Terahertz Acceleration

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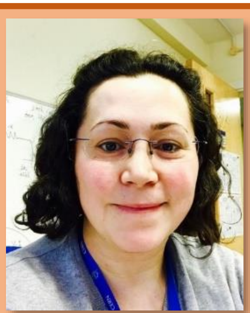
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Dr. Osman Akin

Science & Technology Facilities Council


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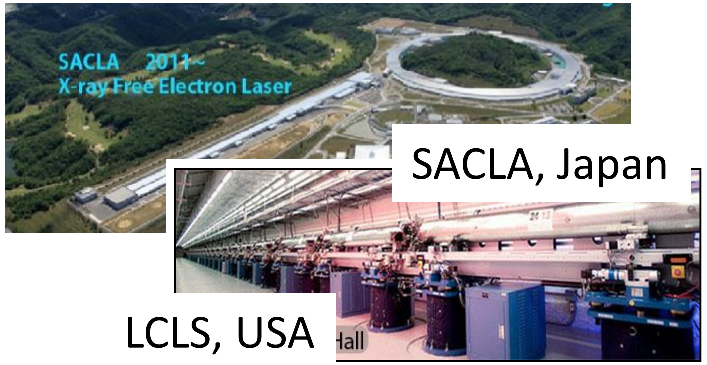
Dr. Edward Snedden

Why THz radiation for particle acceleration?

Light sources: xray Free-electron lasers
for femtosecond x-ray pulses

5GeV beams, <10fs bunches sought



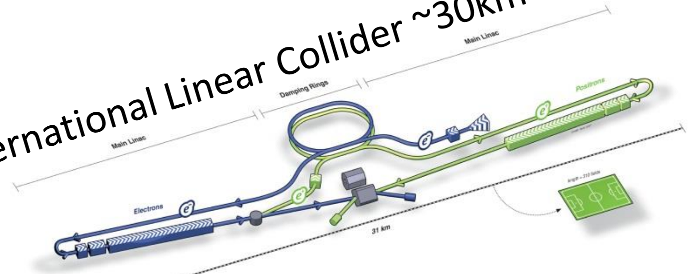
SACLA, Japan

LCLS, USA

Femtosecond manipulation of relativistic electron bunches using nanosecond period Radio Frequency sources

Particle physics

International Linear Collider ~30km



'CERN's 'Compact Linear Collider' ~48km

Scale of accelerators set by O(100MV/m) gradient limitation
(fundamental limits, atomic lattice distortion

THz driven Acceleration

- Field strengths O(100MV/cm)
- Picosecond period, broad-bandwidth, direct waveform control

Why THz radiation for particle acceleration?

Radio freque

- Frequency ≈3 GHz
  period ≈ 300 ps,
- λ ≈ 10 cm
  Cavity aperture ~ 2
- E_{acc} ~ 10 - 100 MV m^{-1}
- Pulse length: 5 ms (su
  5 μs (no

THz frequ

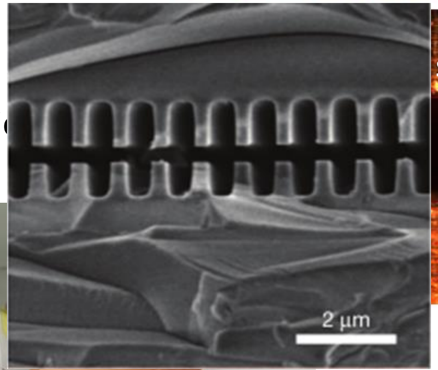
- Frequency ≈1
  period ≈ 1
- λ ≈ 300 μm –
  Cavity aper
- E_{acc} ≈ 100 MV/
- Pulse length 1

Optical frequencies

- Frequency ≈300 THz
  period ≈ 3 fs,
- λ ≈ 0.8 – 1 μm
  Cavity aperture ≈ 1 μm
- E_{acc} ≈ 100 MV m^{-1} to >> GV/m
- Pulse length 20 fs – 1 ps

THz advantages:

durati

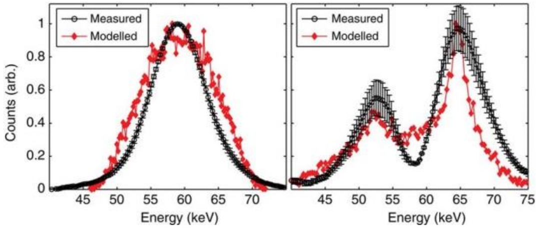


[2] E.A Peralta *et al.*, Nature, 503.7474 (2013): 91-94

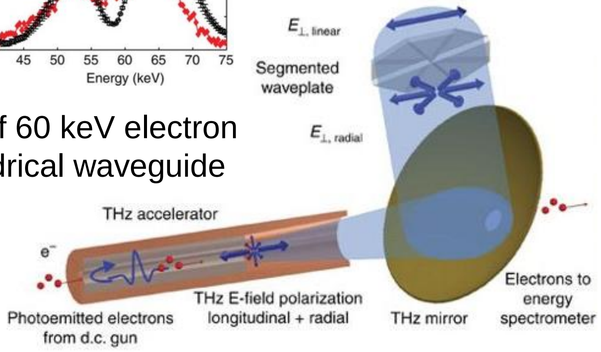
THz challenges:

- Obtaining sub-luminal phase velocities
- Broadband pulses – controlling dispersion
- High field THz sources still challenging

Terahertz-driven interactions: Sub-relativistic electrons (<100 keV)



THz-driven acceleration

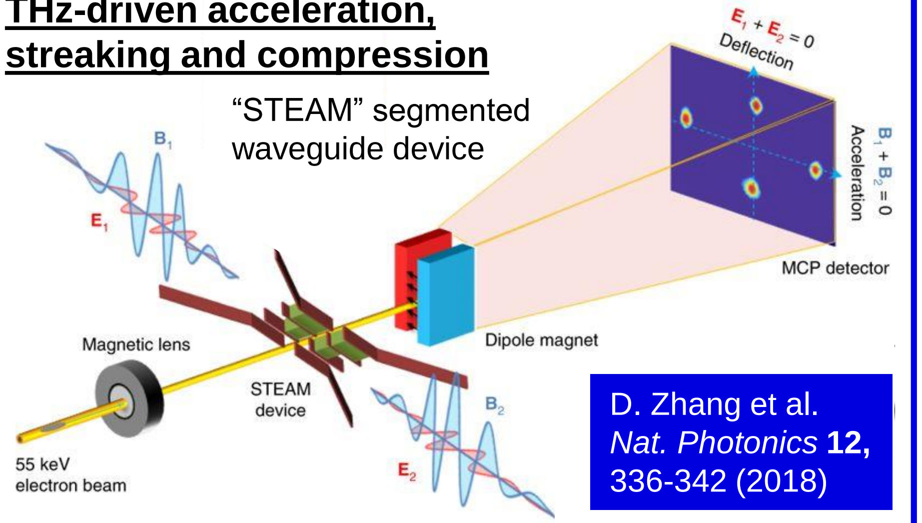


7 keV acceleration of 60 keV electron beams using a cylindrical waveguide

E. A. Nanni et al. *Nat. Commun.* **6,** 8486 (2015)

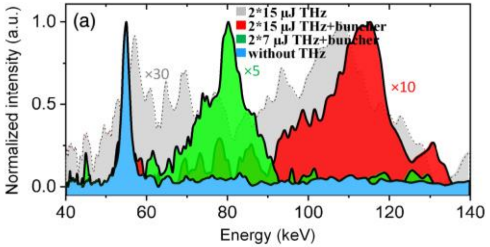
THz-driven acceleration, streaking and compression

“STEAM” segmented waveguide device



D. Zhang et al. *Nat. Photonics* **12,** 336-342 (2018)

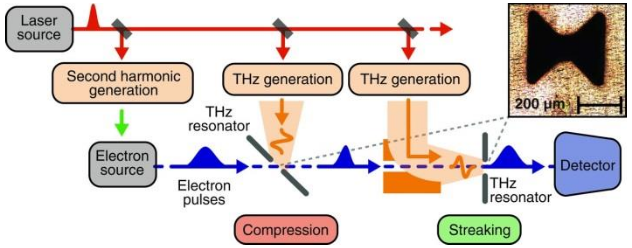
Two-stage STEAM setup for 70 keV acceleration

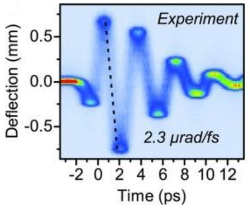


D. Zhang et al. *Optica* **6,** 872-877 (2019)

THz-driven streaking and compression

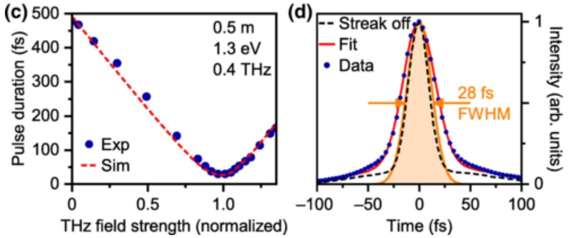
C. Kealhofer et al. *Science* **352,** 429-433 (2016)





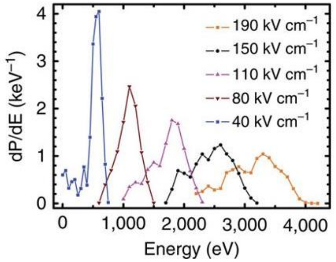
Using metal resonators and a planar mirror membrane

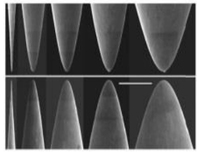
D. Ehberger et al. *Phys. Rev. Appl.* **11,** 024034 (2019)

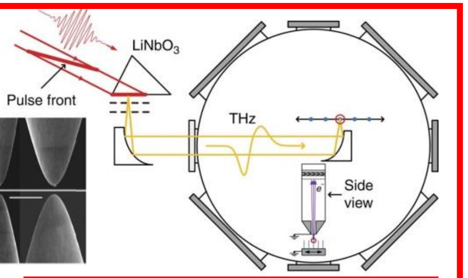


THz-driven emission

<4 keV from metallic nanotips



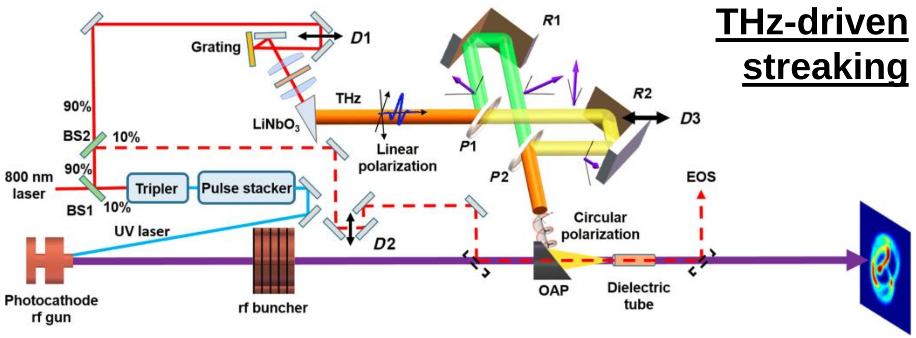




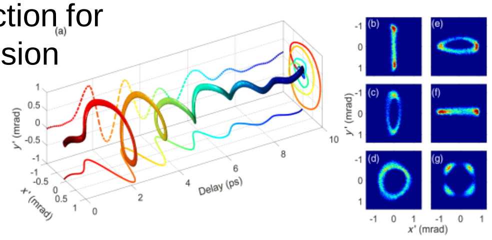
S. Li & R. R. Jones, Nat. Commun. **7,** 13405 (2016)

