Laser-Plasma Accelerators: Particle Acceleration in a Nutshell

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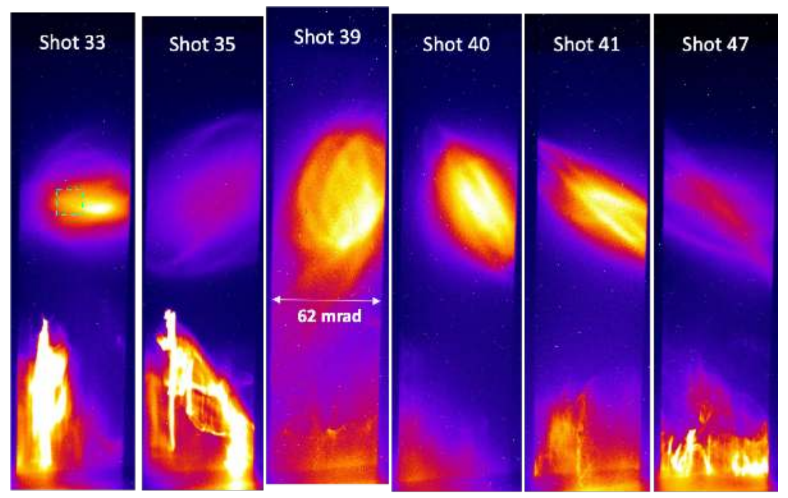
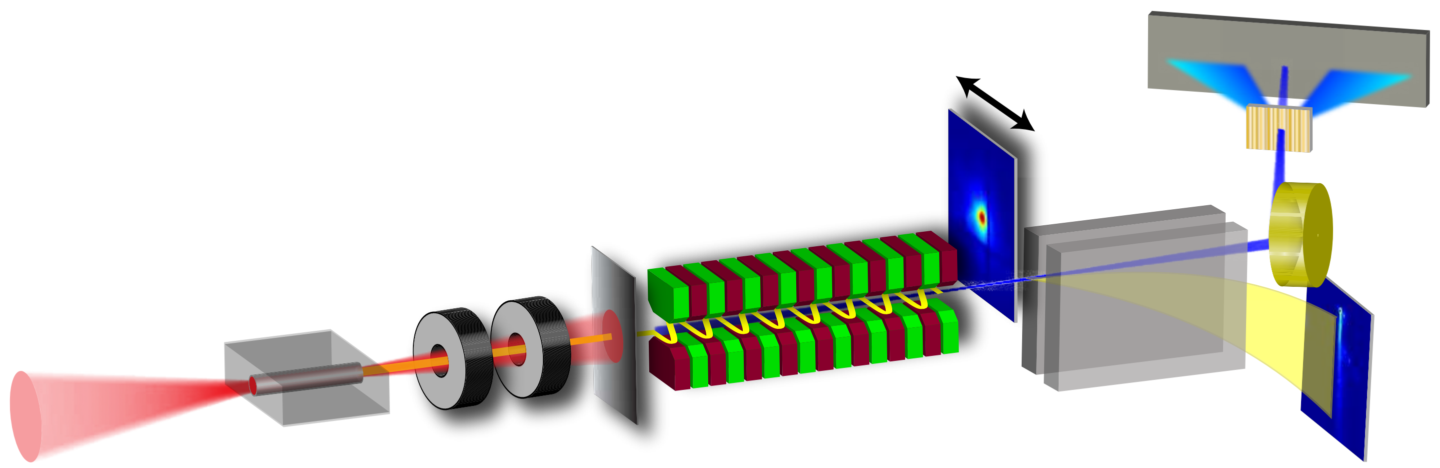
Research Overview

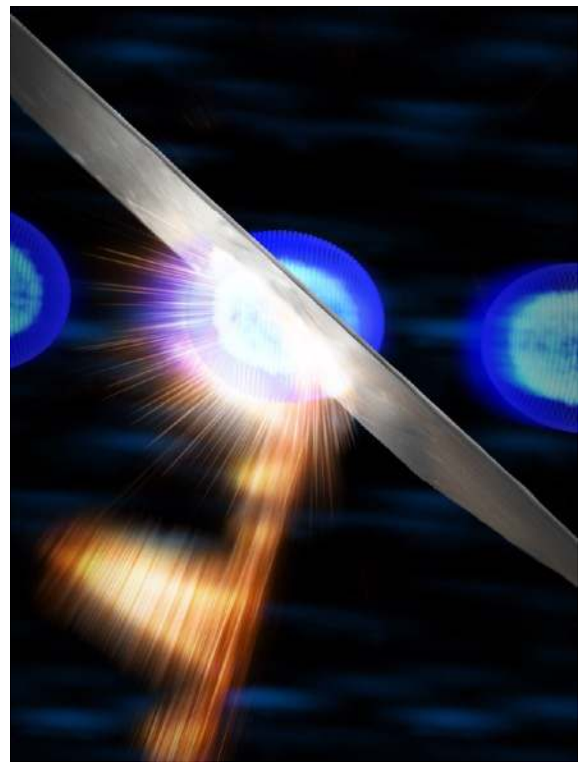
Karlsruher Institut für Technologie

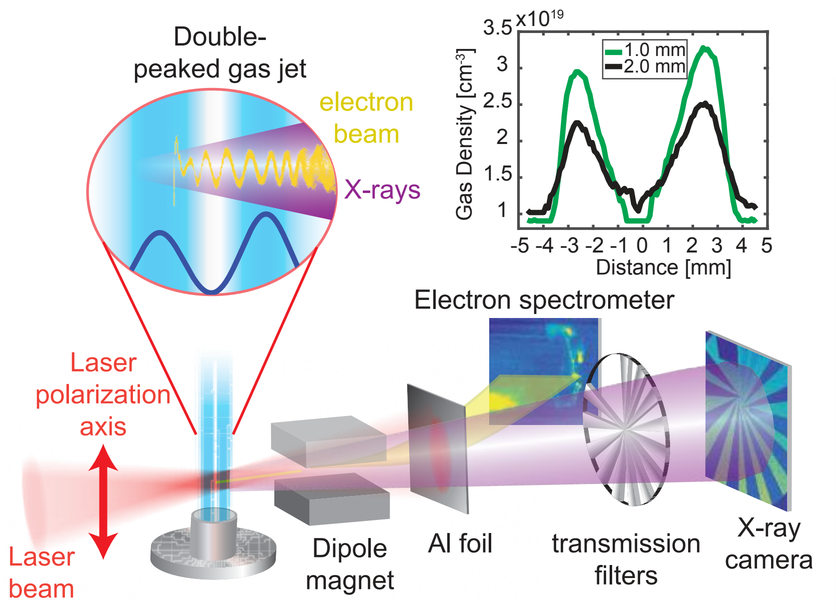
Laser-driven accelerators, ultracompact light sources & applications

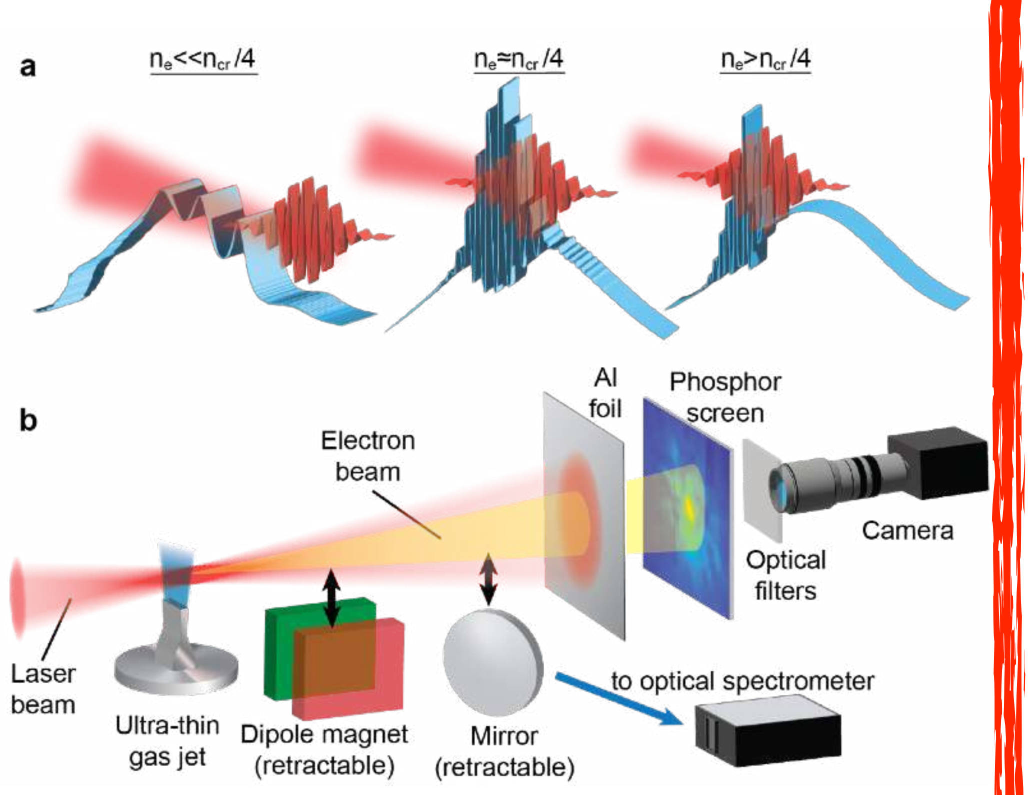
- *Laser-wakefield acceleration*
- *Compact light sources*
- *Next-generation laser-plasma accelerators*











Ultrafast and Nonlinear X-Ray Science and Applications

LETTERS
PUBLISHED ONLINE: 27 OCTOBER 2013 | DOI: 10.1038/NPHYS2788
nature physics

Fourier-transform inelastic X-ray scattering from time- and momentum-dependent phonon–phonon correlations

M. Trigo[1,2]★, M. Fuchs[1,2], J. Chen[1,2], M. P. Jiang[1,2], M. Cammarata[3], S. Fahy[4], D. M. Fritz[3], K. Gaffney[2], S. Ghimire[2], A. Higginbotham[5], S. L. Johnson[6], M. E. Kozina[2], J. Larsson[7], H. Lemke[3], A. M. Lindenberg[1,2,8], G. Ndabashimiye[2], F. Quirin[9], K. Sokolowski-Tinten[9], C. Uher[10], G. Wang[10], J. S. Wark[5], D. Zhu[3] and D. A. Reis[1,2,11]★

ARTICLE
doi:10.1038/nature11340

X-ray and optical wave mixing

T. E. Glover[1], D. M. Fritz[2], M. Cammarata[3], T. K. Allison[4], Sinisa Coh[5,6], J. M. Feldkamp[2], H. Lemke[2], D. Zhu[2], Y. Feng[2], R. N. Coffee[2], M. Fuchs[7], S. Ghimire[7], J. Chen[7,8], S. Shwartz[8], D. A. Reis[7,8,9], S. E. Harris[8,10] & J. B. Hastings[2]

Light–matter interactions are ubiquitous, and underpin a wide range of basic research fields and applied technologies. Although optical interactions have been intensively studied, their microscopic details are often poorly understood and have so far not been directly measurable. X-ray and optical wave mixing was proposed nearly half a century ago as an atomic-scale probe of optical interactions but has not yet been observed owing to a lack of sufficiently intense X-ray sources. Here we use an X-ray laser to demonstrate X-ray and optical sum-frequency generation. The underlying nonlinearity is a reciprocal-space probe of the optically induced charges and associated microscopic fields that arise in an illuminated material. To within the experimental errors, the measured efficiency is consistent with first-principles calculations of microscopic optical polarization in diamond. The ability to probe optical interactions on the atomic scale offers new oppo

ARTICLES
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nature physics

Anomalous nonlinear X-ray Compton scattering

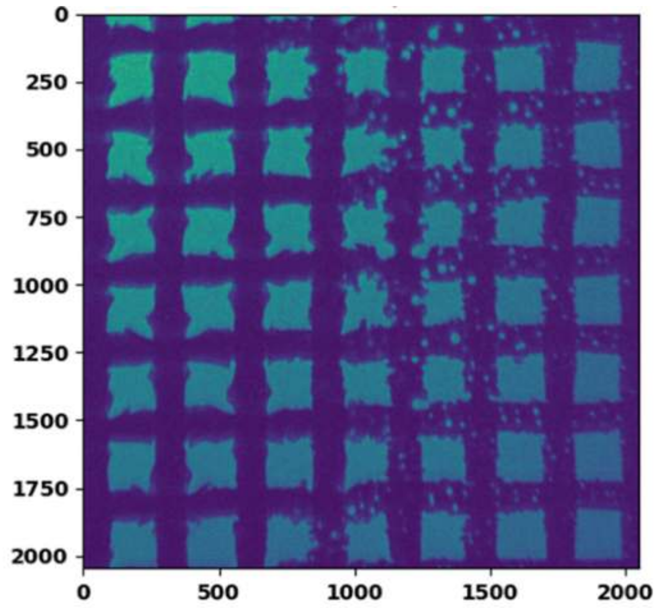
Matthias Fuchs[1,2]★, Mariano Trigo[2,3], Jian Chen[2,3], Shambhu Ghimire[2], Sharon Shwartz[4], Michael Kozina[2,3], Mason Jiang[2,3], Thomas Henighan[2,3], Crystal Bray[2,3], Georges Ndabashimiye[2], Philip H. Bucksbaum[2], Yiping Feng[5], Sven Herrmann[6], Gabriella A. Carini[6], Jack Pines[6], Philip Hart[6], Christopher Kenney[6], Serge Guillet[5], Sébastien Boutet[5], Garth J. Williams[5], Marc Messerschmidt[5,7], M. Marvin Seibert[5], Stefan Moeller[5], Jerome B. Hastings[5] and David A. Reis[2,3]

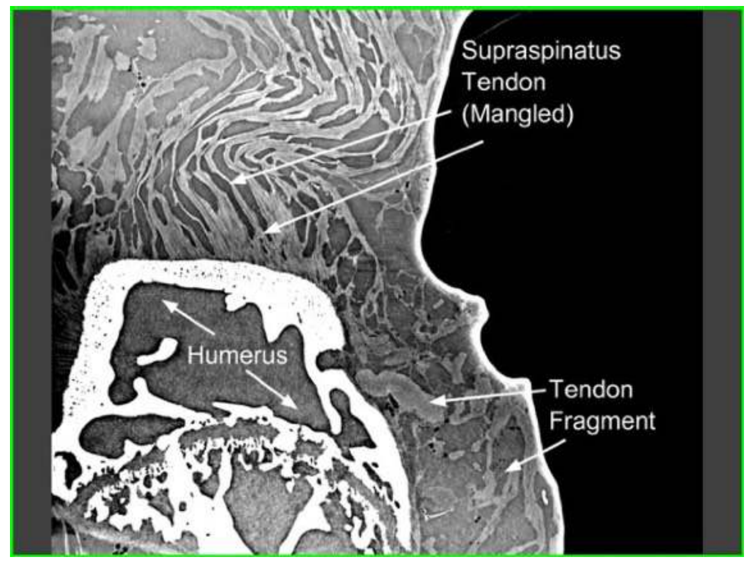
Januar 2016 15. Jahrgang
www.physik-journal.de
Physik Journal
Doppelter Compton-Effekt
Beschleuniger ELBE
Higgs-Mode im Festkörper
DPG-Preise 2016
Deutsche Physikalische Gesellschaft DPG

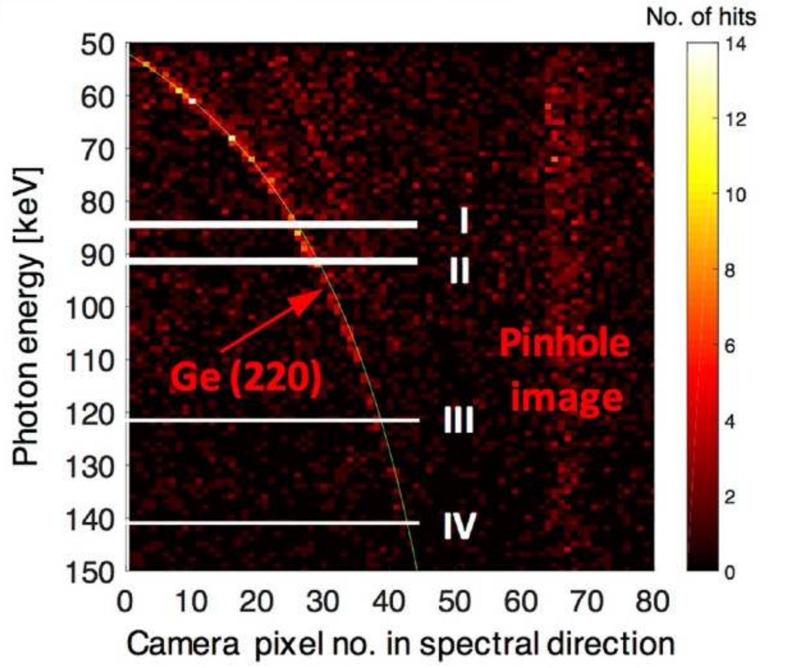
PRL **112,** 163901 (2014) PHYSICAL REVIEW LETTERS week ending 25 APRIL 2014

X-Ray Second Harmonic Generation

S. Shwartz,[1,2,*] M. Fuchs,[3,4] J. B. Hastings,[5] Y. Inubushi,[6] T. Ishikawa,[6] T. Katayama,[7] D. A. Reis,[3,8] T. Sato,[6] K. Tono,[7] M. Yabashi,[6] S. Yudovich,[1] and S. E. Harris[2]







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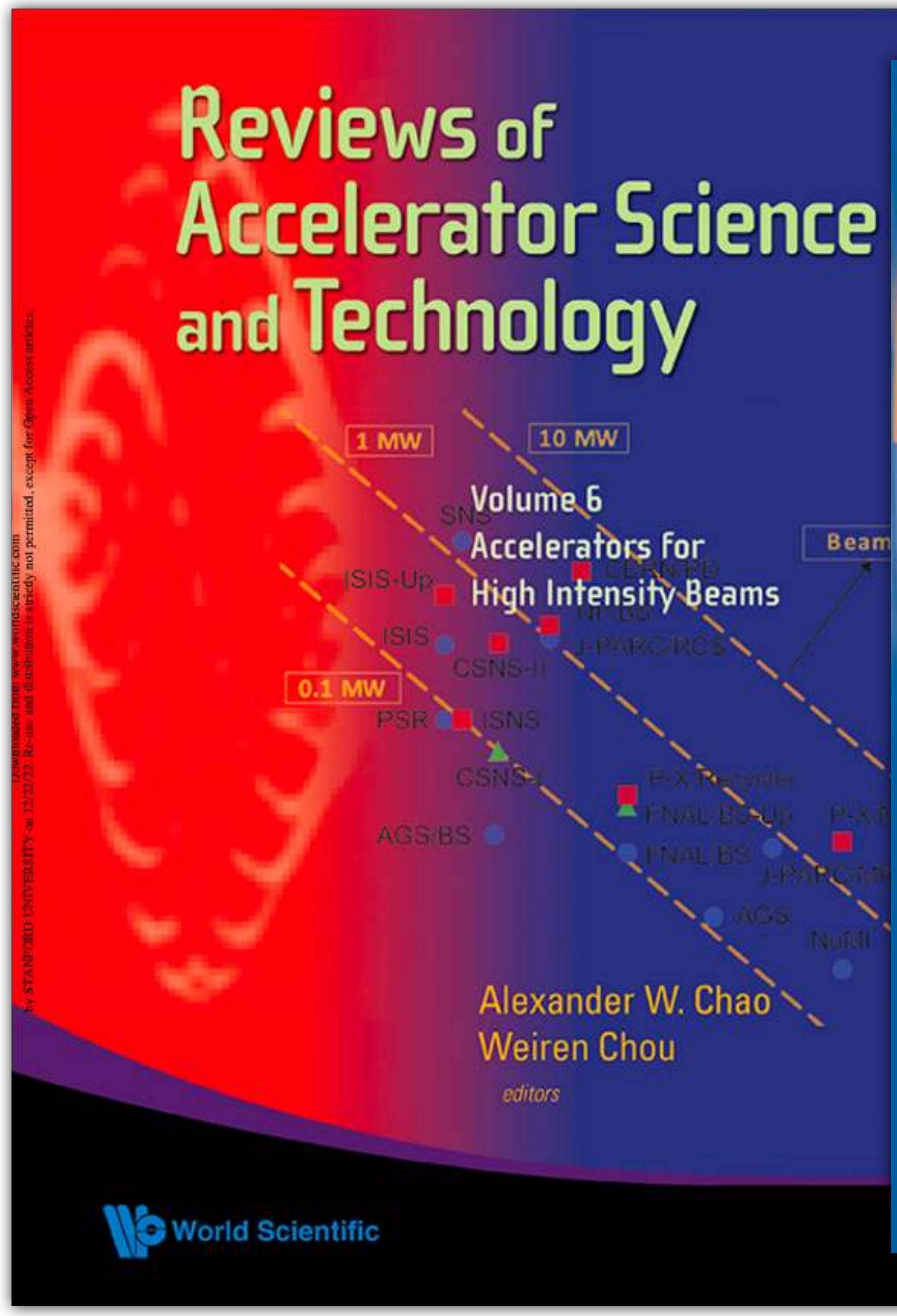
Particle Acceleration in a Nutshell



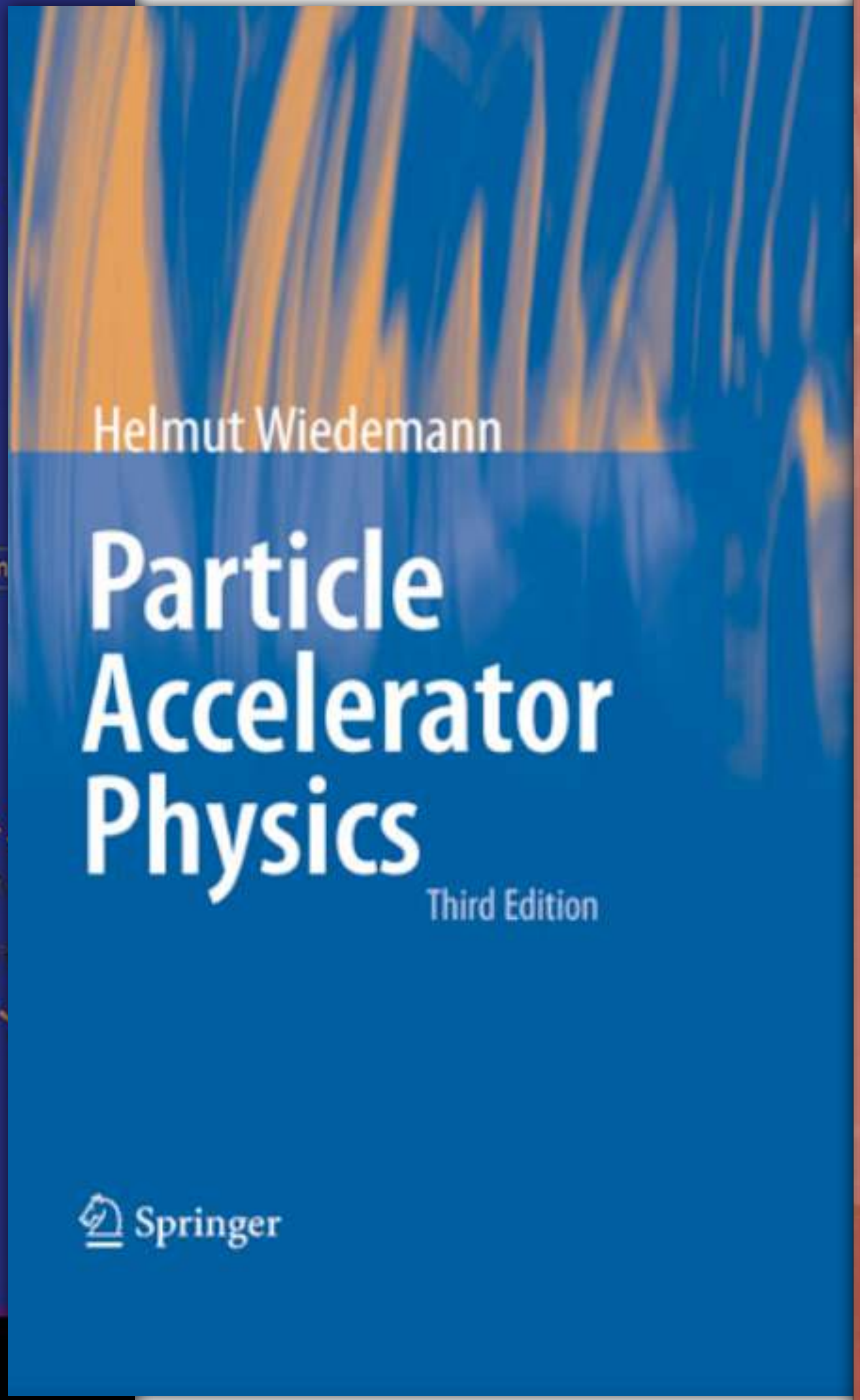
Reviews of Accelerator Science and Technology

Volume 6

Accelerators for High Intensity Beams

Alexander W. Chao
Weiren Chou
editors

World Scientific

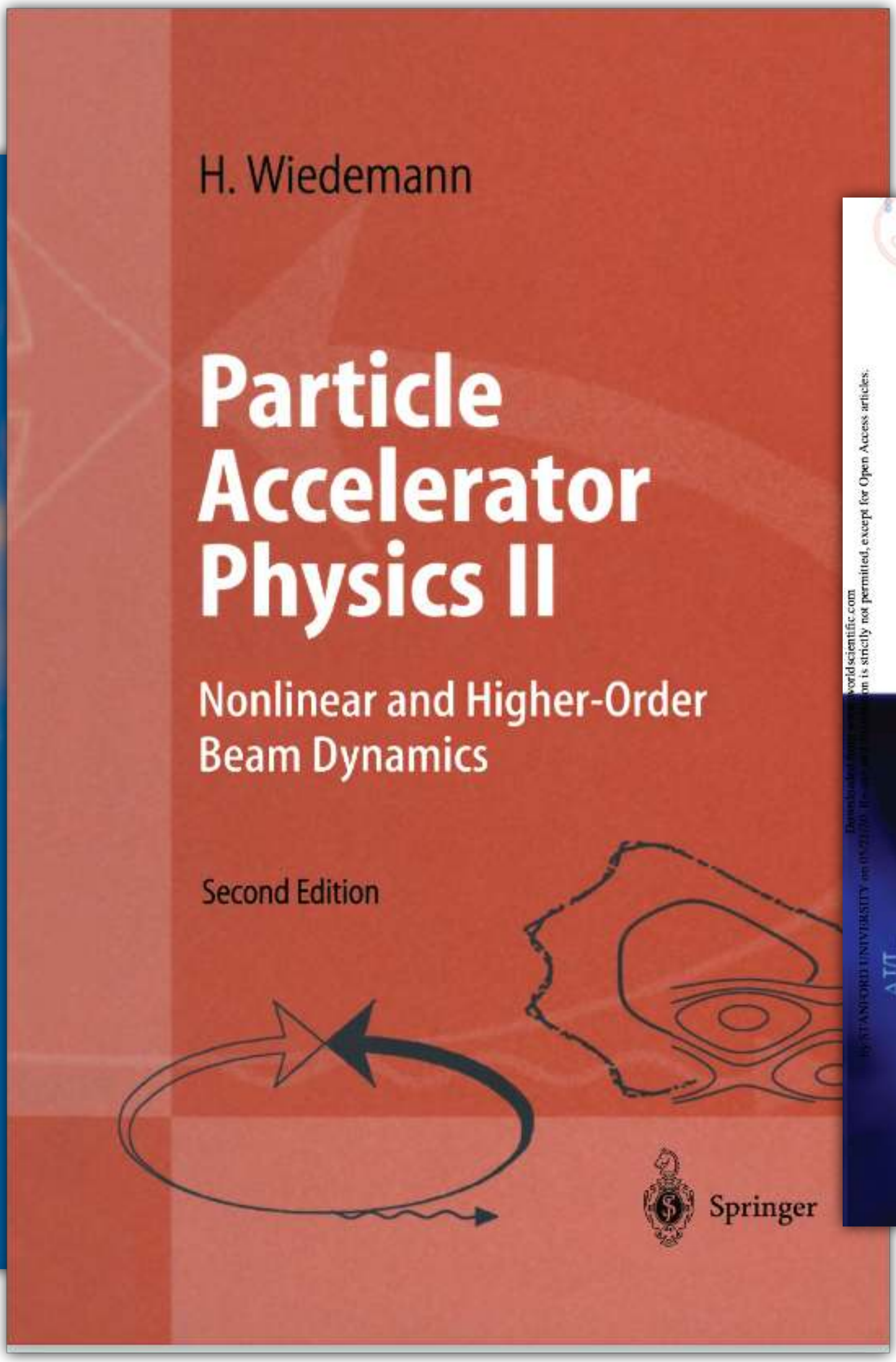


Helmut Wiedemann

Particle Accelerator Physics

Third Edition

Springer



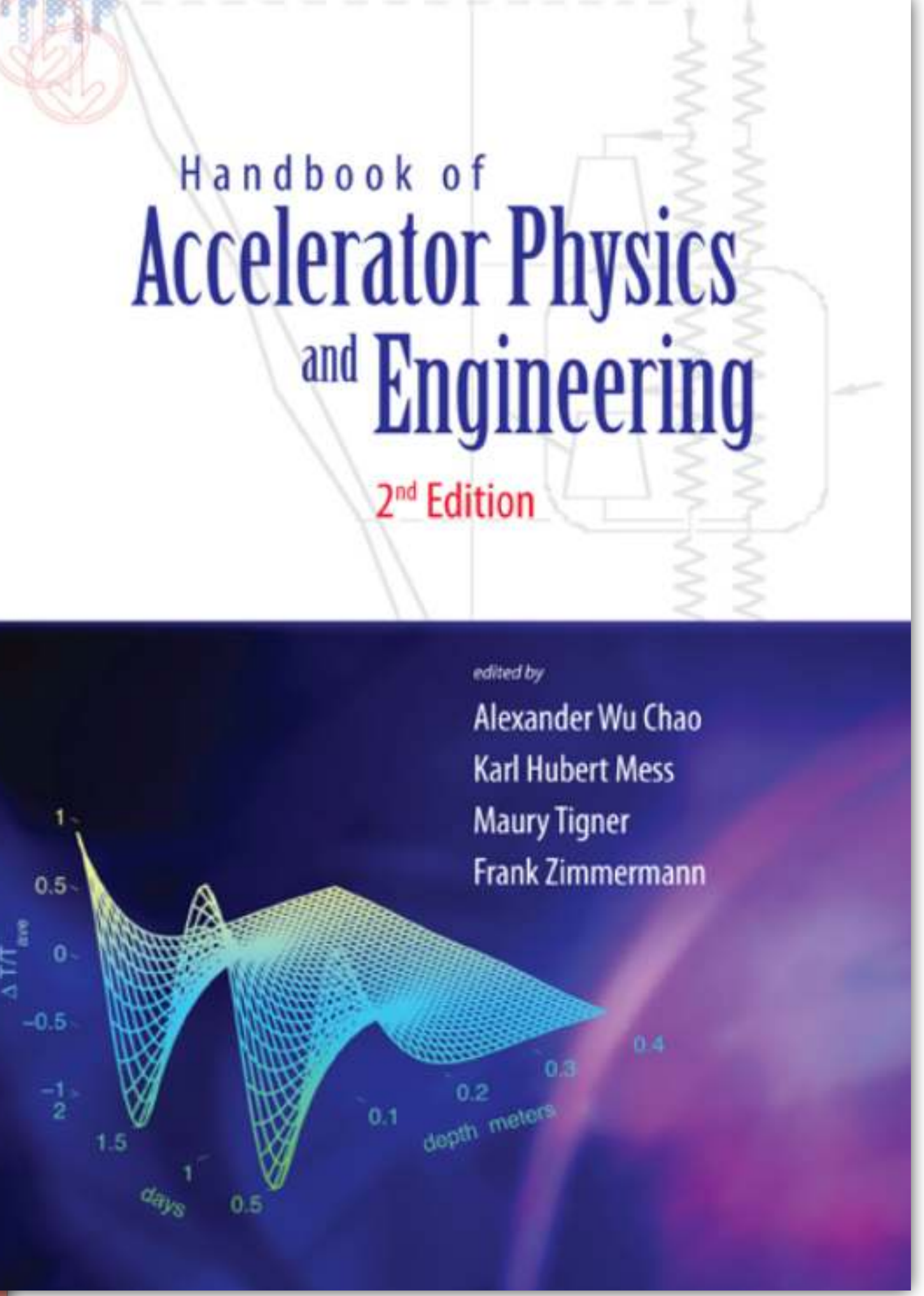
H. Wiedemann

Particle Accelerator Physics II

Nonlinear and Higher-Order Beam Dynamics

Second Edition

Springer



Handbook of Accelerator Physics and Engineering

2^{nd} Edition

edited by
Alexander Wu Chao
Karl Hubert Mess
Maury Tigner
Frank Zimmermann

Particle Accelerator in a Nutshell

Photo: T. Seggebrück

Outline

high-power lasers

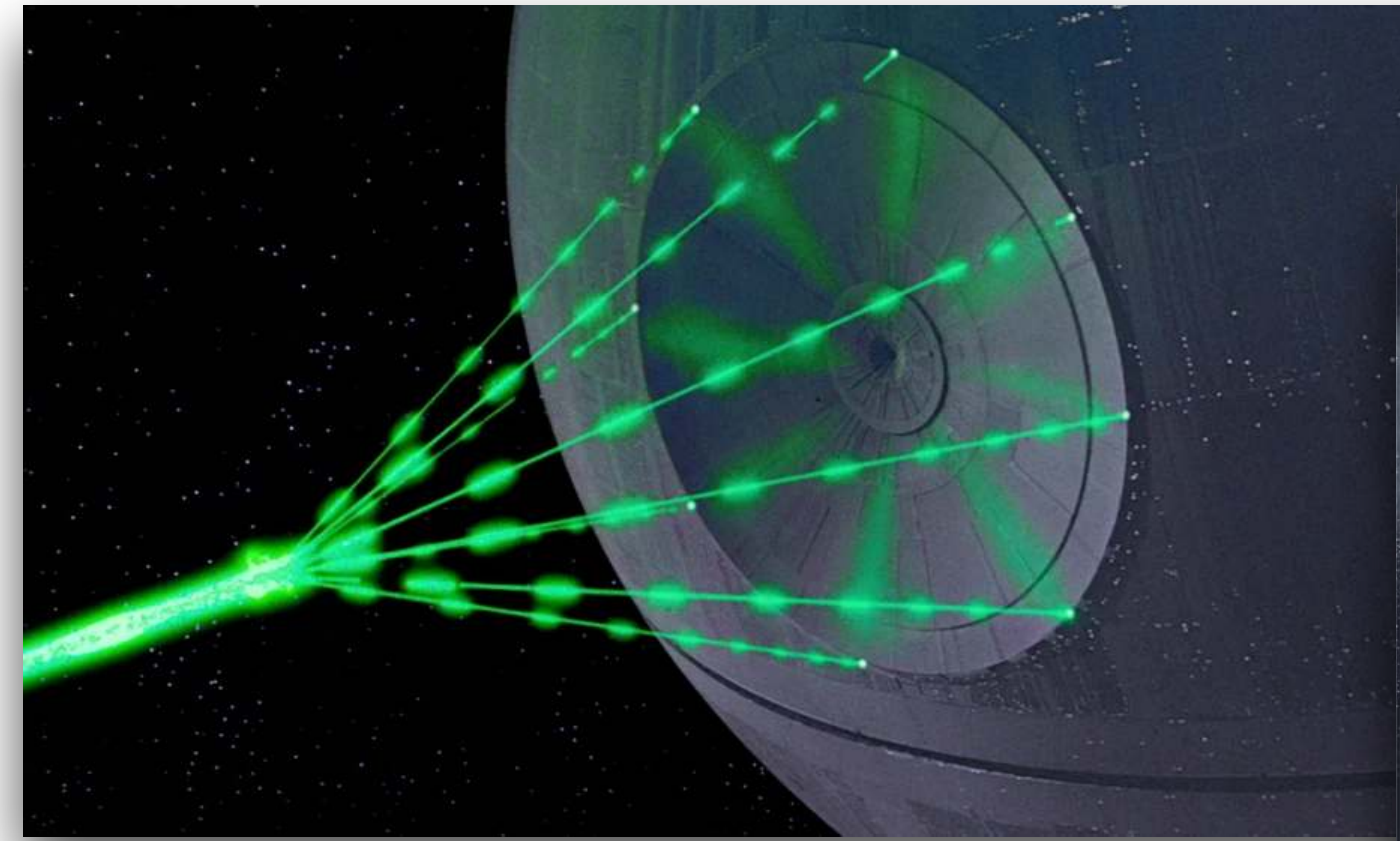
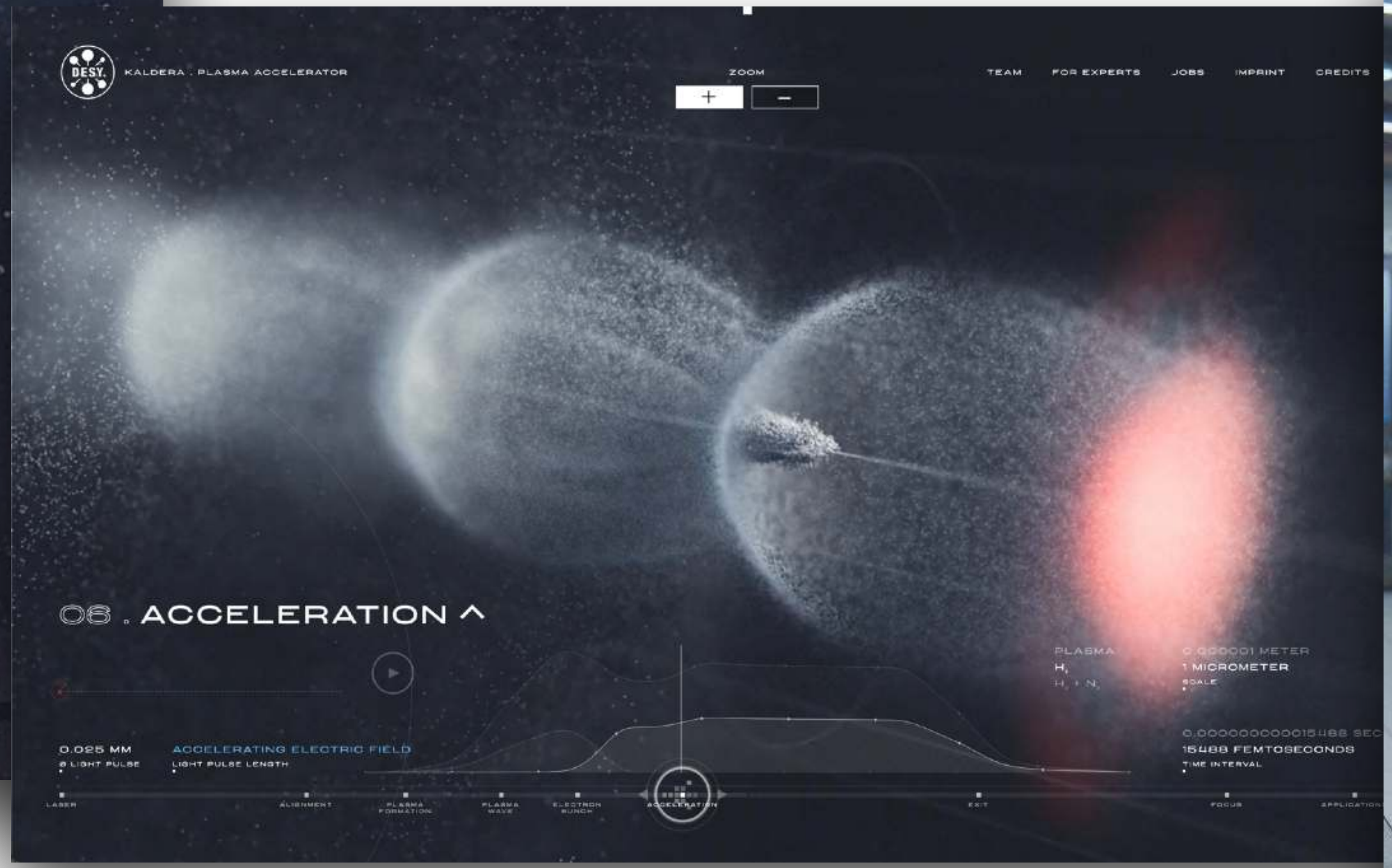


image: wookiepedia.org

plasma accelerators



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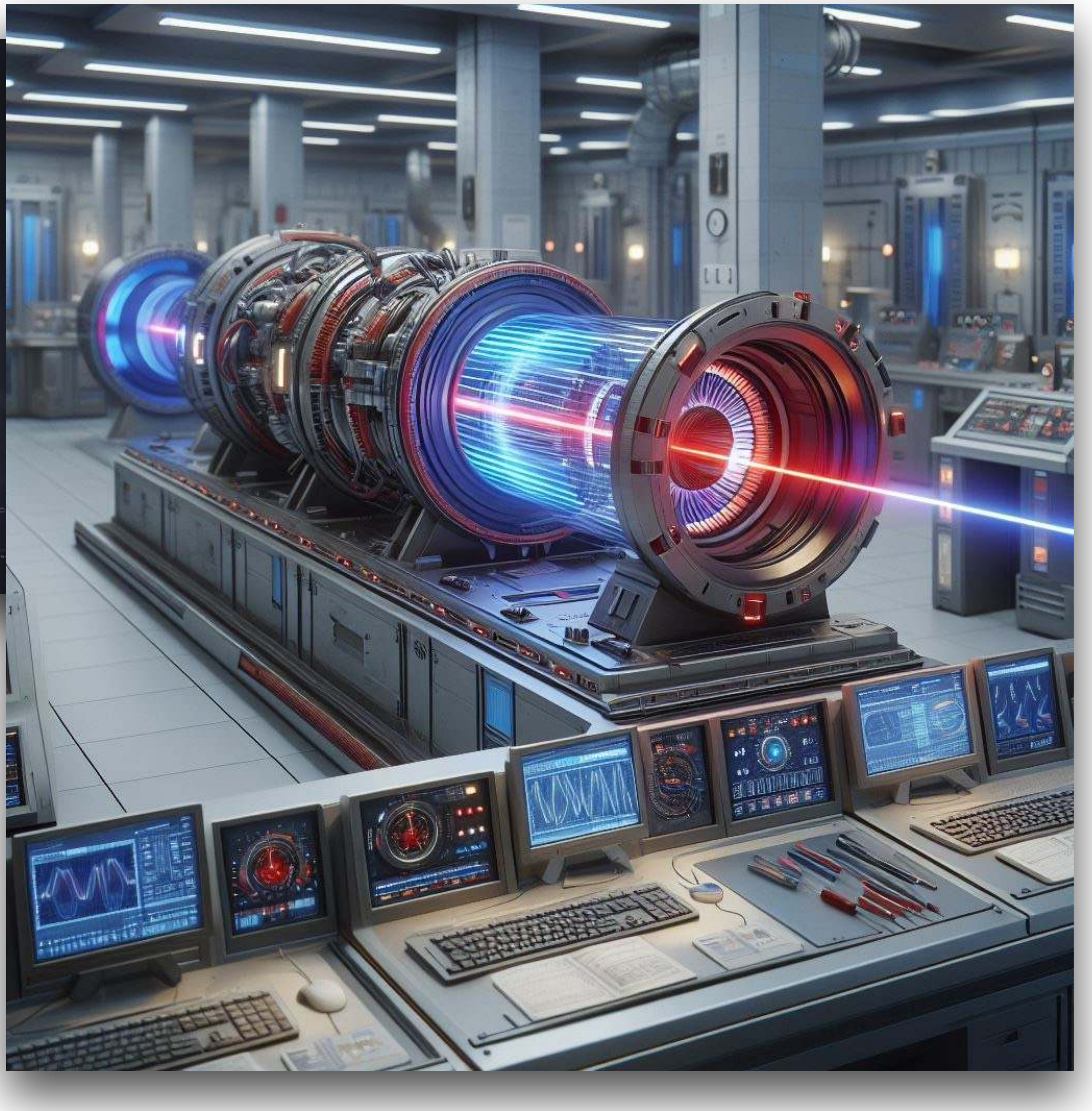
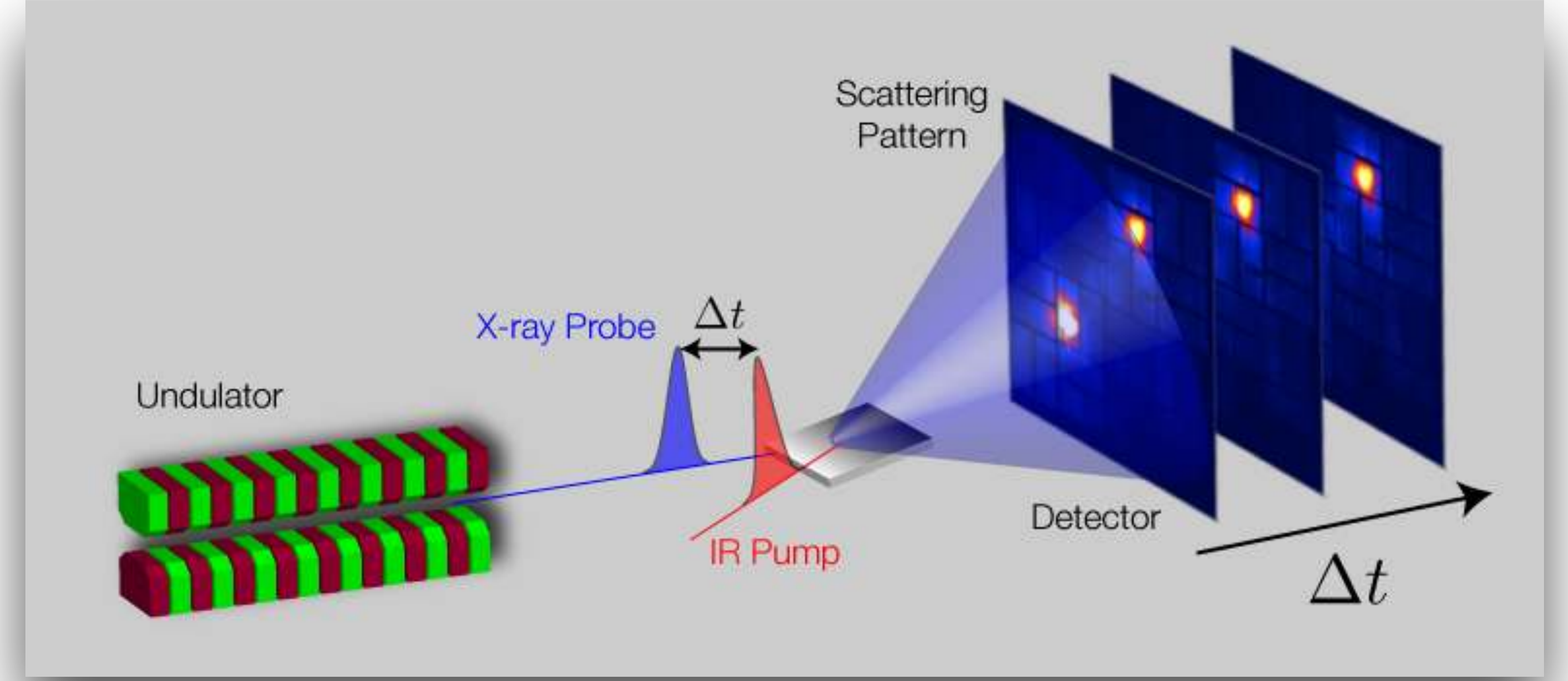


Image: DALL-E

relativistic electron bunches

Bielawski *et al*. Sci Rep (2019)

ultrafast X-ray pulses



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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

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Particle Accelerators

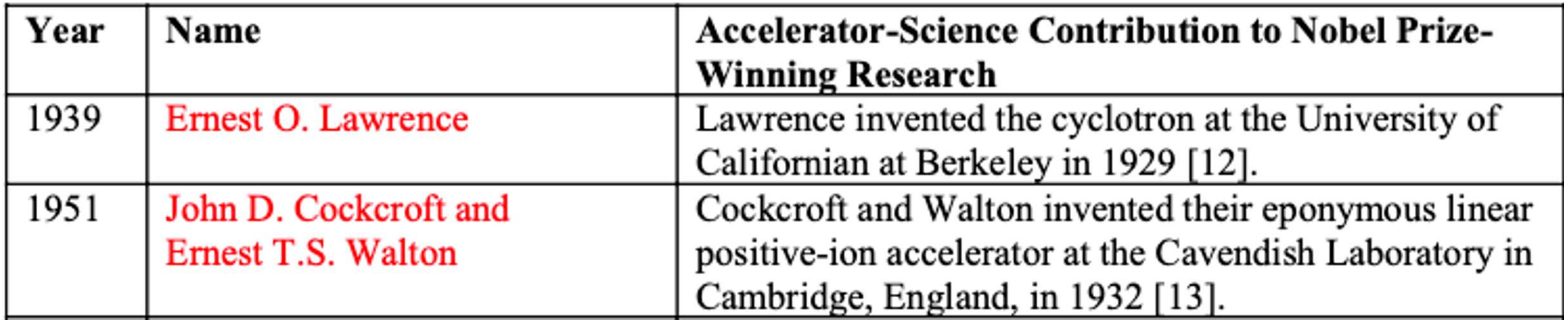
28% of the research in physics between 1939 and 2009 has been influenced by accelerator science.

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

about 30,000 accelerators world wide

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].

