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Terahertz techniques for advanced accelerators

Morgan T. Hibberd

Ernest Rutherford Fellow
morgan.hibberd@manchester.ac.uk

MANCHESTER 1824
The University of Manchester

The Cockcroft Institute of Accelerator Science and Technology

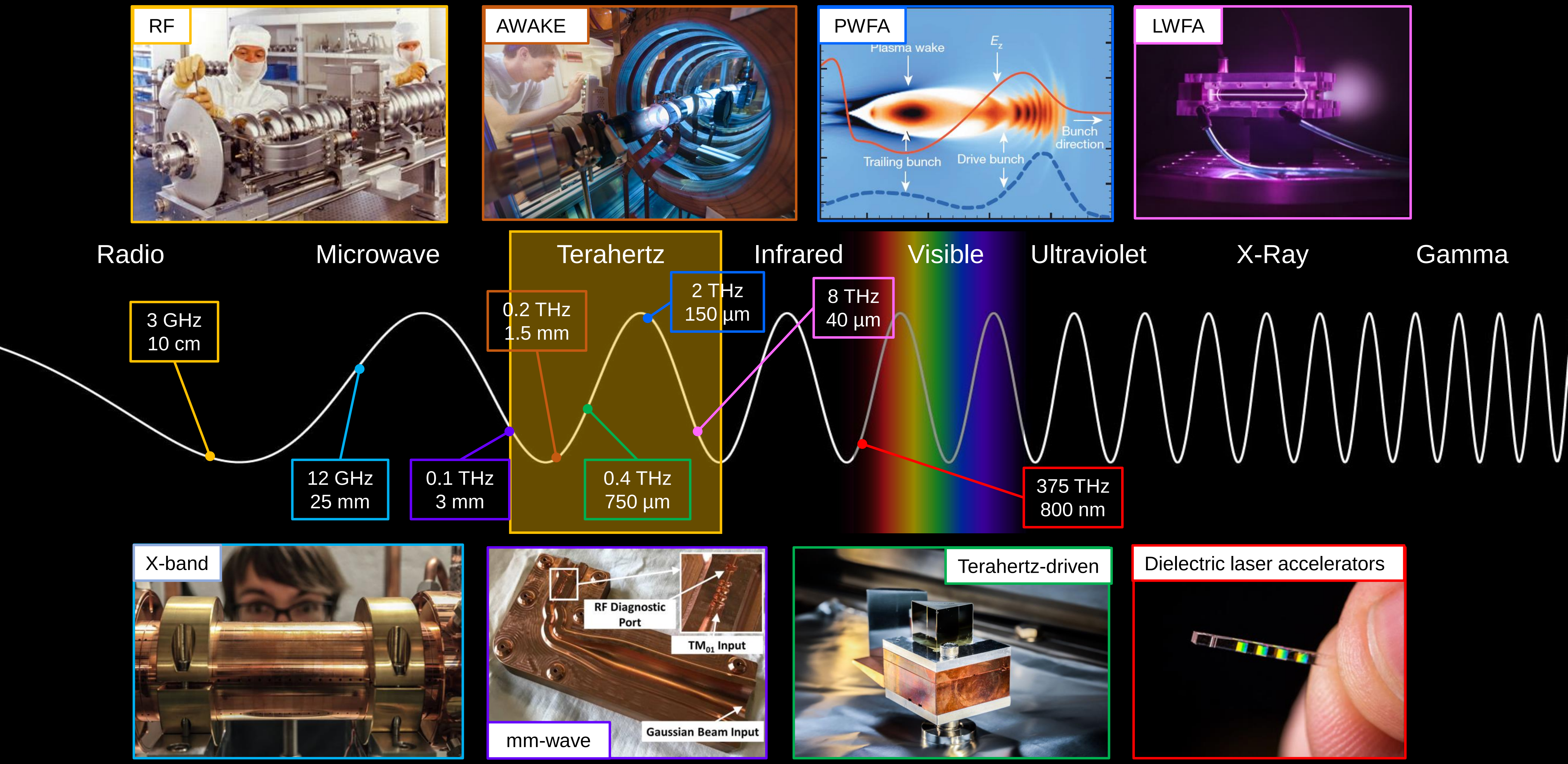
UKRI Science and Technology Facilities Council

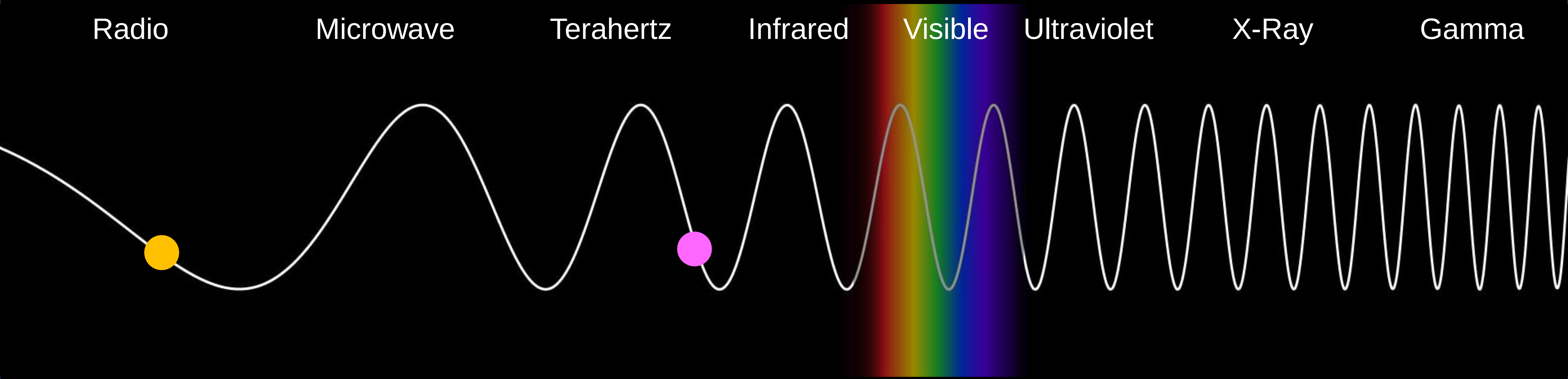
IOP Institute of Physics Particle Accelerators and Beams Group

Outline

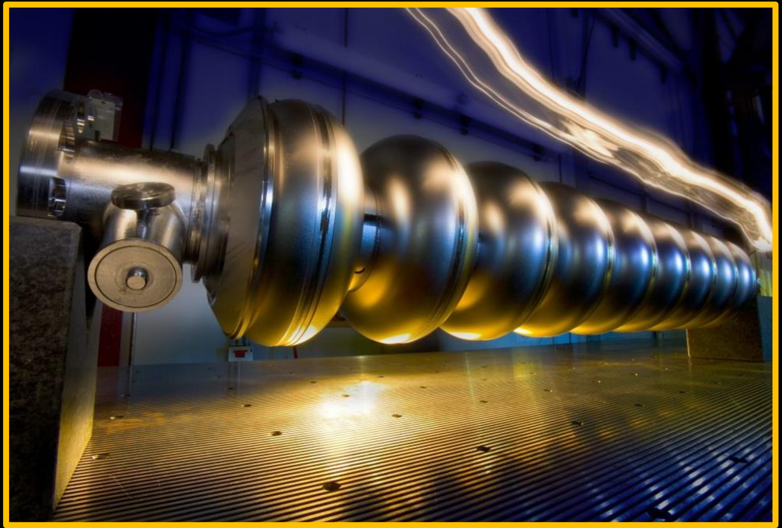
- The accelerator spectrum
- What can terahertz offer?
- Progress in terahertz acceleration
- Our terahertz acceleration research at the Cockcroft Institute
  - Sources and dielectric-lined waveguides
  - Bunch compression, bunch trains and temporal locking
  - External injection into plasma wakefields – can we solve this challenge?
  - Upcoming THz experiments on CLARA
- Summary

Advanced accelerators





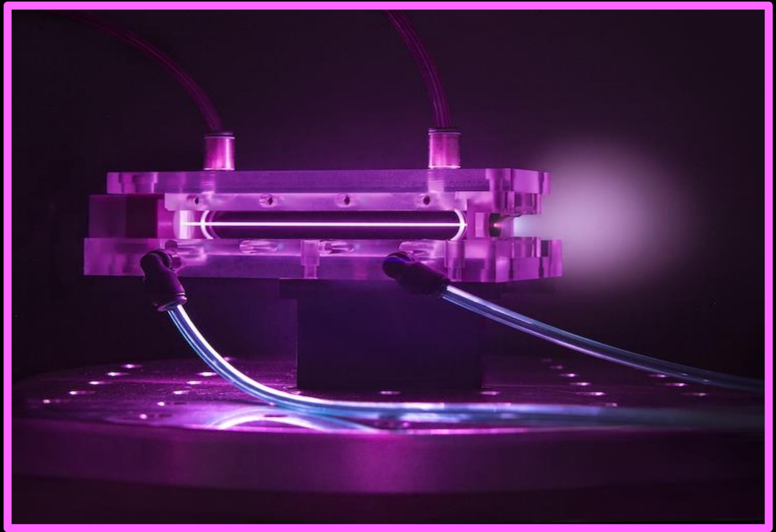
Radio-frequency

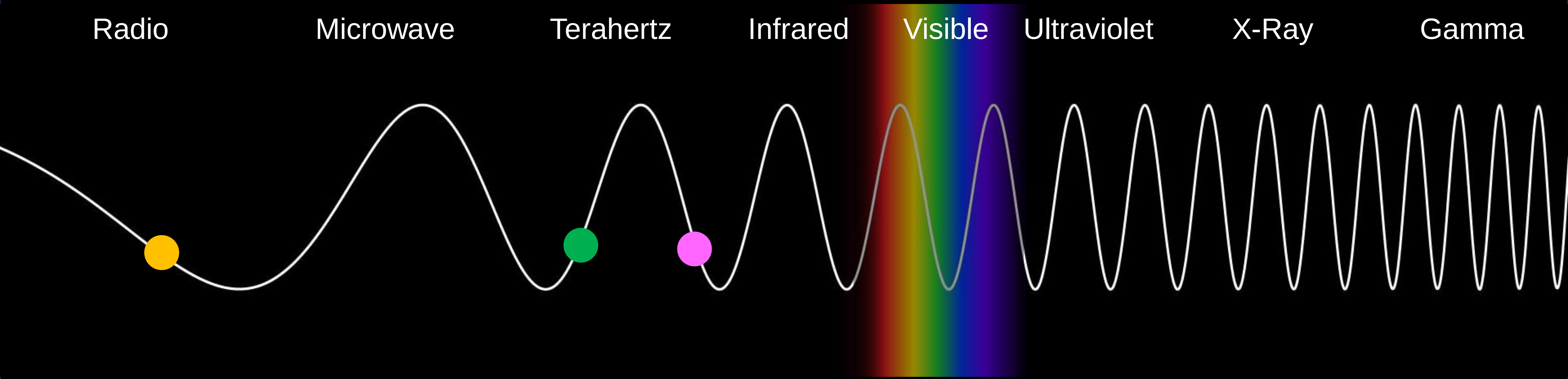


1000x

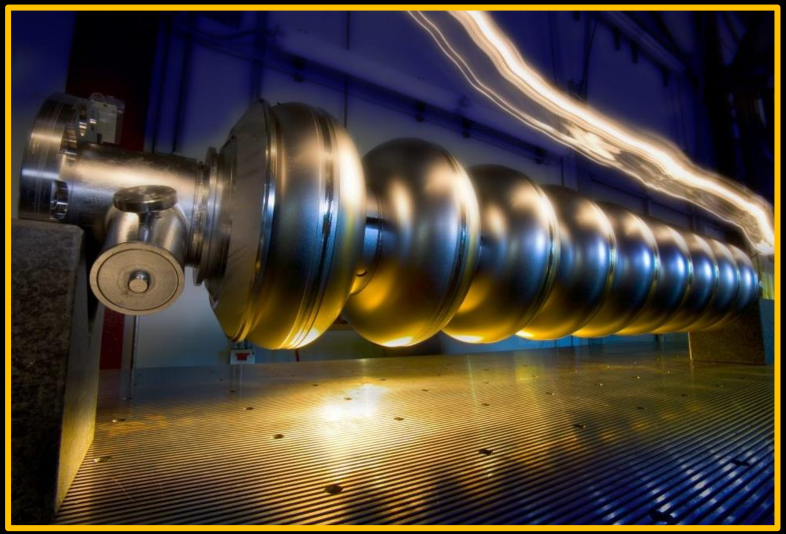
Higher frequency
Higher accelerating gradient
Smaller accelerator

