Advancements in Particle Accelerators: Harnessing THz Technology for Next-Generation Acceleration (Micro Accelerators THz)

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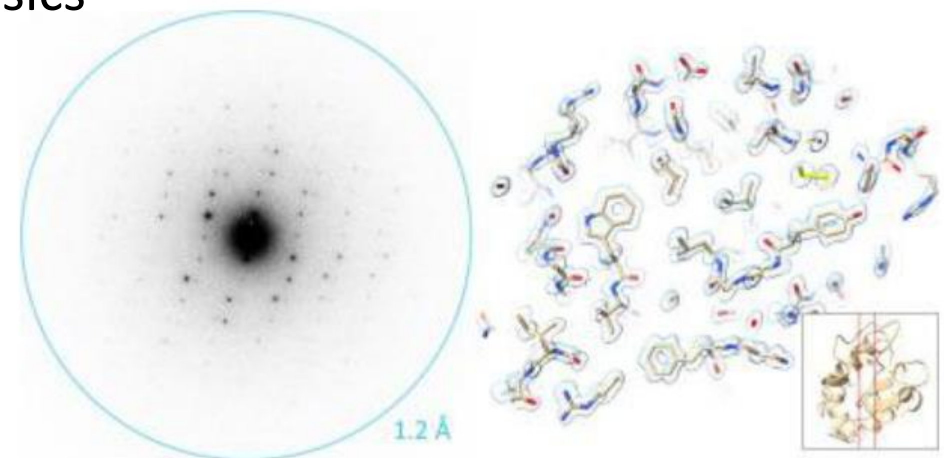
EuPRAXIA Doctoral Network
HUN-REN Hungarian Research Network
UNIVERSITY OF PÉCS SZENTAGOTHAI RESEARCH CENTRE

Outline

Motivation

Applications of particles with different properties

- Medical application
- Light sources
- Industrial applications
- Safety
- Cosmology and Particle Physics

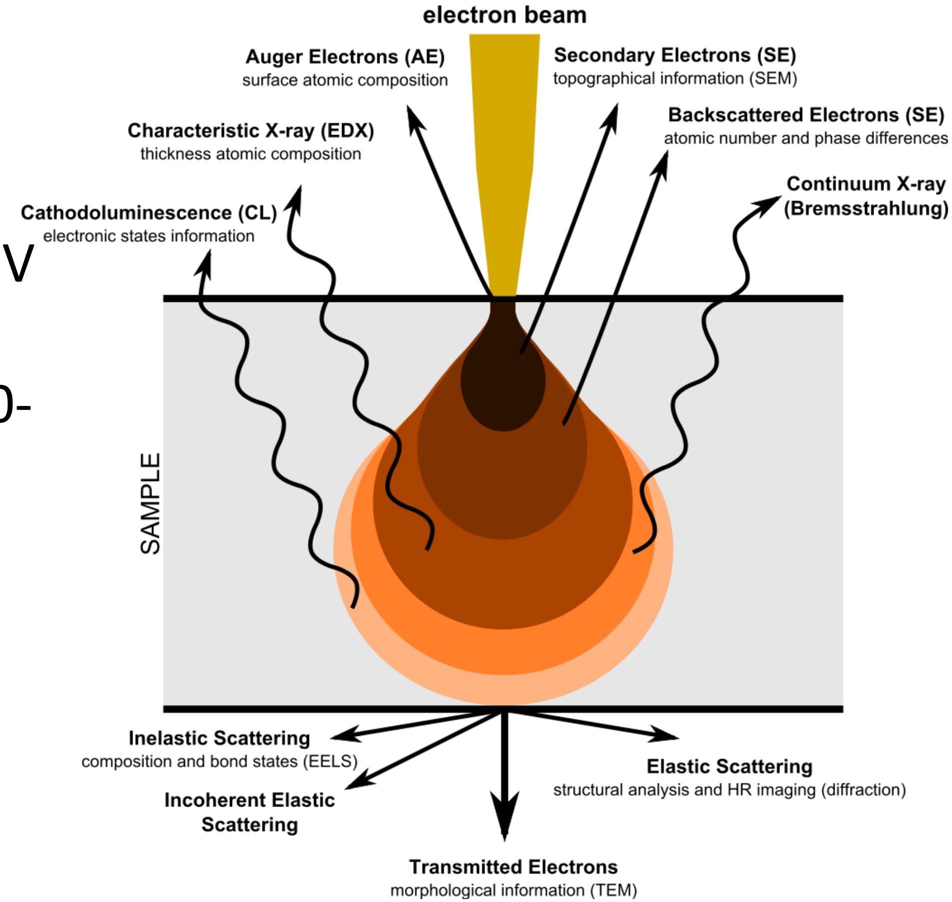


Max T B Clabbers et al., Journal of Structural Biology (2022)

Motivation

Areas of application (electron)

- Electron Microscopy
  - TEM (a few 1 – a few 100 keV)
  - SEM (a few eV – a few keV)
- Auger electron spectroscopy (a few eV – 50 keV)
- Electron energy loss spectroscopy (10-30 keV)
- Electron stimulated desorption experiments (a few eV- a few keV)
- Electron diffraction (a few 100 keV)
- Electron emission experiments
- Particle manipulation experiments
- Other imaging and scanning procedures

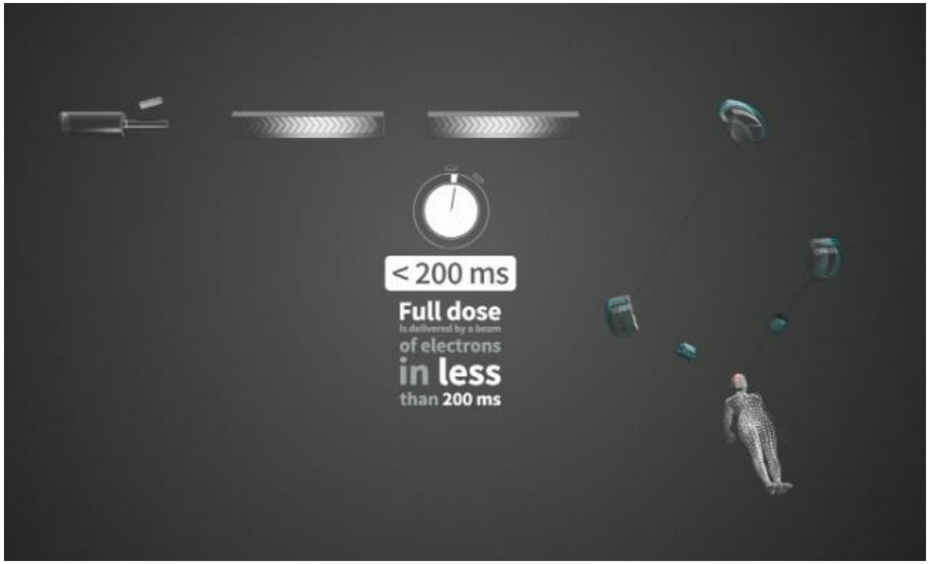


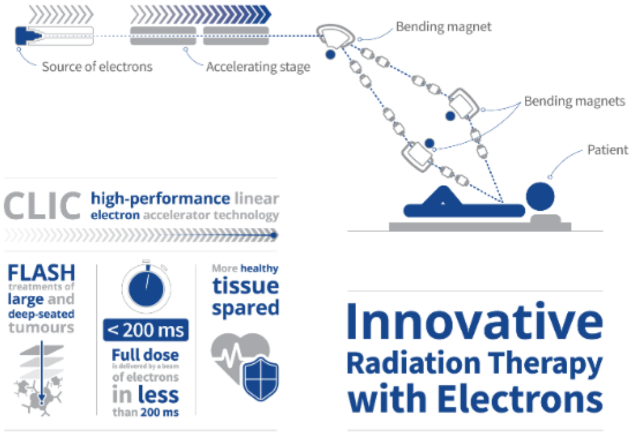
https://en.m.wikipedia.org/wiki/File:Electron_Interaction_with_Matter.svg

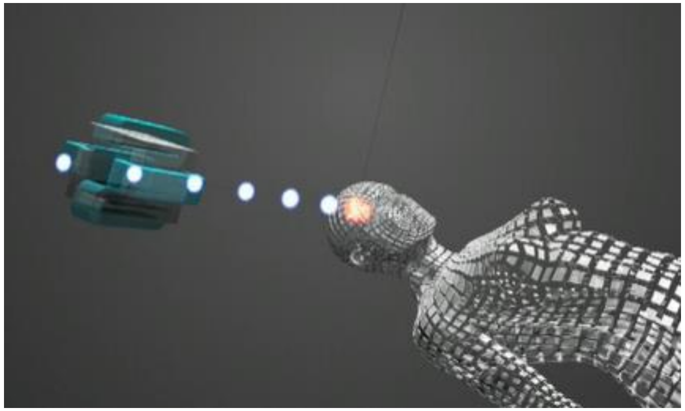
Motivation

Areas of application (electron)

- Particle manipulation experiments
  - X-ray generation
    - Medical imaging
    - X-ray diffraction
    - X-ray spectroscopy
  - FLASH radiotherapy
    - VHEE (few MeV)





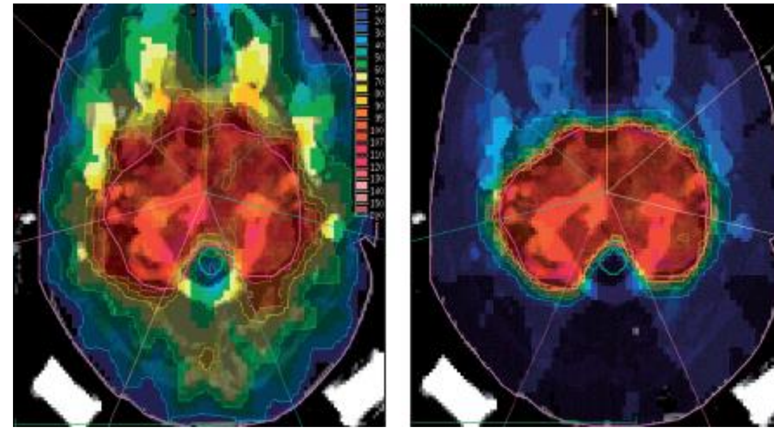


https://kt.cern/flash-radiotherapy

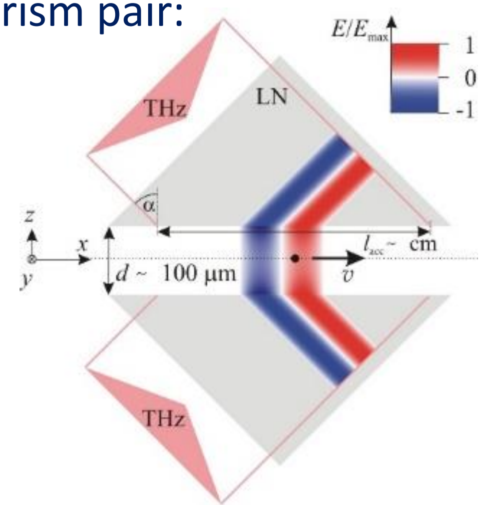
Motivation

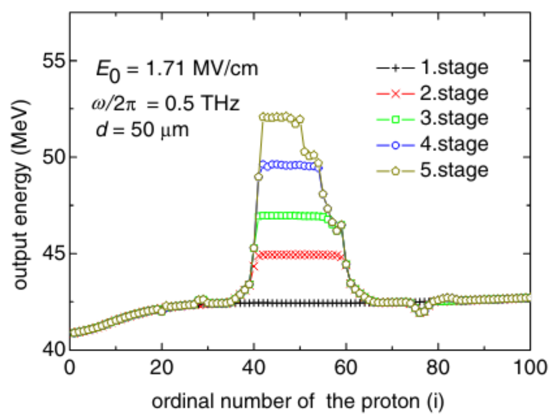
Areas of application (heavy ion)

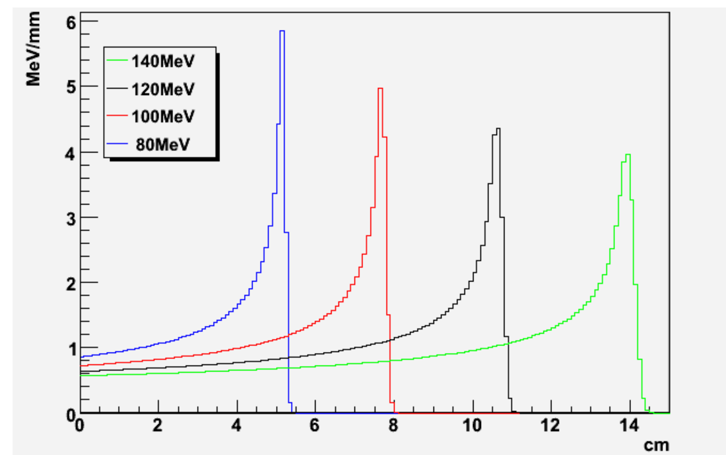
- Hadrontherapy
- Radiobiological Research (LET)
- Space Radiation Research
- Material modification
- Nuclear Physics Research
- Archaeology and Cultural Heritage



Prism pair:







Pálfalvi et al., Phys. Rev. ST Accel. Beams 17, 031301 (2014)

PARTICLE ACCELERATORS

Particle accelerators - Traditional particle accelerators

Traditional particle accelerators are sophisticated machines designed to propel charged particles, such as protons or electrons**, to extremely high speeds and energies.**

- Linear Accelerators (LINACs)
  - **Use a straight path to accelerate particles**. Electric fields are applied along the path to continously accelerate charged particles
  - **Commonly used in medical facilities for cancer treatment, industrial applications (stelirization, material analysis)**
  - High cost of construction and maintenance, limited achievable energy compared to other types of accelerators.

Particle accelerators - Traditional particle accelerators

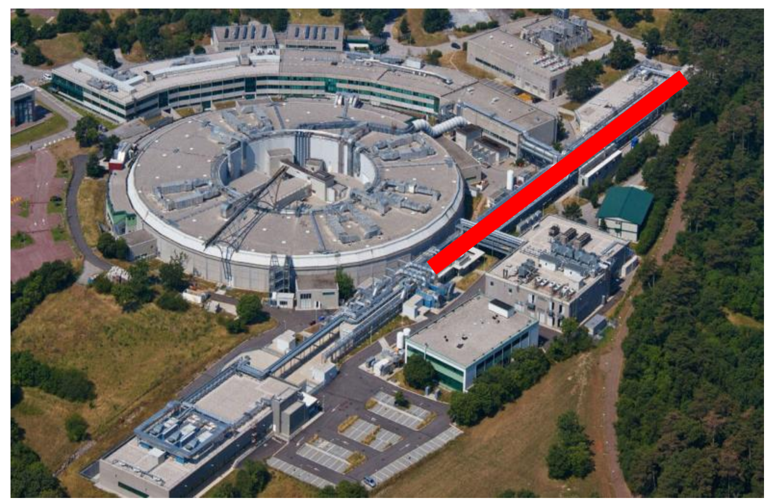
- Linear Accelerators (LINACs)

SACLA

SLAC

FLASH

FERMI



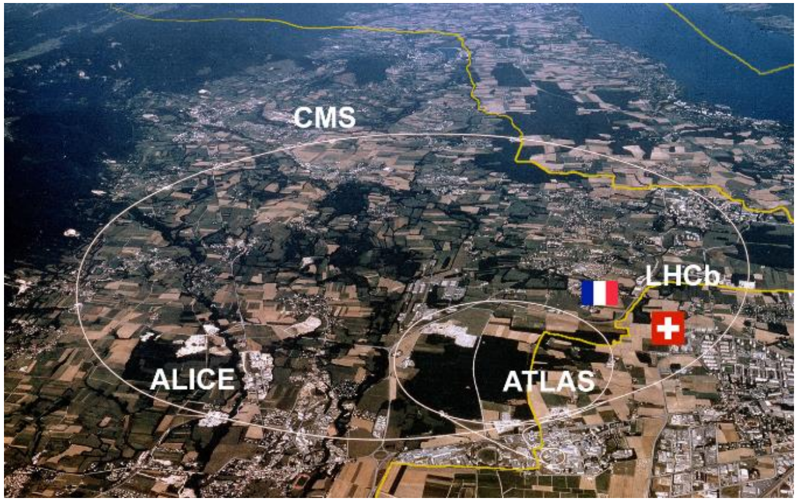
Particle accelerators - Traditional particle accelerators

Traditional particle accelerators are sophisticated machines designed to propel charged particles, such as protons or electrons**, to extremely high speeds and energies.**

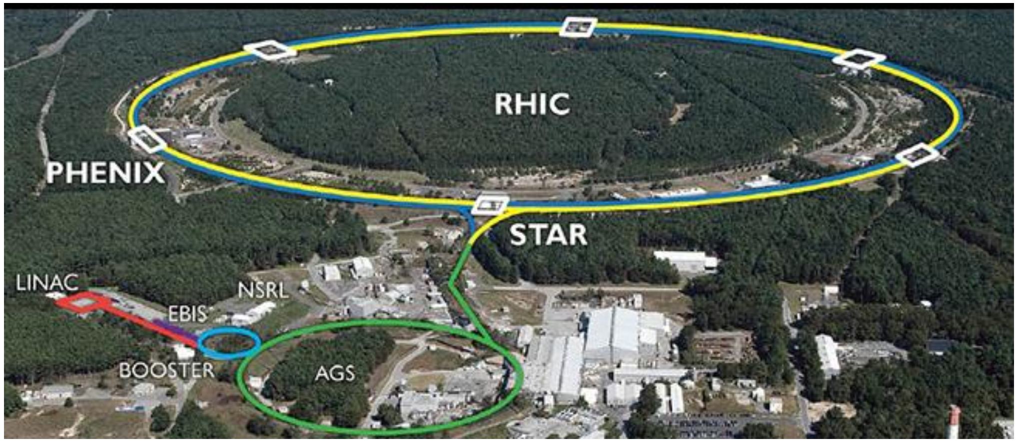
- Circular Accelerators (cyclotrons, synchrotons)
  - **Accelerate particles in circular paths** using magnetic fields to keep them on course.
  - **Commonly used in particle physics experiments, medical imaging, industrial material analysis.**
  - Need for large-scale infrastructure, high energy consumption, **limitations on** achieving extremely **high energies due to the relativistic effects.**

Particle accelerators - Traditional particle accelerators

- Circular Accelerators (cyclotrons, synchrotons)



Large Hadron Collider (LHC, CERN)



Relativistic Heavy Ion Collider (RHIC, New York)

Particle accelerators - Traditional particle accelerators

- Limitations:
  - Cost: Building and maintaining particle **accelerators require substantial financial resources**, often running into **billions of dollars** for large-scale facilities.
  - Size and Infrastructure: Many traditional accelerators are **massive in size** and **require complex infrastructure**, including extensive cooling and power systems.
  - Energy Limitations: **Despite achieving high energies**, there are practical limits to how fast particles can be accelerated due to technological constraints and **energy losses**.
  - Relativistic effects: As particles approach the speed of light, **relativistic effects become significant**, making it **increasingly challenging to accelerate** them further.
  - Beam quality: Maintaining **high-quality particle beams** over extended periods presents **technical challenges**, limiting the efficiency and reliability of accelerators.

Particle accelerators - Micro accelerators (Future!?)