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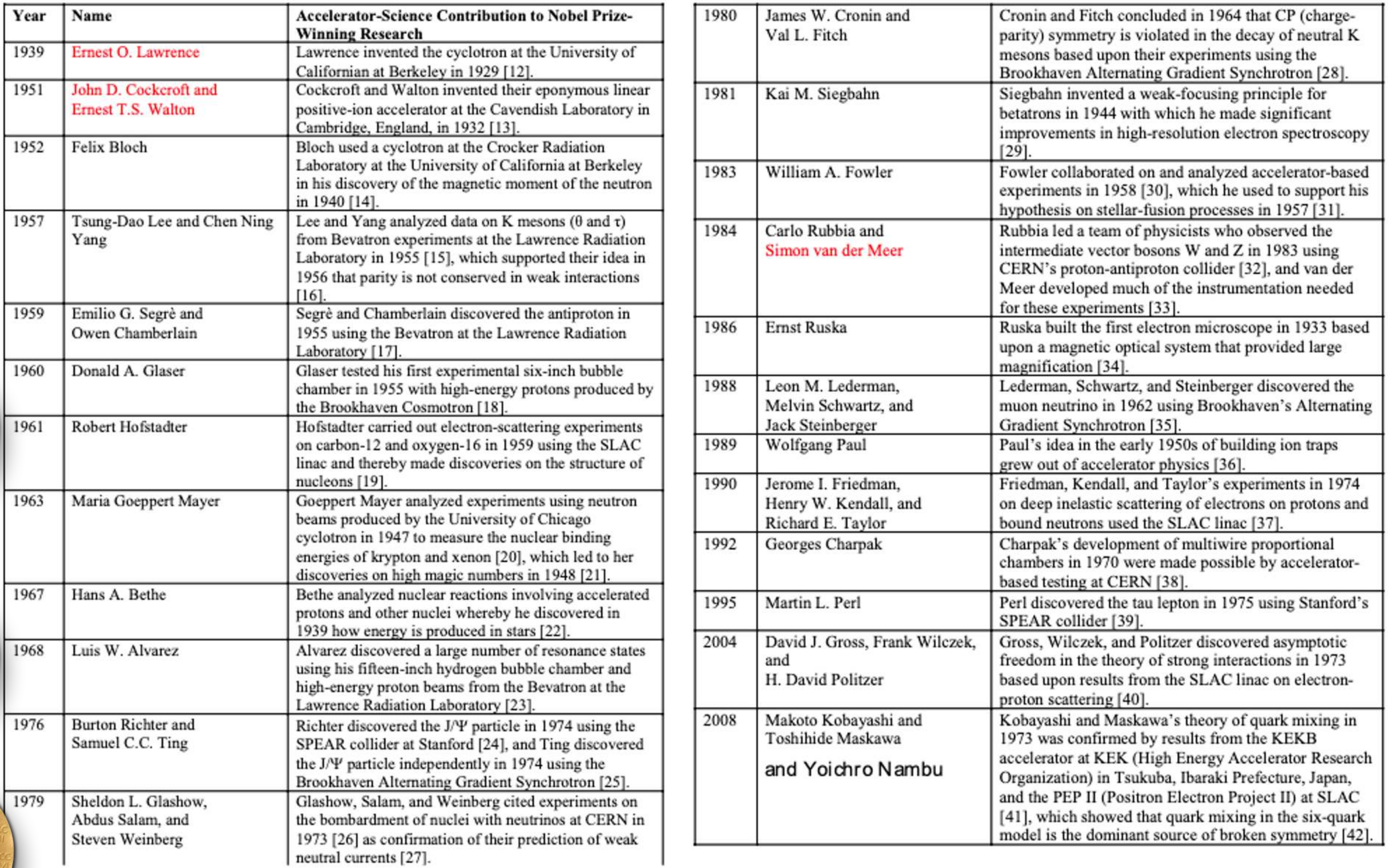
25 Nobel Prizes in Physics that had direct contribution from accelerators



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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 (θ and τ) 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

First Accelerator Concepts and Demonstrations

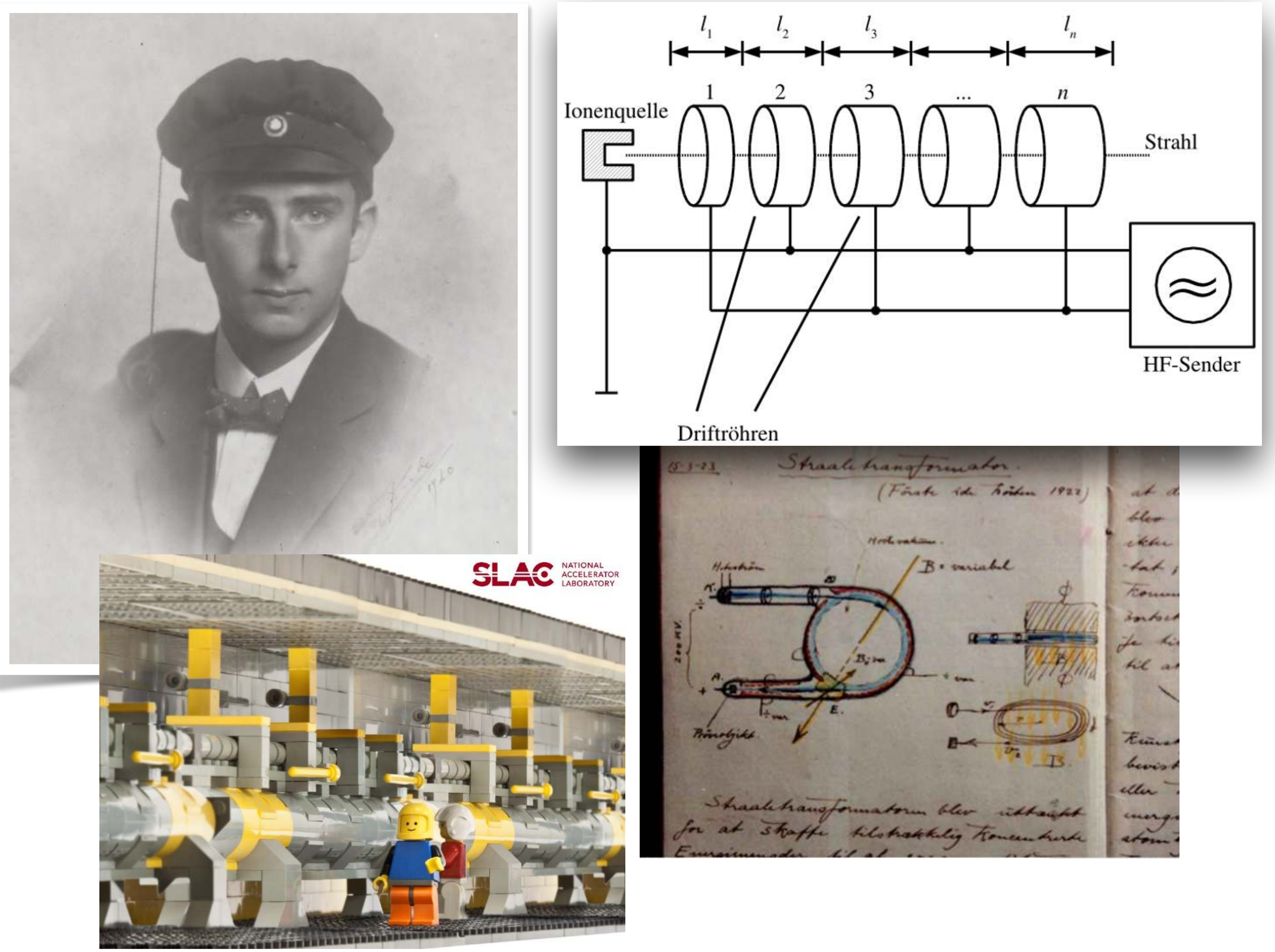


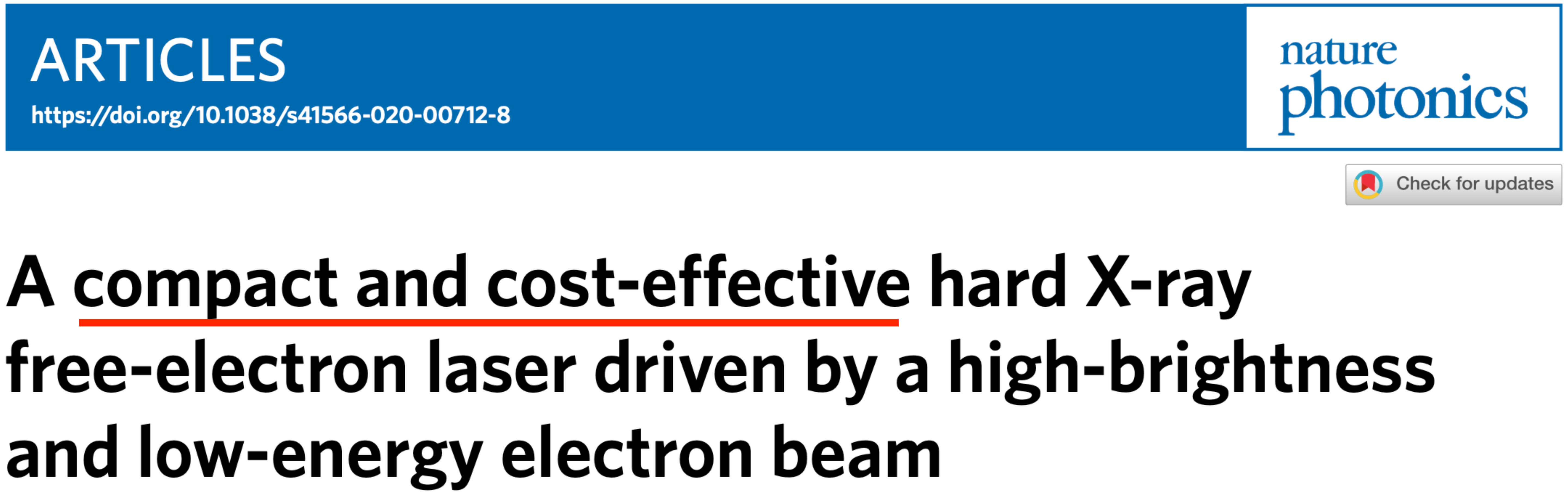
Image:Greg Stewart/SLAC

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)



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

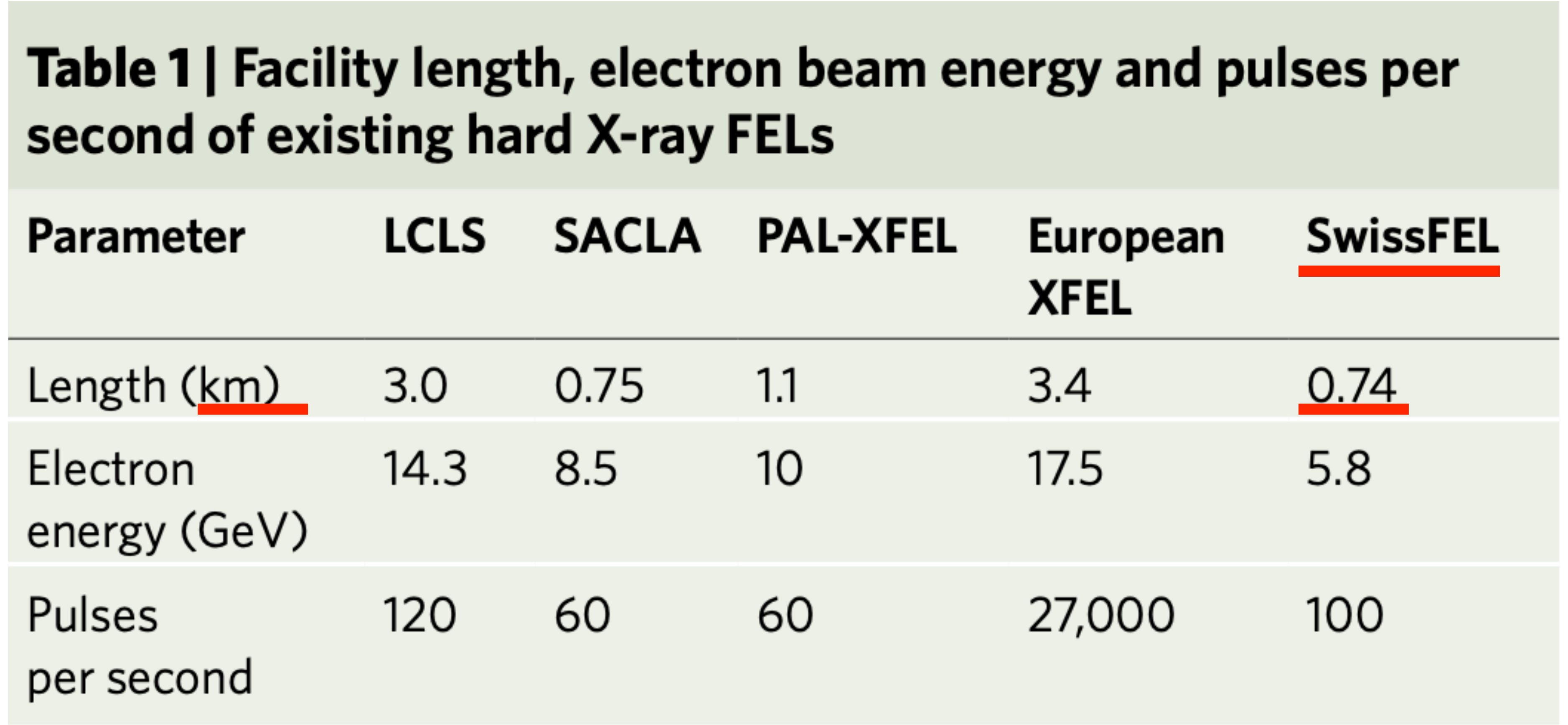
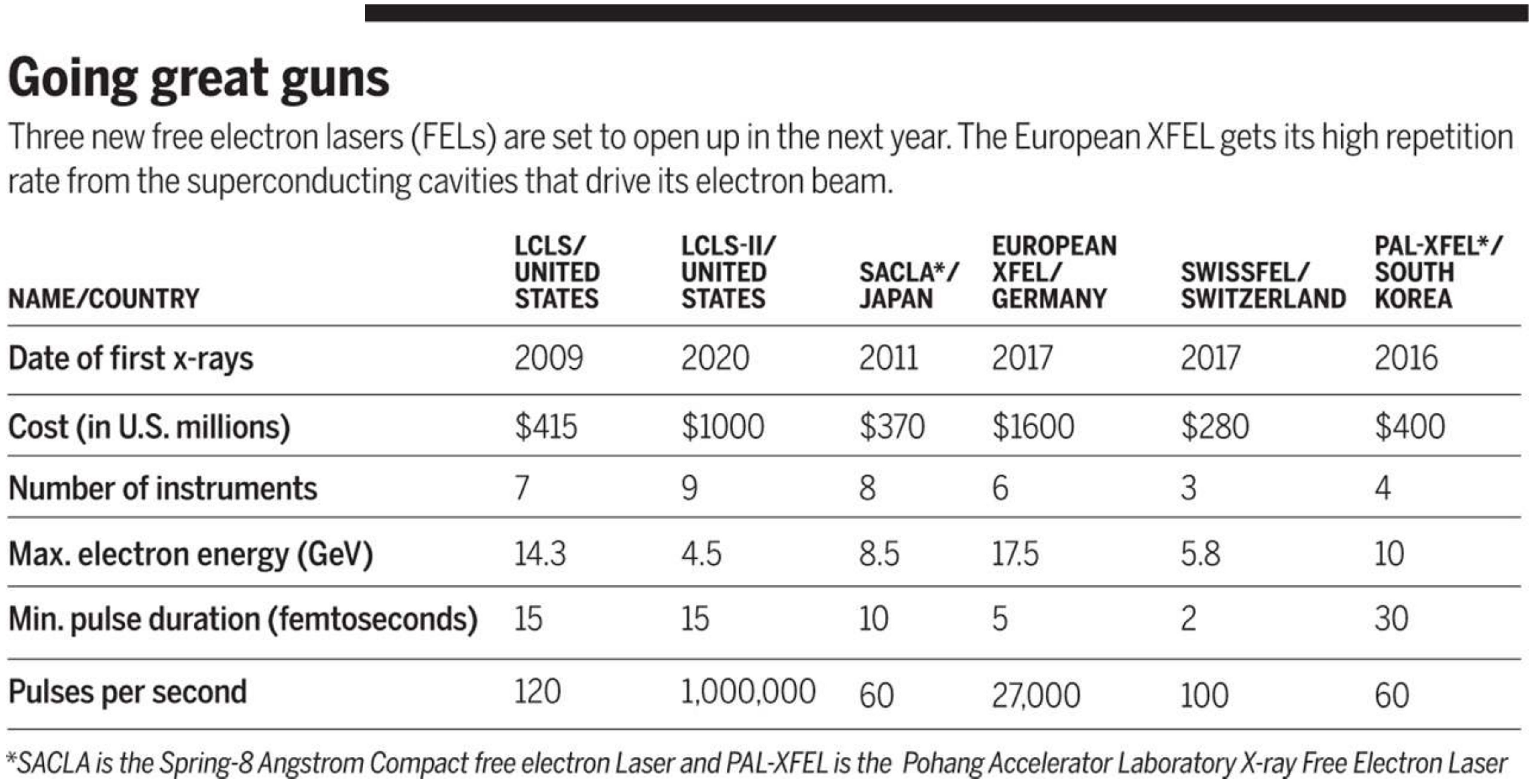


Table 1 | Facility length, electron beam energy and pulses per second of existing hard X-ray FELs

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

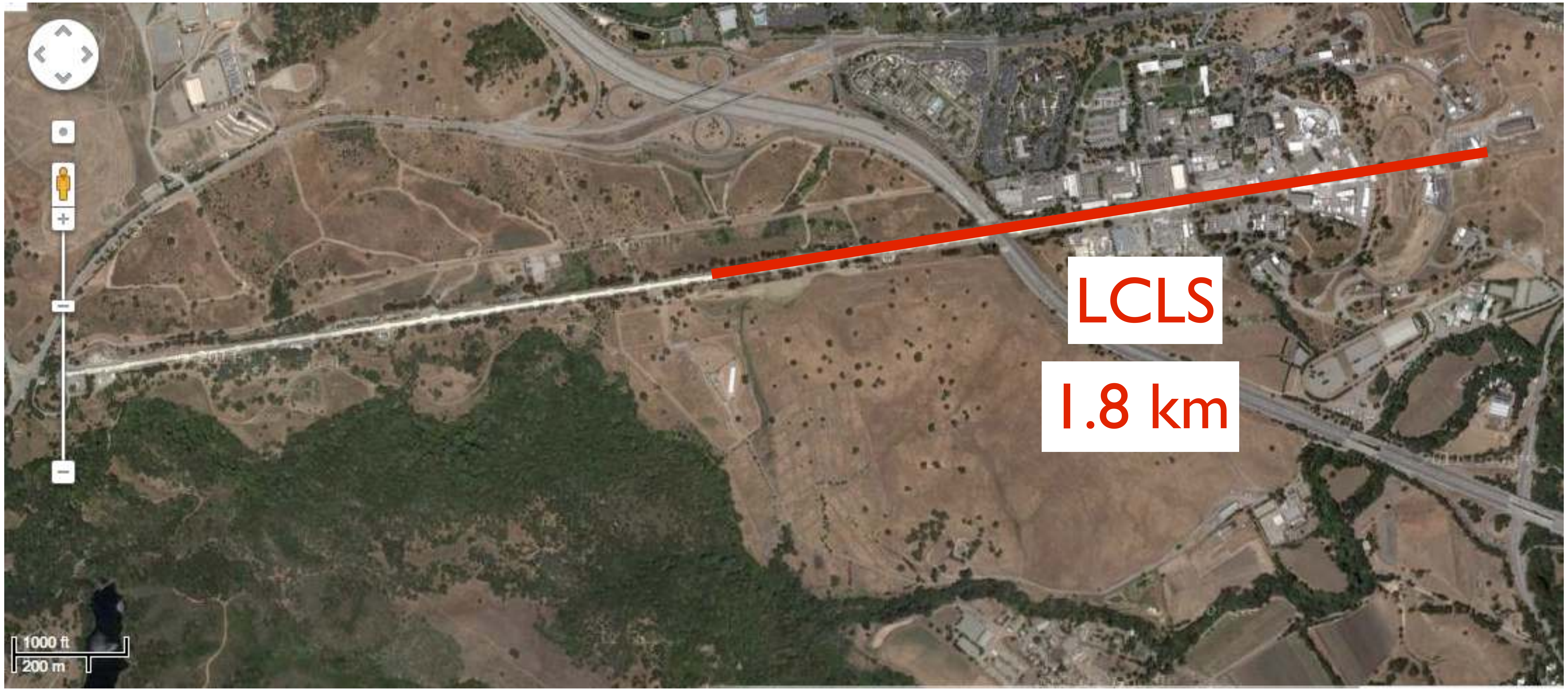
Three new free electron lasers (FELs) are set to open up in the next year. The European XFEL gets its high repetition rate from the superconducting cavities that drive its electron beam.

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

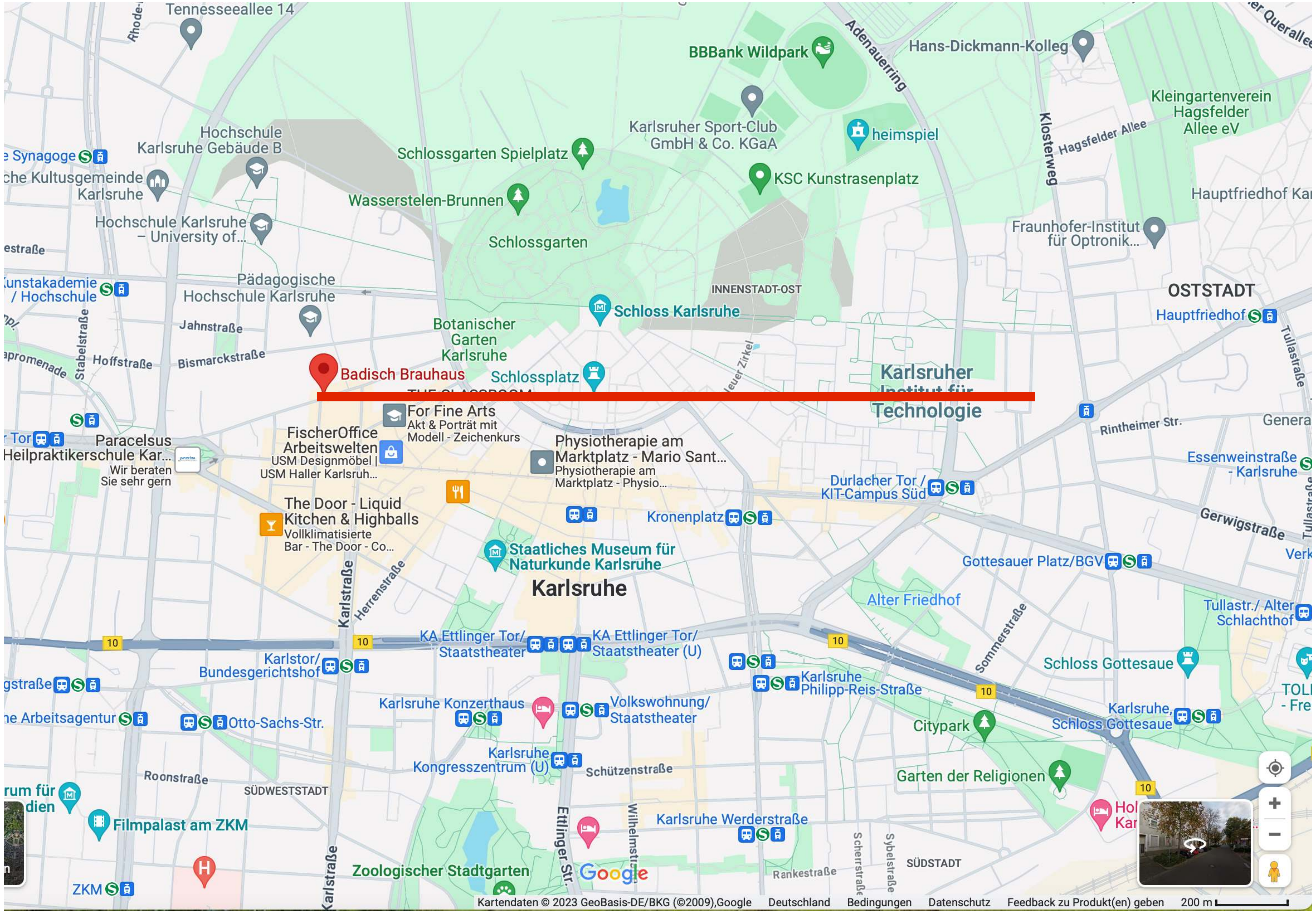
**SACLA is the Spring-8 Angstrom Compact free electron Laser and PAL-XFEL is the Pohang Accelerator Laboratory X-ray Free Electron Laser*

Edwin Cartlidge Science 2016;354:22-23

X-Ray Free-Electron Laser: LCLS at SLAC



LCLS at Karlsruhe



Shrinking Accelerators

Laser-Wakefield Electron Acceleration

laser

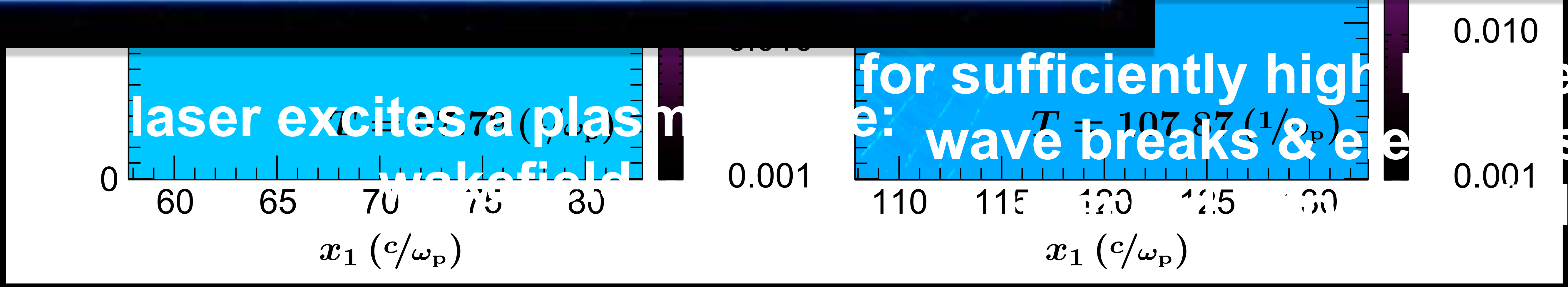
pc

er

pu

Particle-in-Cell Simulation

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

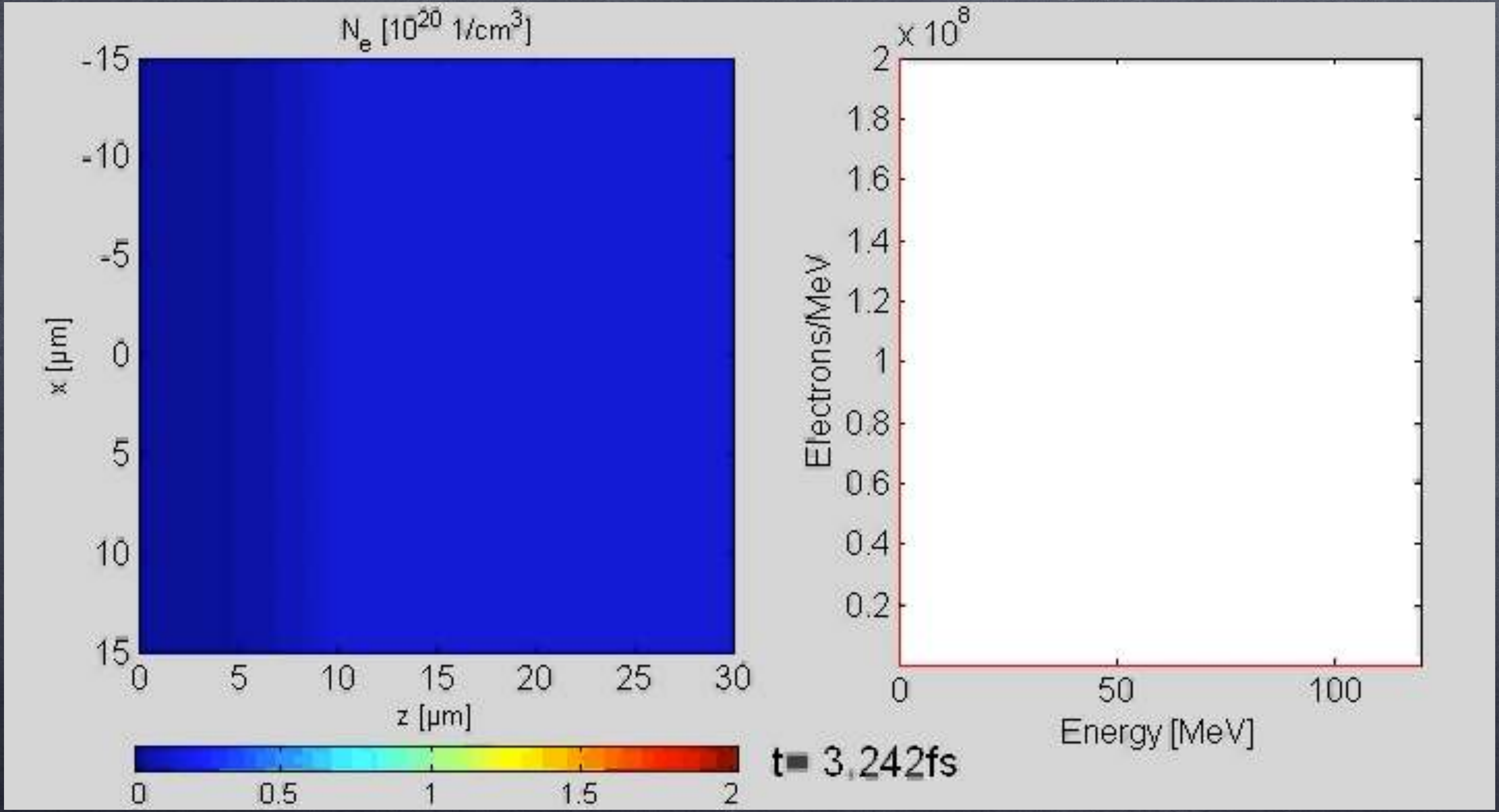


laser excites a plas e: wakefield

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

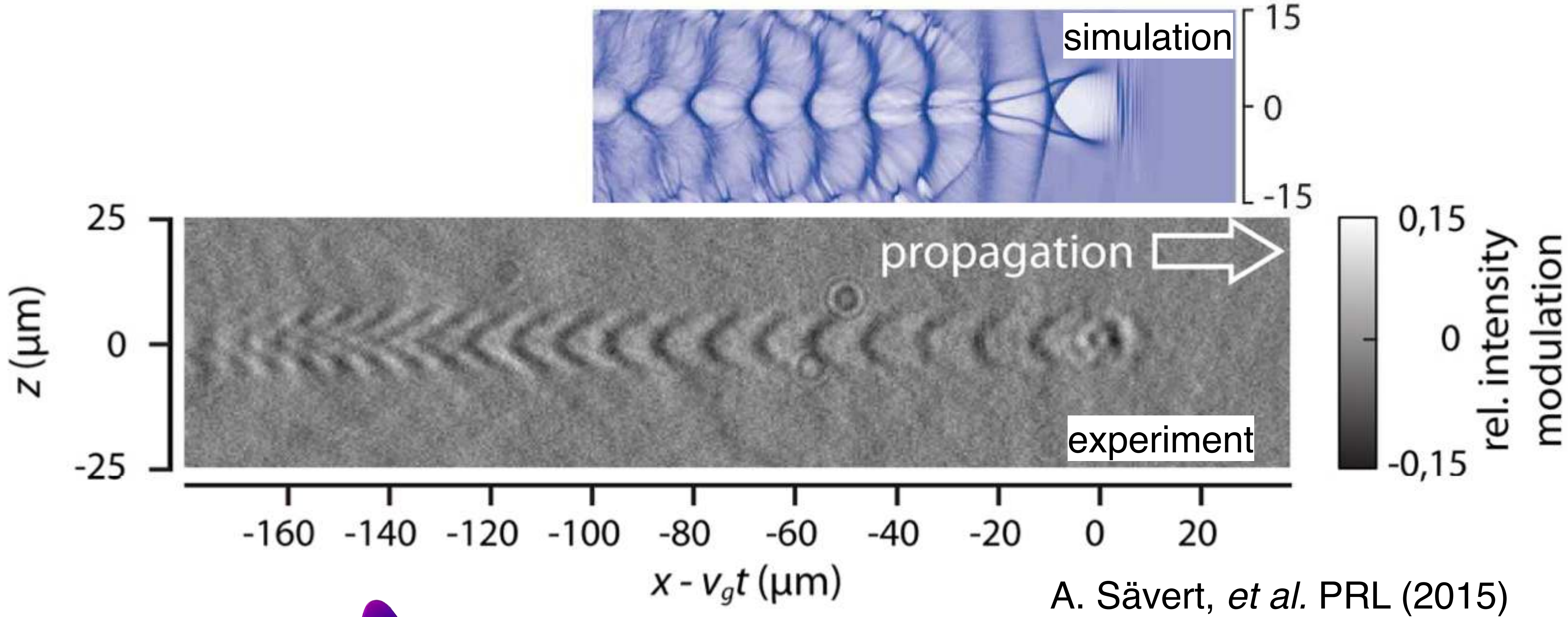
Conventional Accelerator

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

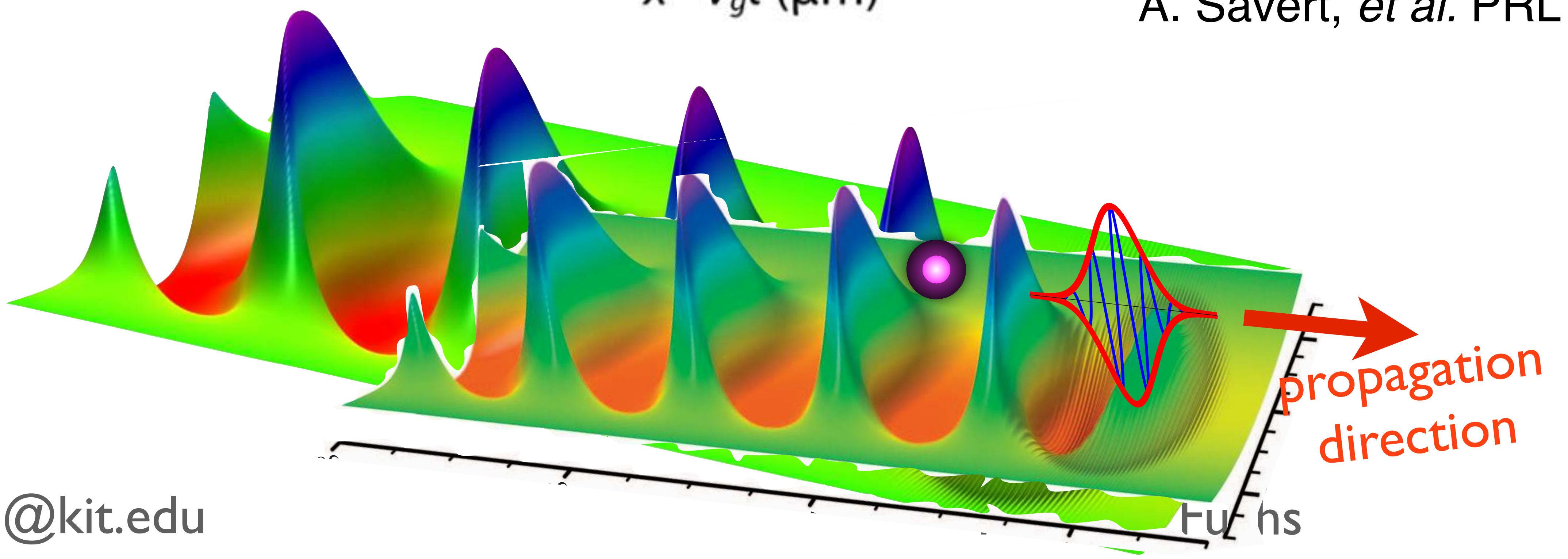
LEP radio-frequency cavity. Source: CERN

Plasma Accelerator

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

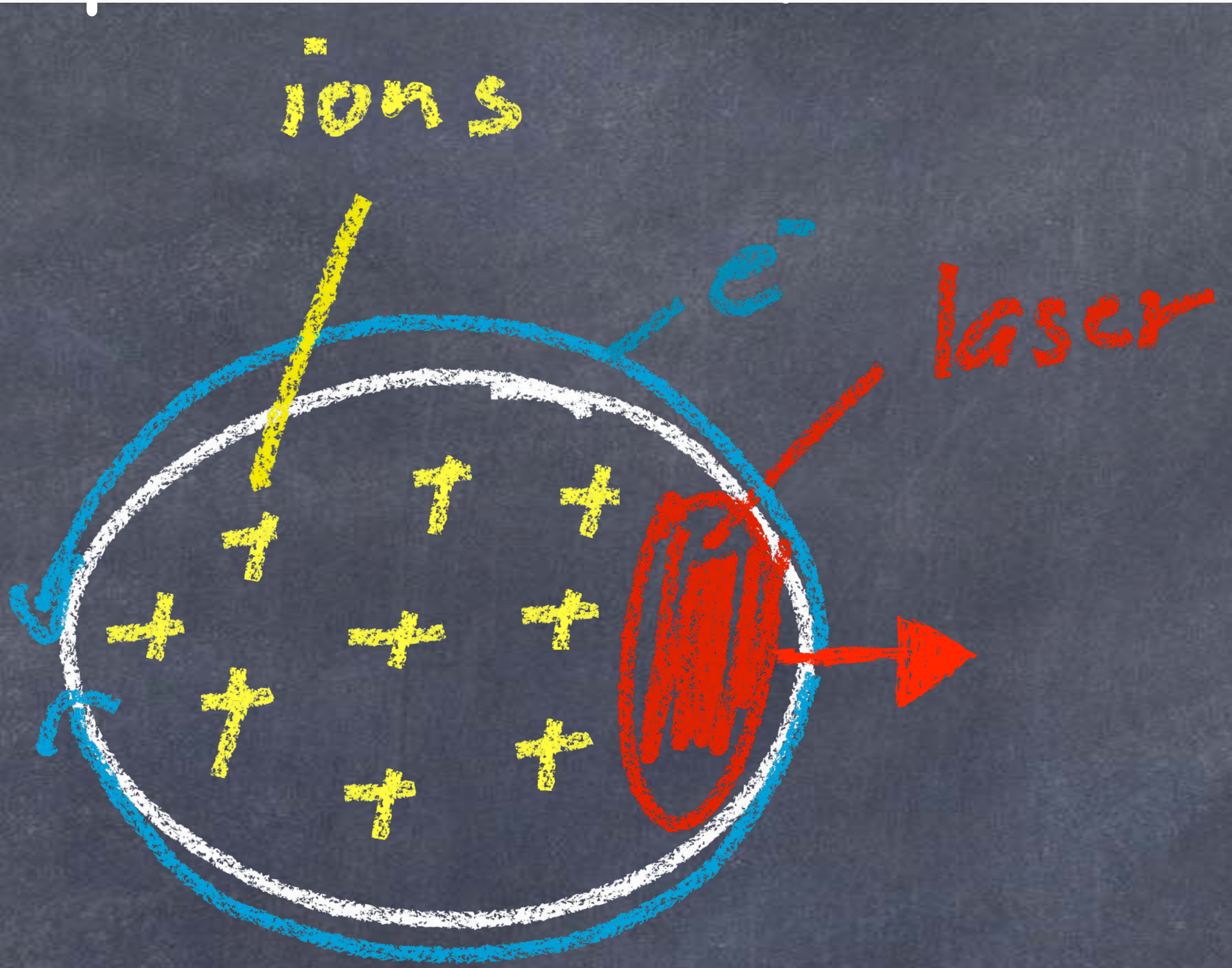


A. Sävert, *et al.* PRL (2015)



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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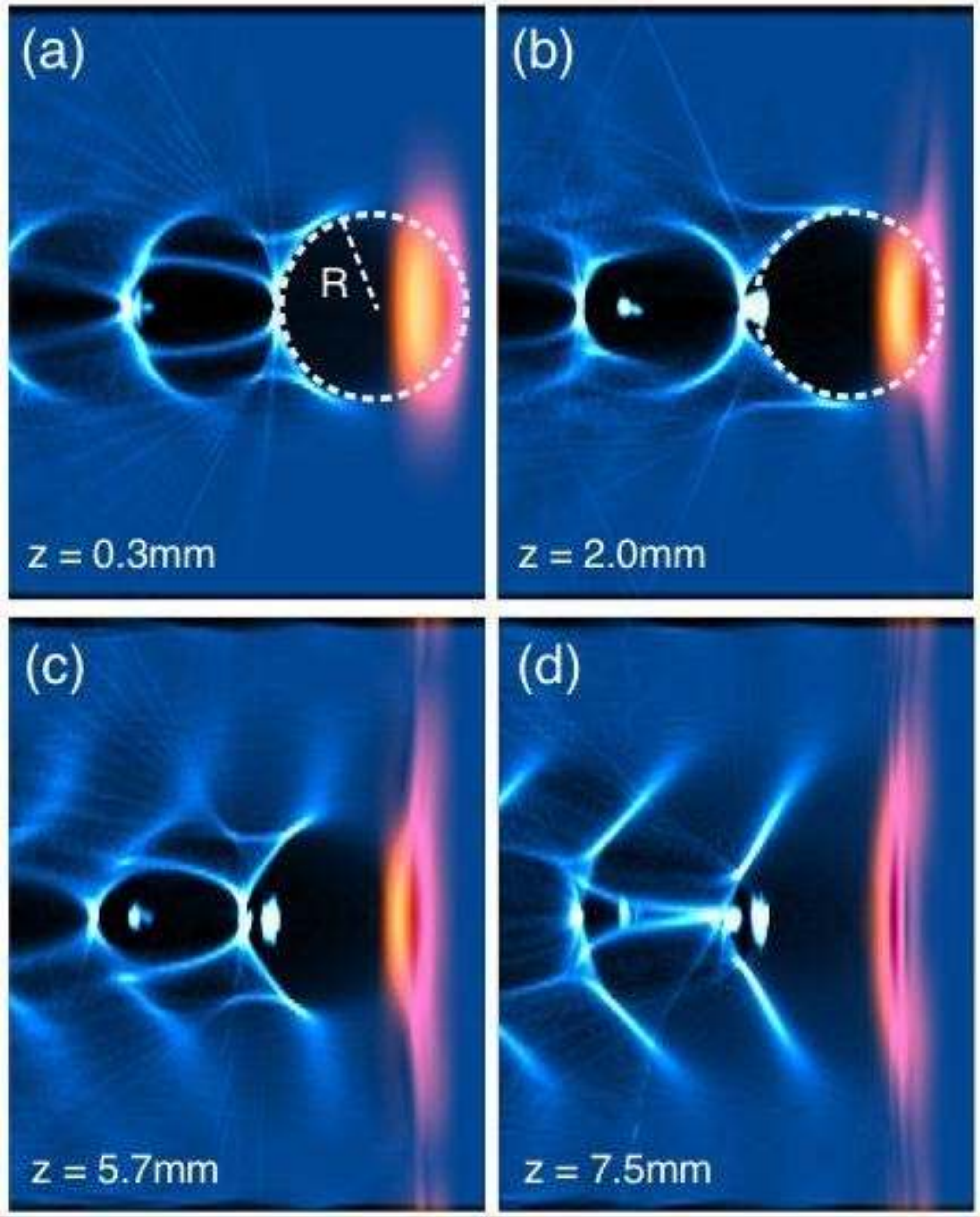
Bubble dynamics & Laser-Plasma Interaction

- dynamics and evolution highly nonlinear
- detailed description need large-scale 3D particle-in-cell (PIC) simulations
- PIC simulations
  - few-cm 3D simulations: millions CPU hours, tens of TB data



Lu et al., PRSTAB (2007)

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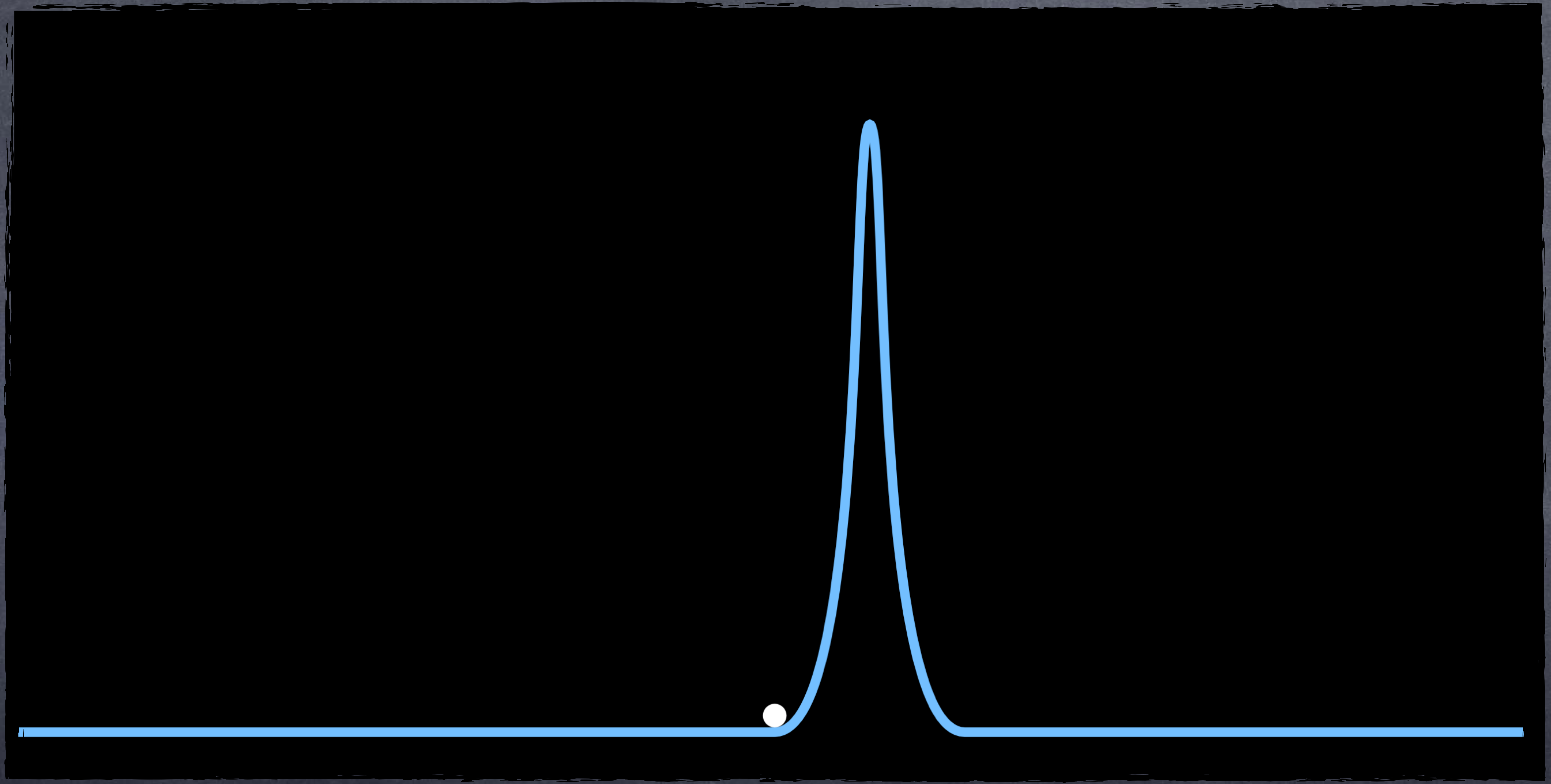
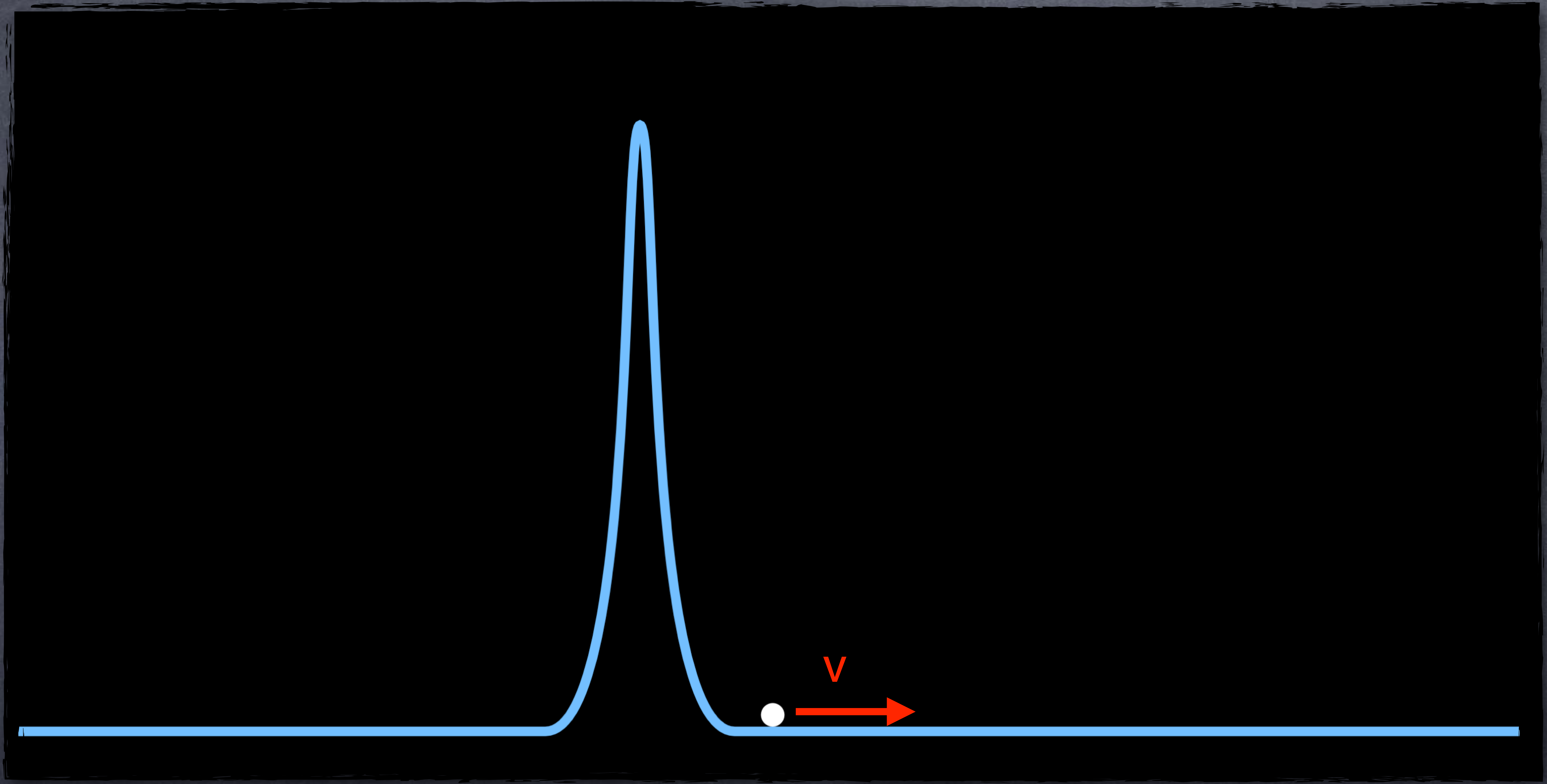
Electron Injection: Untrapped Electron



