PAUL SCHERRER INSTITUT

Rasmus Ischebeck

ADVANCED ACCELERATOR CONCEPTS, AND POSSIBLE APPLICATIONS IN HEP


N
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
Image IBCAO
Image U.S. Geological Survey
Google Earth
eye alt 21202.21 km


CCD ampli 2

LASER-BASED ACCELERATORS

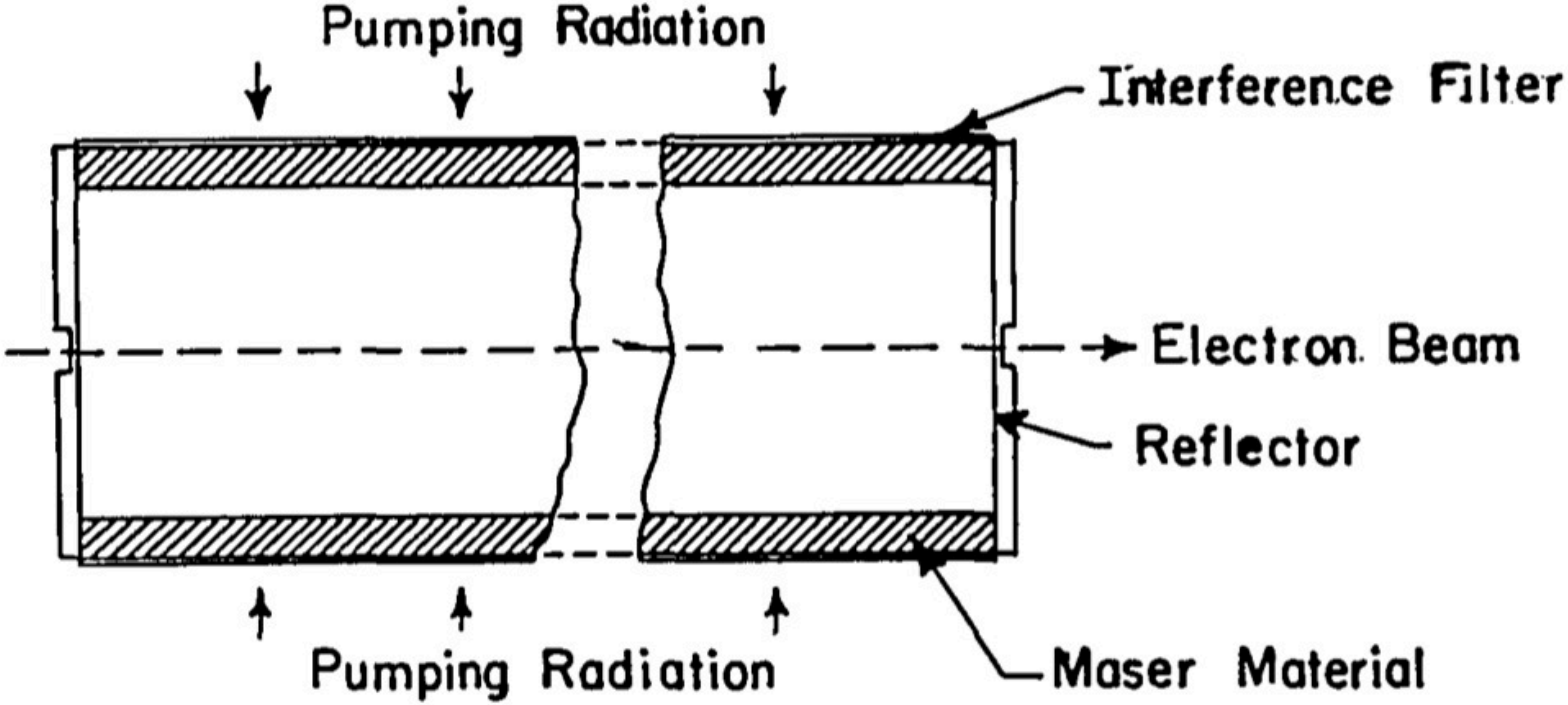


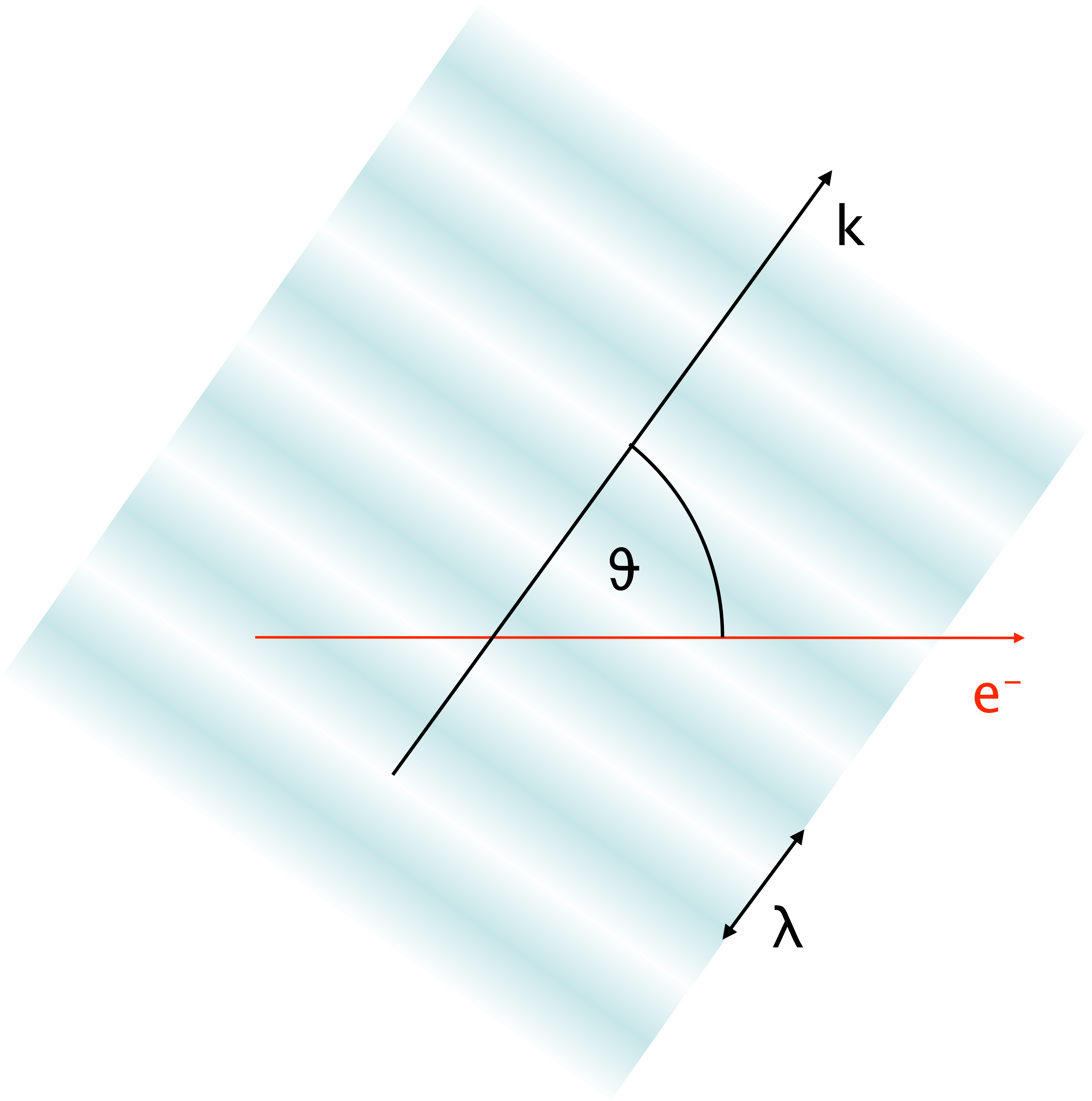
Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.

Shimoda, Appl. Opt. 1 (1), 33 (1961)

HOW TO ACCELERATE CHARGED PARTICLES

Assume:

- an ultrarelativistic particle of charge *e*
- moving along the *z* axis
- accelerated by a plane electromagnetic wave that propagates at an angle ϑ to the *z* axis



HOW TO ACCELERATE CHARGED PARTICLES

Then:

- Position of the electron:

$$\vec{r}(t) = \begin{pmatrix} 0 \\ 0 \\ ct \end{pmatrix}$$

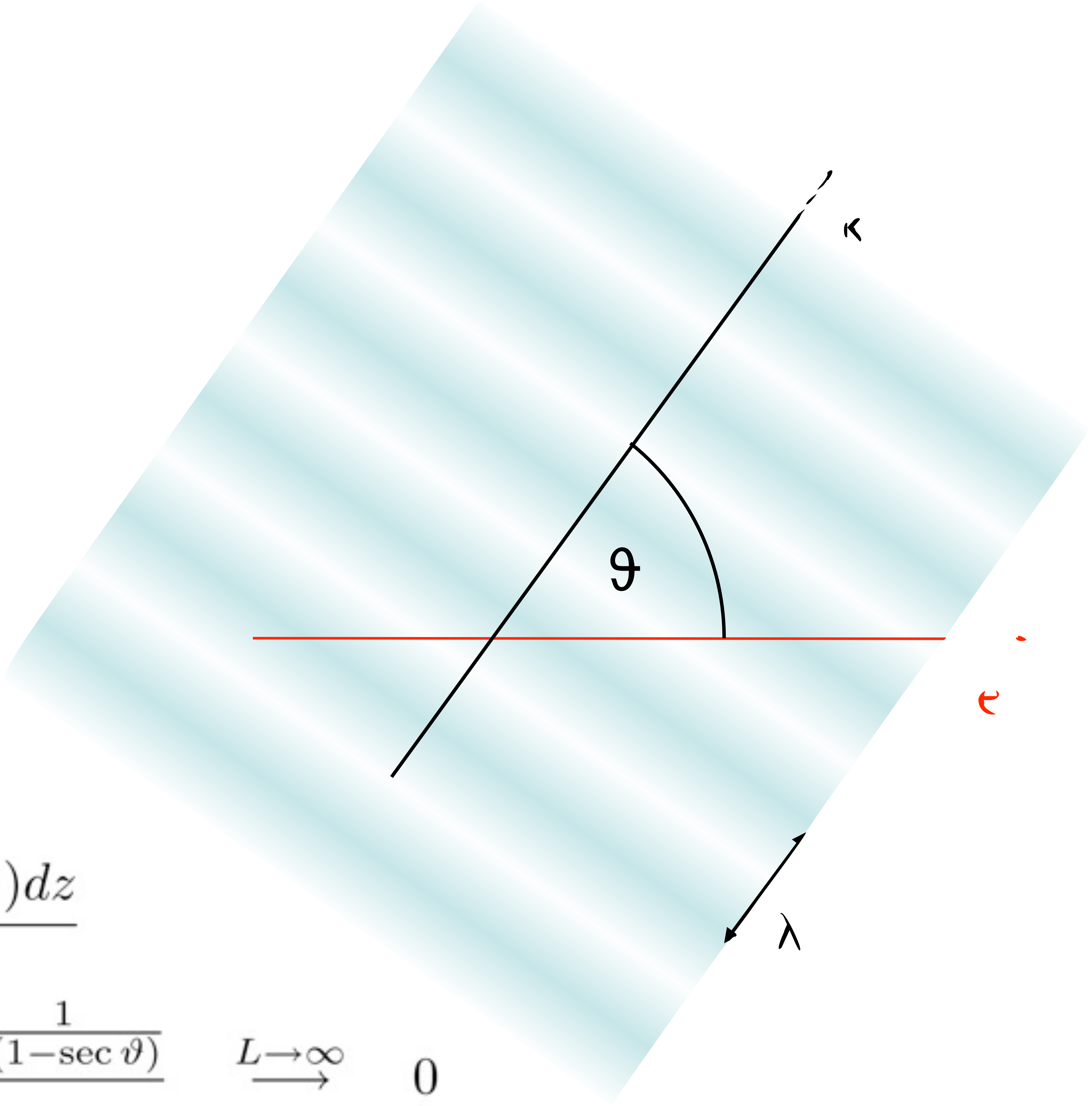
- Electric field

$$E_{\|} = \sin\vartheta \cos\left(\omega t - \frac{z}{2\pi\lambda\cos\vartheta}\right)$$

- Energy gradient:

$$\frac{\Delta W}{L} = \frac{\int_L eE_{\|}dz}{L} = \frac{\int_L \sin\vartheta\cos(kz(1-\sec\vartheta))dz}{L}$$

$$= \frac{\sin\vartheta\sin(kL(1-\sec\vartheta))\frac{1}{k(1-\sec\vartheta)}}{L} \xrightarrow{L\to\infty} 0$$

