# Laser-Plasma Accelerators: Particle Acceleration in a Nutshell


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# Particle Acceleration in a Nutshell

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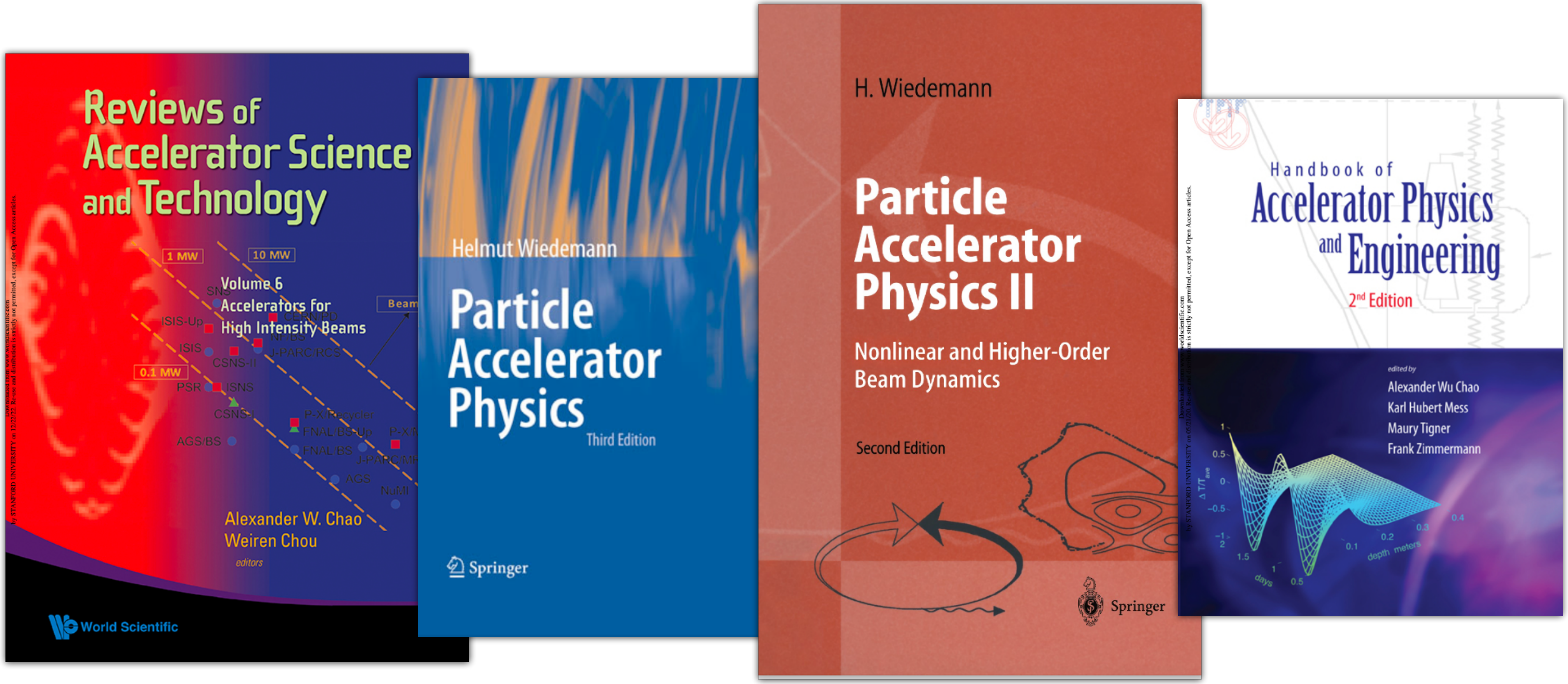

# Particle Accelerator in a Nutshell

Photo: T. Seggebrück

# Outline

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## high-power lasers

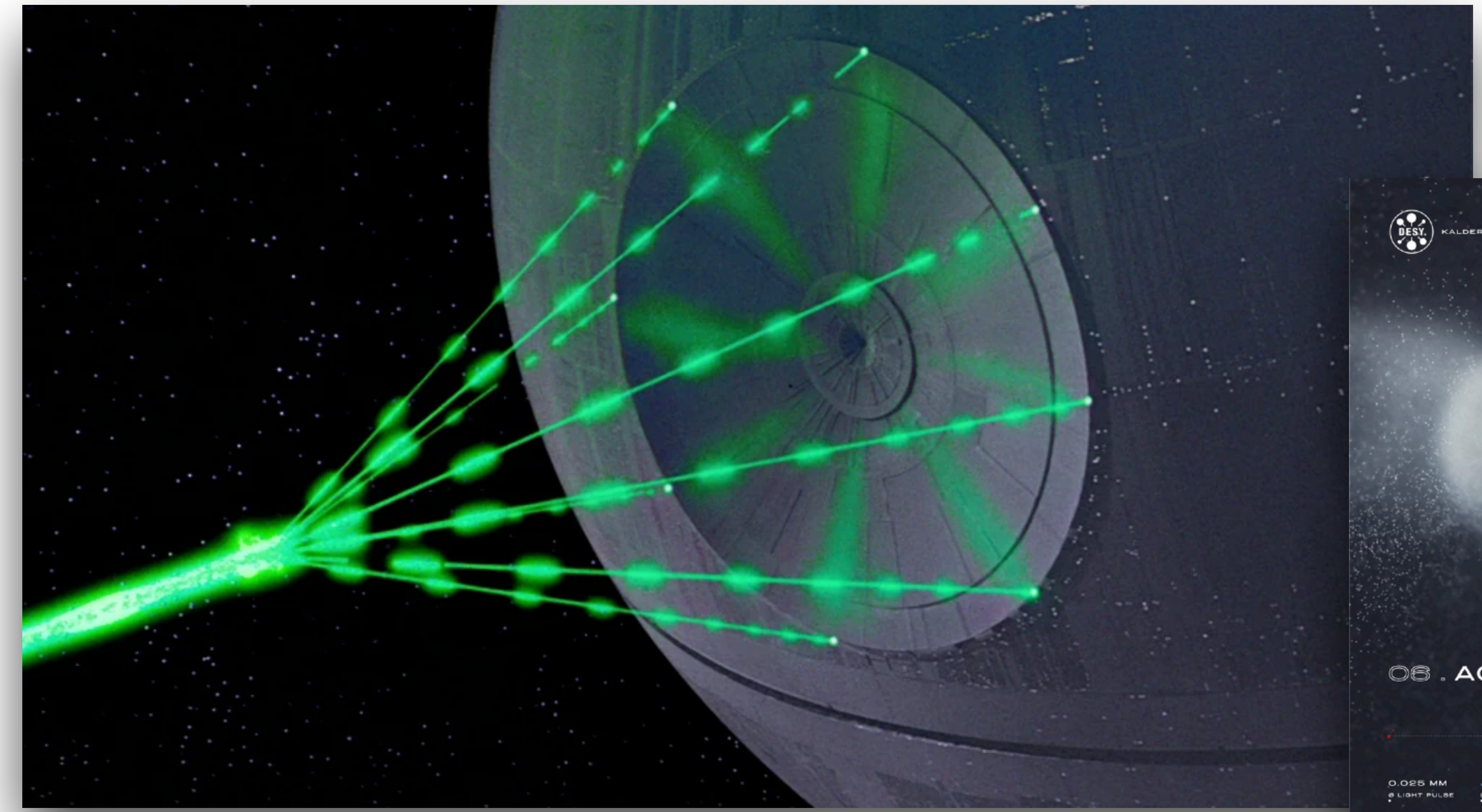
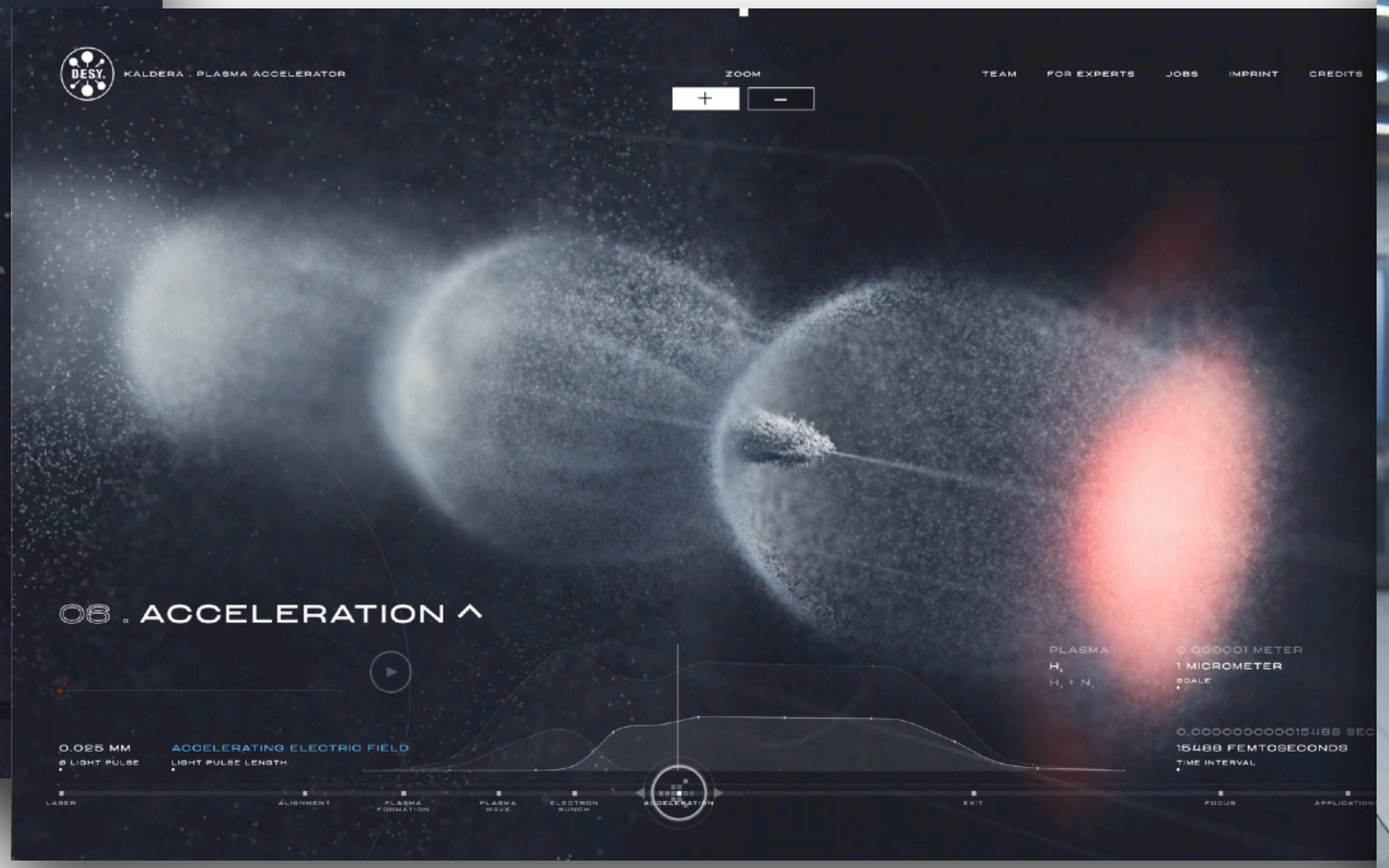


image: wookiepedia.org

## plasma accelerators



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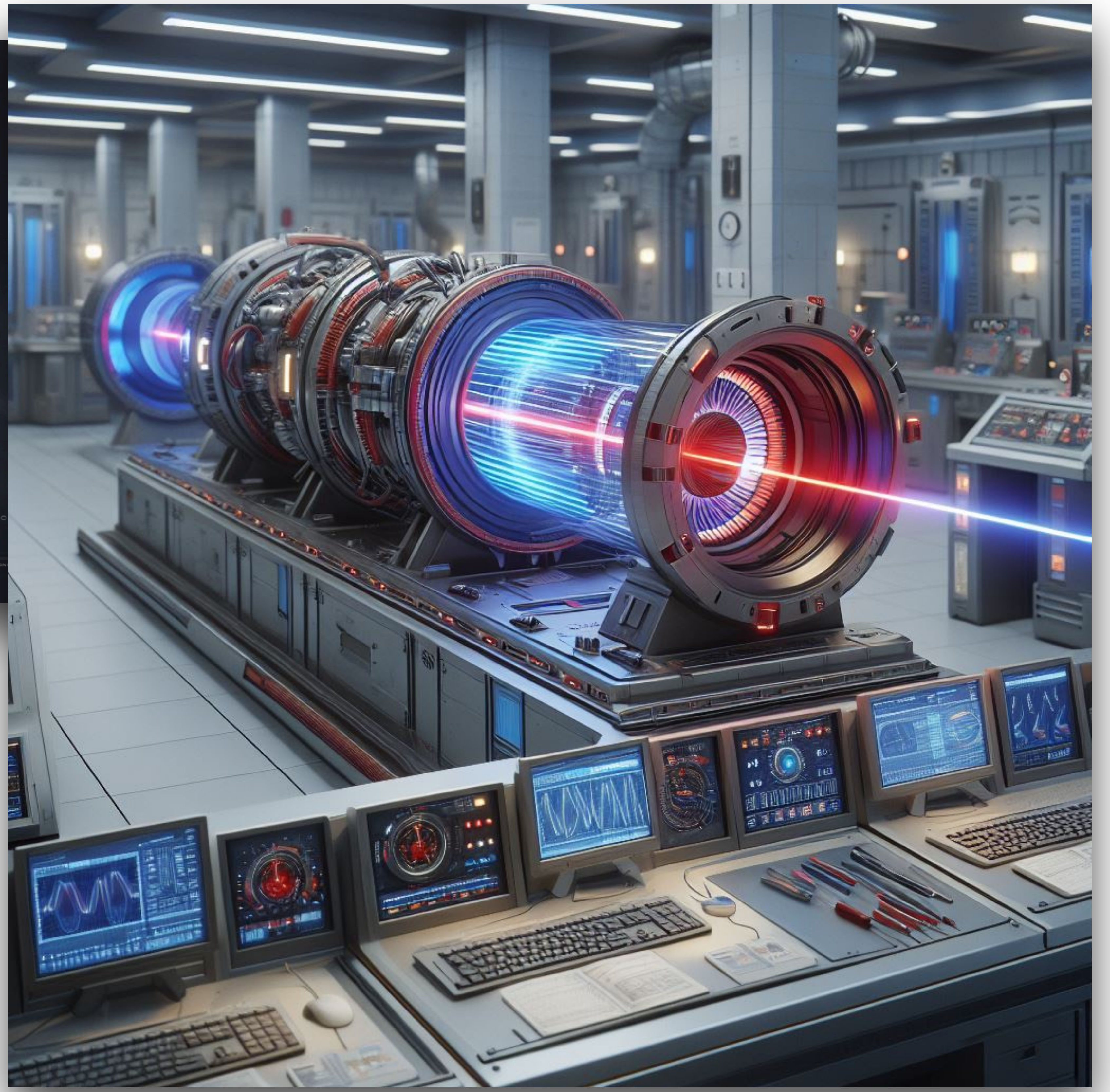


Image: DALL-E

## relativistic electron bunches

Bielawski *et al*. Sci Rep (2019)

## ultrafast X-ray pulses

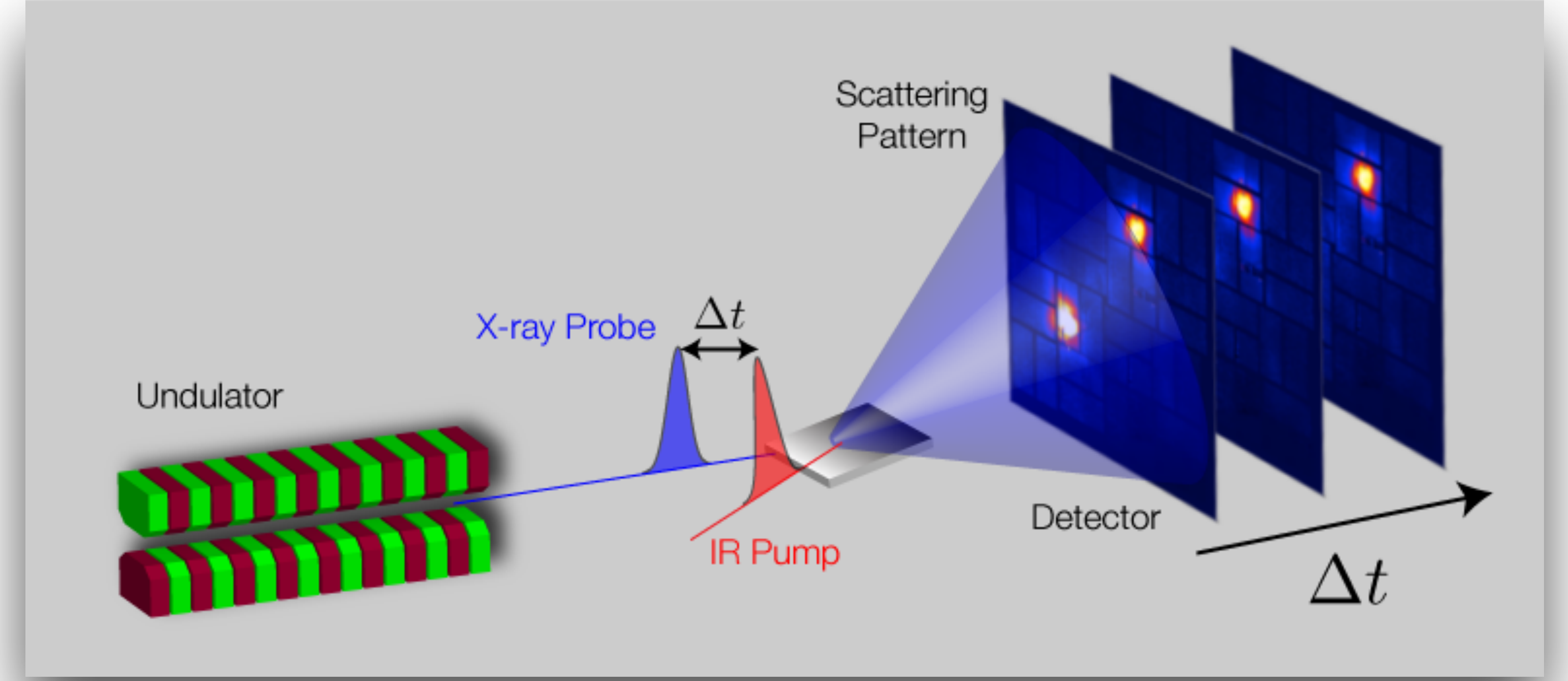
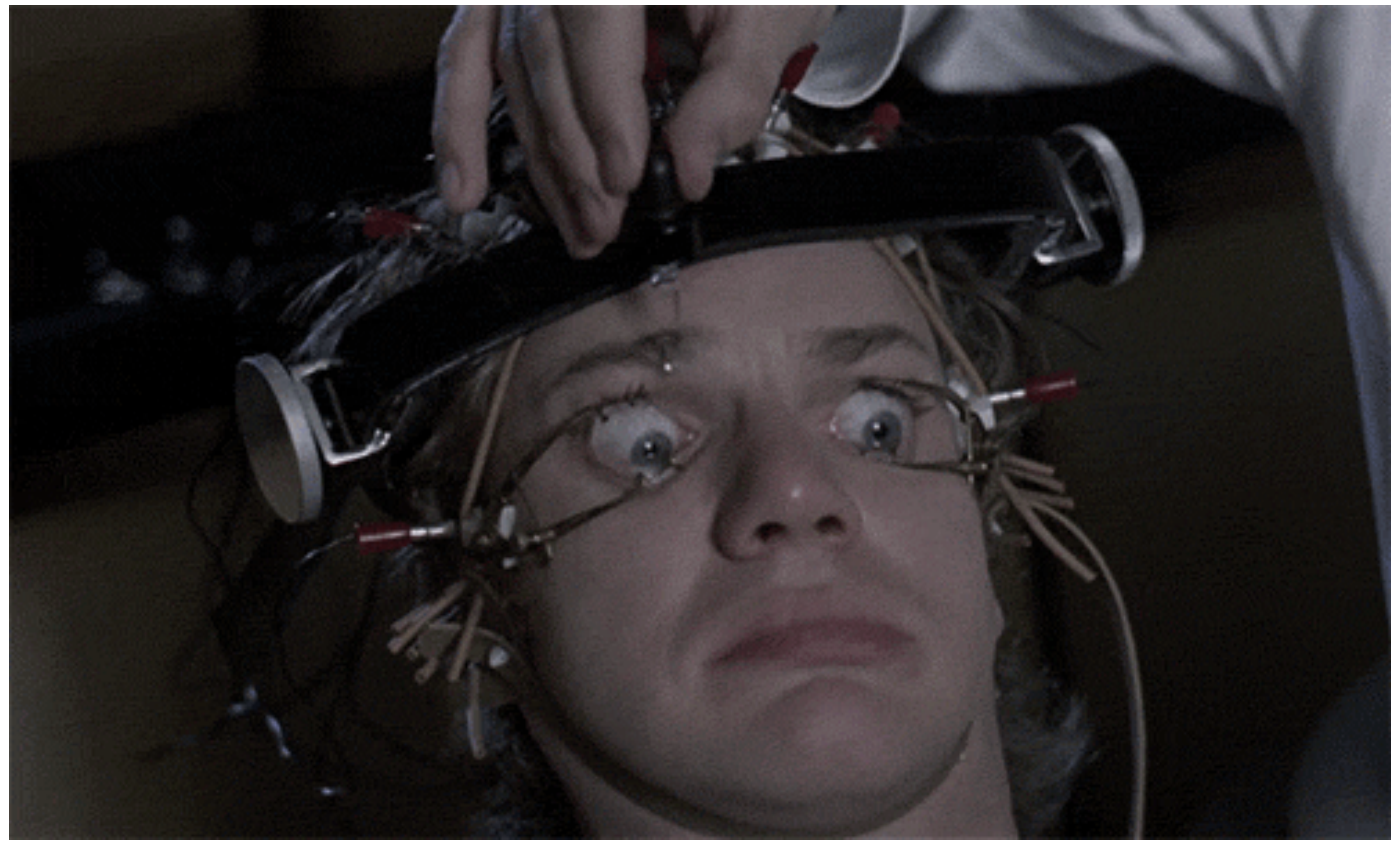


image: MF

# Outline

- **Part I.) Overview of Laser-Plasma Accelerators**
  - Particle Accelerators and Laser-Plasma Acceleration (LPA)
  - Applications of Laser-Plasma Accelerators
    - Laser-driven X-ray Sources
  - Challenges and New Research Directions
    - Next-generation hybrid accelerators
    - Next-generation laser-plasma accelerators
- **Part II.) Introduction to Laser-Plasma Acceleration**
  - Electron interacting with a strong electro-magnetic field
  - Introduction to plasma physics
  - Plasma waves
  - Laser-plasma acceleration



# Outline

- Particle Accelerators and Laser-Plasma Acceleration (LPA)
- Applications of Laser-Plasma Accelerators
  - Laser-driven X-ray Sources
- Challenges and New Research Directions
  - Next-generation hybrid accelerators
  - Next-generation laser-plasma accelerators
- Summary

# Particle Accelerators

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## Particles

## Accelerators

## Products

## Applications

INDUSTRY

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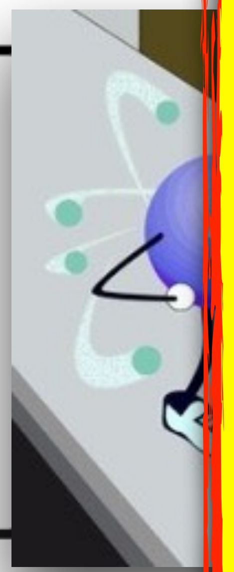

IONS

NE

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YSICS

**28% of the research in physics between 1939 and 2009 has been influenced by accelerator science.**

E. Haussecker & A. Chao, The Influence of Accelerator Science on Physics Research, Phys. Perspect. (2011)

about 30,000 accelerators world wide

CYCLOTRON

NEUTRONS

PARTICLE PHYSICS

adapted from
www.beschleunigerphysik.de

# Nobel Prizes in Accelerator Physics




| Year | Name | Accelerator-Science Contribution to Nobel Prize-Winning Research |
|---|---|---|
| 1939 | Ernest O. Lawrence | Lawrence invented the cyclotron at the University of Californian at Berkeley in 1929 [12]. |
| 1951 | John D. Cockcroft and Ernest T.S. Walton | Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13]. |

# 25 Nobel Prizes in Physics that had direct contribution from accelerators



| Year | Name | Accelerator-Science Contribution to Nobel Prize-Winning Research |
|---|---|---|
| 1939 | Ernest O. Lawrence | Lawrence invented the cyclotron at the University of Californian at Berkeley in 1929 [12]. |
| 1951 | John D. Cockcroft and Ernest T.S. Walton | Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13]. |
| 1952 | Felix Bloch | Bloch used a cyclotron at the Crocker Radiation Laboratory at the University of California at Berkeley in his discovery of the magnetic moment of the neutron in 1940 [14]. |
| 1957 | Tsung-Dao Lee and Chen Ning Yang | Lee and Yang analyzed data on K mesons ($\theta$ and $\tau$) from Bevatron experiments at the Lawrence Radiation Laboratory in 1955 [15], which supported their idea in 1956 that parity is not conserved in weak interactions [16]. |
| 1959 | Emilio G. Segrè and Owen Chamberlain | Segrè and Chamberlain discovered the antiproton in 1955 using the Bevatron at the Lawrence Radiation Laboratory [17]. |
| 1960 | Donald A. Glaser | Glaser tested his first experimental six-inch bubble chamber in 1955 with high-energy protons produced by the Brookhaven Cosmotron [18]. |
| 1961 | Robert Hofstadter | Hofstadter carried out electron-scattering experiments on carbon-12 and oxygen-16 in 1959 using the SLAC linac and thereby made discoveries on the structure of nucleons [19]. |
| 1963 | Maria Goeppert Mayer | Goeppert Mayer analyzed experiments using neutron beams produced by the University of Chicago cyclotron in 1947 to measure the nuclear binding energies of krypton and xenon [20], which led to her discoveries on high magic numbers in 1948 [21]. |
| 1967 | Hans A. Bethe | Bethe analyzed nuclear reactions involving accelerated protons and other nuclei whereby he discovered in 1939 how energy is produced in stars [22]. |
| 1968 | Luis W. Alvarez | Alvarez discovered a large number of resonance states using his fifteen-inch hydrogen bubble chamber and high-energy proton beams from the Bevatron at the Lawrence Radiation Laboratory [23]. |
| 1976 | Burton Richter and Samuel C.C. Ting | Richter discovered the J/Ψ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the J/Ψ particle independently in 1974 using the Brookhaven Alternating Gradient Synchrotron [25]. |
| 1979 | Sheldon L. Glashow, Abdus Salam, and Steven Weinberg | Glashow, Salam, and Weinberg cited experiments on the bombardment of nuclei with neutrinos at CERN in 1973 [26] as confirmation of their prediction of weak neutral currents [27]. |
| 1980 | James W. Cronin and Val L. Fitch | Cronin and Fitch concluded in 1964 that CP (charge-parity) symmetry is violated in the decay of neutral K mesons based upon their experiments using the Brookhaven Alternating Gradient Synchrotron [28]. |
| 1981 | Kai M. Siegbahn | Siegbahn invented a weak-focusing principle for betatrons in 1944 with which he made significant improvements in high-resolution electron spectroscopy [29]. |
| 1983 | William A. Fowler | Fowler collaborated on and analyzed accelerator-based experiments in 1958 [30], which he used to support his hypothesis on stellar-fusion processes in 1957 [31]. |
| 1984 | Carlo Rubbia and Simon van der Meer | Rubbia led a team of physicists who observed the intermediate vector bosons W and Z in 1983 using CERN's proton-antiproton collider [32], and van der Meer developed much of the instrumentation needed for these experiments [33]. |
| 1986 | Ernst Ruska | Ruska built the first electron microscope in 1933 based upon a magnetic optical system that provided large magnification [34]. |
| 1988 | Leon M. Lederman, Melvin Schwartz, and Jack Steinberger | Lederman, Schwartz, and Steinberger discovered the muon neutrino in 1962 using Brookhaven's Alternating Gradient Synchrotron [35]. |
| 1989 | Wolfgang Paul | Paul's idea in the early 1950s of building ion traps grew out of accelerator physics [36]. |
| 1990 | Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor | Friedman, Kendall, and Taylor's experiments in 1974 on deep inelastic scattering of electrons on protons and bound neutrons used the SLAC linac [37]. |
| 1992 | Georges Charpak | Charpak's development of multiwire proportional chambers in 1970 were made possible by accelerator-based testing at CERN [38]. |
| 1995 | Martin L. Perl | Perl discovered the tau lepton in 1975 using Stanford's SPEAR collider [39]. |
| 2004 | David J. Gross, Frank Wilczek, and H. David Politzer | Gross, Wilczek, and Politzer discovered asymptotic freedom in the theory of strong interactions in 1973 based upon results from the SLAC linac on electron-proton scattering [40]. |
| 2008 | Makoto Kobayashi and Toshihide Maskawa and Yoichro Nambu | Kobayashi and Maskawa's theory of quark mixing in 1973 was confirmed by results from the KEKB accelerator at KEK (High Energy Accelerator Research Organization) in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II (Positron Electron Project II) at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42]. |

**2013**: François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at **CERN's Large Hadron Collider**"

slide: courtesy L. Rivkin, PSI

# Karlsruher Contributions to the Beginning of the Field

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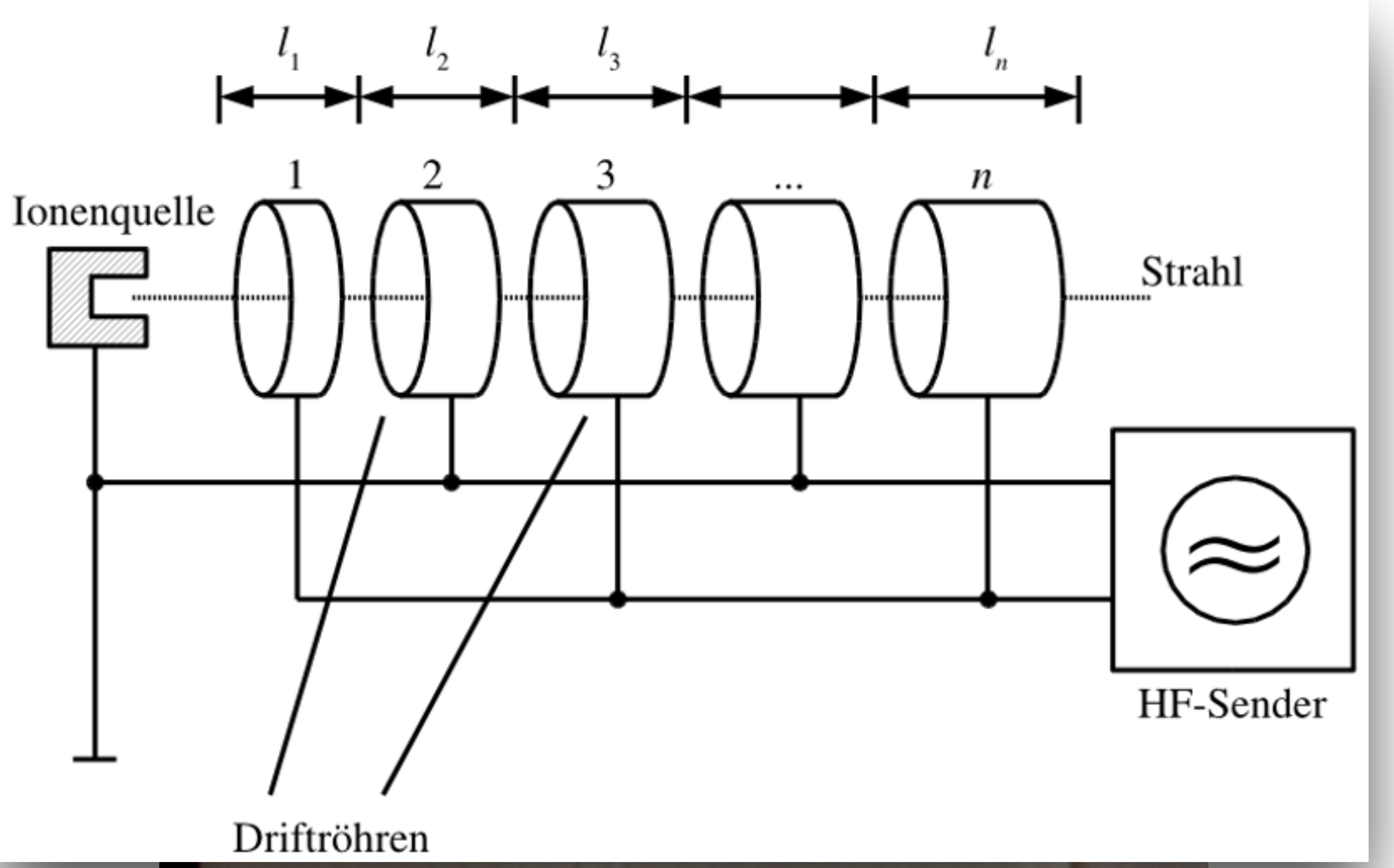
## First Accelerator Concepts and Demonstrations



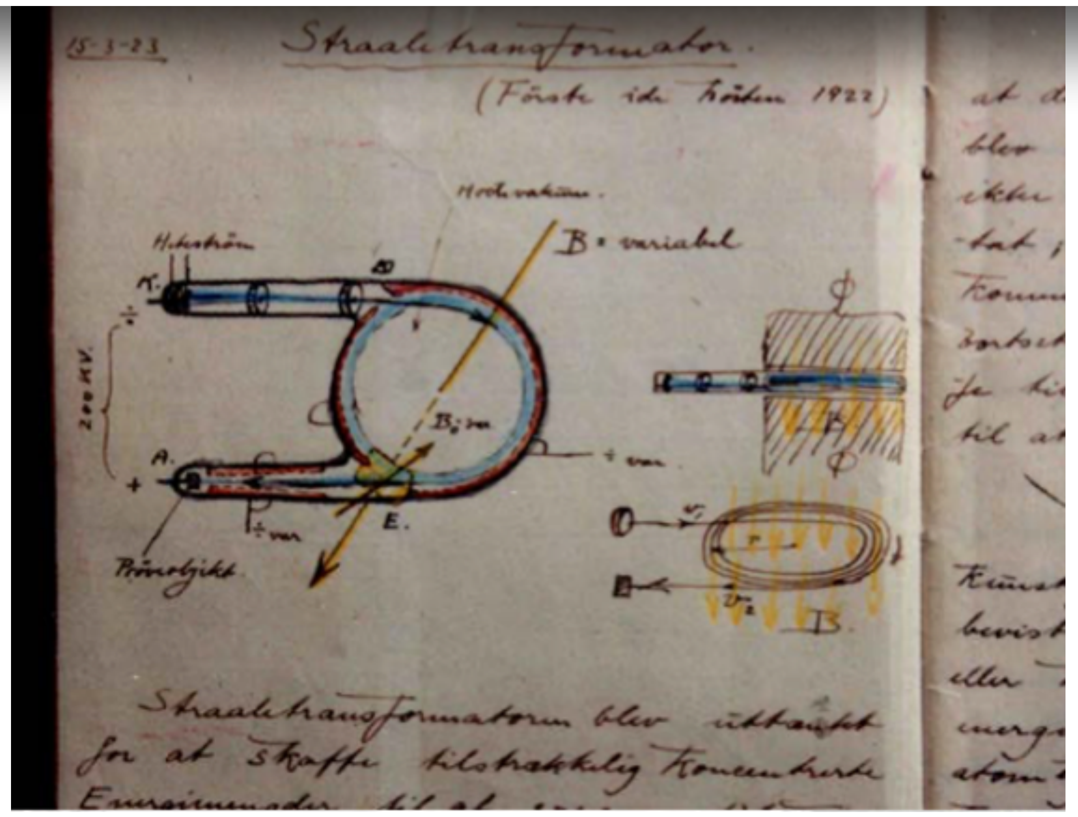




Image:Greg Stewart/SLAC

Rolf Wideröe (1902 – 1996)
1920 – 1924 TH Karlsruhe (Dipl.Ing)

## Discovery of Emission of Electromagnetic Waves



Heinrich Hertz (1857 – 1894)
1885 – 1889 TH Karlsruhe

# Accelerator-Based X-ray Sources: X-ray Free-Electron Lasers (XFELs)

Karlsruher Institut für Technologie

ARTICLES

https://doi.org/10.1038/s41566-020-00712-8

nature photonics

Check for updates

## A compact and cost-effective hard X-ray free-electron laser driven by a high-brightness and low-energy electron beam

**Table 1 | Facility length, electron beam energy and pulses per second of existing hard X-ray FELs**

| Parameter | LCLS | SACLA | PAL-XFEL | European XFEL | SwissFEL |
|---|---|---|---|---|---|
| Length (km) | 3.0 | 0.75 | 1.1 | 3.4 | 0.74 |
| Electron energy (GeV) | 14.3 | 8.5 | 10 | 17.5 | 5.8 |
| Pulses per second | 120 | 60 | 60 | 27,000 | 100 |

Prat *et al.*, Nat. Phys (2020)

### Going great guns

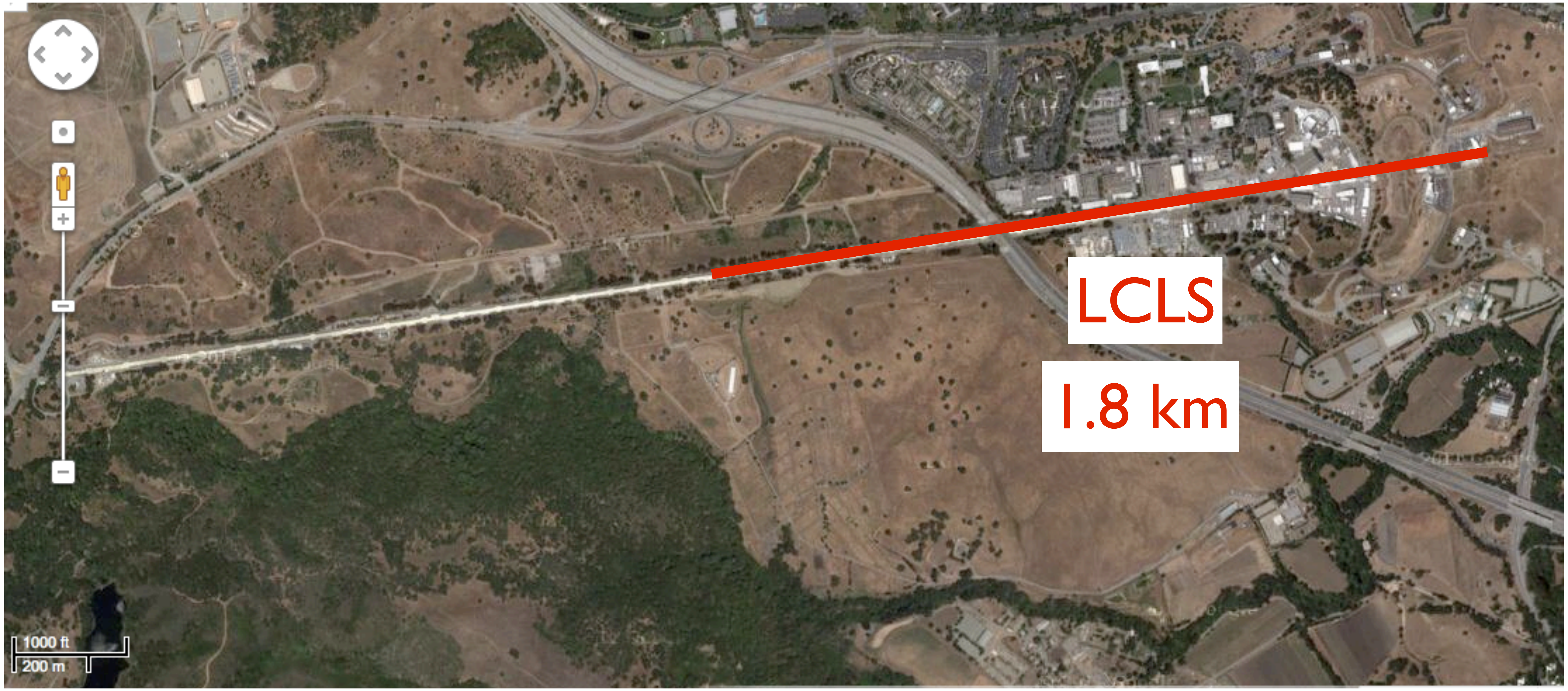
Three new free electron lasers (FELs) are set to open up in the next year. The European XFEL gets its high repetition rate from the superconducting cavities that drive its electron beam.

| NAME/COUNTRY | LCLS/ UNITED STATES | LCLS-II/ UNITED STATES | SACLA*/ JAPAN | EUROPEAN XFEL/ GERMANY | SWISSFEL/ SWITZERLAND | PAL-XFEL*/ SOUTH KOREA |
|---|---|---|---|---|---|---|
| Date of first x-rays | 2009 | 2020 | 2011 | 2017 | 2017 | 2016 |
| Cost (in U.S. millions) | $415 | $1000 | $370 | $1600 | $280 | $400 |
| Number of instruments | 7 | 9 | 8 | 6 | 3 | 4 |
| Max. electron energy (GeV) | 14.3 | 4.5 | 8.5 | 17.5 | 5.8 | 10 |
| Min. pulse duration (femtoseconds) | 15 | 15 | 10 | 5 | 2 | 30 |
| Pulses per second | 120 | 1,000,000 | 60 | 27,000 | 100 | 60 |

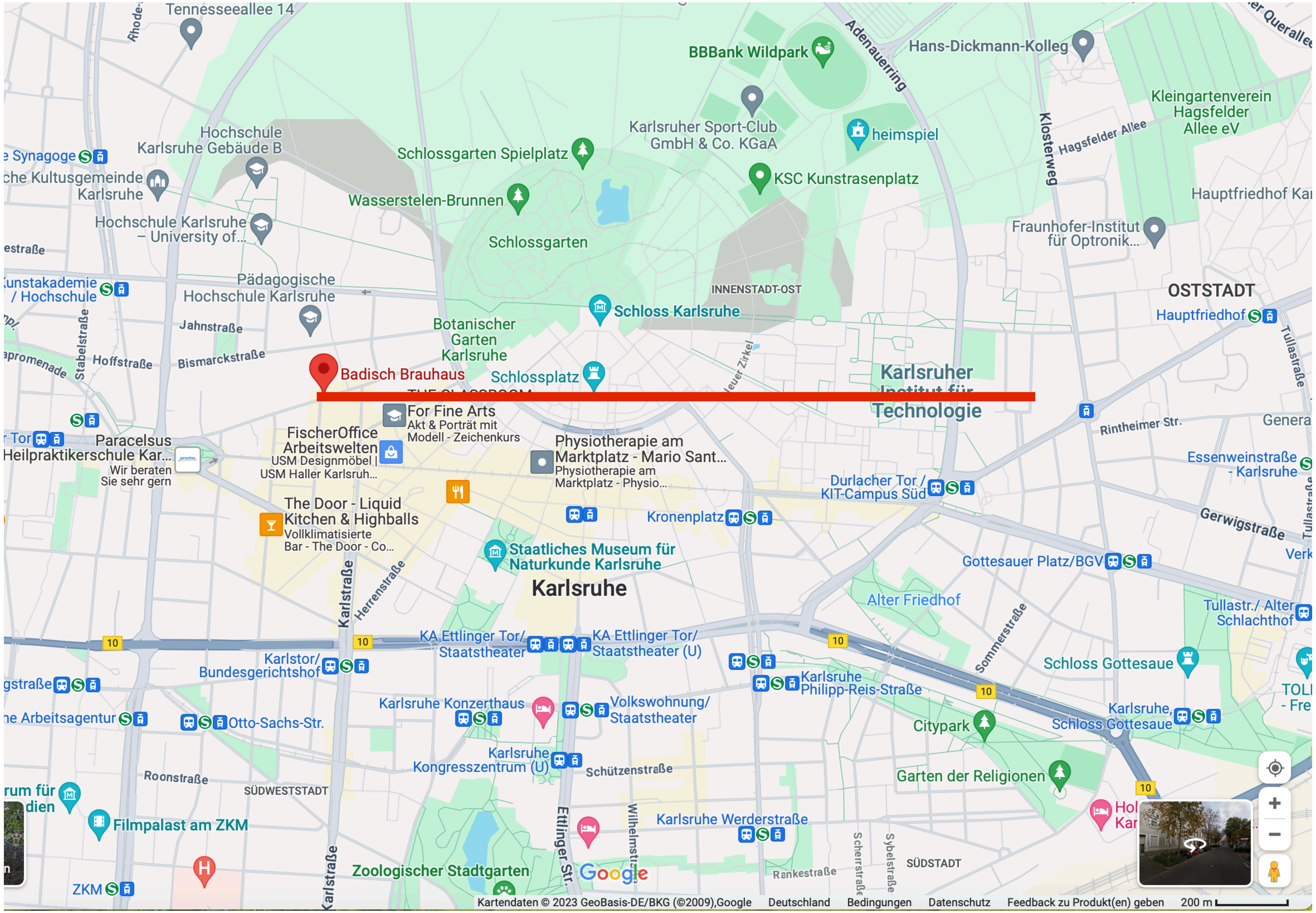
**SACLA is the Spring-8 Angstrom Compact free electron Laser and PAL-XFEL is the Pohang Accelerator Laboratory X-ray Free Electron Laser*

Edwin Cartlidge Science 2016;354:22-23

# X-Ray Free-Electron Laser: LCLS at SLAC



# LCLS at Karlsruhe

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# Shrinking Accelerators

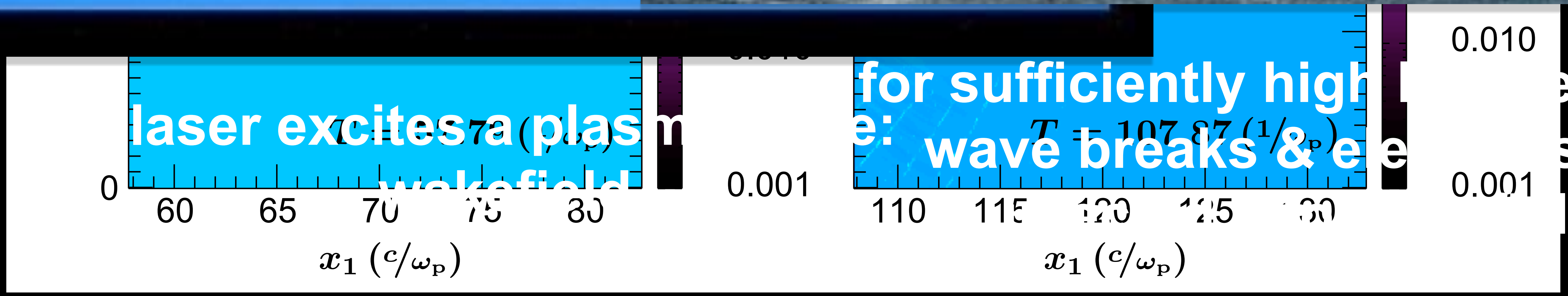
# Laser-Wakefield Electron Acceleration

laser

pc
er
pι

Particle-in-Cell Simulation

"Bubble"
Meyer-ter-Vehn, Pukhov
Appl Phys B, 74, 355 (2002)



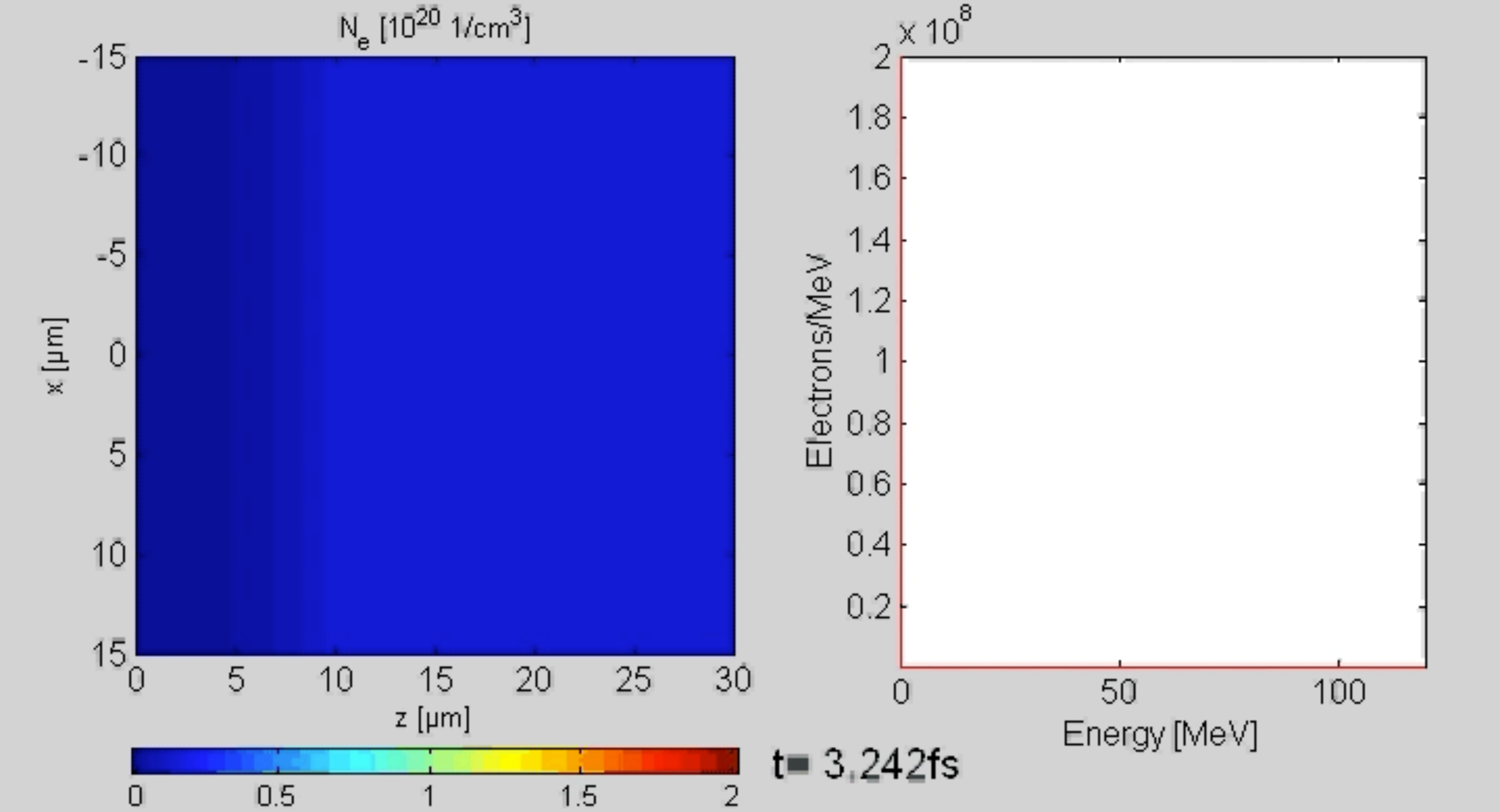

laser excites a plasm... wakefield

for sufficiently high ... energy: wave breaks & e... s are ...ld



simulation: courtesy J. Osterhoff

# Particle-in-Cell simulation of LWFA

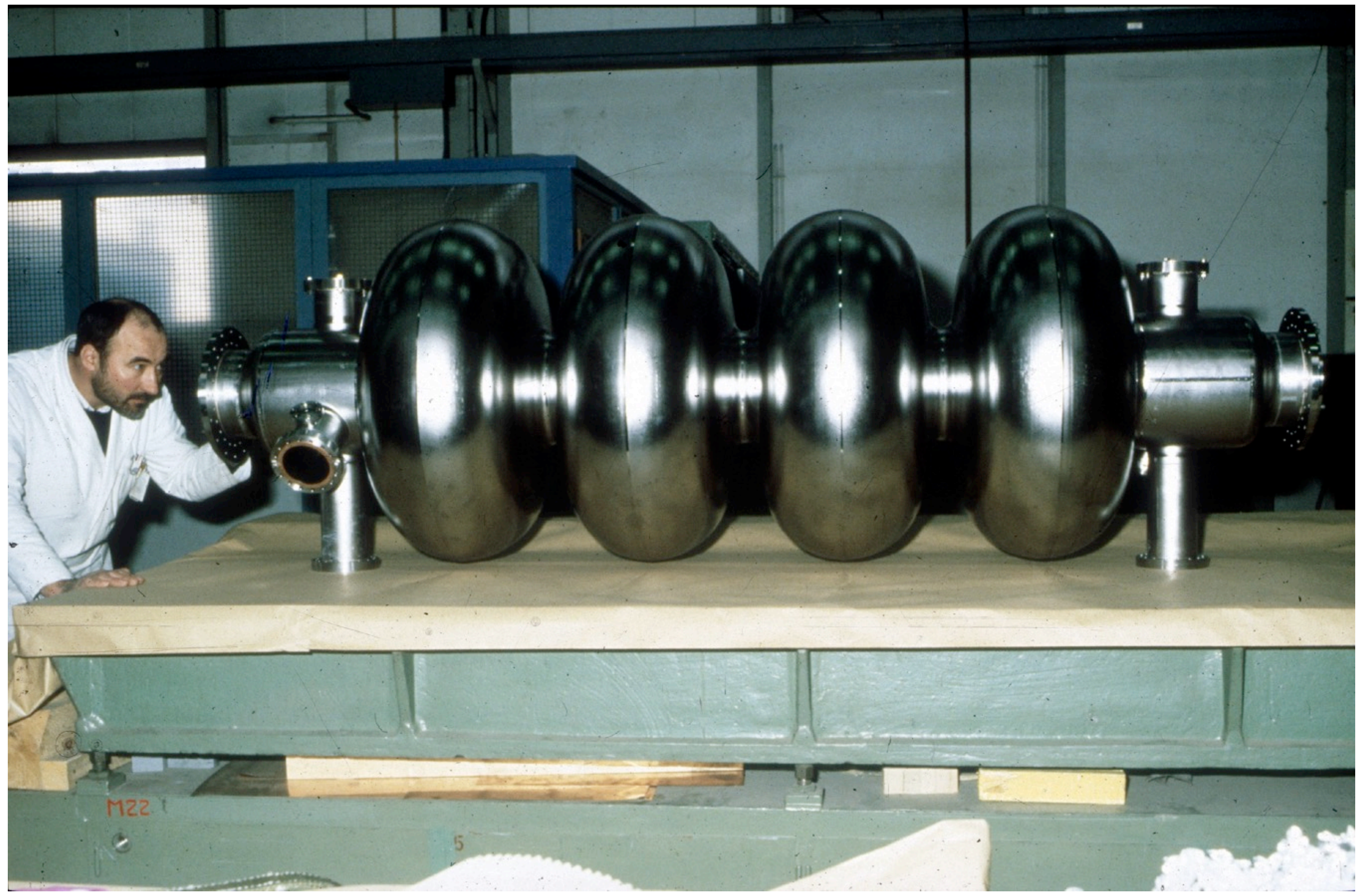



PIC simulation (M. Geissler, Belfast)