Particle accelerators

Small really is beautiful

Fundamental physics seems to have an insatiable appetite for bigger, more expensive machines. There may, though, be a way to shrink them radically

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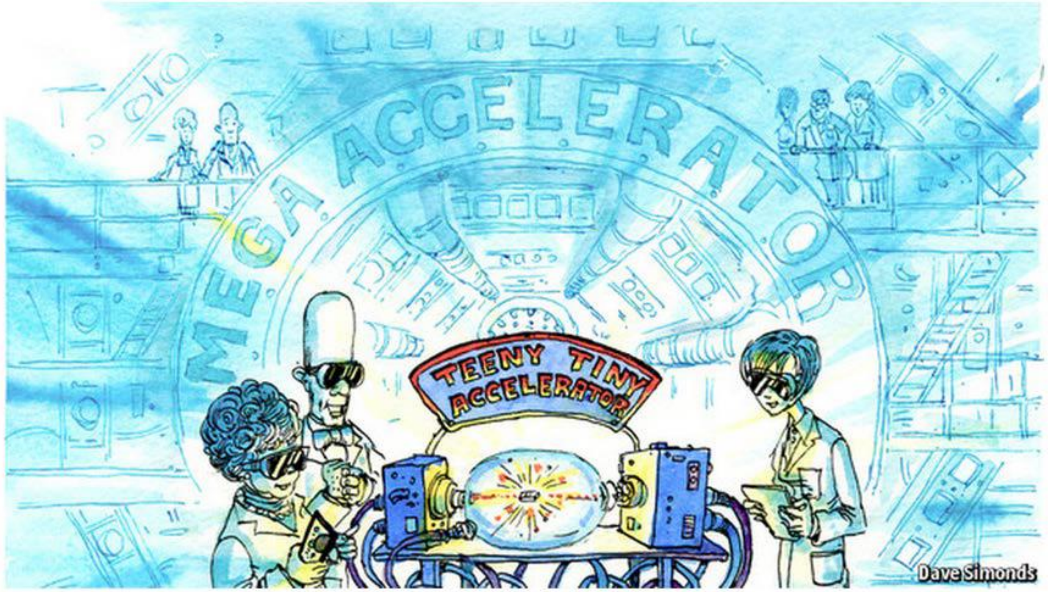


BIG science tends to get bigger with time. The first modern particle accelerator, Ernest Lawrence's cyclotron, was 10cm across and thus fitted comfortably on a benchtop. It cost (admittedly at 1932 prices) $25. Its latest successor, the Large Hadron Collider (LHC), has

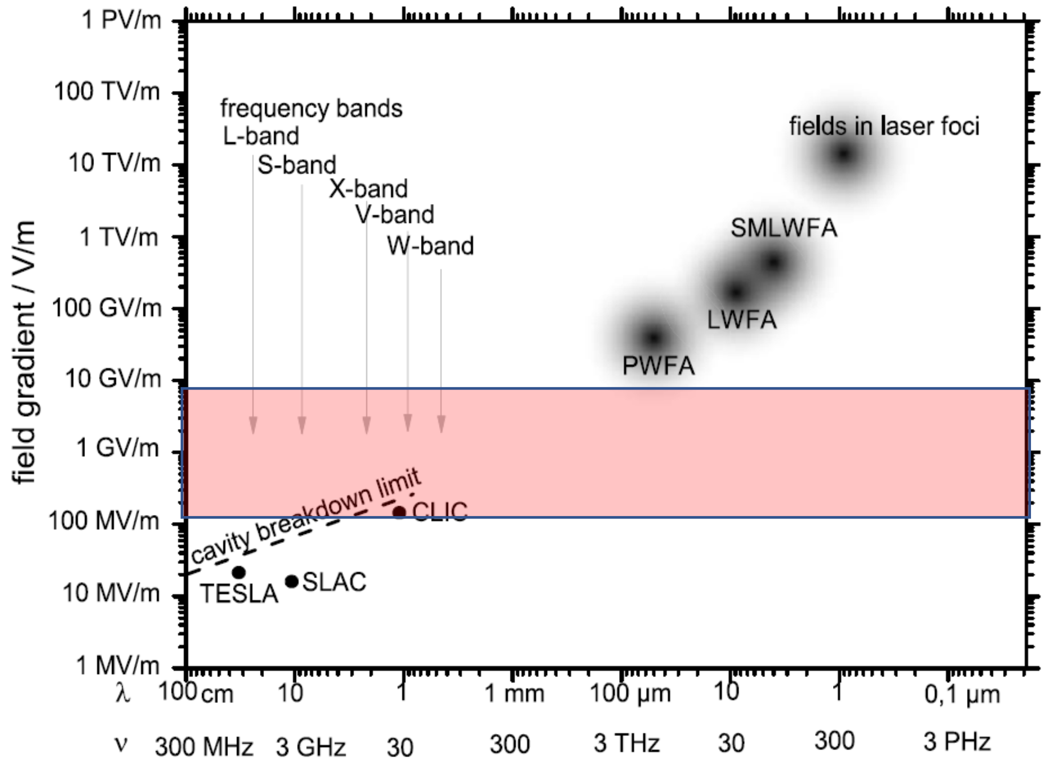
https://www.economist.com/science-and-technology/2013/10/19/small-really-is-beautiful

Particle accelerators - Micro accelerators (Future!?)

MAIN GOAL

High gradients innovative **accelerating structures** enable miniaturized particle accelerators

Accelerating Gradient:
~ 100 MV/m - 10 GV/m



schematic overview of the accelerating gradient for different types of accelerators

Particle accelerators - Micro accelerators (Future!?)

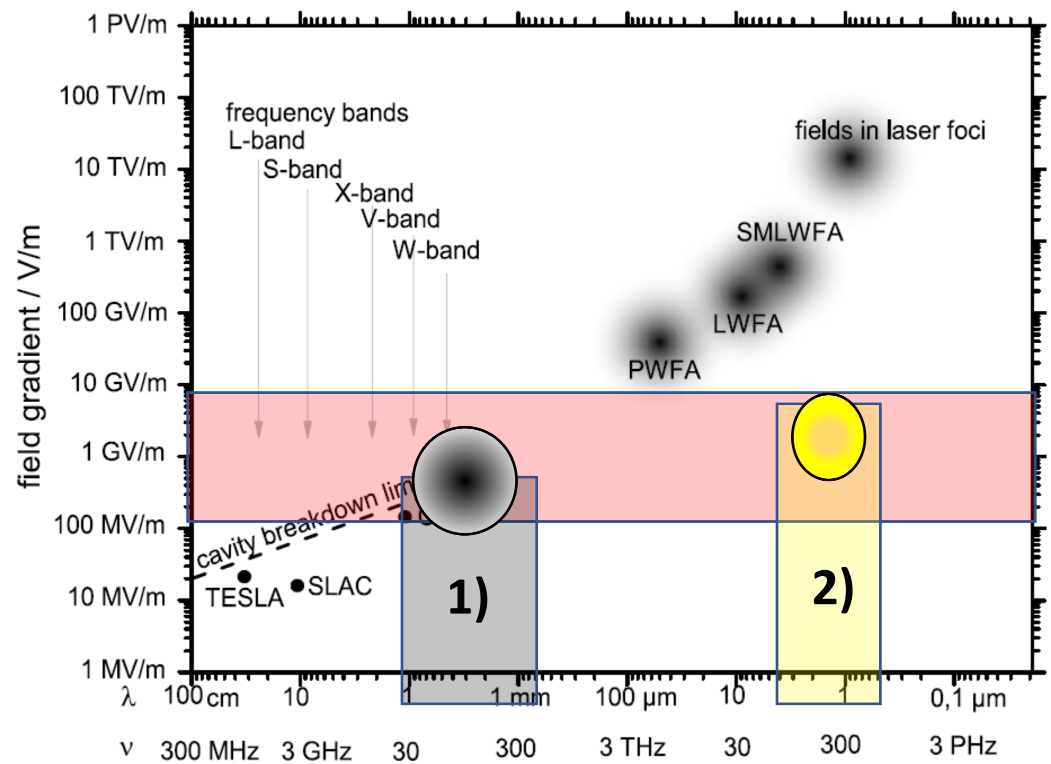
MAIN GOAL

High gradients innovative **accelerating structures** enable miniaturized particle accelerators

Accelerating Gradient:
~ 100 MV/m - 2 GV/m

1) **Metallic Structure from Ka to W-band (35-200 GHz, mm-wavelength)**
- **30 – 50 MeV/m**

2) Dielectric Laser Accelerator (DLA) structures operating at optical wavelengths (~ 1- 5 µm)



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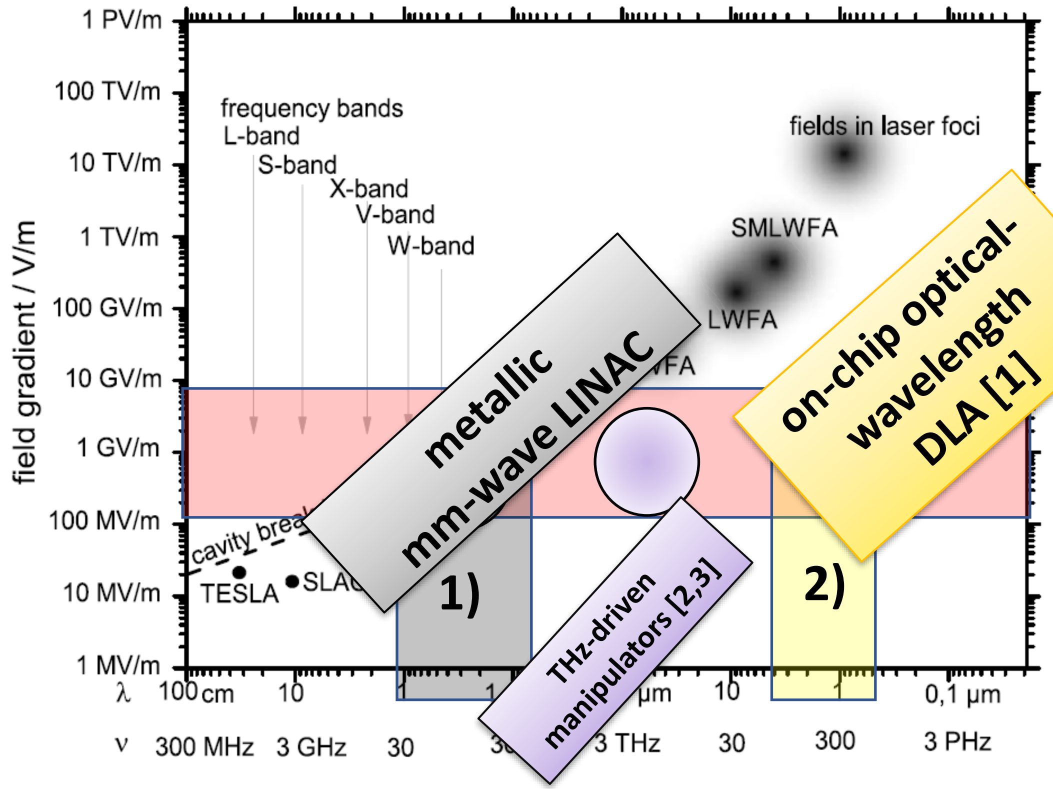
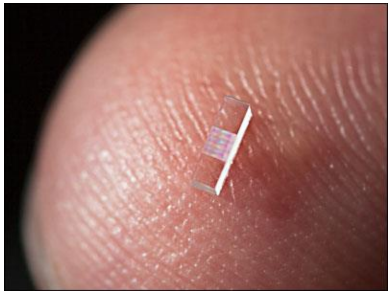
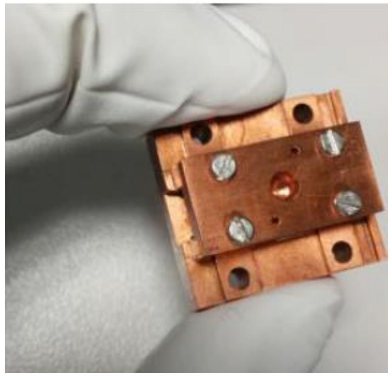


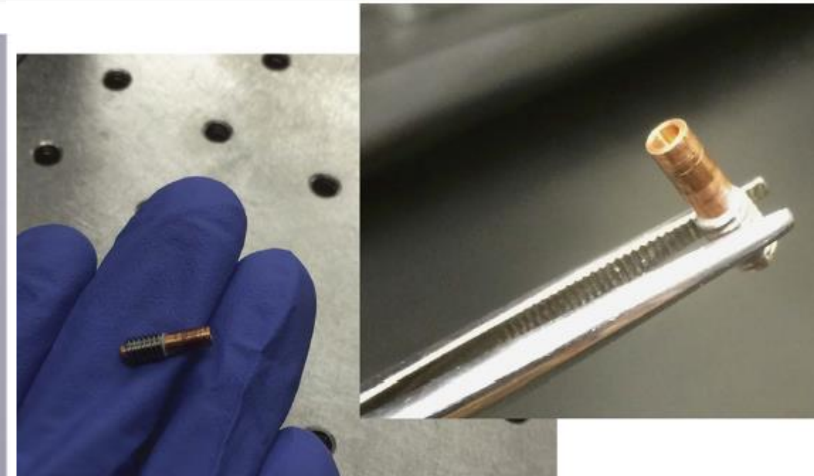
schematic overview of the accelerating gradient for different types of accelerators

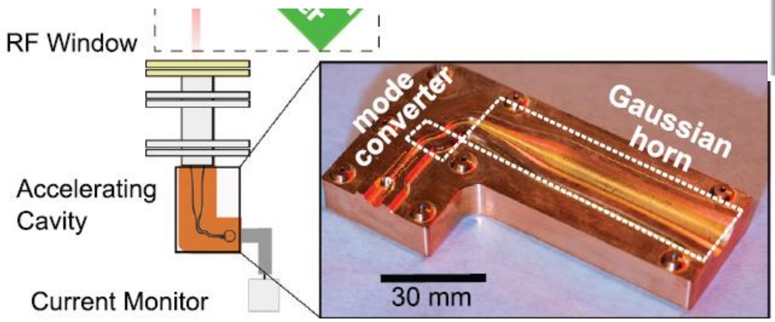
[1] R. Joel England et al., Rev. Mod. Phys. 86, 1337 (2014)
[2] E. Nanni, et al., Nat Commun 6, 8486 (2015).
[3] F. Lemery, et al." Commun Phys 3, 150 (2020).

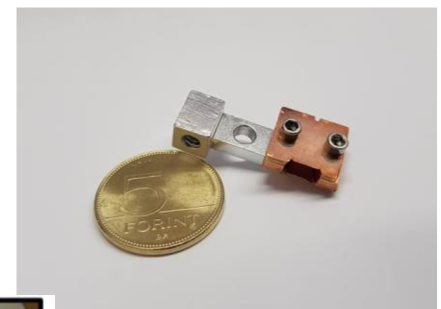
Particle accelerators - Micro accelerators (Future!?)

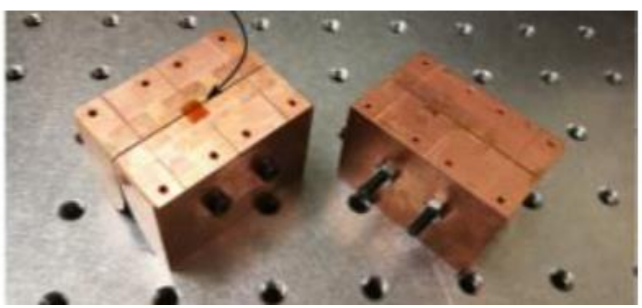


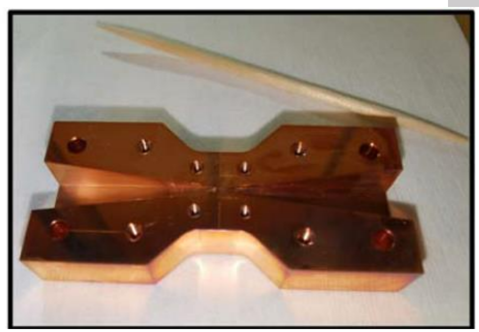


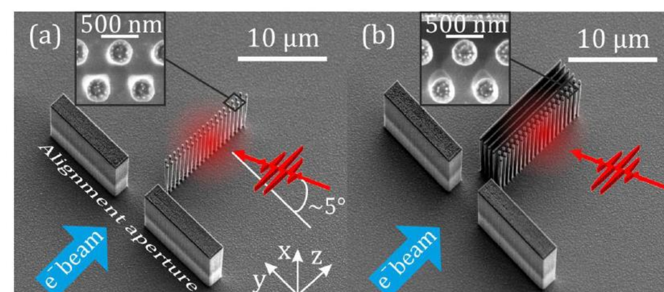








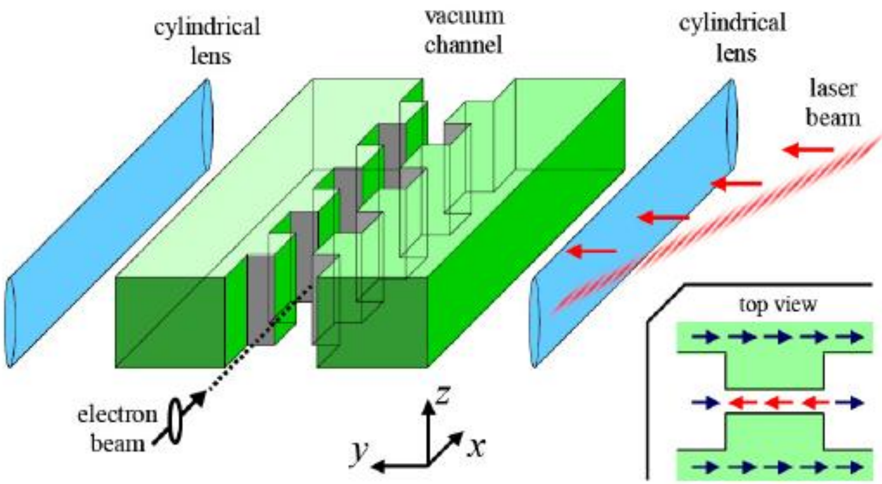


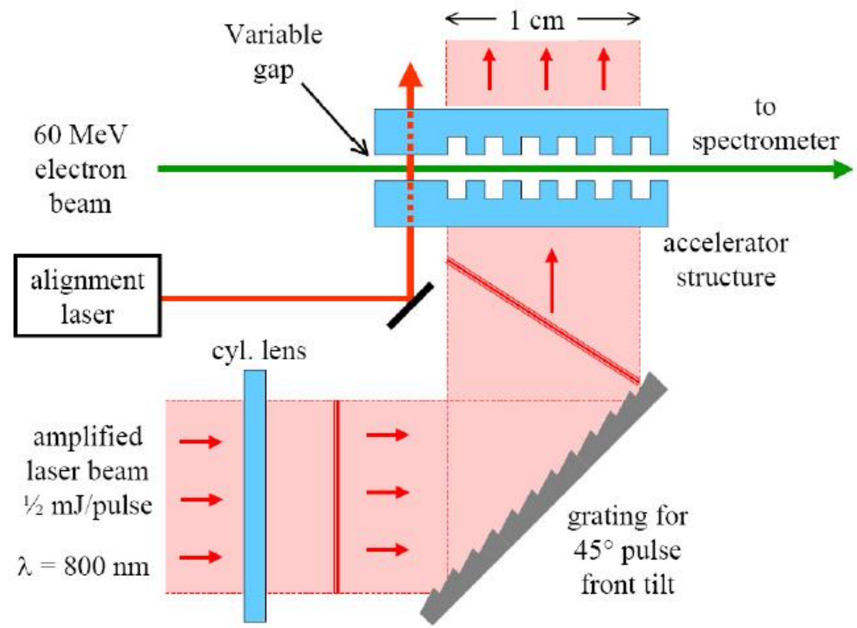


Particle accelerators - Micro accelerators (Future!?)