Laser plasma wakefield

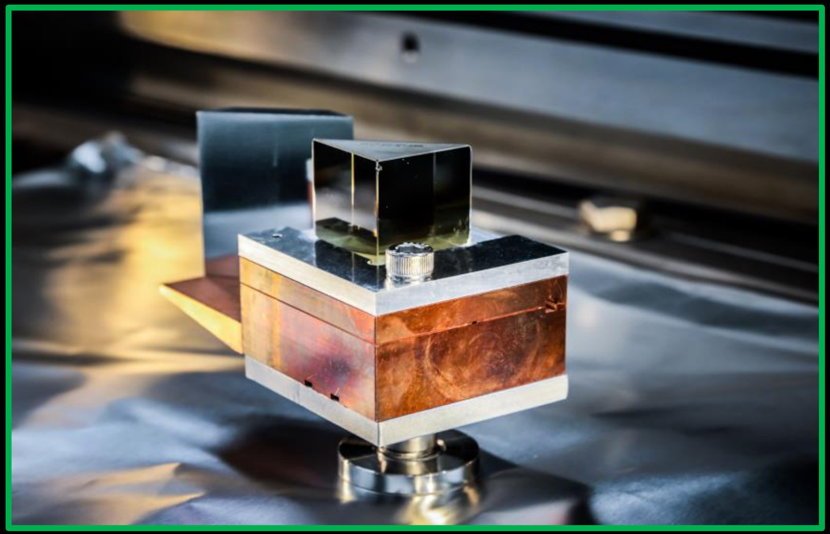




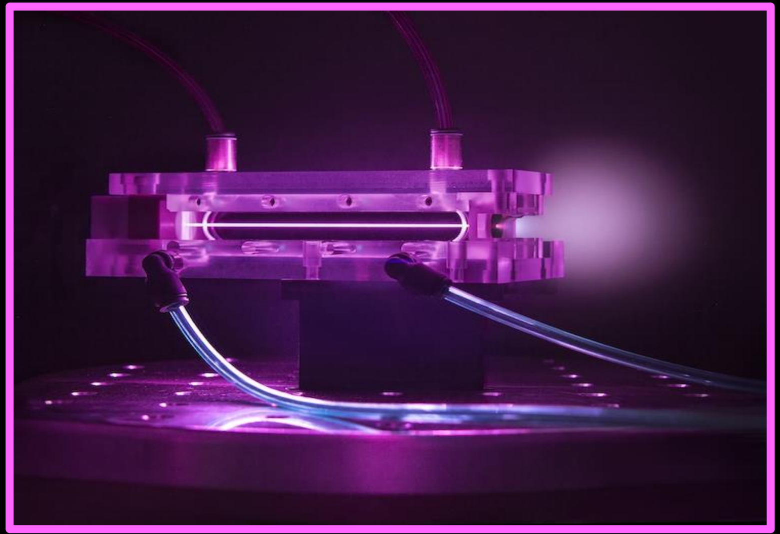
Radio-frequency



Terahertz

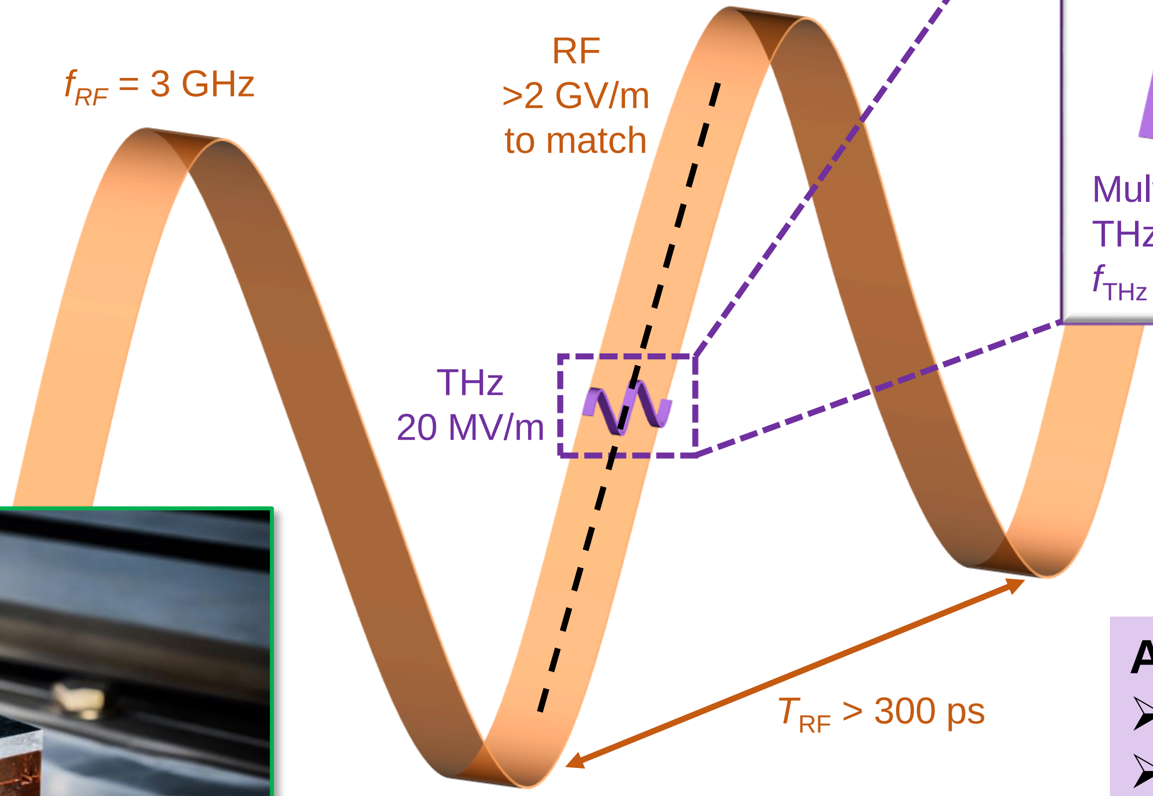


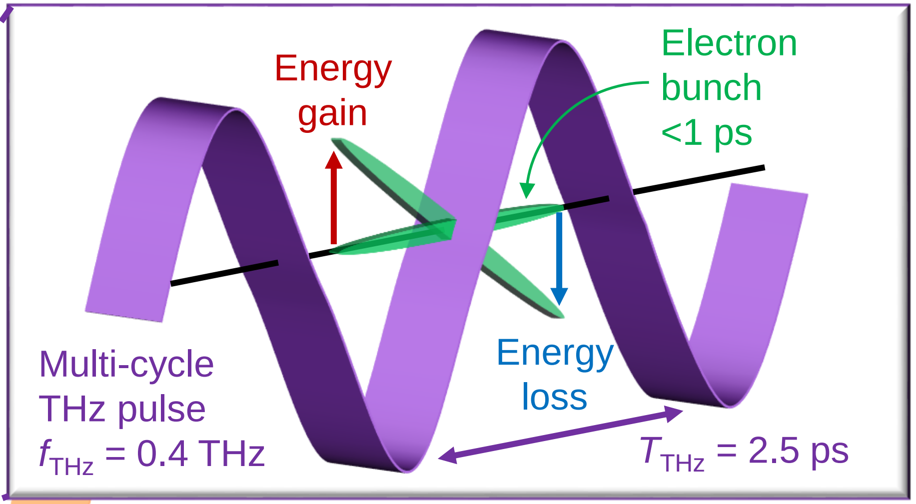
Laser plasma wakefield



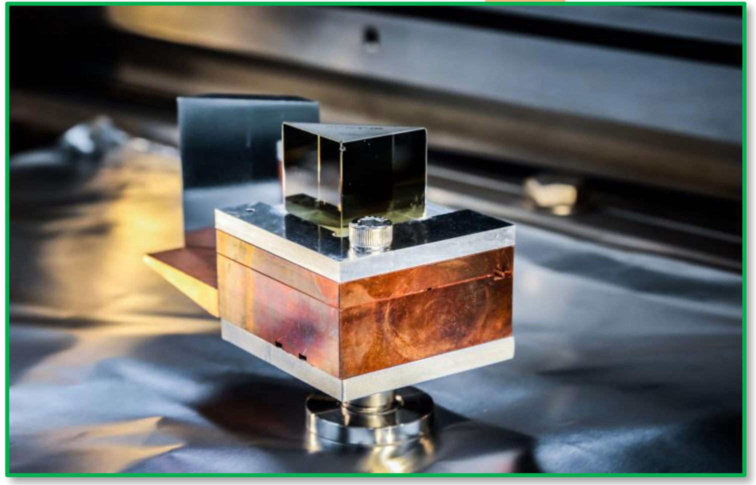
What does terahertz offer?

- **Laser-driven** sources of terahertz (THz) radiation
- Frequency range between RF/microwave and infrared (lasers)
- Exploit advantages from both technologies





Terahertz **dielectric-lined waveguide** structure

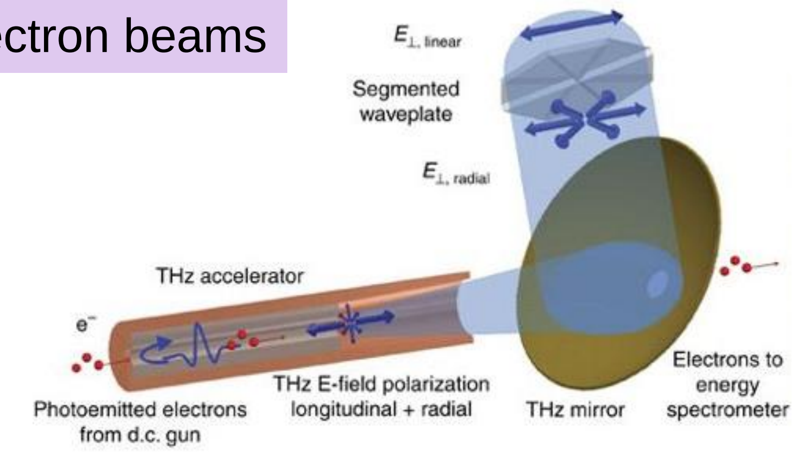


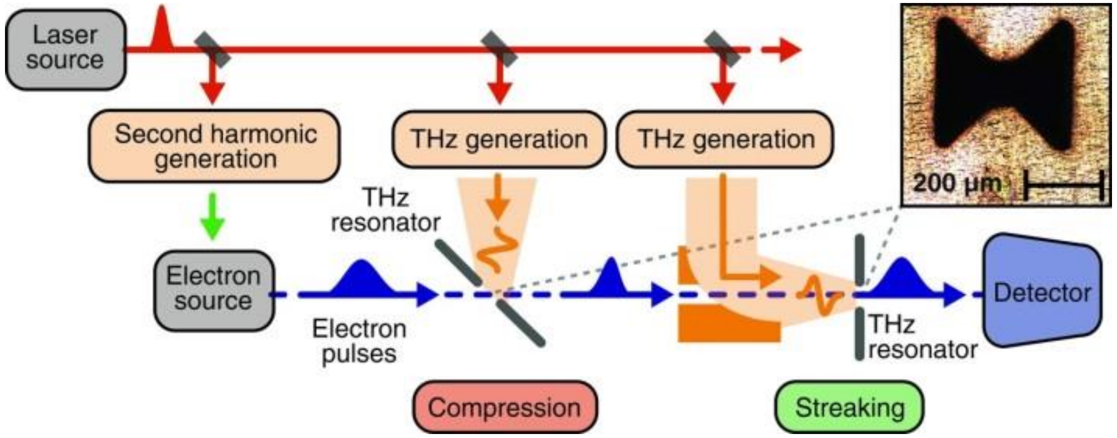
Advantages of THz accelerators
- High electric field strengths
- Laser and THz pulse shaping
- Laser timing synchronisation
- Compact mm-scale structures
- Optimal frequency for manipulation

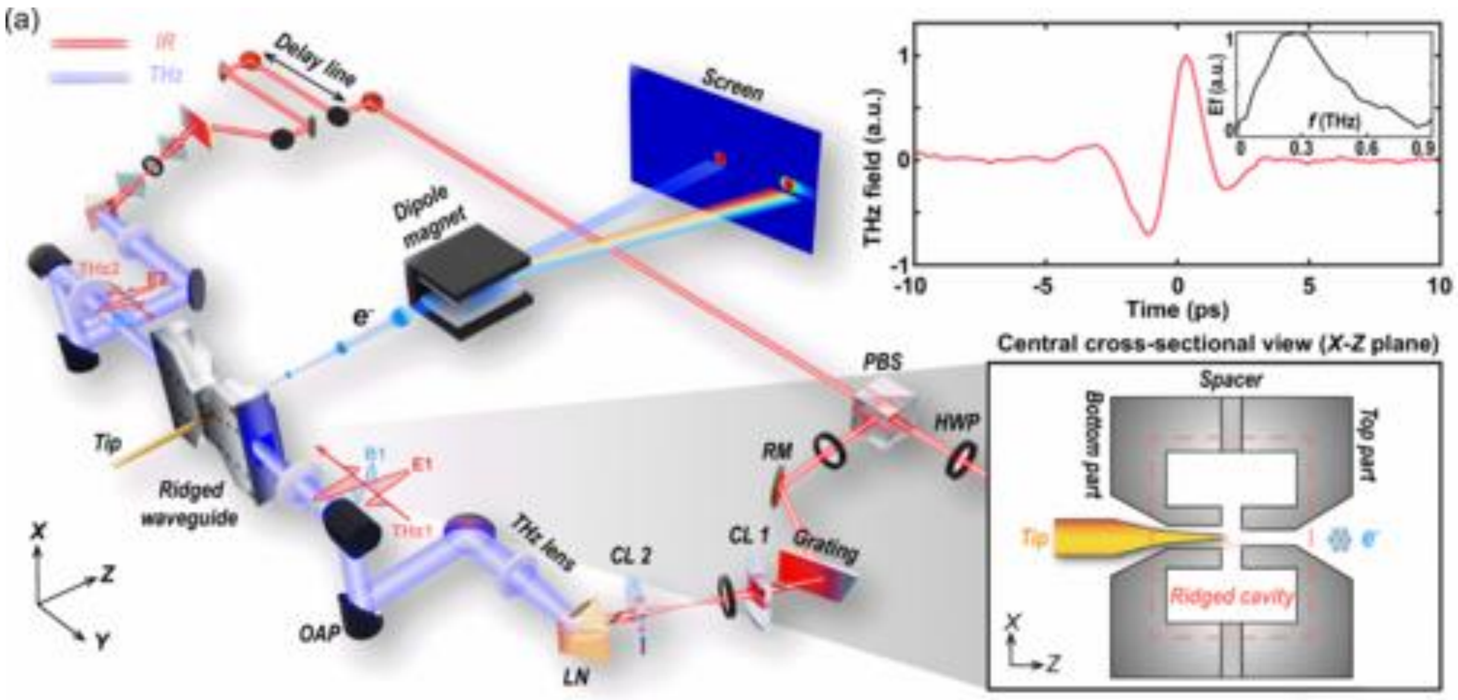
A decade of terahertz acceleration

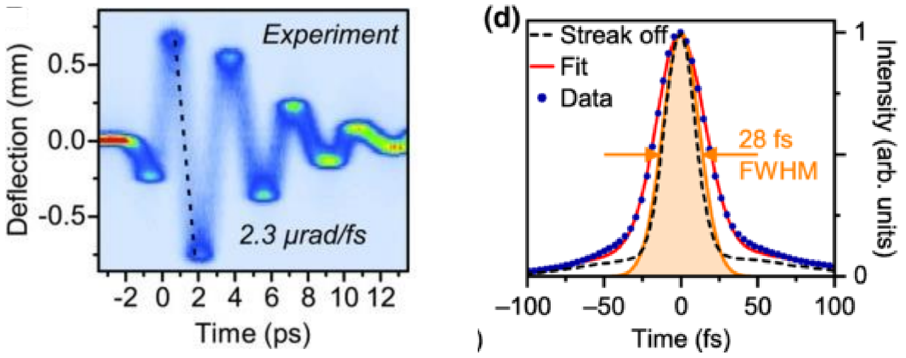
Sub-relativistic electron beams

- Acceleration
- Streaking
- Compression
- Focusing
- Photoemission
- Electron guns







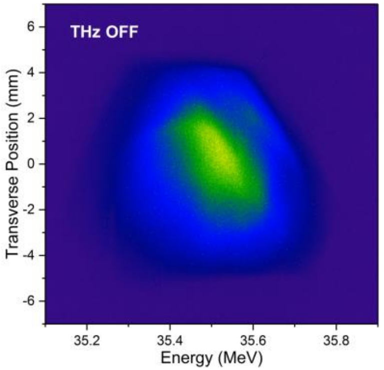


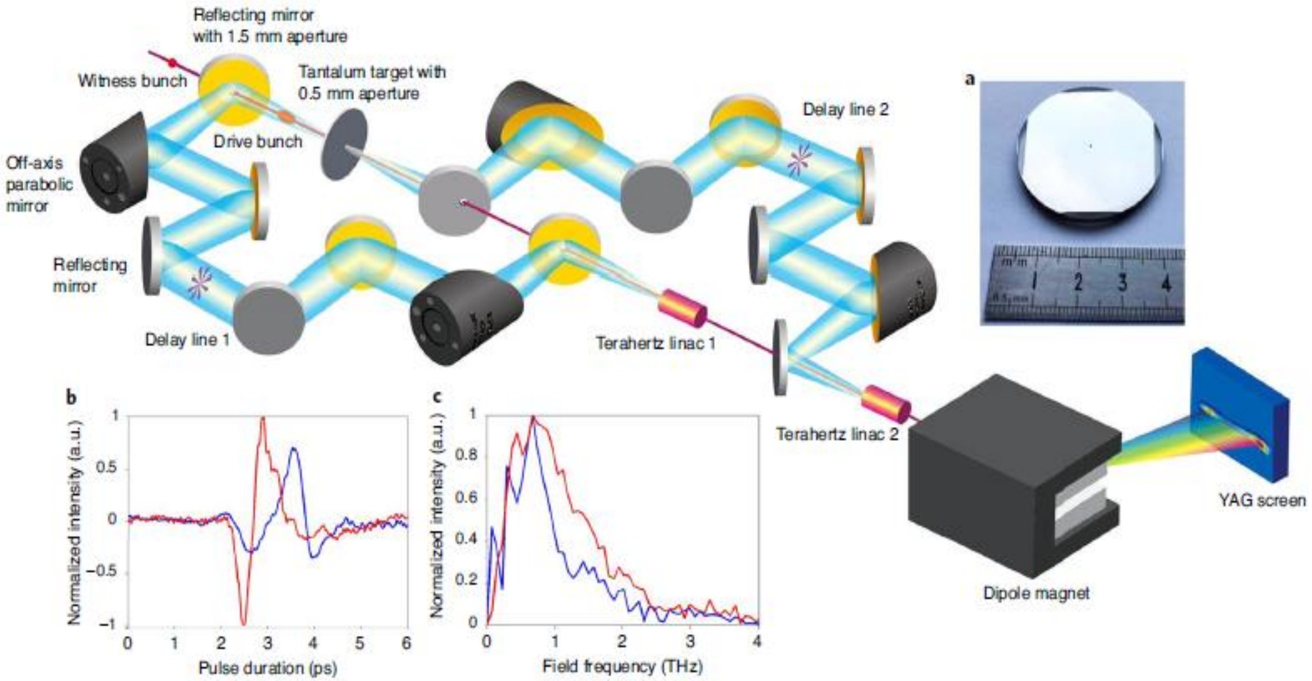
Selected examples
E. A. Nanni et al. *Nat. Commun.* 6, 8486 (2015)
C. Kealhofer et al. *Science* 352, 429-433 (2016)
D. Zhang et al. *Nat. Photonics* 12, 336-342 (2018)
D. Ehberger et al. *Phys. Rev. Appl.* 11, 024034 (2019)
S. Li et al. *Nat Commun*. 14, 6596 (2023)
J. Ying et al. *Phys. Rev. X* 15, 021095 (2025)

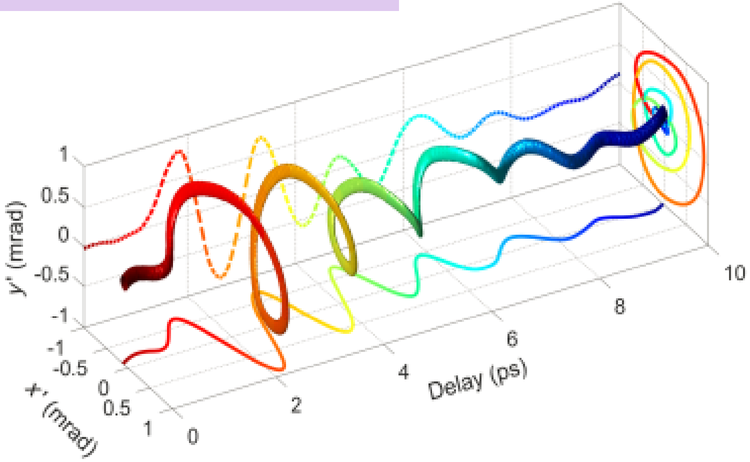
A decade of terahertz acceleration

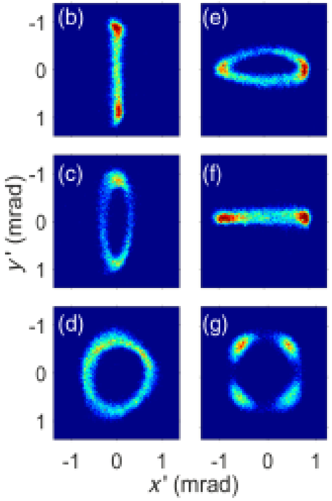
Relativistic electron beams

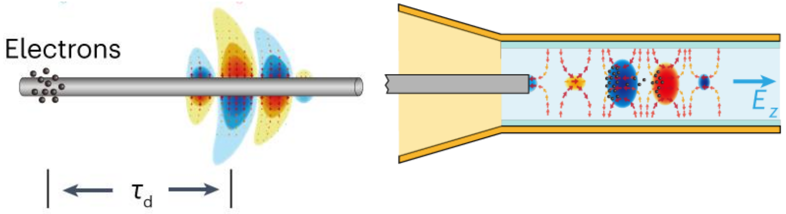
- Acceleration
- Streaking
- Compression
- Jitter suppression
- Bunch trains
- Spin-polarization