Electron velocity too small for trapping

Trapping And Acceleration



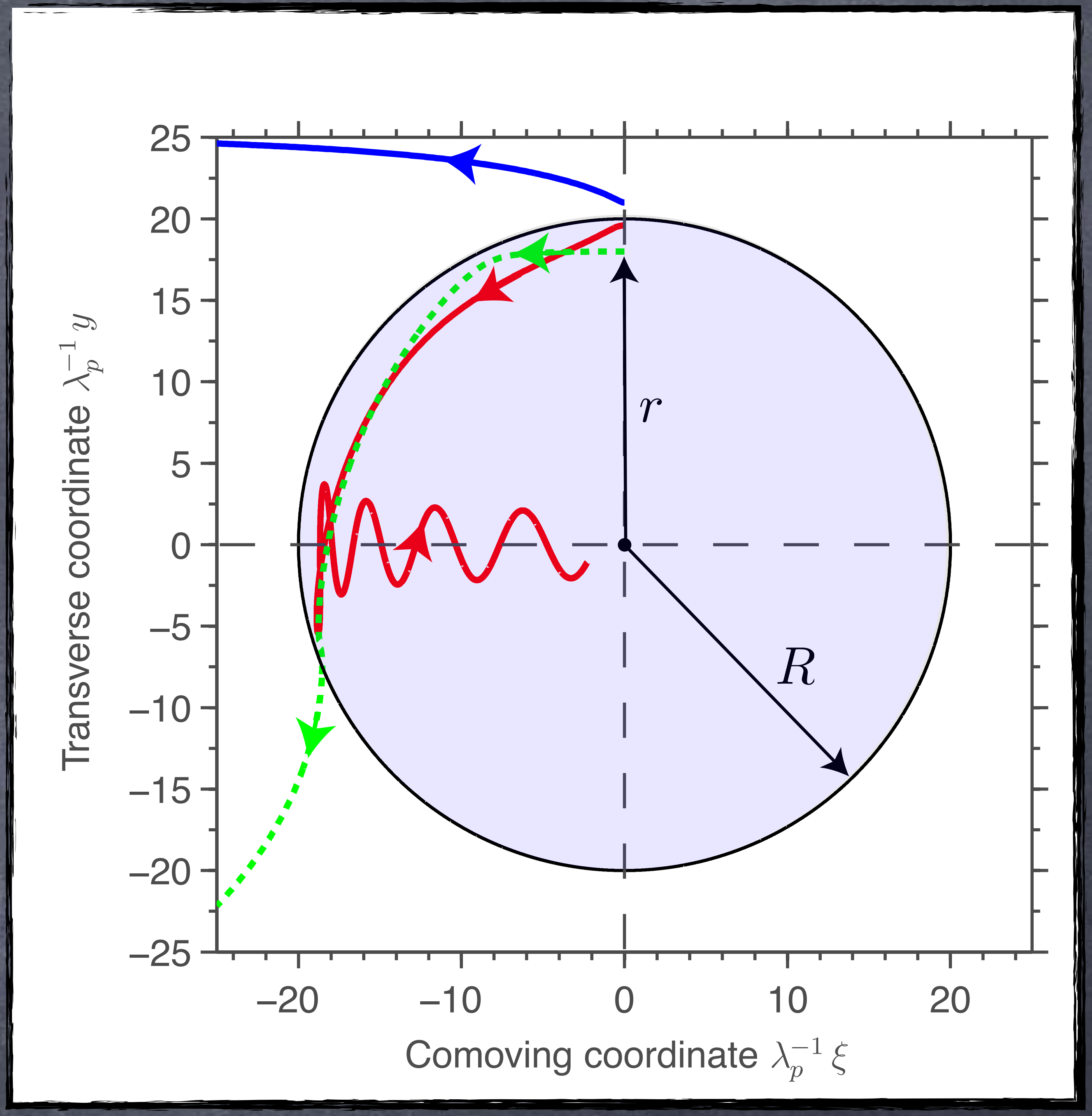
Electron with sufficiently high velocity

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

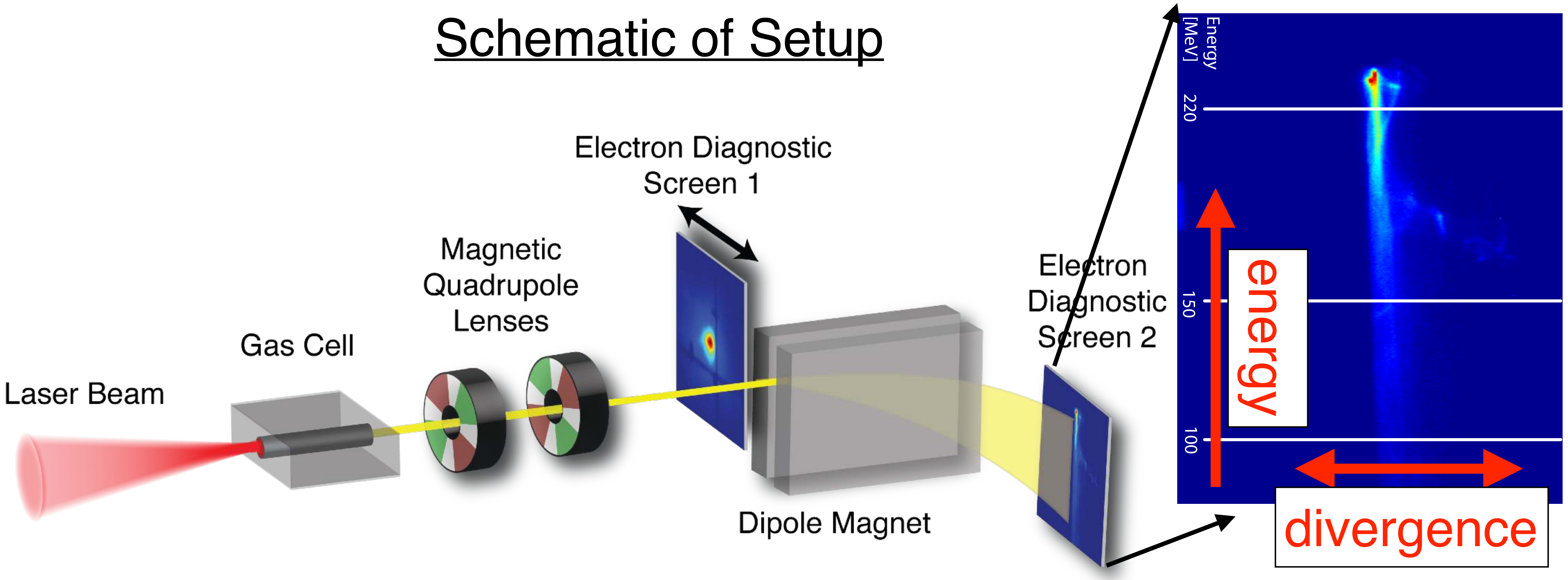


Kostyukov, PRL (2009)

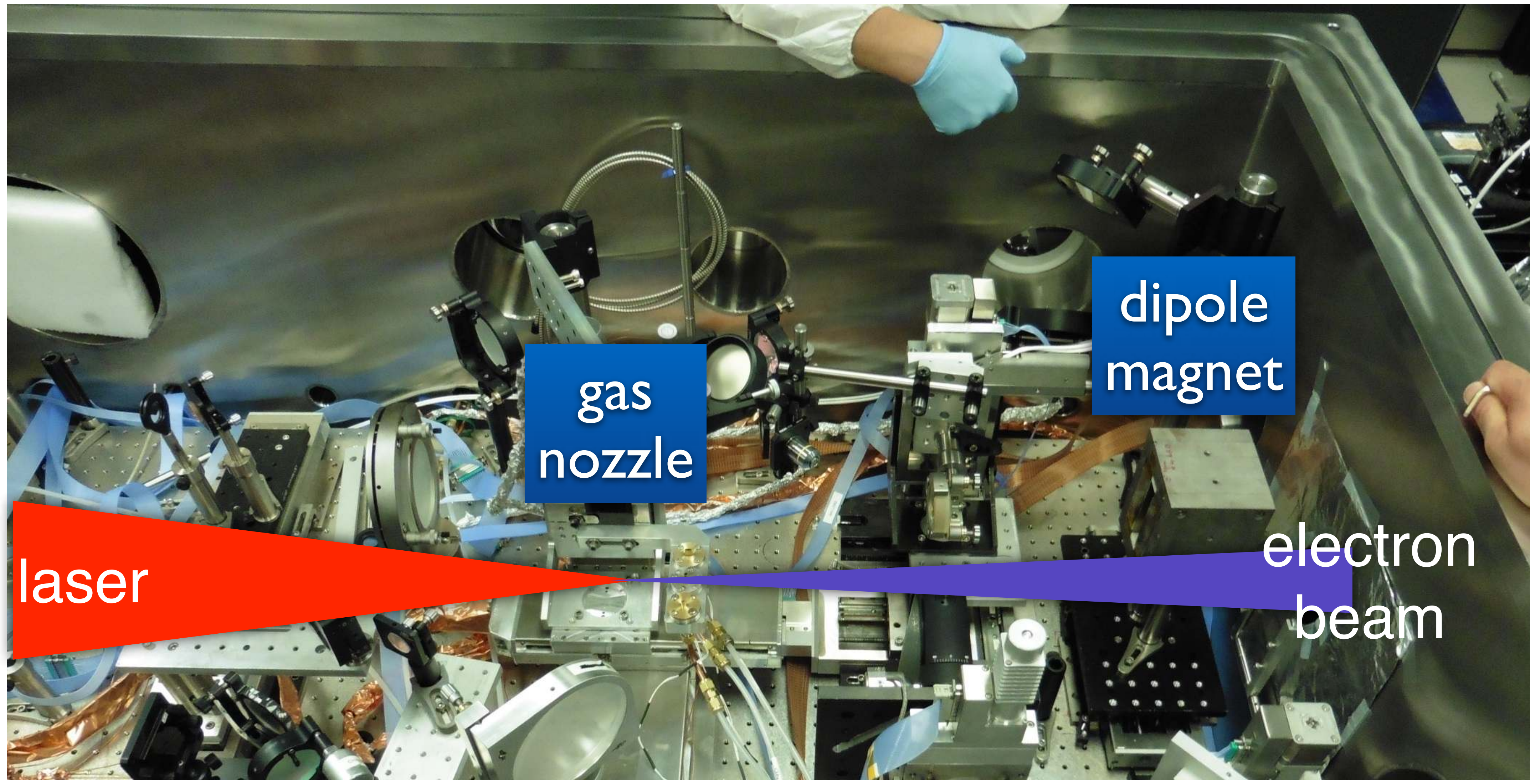
Typical Laser-Wakefield Accelerator

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

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

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

100 TW System@KIT (under commissioning)

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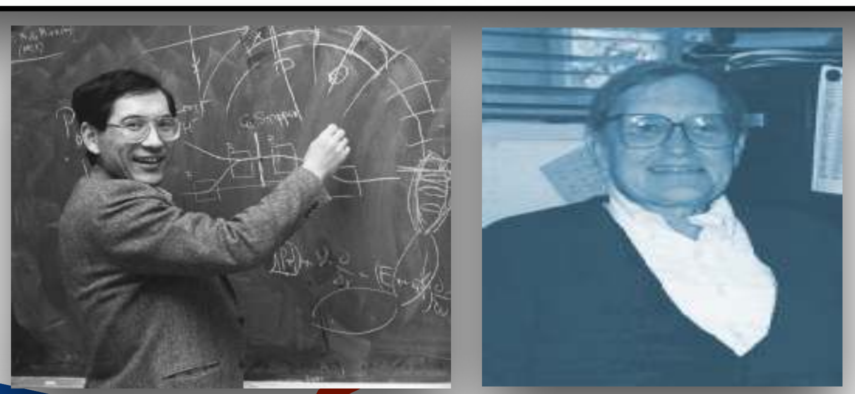
Matthias Fuchs

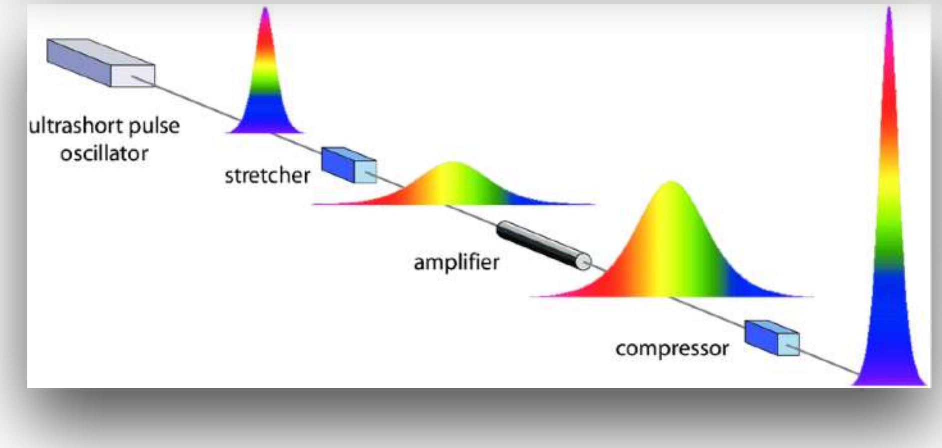
Some Milestones in LWFA

<u>First theoretical proposal</u>
Tajima & Dawson, PRL (1979)
required lasers did not exist



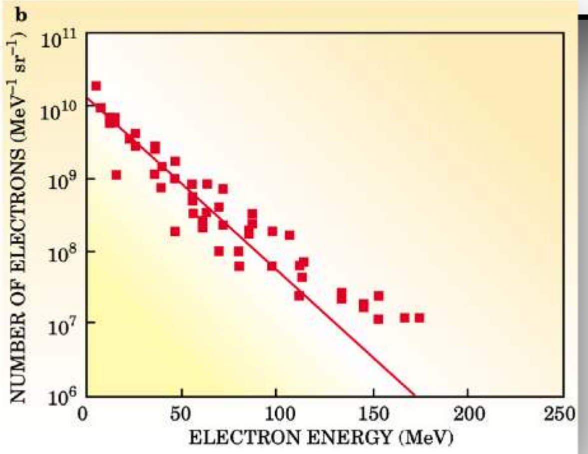
1979

<u>Invention of Chirped Pulse Amplification (CPA)</u>
Strickland & Mourou, Opt. Comm (1985)
ultrashort laser pulses



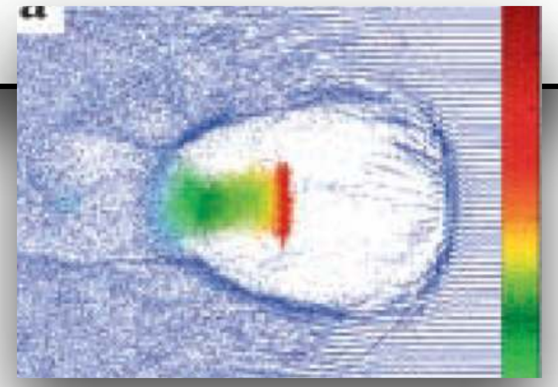
1985

<u>First laser-plasma electron beams</u>
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



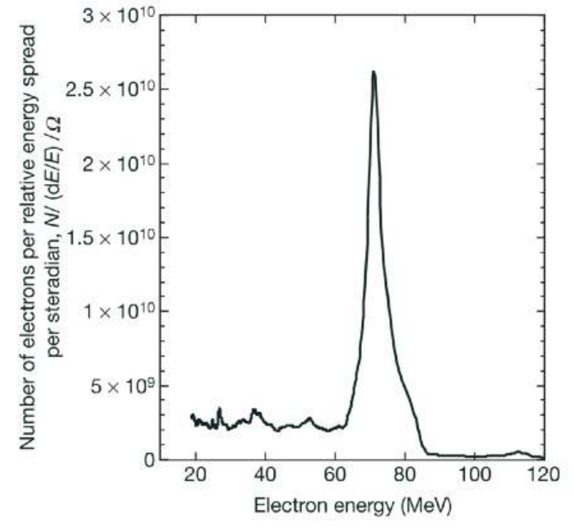
1995- 2002

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



2002

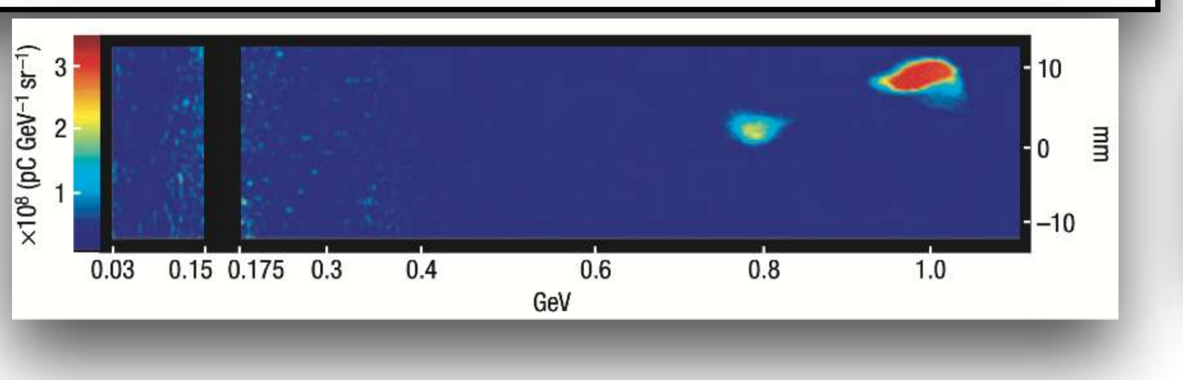
<u>Experimental observation of quasi-monoenergetic beams</u>
Mangles *et al.* Nature (2004). Faure, J. *et al.* Nature (2004). Geddes, *et al.* Nature (2004).
Lasers finally can drive "bubbles"



2004

Development of laser technology

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

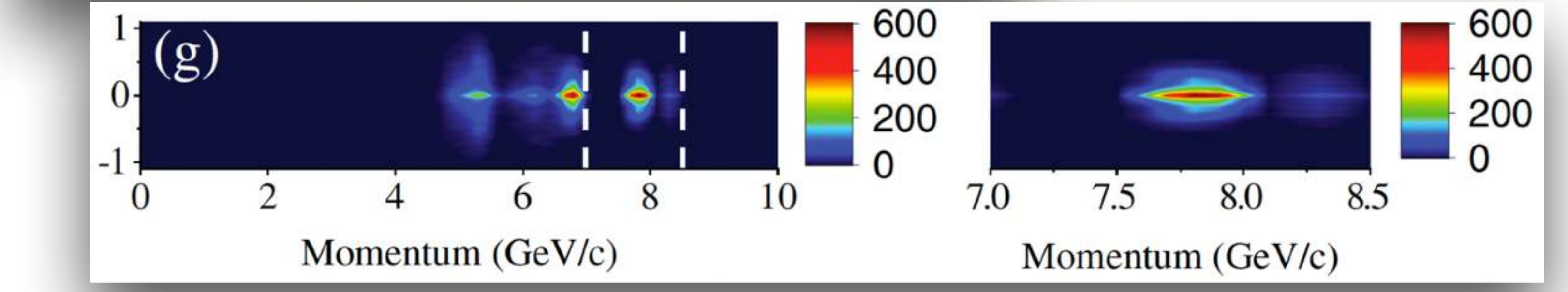


2006

<u>Nobel Prize: Strickland & Mourou</u>
for Chirped Pulse Amplification

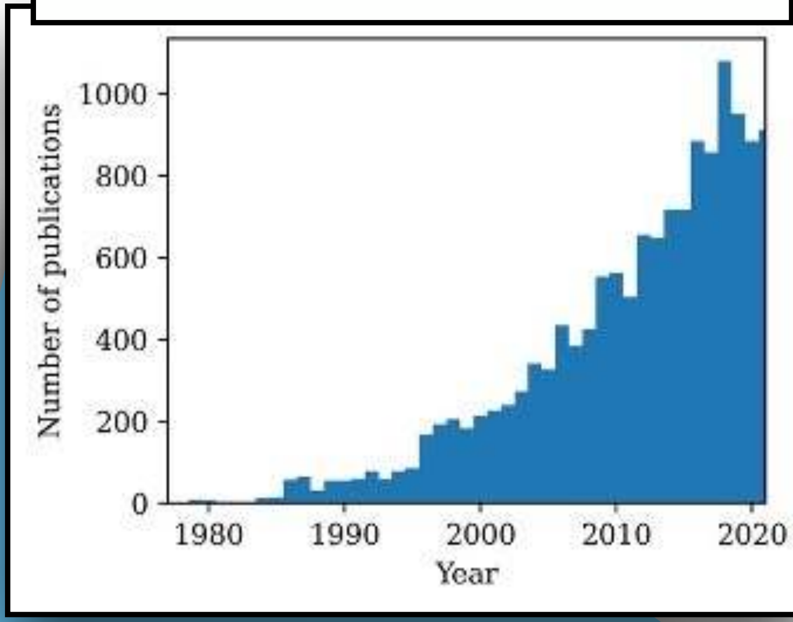
2018

<u>8 GeV LWFA electron beam</u>
Gonsalves *et al.*, PRL (2019)



2019

<u>~1000 citations/year</u>
for LWFA



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More Recent Progress
From Acceleration to Accelerator

- 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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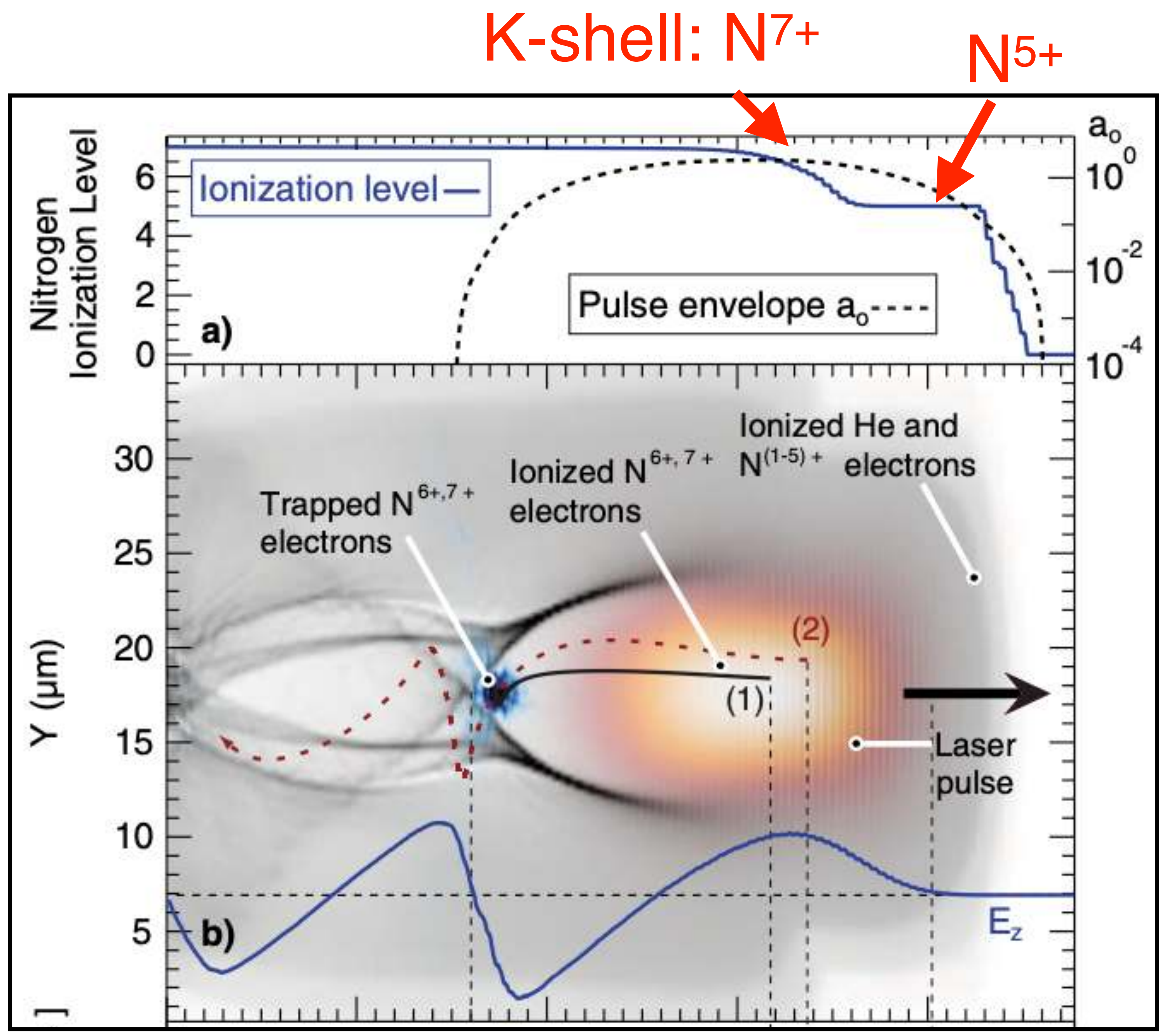
Controlled Injection

- <u>Ionization-induced injection</u>
  - inner-shell electrons of higher-Z ionized at peak laser intensity
  - electrons “born” on axis & in accelerating phase

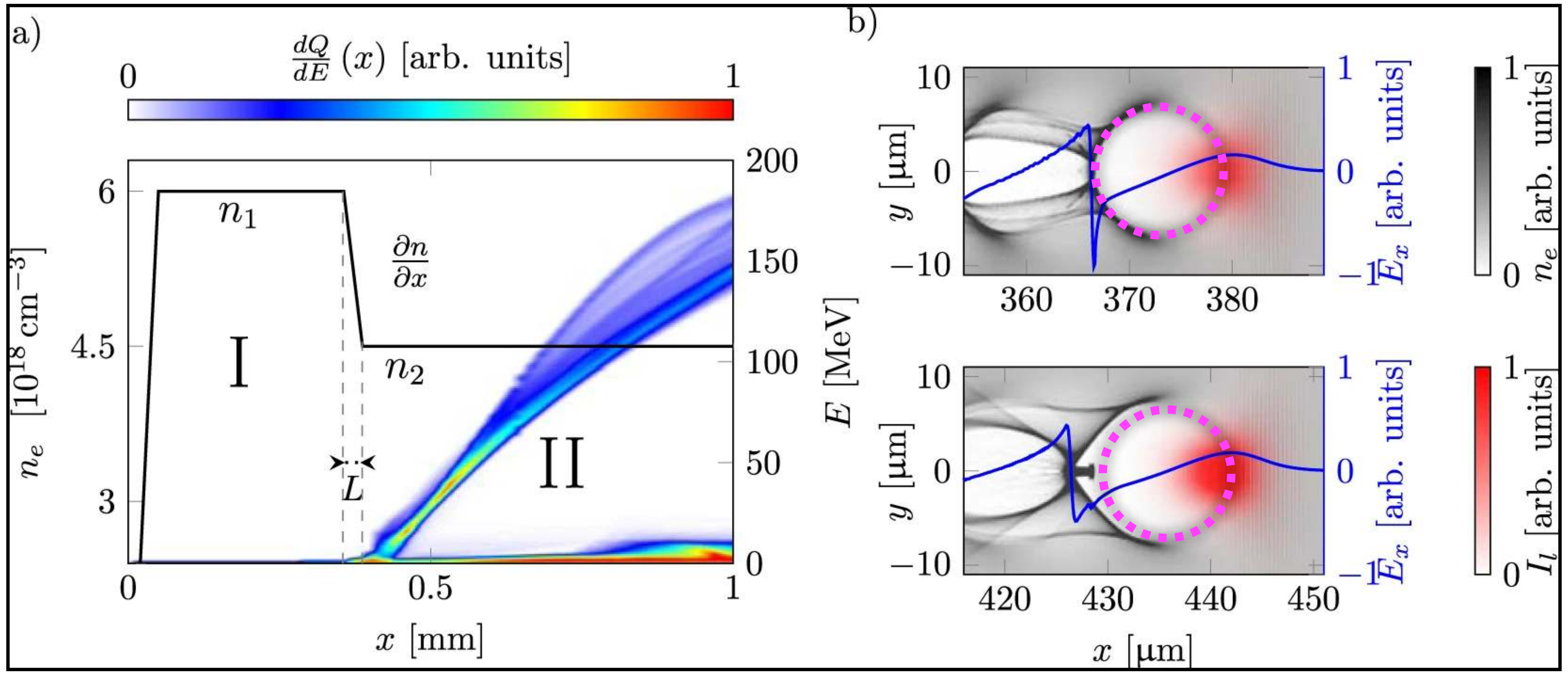
  Chen *et al.*, J. Appl. Phys. (2006); McGuffey *et al*., PRL (2010)

- <u>Density-downramp injection</u>
  - decrease phase velocity of wake
  - controlled & localized injection

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



Pak *et al*. PRL (2010)



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

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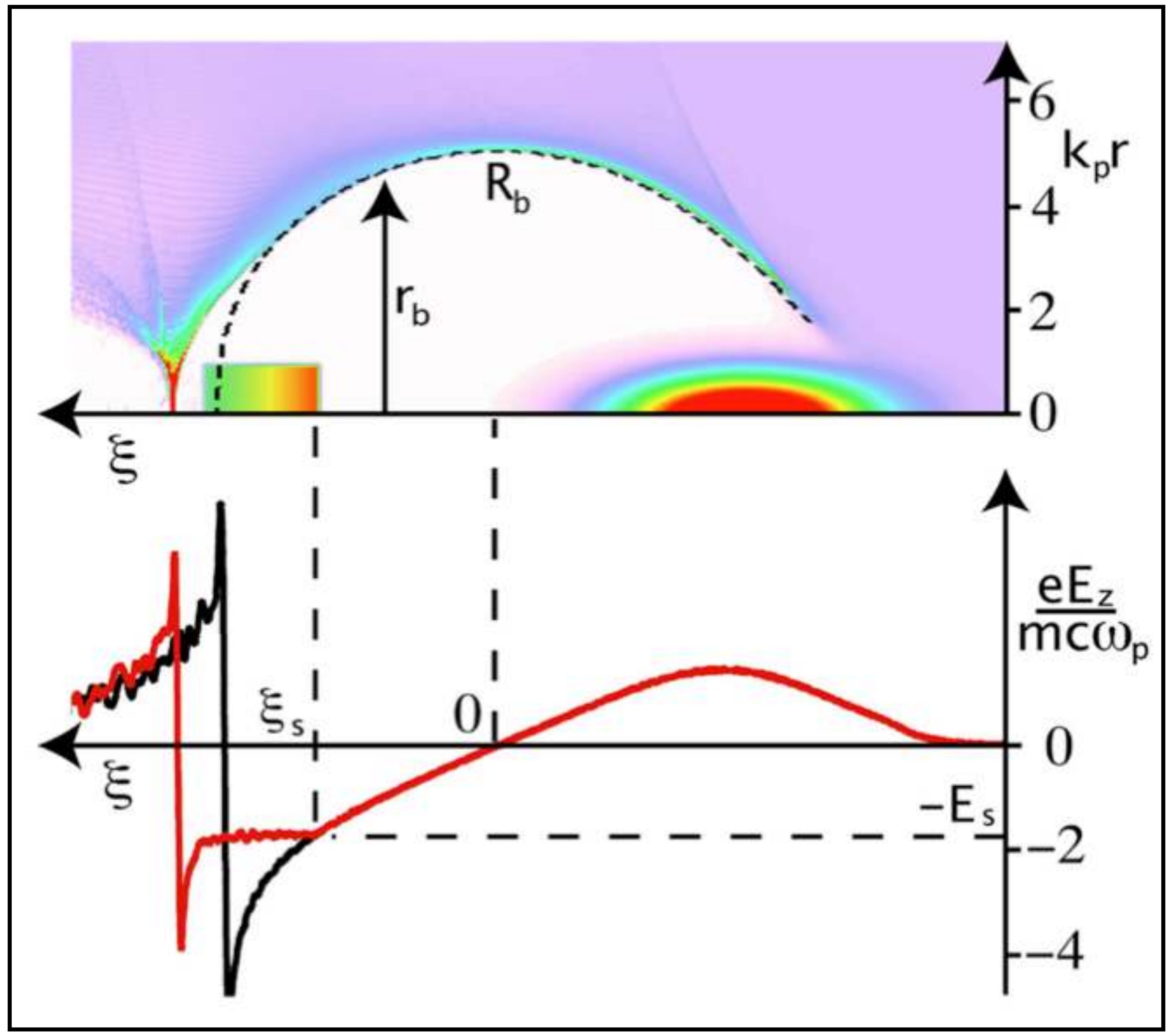
Controlled Acceleration: Beam Loading

- Beam loading
  - 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)

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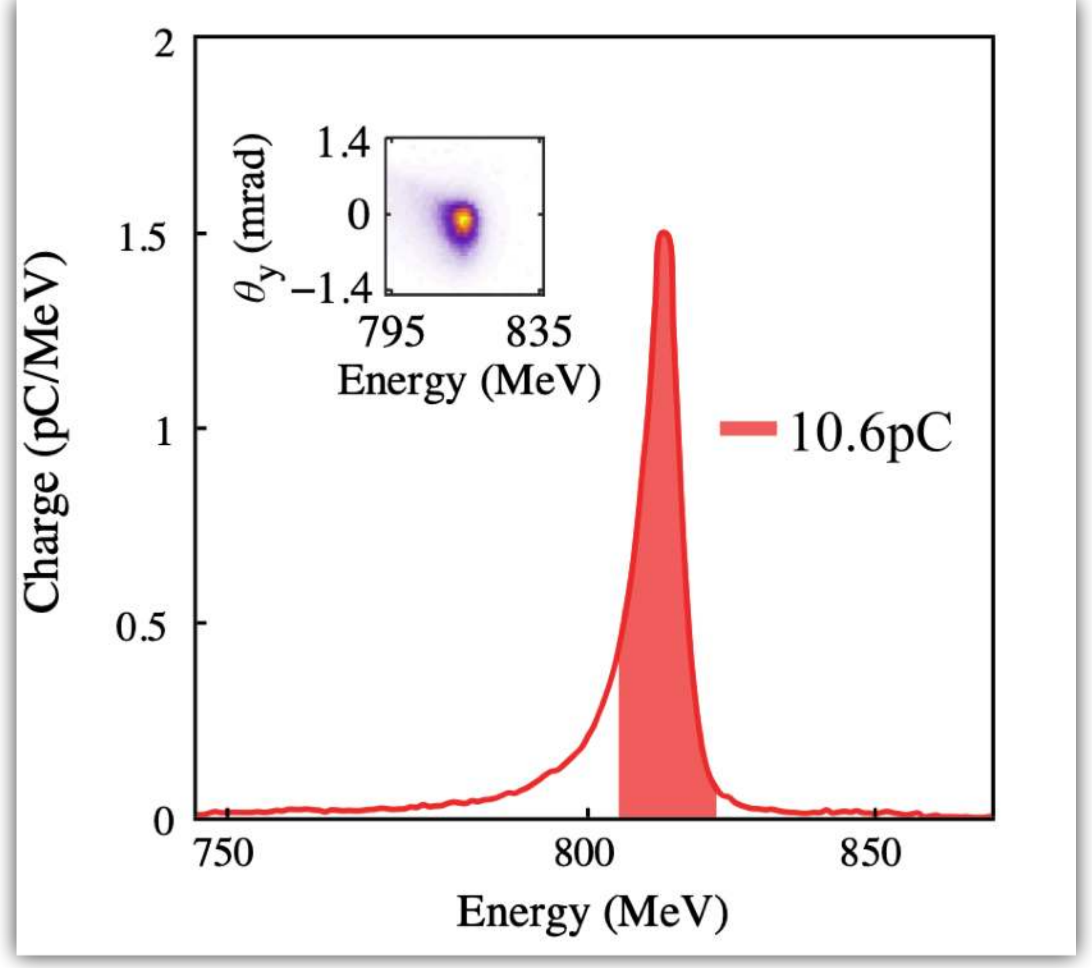
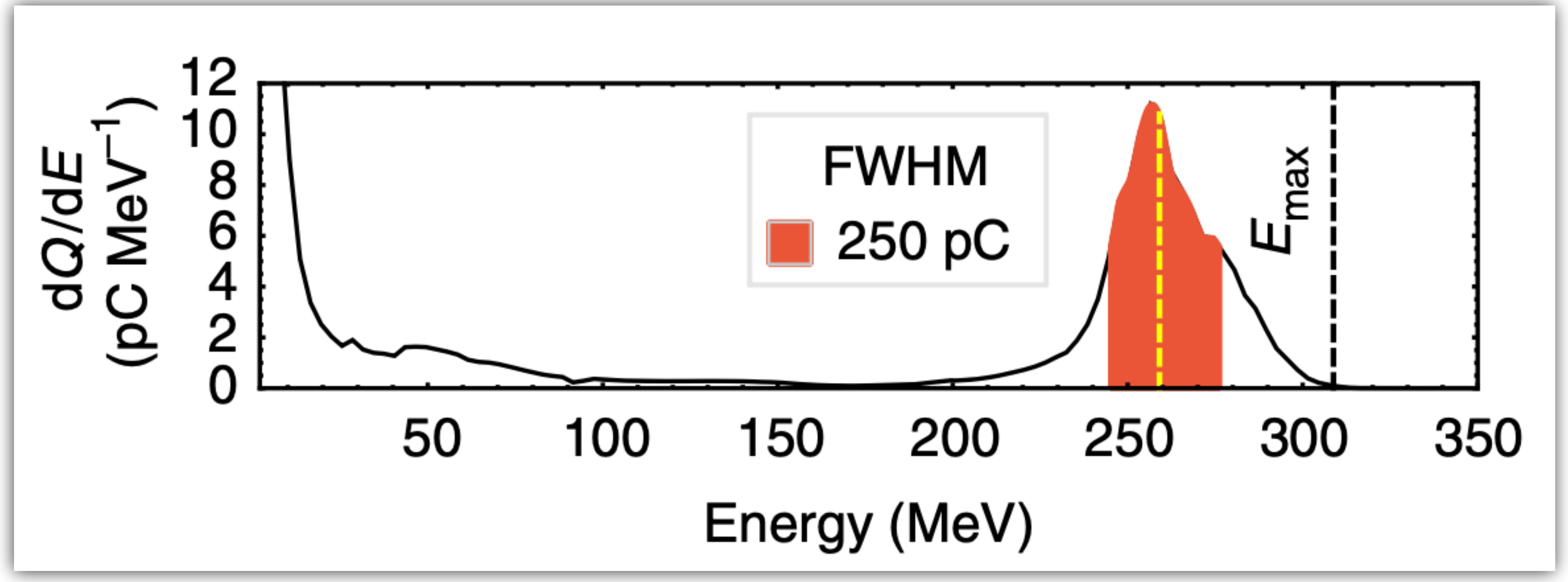
Selected Highlights of Experimental Progress

0.3% relative energy spread



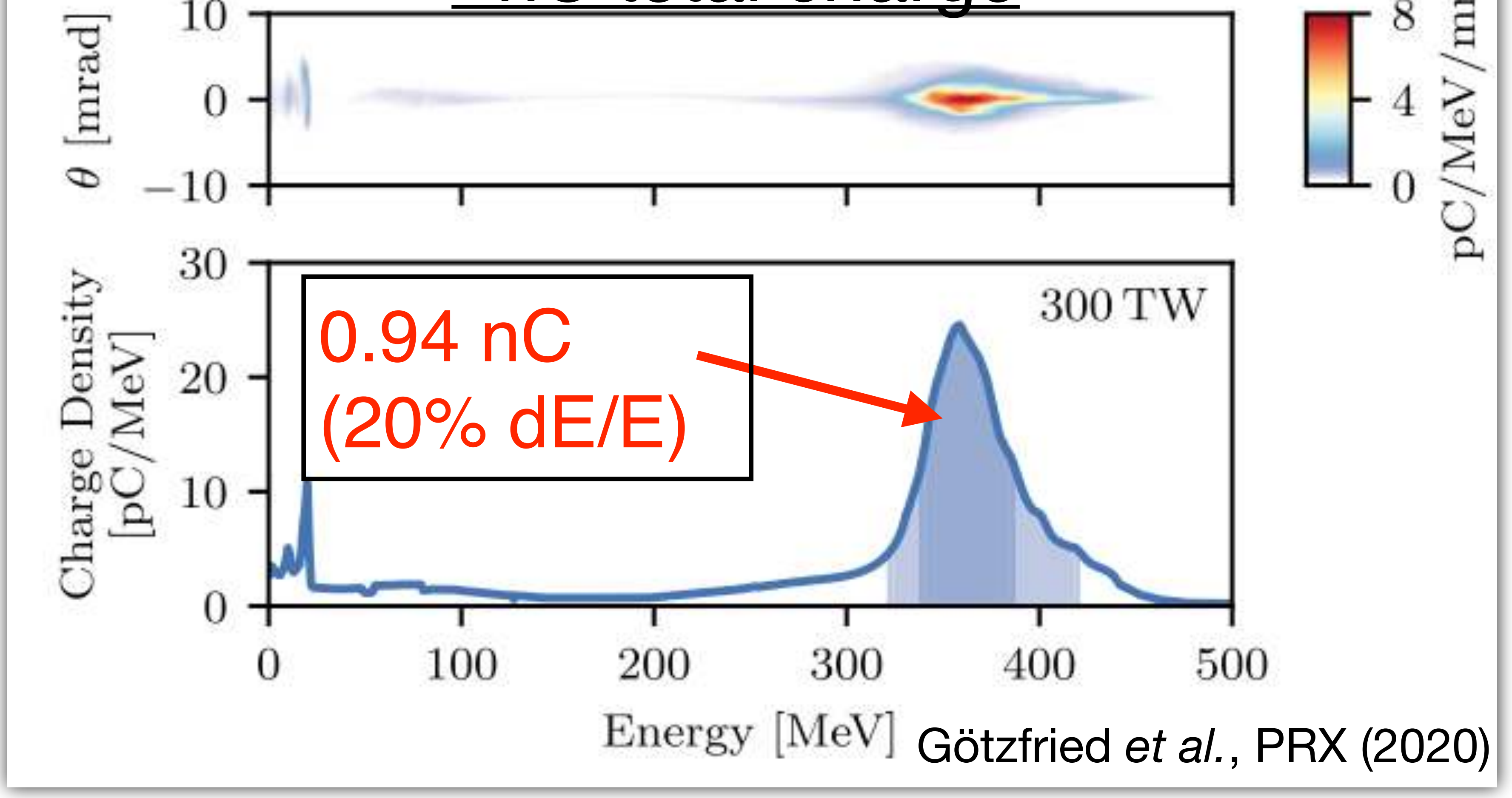
Ke *et al.*, PRL (2021)

>10 pC/MeV spectral charge density



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

~nC total charge

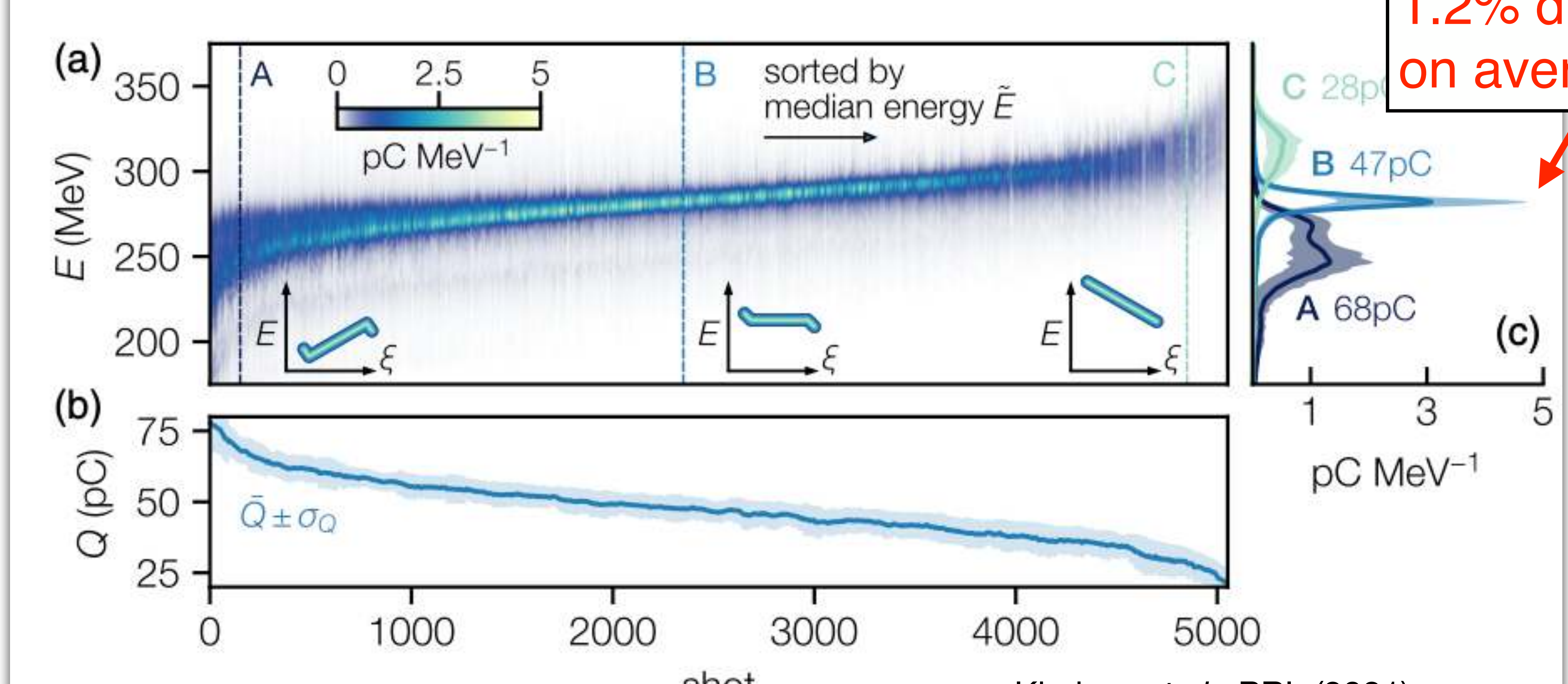


0.94 nC (20% dE/E)

Götzfried *et al.*, PRX (2020)

tuning of optimal beam loading

1.2% dE/E on average



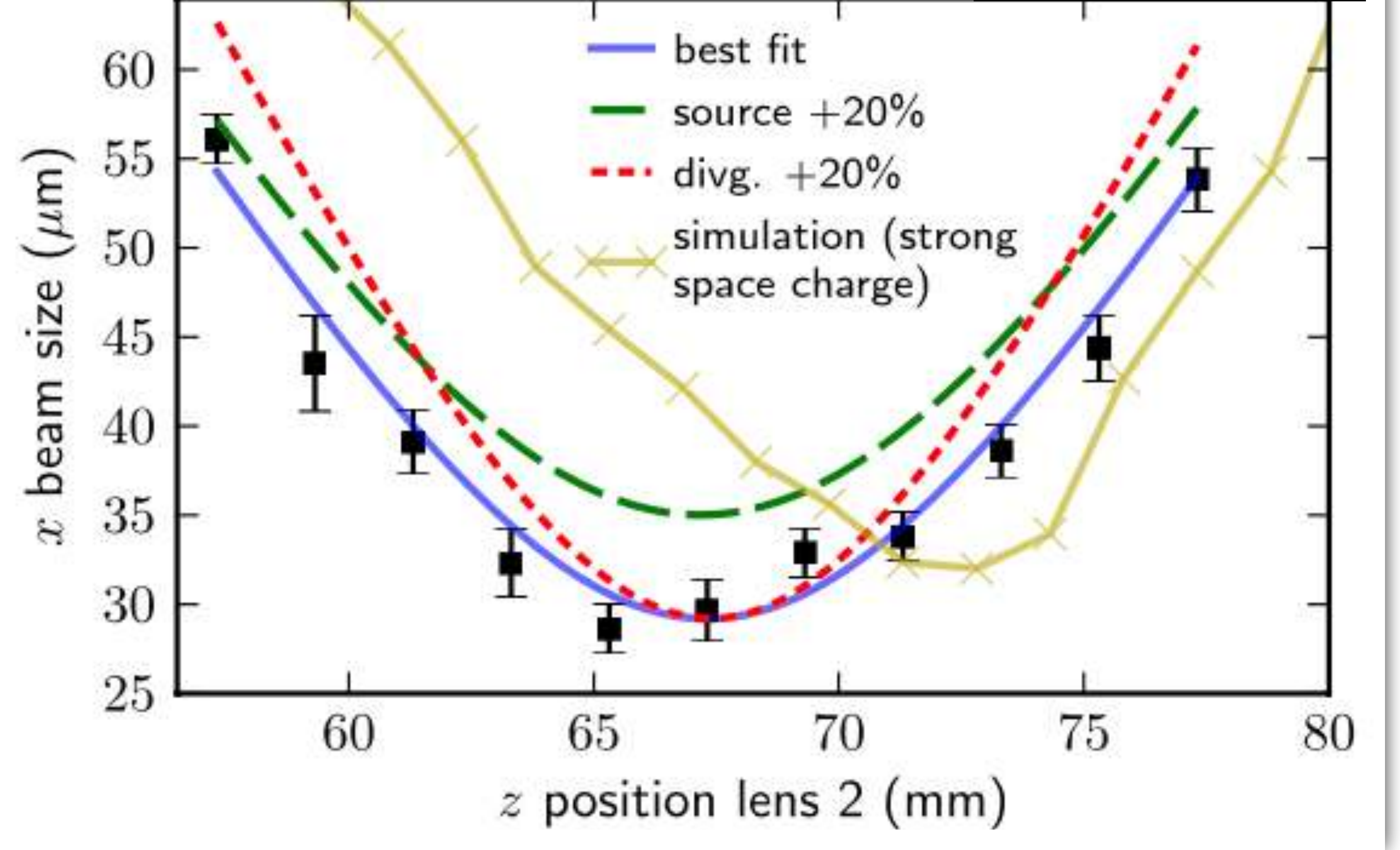
Kirchen *et al.*, PRL (2021)

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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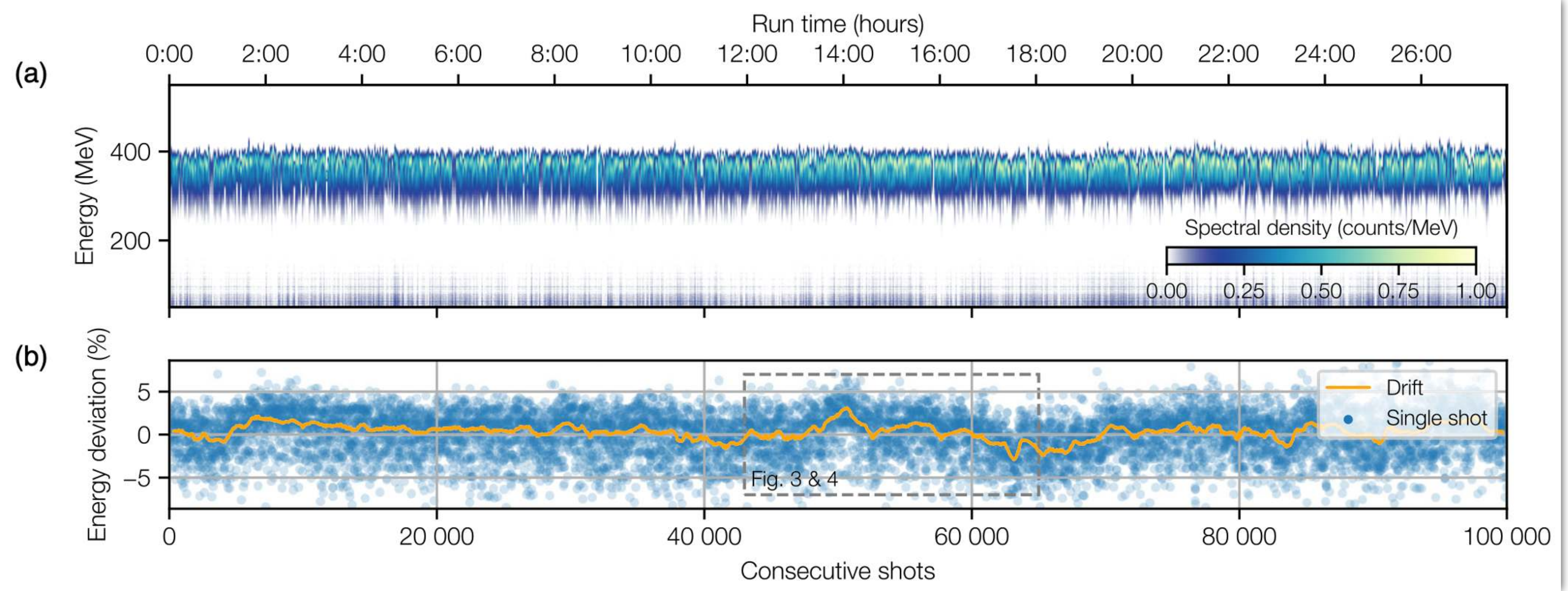
Selected Highlights of Experimental Progress

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)

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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

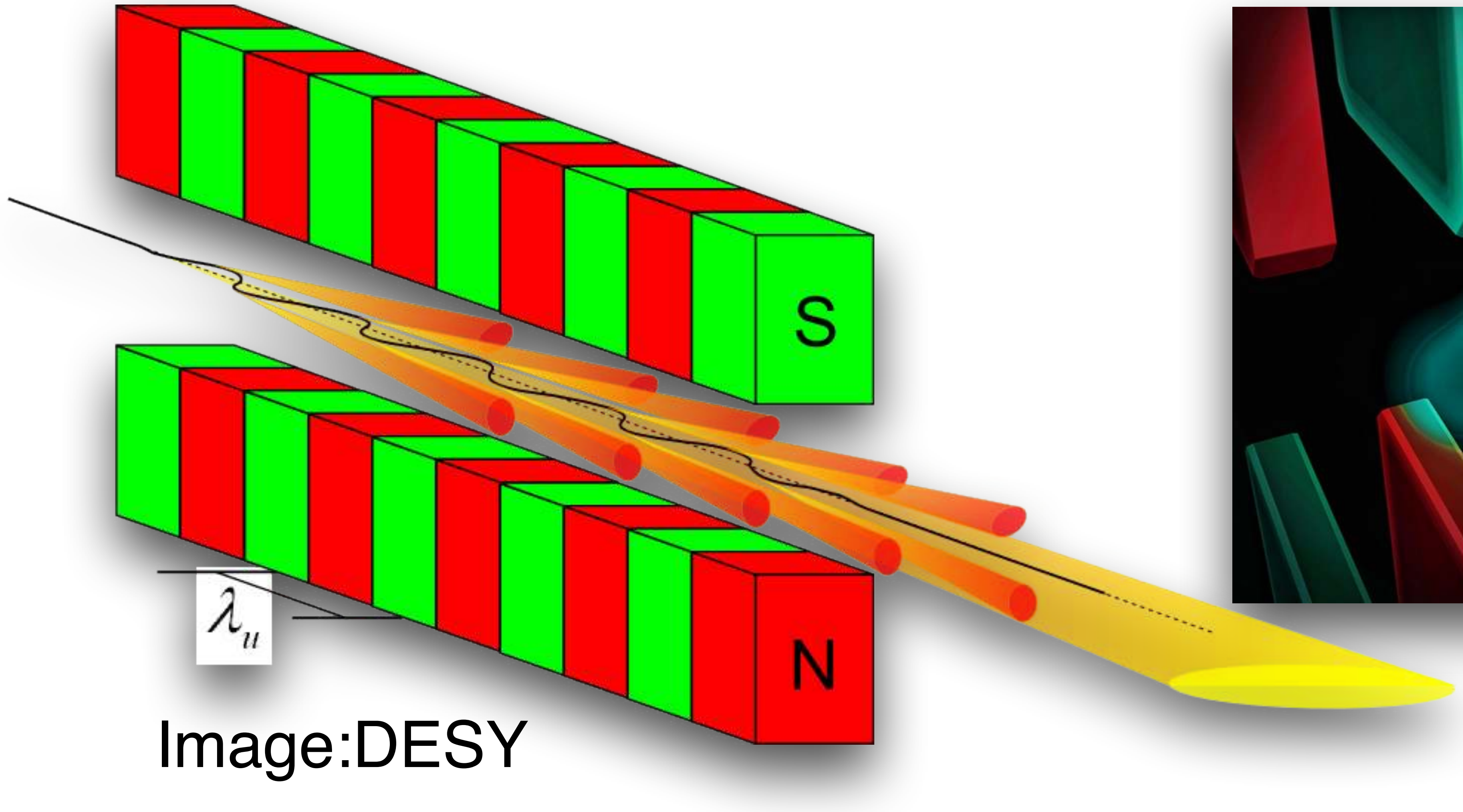

Image:DESY

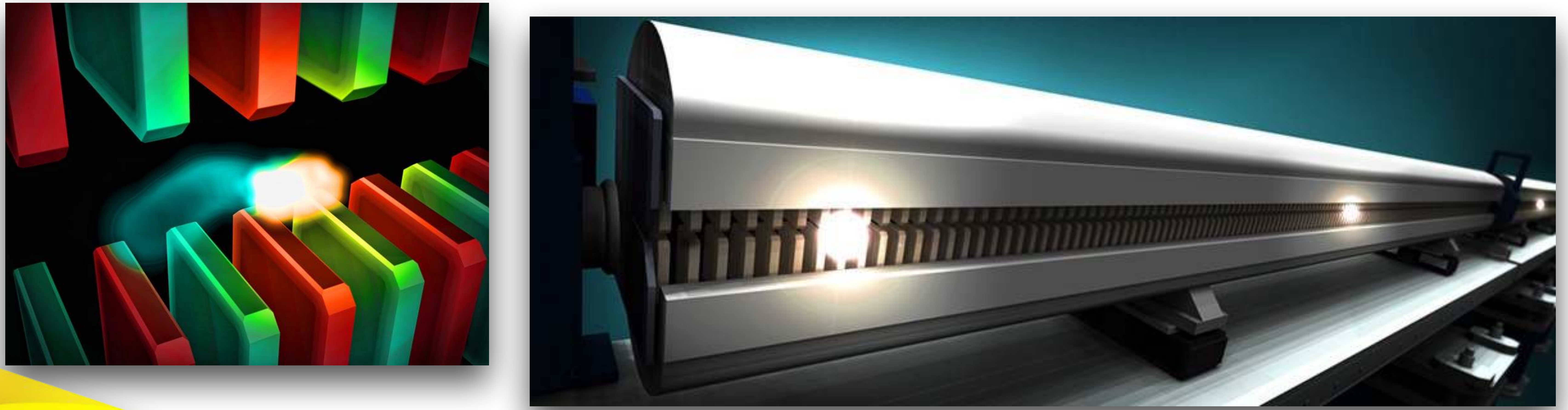

Image:Greg Stewart/SLAC

- 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

λ_u : ~mm, cm

γ : ~ 1000-10,000

λ : ~Angstrom (10^{-10} m): X-rays!

