

Particle Accelerator and Beams Conference | 29-30th June 2023

Terahertz-driven electron bunch manipulation for advanced accelerators

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Terahertz Acceleration Group @ The Cockcroft Institute | www.THzAG.uk



Science and
Technology
Facilities Council



Why do THz techniques complement other advanced accelerators?

Advanced accelerators use THz frequency fields

- Wakefields driven by lasers, electrons or protons
- Plasma frequency ranges from **0.1 – 10 THz**



The Advanced Wakefield Experiment (AWAKE)

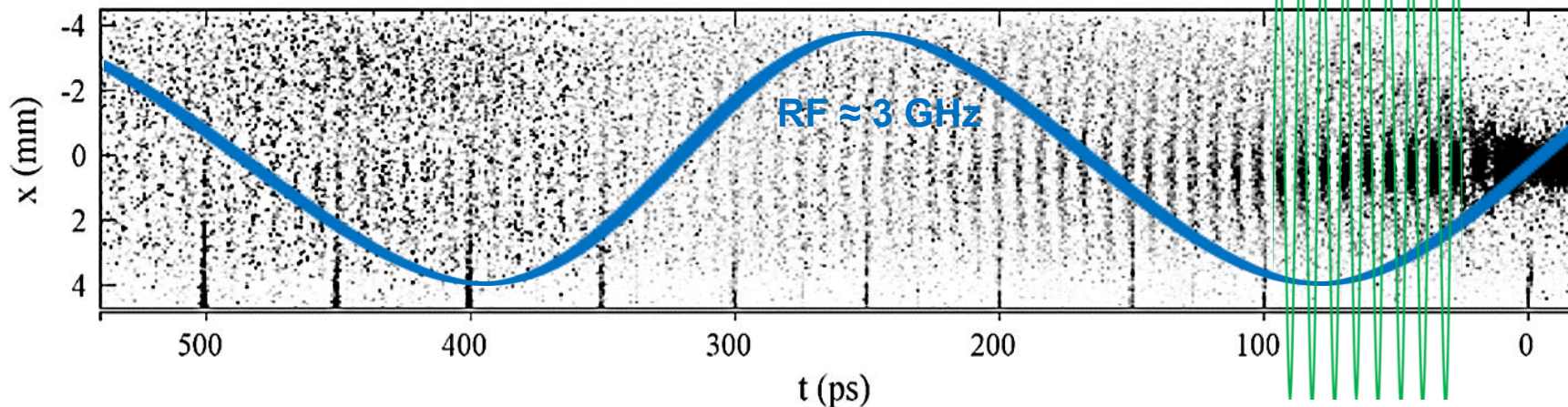
- Proton beam-driven wakefield
- Plasma frequency \approx **0.25 THz**



In this talk



Image of modulated proton bunch



THz-driven bunching

- Ultrashort duration
- Temporal locking
- Bunch trains at THz rep rates

For AWAKE

- External injection schemes

E. Gschwendtner *et al.* *Symmetry* 14,1680 (2022)

THz pulse \approx 0.1-10 THz

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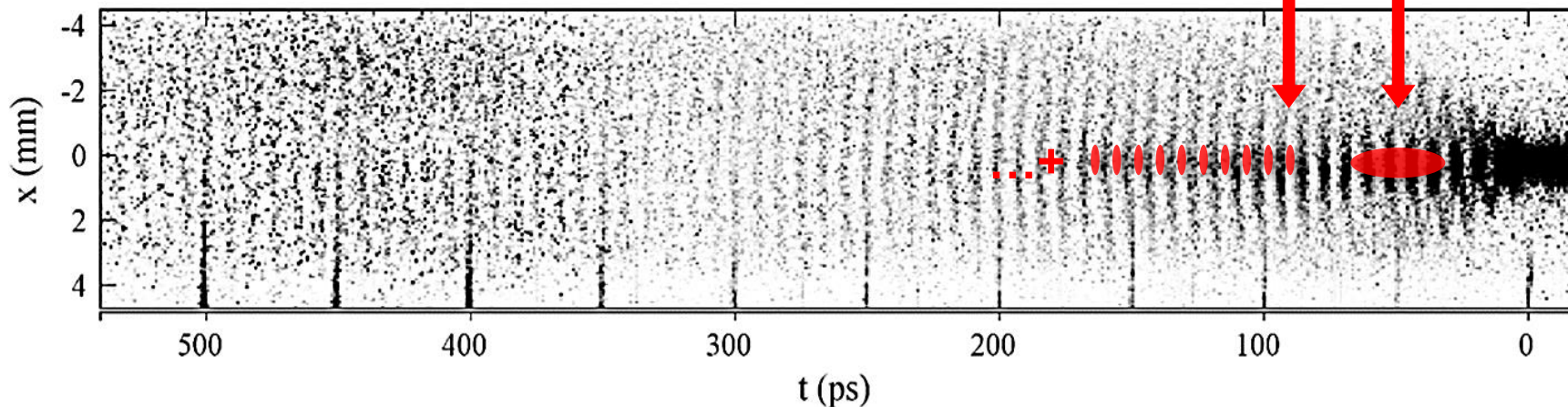
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Why are terahertz pulses ideal for bunch manipulation?