- Dielectric Laser-driven Accelerators – Dielectric grating accelerator

- Dual grating accelerator structure designed for ultrashort laser pulse operation
- Periodic field reversal to achieve phase synchronicity fo relativistic particles
- Potential for unloaded gradient of 10 GeV/m with 10 fs laser pulse
- 8 % acceleration efficiency

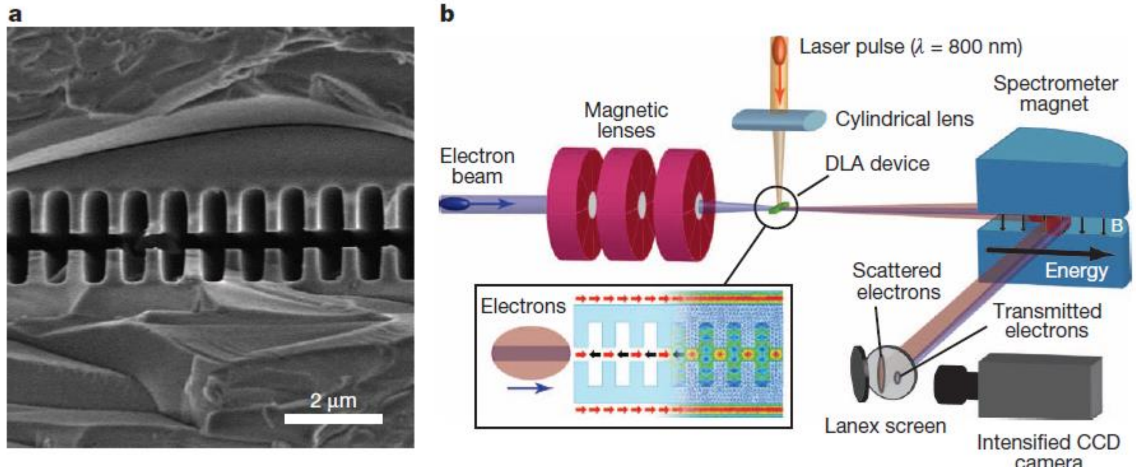


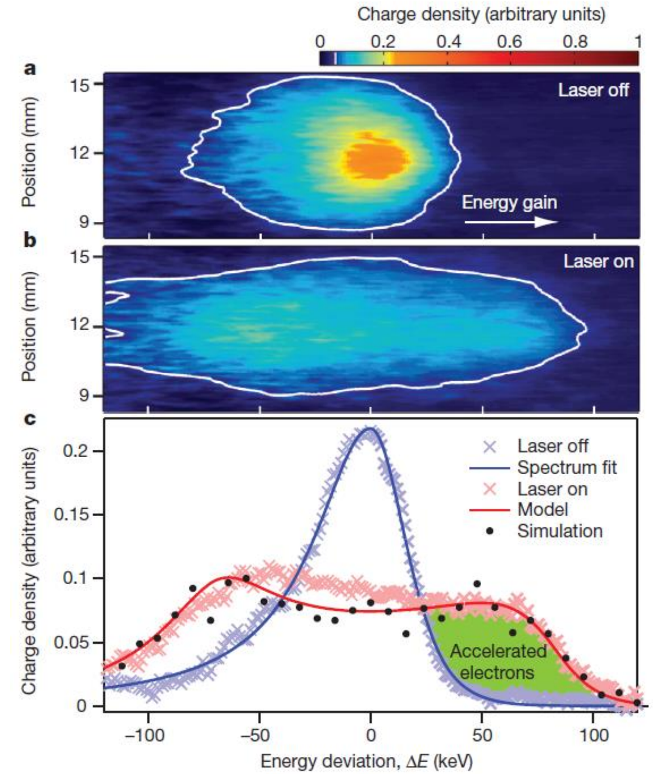


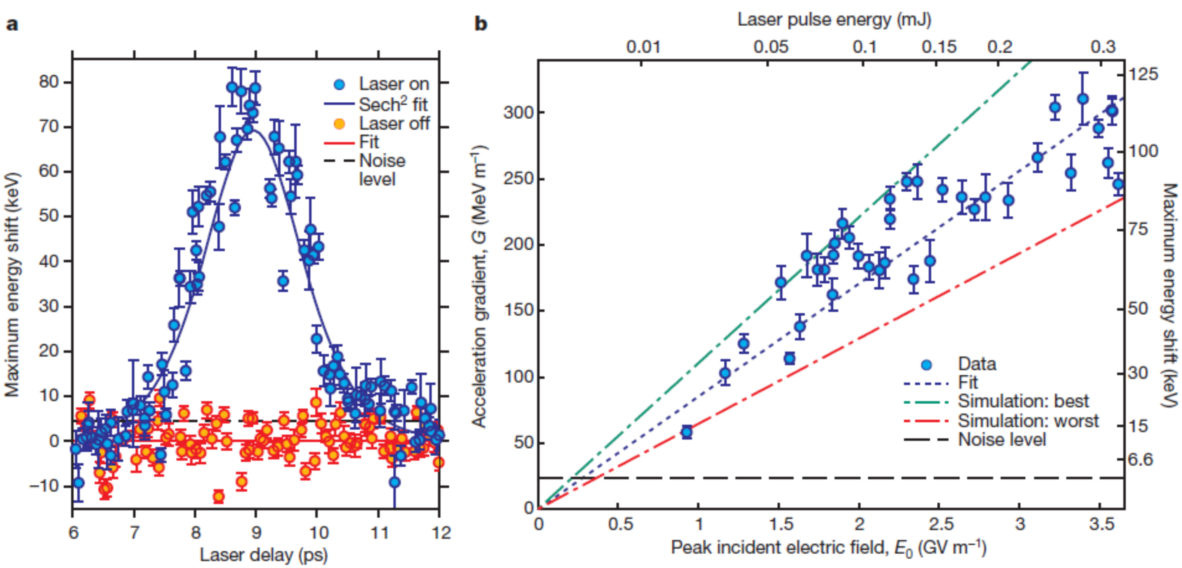
Plettner et al., Phys. Rev. Special Topics-Accelerators and Beams, 9, 111301 (2006).

Particle accelerators - Micro accelerators (Future!?)

- <u>Dielectric Laser-driven Accelerators – Dielectric grating accelerator</u>





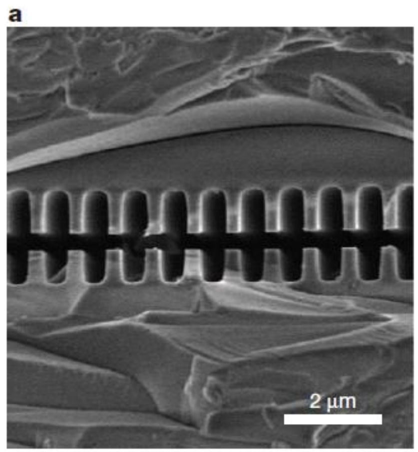


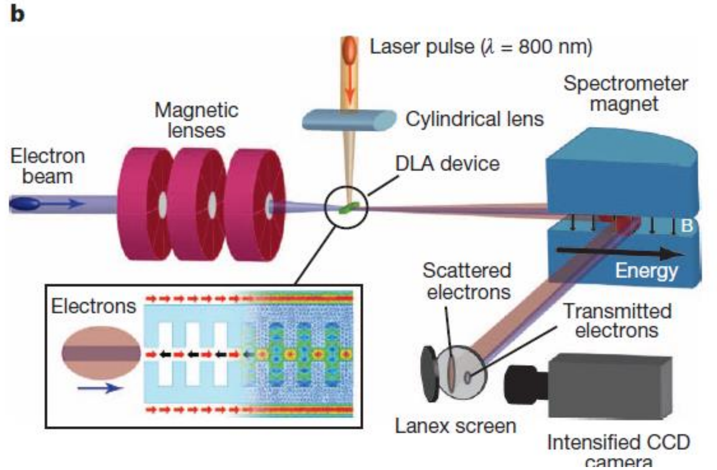
Max. energy shift: 70 keV
Acc. Gradient: 190 MeV/m

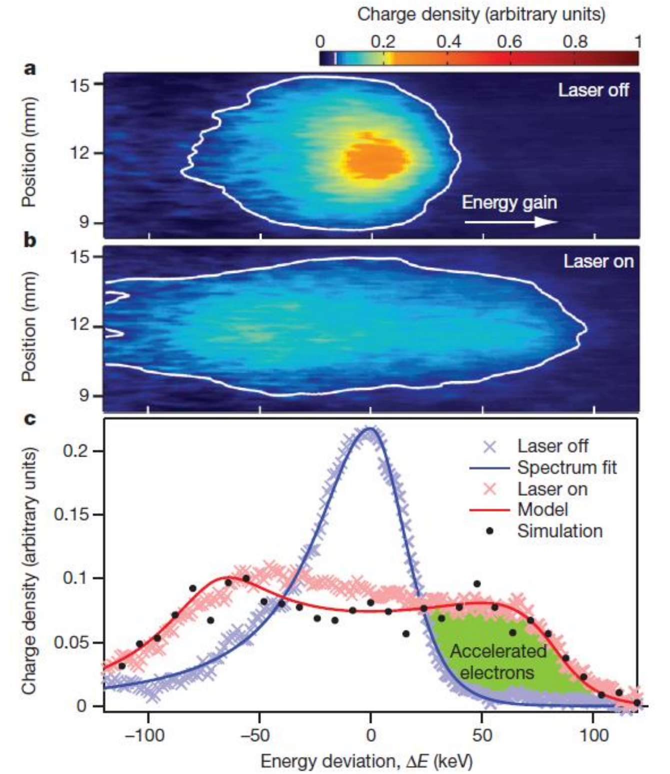
E. Peralta et al., Nature 503, 91–94 (2013)

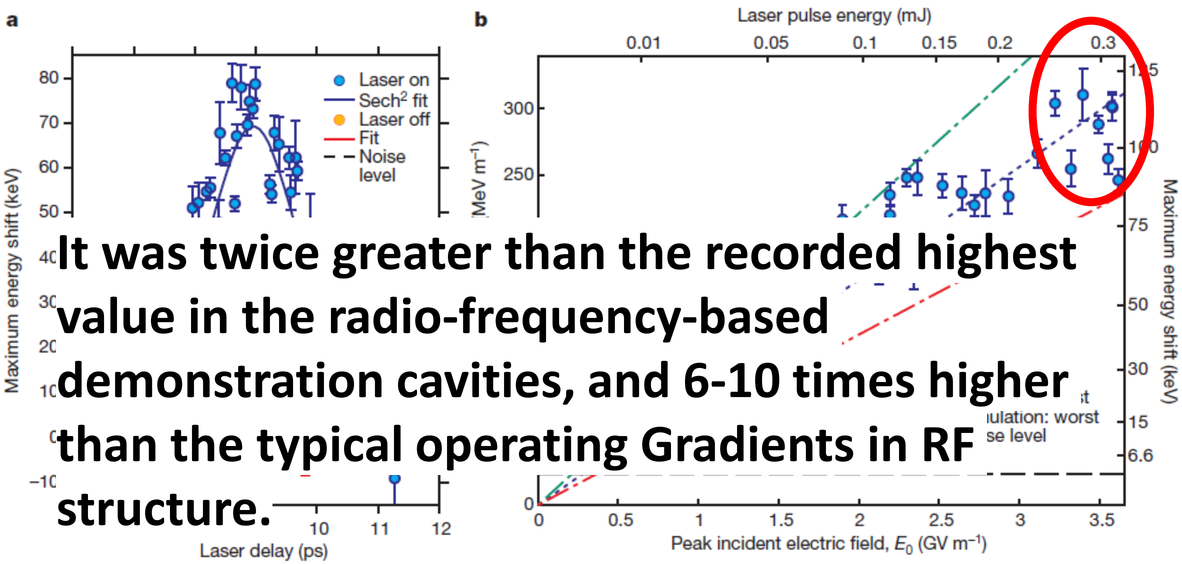
Particle accelerators - Micro accelerators (Future!?)

- Dielectric Laser-driven Accelerators – Dielectric grating accelerator









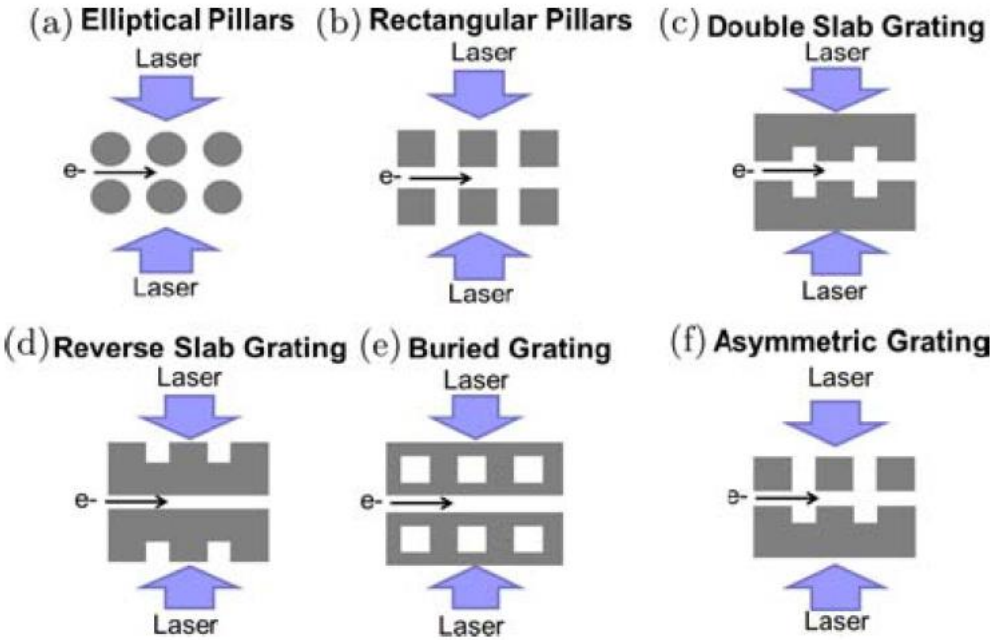
It was twice greater than the recorded highest value in the radio-frequency-based demonstration cavities, and 6-10 times higher than the typical operating Gradients in RF structure.

Increasing the pump energy:
Acc. Gradient: 310 MeV/m

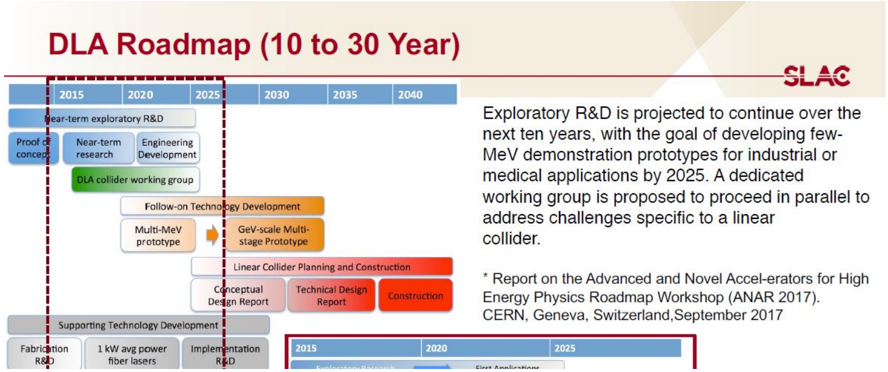
E. Peralta et al., Nature 503, 91–94 (2013)

Particle accelerators - Micro accelerators (Future!?)

- <u>Dielectric Laser-driven Accelerators – Dielectric grating accelerator</u>



[1]



[2]

[1] K. P. Wotton et al, Reviews of Accelerator Science and Technology 9, 105–126 (2016)

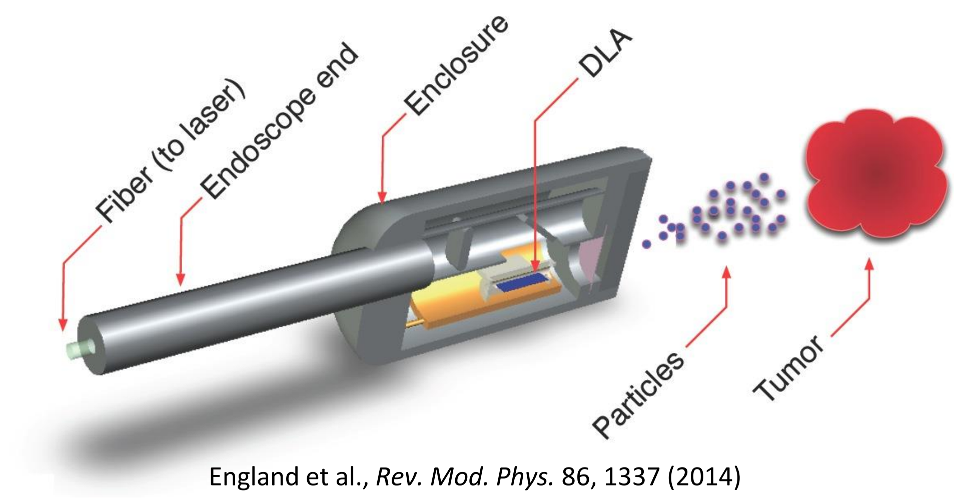
[2] R. J. England et al., LCWS 2021 – ANA Session 1, March 16, (2021)

Particle accelerators - Micro accelerators (Future!?)

Importance and Potential Applications of Micro Accelerators

- Compactness and portability
  - Tabletop, portable devices → medical clinics, research laboratories, industrial facilities.

Transfromative technology with broad applications across

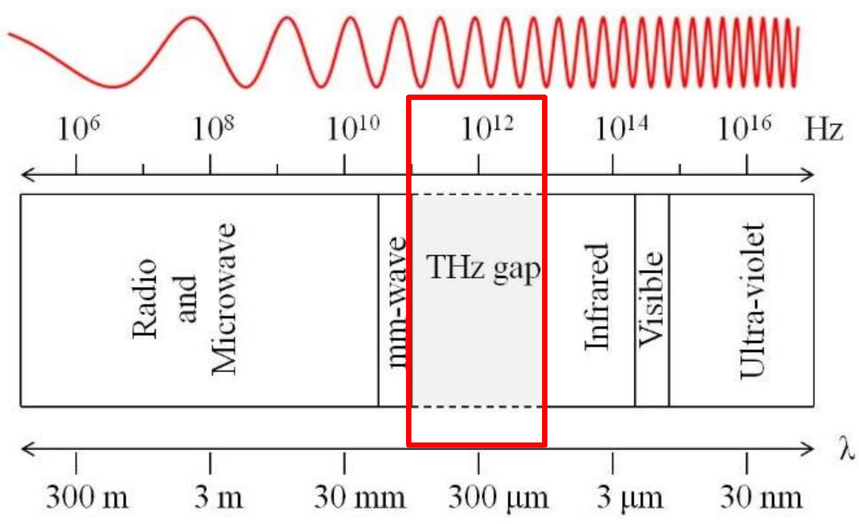


England et al., *Rev. Mod. Phys.* 86, 1337 (2014)

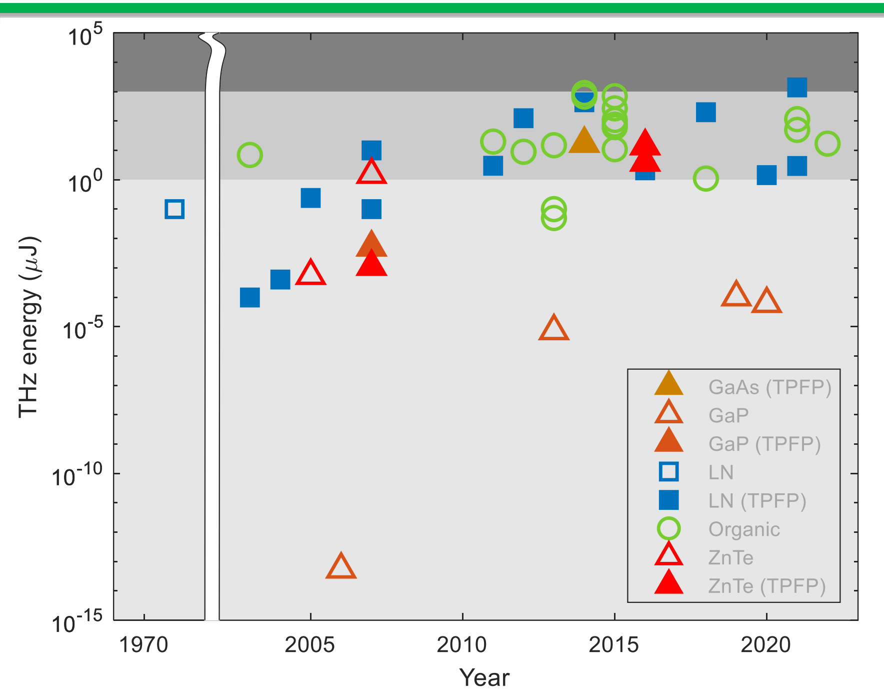
- High energy physics
- Radiation generation
- Electron diffraction and imaging

