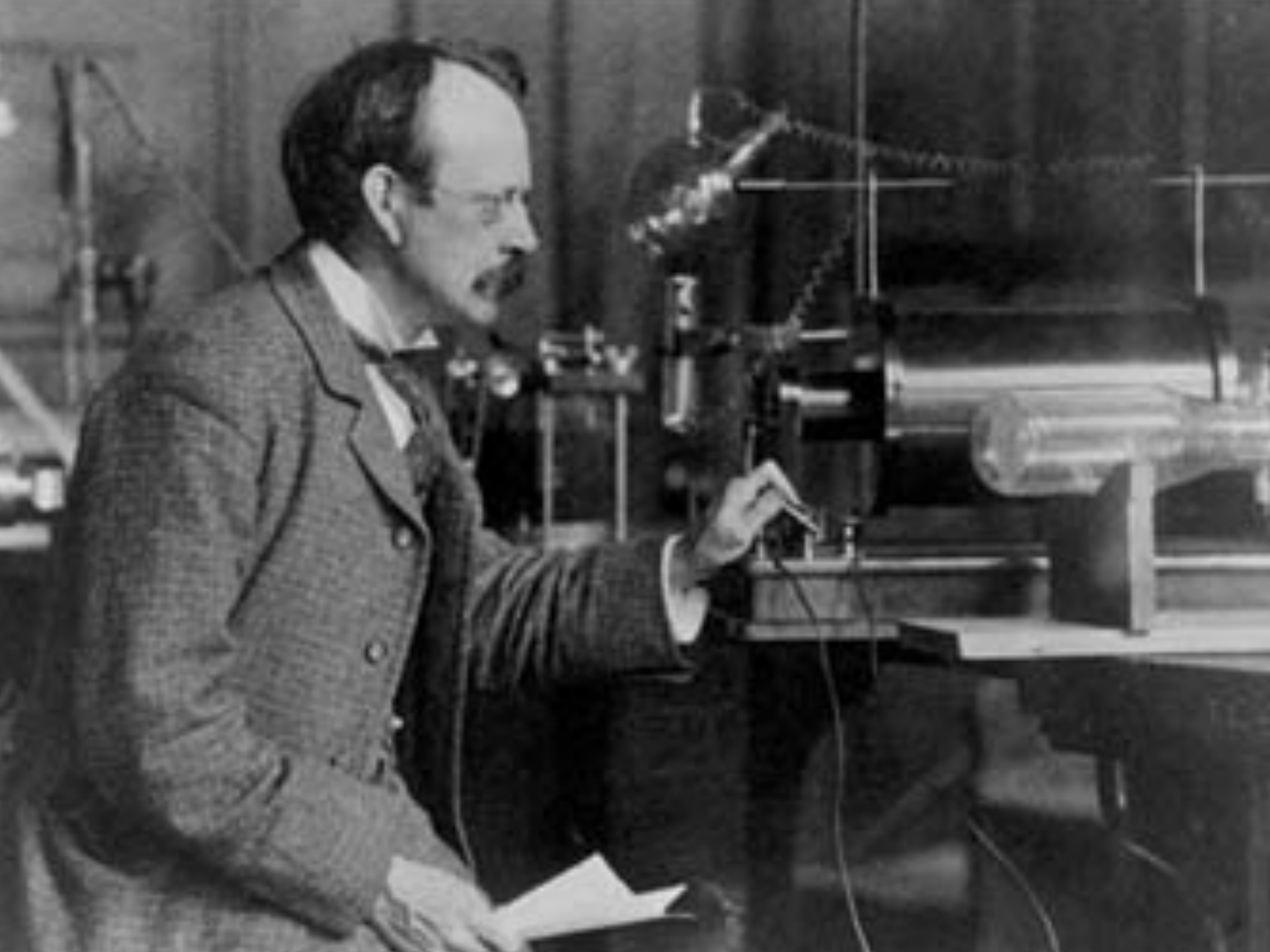
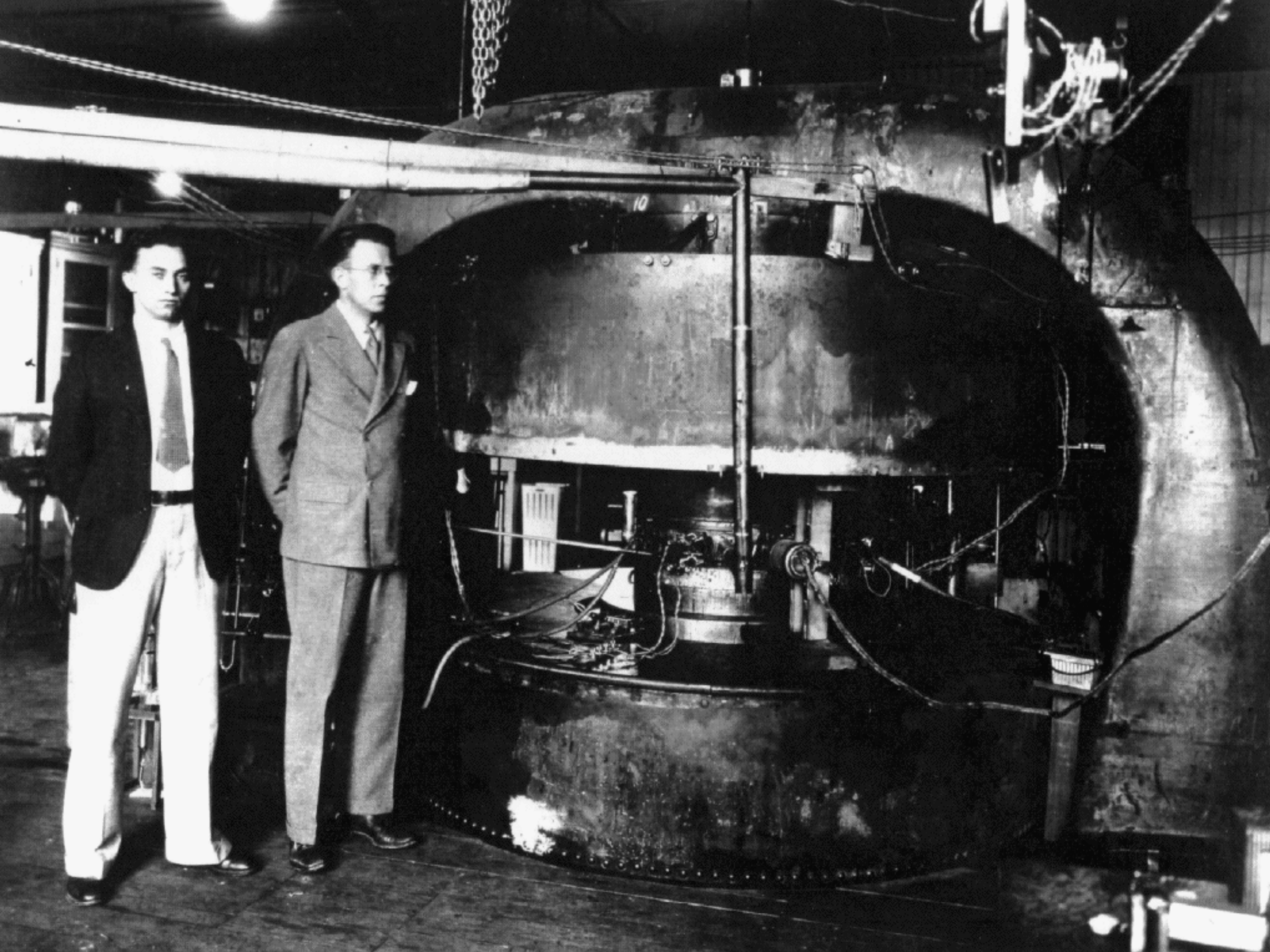
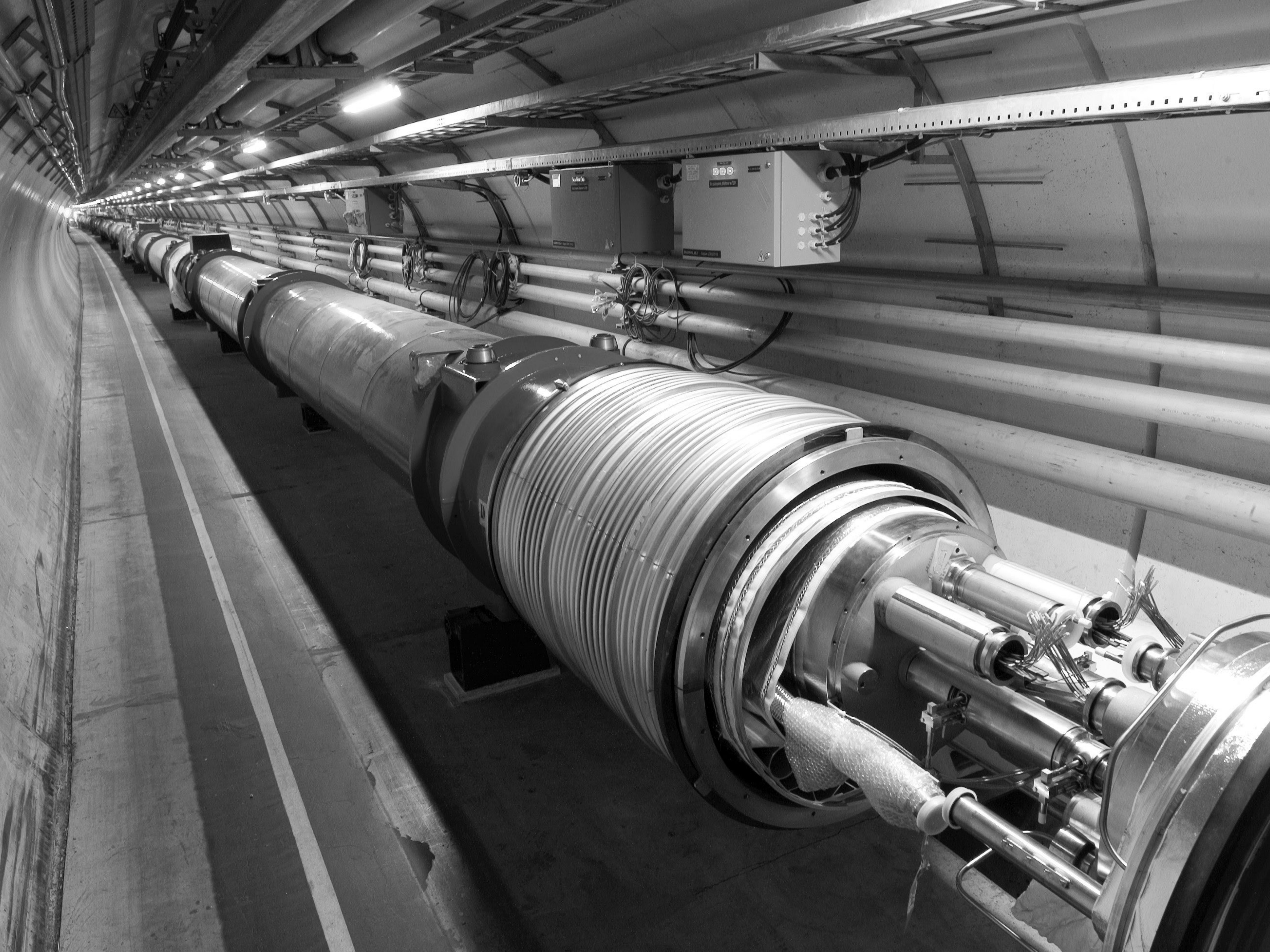
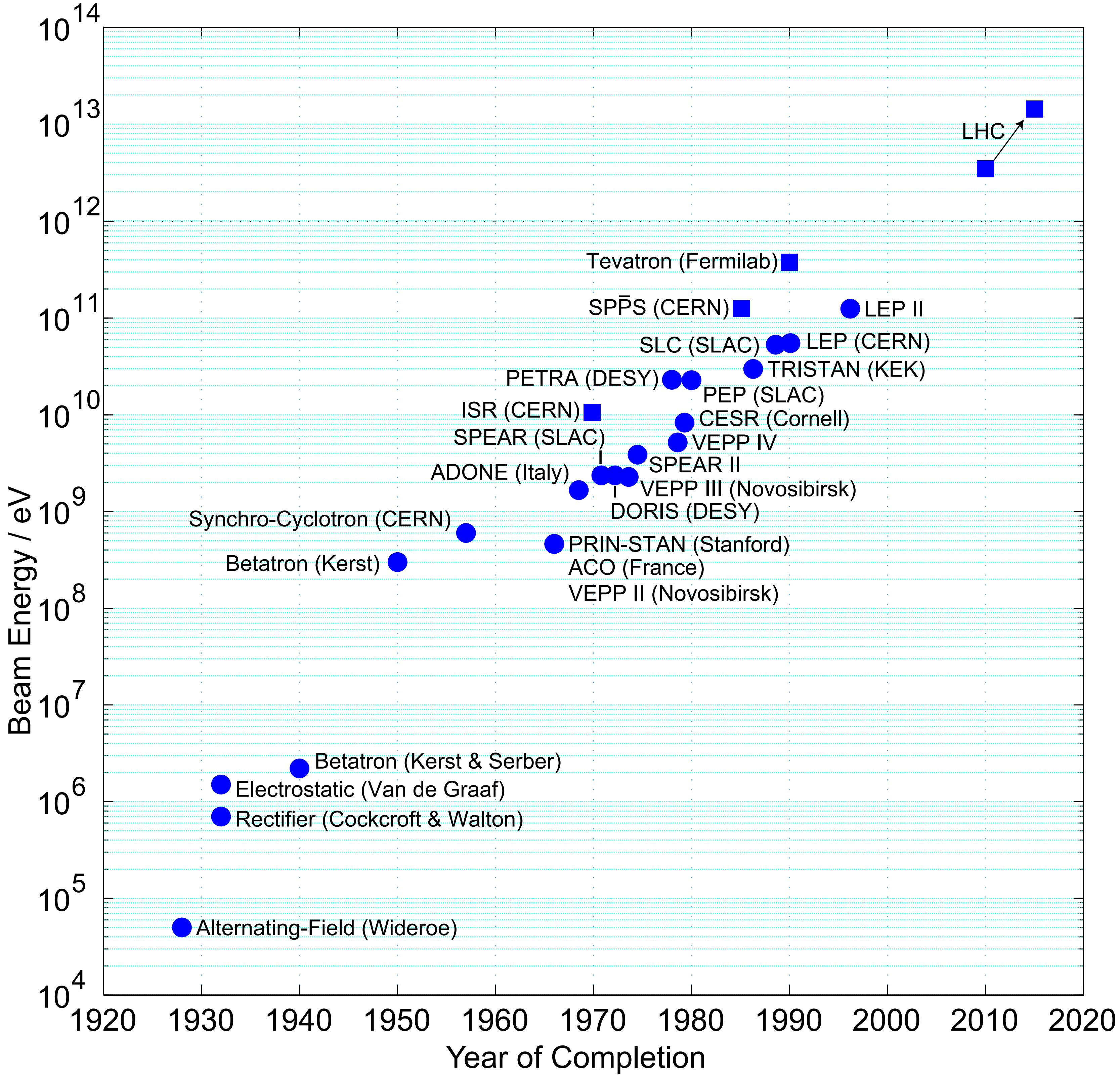
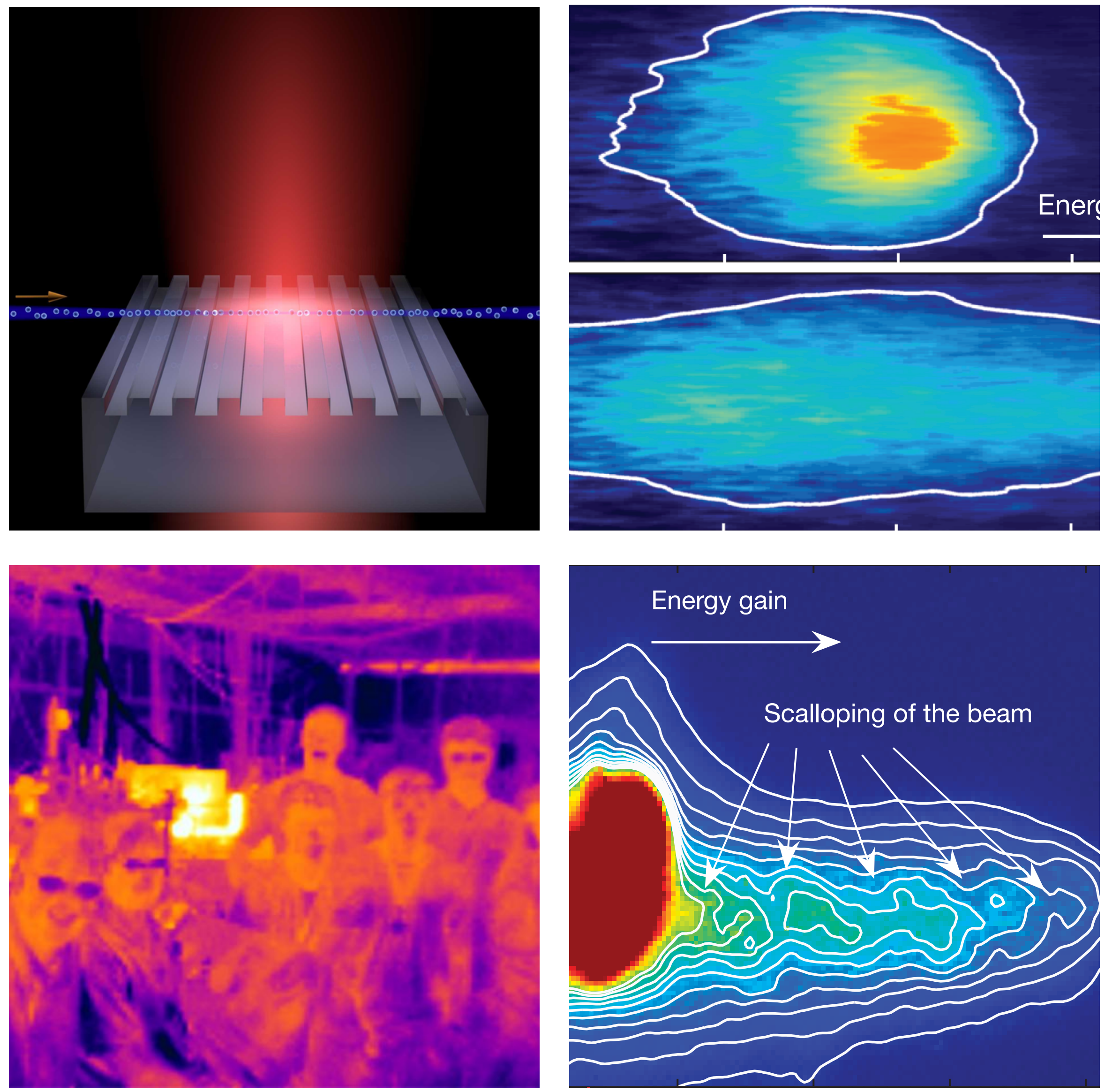