High electric field strengths

- 100 MV/m to >GV/m possible

Laser and THz pulse shaping

- Bandwidth and frequency tuning
- Polarisation modes

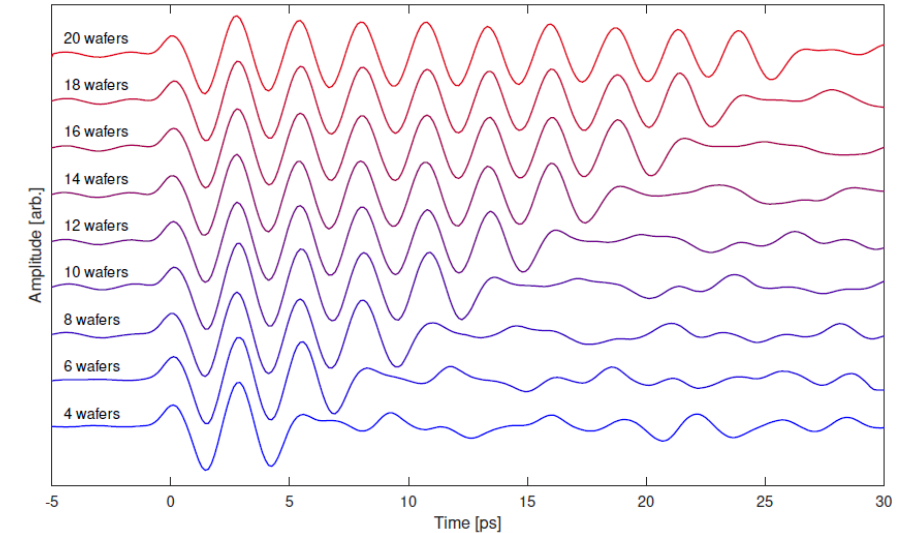
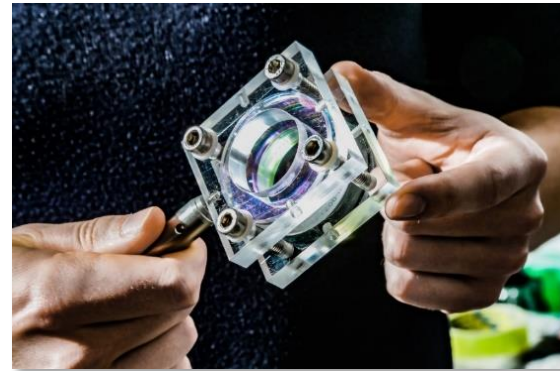
Laser timing synchronisation

- THz sources generated by drive laser
- Synchronise to the fs-scale

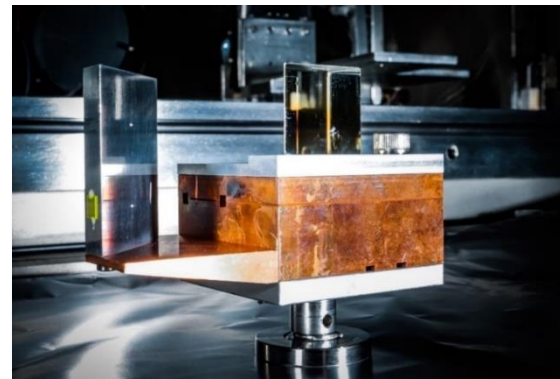
Compact mm-scale structures

- Minimal beam-line footprint
- High-charge throughput (>100 pC)