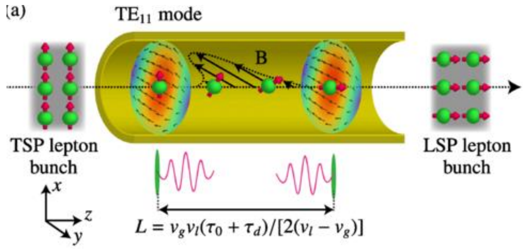








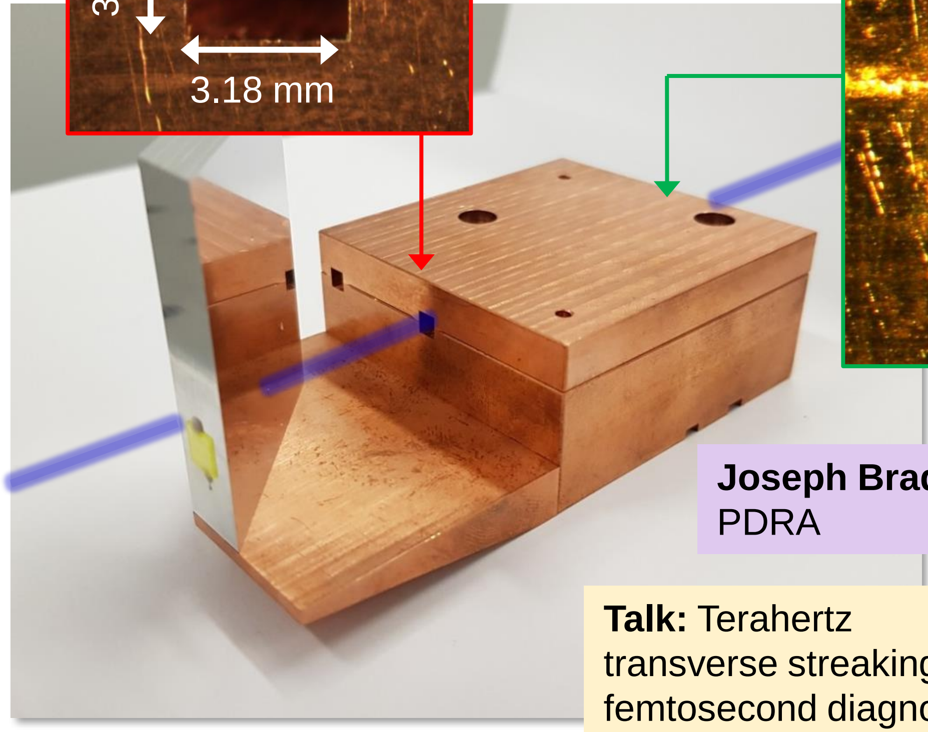


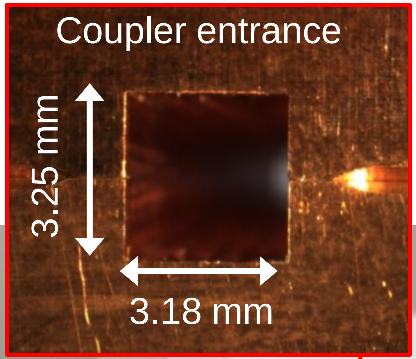


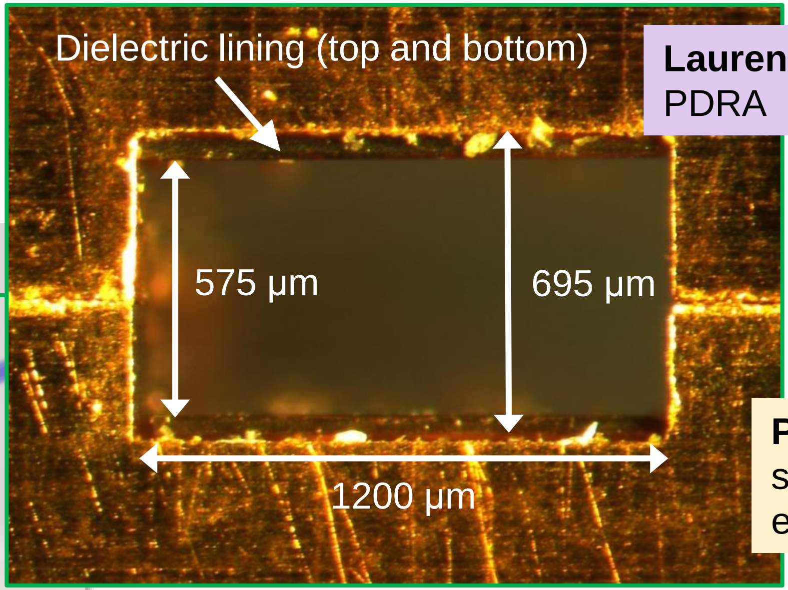
Selected examples

E. Curry et al. *Phys. Rev. Lett.* 120, 094801 (2018)
L. Zhao et al. *Phys. Rev. Lett.* 122, 144801 (2019)
M.T. Hibberd et al. *Nat. Photon. 14, 755-759* (2020)
E.C. Snively et al. *Phys. Rev. Lett*. 124, 054801 (2020)
H. Tang et al. *Phys. Rev. Lett*. 127, 074801 (2021)
H. Xu *et al. Nat. Photon.* 15, 426-430 (2021)
X.Q. Yu et al. *Nat. Photon.* 17, 957–963 (2023)
Z.P. Li et al. *Phys. Rev. Lett.* 134, 075001 (2025)

Our approach: Terahertz dielectric-lined waveguides







Laurence Nix
PDRA

Poster: Advances in coupling schemes for terahertz-driven electron beam manipulation

Joseph Bradbury
PDRA

Talk: Terahertz transverse streaking for femtosecond diagnostics

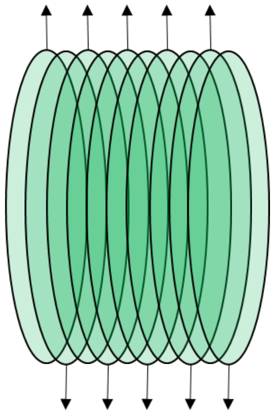
Filip Peczek
PhD student

Poster: Machine learning for terahertz waveguide design

- Field confinement boosts accelerating gradient
- Create longitudinal fields for acceleration
- Velocity-matching with the dielectric lining

L. Nix et al., *Phys. Rev. Accel. Beams* 27, 041302 (2024)
O. Apsimon et al. *Phys. Rev. Accel. Beams* 24, 121303 (2021)
V. Georgiadis et al., *App. Phys. Lett.* 118, 14 (2021)

Terahertz sources: Periodically-poled lithium niobate wafer-stacks

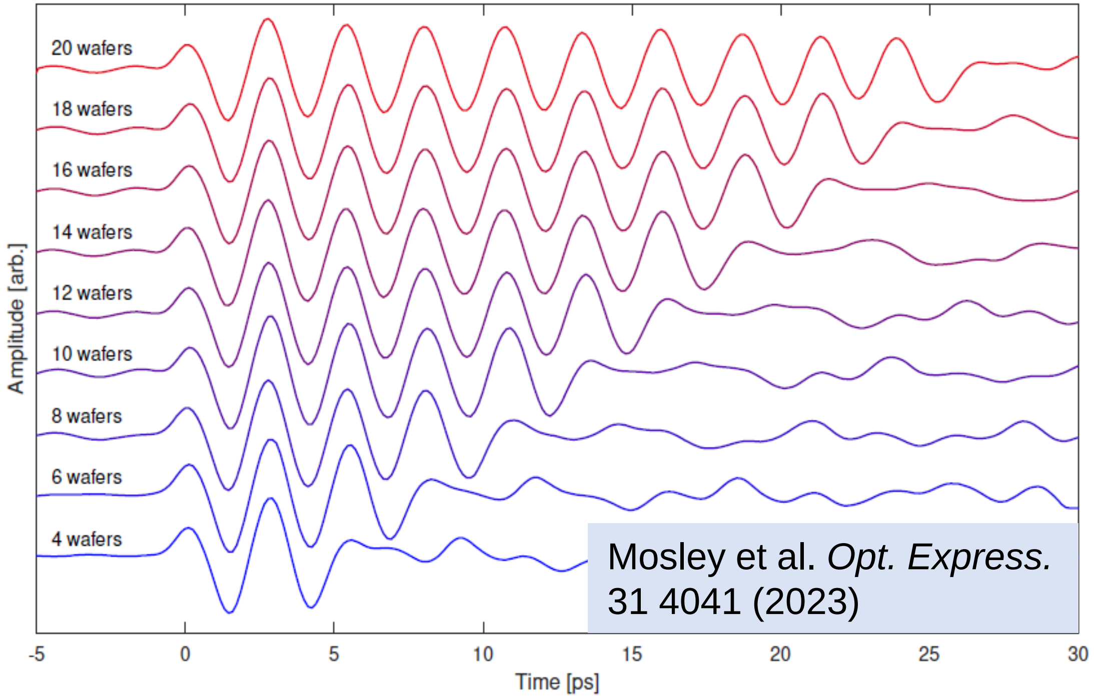


+ more wafers

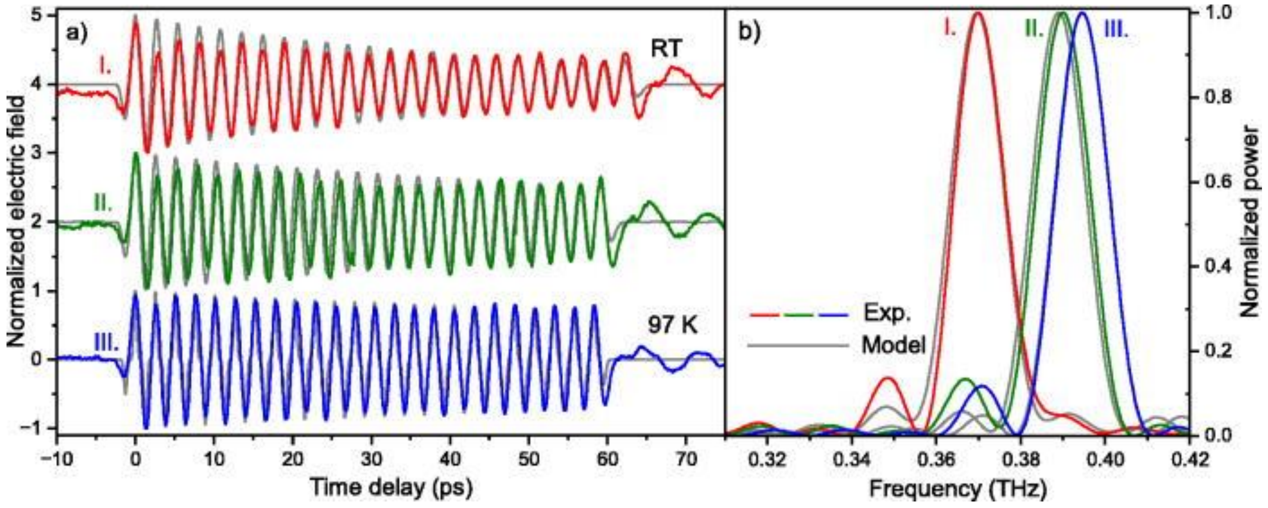
Patrick Dalton
PhD student

Poster: Optimisation of a lithium niobate wafer narrowband THz source for driving THz accelerators

Dalton et al. *Appl. Phys. Lett.* 125, 141101 (2024)
Dalton et al. *Opt. Lett.* 51, 5-8 (2026)



Mosley et al. *Opt. Express.* 31 4041 (2023)

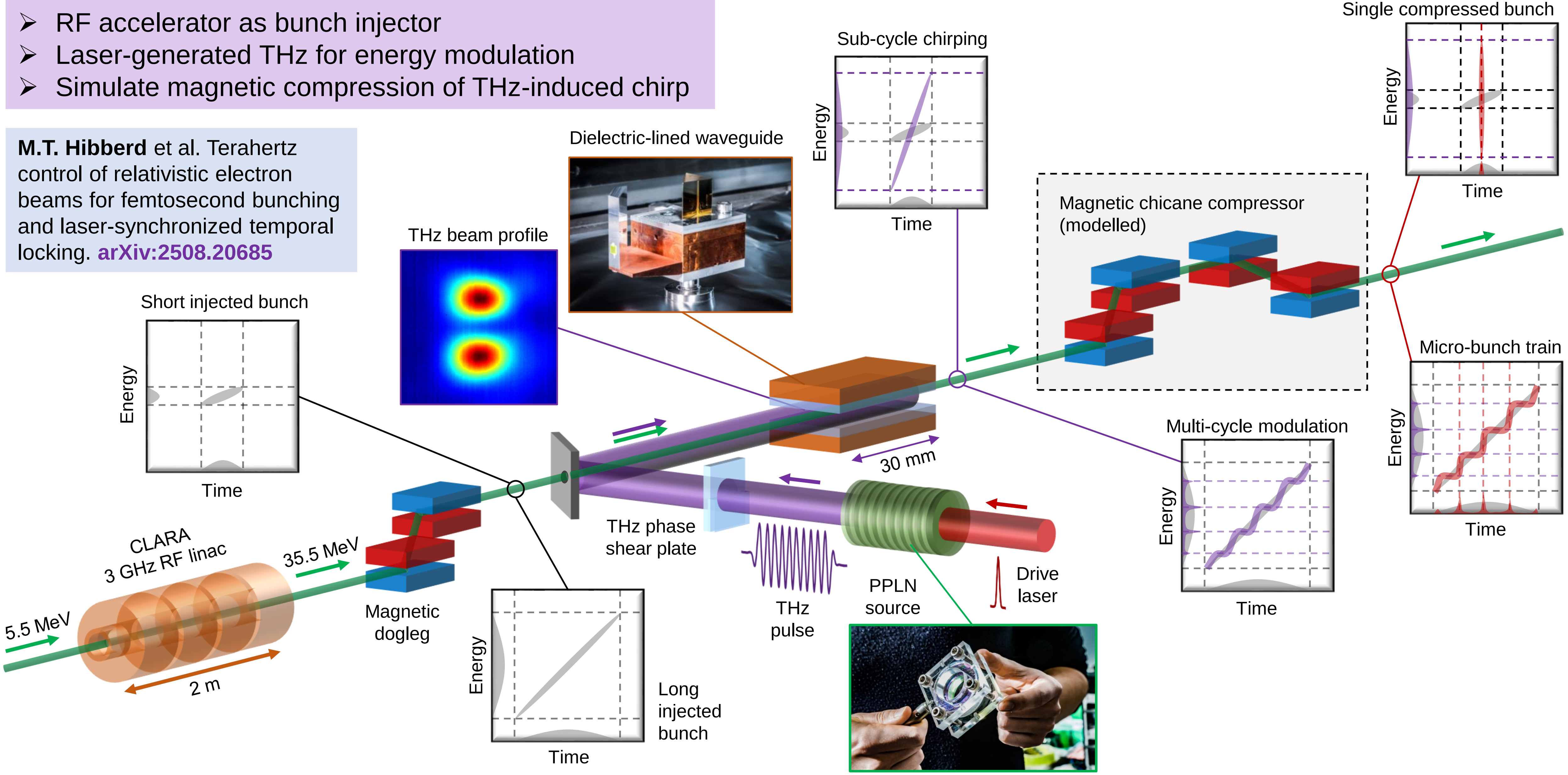


- **Narrowband** frequency matched to dielectric-lined waveguide
- **Cryo-cooling** boosts THz field and provides frequency tuning
- **Large-area** sources for high-power laser systems

Terahertz acceleration: Experiments on CLARA @ Daresbury Laboratory

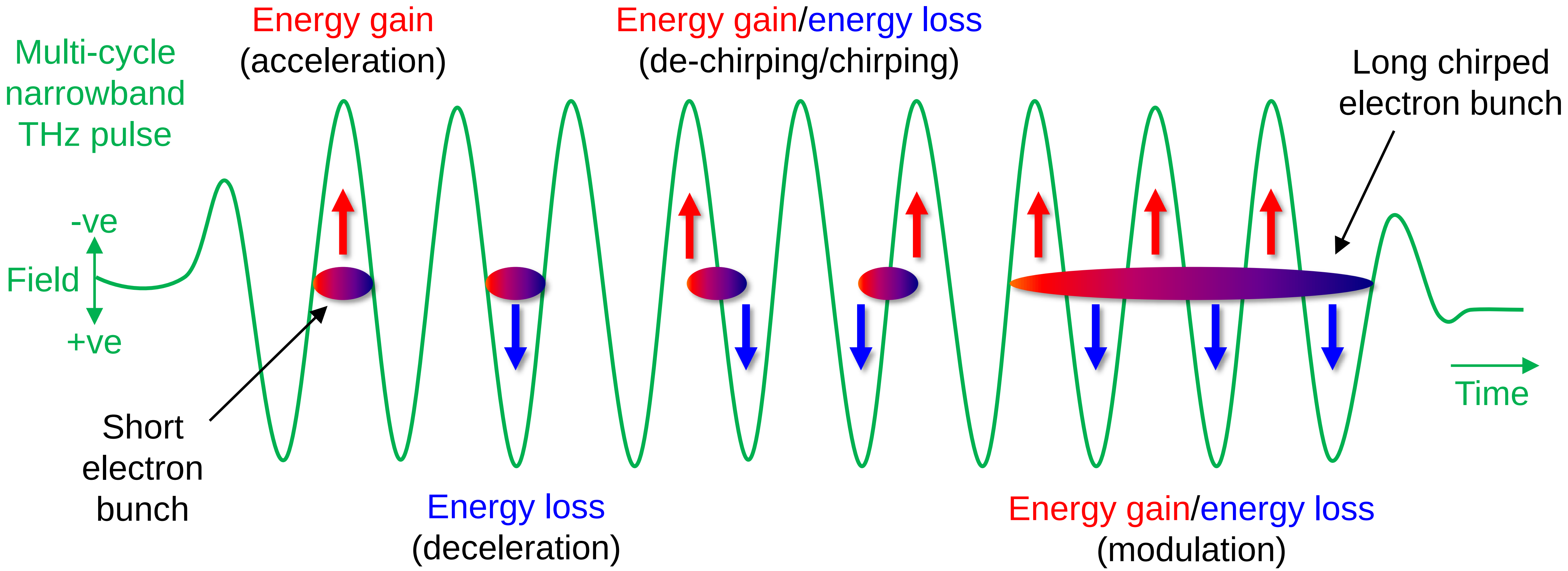
- ➢ RF accelerator as bunch injector
- ➢ Laser-generated THz for energy modulation
- ➢ Simulate magnetic compression of THz-induced chirp