Terahertz-driven interactions: Relativistic electrons

THz-driven streaking

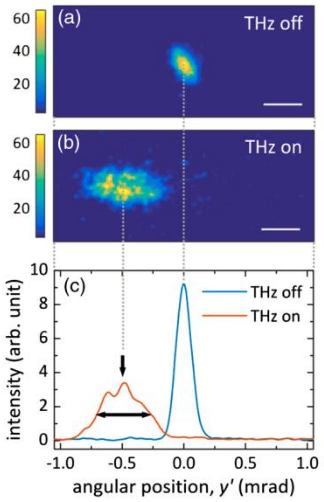


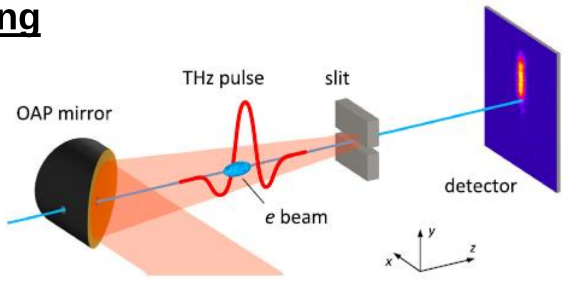
Dielectric tube, helical deflection for 50-fold longitudinal compression of 3.4 MeV beam



L. Zhao et al. *Phys. Rev. Lett.* **122,** 144801 (2019)

THz-driven streaking





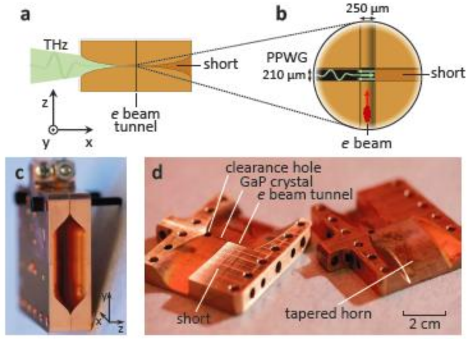
Streaking of a 3.1 MeV electron beam using a parallel-plate waveguide

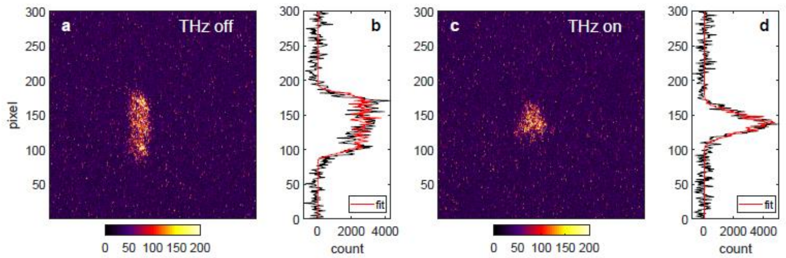
R. K. Li et al. *Phys. Rev. Accel. Beams* **22,** 012803 (2019)

THz-driven compression

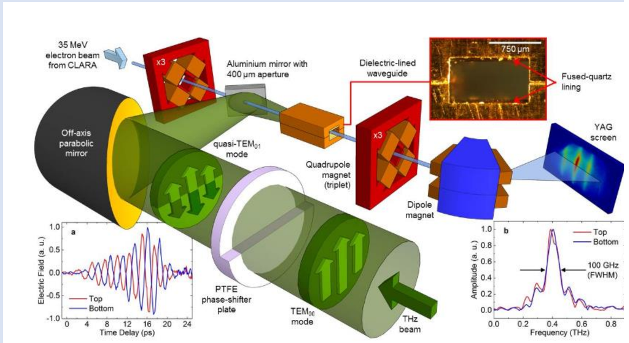
2.5 MeV electron beam
x3 compression
x2 timing jitter reduction

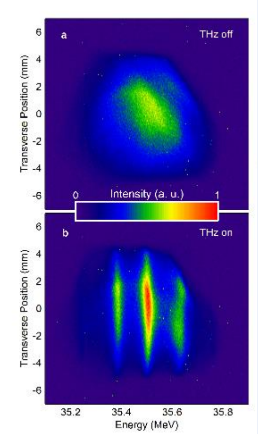
E. C. Snively et al. arXiv:1906.03358 (2019)





THz-driven acceleration





Dielectric lined waveguide
Quasi-monochromatic THz
Energy modulation & acceleration on 35MeV beam

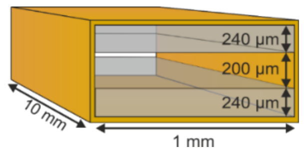
M.T. Hibberd et al, arXiv 1908.04055 (2019) Nature Photonics, August 2020

What is needed for THz acceleration?

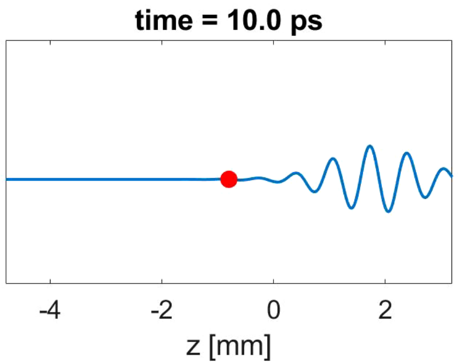
- Strong longitudinal field component
- Phase matched to particle velocity

- Dielectric Lined Waveguides used to achieve both

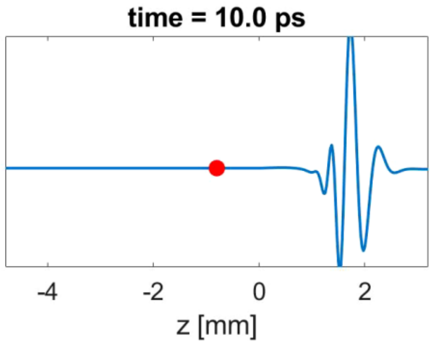
- Phase velocity matching, $v_\phi = \beta c$
- Group velocity $v_g << v_\phi$

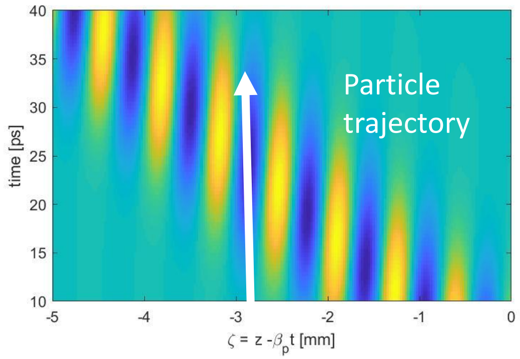


few-cycle THz input (quasi-monochromatic)

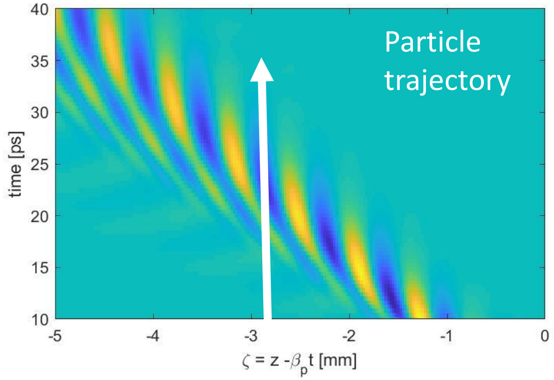


Single-cycle THz input



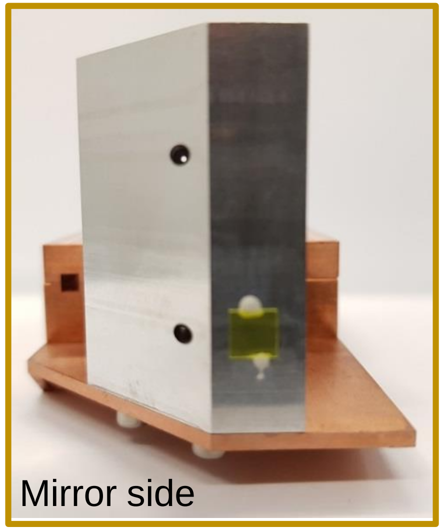


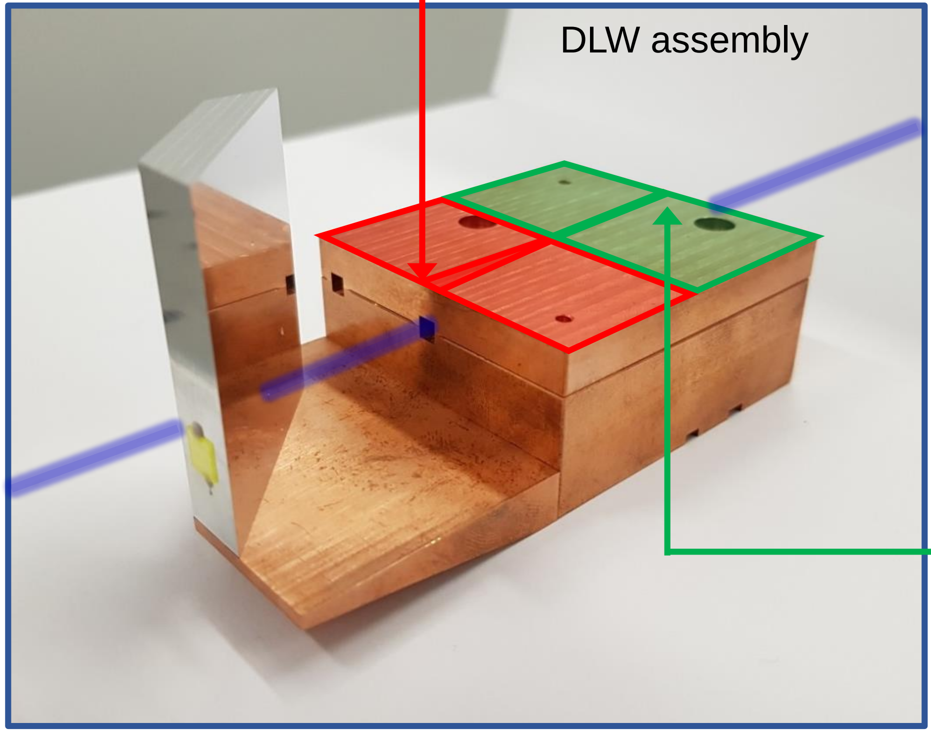
Field in frame of 50MeV electron beam (v = 0.9995 c)