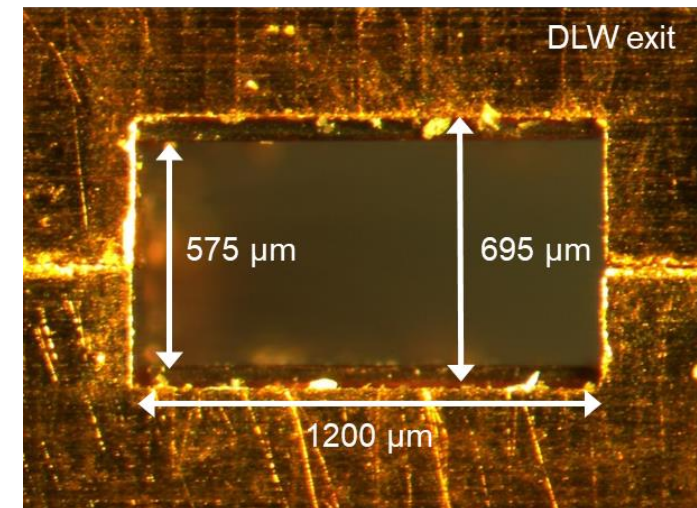
Periodically-poled lithium niobate wafer stack source



C. D. W. Mosley *et al.* *Opt. Express* 31,4041 (2023)



Dielectric lined THz waveguide structure



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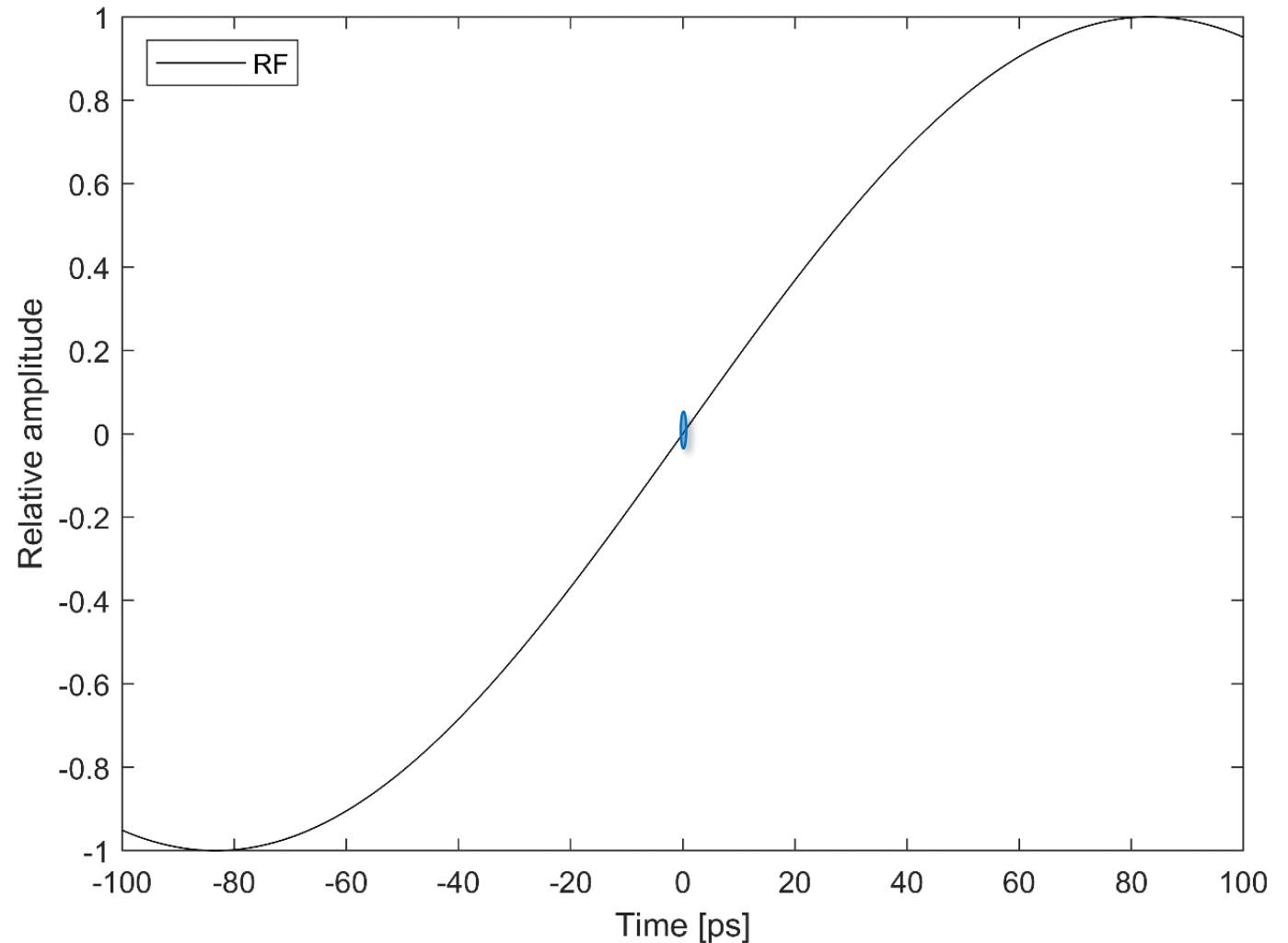
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Optimal frequency for manipulation