10



History of Particle Accelerators — Livingston Plot





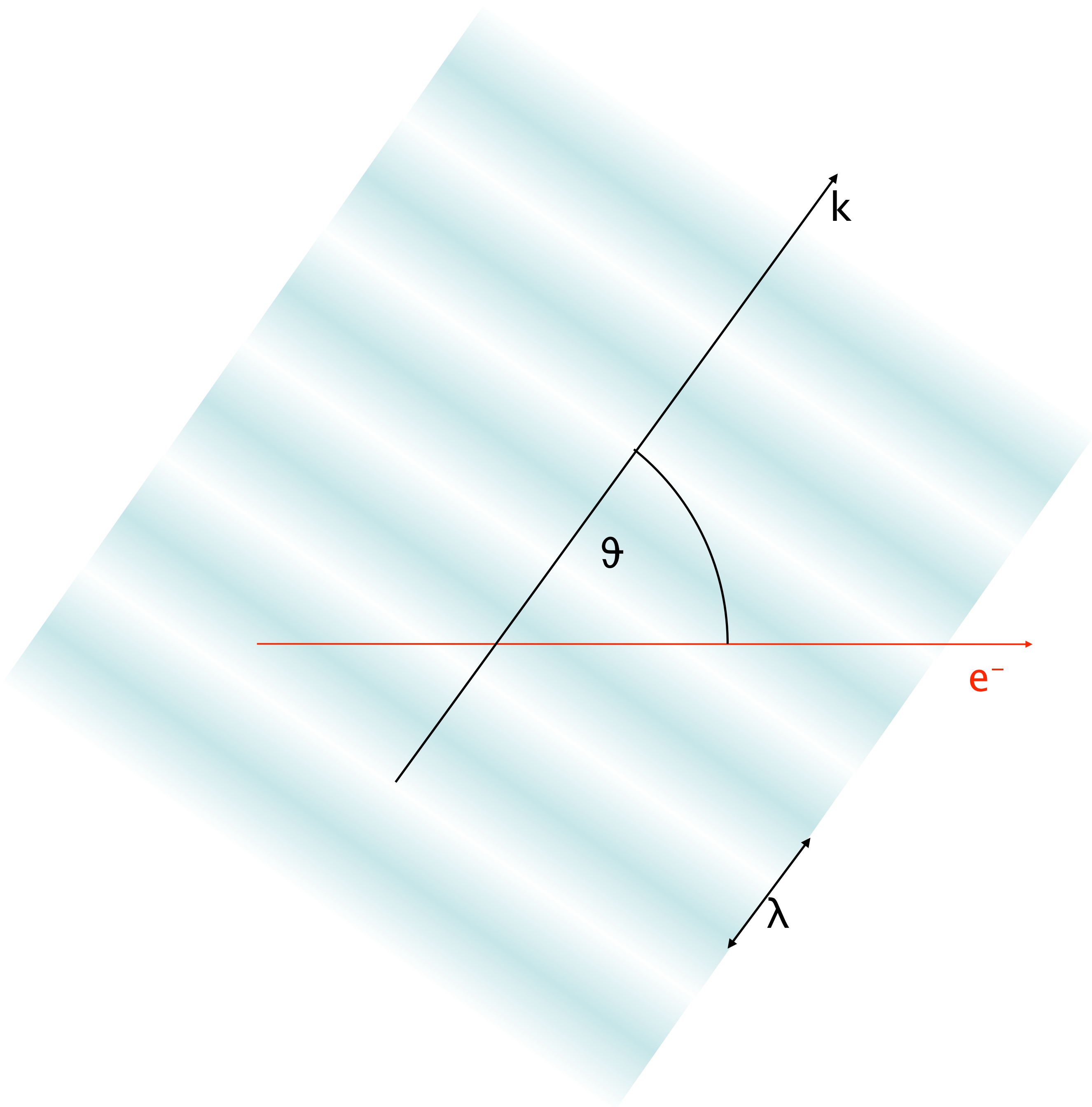
Accelerator R&D Towards Highest Energies

Rasmus Ischebeck, Paul Scherrer Institut

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

not

Then:

- Position of the electron

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

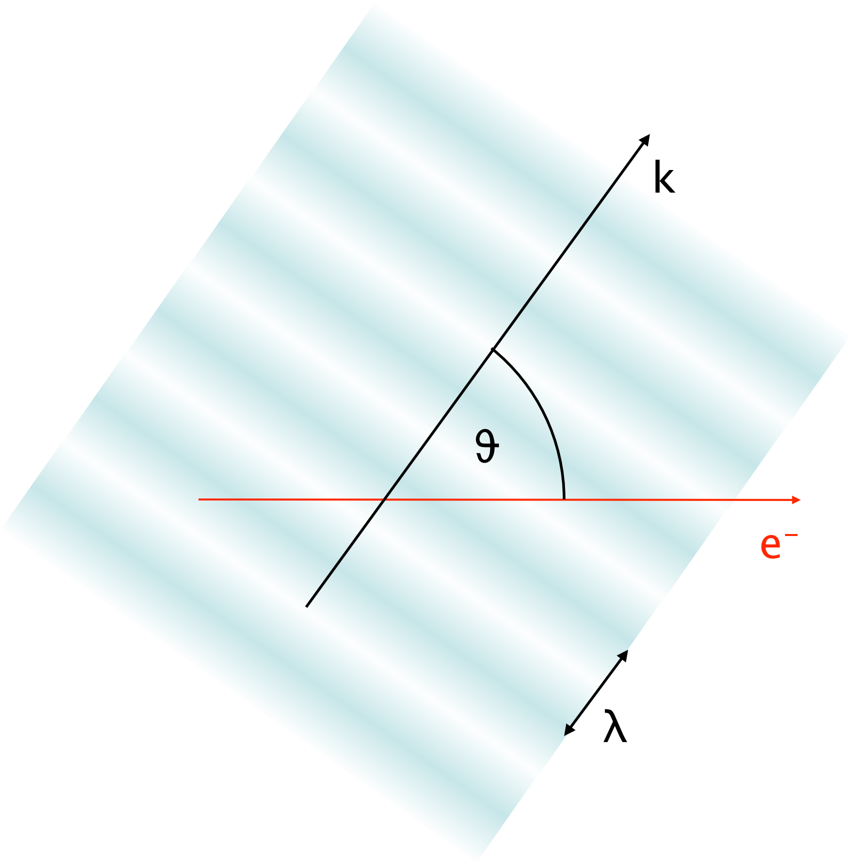
- Electric field

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

- Energy gradient

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

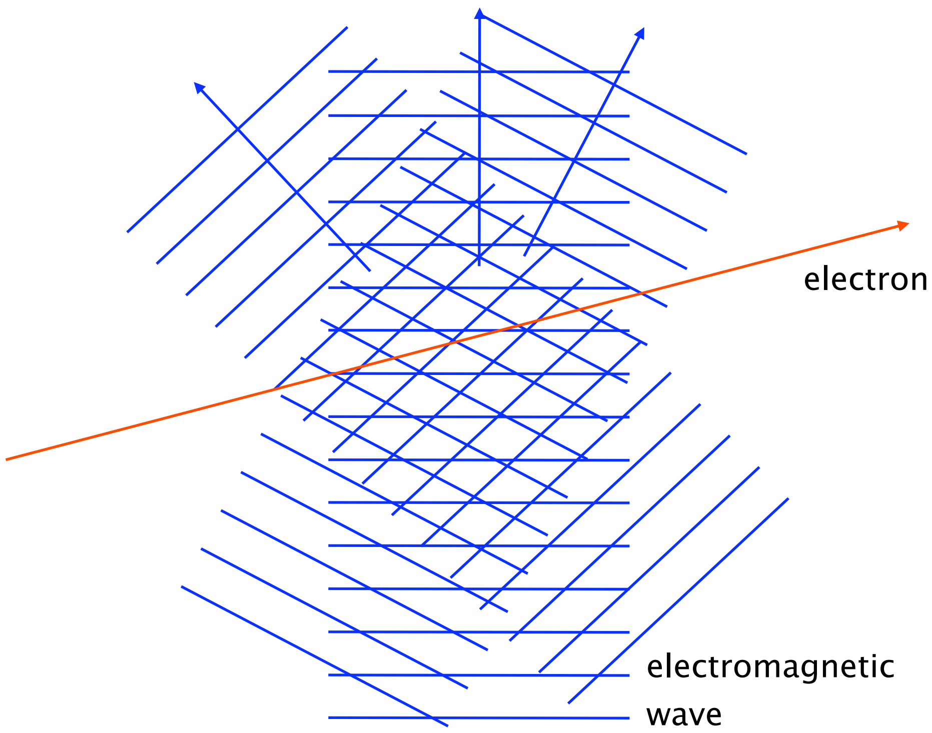
$$= \frac{\sin\vartheta\sin(kL(1-\sec\vartheta))\frac{1}{k(1-\sec\vartheta)}}{L} \xrightarrow{L\to\infty} 0$$