M.T. Hibberd et al. Terahertz control of relativistic electron beams for femtosecond bunching and laser-synchronized temporal locking. **arXiv:2508.20685**

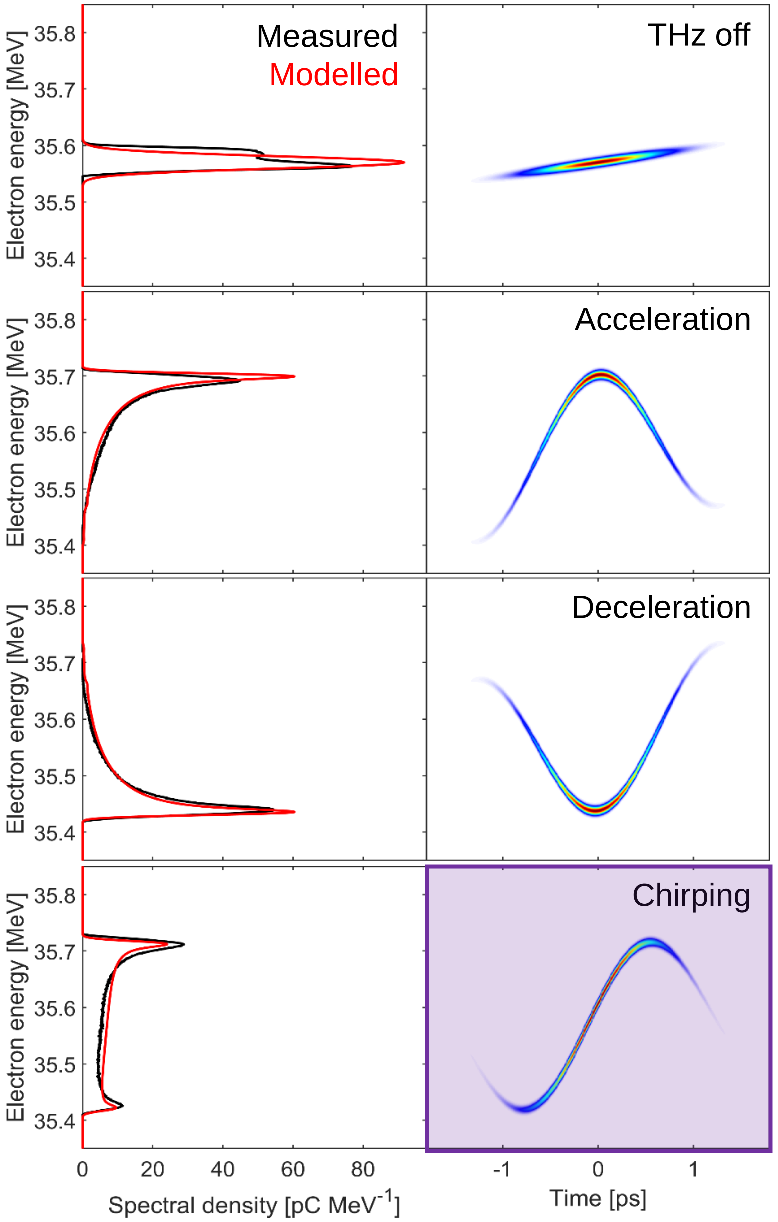


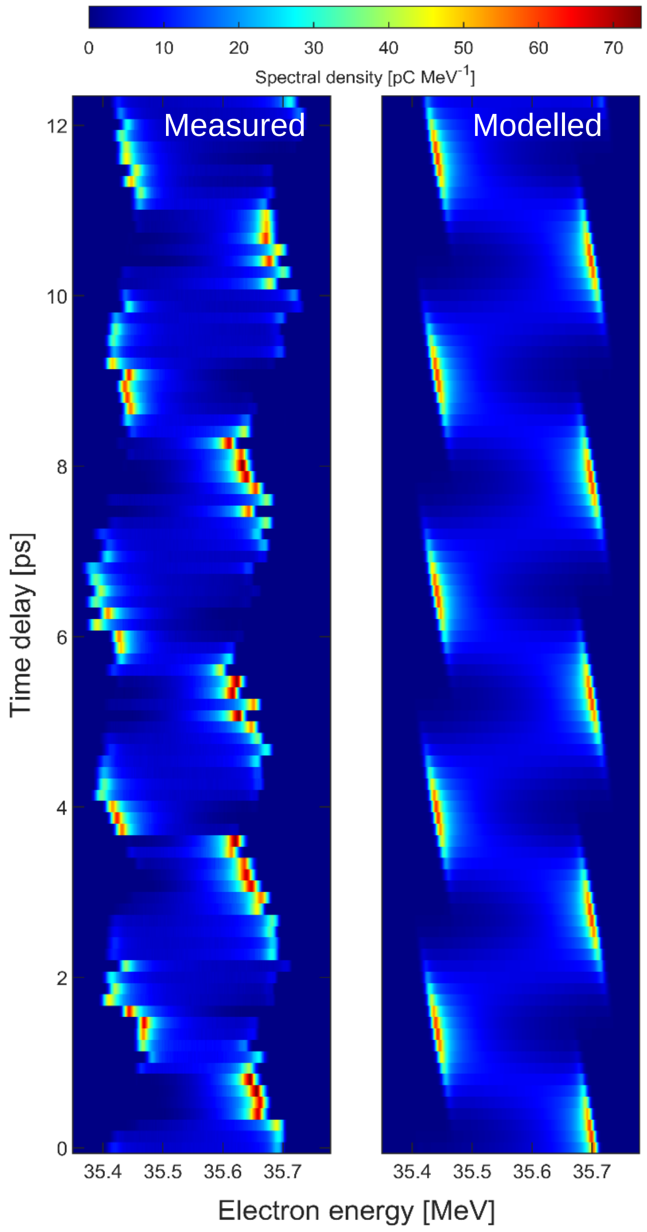
Different interaction depending on **injection timing** of the electron bunch relative to the THz field

- ➢ We have precise femtosecond control using an optical delay stage on the THz drive laser

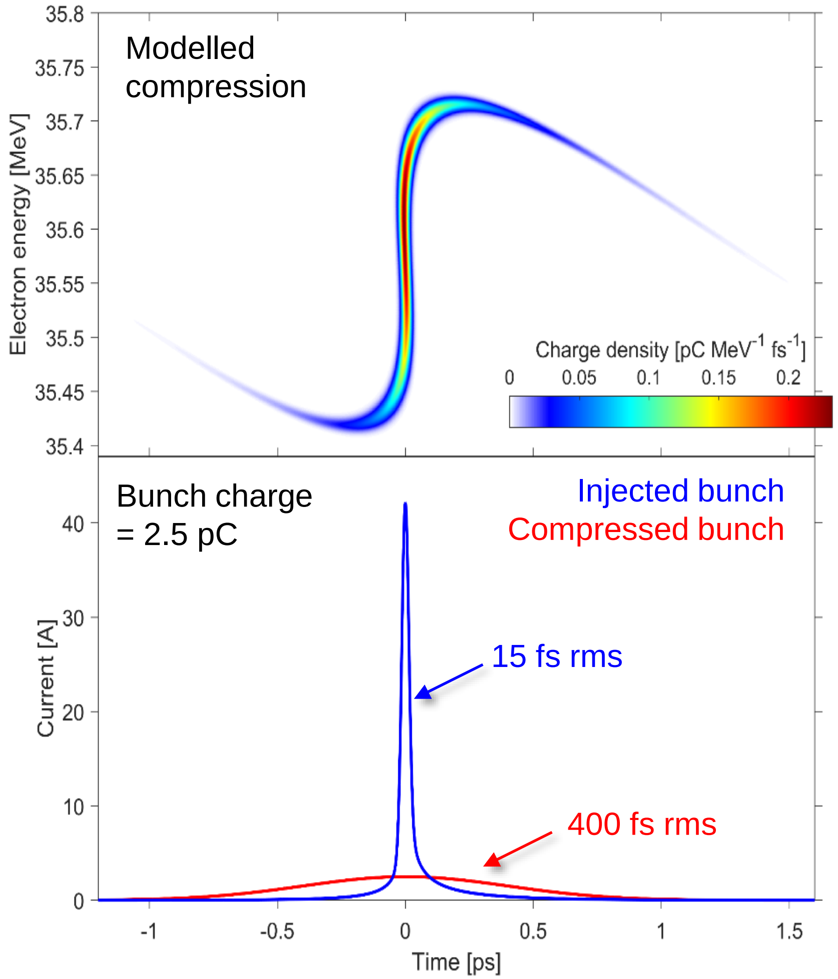


Sub-cycle acceleration and manipulation: For bunch compression



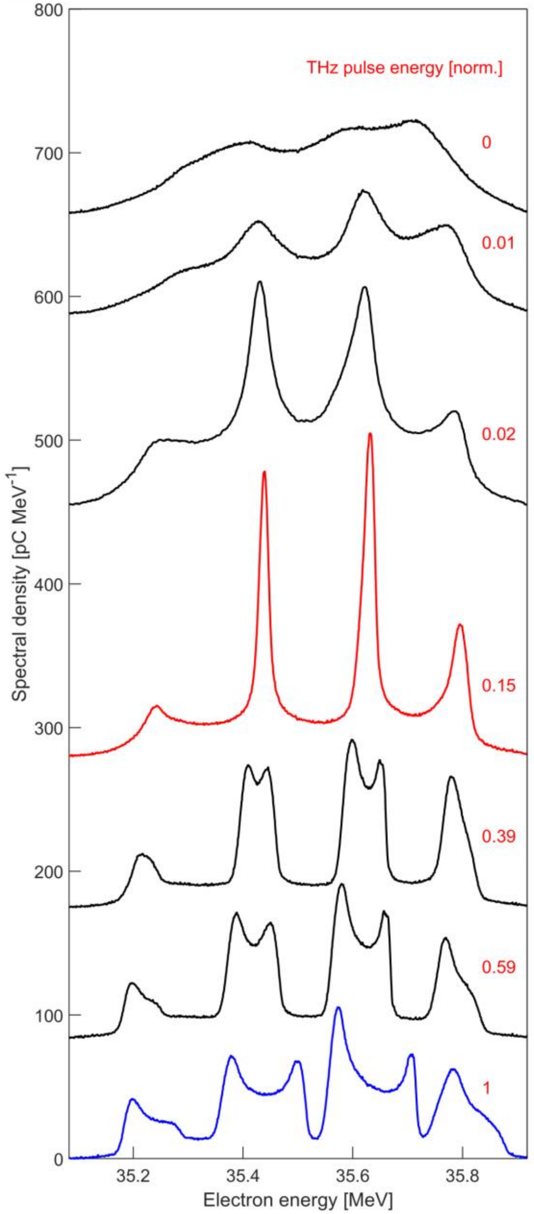


THz-driven chirping followed by magnetic compression

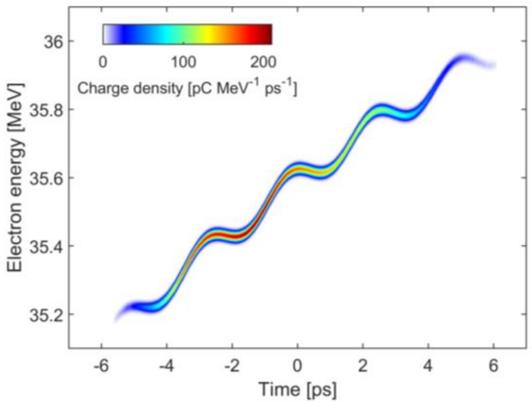


With improvements to the THz and bunch parameters
→ **sub-10 fs** bunches with >**kA peak currents** achievable

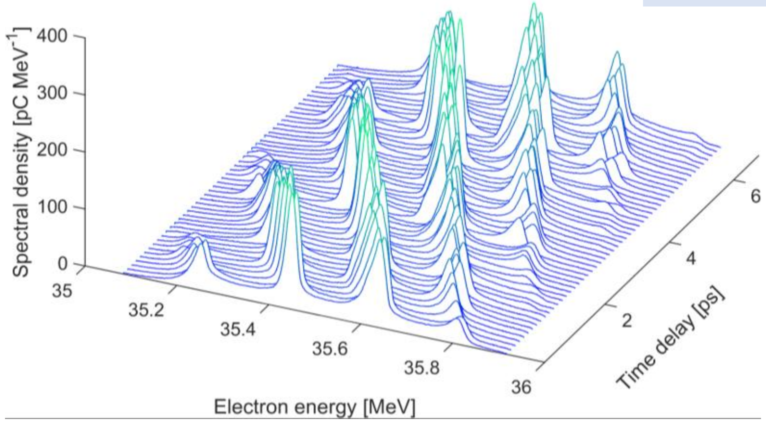
M.T. Hibberd et al. **arXiv:2508.20685**



Energy modulation (matched chirp)



THz injection phase scan



M.T. Hibberd et al. **arXiv:2508.20685**

Can be used as a **longitudinal bunch diagnostic**

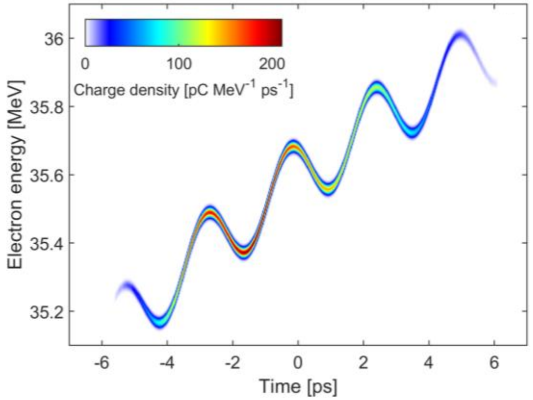
- ➢ Peak width provides direct measurement of **slice uncorrelated energy spread**

Increase THz field

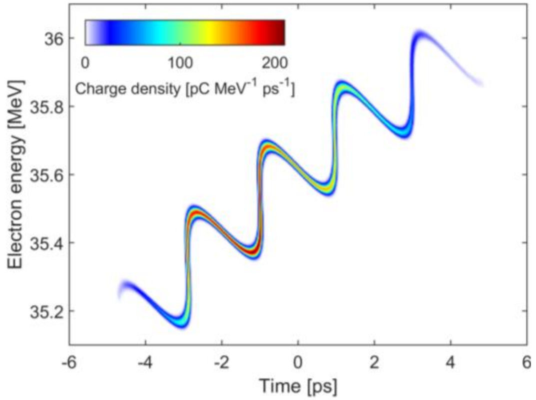
Ultrashort **micro-bunch trains** with picosecond spacing

- ➢ Can't be done with conventional RF techniques
- ➢ Tunable spacing using THz frequency or R_{56}

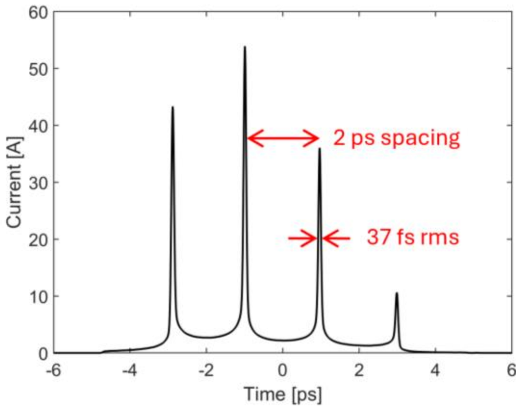
Energy modulation (over-modulated)