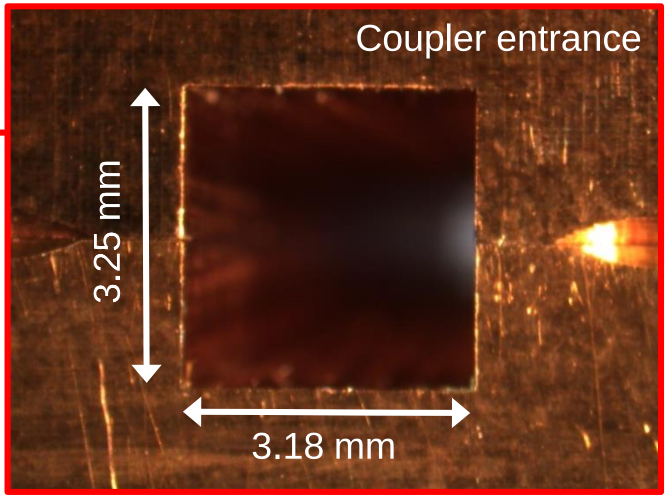


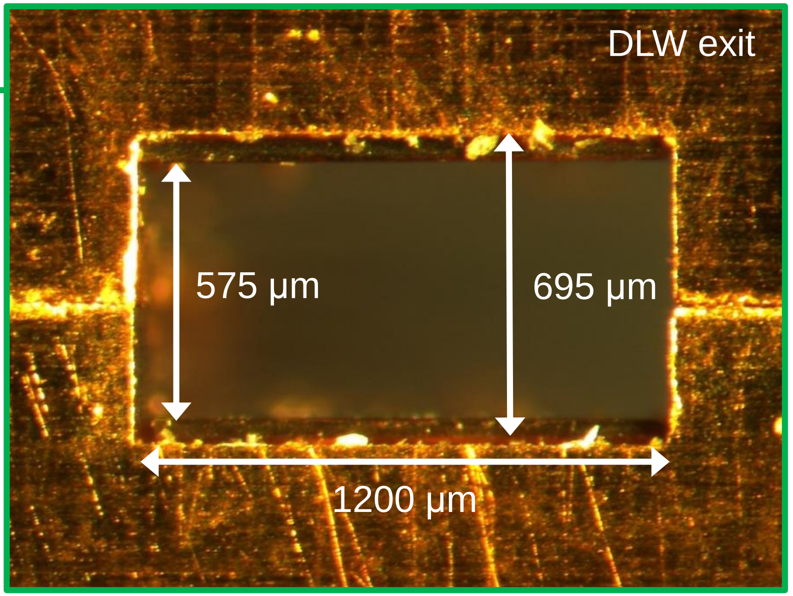
Particle see constant electric field phase (accelerator or decelerating)

Our approach: Rectangular dielectric-lined waveguide







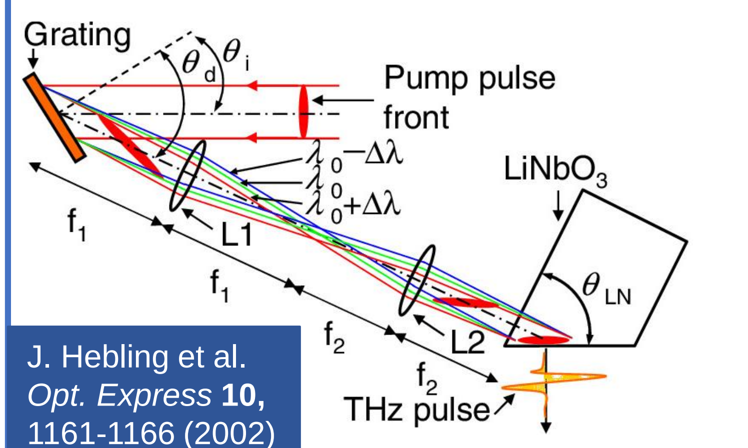


Dielectric lining results in:
Longitudinal **S**ection **M**agnetic modes

→ LSM_{11} for acceleration
→ Designed for velocity-matching to the 35 MeV electron beam

Our approach: Narrowband terahertz source

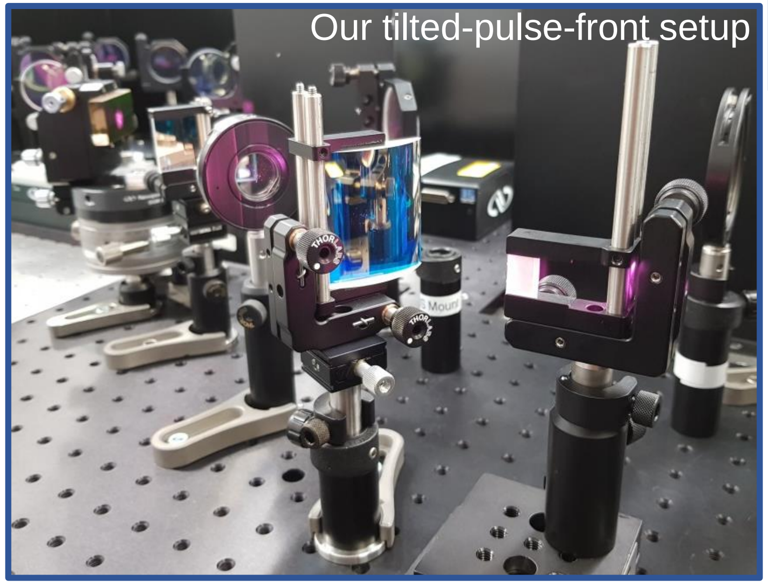
Tilted-pulse-front pumping in $LiNbO_3$



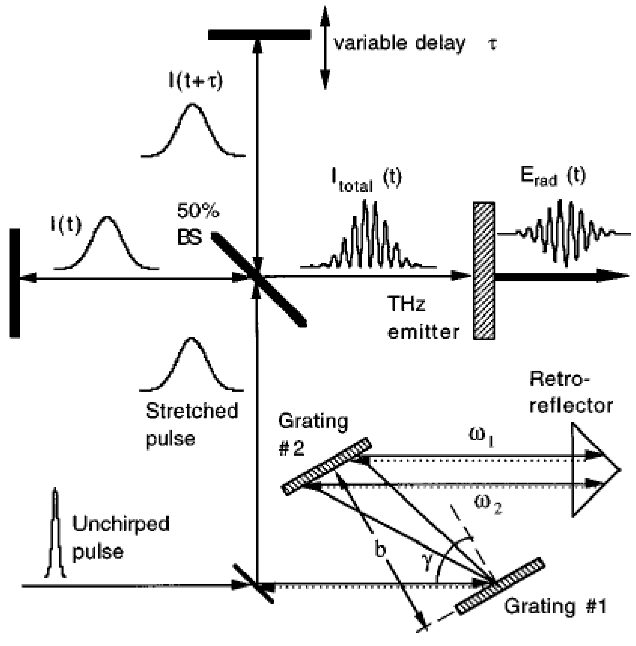
J. Hebling et al. *Opt. Express* **10,** 1161-1166 (2002)

Diagram from:
H. Hirori et al. *Appl. Phys. Lett*. **98**, 091106 (2011)

Our tilted-pulse-front setup



Chirped-pulse beating for narrowband THz generation

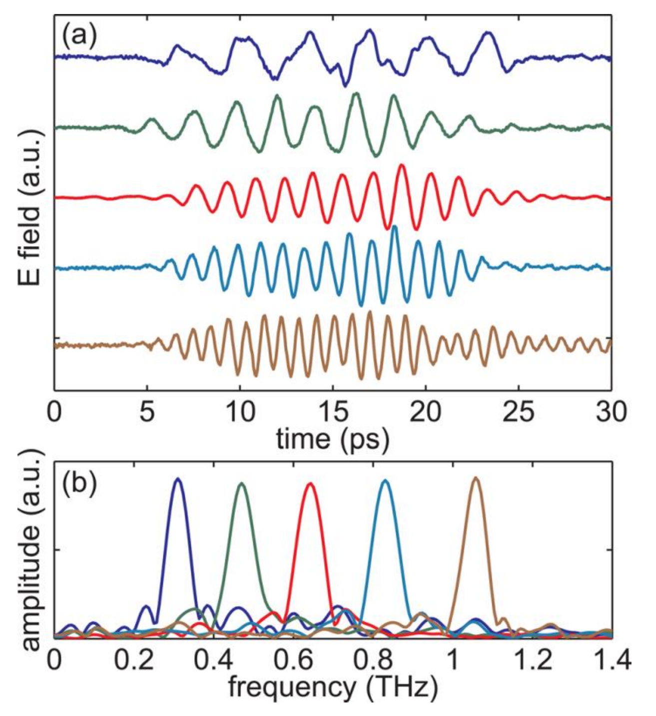


First demonstrated using a Michelson interferometer with a photoconductive antenna

A.S. Weling & D.H. Auston, *J. Opt. Soc. Am. B* **13**, 2783 (1996)

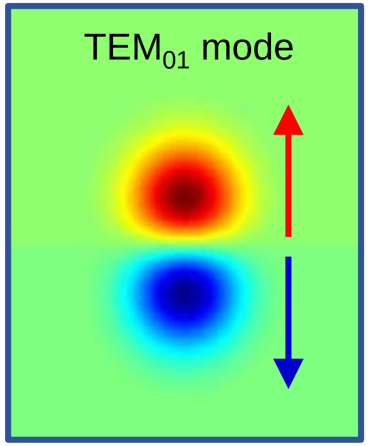
Also shown using an etalon with a $LiNbO_3$ crystal for a high-power, tunable multi-cycle THz source