# Comparison Conventional and Plasma Accelerator

## Conventional Accelerator

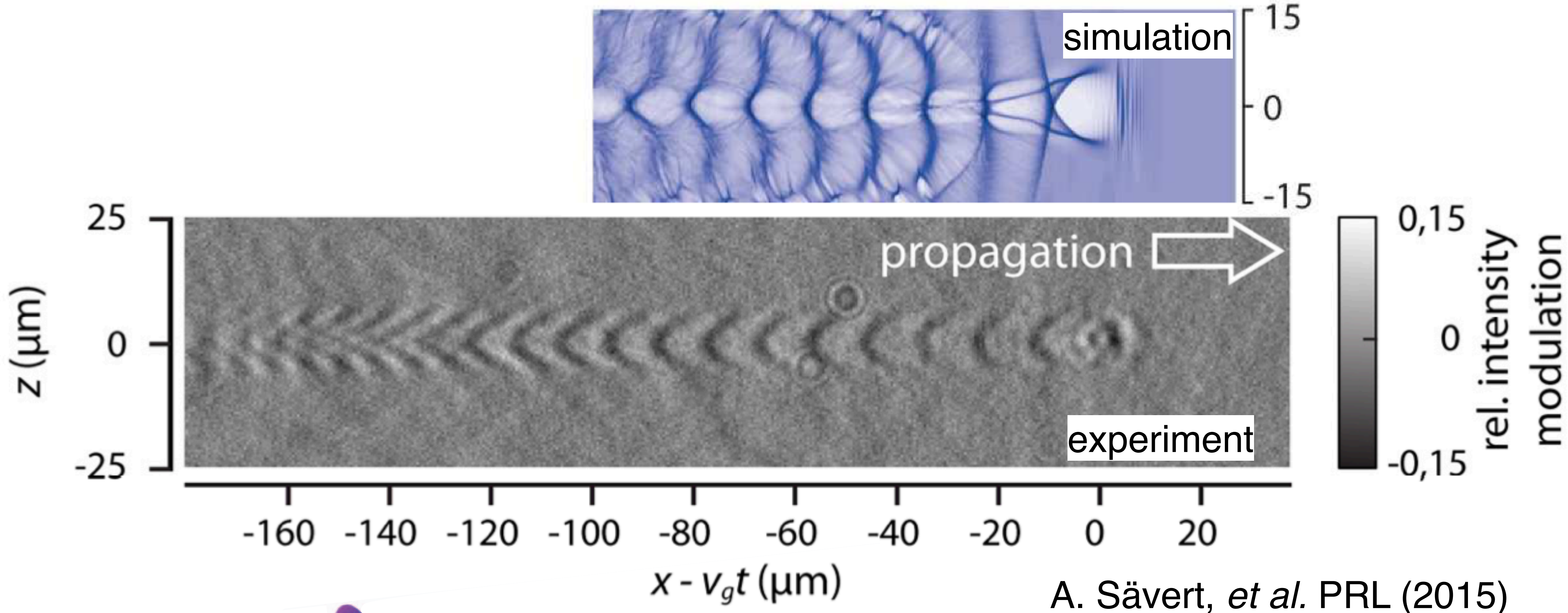
- Accelerating field gradient limited by RF power and vacuum breakdown
- Max. accelerating field gradients: 20 - 100 MV/m
- Typical cavity size: ~10 cm



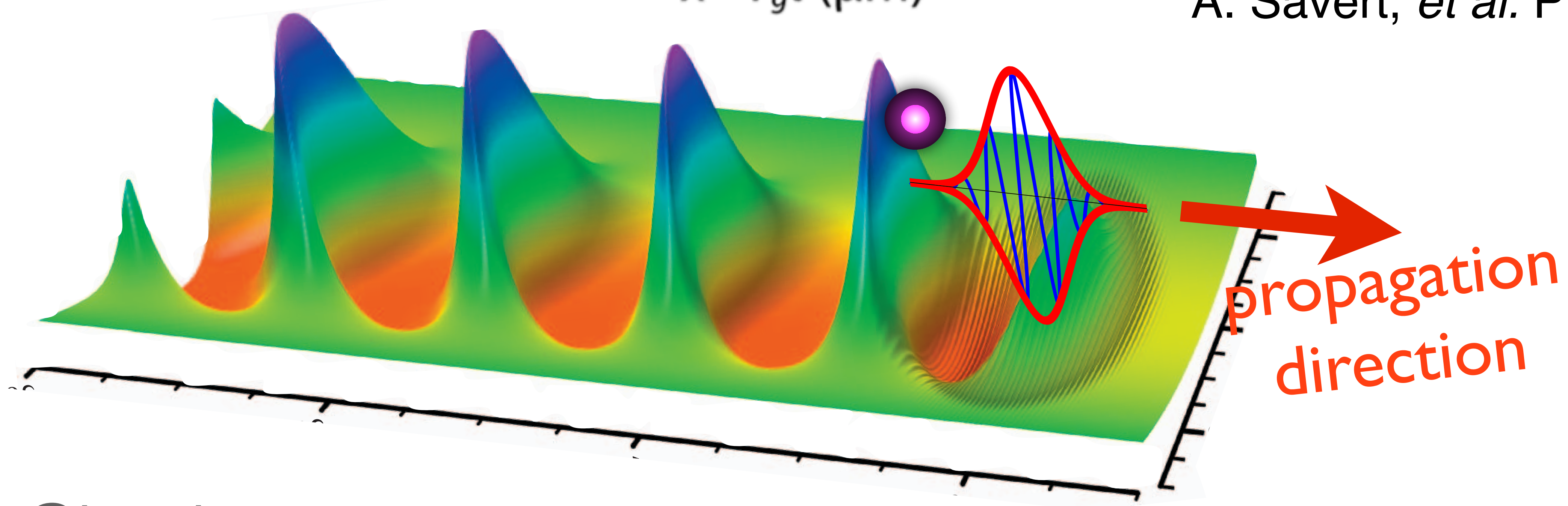
LEP radio-frequency cavity. Source: CERN

## Plasma Accelerator

- no breakdown limit
- Max. accelerating field gradients: 10 - 100 GV/m
- Typical cavity size: ~100 μm

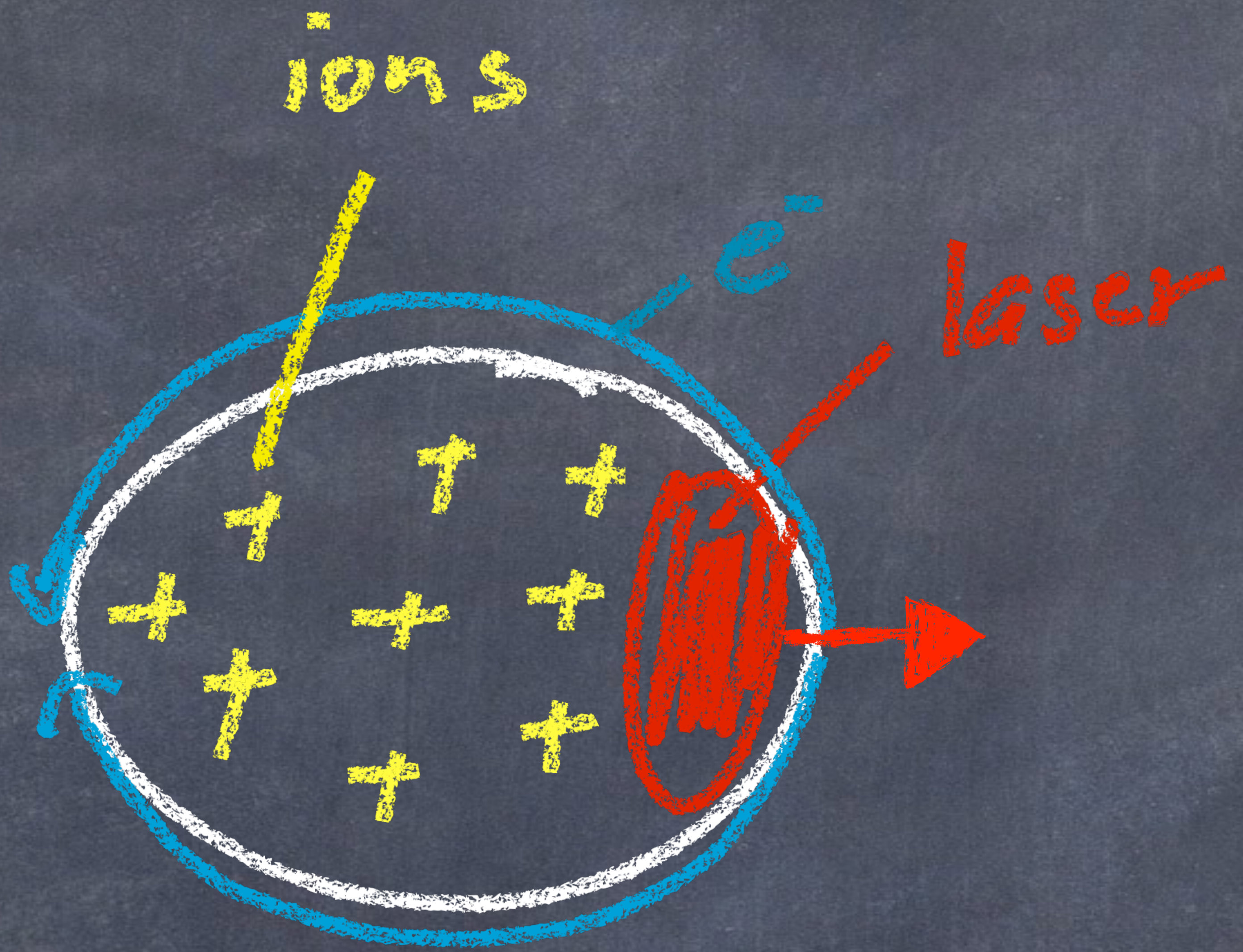



A. Sävert, *et al.* PRL (2015)



# LWFA in the "Bubble" Regime

for highly intense short-pulse lasers (relativistic intensities):




- electrons completely transversely expelled
- completely cavitated spherical ion "bubble" with radius of plasma wavelength trailing laser pulse
- electrons pulled back on axis through space charge forces
- extremely nonlinear laser-plasma interaction (relativistic electrons)
- but: bubble stable & reproducible
- laser pulse needs to be significantly shorter than plasma wavelength

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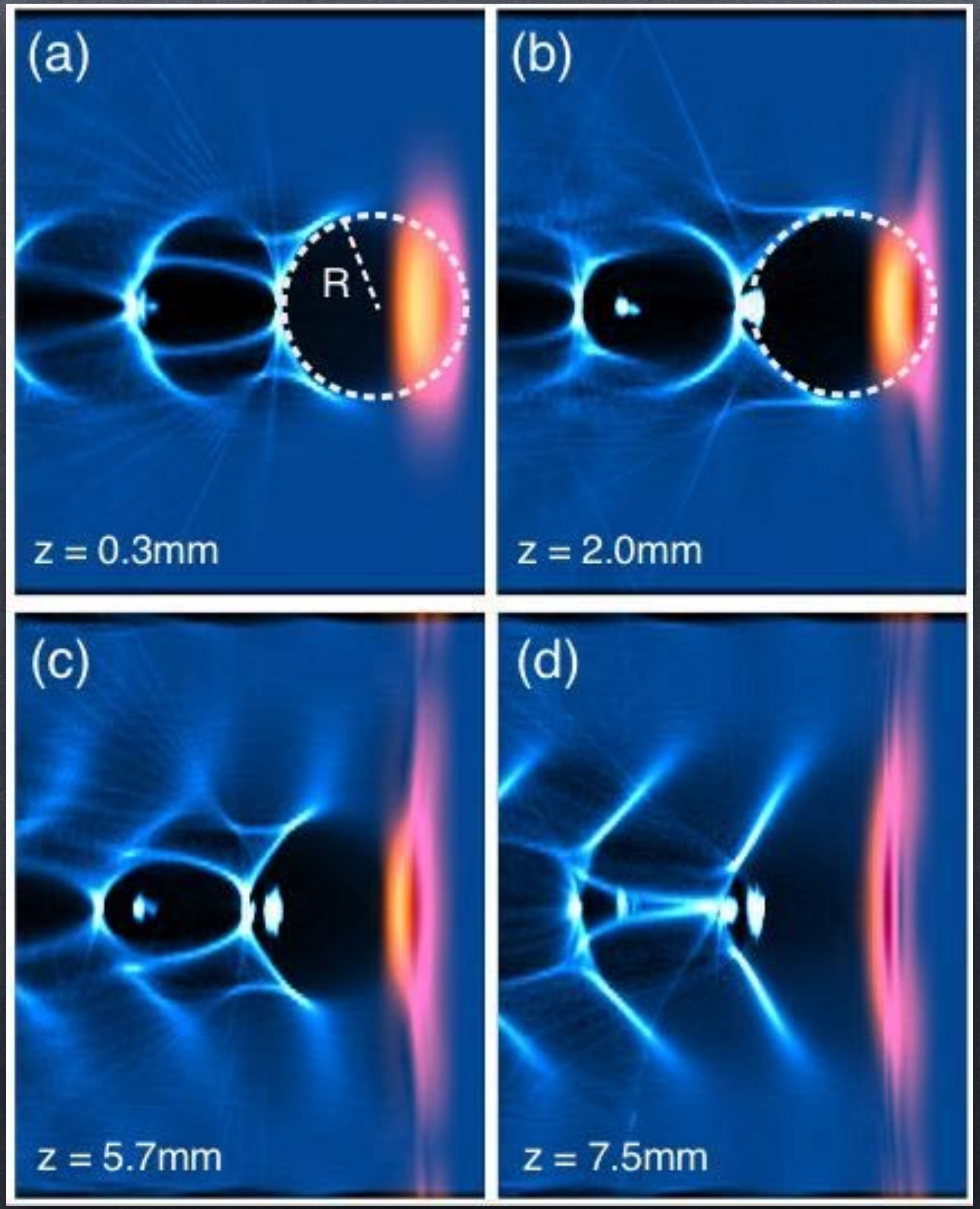
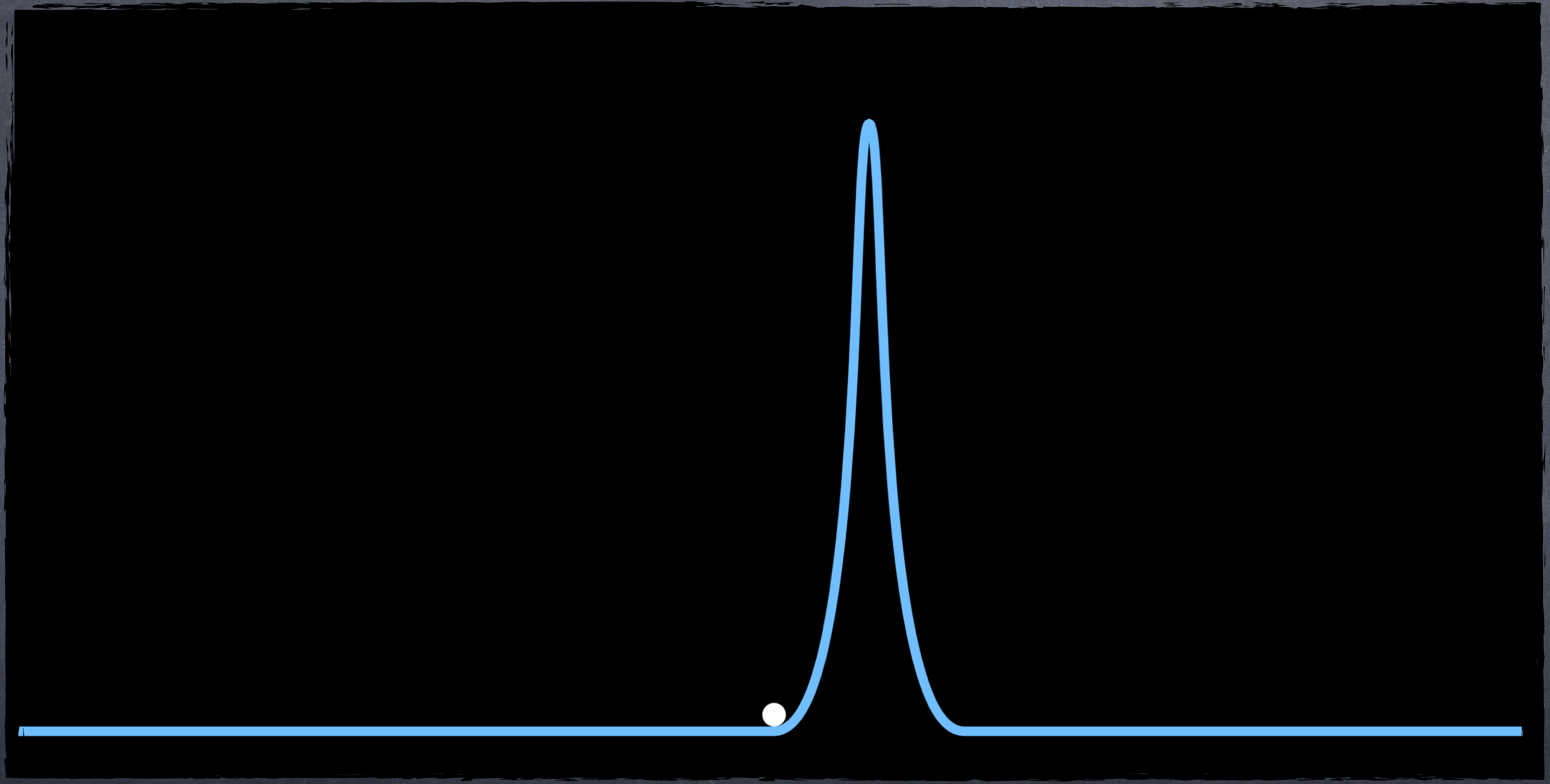
# Bubble dynamics & Laser-Plasma Interaction

- dynamics and evolution highly nonlinear
- detailed description need large-scale 3D particle-in-cell (PIC) simulations
- PIC simulations
  - typical densities: ~$10^{18}$ particles/cm$^3$
  - resolution: sub laser wavelength ~0.1 $\mu$m
  - few-cm 3D simulations: millions CPU hours, tens of TB data



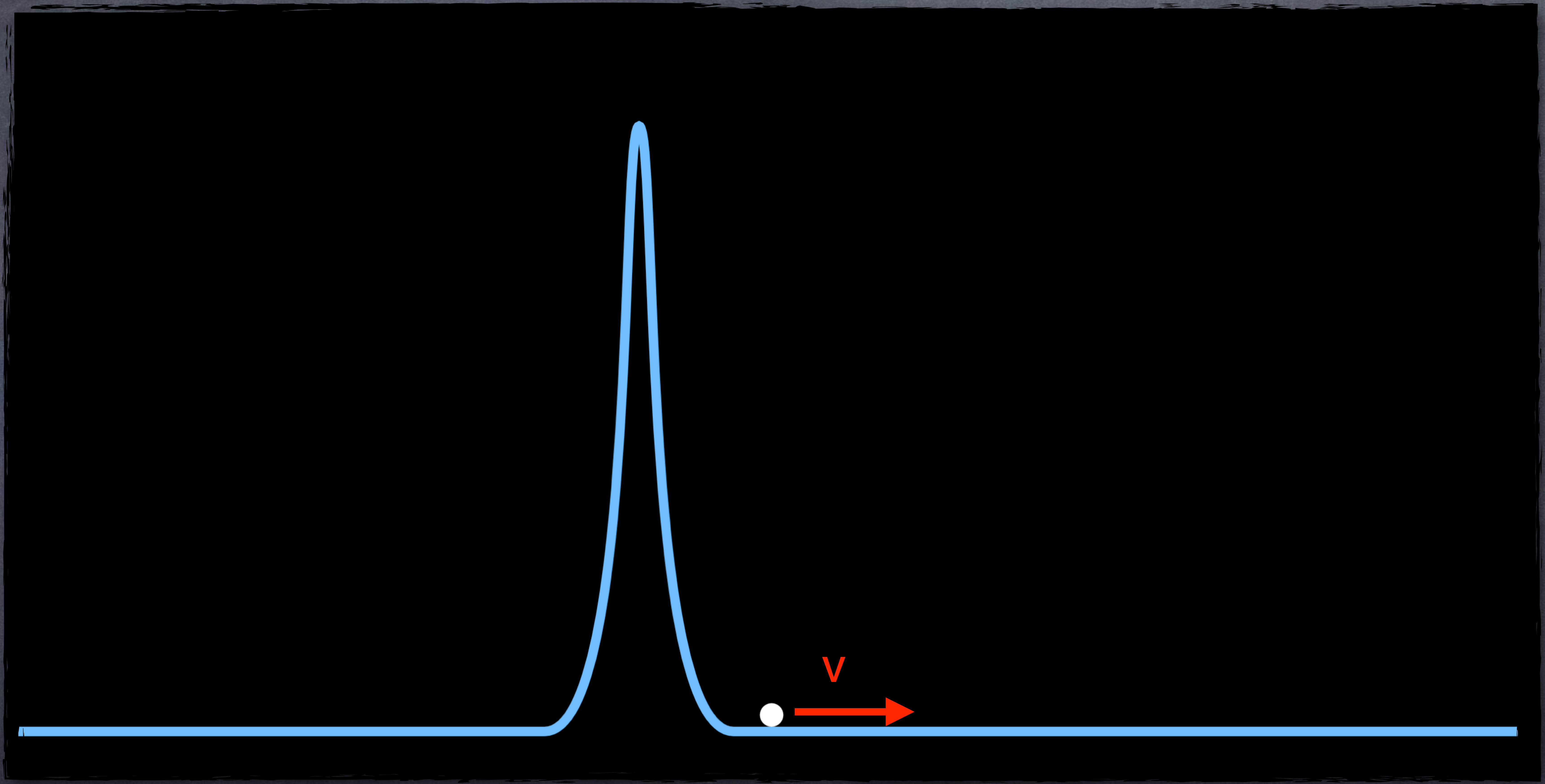

Lu et al., PRSTAB (2007)

# Electron Injection: Untrapped Electron



Electron velocity too small for trapping

# Trapping And Acceleration




Electron with sufficiently high velocity

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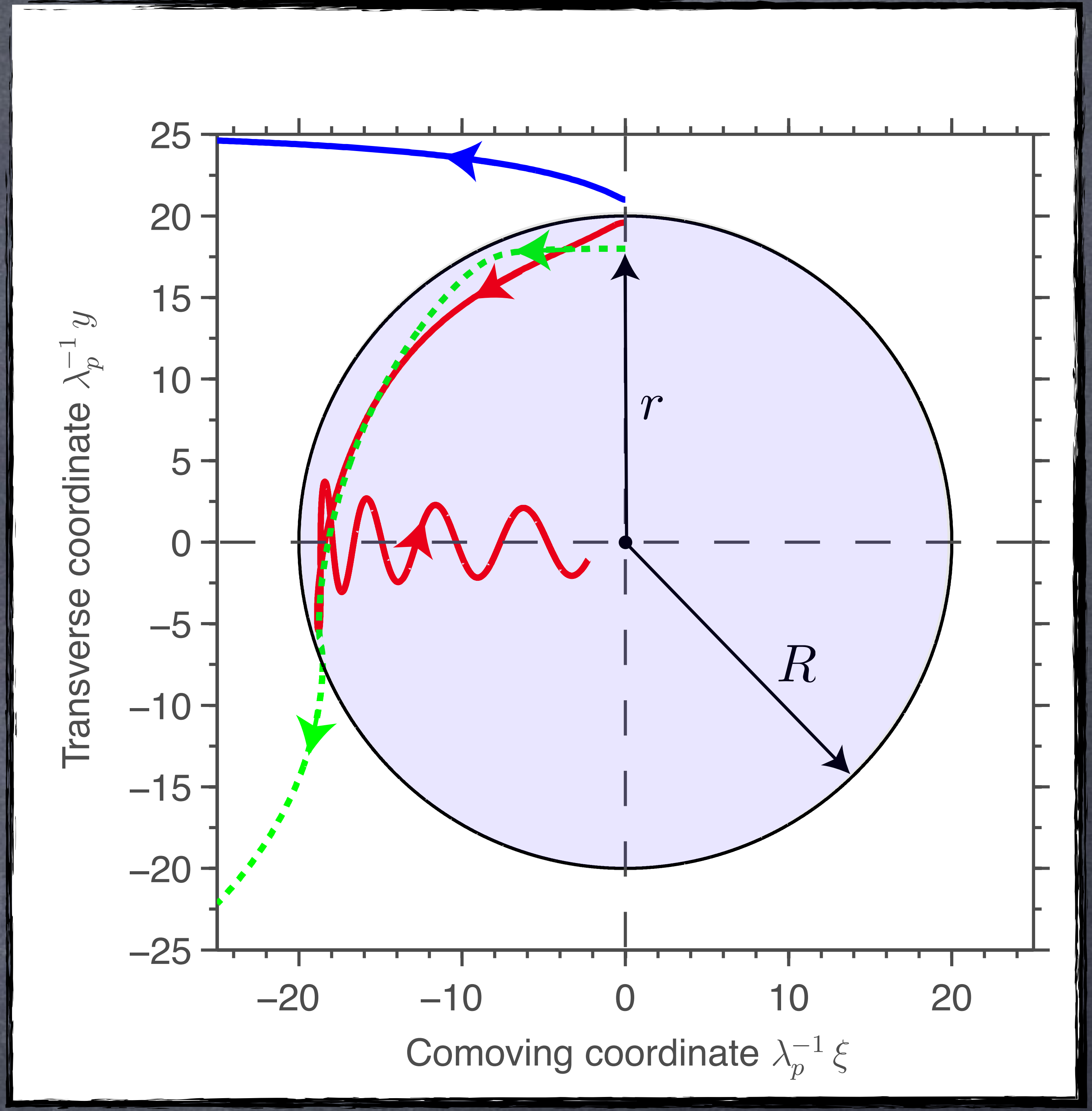
# Trapping And Acceleration

Electron with sufficiently high velocity

# “Self”-Injection into Bubble

- electrons with suitable initial conditions (red) undergo sufficient longitudinal acceleration while bubble passes by
- injection at back of bubble
- electron have finite transverse momentum
- perform transv. (betatron) oscillations -> move on sinusoidal trajectory during acceleration



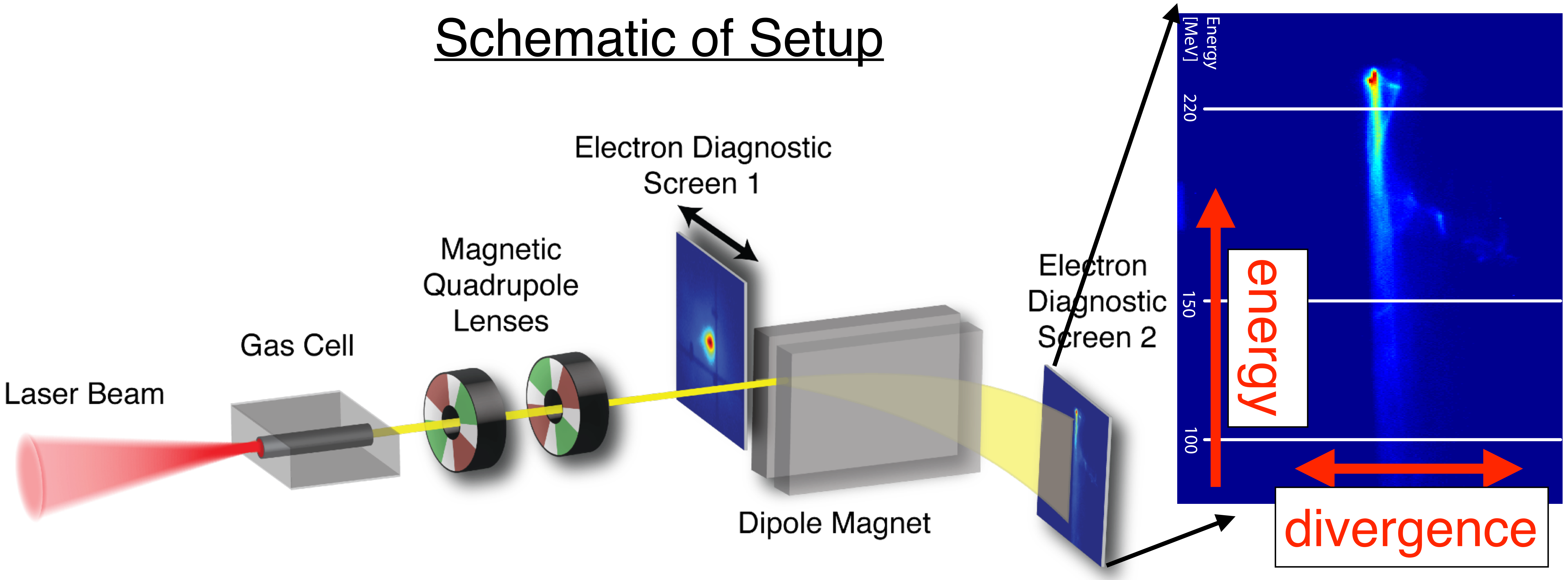

Kostyukov, PRL (2009)

# Laser Wakefield Acceleration
# “Surfing the Plasma”

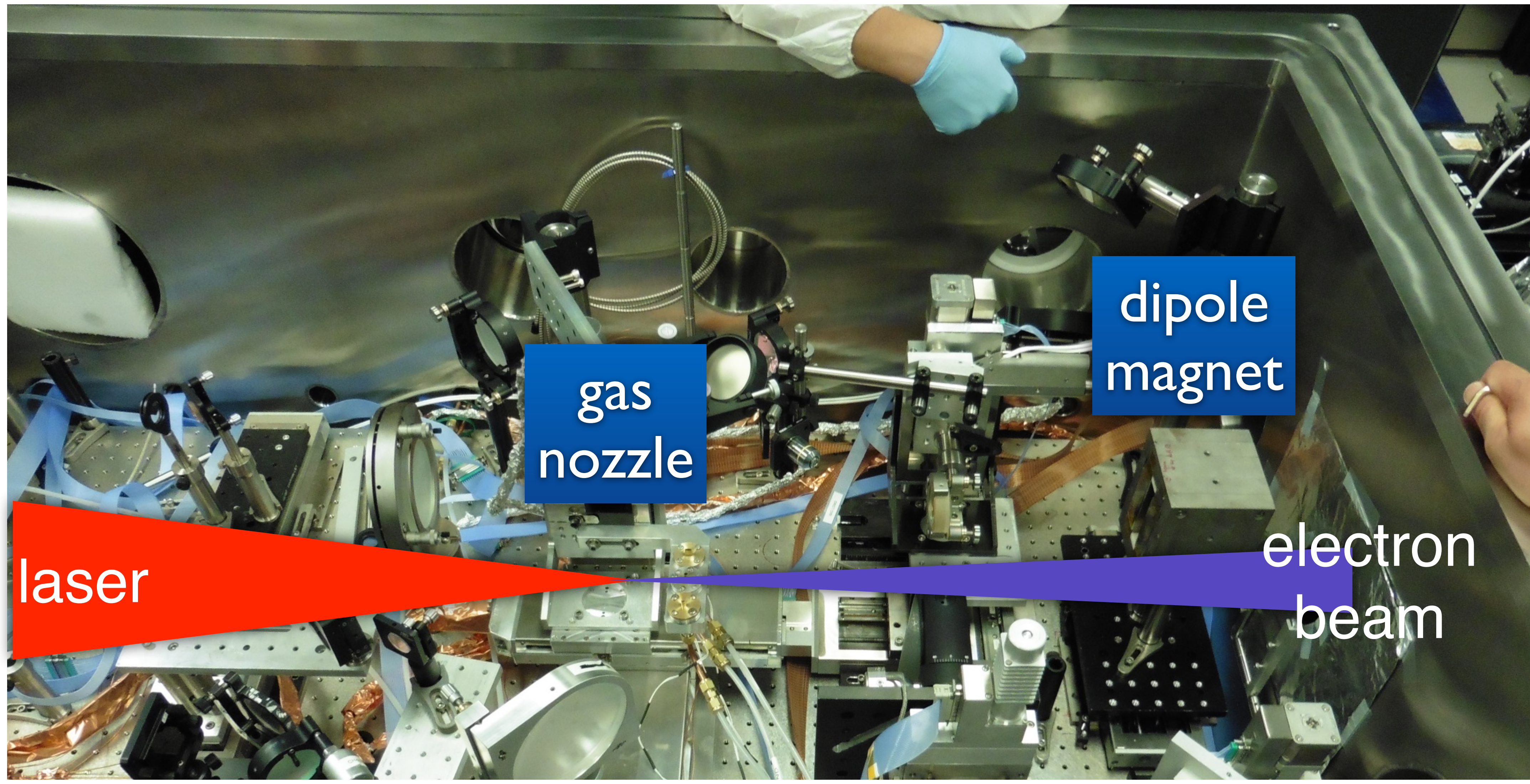
# Typical Laser-Wakefield Accelerator

Schematic of Setup

electron beam spectrum




Target Chamber



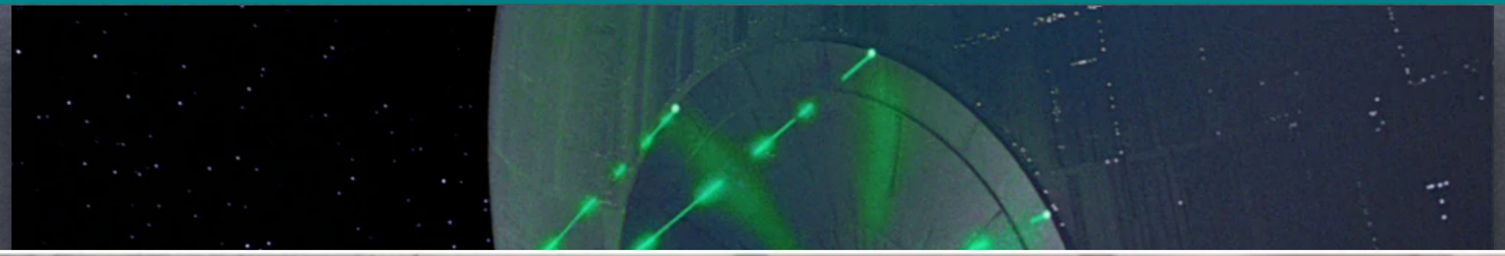

- Laser: ~100 TW - PW (~3J, 30 fs, 10 Hz)
- Gas target
- Diagnostics (electron beam, laser, plasma, … )
- Optional: electron beam optics

# Driver Laser Properties

- Laser parameters:
  - pulse e
  - pulse d

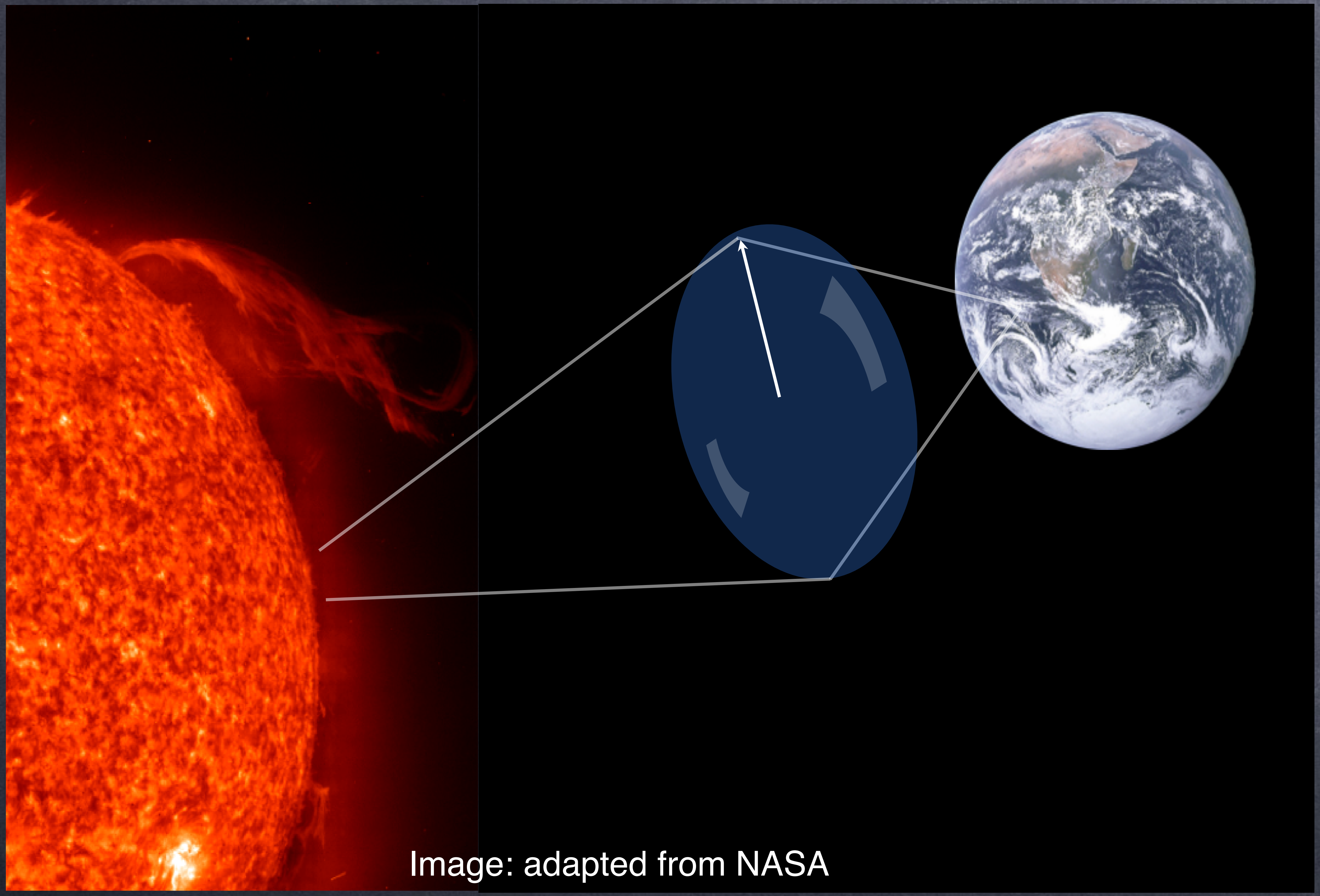
$\frac{1\,\mathrm{fs}}{1\,\mathrm{s}}$

$P = \frac{\Delta E}{\Delta t}$




# Driver Laser Properties

- 1 PW focused to 1 $\mu m$ spot size : $I = 10^{22}\ W/cm^2$




to achieve an intensity of $I = 10^{22}\ W/cm^2$, all of the sun light that hits the Earth surface must be focused into a area comparable to:

A) a mid-sized country (Germany): 350,000 $km^2$
B) a city: 250 $km^2$
C) football field: 7,000 $m^2$
D) human hair: 2,000 $\mu m^2$

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# Driver Laser Properties

• 1 PW focused to 1 $\mu m$ spot size : $I = 10^{22}\ W/cm^2$

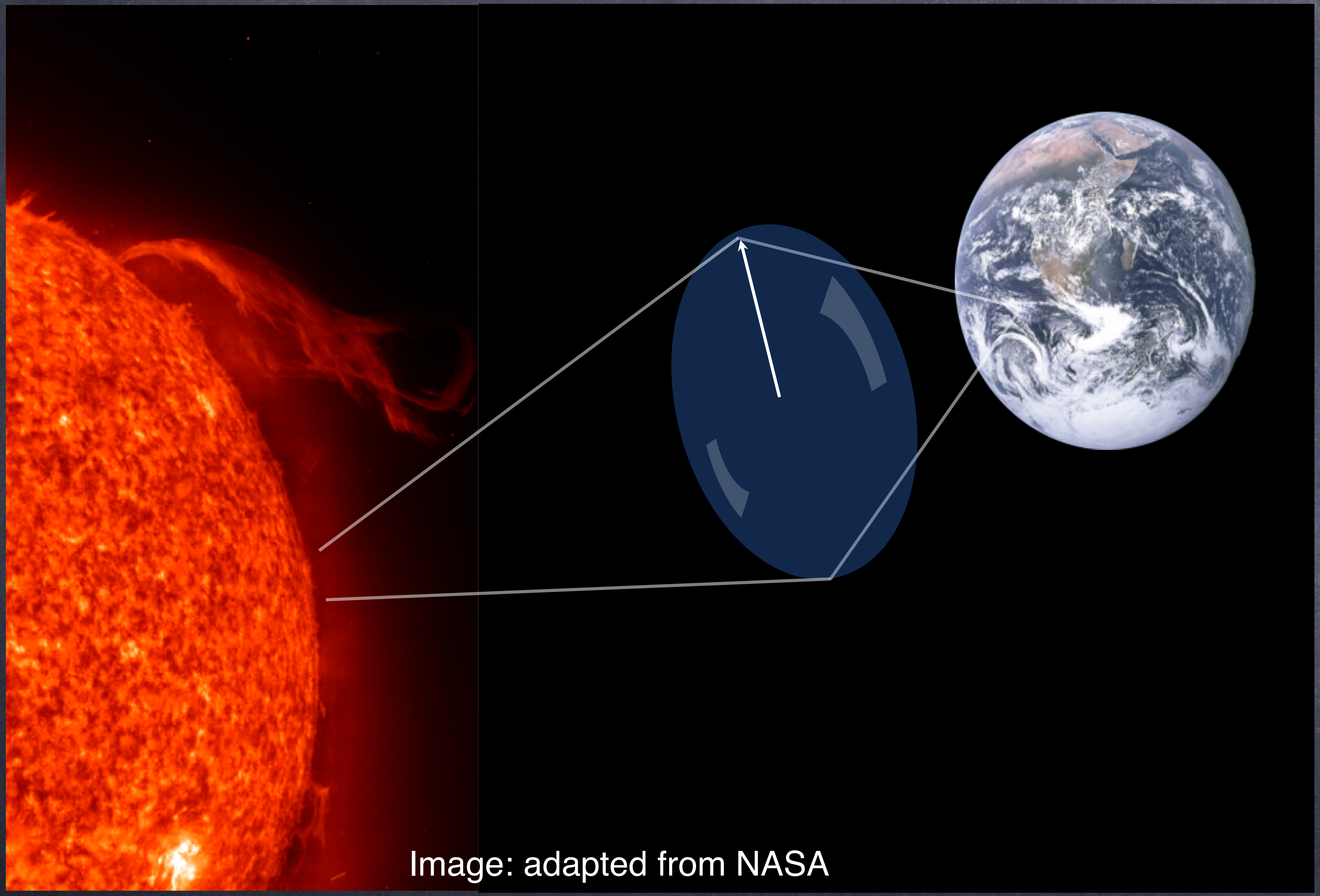
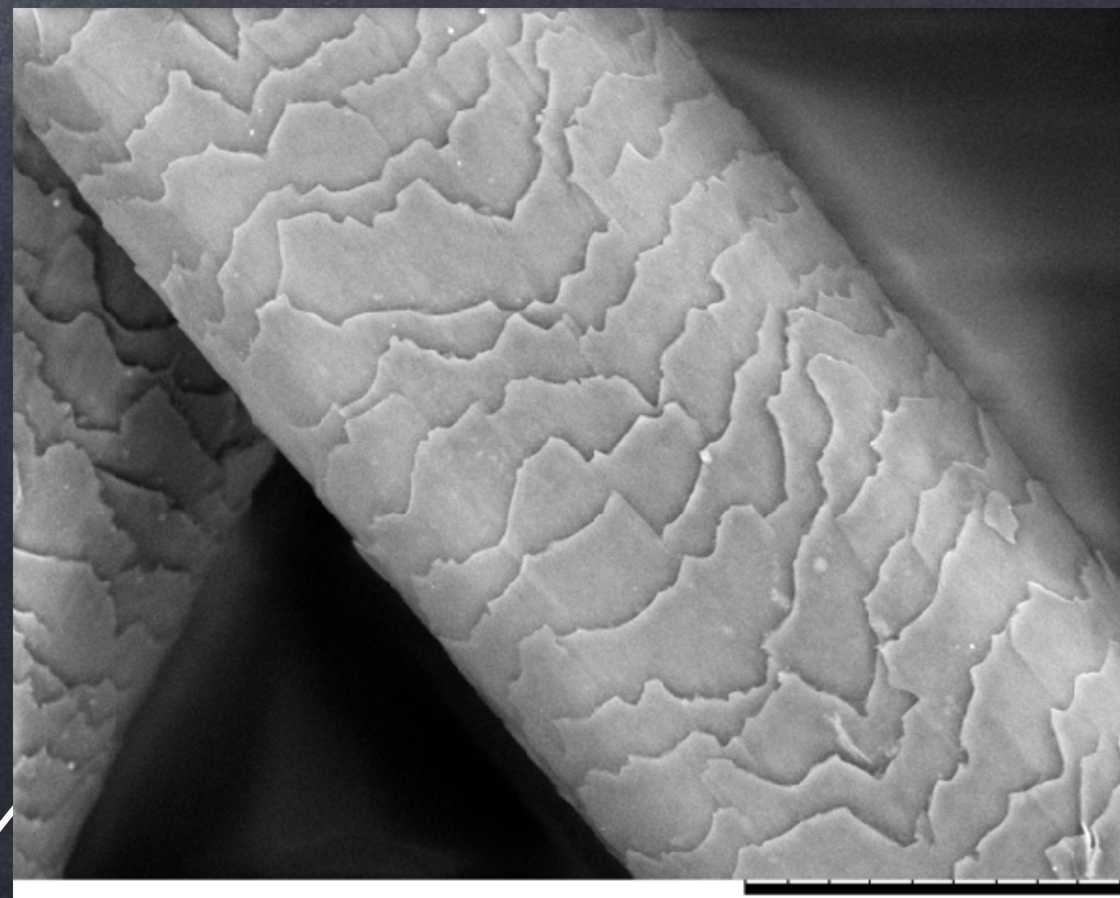


Image: adapted from NASA

to achieve an intensity of $I = 10^{22}\ W/cm^2$, all of the sun light that hits the Earth surface must be focused into a area comparable to:

A) a mid-sized country (Germany): 350,000 $km^2$
B) a city: 250 $km^2$
C) football field: 7,000 $m^2$
D) human hair: 2,000 $\mu m^2$

Human hair



total radiation power hitting the earth: $1.7 \times 10^{17}$ W

# Some Milestones in LWFA

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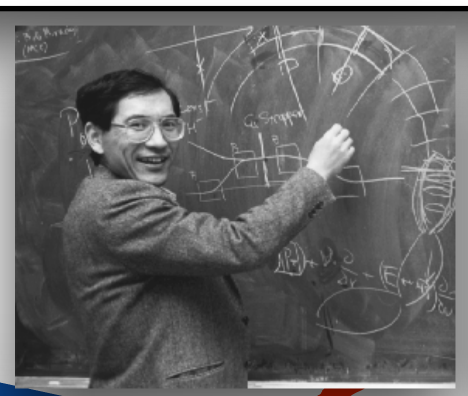
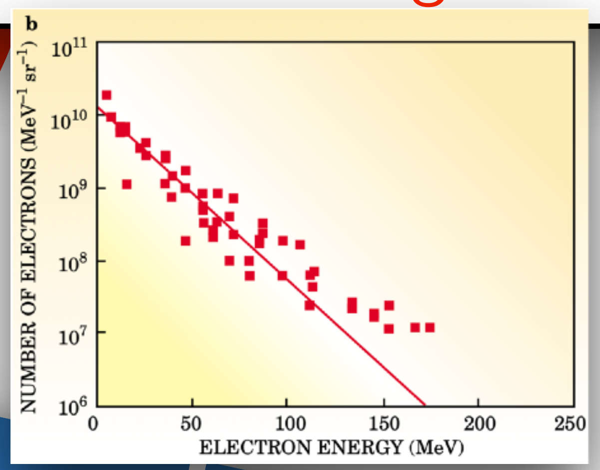
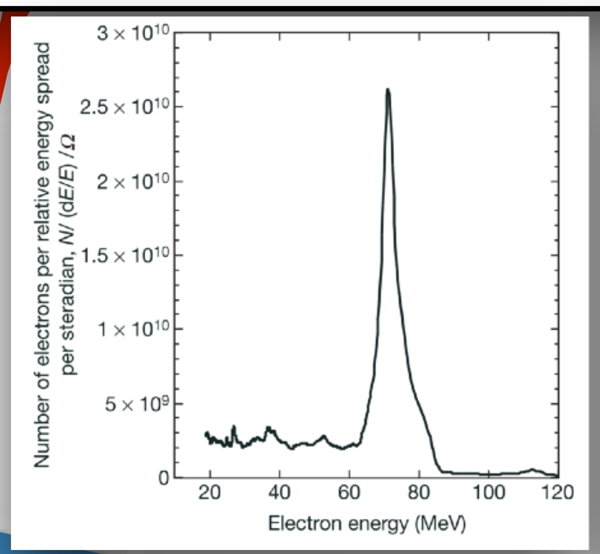
**First theoretical proposal**
Tajima & Dawson, PRL (1979)
required lasers did not exist




**First laser-plasma electron beams**
Modena *et al.*, Nature (1995); Nakajima *et al.*, PRL (1995); Umstadter *et al.*, Science (1996); Malka *et al.*, Science (2002).
e beams w large energy spread;
laser pulses still too long and too weak



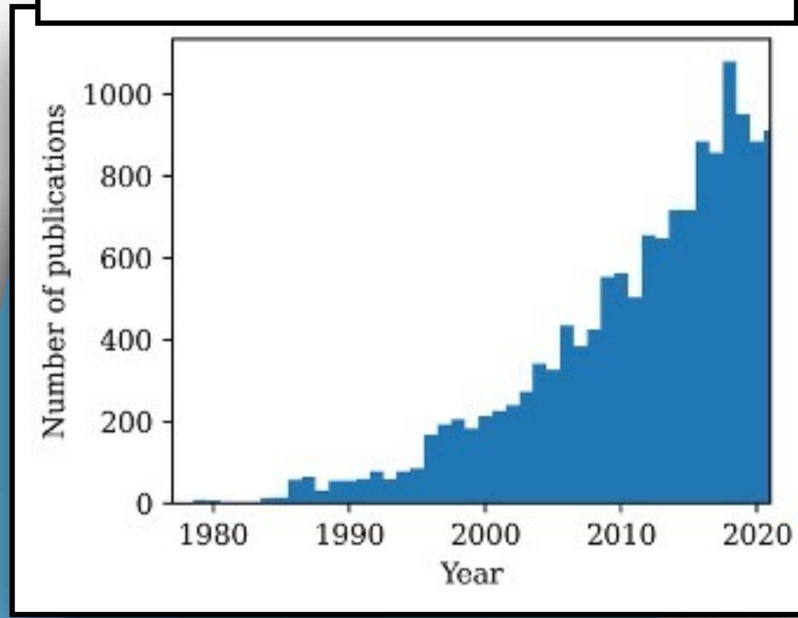

**Experimental observation of quasi-monoenergetic beams**
Mangles *et al.* Nature (2004). Faure, J. *et al.* Nature (2004). Geddes, *et al.* Nature (2004).
Lasers finally can drive "bubbles"





**Nobel Prize: Strickland & Mourou**
for Chirped Pulse Amplification

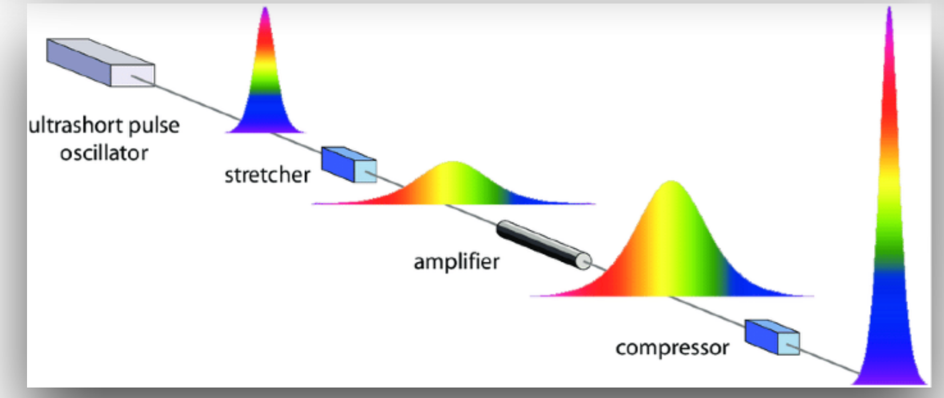
**~1000 citations/year**
for LWFA



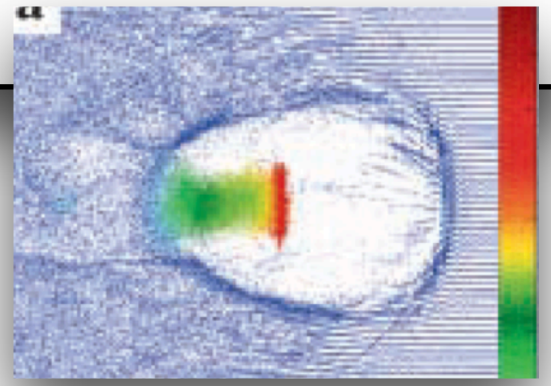

1979 | 1985 | 1995- 2002 | 2002 | 2004 | 2006 | 2018 | 2019

Development of laser technology

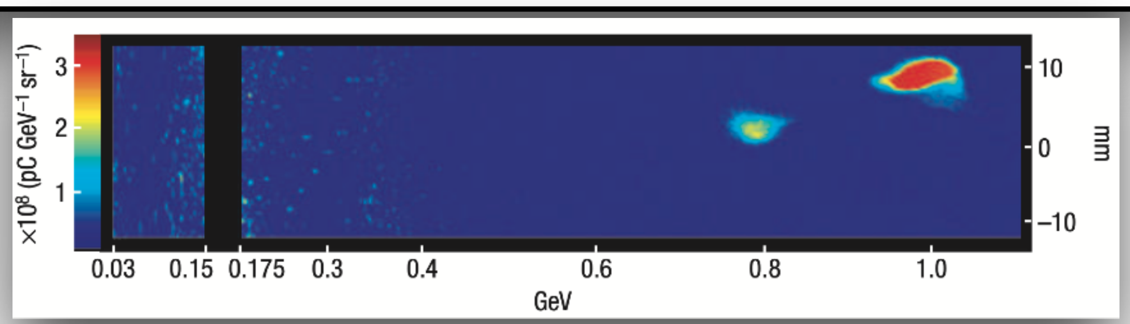
**Invention of Chirped Pulse Amplification (CPA)**
Strickland & Mourou, Opt. Comm (1985)
ultrashort laser pulses