Lawson-Woodward-Palmer 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

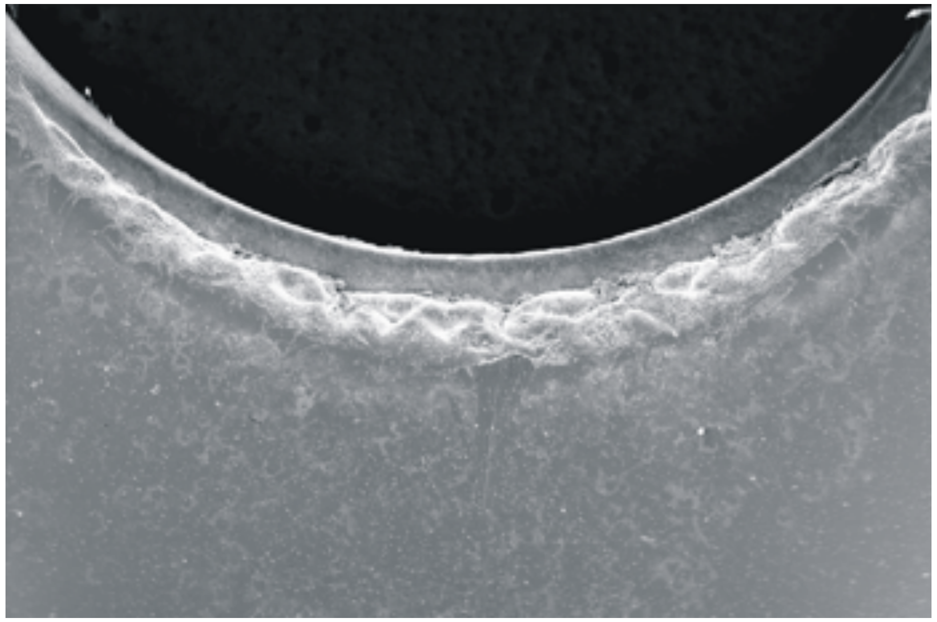
⇒ Need near-field structures



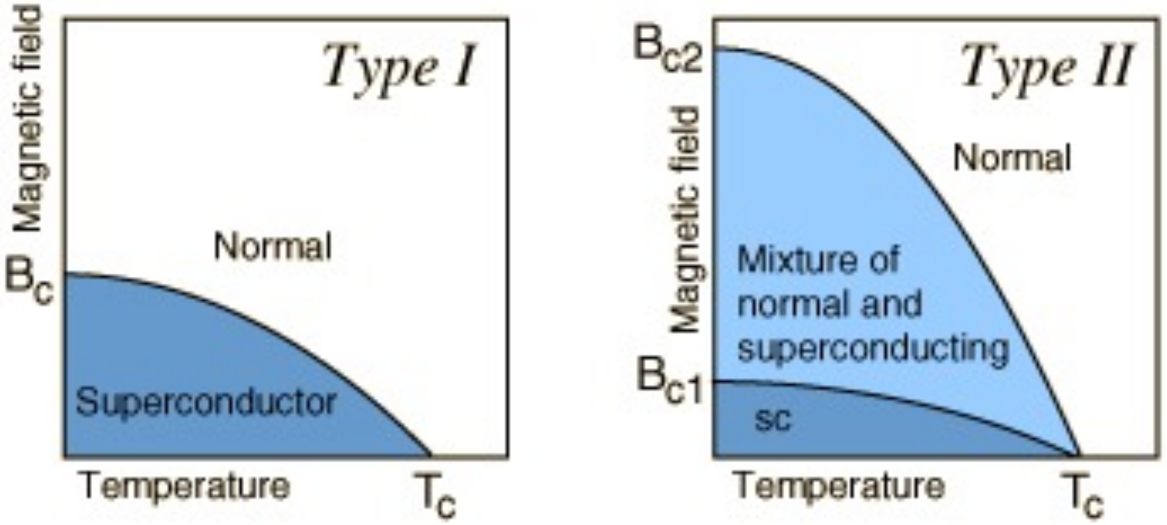
Woodward, J. IEE 93 (1947)
Lawson, IEEE Trans. Nucl. Sci. 26 (1979)
Palmer, Part. Accel. 11 (1980)

Limits to the Accelerating Field

- Normal-conducting accelerators
  - Breakdown on the surface

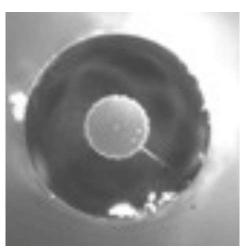
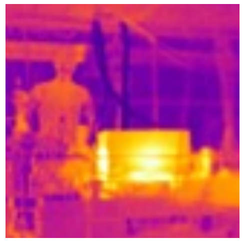


- Superconducting accelerators
  - Critical magnetic field



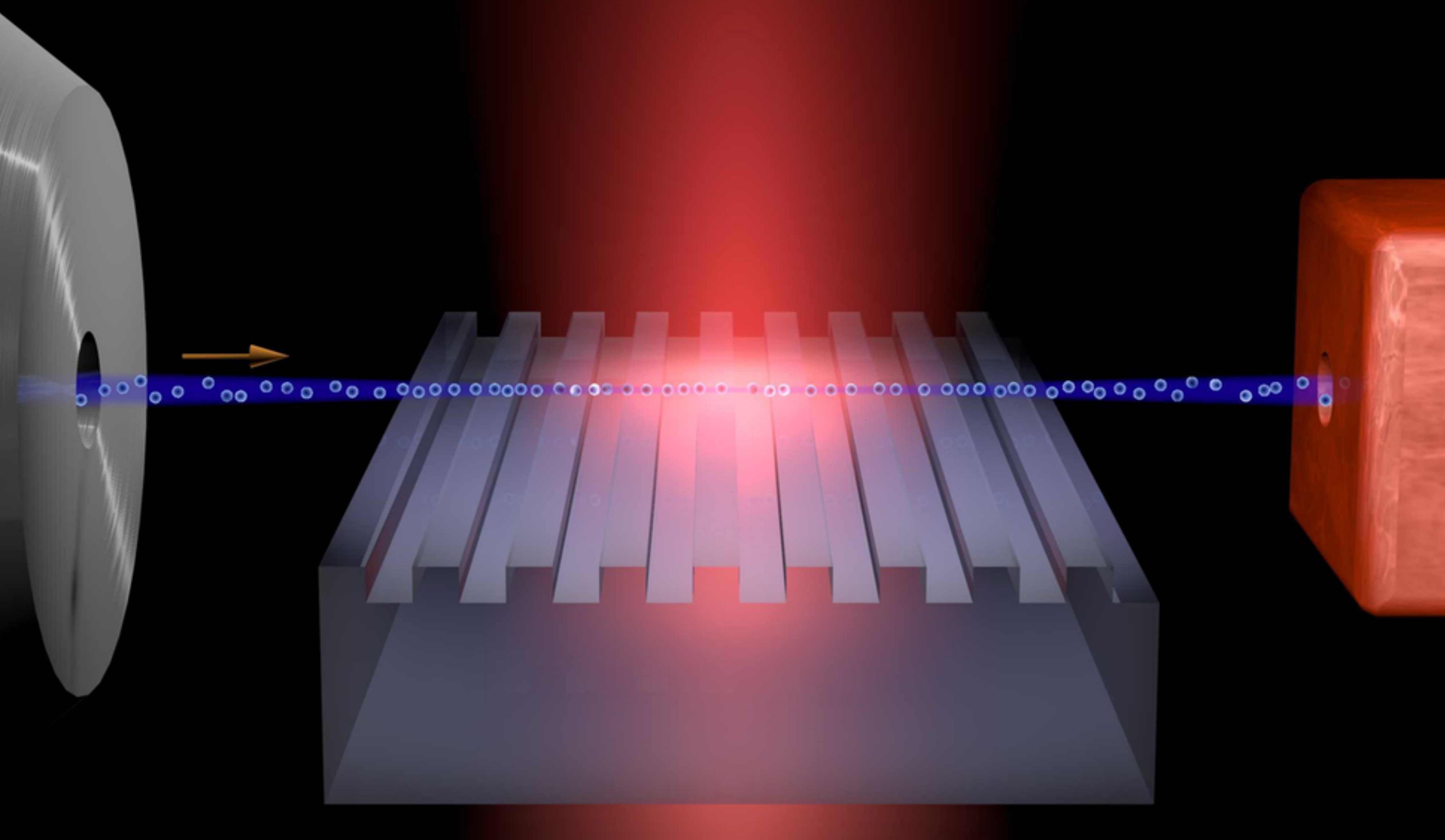
http://hyperphysics.phy-astr.gsu.edu/hbase/solids/scbc.html

Possibilities for Accelerating Structures

	Structure	max. Field (V/m)	Power Sources	
	Superconducting	$5 \cdot 10^7$	solid state	electron beams: klystrons
	Metallic	$2 \cdot 10^8$	solid state	electron beams: klystrons or integrated structure
	Dielectric	10^9	laser	electron beams
	Plasma	$\geq 10^{11}$	laser	electron beams

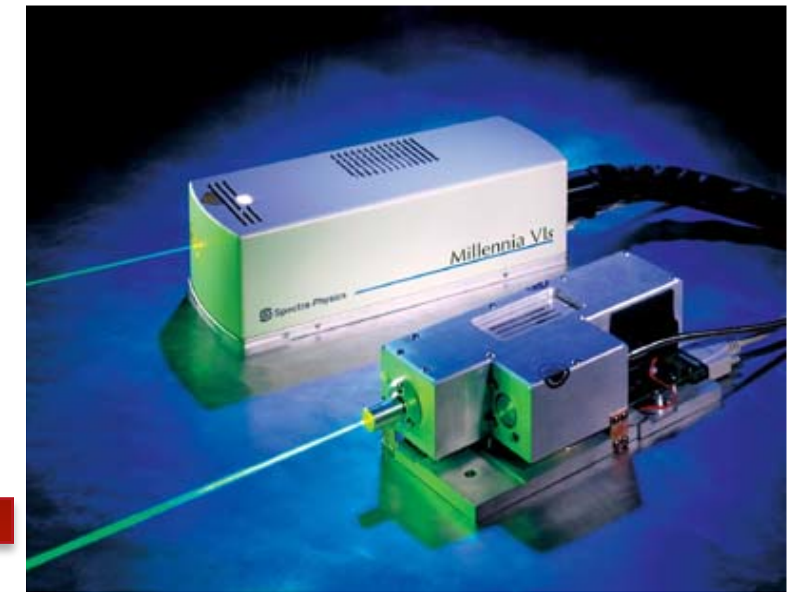
Plus: Inverse FEL, disposable structures, excited atoms, muon colliders

Laser-Based Acceleration



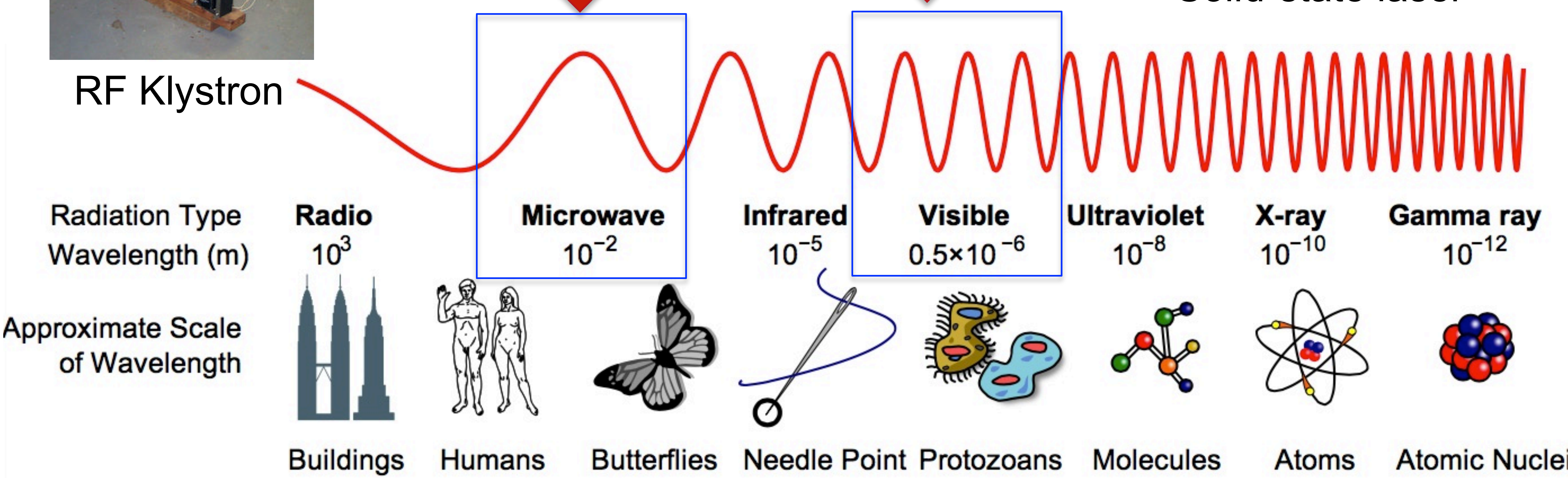
Laser as a source of electromagnetic fields

1. Smaller/less expensive than RF.
2. Energy efficient (near 50%).
3. High repetition rate (1 to 100 MHz).
4. Large electric fields (GV/m).



Solid-state laser

RF Klystron



Laser Acceleration (1961)

Koichi Shimoda, Applied Optics 1 (1), 33 (1961)