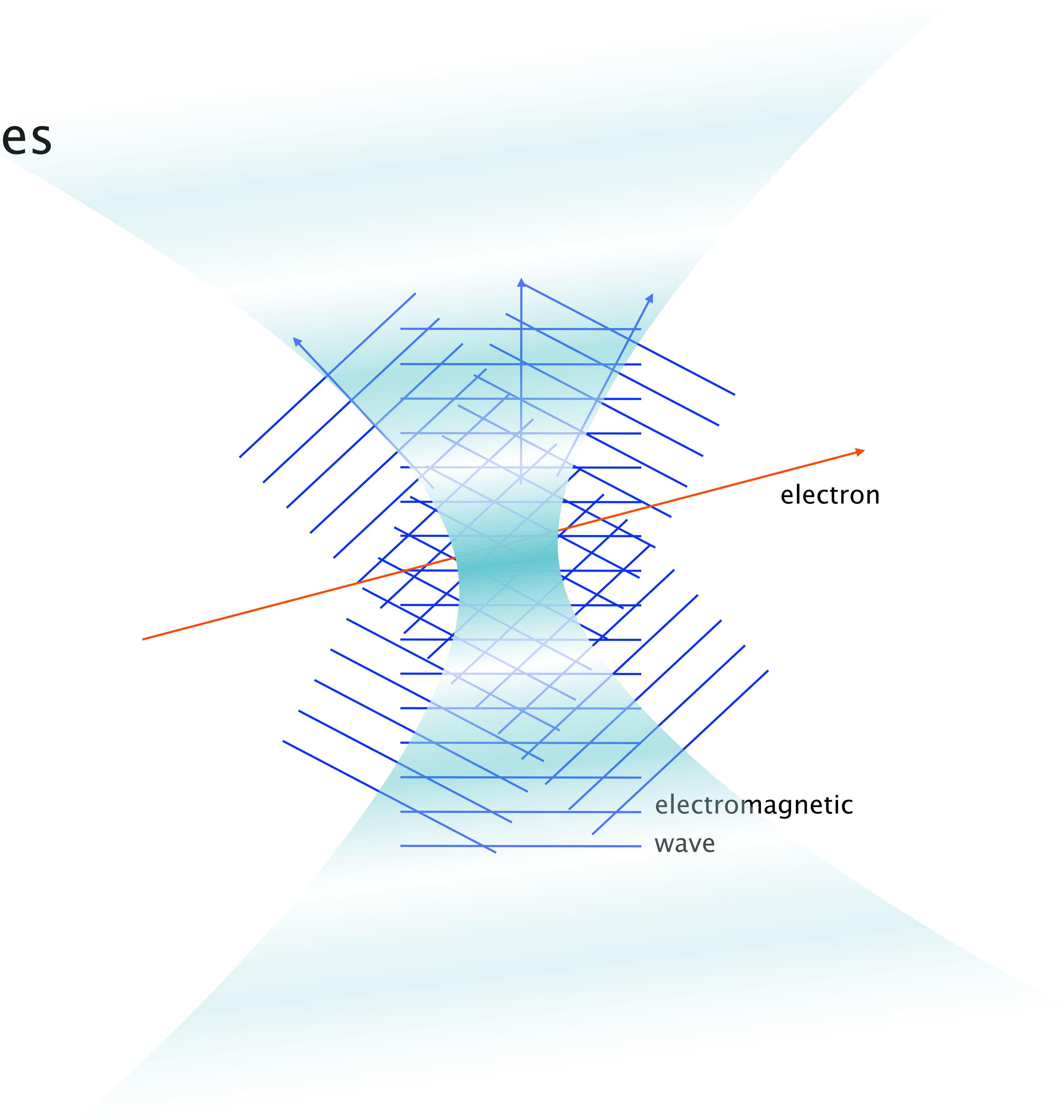


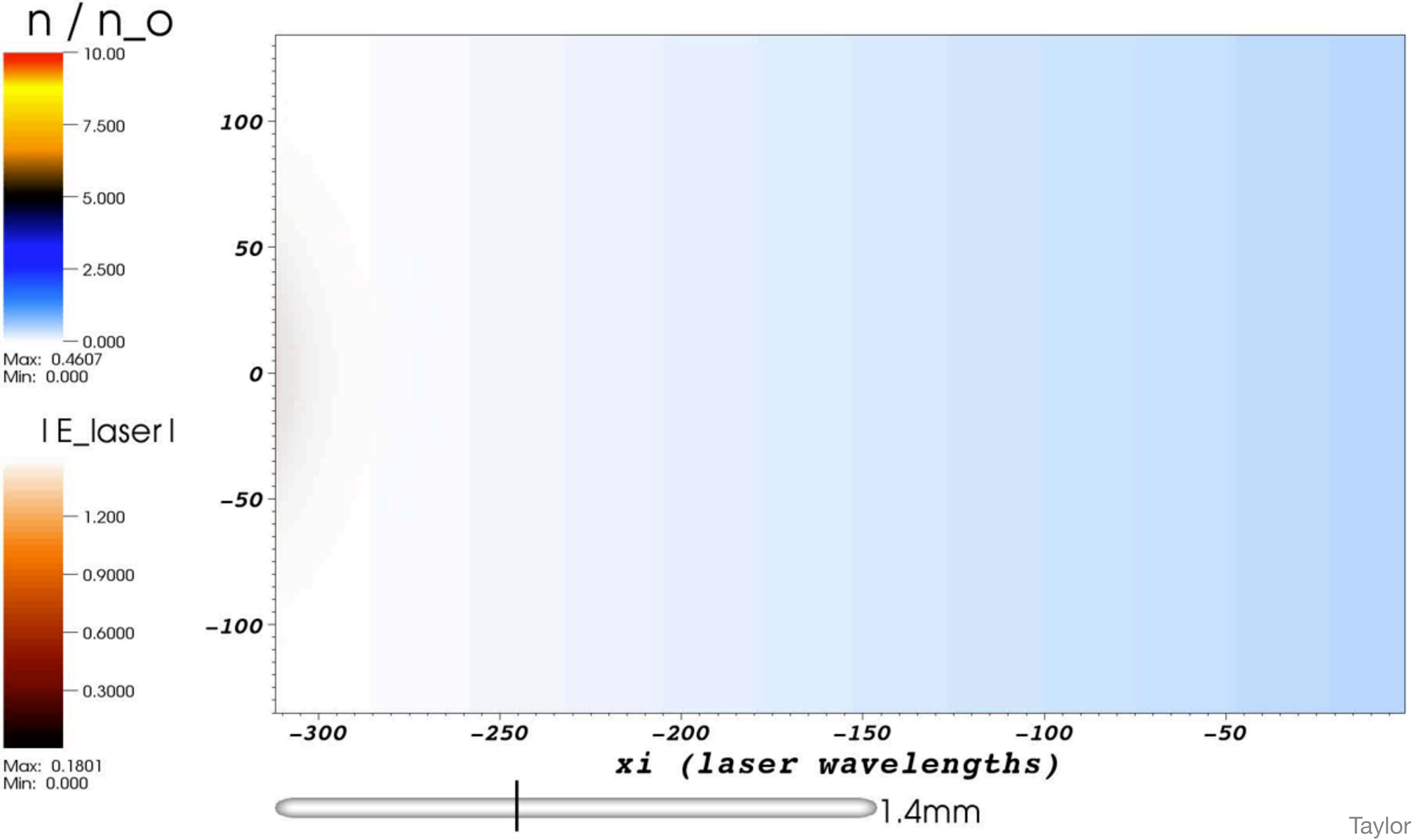
LAWSON WOODWARD THEOREM

- Every wave in far field can be written as a superposition of plane waves
- The Lawson-Woodward Theorem states:
  - the total acceleration
    - of ultrarelativistic particles
    - by far-field electromagnetic waves
  - is zero

⇒ Need near-field structures

Woodward, J. IEE 93 (1947)
Lawson, IEEE Trans. Nucl. Sci. 26 (1979)
Palmer, Part. Accel. 11 (1980)





Taylor Ratliff

PLASMA WAKEFIELD ACCELERATORS

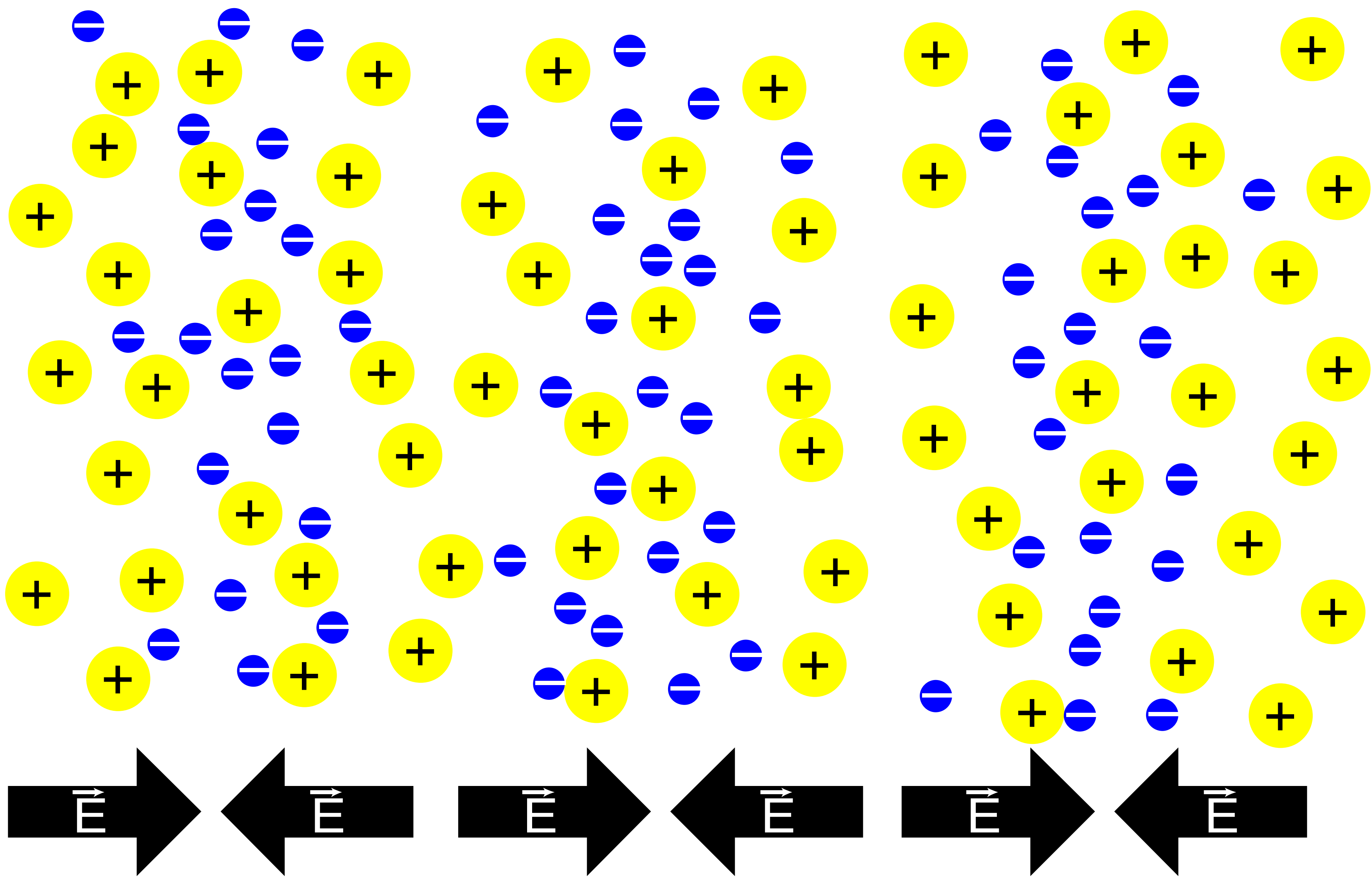
PLASMA WAKES - THEORY

- Unlike electromagnetic waves in vacuum, plasma wakes can have a longitudinal electric field
- Tajima & Dawson, PRL, 43, 267(1979)
- For a plasma with (initial) density n_0
- Linear plasma wake has a wavelength:

$$\lambda_p \approx \sqrt{10^{15}\frac{\mathrm{cm}^{-3}}{n_0}}\mathrm{mm}$$

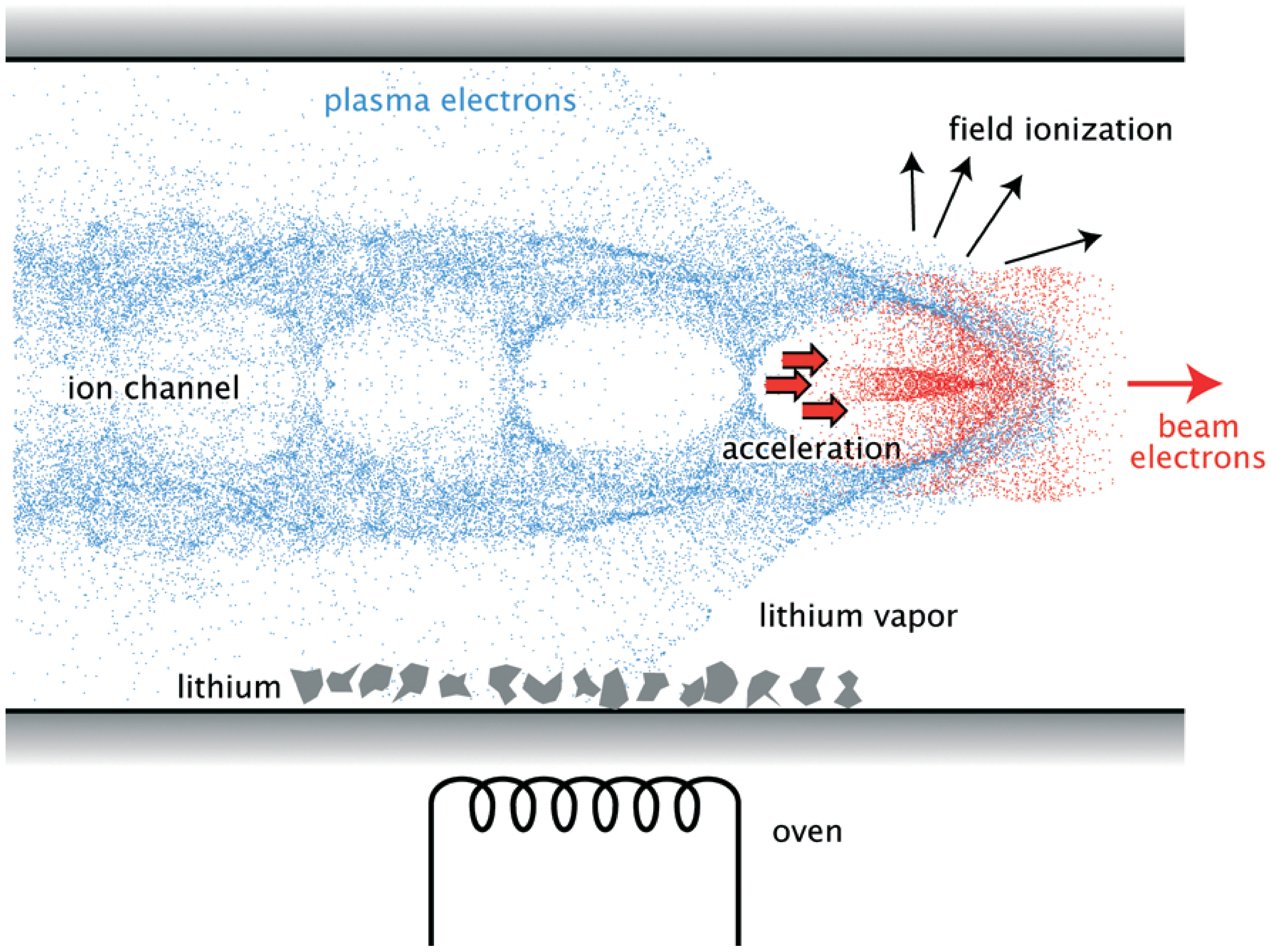
- Limit:

$$E_0 = \frac{4\pi\varepsilon_0\, c\, m_e}{e}\omega_p \approx \sqrt{\frac{n_0}{\mathrm{cm}^{-3}}}\frac{\mathrm{V}}{\mathrm{cm}}$$



PLASMA WAKES - THEORY

- Above this limit: non-linear wakes, “Blow-out regime”
- Fields can be calculated only with numerical methods



- Typical wavelength: 50 μm
- Accelerating fields ≫ GV/m

THE CHOICE OF THE DRIVER FOR PLASMA WAKEFIELDS

- The plasma wakefields can be excited by several means:
  - Short high power **laser pulses** → many places
  - Short **electron bunches** → SLAC, BNL, Frascati, DESY
  - Short (and long) **proton bunches** → CERN
- Each method has its advantages and disadvantages.
- All must be explored to propose optimal solution for a given project (can also be combination of different technologies).