EVOLUTION OF THZ SOURCES

Evolution of THz sources



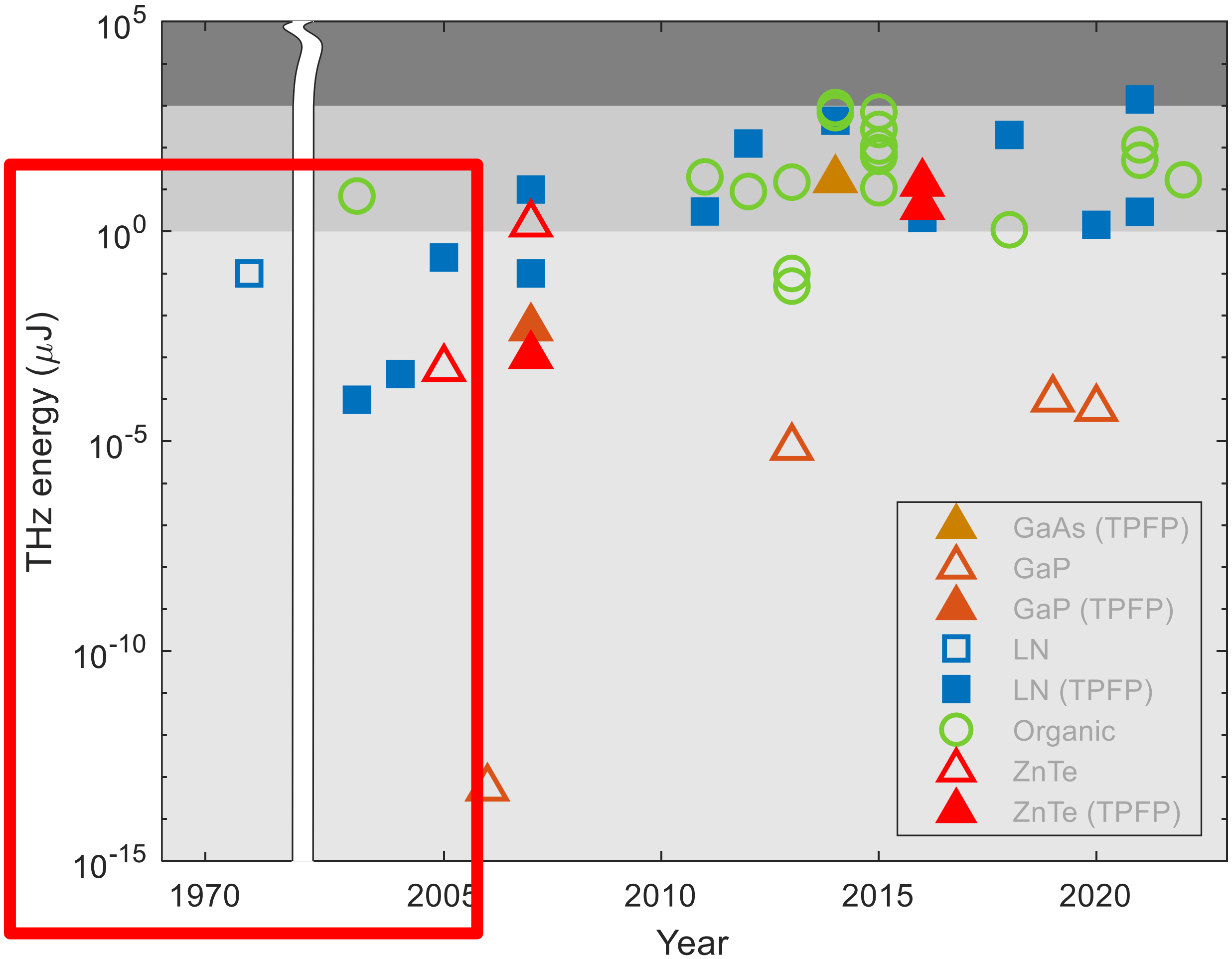
Dr. Neda Khiabani, Introduction to the Terahertz Band (2019)



Gy. Tóth et al., Light: Sci. & Appl. (2023)

- 0.1 – 10 THz
- 3 mm - 30 µm
- The research related to the **first terahertz sources dates back a few decades** (late 1970s; astronomical observations)
- Useful for various applications

Evolution of THz sources

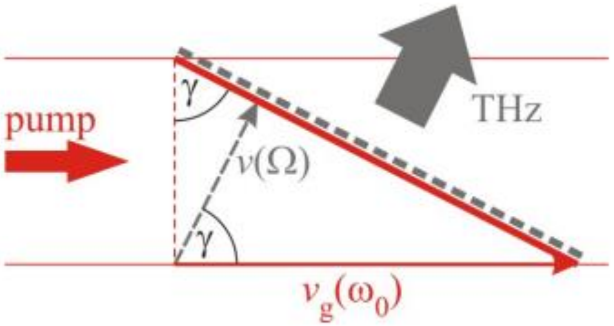


Gy. Tóth et al., Light: Sci. & Appl. (2023)

Evolution of THz sources

- <u>Generation of extremely high-energy THz pulses</u>
  - Application of electro-optic crystals with good nonlinear optical properties (LiNbO3, LiTaO3) for THz pulse generation → $n_g \neq \ n_{THz}$ →
  - $v_g\ (w_0) \neq \ v_{THz}(\Omega)$) → TPFP is a solution [1] [2].
    - Fulfillment of phase matching: $v_g\ (w_0) = \ v_{THz}(\Omega)$
  - **By** sufficiently **tilting (γ) the pulse front of the pumping pulse, the difference in velocity components and hence the phase difference can be balanced.**
  - According to the **Huygens principle, $v_{THz}(\Omega)$ becomes perpendicular to the tilted pulse front of the pumping beam.**

[1] J. Hebling et. al., Velocity matching by pulse front tilting for large area THz-pulse generation (2002)
[2] J. Hebling et. al., Generation of high-power terahertz pulses by tilted-pulse-front excitation and their application possibilities (2008)
[3] M. C. Hoffmann and J. A. Fülöp, Journal of Physics D: Applied Physics 44, 083001 (2011)



[3]

Evolution of THz sources

- Generation of extremely high-energy THz pulses
  - To fulfill the phase matching, the equaiton: $\boldsymbol{v_g\,(w_0)\cdot\ \cos\gamma = \ v_{THz}(\Omega)}$

$$\boldsymbol{n_{THz}\cdot\ \cos\gamma = \ n_g}$$

- Advantages:
  - It is possible to use several new materials as a source
  - In the case of a selected material, the pumping wavelength can be freely chosen within a given range.

- Disadvantages:
  - To be able to tilt the pulse front: using prism or grating → $\tan\gamma = \bar{\lambda}\cdot\frac{d\varepsilon}{d\lambda}$

$$\tan\gamma = \frac{n(\omega_0)}{n_g(\omega_0)}\omega_0\left(\frac{d\epsilon}{d\omega}\right)\Big|_{\omega_0}$$

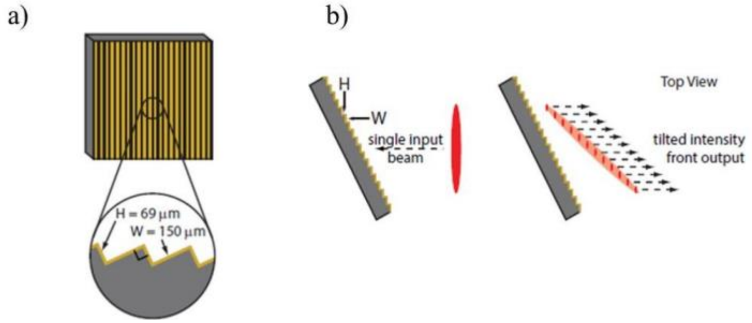
  - Imaging errors
  - Distortion of the output beam, different spectrum, less effective focusing

Zs. Bor et al., Opt. Communications 54, 165 (1985)

J. Hebling et al., Opt. Express 10, 1161 (2002)

Evolution of THz sources

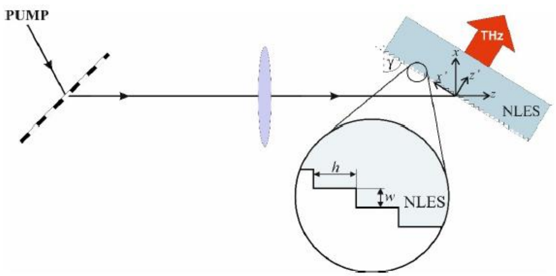
- Generation of extremely high-energy THz pulses



Reflective stair-step echelon

- Experiement of THz generation
- Single-cycle THz pulse
- 500 kV/cm peak electric field
- 3.1 μJ energy

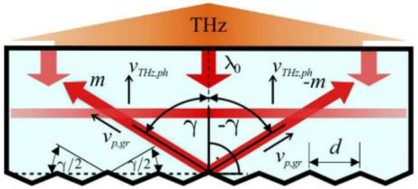
Benjamin K. Ofori-Okai et al., Opt. Express 24, 5057 (2016)



Segmented tilted-pulse-front excitation

- Single-cycle THz pulse
- 0.5 mJ THz energy

L. Pálfalvi et al., Opt. Express 25, 29560 (2017)



Reflective nonlinear slab

- Single-cycle THz pulse
- 50 MV/cm peak electric field prediction
- Proton or deuteron acceleration!?

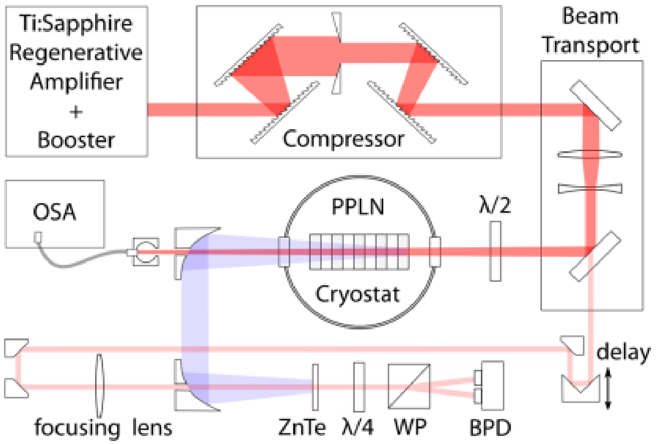
G. Tóth et al., Optics express, 27(21): p. 30681-30691. (2019)

Evolution of THz sources

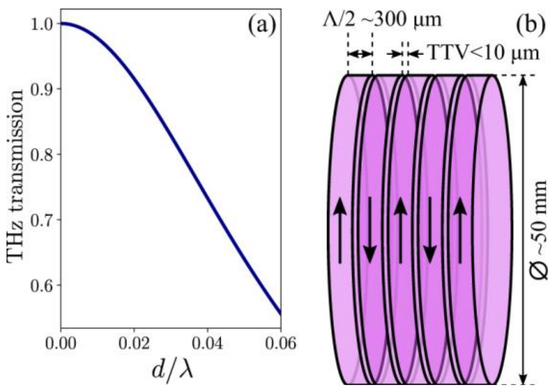
- <u>Generation of high-energy THz pulses (multi-cycle)</u>

1 pump pulse in PPLN

- S. Carbajo et al (2015)
  - THz generation in cryogenic PPLN
- F. Lemery et al (2020)
  - Wafer stack instead of PPLN
- C. D. W. Mosley et al (2023)
  - Comprehensive analyses, wafer-wise EOS



S. Carbajo et al, Opt. Letters **40**, 5762 (2015)



F. Lemery et al, Commun Physics **3, 150** (2020)

$$T = \frac{4n_{THz}^2}{4n_{THz}^2 + (1 - n_{THz}^2)^2 \sin\left(\frac{2\pi d}{\lambda_{THz}}\right)^2}$$

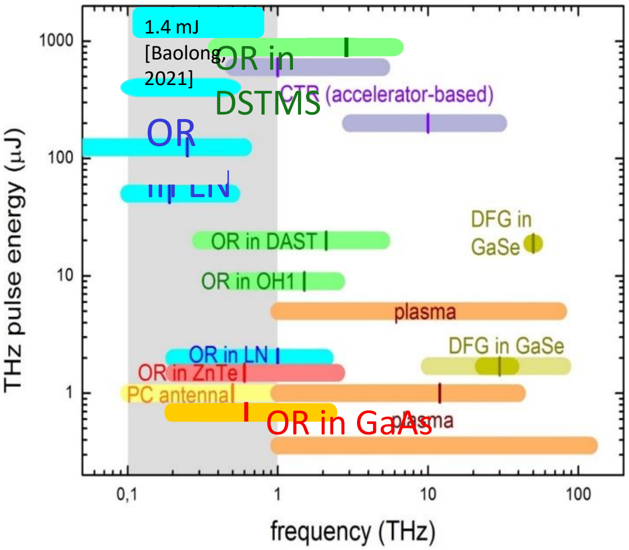
$$f_{\text{THz}} = \frac{c}{\Lambda\,(n_{\text{THz}} - n_{\text{IR}})}$$

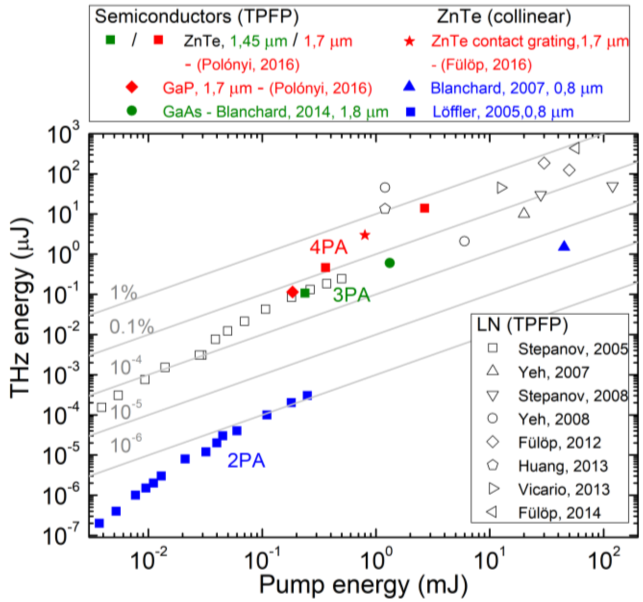
<u>Highly scalable multicycle THz</u>

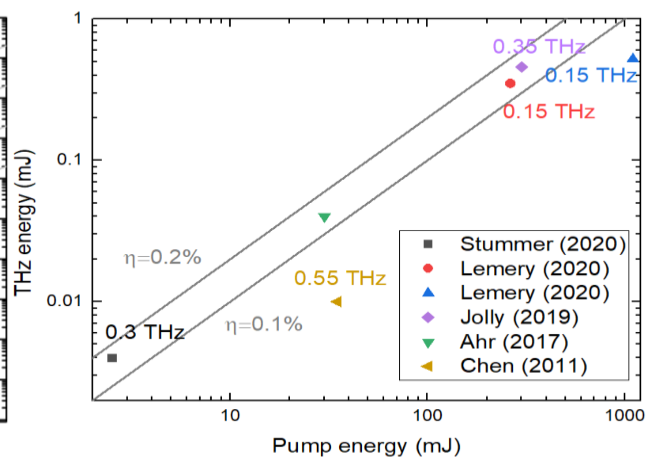
- 1.3 mJ energy (0.14 % conv. efficiency)
- 1.6 MV/cm
- 0.16 THz central frequency
- Application to drive particle accelerators

Evolution of THz sources

- <u>Generation of extremely high-energy THz pulses</u>
  - Using optical rectification in LNs and semiconductors
  - The energy of THz pulses increased by 7 orders of magnitude







Development of singe-cycle sources

Development of multicycle sources

THZ-DRIVEN PARTICLE ACCELERATORS (MANIPULATORS)

THz-driven particle accelerators (manipulators)

- **Electron acceleration**
  - Hebling et al., arXiv:1109.685 (2011)
  - Electron acceleration in vacuum
    - Sz. Turnár et al., Appl. Phys. B 130, 24 (2024)
  - Linear accelerator
    - Nanni, E.A., et al.,. Nature communications, 6(1): p. 1-8., (2015)
    - Heng Tang et al., Phys. Rev. Lett. 127, 074801 (2021)
  - Waveguide structure & Dielectric accelerator
    - Huang, W.R., et al.. Scientific reports, 5(1): p. 1-8. (2015)
    - Zhang, D., et al., Nature photonics, 12(6): p. 336-342. (2018)
    - Morgan T. Hibberd et al., Nature Photonics, 14, pages755–759 (2020)
    - Mohamed A. K. Othman et al., Optics Express, 27(17), 23791-23800 (2019)
    - Mohamed A. K. Othman et al., Appl. Phys. Lett. 117, 073502 (2020)
    - Weihao Liu et al., Optics Letters, 46(17), pp. 4398-4401 (2021)

THz-driven particle accelerators (manipulators)

- **Proton acceleration**
  - Accelerate from 40 MeV to 70 MeV at less than 60 cm using 1 mJ THz energy
    - Patent (https://patents.google.com/patent/US9497848B2/en)
      L. Pálfalvi … J. Hebling, Phys. Rev. ST Accel. Beams, (2014)
    - A new route has opened for fight to overcome the cancer

- **Proton acceleration**
  - Terahertz-driven ion acceleration by Coulomb explosion
    - Sz. Turnár et al., OTST conference, Marburg (2024)


Health

A team of scientists from the University of Pécs who developed a method for producing ultra-short high-energy terahertz pulses, are now confident that they will be able to increase the electric field value of these pulses by a magnitude of 100. This development could lead to a variety of new and exciting applications, ranging from cancer therapy to semiconductor research. We spoke to **János Hebling** and **József Fülöp** to find out more.

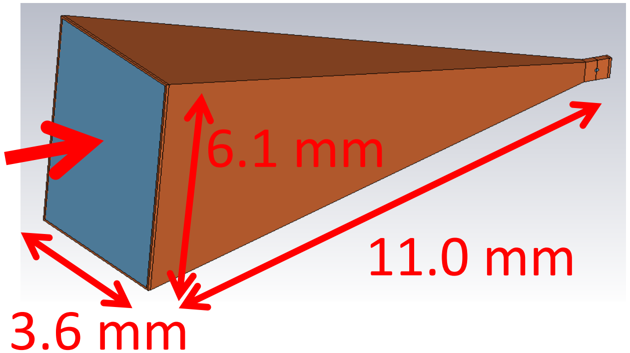
THz Pulse technology brings new hope to cancer sufferers

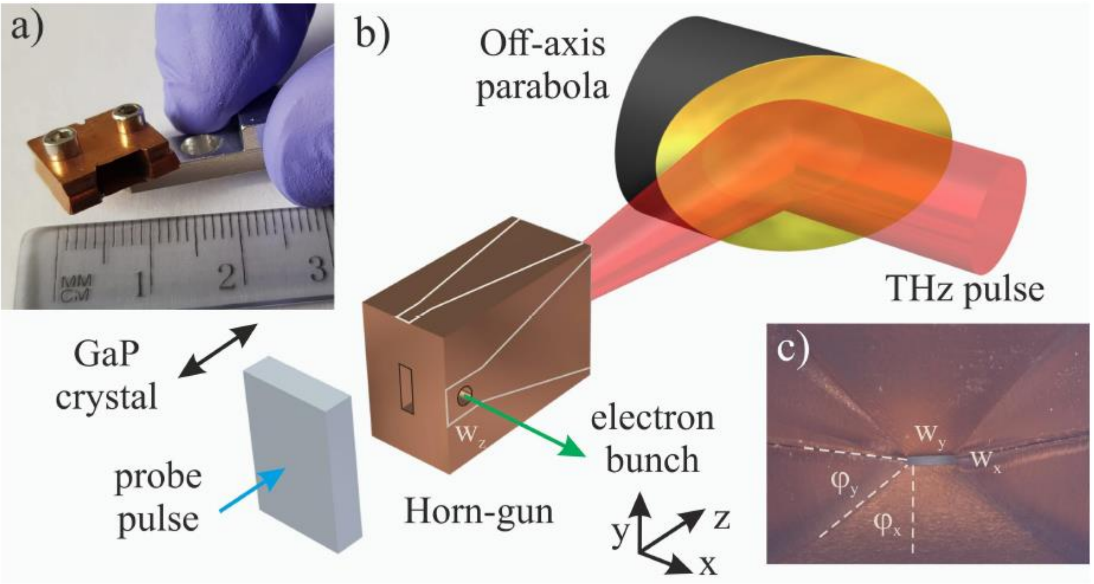
THz-driven particle accelerators (manipulators)

- Micro accelerator structures - Waveguide structure (1)

Parameters

- Single-cycle THz pulse
- 0.98 µJ THz energy
- 0.55 THz
- 11 mm long waveguide
- 114 kV/cm peak electric field
- 3.6 mm x 6.1 mm (x,y)
- $\phi_x = 16°$; $\phi_y = 10°$