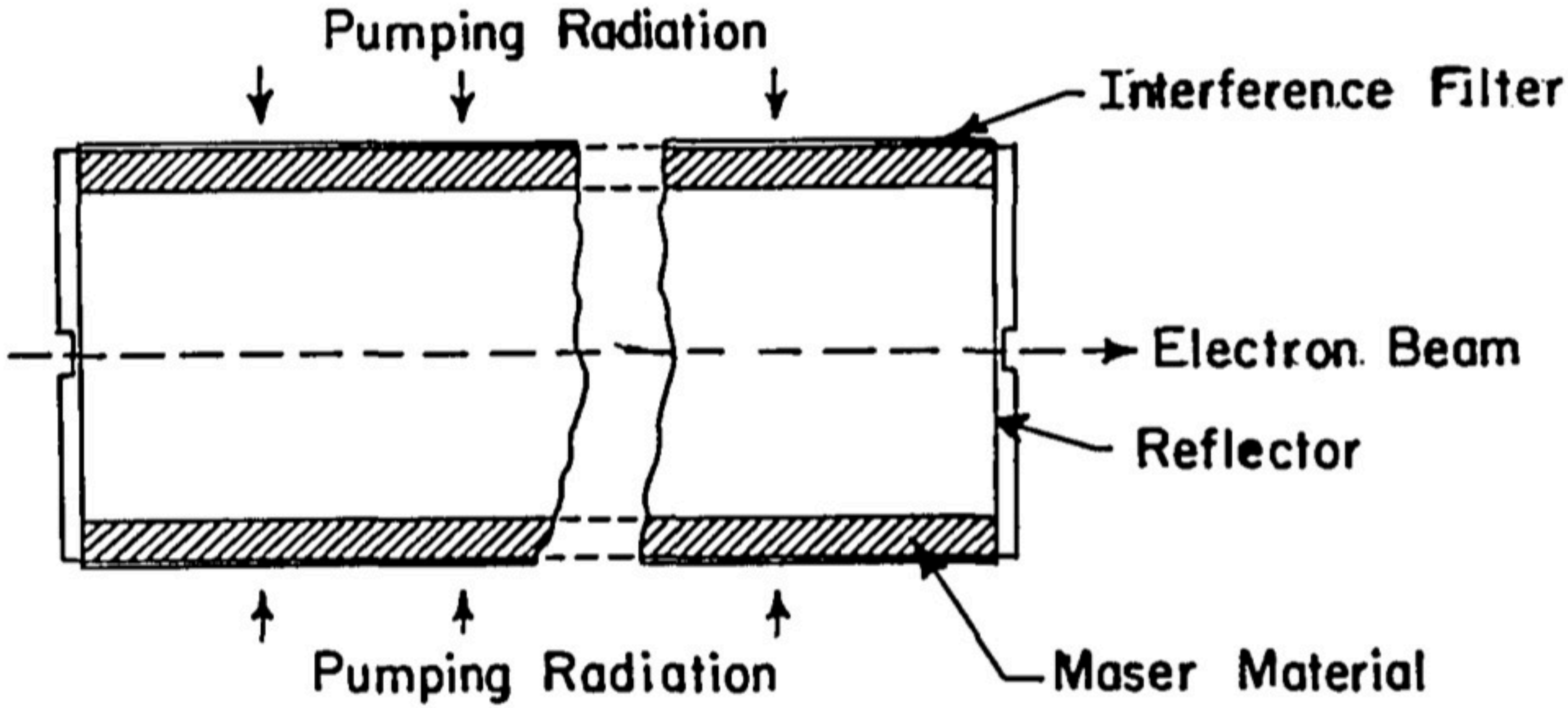
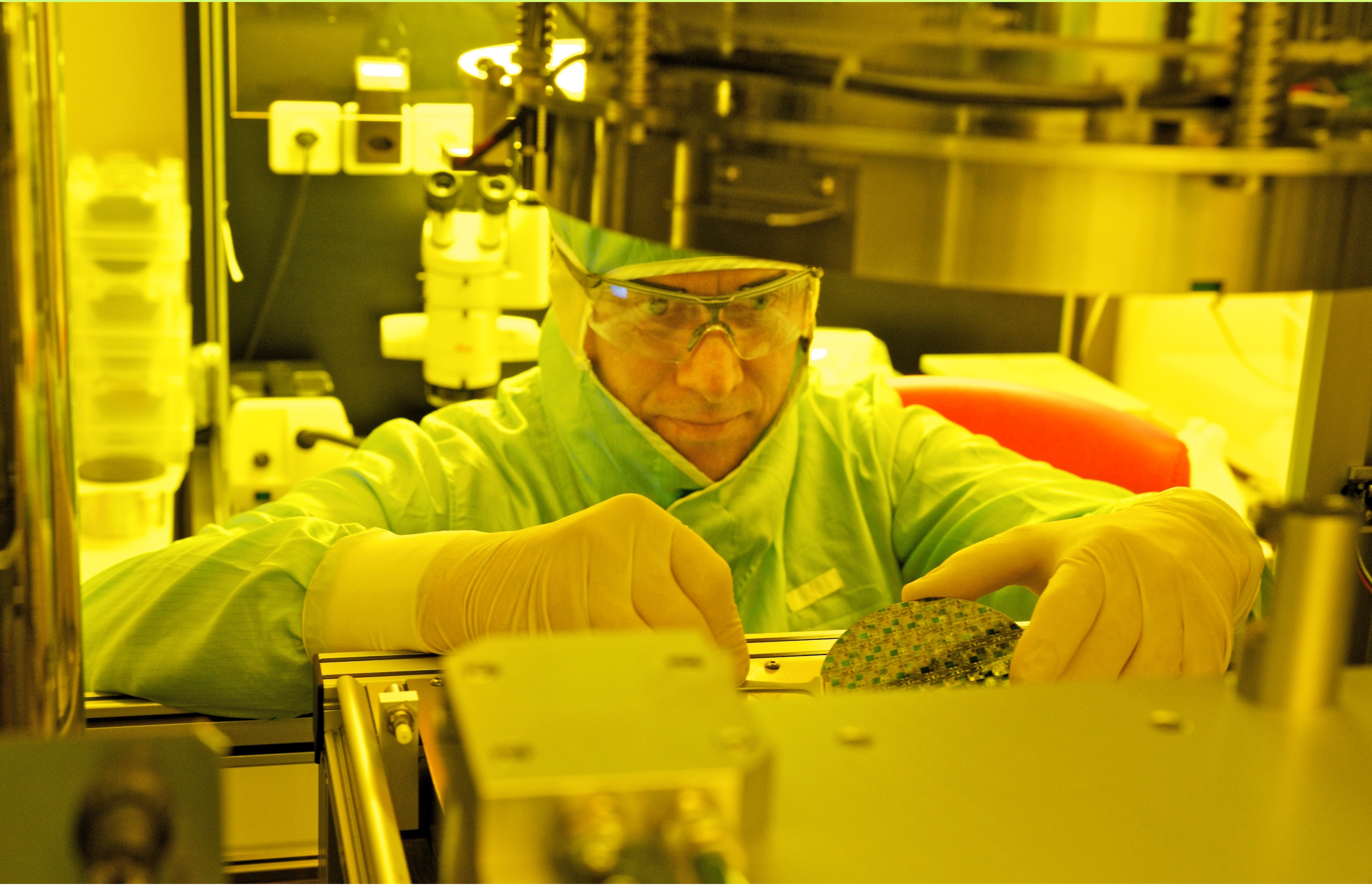


Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.

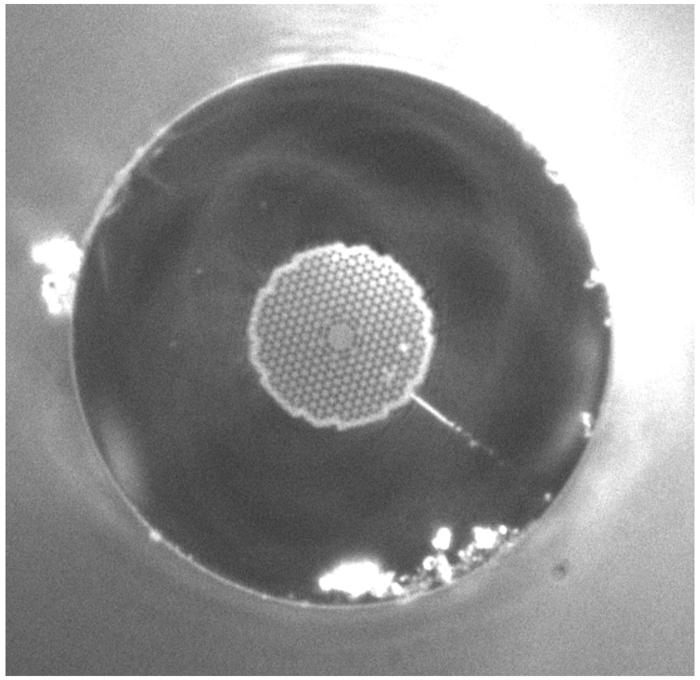
Semiconductor Industry



Dielectric Accelerator Structures

- Using much higher frequencies: THz to optical
- Using dielectrics (e.g. SiO_2)
- Advantages: higher damage threshold
  ⇒ Higher accelerating fields, up to ~GV/m

- Generate the electromagnetic field
  - Cherenkov radiation from an electron beam
  - Laser
- Confine the field
  - Photonic band gap



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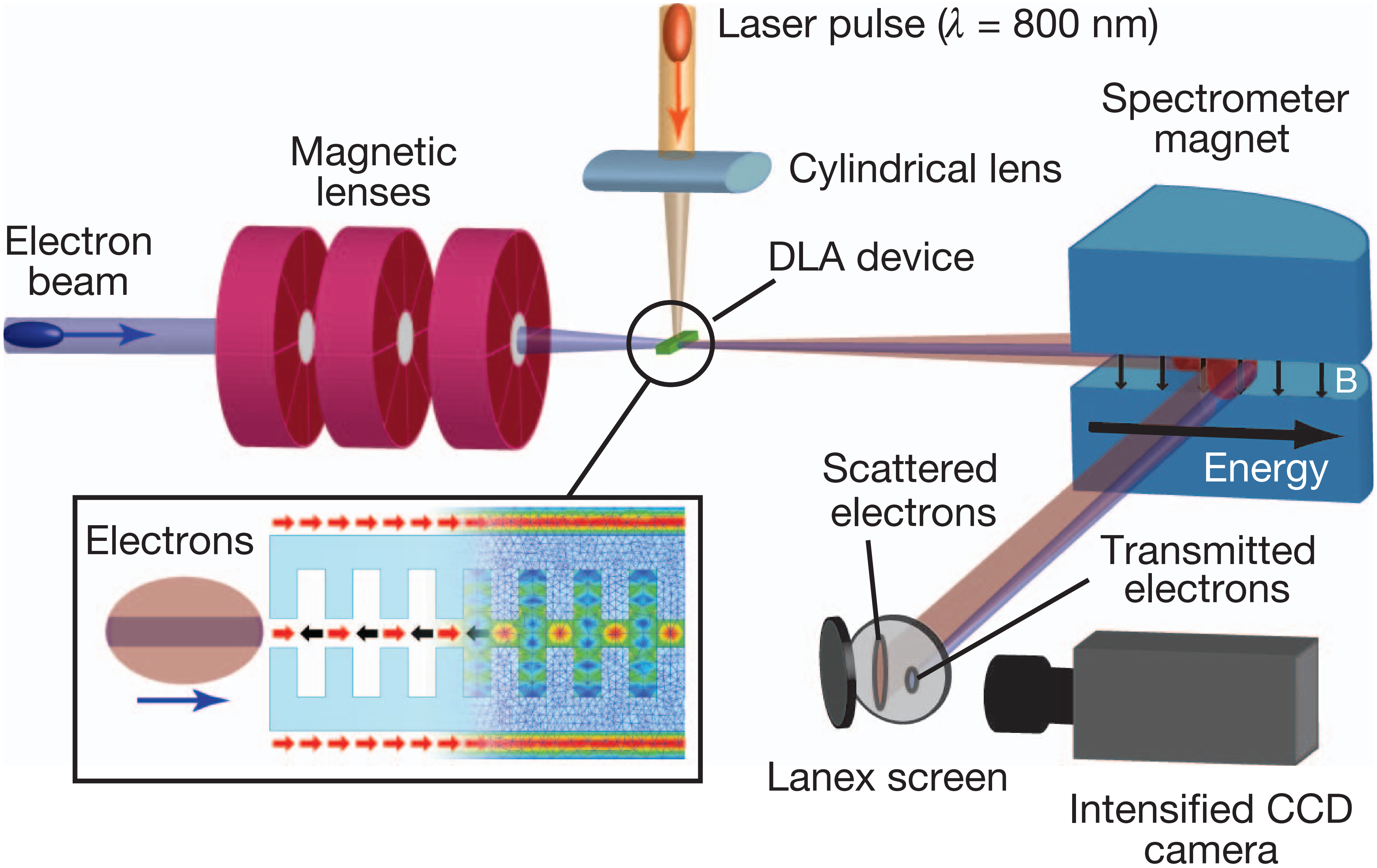
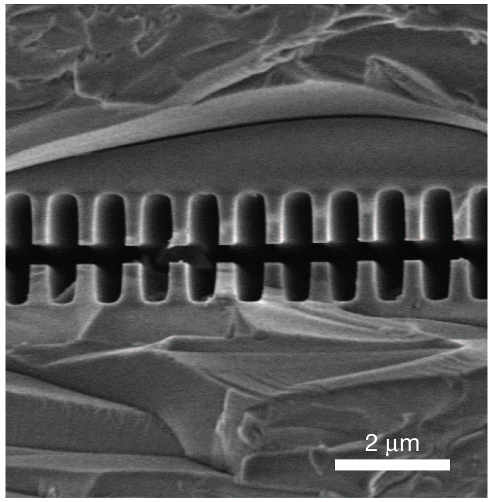
Acceleration Experiments with a Dielectric Structure

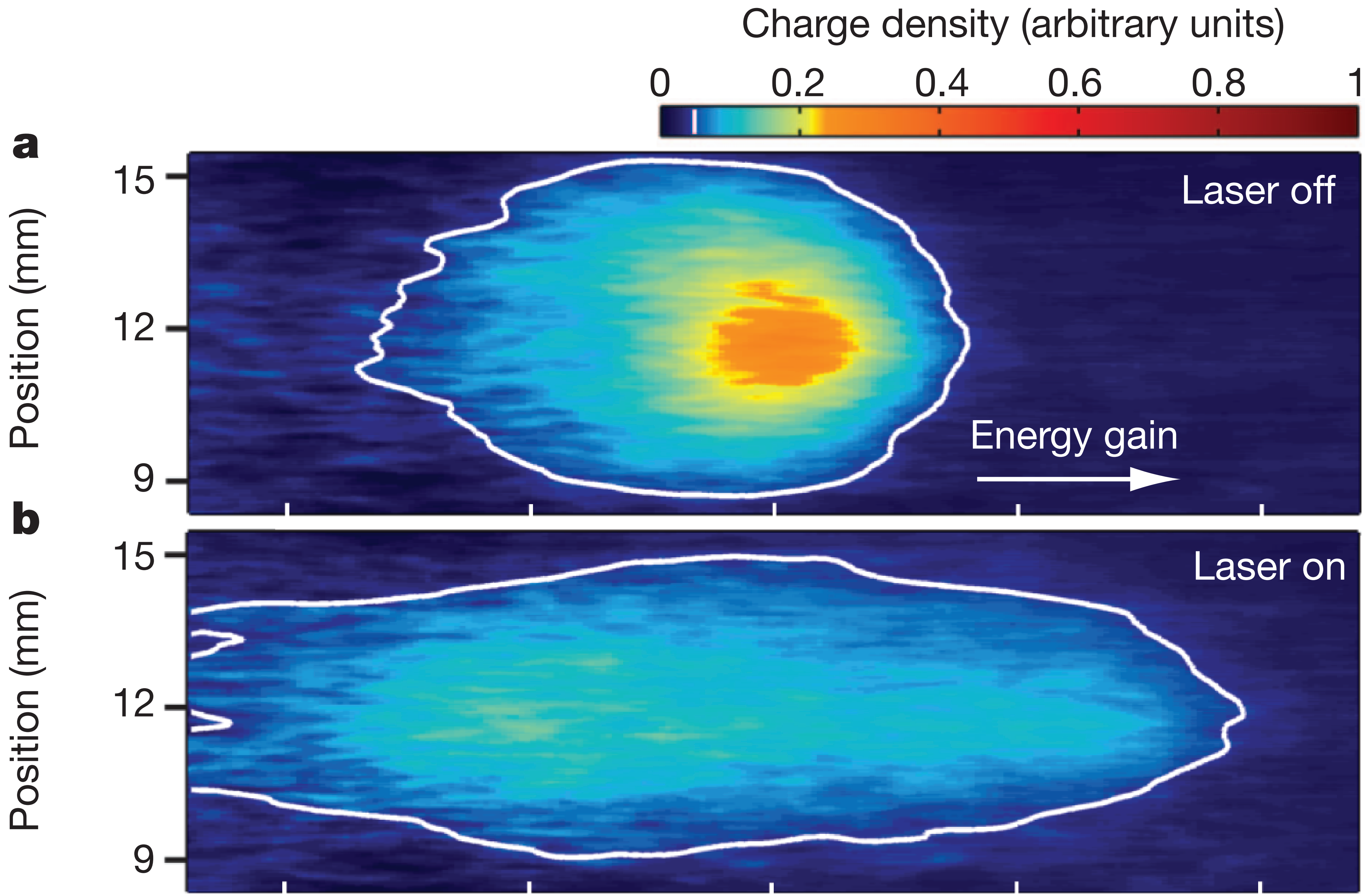




Peralta et al.,
Nature **503**, 91 (2013)