DRIVE THE WAKE

- For laser wakefield accelerators wake driven by ponderomotive force

$$\frac{d\mathbf{p}}{dt} = -\frac{e^2}{2m_e\omega_0^2}\nabla\langle E^2\rangle = -\frac{e^2}{2m_e}\nabla\langle A^2\rangle = -\frac{1}{2}m_e c^2\nabla\langle a^2\rangle$$

- For particle beam drivers wake driven by space charge field of drive bunch

$$\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = -e\mathbf{E}$$

$$\left(\frac{\partial^2}{\partial t^2} + \omega_p^2\right)\frac{n_1}{n_0} = -\frac{c^2}{2}\frac{\partial^2 a_{\mathrm{laser}}^2}{\partial x^2} - \omega_p^2\frac{n_{\mathrm{beam}}}{n_0}$$

Where:

n_0 is the initial plasma density

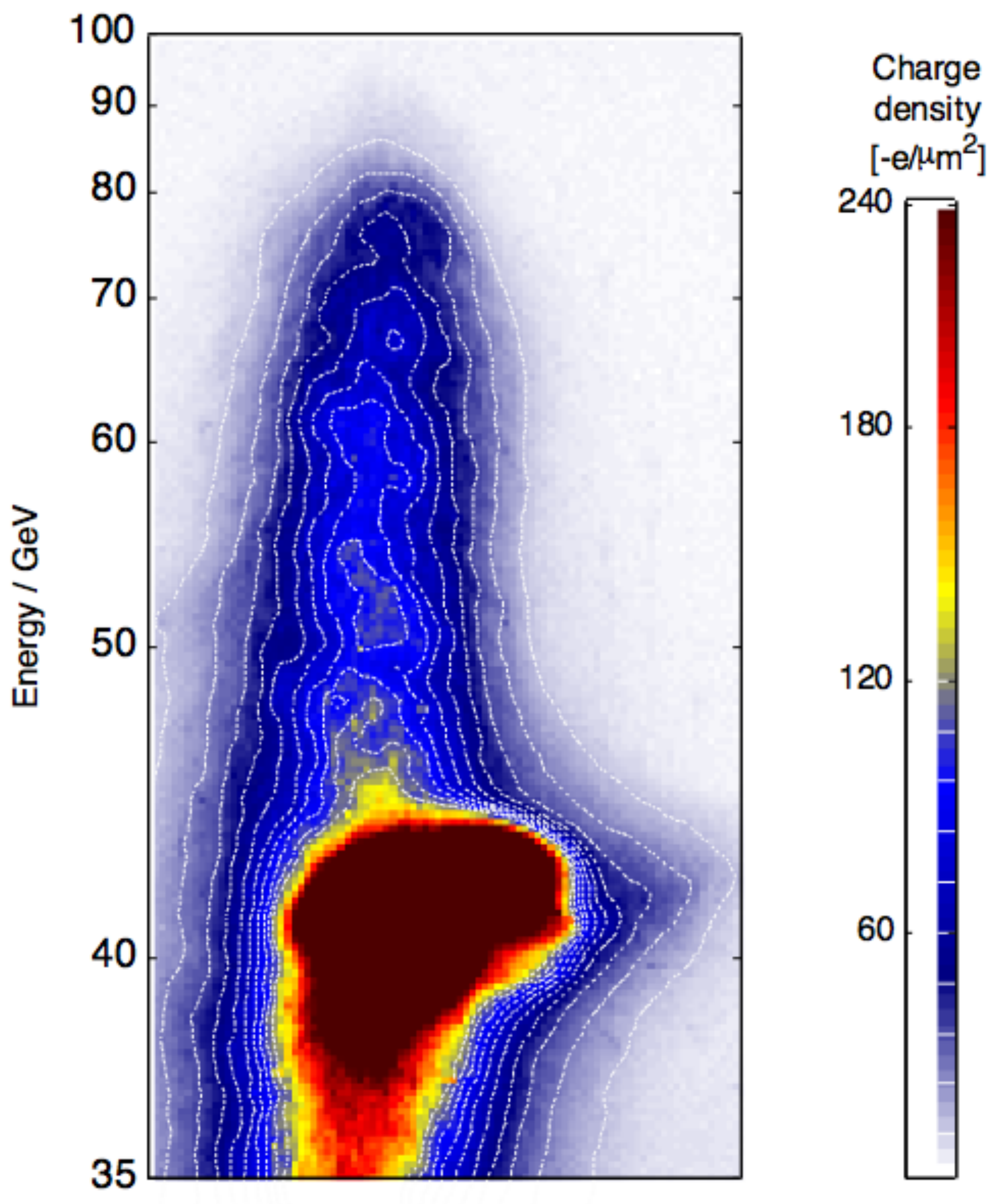
n_1 is the density of plasma electrons in the wake

n_{beam} is the density of the drive beam

EXPERIMENTAL RESULTS

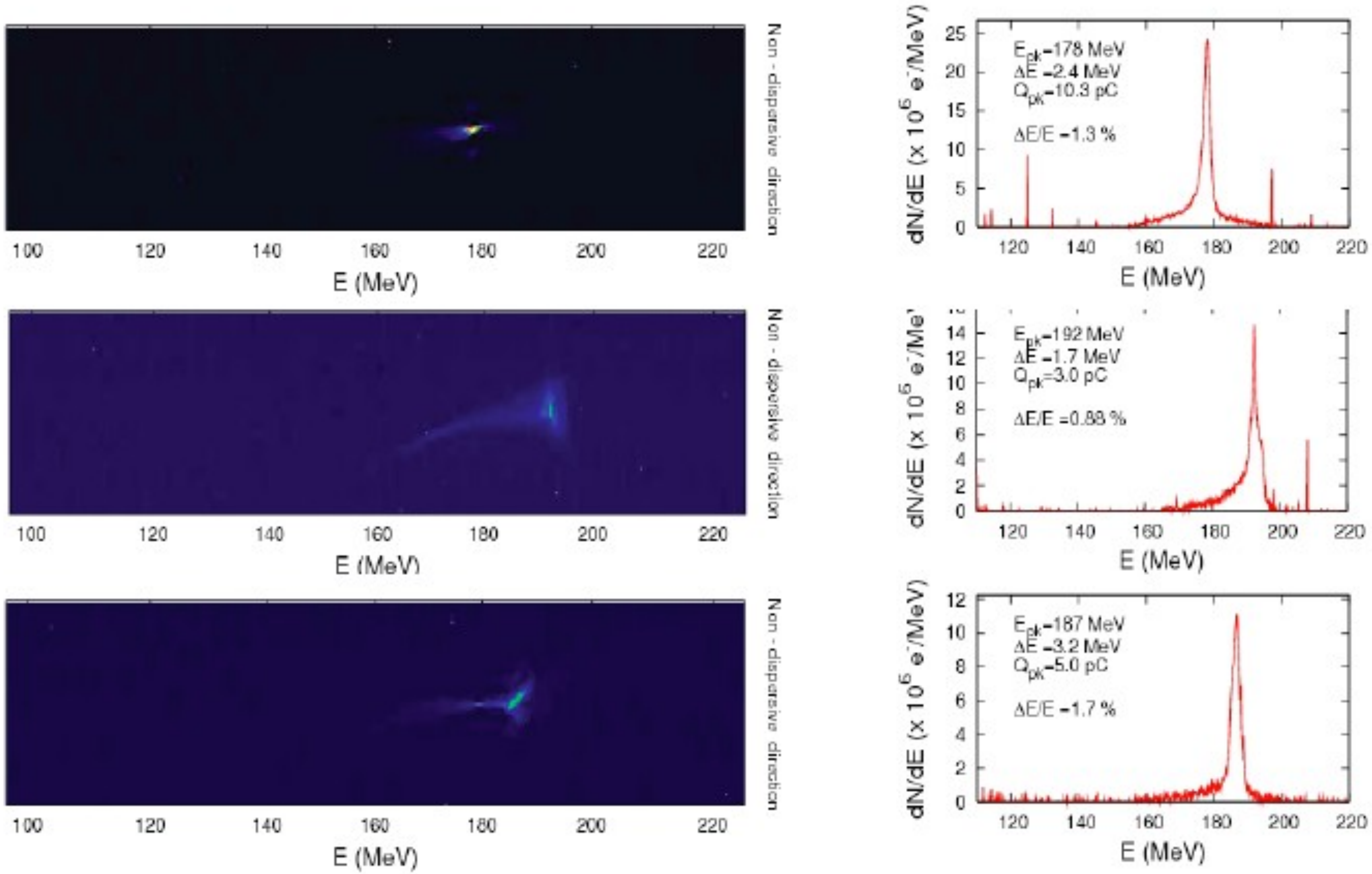
ENERGY DOUBLING

- Plasma length: 85 cm
- Density: $2.7 \cdot 10^{23}\ \mathrm{m}^{-3}$
- Incoming energy: 42 GeV
- Peak energy: 85±7 GeV



Blumenfeld et al., Nature **445**, 741–744 (2007)

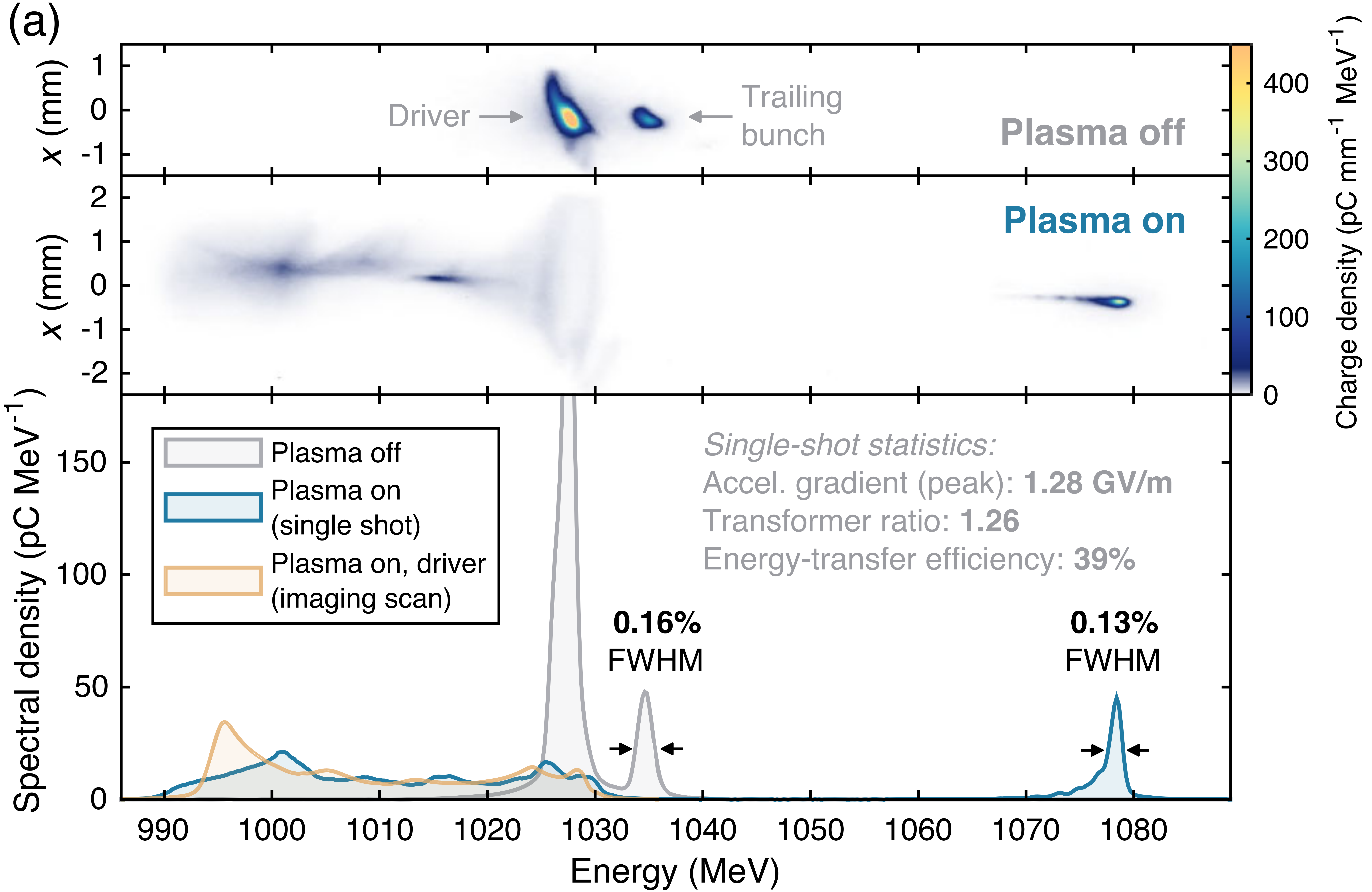
1% RELATIVE ENERGY SPREAD



C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 194804 (2009)

V. Malka

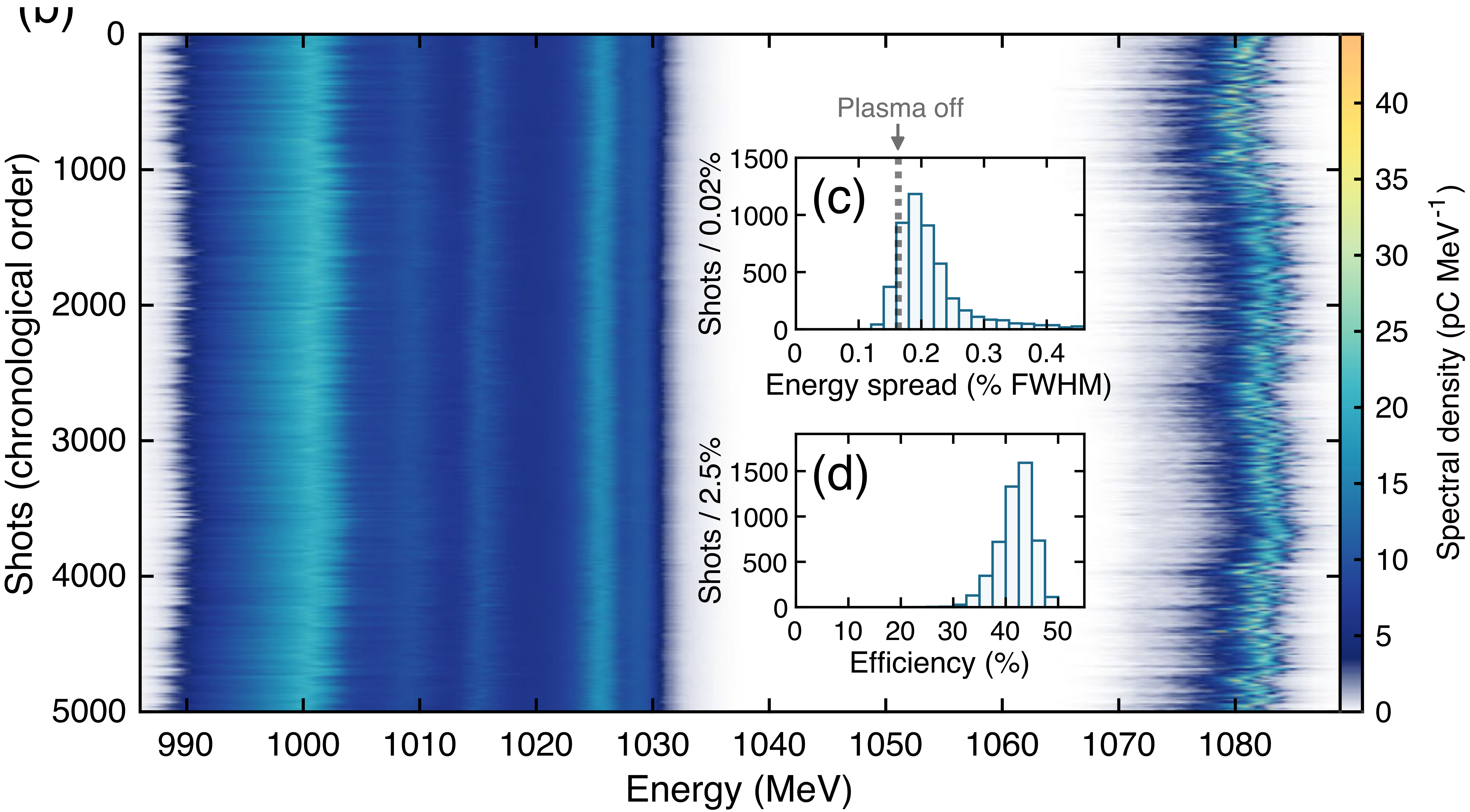
LOW ENERGY SPREAD IN BEAM-DRIVEN PLASMA WAKES



Single-shot statistics:
Accel. gradient (peak): **1.28 GV/m**
Transformer ratio: **1.26**
Energy-transfer efficiency: **39%**

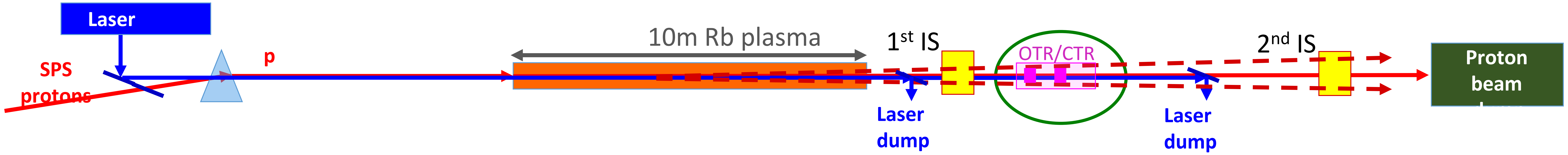
Lindstrøm et al., PRL 126, 014801 (2021)

