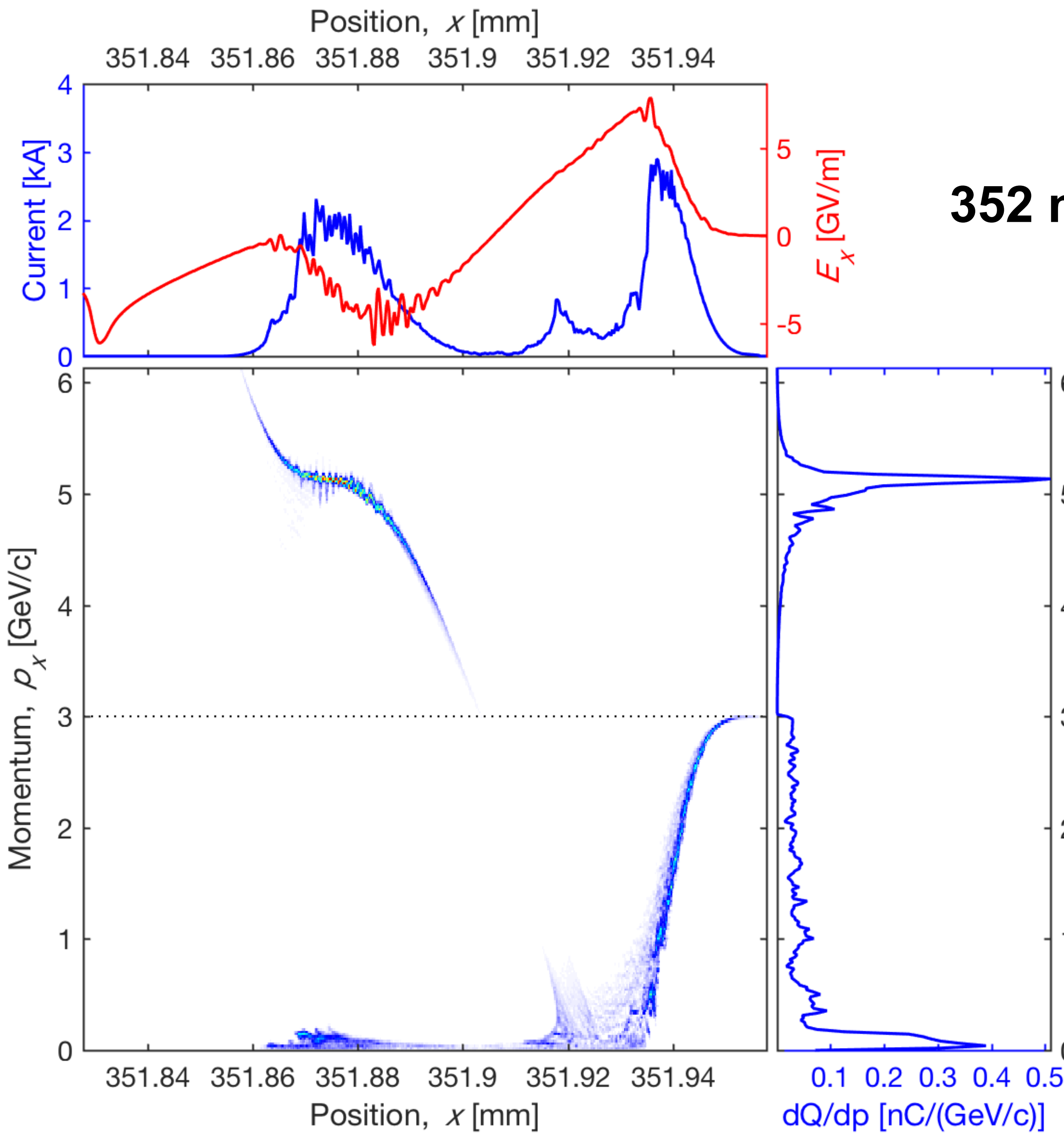


Position, x [mm]
176.72
176.74
176.76
176.78
176.8
176.82
Current [kA]
E_x [GV/m]
Momentum, p_x [GeV/c]
dQ/dp [nC/(GeV/c)]