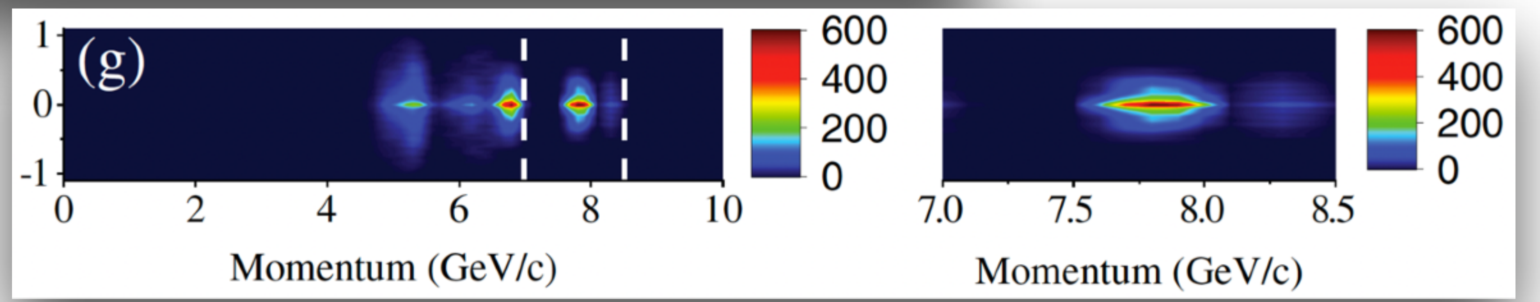

**First Simulation of "Bubble" Regime**
Pukhov & Meyer-ter-Vehn, Appl. Phys B (2002)
Quasi-monoenergetic electron bunches in simulations



**1 GeV LWFA electron beam**
Leemans *et al.*, Nature Phys (2006)




**8 GeV LWFA electron beam**
Gonsalves *et al.*, PRL (2019)



# More Recent Progress
# From Acceleration to Accelerator

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- Move from proof-of principle (single shot) experiments to applications:
- Higher reproducibility
- Improved beam performance
    - higher beam energy (10 GeV+)
    - relative energy spread: << 1% with >100 pC of charge
    - repetition rates: kHz - MHz
- Improved energy efficiency (including laser)
- Better control over electron parameters
- Improved diagnostics

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# Controlled Injection

- Ionization-induced injection
  - inner-shell electrons of higher-Z ionized at peak laser intensity
  - electrons "born" on axis & in accelerating phase

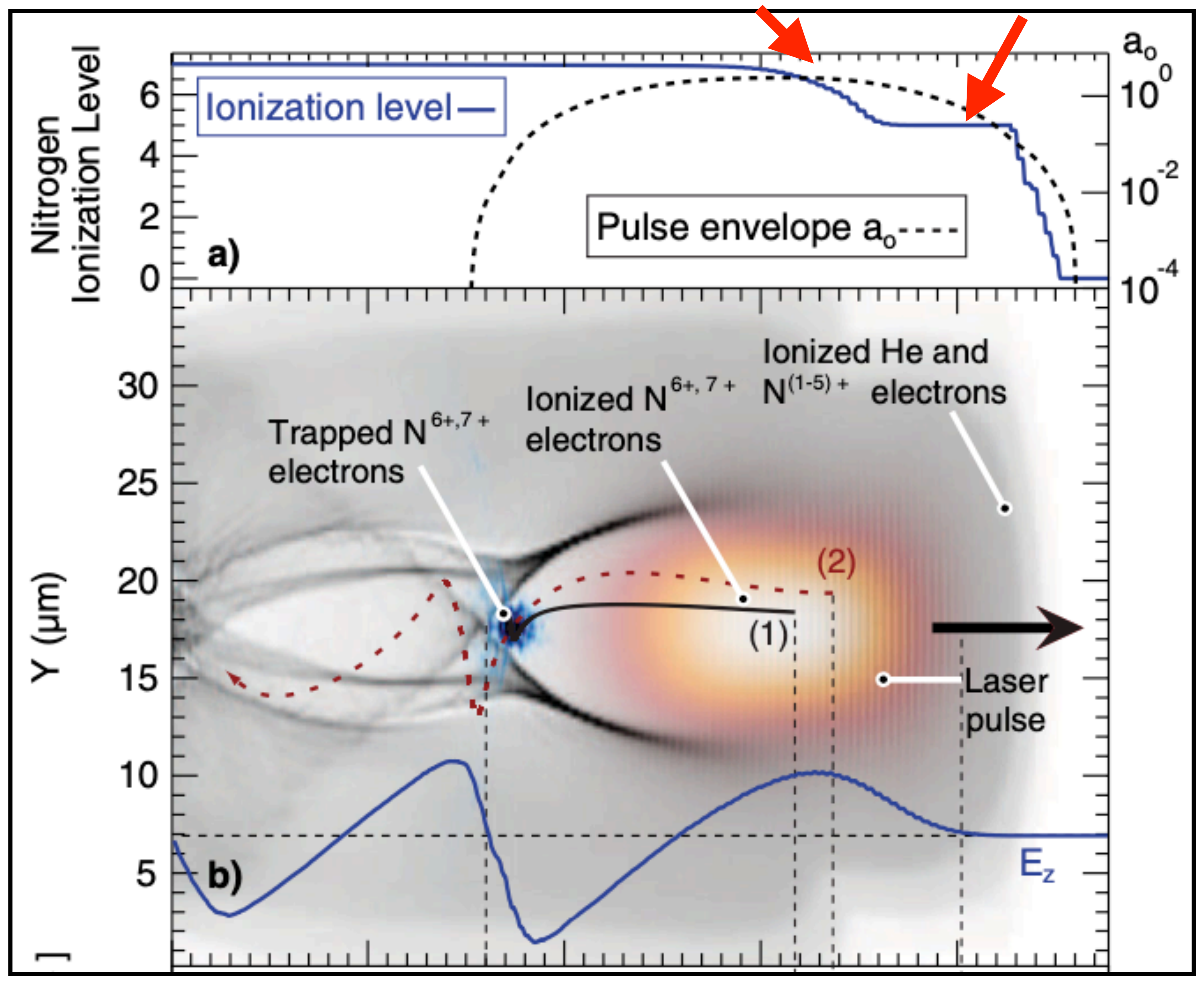
  Chen *et al.*, J. Appl. Phys. (2006); McGuffey *et al*., PRL (2010)

- Density-downramp injection
  - decrease phase velocity of wake
  - controlled & localized injection

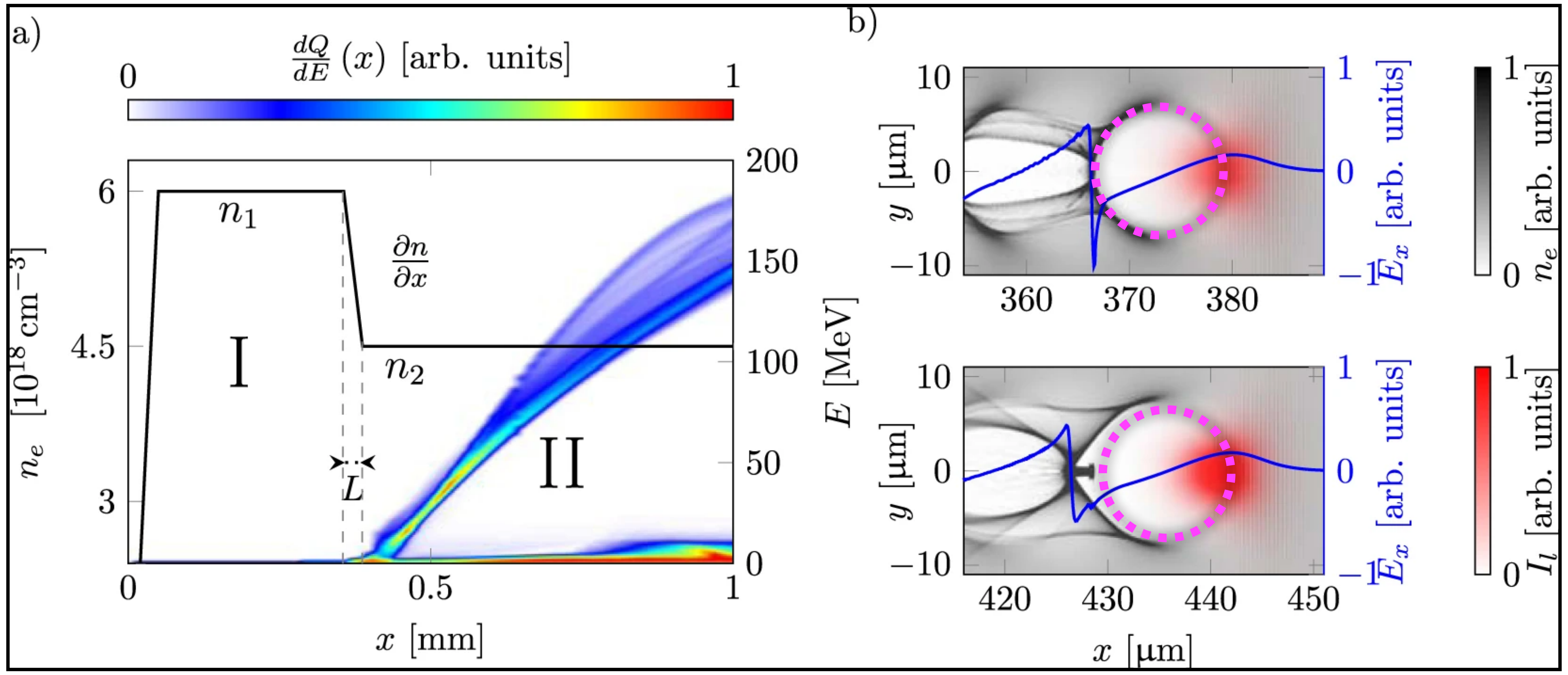
  Bulanov *et al*., PRE (1998); Geddes *et al.,* PRL (2008)

K-shell: $N^{7+}$

$N^{5+}$




Pak *et al*. PRL (2010)

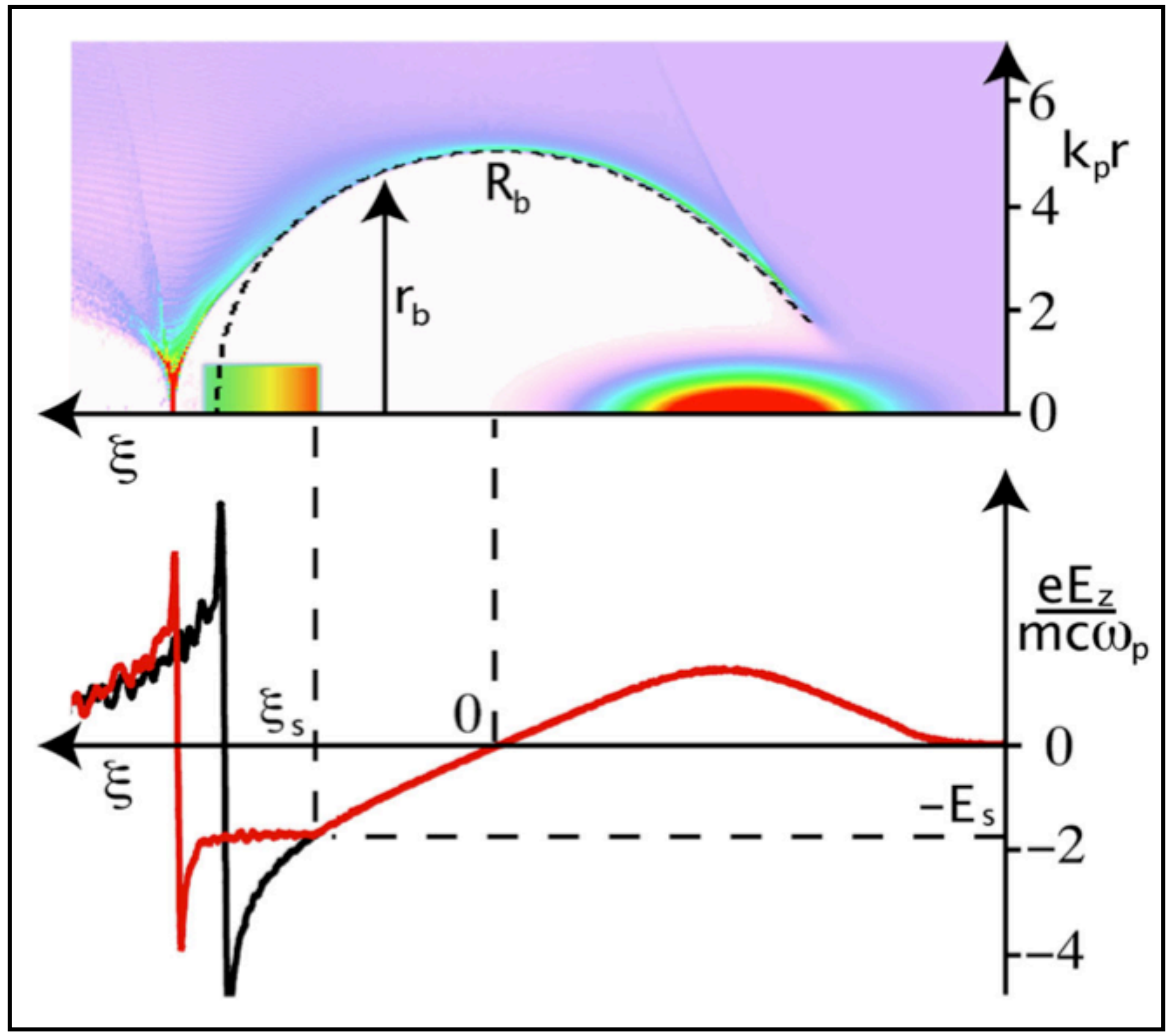



Ekerfelt, *et al.,* Sci Rep (2017)

# Controlled Acceleration: Beam Loading

Karlsruher Institut für Technologie

- <u>Beam loading</u>
  - charge of injected electron bunch modifies accelerating field
  - match bunch to achieve flat acc. field (same acceleration for whole bunch)
    Tzoufras et al., PRL (2008)

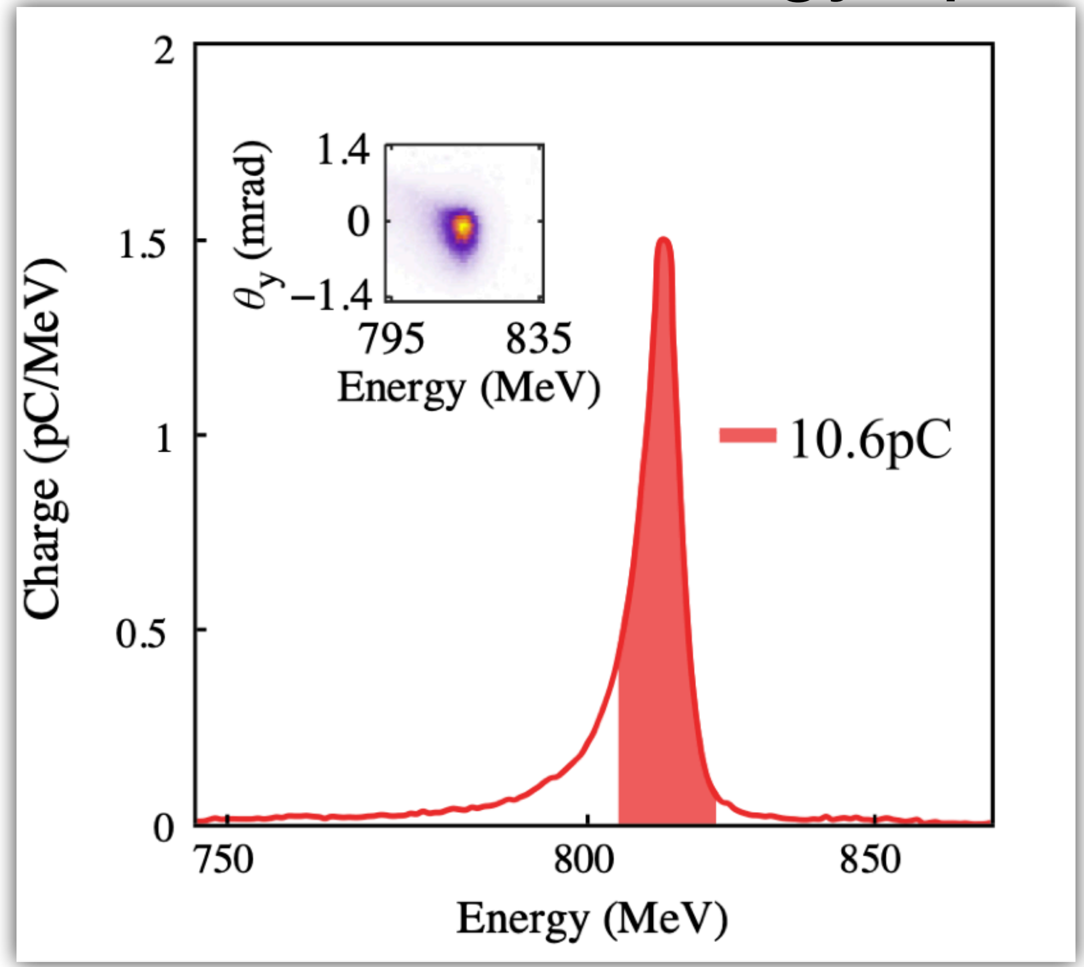



Tzoufras et al., PRL (2008)

# Selected Highlights of Experimental Progress

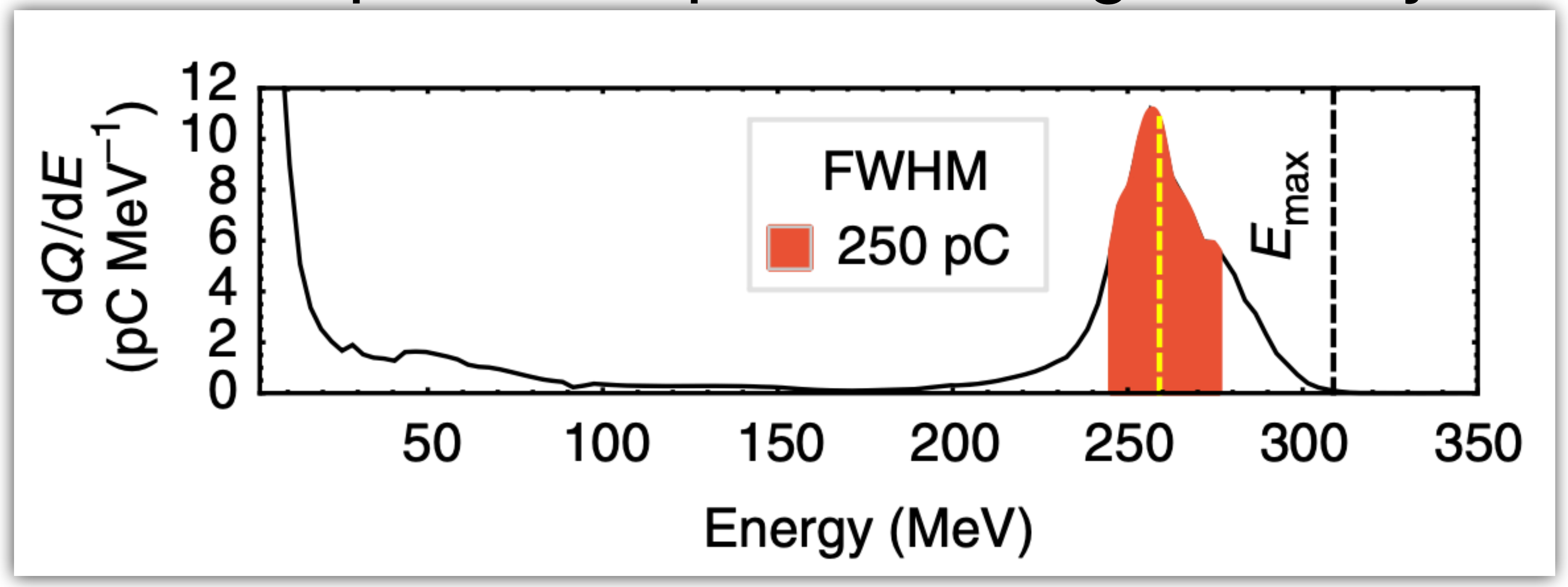
Karlsruher Institut für Technologie

## 0.3% relative energy spread



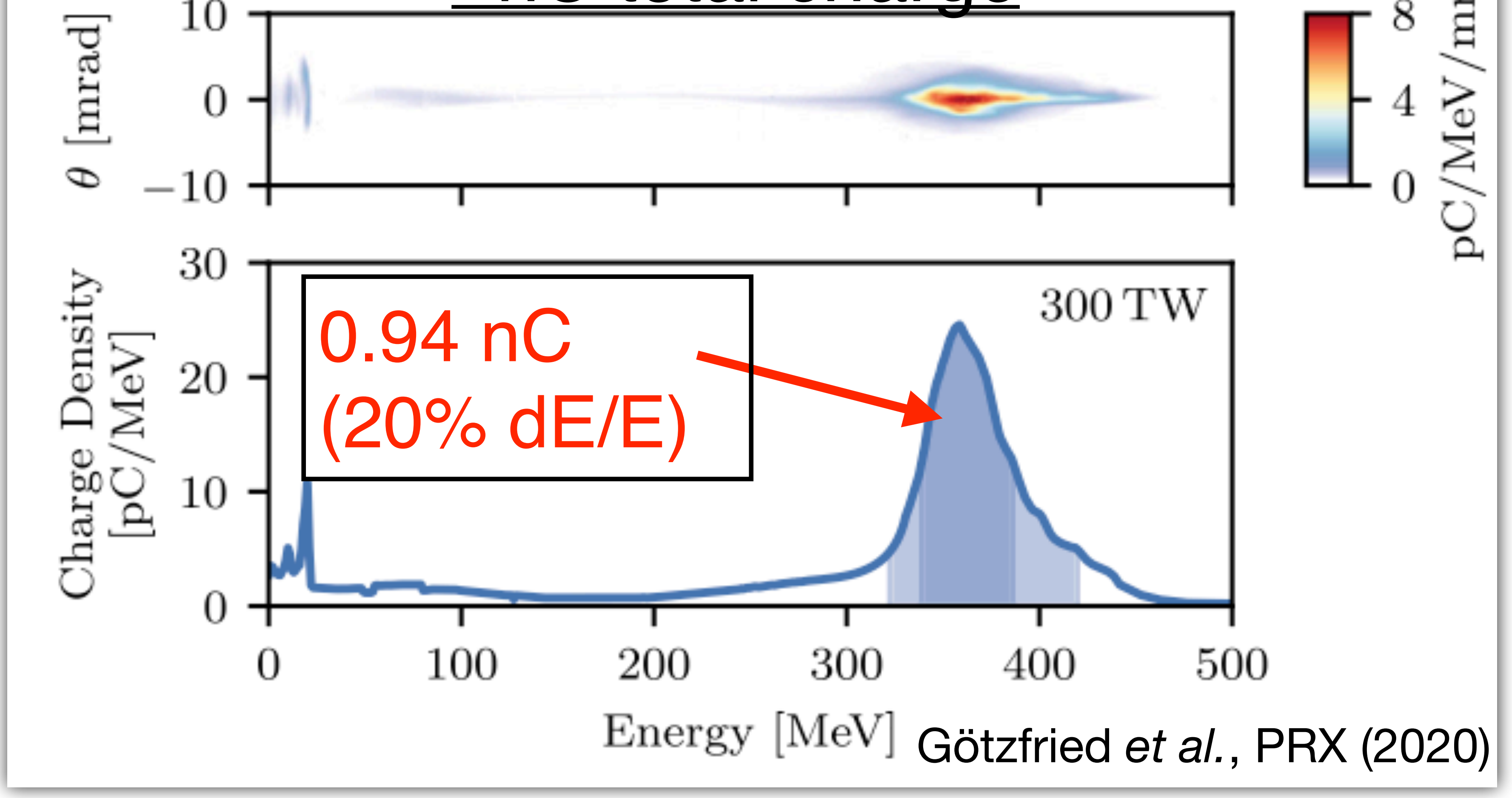

Ke *et al.*, PRL (2021)

## >10 pC/MeV spectral charge density



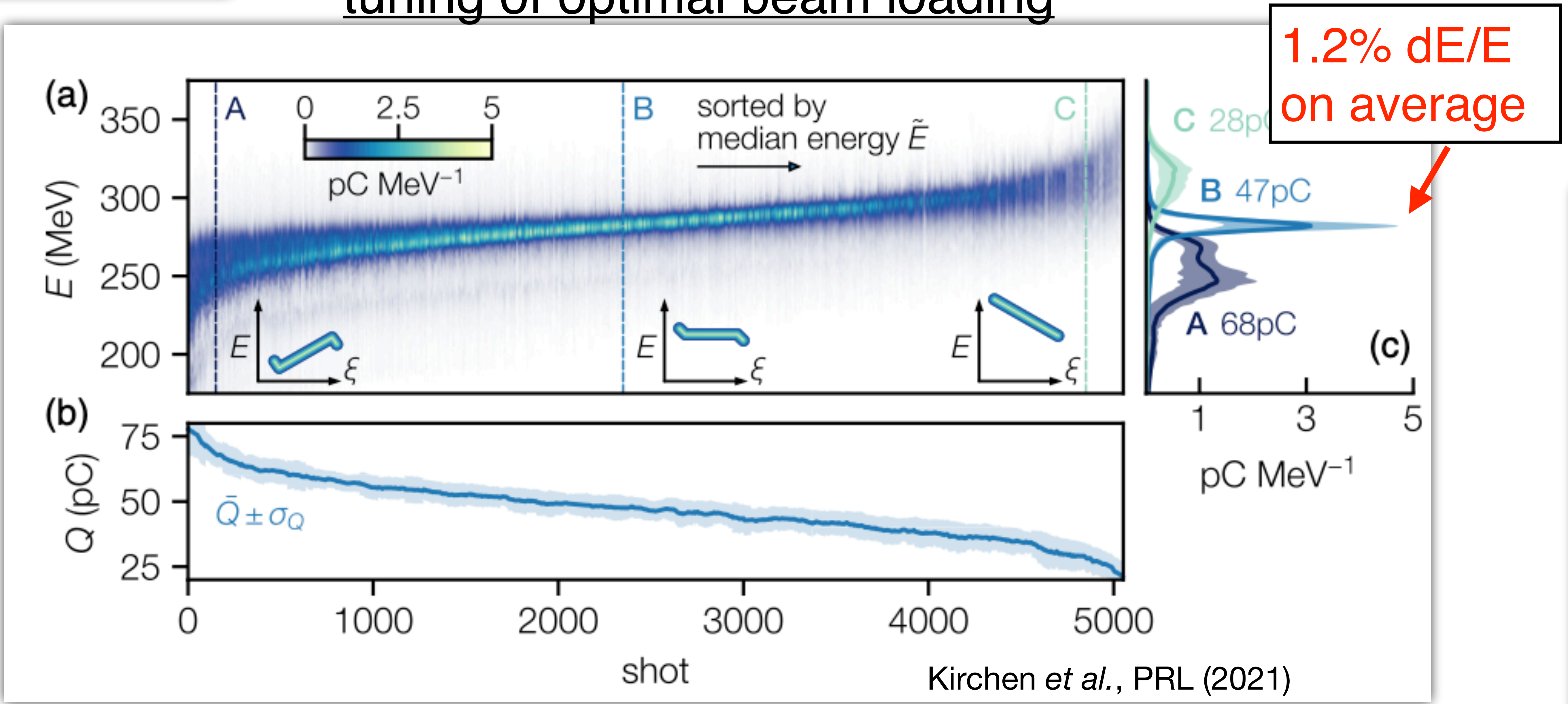

Couperus *et al.*, Nat. Comm (2017)

## ~nC total charge




Götzfried *et al.*, PRX (2020)

## tuning of optimal beam loading



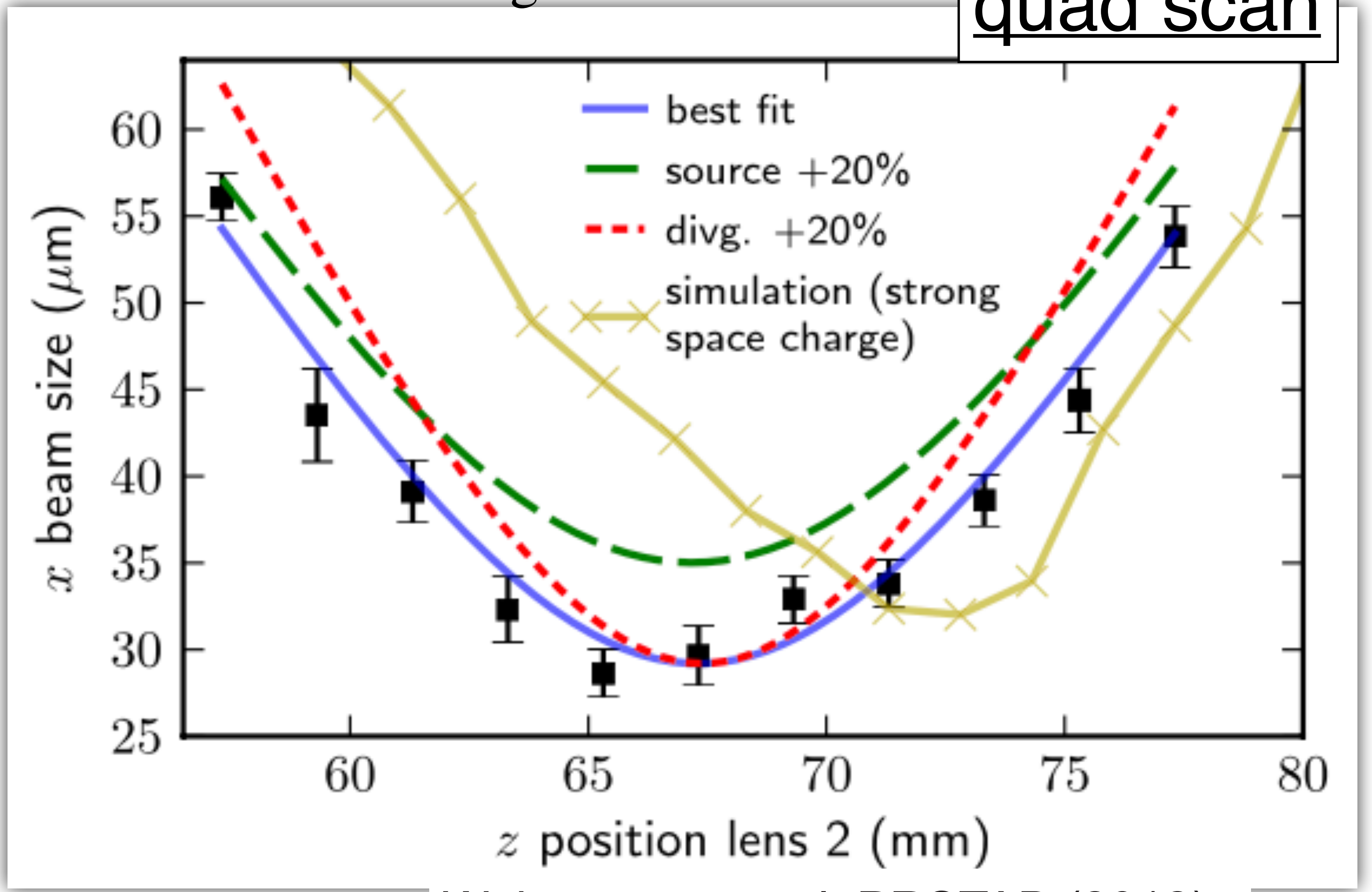

Kirchen *et al.*, PRL (2021)

## Emittance Measurement

$$\epsilon_n = \gamma\beta_z\epsilon_{\text{geom}} = 0.21^{+0.01}_{-0.02}\pi \text{ mm mrad at 245 MeV.}$$

$$\epsilon_{\text{geom}} \sim 1 \text{ nm}$$

quad scan




Weingartner, et al. PRSTAB (2012)

Overview over current parameters:
MF *et al.*, Plasma Based Particle Sources, JINST 19 (2024)

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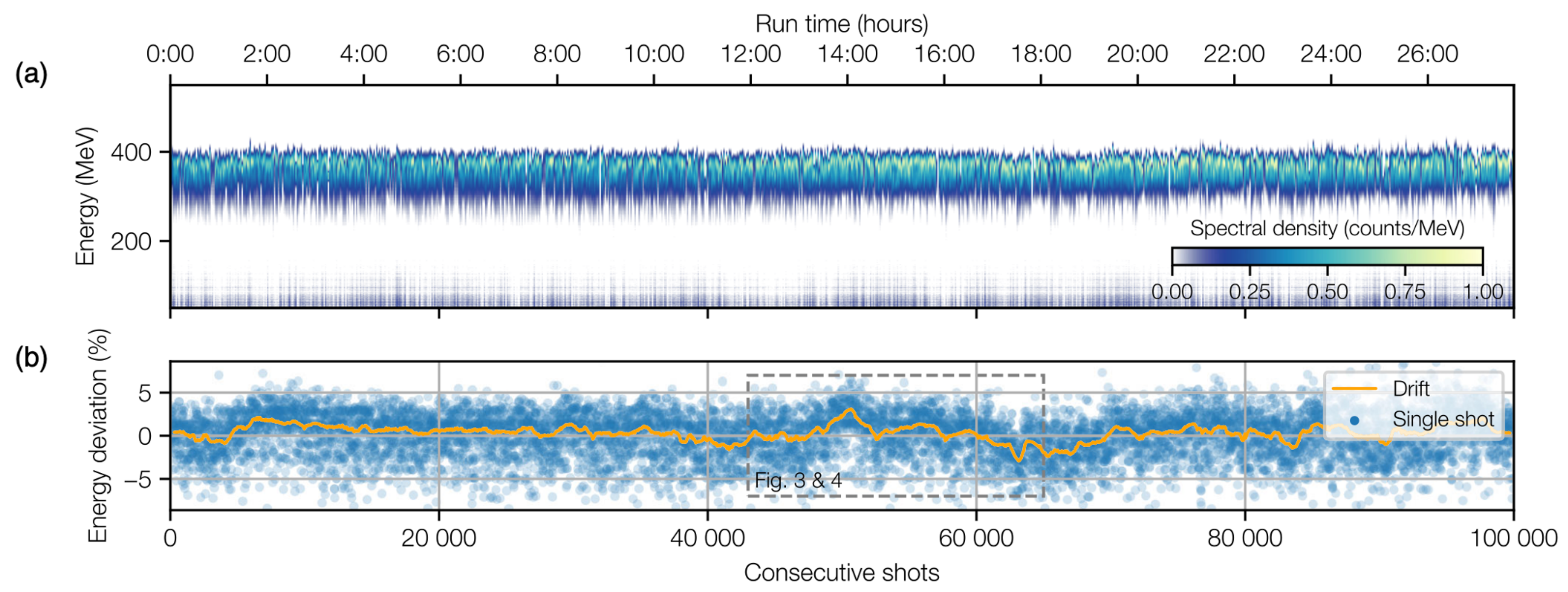
# Selected Highlights of Experimental Progress

24-hour operation@ 1Hz (100,000 consecutive shots)

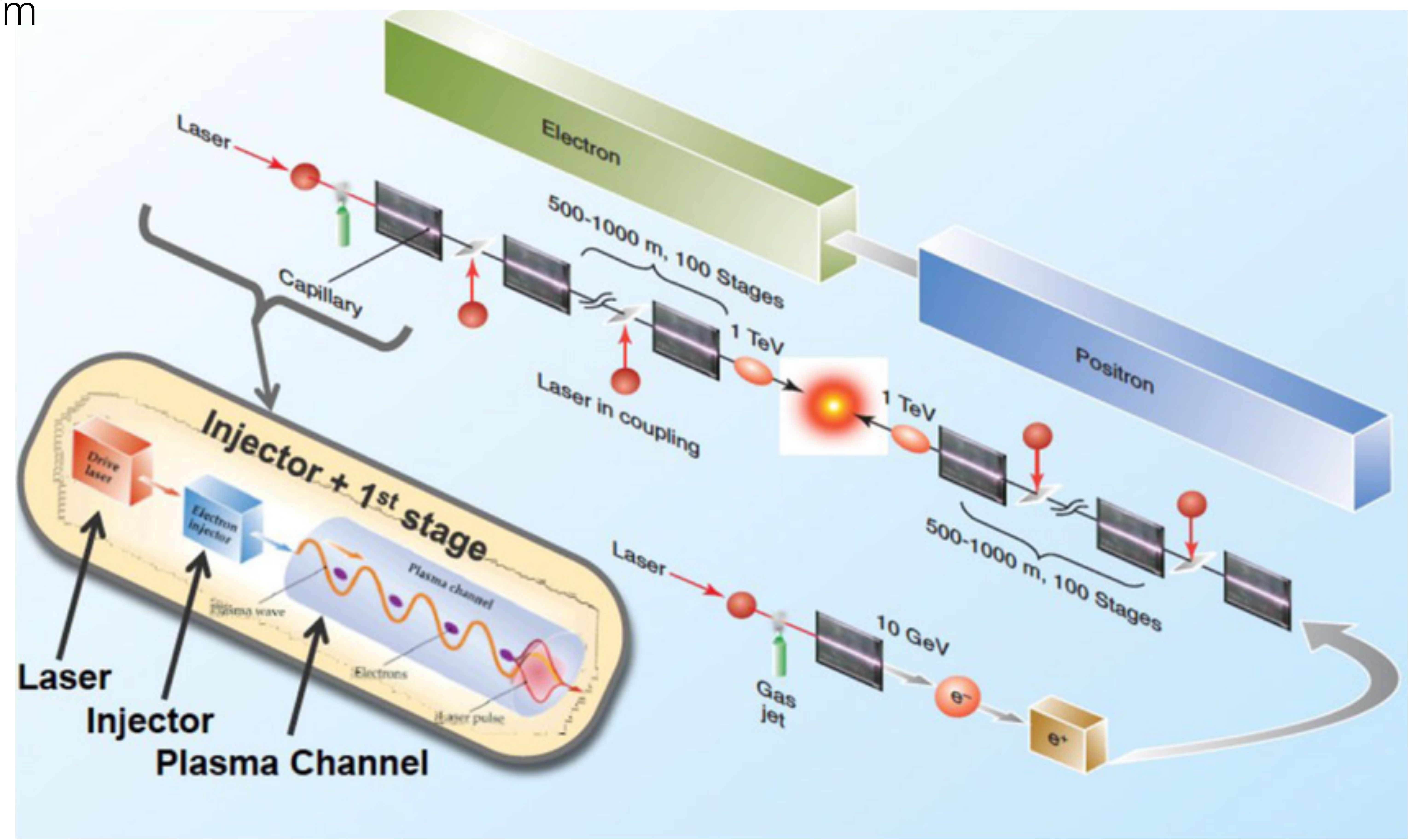



Maier *et al.,* PRX (2020)

Overview over current parameters:
MF *et al.,* Plasma Based Particle Sources, JINST 19 (2024)

# Toward A TeV Collider

- Using 10 GeV stages
- average gradient ~10 GV/m




Esarey, Leemans

# First Staging Experiments

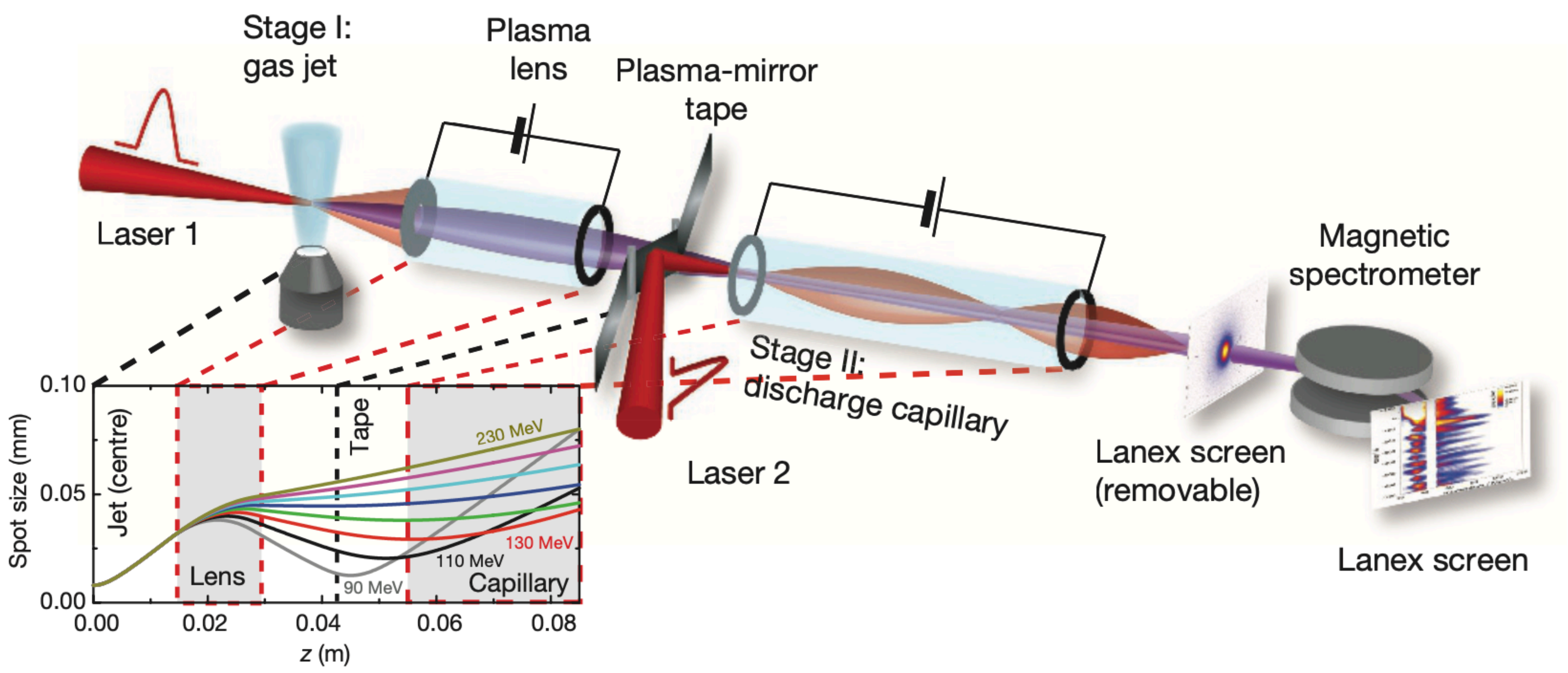
Karlsruher Institut für Technologie

Letter | Published: 01 February 2016

## Multistage coupling of independent laser-plasma accelerators

S. Steinke, J. van Tilborg, C. Benedetti, C. G. R. Geddes, C. B. Schroeder, J. Daniels, K. K. Swanson, A. J. Gonsalves, K. Nakamura, N. H. Matlis, B. H. Shaw, E. Esarey & W. P. Leemans

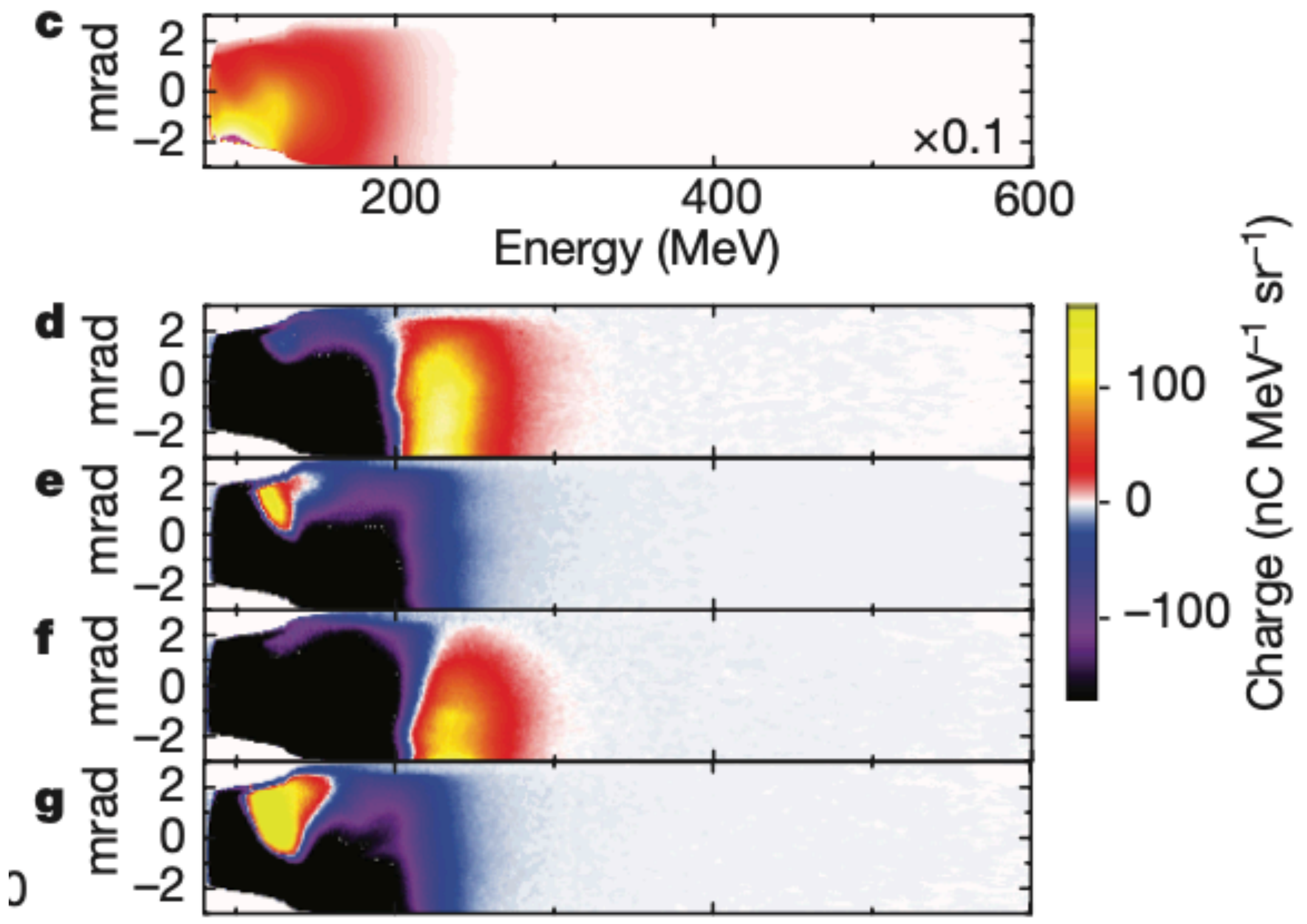
*Nature* **530**, 190–193 (2016) | Cite this article




**electron spectra**

single stage

2 stages different laser delays



# Using Electron Beams as Drivers

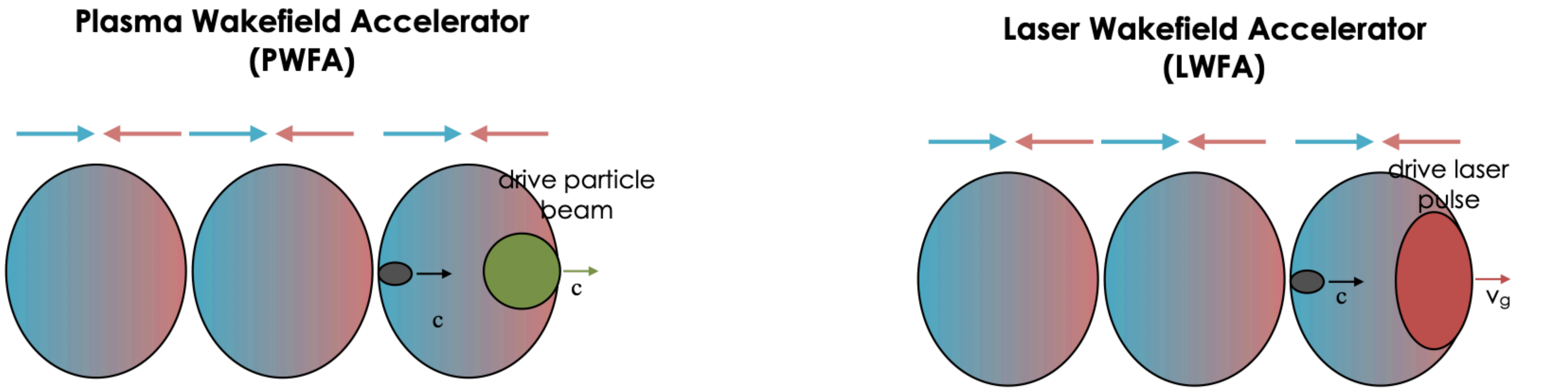
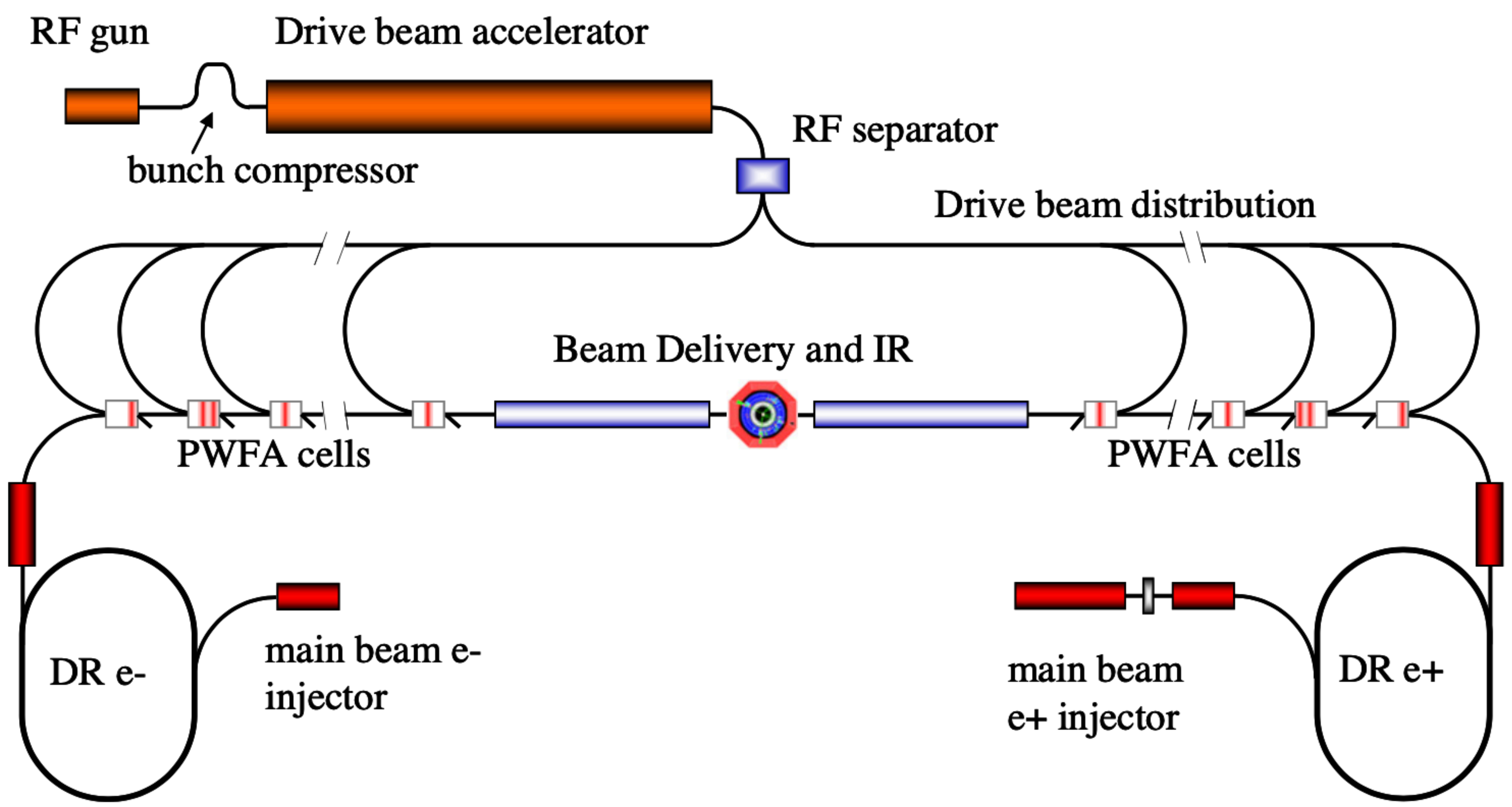