STABLE OPERATION

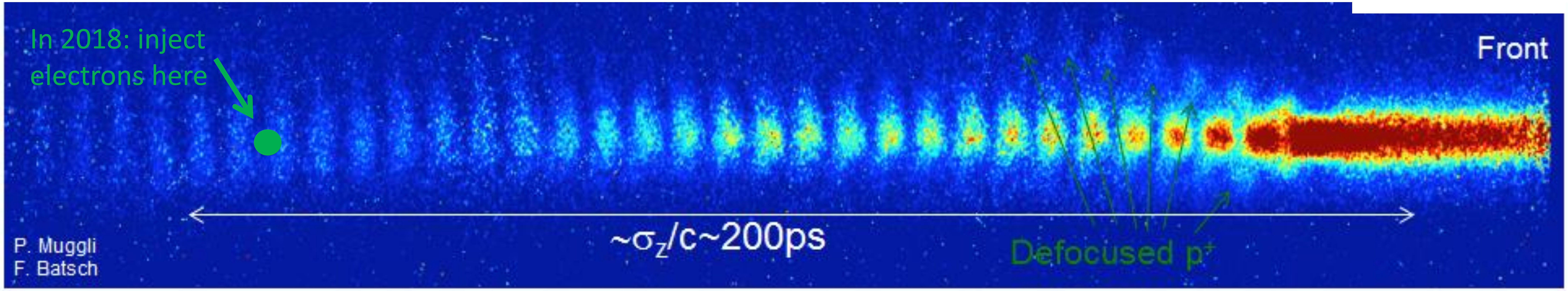


Lindstrøm et al., PRL 126, 014801 (2021)

SELF-MODULATION OF THE PROTON BEAM



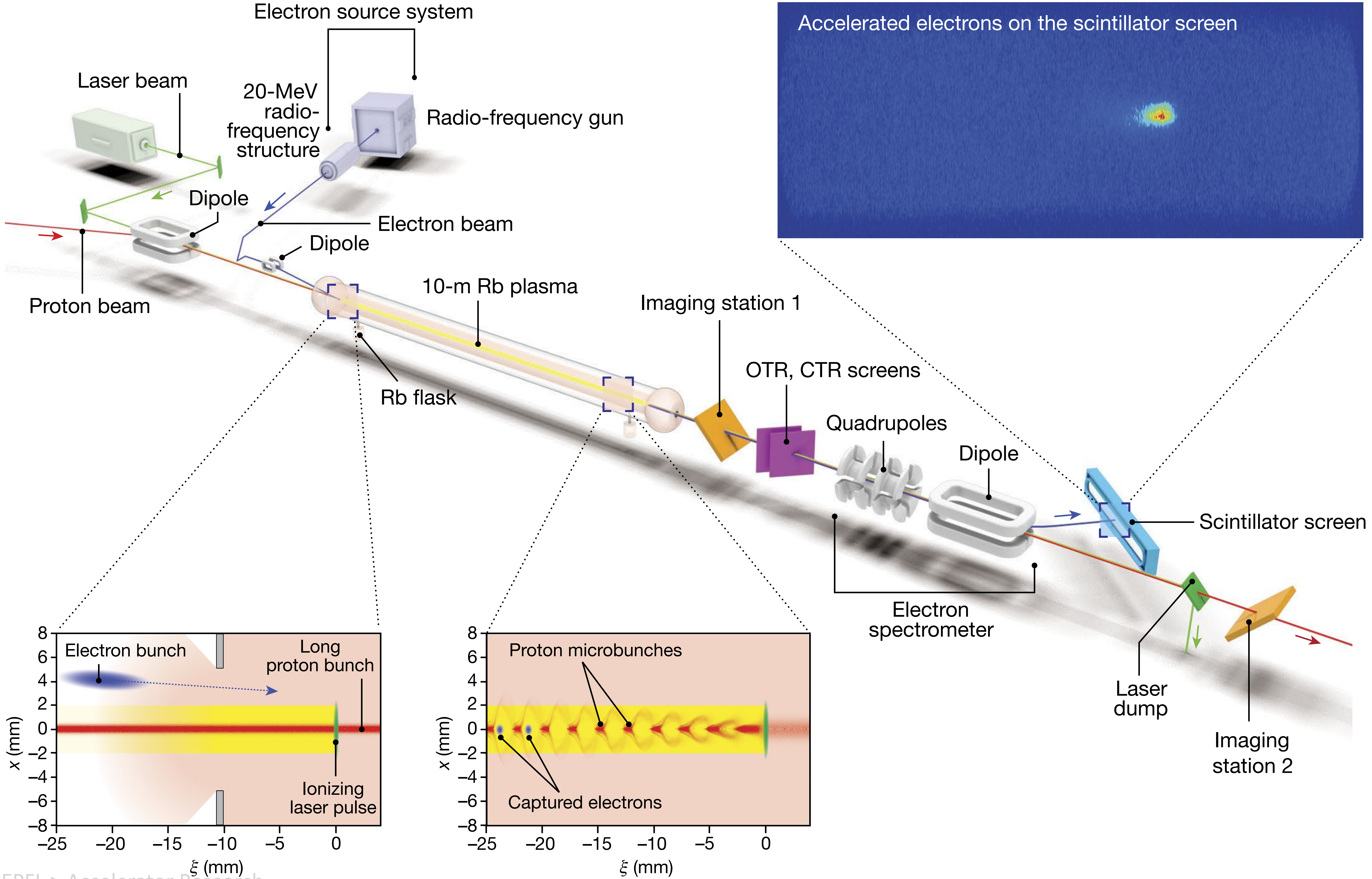
$n_{Rb}=2.1\times10^{14}cm^{-3}$



First milestone reached!

- **Self-modulated proton bunches** present over long time scale from seed point
- **Reproducibility** of the **self-modulated proton bunches** process against bunch parameters variation
- **Phase stability** essential for e^- external injection

ELECTRON ACCELERATION

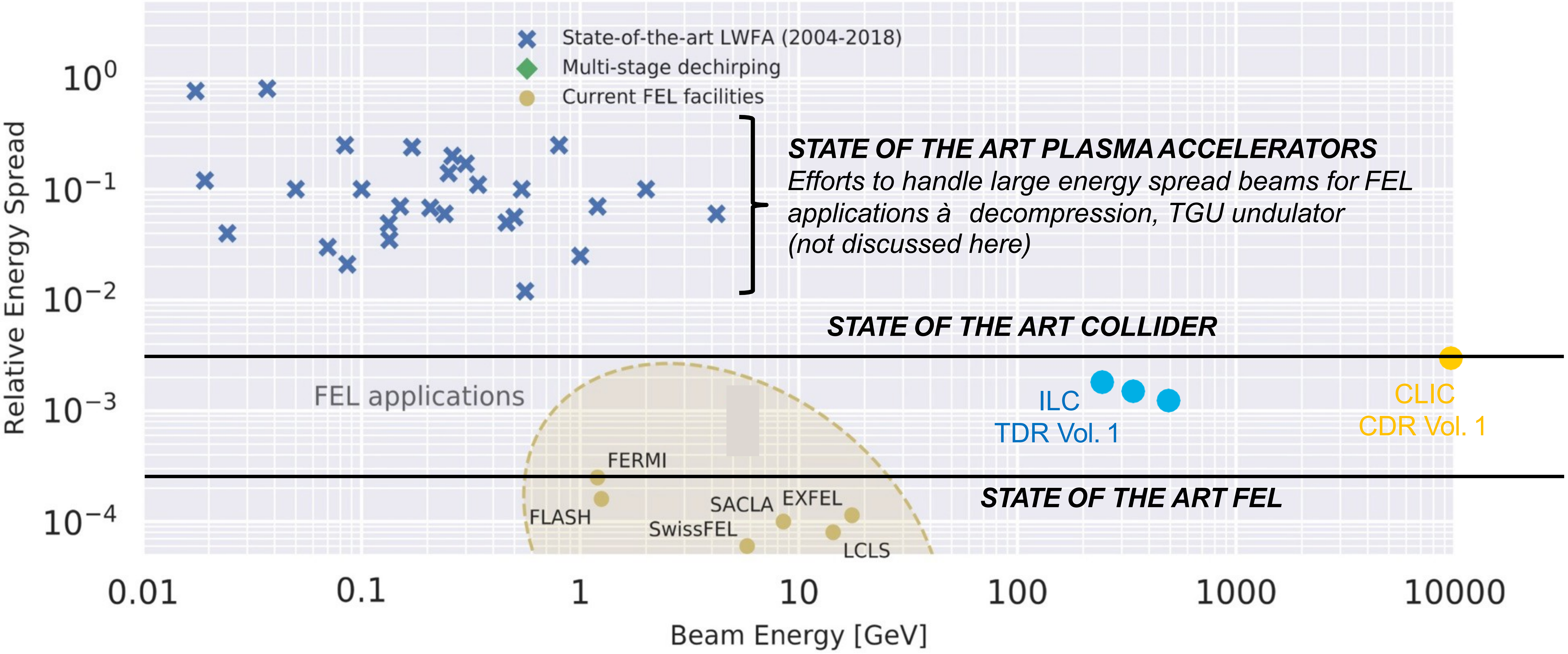


Adli et al., Nature 561, 363 (2018).

ENERGY SPREAD CHALLENGE

STATE OF THE ART IN PLASMA ACCELERATORS VERSUS REQUIREMENTS

Plot version A. Walker et al

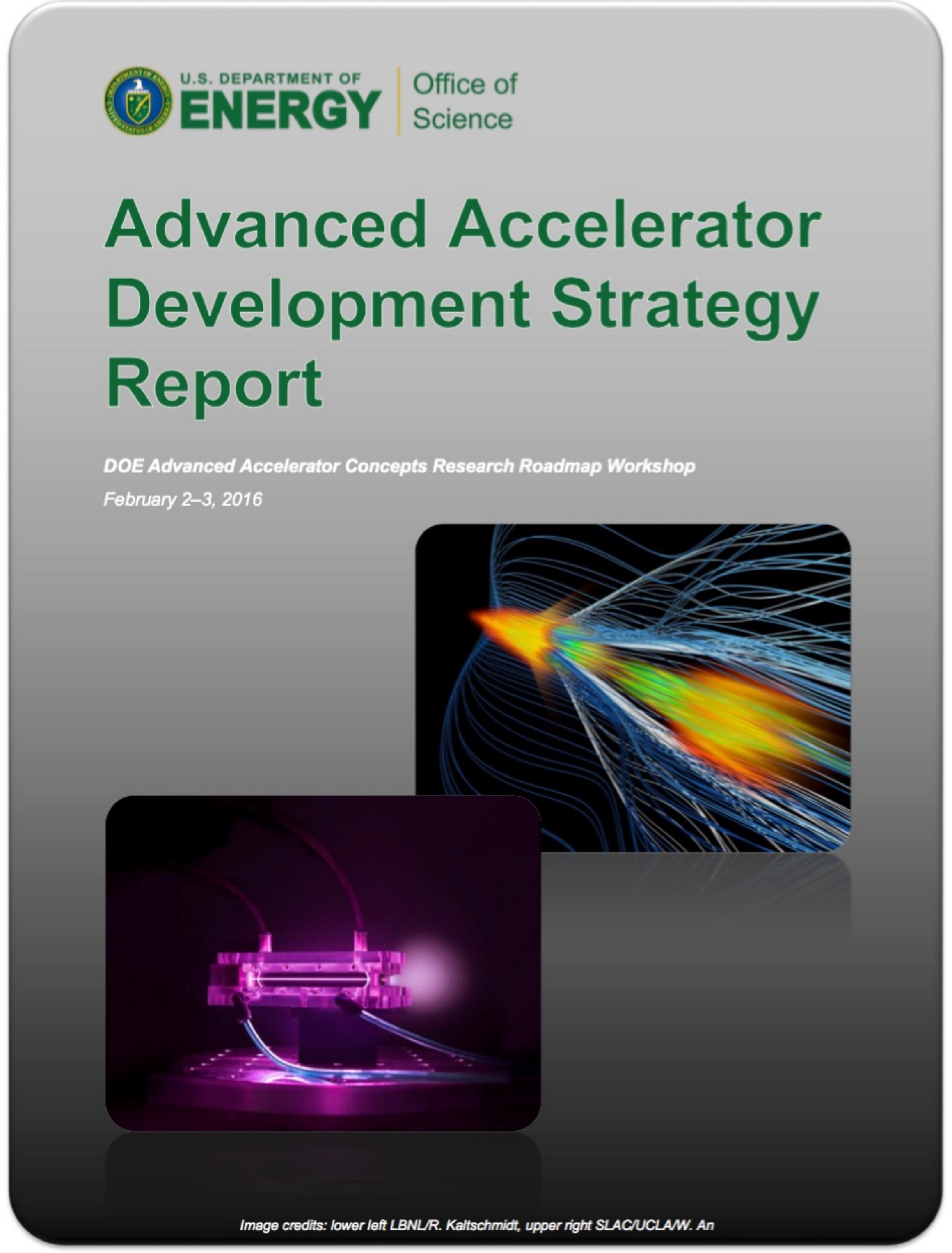


STATE OF THE ART PLASMA ACCELERATORS
Efforts to handle large energy spread beams for FEL applications à decompression, TGU undulator (not discussed here)

STATE OF THE ART COLLIDER

STATE OF THE ART FEL

POSSIBLE APPLICATION IN HIGH ENERGY PHYSICS



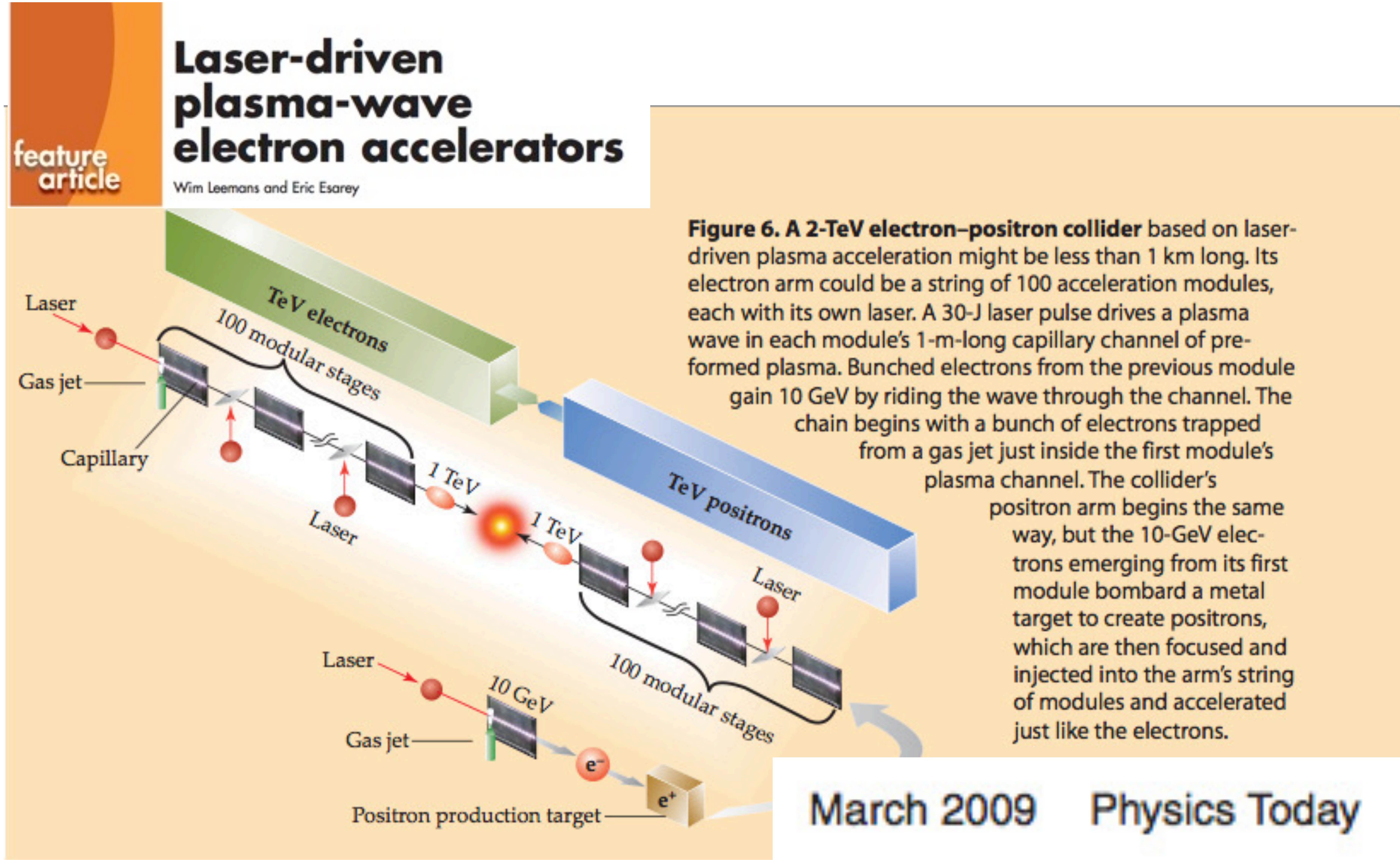
U.S. DEPARTMENT OF ENERGY | Office of Science

Advanced Accelerator Development Strategy Report

DOE Advanced Accelerator Concepts Research Roadmap Workshop

February 2–3, 2016

Image credits: lower left LBNL/R. Kaltschmidt, upper right SLAC/UCLA/W. An



feature article

Laser-driven plasma-wave electron accelerators

Wim Leemans and Eric Esarey

Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of preformed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

March 2009 Physics Today

Wim Leemans

OTHER APPLICATIONS

Proposal for a distributed research facility towards the realization of a FEL plasma based accelerator, organization, current status and outlook

Conceptual Design Report (Horizon2020 grant) finished in 2019 and published in December 2020.