Z. Chen et al. *Appl. Phys. Lett*. **99,** 071102 (2011)

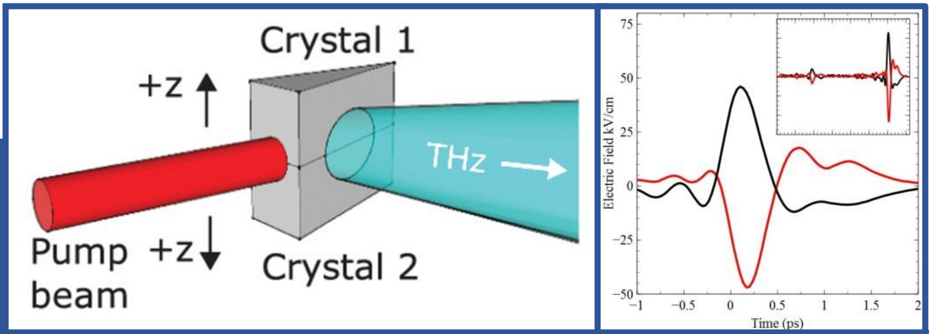


Our approach: Polarisation of the terahertz beam

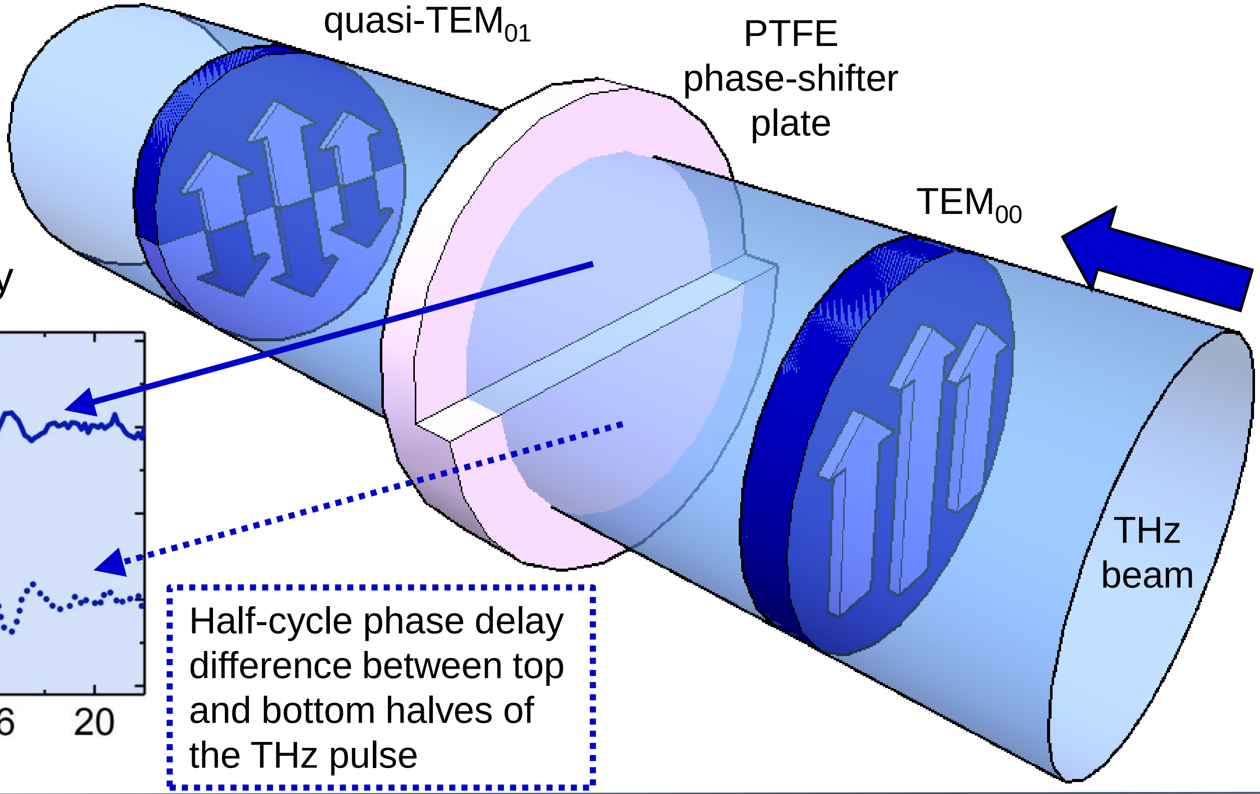
To excite the accelerating mode of the DLW
→ THz beam with a TEM_{01} mode is required



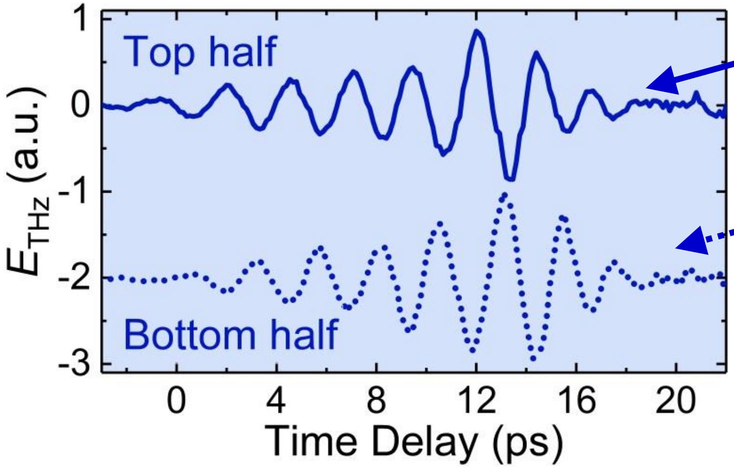
Previously demonstrated using the interferometric recombination of two polarity-inverted, linearly polarised THz beams



M. Cliffe et al. *Appl. Phys. Lett*. **108**, 221102 (2016)

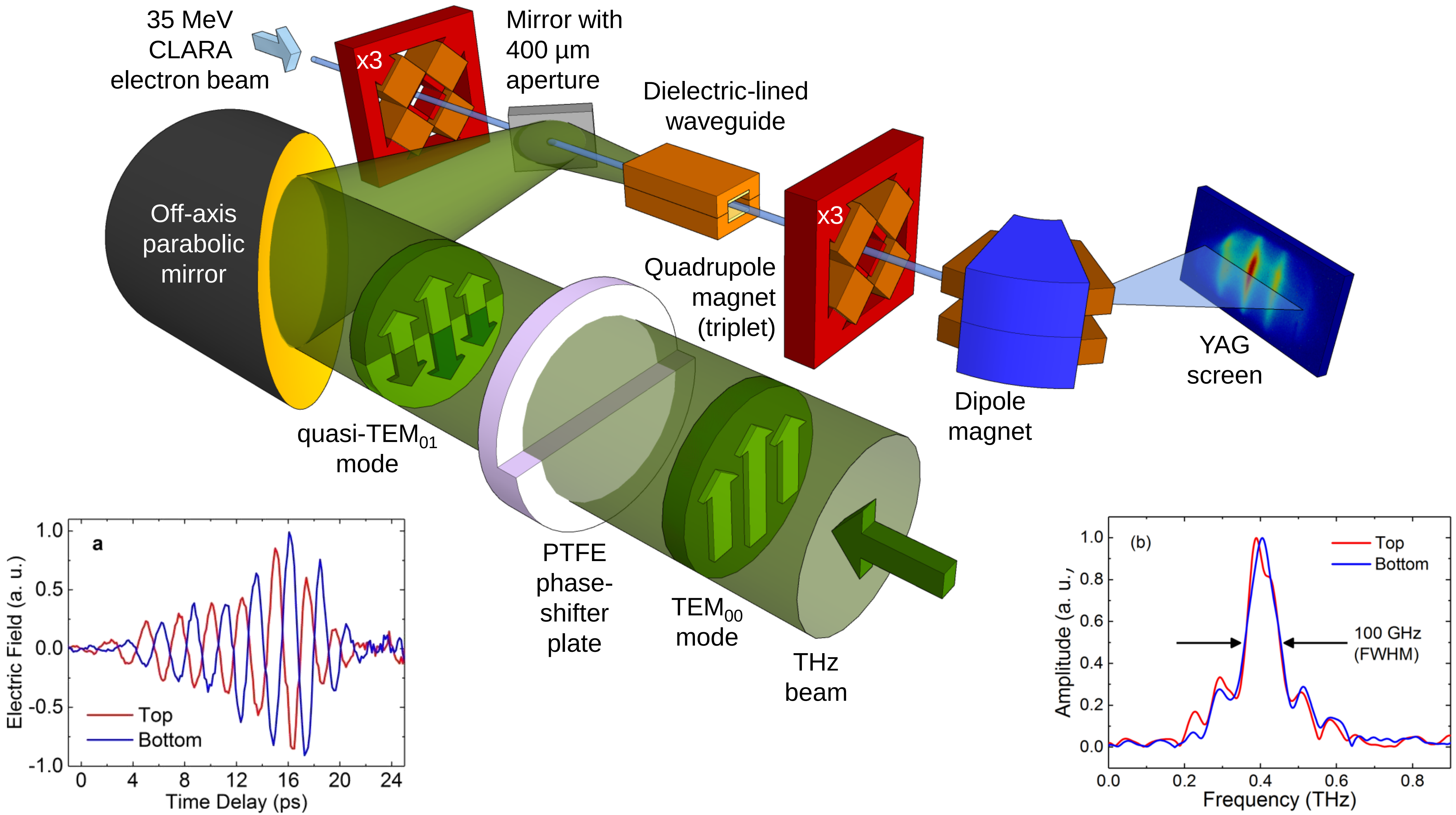


<u>Phase-shifter plate</u>
Achieve effective polarity inversion by using a phase delay