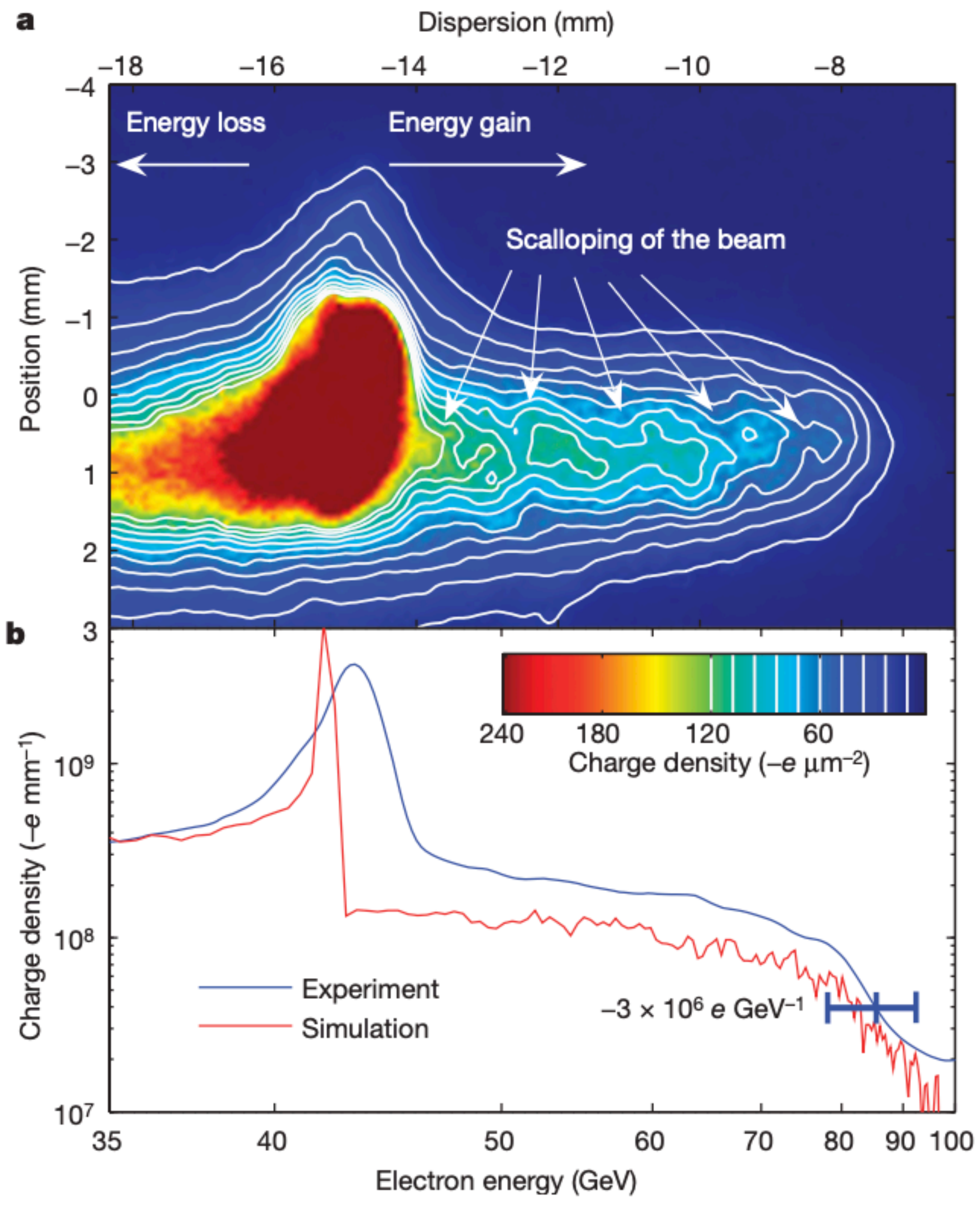

image: S. Corde

- longer dephasing length: more energy gain in single stage
- 10s of GeV per stage

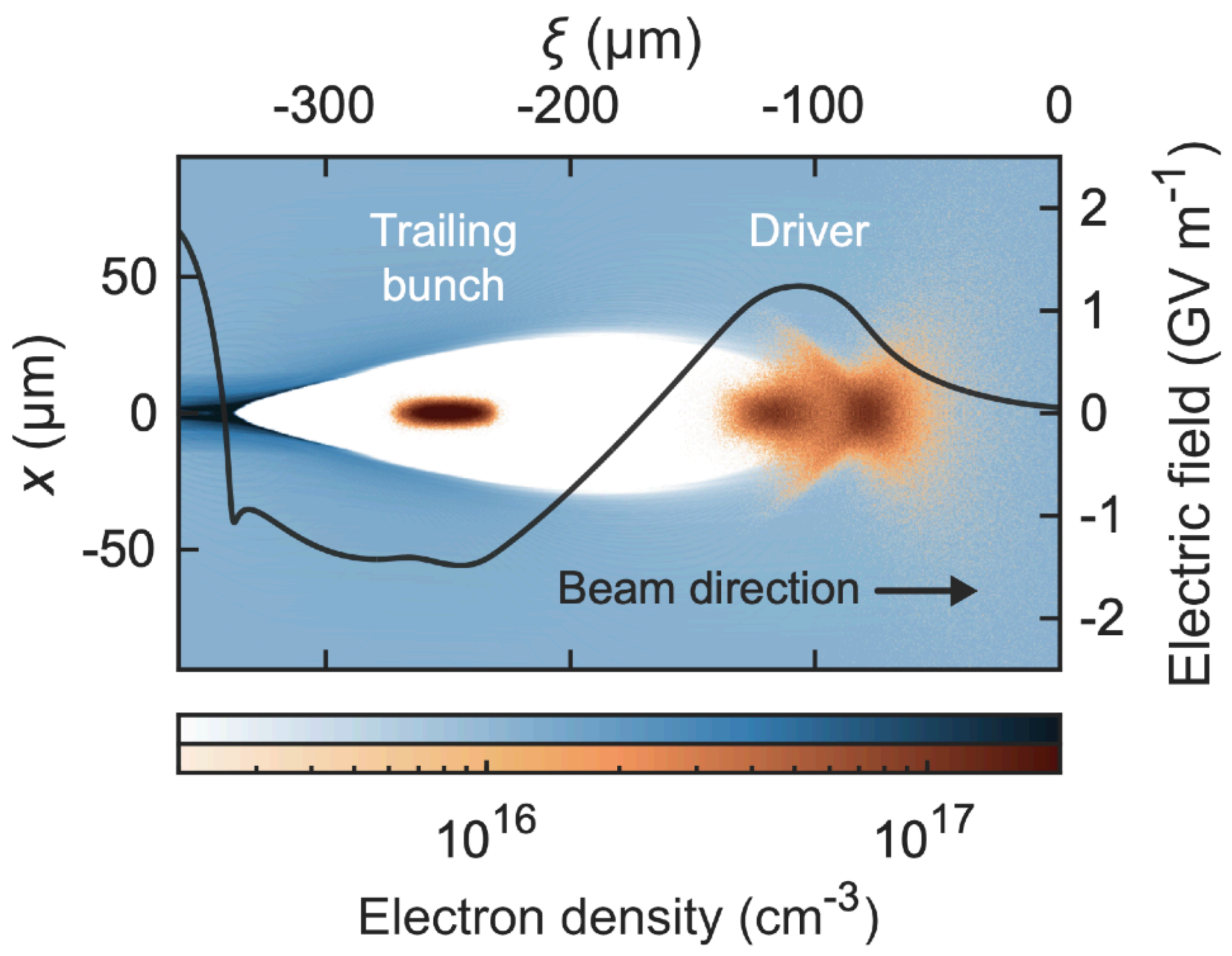


# Beam Driven Plasma Accelerator

40 GeV energy gain in 85 cm




Blumenfeld et al (2007)

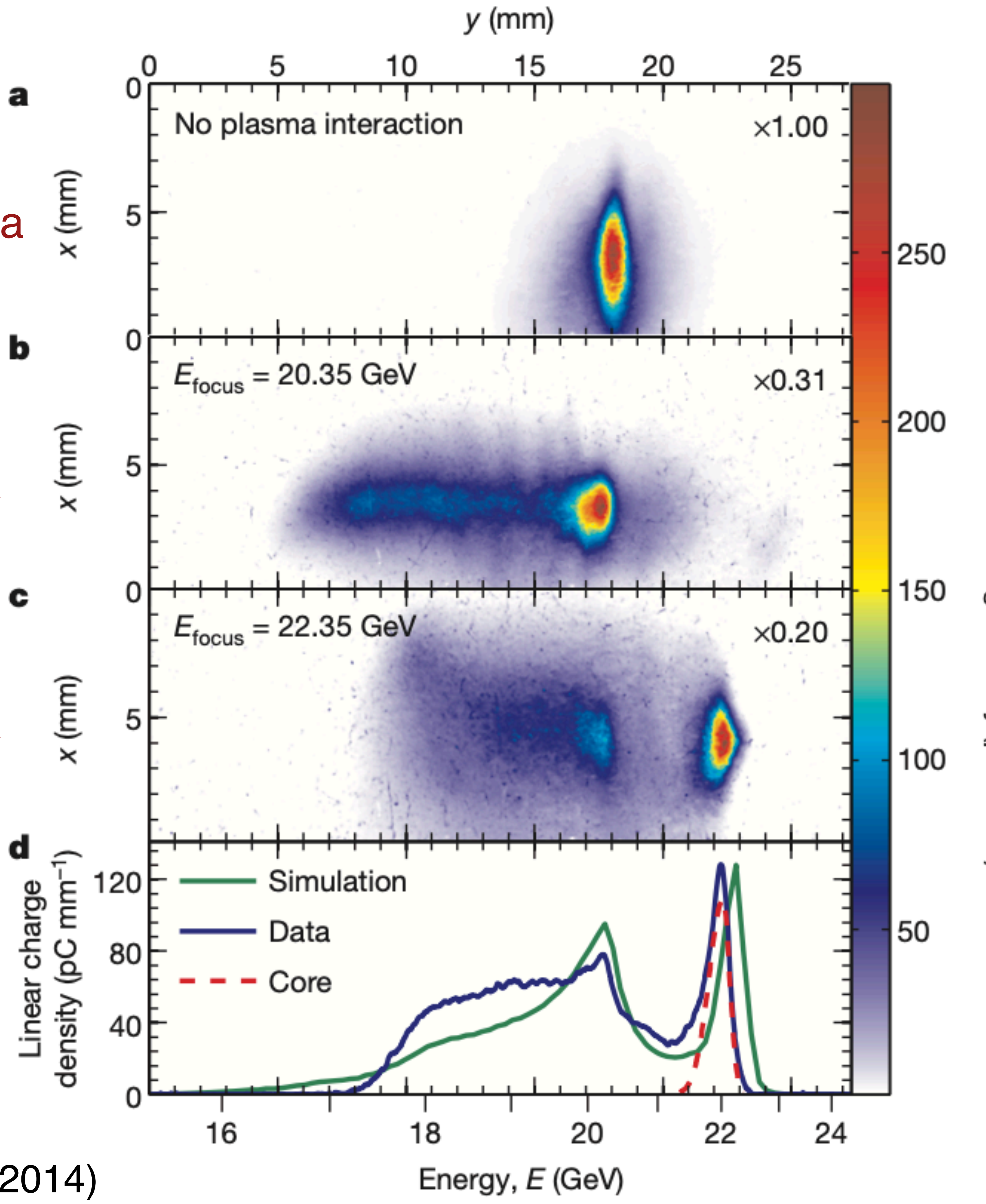



Using a trailing bunch:
Lower energy spread

no plasma

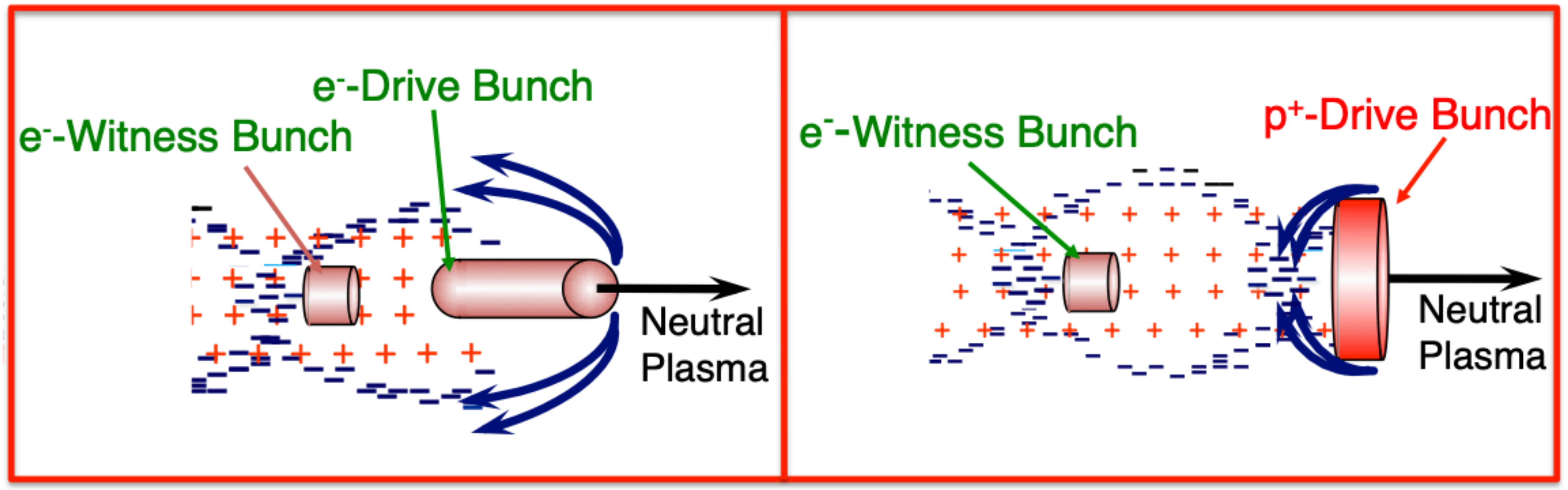
plasma:
spectrometer
at 20.35 GeV

plasma:
spectrometer
at 22.35 GeV

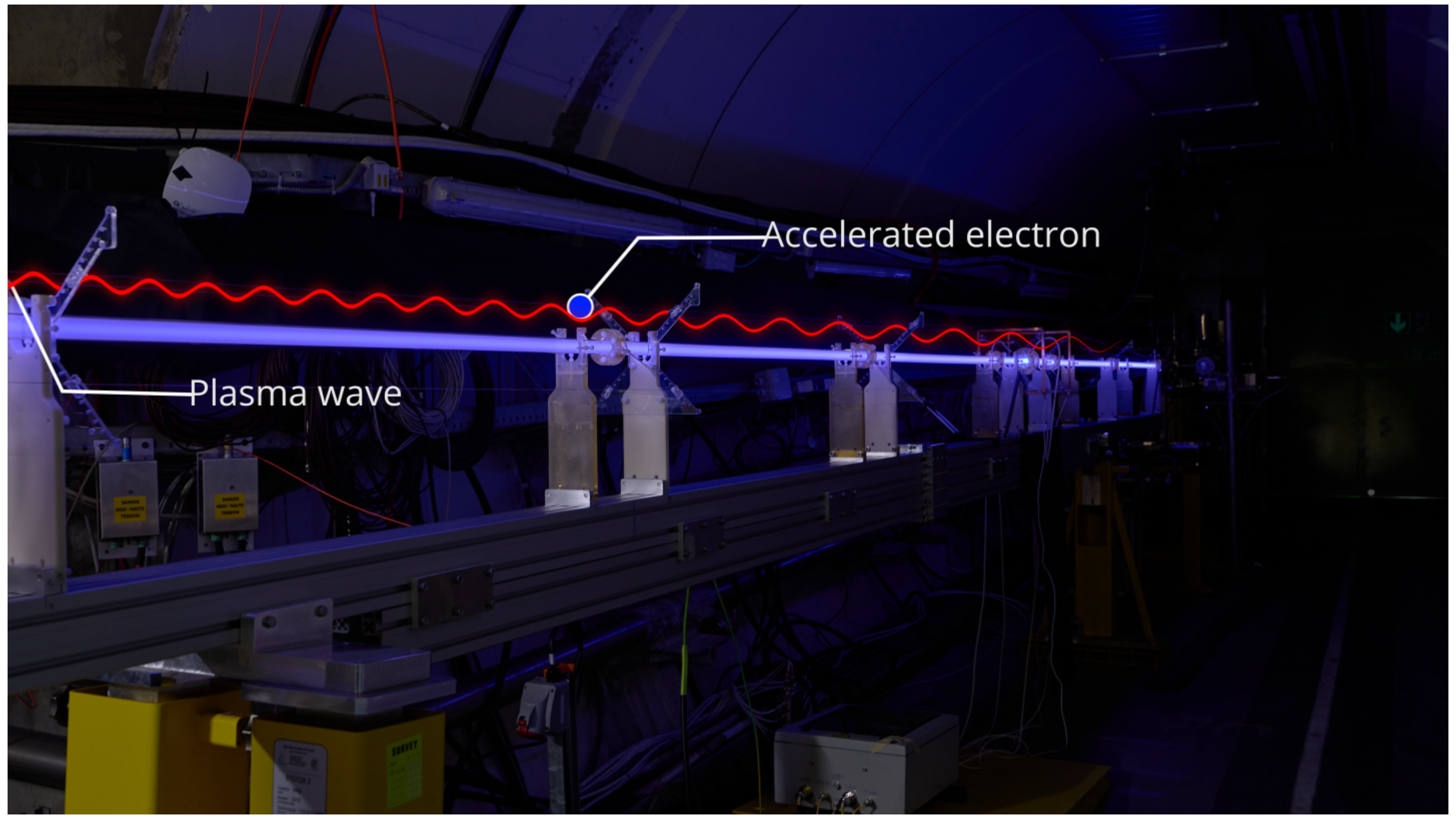


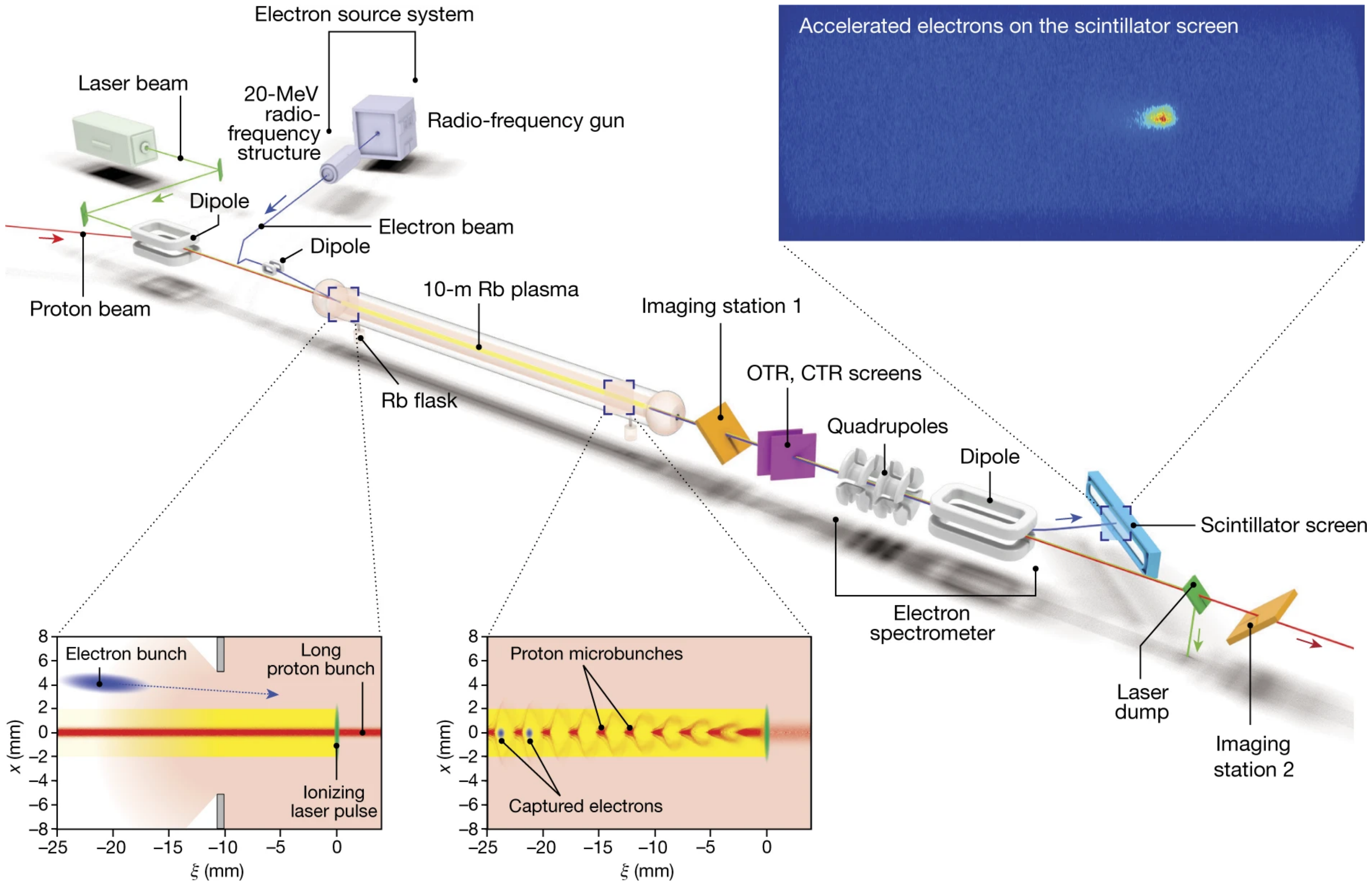

Litos et al., Nature (2014)

# Using (SPS) Proton Driver




AWAKE @ CERN





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# ALiVE: Future Proton-Driven Accelerator

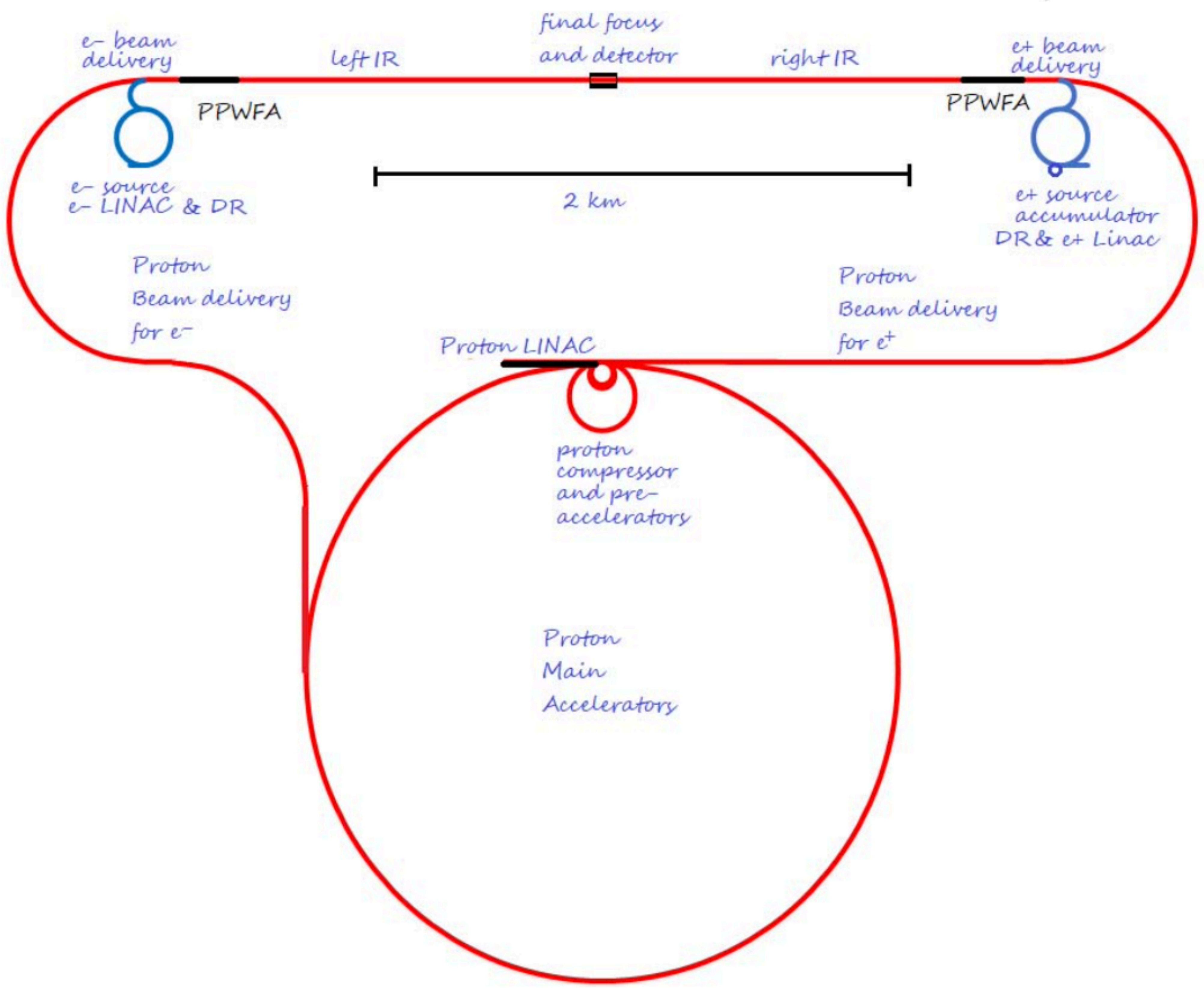
Karlsruher Institut für Technologie

## ALIVE@ CERN     Single stage: 125 GeV/1km

### Accelerated electrons

| Parameter | | Value | unit |
|---|---|---|---|
| Beam Energy | $E$ | 125 | GeV |
| Number of Particles per bunch | N | $2 \times 10^{10}$ | |
| $e^-$ bunch length | $\sigma_{e^-,z}$ | 105 | µm |
| $e^+$ bunch length | $\sigma_{e^+,z}$ | 75 | µm |
| Horizontal $\beta$-function at IP | $\beta_x^*$ | 13 | mm |
| Vertical $\beta$-function at IP | $\beta_y^*$ | 0.41 | mm |
| Norm. horizontal $e^-$ emittance | $\varepsilon_{e^-,x}$ | 100 | nm |
| Norm. vertical $e^-$ emittance | $\varepsilon_{e^-,y}$ | 100 | nm |
| Norm. horizontal $e^+$ emittance | $\varepsilon_{e^+,x}$ | 400 | nm |
| Norm. vertical $e^+$ emittance | $\varepsilon_{e^+,y}$ | 400 | nm |
| Bunch frequency | $f$ | 7.2 | kHz |
| Centre-of-mass energy | $E_{cm}$ | 250 | GeV |
| Geometric luminosity | $\mathcal{L}_{\mathrm{geom}}$ | 1 | $10^{34}$ cm$^{-2}$s$^{-1}$ |
| Simulated luminosity | $\mathcal{L}$ | 9.3 | $10^{34}$ cm$^{-2}$s$^{-1}$ |
| Luminosity in the top 1% | $\mathcal{L}_{1\%}$ | 0.34 | $10^{34}$ cm$^{-2}$s$^{-1}$ |

- 500 GeV proton bunch
- (Ultrashort) proton bunch (3 ps)



# Outline

- Particle Accelerators and Laser-Plasma Acceleration (LPA)
- Applications of Laser-Plasma Accelerators
  - Laser-driven X-ray Sources
- Challenges and New Research Directions
  - Next-generation hybrid accelerators
  - Next-generation laser-plasma accelerators
- Summary

# Undulator Radiation

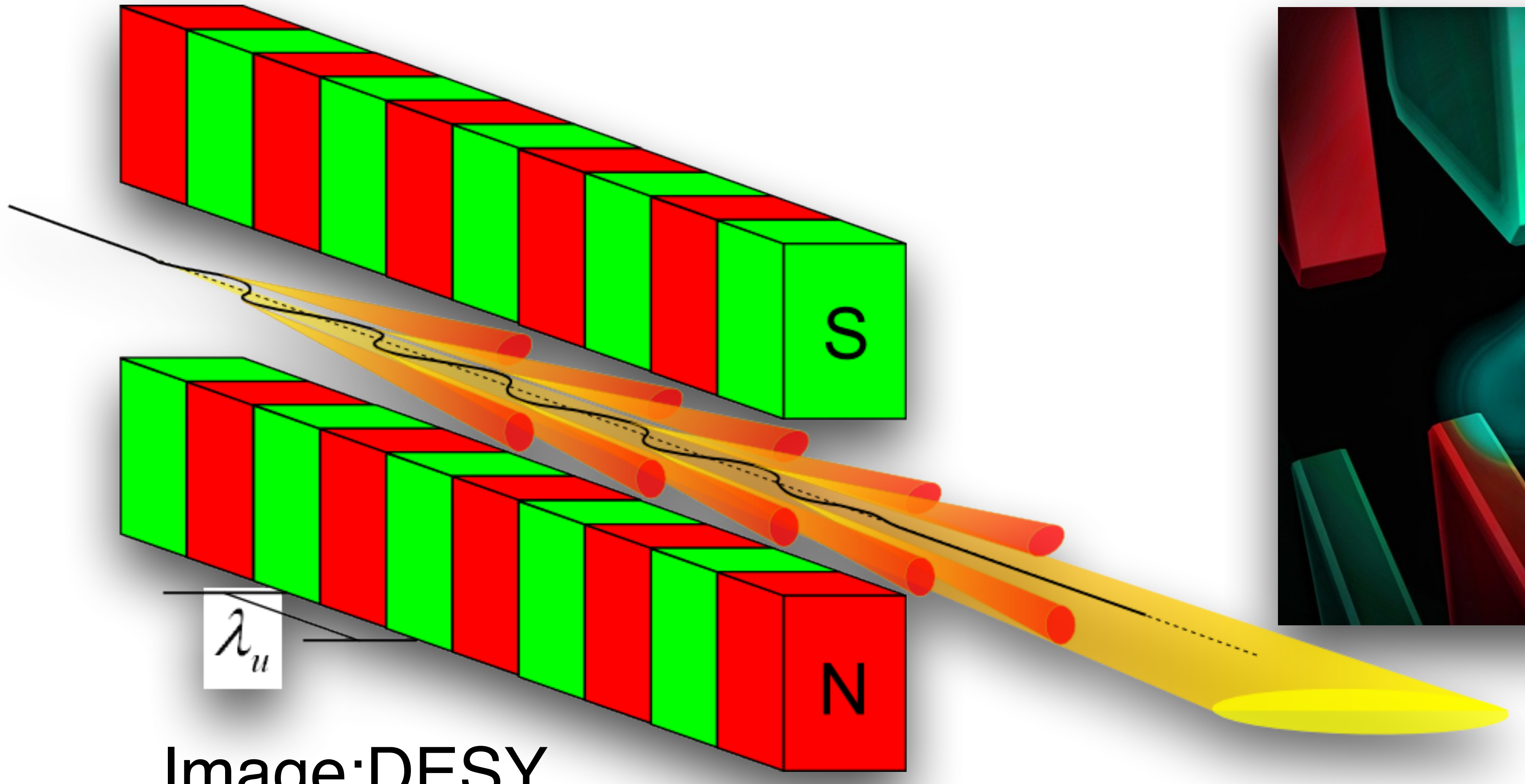
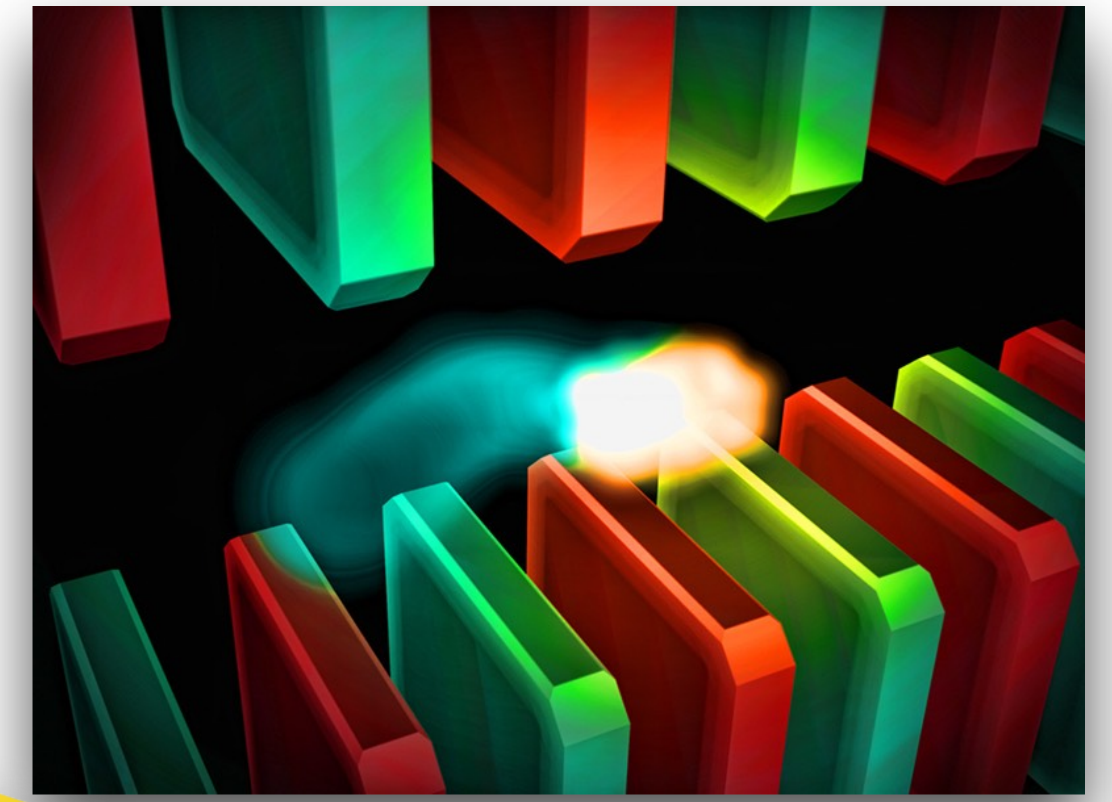



Image:DESY



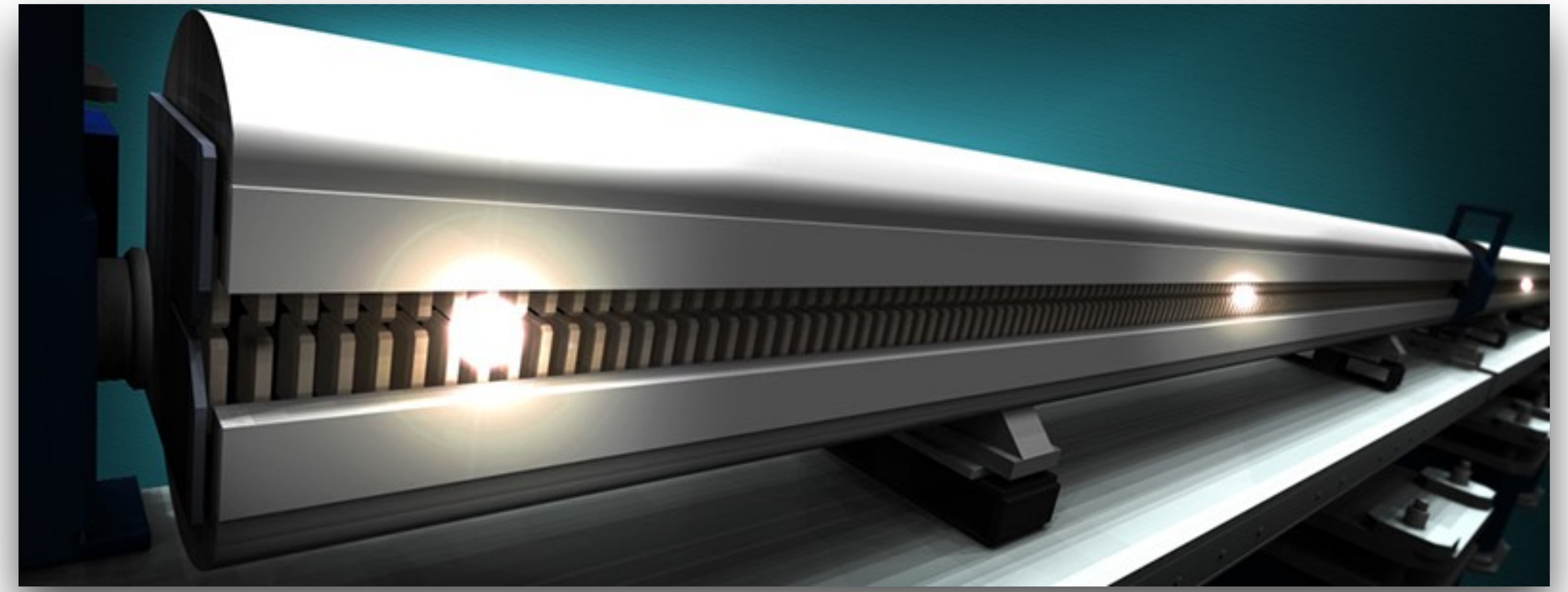


Image:Greg Stewart/SLAC

- Undulator: alternating magnetic field
- forces electron onto sinusoidal trajectory (transverse oscillation)
- emission of dipole radiation in electron rest frame at Lorentz-contracted undulator period
- in lab frame, emitted wavelength Lorentz-contracted again

undulator period

Emitted wavelength: $\boxed{\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\gamma^2\Theta^2\right)}$

emission angle

electron energy

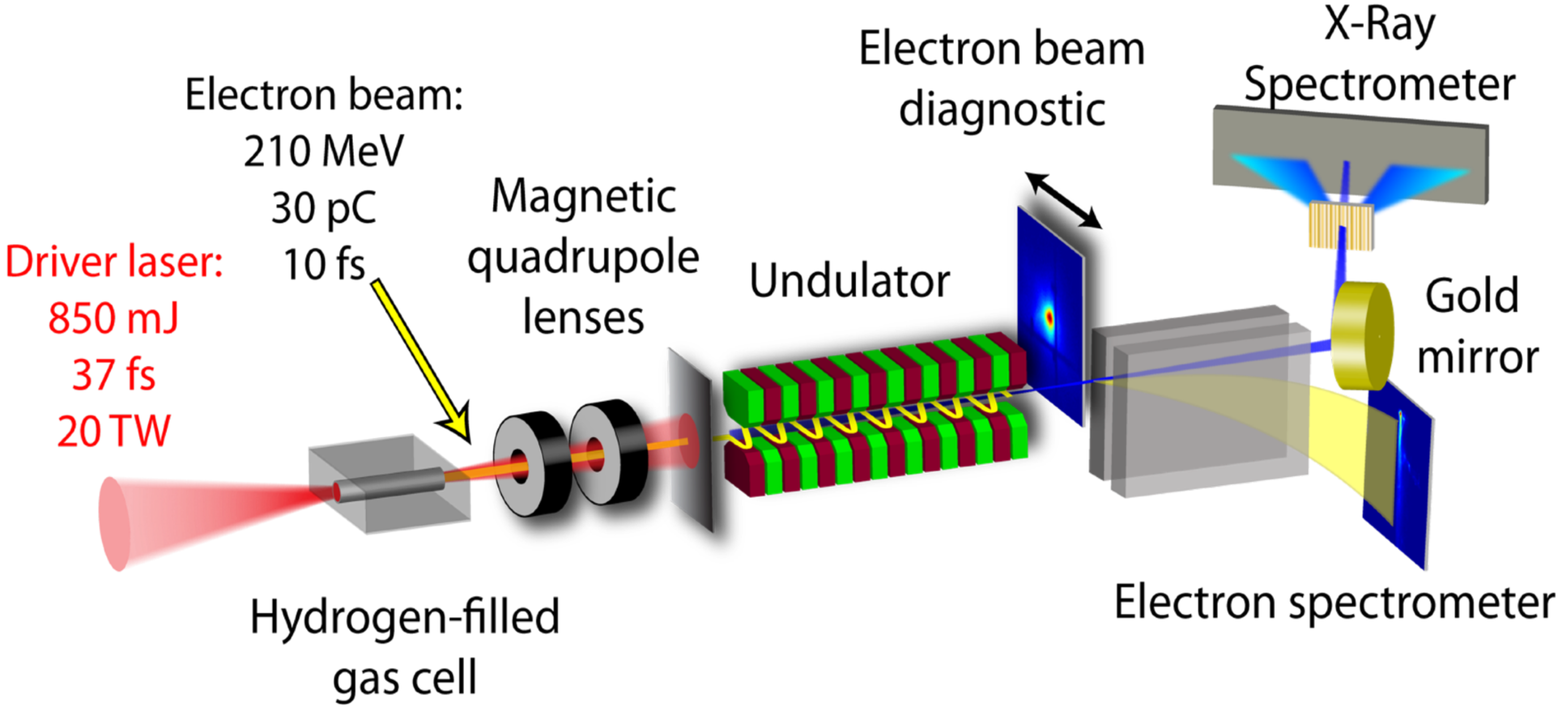
$\lambda_u$ : ~mm, cm

$\gamma$ : ~ 1000-10,000

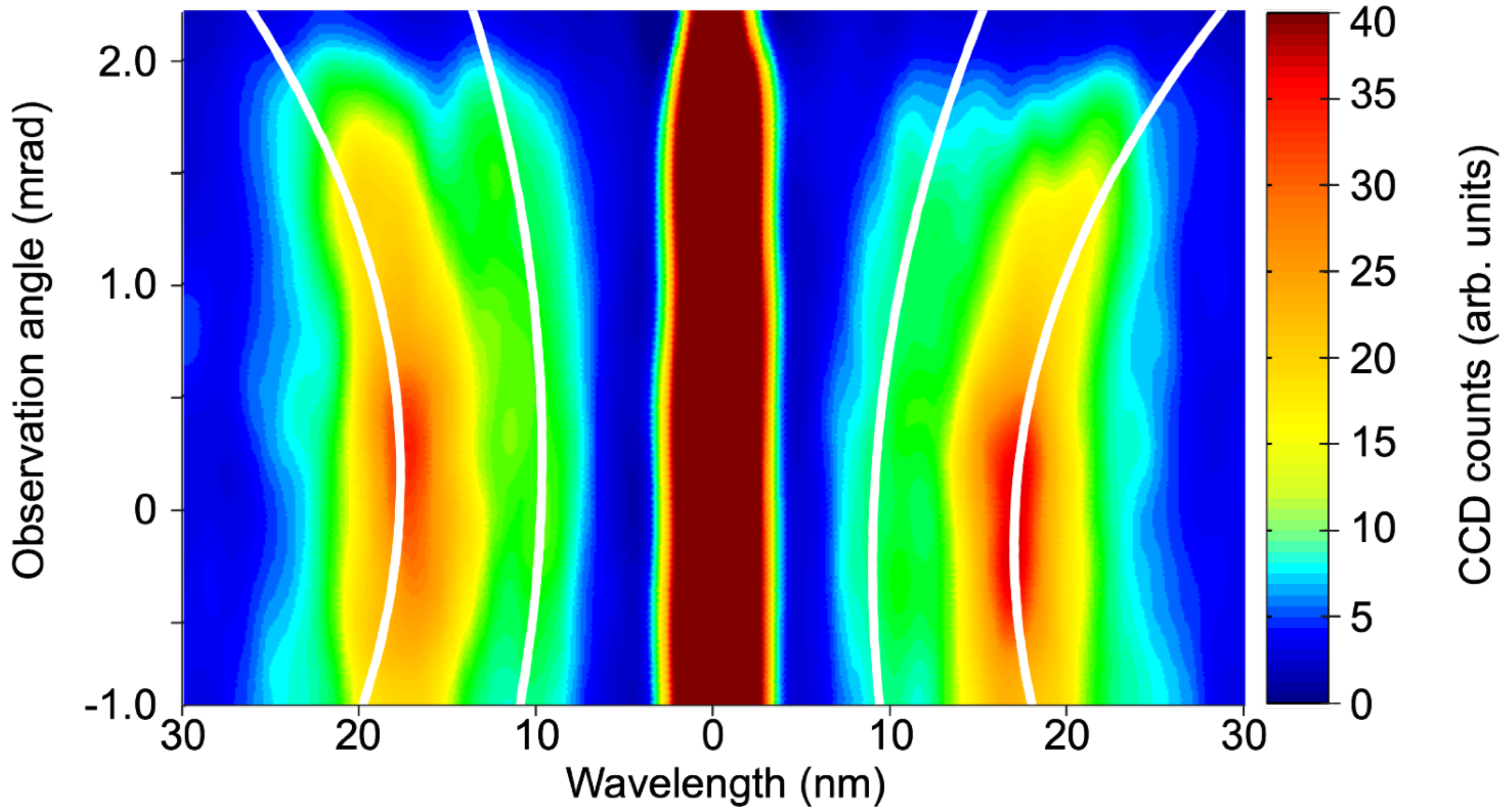
$\lambda$ : ~Angstrom ($10^{-10}$ m): X-rays!

# Undulator Source Driven by Laser-Plasma Electron Accelerator

## Setup




## Soft X-ray Spectrum





LETTERS
PUBLISHED ONLINE: 27 SEPTEMBER 2009 | DOI: 10.1038/NPHYS1404
nature physics


**Laser-driven soft-X-ray undulator source**

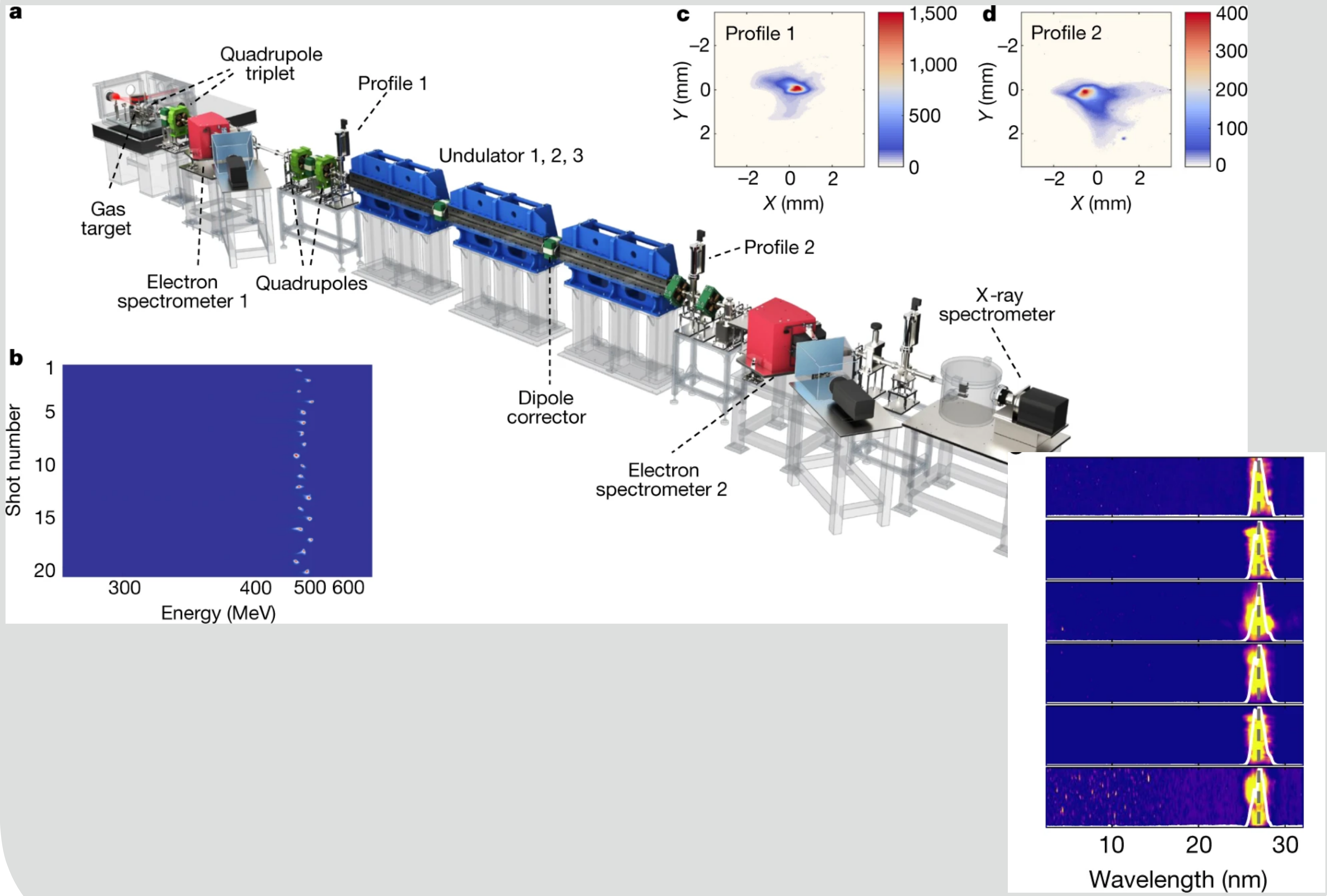

Matthias Fuchs[1,2], Raphael Weingartner[1,2], Antonia Popp[1], Zsuzsanna Major[1,2], Stefan Becker[2], Jens Osterhoff[1,2], Isabella Cortrie[2], Benno Zeitler[2], Rainer Hörlein[1,2], George D. Tsakiris[1], Ulrich Schramm[3], Tom P. Rowlands-Rees[4], Simon M. Hooker[4], Dietrich Habs[1,2], Ferenc Krausz[1,2], Stefan Karsch[1,2]* and Florian Grüner[1,2]*

# Laser-driven Free-Electron Laser (FEL)

- Coherent emission of undulator radiation $P \sim n_e^2$ (incoh: $P \sim n_e$)
- Proposal to use LWFAs to drive FELs [Grüner *et al.*, Appl. Phys. B (2006)]
- First experimental demonstrations: LWFAs have sufficiently high quality to drive (optical-VUV) FELs

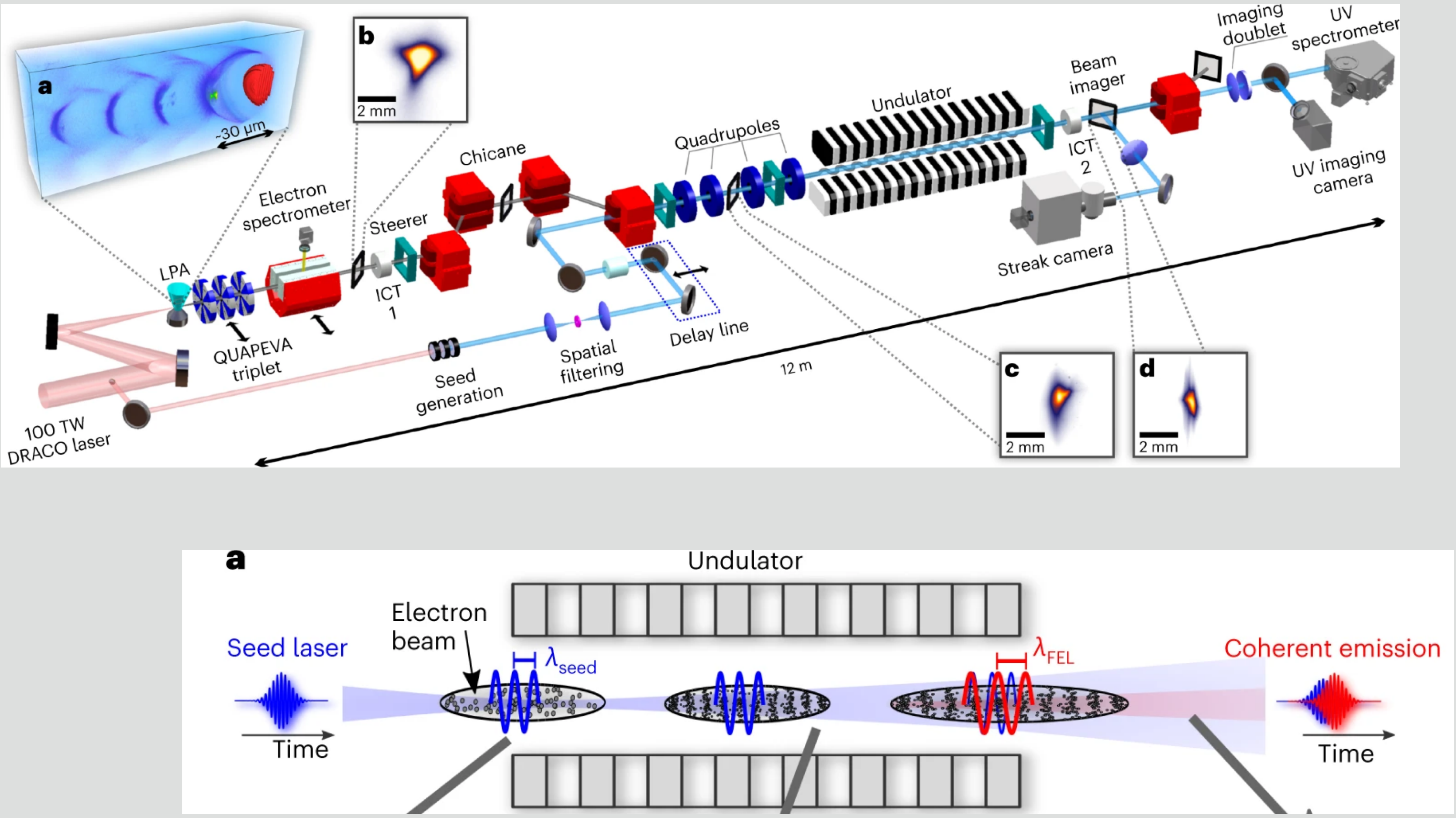
## First observation of FEL gain @27 nm

Wang *et al.*, Nature (2021)




## seeded FEL emission @280 nm

Labat *et al.*, Nat. Photon.(2023)

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# Plasma Wiggler Source (Betatron Source)

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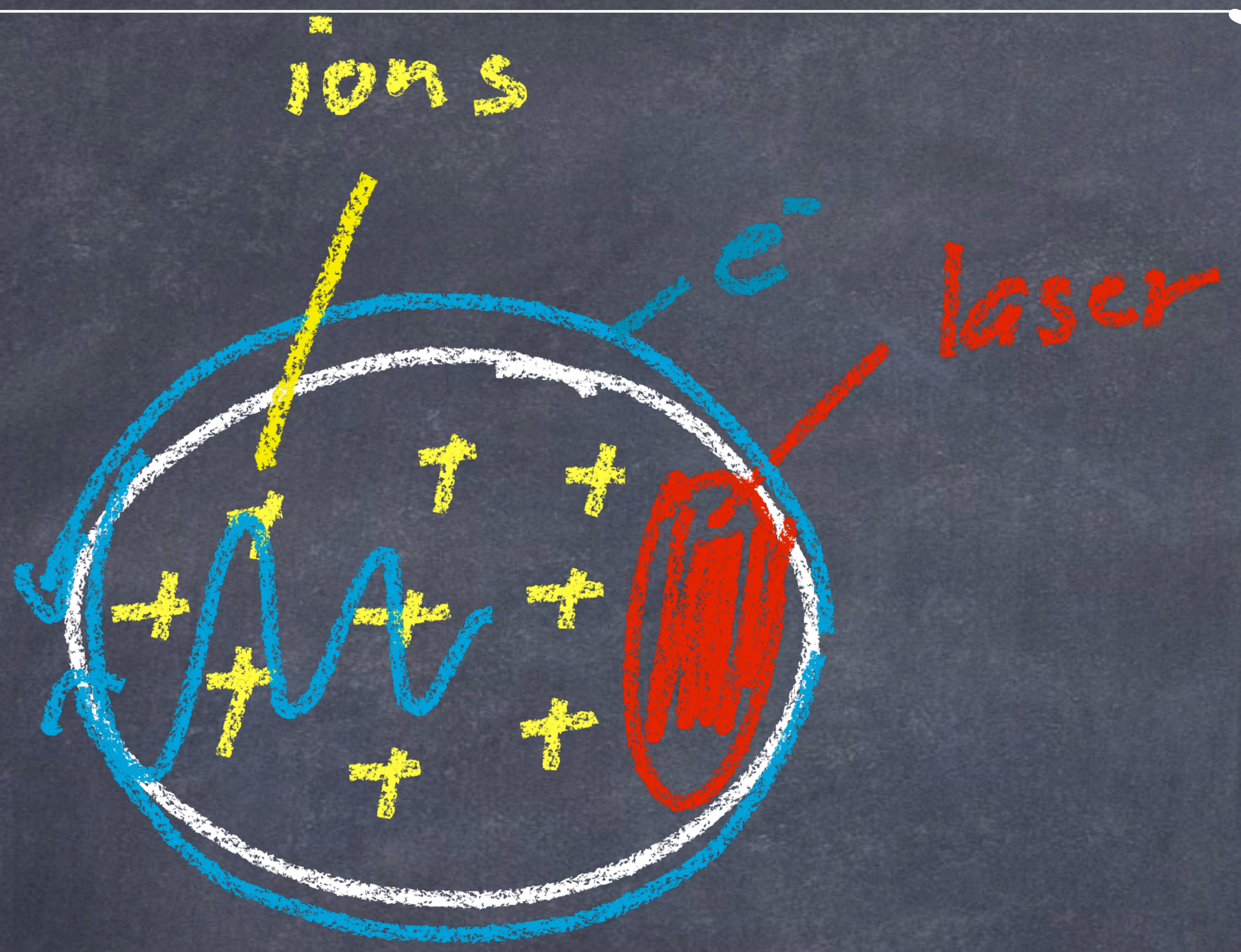
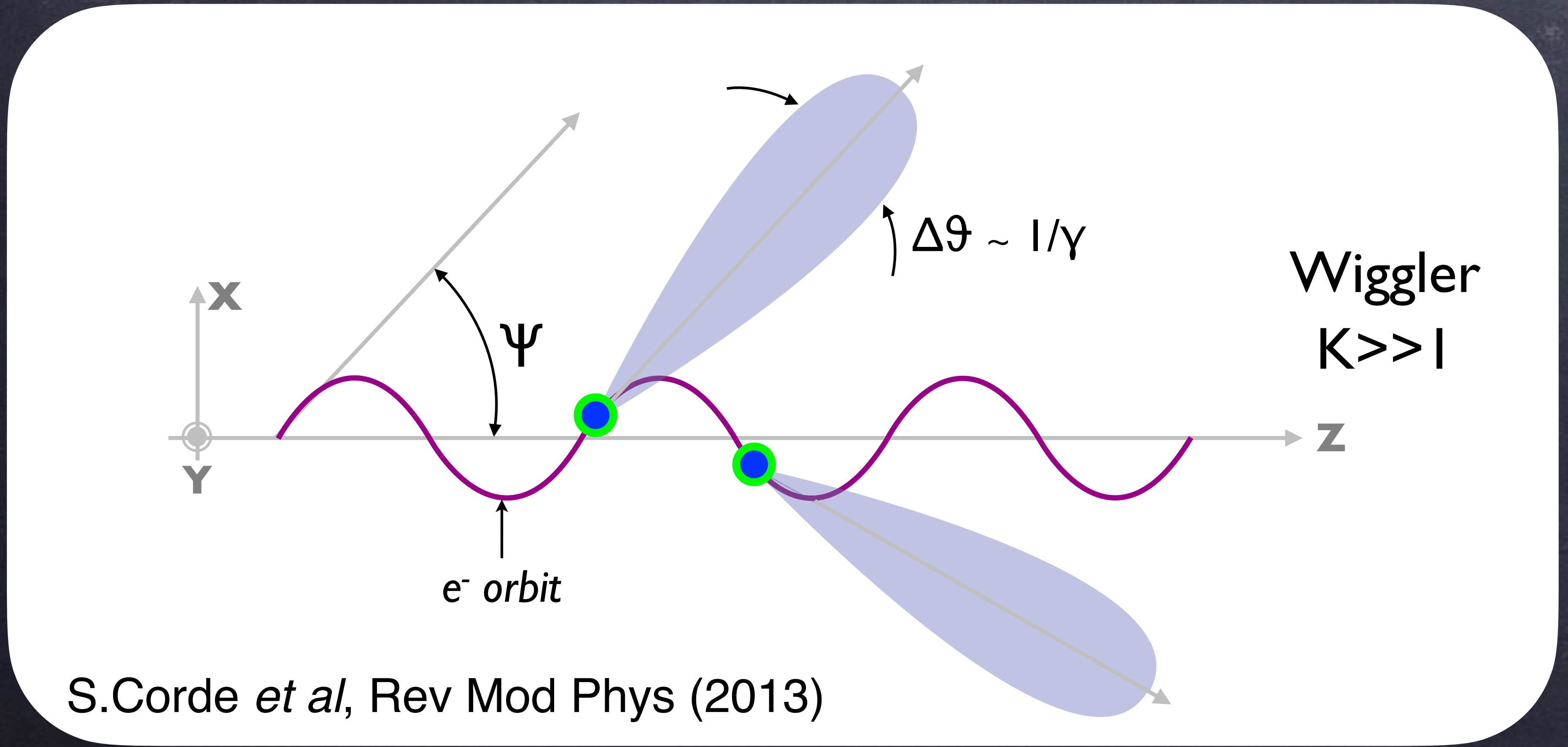
self-injection in the “bubble” regime:




injection of electrons with transverse momentum: X-ray emission!