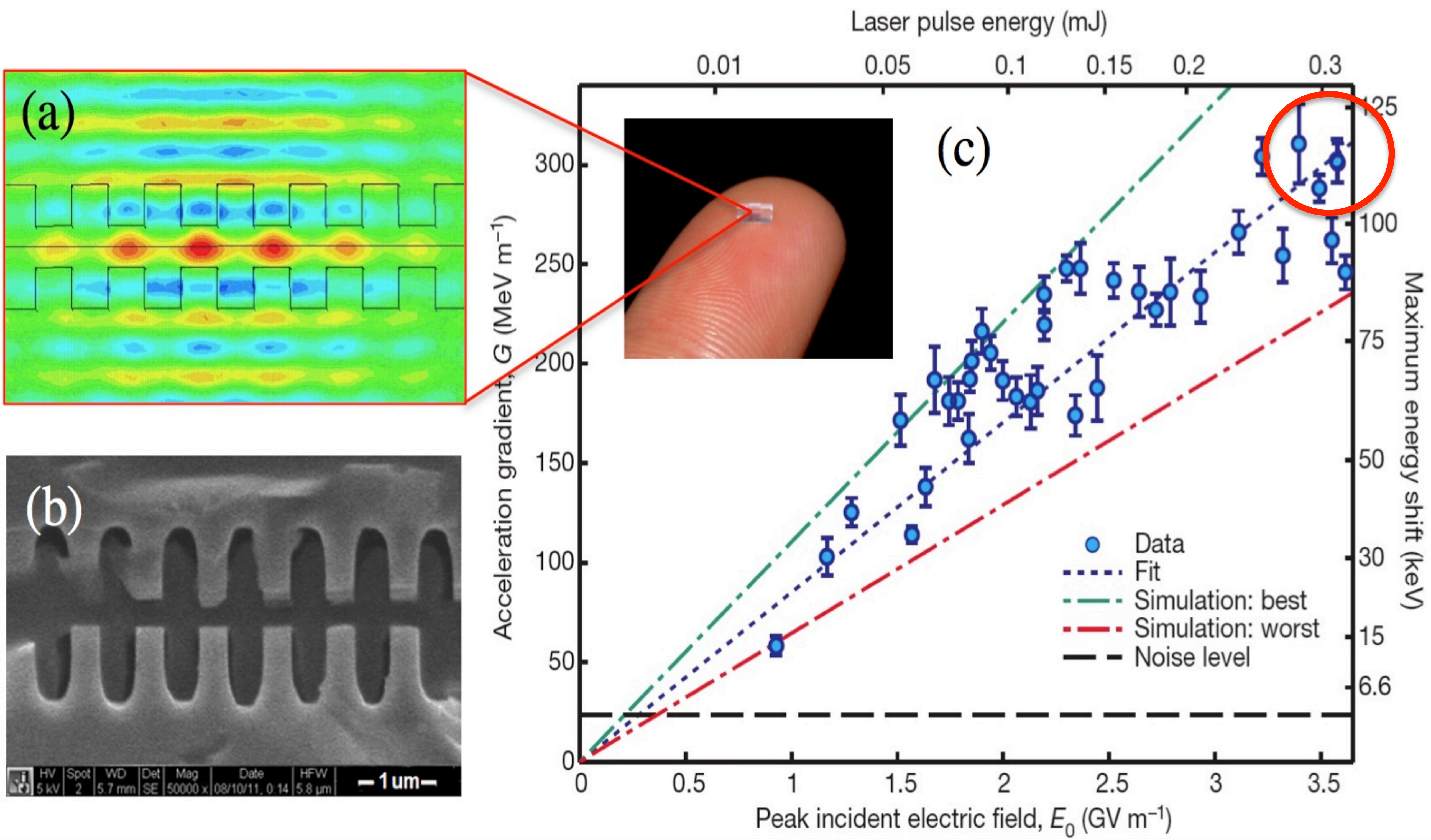
Acceleration Experiments with a Dielectric Structure

> Depending on their phase, some electrons are accelerated, some are decelerated



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

Planar Structures: Measurements



> Joel England

Dielectric Accelerators — Current Research Topics

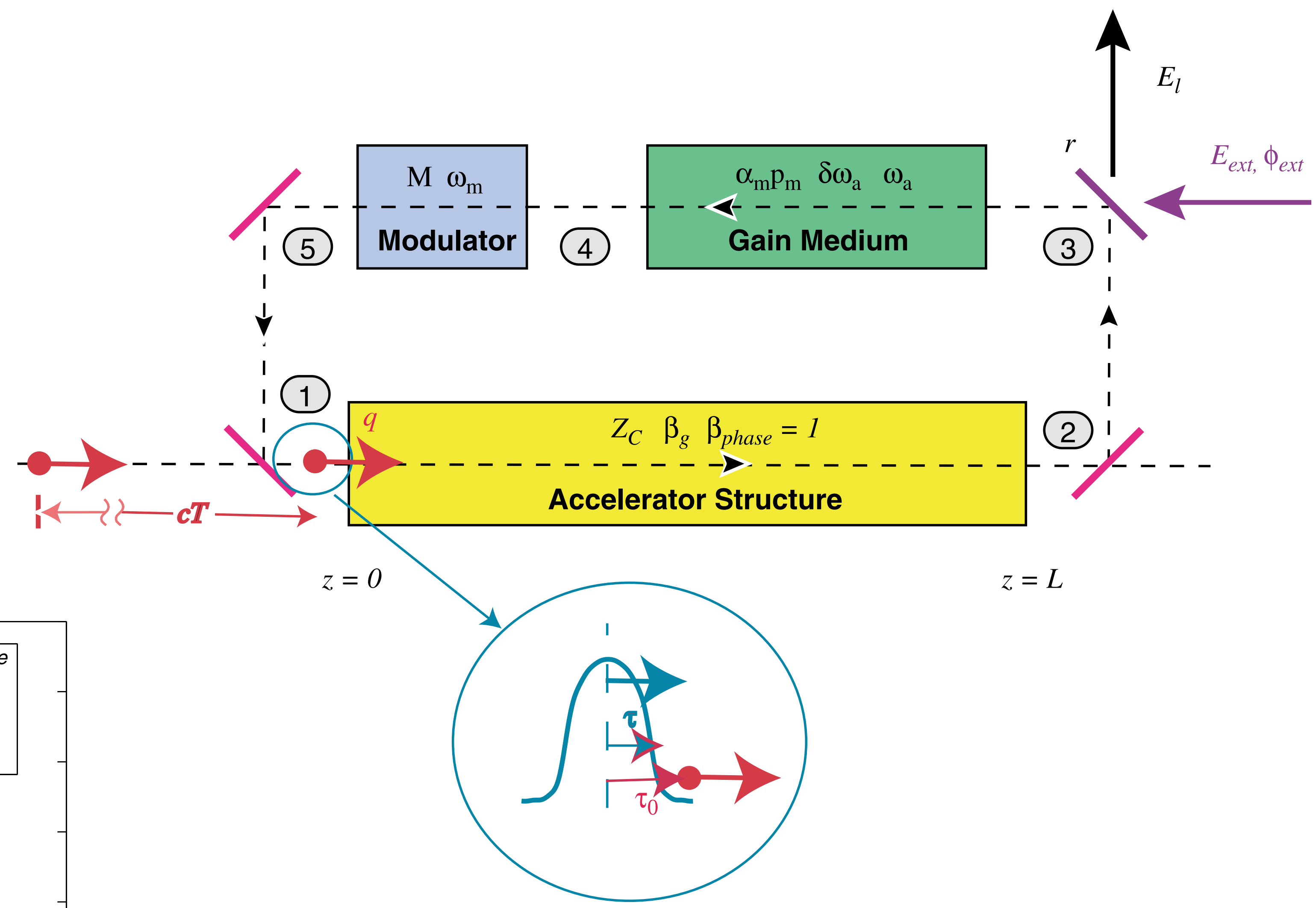
- Achievements of recent years
  - Proof-of-principle experiments demonstrating accelerating fields of GV/m
  - Efficient generation of the electromagnetic fields

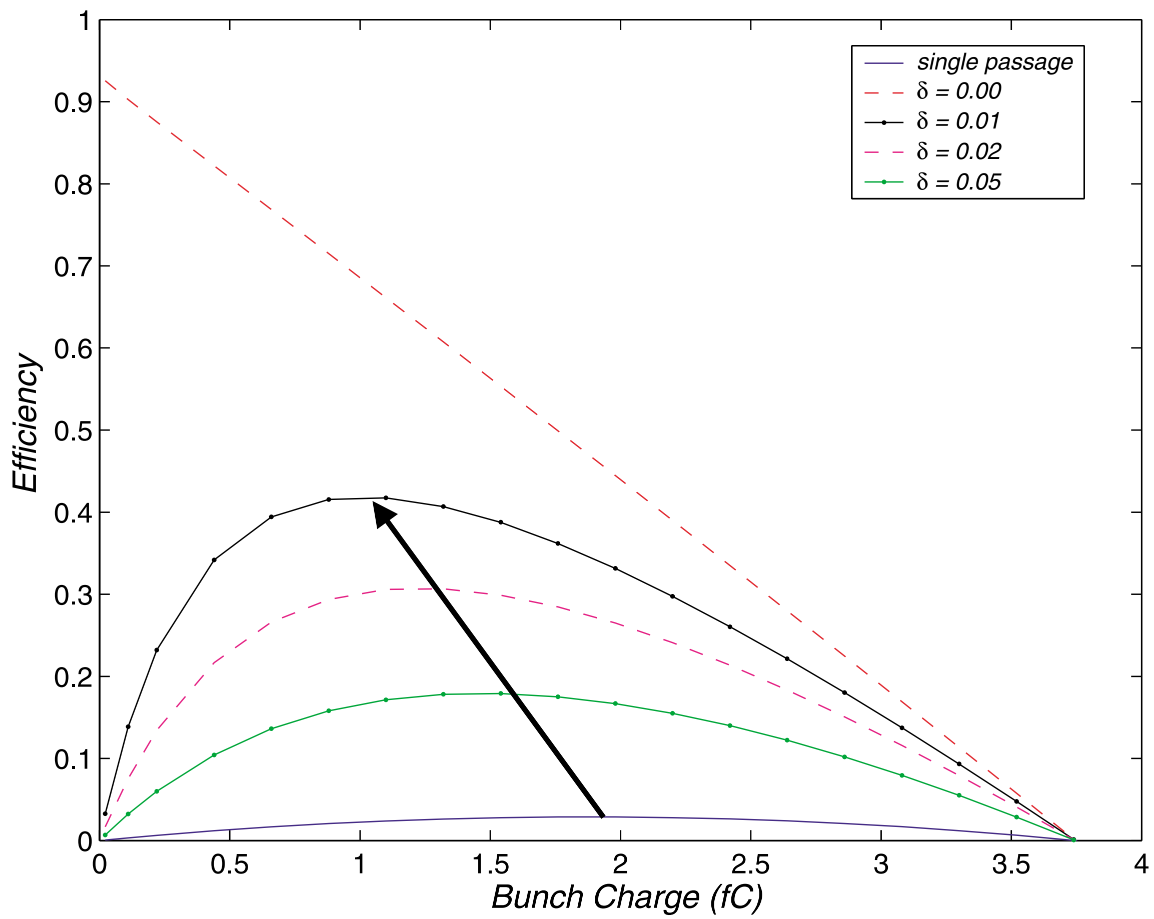
- Ongoing research projects
  - Accelerating of high-charge bunches
  - Staging of accelerating structures
  - Damage threshold of the materials (laser, electrons)

- Future research topics
  - Efficient coupling of the electromagnetic fields
  - Confinement by photonic band gap structures
  - Acceleration of ions
  - Efficiency of particle acceleration

Efficiency of particle acceleration

> Incorporate the accelerator structure into the laser cavity

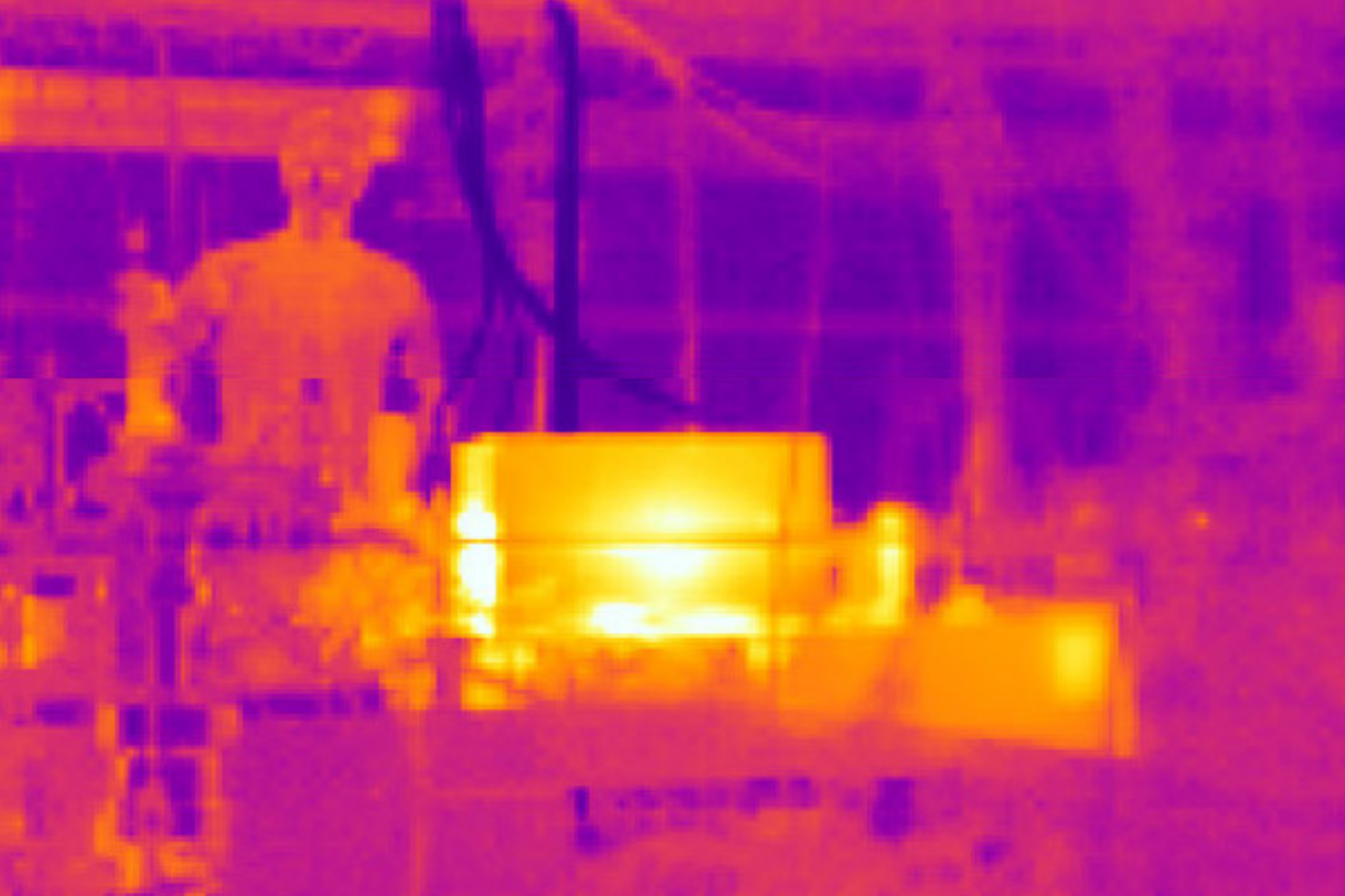




Siemann, PRST-AB **7**, 061303 (2004)