Currently in the technical design phase.

Candidate to be included in the ESFRI 2021 Roadmap (outcome soon).

The European Physical Journal volume 229 · number 24 · December 2020

EPJ ST

Recognized by European Physical Society

Special Topics

EuPRAXIA Conceptual Design Report

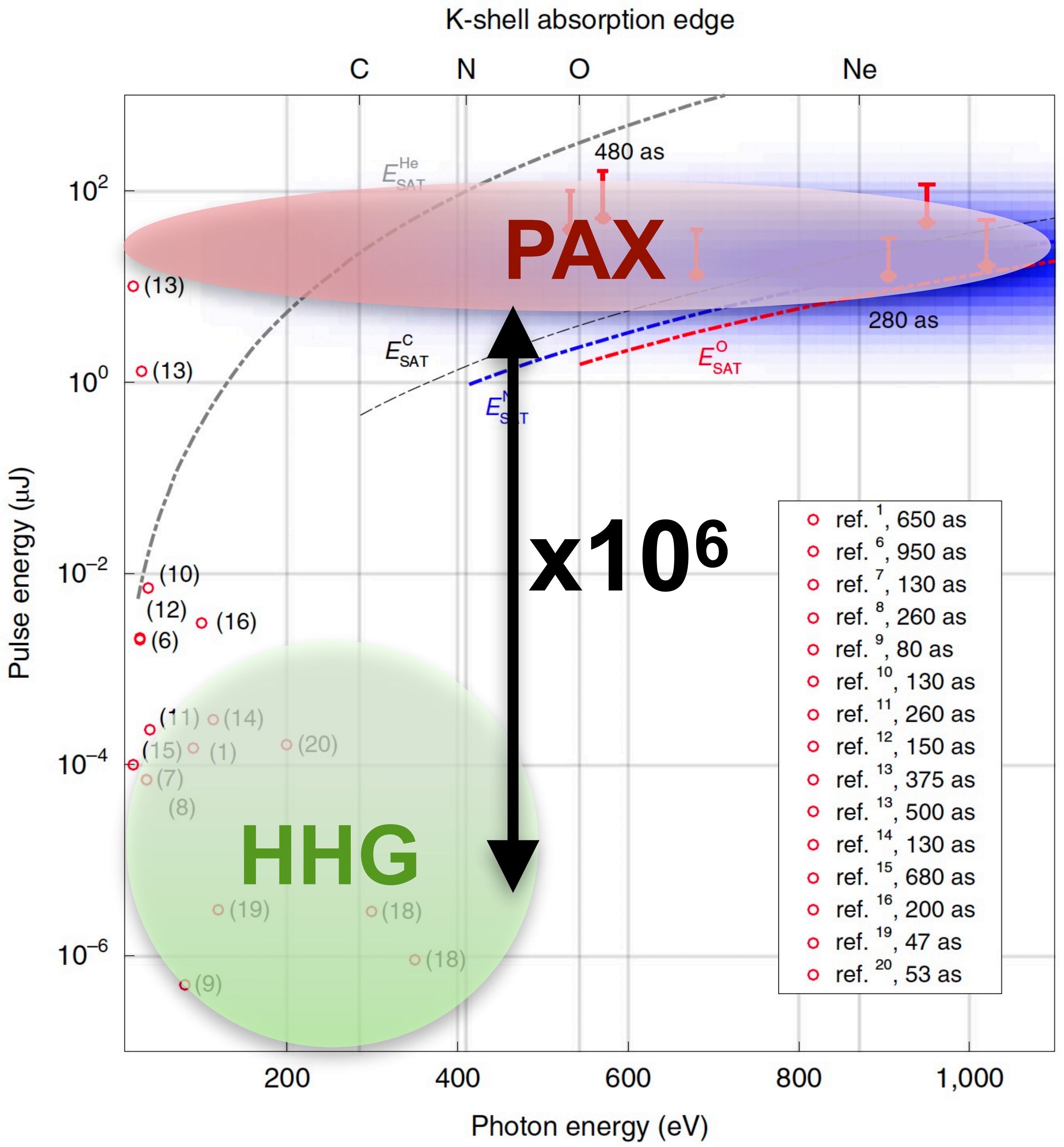
Ralph Assmann and Maria Weikum (Eds.)

edp sciences Springer

OTHER IDEAS

Attosecond photon beams in plasma-driven FELs

- X-ray pulses with 50-100as and μJ-energy desirable for studying e- motion in atoms on its natural timescale.
- HHG (XFEL) sources reach 40 (200) as length with pJ (uJ)-level energy.
- XFELs min pulse length limited to ~ 200as by emittance ($\Delta t_{min} \propto \epsilon^{5/6}$)
- A plasma-driven attosecond photon source can combine the benefits of HHG sources & XFELs based enabling new capabilities.



Plasma accelerators offers path to short, higher power photon pulses than state-of-the-art attosecond HHG/XFEL sources

- J. Duris *et al. Nat. Photonics* 14, 30–36 (2020)
- Z. Zhang *et al.* New J. Phys. 22 083030 (2020)

Attosecond e-beams for short bunch colliders

- Ultra-short bunches are being considered for next gen. e+/e- colliders due to reduced beamstrahlung
- Beamstrahlung effects can be “switched off” if the bunch length is made small enough (attosecond-level)

Parameter	NPQED Collider	LCLS	PAX
Beam Energy [GeV]	125	3-15	1-10
Bunch Charge [nC]	0.14 - 1.4	0.01-0.2	0.01 - 0.1
Peak Current [kA]	1700	1-5	10-700
Energy Spread [%]	0.1	0.01	1
RMS Bunch Length [μm]	0.01 - 0.1	1-100	0.003 - 0.1
RMS Spot Size [μm]	0.01	10	1-10

Attosecond e- beams allow the study of MA-compression relevant for short-bunch colliders

- V. Yakimenko et al. Prospect of Studying Nonperturbative QED with Beam-Beam Collisions, PRL. 122, 190404 (2019).
- G. White and V. Yakimenko, Ultra-Short-Z Linear Collider Parameters, Workshop on Future Linear Colliders (LCWS2018),
- HEP GARD Accelerator and Beam Physics: Community-driven strategic Roadmap Workshop, LBNL December 2019

3

SIMULATIONS

Requirements for LWFA TeV collider (full PIC)

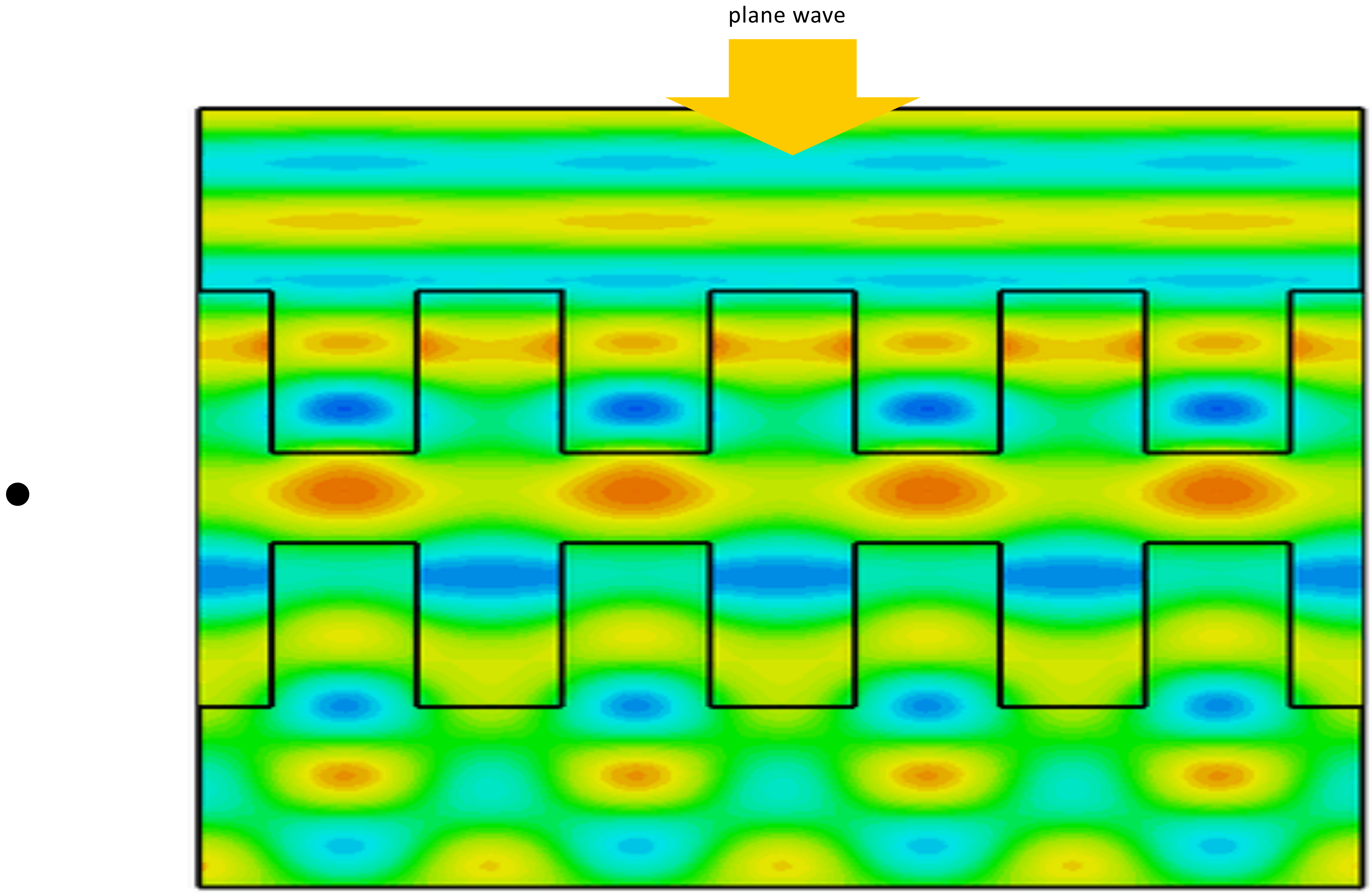
- 10^5-10^6 core-hours/GeV
- 10^8-10^9 core-hours/TeV
- ~0.01 €/core-hour
- >10^6-10^7 €/simulation