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

Particles in parabolic potential

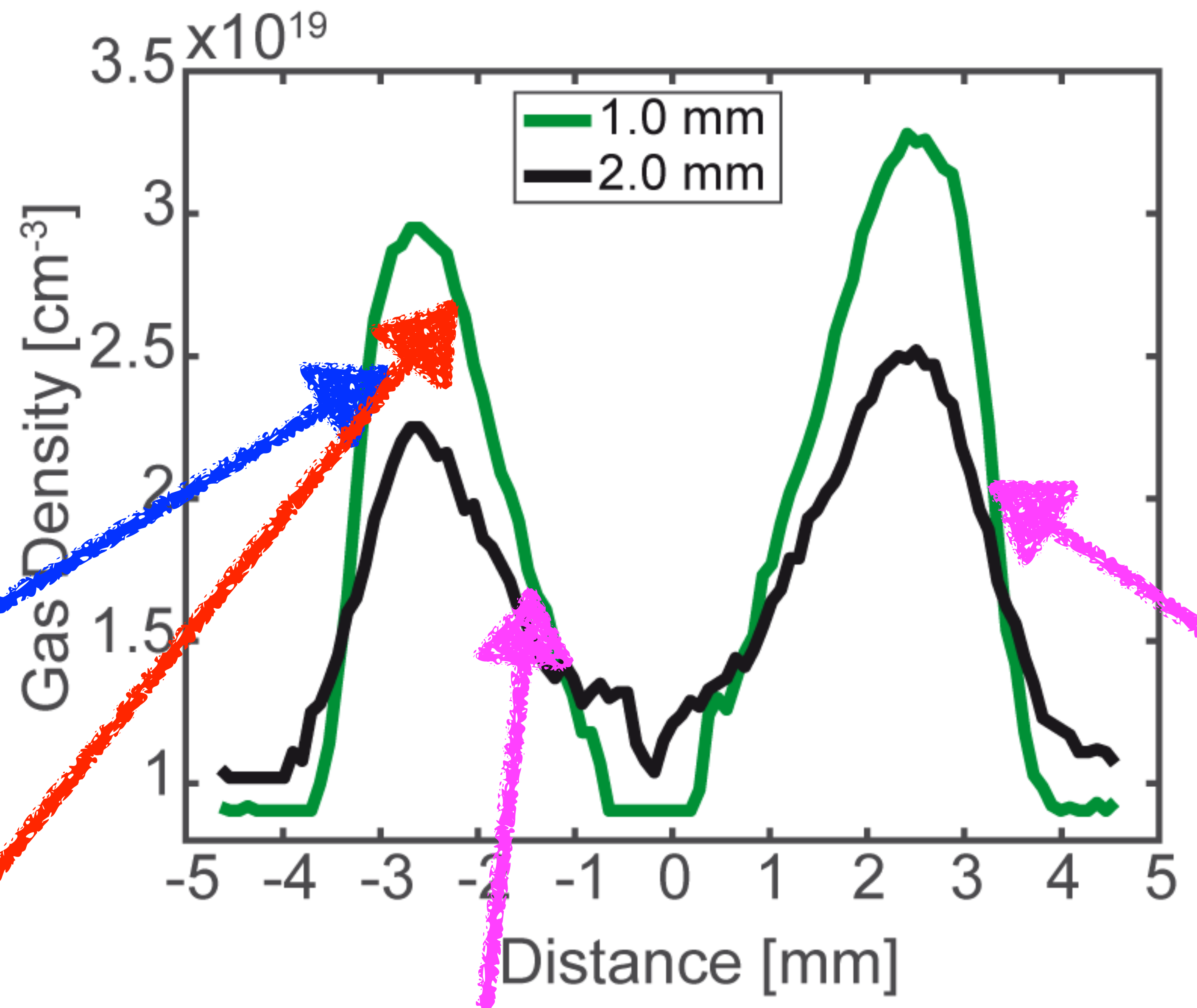
deliberately INCREASE oscillation amplitude (emittance) as X-ray source

- Photon number: $N_\gamma \sim r_\beta$
- Photon energy: $\hbar\omega \sim r_\beta$

matthias.fuchs@kit.edu Matthias Fuchs

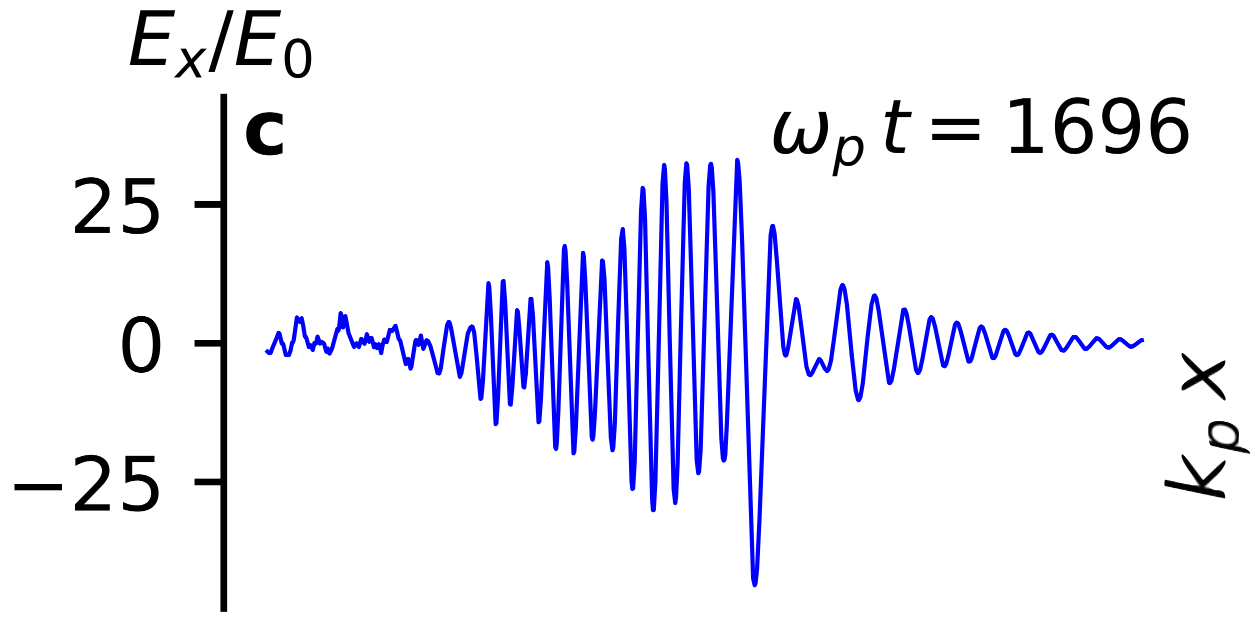
# Control and Enhancement of the Betatron Oscillation Amplitude

- Use a tailored plasma density to control injection and increase betatron oscillation amplitude
- Orchestrated laser & bubble evolution
- Laser evolution during first peak
- Electron injection during downramp
- Coherent betatron oscillations
- Transverse Oscillating Bubble Enhanced Betatron Radiation (TOBER)

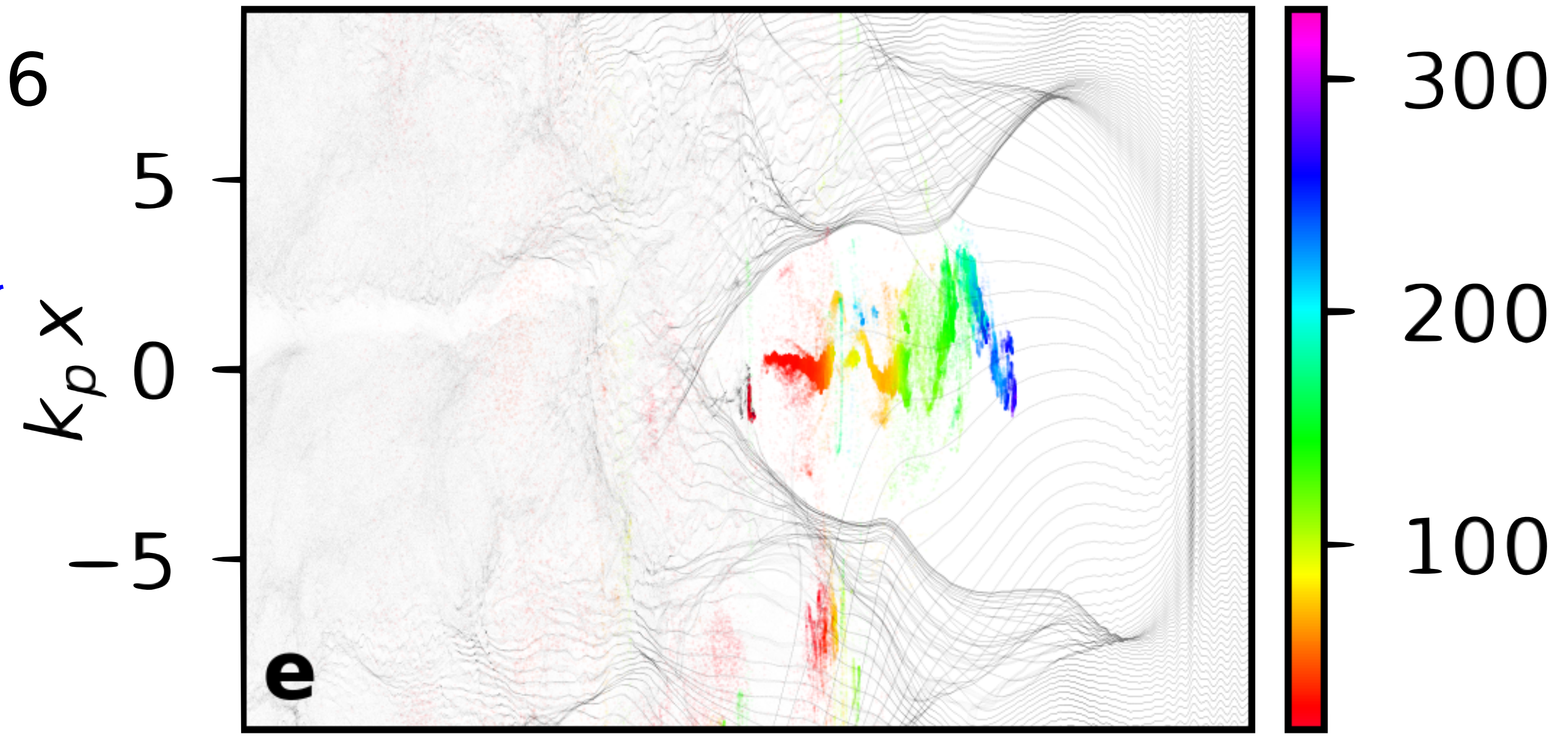



“M” shaped plasma density

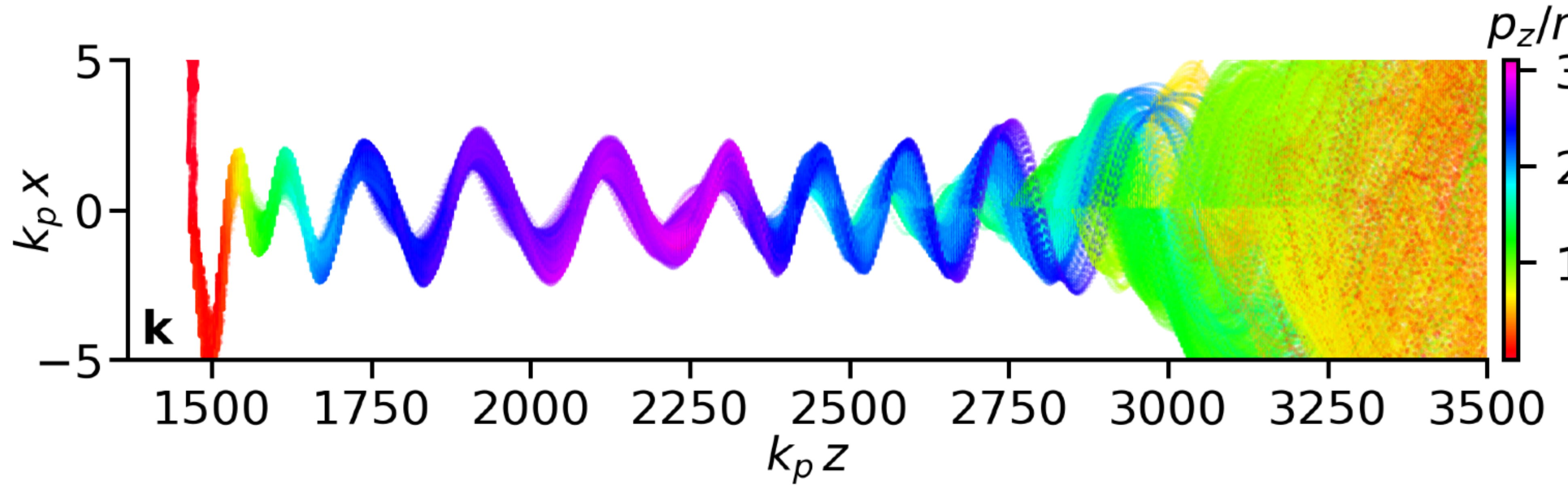
**laser evolution**



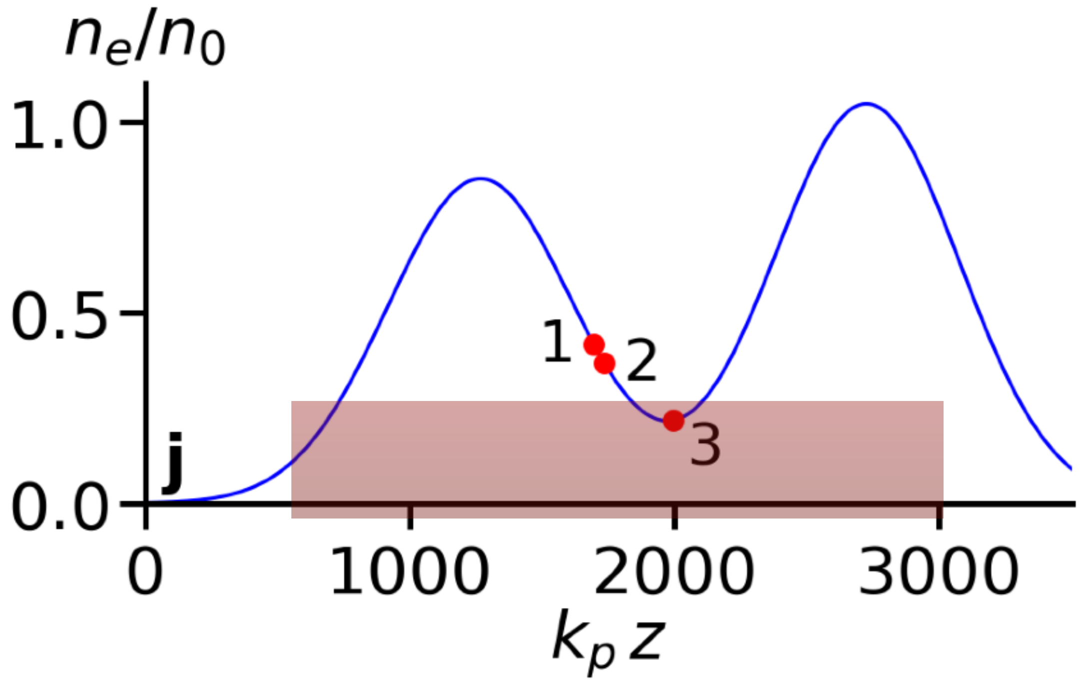

**off-axis injection during downramp**




**coherent betatron oscillation**
nearly constant electron energy

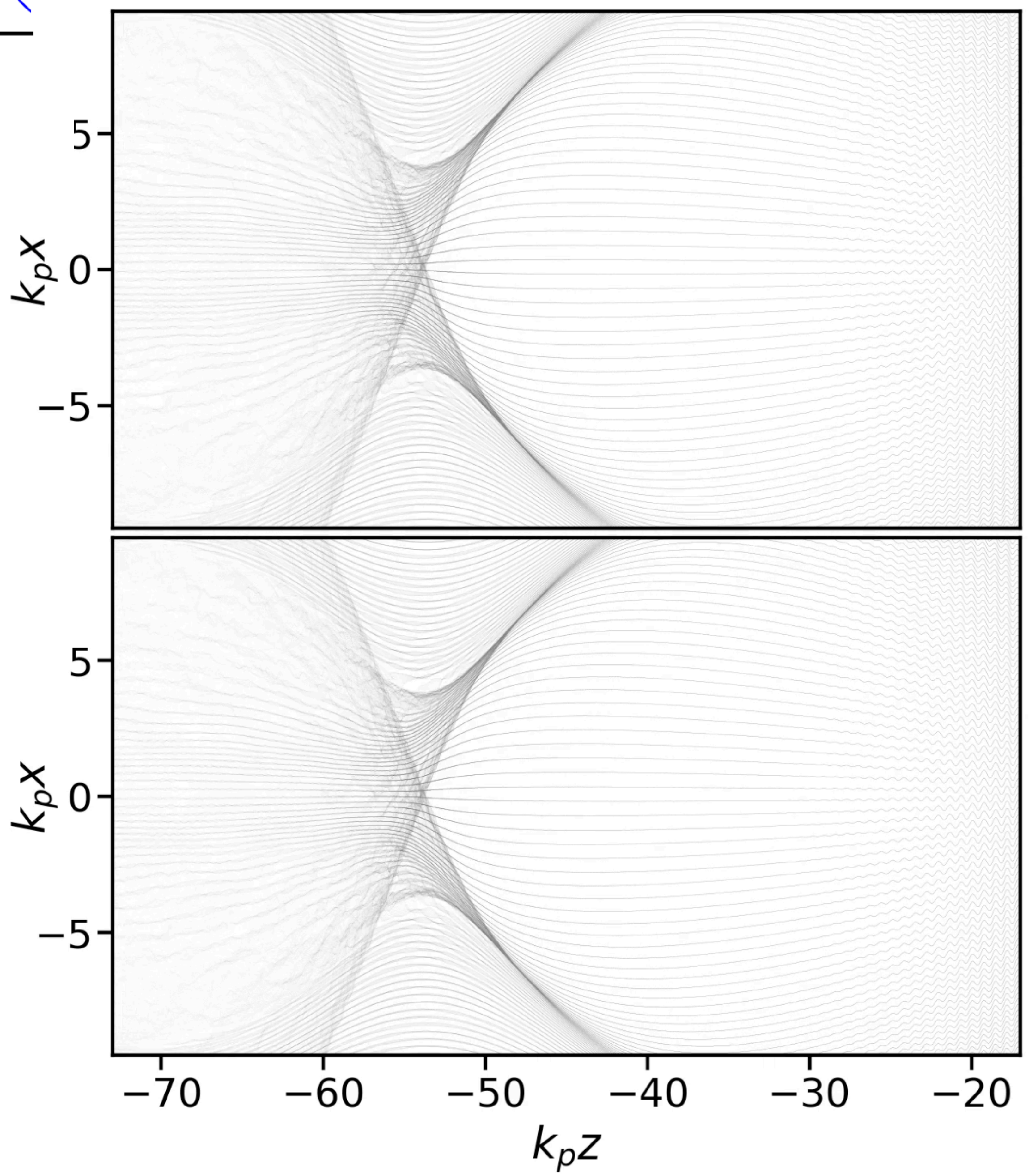


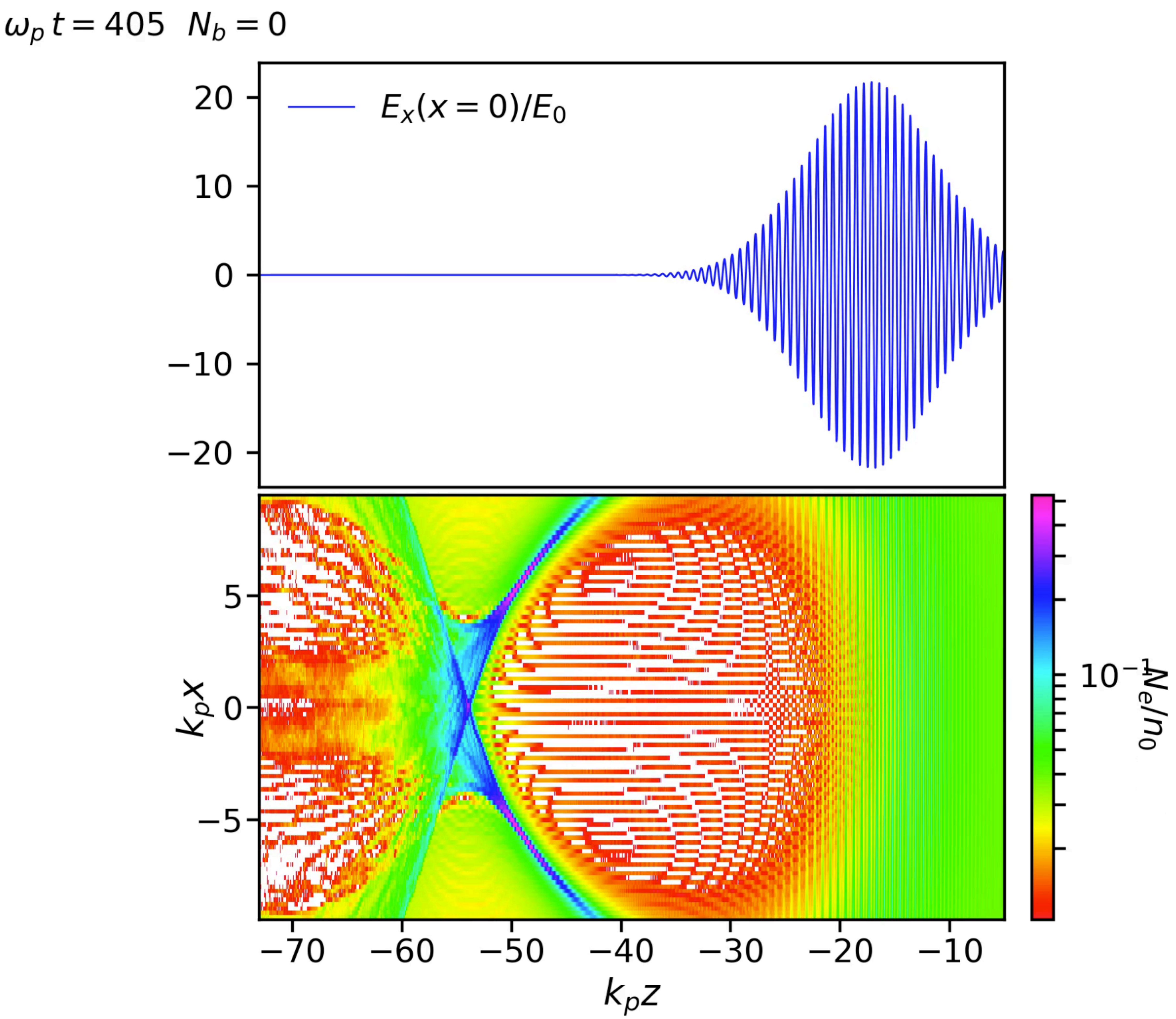
# Increase of Betatron Amplitude Through Transverse Oscillating Bubble: Simulation




longitudinal momentum

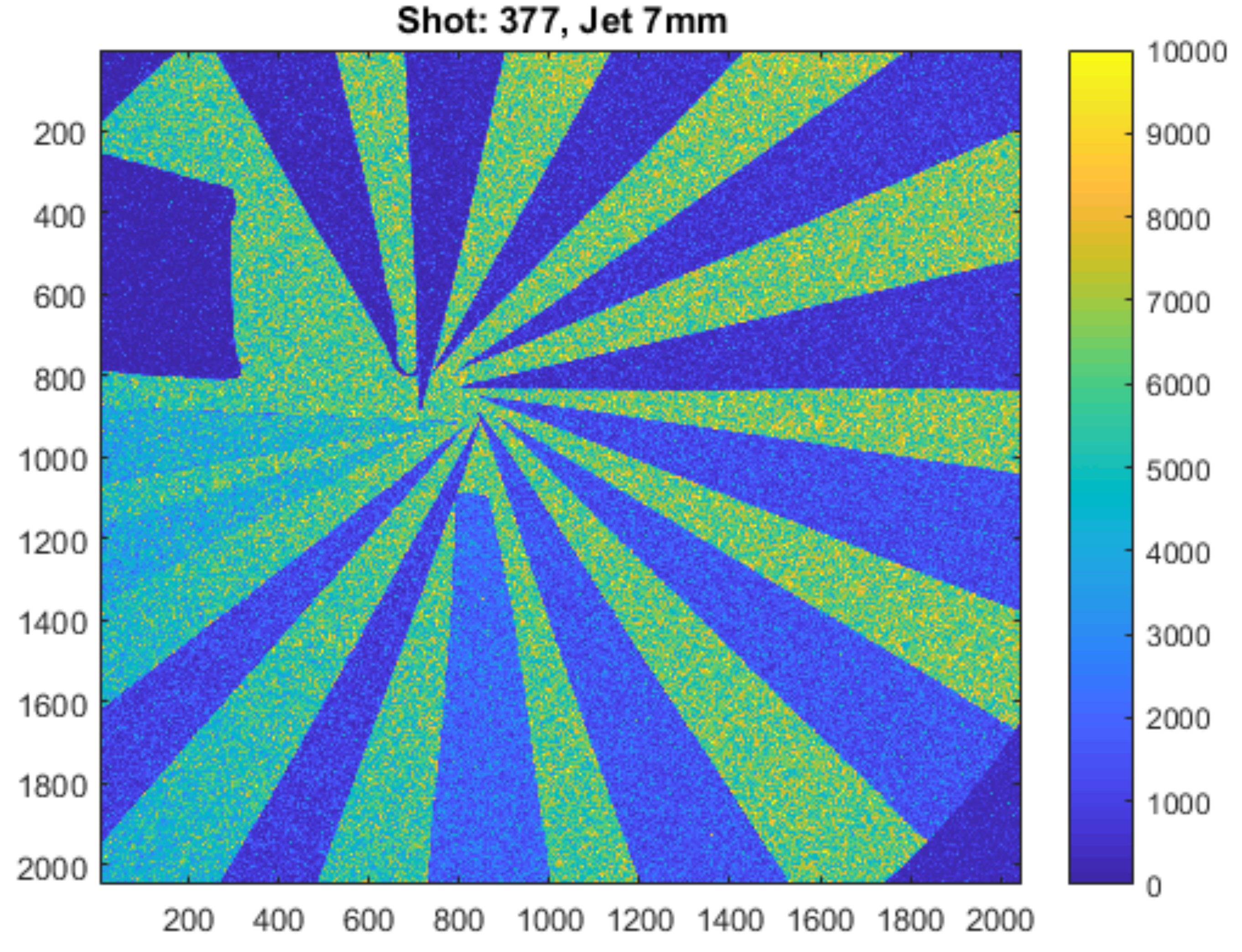
transverse momentum

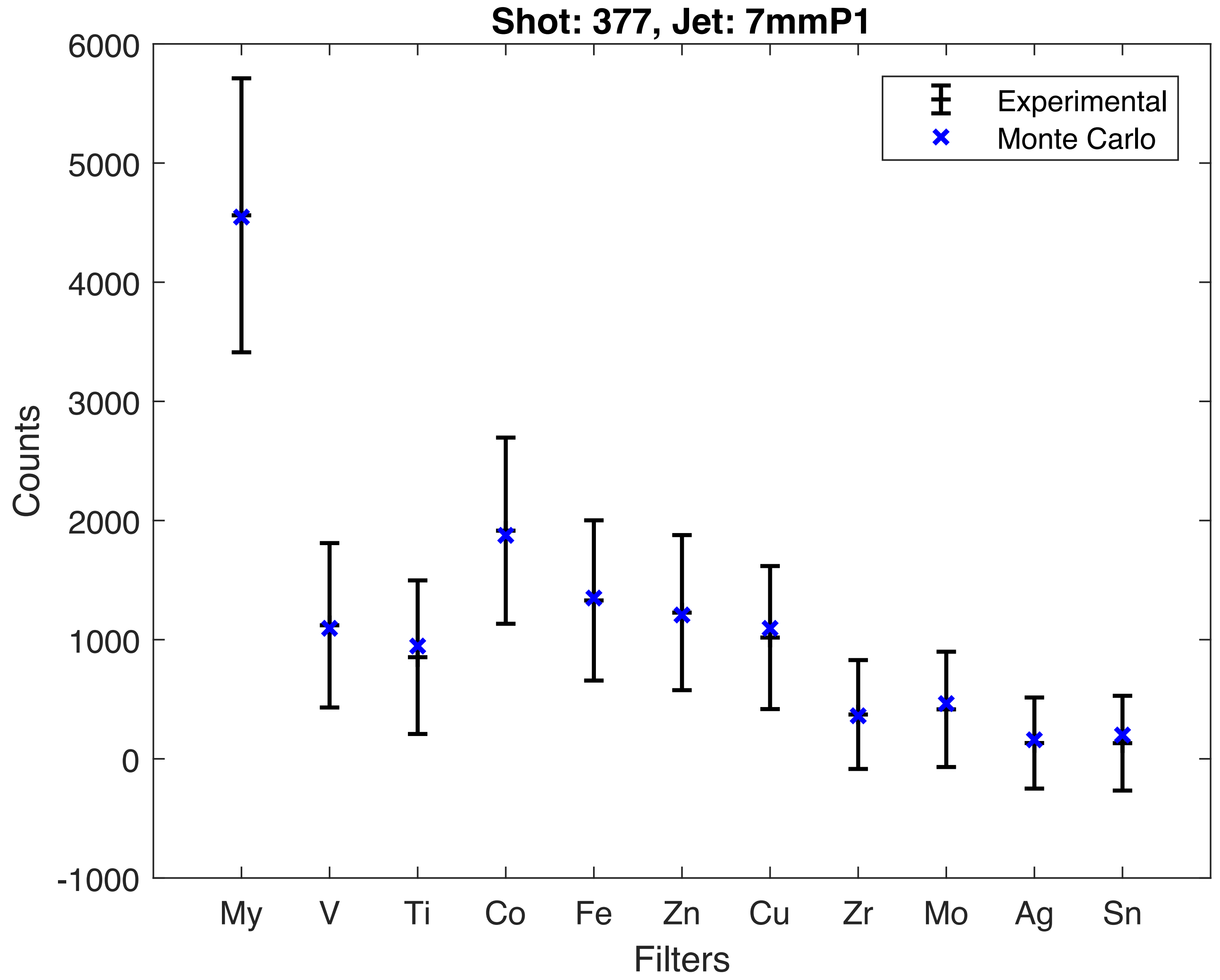


# Measured X-ray Spectra

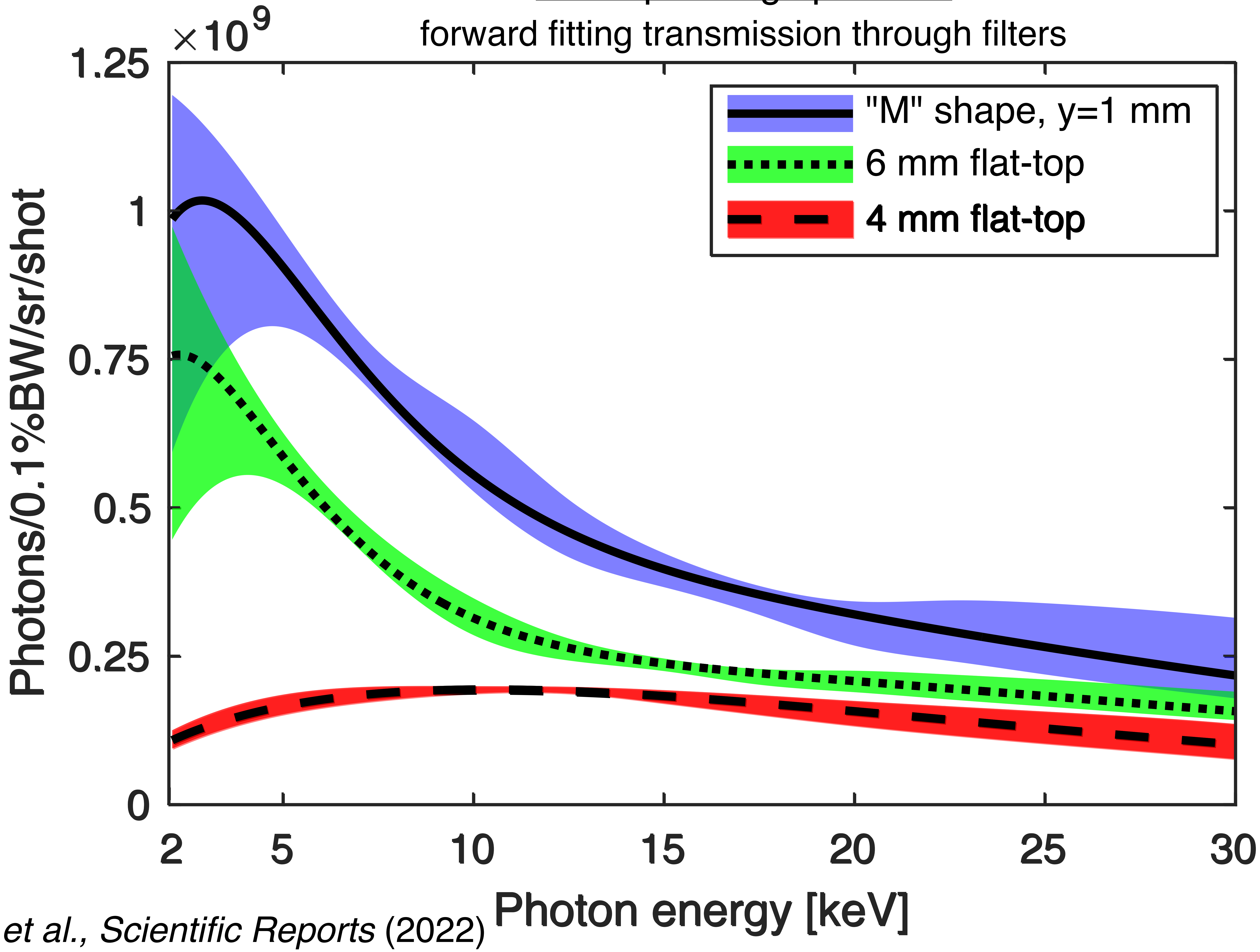
compare structured profile to flat-top jets



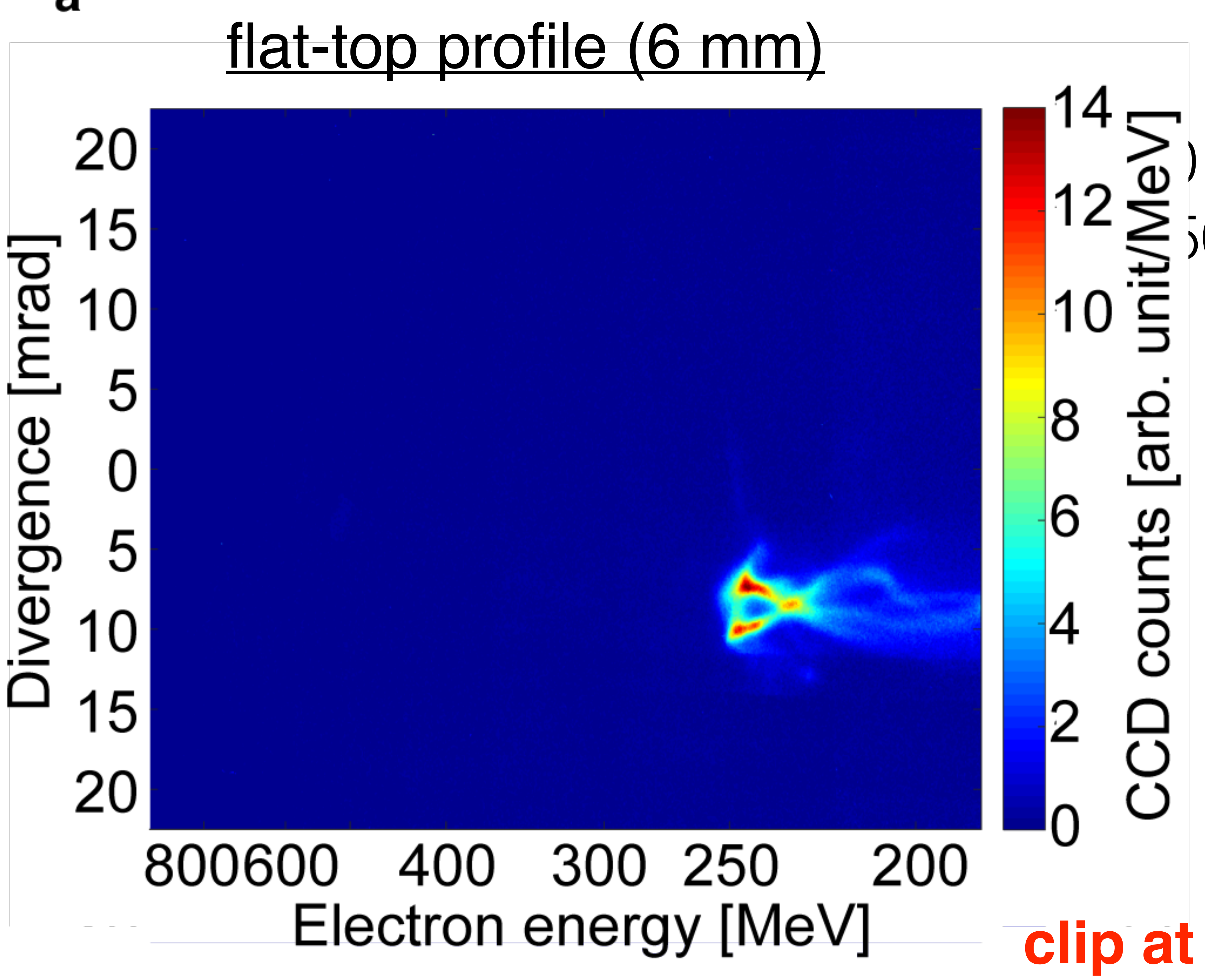

corresponding spectrum

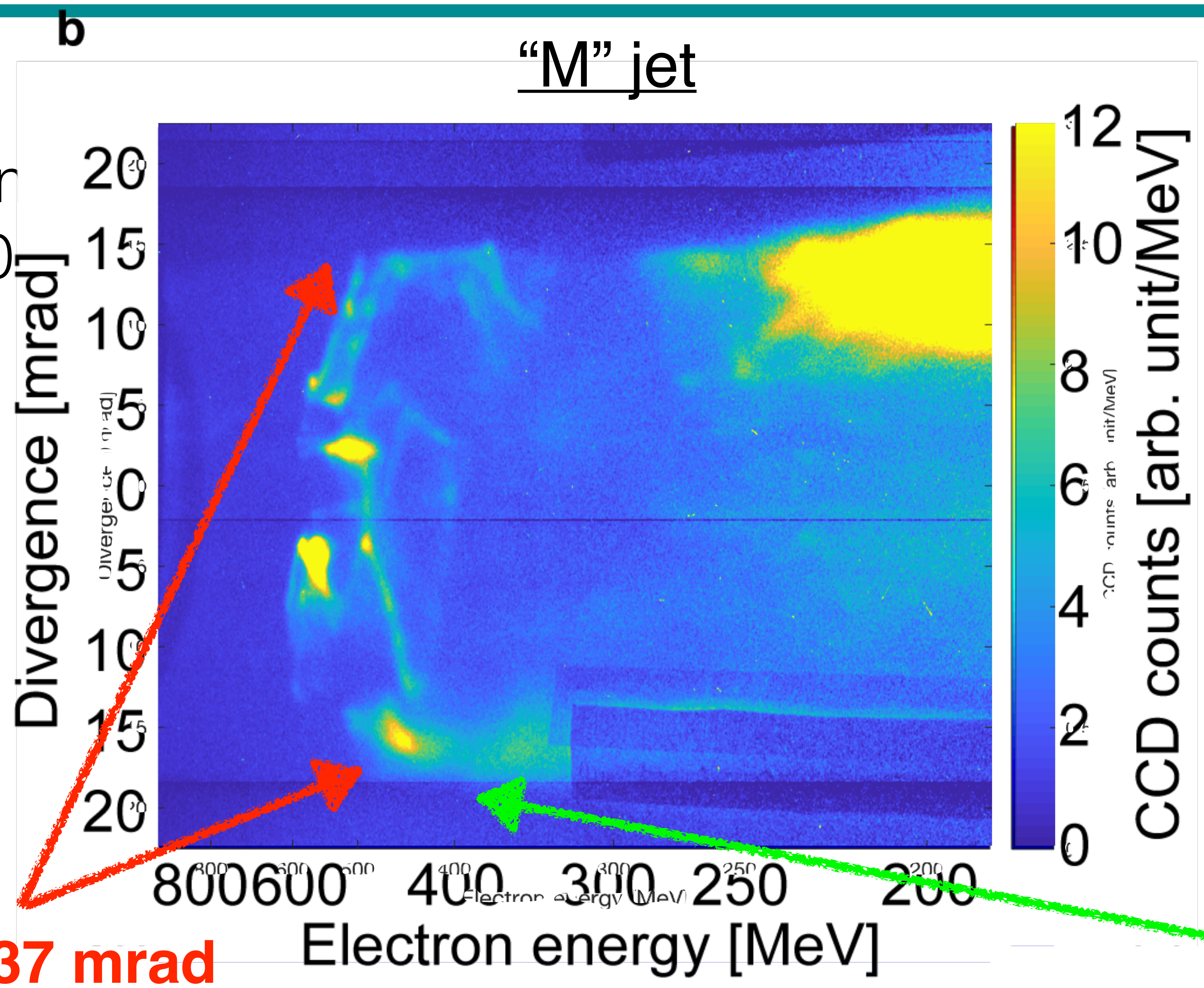
forward fitting transmission through filters




Rakowski *et al.*, *Scientific Reports* (2022)

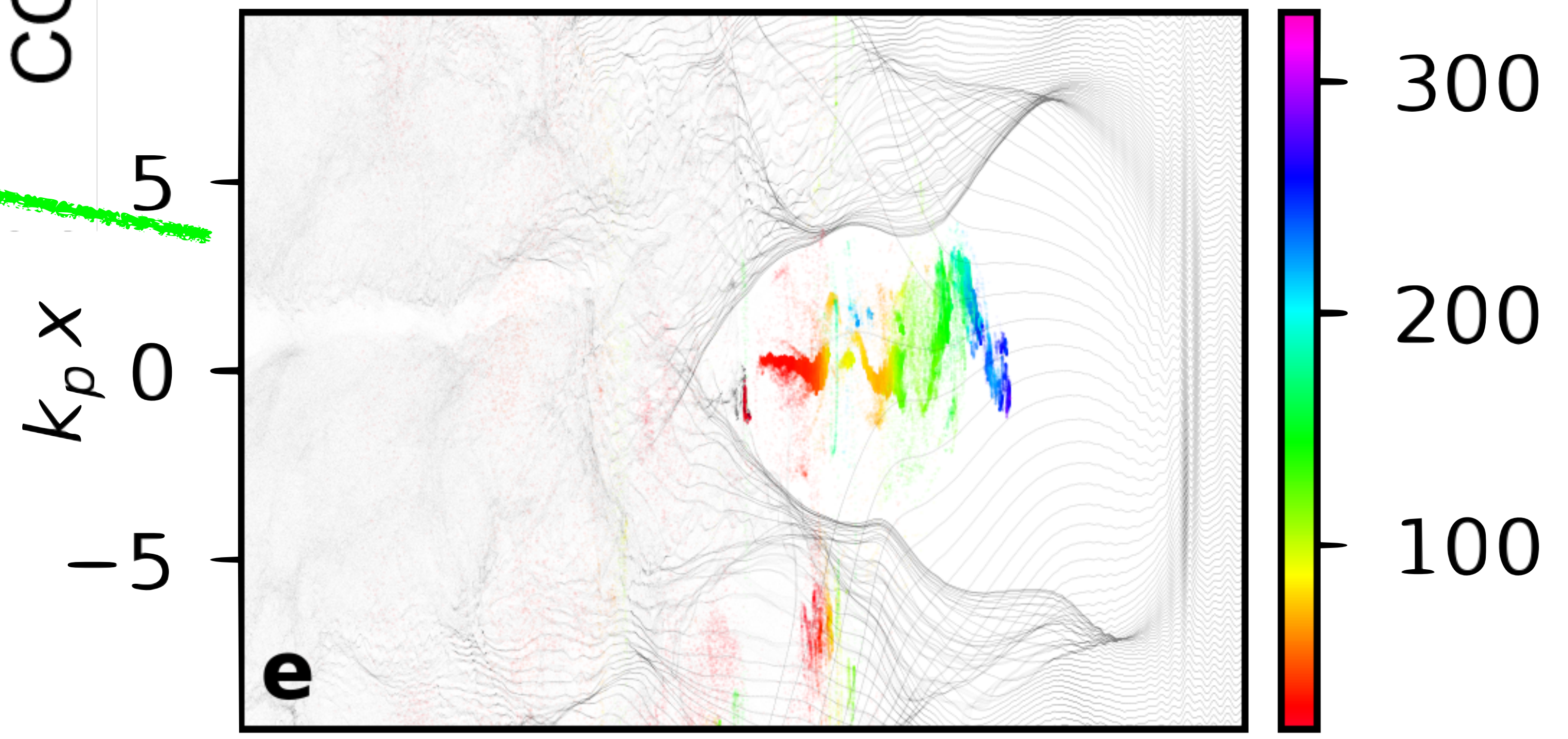
# Corresponding Electron Spectra




clip at 37 mrad
dipole magnet aperture

in qualitative agreement with simulation




| jet | θ | γ | $n_e$ [$10^{19}$/cm³] | K | $E_{crit}$ |
|---|---|---|---|---|---|
| 6 mm | 9 | 500 | 2 | 4.5 | 11 keV |
| "M" | 37 | 1000 | 1 | 37 | 146 keV |

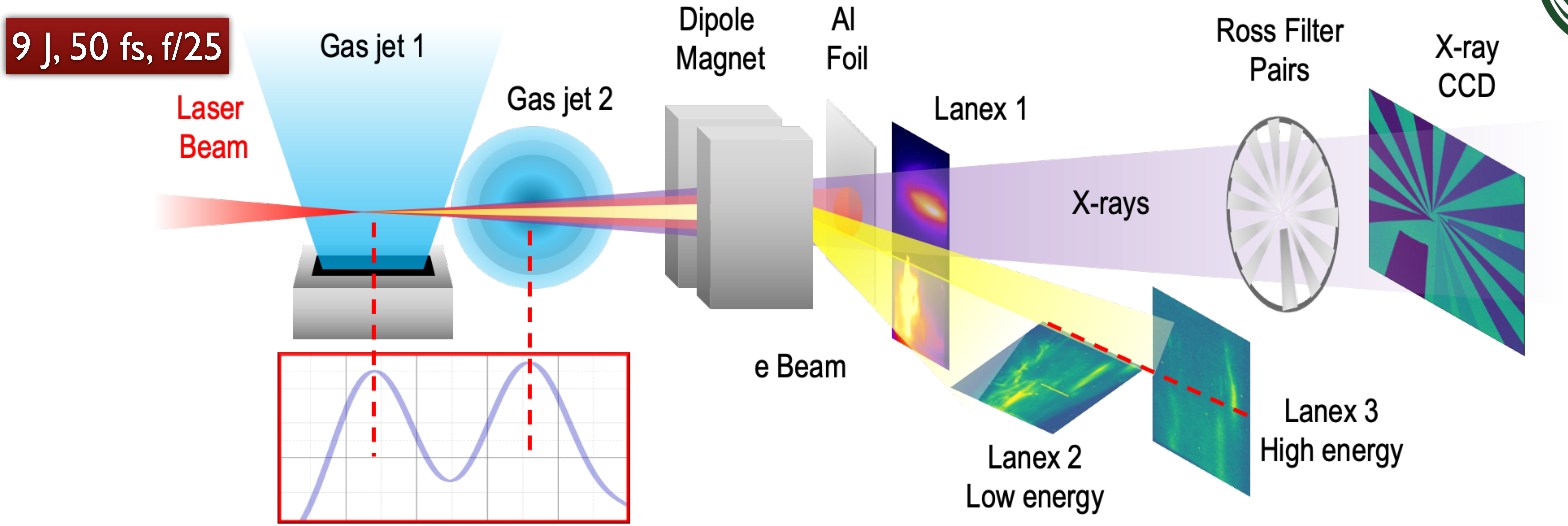
$$K \approx \gamma\theta$$

$$N_\gamma \sim K$$

expect ~1 order of magnitude increase in photon number

Rakowski *et al.*, *Scientific Reports* (2022)

# Double-jet Experiment



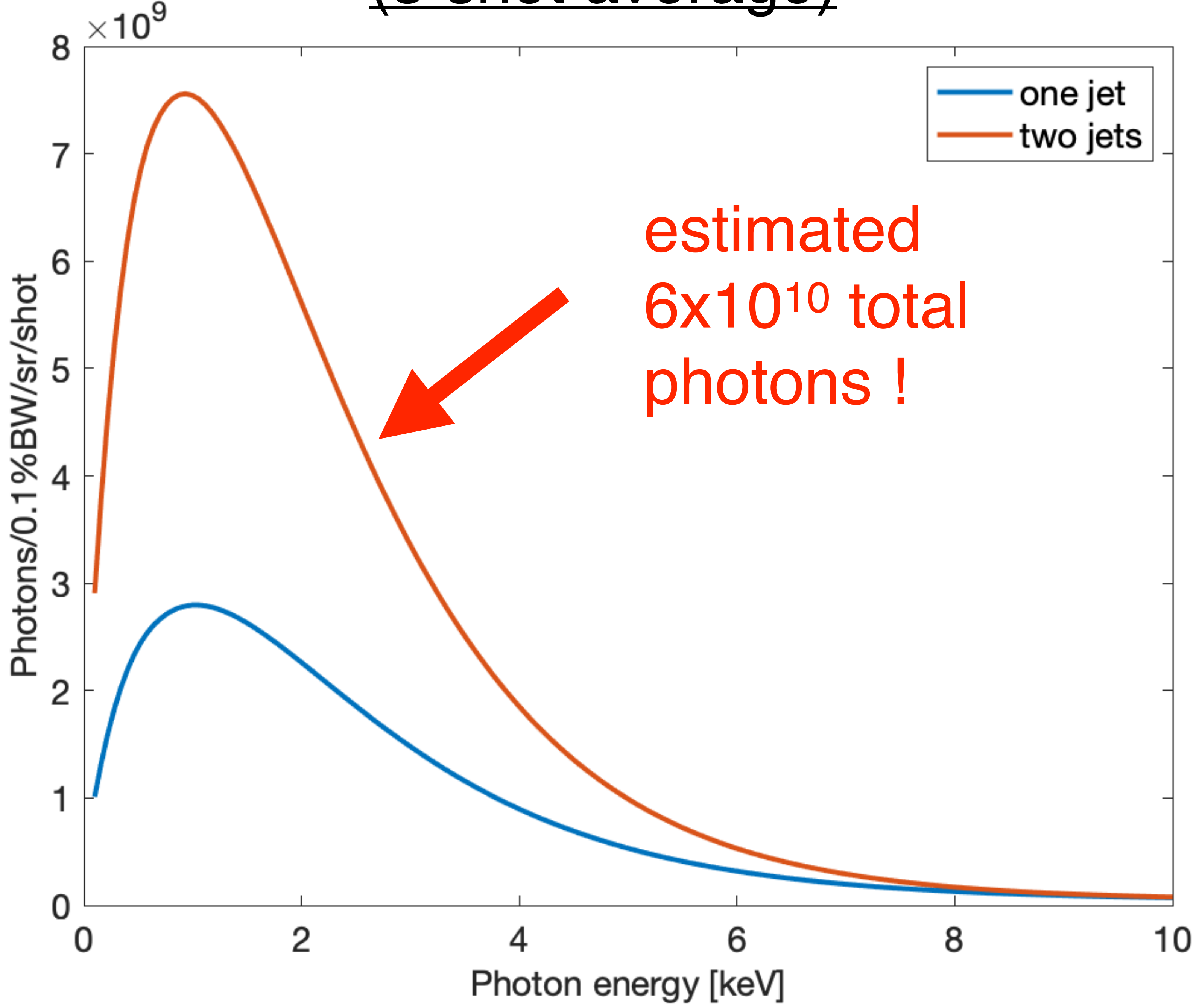

jets: 4 mm + 4mm
- gas density individually adjustable
- distance between jets adjustable

# Measured X-ray Spectra

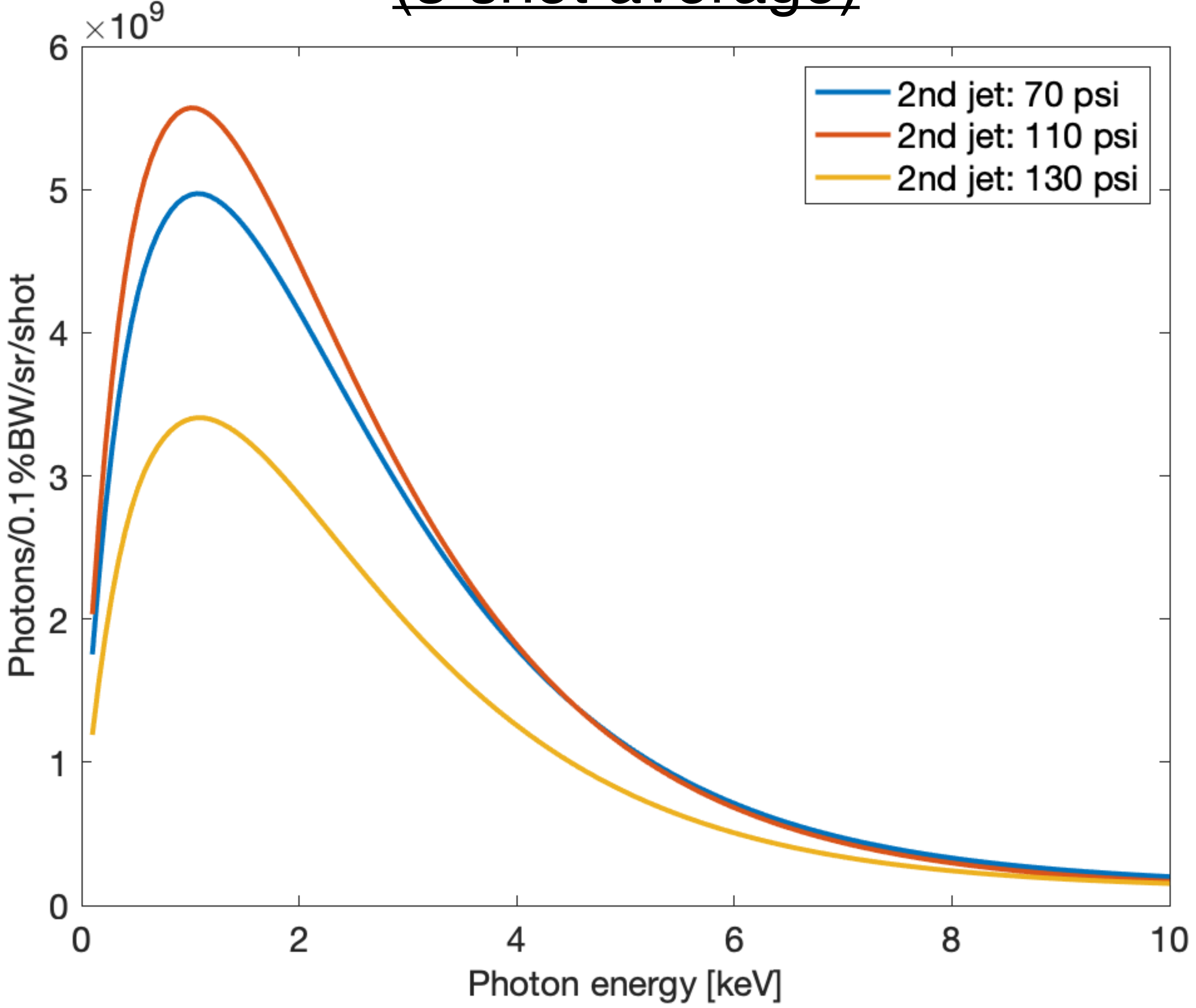
Preliminary !