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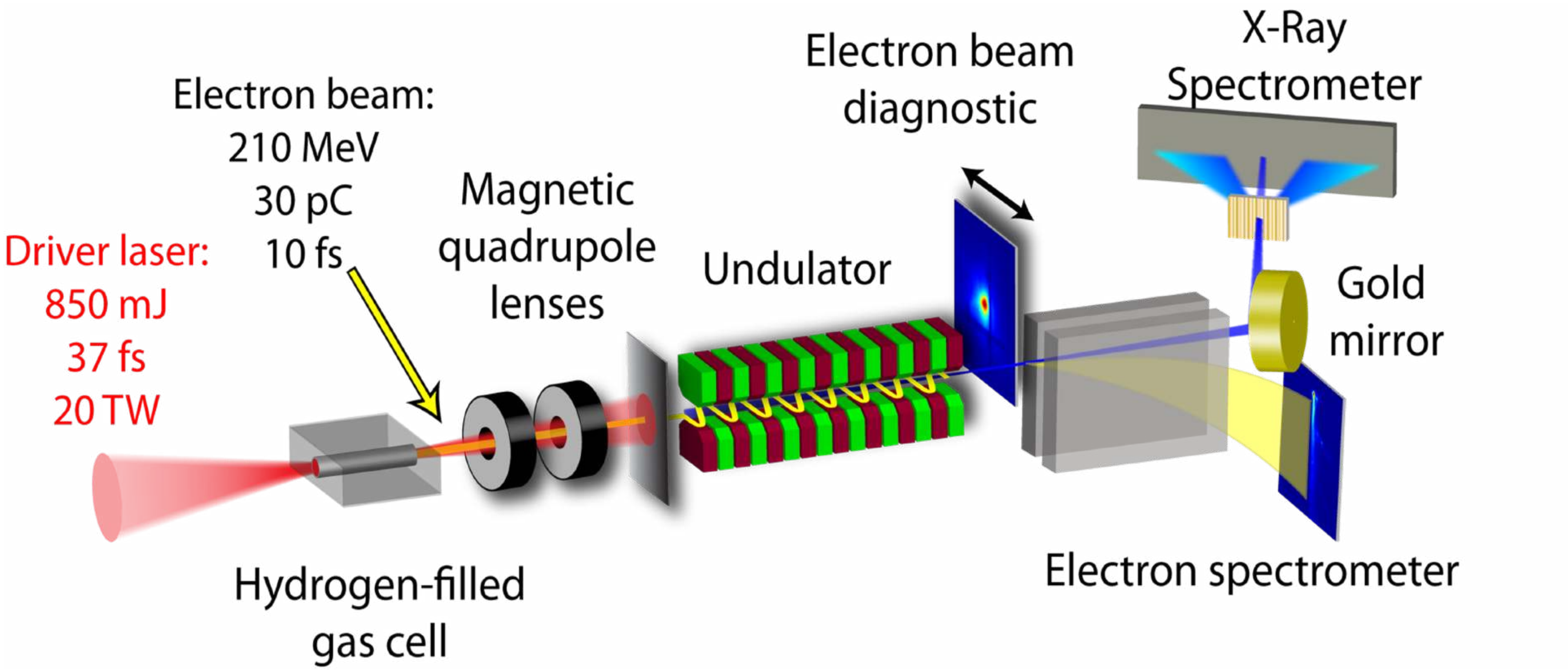
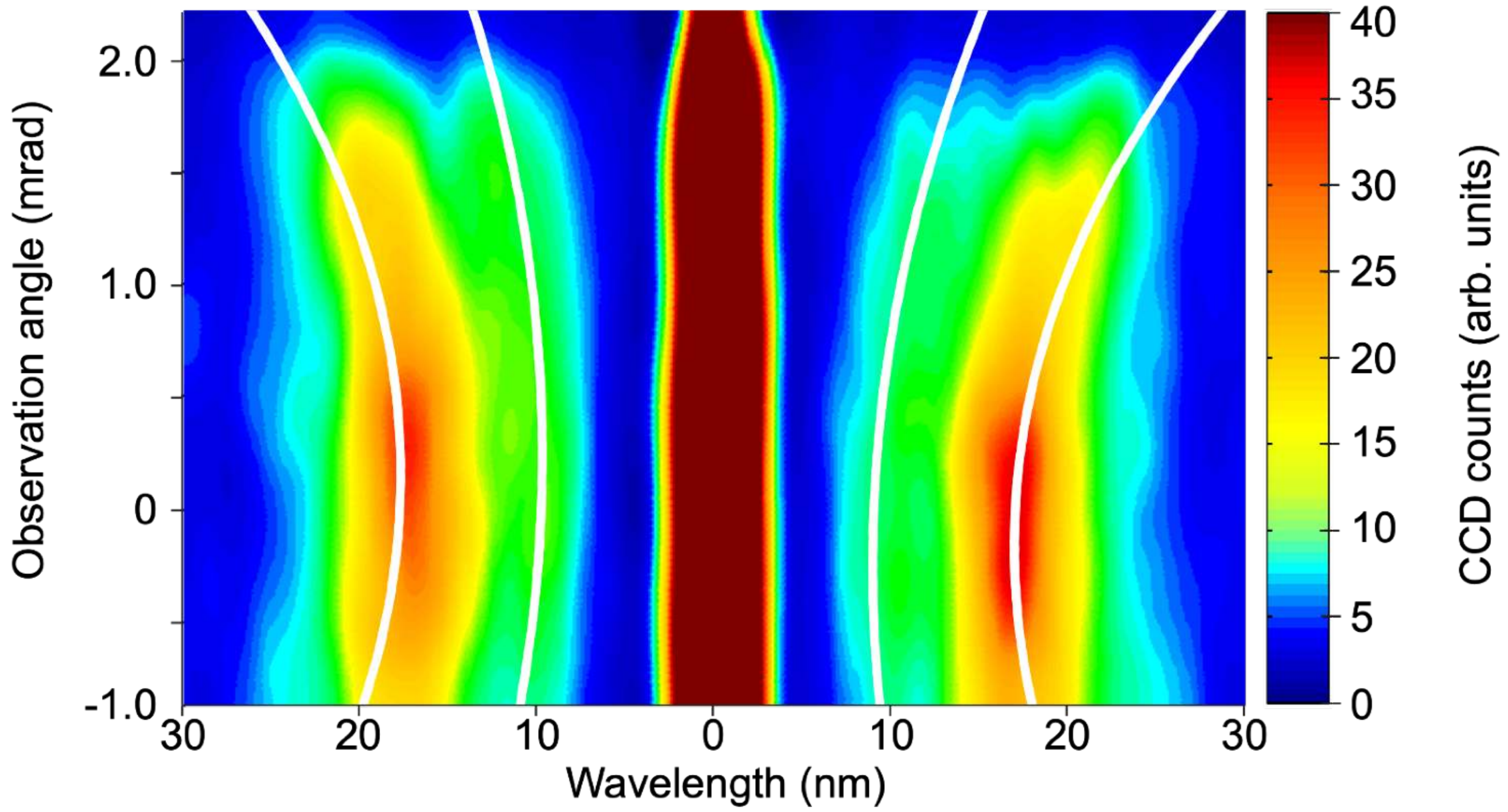
Undulator Source Driven by Laser-Plasma Electron Accelerator

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]*

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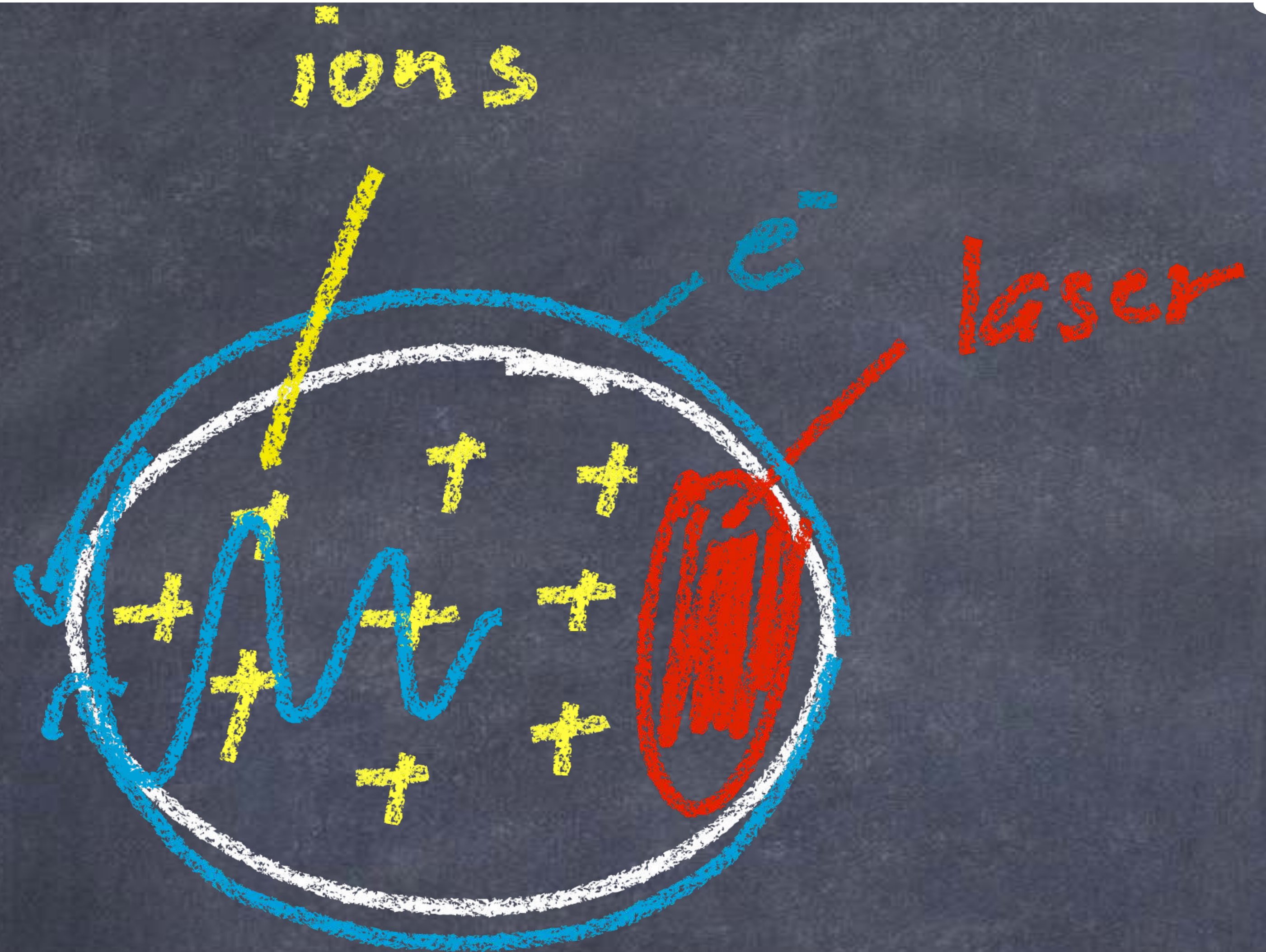
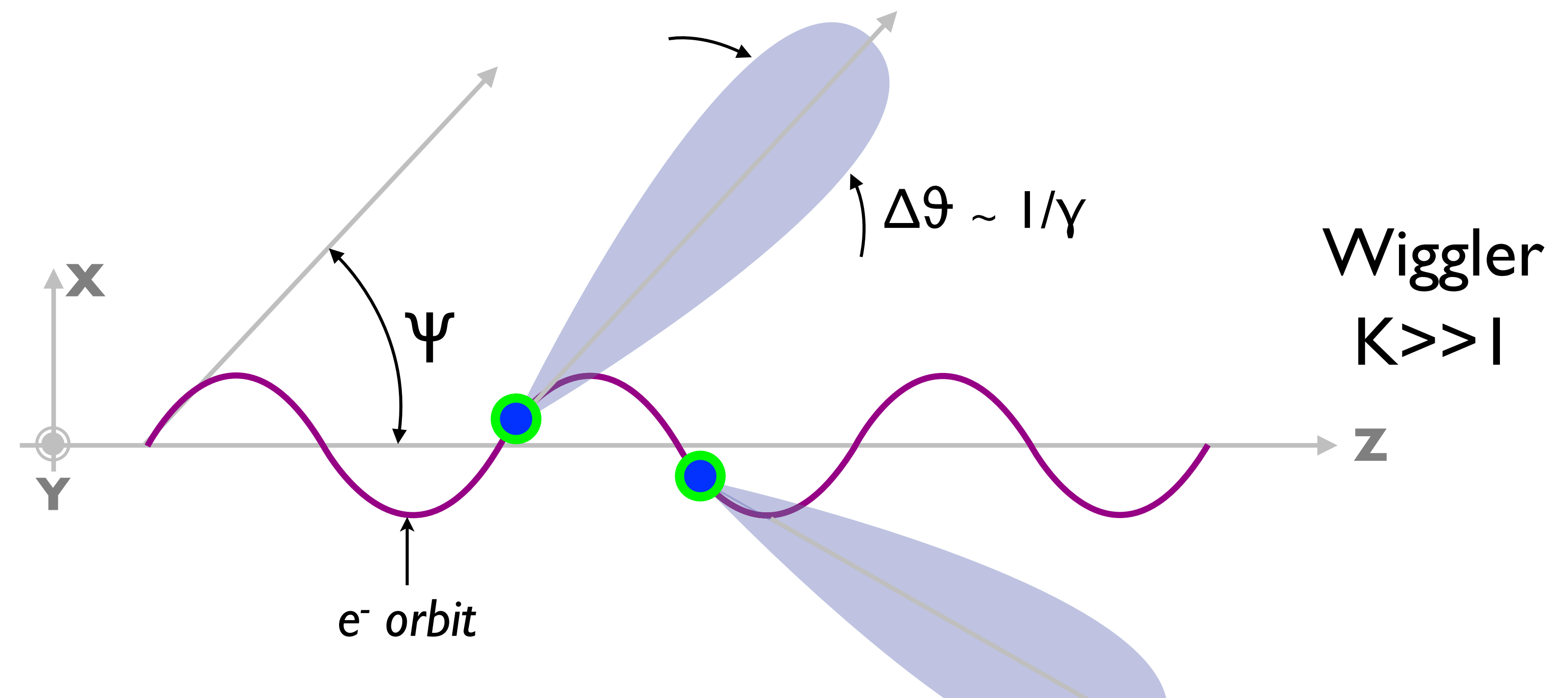
Plasma Wiggler Source (Betatron Source)

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: $\hbar\omega \sim r_\beta$

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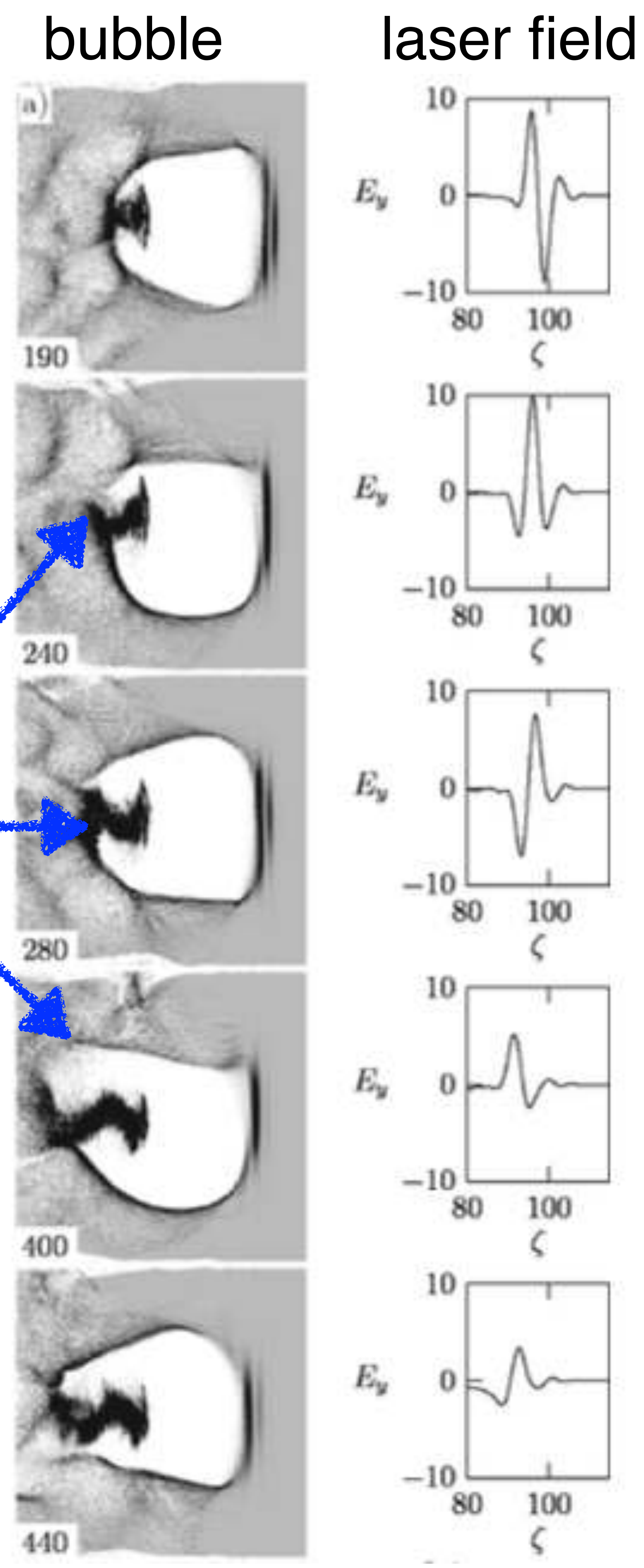
Control and Enhancement of the Betatron Oscillation Amplitude

- Manipulate betatron amplitude through controlled off-axis electron injection
- For few-cycle laser pulses: transverse asymmetry of bubble shape
- Asymmetry depends on sign of leading laser electric field (CEP)
- Laser depletion and evolution -> oscillating sign of leading electric field
- => transverse oscillation of bubble
- Transverse oscillation of high-plasma density peak at back of bubble from which electrons are self-injected (off-axis injection)
- To be avoided for high-brightness *electron* beam generation
  (B Lei, et al. - PhysRev E 2024)



off-axis injection & betatron oscillation

E. N. Nerush and I. Y. Kostyukov. PRL (2009).

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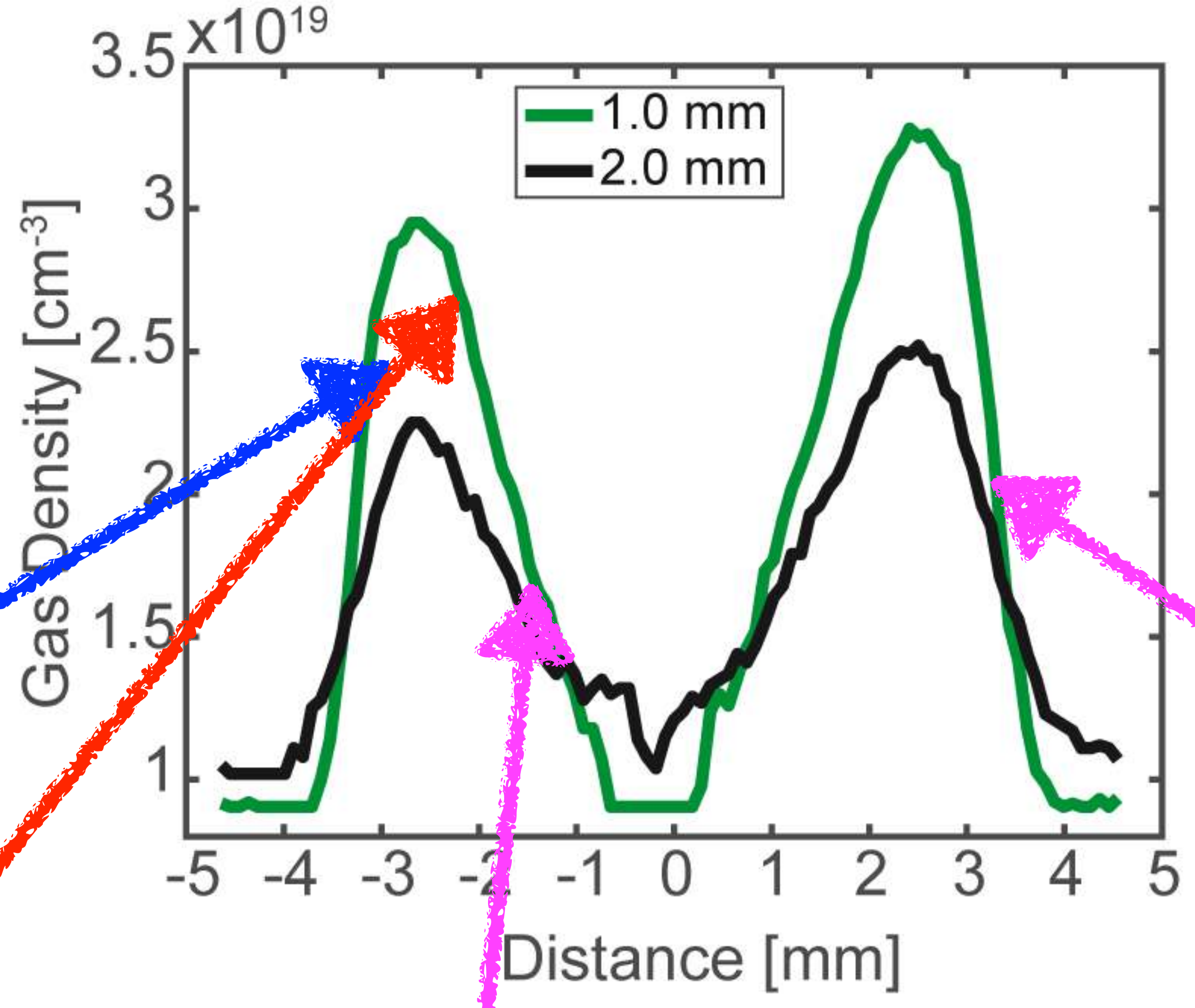
Matthias Fuchs

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)



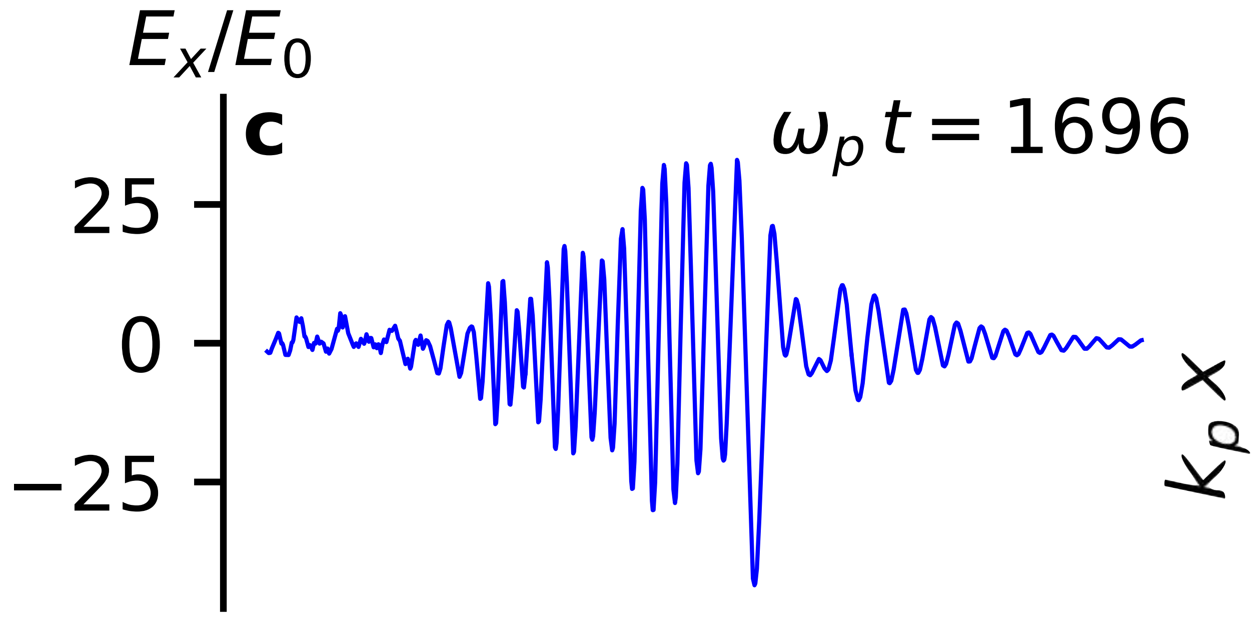
“M” shaped plasma density

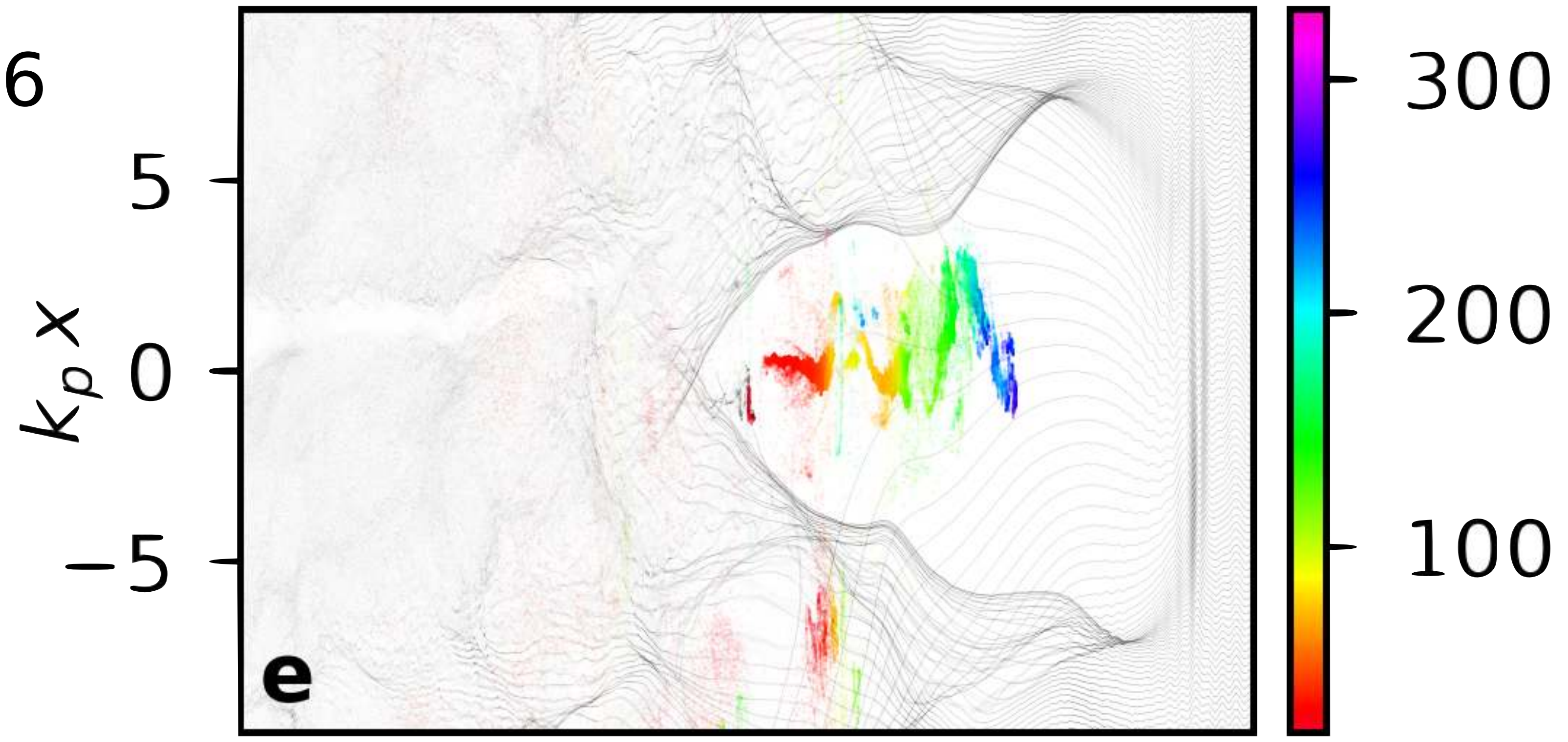
laser evolution

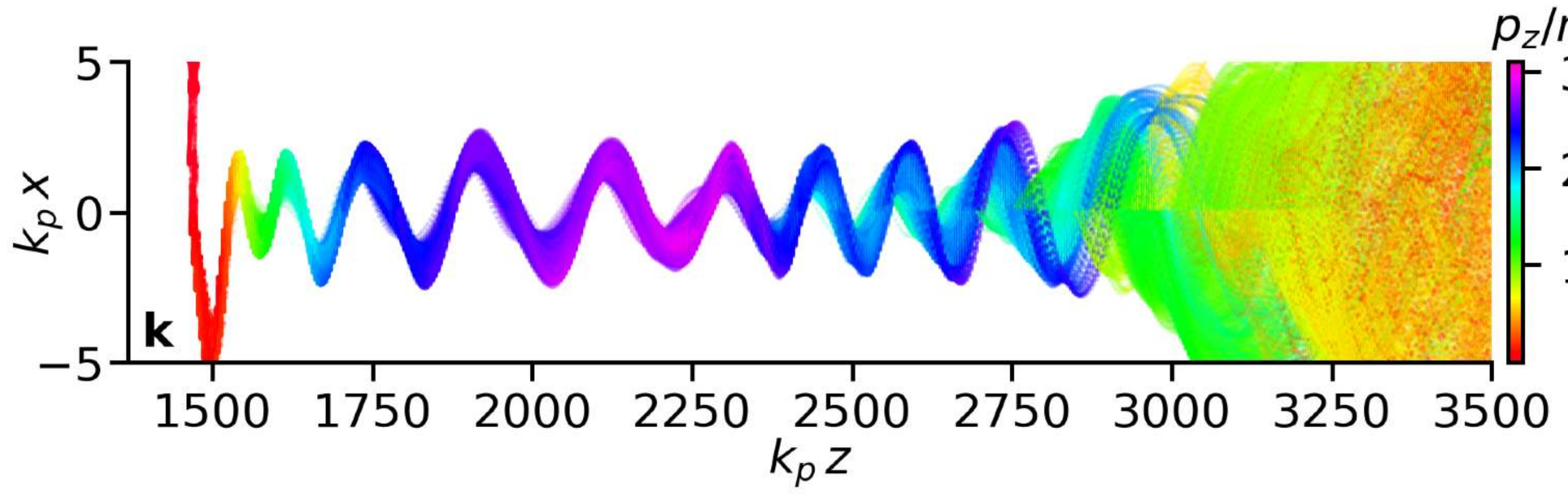
off-axis injection during downramp

coherent betatron oscillation

nearly constant electron energy







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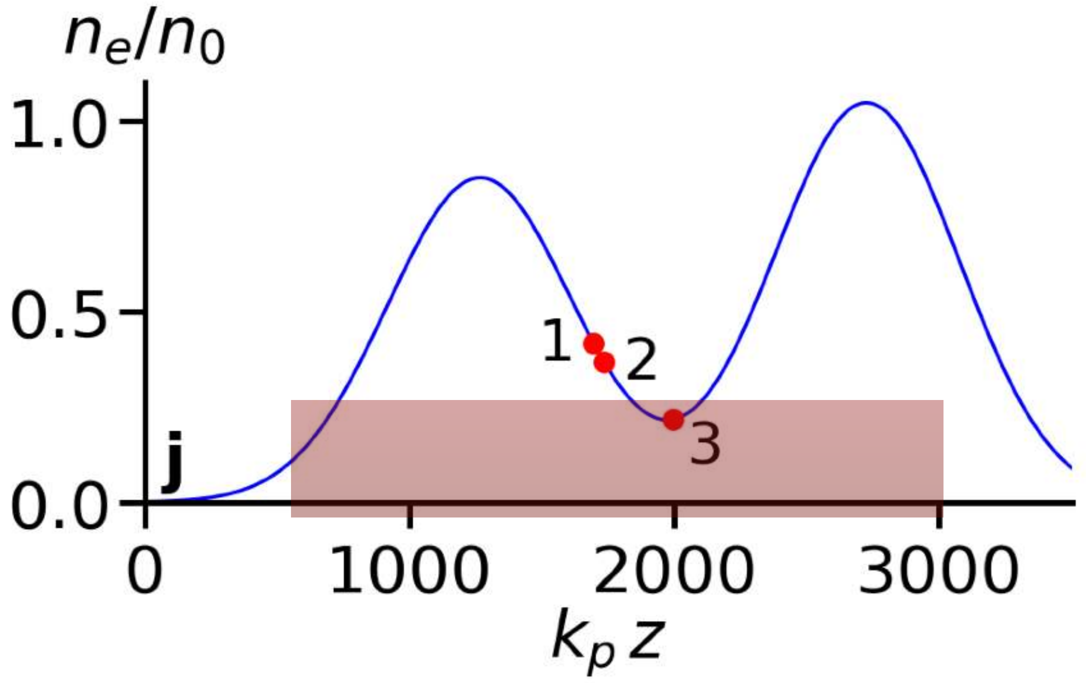
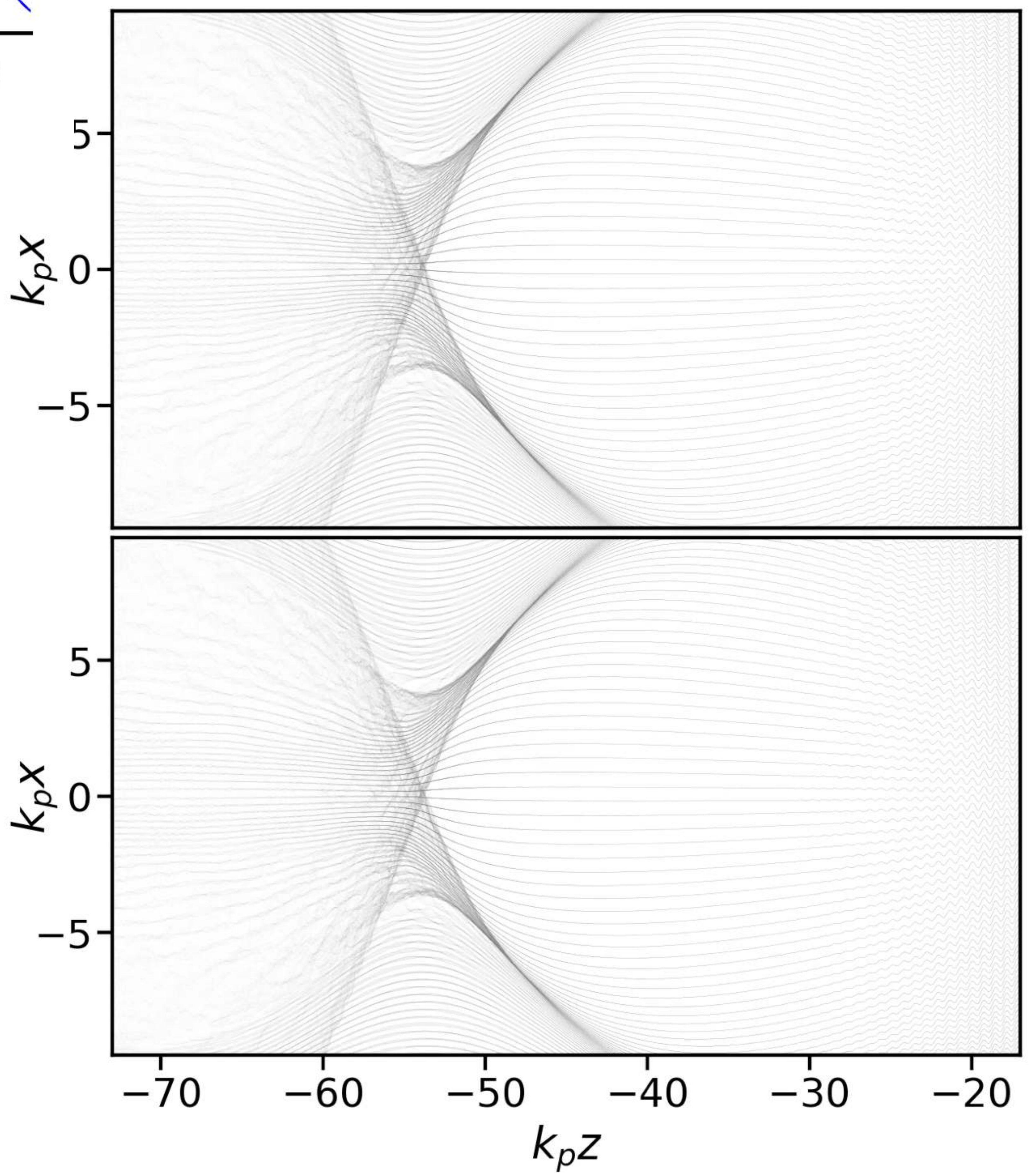
Increase of Betatron Amplitude Through Transverse Oscillating Bubble: Simulation