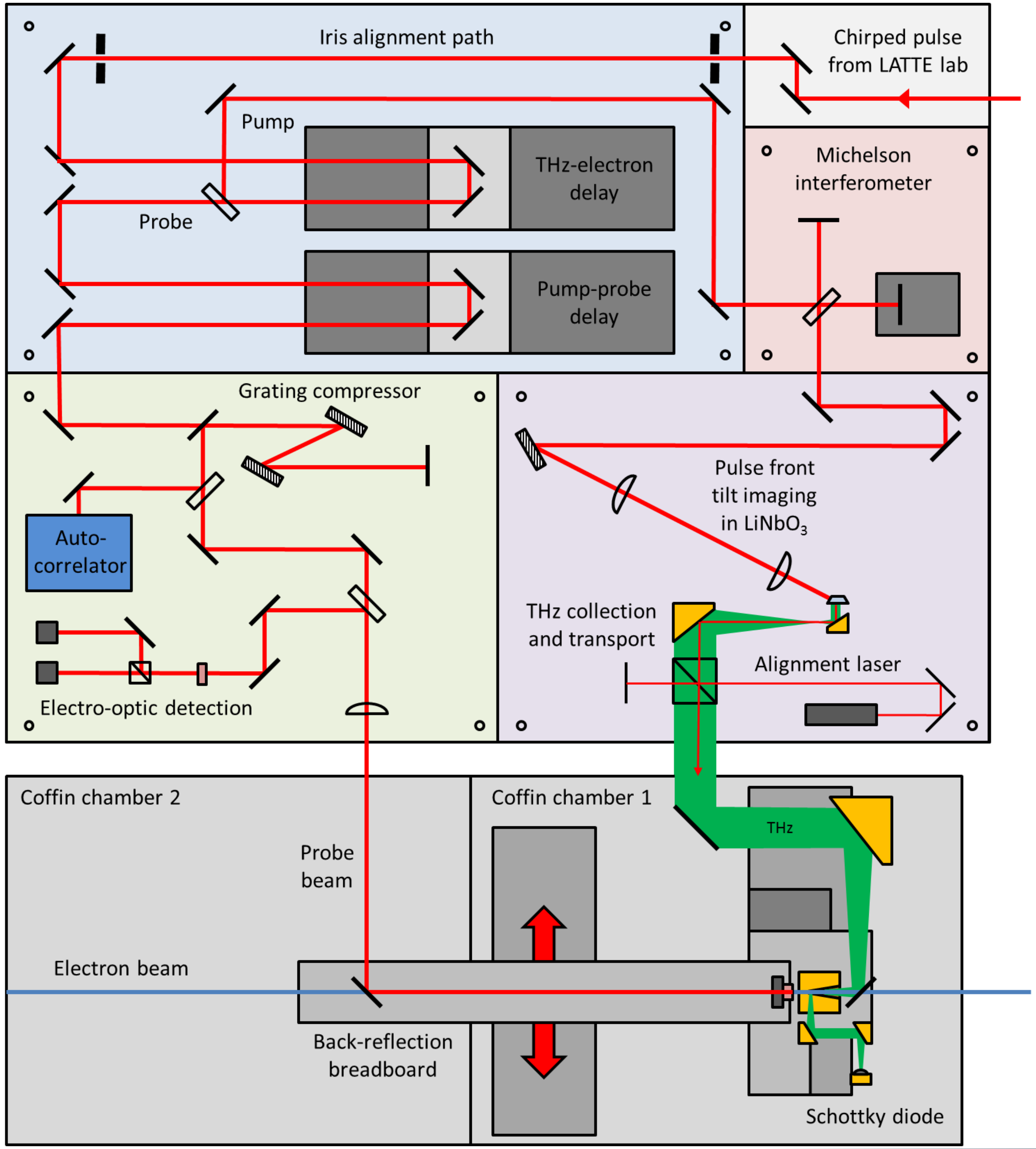


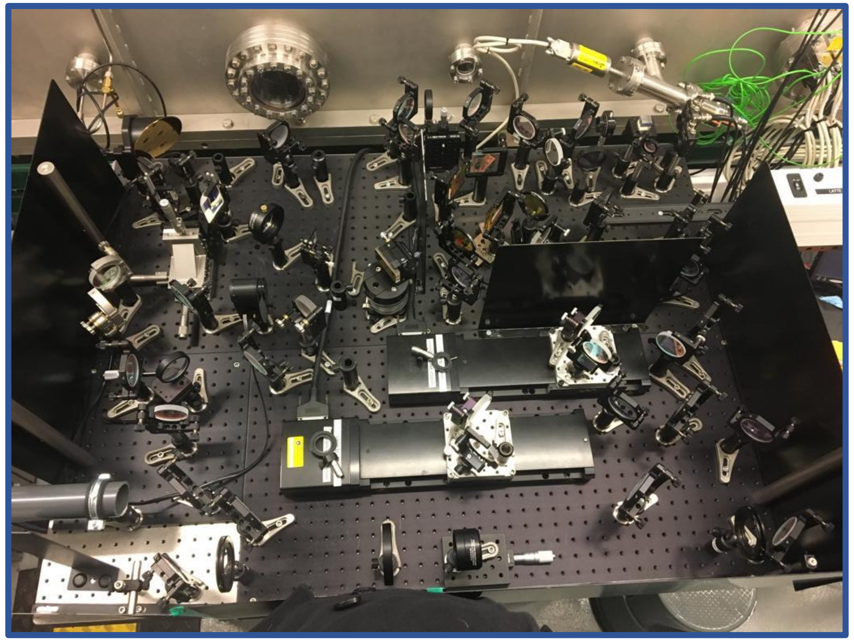
Half-cycle phase delay difference between top and bottom halves of the THz pulse

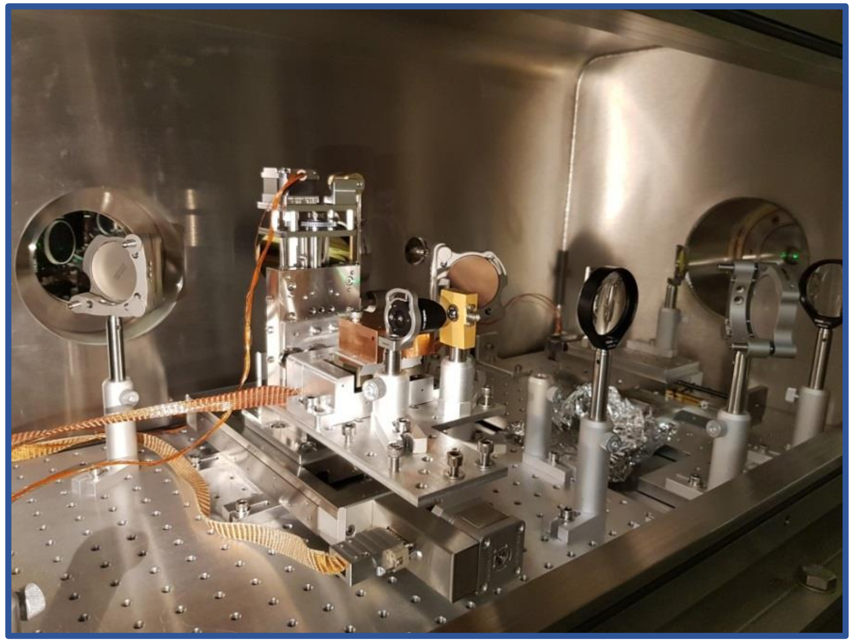
Our approach: Experimental approach



Our approach: Experimental setup





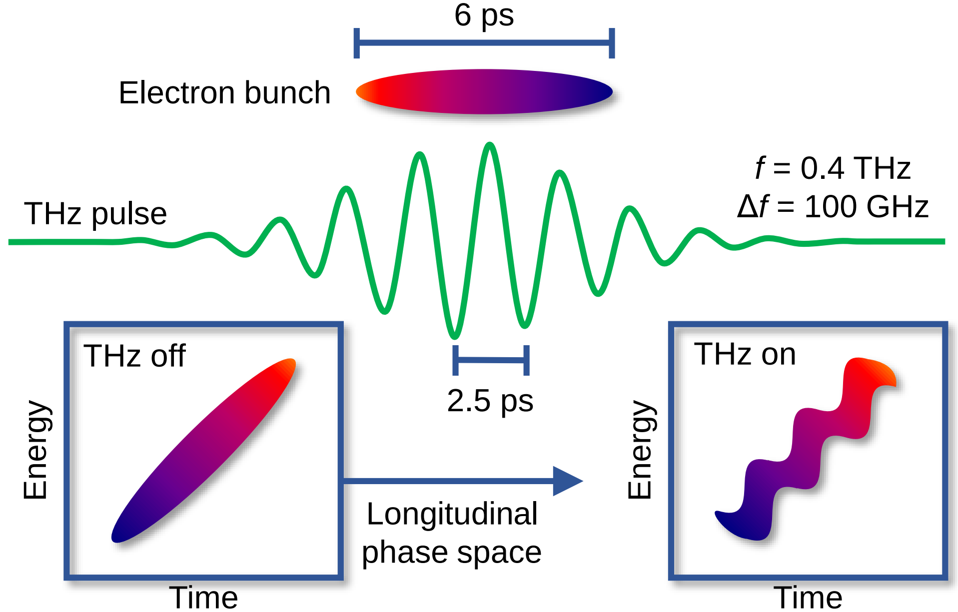


Results: Chirped electron bunch

CLARA operated in a long electron bunch configuration

- → Bunch duration of 6 ps FWHM
- → Linear (approx.) chirp of 53 keV/ps
- → Bunch charge of 60 pC

Estimated from beam dynamics simulations



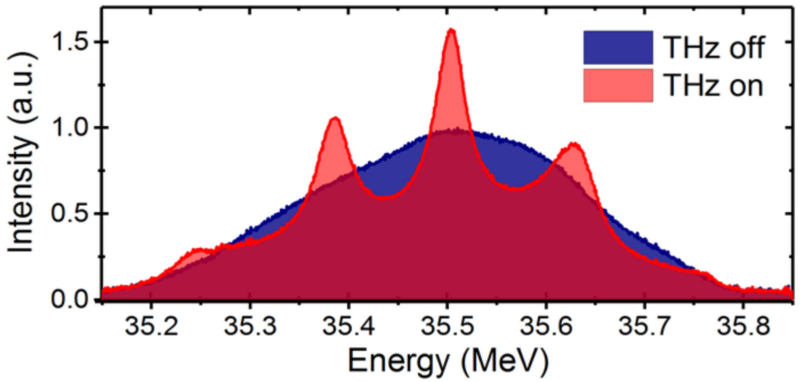
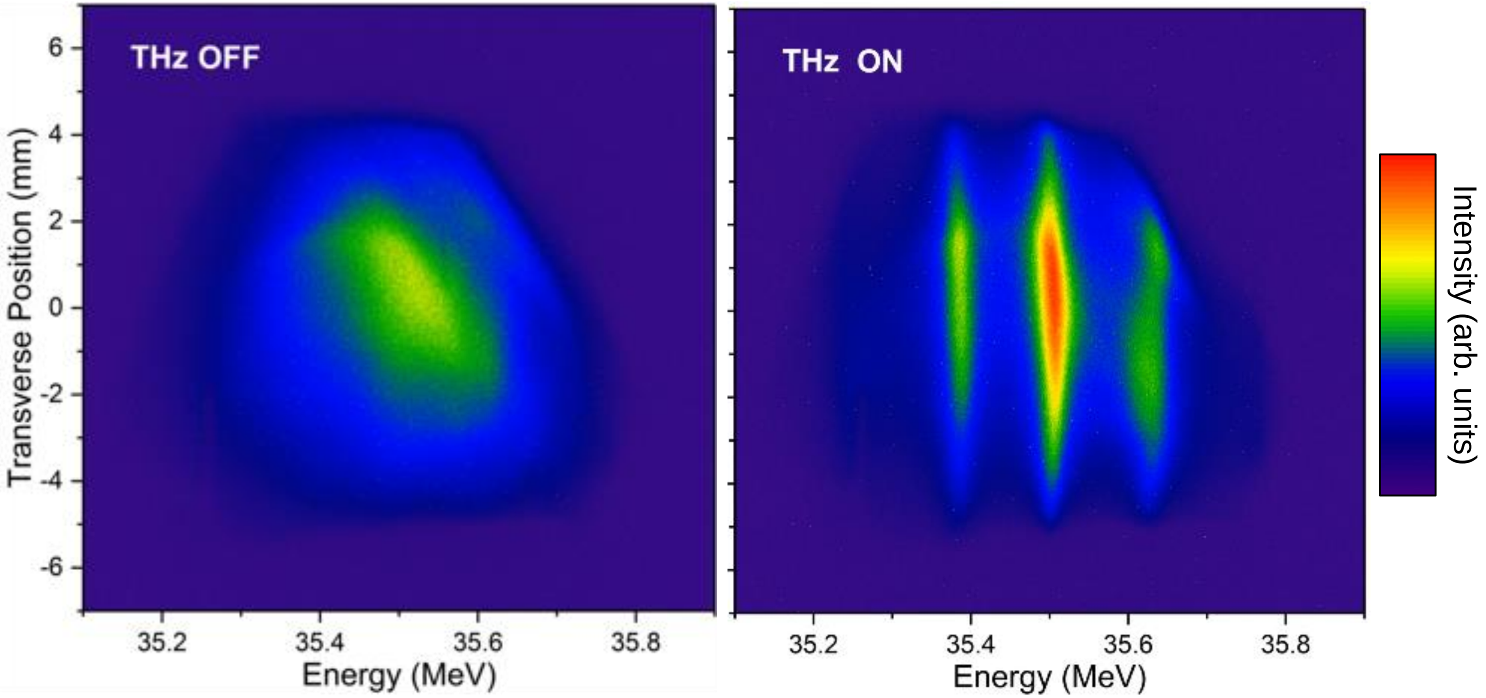
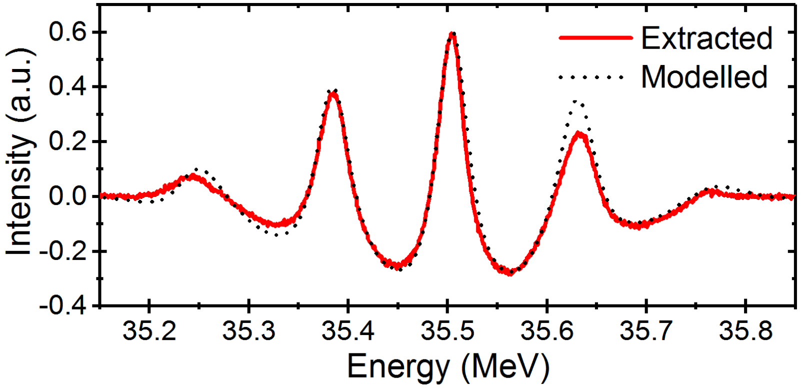