J.Vieira, S. Corde, P. Nghiem

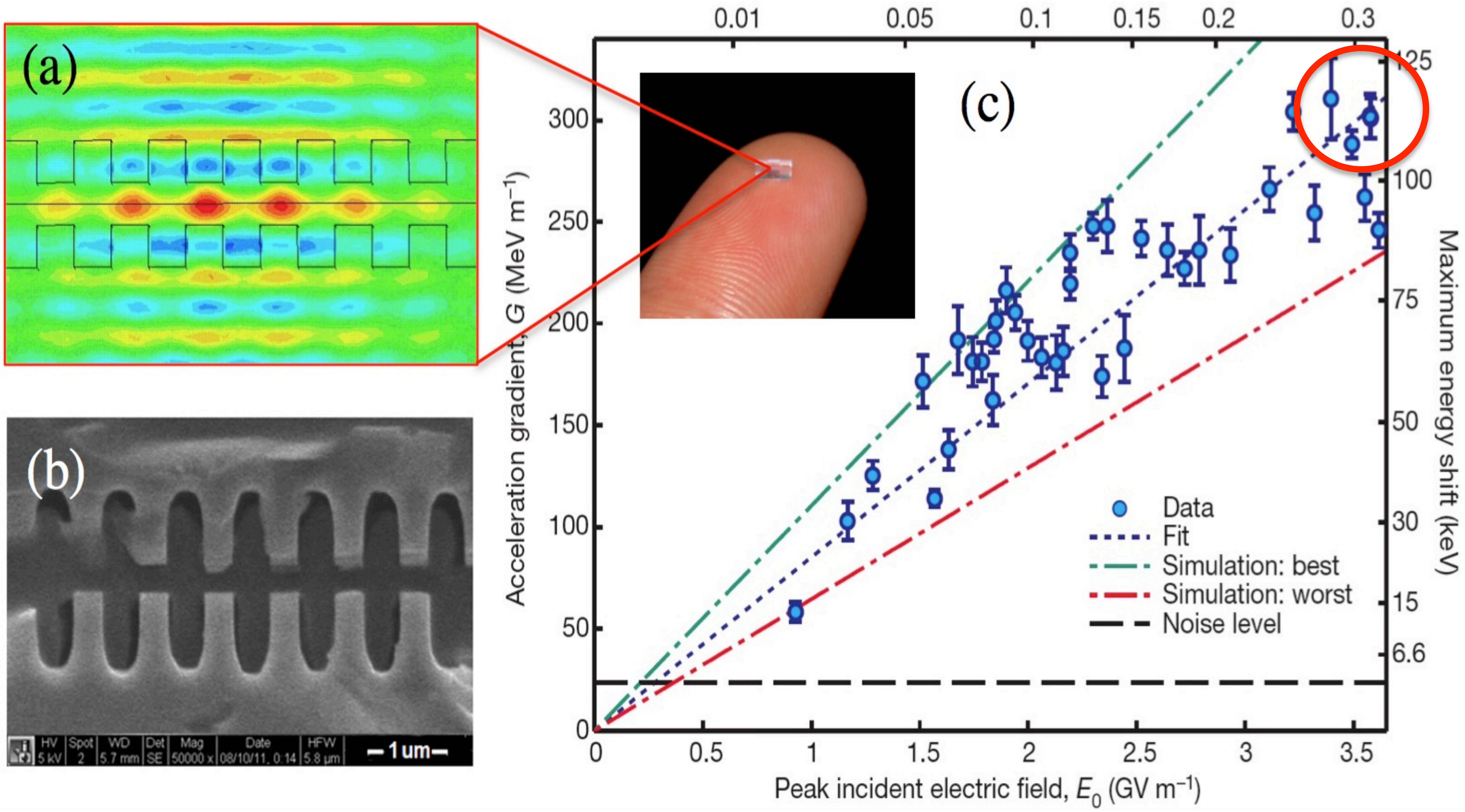
DIELECTRIC LASER ACCELERATORS

Neil Sapra et al., Science 367 (6473), 97-83

DOUBLE GRATING STRUTURE

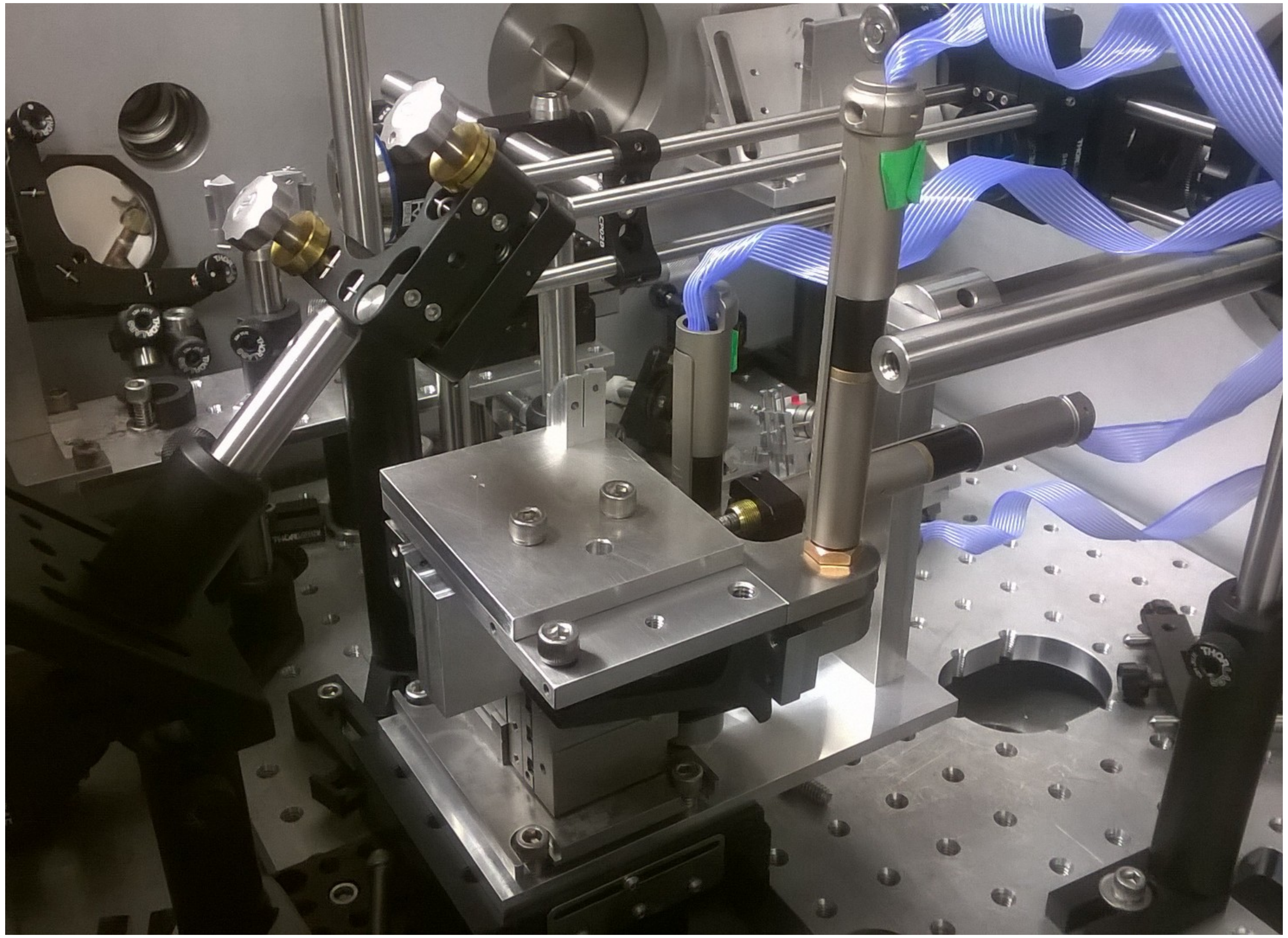


ACCELERATING STRUCTURES

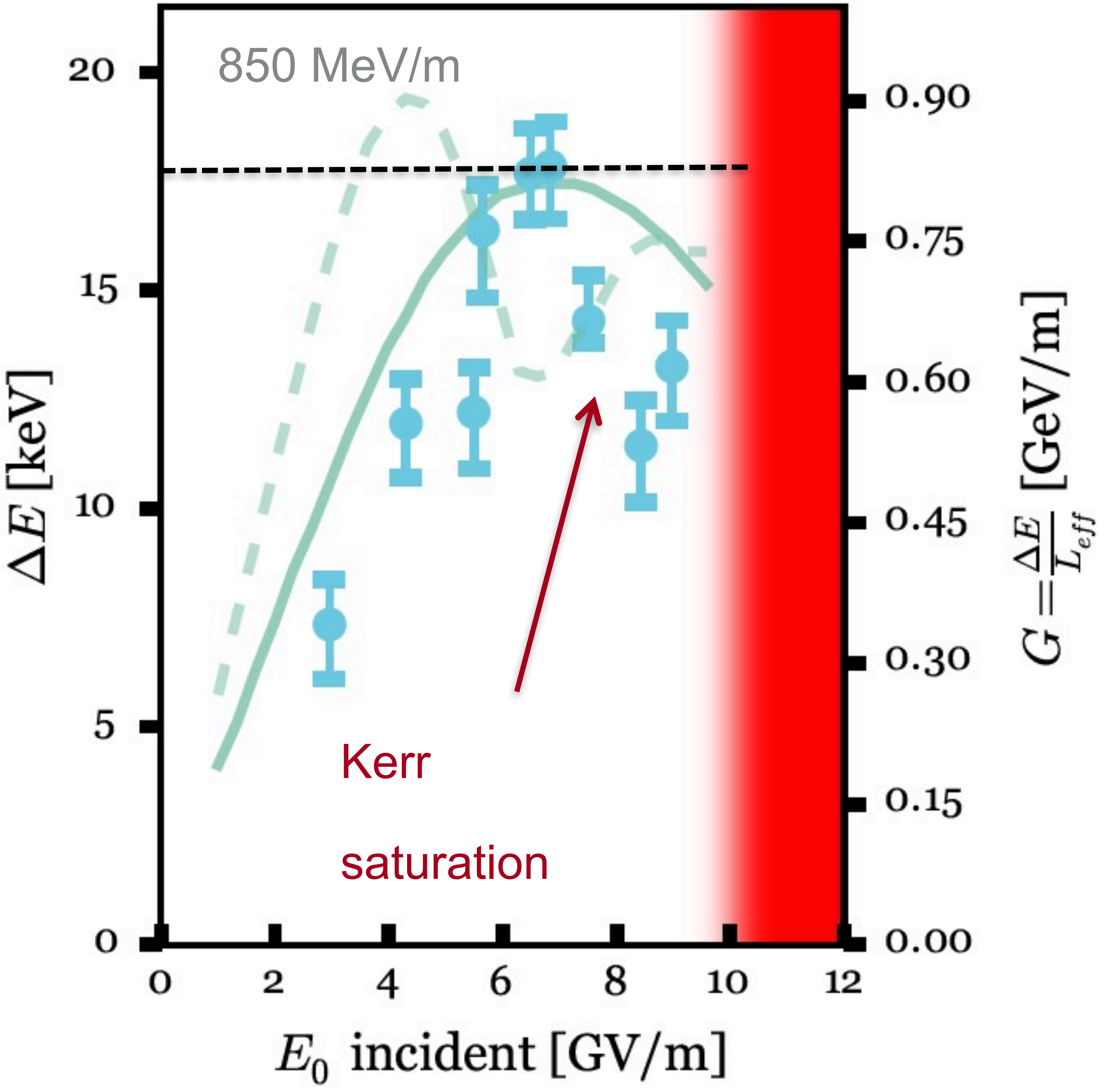


Peralta et al., Nature 503, 91 (2013)

ACCELERATING GRADIENT: 850 MeV/m

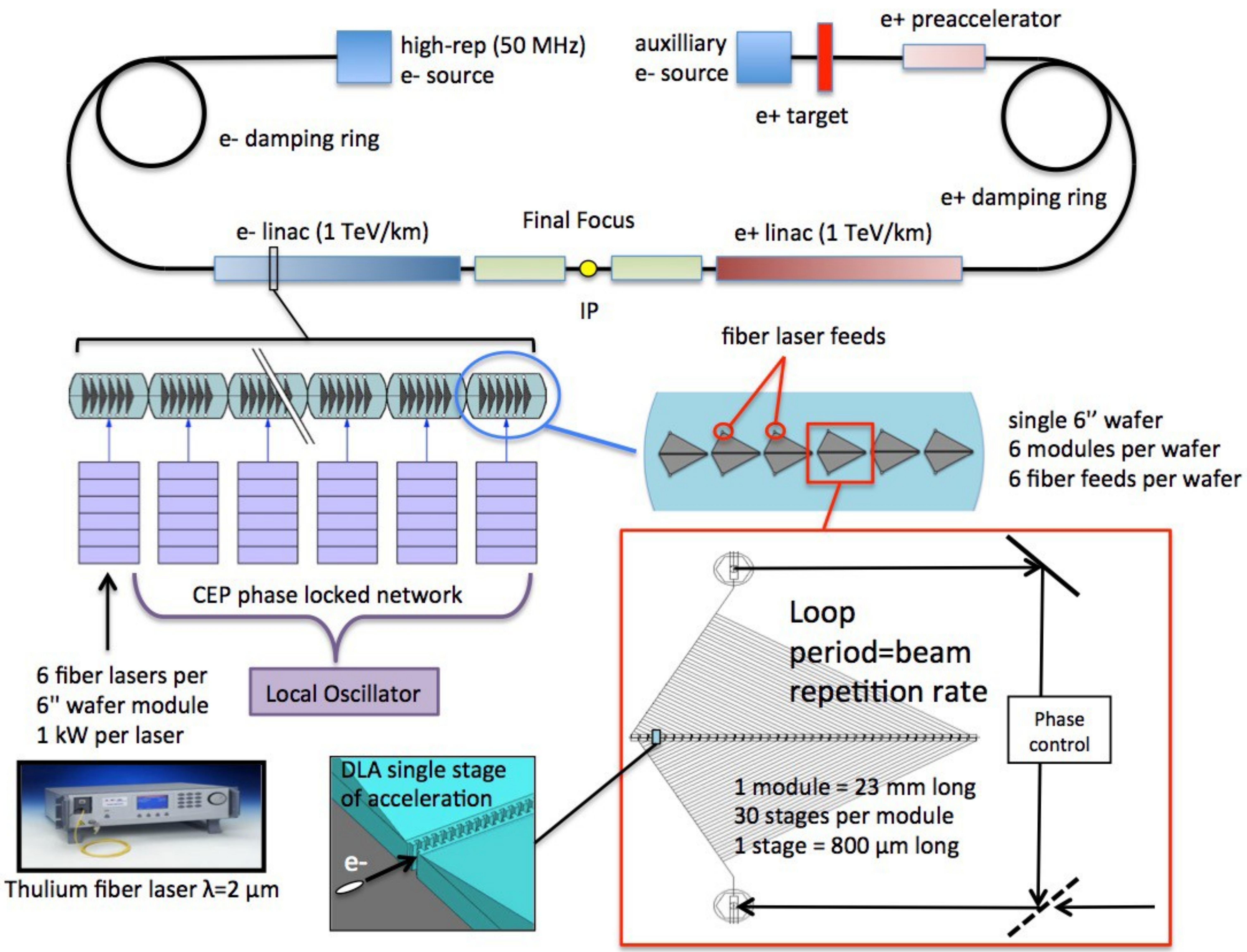


Energy gain vs. incident laser field



Cesar et al., Communications Physics 1(1), 46 (2018)

DLA-BASED COLLIDER CONCEPT — ALEGRO / ANAR

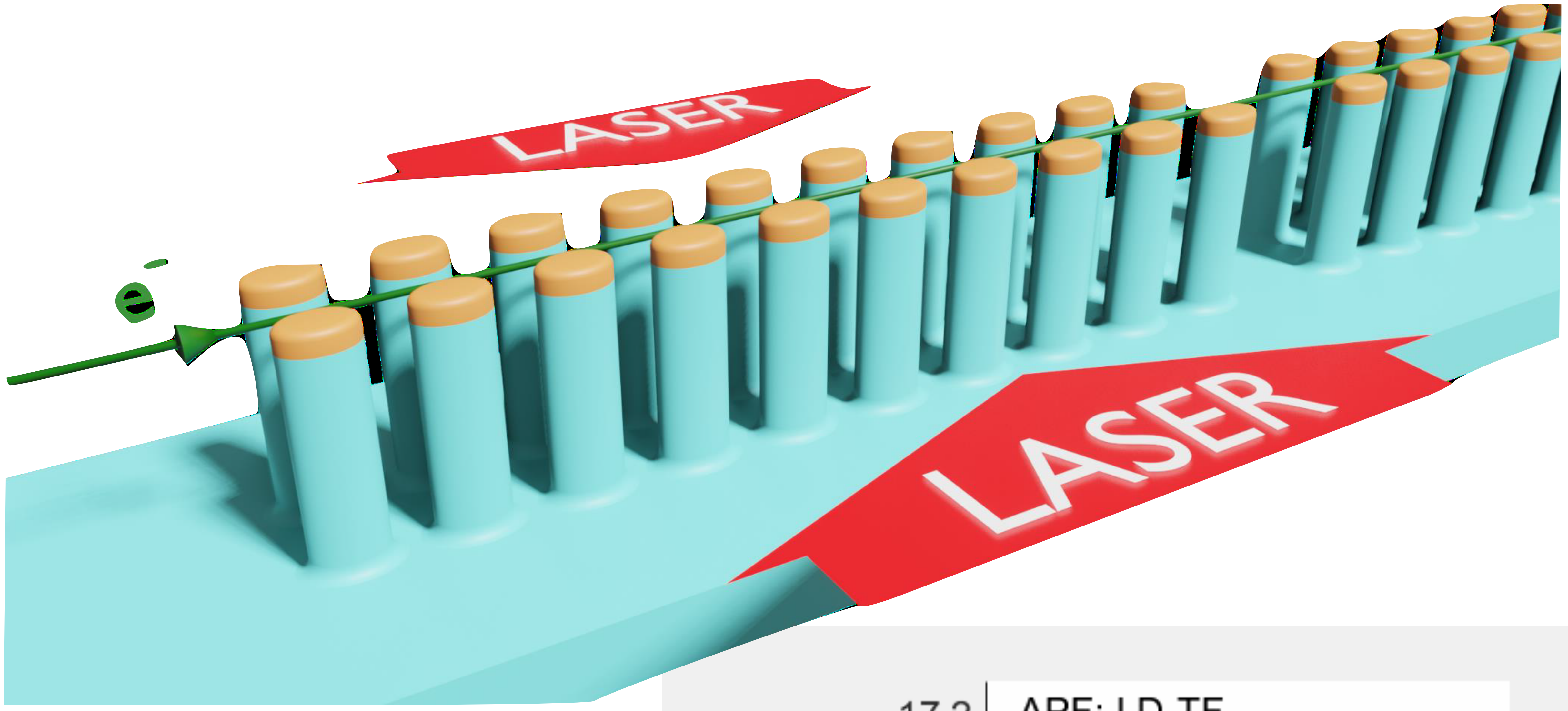


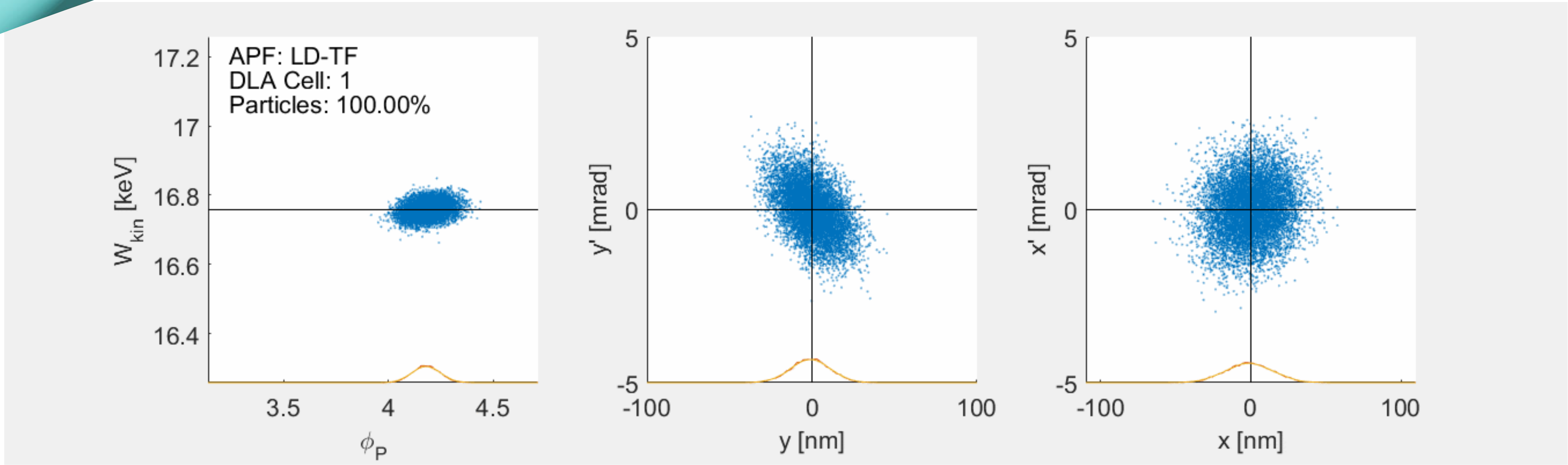
BEAM PARAMETERS

Parameter	**Units**	**CLIC**	**DLA 3TeV**
Center-of-Mass Energy	GeV	3000	3000
Bunch Charge	e	3.7E+09	38000
Bunches per Train		312	159
Train Repetition Rate	MHz	5.0E-5	30
Bunch Train Length	ps	26005	1.0
Single Bunch Length	μm	34.7	0.0026
Design Wavelength	μm	230609	2.0
Invariant X Emittance	μm	0.66	0.0001
Invariant Y Emittance	μm	0.02	0.0001
IP X Spot Size	nm	45	1
IP Y Spot Size	nm	1	1
Beamstrahlung Energy Loss	%	36.2	1.1
Enhanced Luminosity / top 1%	**cm^{-2}/s**	**8.6E+34**	**8.1E+34**
Beam Power	MW	13.9	43.6
Wall-Plug Efficiency	%	7.0	15.1
Wall-Plug Power	MW	200	289
Gradient	MV/m	100	400
Total Linac Length	km	42.0	7.5