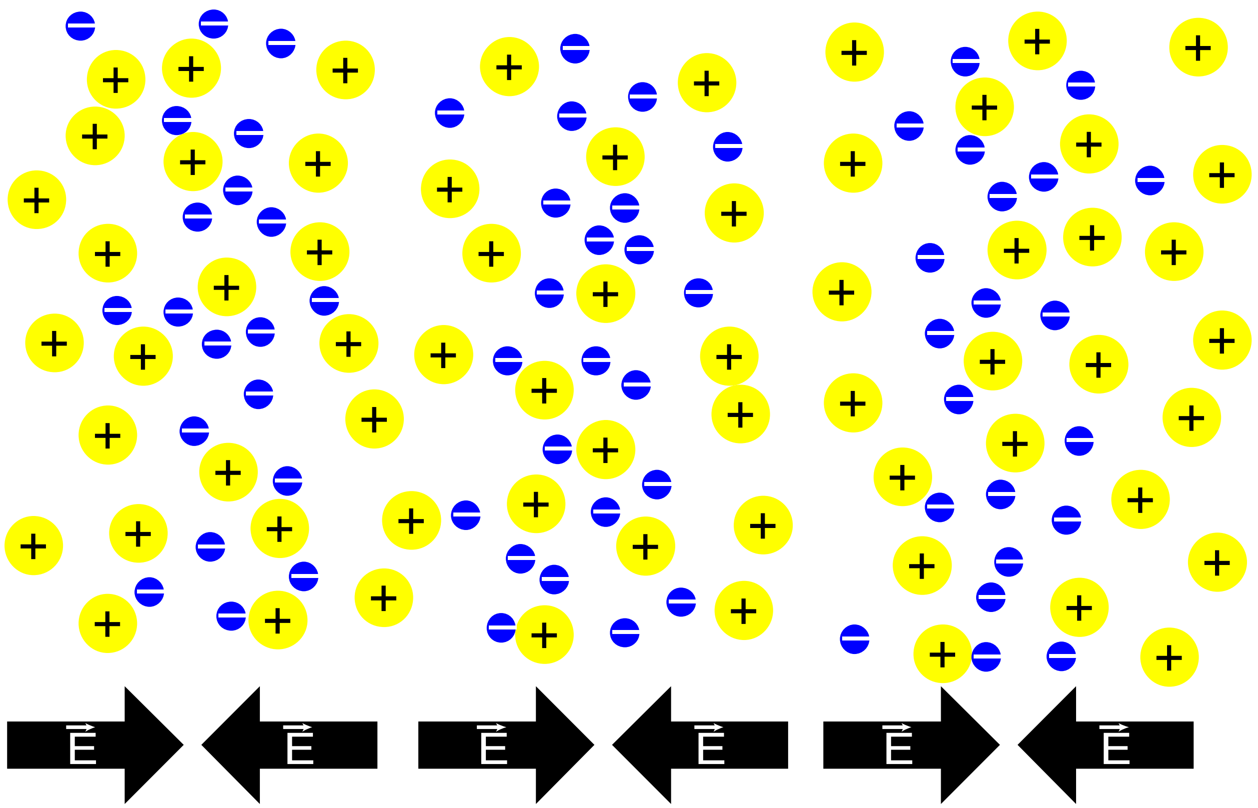
Bob Siemann

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)

- Linear plasma wake:

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

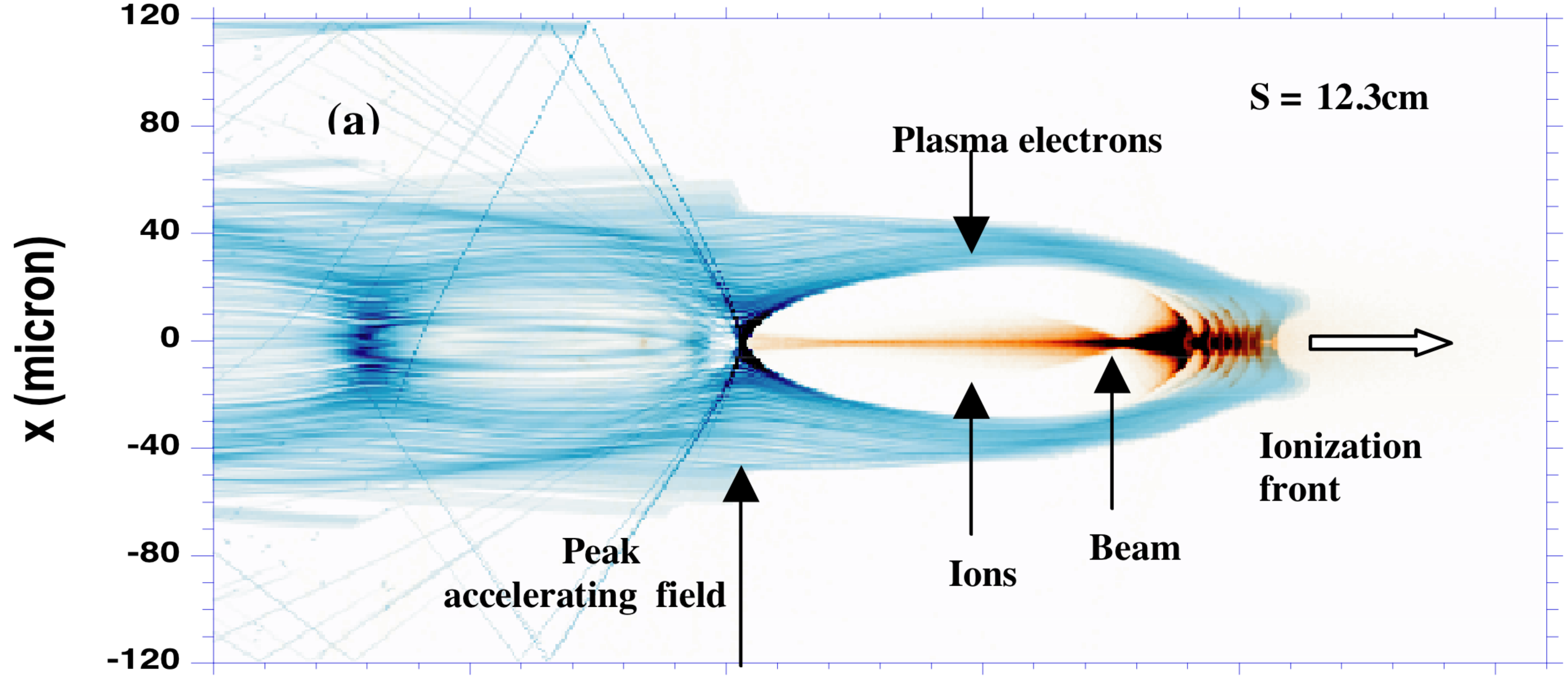
  - Limit:

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

Plasma Wakes – Theory

> Above this limit: non-linear wakes, “Blow-out regime”

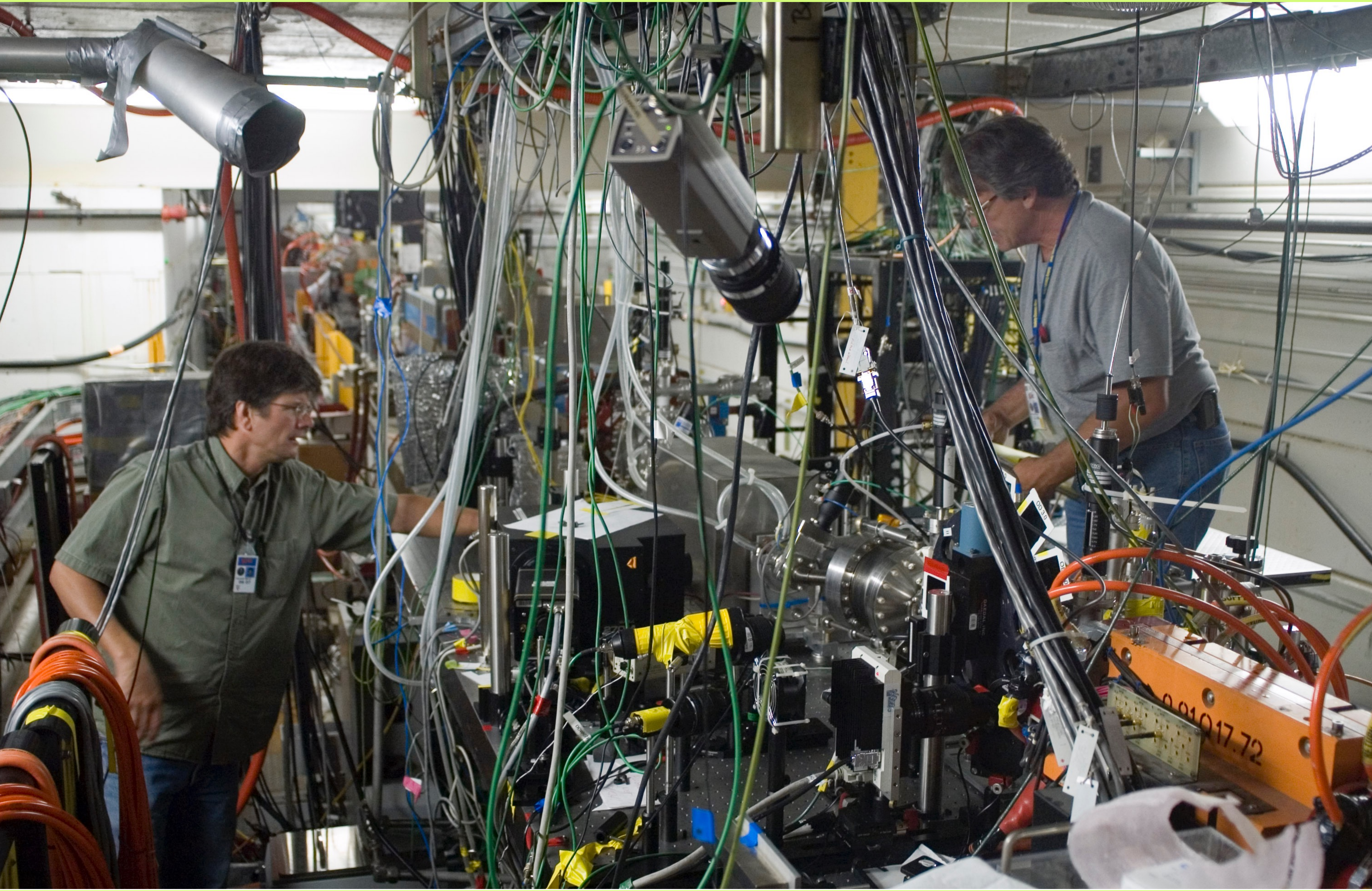
> Fields can be calculated only with numerical methods