Magnetic compression

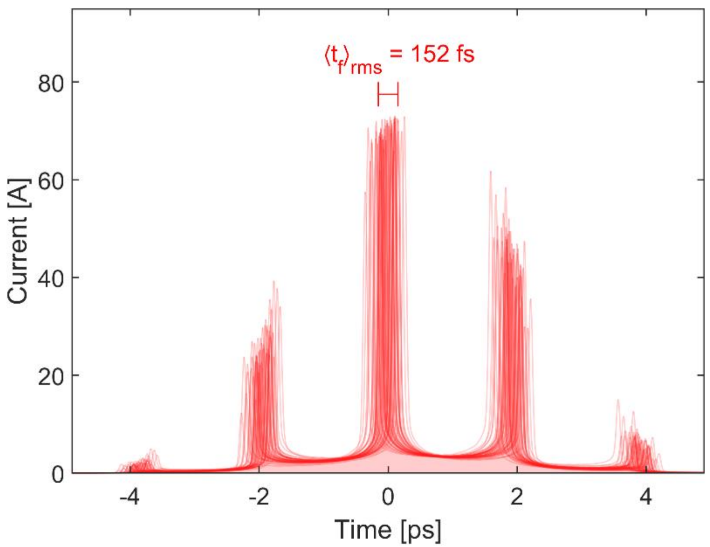


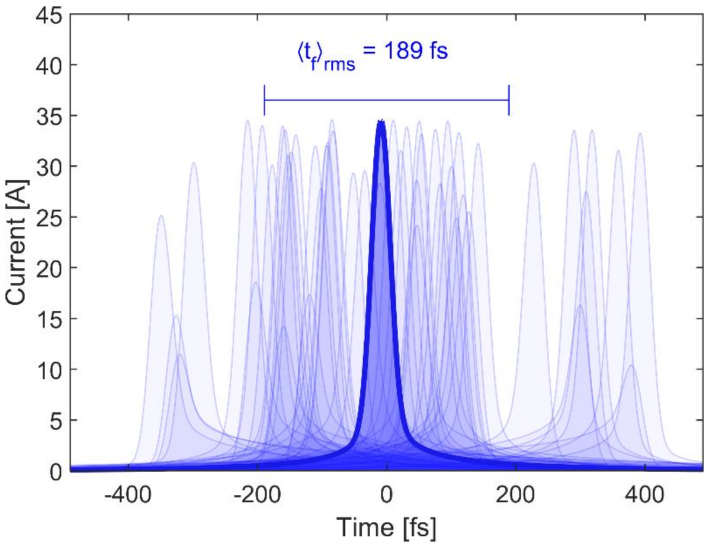
Micro-bunch trains



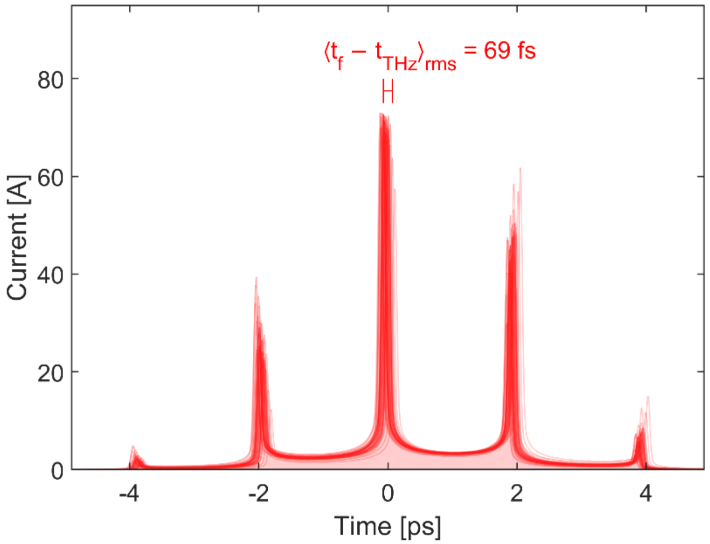
Electron-to-laser temporal locking

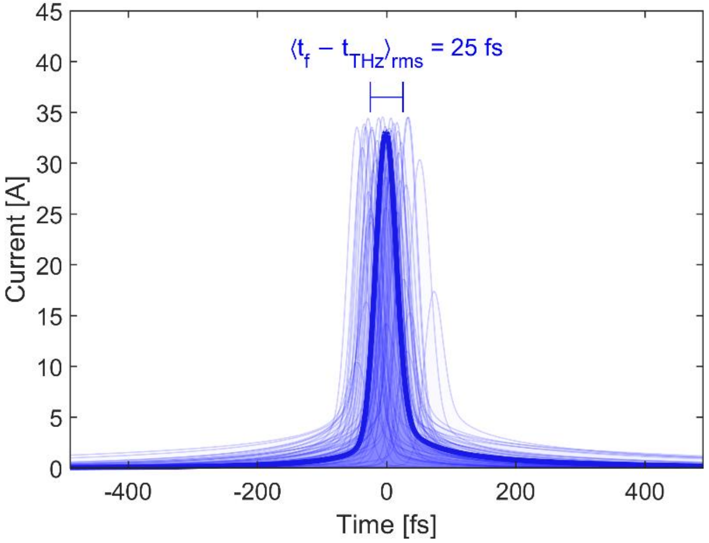
Laboratory reference frame





THz drive laser reference frame





M.T. Hibberd et al. **arXiv:2508.20685**

Bunches are "**temporally locked**" to the THz fields and the THz drive laser

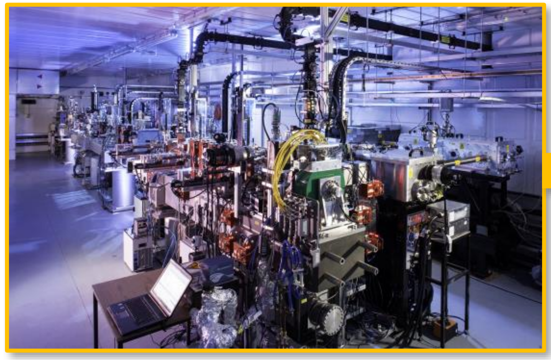
- Improvements required to push towards the femtosecond scale

Lased-based accelerator applications

- FEL pump-probe experiments
- Ultrafast electron diffraction
- Compton scattering for strong-field QED
- **External injection into LWFA**

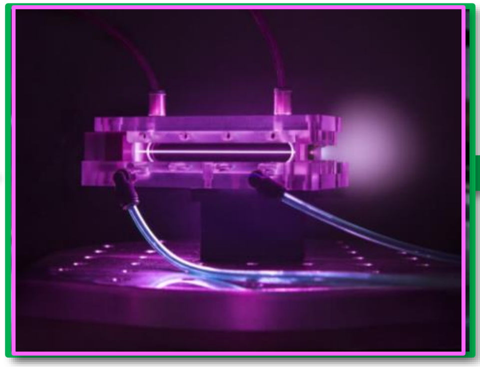
External injection of electrons into a laser-driven plasma wakefield

RF-based accelerator

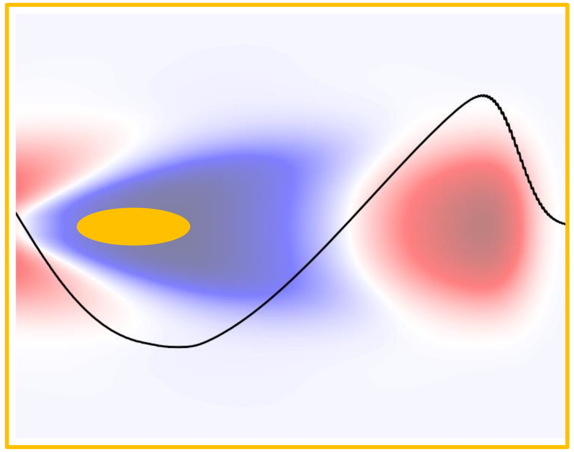


CLARA (250 MeV electrons)

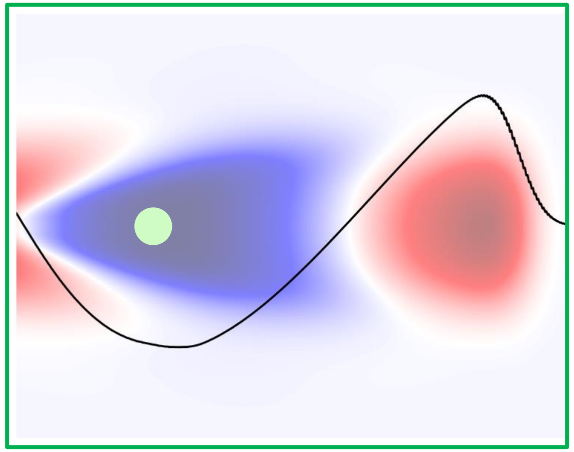
Laser-driven plasma wakefield
Terahertz-driven "accelerator"



Laser



Poor beam quality



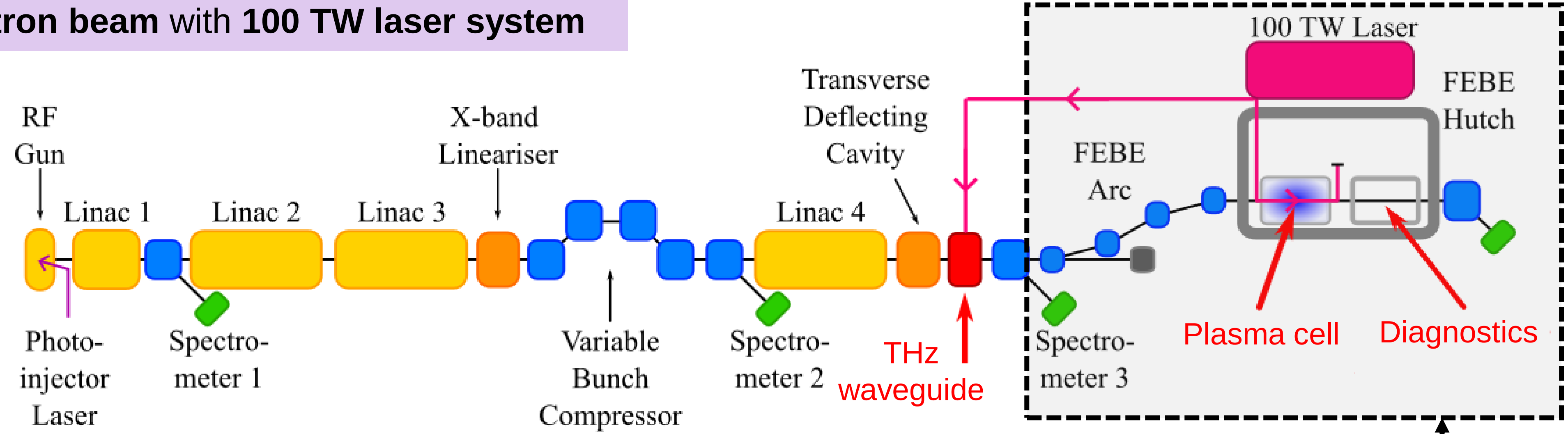
Maintains high beam quality

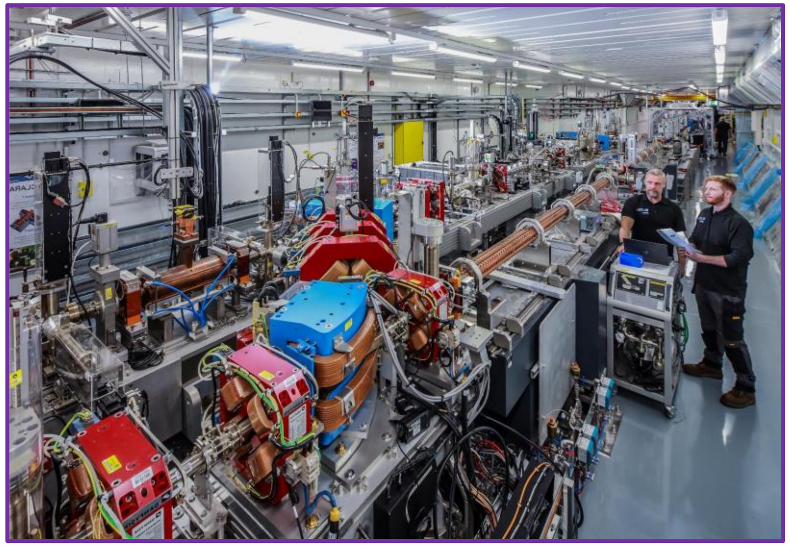
H3+BEAMS
HIGH QUALITY HIGH GRADIENT HIGH ENERGY

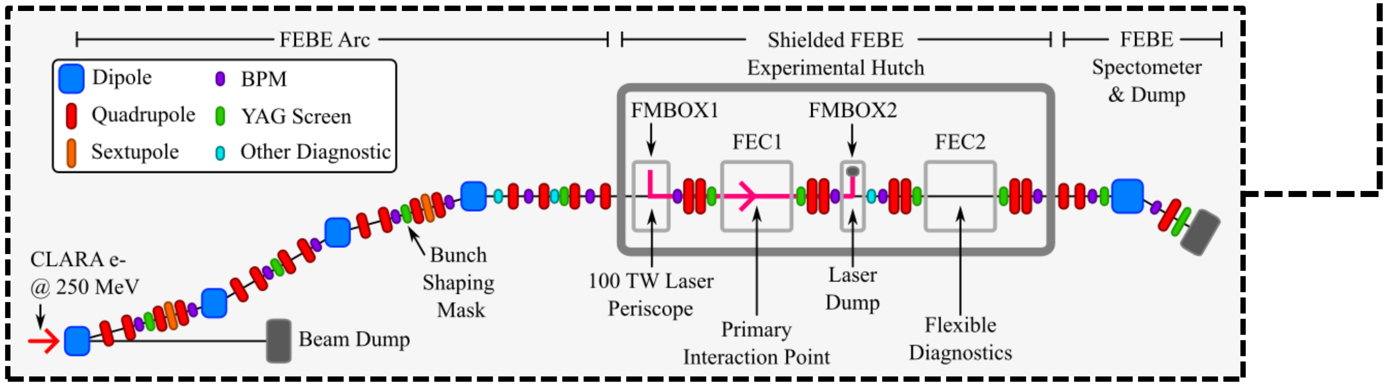
- Combines 3 accelerator technologies
- THz **"bridge"** between RF and LWFA

CLARA/FEBE @ Daresbury Laboratory one of only a few facilities in the world with this capability

- Combine **250 MeV electron beam** with **100 TW laser system**







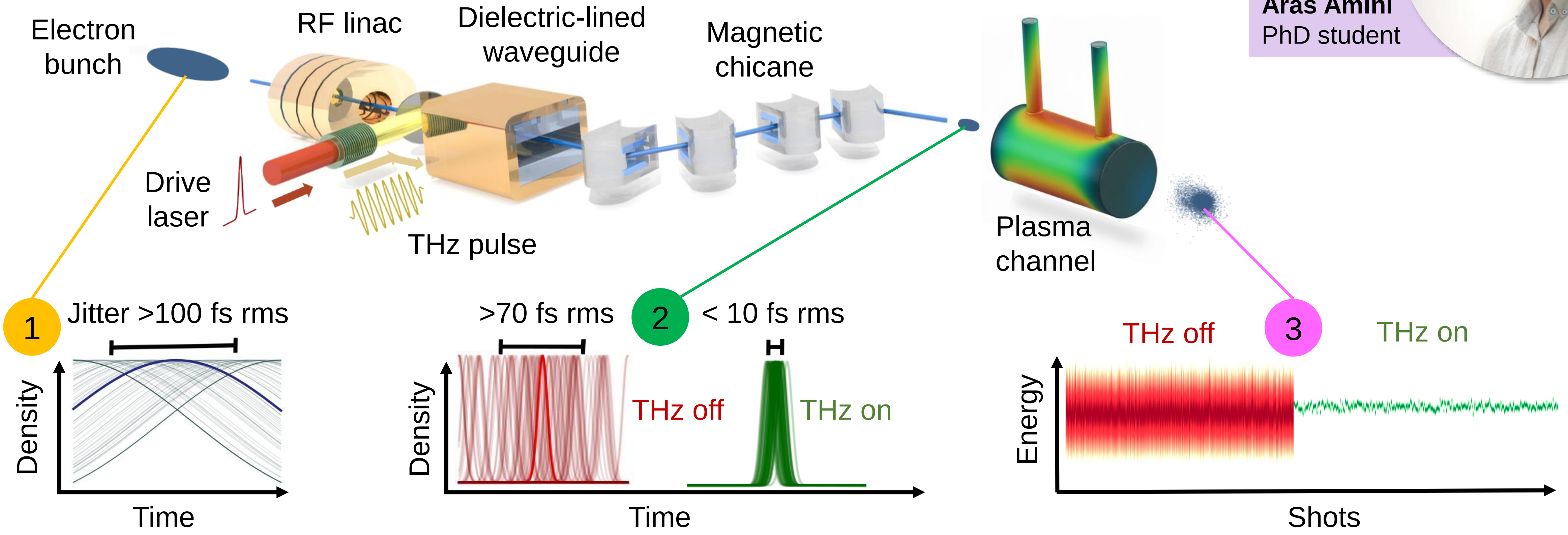
Start-to-end simulations for high-quality GeV beams

- Electron bunch from CLARA RF linac
- THz-driven energy modulation/chirping
- Magnetic chicane compression
- Injection, transverse matching and acceleration in LWFA

A. Amini et al. Controlling external injection in laser-plasma accelerators with terahertz frequency bunch manipulation. **arXiv:2604.16059**

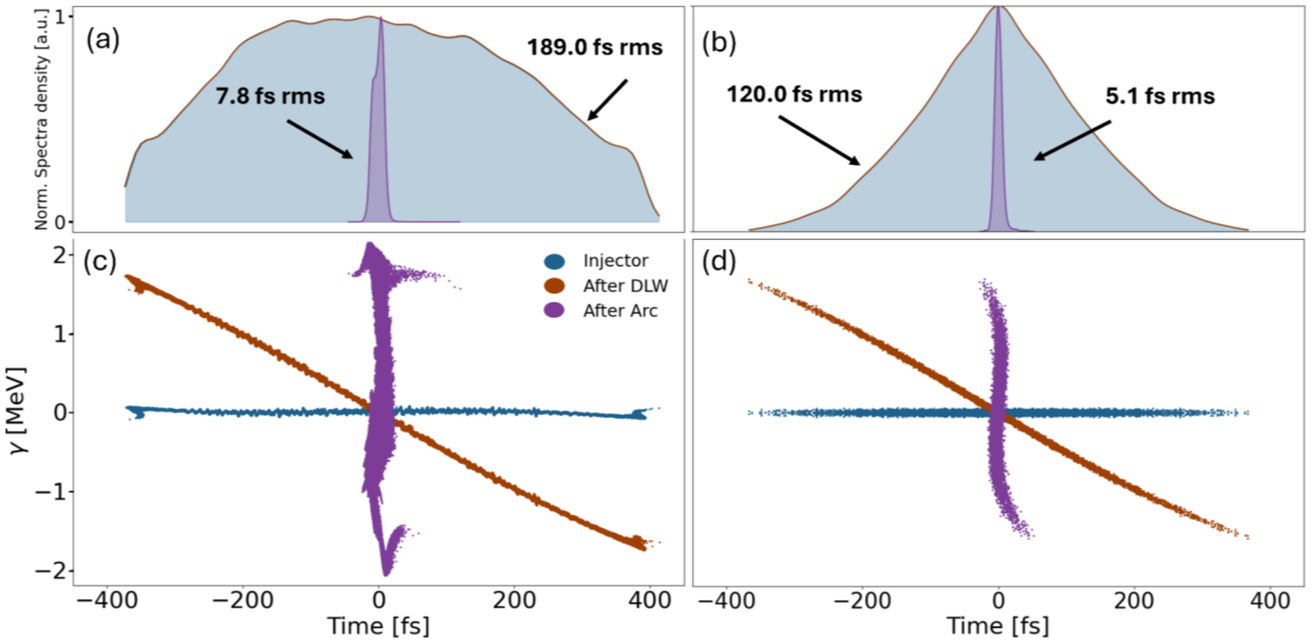
Poster: Sub-10 fs synchronization in laser-plasma accelerators with THz frequency bunch manipulation