Image on electron energy spectrometer





Results: Chirped electron bunch

CLARA operated in a long electron bunch configuration

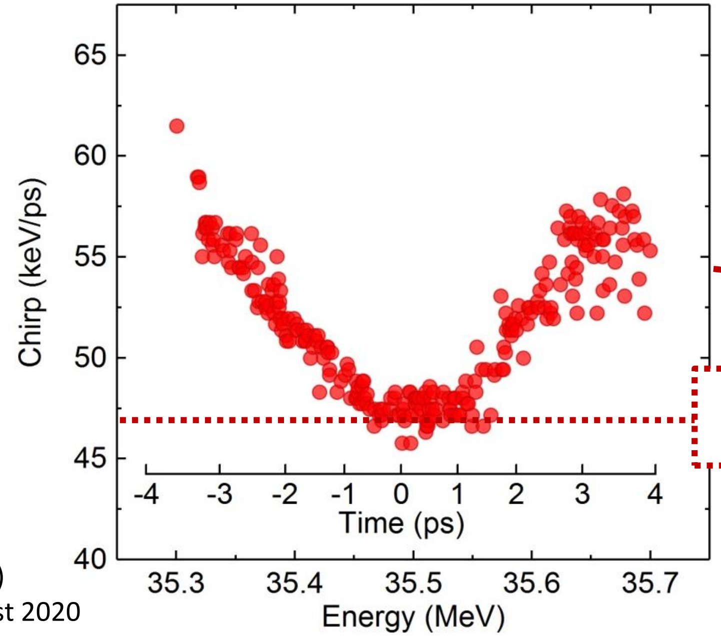
→ Bunch duration of 6 ps FWHM
→ Linear (approx.) chirp of 53 keV/ps
→ Bunch charge of 60 pC

Estimated from beam dynamics simulations

Measured longitudinal phase-space distribution

Obtained from 100 single-shot spectra with varying THz-electron bunch timing, using:

→ The measured energy modulation period **$\delta E(E)$**
→ The known THz period **τ = 2.5 ps** (0.4 THz)

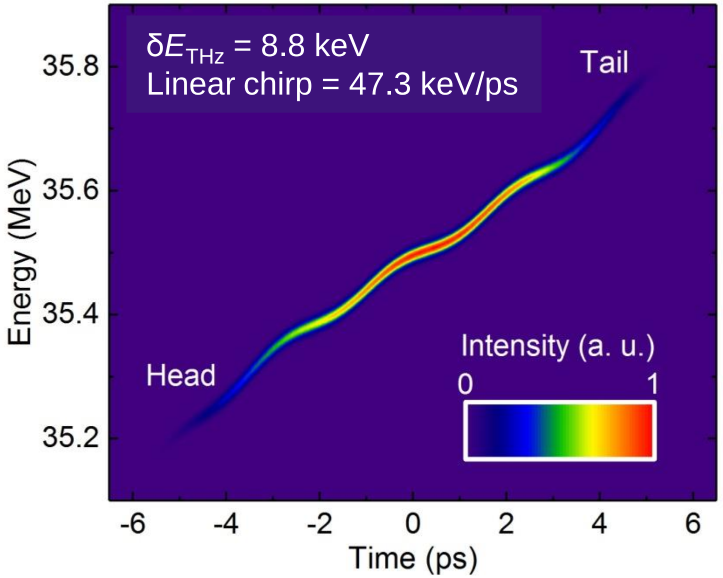


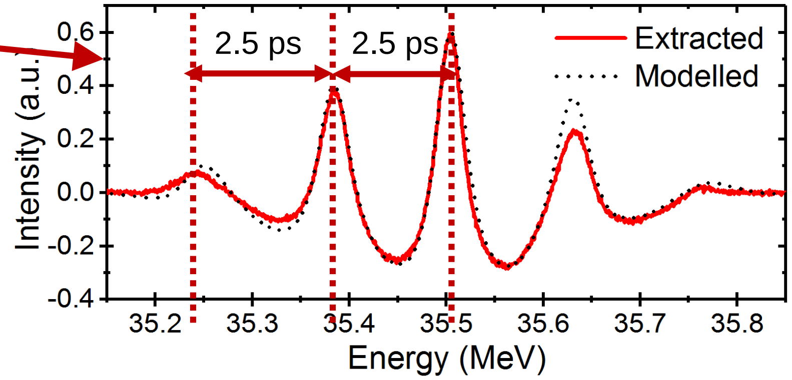
100 shots

M.T. Hibberd et al,
arXiv 1908.04055 (2019)
Nature Photonics, August 2020

Determining the peak terahertz-driven acceleration

Calculation imposing a sinusoidal THz-driven modulation on to a model electron bunch, including:
→ Bunch emittance, energy spread and chirp



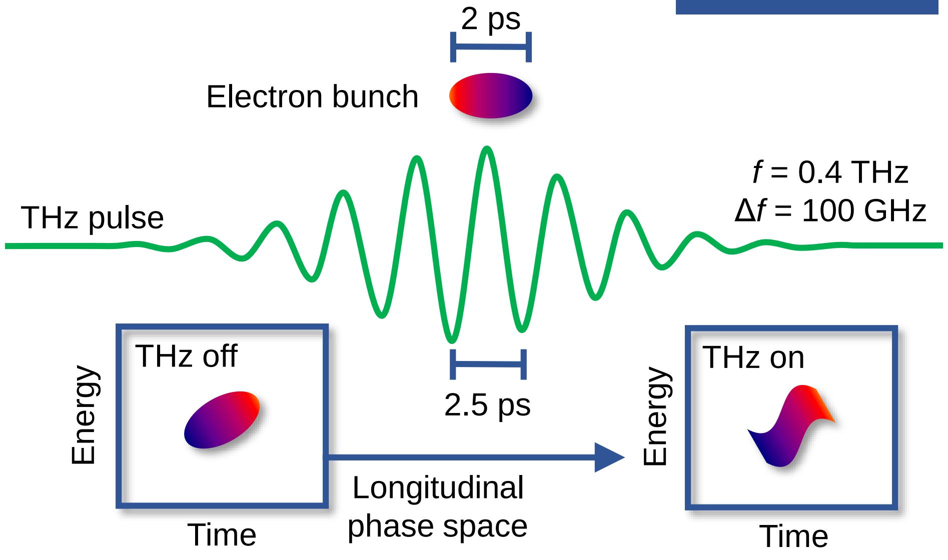


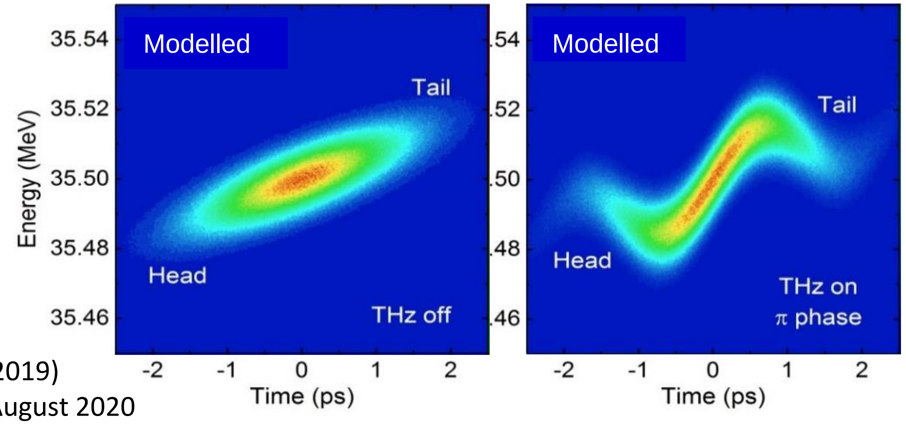
Results: Short electron bunch

CLARA operated in a short electron bunch configuration

→ Bunch duration of 2 ps FWHM
→ Residual linear chirp of <10 keV/ps

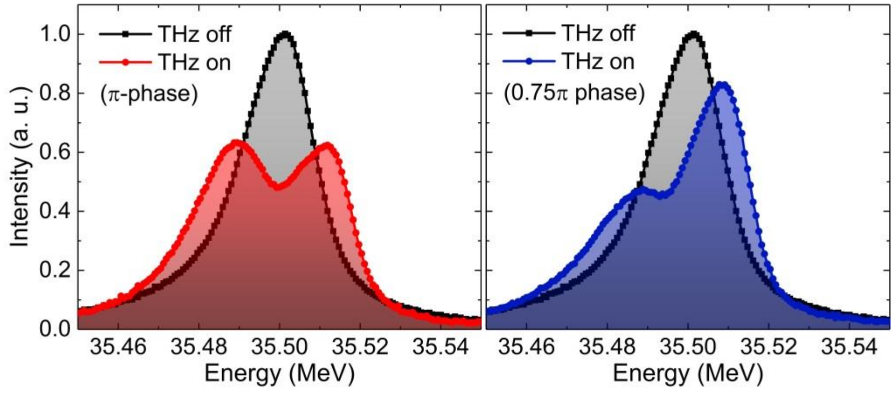
Estimated from beam dynamics simulations