> Typical wavelength: 50 μm

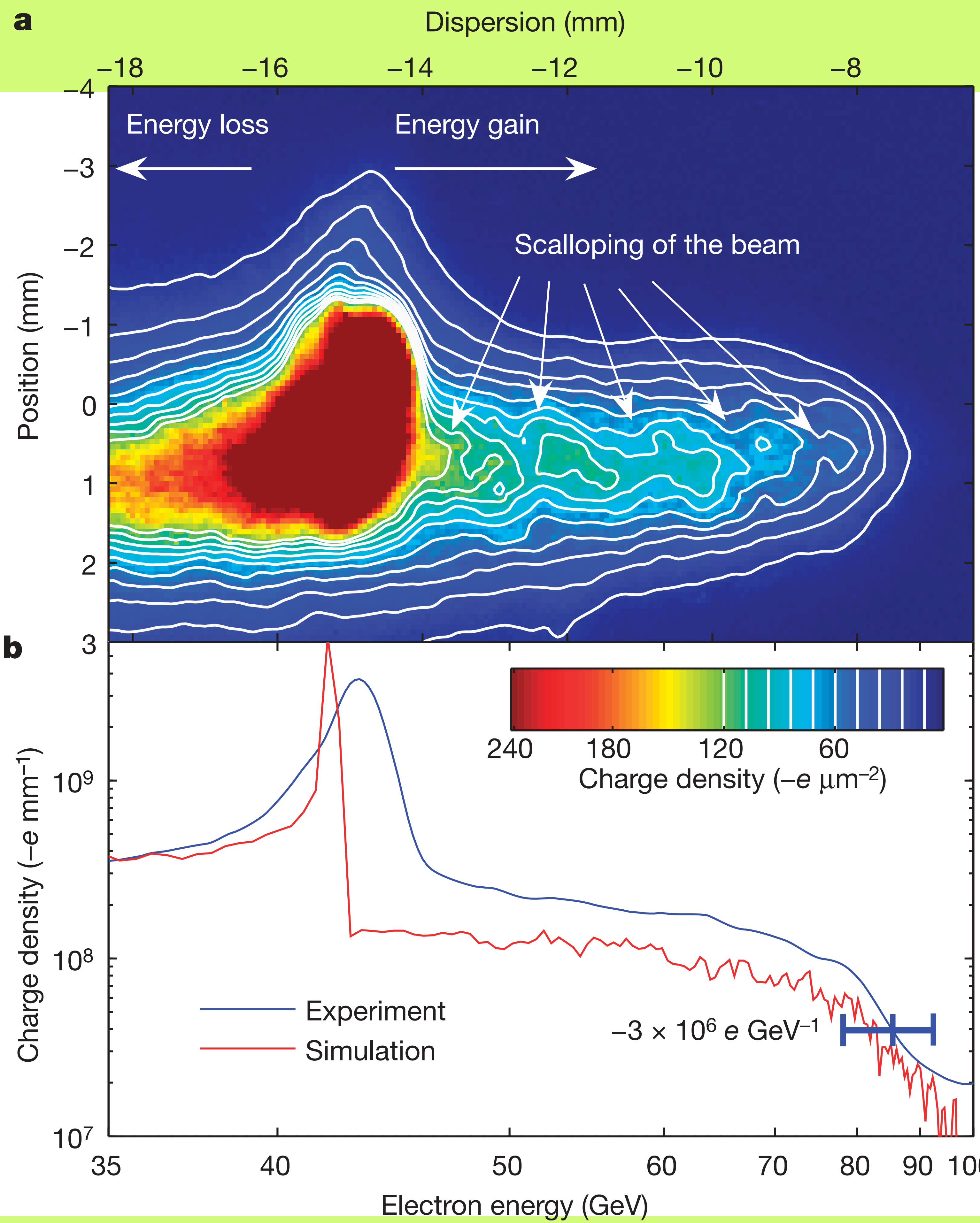
> Accelerating fields up to 50 GV/m

Plasma Wakes – Reality



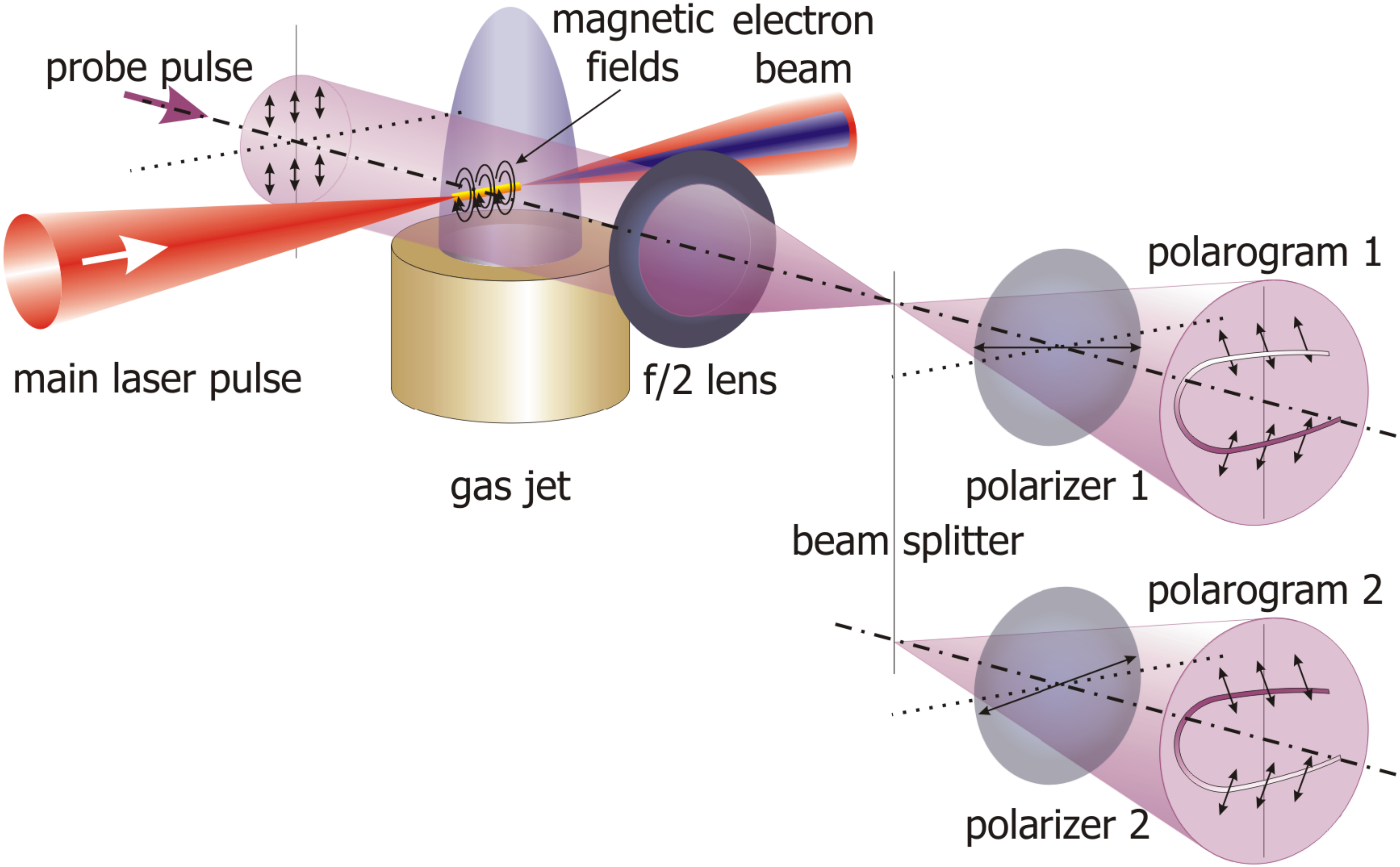
Energy Doubling

> Plasma length: 85 cm
> Density: 2.7•10^{23} m^{-3}
> Incoming energy: 42 GeV
> Peak energy: 85±7 GeV



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

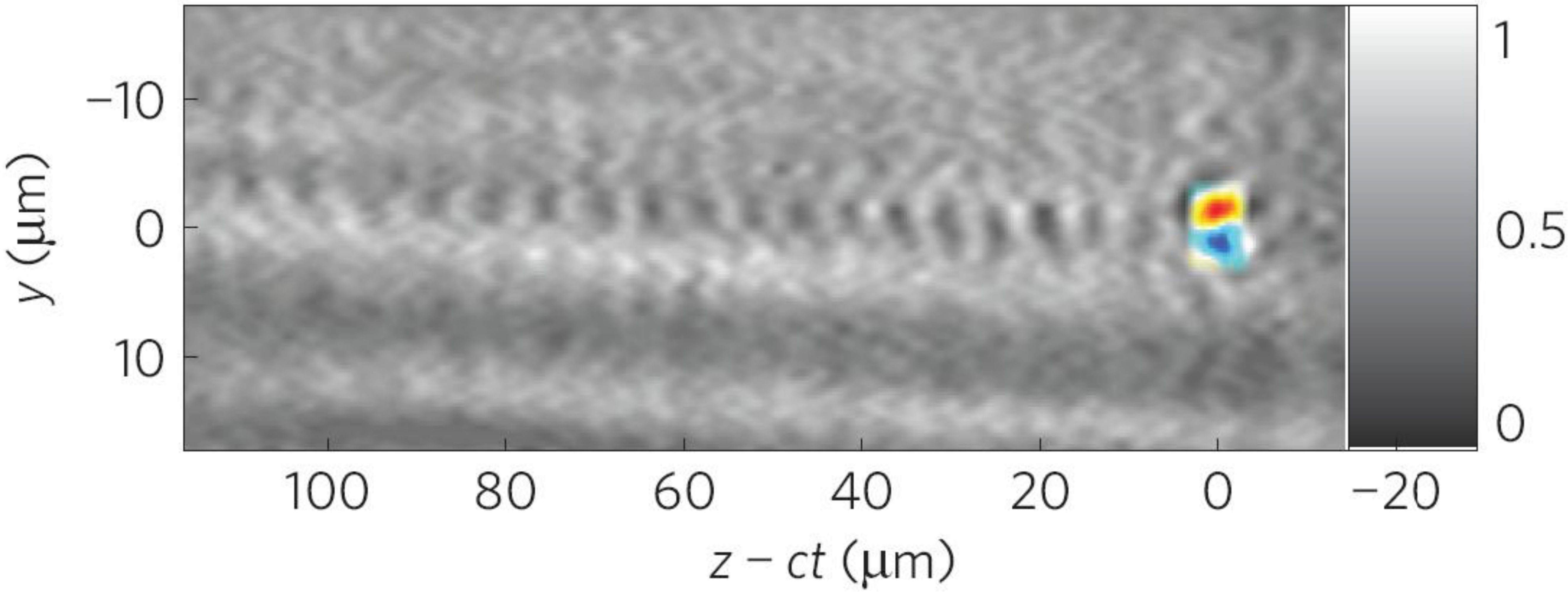
Measurement of Electromagnetic Fields



Malte Kaluza, private communication

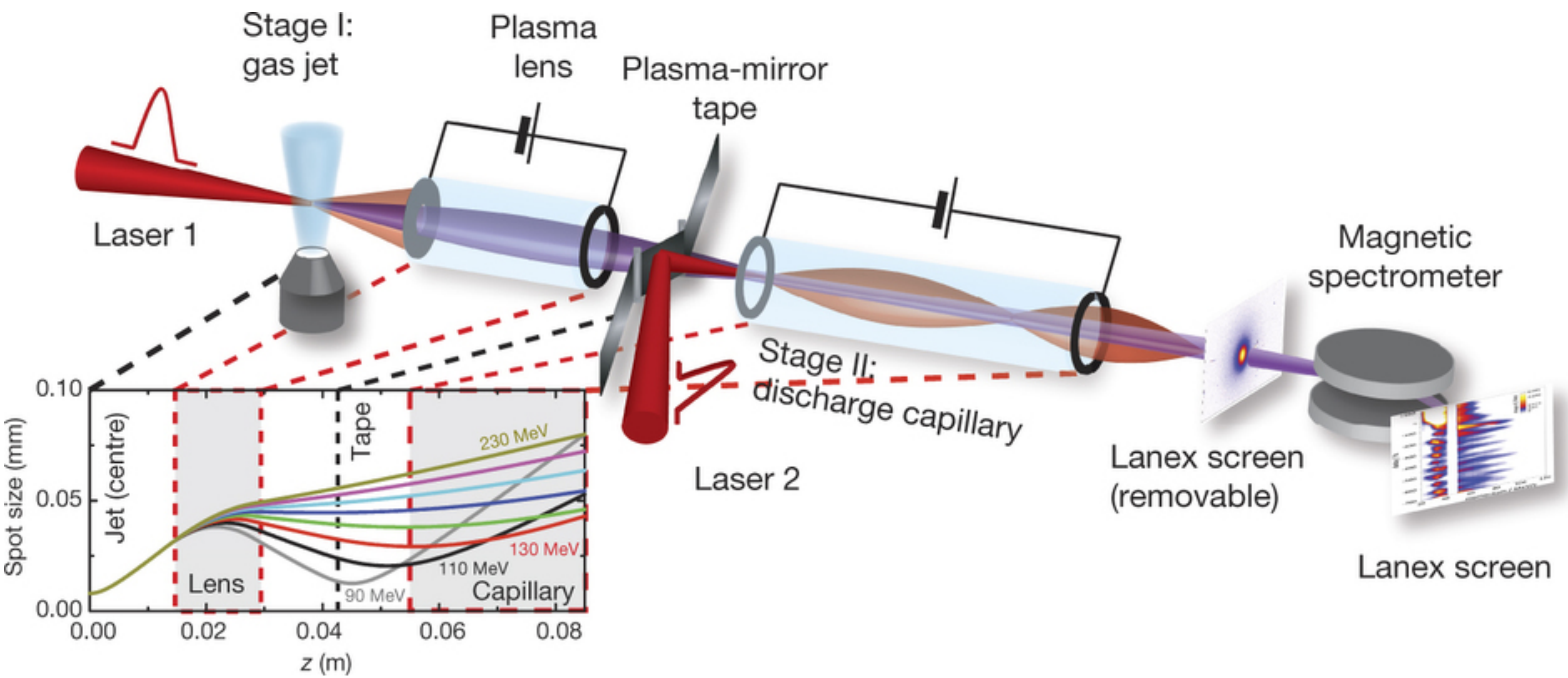
Measurement of Electromagnetic Fields

> Measurement of Plasma Wake (b/w) and Injected Electrons (color)



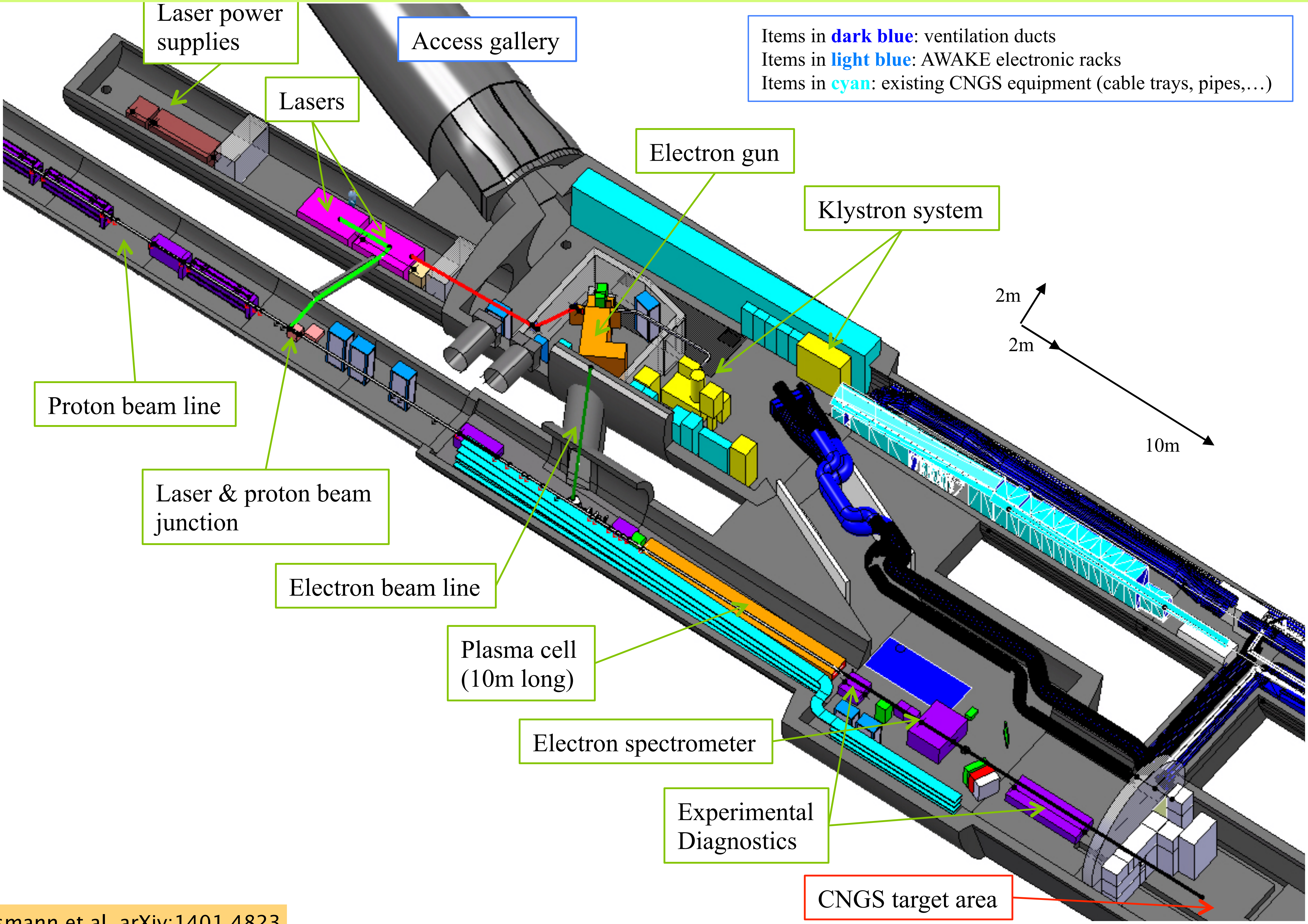
Malte Kaluza, private communication

Staging of Two Accelerators



Steinke et al., Nature **530**, 190 (2016)