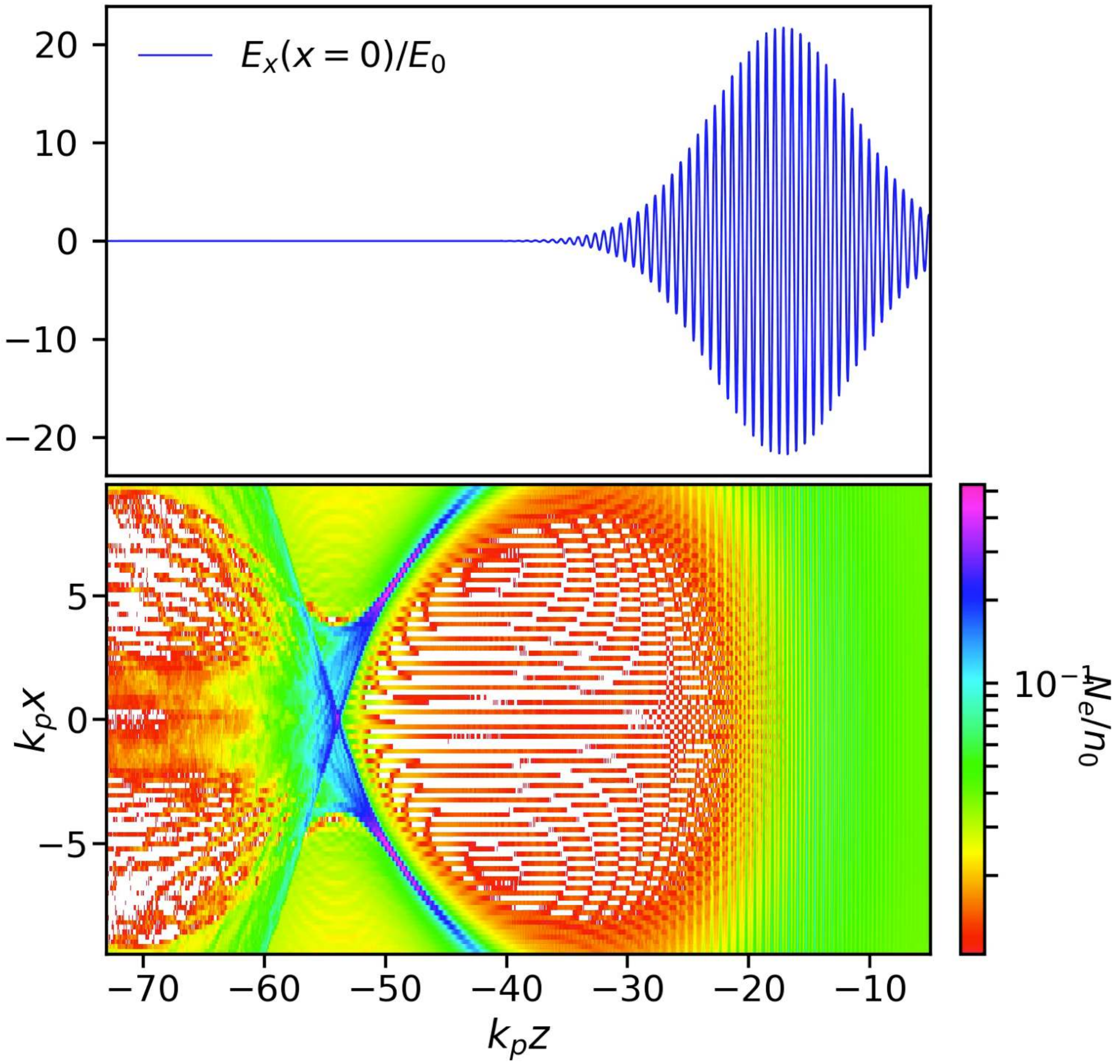


$\omega_p\,t = 405 \quad N_b = 0$

longitudinal momentum

transverse momentum





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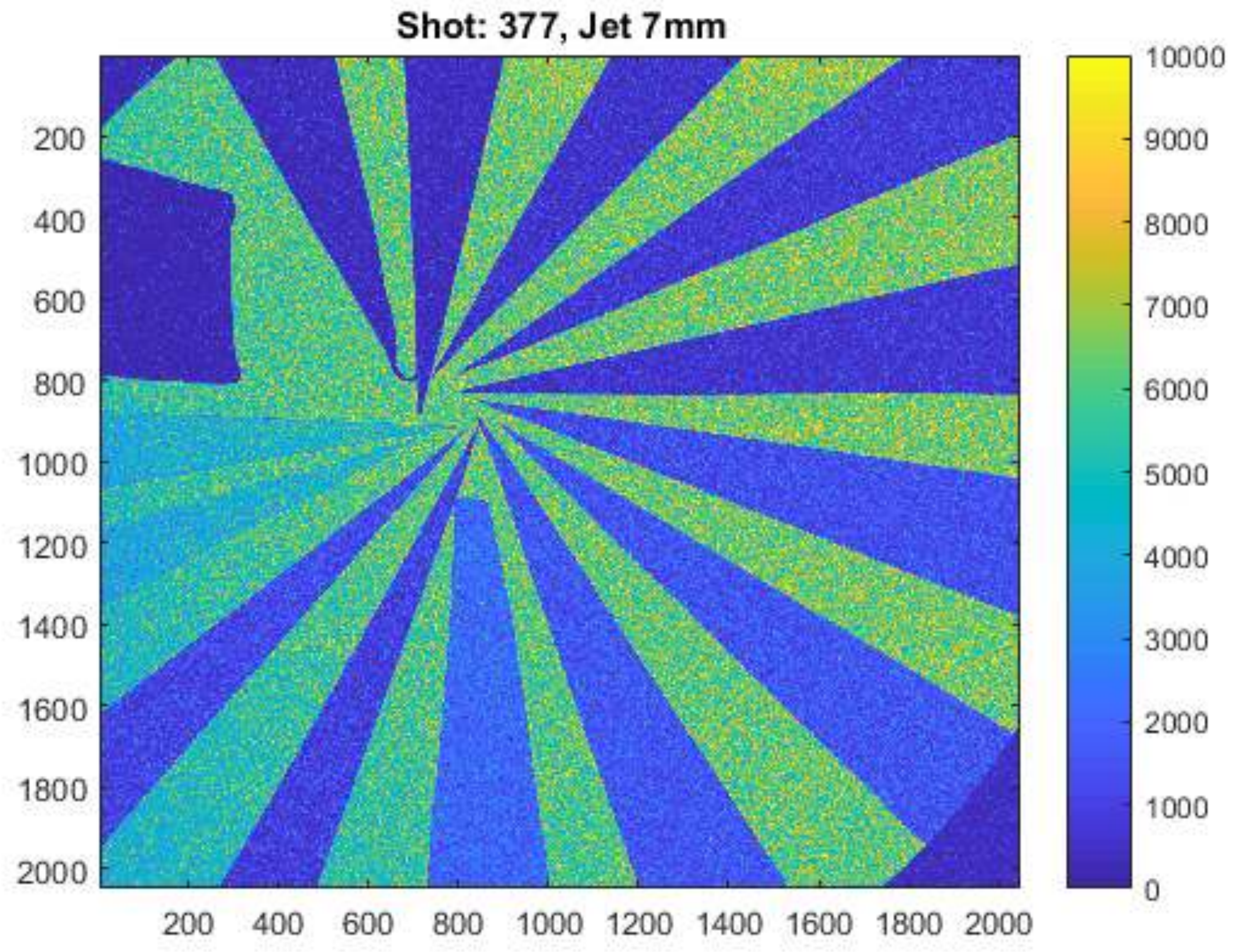
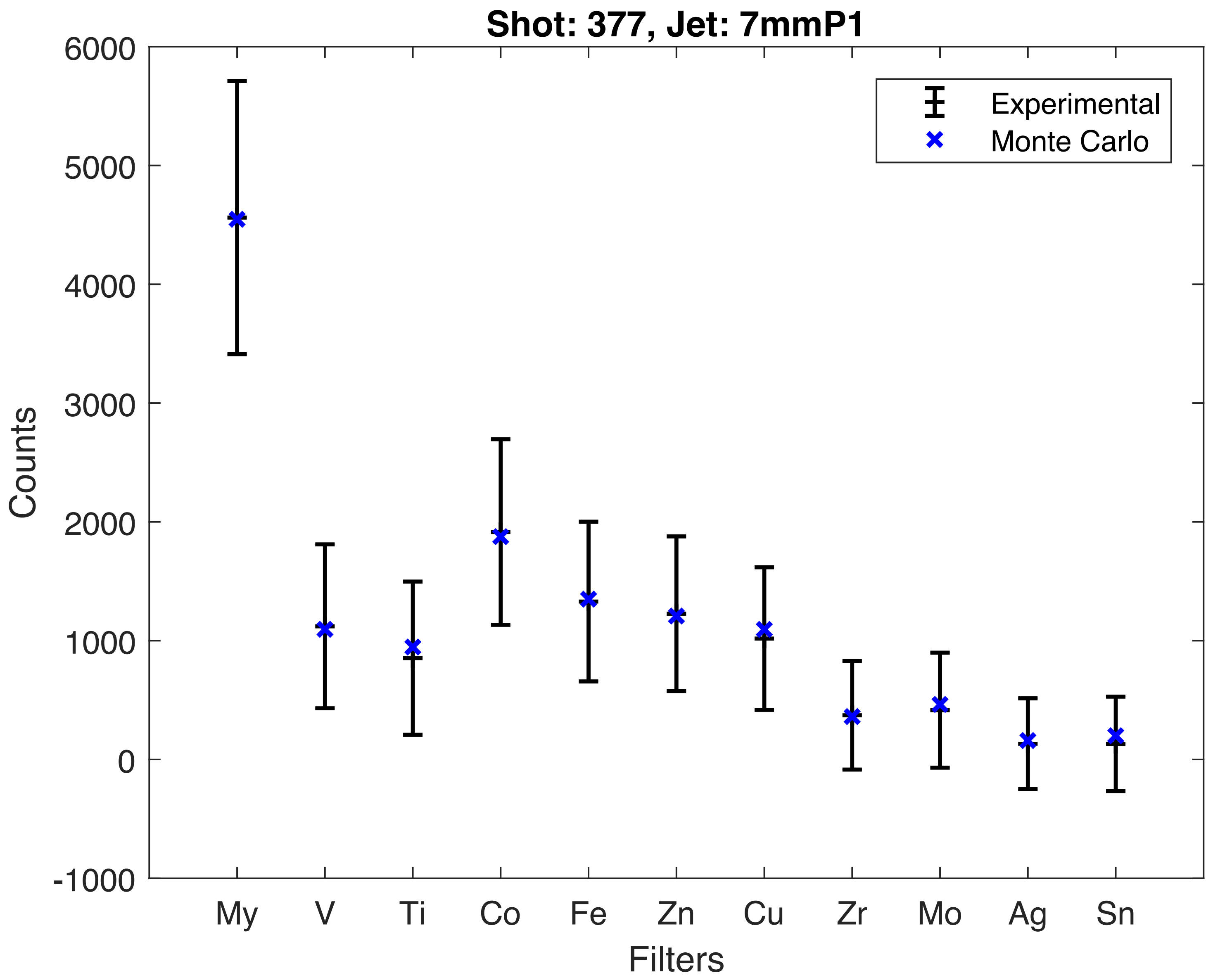
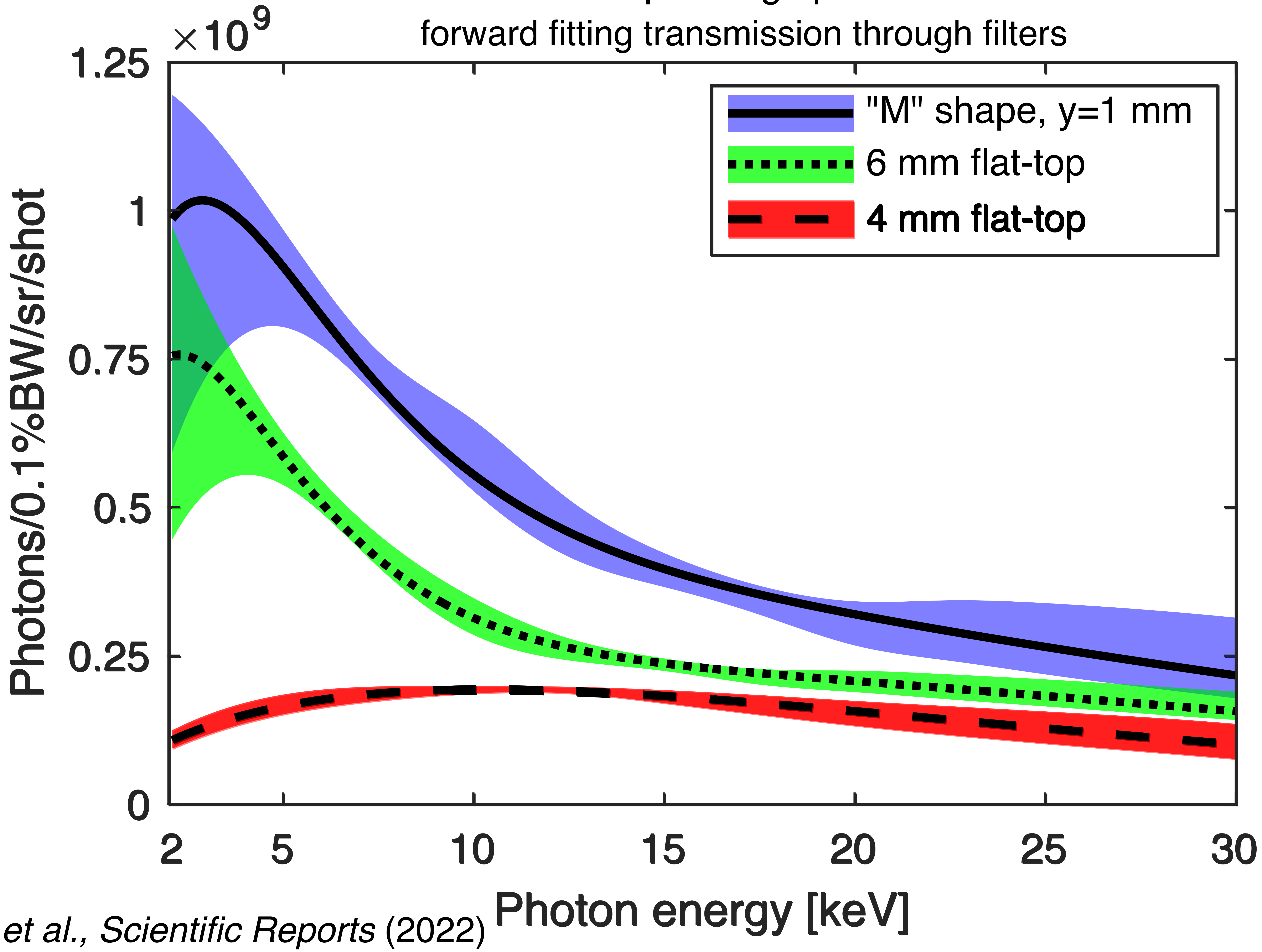
Measured X-ray Spectra

compare structured profile to flat-top jets





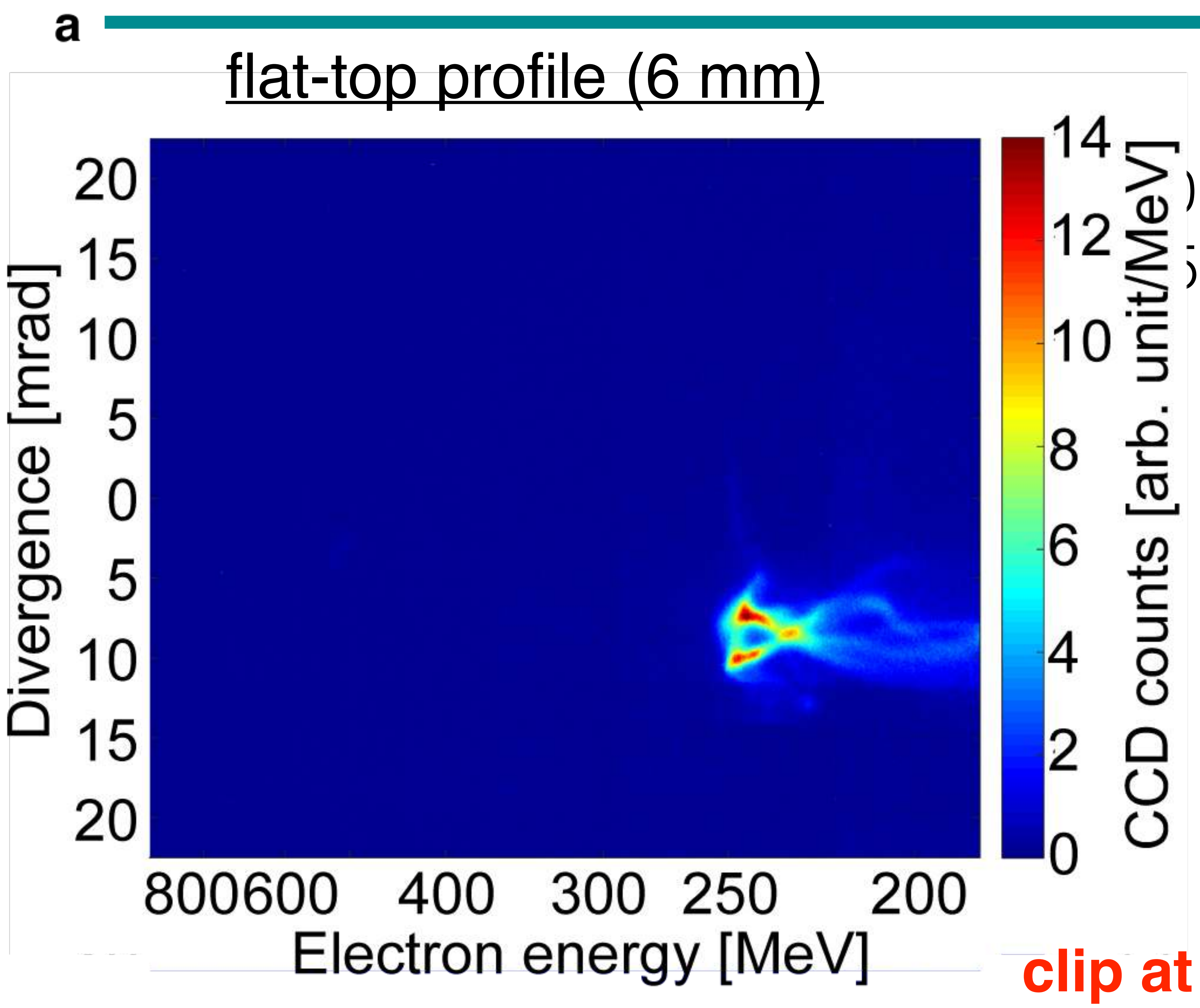
corresponding spectrum

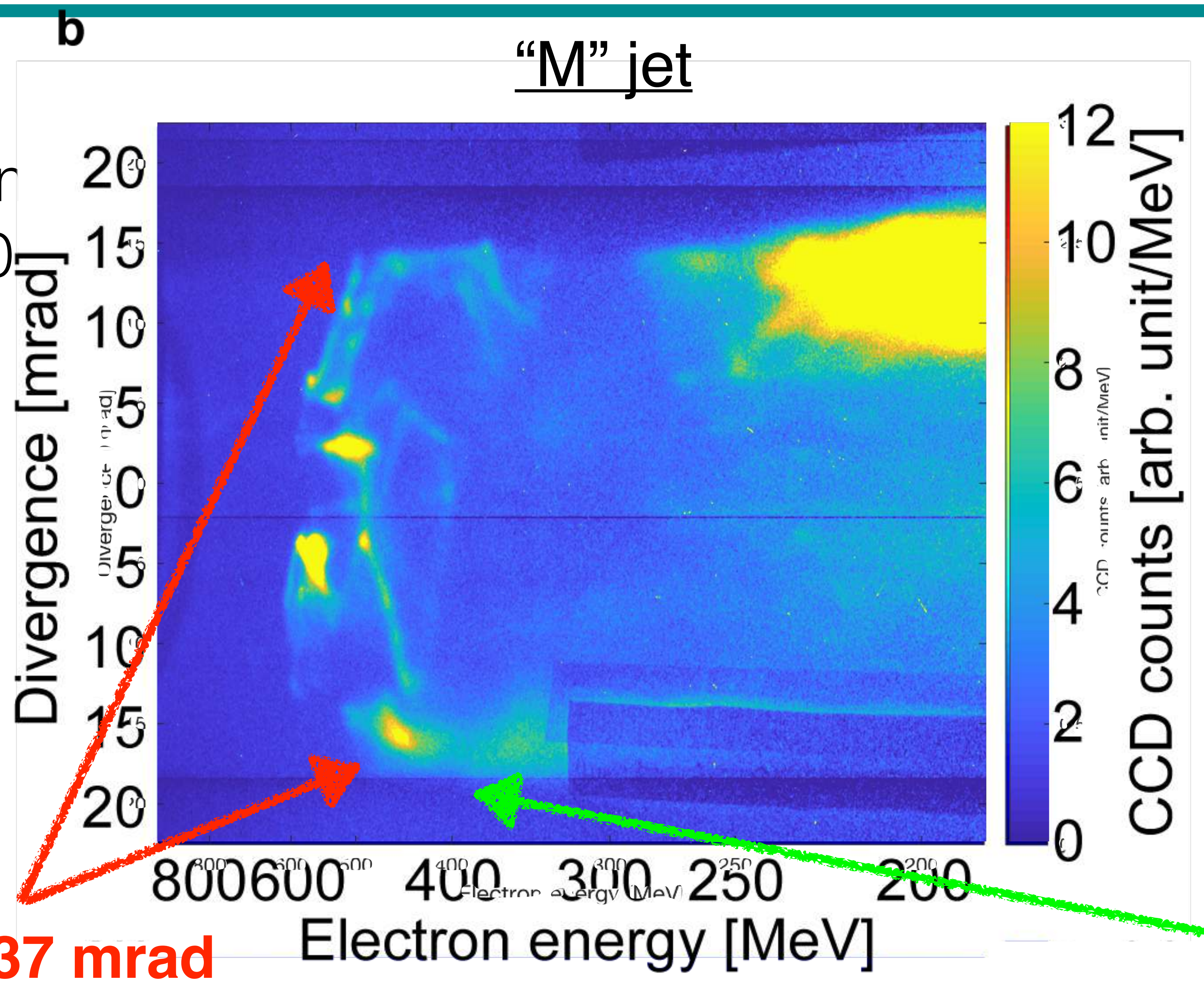


Rakowski *et al.*, *Scientific Reports* (2022)

Corresponding Electron Spectra

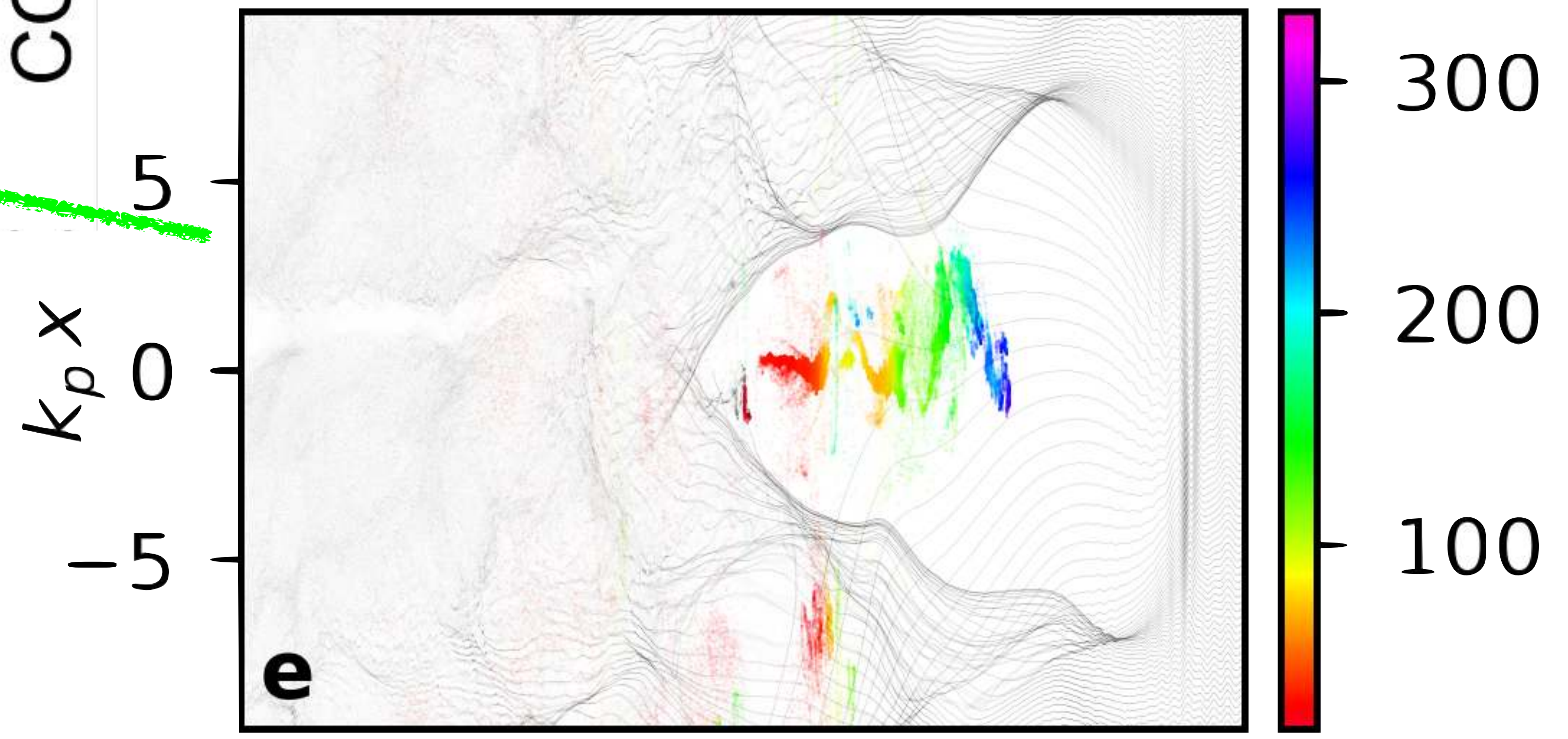
Karlsruher Institut für Technologie





clip at 37 mrad dipole magnet aperture

in qualitative agreement with simulation



jet	θ	γ	n_e [10^{19}/cm^3]	K	E_{crit}
6 mm	9	500	2	4,5	11 keV
“M”	37	1000	1	37	146 keV

$$K \approx \gamma\theta$$

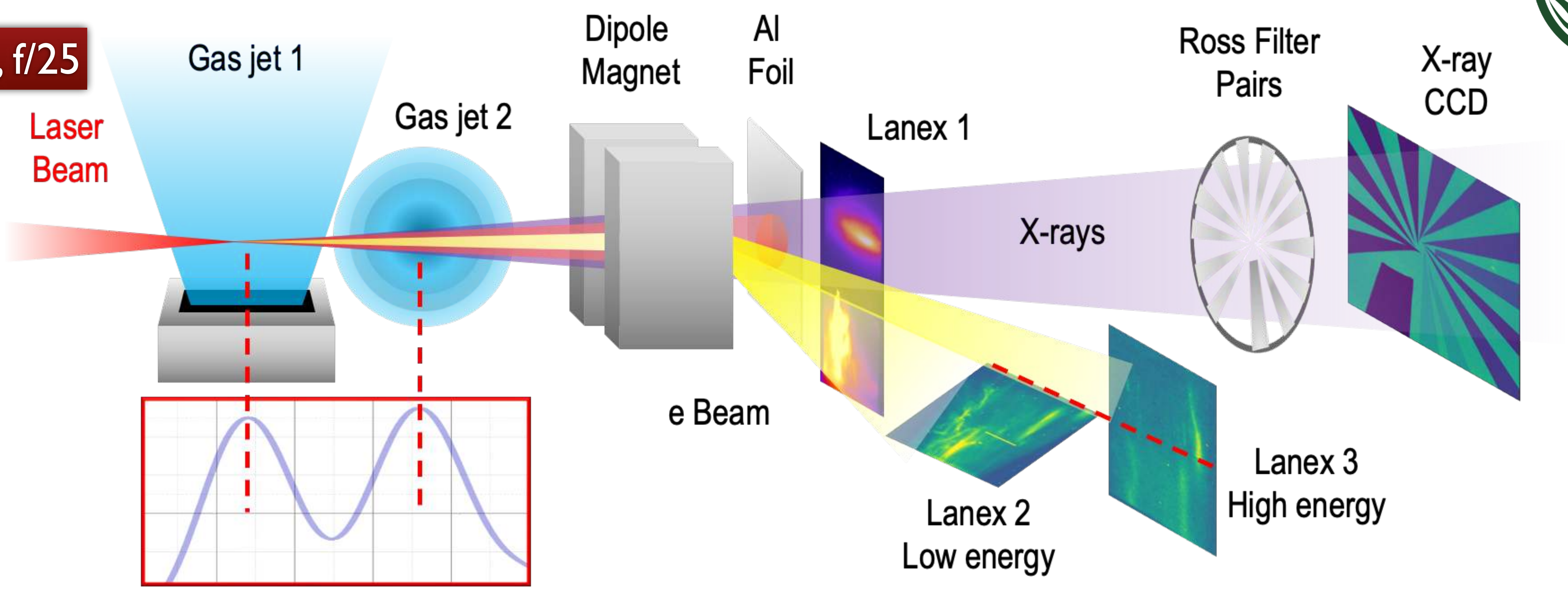
$$N_\gamma \sim K$$

expect ~1 order of magnitude increase in photon number

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

Double-jet Experiment

9 J, 50 fs, f/25



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

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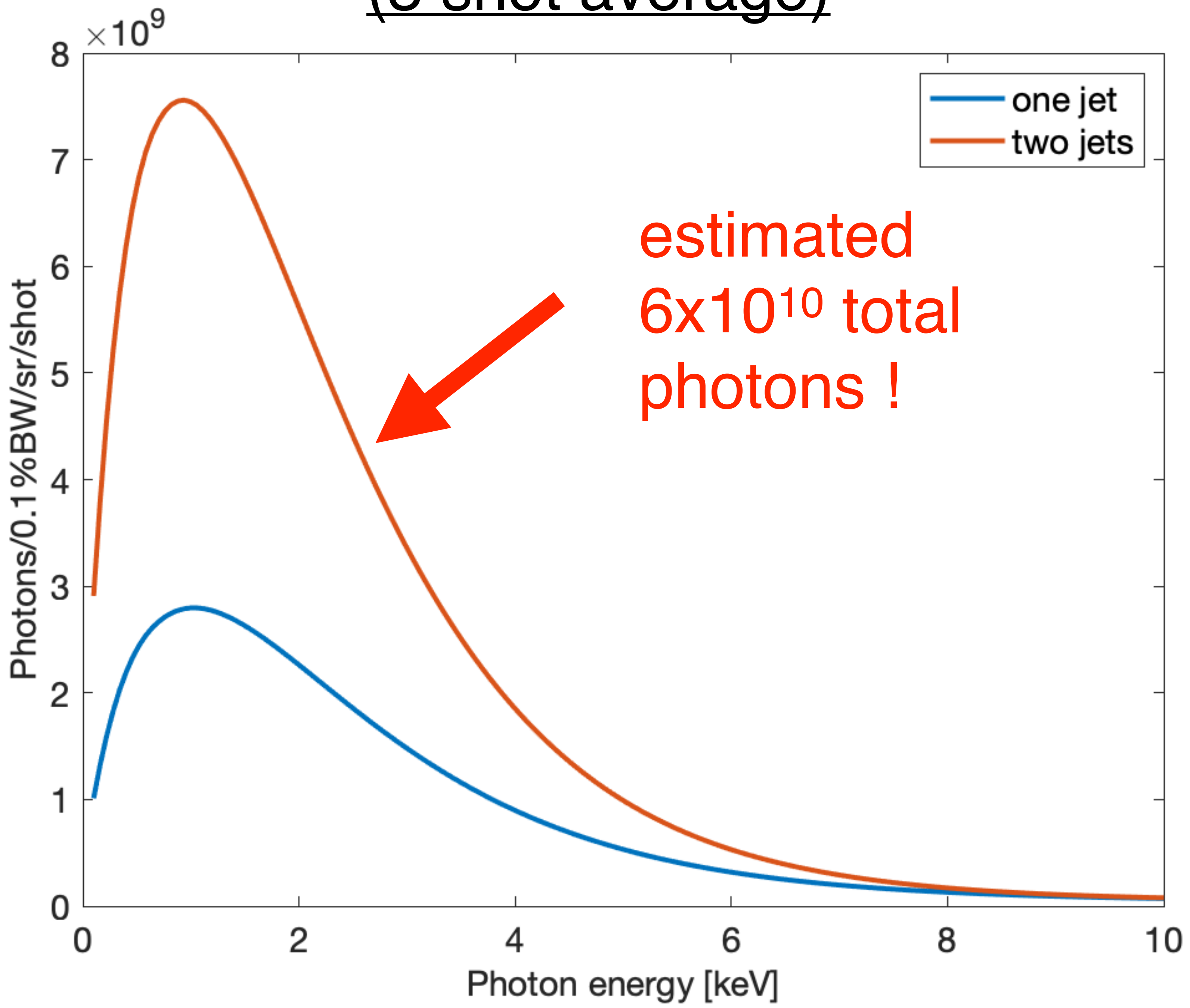
Measured X-ray Spectra

Preliminary !

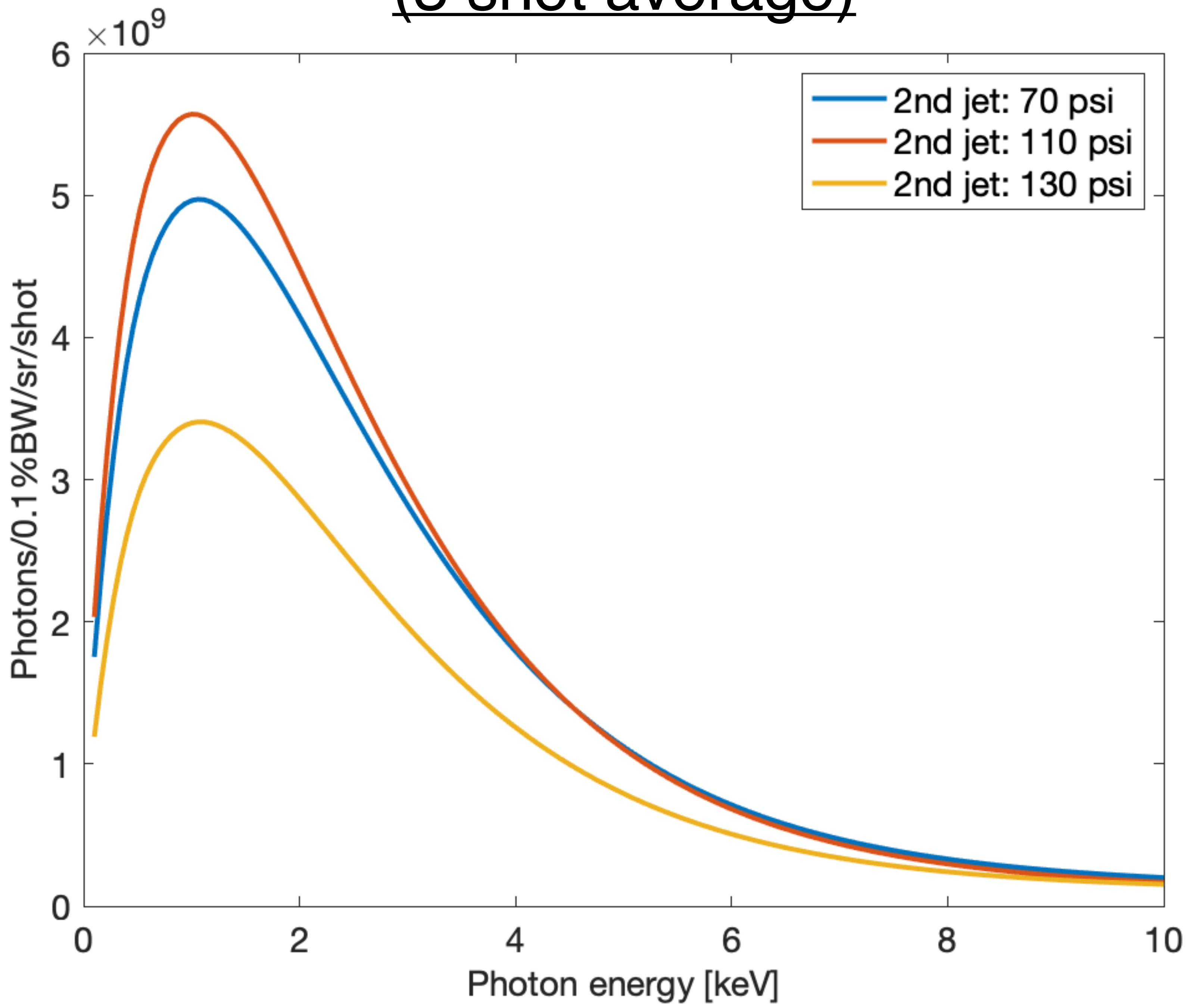
Karlsruher Institut für Technologie

One jet vs double jet
(3 shot average)

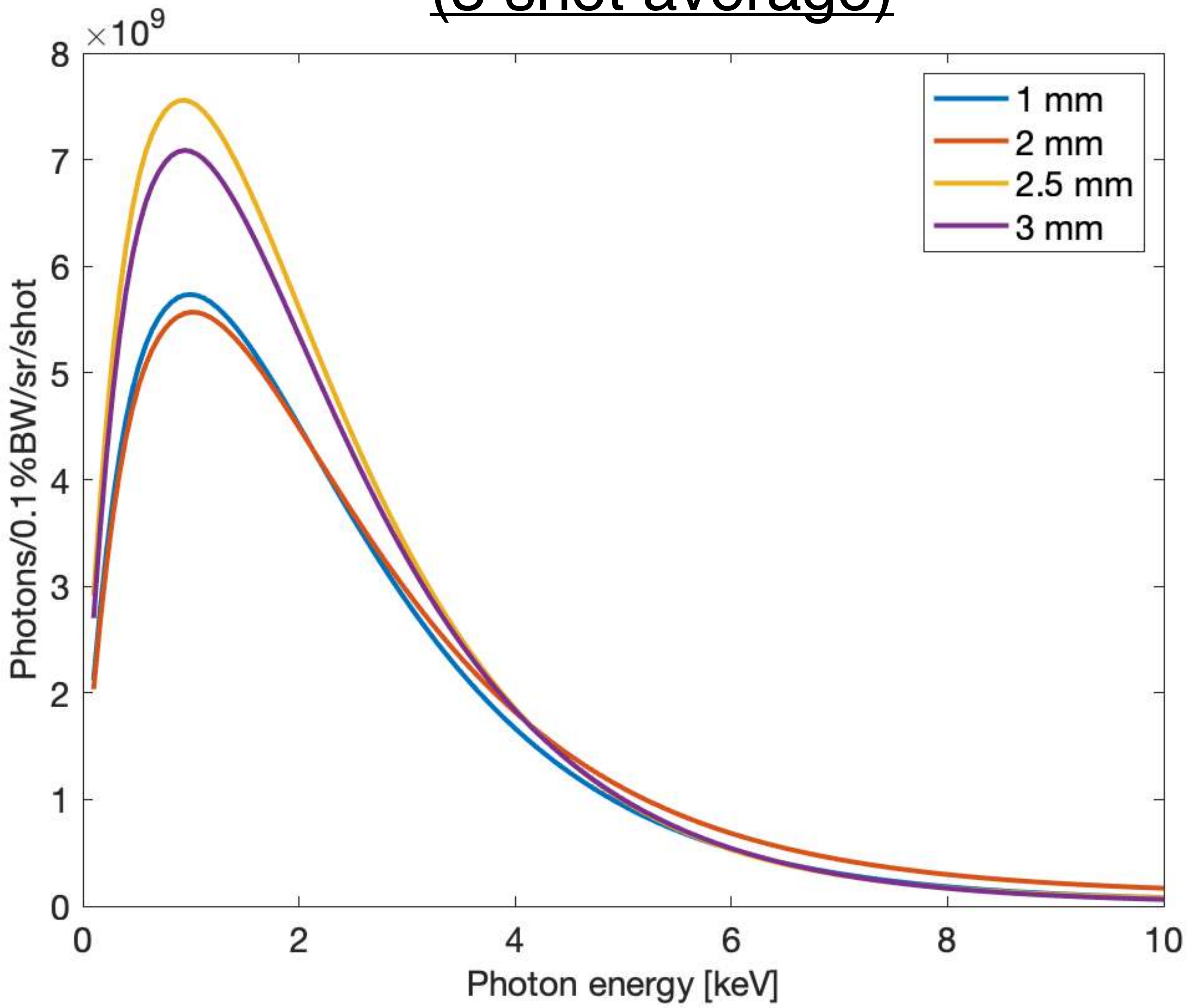


estimated 6x10^{10} total photons !

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



Double jet:
Jet separation
(3 shot average)



Source	Photons/ shot	Pulse duration	Bandwidth
This source	6x10^{10}	50 fs	100 %
APS, Argonne	1x10^{10}	100 ps	0,01 %
LCLS FEL	10^{11}	30 fs	0,1 %

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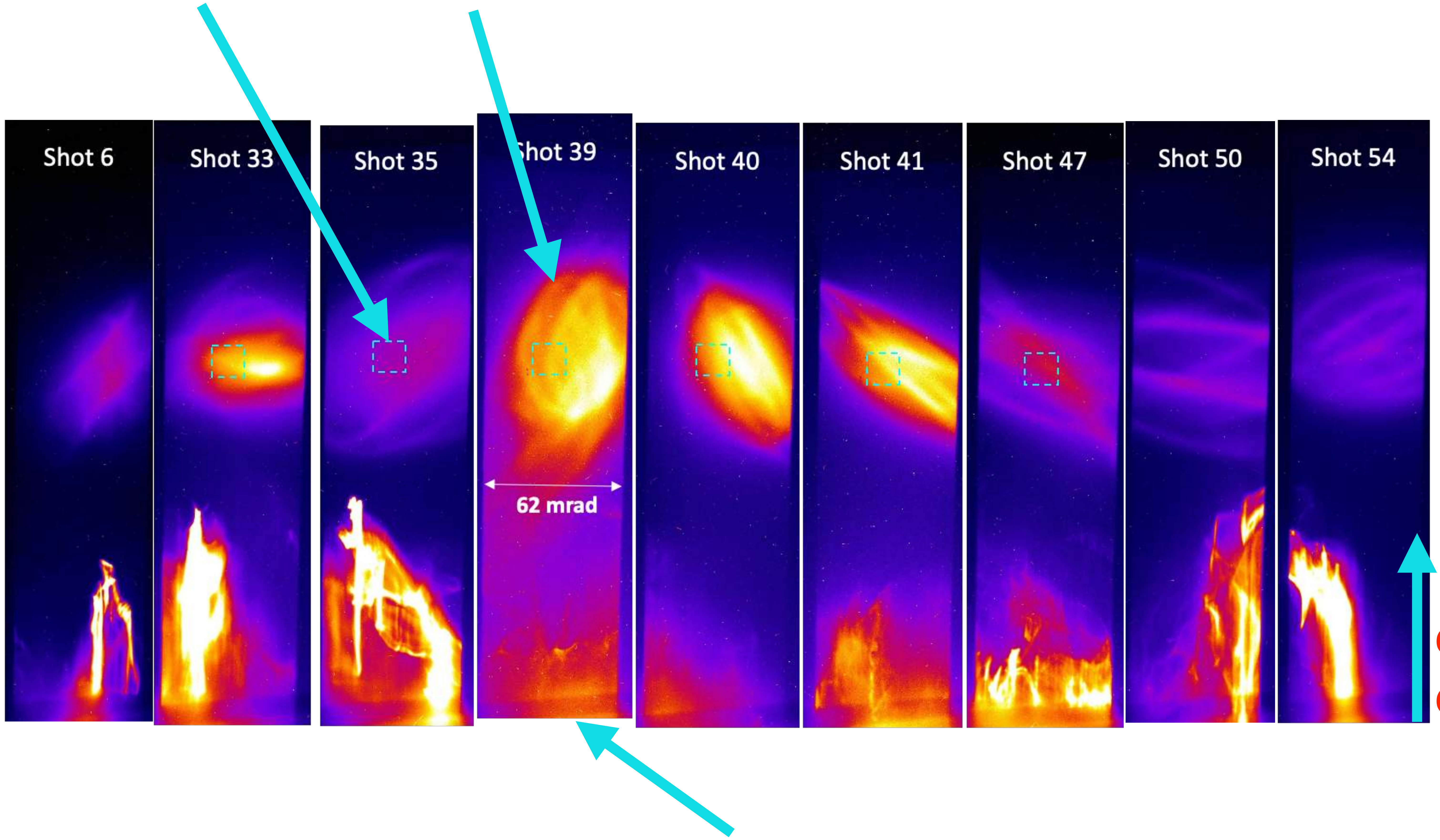
X-ray Beam Profiles

Ω X-ray CCD

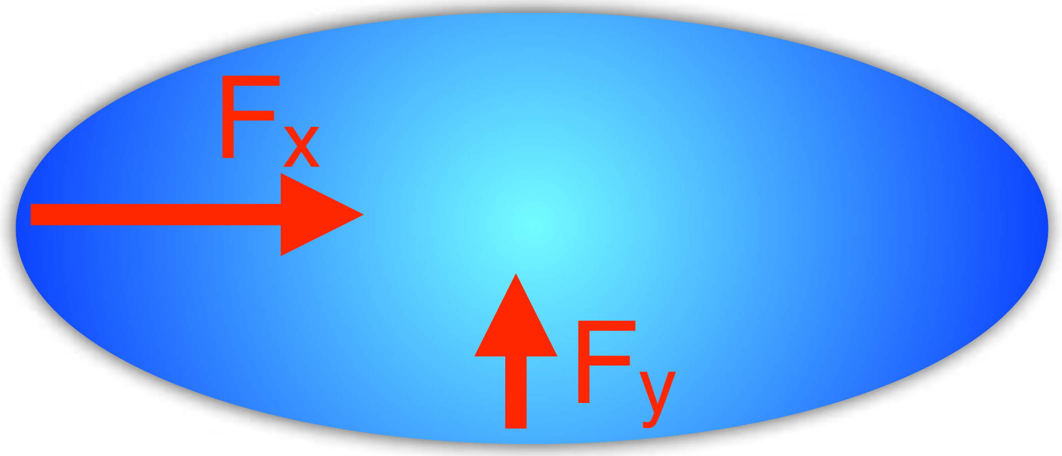
X-rays



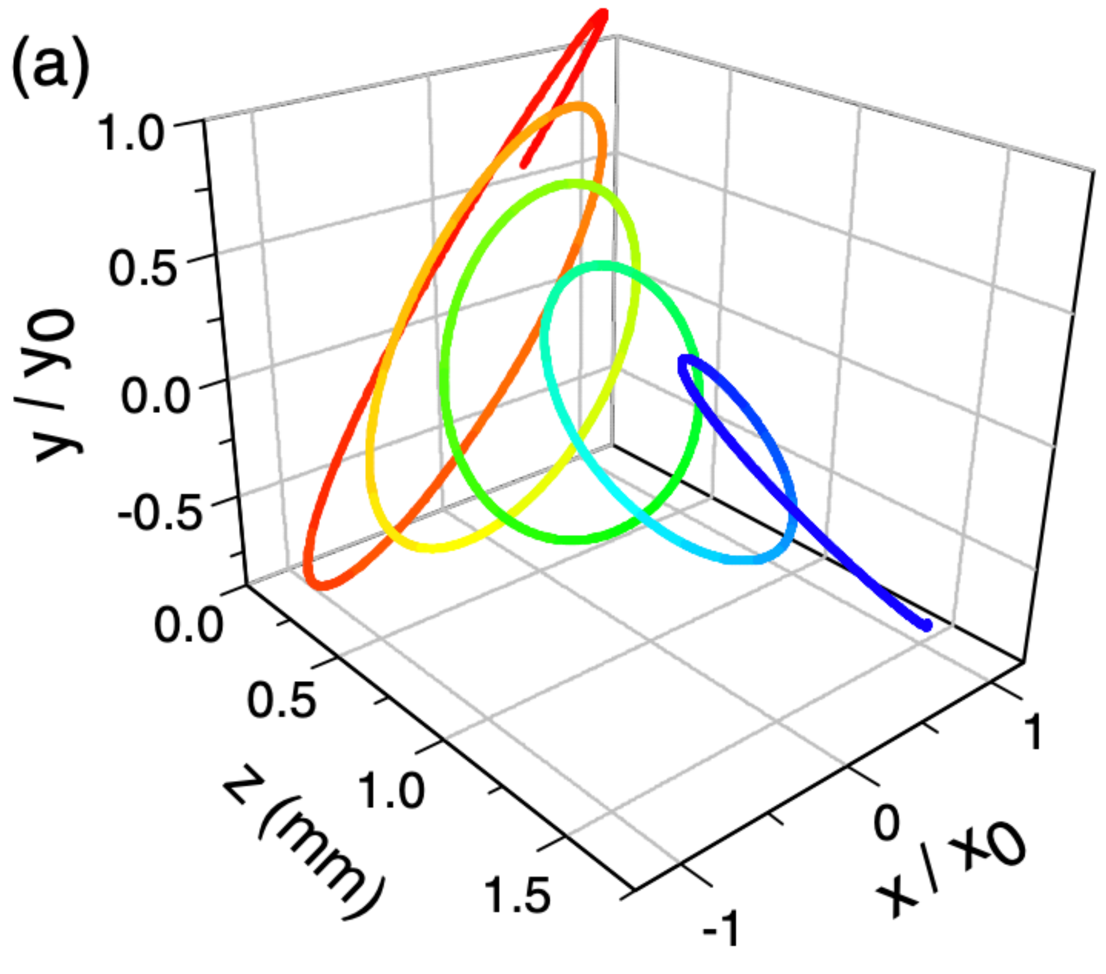
electrons

electron energy

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)

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Outline

- Particle Accelerators and Laser-Plasma Acceleration (LPA)
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  - Next-generation laser-plasma accelerators
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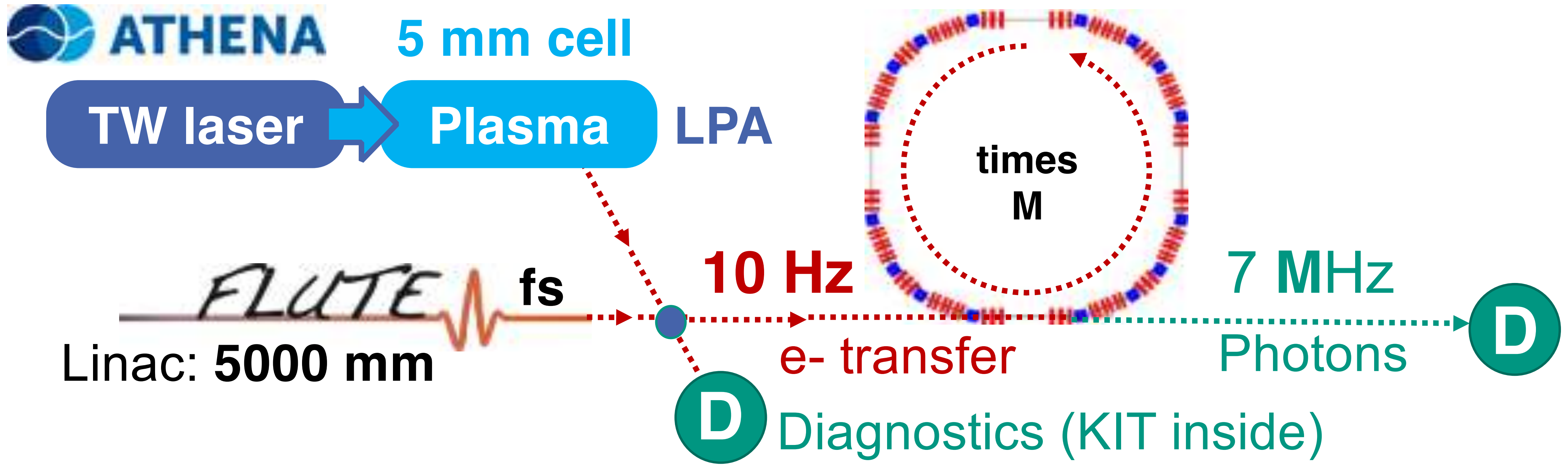
Next-Generation Storage Rings: LPA Injectors & Ultrashort Bunches

- 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”

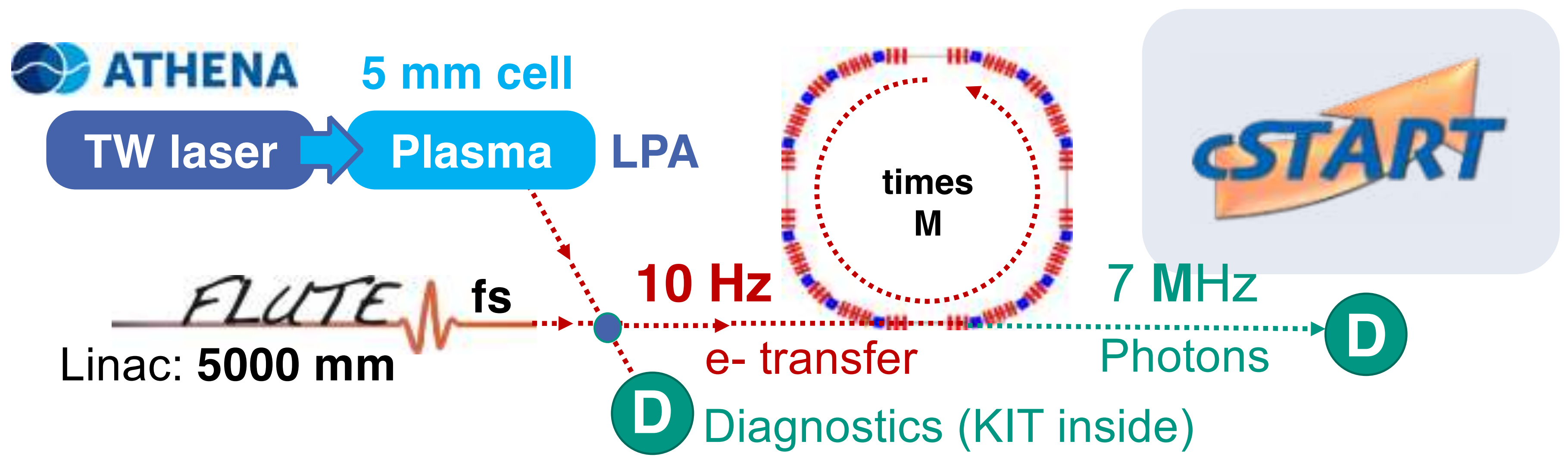
European Synchrotron Radiation Facility (ESRF), Grenoble

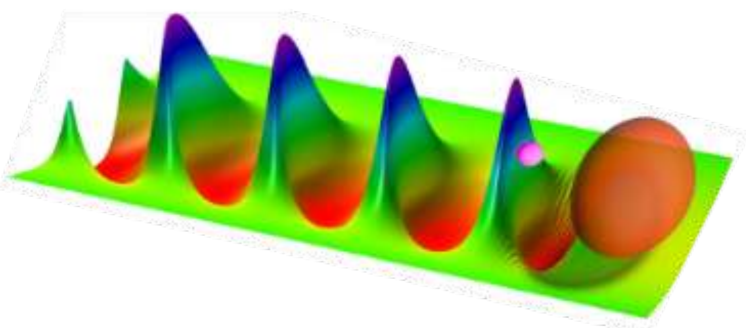
cSTART



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


ATHENA
5 mm cell
TW laser → Plasma LPA
times M
FLUTE fs
Linac: 5000 mm
10 Hz
e- transfer
7 MHz
Photons
D
D Diagnostics (KIT inside)
cSTART