Joel England, Robert J. Noble, Ziran Wu, Minghao Qi: Rev. Mod. Phys. **86**, 1337 (2014)

LASER-BASED FOCUSING

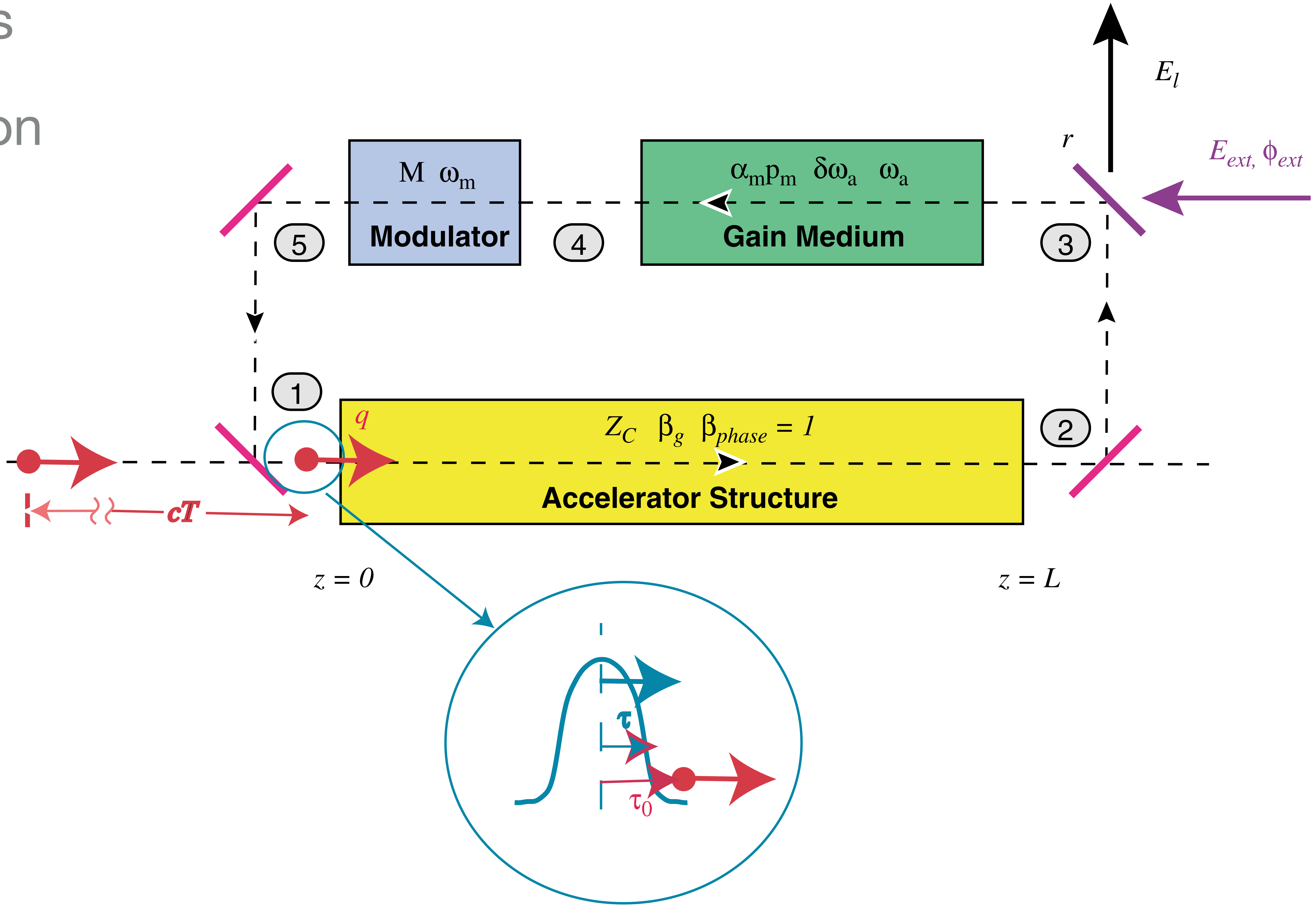




Niedermayer et al., Phys. Rev. Lett. 125, 164801 (2020)

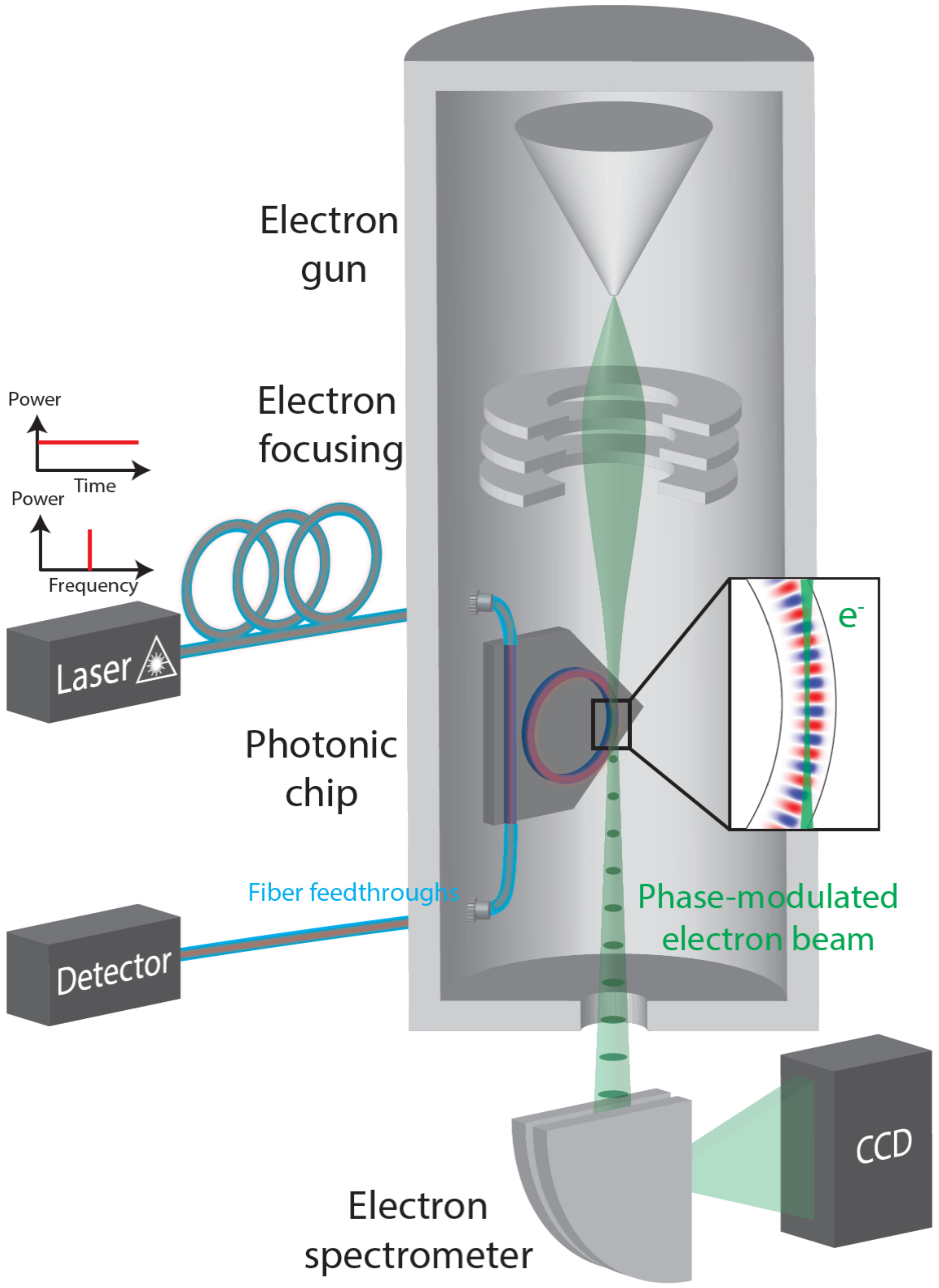
EFFICIENCY OPTIMIZATION

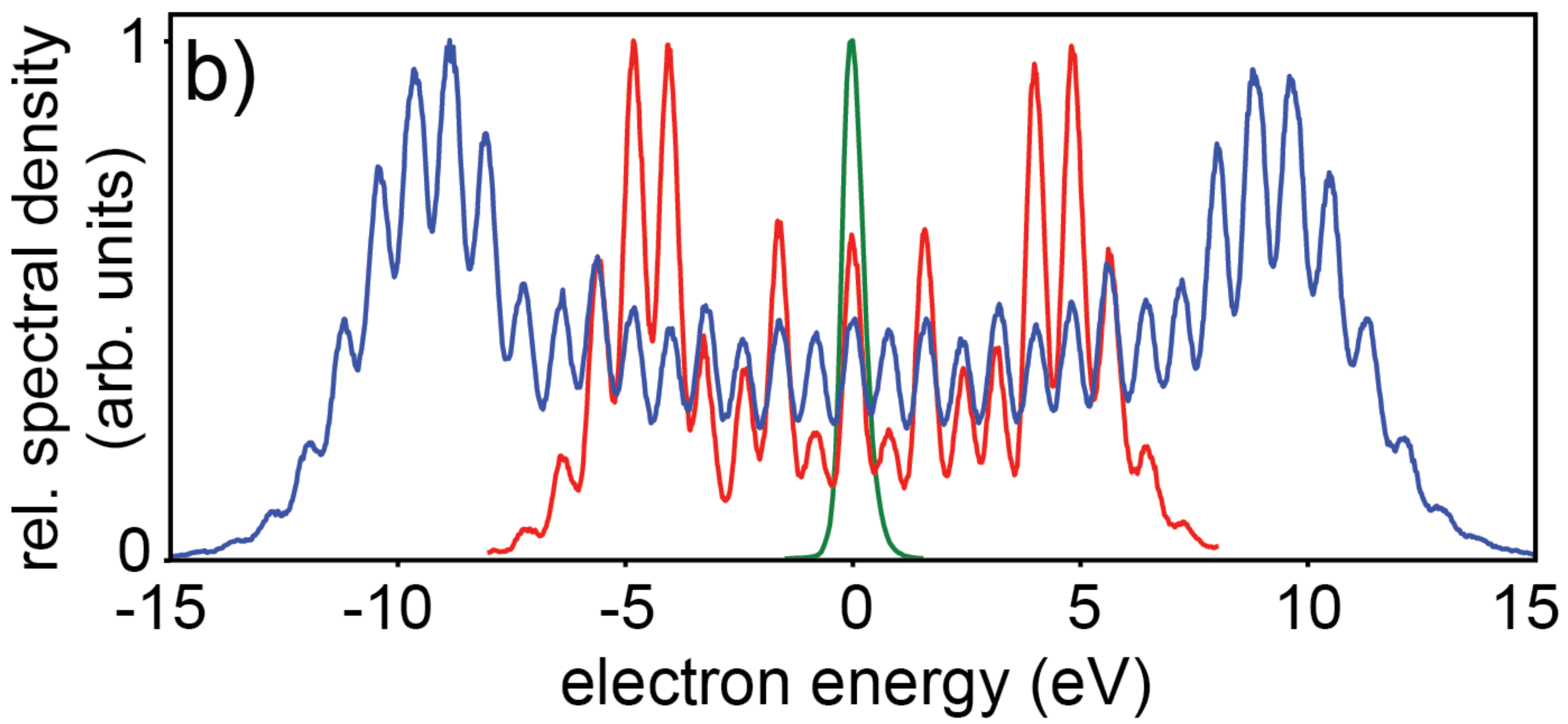
- Traveling wave structures
- Laser energy re-circulation

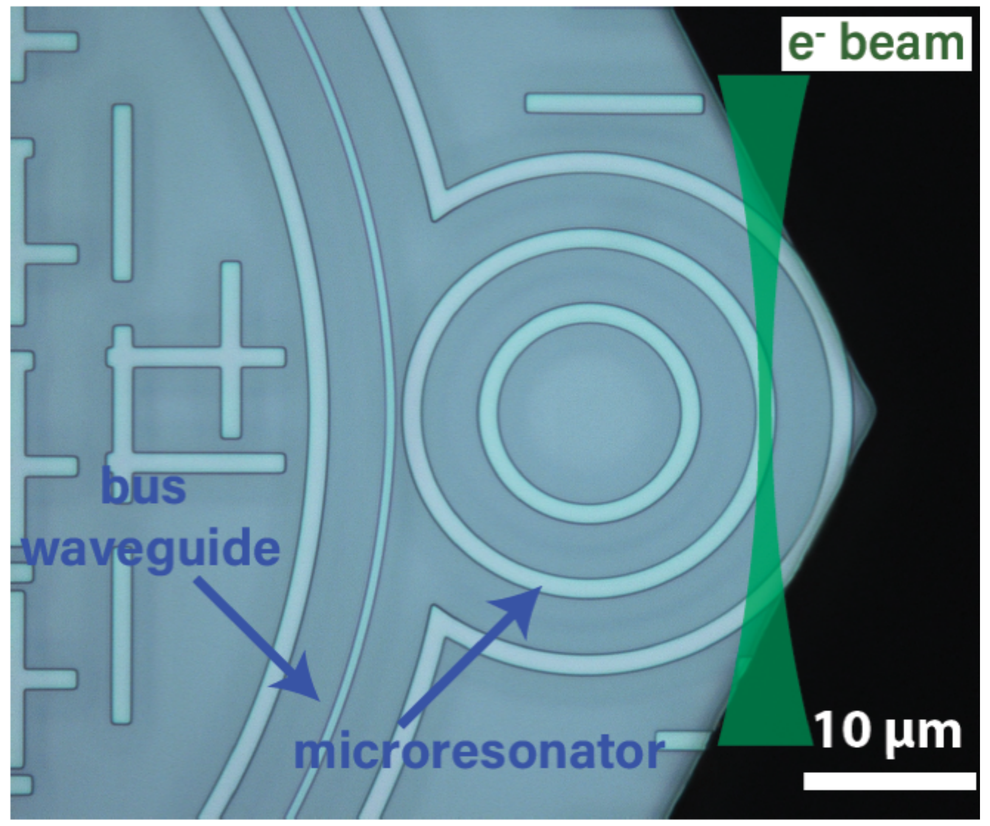


Siemann, Phys. Rev. ST Accel. Beams 7, 061303 (2004)