Sz. Turnár et al., Optics Express, 30,15, pp. 27602-27608 (2022)

- Peak electric field **15 times** higher
- Few hundreds of kV/cm → ~ MV/cm

Parameters

- w_x = 50 µm
- w_y = 400 µm
- w_z = 300 µm

Rectangular channel (applies to w_x, w_y)

THz-driven particle accelerators (manipulators)

- Micro accelerator structures - Waveguide structure (1)

Simulation

- Closed waveguide
- Single-cycle THz pulse
  - 0.55 THz
  - 500 kV/cm → 8 MV/cm
  - 6000 macroparticles
  - 0.1 eV initial mean kinetic energy
  - 1 fC bunch charge

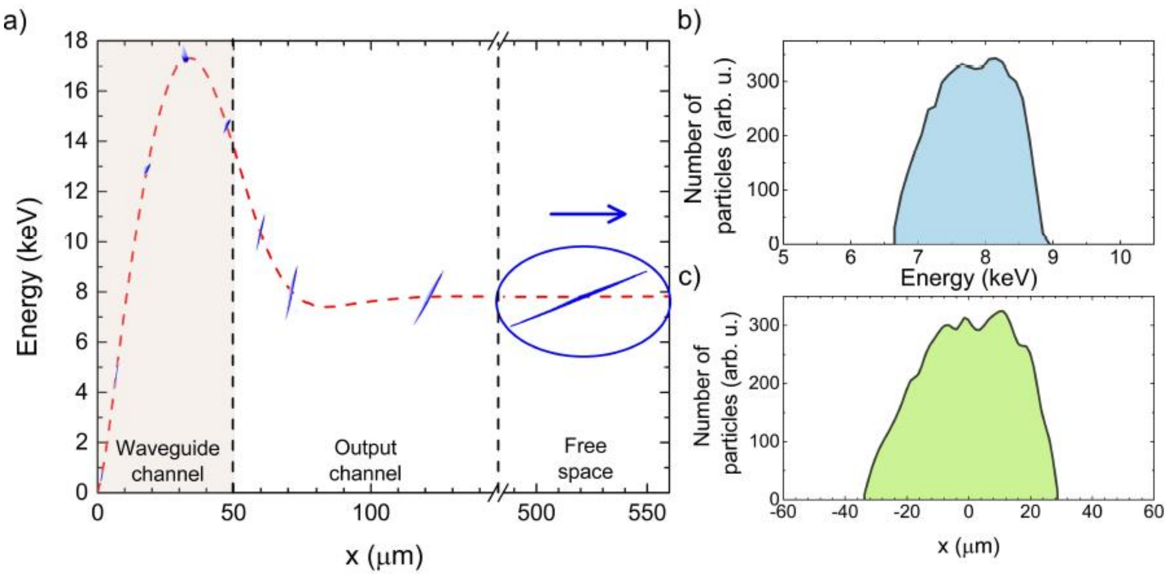
- 6.7 % energy spread (rms)
- 0.63 ps bunch size (FWHM = 33 µm)
- $\varepsilon_{n,x}$ = 6.18 nm rad and $\varepsilon_{n,y}$ = 8.10 nm rad
- deflection angles are $\alpha_x = 2.8°$, $\alpha_y = 0°$

Sz. Turnár et al., Optics Express, 30,15, pp. 27602-27608 (2022)

- 8 keV acceleration
- Machining difficulties
- Large energy spread
- Short interaction length

solution

- Relativistic bunch energy
- Simulating/measuring post. acc
- Bunch compression (shaping)

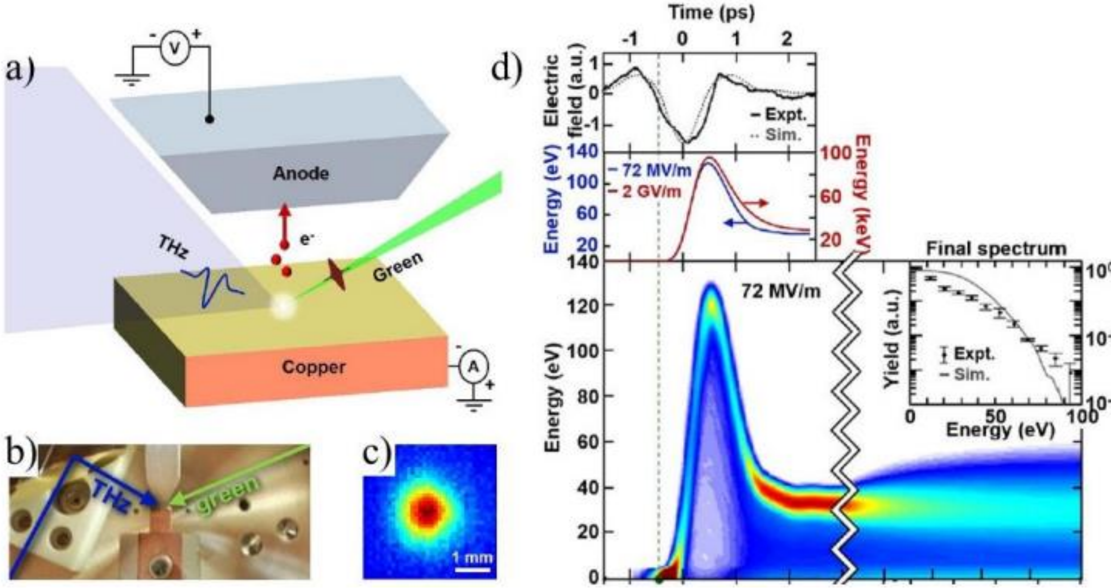


THz-driven particle accelerators (manipulators)

- Micro accelerator structures - Waveguide structure (2)

Parameters

- 525 fs (515 nm) ionization laser
- 50 fC emitted charge
- 0.18 eV initial energy
- Single-cycle THz pulse
  - 0.45 THz
  - 36 MV/m
  - 6 μJ THz energy



Huang, W.R., et al., Toward a terahertz-driven electron gun. Scientific reports, 2015. 5(1): p. 1-8.

Simulation

- Single-cycle THz pulse
  - 0.45 THz
  - 2 GV/m
  - 27 keV final kinetic energy
  - 3.5 % energy spread (rms)

- A few eV acceleration
- Relatively easy feasibility
- Relatively large energy spread
- A few eV acceleration

THz-driven particle accelerators (manipulators)

- <u>Micro accelerator structures - Waveguide structure (2)</u>

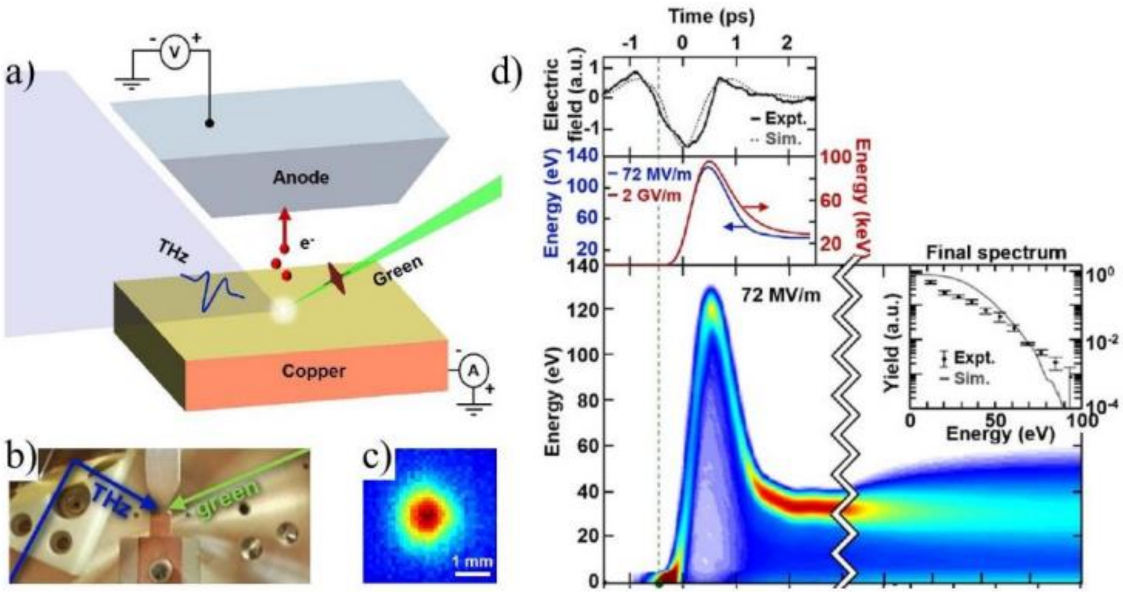
- Relatively large energy spread

The emitted electron bunch duration corresponds to the 17 % of period of the THz pulse

solution

- Applying much shorter (<50 fs ionizing laser pulse
- A few eV acceleration

solution



Huang, W.R., et al., Toward a terahertz-driven electron gun. Scientific reports, 2015. 5(1): p. 1-8.

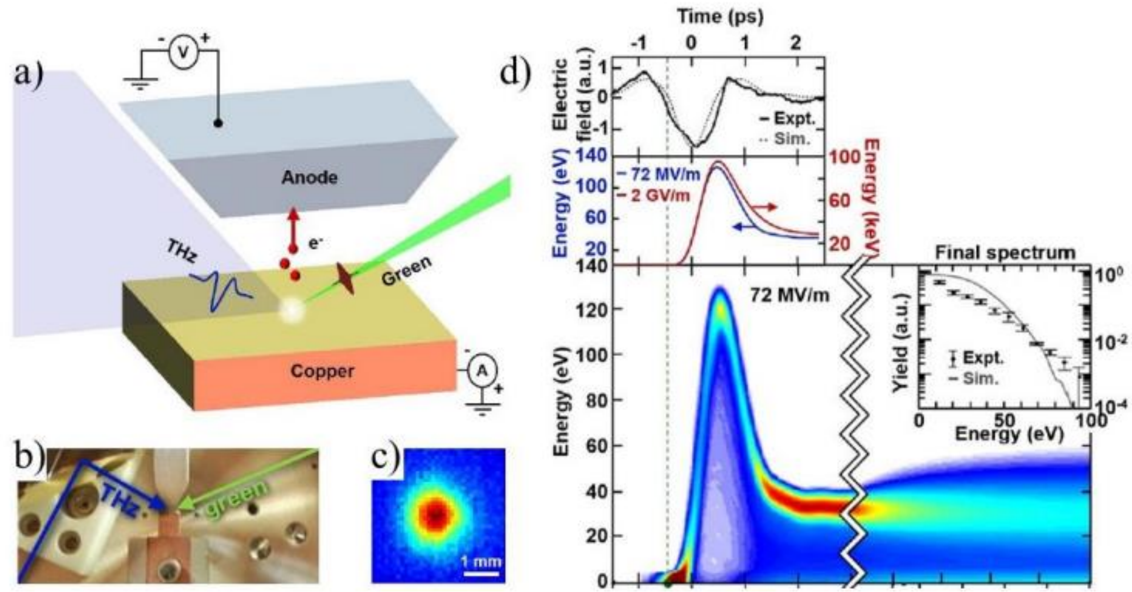
- PPWG (Paralell Plate Waveguide): Decreasing the gap between anode and cathode to 83 μm (2 GV/m) to eliminate the deacceleration effect → hole fabrication on the anode → Coupling is manageable by using tapered

THz-driven particle accelerators (manipulators)

- Micro accelerator structures - Waveguide structure (2)

- After the optimization (125 µm after the cathode; using 2 GV/m E-field)

- 100 keV average kinetic energy
- 1.3 % energy spread (rms)



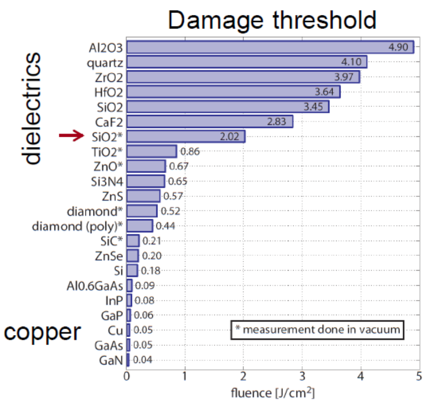
Huang, W.R., et al., Toward a terahertz-driven electron gun. Scientific reports, 2015. 5(1): p. 1-8.

! When considering peak field strengths in the range of several GV/m, one must also take into account the emitting effect of the THz pulse as a negative factor affecting acceleration efficiency.

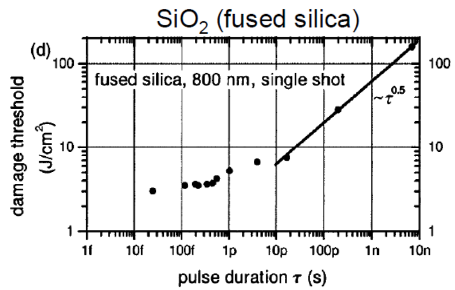
Herink, G., L. Wimmer, and C. Ropers, Field emission at terahertz frequencies: ACtunneling and ultrafast carrier dynamics. New Journal of Physics, 2014. 16(12): p. 123005.

THz-driven particle accelerators (manipulators)

- <u>Dielectric THz-driven Accelerators – Main idea, reminder</u>

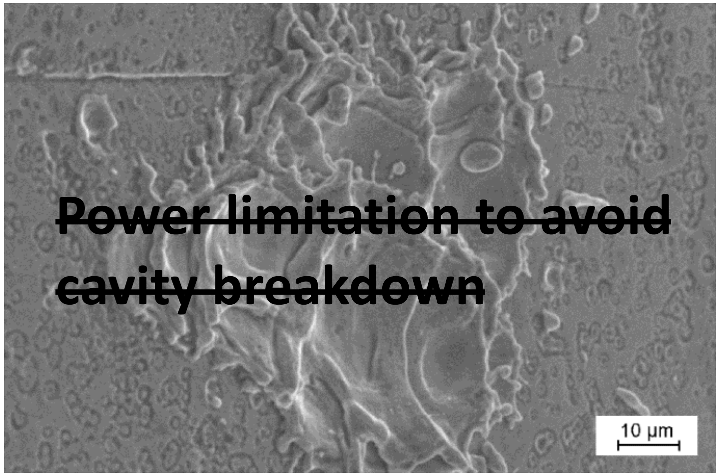


K. Soong, et al., AIP Conf. Proc., 1507, p. 511 (2012)

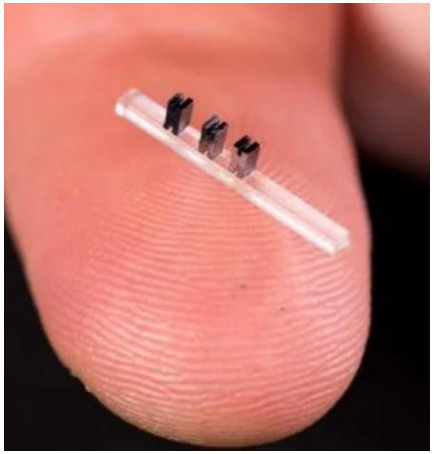


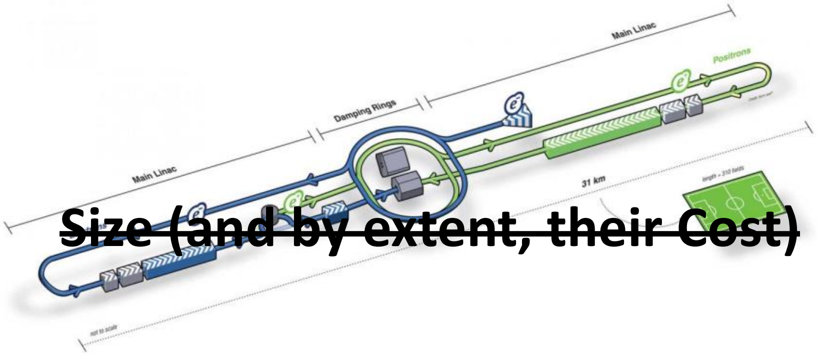
A.-C. Tien, et al., Phys. Rev. Lett., 82, p. 3883 (1999)

$$E = \sqrt{\frac{2FZ_0}{\tau}} \qquad F = 2\ \mathrm{J\ cm^{-2}},\ \tau = 100\ \mathrm{fs}, \quad E = 12\ \mathrm{GV\ m^{-1}}$$



~~Power limitation to avoid cavity breakdown~~





~~Size (and by extent, their Cost)~~

https://www6.slac.stanford.edu/news/2015-11-19-135m-moore-grant-develop-working-accelerator-chip-prototype ACHIP Collaboration

THz-driven particle accelerators (manipulators)

- Dielectric THz-driven Accelerators – Main idea, reminder

$$E(x,t) = E_0 \cdot e^{2\pi i \frac{x-ct}{\lambda}} = E_0 \cdot e^{i(kx-\omega t)}$$

The propagation velocity of the wave is the **phase velocity**: $c = \frac{\lambda}{T} = \frac{\omega}{k}$

In the Fourier definition the pulse can be decomposed into the sum of harmonic waves. (It is usually called as wave group.)

The **group velocity** can be calculated using Rayleigh's formula: $c^* = c - \lambda \frac{dc}{d\lambda} = \frac{d\omega}{dk}$

In the absence of dispersion, all components propagate with the same velocity, so their position relative to each other does not change. Therefore, in the absence of dispersion, **the sum of the components – that is, the wave group – propagates with the same common speed**. The shape of the wave does not change during propagation.