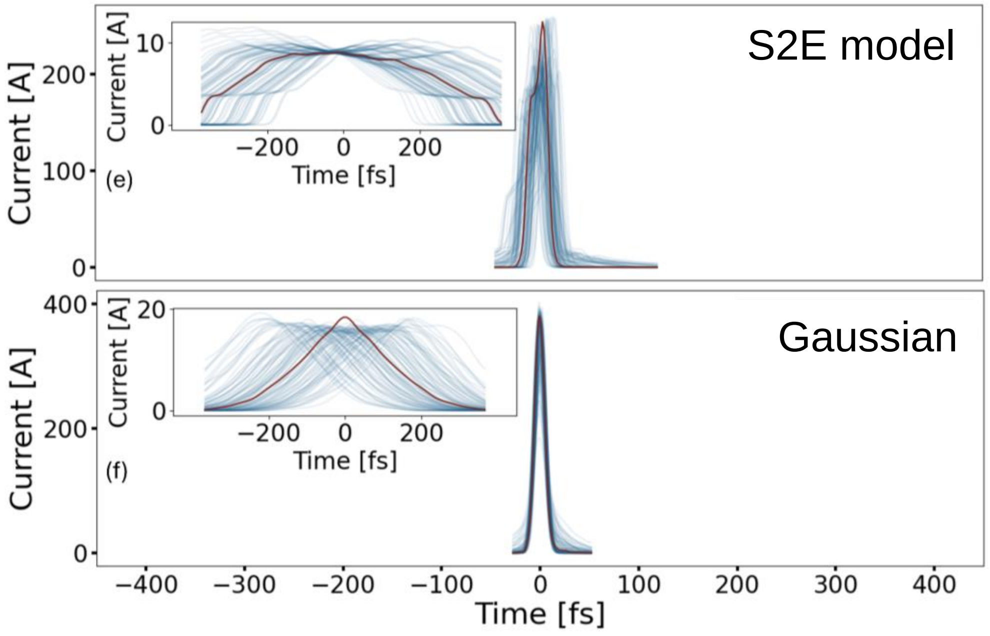
Aras Amini
PhD student



A. Amini et al. **arXiv:2604.16059**

S2E model of CLARA beam | Gaussian bunch





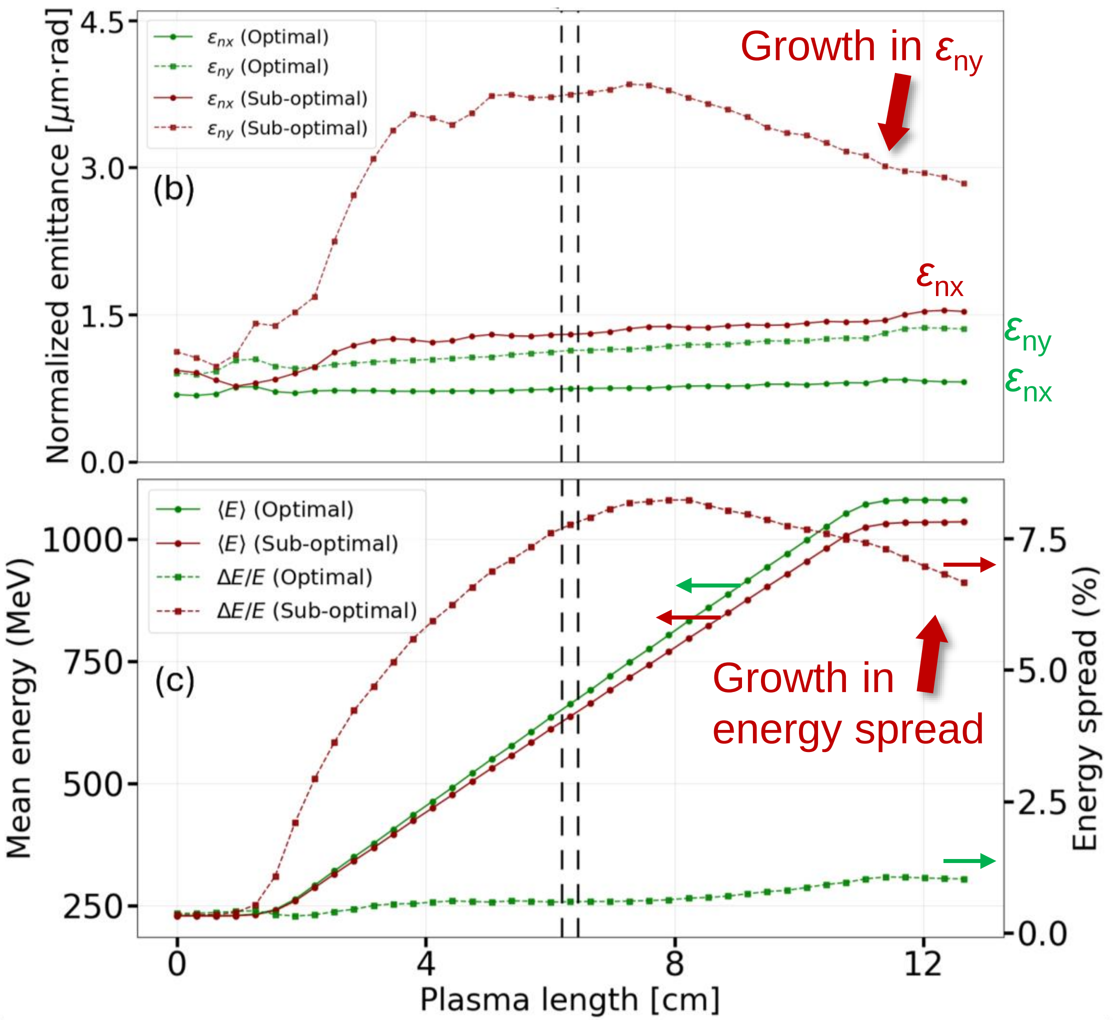
Initial bunch parameters	S2E	Gaussian
Charge (pC)	5	5
Energy (MeV)	230	250
Bunch length (fs rms)	189	120
Transverse size (μm)	≈ 50	≈ 50
Uncorrelated energy spread (keV)	22	20
Norm. emittance (mm mrad)	0.23	0.3
Arrival time jitter (fs rms)	100	100

After THz compression and temporal locking →

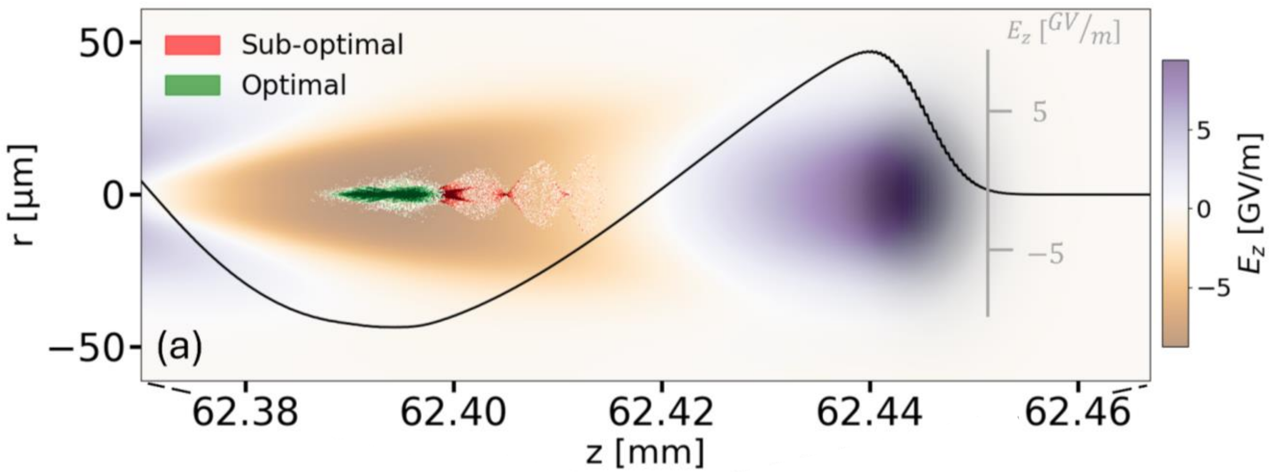
At LWFA injection point	S2E	Gaussian
Charge (pC)	5	5
Energy (MeV)	229.8	249.9
Bunch length (fs rms)	8.5	5.9
Transverse size (μm)	≈ 3-4	≈ 3-4
Energy spread (%)	0.4	0.31
Norm. emittance x/y (mm mrad)	0.82/0.94	0.6/0.3
Arrival time jitter (fs rms)	8.0	3.7

Emittance and energy spread along the plasma for:

- Optimal and sub-optimal injection (only 12.3 fs offset)



A. Amini et al. arXiv:2604.16059

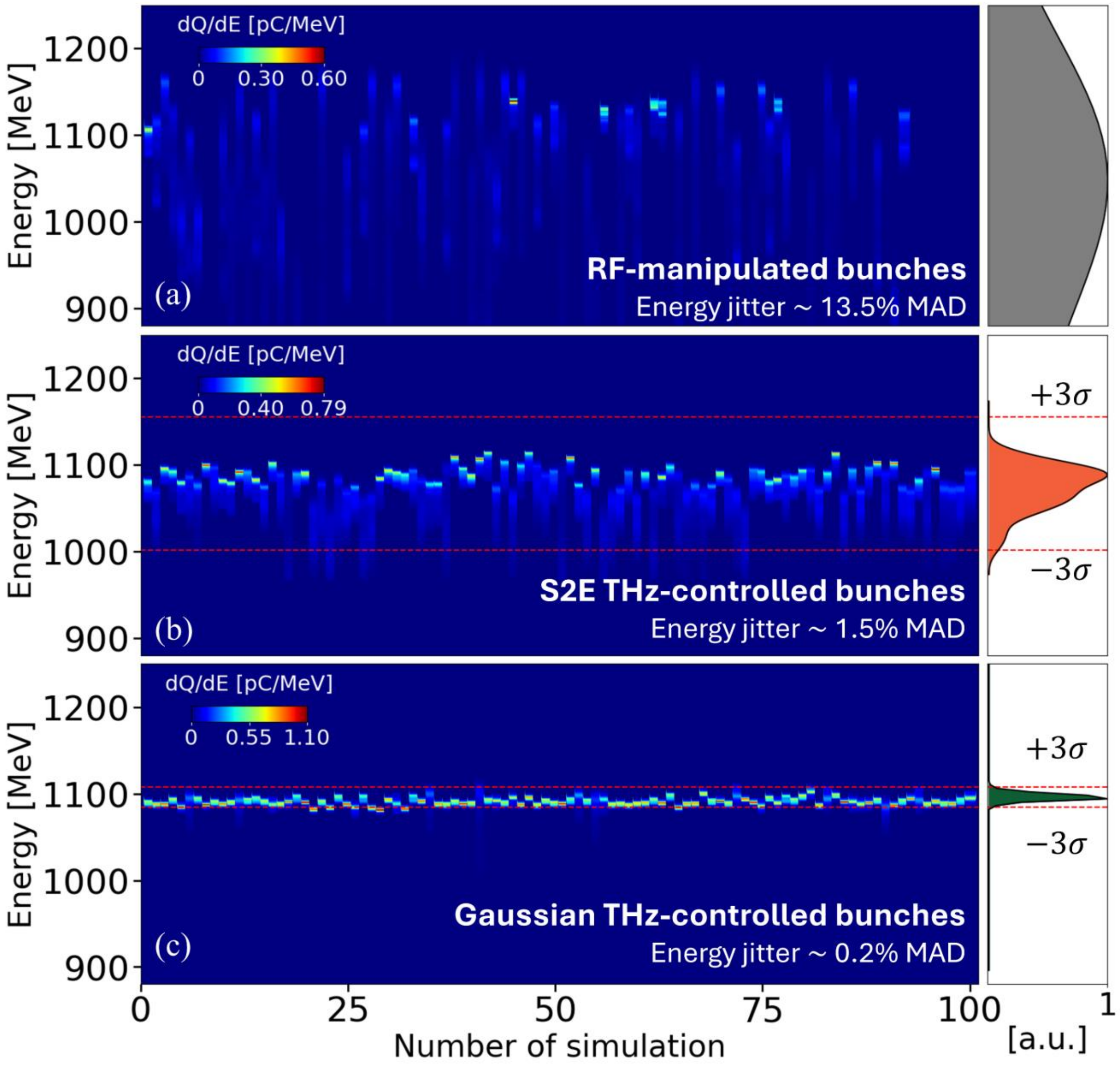


Laser parameters	
Wavelength	800 nm
Pulse energy	2 J
Waist size	30 µm
Pulse length FWHM	25 fs

Plasma parameters	
Plasma density (on-axis)	1×10^{17} cm^{-3}
Ramp-up/down length	5.5 λ_β
Plateau length	9 cm

Injection timing critical at the sub-10 fs level

- Maintain low emittance (< 1 um) and energy spread (< 1%)



A. Amini et al. **arXiv:2604.16059**

No THz control (RF-manipulated bunches)
Large energy jitter ≈ 20% rms
Dominated by relative arrival time jitter (> 70 fs rms)

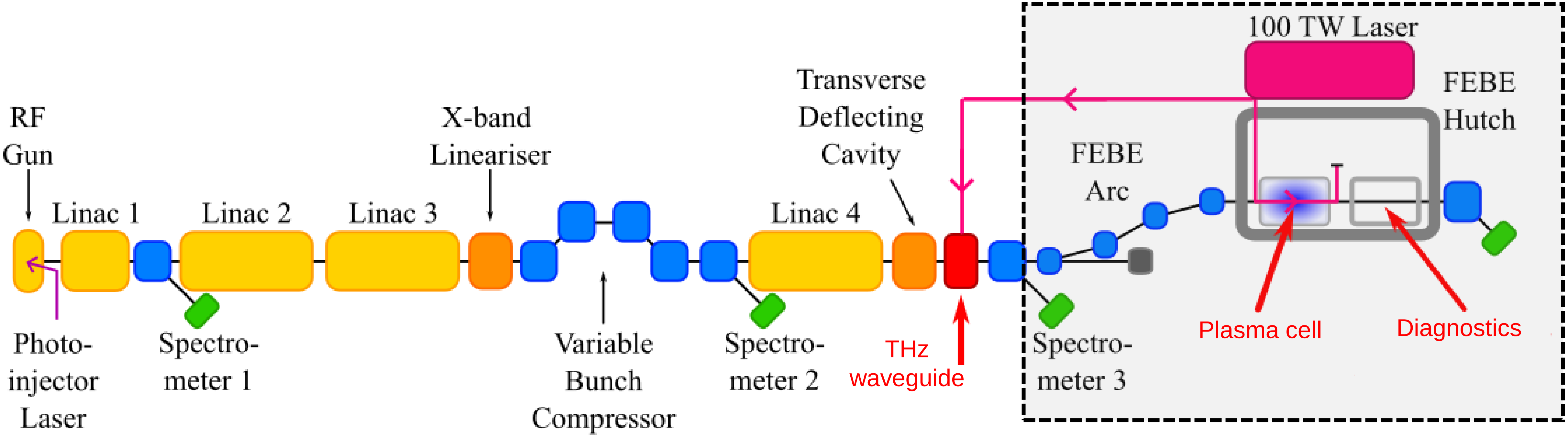
With THz control (S2E beam)
Median energy spread ≈ 1.1% rms
Energy jitter reduced to ≈ 2.2% rms

With THz control (Gaussian beam)
Median energy spread ≈ 0.30% rms
Energy jitter reduced to ≈ 0.29% rms

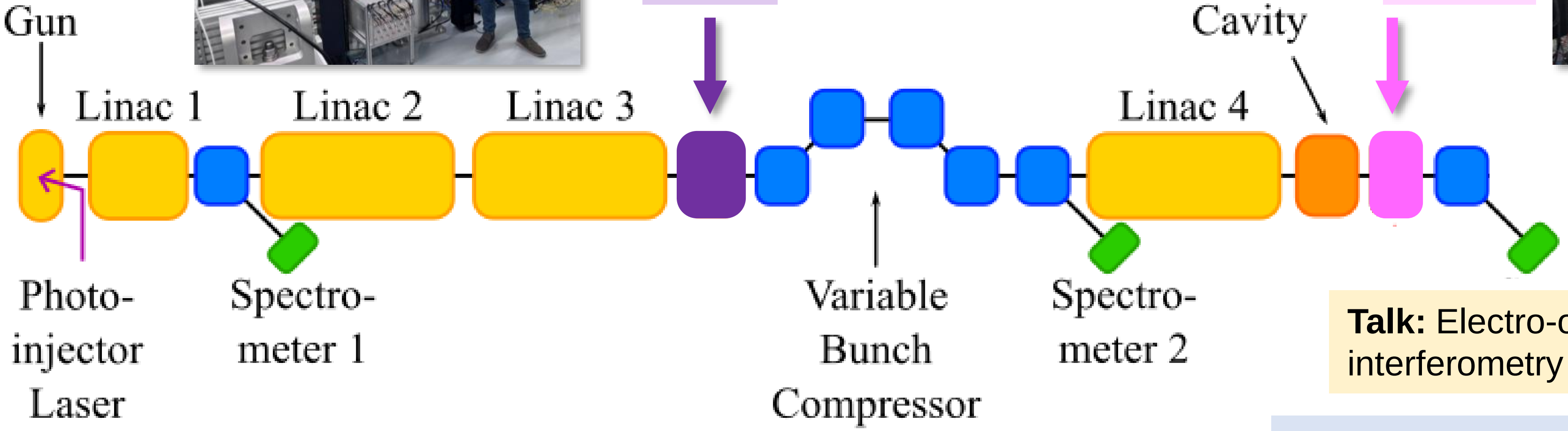
THz controlled injection enables high quality beams