- Short enough field cycle for fs control
- Long enough for ps-scale bunch lengths



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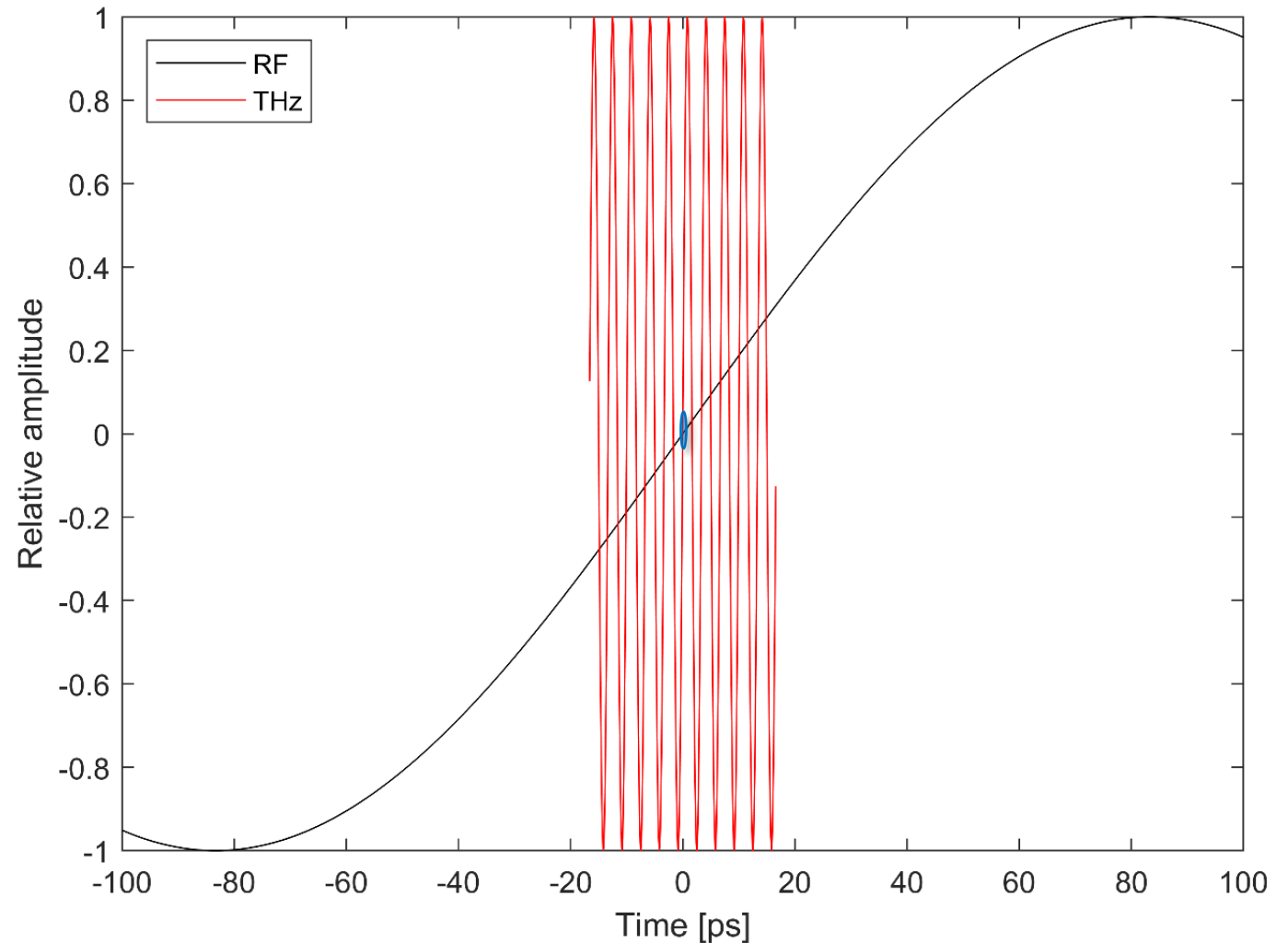
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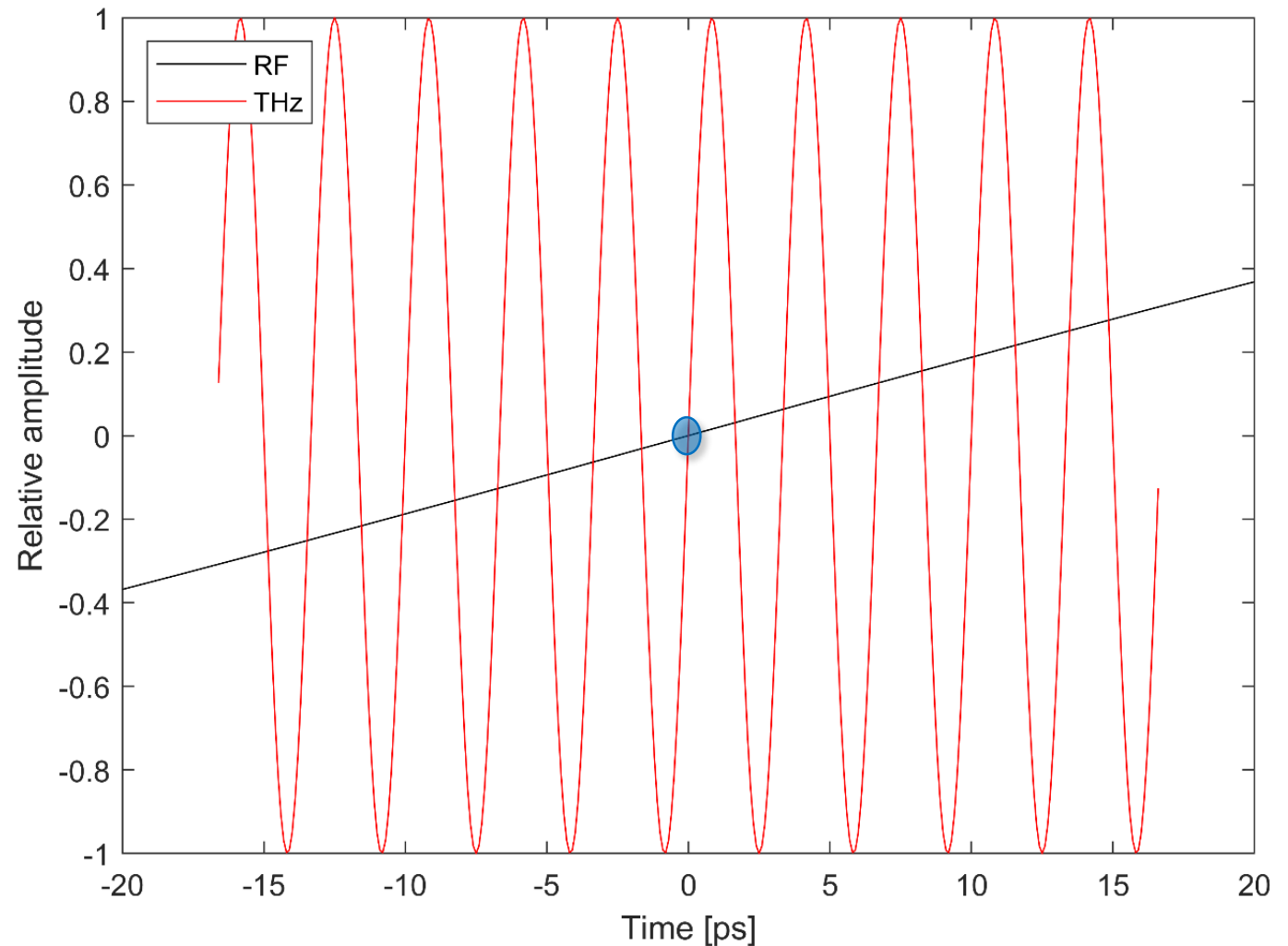