Linear dispersion relation: $v = \frac{\omega}{k} = \frac{d\omega}{dk} = c$

THz-driven particle accelerators (manipulators)

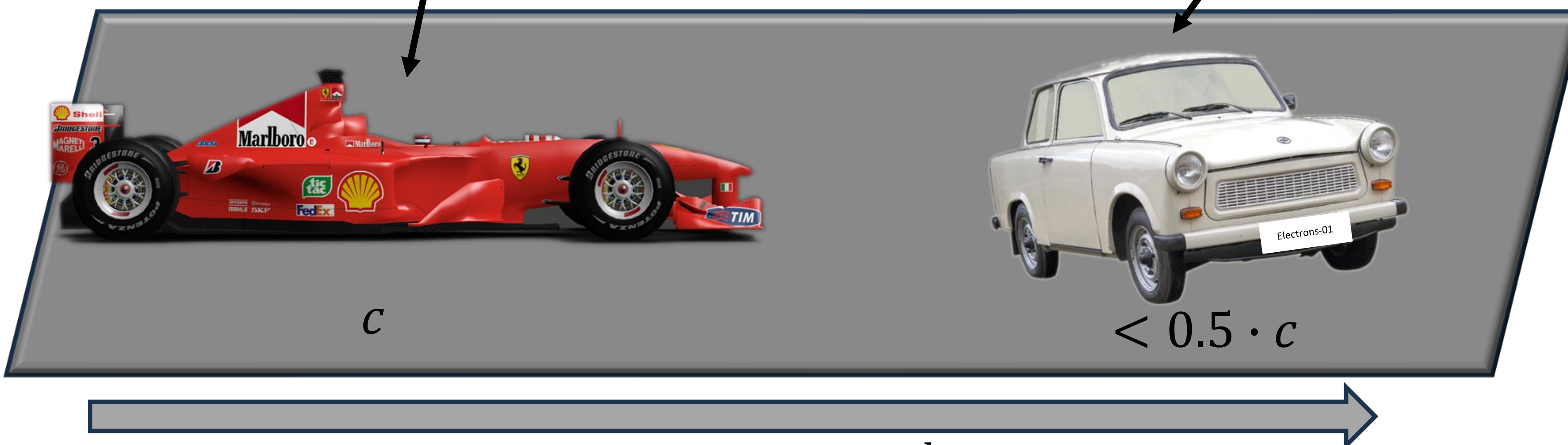
- Dielectric THz-driven Accelerators – Main idea, reminder

The challange to overcome:

Accelerator laser pulse (THz)

Non-relativistic electrons

without dielectric



Linear dispersion relation: $v = \frac{\omega}{k} = \frac{d\omega}{dk} = c$

THz-driven particle accelerators (manipulators)

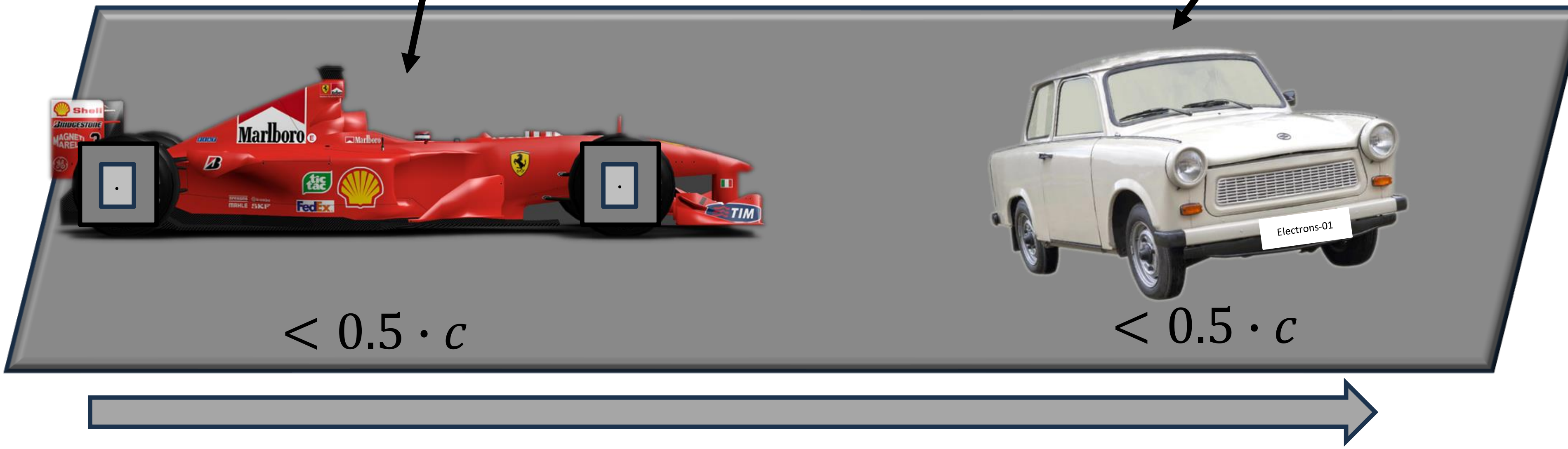
- Dielectric THz-driven Accelerators – Main idea, reminder

The challange to overcome:

Accelerator laser pulse (THz)

Non-relativistic electrons

with dielectric $c = c(k)$



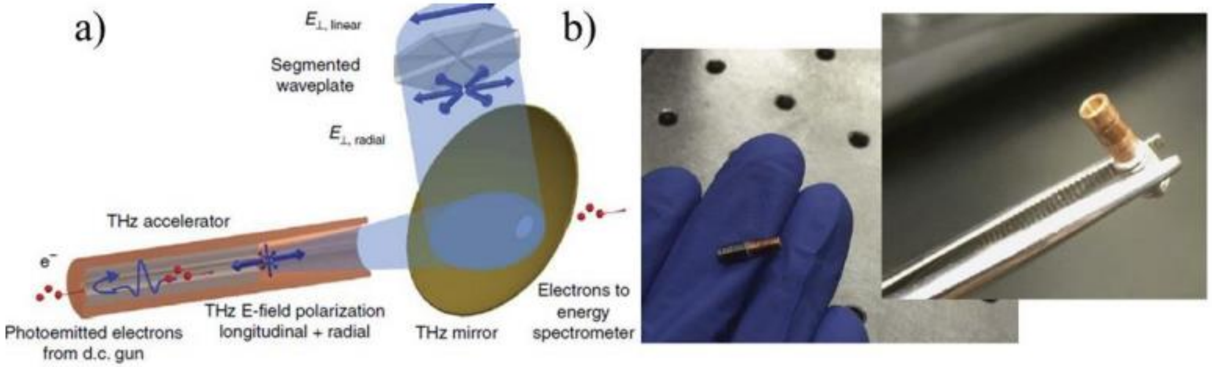
dispersion relation: $\omega = \omega(k)$ $\qquad \omega(k) = c(k) \cdot k$

THz-driven particle accelerators (manipulators)

- Dielectric THz-driven Accelerators – THz LINAC

Parameters

- 10 mm linear accelerator
- Dielectric (quartz)
- Singe-cyle THz pulse
- 60 keV initial kinetic energy
- 25 fC total charge
- Radially polarized THz pulse
  - 0.45 THz
  - 10 MV/m
- 60 keV ≈ 0.446 · c
- v_g = 0.46 · c
- v_{phase}=0.505 · c



- 7 keV post acceleration
- Relatively easy feasibility
- Short (3 mm) interaction length
- Multi-cycle THz pulse inside the structure (dispersion)

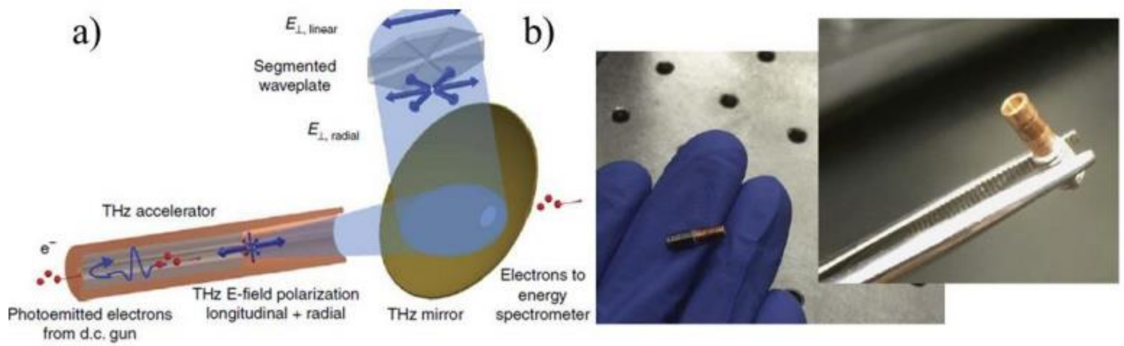
Nanni, E.A., et al., Terahertz-driven linear electron acceleration. Nature communications, 2015. 6(1): p. 1-8.

THz-driven particle accelerators (manipulators)

- <u>Dielectric THz-driven Accelerators – THz LINAC</u>

- Short interaction length
- Multi-cycle THz pulse inside

the structure (dispersion)



The bunch length is around 200 µm. The wavelength of the multi-cycle THz pulse is around 315 µm → electrons experience the decelerating part of the THz.

Nanni, E.A., et al., Terahertz-driven linear electron acceleration. Nature communications, 2015. 6(1): p. 1-8.

solution

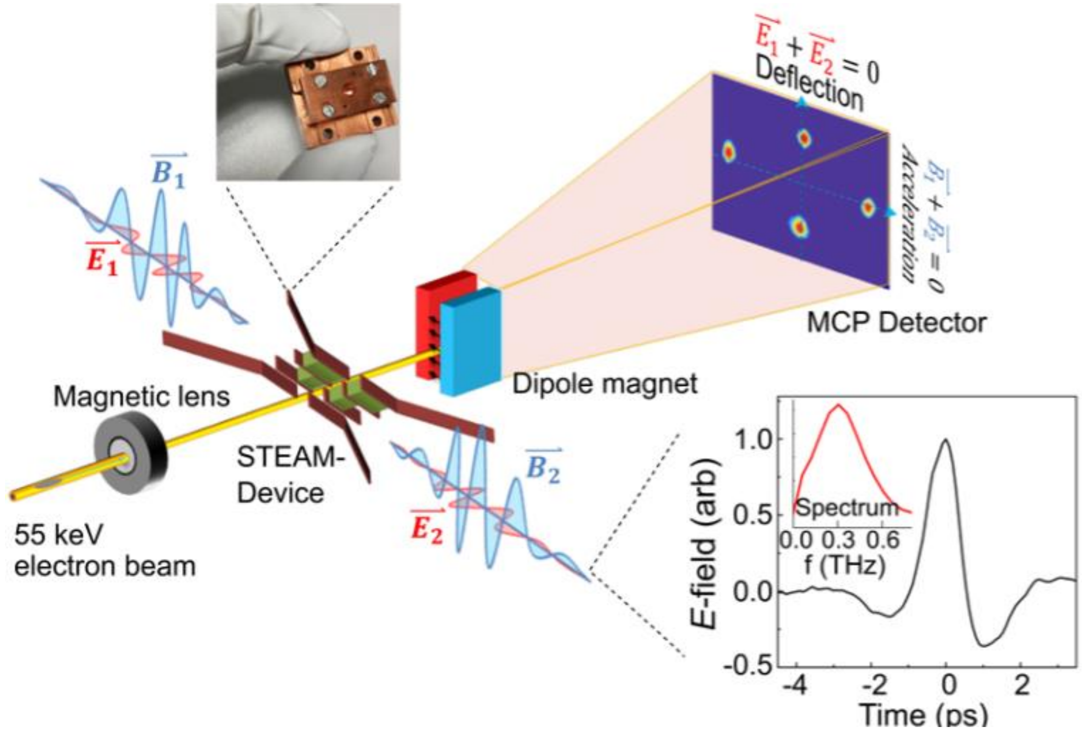
- Applying relativistic electron bunch → longer interaction length
- Decreasing the width of the dielectric layer and thereby reducing the radius of the waveguide → reducing the dispersion → higher peak electric field

Simulation

- 10 mJ THz energy (~GV/m)
- 1 MeV initial kinetic energy
- 10 – 15 MeV relative energy increase

THz-driven particle accelerators (manipulators)

- <u>Dielectric THz-driven Accelerators – Dielectric-lined waveguide</u>



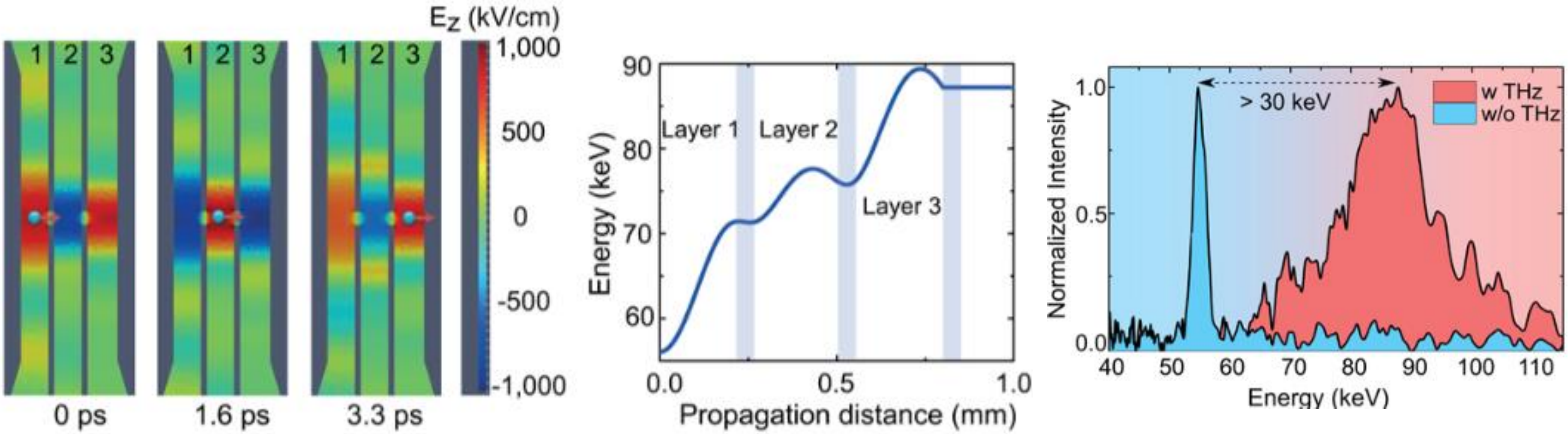
<u>Associated with several records</u>

- 30 keV post acceleration (record)
- 140 μradfs^{-1} streaking gradient
- 2 kT/m focusing gradient
- Decrease the bunch length below 100 fs
- Ultrafast electron diffraction experiments with resolutions down to 10 fs

Zhang, D., et al., Segmented terahertz electron accelerator and manipulator (STEAM). Nature photonics, 2018. 12(6): p. 336-342.

THz-driven particle accelerators (manipulators)

- Dielectric THz-driven Accelerators – Dielectric-lined waveguide



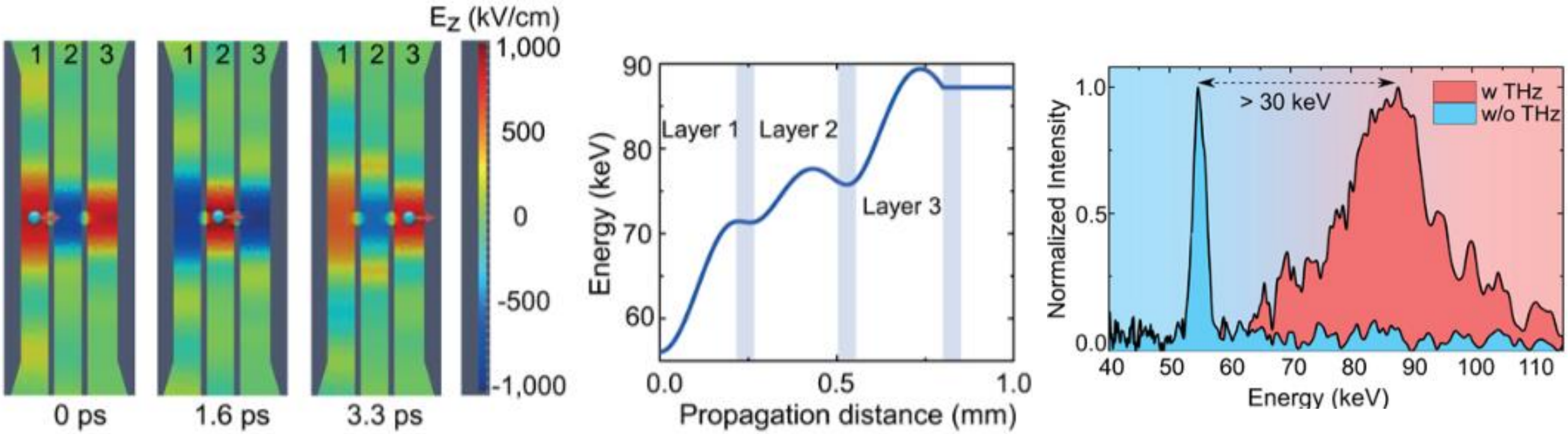
Parameters

- Two Single-cycle THz pulses
- 6 μJ THz energy per pulse
- 70 MV/m peak electric field
- ~55 keV initial kinetic energy
- 5 fC total charge

Zhang, D., et al., Segmented terahertz electron accelerator and manipulator (STEAM). Nature photonics, 2018. 12(6): p. 336-342.

THz-driven particle accelerators (manipulators)

- Dielectric THz-driven Accelerators – Dielectric-lined waveguide



Simulation

- mJ THz energy level
- 4 or more segments → • Machining difficulties
- MeV level of kinetic energy (10 pC charge)

Possibility to implement the device to European XFEL or SwissFEL.

Zhang, D., et al., Segmented terahertz electron accelerator and manipulator (STEAM). Nature photonics, 2018. 12(6): p. 336-342.

THz-driven particle accelerators (manipulators)

- Dielectric THz-driven Accelerators – Dielectric grating accelerator

Nuclear Inst. and Methods in Physics Research, A 877 (2018) 173–177

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Investigations into dual-grating THz-driven accelerators

Y. Wei [a,b,*], R. Ischebeck [c], M. Dehler [c], E. Ferrari [c], N. Hiller [c], S. Jamison [d], G. Xia [a,e], K. Hanahoe [a,e], Y. Li [a,e], J.D.A. Smith [f], C.P. Welsch [a,b]

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Nuclear Inst. and Methods in Physics Research, A 942 (2019) 162362

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

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Numerical investigations into a THz-driven dielectric accelerator with a Bragg reflector

M. Xiriai [a], Baifei Shen [a], P. Zhang [b], A. Aimidula [c,*]

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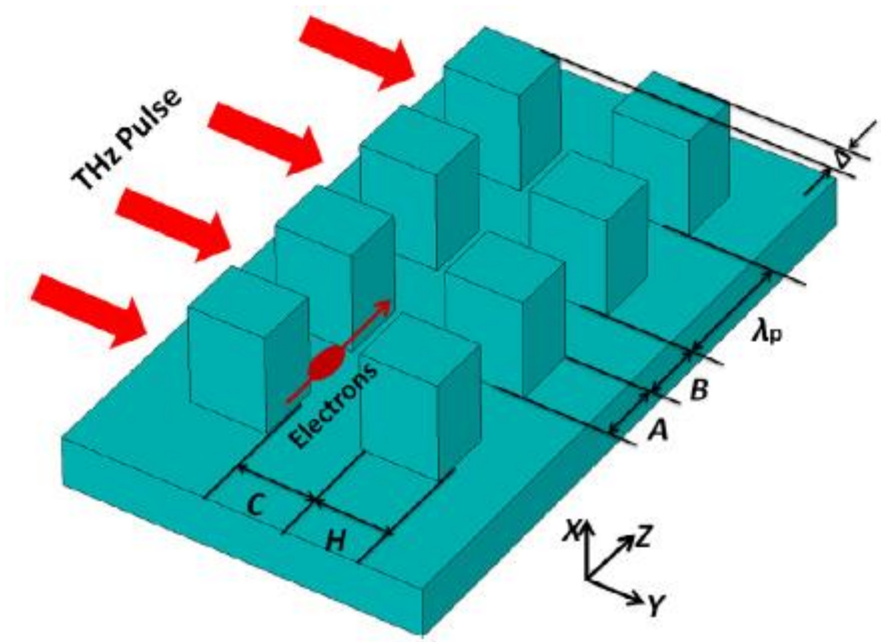
[b] School of electronic science and engineering, University of Electronic Science and Technology of China, Chengdu, 610054, China
[c] School of Physics Science and Technology, Xinjiang University, Urumqi 830046, China

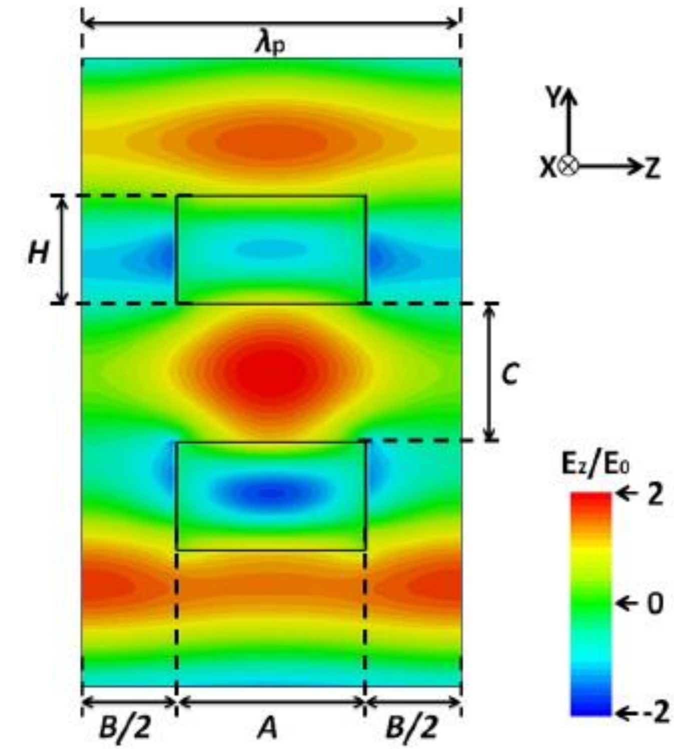
[1] Y. Wei et al., NIMA 877 173-177 (2018)

[2] M. Xiriai et al., NIMA 942 162362 (2019)

THz-driven particle accelerators (manipulators)