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

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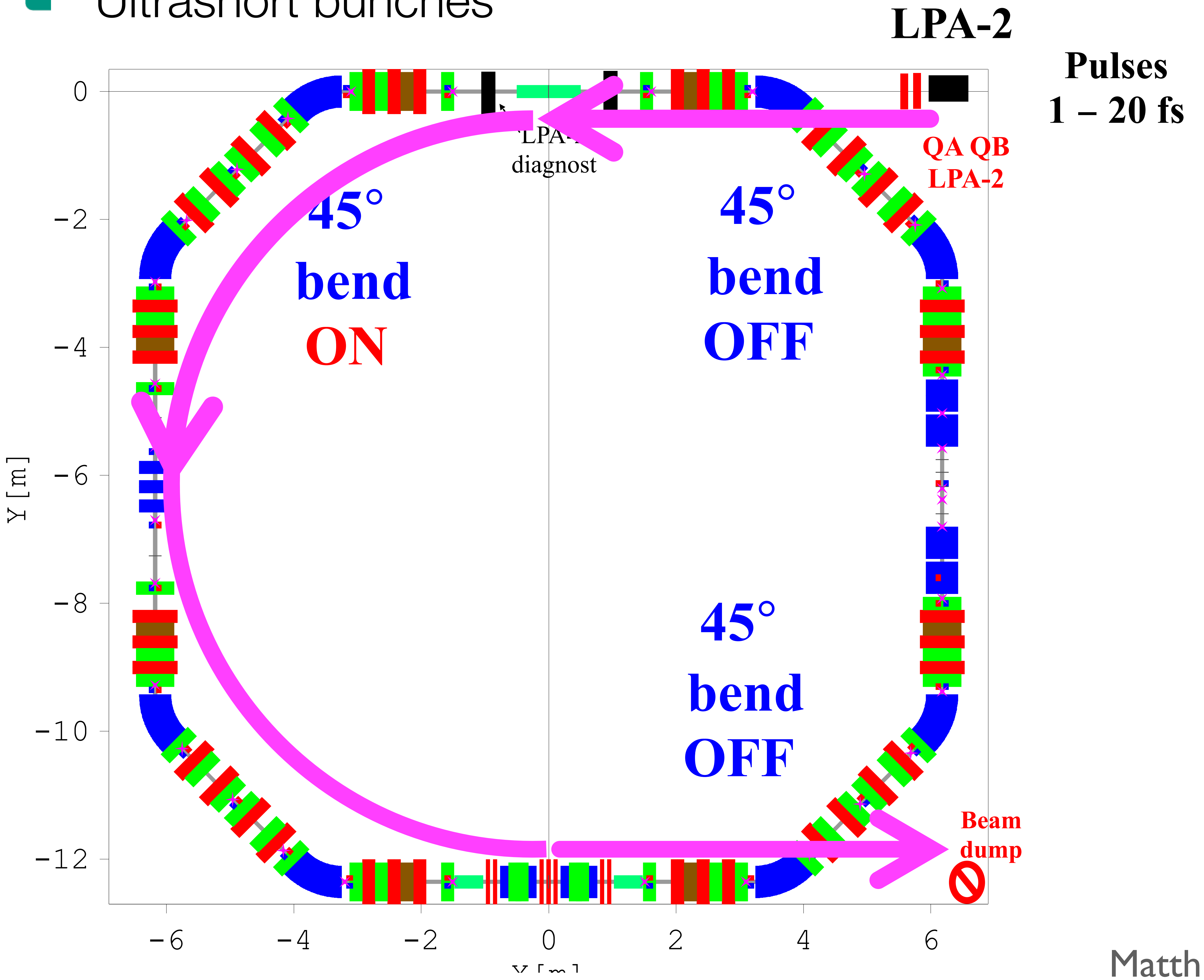
LPAs & cSTART

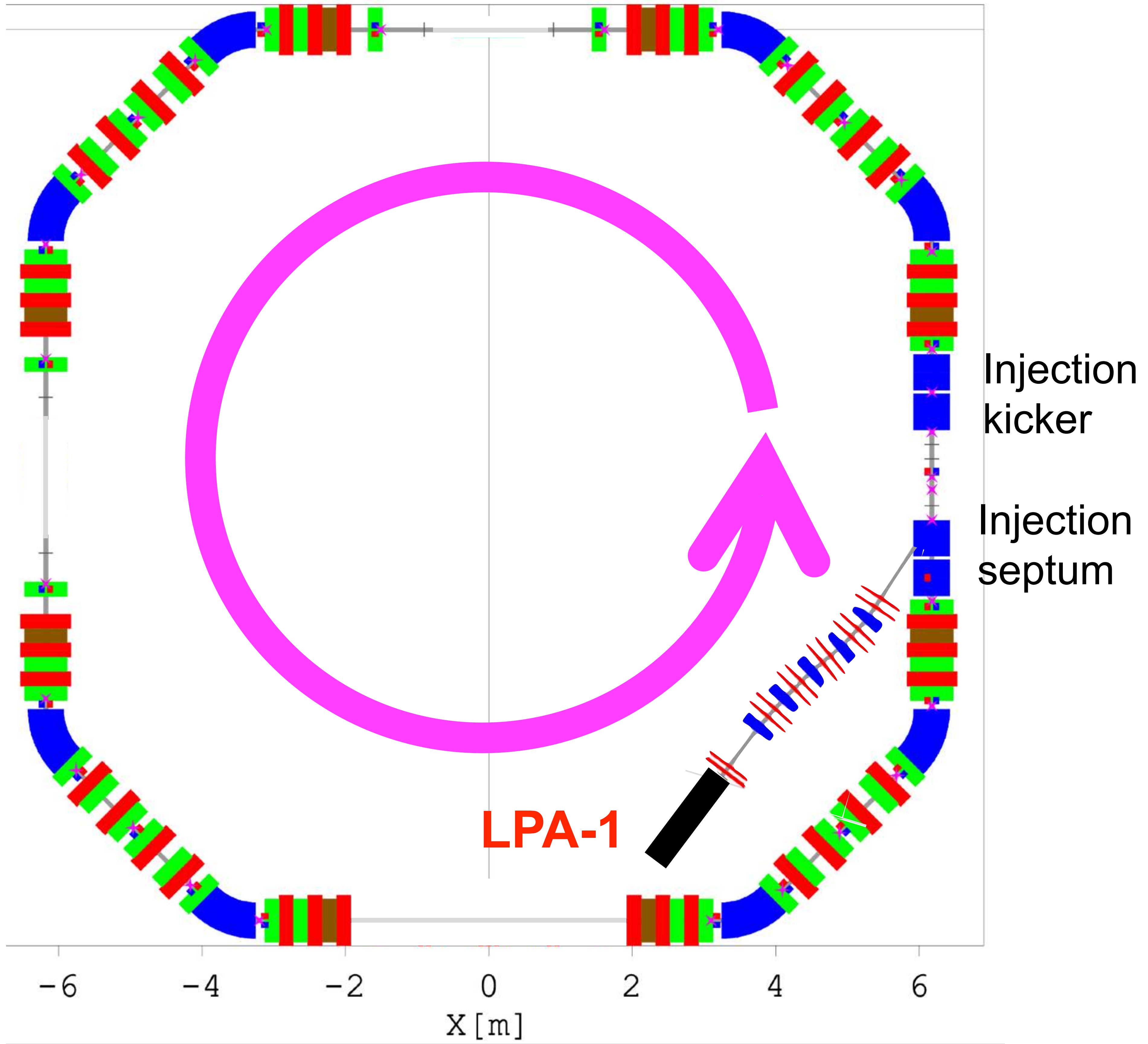
LPA - 2

- 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



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Matthias Fuchs

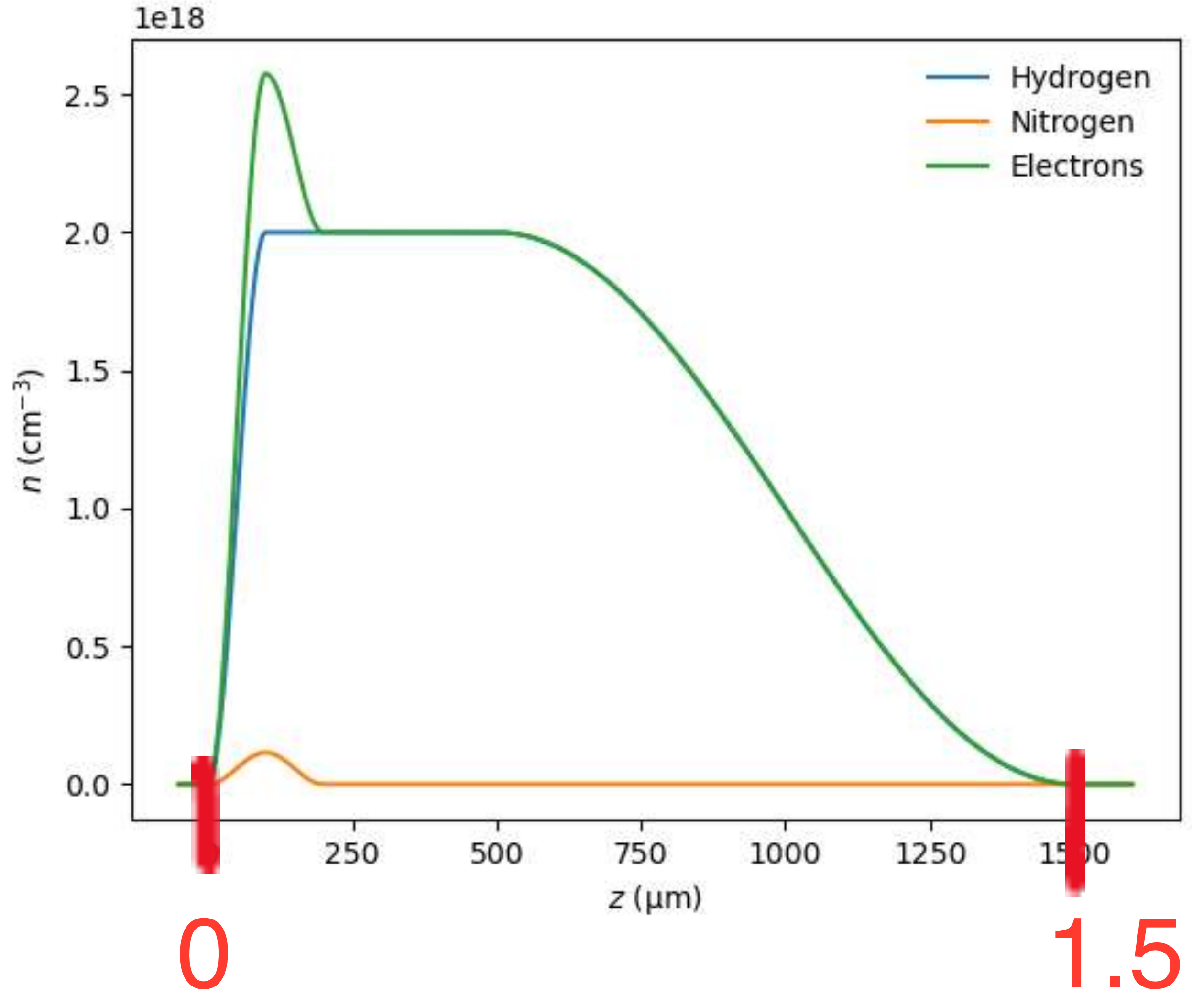
Laser-Plasma Accelerator as Injector for Storage Ring

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

LPA Injector: Simulations

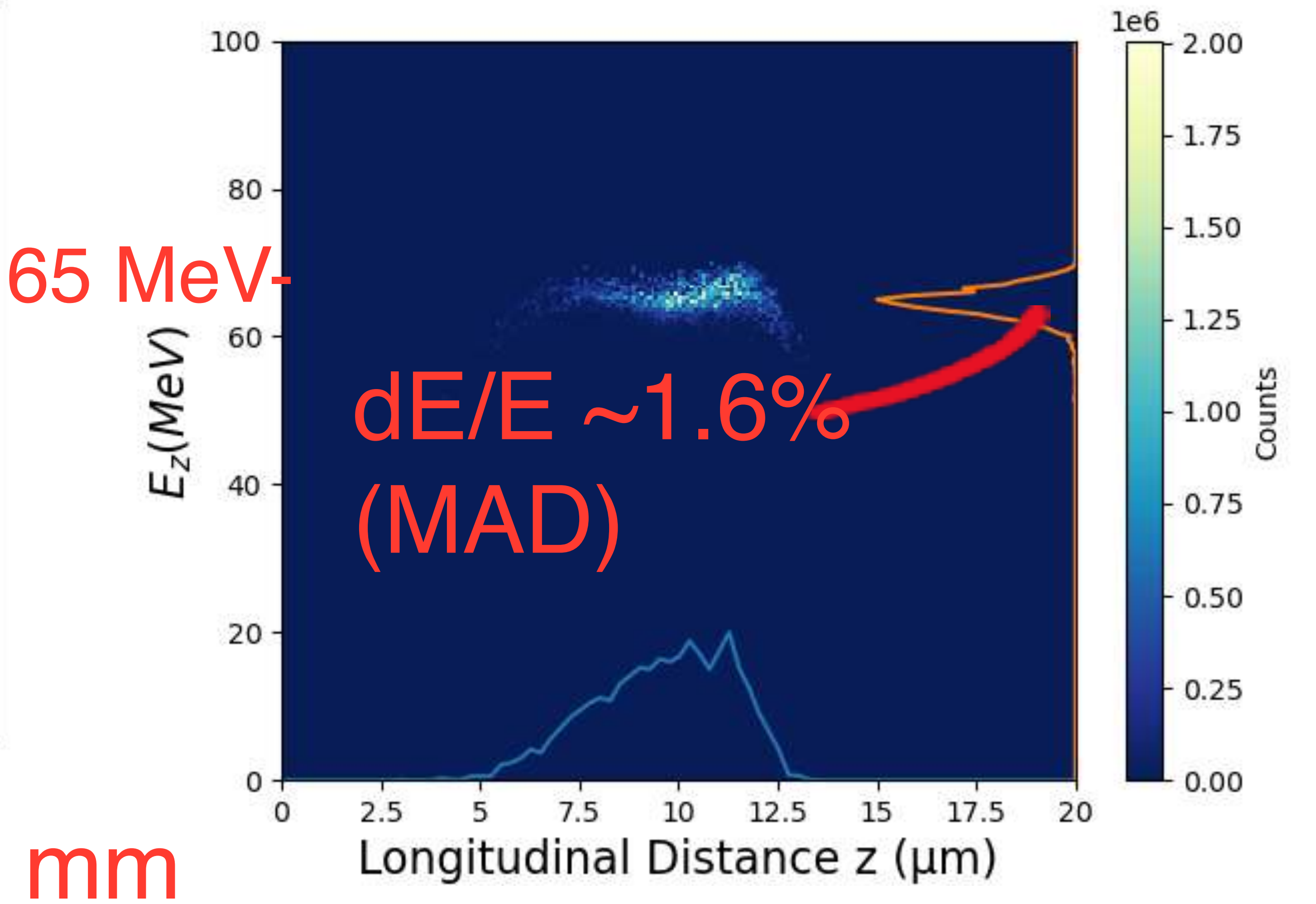
- Hydrogen-nitrogen gas mixture for localized ionization injection
- “One knob” tuning via N_2 density
- Density down ramp to adjust dephasing length
- 1.5 mm accelerator

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



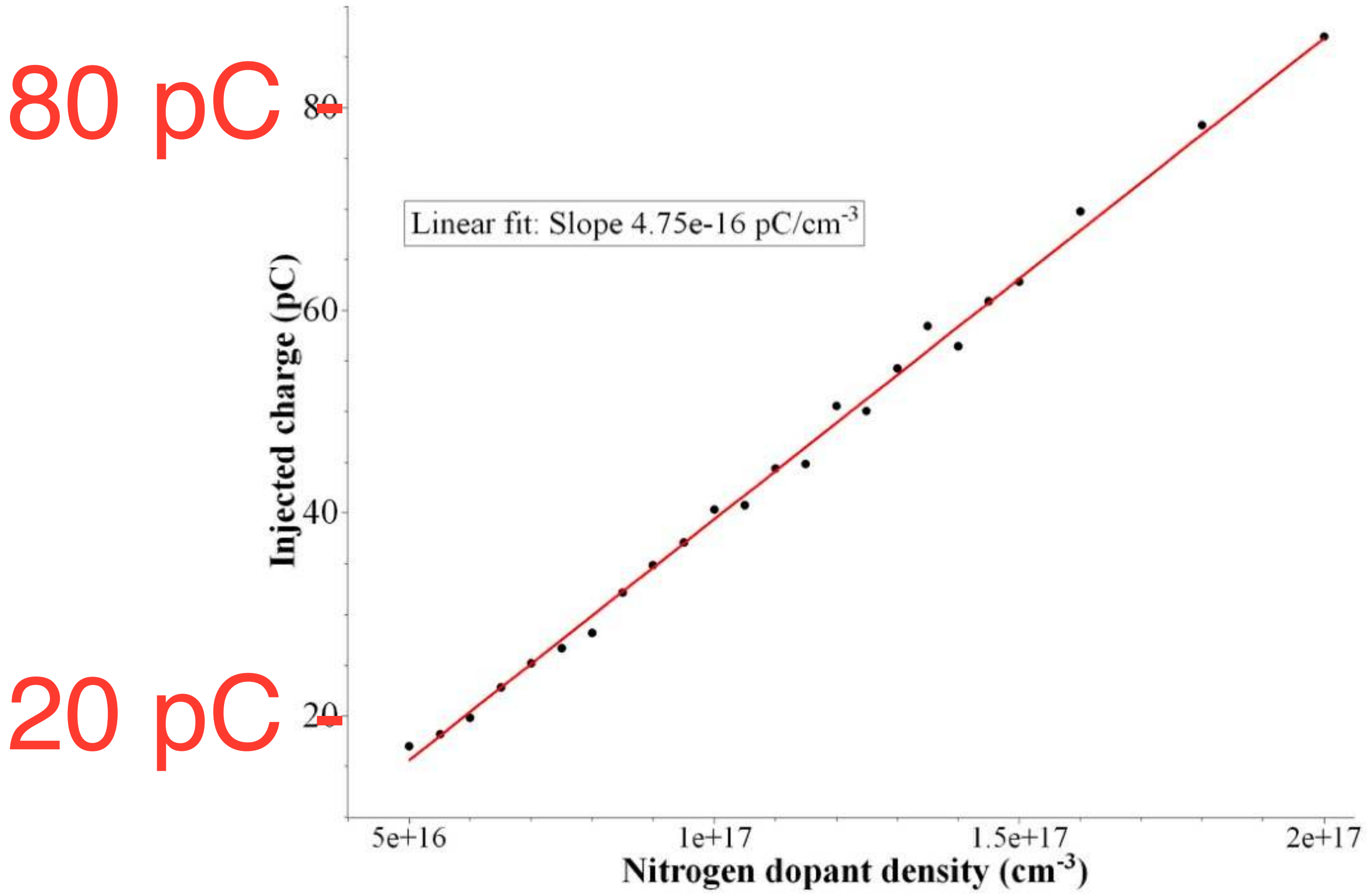
0

1.5 mm



65 MeV

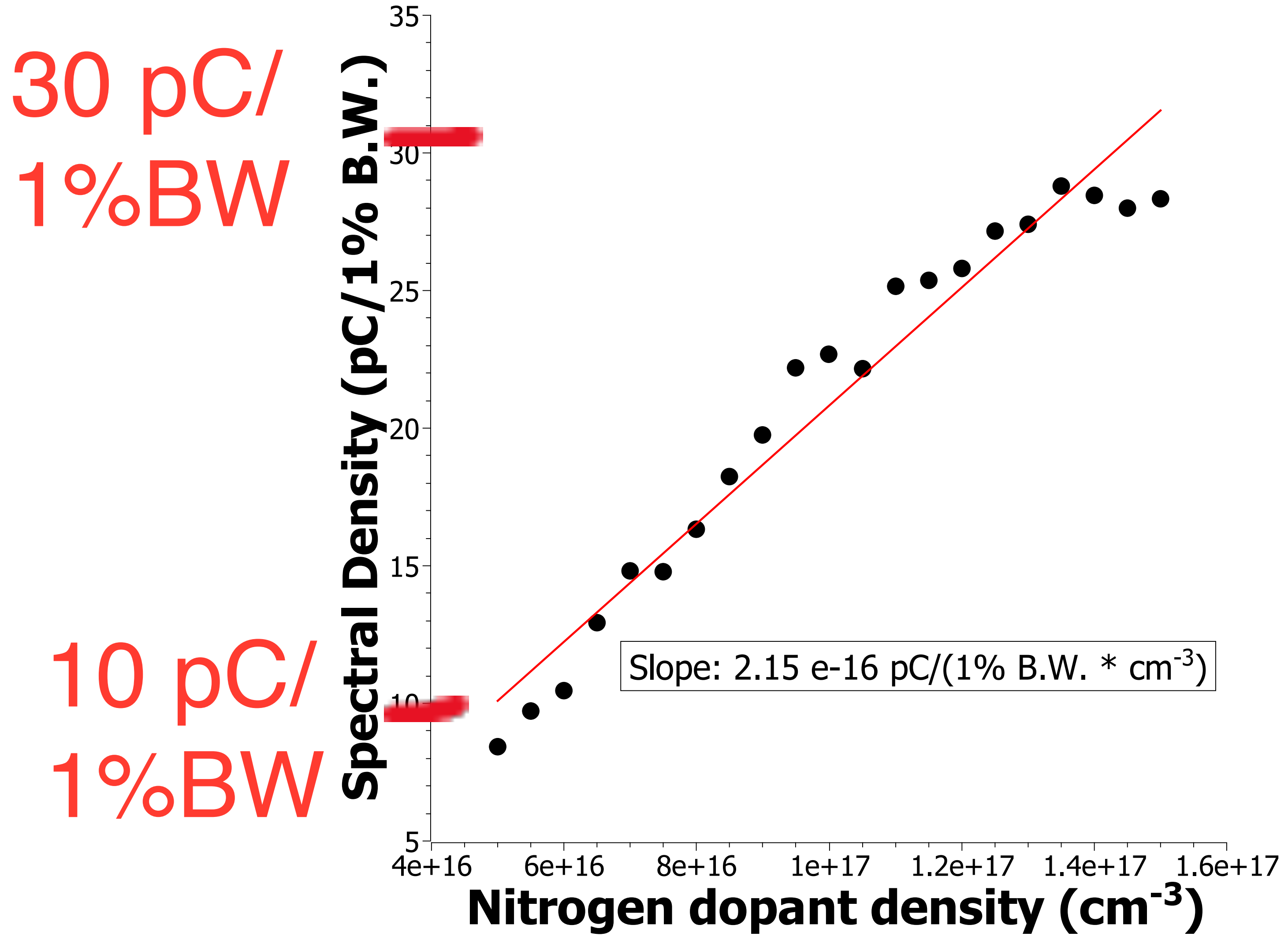
dE/E ~1.6% (MAD)



Linear fit: Slope 4.75e-16 pC/cm⁻³

80 pC

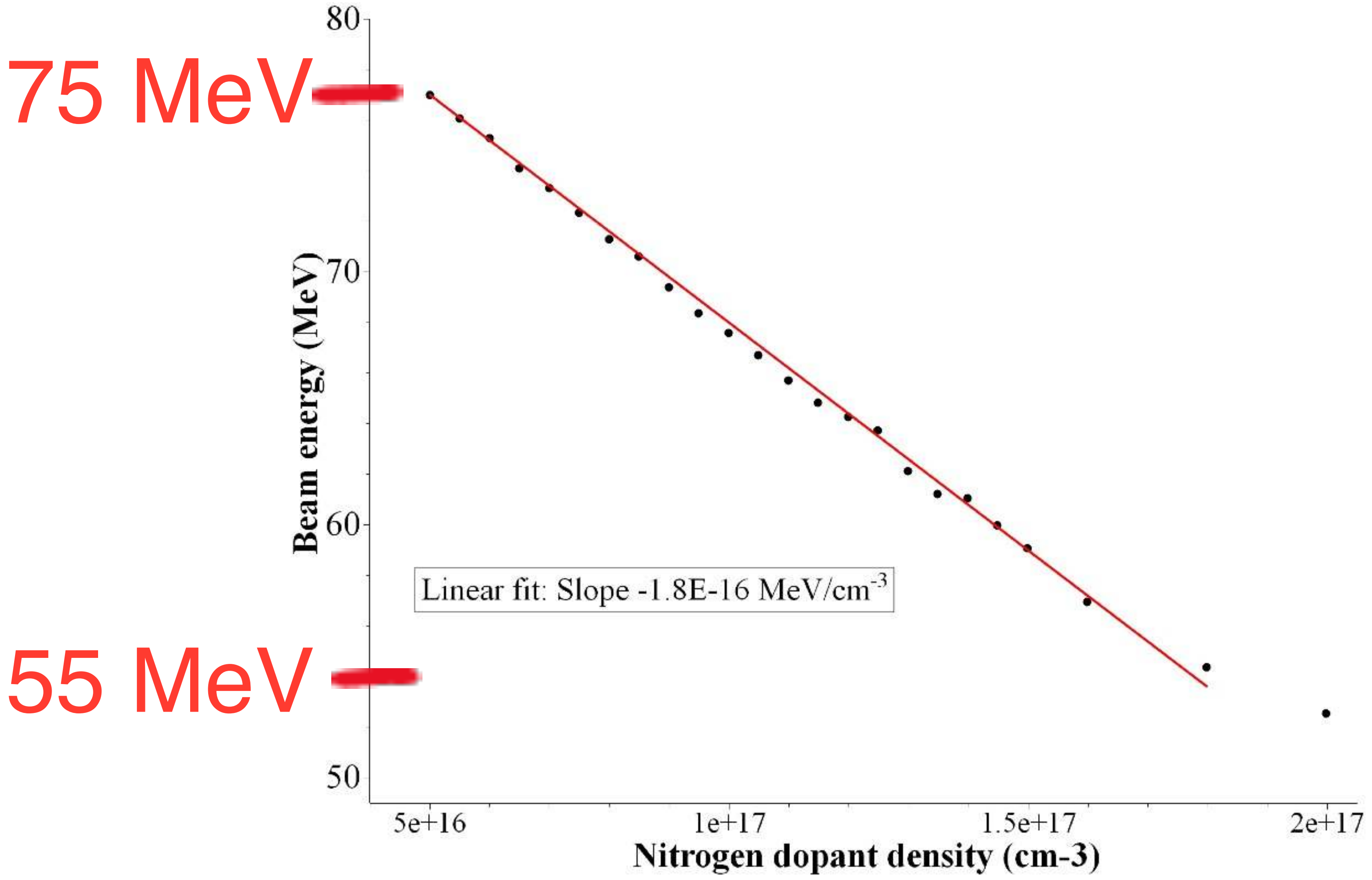
20 pC



Slope: 2.15 e-16 pC/(1% B.W. * cm⁻³)

30 pC/ 1%BW

10 pC/ 1%BW



Linear fit: Slope -1.8E-16 MeV/cm⁻³

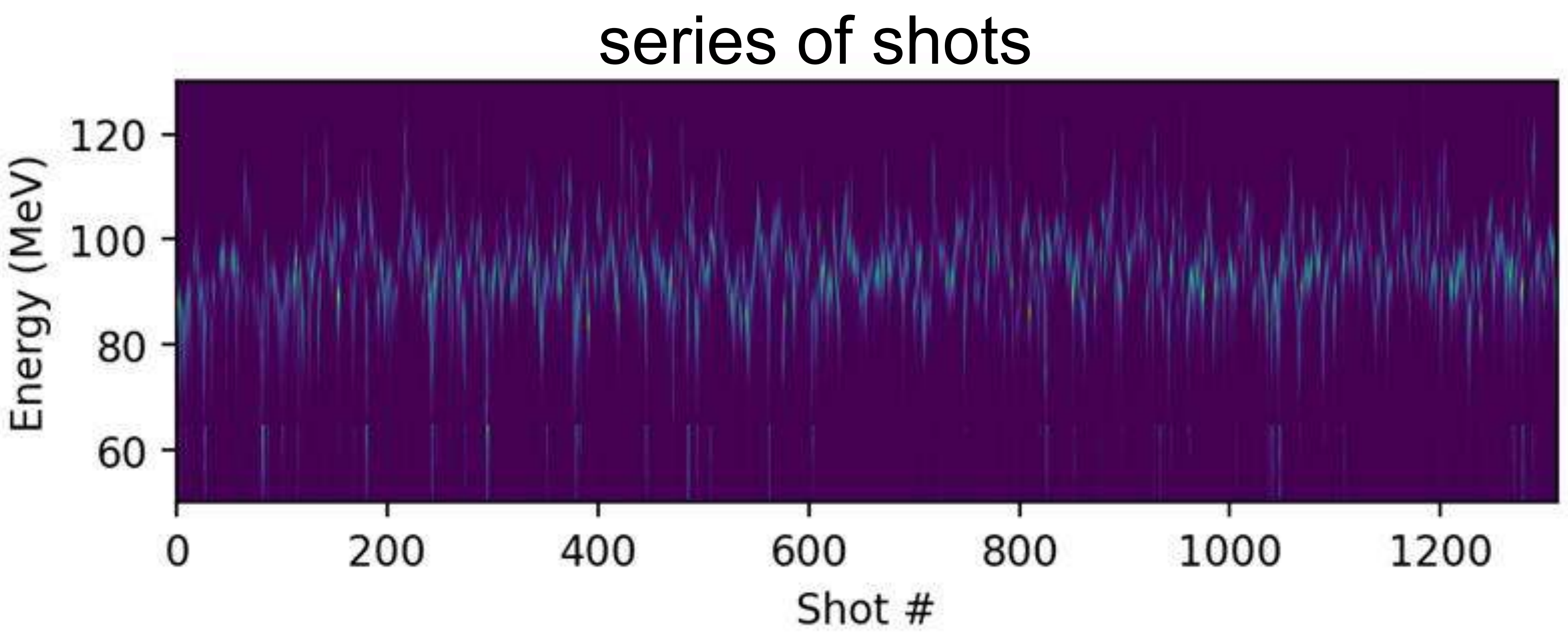
75 MeV

55 MeV

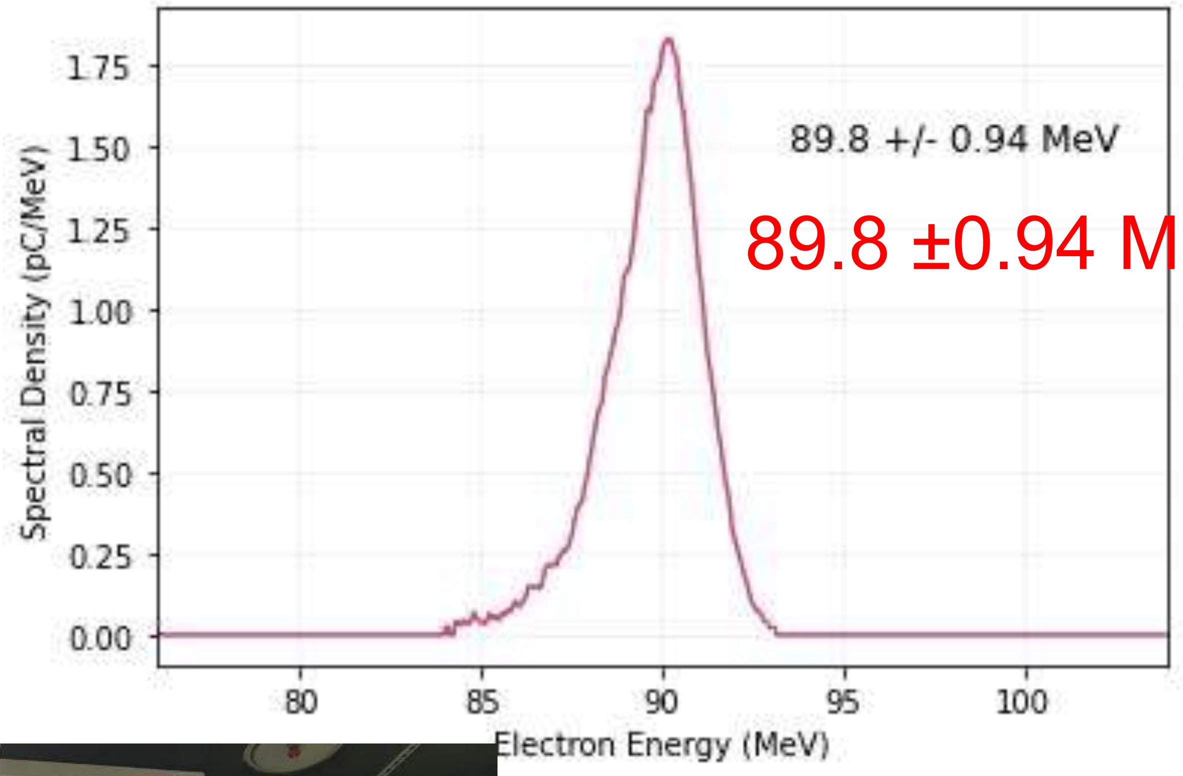
D. Squires; N. Ray *et al* IPAC 2024

LPA Injector: First LPA Experiments

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

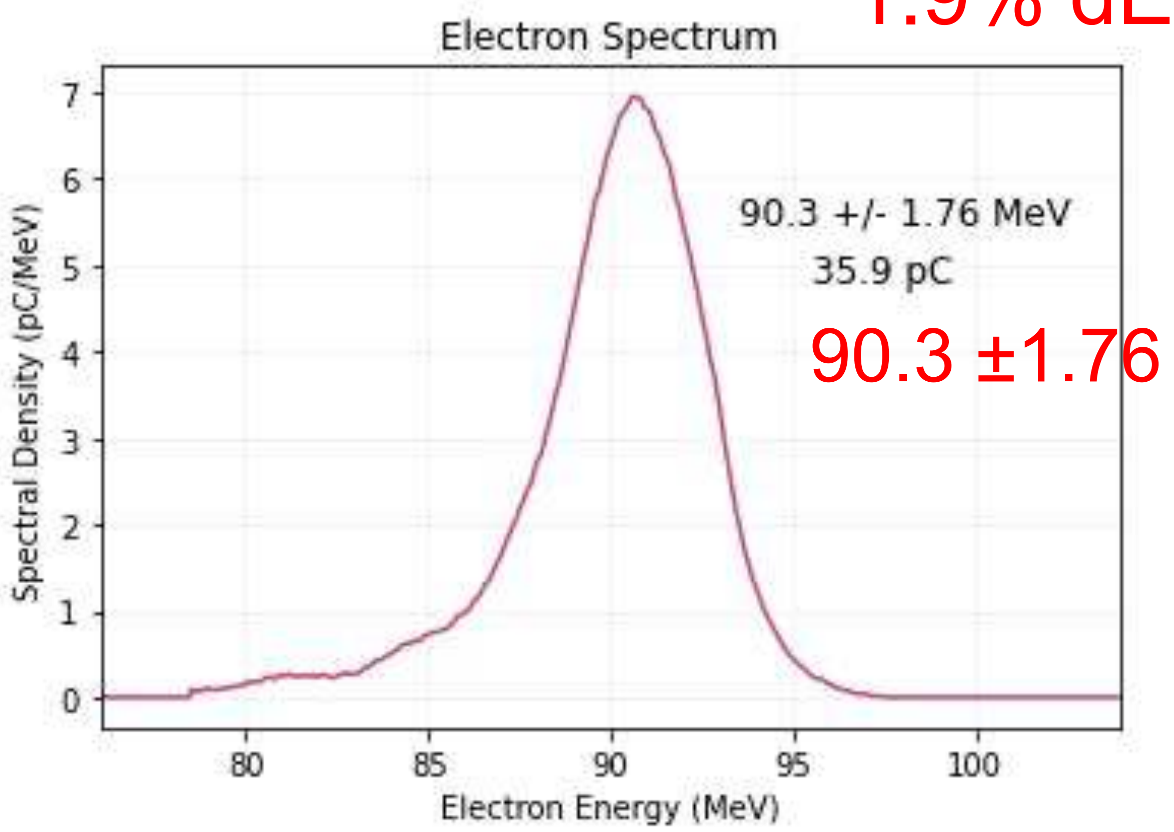


series of shots



1% dE/E; 5 pC

89.8 ±0.94 MeV

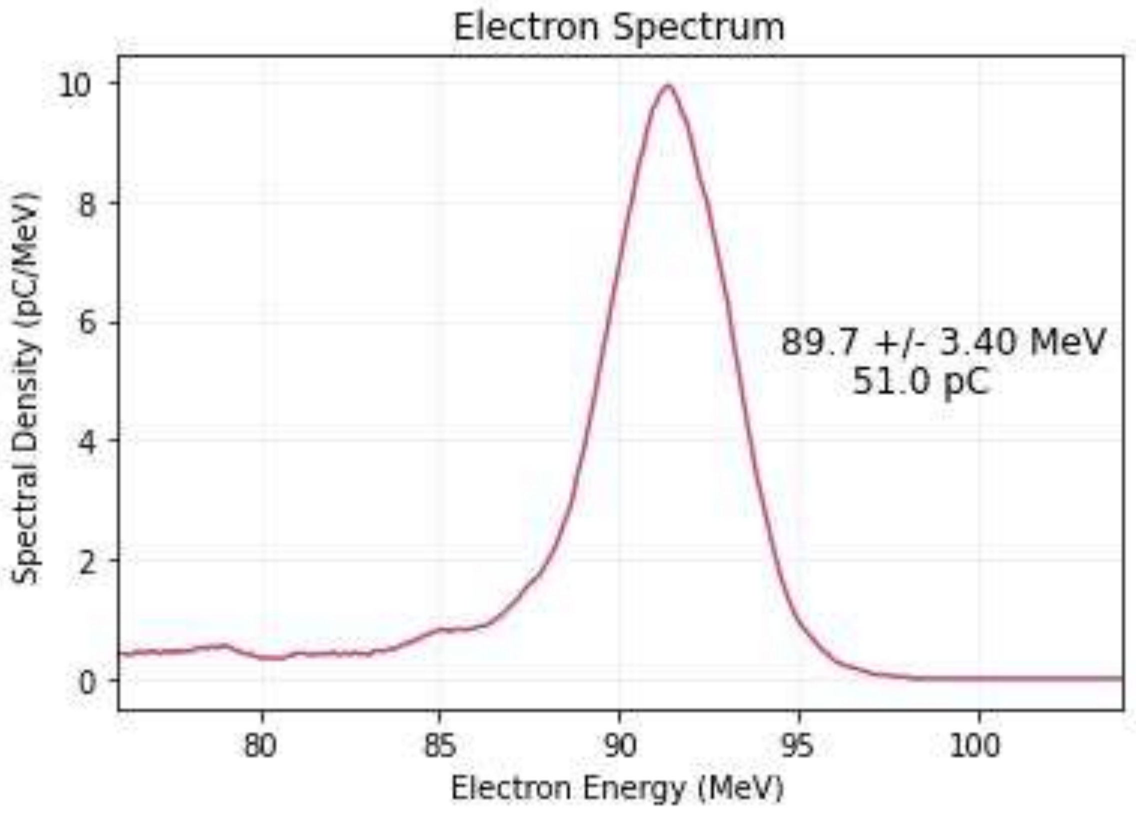


1.9% dE/E; 36 pC

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)



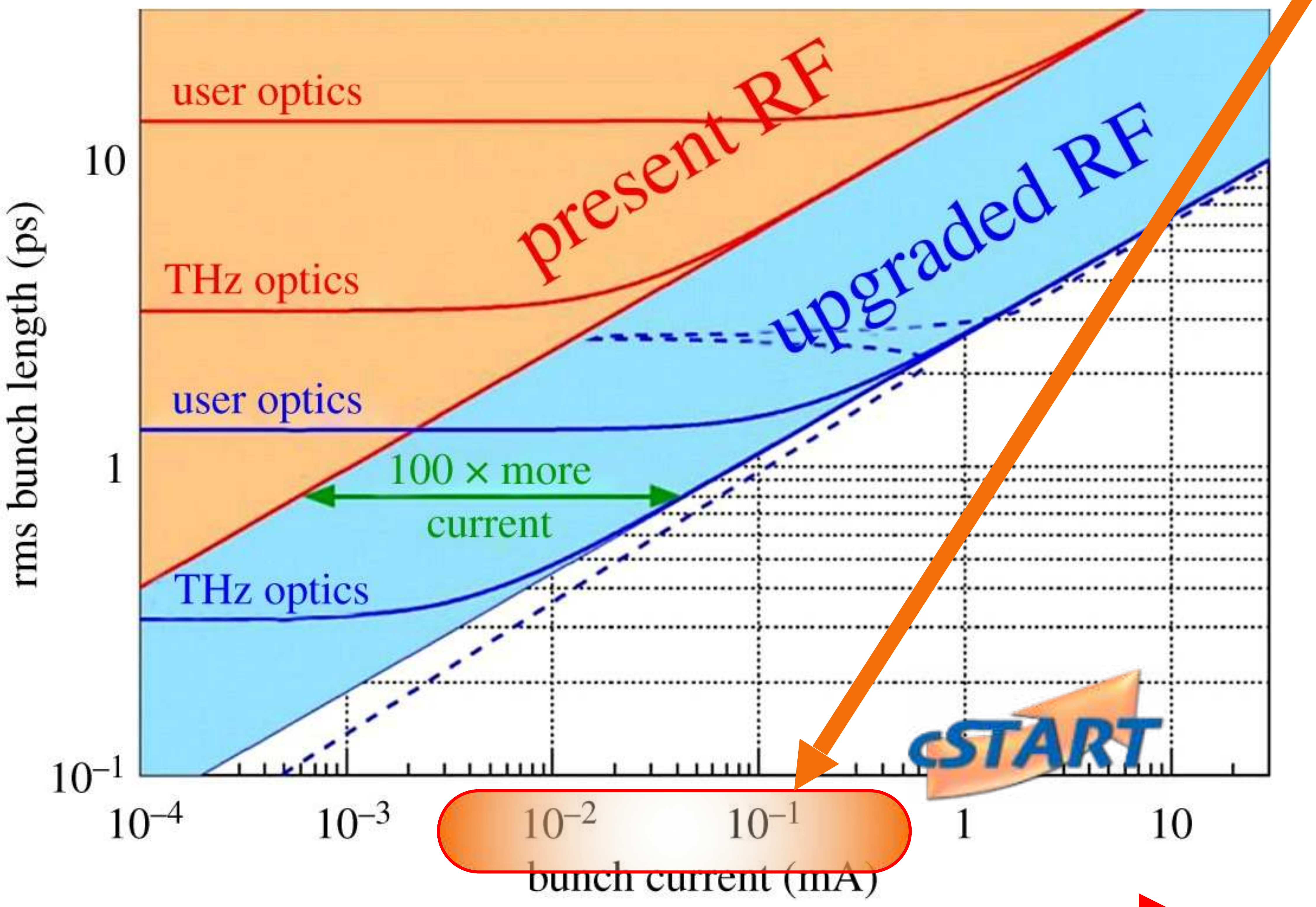
3.8% dE/E;
51 pC

89.7 ±3.4 MeV

cSTART: Injection & Storage of Ultrashort Electron Bunches

BESSY II (VSR Upgrade)

shorter bunches



higher bunch current

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)

compared to BESSY II:

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

- cSTART prototype experiments
- 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)

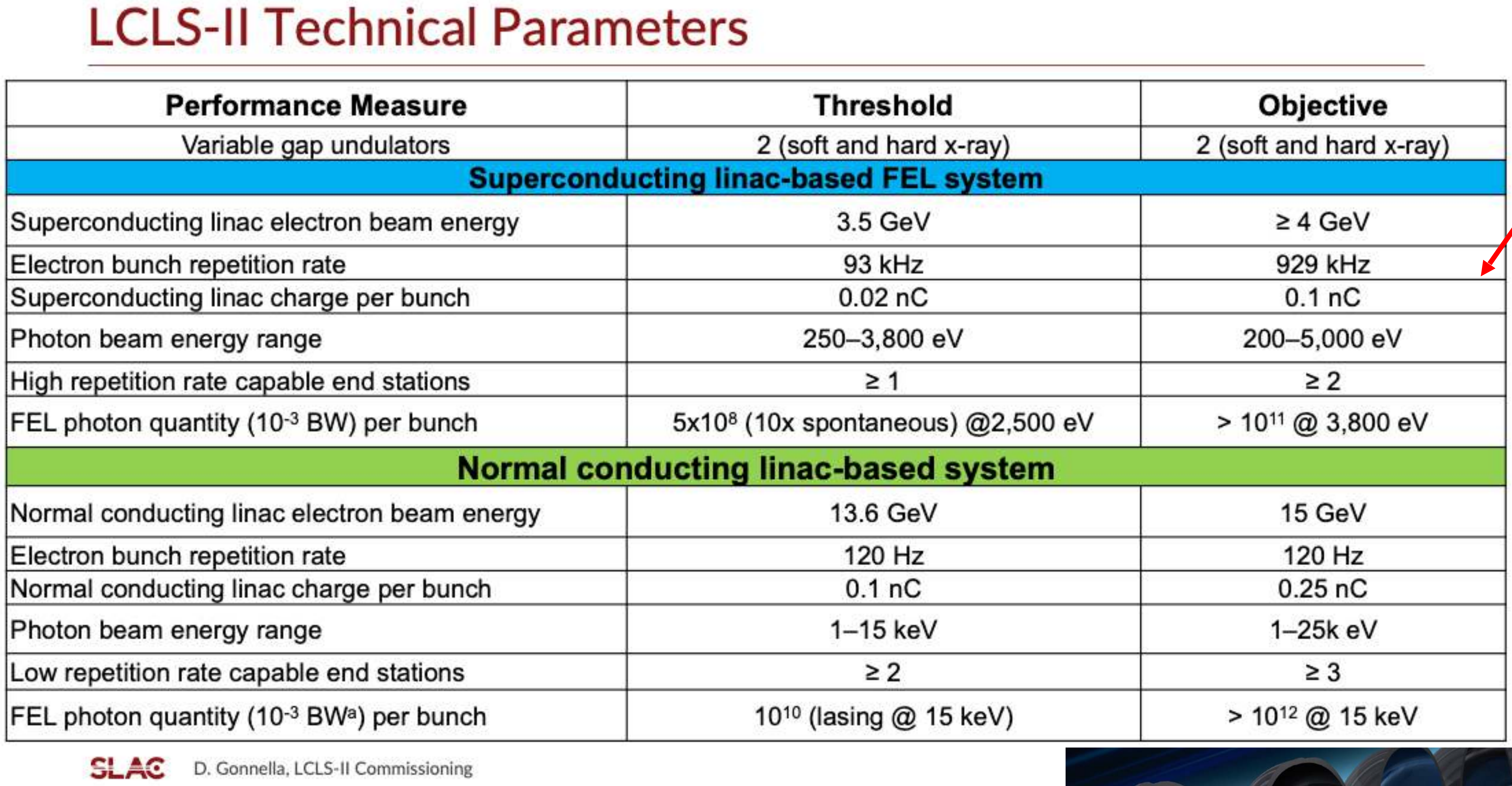
www.aps.anl.gov

LCLS XFEL, SLAC
(2km long)

lcls.slac.stanford.edu

Motivation: X-ray Free Electron Lasers (XFELs)

Karlsruhe Institute of Technology



LCLS-II Technical Parameters

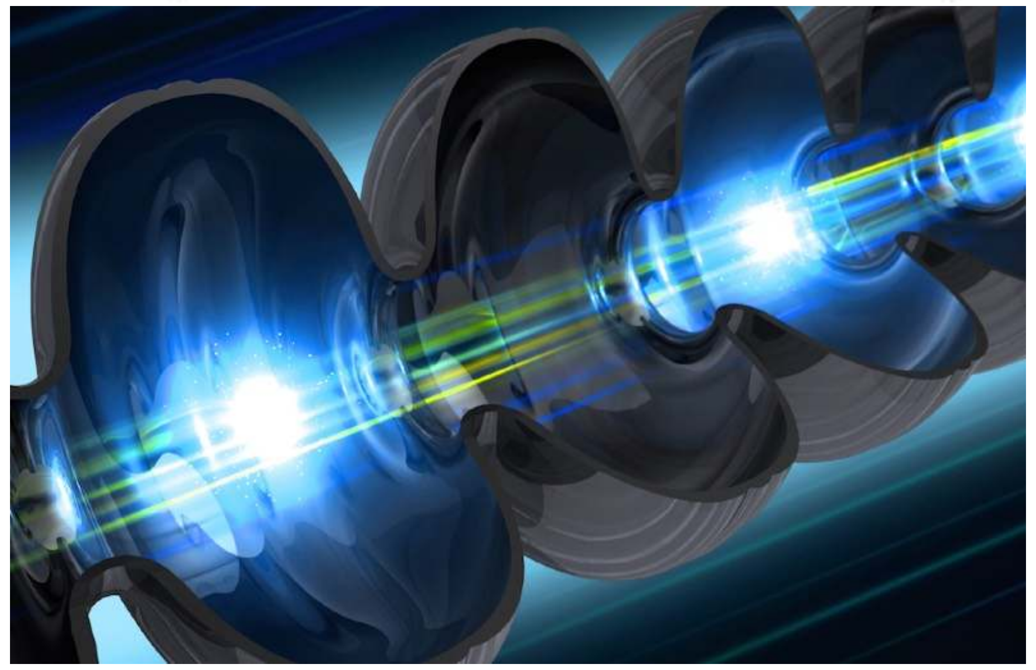
Performance Measure	Threshold	Objective
Variable gap undulators	2 (soft and hard x-ray)	2 (soft and hard x-ray)
Superconducting linac-based FEL system		
Superconducting linac electron beam energy	3.5 GeV	≥ 4 GeV
Electron bunch repetition rate	93 kHz	929 kHz
Superconducting linac charge per bunch	0.02 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	$5x10^8$ (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

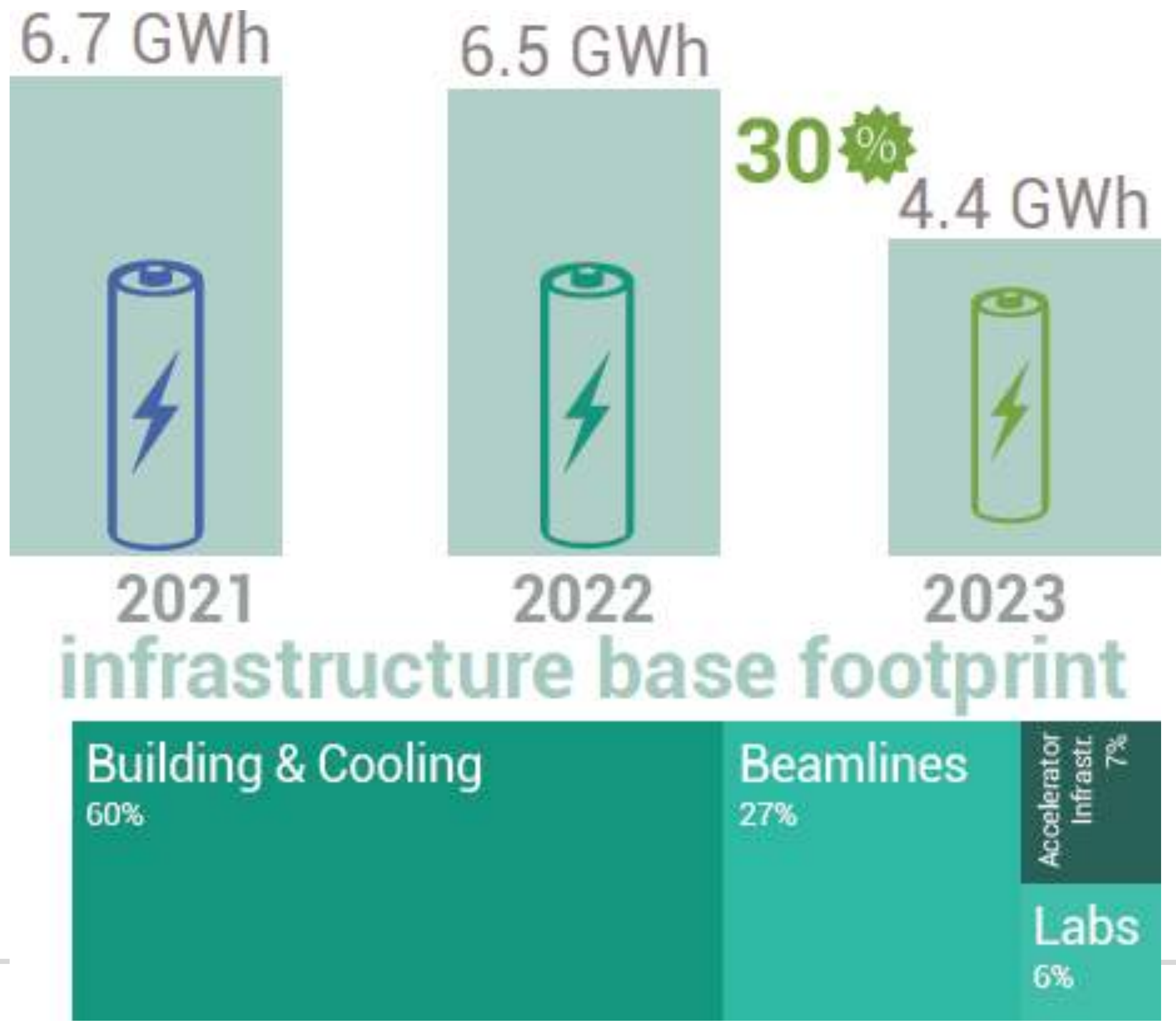
P_{avg} = 0.4 MW in beam!