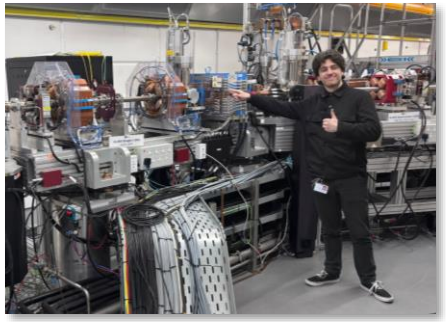
- Reduce energy jitter by 1-2 orders-of-magnitude

- First experimental demonstration of THz compression and temporal locking in September



- First experimental demonstration of THz compression and temporal locking during September beam-time



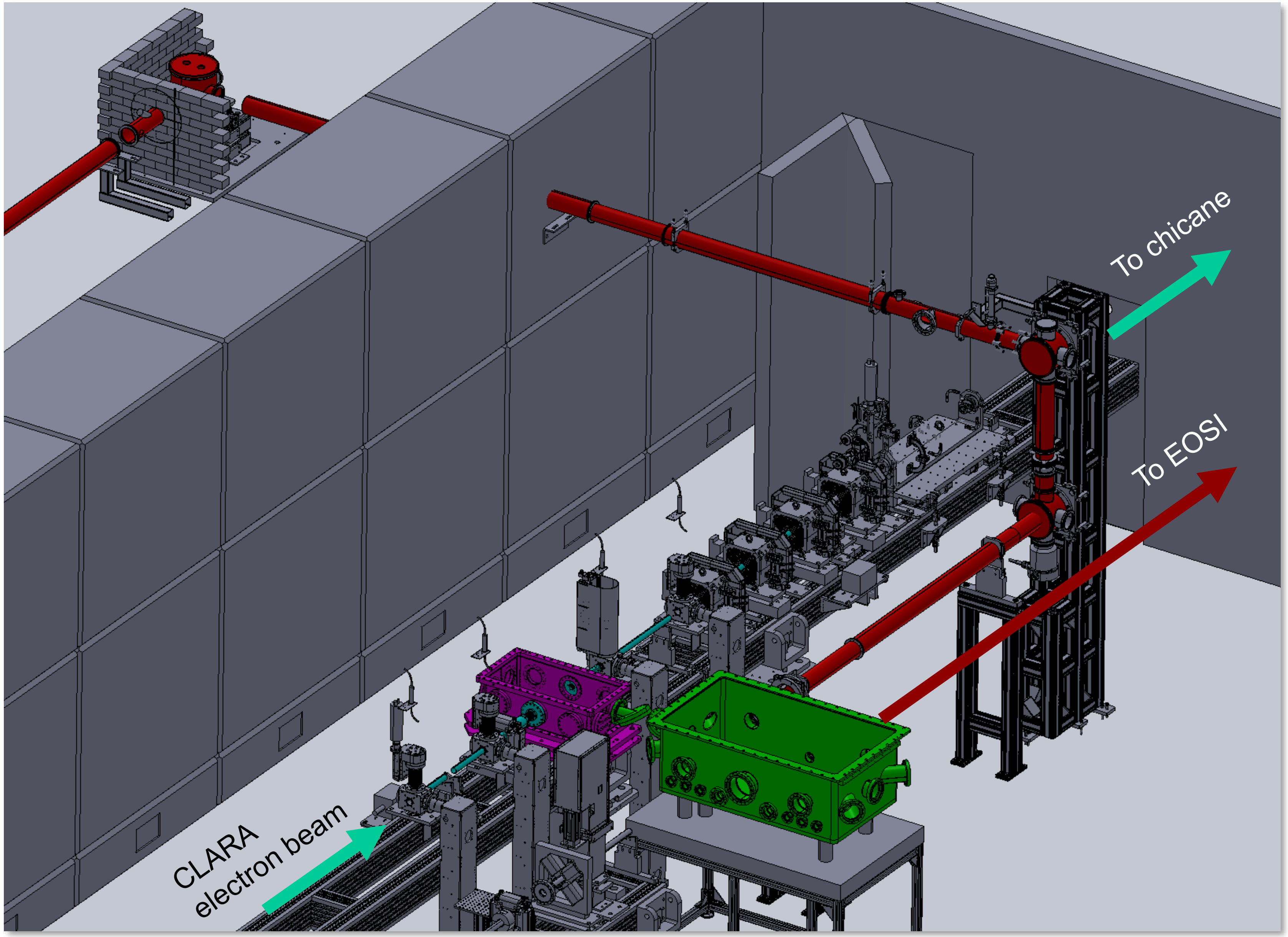


Samuel Norman
PhD student

Talk: Electro-optic spectral interferometry bunch profile monitor

S. Norman et al. *Proc. 14th International Beam Instrumentation Conference (IBIC 2025)*, Liverpool, UK, 2025 WEPCO40

- Longitudinal bunch diagnostics are critical
  - Transverse deflecting cavity (TDC) for full longitudinal phase-space (LPS) measurement
  - Electro-optic spectral interferometry (EOSI) for bunch profile and arrival time jitter (relative to the laser)



Experimental design and preparation underway

- New laser beamline
- New THz source chamber
- New interaction chamber

Christopher Shaw
PDRA

Experimental goals

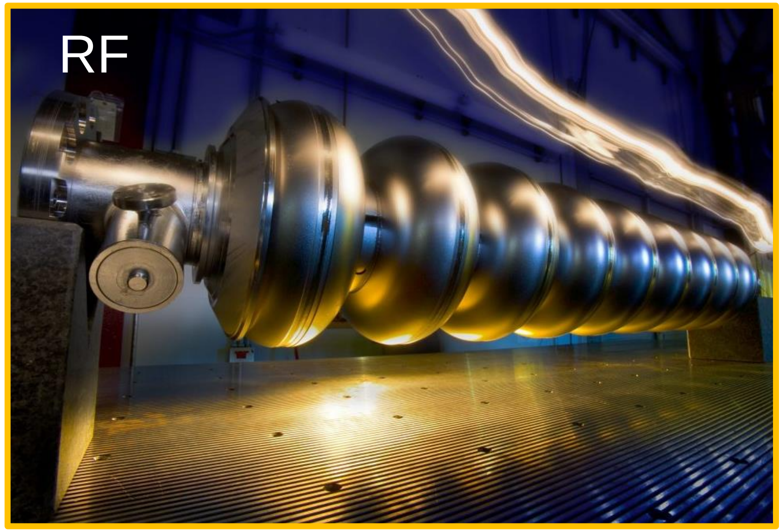
- Single and multi-bunch trains
- Bunch compression and synchronisation at 10 fs level
- First component for external LWFA injection

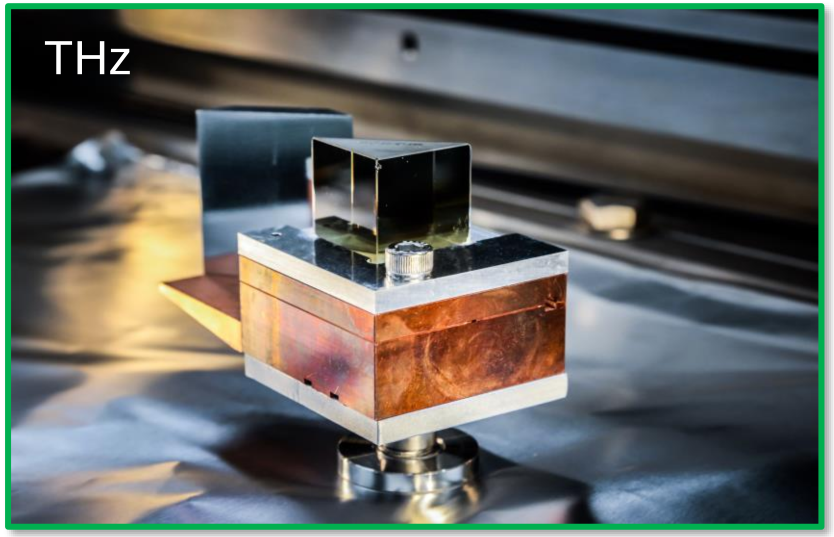
Summary

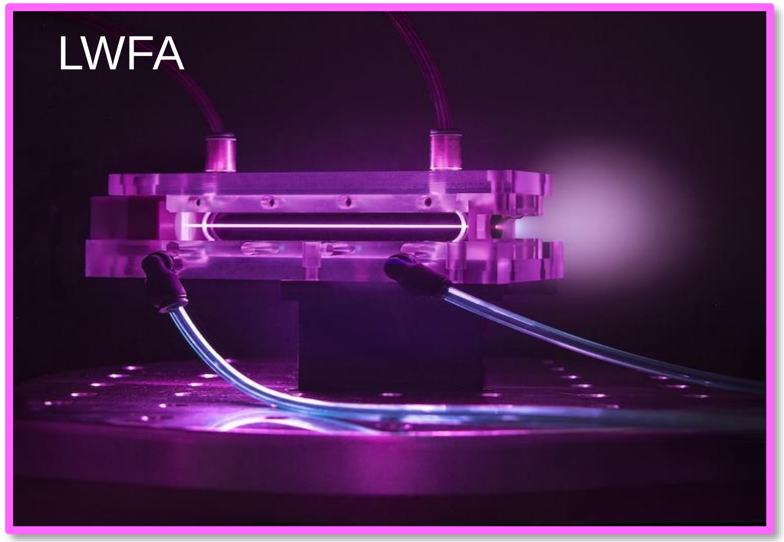
- Laser-based THz acceleration offers **unique advantages** for compact high-frequency bunch control
- **Ultrashort bunch compression** and **tunable micro-bunch trains**
- Towards femtosecond-scale **electron-to-laser temporal-locking**
- Provide **“bridge”** between conventional and plasma wakefield technologies
- Solve challenge of **external injection** into LWFA for high quality GeV beams

M.T. Hibberd et al. Terahertz control of relativistic electron beams for femtosecond bunching and laser-synchronized temporal locking. **arXiv:2508.20685**

A. Amini et al. Controlling external injection in laser-plasma accelerators with terahertz frequency bunch manipulation. **arXiv:2604.16059**







Academic leads

Morgan Hibberd
Darren Graham
Rob Appleby

Steven Jamison
Graeme Burt
Rosa Letizia

The University of Manchester
Lancaster University

PDRAs

Laurence Nix
Christopher Shaw
Joseph Bradbury
Dan Lake
Sergey Siaber
Connor Mosley
Rohit Kumar

PhDs

Aras Amini
Patrick Dalton
Filip Peczek
Sam Norman
Ryan McGuigan
Thomas Wilson
Xi Luo
Beatriz Higuera Gonzalez
Vasileios Georgiadis
Oliver Finlay
Alisa Healy

Additional collaborators

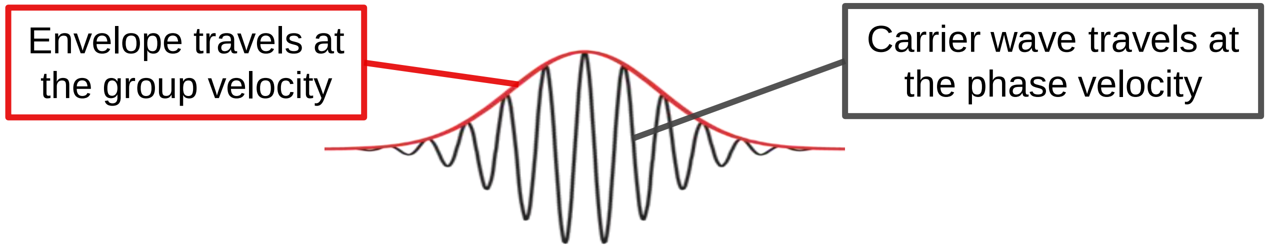
Ed Snedden
David Walsh
Tom Pacey

James Jones
Lewis Reid

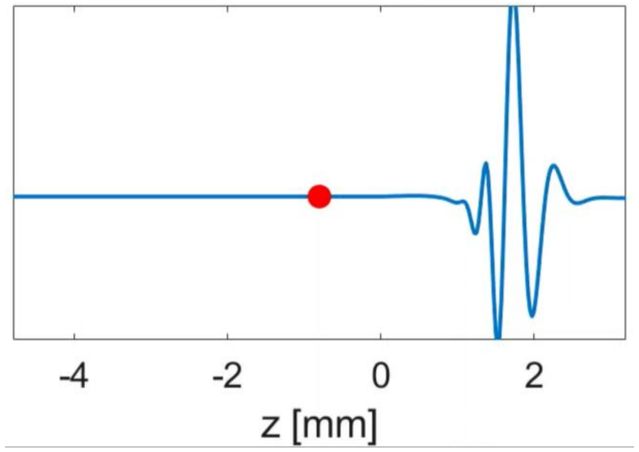
Laura Corner

UKRI Science and Technology Facilities Council
University of Liverpool

Thank you for your attention



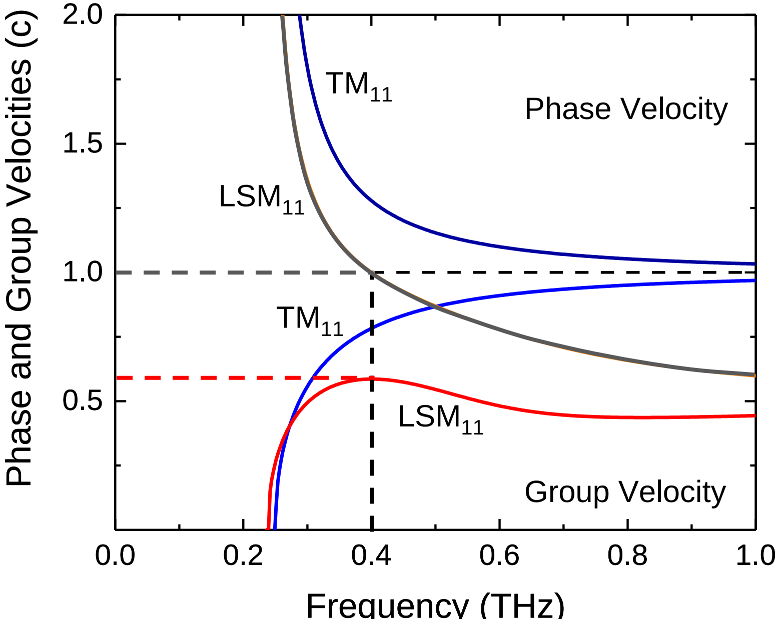
Single-cycle THz pulse



Broadband not good
- ➢ Lots of dispersion
- ➢ Phase-slippage
- ➢ Weak interaction

Normal waveguide has TM_{11} accelerating mode
- ➢ Phase-velocity $v_p > c$ → Can't match to particle bunch velocity

Dielectric-lined waveguide has LSM_{11} accelerating mode
- ➢ Phase-velocity $v_p = c$ at specific frequency → Can match particle velocity

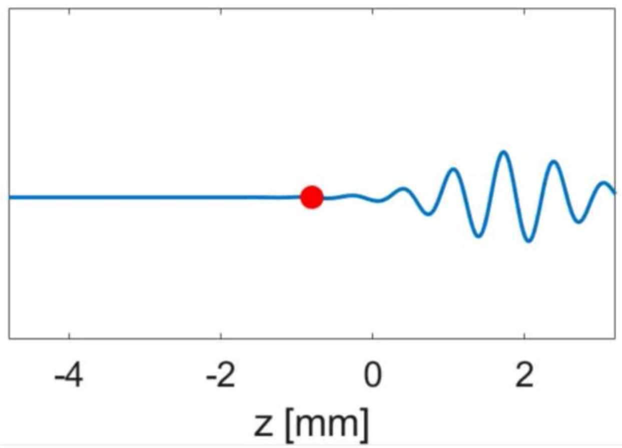


at 0.4 THz

$v_p = 0.999c = v_e$

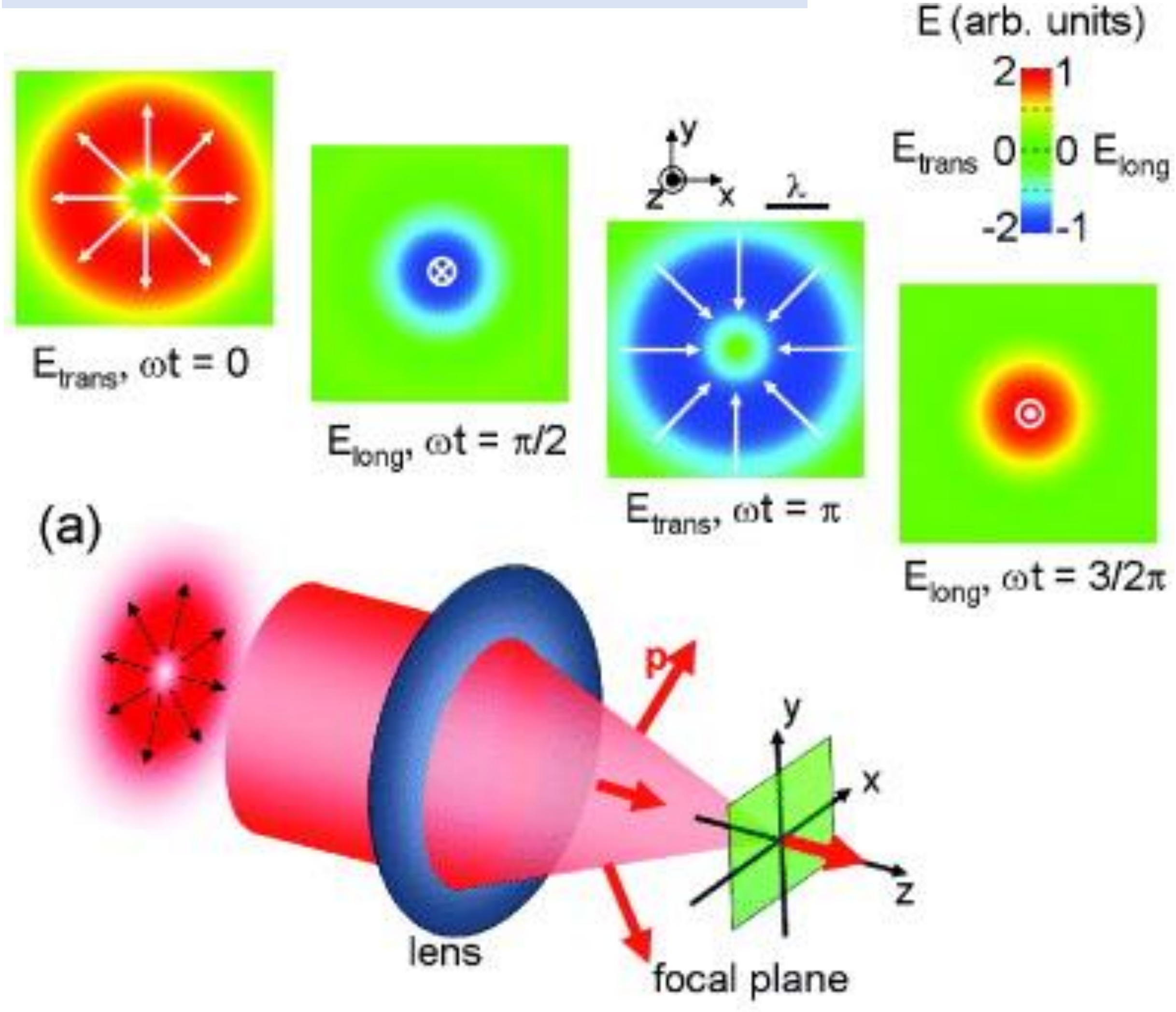
$v_g = 0.585c$

Multi-cycle THz pulse



Narrowband much better!
- ➢ Less dispersion
- ➢ Phase-velocity matched
- ➢ Strong interaction