177 mm



Position, x [mm]
240.4
240.42
240.44
240.46
240.48
240.5
Current [kA]
0
1
2
3
4
E_x [GV/m]
10
0
-10
-20
240 mm
Momentum, p_x [GeV/c]
0
1
2
3
4
5
6
dQ/dp [nC/(GeV/c)]
0.2
0.4



Position, x [mm]
351.84
351.86
351.88
351.9
351.92
351.94
Current [kA]
E_x [GV/m]
Momentum, p_x [GeV/c]
dQ/dp [nC/(GeV/c)]

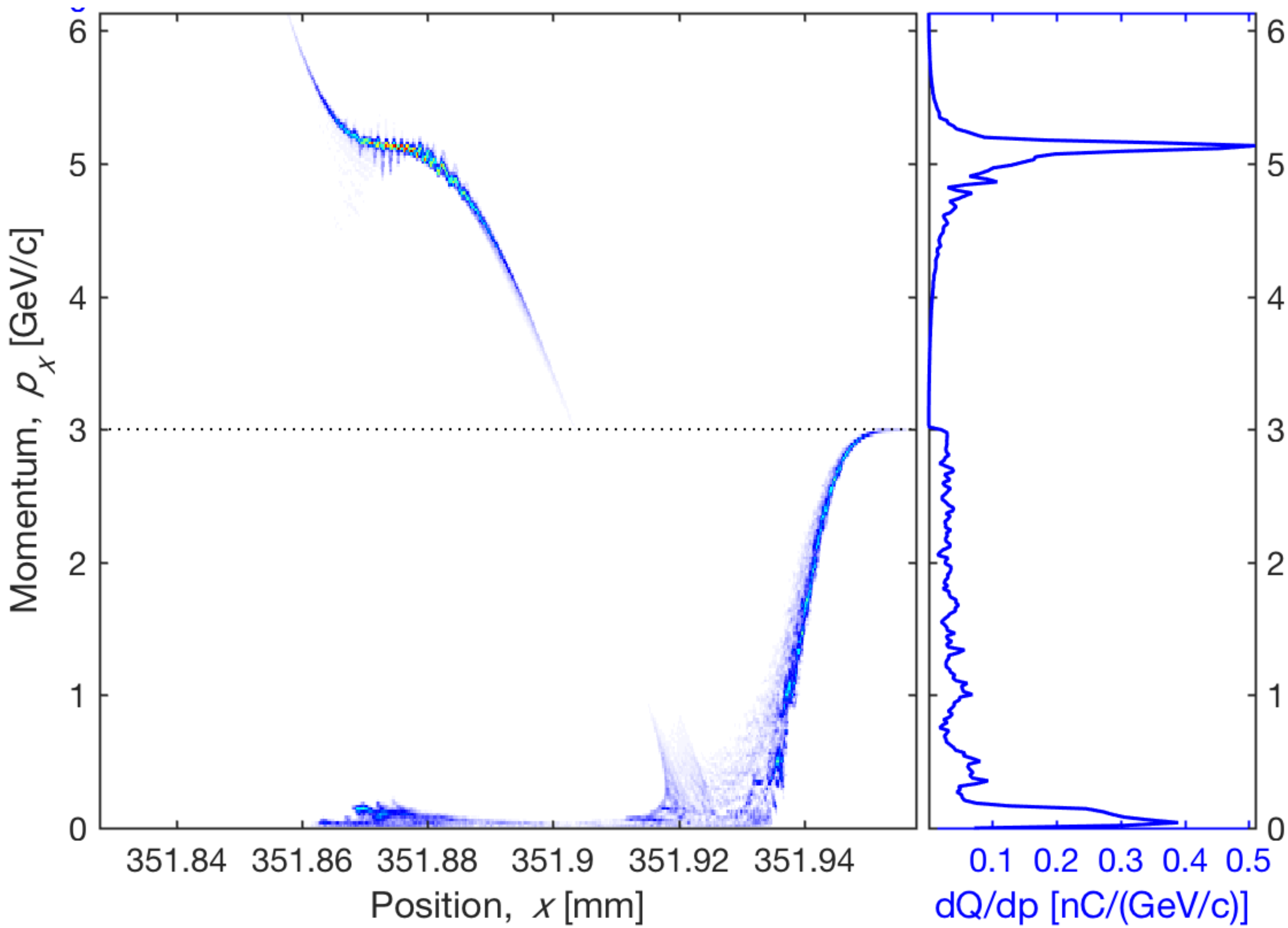
352 mm

Depletion of the driver after 35 cm

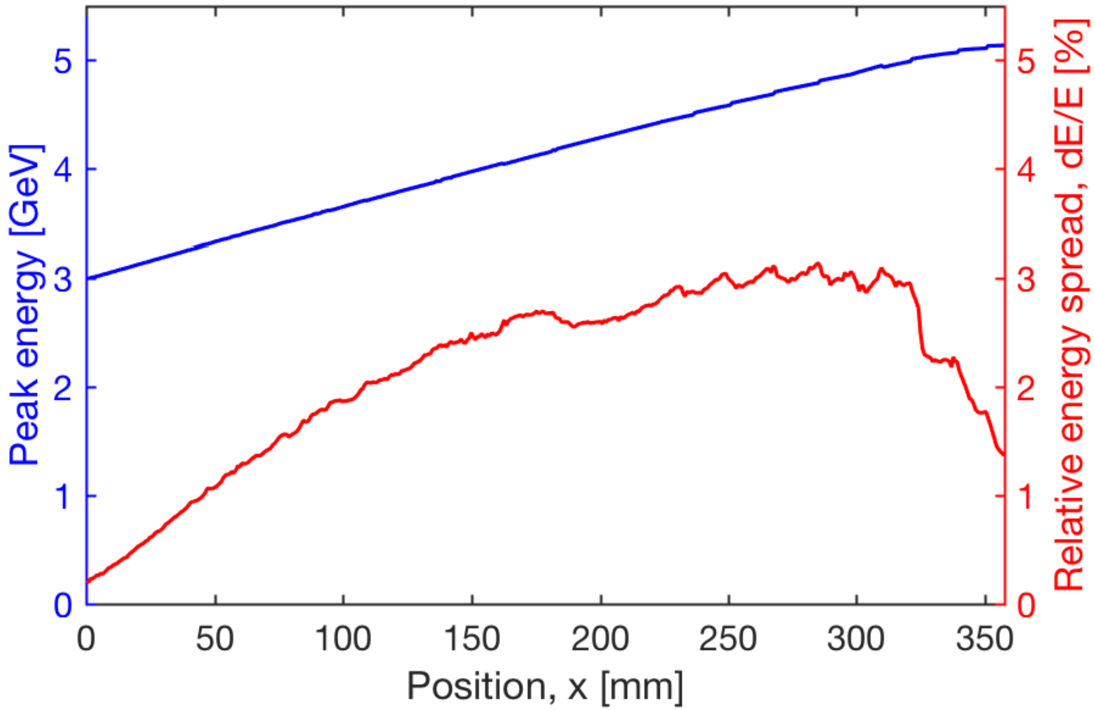
Witness energy = 5.1 GeV (2.1 GeV gain)