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

D. Gonnella, SLAC

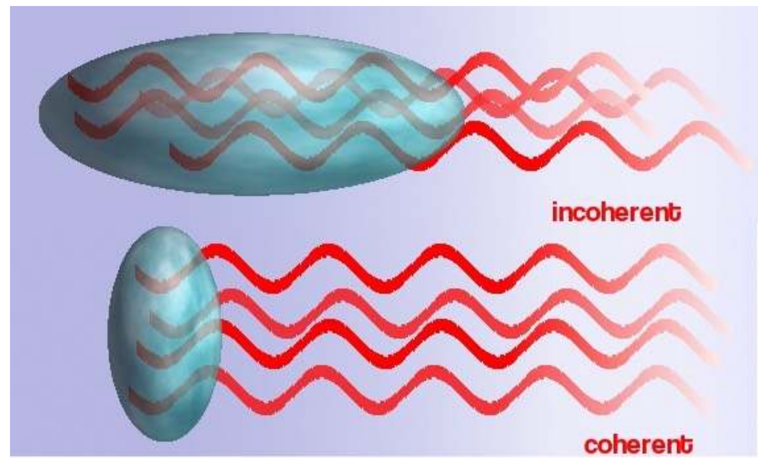


KARA (incl. building, labs, etc)

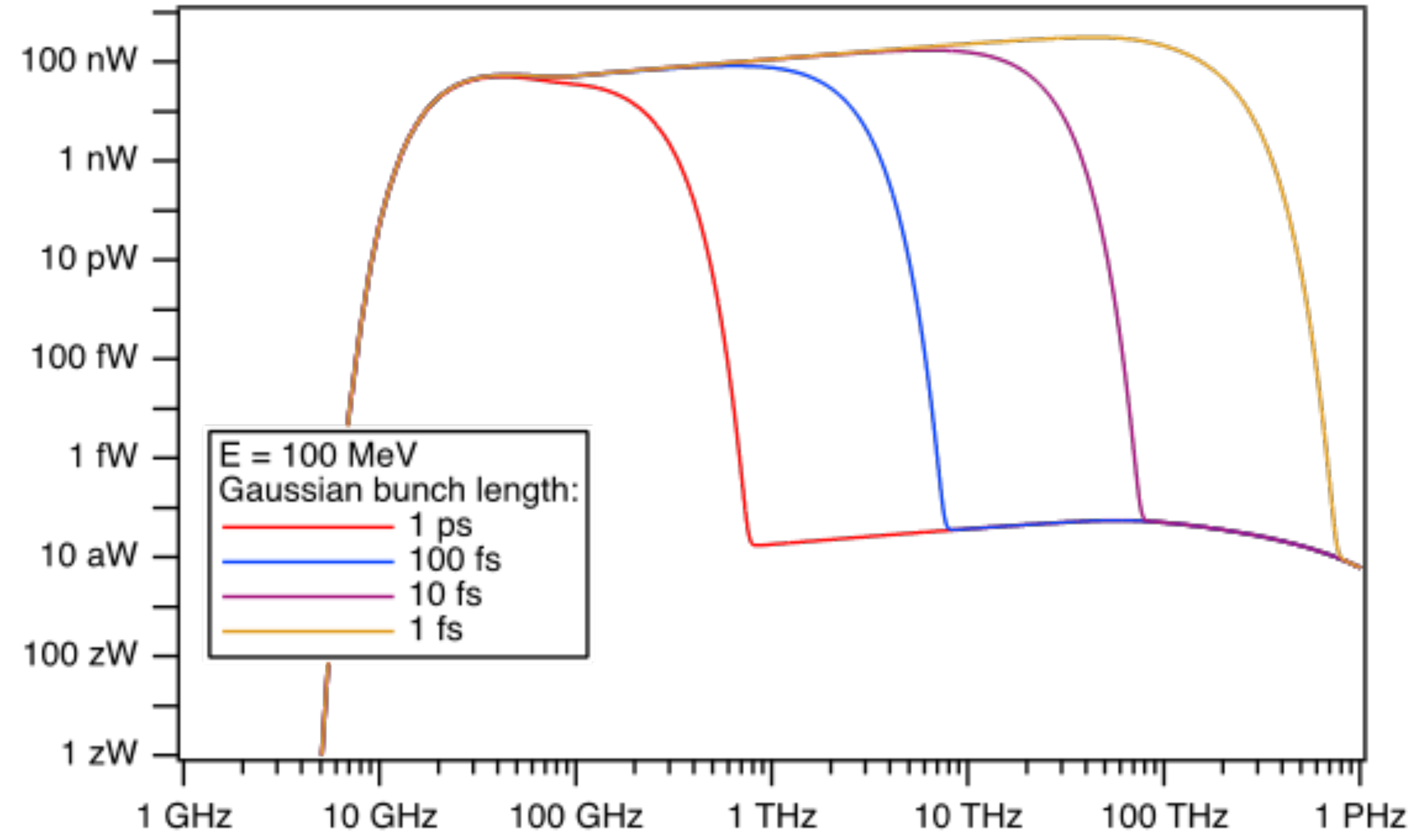


High Power THz Generation@cSTART

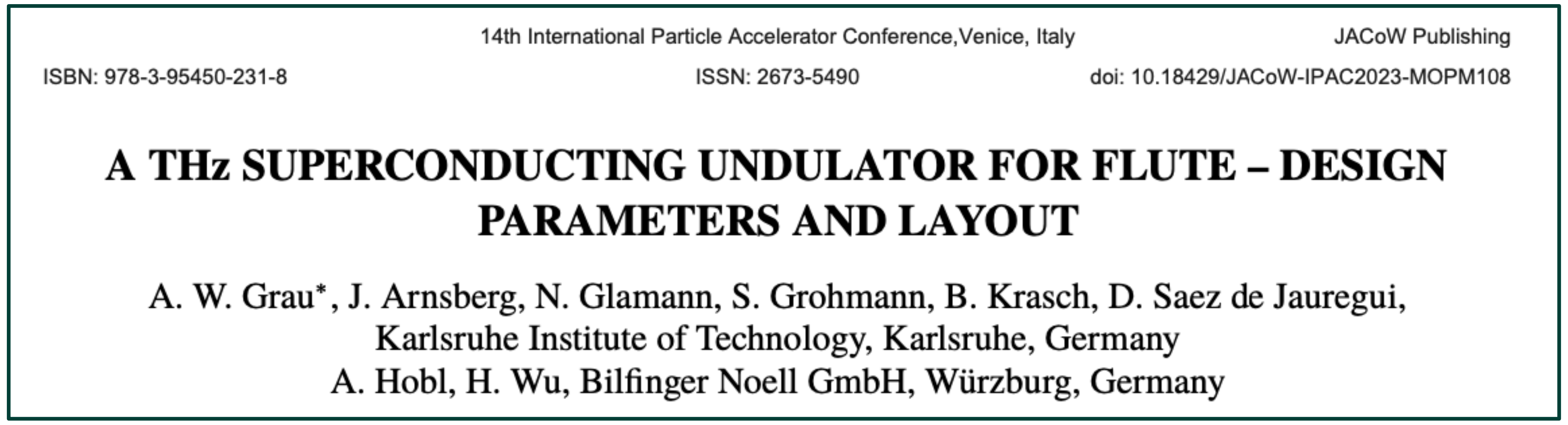
- Coherent emission of THz radiation (cSR or undulator)
- Wavelength > emitting structure ⇒ intensity $\propto N^2$



[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

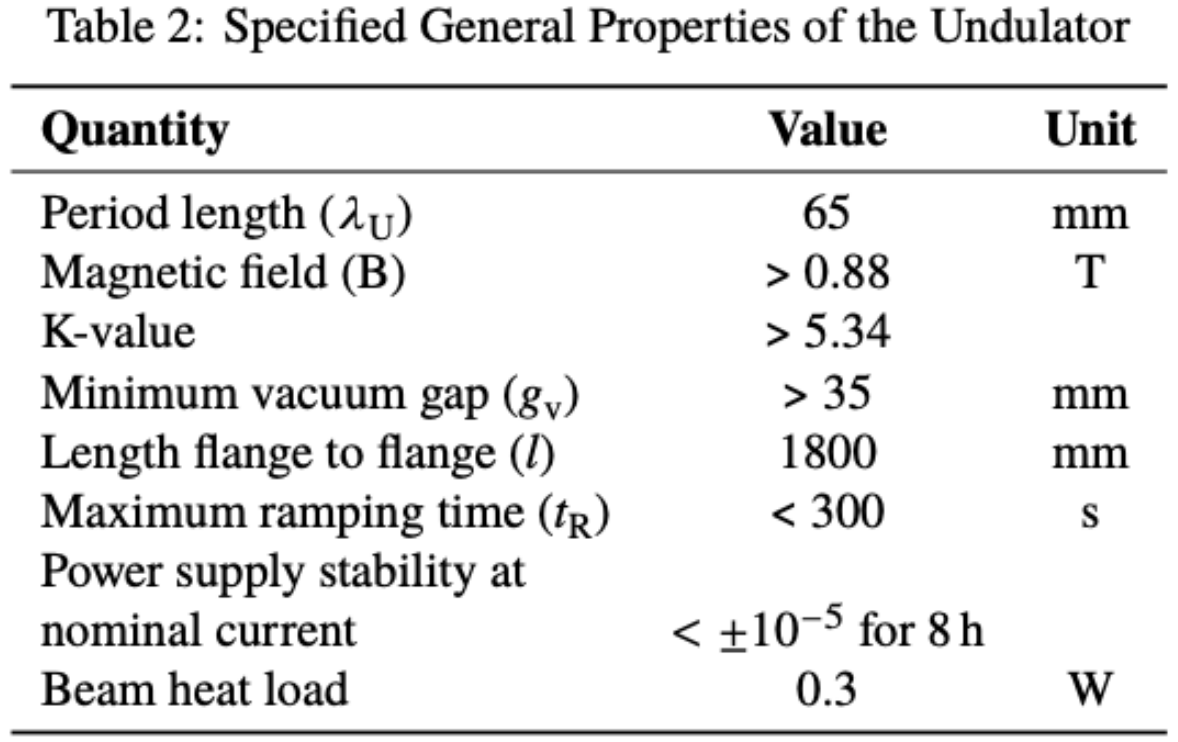
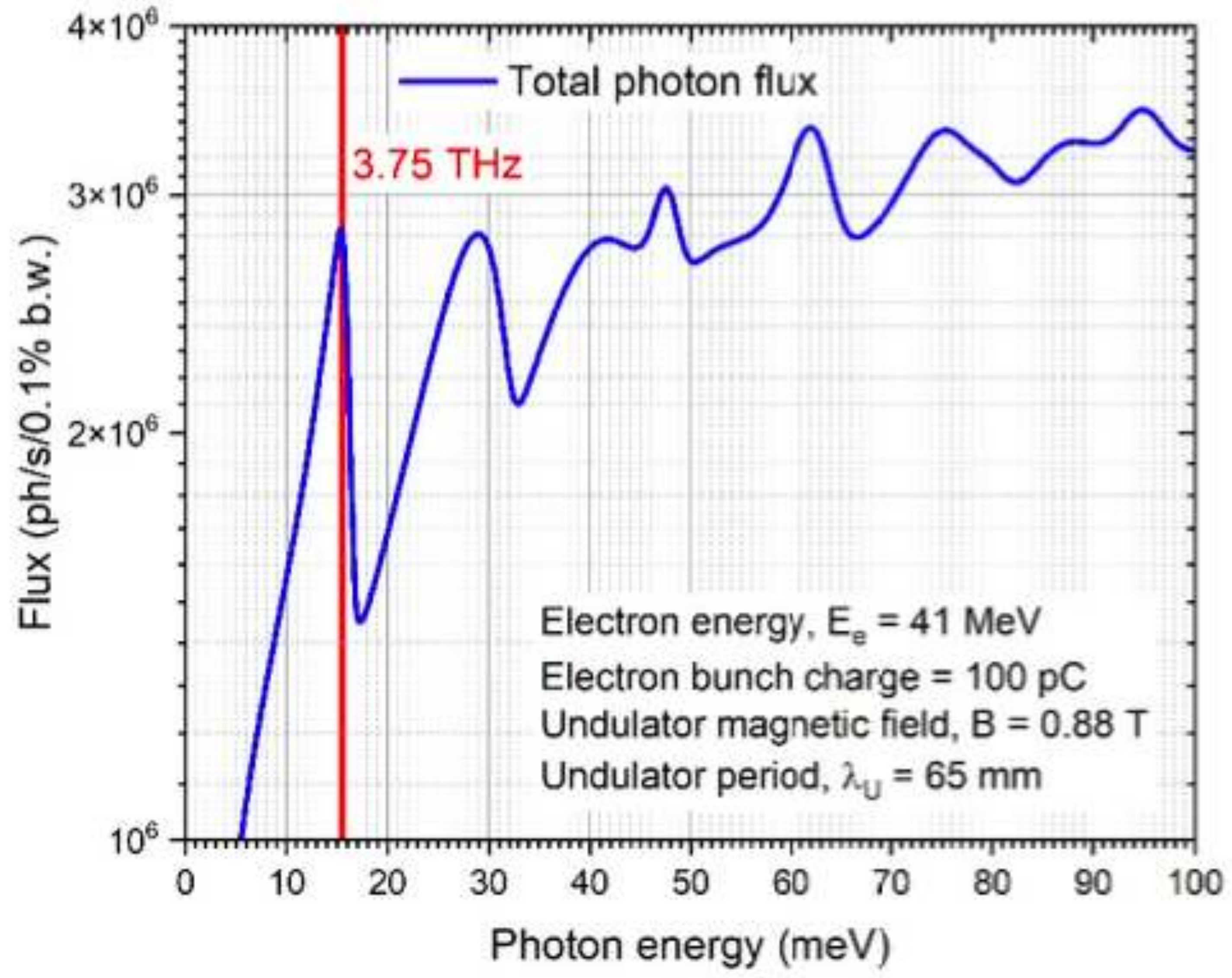


Table 2: Specified General Properties of the Undulator

Quantity	Value	Unit
Period length (λ_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)



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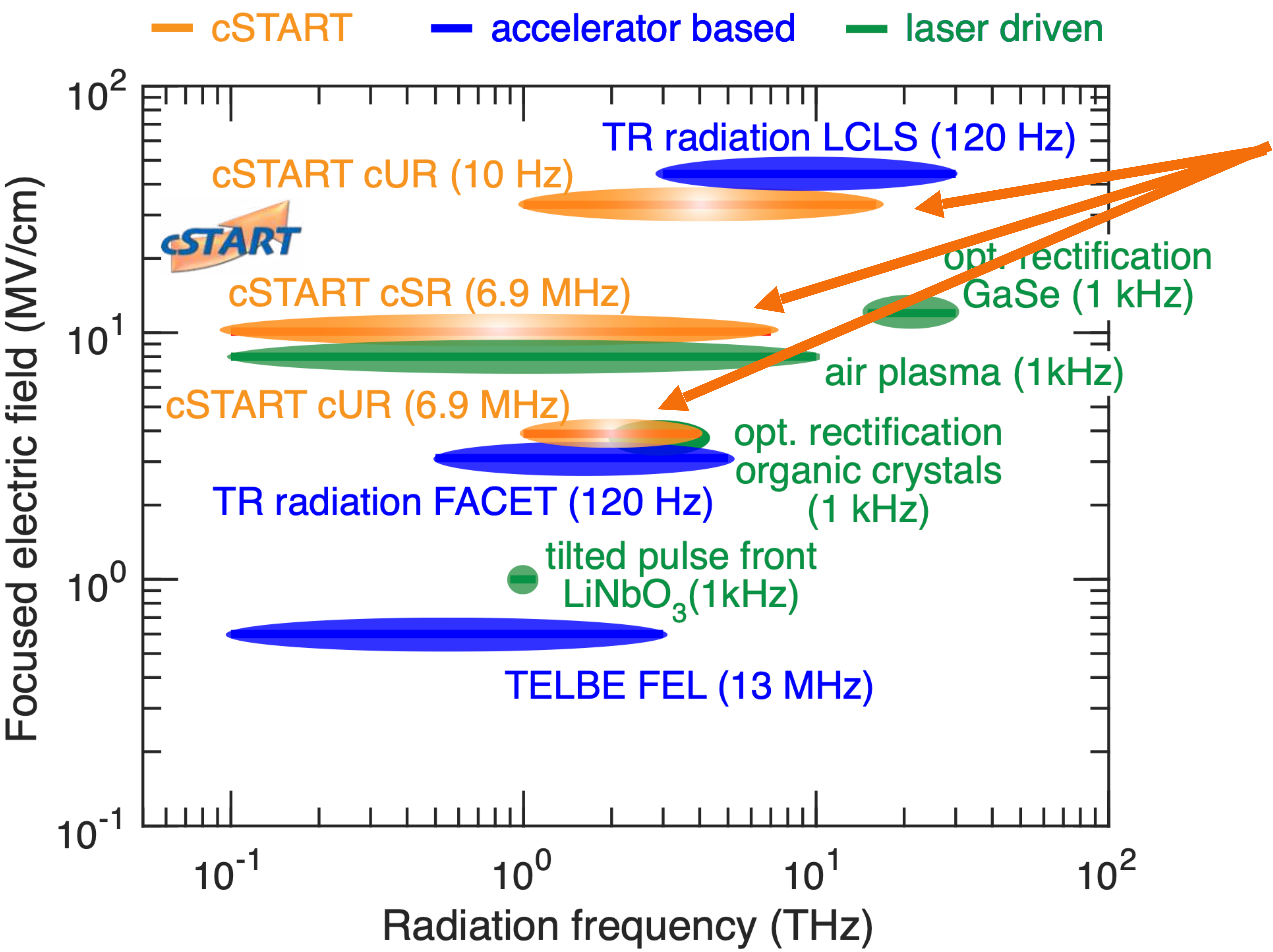
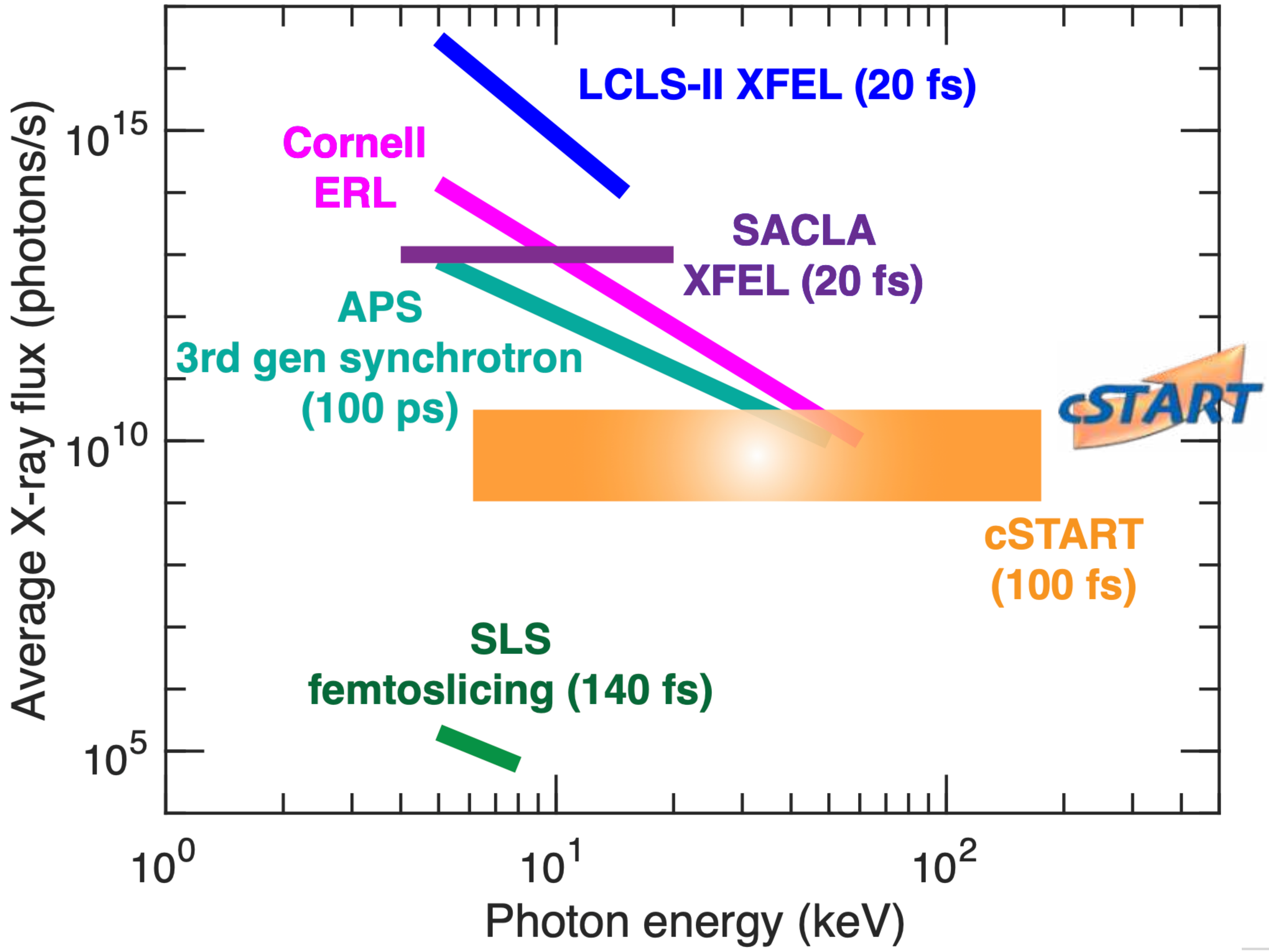
Future Light Source I:
Ultrafast High-field THz Radiation Source



cUR: coherent undulator radiation
cSR: coherent synchrotron radiation
TR: transition 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 (~2x10^{10} phot/sec)
- High photon energy (up to 200 keV)
- Compact, energy efficient machine

APS Synchrotron Light Source

www.aps.anl.gov

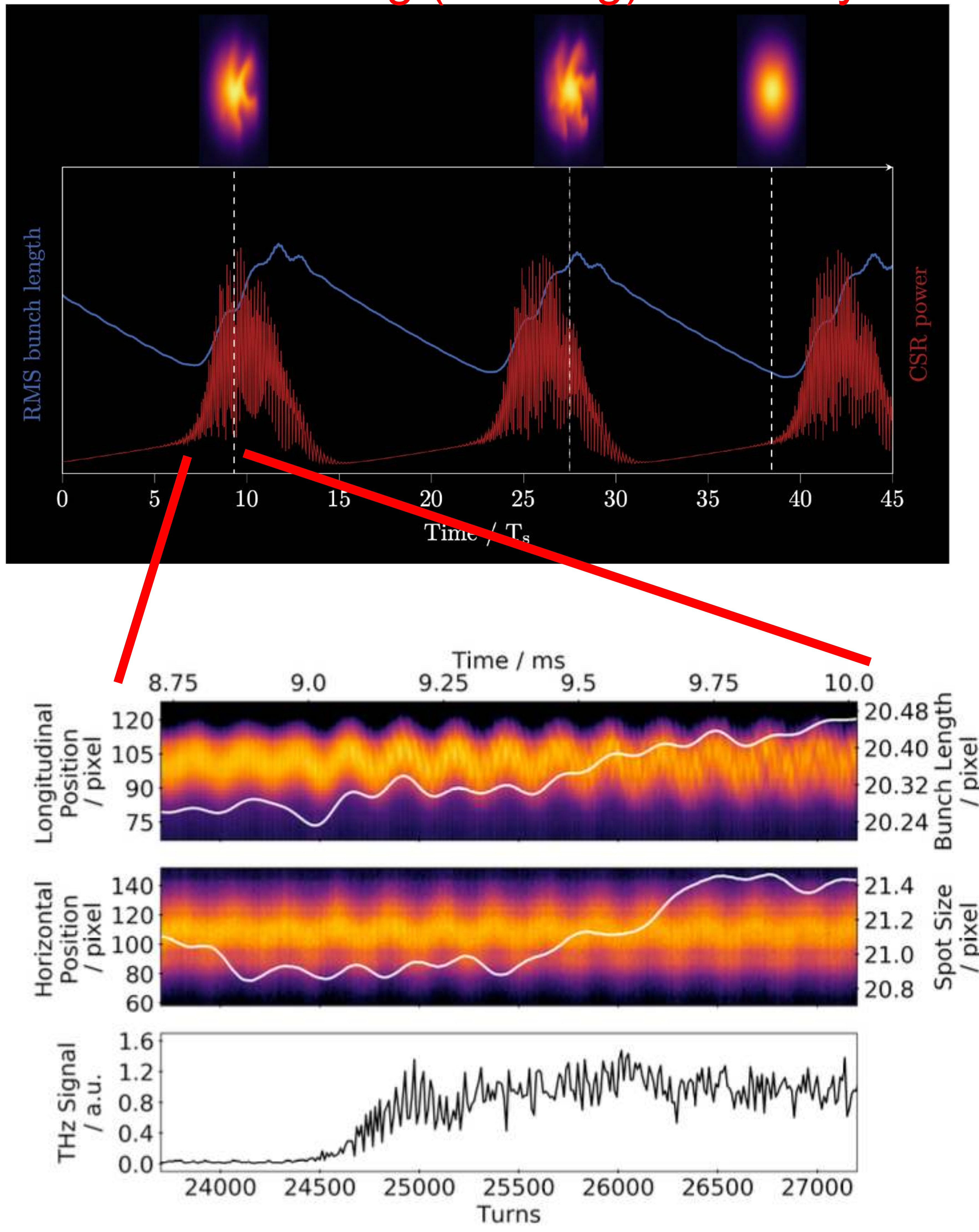
LCLS X-ray Free Electron Laser

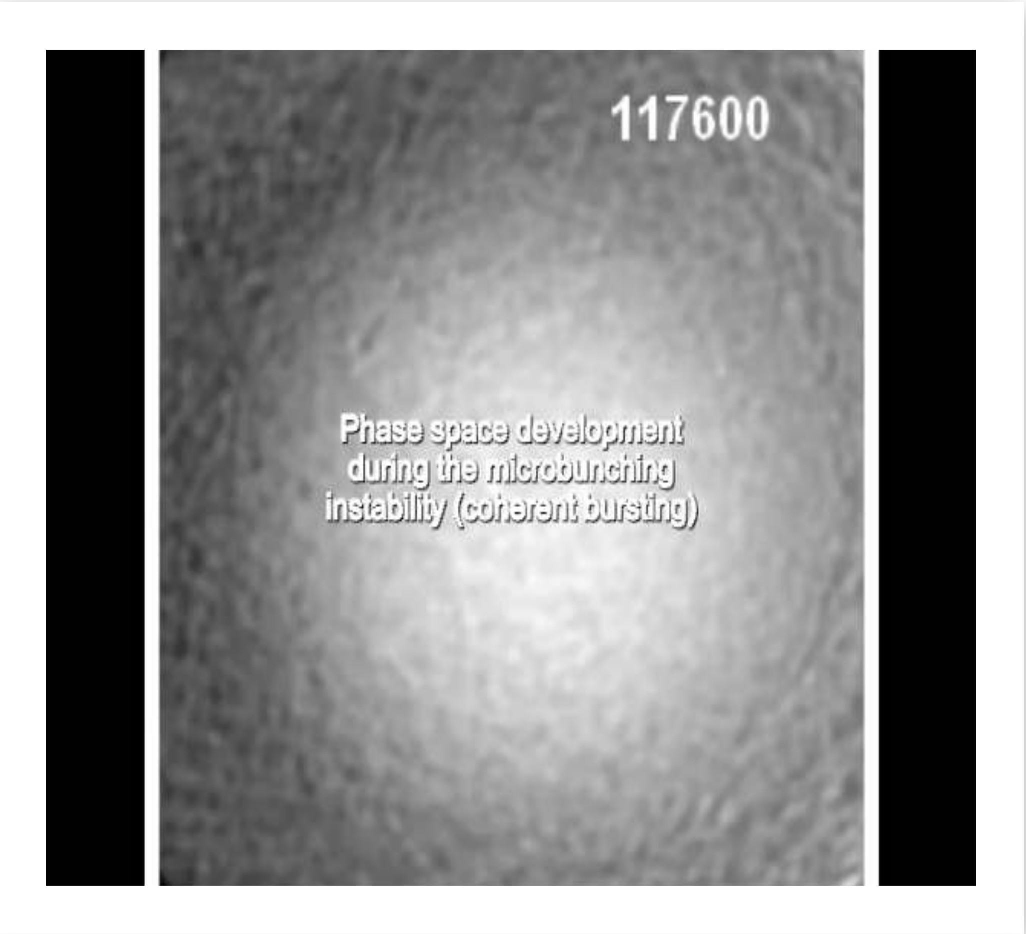
lcls.slac.stanford.edu

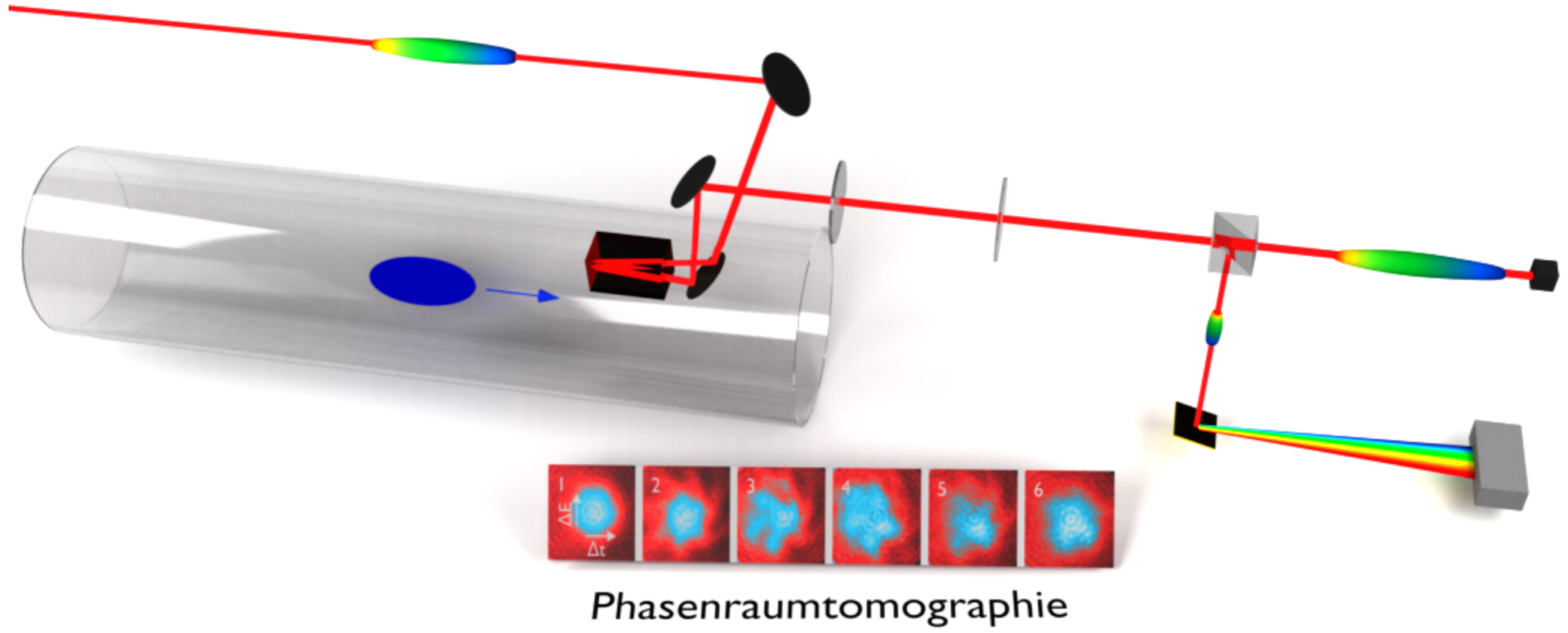
Non-equilibrium Beam Physics@KARA 2.5 GeV Storage Ring

- 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





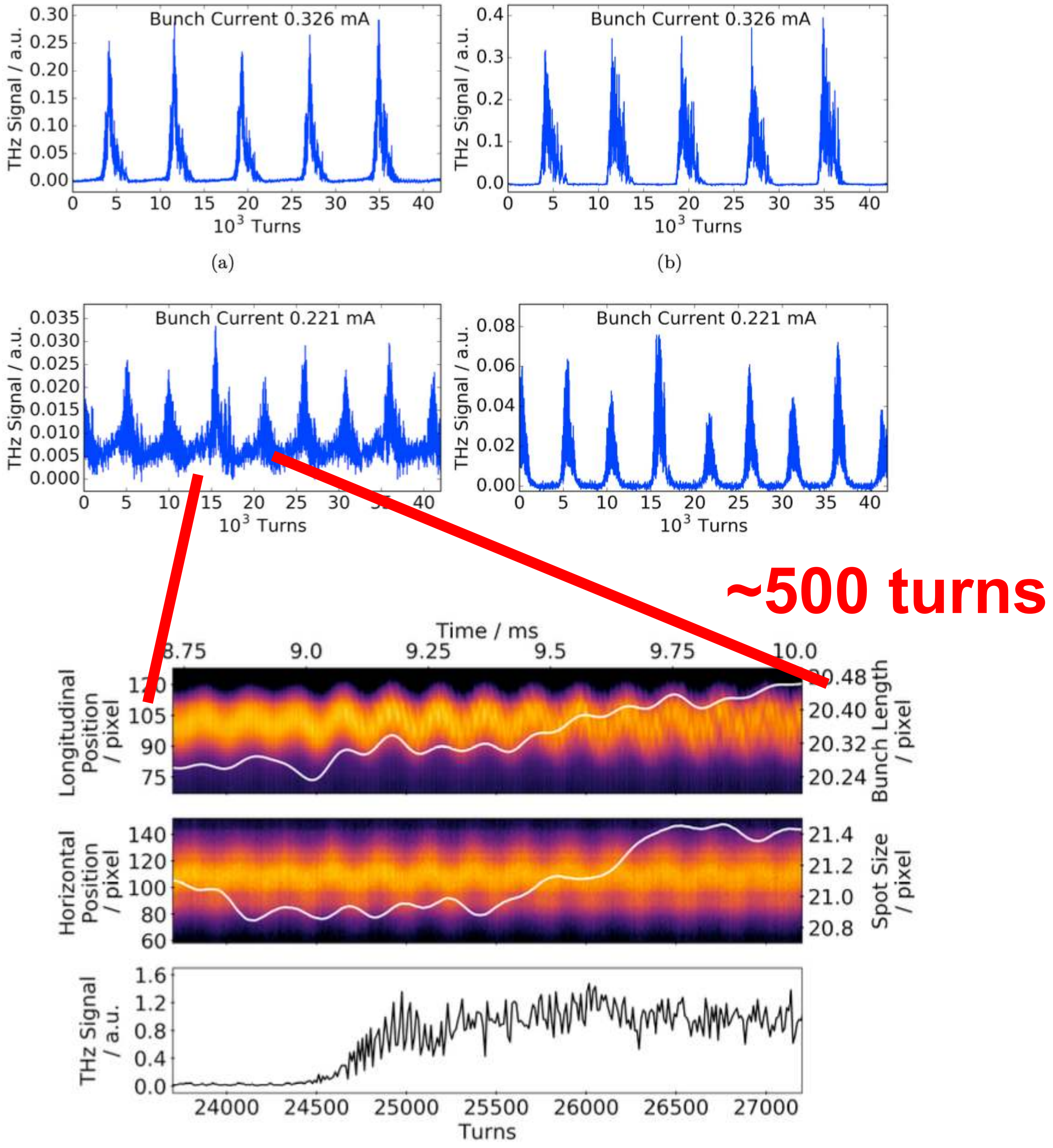


Funkner et al. ***Scientific Reports*** 13 (2023)
doi:10.1038/s41598-023-31196-5

M. Brosi, Dissertation

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

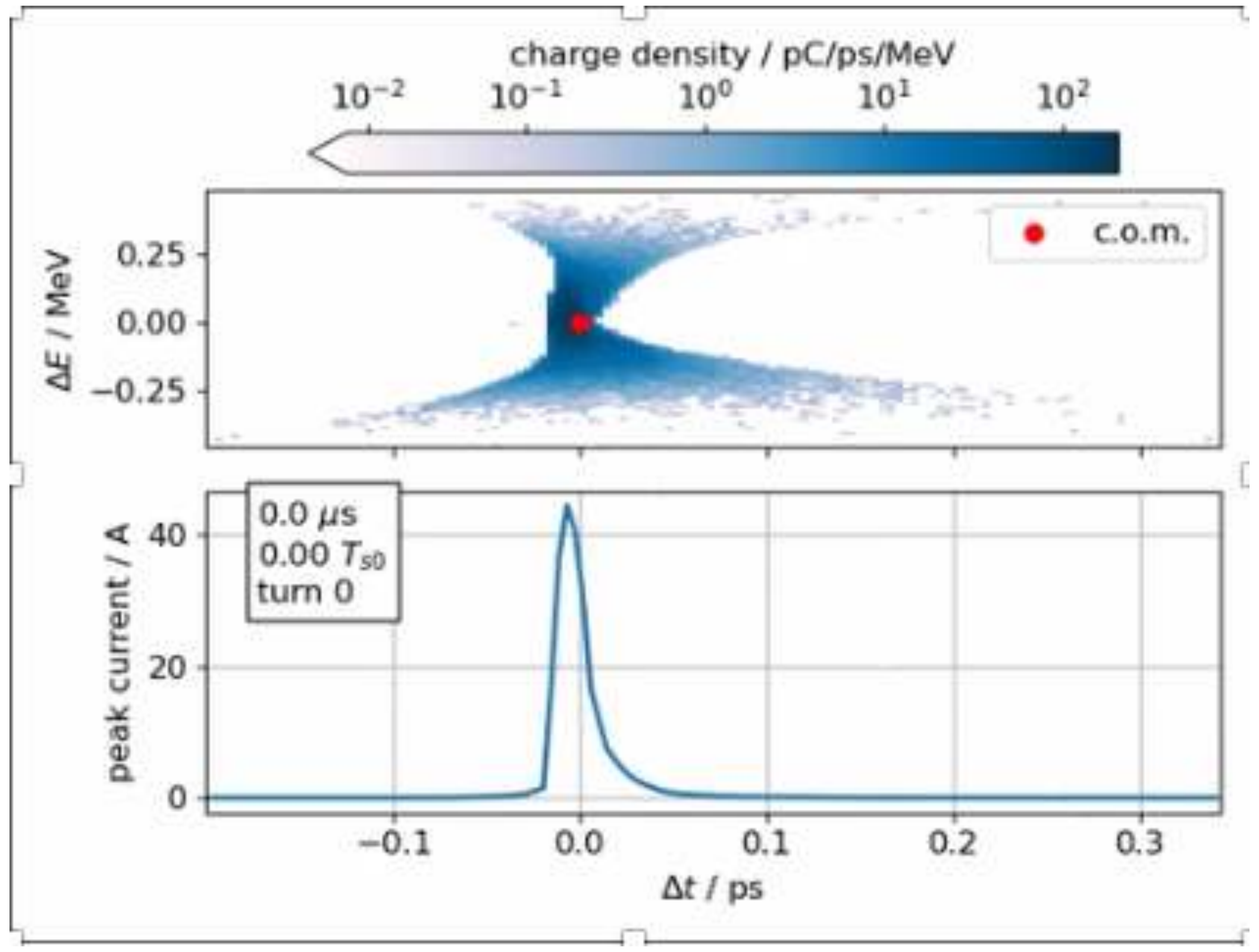
Microbunching instability@KARA 3 ps bunches



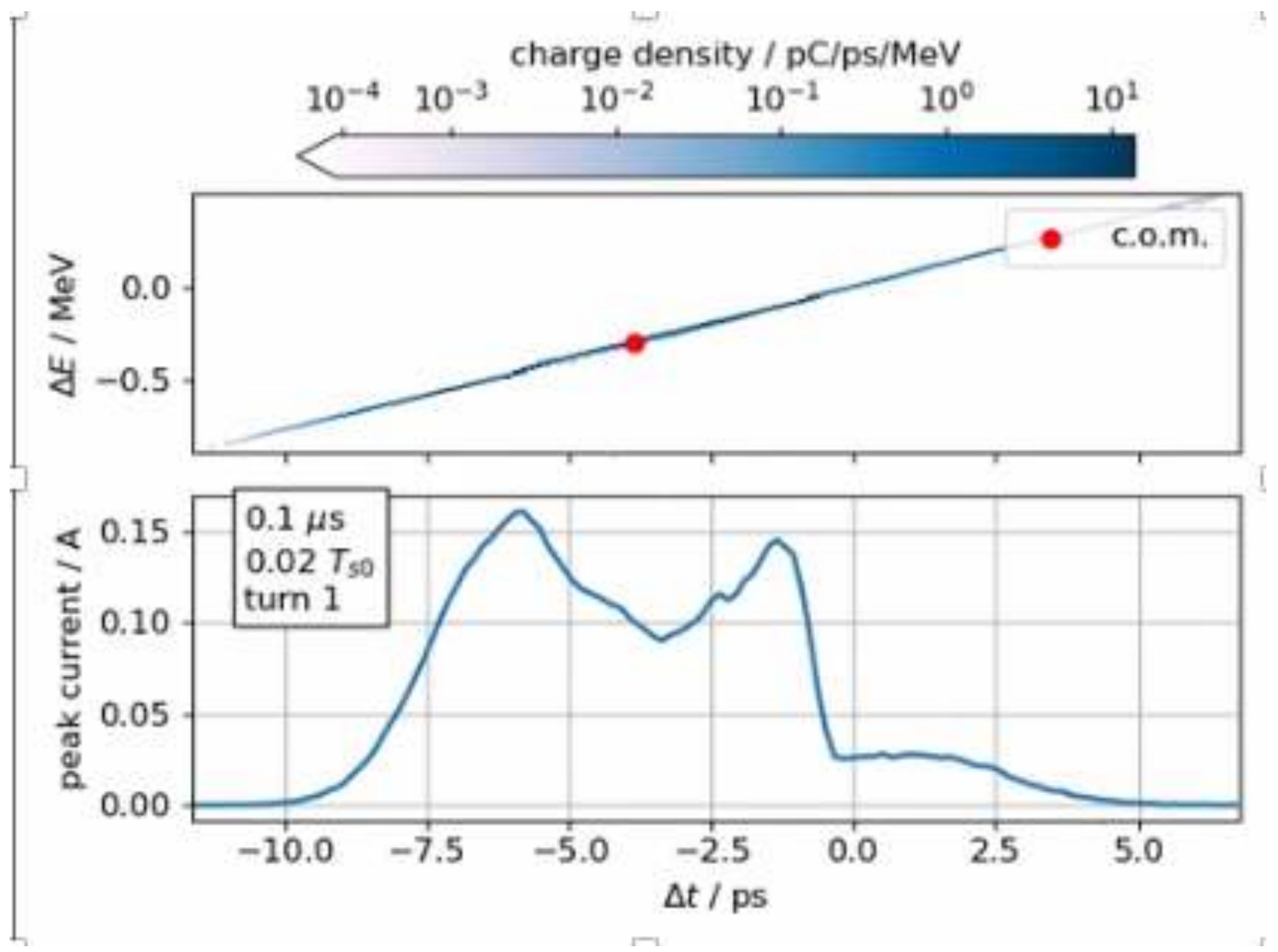
M. Brosi, Dissertation

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

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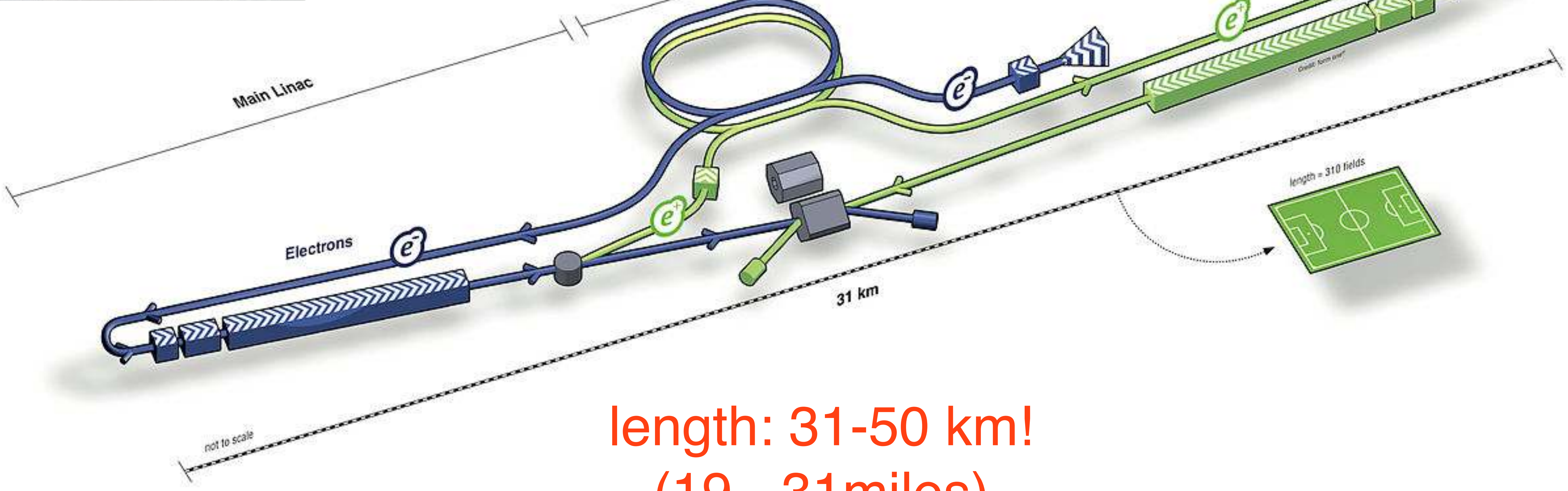
Future Particle Collider

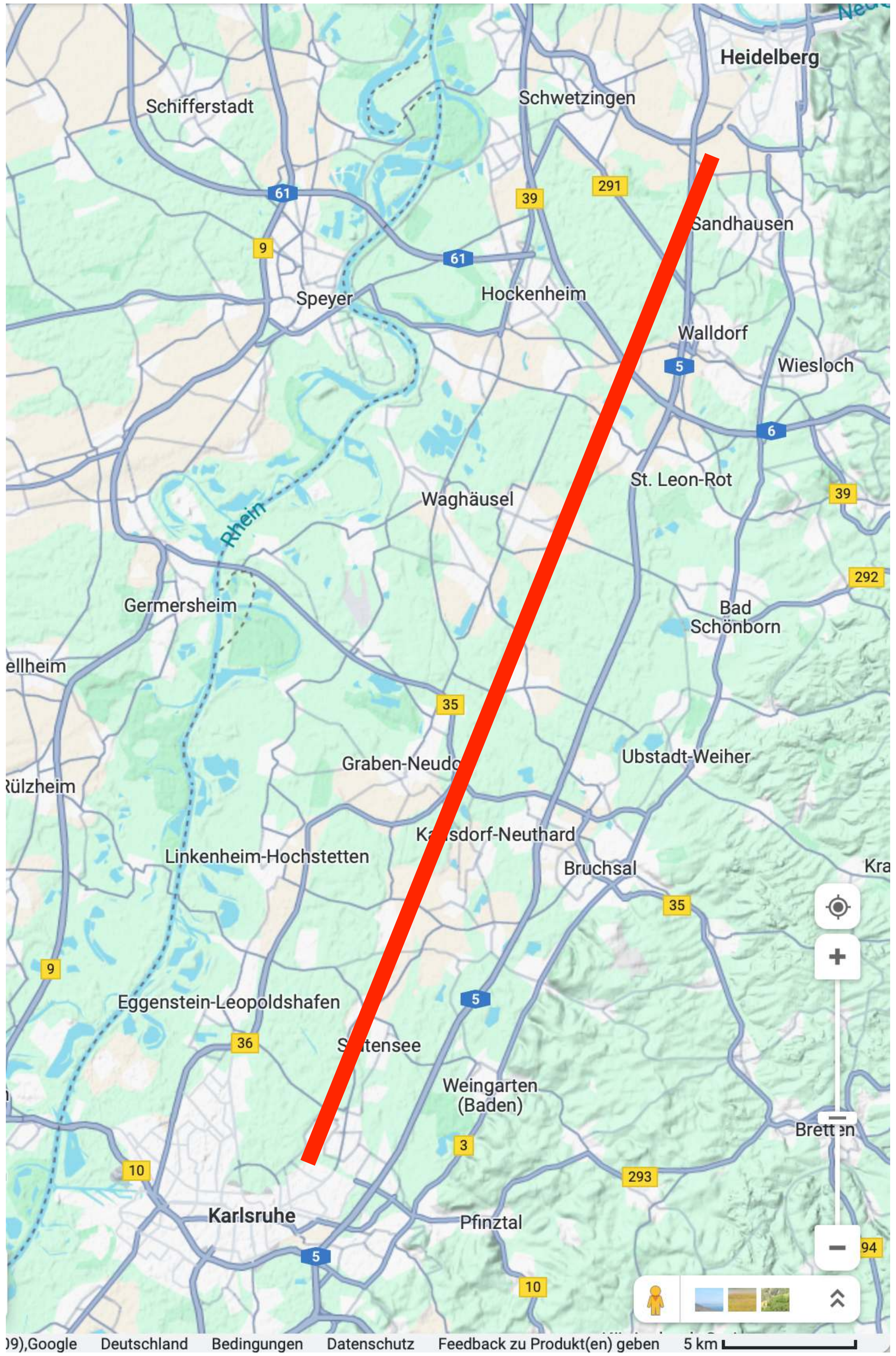
- 10 TeV center of mass energy
- One proposed incarnation: International Linear Collider (ILC)


LHC@CERN

International Linear Collider (ILC)