- Dielectric THz-driven Accelerators – Dielectric grating accelerator



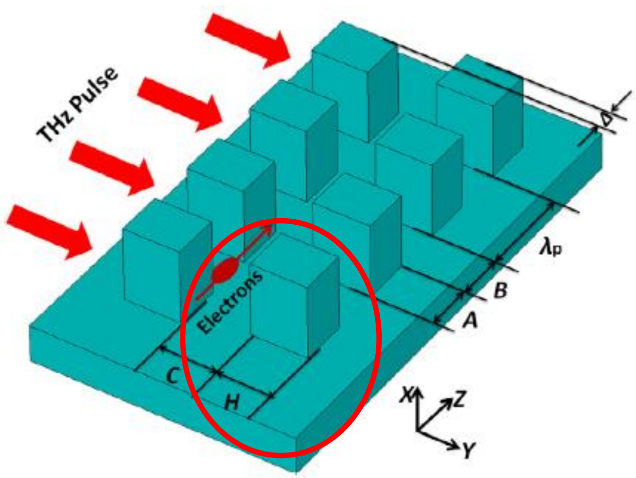


[1] A. Aimidula, C.P. Welsch, …, NIMA 740 108-113 (2014)

[2] Y. Wei et al., NIMA 877 173-177 (2018)

THz-driven particle accelerators (manipulators)

- <u>Dielectric THz-driven Accelerators – Dielectric grating accelerator</u>



<u>Conditions necessary for proper operation</u>

1. π phase shift between the space of dielectric columns and the space formed in free space

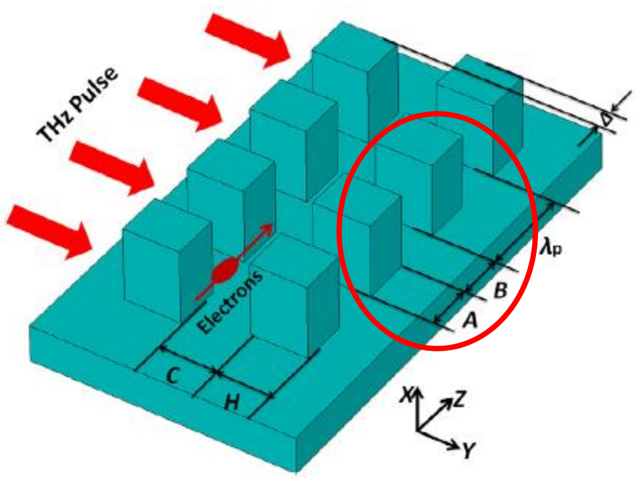
$$H = \frac{\lambda_{THz}}{2(n-1)}$$

[1] A. Aimidula, C.P. Welsch, …, NIMA 740 108-113 (2014)

[2] Y. Wei et al., NIMA 877 173-177 (2018)

THz-driven particle accelerators (manipulators)

- Dielectric THz-driven Accelerators – Dielectric grating accelerator



Conditions necessary for proper operation

1. π phase shift between the space of dielectric columns and the space formed in free space:

$$H = \frac{\lambda_{THz}}{2(n-1)}$$

2. The wavelength of a standing wave must be matched to the electron energy to achieve continuous acceleration:

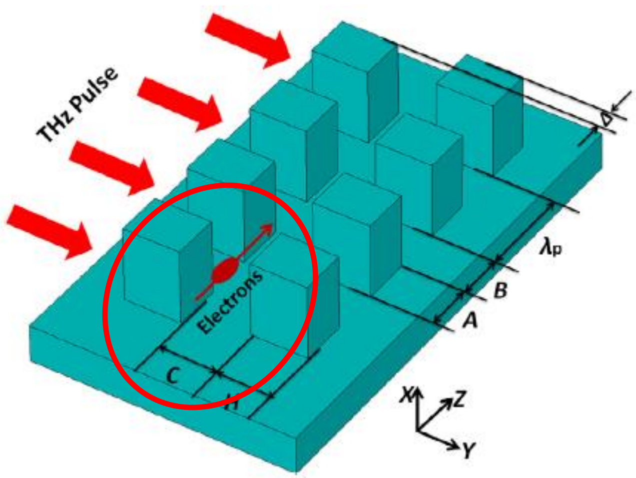
$$A = B = \beta \cdot \frac{\lambda_{THz}}{2} \qquad \beta = v/c$$

[1] A. Aimidula, C.P. Welsch, …, NIMA 740 108-113 (2014)

[2] Y. Wei et al., NIMA 877 173-177 (2018)

THz-driven particle accelerators (manipulators)

- Dielectric THz-driven Accelerators – Dielectric grating accelerator



Conditions necessary for proper operation

1. π phase shift between the space of dielectric columns and the space formed in free space:

$$H = \frac{\lambda_{THz}}{2(n-1)}$$

2. The wavelength of a standing wave must be matched to the electron energy to achieve continuous acceleration:

$$A = B = \beta \cdot \frac{\lambda_{THz}}{2} \qquad \beta = v/c$$

3. Find the golden mean to determine the width of the accelerator channel

$$bunch\ width < C < A,$$

[1] A. Aimidula, C.P. Welsch, …, NIMA 740 108-113 (2014)

[2] Y. Wei et al., NIMA 877 173-177 (2018)

THz-driven particle accelerators (manipulators)

- Dielectric THz-driven Accelerators – Dielectric grating accelerator

Simulation

1. Geometry optimization to find the optimum dual-grating structure
2. Detailed wakefield study of an optimized 100-period dual-grating structure
3. Linearly-polarized THz pulse was simulate to interact with the electron bunch inside the optimized 100 period structure.

Y. Wei et al., NIMA 877 173-177 (2018)

THz-driven particle accelerators (manipulators)

- Dielectric THz-driven Accelerators – Dielectric grating accelerator

Simulation

1. Geometry optimization to find the optimum dual-grating structure

1. Detailed geometry optimization to maximize the Accelerating Factor (AF)

- **Material: quartz (n ≈2; Damage-threshold is around 13.8 GV/m [2])**
- **Plan wave with the wavelength of 150 µm (λ_0)**
- **Grating period (λ_p) was 150 µm**
- **Golden mean: $H = 0.8 \cdot \lambda_p$; $C = 0.5 \cdot \lambda_p$ →Determine the optimal pillar width ($C = 0.5 \cdot \lambda_p$) → AF= 0.141**

$$G_0 = \frac{1}{\lambda_p} \int_0^{\lambda_p} E_z[z(t), t]\, dz \longrightarrow AF = G_0 / E_{max}$$

$$0.141 \cdot 13.8 \frac{GV}{m} = 1.95 \frac{GV}{m}$$

[1] Y. Wei et al., NIMA 877 173-177 (2018)

[2] M.C. Thompson et al., Phys. Rev. Lett. 100 (2008) 214801.

THz-driven particle accelerators (manipulators)

- Dielectric THz-driven Accelerators – Dielectric grating accelerator

Simulation

1. Geometry optimization to find the optimum dual-grating structure
2. Detailed wakefield study of an optimized 100-period dual-grating structure
3. Linearly-polarized THz pulse was simulate to interact with the electron bunch inside the optimized 100 period structure.

CLARA bunch parameters used in the simulation.

Bunch parameters	CLARA [2]	Simulation
Bunch energy [MeV]	50	50
Bunch charge [pC]	≤250	0.3
Bunch RMS length [μm]	9–300	90
Bunch RMS radius [μm]	10–100	5
Normalized emittance [mm mrad]	≤1	0.15
Energy spread	<0.1%	0.05%

[1]

[1] Y. Wei et al., NIMA 877 173-177 (2018)

[2] J.A. Clarke et al., CLARA conceptual design report, J. Instrum. 9 (05) (2014) T05001.

THz-driven particle accelerators (manipulators)

- Dielectric THz-driven Accelerators – Dielectric grating accelerator

Simulation

1. Geometry optimization to find the optimum dual-grating structure
2. Detailed wakefield study of an optimized 100-period dual-grating structure
3. Linearly-polarized THz pulse was simulate to interact with the electron bunch inside the optimized 100 period structure.

Parameters of the THz pulse used in the simulation.

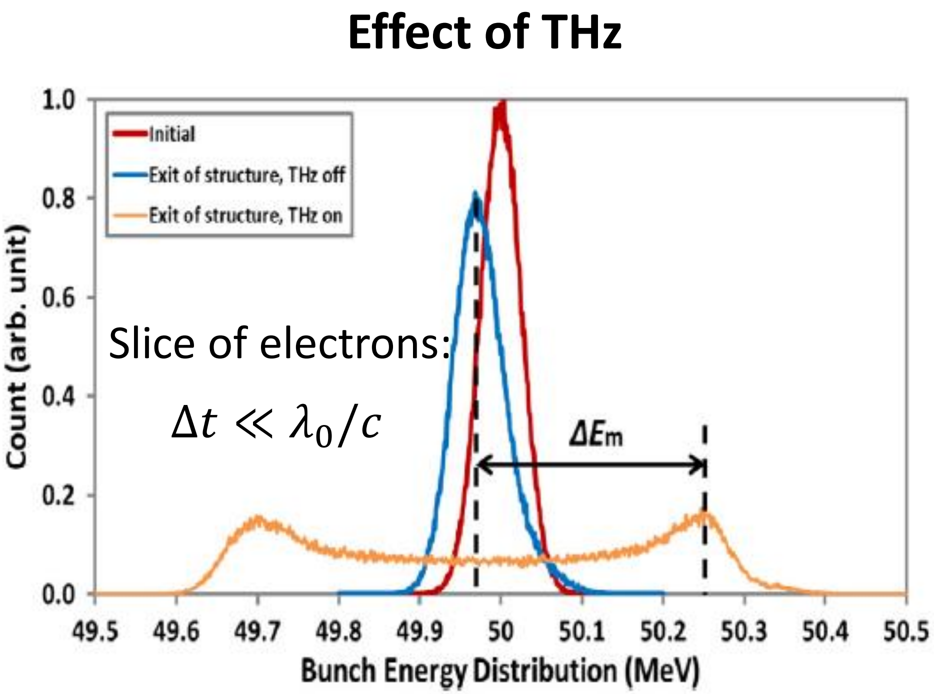
THz pulse characteristics	
Propagation direction	$+y$
Wavelength λ	150 μm
Frequency f	2.0 THz
Peak field	1.0 GV/m
FWHM duration τ	2 ps
Waist radius w_z	1.0 mm

Y. Wei et al., NIMA 877 173-177 (2018)

THz-driven particle accelerators (manipulators)

- Dielectric THz-driven Accelerators – Dielectric grating accelerator

Simulation results



Net energy shift:

$$g(\Delta t, \Delta E_m) = \Delta E_m \cos\left(\frac{2\pi c}{\lambda_0}\right)\Delta t$$

Energy spread:

$$\frac{\Delta E}{E} = 0.42\ \%$$

Maximum energy gain:

$$\Delta E_m = 280\ \pm 10\ keV$$

Maximum accelerating gradient:

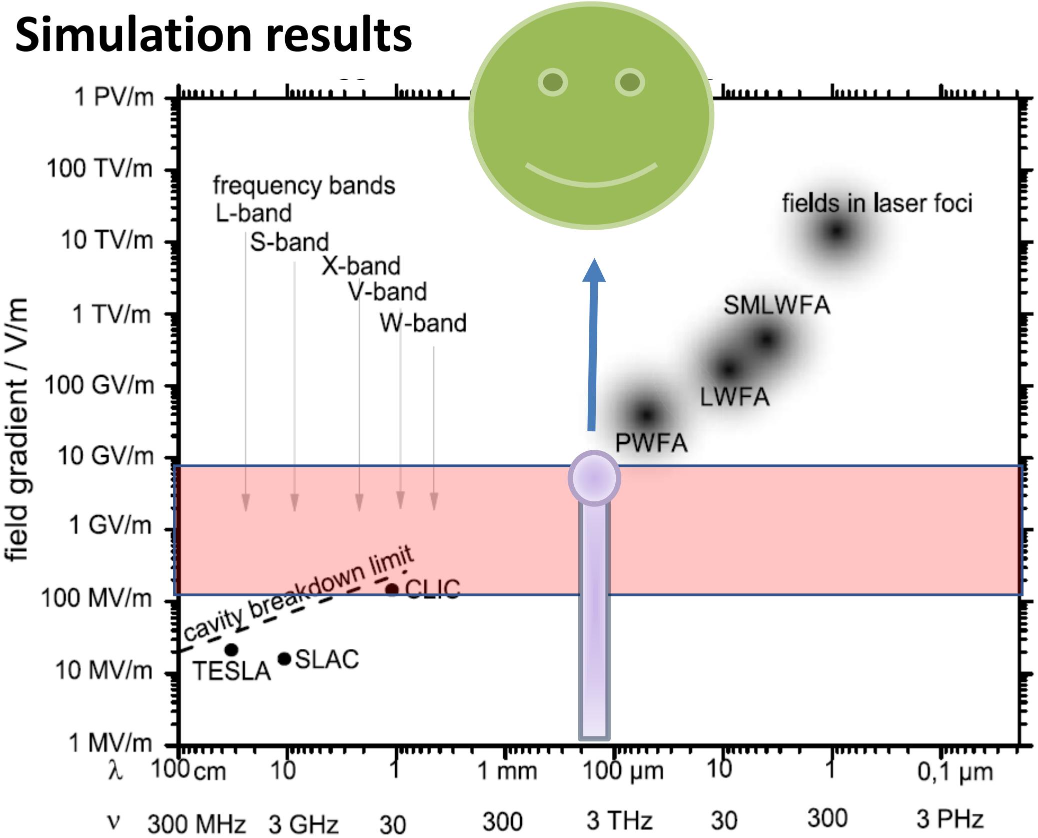
$$G_m = 348\ \pm 12\ MV/m$$

Y. Wei et al., NIMA 877 173-177 (2018)

THz-driven particle accelerators (manipulators)

- Dielectric THz-driven Accelerators – Dielectric grating accelerator

Simulation results



Effect of THz

THz field of 3.0 GV/m leads to a maximum field of 9.37 GV/m

Y. Wei et al., NIMA 877 173-177 (2018)

THz-driven particle accelerators (manipulators)

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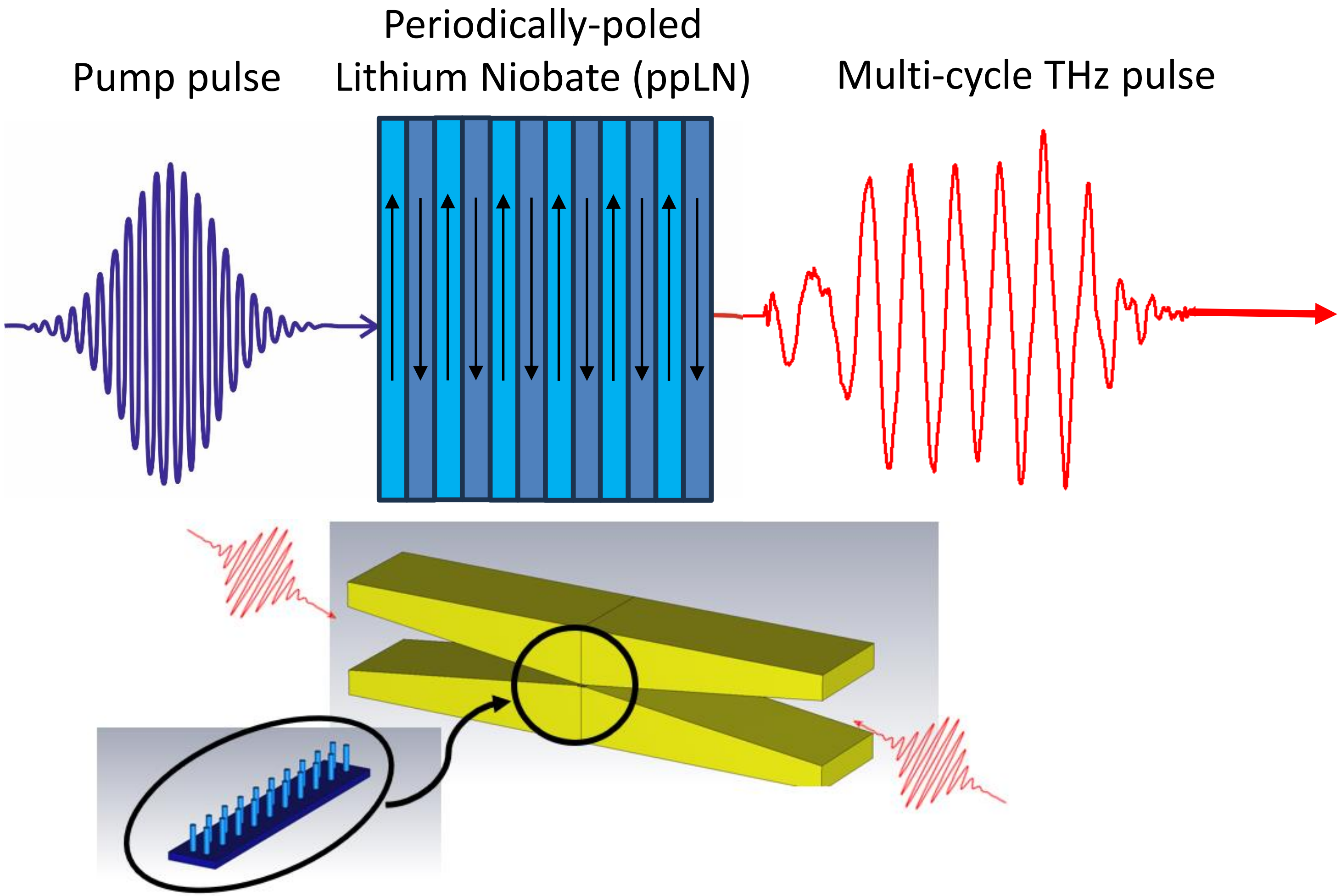

A. L. Genre et al., under preparation (2024)

THz-driven particle accelerators (manipulators)

- Dielectric THz-driven Accelerators – Dielectric grating accelerator

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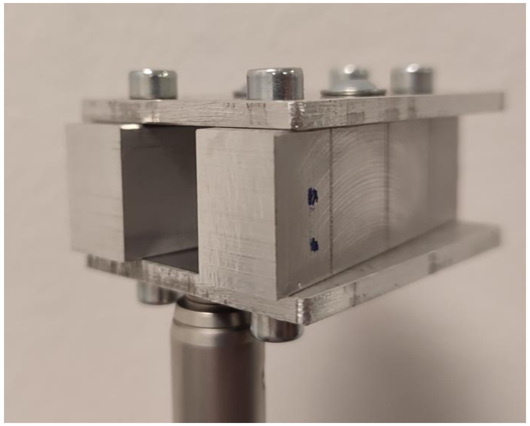
- Length of the structure → maximize the Electri field
- Subtense of the structure → maximize the Electric field
- Width of the acc. channel → maximize the acc. gradient
- Height of the acc. channel → maximize the acc. gradient



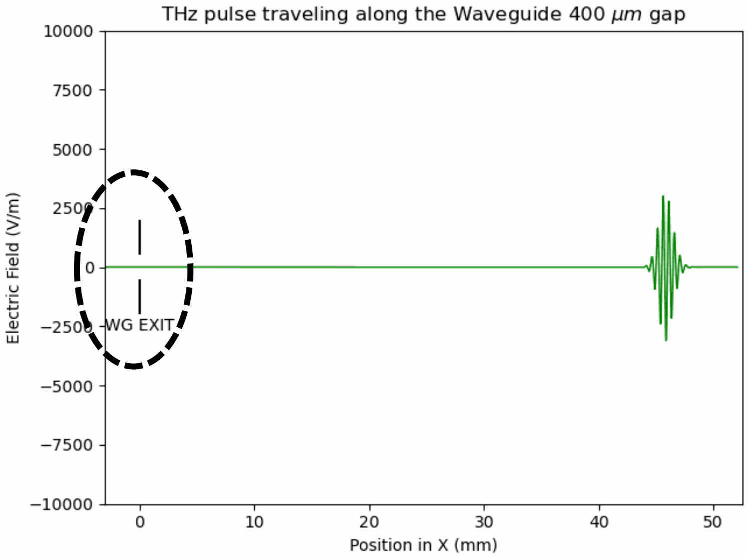
Machining limitations of dielectric

$$f_c = \frac{1}{2a\sqrt{\mu\epsilon}} = \frac{c}{2a}$$

A. L. Genre et al., under preparation (2024)

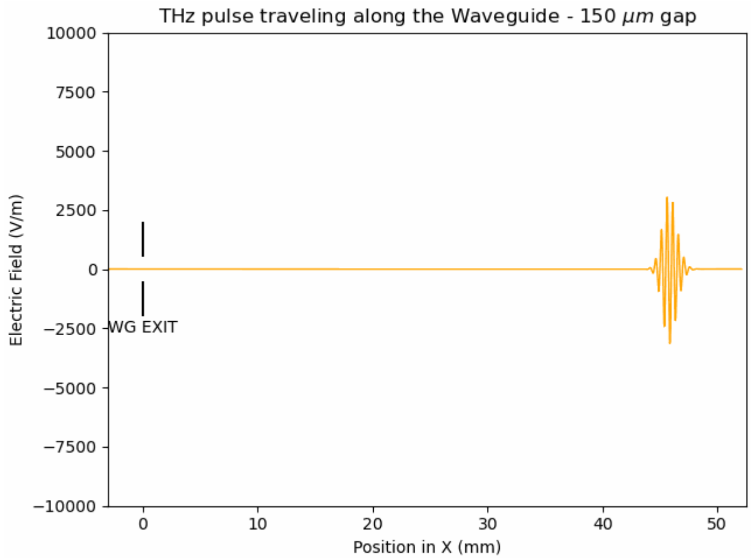
THz-driven particle accelerators (manipulators)