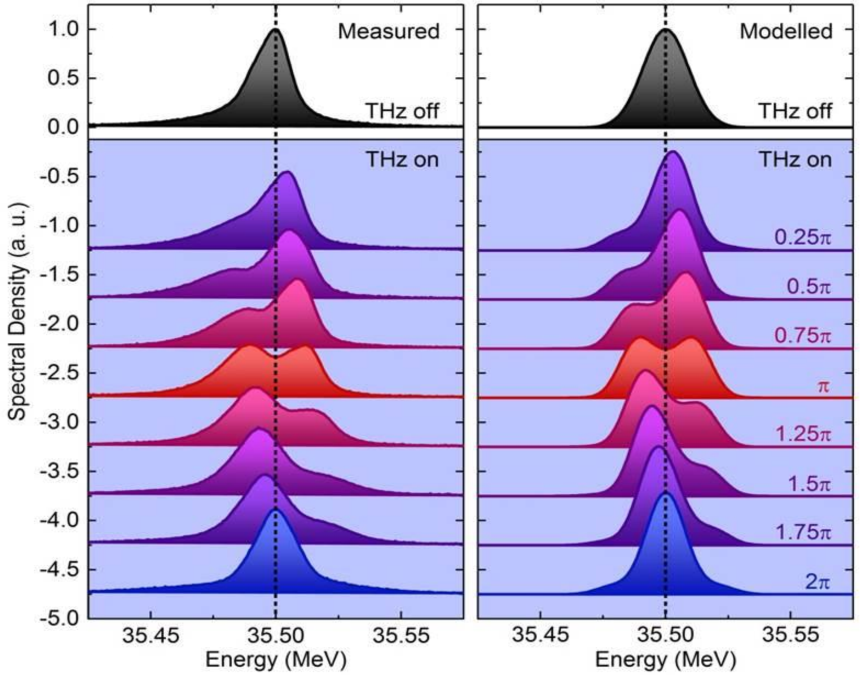




M.T. Hibberd et al,
arXiv 1908.04055 (2019)
Nature Photonics, August 2020

“Single-bucket” acceleration

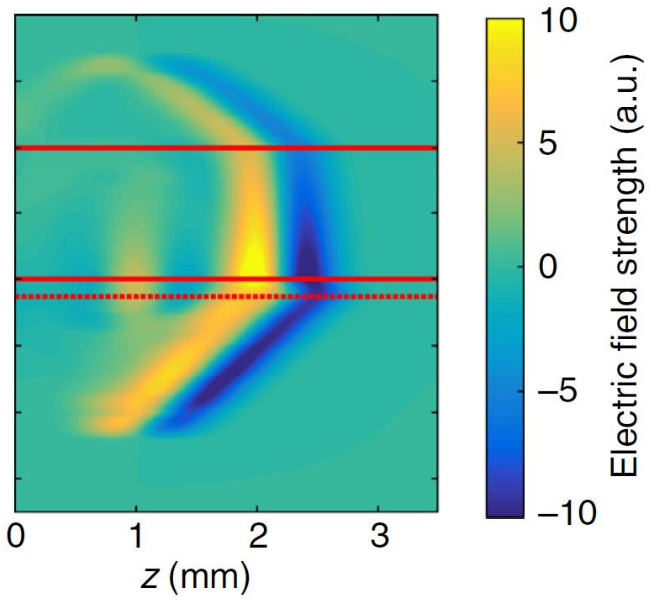


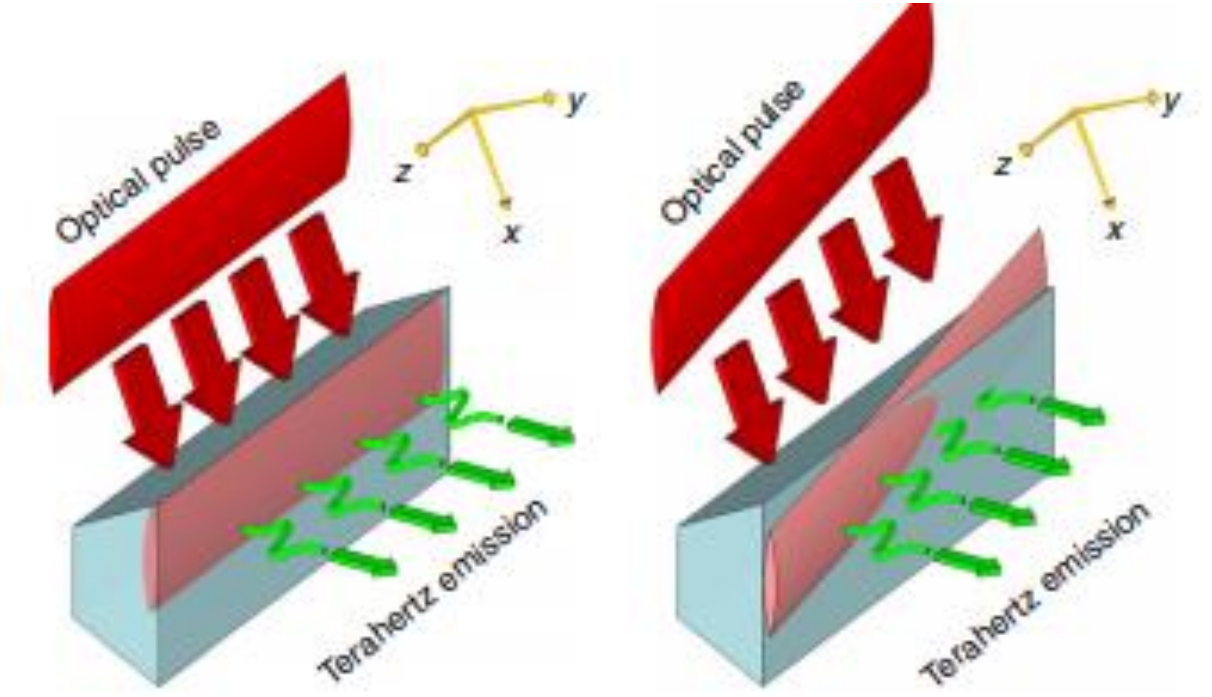


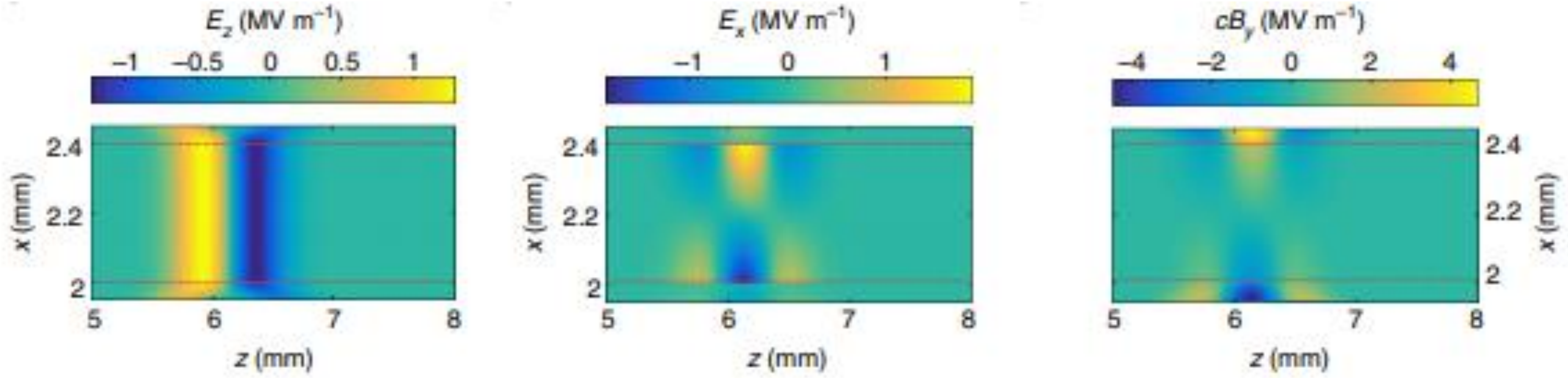
Another Approach: Travelling Wave THz Source

Use evanescent wave formed at crystal-vacuum boundary

- → Additional pulse-front-tilt gives time delay across THz pulse
- → Effective phase velocity matched to particles by tuning angle of extra tilt
- → Can use single cycle pulse – No need for narrowband
- → No need for a 'structure'