Effective accelerating gradient 6 GV/m

Energy spread 1.5 %



Energy gain and spread



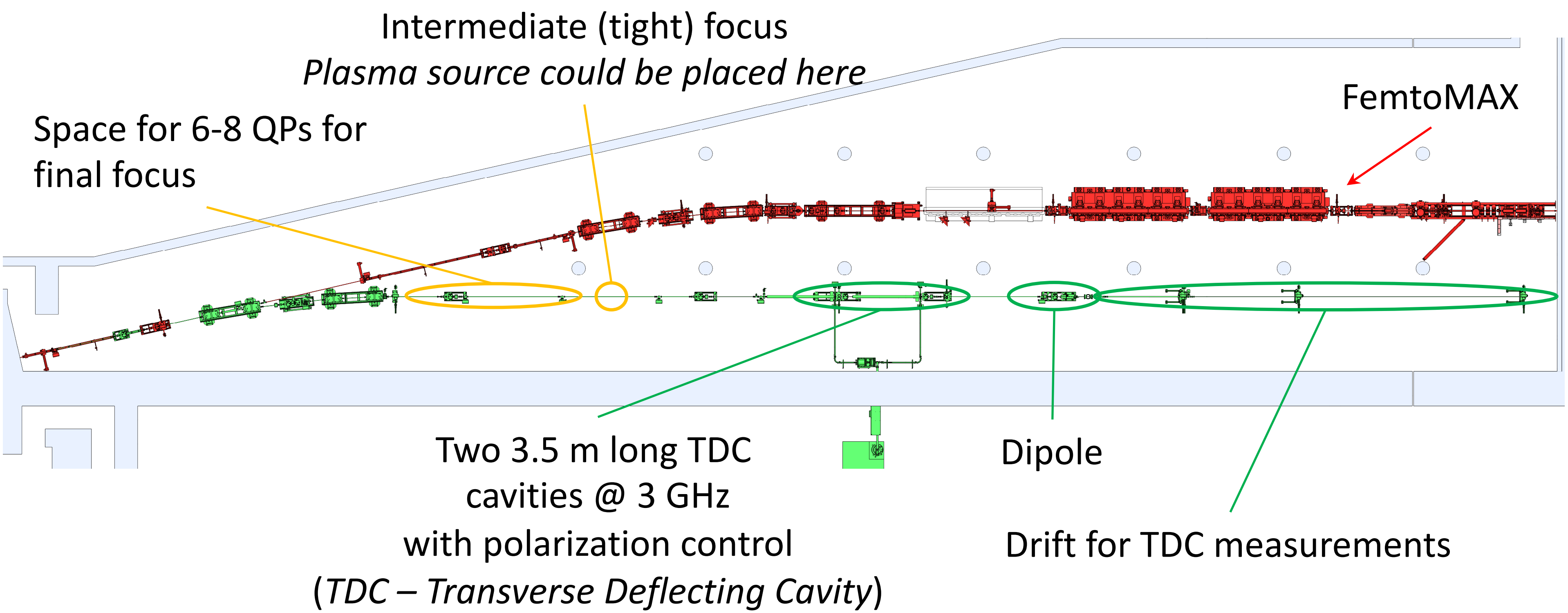
Energy spread grows during acceleration to ~3%

Momentum compression during driver depletion

$\Delta E/E$ = 1,5% at 5.1 GeV

Short Pulse Facility overview

PlasMAX could be an extension of the soft-X-ray laser (SXL) design study



PlasMAX objectives

To explore the use of plasma for particle acceleration and advanced X-ray sources