S Winnerl *et al.* *New J. Phys.* **14** 103049 (2012)



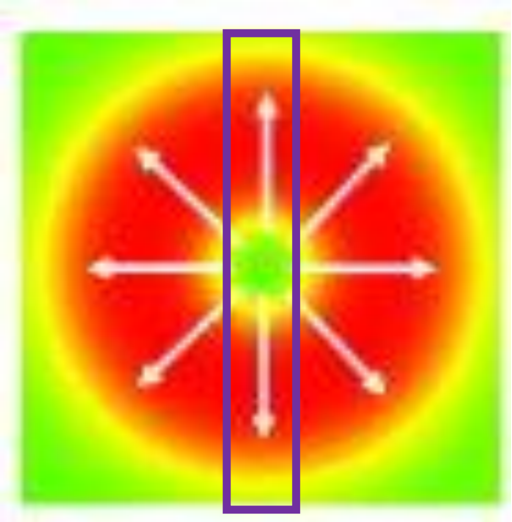
Electromagnetic waves typically propagate with transverse electric and magnetic fields

- Due to finite size, they also have longitudinal components

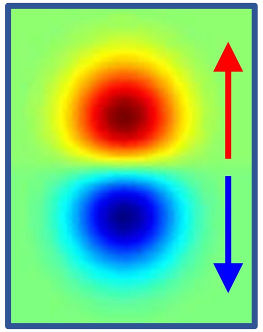
Can enhance longitudinal component by focusing a radially-polarised beam

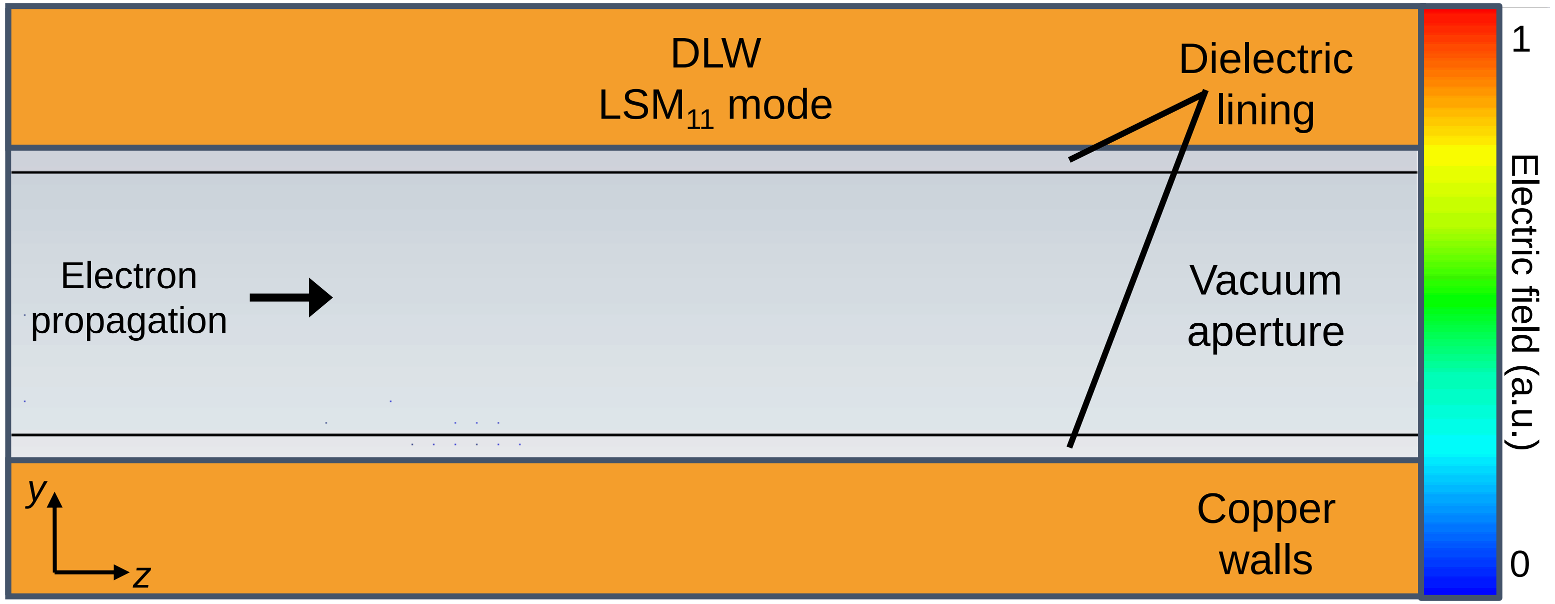
- Radially-polarised THz can be different to generate

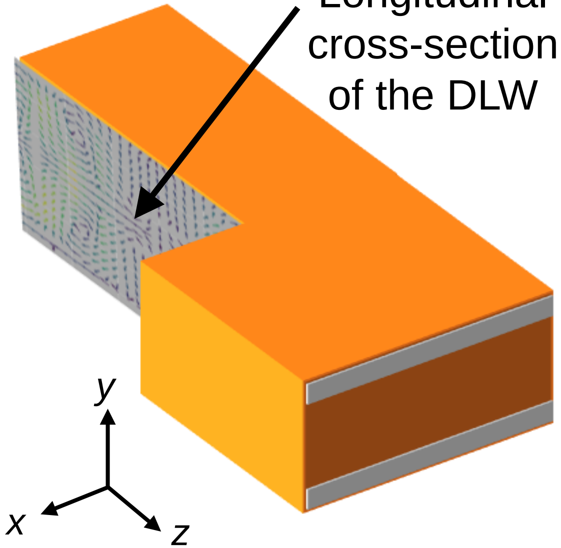
Can we use a simpler mode?

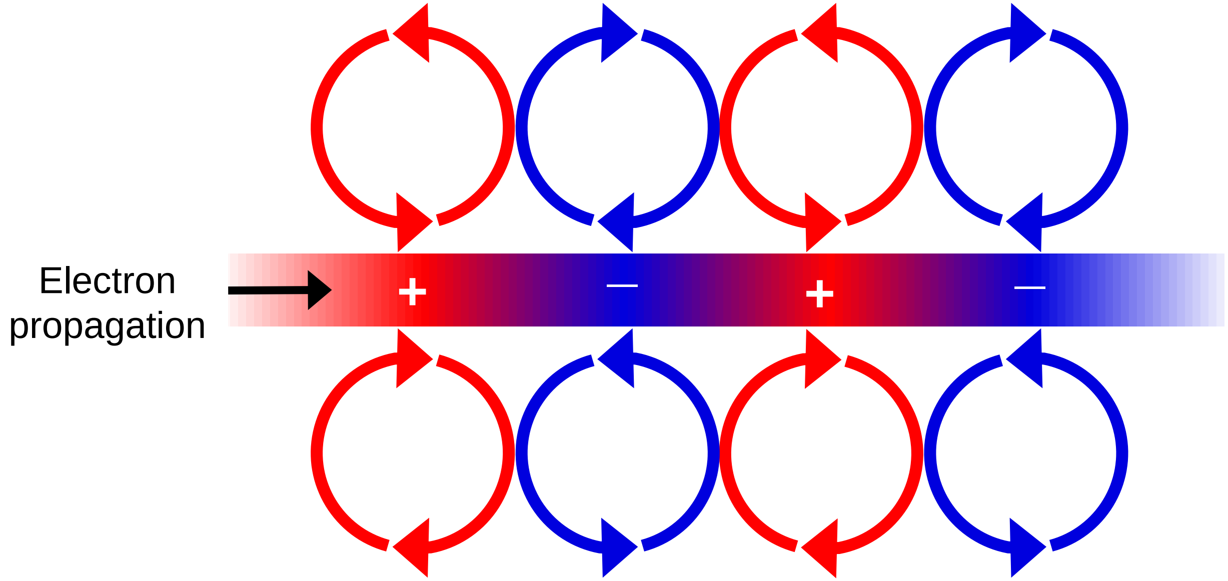


Terahertz acceleration: Waveguide modes



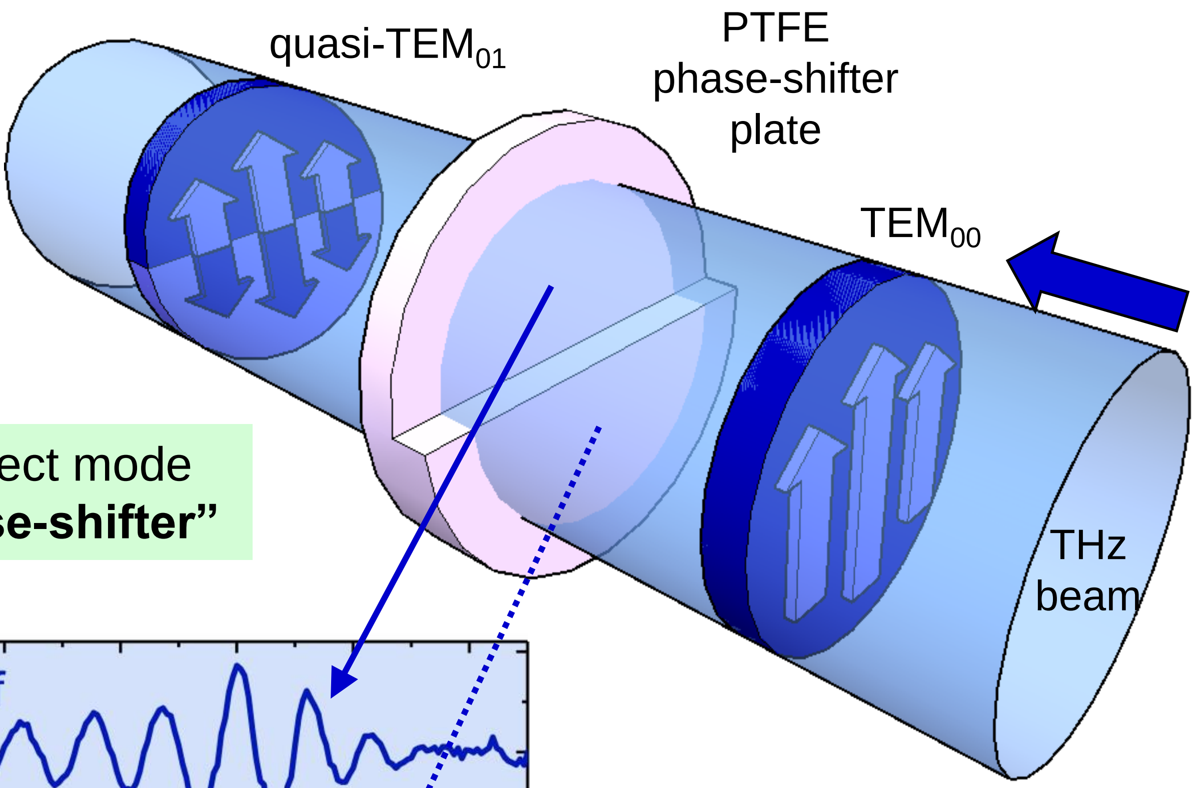




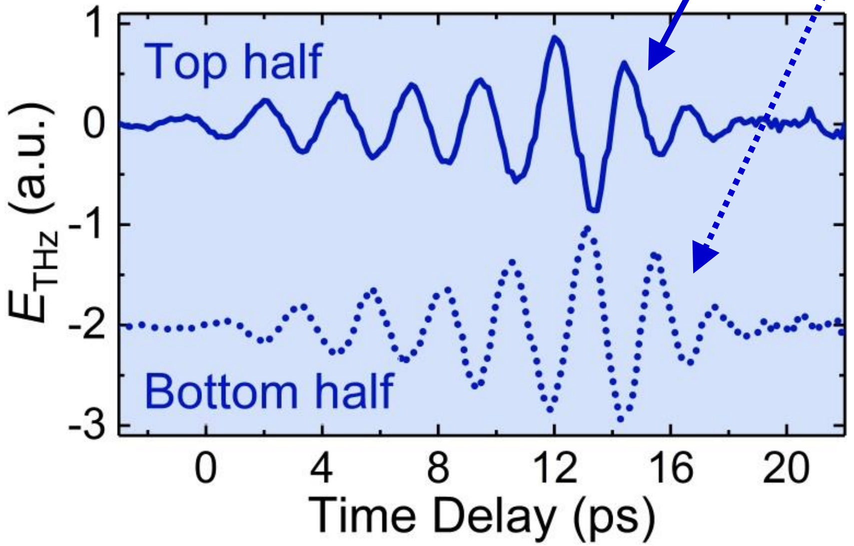


TEM_{01} free-space mode → LSM_{11} waveguide mode

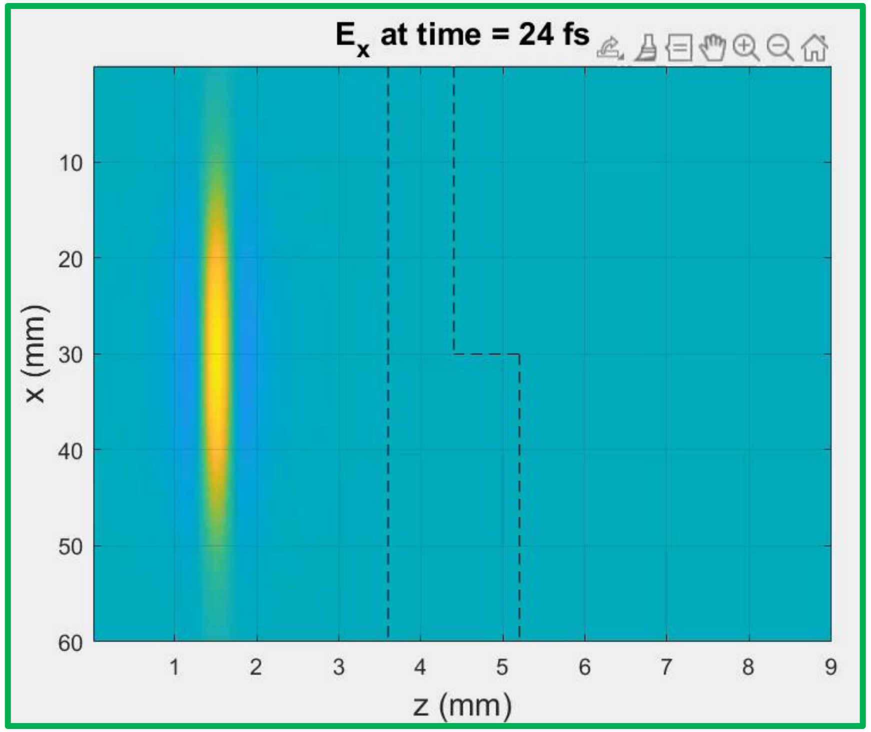
- Transverse fields off-axis (deflect particles)
- Longitudinal fields on-axis (accelerate particles)

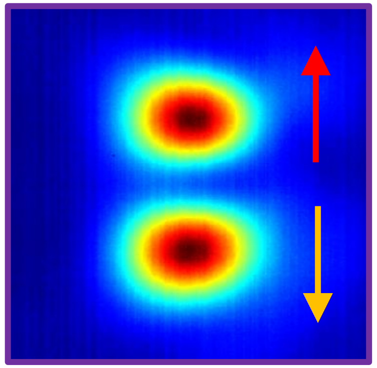


Make the correct mode using a **"phase-shifter"**



Measured THz electric fields showing 180º phase change between top and bottom





THz camera image of TEM$_{01}$ mode at entrance to waveguide