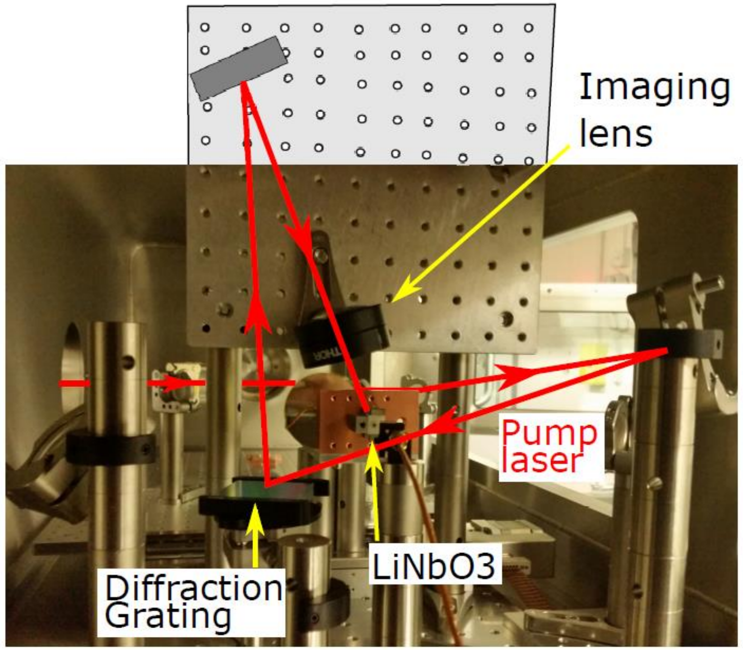


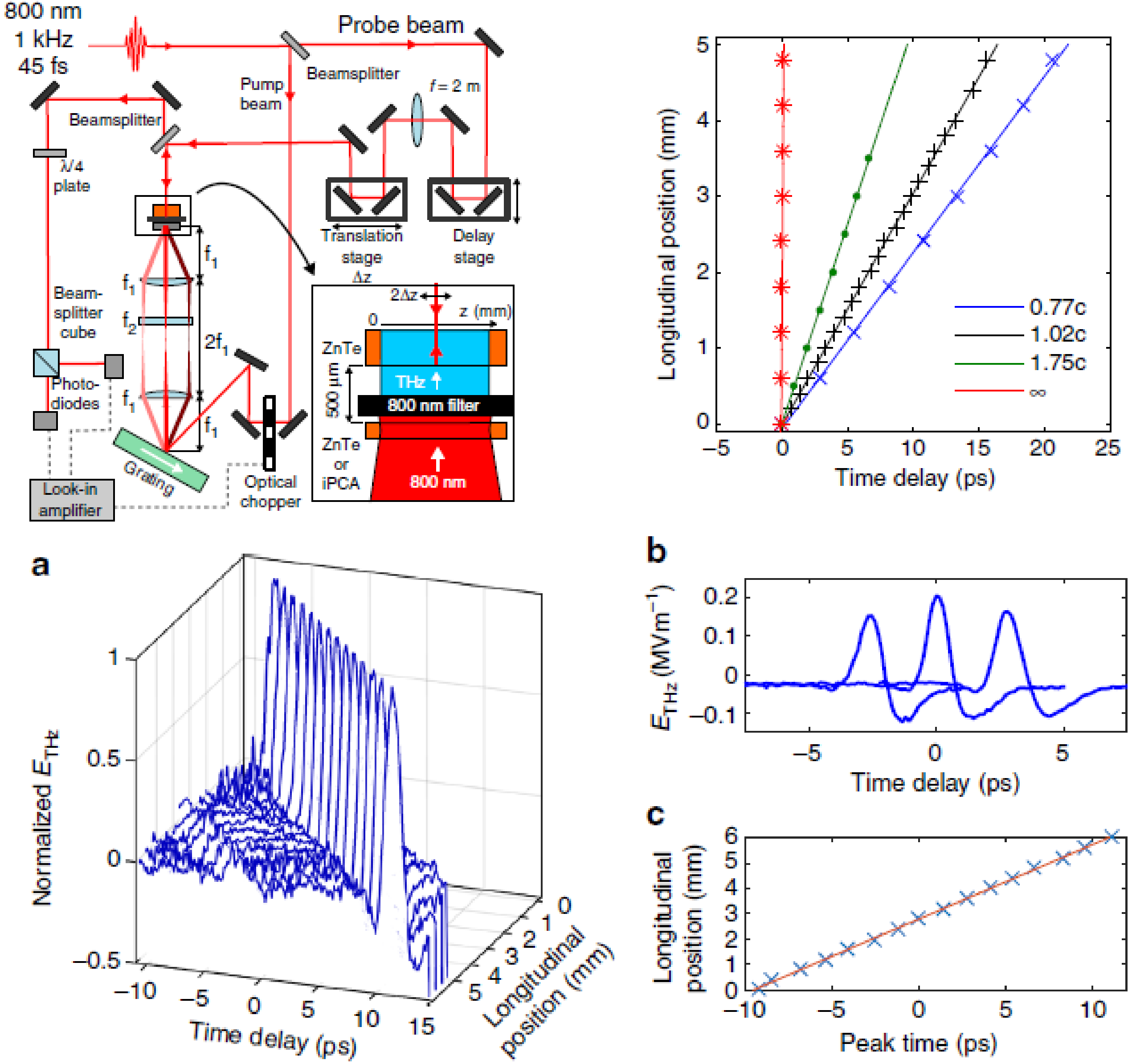
D.A. Walsh et al,
Nature Communications, September 2017

Our Approach: Travelling Wave THz Source

Proof of principle experiment
Showed Velocity matching possible over wide range
Accelerating fields behave as dispersion free

Requires complex 3d geometries to generate the THz when compared to waveguide schemes.





D.A. Walsh et al,
Nature Communications, September 2017

Our Approach: 100 keV Gun Experiment

Similar to the experiment with the DLW and relativistic electrons

- 100 keV photo-electron gun
- Vacuum chamber designed for two interaction points
- MCP detector

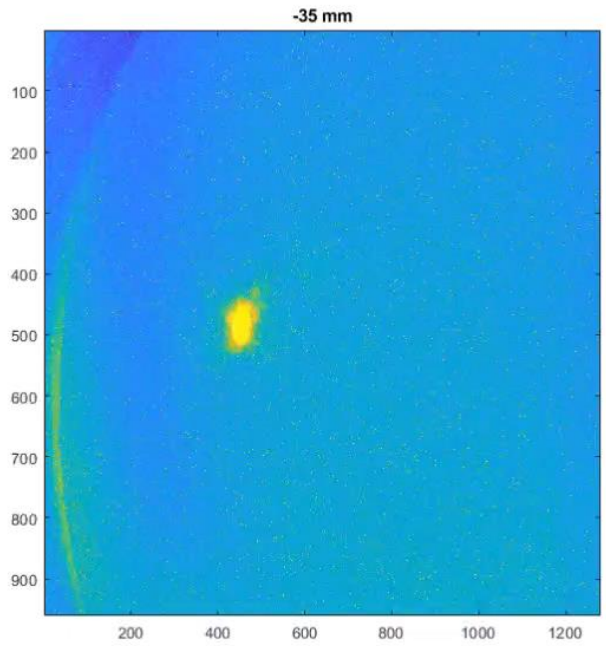
→ Different waveguide matched to 100 keV electrons

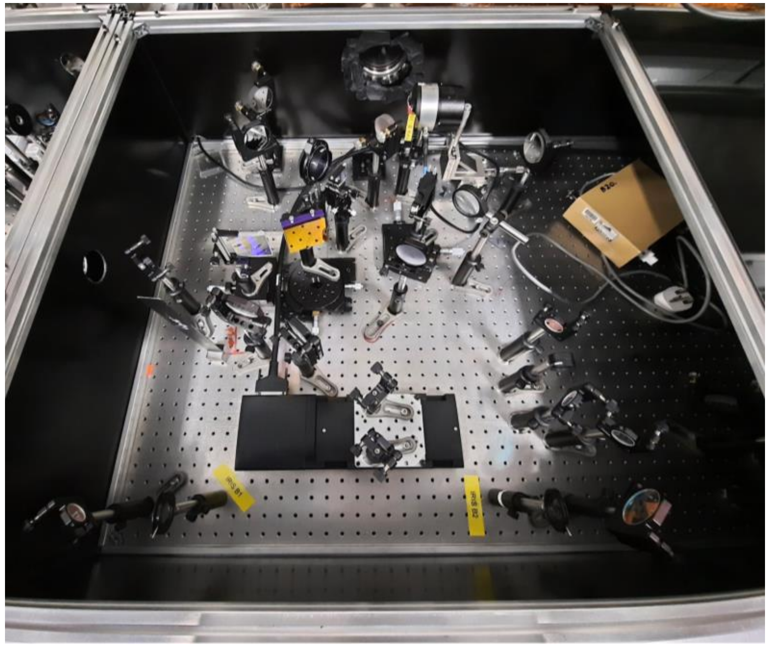
Short term goals

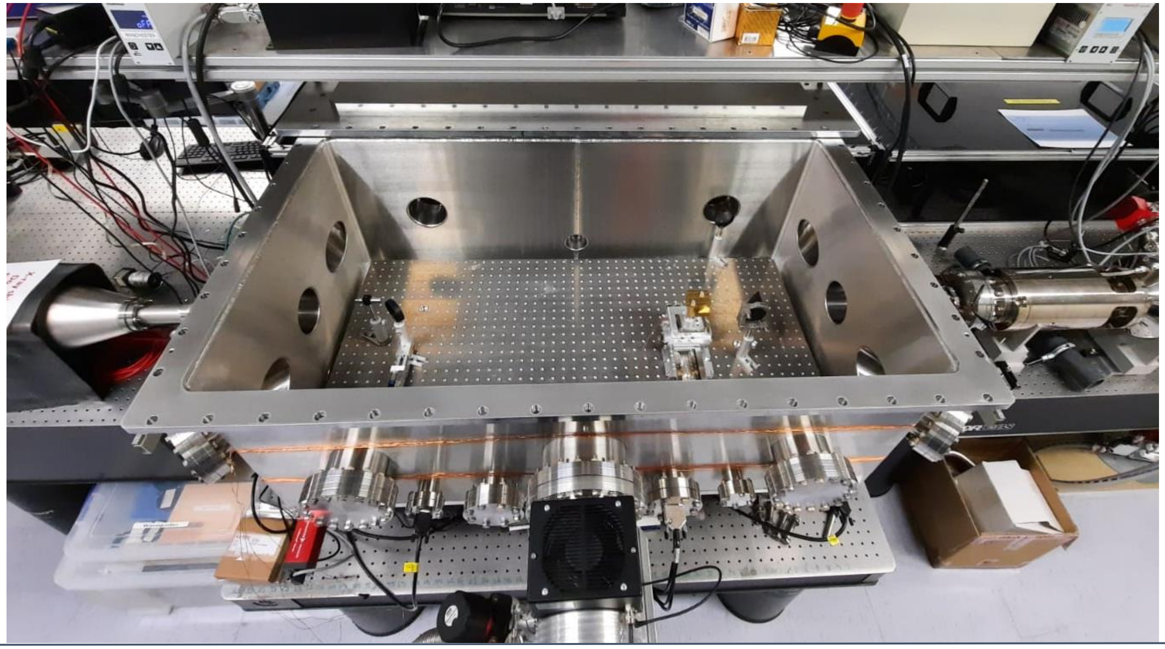
→ Terahertz driven electron deflection

→ Terahertz driven compression

→ Terahertz driven acceleration of compressed bunch







Summary

Demonstrated THz-driven linear acceleration of a 35 MeV relativistic electron beam

- Measurements performed at the CLARA test facility, Daresbury Laboratory
- Generation of narrowband THz pulses with required polarity-inversion
- Energy spectra modulation of chirped electron beams,
- Near-single bucket acceleration/deceleration of short bunches

Progress towards THz-driven compression and acceleration of non-relativistic bunches

- Early stages of experiments
- THz deflection observed
- Eventual goal of acceleration to from 100 keV to MeV and above