Karlsruher Institut für Technologie

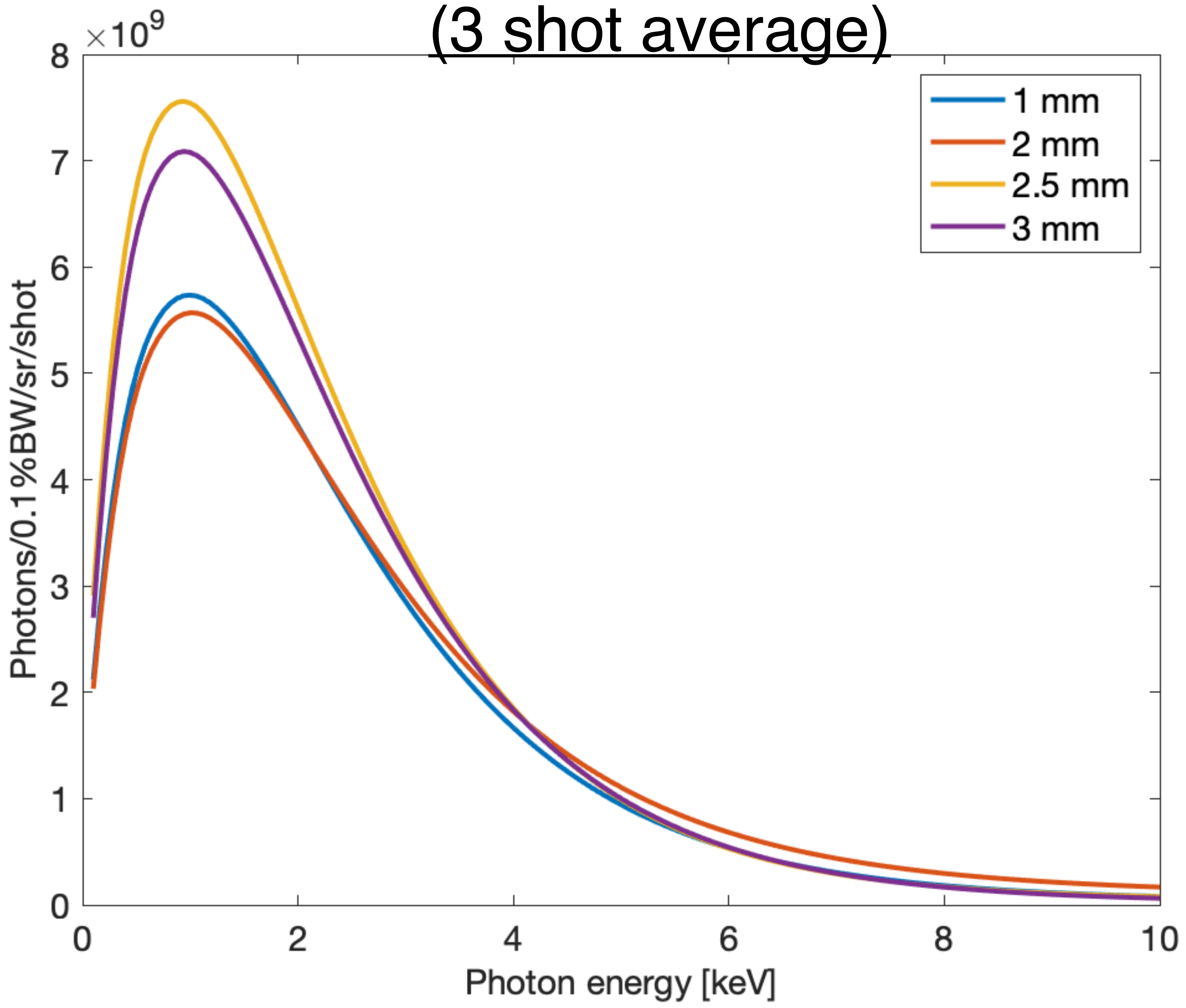
One jet vs double jet
(3 shot average)




Double jet:
2nd jet density
(3 shot average)




Double jet:
Jet separation
(3 shot average)




| Source | Photons/ shot | Pulse duration | Bandwidth |
|---|---|---|---|
| This source | $6 \times 10^{10}$ | 50 fs | 100 % |
| APS, Argonne | $1 \times 10^{10}$ | 100 ps | 0.01 % |
| LCLS FEL | $10^{11}$ | 30 fs | 0.1 % |

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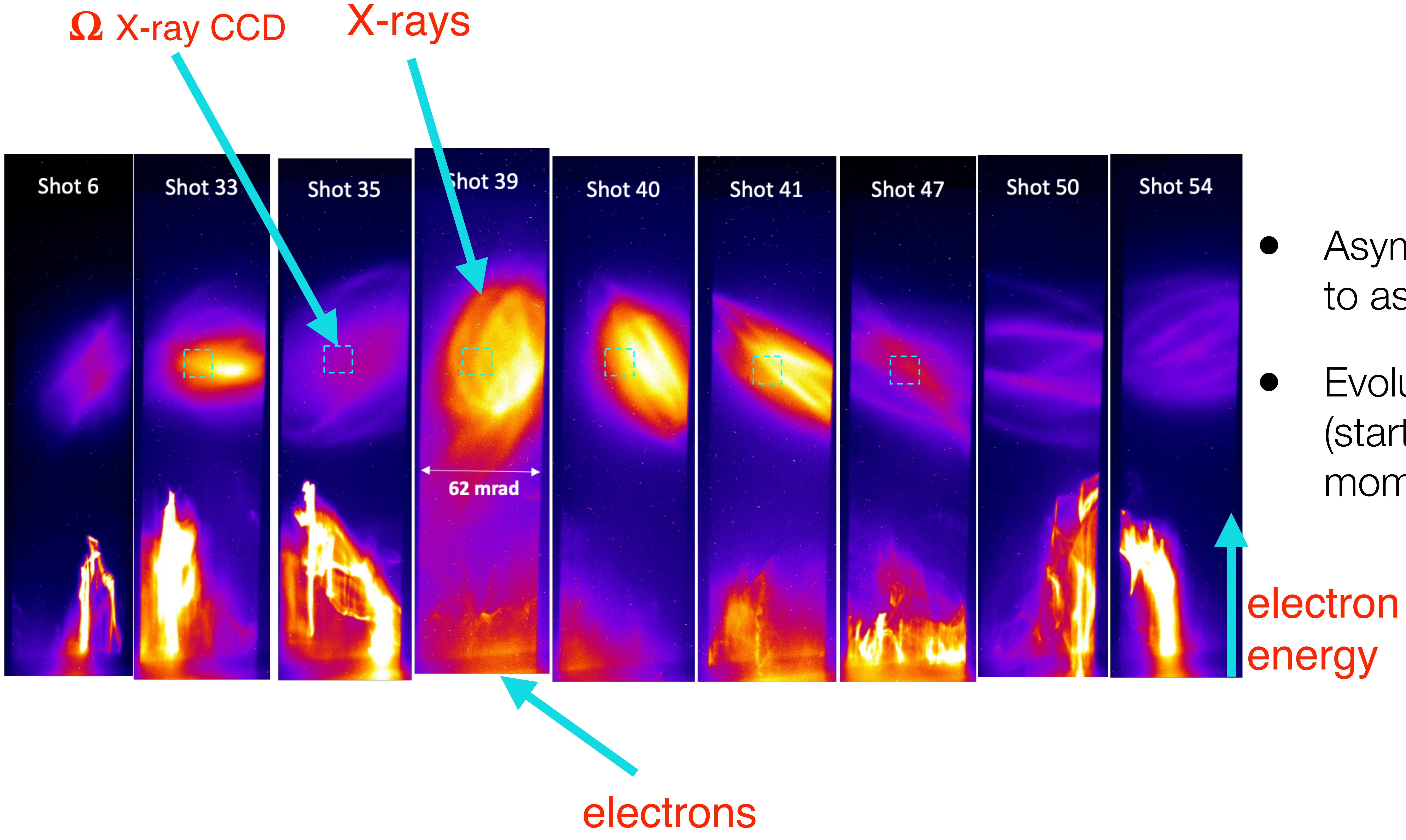
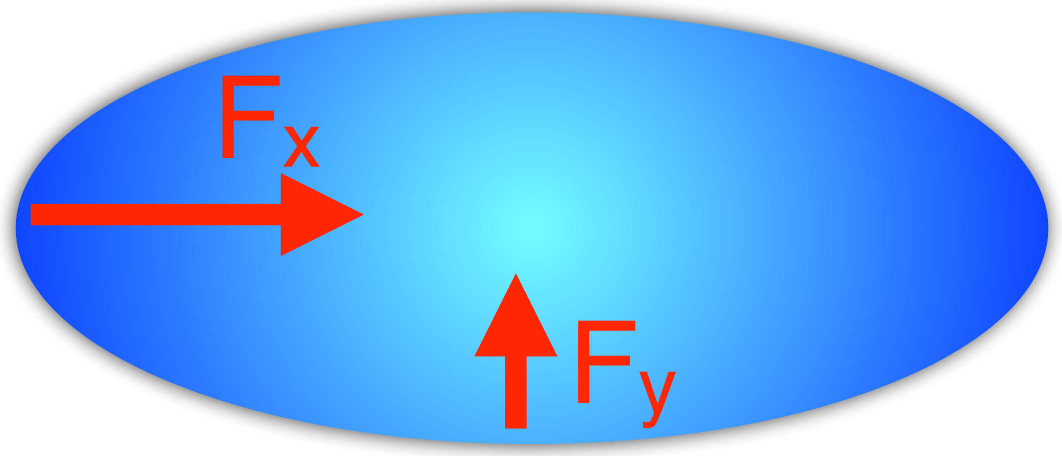
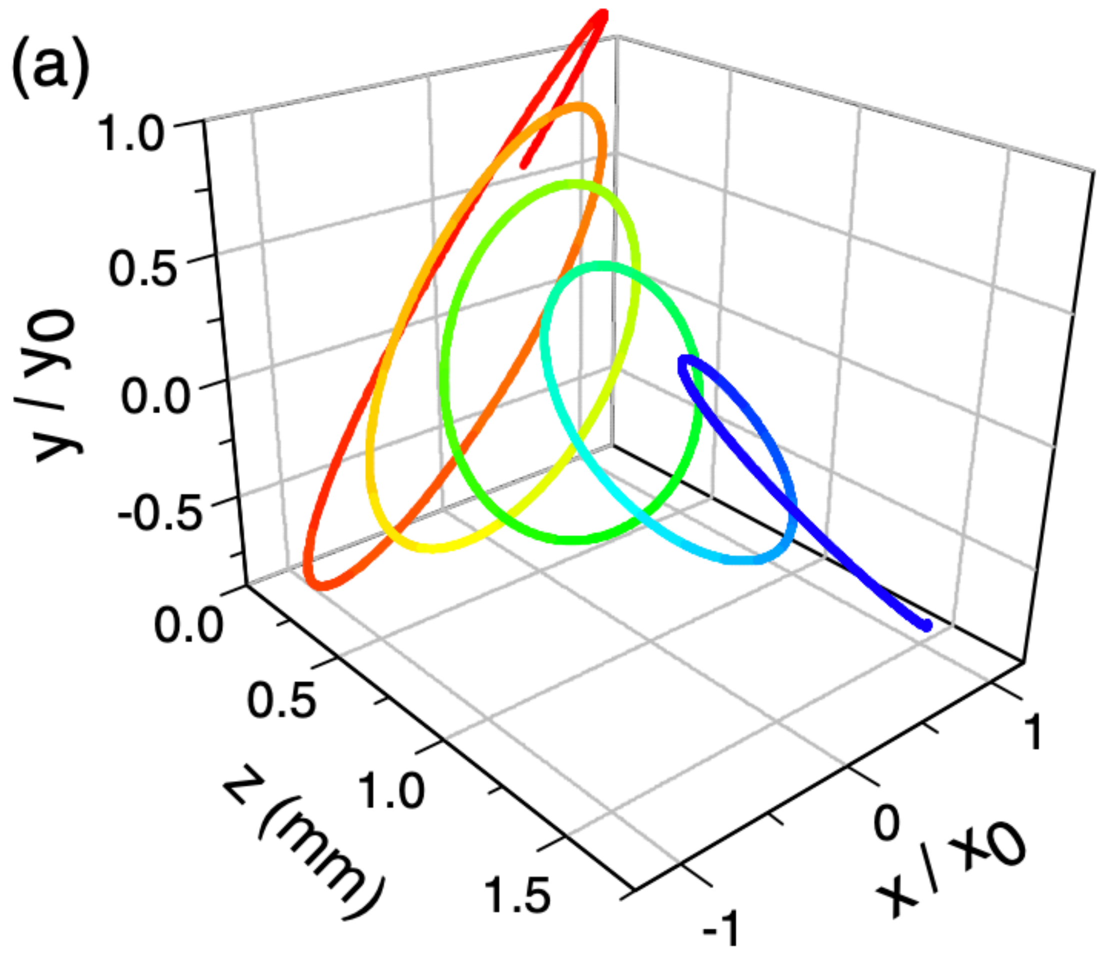
# X-ray Beam Profiles




**Asymmetric transverse bubble profile**




- Asymmetric transverse bubble shape leads to asymmetric restoring forces
- Evolution of electron trajectories into helical (starting from planar with 0 angular momentum)




C. Thaury et al., PRL (2013)

# Outline

Karlsruher Institut für Technologie

- Particle Accelerators and Laser-Plasma Acceleration (LPA)
- Applications of Laser-Plasma Accelerators
  - Laser-driven X-ray Sources
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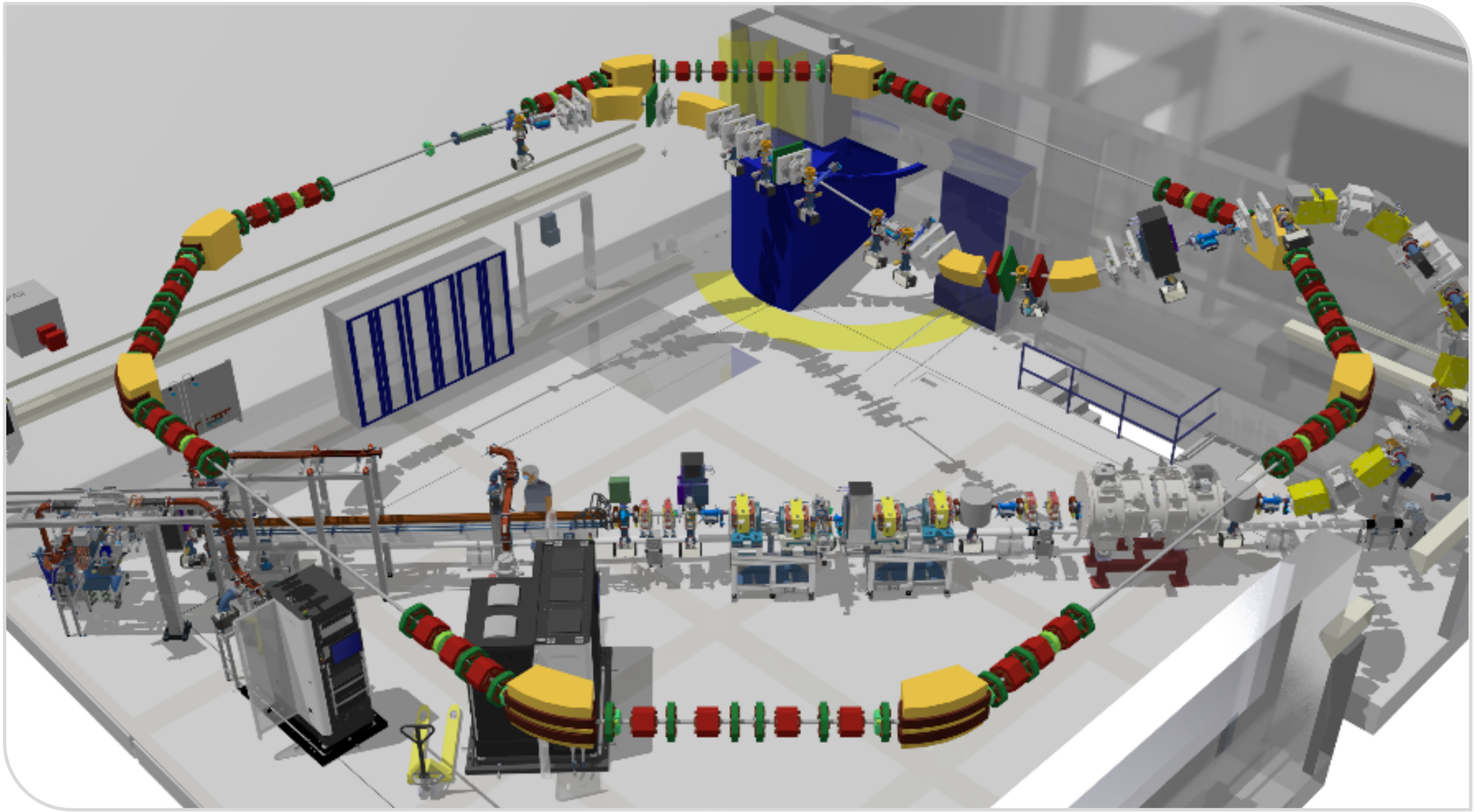
  - Next-generation laser-plasma accelerators
- Summary

# Next-Generation Storage Rings: LPA Injectors & Ultrashort Bunches

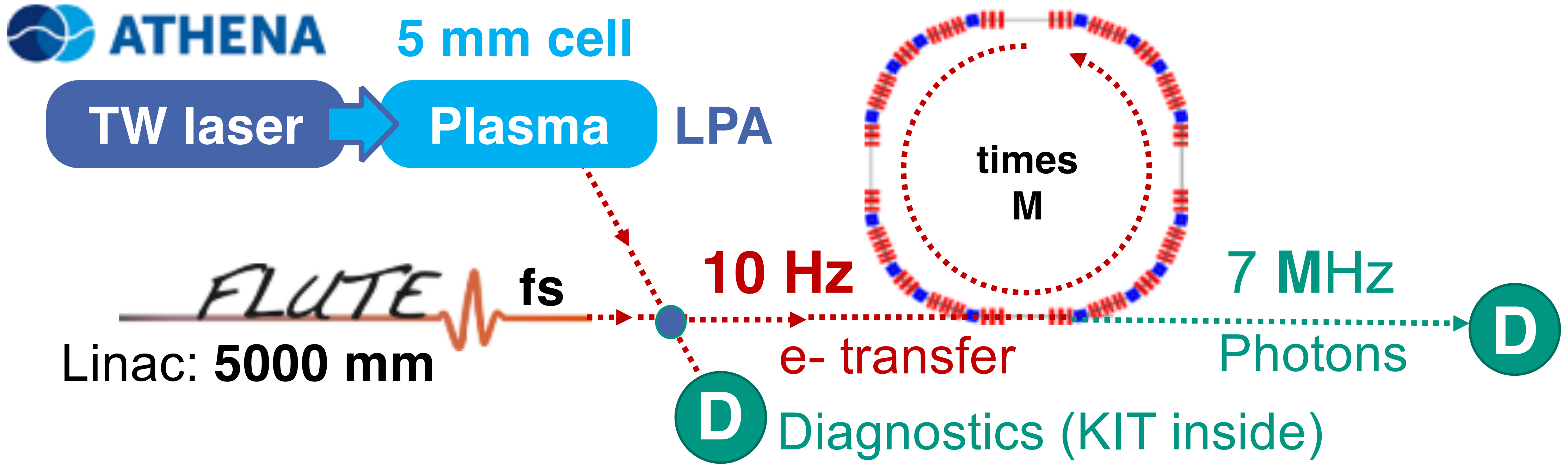
Karlsruher Institut für Technologie

- Electron bunch circulating in storage ring increase:
  - repetition rate (average power of light sources)
  - energy efficiency
  - control over beam parameters
  - feed multiple experiments/users at the same time
- Common wisdom: "Ultrashort bunches can only be generated by and used in single-pass linear accelerators"

European Synchrotron Radiation Facility (ESRF), Grenoble

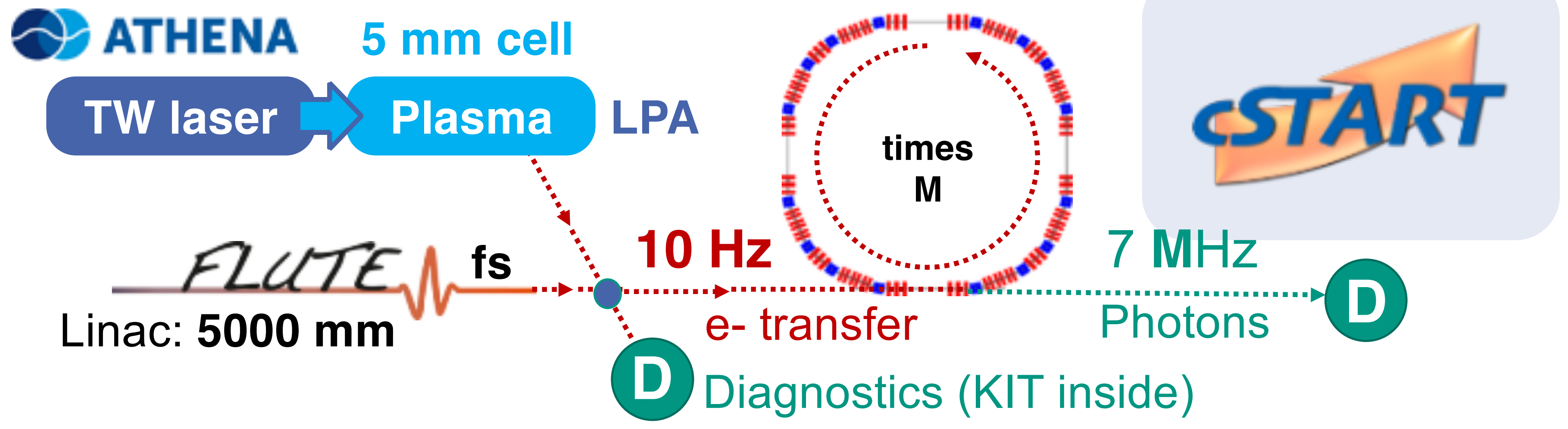


cSTART

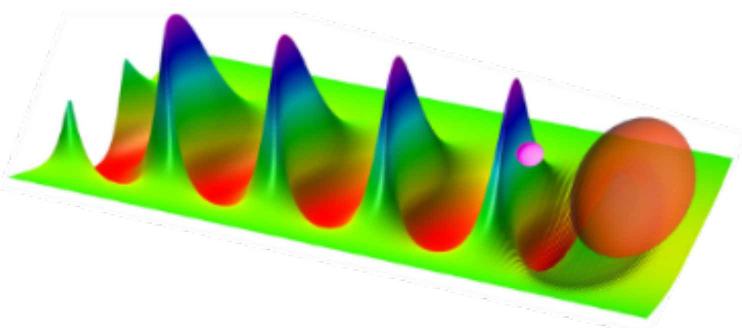


# cSTART Ring @KIT
## non-linear linear accelerator (NL-LINAC, nonLINAC?)

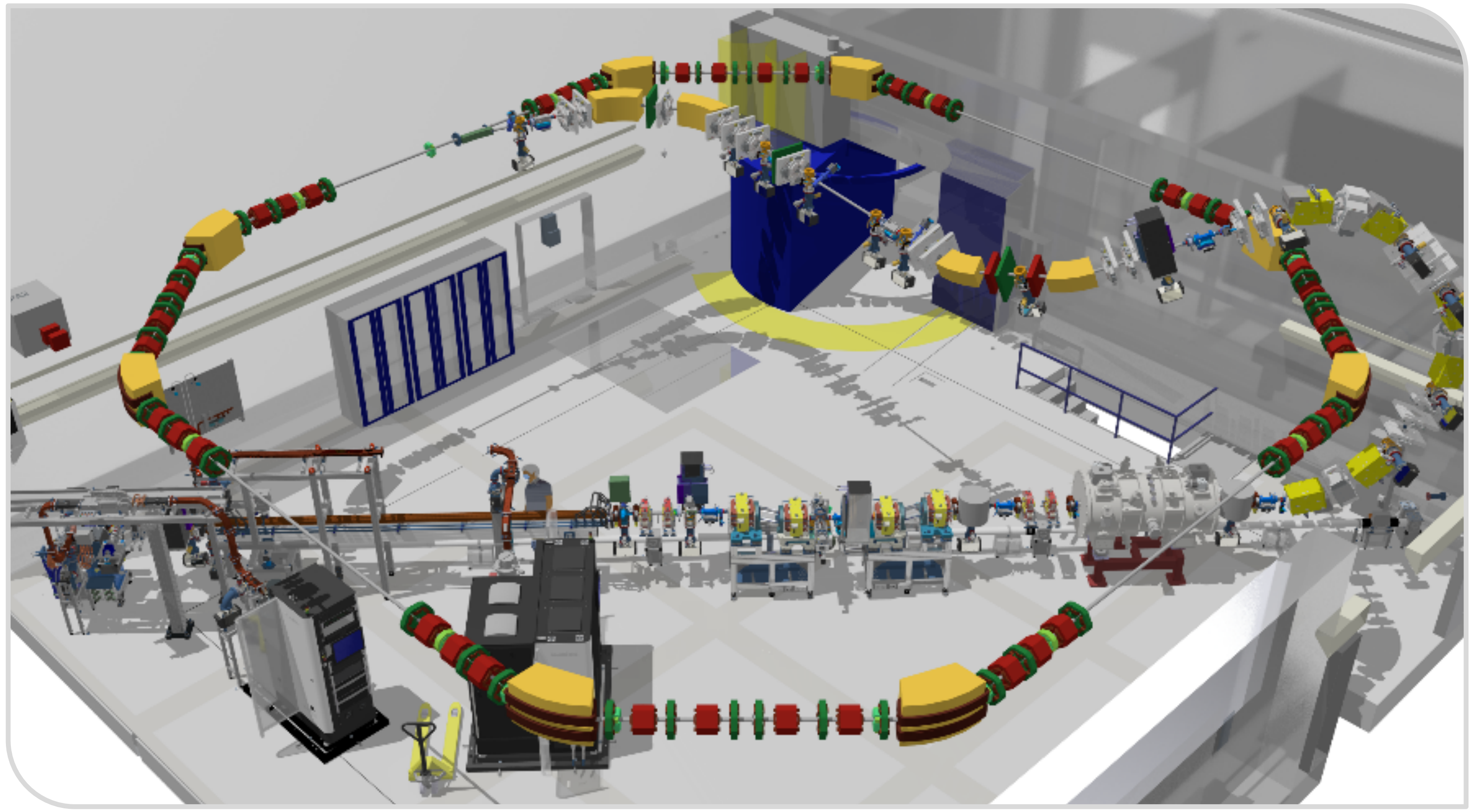
**Unique storage ring**
- Compact (14 m diameter), energy efficient
- Large acceptance of electron energies (~4%)
- Lattice to store ultrashort electron bunches (<100 fs)
- Testbed for widely unexplored accelerator physics
- Prototype for future accelerator concepts




**First injection of laser-plasma electron bunches**



- future hybrid LPA - RF accelerator
- Combination of LPAs and complex electron beam optics
- Testbed for LPA experiments in storage rings



**First storage ring for ultrashort bunches**
- Storage of <100 femtosecond electron bunches (similar to LINACs, 2-3 orders of magnitude shorter than conventional rings)

- 2024: TDR Technical design report
- 2026: Assembly
- 2027: Commissioning

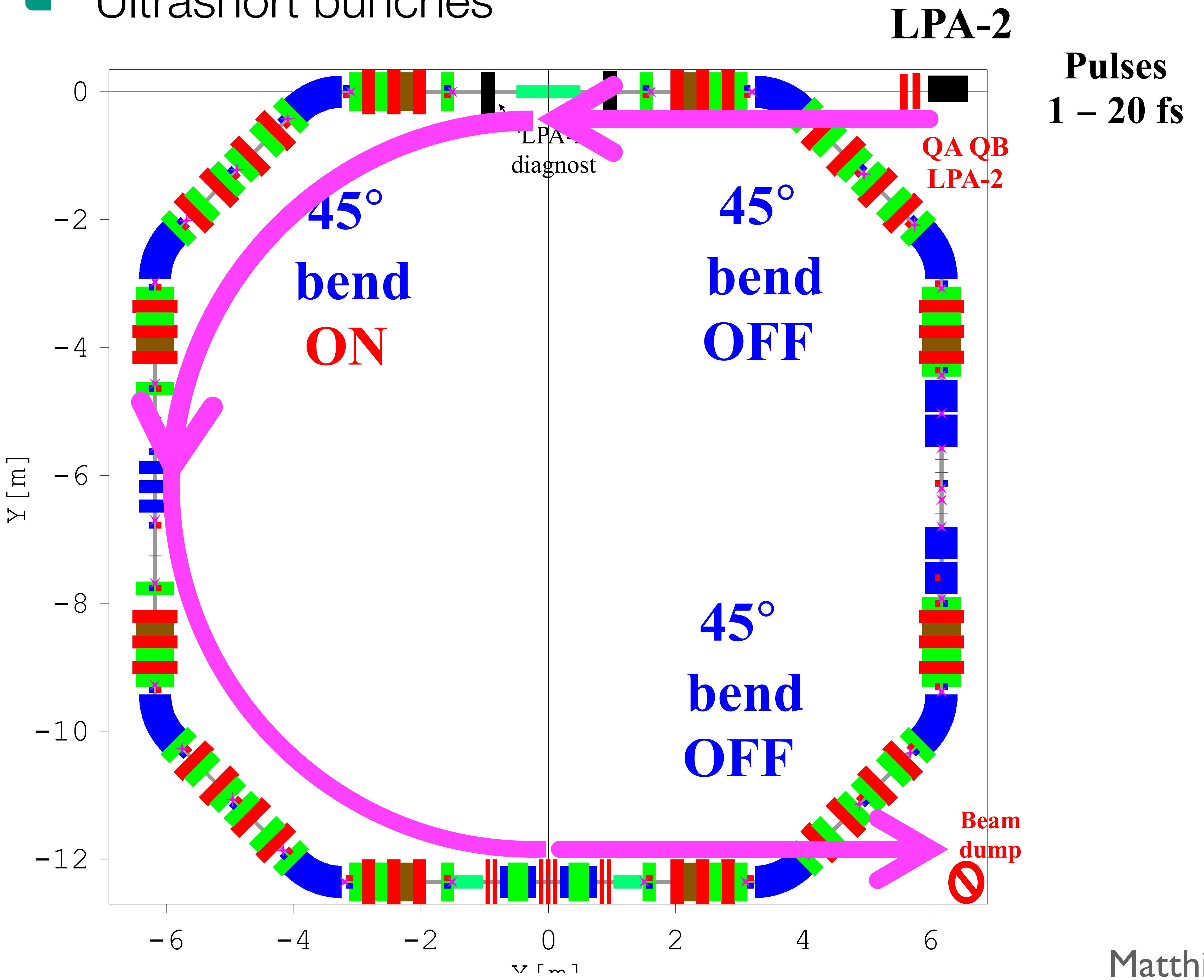
research instruments

**Research and Applications**
- Study of non-equilibrium dynamics of fs bunches
- Study and manipulation of longitudinal phase space
- Advanced turn-by-turn high-repetition rate diagnostics
- Potential for next-generation of light source with transformative impact

# LPAs & cSTART

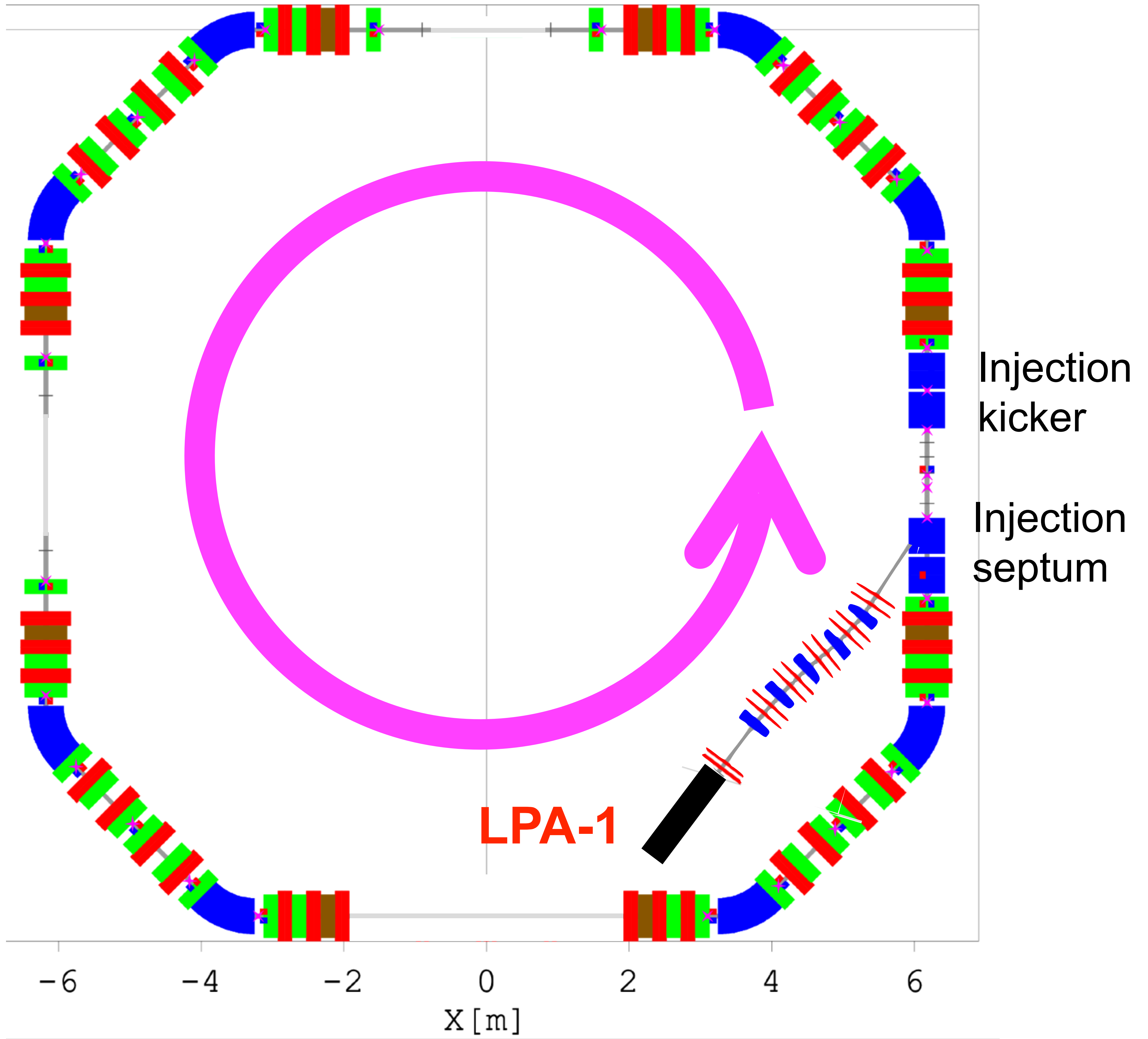
## LPA - 2

- Injection through de-energized dipole magnet
- 3/4 circulation
- Full LPA energy spread & charge
- Ultrashort bunches



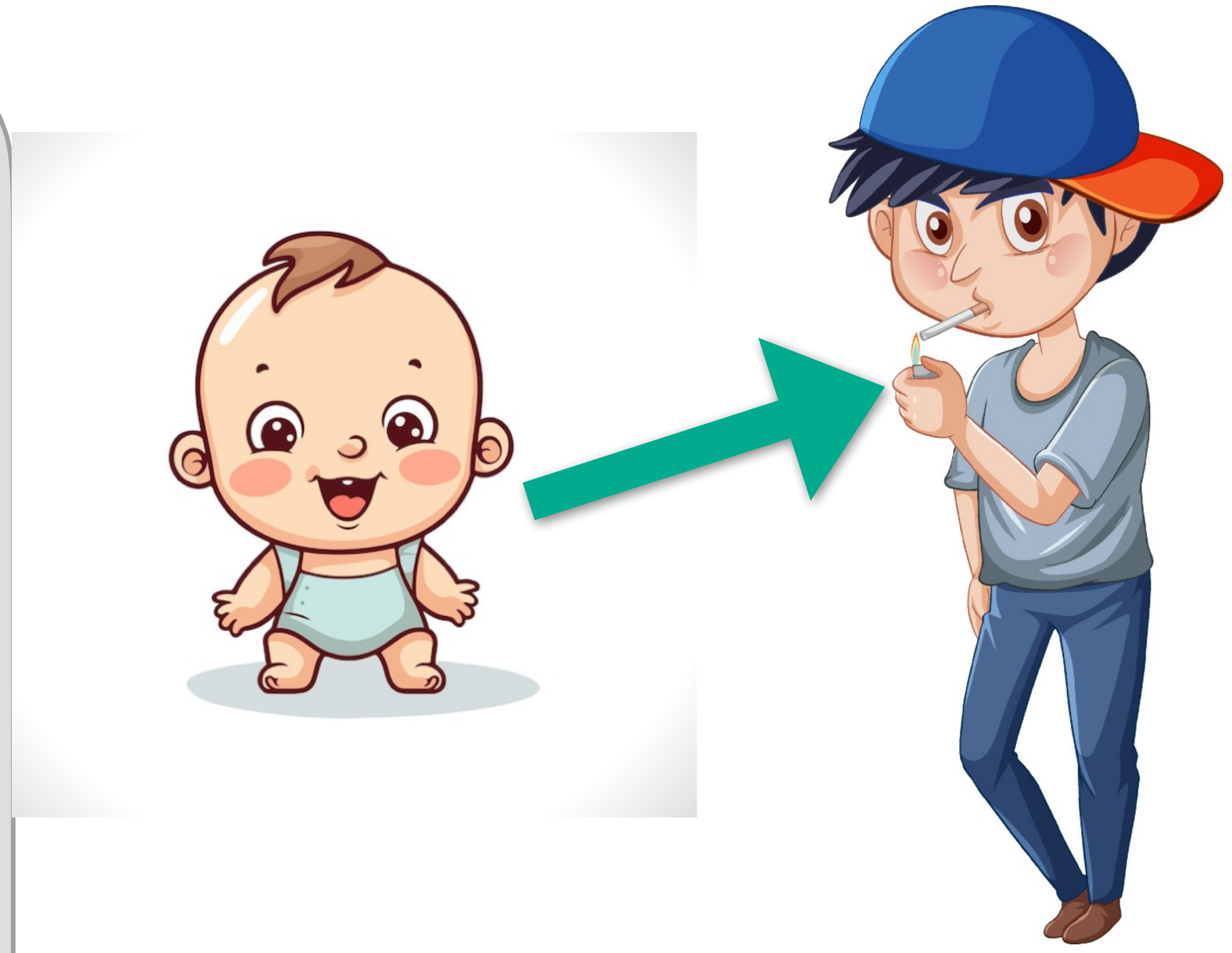

## LPA - 1

- Injection through transfer line & septum
- Full circulation
- <1% dE/E ; lower charge
- <50 fs bunches



# Laser-Plasma Accelerator as Injector for Storage Ring

- Stable, reproducible generation of
  - 50-90 MeV electrons,
  - dE/E < 4%,
  - transverse emittance: $\epsilon$ = 10 nm
  - 1 -10 Hz
- fully remote controlled ; maximally automized (i.e., minimal manual adjustments/ operation)
- different ring (LPA) operation regimes:
  - Short (<50 fs) sustained bunch circulation in ring (low alpha) (LPA-1)
    - LPA: High brightness e beam: dE/E <1%; $\epsilon$ = 10 nm ; ~1-10 pC; few fs out of LPA
  - Maximum charge & acceptance (LPA-2)
    - LPA: dE/E <4%; Q = 100+ pC; variable bunch duration (few fs - tens of fs)



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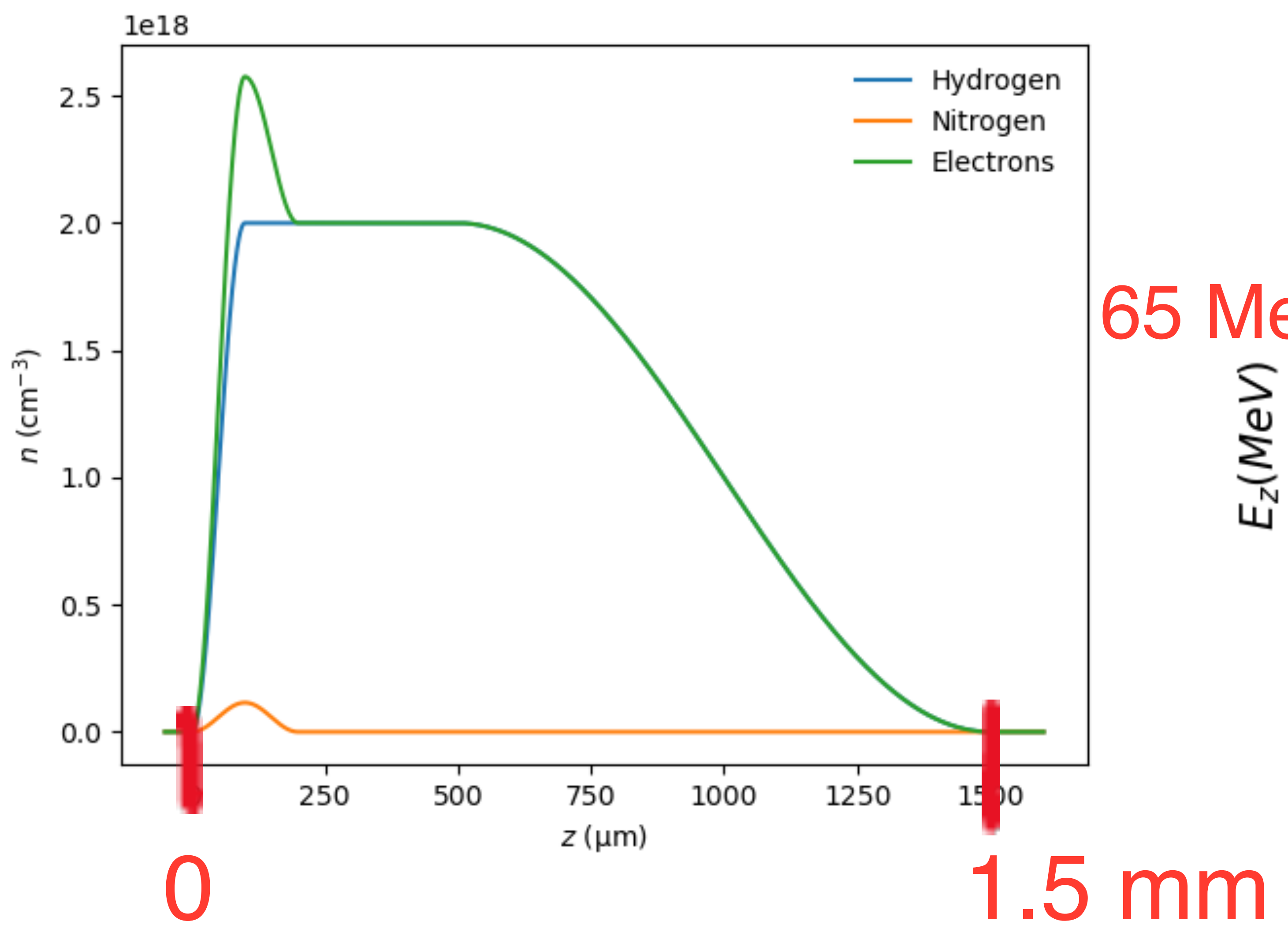
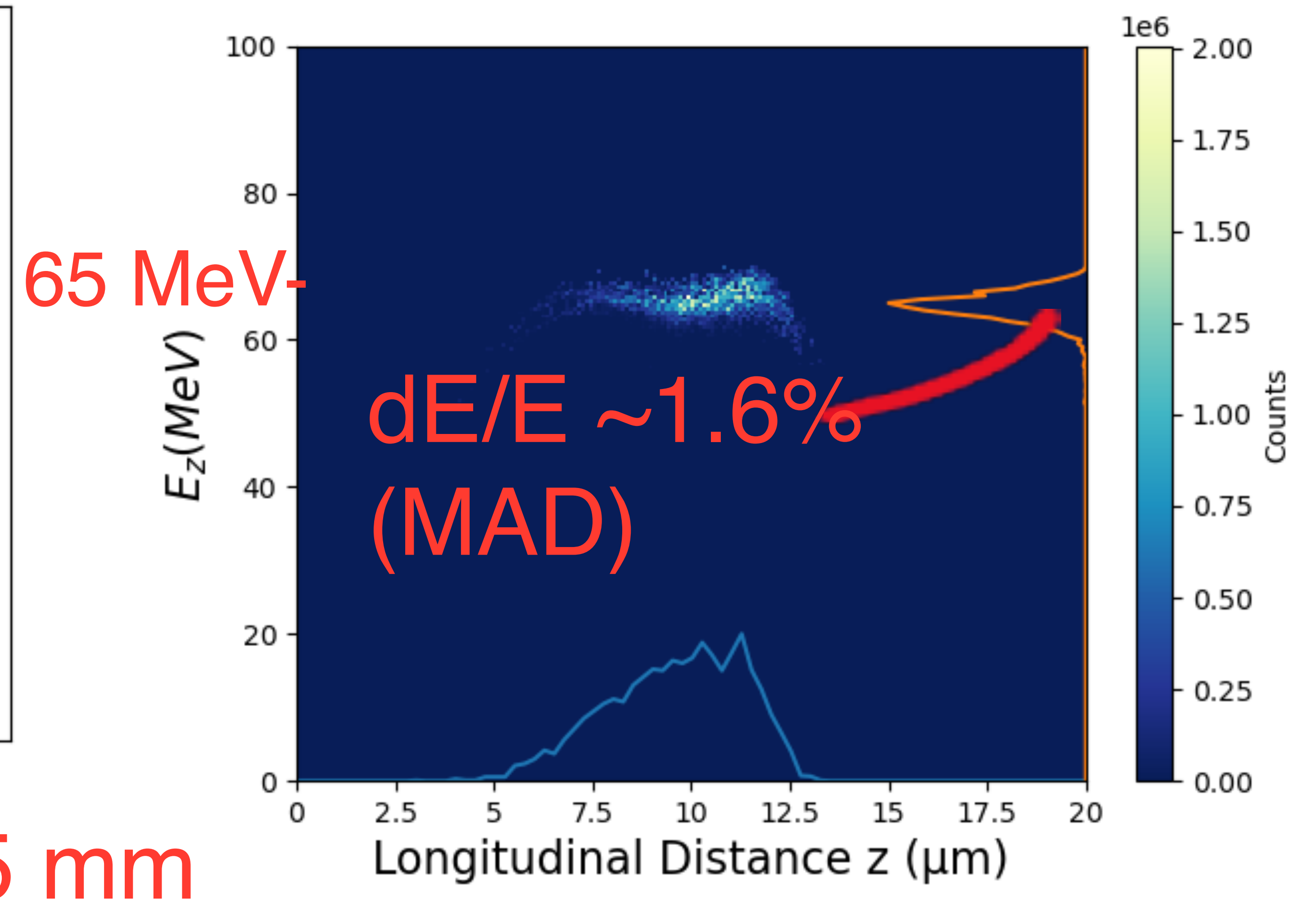
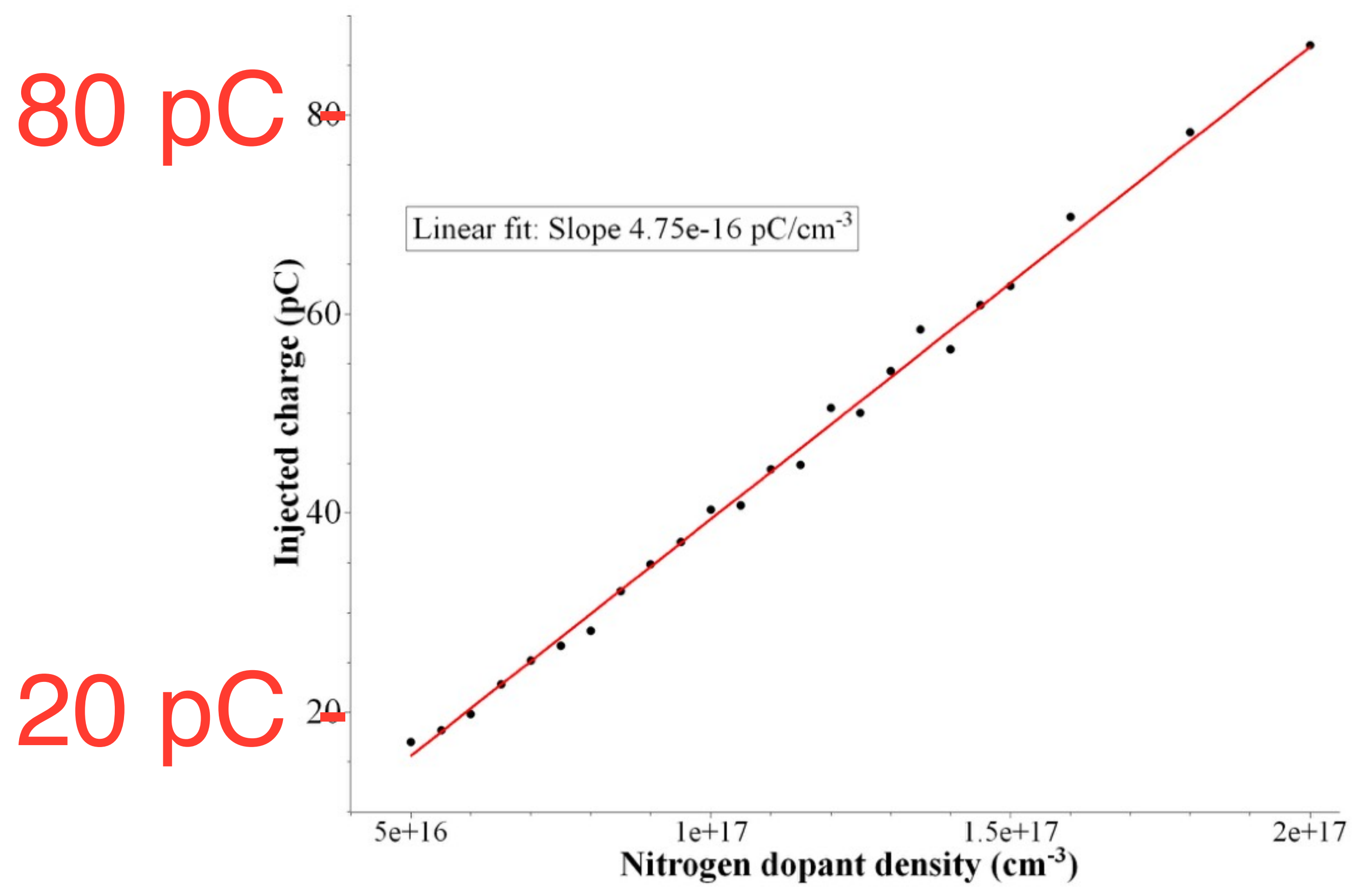
# LPA Injector: Simulations