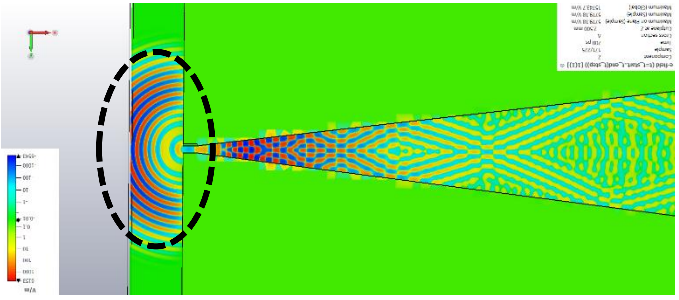
- Dielectric THz-driven Accelerators – Dielectric grating accelerator

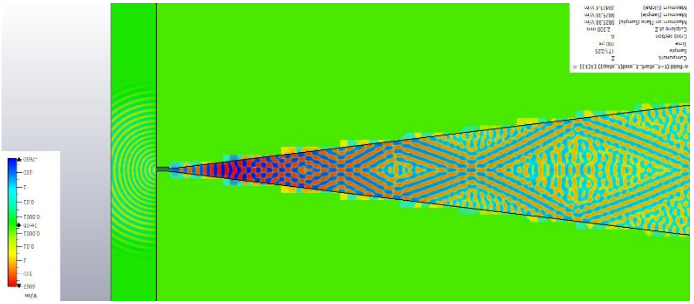


f=0.65 THz

gap =230 µm







Transmision of the pulse depends on the operational wavelength and the waveguide gap

A. L. Genre et al., under preparation (2024)

THz driven particle accelerators (manipulators)

- <u>Dielectric THz-driven Accelerators – Dielectric grating accelerator</u>

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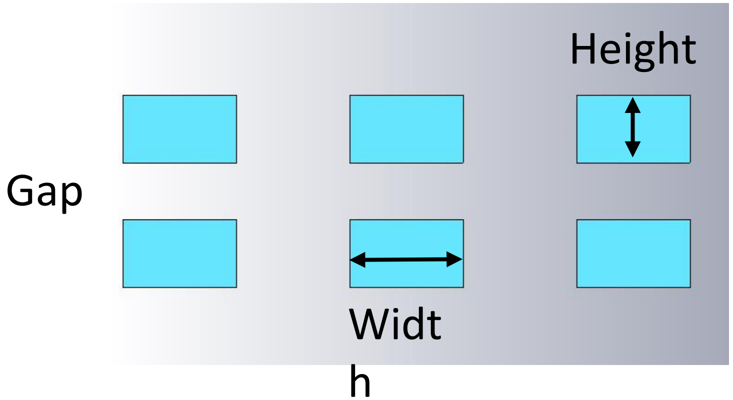
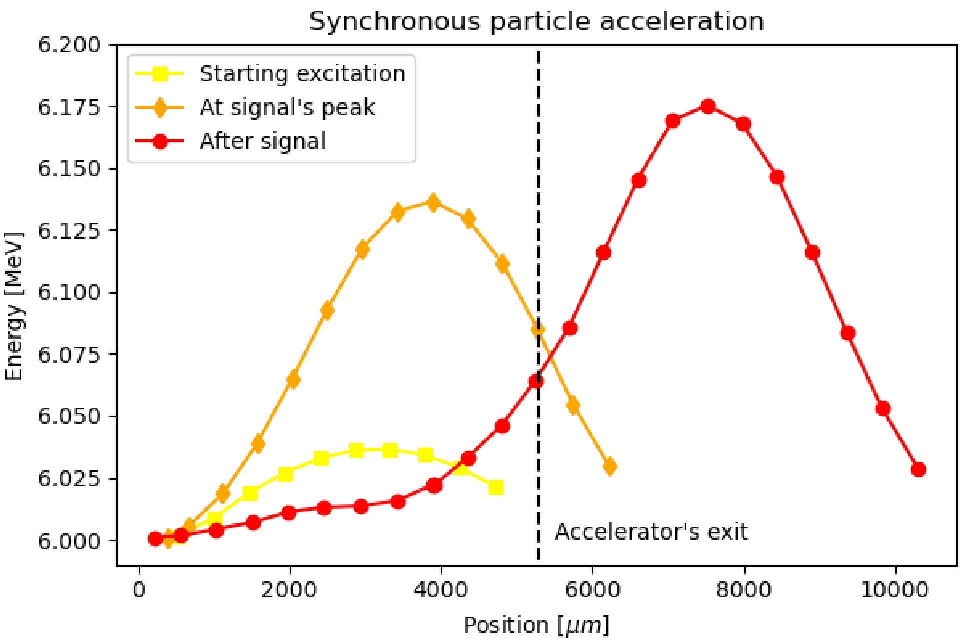
The optimization of the DLA parameters were carried out minding the figure of merits **acceleration factor (AF)**. The accelerating gradient is calculated in one period (λ_p), for the optimal electron path z(t).

Simulation

- 3 MV/cm
- 6 MeV initial kinetic energy
- 175 keV relative energy increase





$$AF = \frac{G_0}{E_{max}},$$

$$G_0 = \frac{q}{\lambda_p}\int_0^{\lambda_p} E_z(z(t),t)\,dz$$

A. L. Genre et al., under preparation (2024)

CONCLUSION & SUMMARY

Conclusion & Summary

- Comparing different types of accelerators

Main bunch properties (parameters)

- Normalized emittance
- Brightness
- Beam energy
- Energy spread
- Bunch length

Conclusion & Summary

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Main bunch properties (parameters)

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$$\varepsilon_{n,x} = \frac{1}{m \cdot c} \cdot \sqrt{\langle x^2 \rangle \cdot \langle p_x^2 \rangle - \langle x \cdot p_x \rangle^2}$$

$$B_n \equiv \frac{1}{m \cdot c} \cdot \frac{Q}{(2 \cdot \pi)^2 \cdot \varepsilon_{n,x}^2}$$

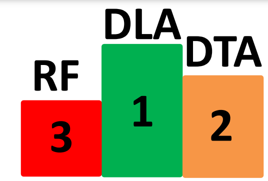
Conclusion & Summary

Parameter	RF	DLA	DTA	THz in vacuum
Power source	Microwave Klystron	Commercial IR laser	THz pulse	THz pulse
Wavelength	2-10 cm	1-10 µm	30 -3000 µm	30 -3000 µm
Bunch length	1-5 ps	10-100 as	1-5 ps	1-5 ps
Bunch charge	0.1-4 nC	1-10 fC	fC-pC	fC-few tens of nC
Req. Norm. Emittance	0.1-1 µm rad	1-10 nm rad	nm rad - µm rad	nm rad - µm rad
Rep. Rate	1-1000 Hz	10-200 MHz	kHz-GHz	kHz-GHz
Confinement of mode	Metal Cavity	Photonic crystal (1D,2D,3D)	Metal	Vacuum
Material	Metal	Dielectric	Dielectric	-
Unloaded gradient	30-100 MV/m	1-10 GV/m	~ GV/m	few hundres of MV/m
Power coupling	Critically-coupled metal WG	Free-space/Silicon wg	Free-space/metal wg	-

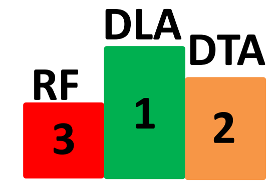
Conclusion & Summary

RF vs DLA vs DTA

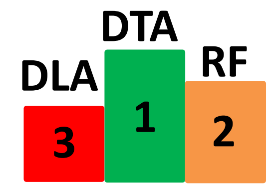
- RF induced breakdown threshold: $E_s \approx f^{1/2}\tau^{-1/4}$



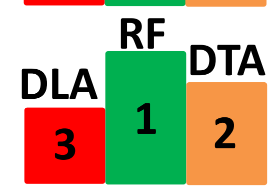
- Peak electric field + damage threshold



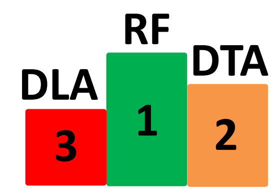
- Machining tolerances ($\sim\lambda$)



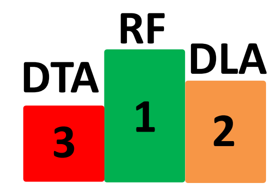
- Bunch charge



- Timing jitter

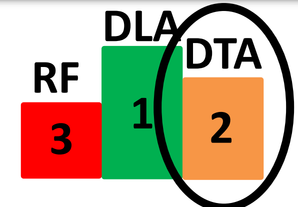


- Beam energy

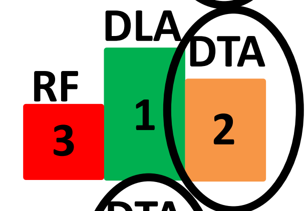


Conclusion & Summary

- RF induced breakdown threshold: $E_s \approx f^{1/2}\tau^{-1/4}$

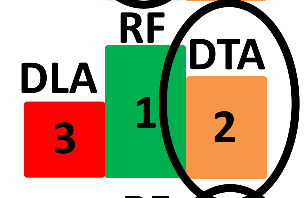


- Peak electric field + damage threshold

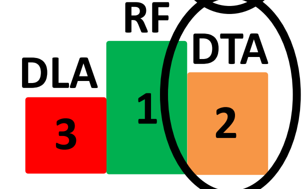


- Machining tolerances ($\sim\lambda$)

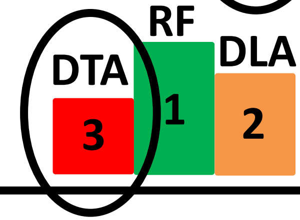
- Bunch charge



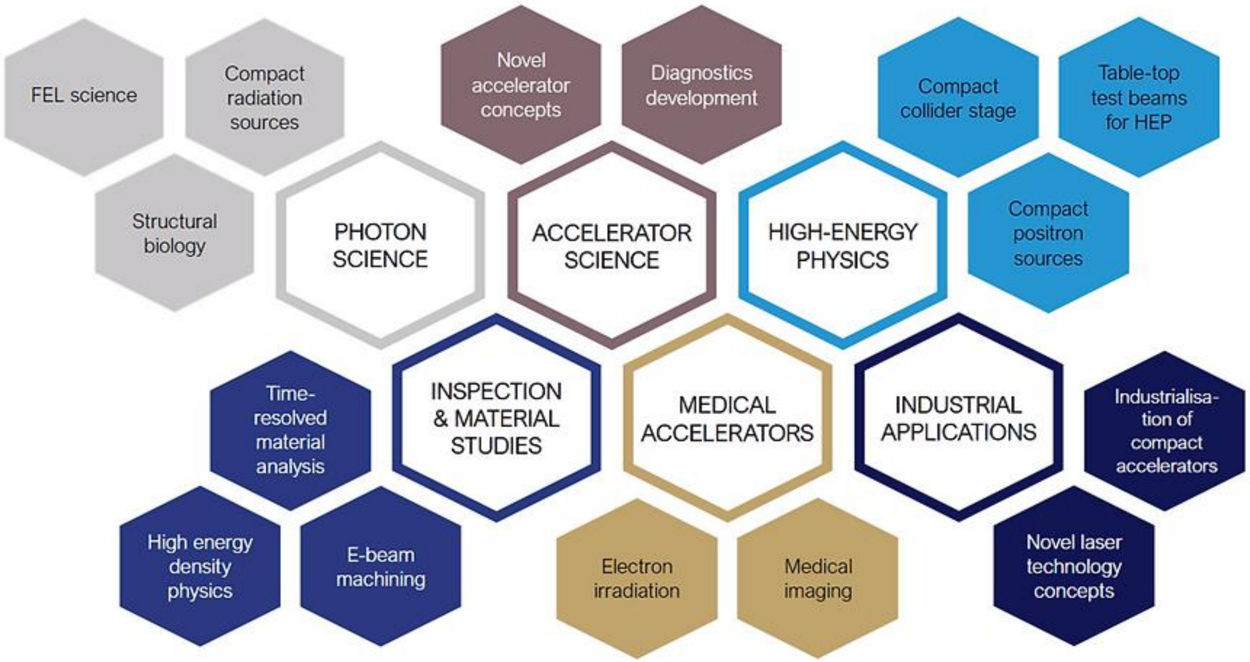
- Timing jitter



- Beam energy



Conclusion & Summary



Expected impact of EuPRAXIA on different fields.

https://www.eupraxia-dn.org/about

RF ~~vs~~ DLA ~~vs~~ DTA ~~vs~~ PWA

RF ~~vs~~ DLA ~~vs~~ DTA ~~vs~~ PWA

RF ~~vs~~ DLA ~~vs~~ DTA ~~vs~~ PWA

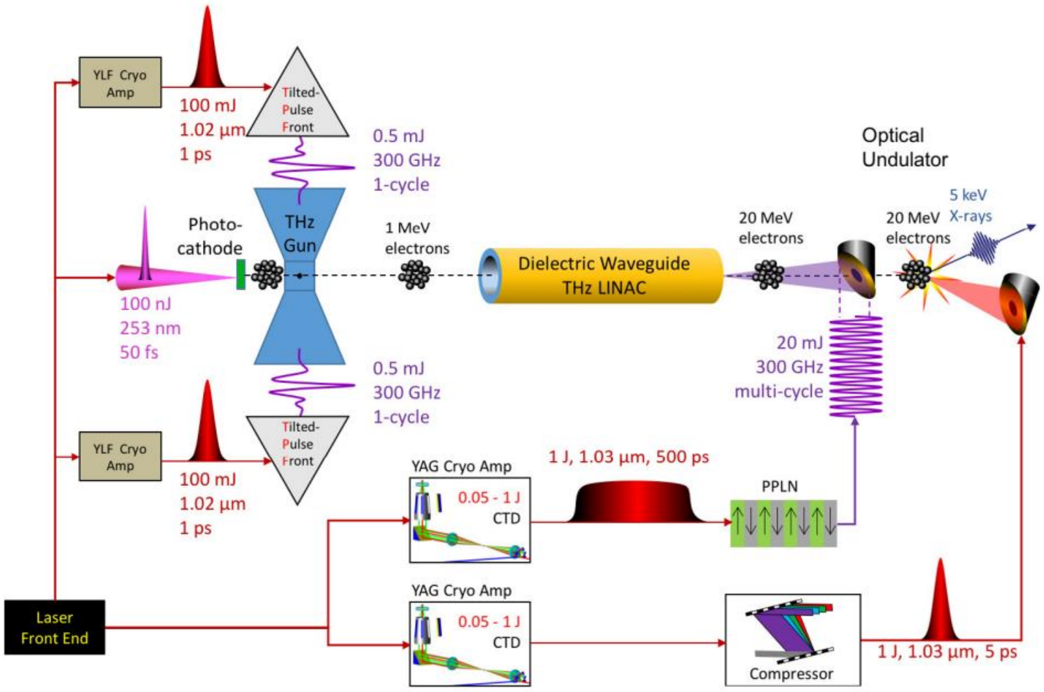
RF ~~vs~~ DLA ~~vs~~ DTA ~~vs~~ PWA

RF ~~vs~~ DLA ~~vs~~ DTA ~~vs~~ PWA

RF ~~vs~~ DLA ~~vs~~ DTA ~~vs~~ PWA

Conclusion & Summary

Importance and Potential Applications of Micro Accelerators



N.H. Matlis, F. Ahr, A.-L. Calendron et al. Nuclear Inst. and Methods in Physics Research, A 909 (2018) 27–32

APPLICATION	FIELD	TIME-SCALE
Compton X-ray Source	Medical	Mid
Catheterized Electron Source	Medical	Mid
Proton/Hadron Therapy	Medical	Long
Low-power EUV for inspection	Medical	Long
Linear Collider	HEP	Long
Micro-beams for radiobiology	Science	Near
UED/UEM Source	Science	Near
Compact XFEL	Science	Long
Multi-Axis Tomography	Science	Long

Thank you for your attention!

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Project 101073480 – EuPRAXIA-DN

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EXTRA SLIDES

Extra slides

- Additional references

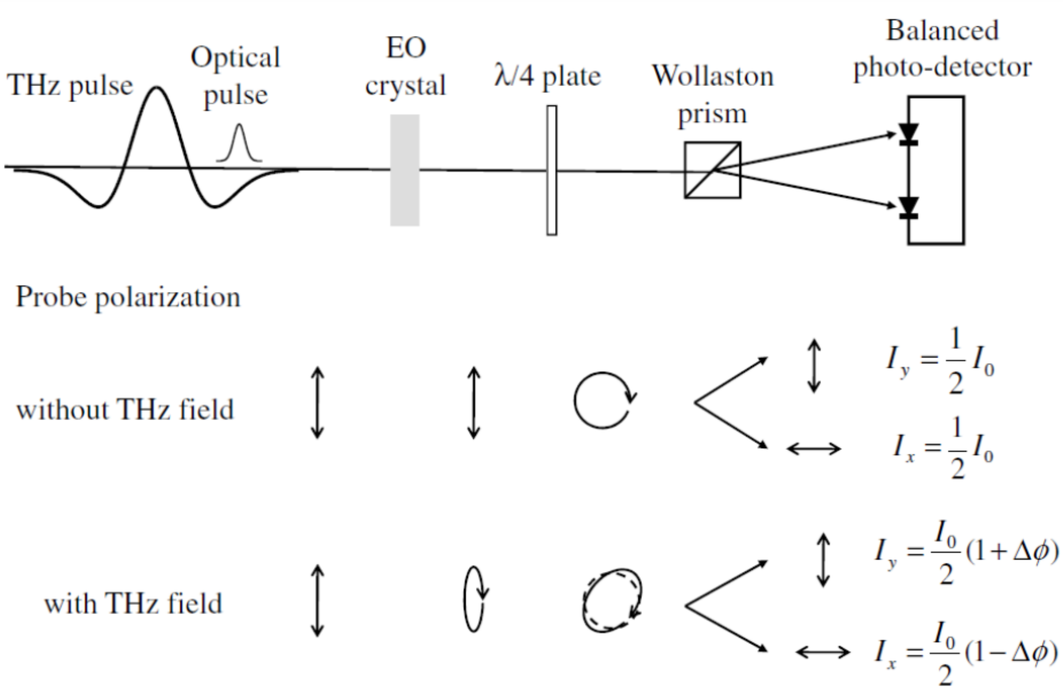
- **Electron acceleration**
  - THz-driven electron gun
    - Huang W.R. et al., Optica, 3(11), pp. 1209-1212 (2016)
    - Arya Fallahi et al., Phys. Rev. Accel. Beams 19, 081302 (2016)
  - Dielectric accelerator
    - Y. Wei et al., Applied Optics, 56(29), pp. 8201-8206 (2017)
    - Y. Wei et al., Physics Procedia, 77 (2015)
    - U. Niedermayer et al.,JINST, 17, P05014 (2022)
    - Li Sun et al.,International Conference on Microwave and Millimeter Wave Technology (ICMMT) (2021)

Extra slides

- <u>Electro-optic sampling</u>

Pockels effect

- **An electro-optic crystal becomes birefringent in a static electric field, and the degree of this birefringence is proportional to the field's magnitude.**



Y.-S. Lee, Principles of terahertz science and technology, vol. 170. Springer Science & Business Media, (2009).