Drive the wake by a Proton Beam



Assmann et al, arXiv:1401.4823

Plasma Accelerators — Current Research Topics

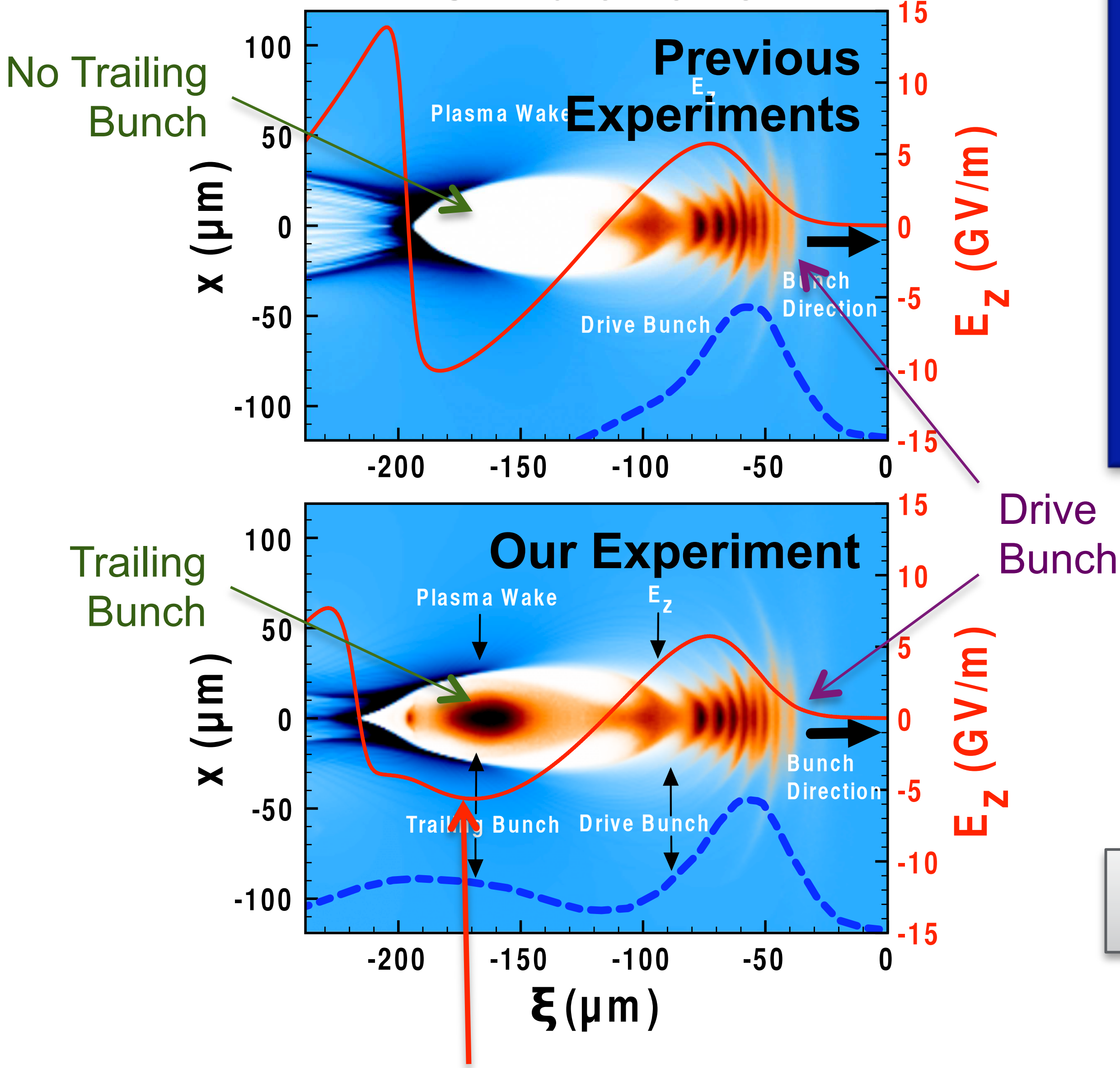
- Achievements of recent years
  - Proof-of-principle experiments demonstrating accelerating fields of tens of GV/m
  - Meter-scale plasmas that allow high energy gain
  - Characterization of plasma wakes

- Ongoing research projects
  - Staging of accelerating structures
  - Control energy spread
  - Efficiency of particle acceleration

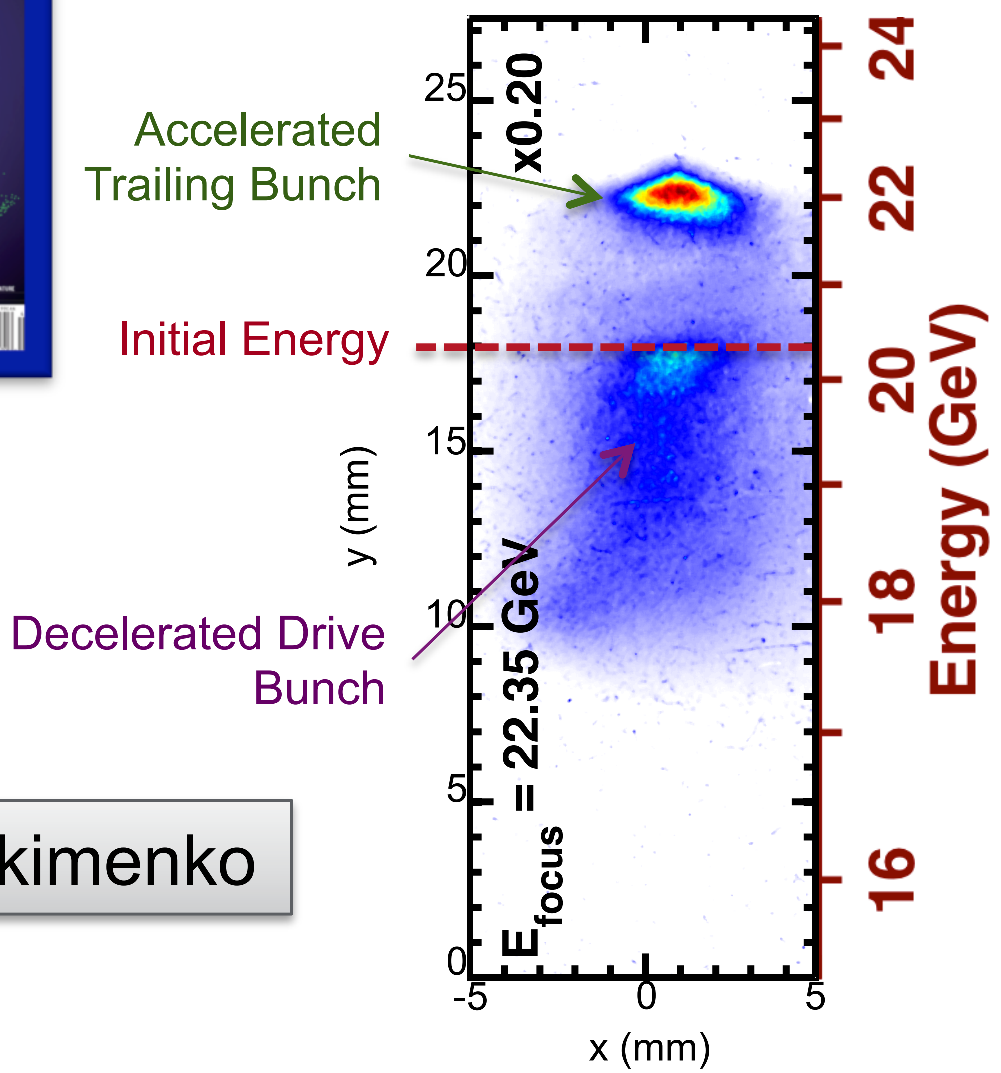
- Future research topics
  - Efficient generation of plasma wakes with proton beams
  - Match electron beam into plasma with micrometer precision

Energy Efficiency

Simulations



Energetically Dispersed Beam After Plasma (**Data**)

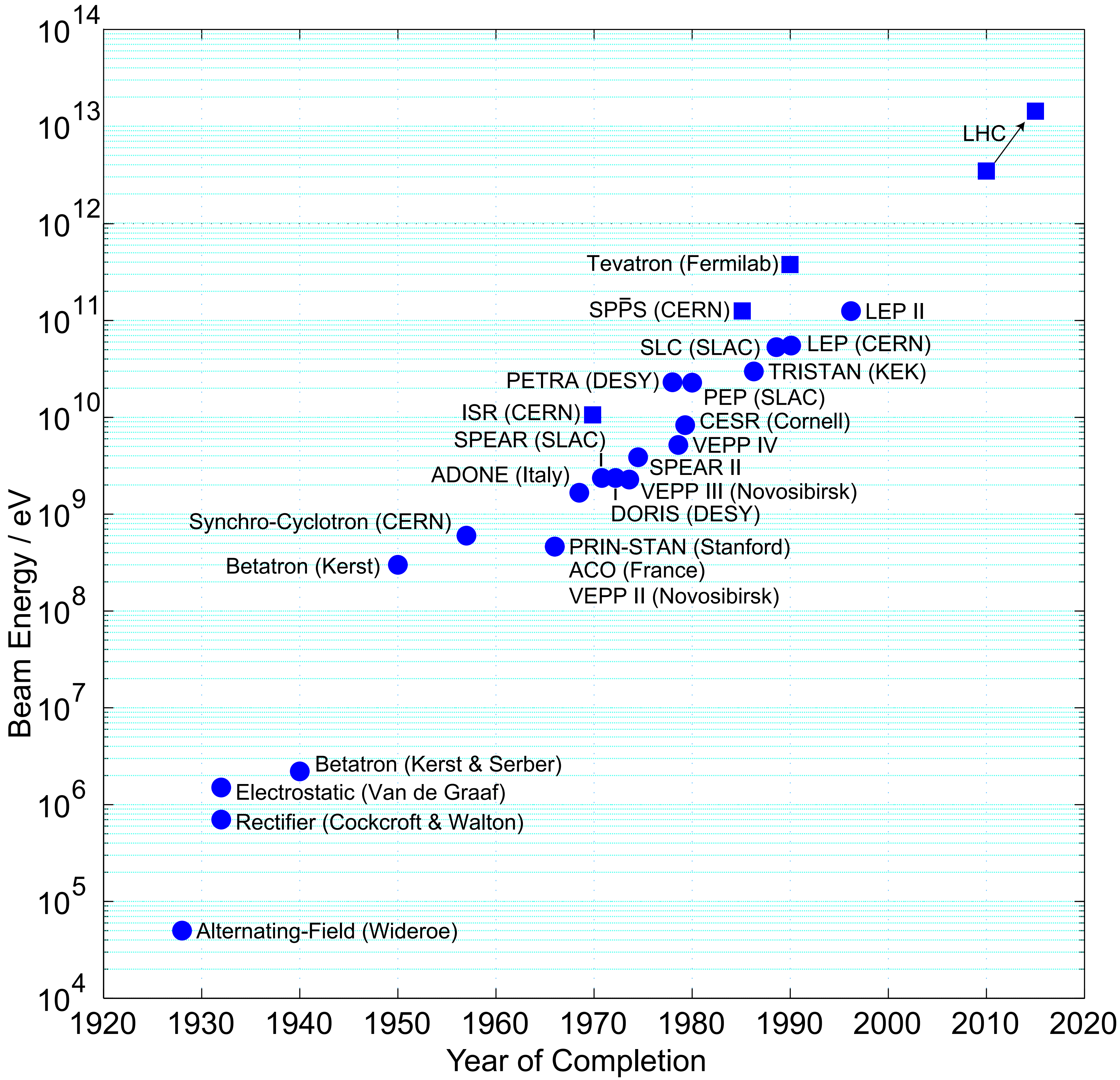


Slide: V. Yakimenko

Applicability of Plasma Wakefield Accelerators to HEP

- Arnd Specka, Ecole Polytechnique Paris
- Roman Walczak, Uni Oxford
- Meeting Paris October 2016

History of Particle Accelerators — Livingston Plot



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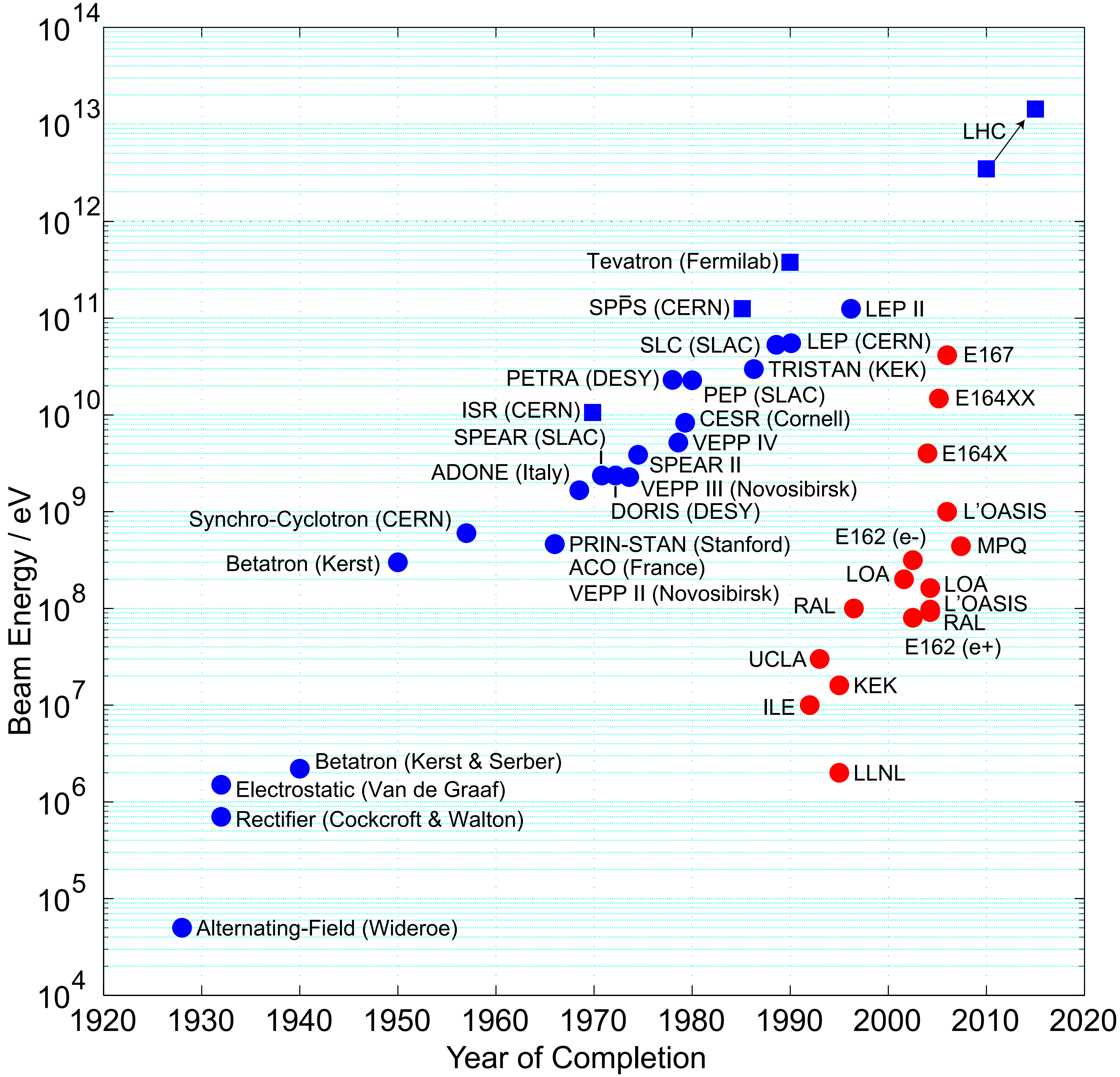
An Unfair Comparison



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