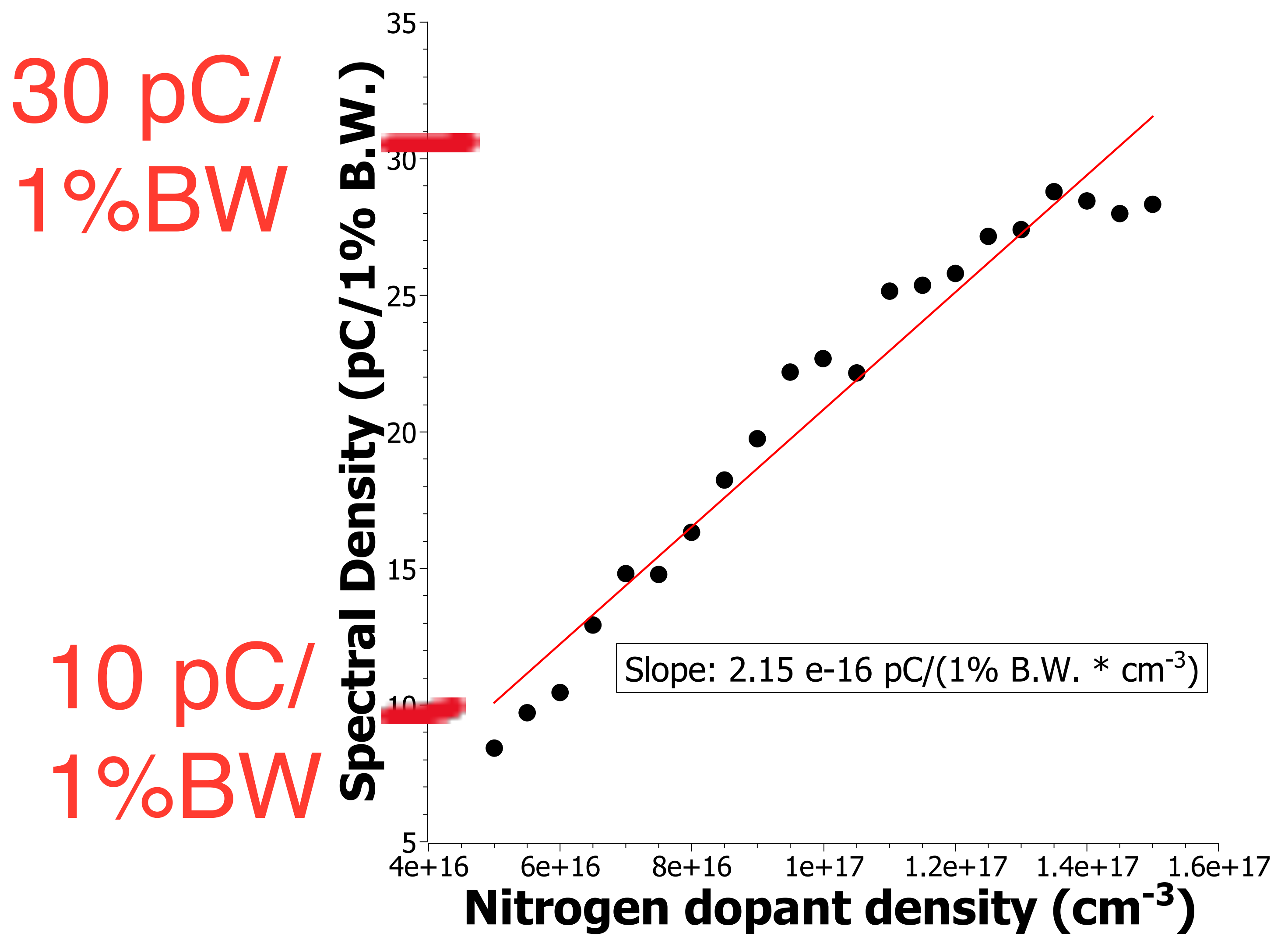
- Hydrogen-nitrogen gas mixture for localized ionization injection
- "One knob" tuning via $N_2$ density
- Density down ramp to adjust dephasing length
- 1.5 mm accelerator

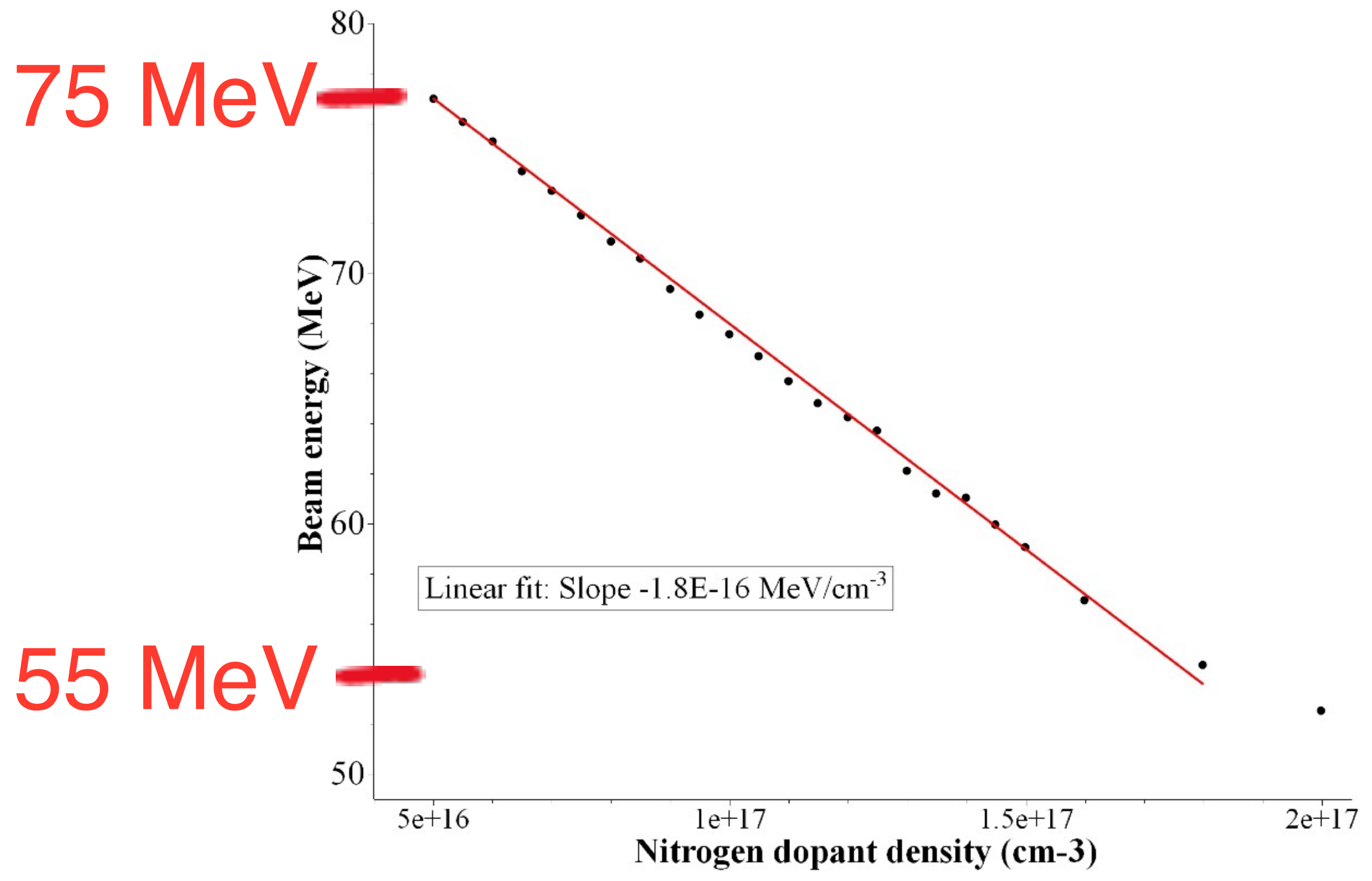
| Electron beam parameters at target exit | |
|---|---|
| Energy | 50 - 90 MeV |
| Rep. rate | 10 Hz |
| Energy spread (RMS) | <2.7% |
| Bunch charge | ~ 20 – 80 pC |



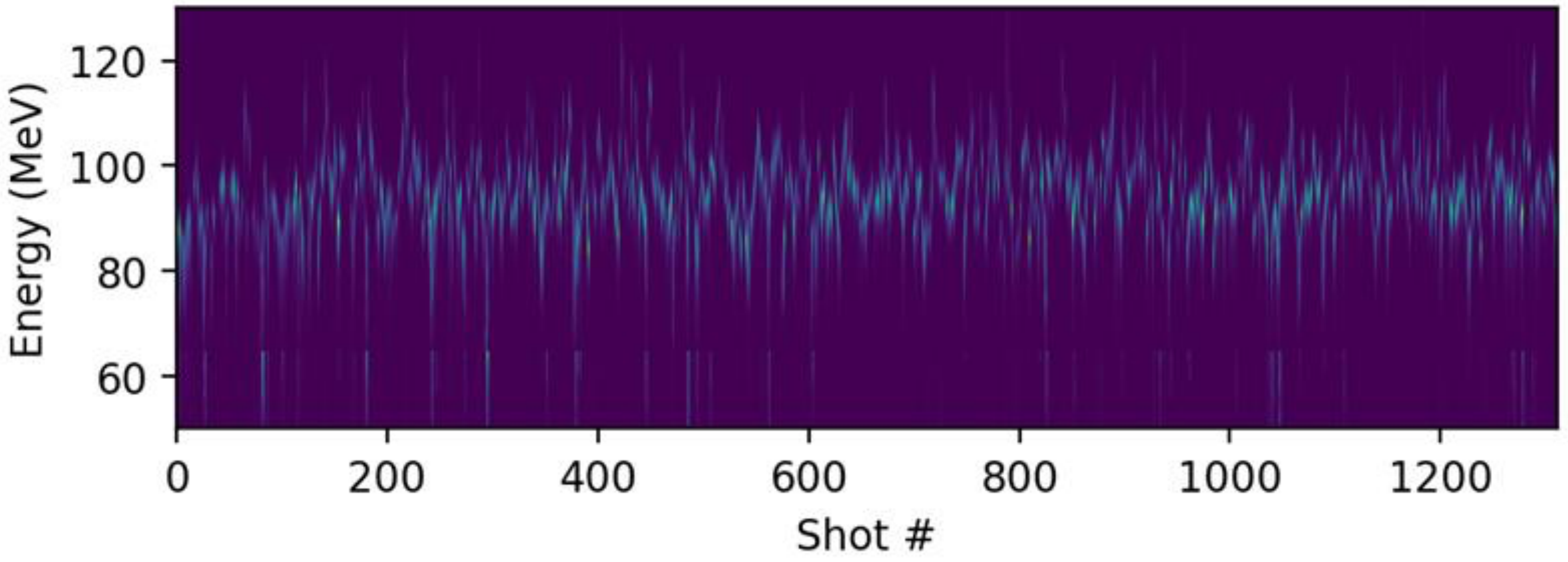




D. Squires; N. Ray *et al* IPAC 2024

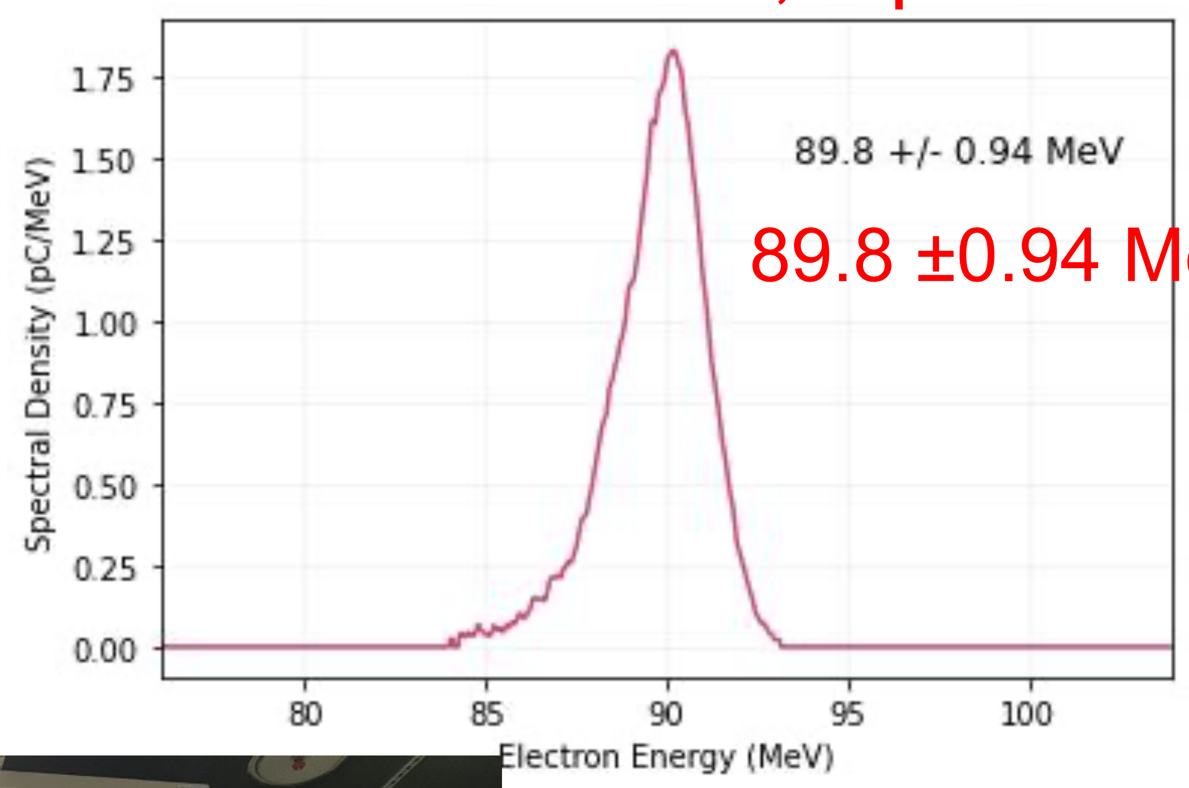
# LPA Injector: First LPA Experiments

- First experiments performed at DESY (03./04. Sept. 2024)
- LPA Setup@KIT currently being designed, first experiments spring 2025

series of shots

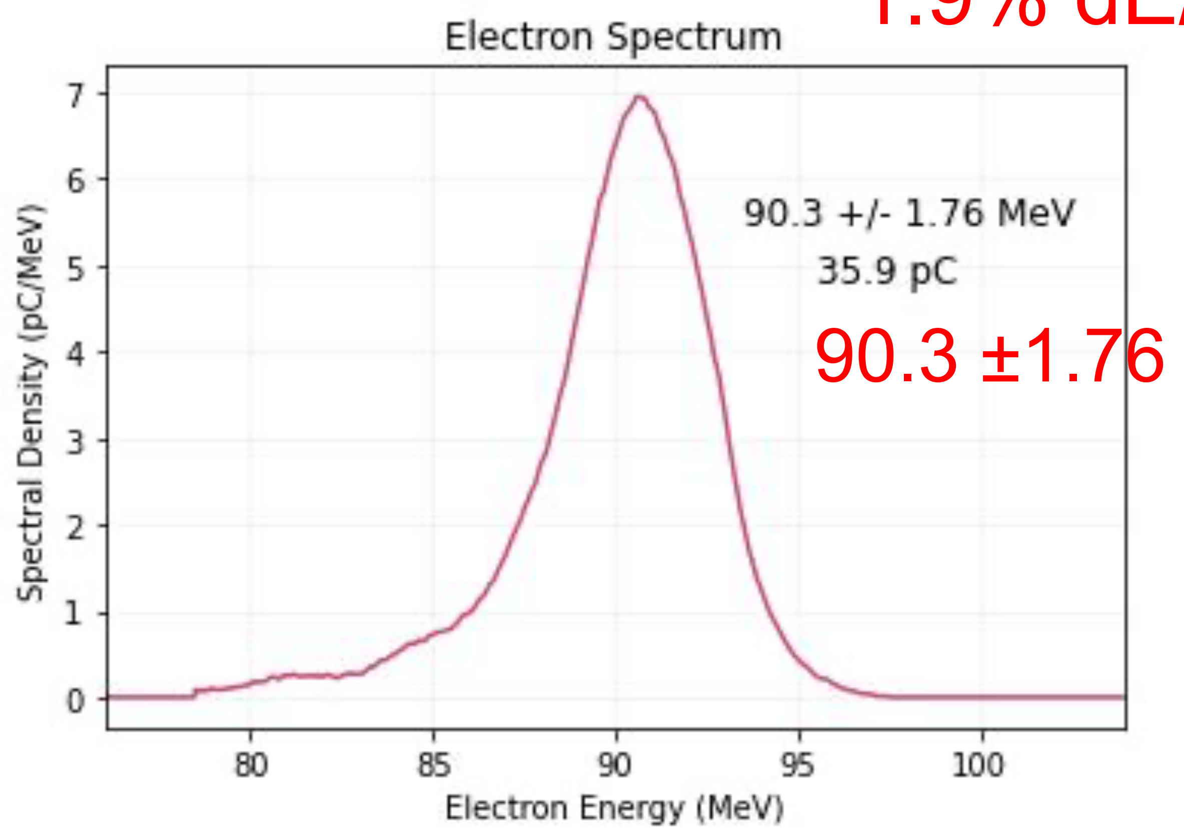



1% dE/E; 5 pC




89.8 ±0.94 MeV

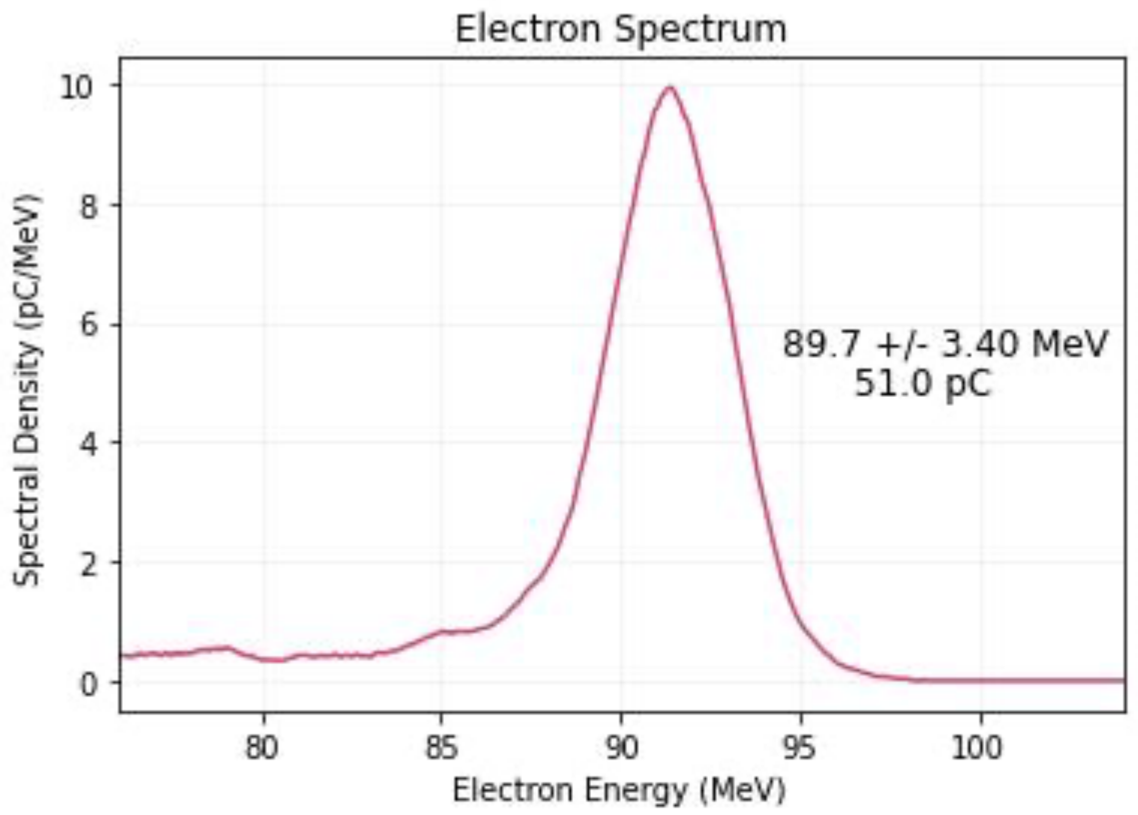
1.9% dE/E; 36 pC




90.3 ±1.76 MeV

N. Ray, J. Natal, A. Saw, D. Squires
M.F. (KIT)

S. Jalas, P. Winkler, J. Hörning,
A. Maier group (DESY)

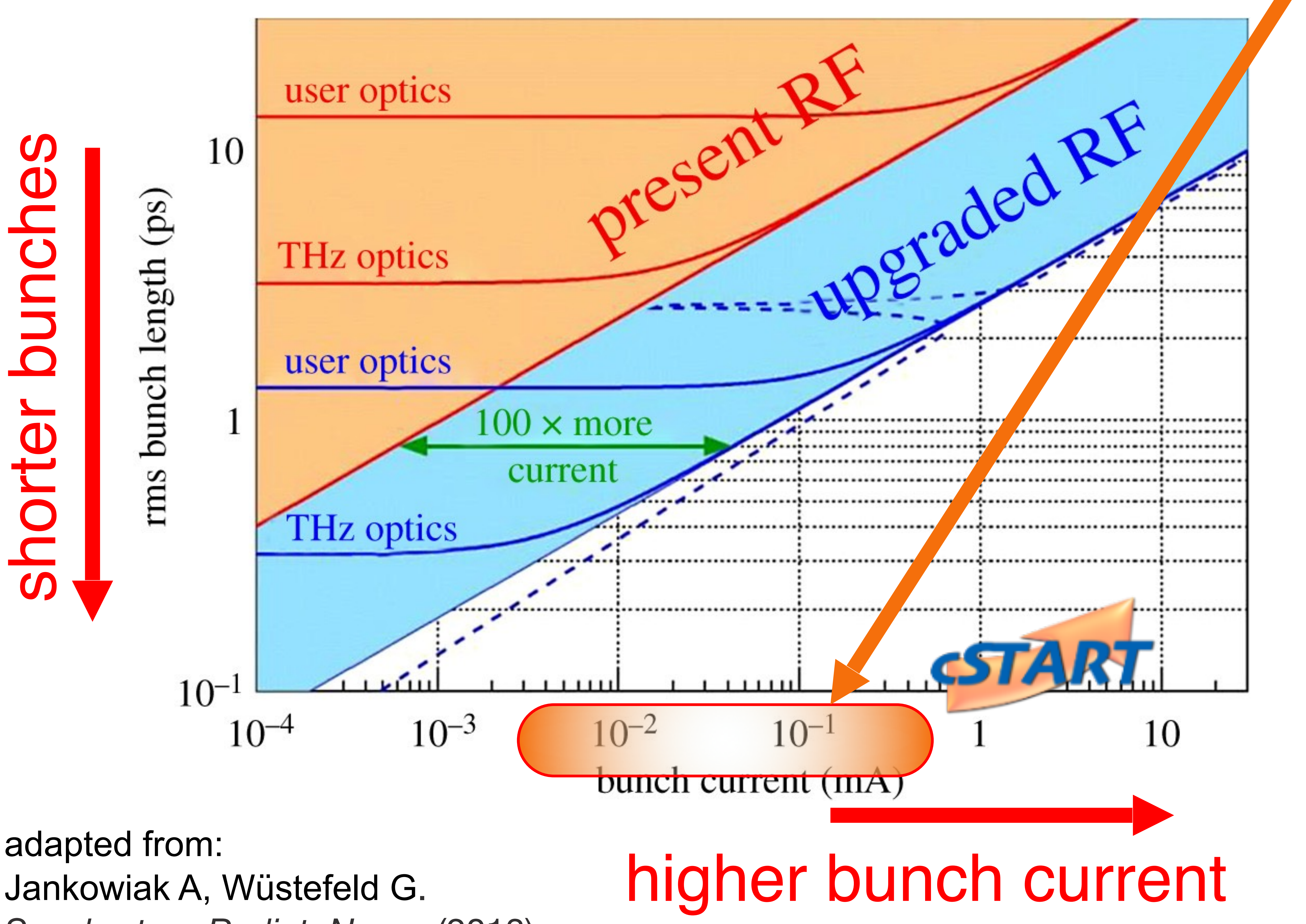



3.8% dE/E;
51 pC

89.7 ±3.4 MeV

# cSTART: Injection & Storage of Ultrashort Electron Bunches

<u>BESSY II (VSR Upgrade)</u>




adapted from:
Jankowiak A, Wüstefeld G.
*Synchrotron Radiat. News* (2013)

- expected stored bunch duration: <80 fs
- bunch charge: 1 – 100 pC (6.5 – 650 μA)

<u>compared to BESSY II:</u>

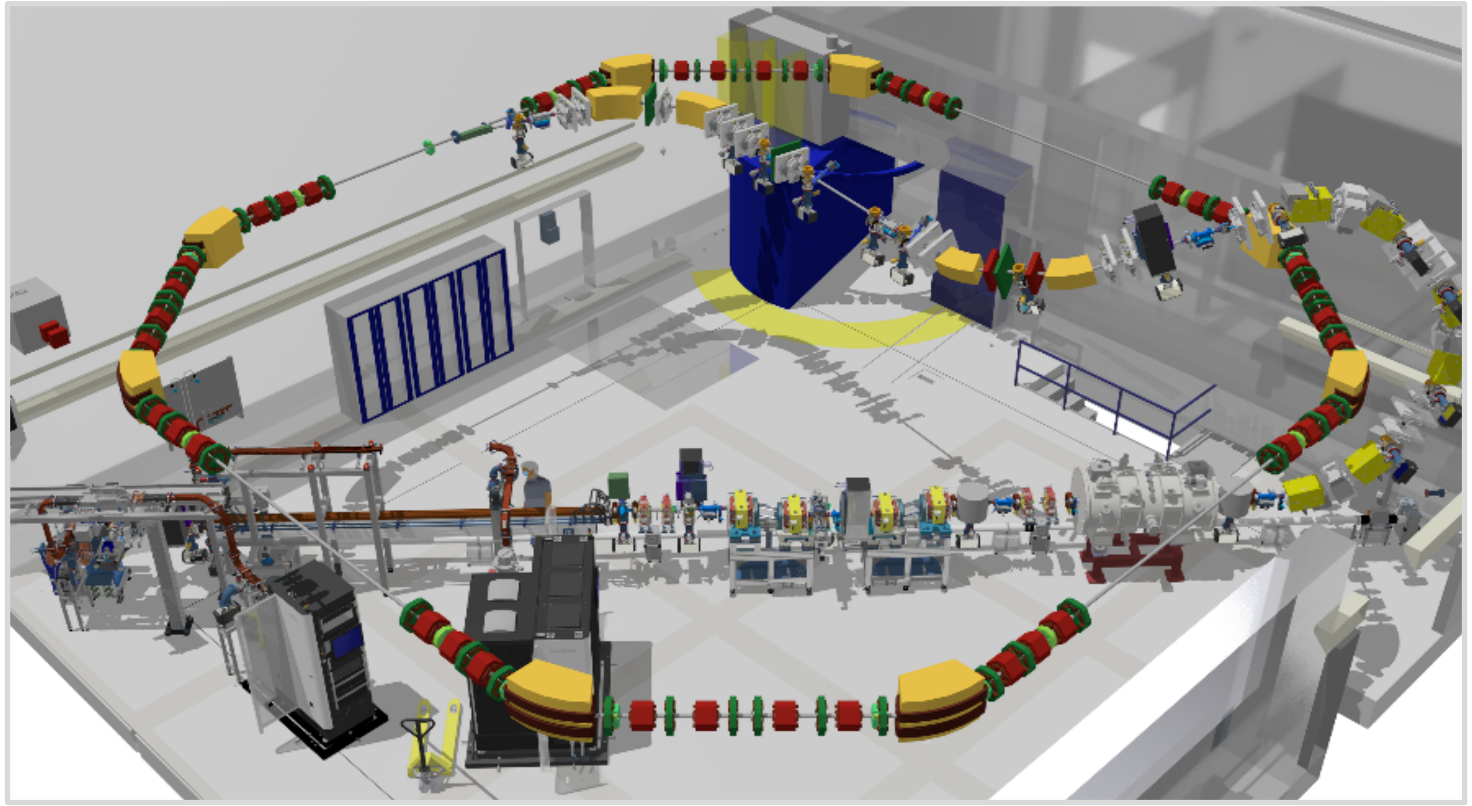
- ~30 times shorter bunches
- ~10-100 x more current

- <u>cSTART prototype experiments</u>
- direct injection of ultrashort electron bunches
- circulation and manipulation of ultrashort bunches

# cSTART: Motivation

- Lack of compact sources for ultrashort (<100 fs) X-ray, EUV, THz- sources with high repetition rate
- <u>Currently available:</u>
  - Ultrashort X-rays: XFELs (6): ~large facilities; expensive to build and operate
  - Synchrotrons (~50 world wide): longer bunch durations, typically ~10-100 ps

cSTART
(14 m diameter)



APS Synchrotron
Light Source (350m diameter)

www.aps.anl.gov

LCLS XFEL, SLAC
(2km long)


lcls.slac.stanford.edu

# Motivation: X-ray Free Electron Lasers (XFELs)

## LCLS-II Technical Parameters

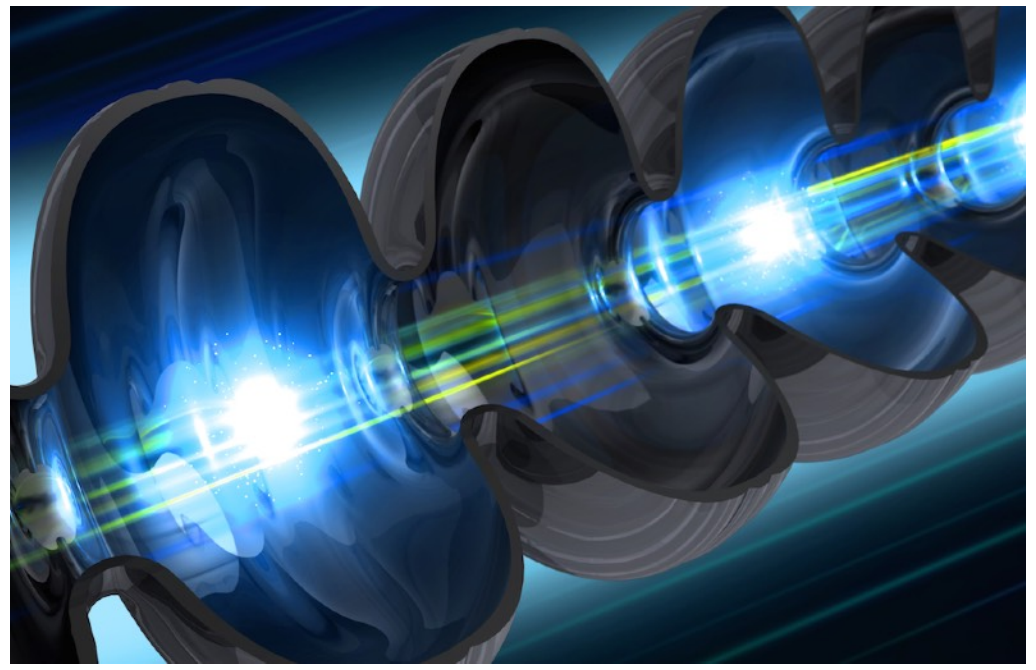
| Performance Measure | Threshold | Objective |
|---|---|---|
| Variable gap undulators | 2 (soft and hard x-ray) | 2 (soft and hard x-ray) |
| **Superconducting linac-based FEL system** | | |
| Superconducting linac electron beam energy | 3.5 GeV | ≥ 4 GeV |
| Electron bunch repetition rate | 93 kHz | 929 kHz |
| Superconducting linac charge per bunch | 0.02 nC | 0.1 nC |
| Photon beam energy range | 250–3,800 eV | 200–5,000 eV |
| High repetition rate capable end stations | ≥ 1 | ≥ 2 |
| FEL photon quantity ($10^{-3}$ BW) per bunch | $5\times10^{8}$ (10x spontaneous) @2,500 eV | > $10^{11}$ @ 3,800 eV |
| **Normal conducting linac-based system** | | |
| Normal conducting linac electron beam energy | 13.6 GeV | 15 GeV |
| Electron bunch repetition rate | 120 Hz | 120 Hz |
| Normal conducting linac charge per bunch | 0.1 nC | 0.25 nC |
| Photon beam energy range | 1–15 keV | 1–25k eV |
| Low repetition rate capable end stations | ≥ 2 | ≥ 3 |
| FEL photon quantity ($10^{-3}$ BW[a]) per bunch | $10^{10}$ (lasing @ 15 keV) | > $10^{12}$ @ 15 keV |

SLAC D. Gonnella, LCLS-II Commissioning

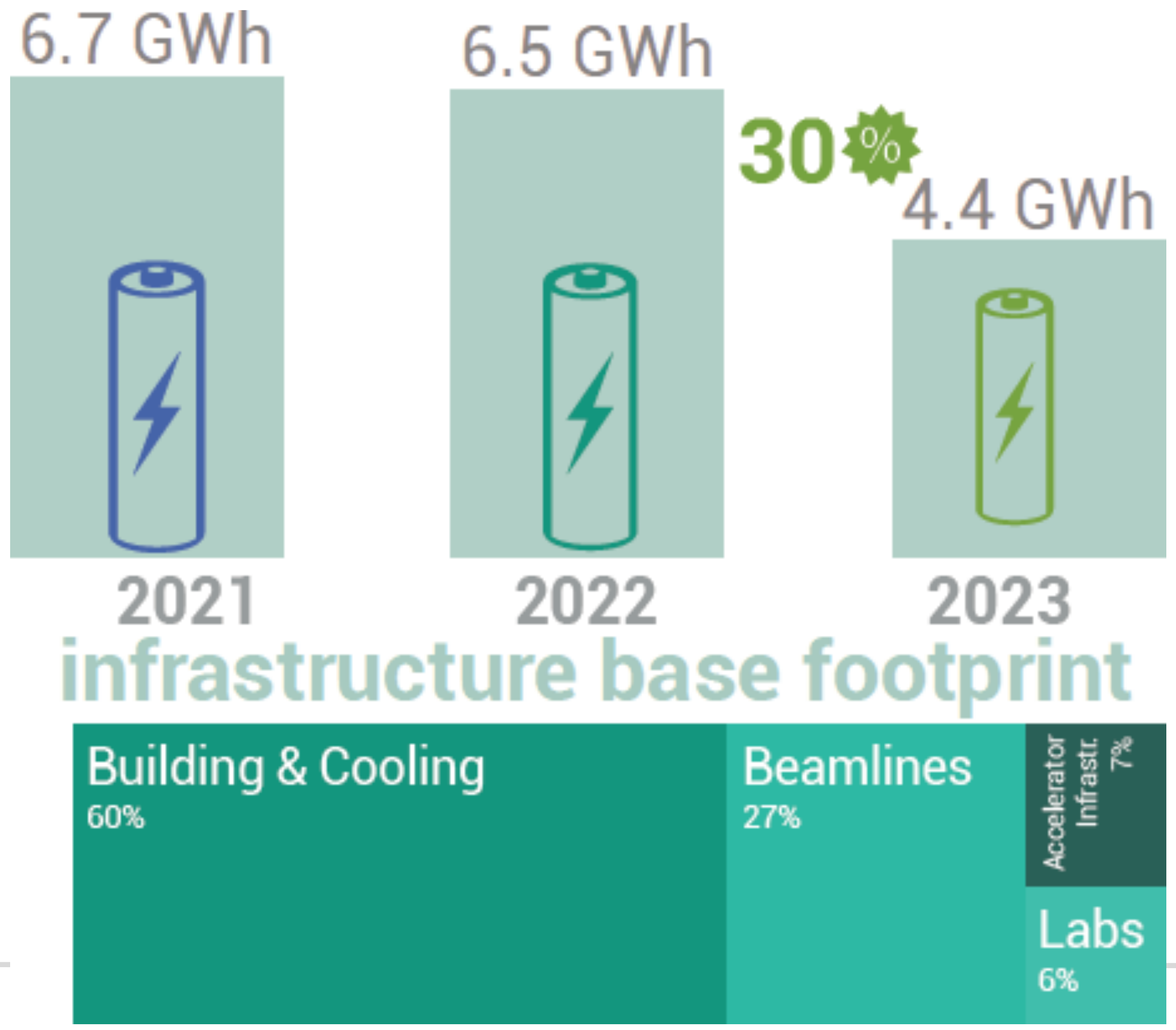
D. Gonnella, SLAC

$P_{avg}$ = 0.4 MW in beam!

single pass machine, beam gets dumped after each pass!
=> ~3 GWh/year loss only in beam (not including klystrons, cooling, power efficiency, …)!

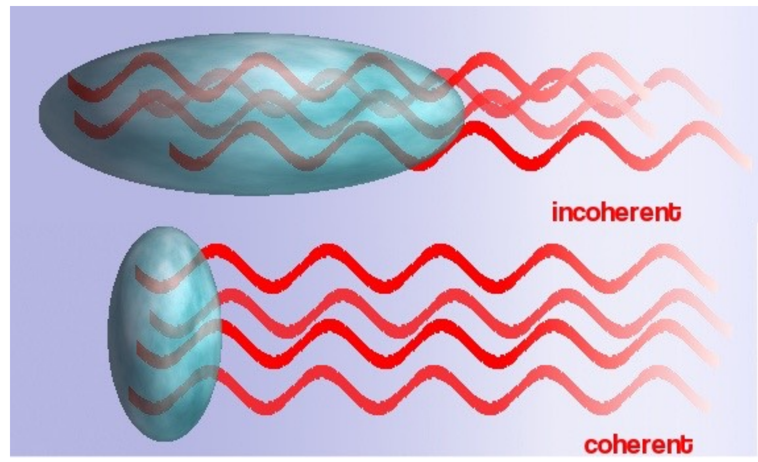


KARA (incl. building, labs, etc)

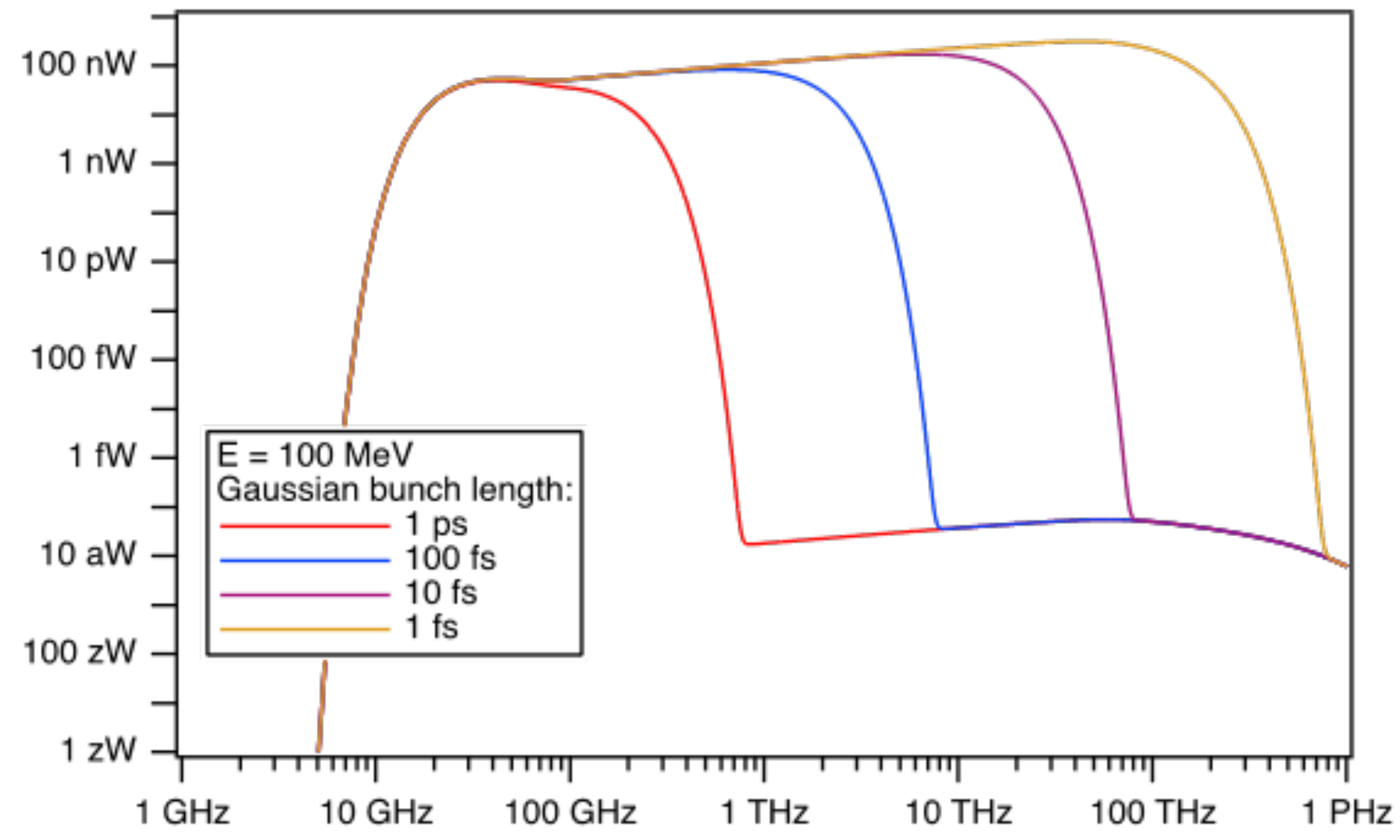


# High Power THz Generation@cSTART

- Coherent emission of THz radiation (cSR or undulator)
- Wavelength > emitting structure ⇒ intensity $\propto N^2$




[Courtesy A.-S. Müller]




courtesy: J. Steinmann


14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM108

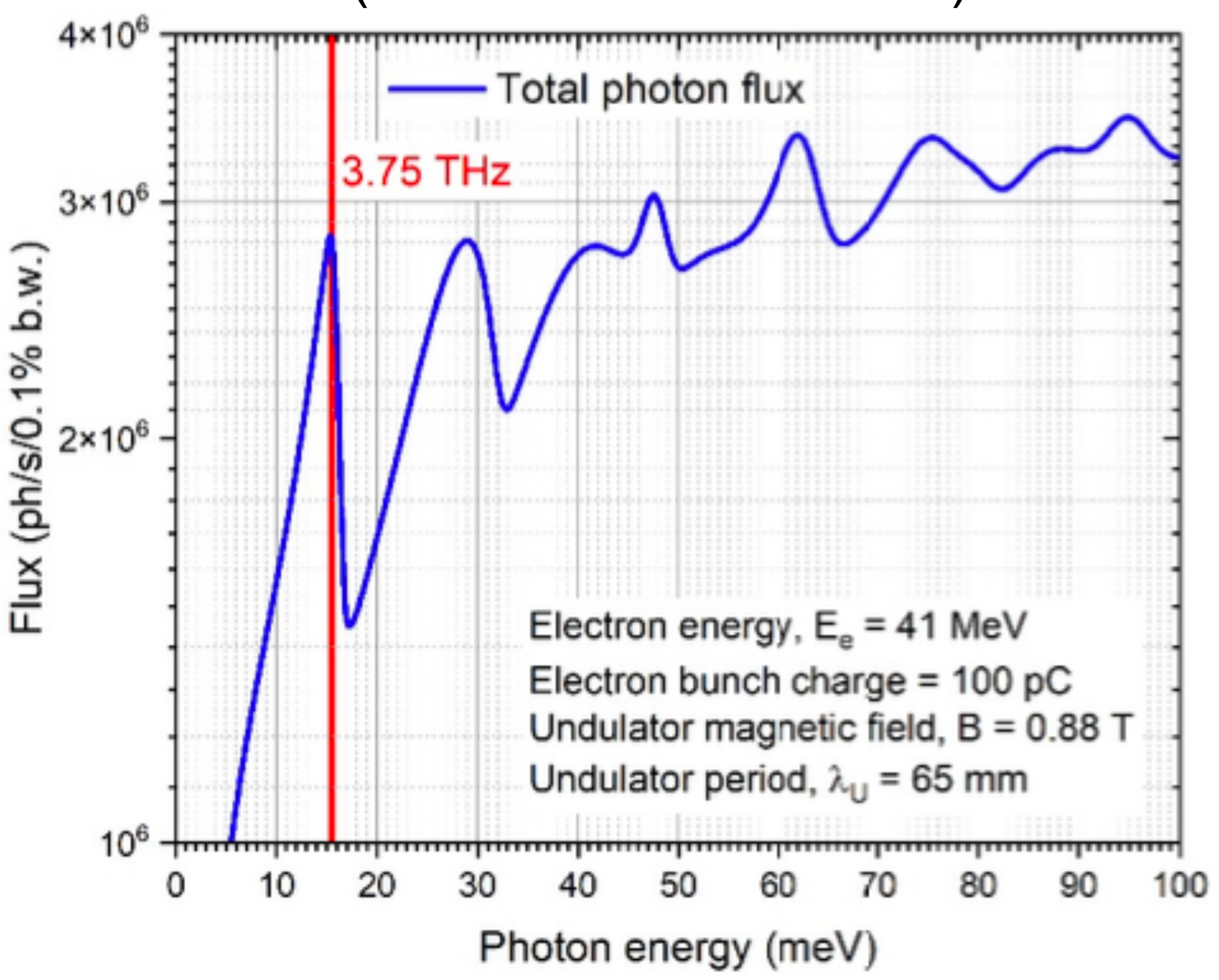

**A THz SUPERCONDUCTING UNDULATOR FOR FLUTE – DESIGN PARAMETERS AND LAYOUT**


A. W. Grau*, J. Arnsberg, N. Glamann, S. Grohmann, B. Krasch, D. Saez de Jauregui,
Karlsruhe Institute of Technology, Karlsruhe, Germany
A. Hobl, H. Wu, Bilfinger Noell GmbH, Würzburg, Germany

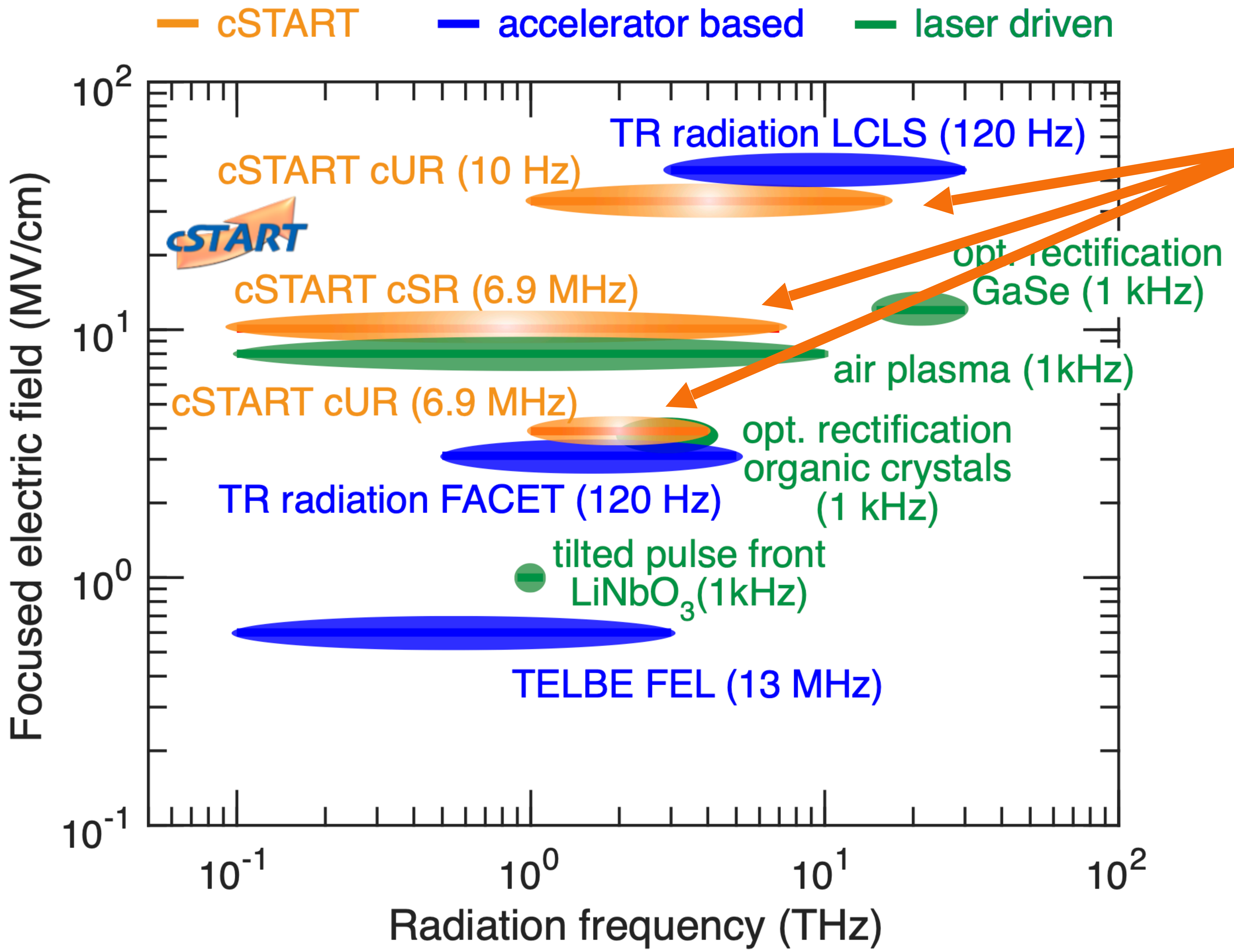

Table 2: Specified General Properties of the Undulator

| Quantity | Value | Unit |
|---|---|---|
| Period length ($\lambda_U$) | 65 | mm |
| Magnetic field (B) | > 0.88 | T |
| K-value | > 5.34 | |
| Minimum vacuum gap ($g_v$) | > 35 | mm |
| Length flange to flange ($l$) | 1800 | mm |
| Maximum ramping time ($t_R$) | < 300 | s |
| Power supply stability at nominal current | $< \pm 10^{-5}$ for 8 h | |
| Beam heat load | 0.3 | W |

(simulation: incoherent)