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



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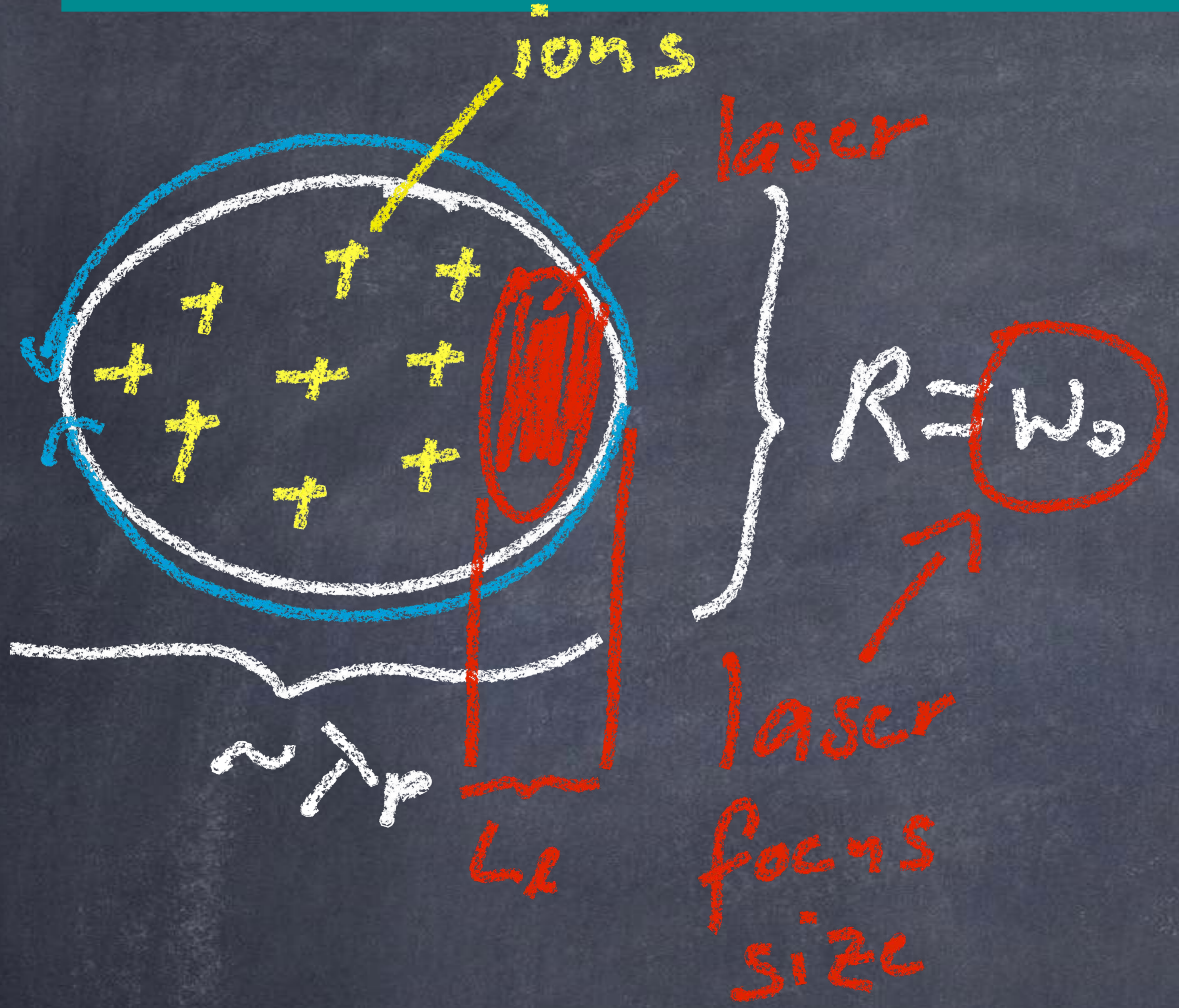
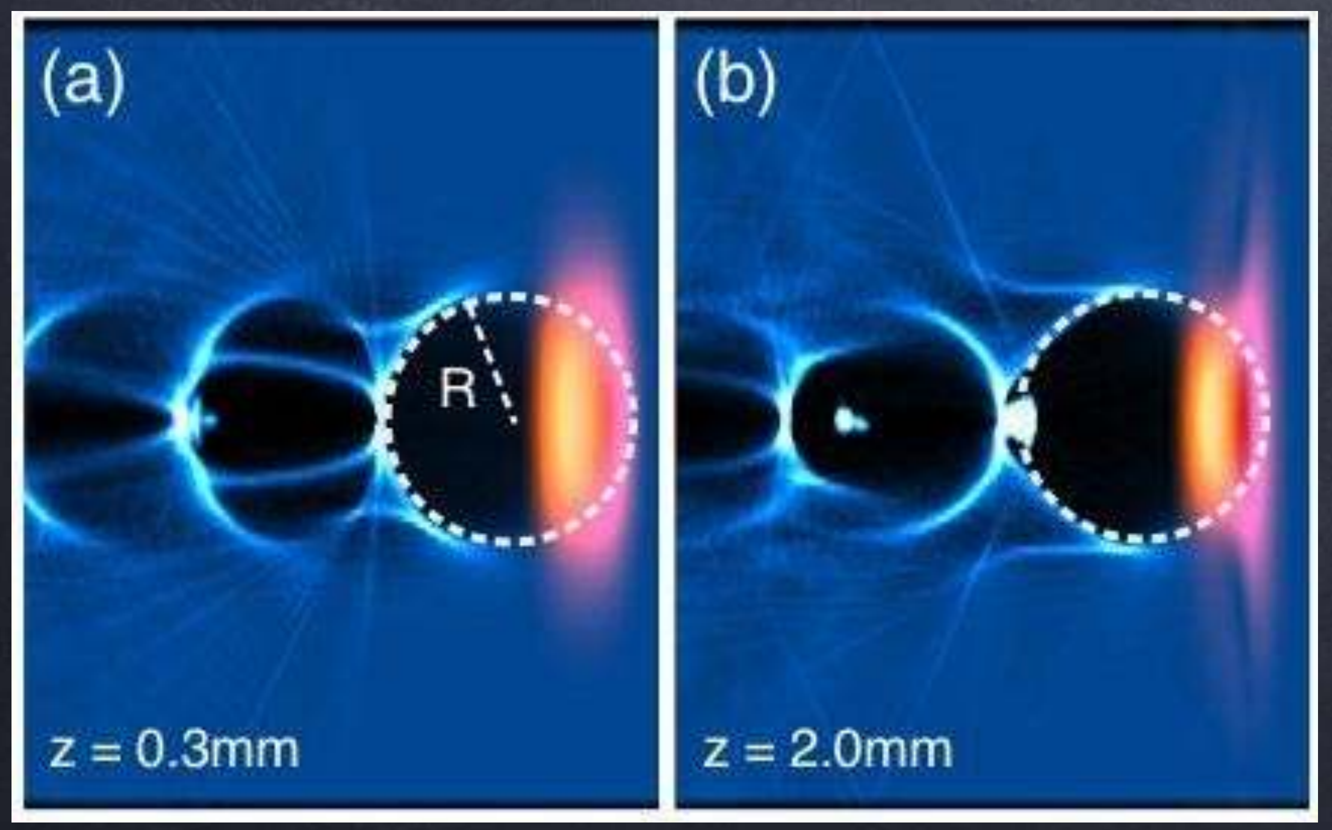
LWFA in the “Bubble” Regime





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

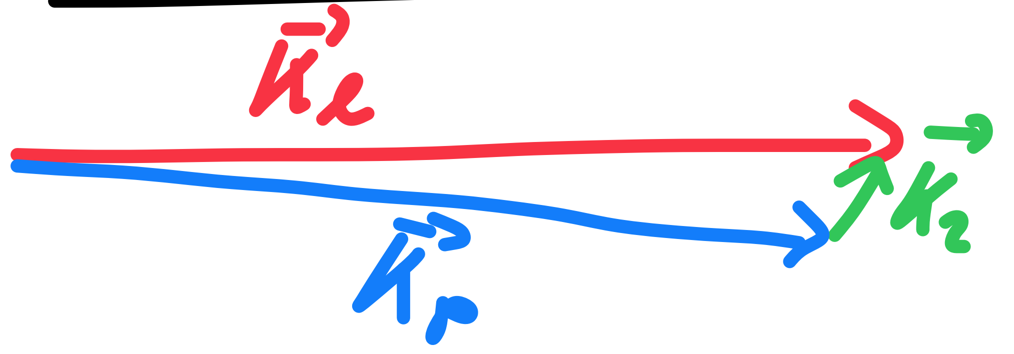
Next-Generation Laser-Plasma Acceleration: A Novel Regime and Shift in Paradigm

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

- Stimulated Raman Scattering (SRS)[1]

$$\left.\begin{array}{l}\cdot\, 1: \text{plasma wave}\\ .\, 2: \text{Raman scattered light}\end{array}\right\} @\, n_{cr}/4: \quad \begin{array}{l} \omega_p = \frac{\omega_l}{2};\ \vec{k}_p \approx \vec{k}_l \\ \omega_2 = \frac{\omega_l}{2};\ \vec{k}_2 \approx 0 \end{array}$$

<u>absolute instability!</u>



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

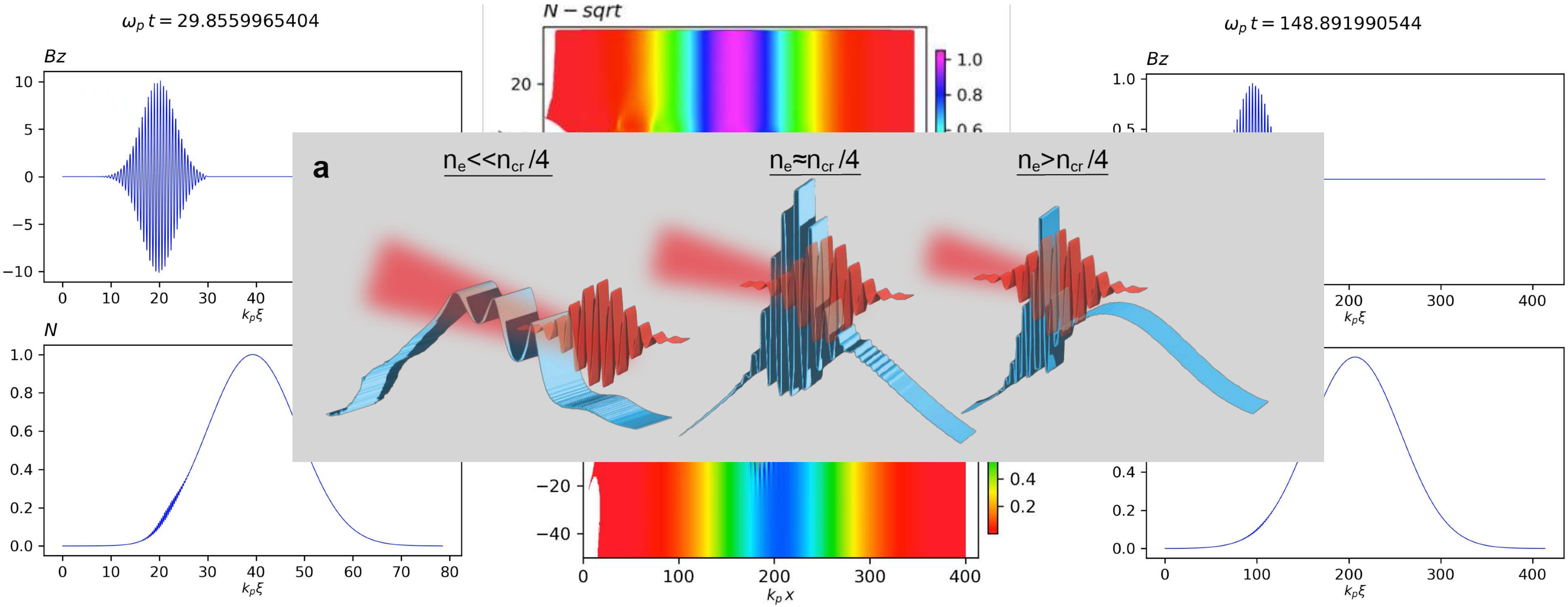
Parametrically-Excited Laser-Plasma Acceleration (PEPA)

$a_0 = 0.5$

density << ¼ n_{cr} ($k_l/k_p = 20$)

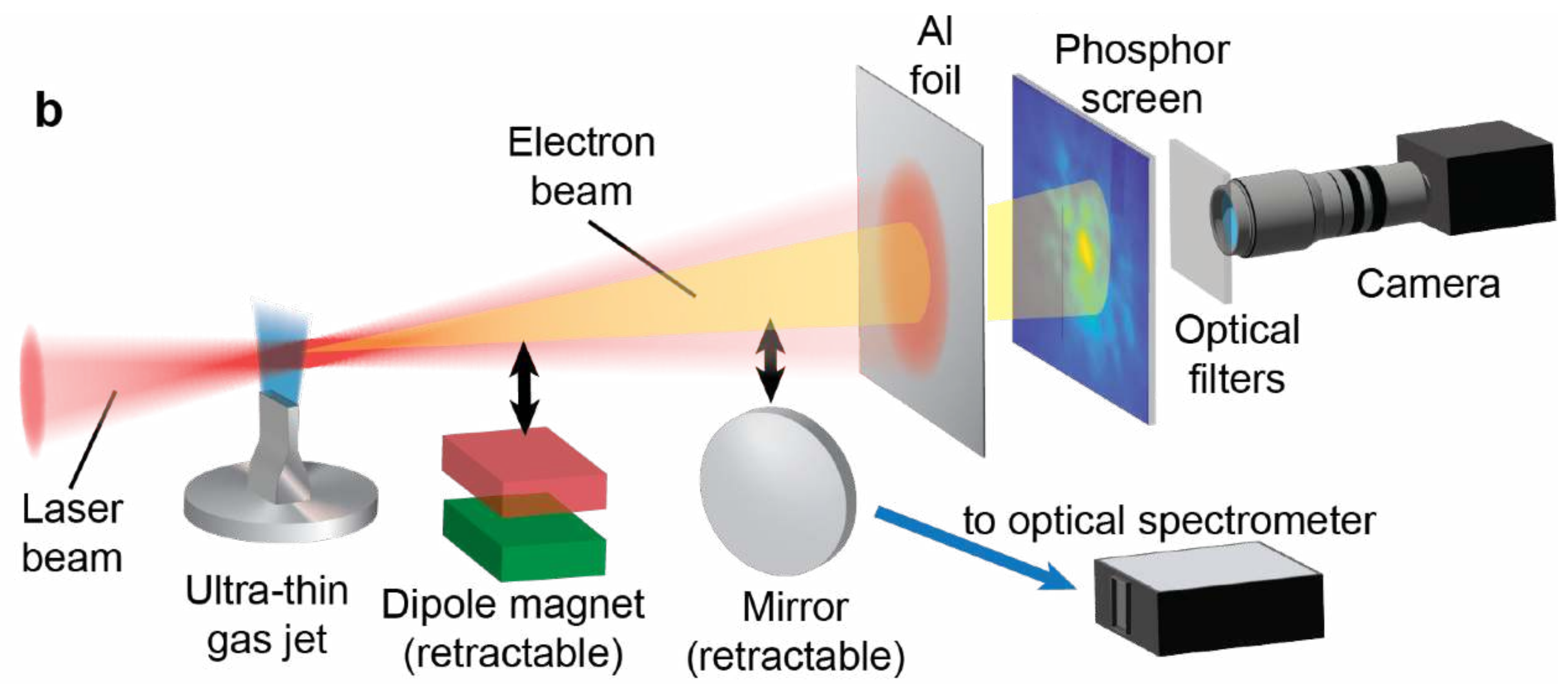
2D density snapshot

density ~ ¼ n_{cr} ($k_l/k_p = 1.9$)



Novel Acceleration Regime: Parametrically-Excited LPA (PEPA)

Experimental Setup



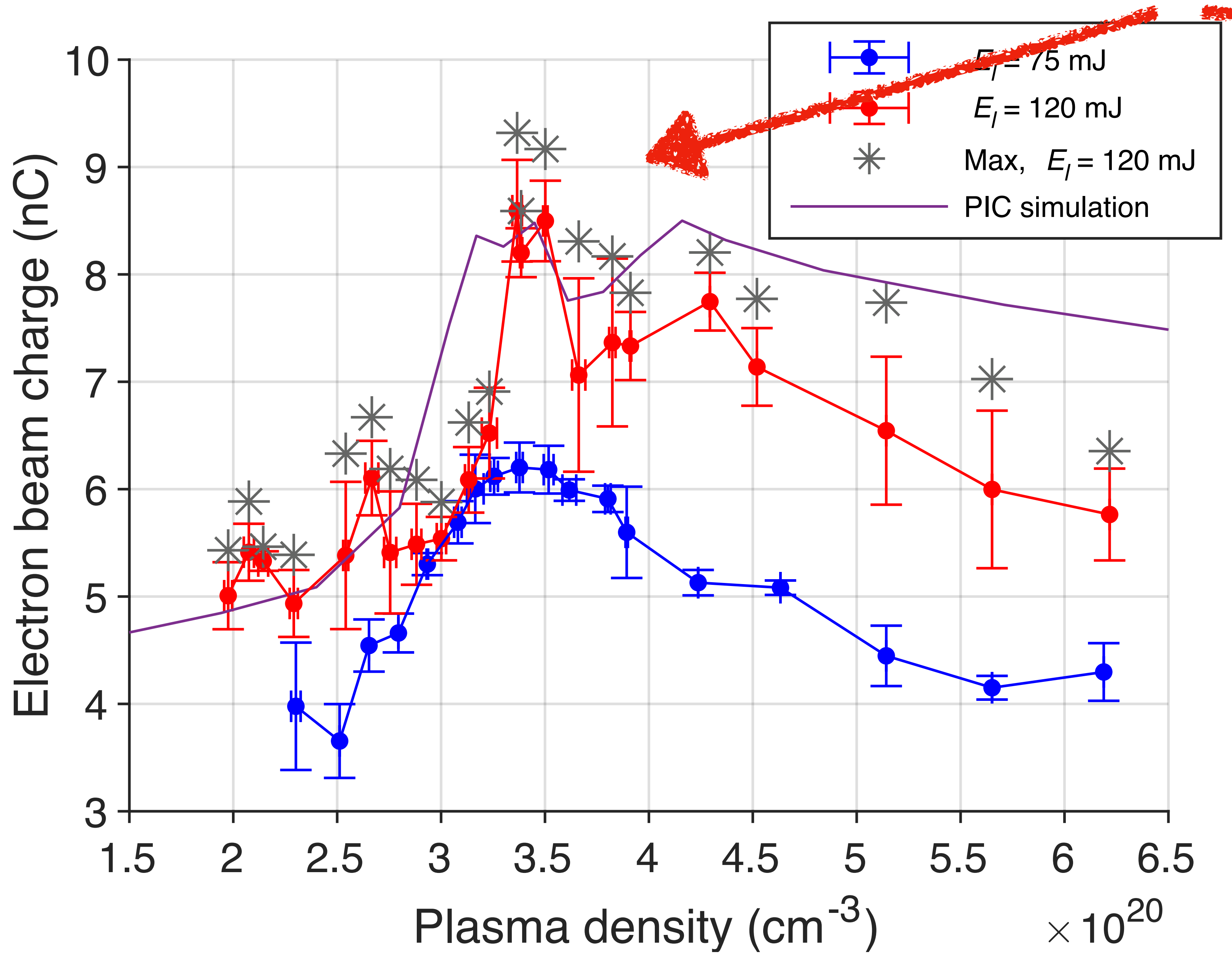
- laser: 120 mJ, 40 fs, $a_0 = 2.2$
(laser pulse duration many plasma periods long!)

- gas target: 20 µm thick,
up to 1/2 n_{cr} (~8x10^{20}/cm^3)

Experimental Results

Charge vs plasma density

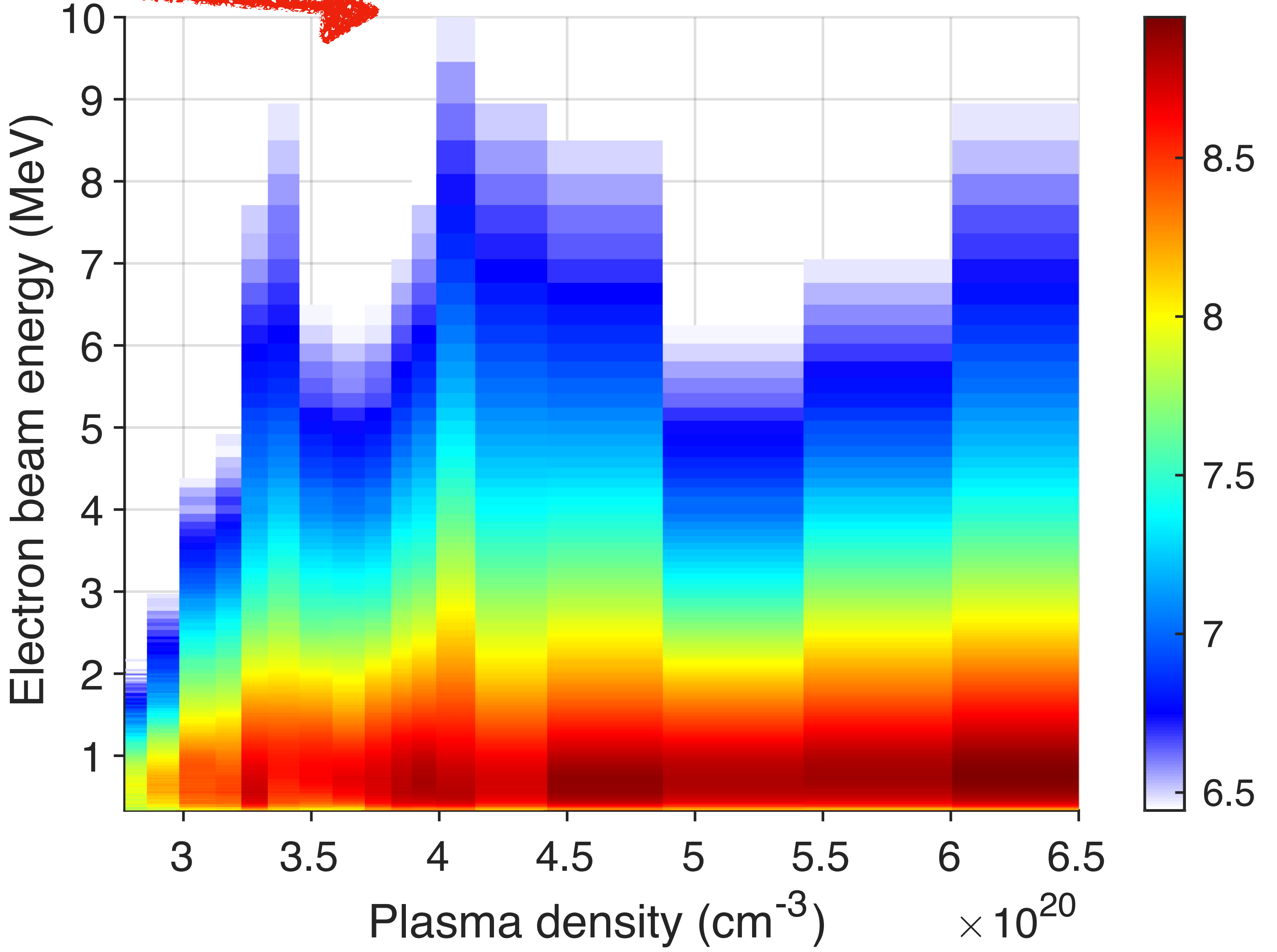
5-shot average



1/4*n_{cr}

e-beam spectrum vs plasma density

3-shot average



P. Zhang et al. (under review)

- ~ 10 nC !! (100-1,000 x more than typical bubble LWFA bunches)

- ~ 16 % energy conversion efficiency laser to electron beam !!
(bubble: max: 4% [Streeter et al., PRAB (2022)])

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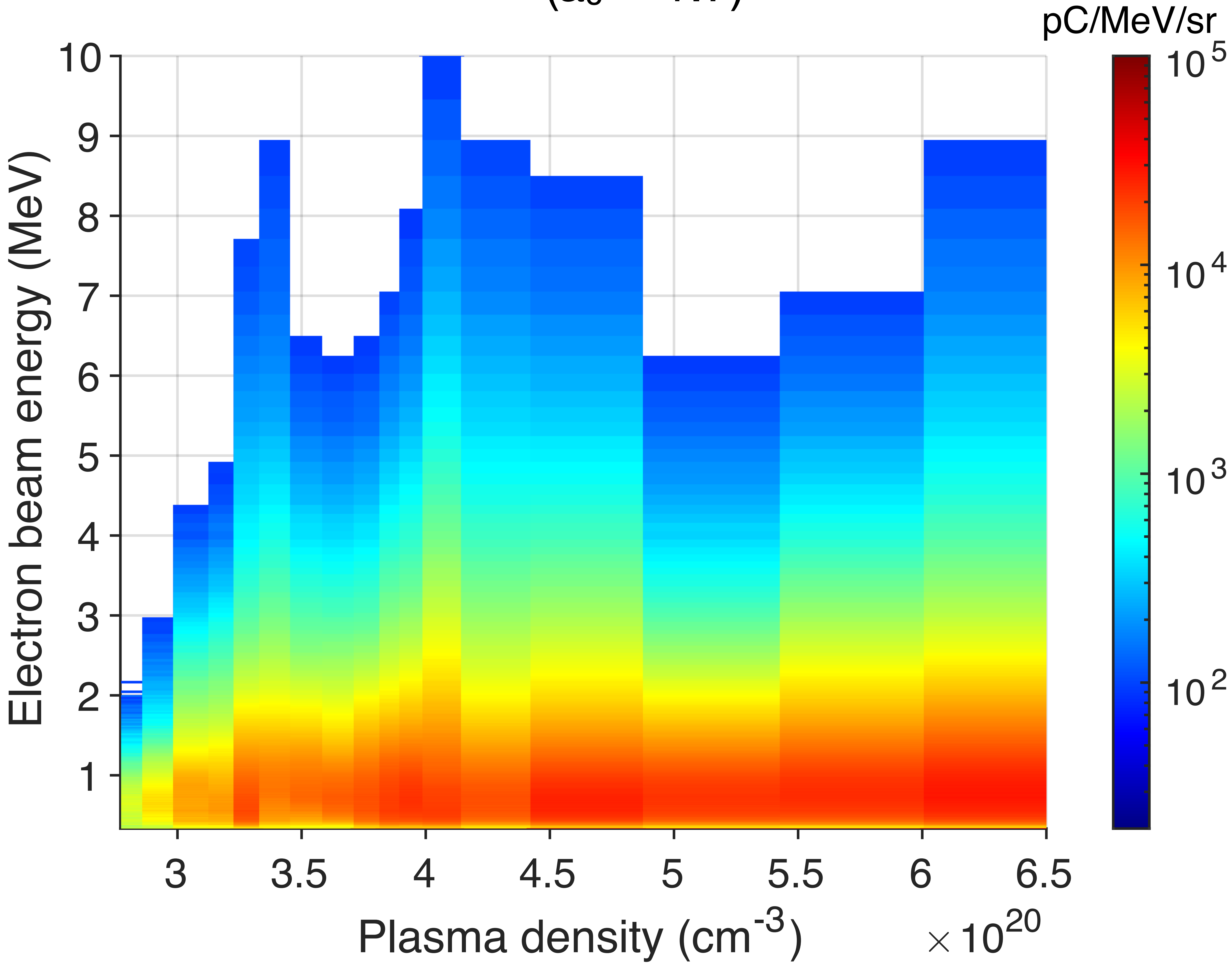
Experimental Results: e Spectrum

5-shot average

(a_0 = 1.7)



Comparison to 1D ponderomotive (assume Gaussian driver)[1]

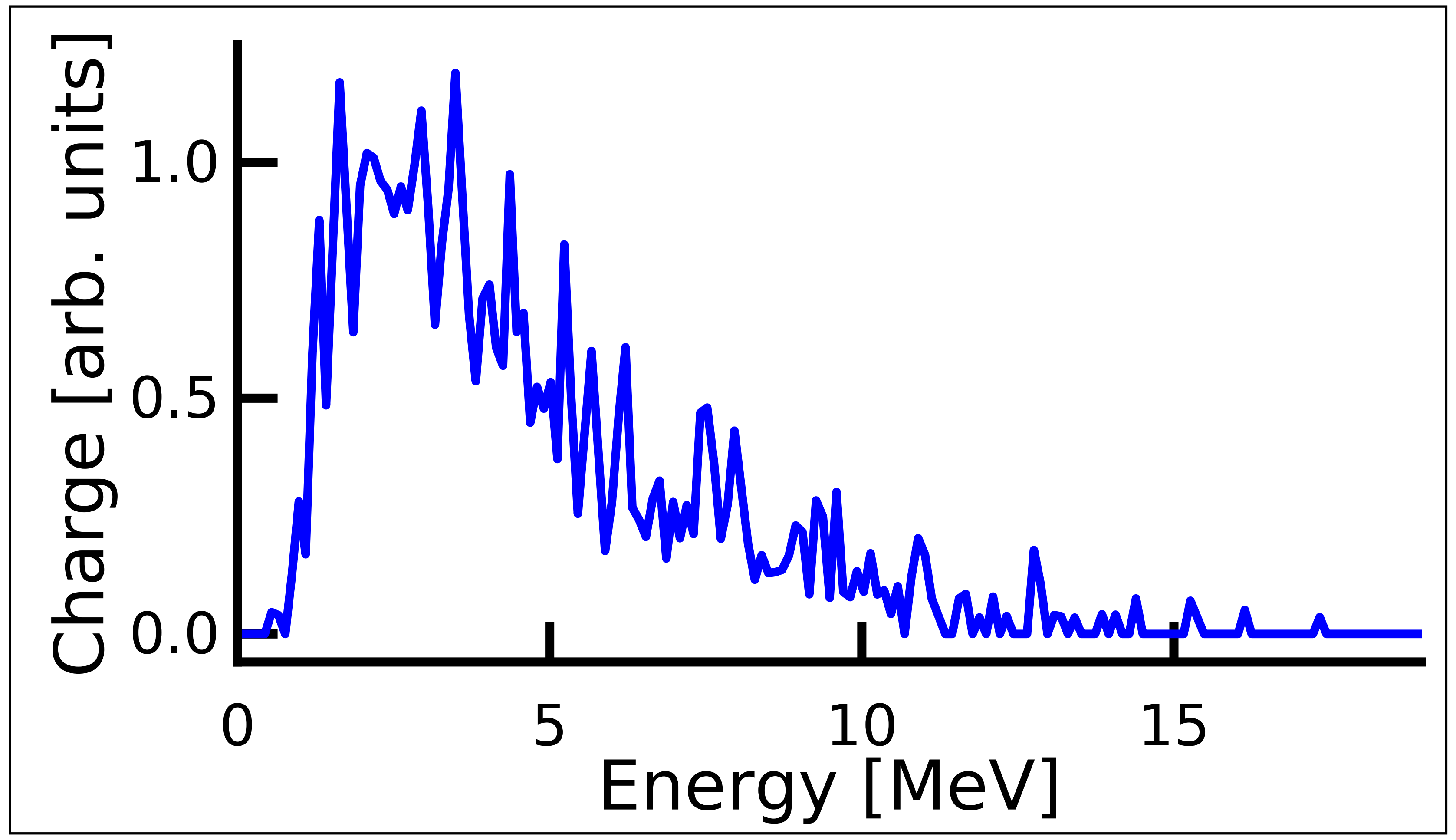
- accelerating field (relativistic wavebreaking field)

$$E_{\rm rel} = \frac{a_0^2/2}{1+a_0^2/2}\frac{cm_e\omega_p}{e} \simeq 2.6\ \mathrm{TV/m}\ !!$$

($E_{\rm rel} \simeq 1/3\, E_{\rm laser}$!!)

- dephasing length: $l_d = \pi k_l^2/k_p^3 = 3.2\ \mu\mathrm{m}$
- max. energy: $\Delta W = eE_z L_d \simeq 8.3\ \mathrm{MeV}$

Particle-in-cell simulation



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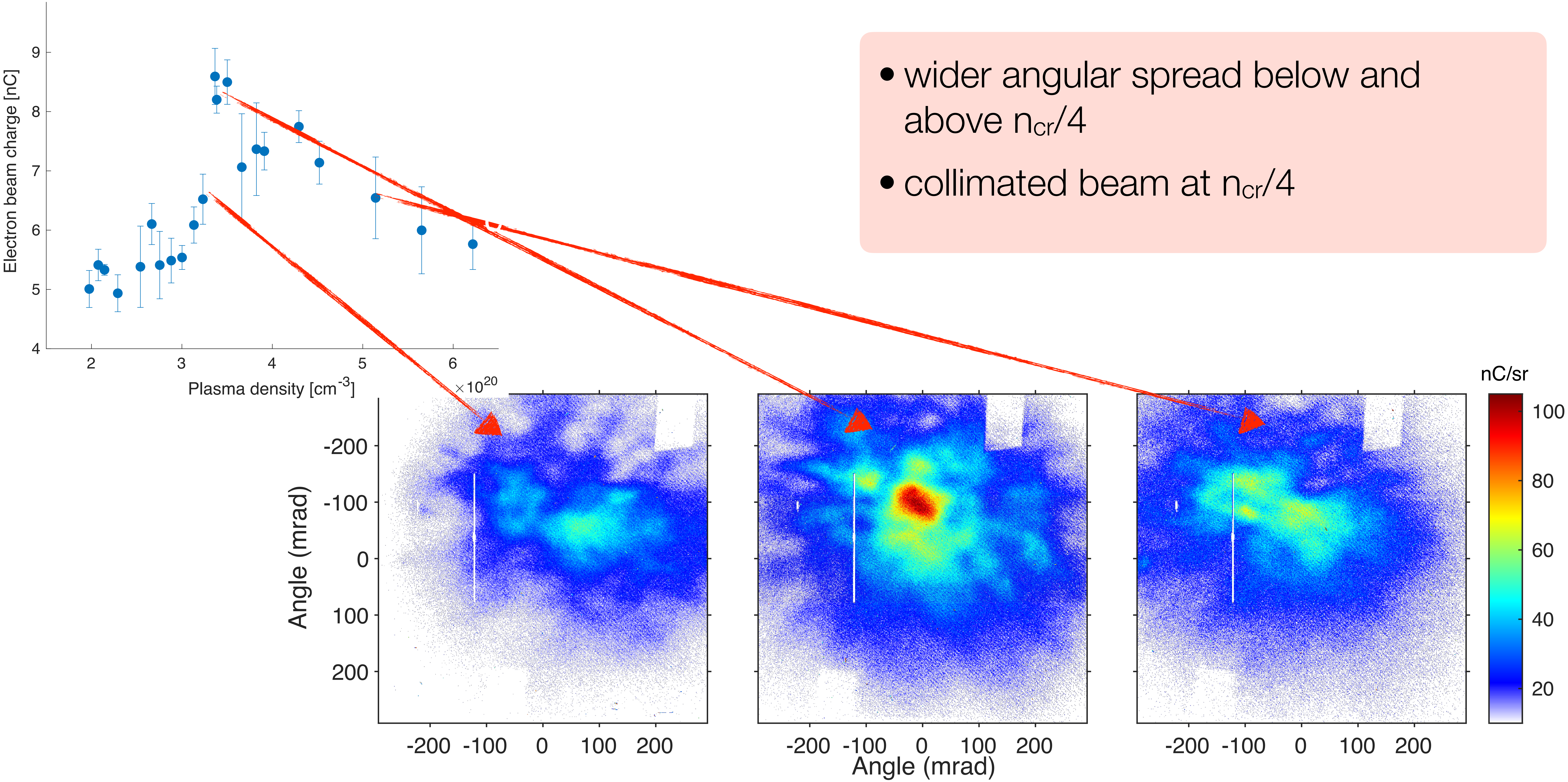
[1] Esarey , Schroeder, Leemans, Rev. Mod. Phys (2009)

Electron Beam Profiles

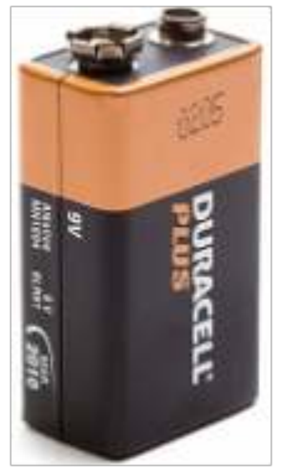
- wider angular spread below and above $n_{cr}/4$
- collimated beam at $n_{cr}/4$



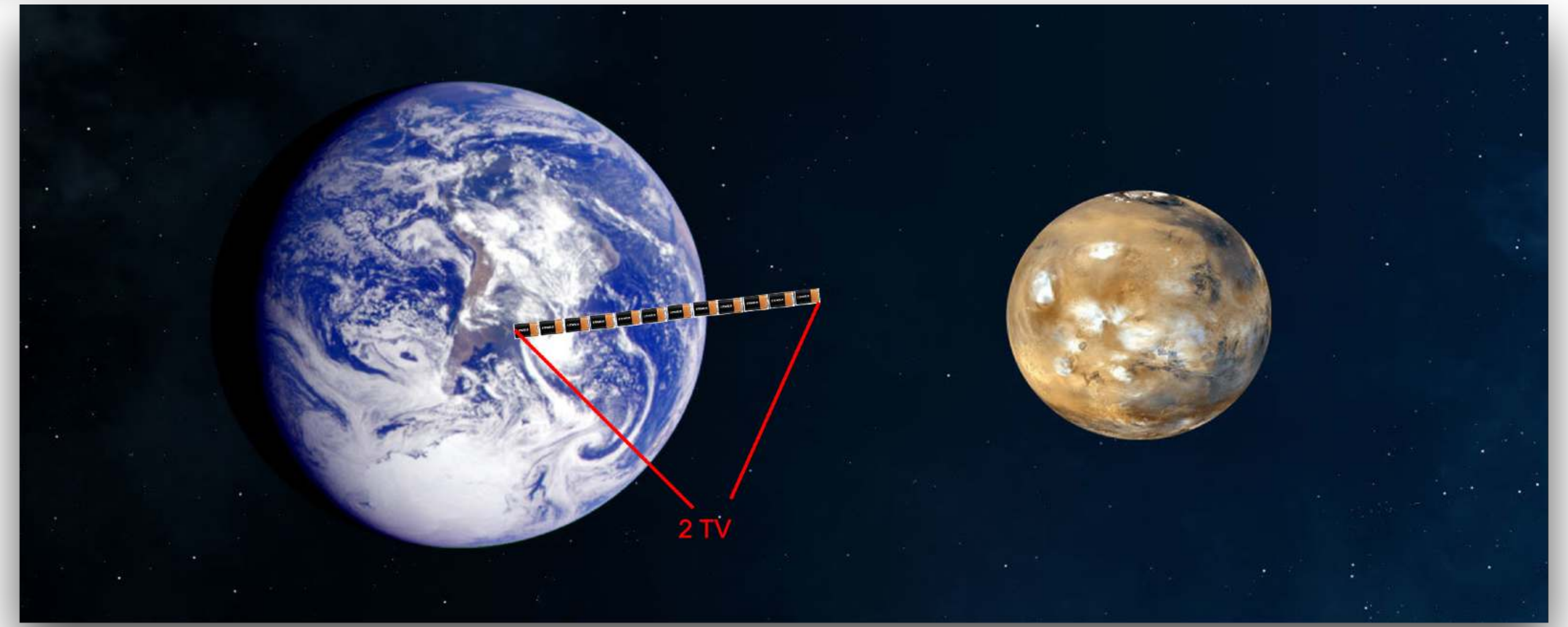
Next-Generation Laser-Plasma Acceleration

- 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)

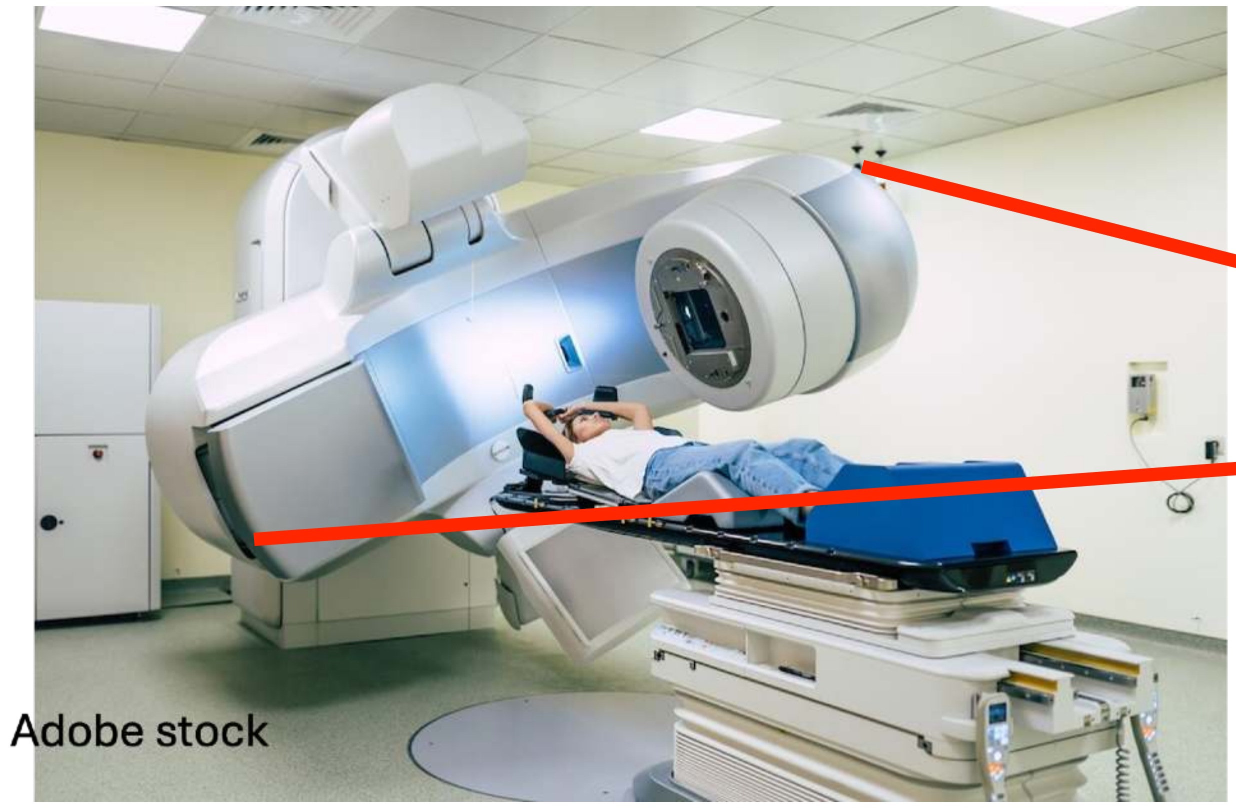


height 50 mm

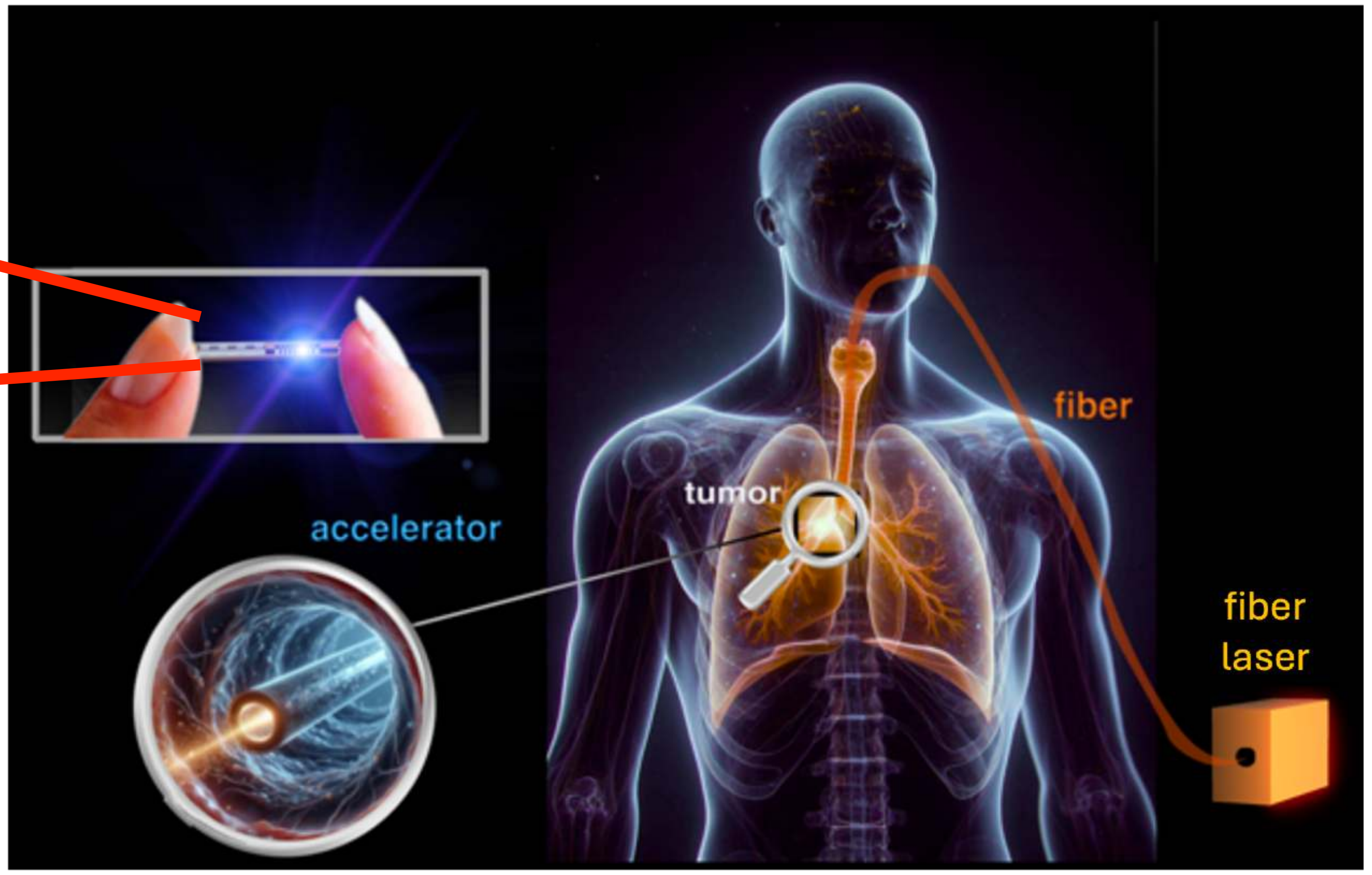


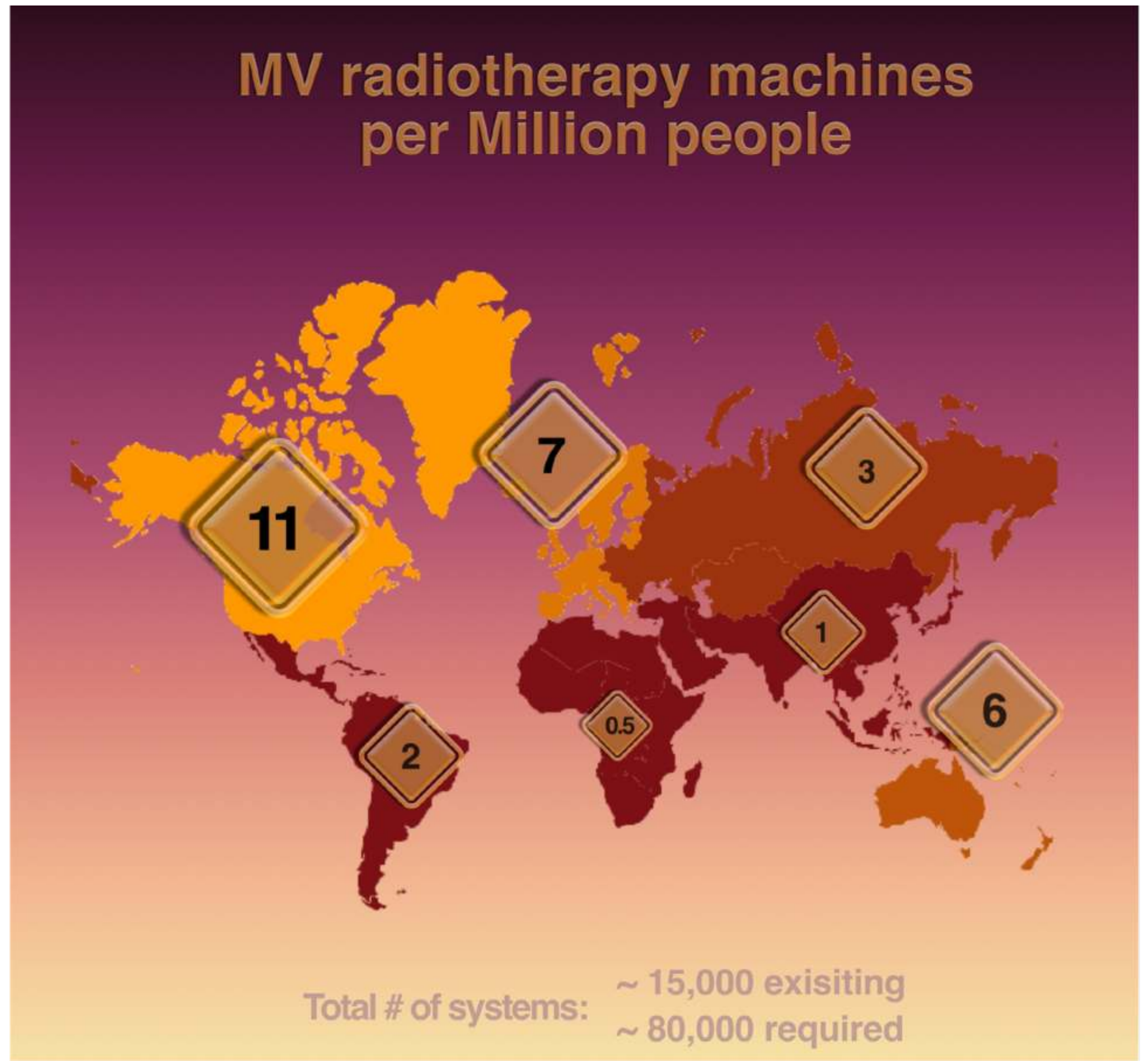
µm-scale Accelerator for Radiotherapy

- **Fundamentally new** parametrically-excited **laser-plasma acceleration** regime: **9 MeV in (!) 3 µm** (P. Zhang, …, MF under review Nature Communications)
- Substantially **relaxed laser requirements**: can be driven by fiber laser
- Intra-body radiotherapy: **major reduction of collateral damage** to healthy tissue
- **Low-cost, turn-key systems** to fill gap of several 10,000s currently missing accelerators for radiotherapy



Adobe stock





Data from https://dirac.iaea.org

Conclusions

- 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