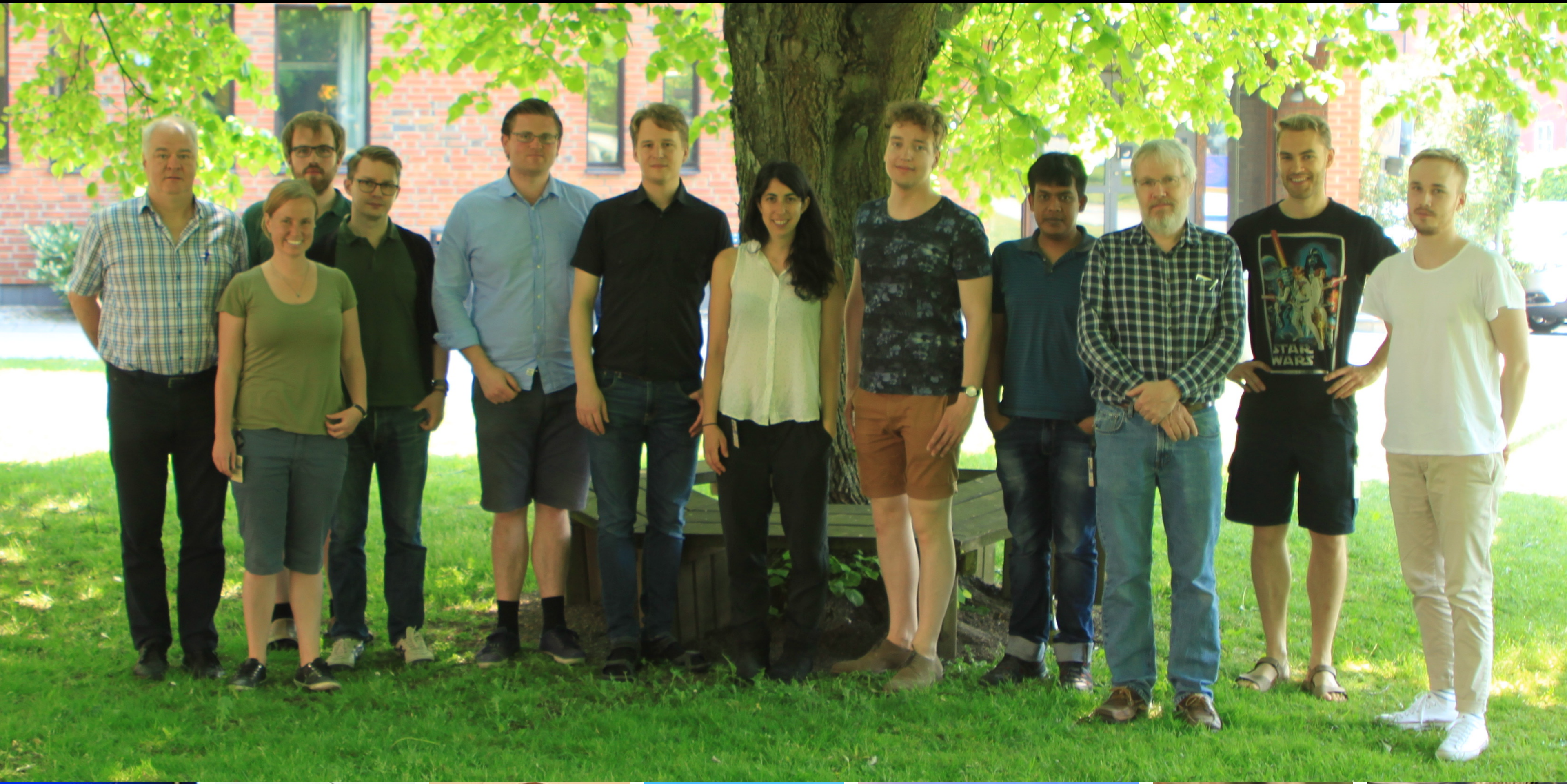
- **Double the energy** of the MAX IV 3 GeV accelerator with preserved emittance and energy spread
- Demonstrate **plasma injector** capable of producing smaller emittance beam than the MAX IV accelerator
- Demonstrate a **plasma de-chirper**, capable of reducing the energy spread

J. B. Svensson *et al*, *"Start-to-end simulations of plasma-wakefield acceleration using the MAX IV Linear Accelerator"*, NIMA **1033**, 166591 (2022)

J. B. Svensson *et al*, *"Third-order double-achromat bunch compressors for broadband beams"*, Phys Rev AB **22**, 104401 (2019)

J. B. Svensson *et al*, *"Beamline design for plasma-wakefield acceleration experiments at MAX IV"*, IEEE Advanced Accelerator Workshop 2018

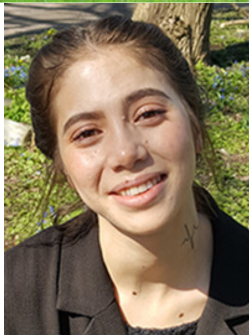
Acknowledgment











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Fellow in Marie-Curie network EuPRAXIA-DN

Apply before September 25

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