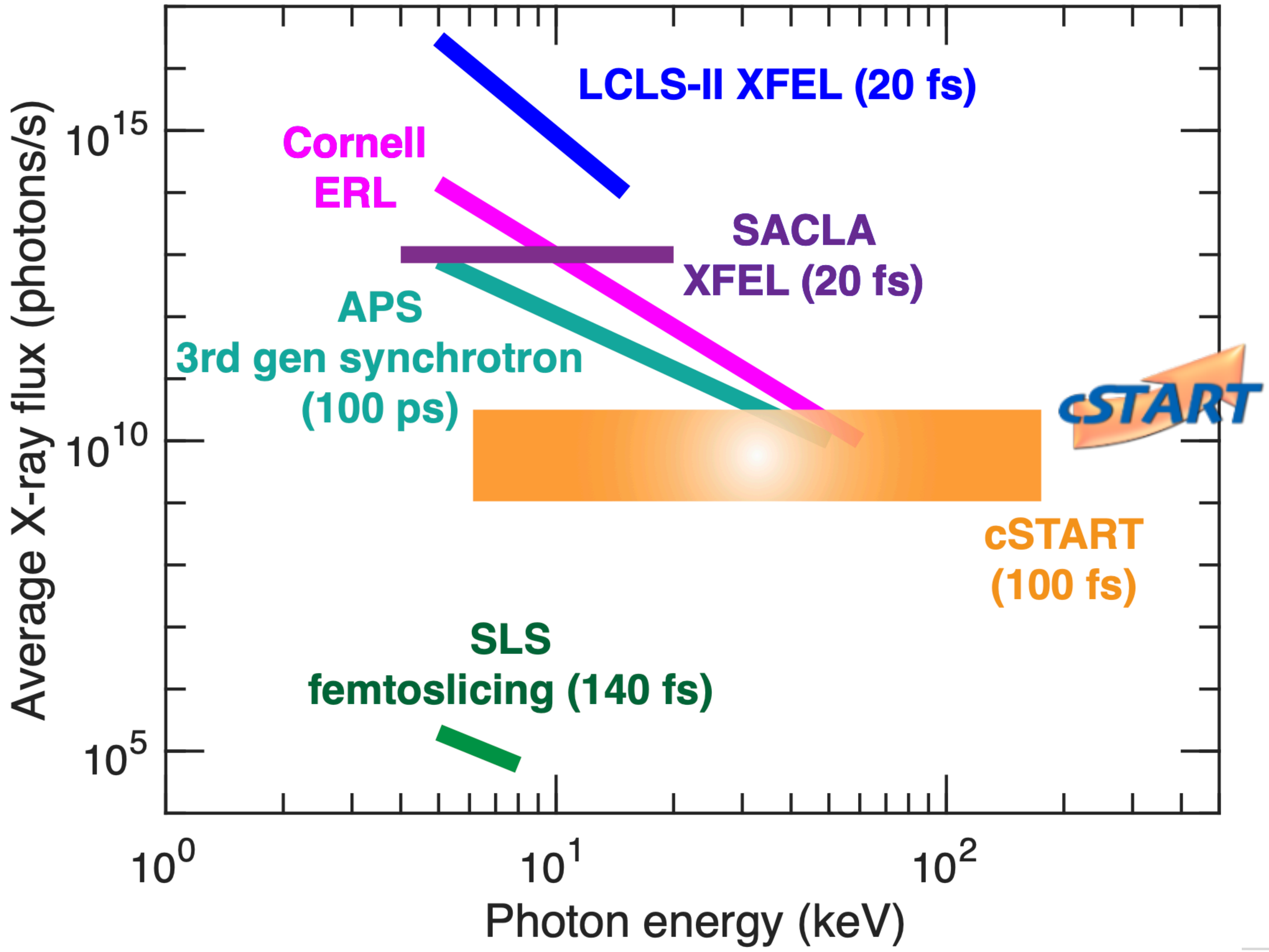
# Future Light Source I:
# Ultrafast High-field THz Radiation Source




cUR: coherent undulator radiation  TR: transition radiation
cSR: coherent synchrotron radiation  FEL: free electron laser

- THz generated via coherent synchrotron/ undulator emission
- Ultrashort (few 100 fs) THz pulses
- High repetition rate
- Extreme electric fields
  - 33 MV/cm = 3.3 GV/m @10Hz
  - 10 MV/cm = 1.0 GV/m @6MHz

# Future Light Source II:
## Ultrashort X-ray Pulses with High Average Power




- X-rays generated via inverse laser-driven inverse Compton scattering
- Ultrashort (<100 fs) X-ray pulses
- High avg. photon flux (~2x$10^{10}$ phot/sec)
- High photon energy (up to 200 keV)
- Compact, energy efficient machine

APS Synchrotron Light Source

www.aps.anl.gov

LCLS X-ray Free Electron Laser

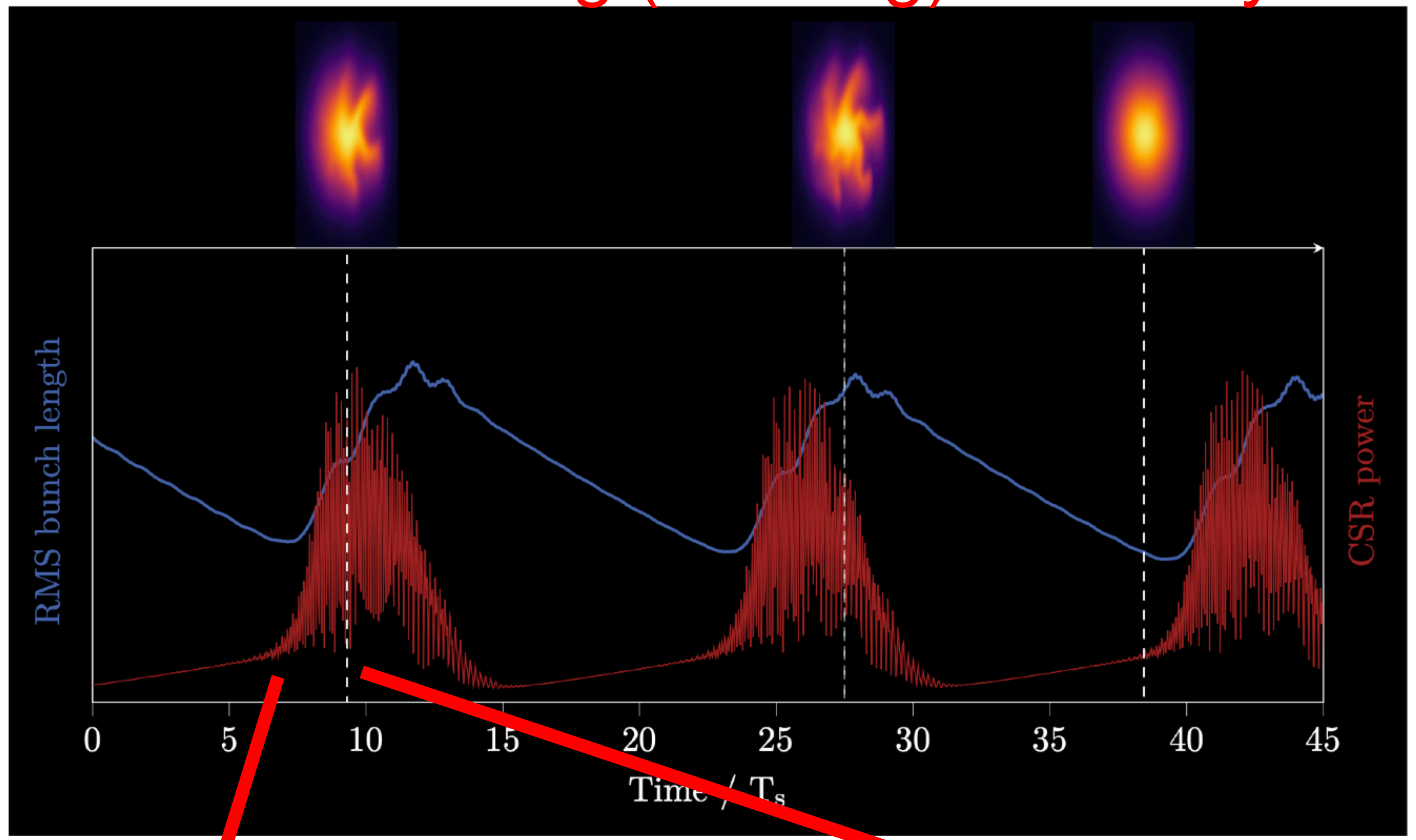

lcls.slac.stanford.edu

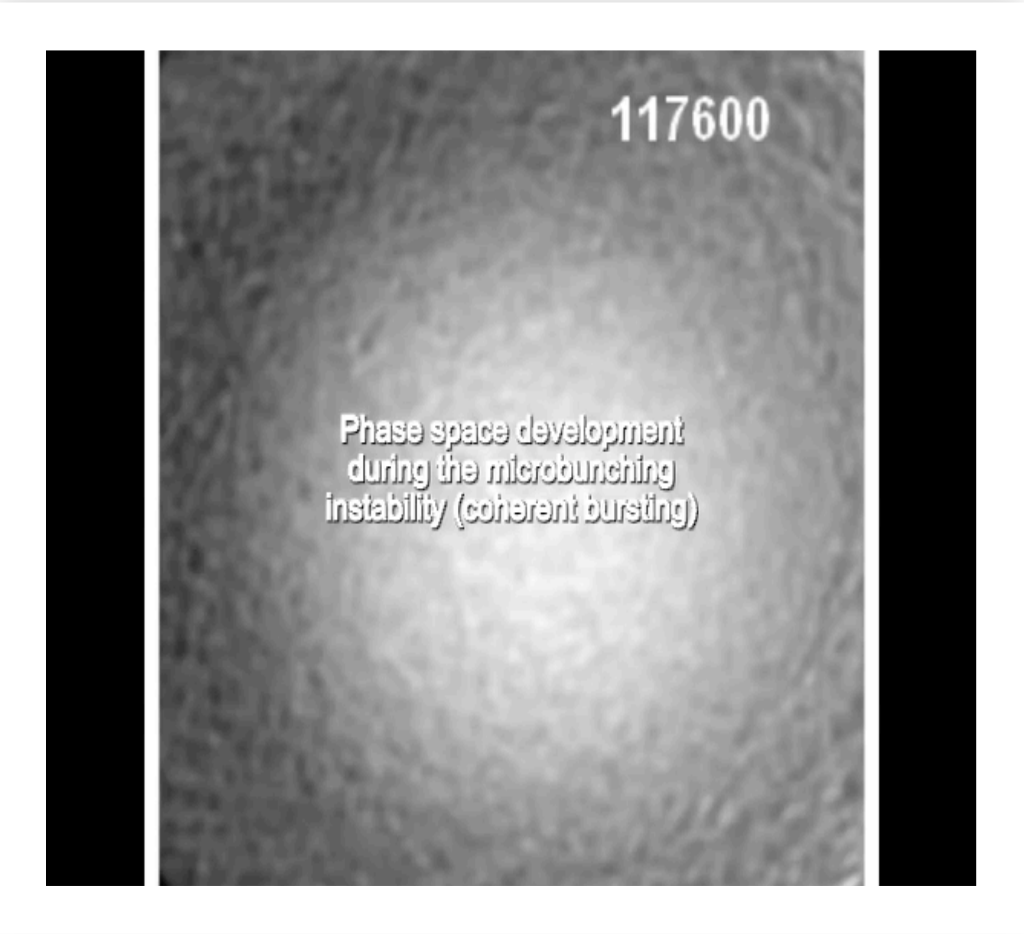
# Non-equilibrium Beam Physics@KARA 2.5 GeV Storage Ring

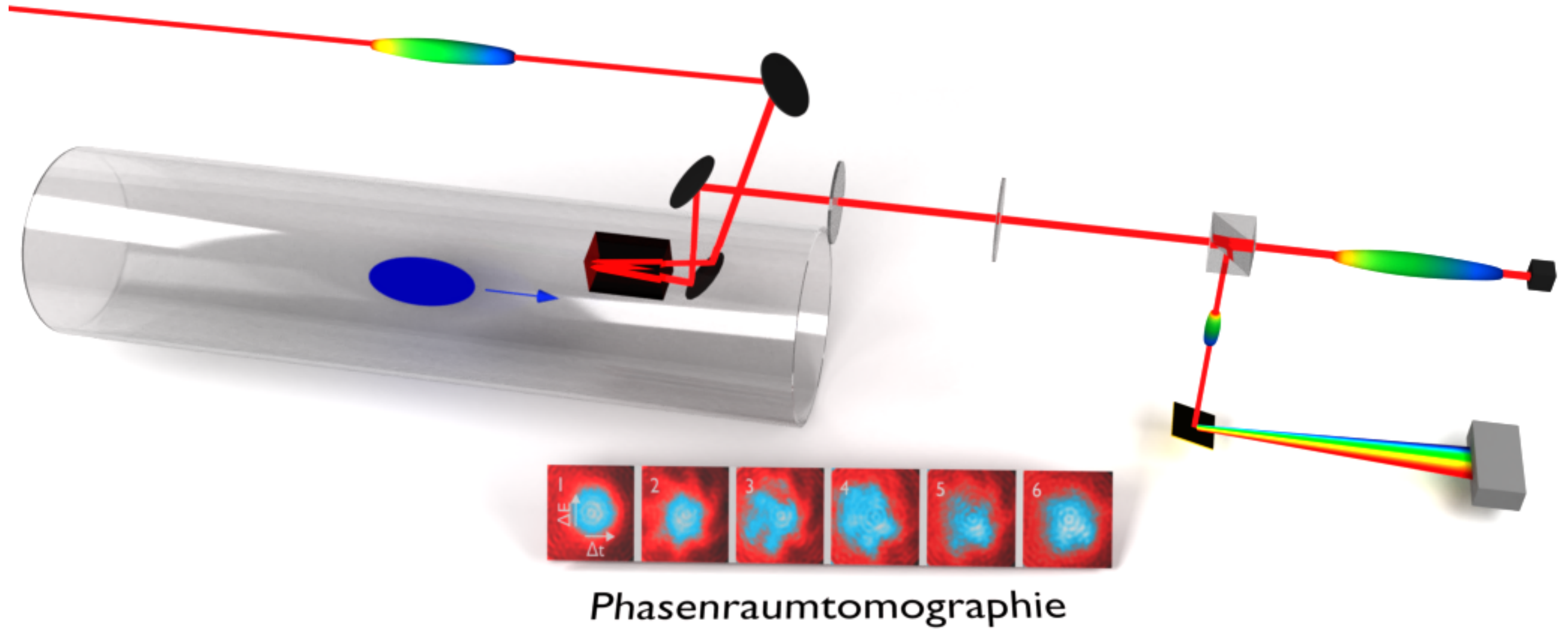
Karlsruher Institut für Technologie

- Bunch duration ~3 ps
- Fundamental accelerator physics study: microbunching instability
- Provides holistic understanding of non-equilibrium physics of short-pulsed particle beams
- highly relevant also for other fields: plasma physics, inertial & magnetic confinement fusion, free-electron lasers, future light sources, …
- Currently limitation for high-current ultrashort bunches in storage rings

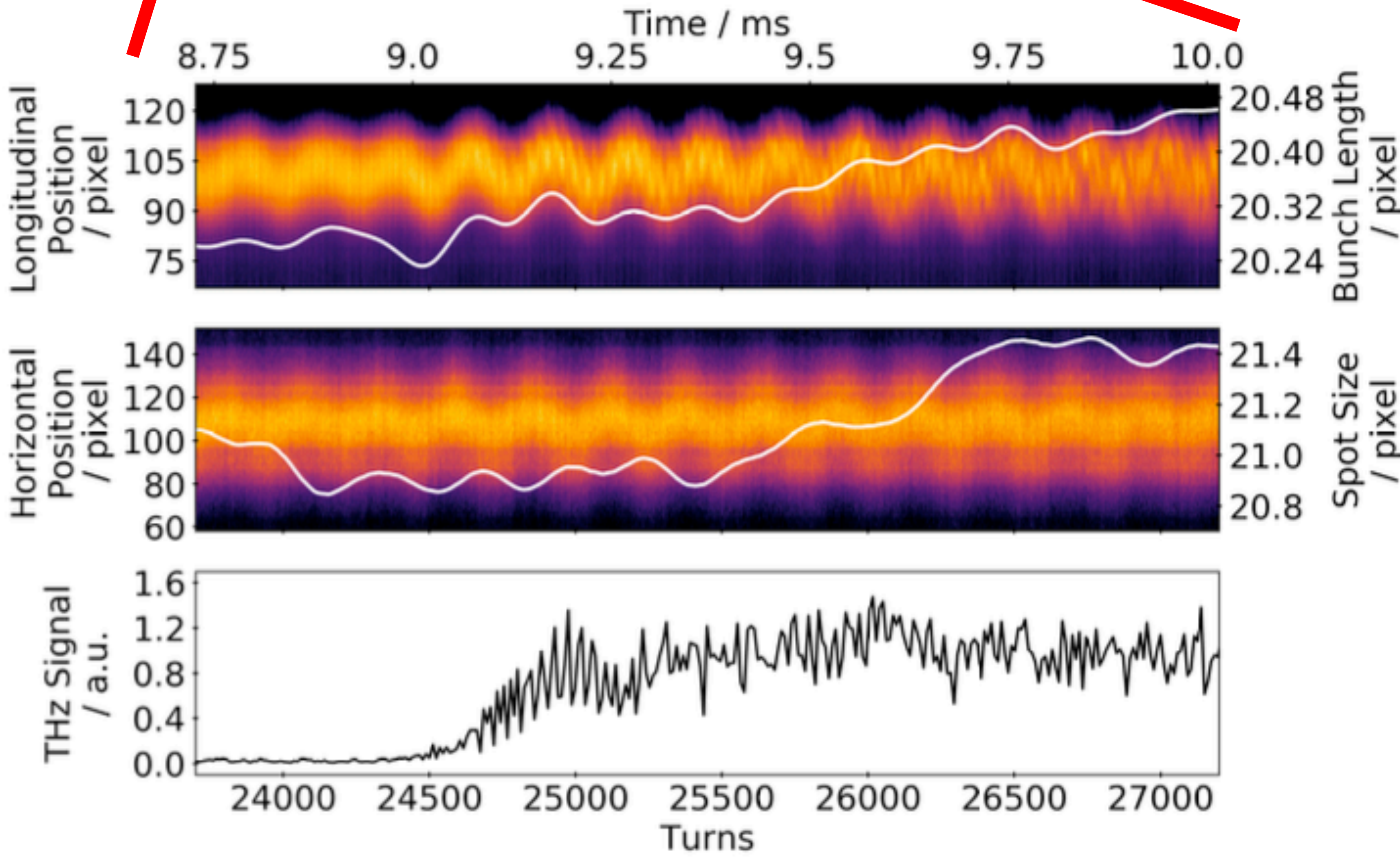
microbunching (bursting) instability




Funkner et al. ***Scientific Reports*** 13 (2023)
doi:10.1038/s41598-023-31196-5




M. Brosi, Dissertation



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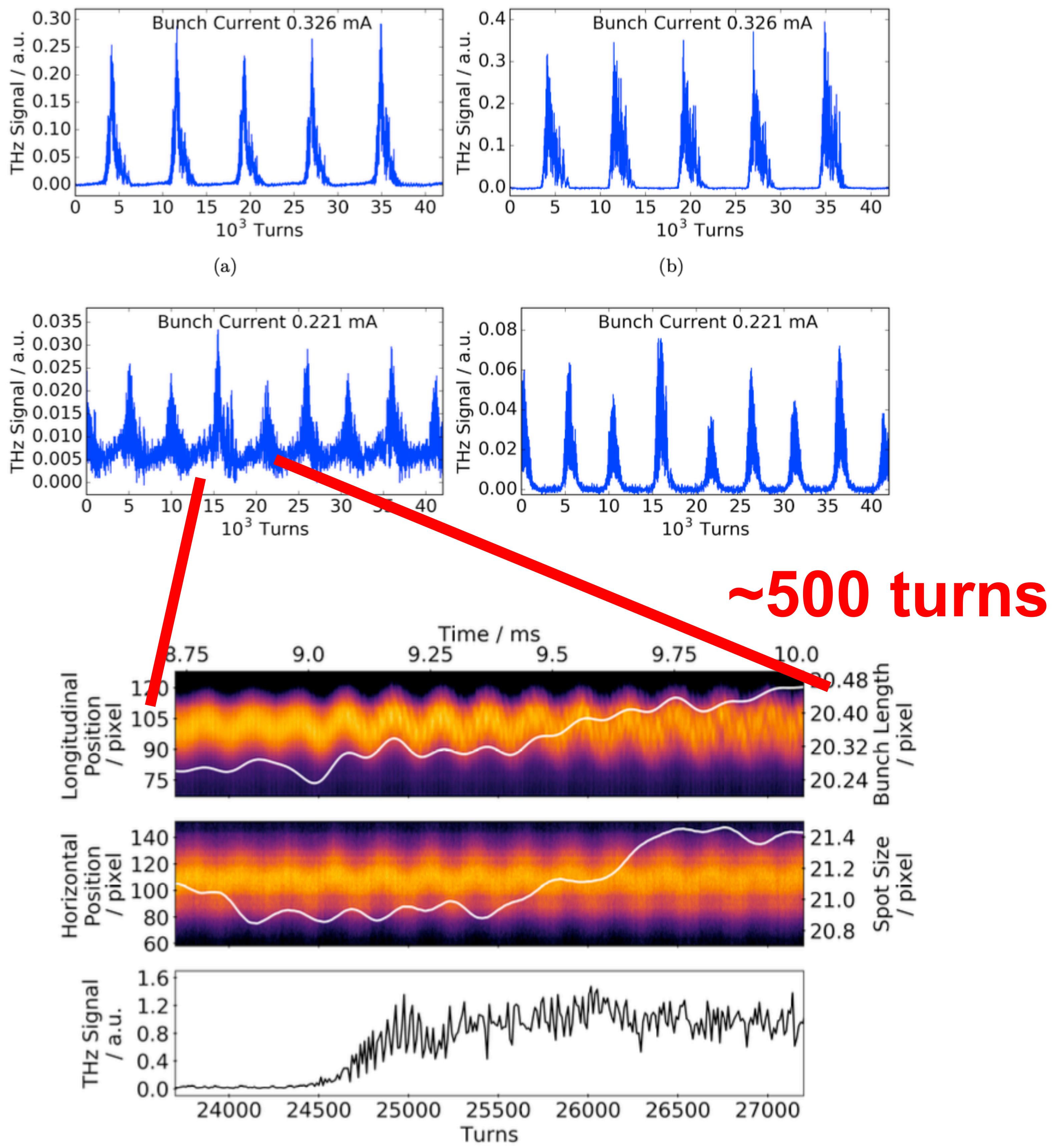
# cSTART Scientific Goals: Study of Ultrafast Beam Dynamics of Ultrashort Electron Bunches

Karlsruhe Institute of Technology

## Microbunching instability@KARA 3 ps bunches

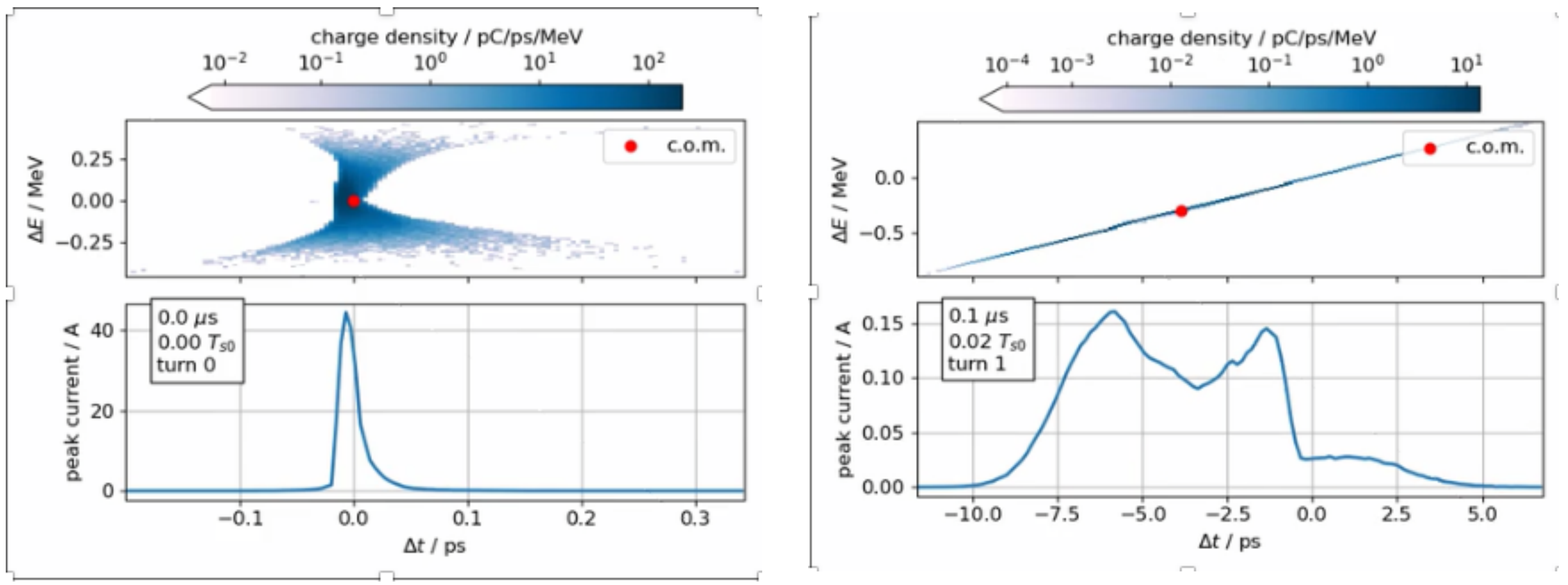



M. Brosi, Dissertation

## Superradiance @cSTART 17 fs bunches

initial bunch: 17 fs

**turn 1**: 6 ps



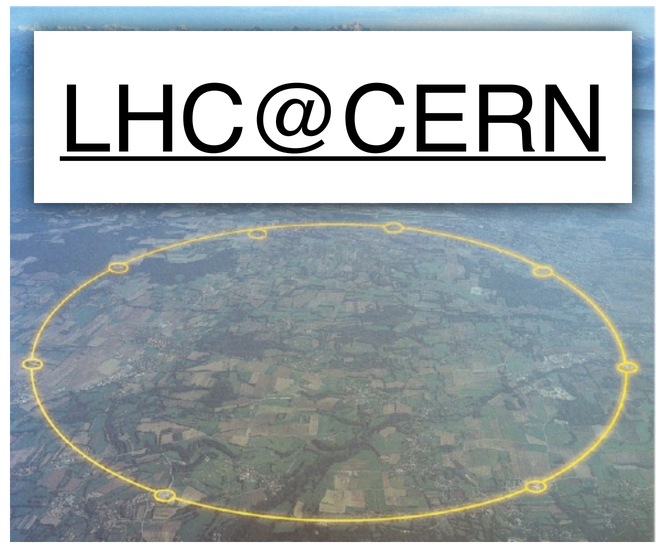

- ultrafast, highly nonlinear beam dynamics: already significant dynamics within 1 turn
- even within 1 dipole bend!

# Outline

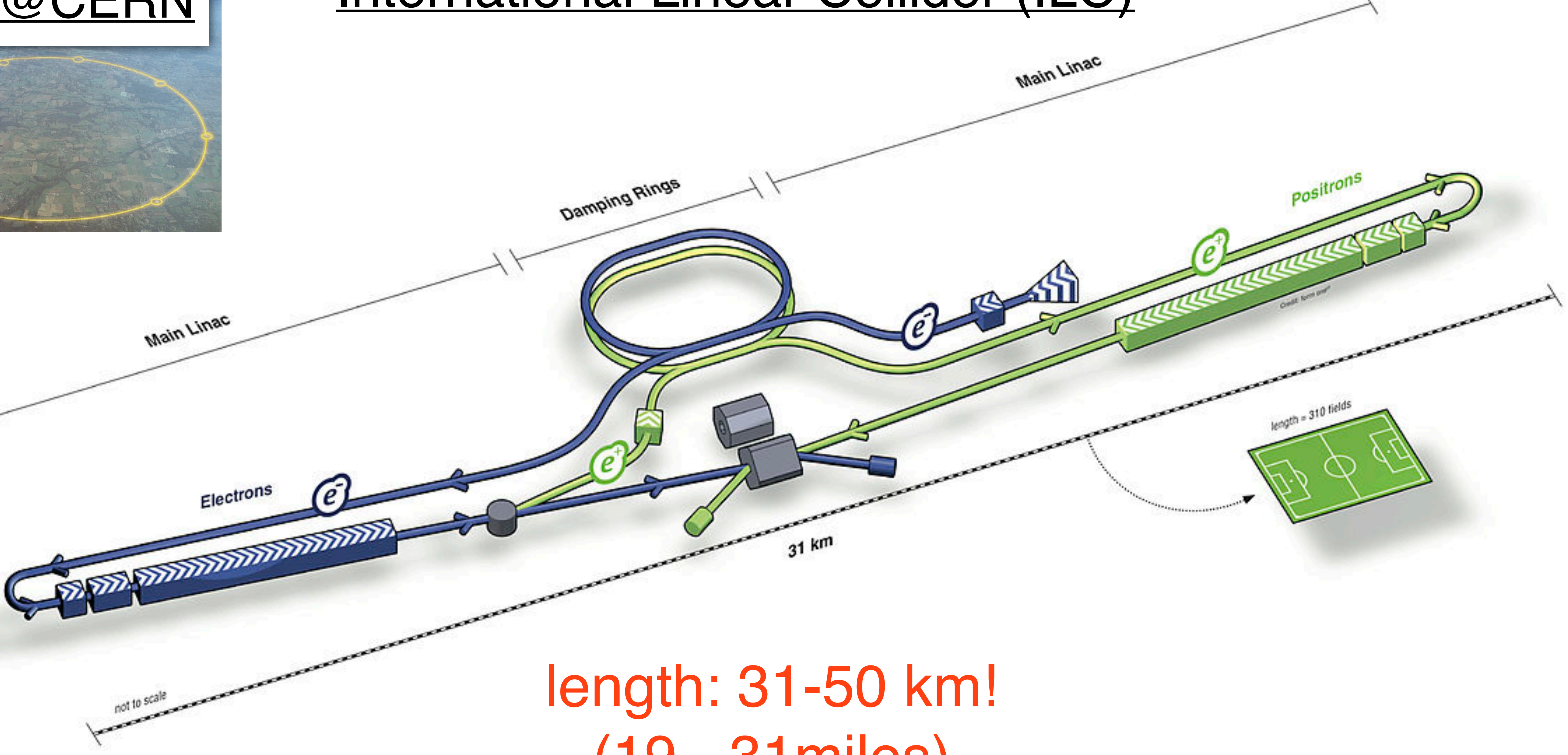
- Particle Accelerators and Laser-Plasma Acceleration (LPA)
- Applications of Laser-Plasma Accelerators
  - Laser-driven X-ray Sources
- Challenges and New Research Directions
  - Next-generation hybrid accelerators
  - Next-generation laser-plasma accelerators
- Summary

# Future Particle Collider

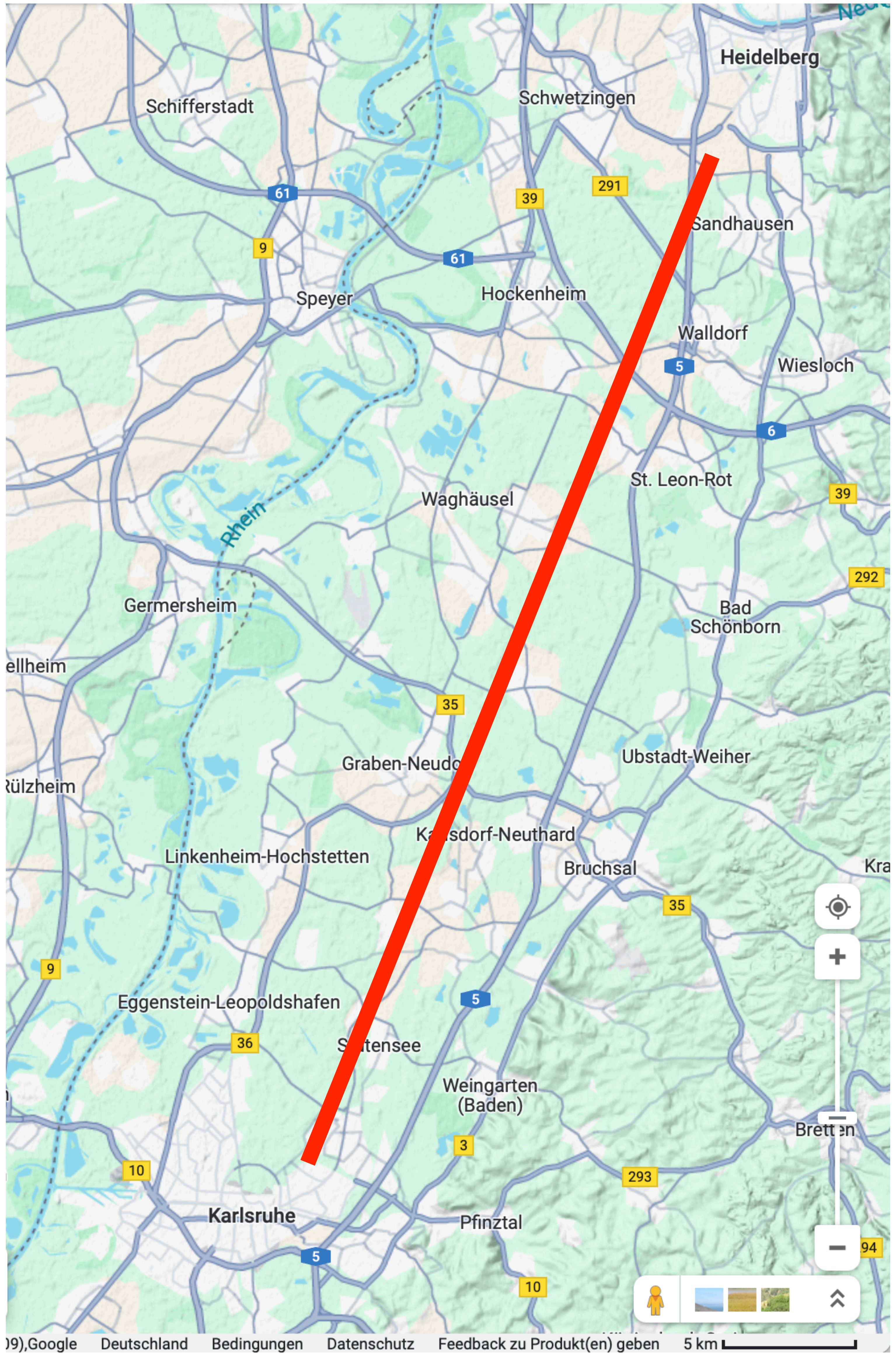
- 10 TeV center of mass energy
- One proposed incarnation: International Linear Collider (ILC)



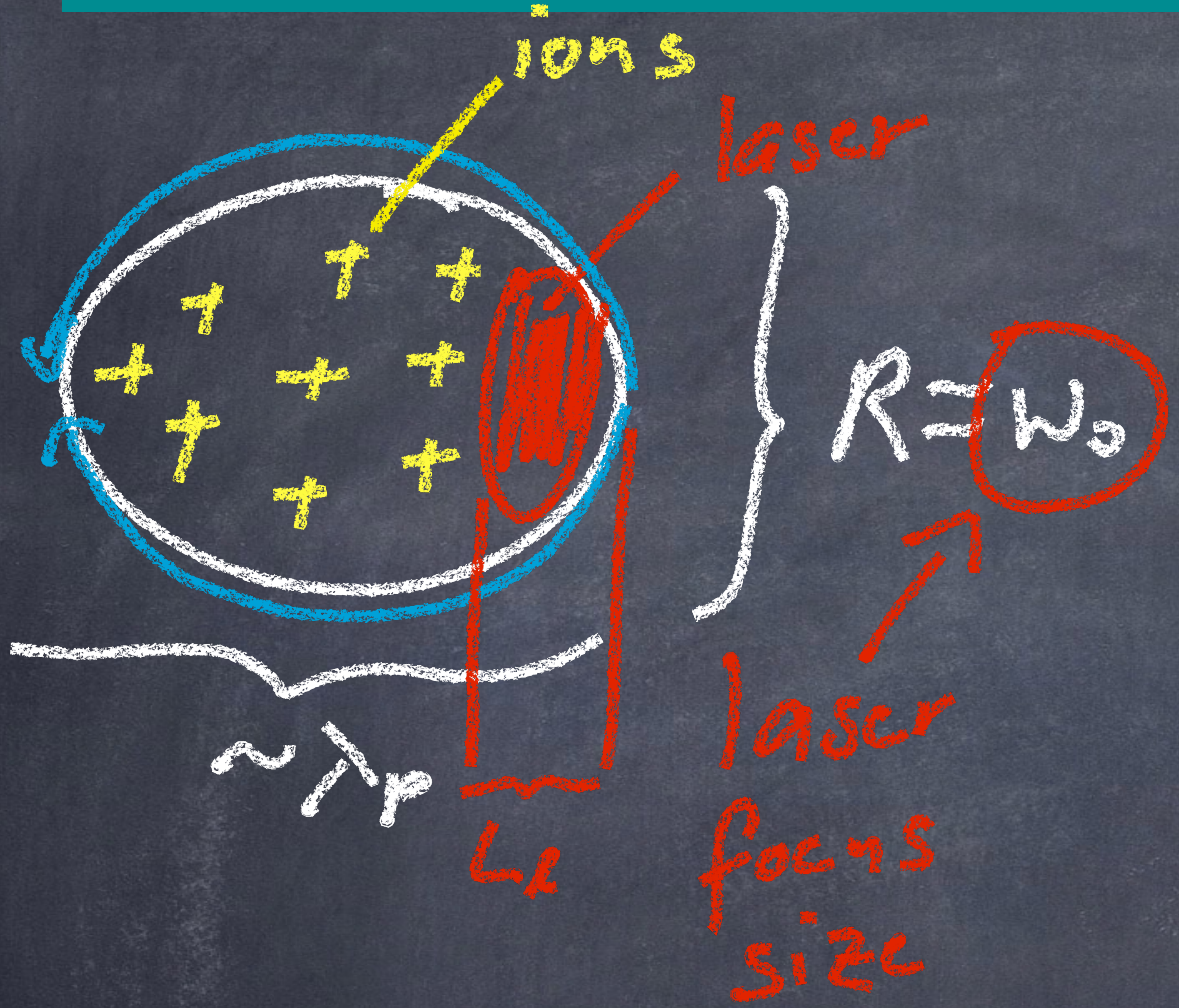

International Linear Collider (ILC)

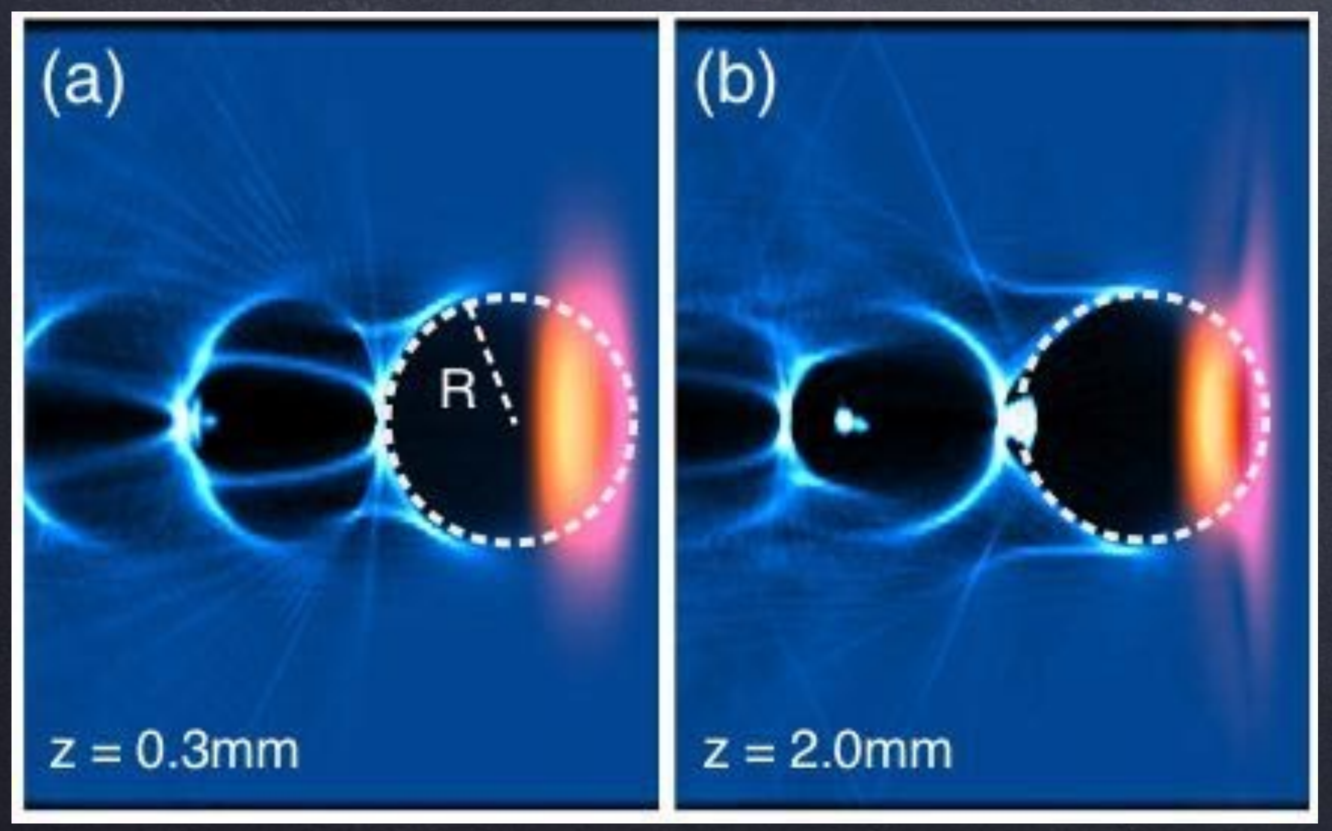



length: 31-50 km!
(19 - 31miles)



# LWFA in the “Bubble” Regime




Lu et al., PRSTAB (2007)

**Required laser parameters:**

- Laser pulse duration: < plasma period
- intensity: $a_0 > 3$
- focus size: $k_p w_0 = 2\sqrt{a_0}$

=> P > 100 TW !

- Short-pulse, high laser power (>100 TW)
  -> restricts usable driver laser technology
    -> challenging to achieve high repetition rate
    -> limiting LPA operation and its wide spread
- Comparably low laser-to-electron beam energy conversion efficiency (instrinic, few percent)
- Limited accelerating fields (few 10s of GV/m)
- Highly nonlinear regime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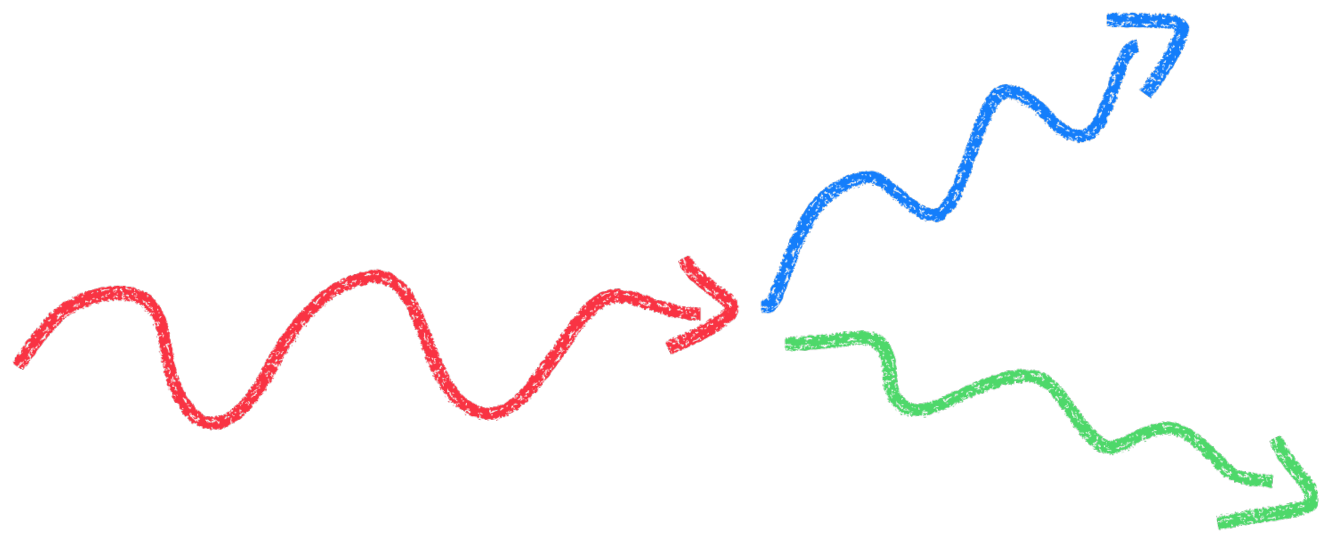
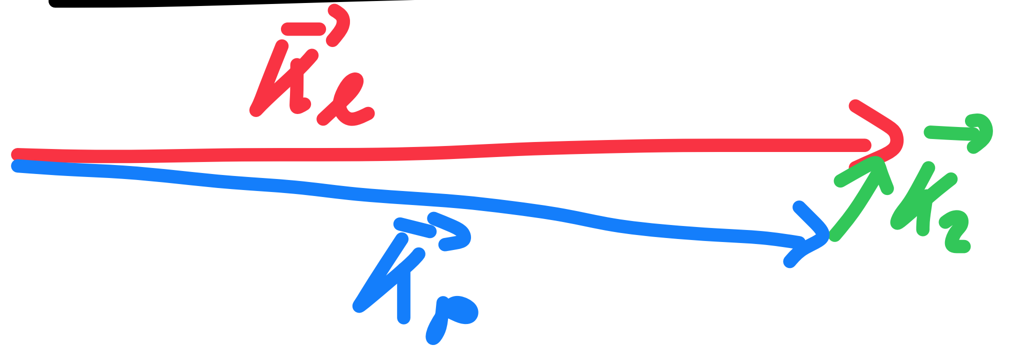
# Parametric Laser-Plasma Acceleration (PEPA)
# A Fundamentally New Regime and Shift in Paradigm

- Parametric laser-plasma interactions near the quarter-critical plasma density
  - energy conservation: $\omega_\ell = \omega_1 + \omega_2$
  - momentum conservation: $\underbrace{\vec{k}_\ell}_{\text{laser}} = \vec{k}_1 + \vec{k}_2$



- Stimulated Raman Scattering (SRS)[1]

absolute instability!




· 1: plasma wave
· 2: Raman scattered light

$$\Bigg\}\ @\ n_{cr}/4:\quad \omega_p = \frac{\omega_\ell}{2};\ \vec{k}_p \approx \vec{k}_\ell \qquad \omega_2 = \frac{\omega_\ell}{2};\ \vec{k}_2 \approx 0$$

[1]J.F. Drake & Y.C. Lee, PRL (1973)

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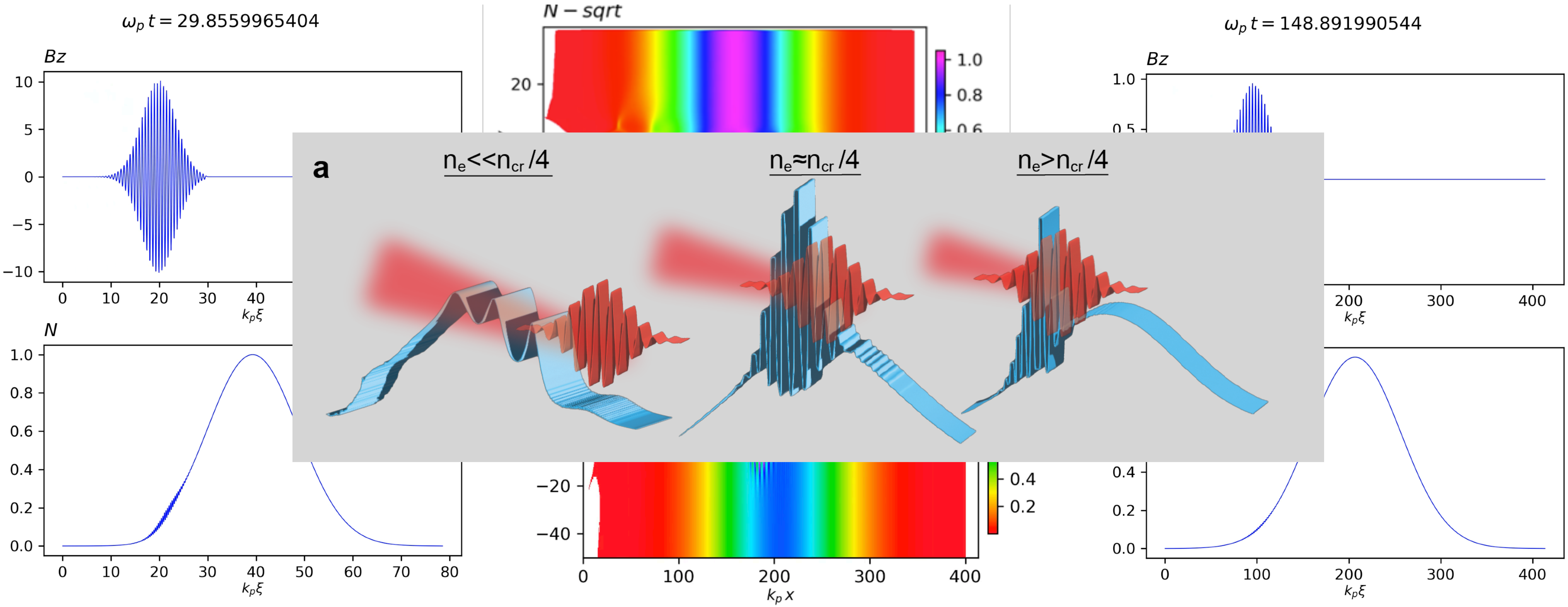
# Parametrically-Excited Laser-Plasma Acceleration (PEPA)

## $a_0$ = 0.5

density << ¼ $n_{cr}$ ($k_l/k_p$ = 20)

2D density snapshot

density ~ ¼ $n_{cr}$ ($k_l/k_p$ = 1.9)

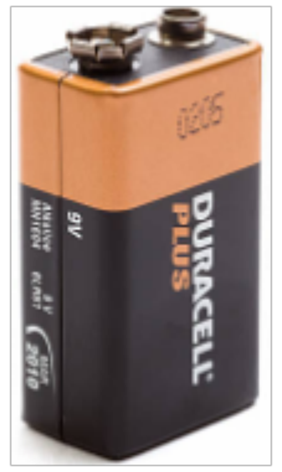


# Next-Generation Laser-Plasma Acceleration

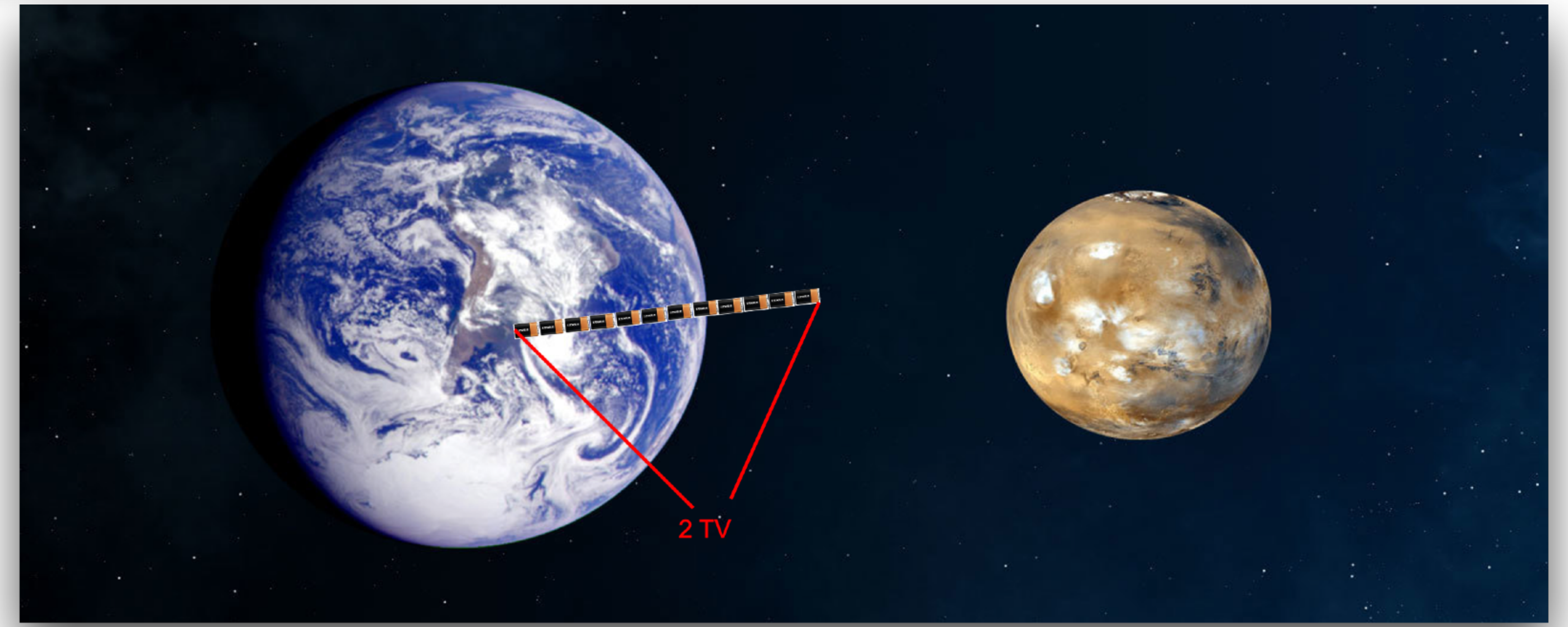
Karlsruher Institut für Technologie

- Demonstration of efficient electron generation in fundamentally new parametrically excited laser-plasma acceleration (PEPA) regime
- Generation of bunches with charge of up to 10 nC (using 3 TW, 120 mJ laser)
- 16% laser-to-electron beam energy conversion efficiency
- Efficient plasma wave generation for laser with pulse length many plasma periods long!
  -> potential to explore different driver laser technology
- Accelerating fields: 3 TV/m!
- Laser-plasma interaction (plasma wave excitation, laser evolution) markedly different from LPI at lower densities (bubble regime)


<u>To generate 3 TV-field with 9 V batteries:</u>
Requires ~300 billion batteries (in series)
or a length of 15 million km
(1/3 distance Earth to Mars)




height 50 mm



# Conclusions

Karlsruher Institut für Technologie

- Tremendous progress in LWFA over the last two decades
  - first applications of LWFA electron bunches: lightsources (undulator, betatron, Thomson)
  - first applications of those lightsources
- Field has become more mature, moving from proof-of principle experiments to first devices and applications
  - going from: hitting target with sledge hammer blindfolded to: hitting with an even bigger hammer while slightly peaking
- Research community is vibrant and highly dynamic; game-changing new ideas are quickly implemented
  - New solutions directly applicable for industry and potential startups
- Still many challenges ahead: improve beam quality for:
  - compact light sources, table-top XFELs, future particle colliders, applications
- New projects @KIT:
  - cSTART ring, next-generation plasma accelerators, compact light sources, diagnostics
- Also: Compact sources for medical applications:
  - less radiation-toxic cancer treatment
  - higher resolution imaging with less dose