COHERENT CONTROL OF ELECTRONS WITH INTEGRATED OPTICAL MICRORESONATORS

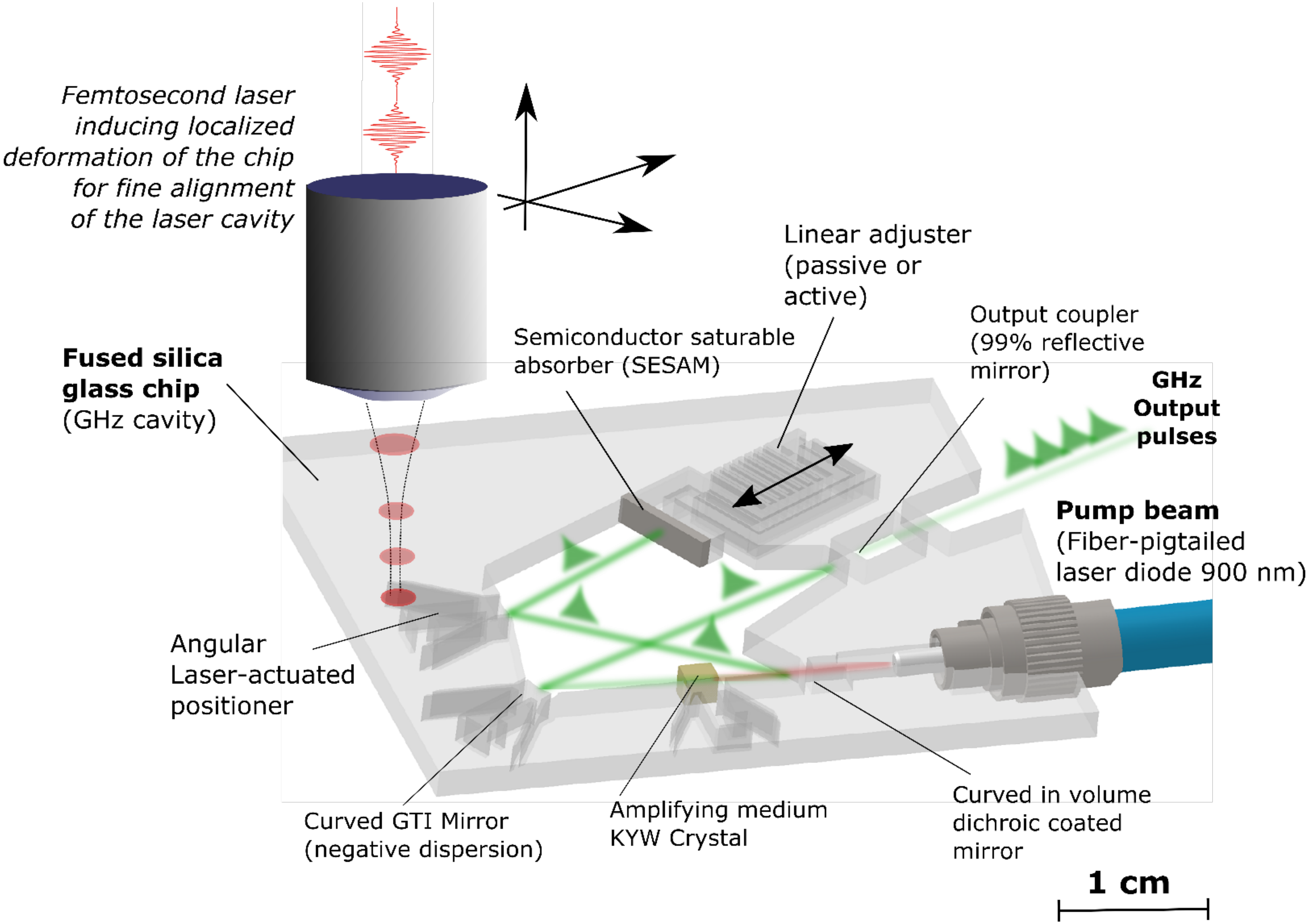






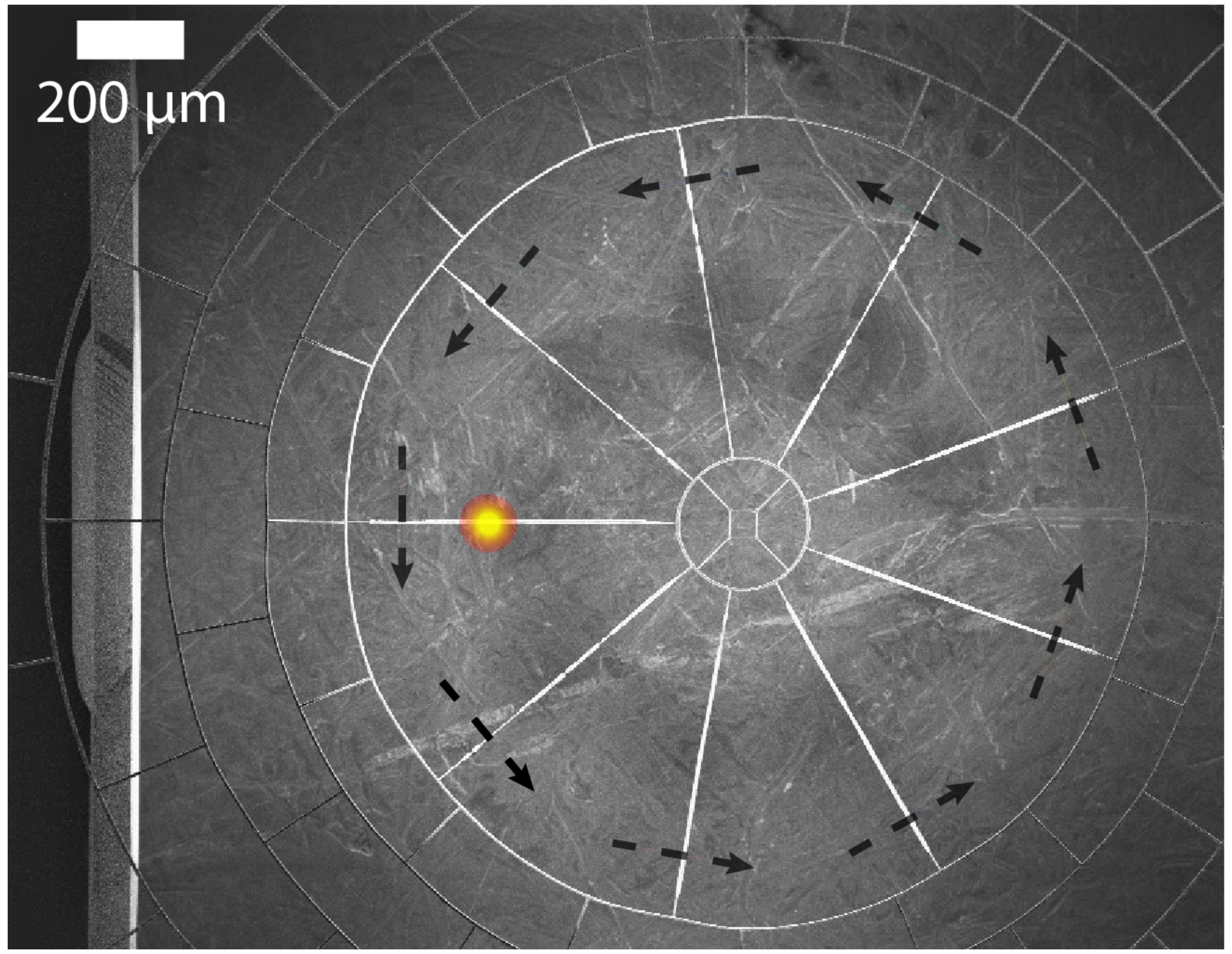
Tobias Kippenberg, EPFL, and Claus Ropers, Uni Göttingen

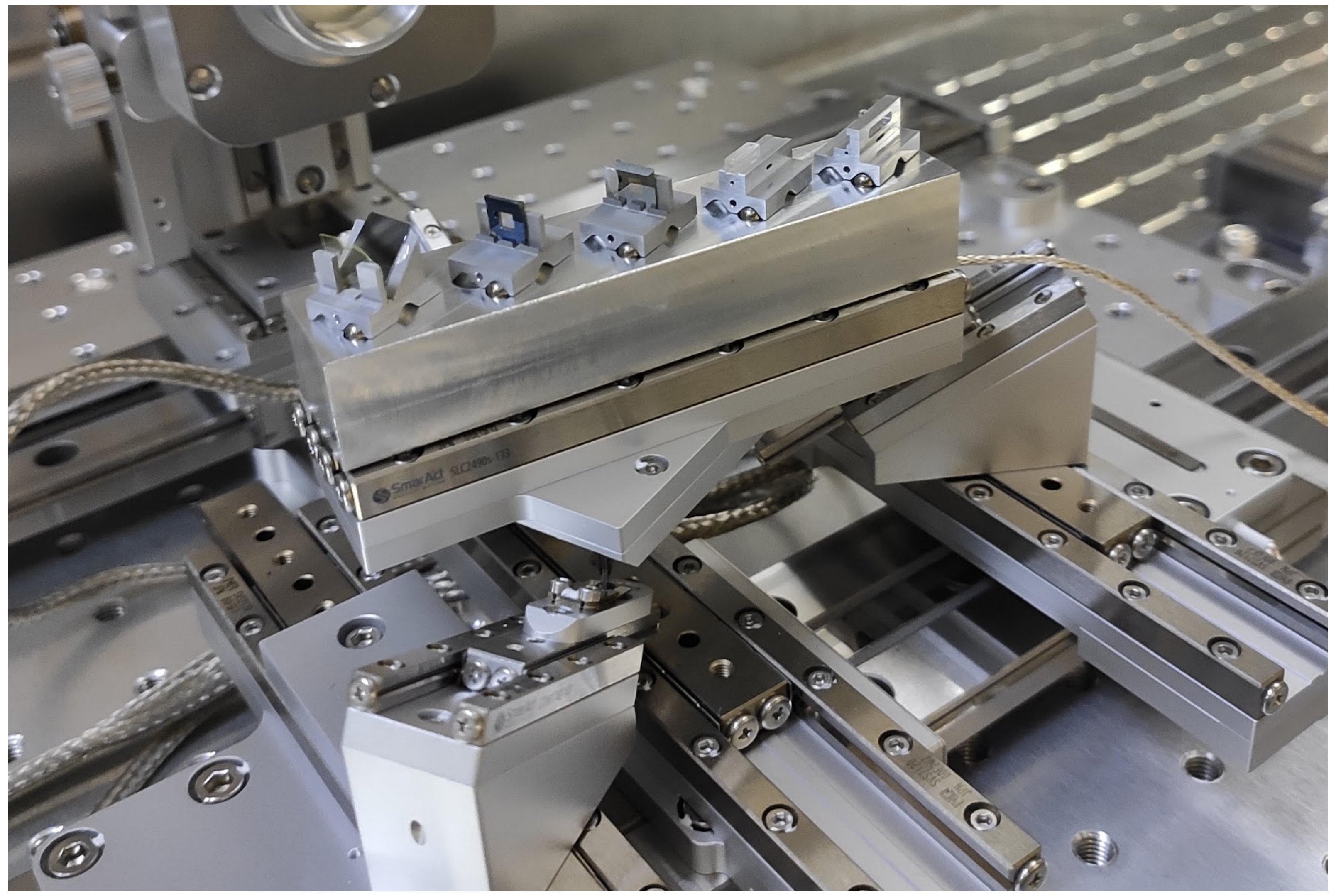
ILLUSTRATION: GHZ CAVITY CONCEPT

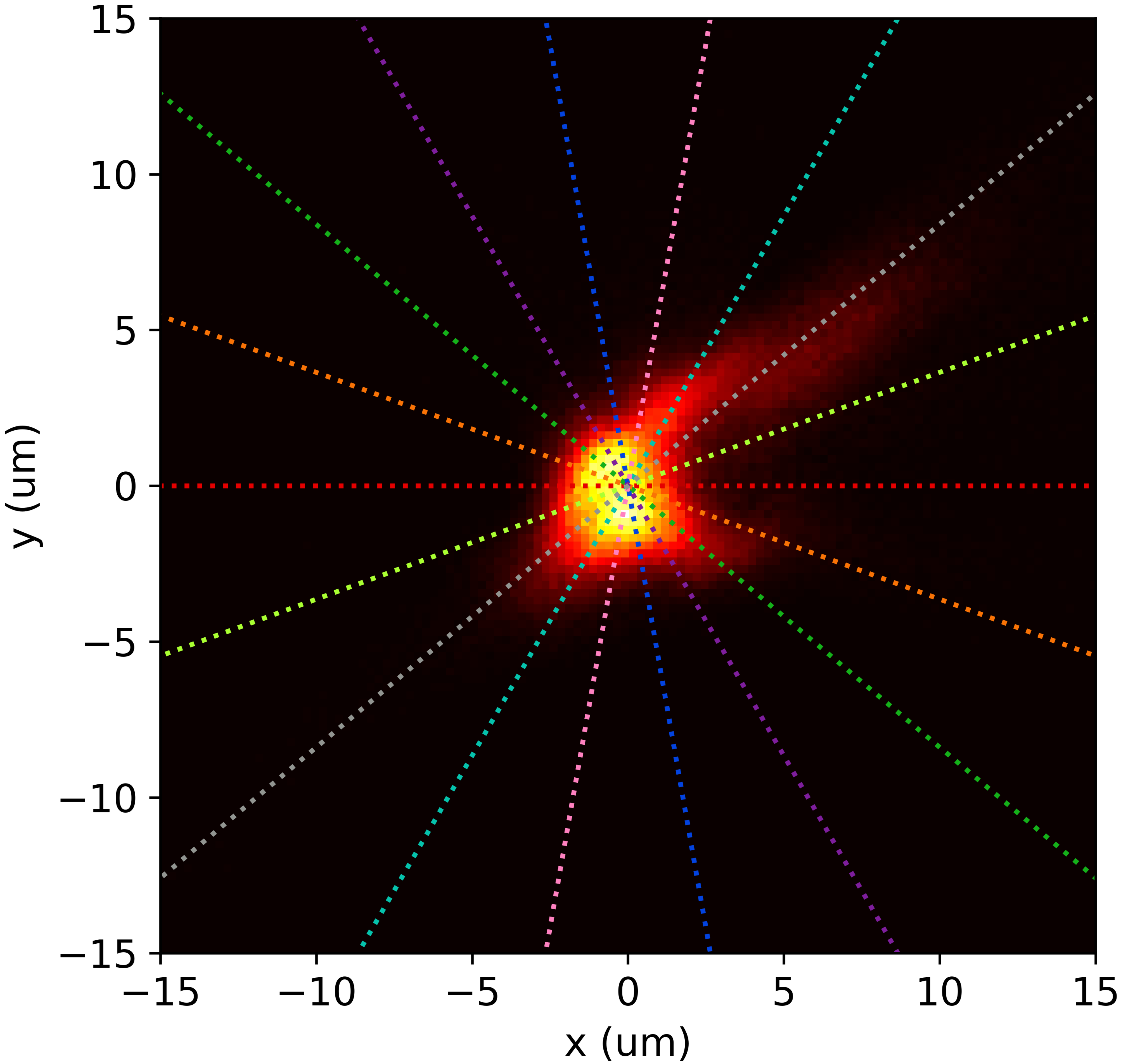


Yves Bellouard, EPFL

DIAGNOSTICS AND INSTRUMENTATION







Hermann et al., Phys. Rev. Accel. Beams 24, 022802

QUESTIONS?

Nick Veasey