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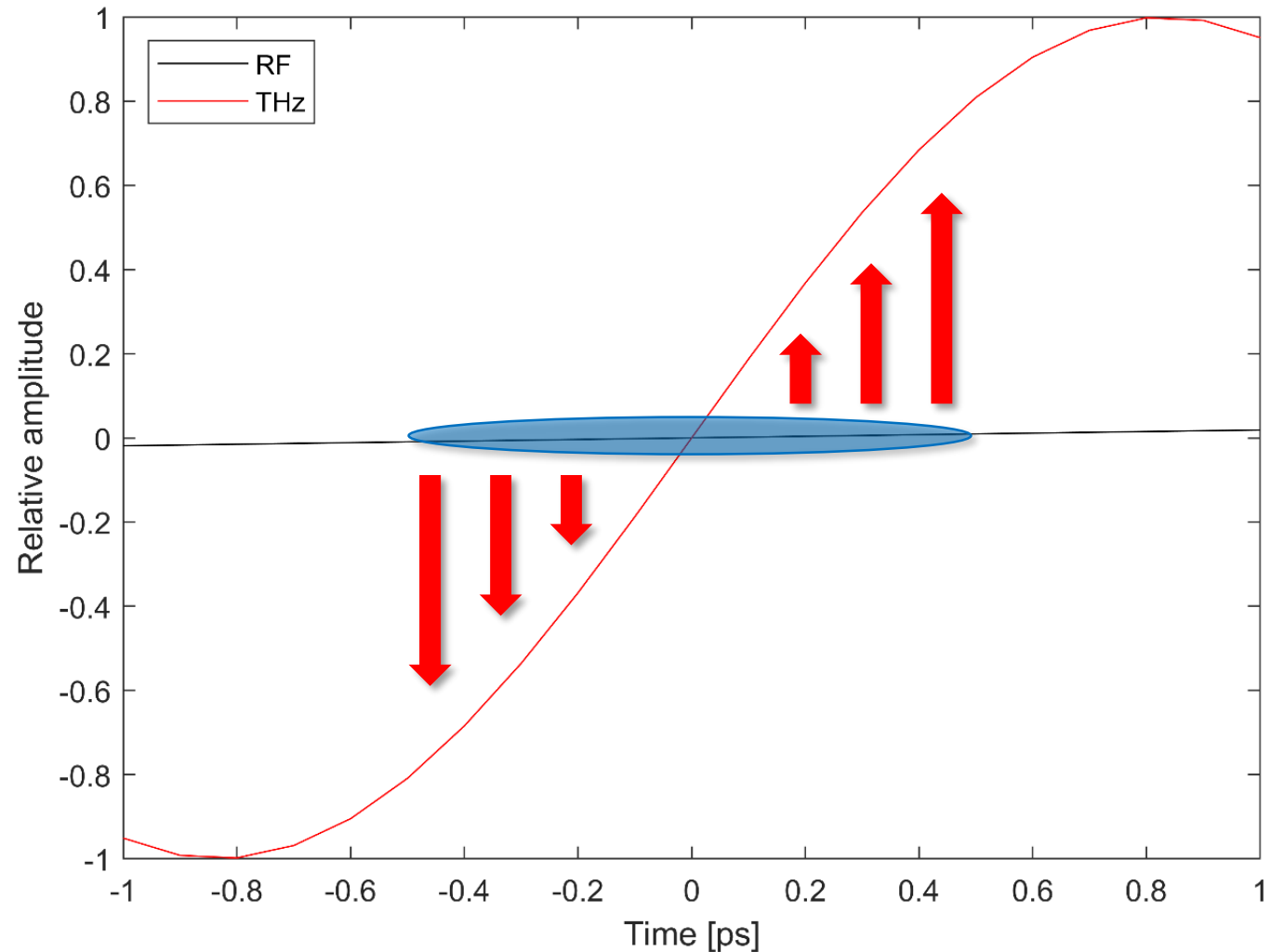
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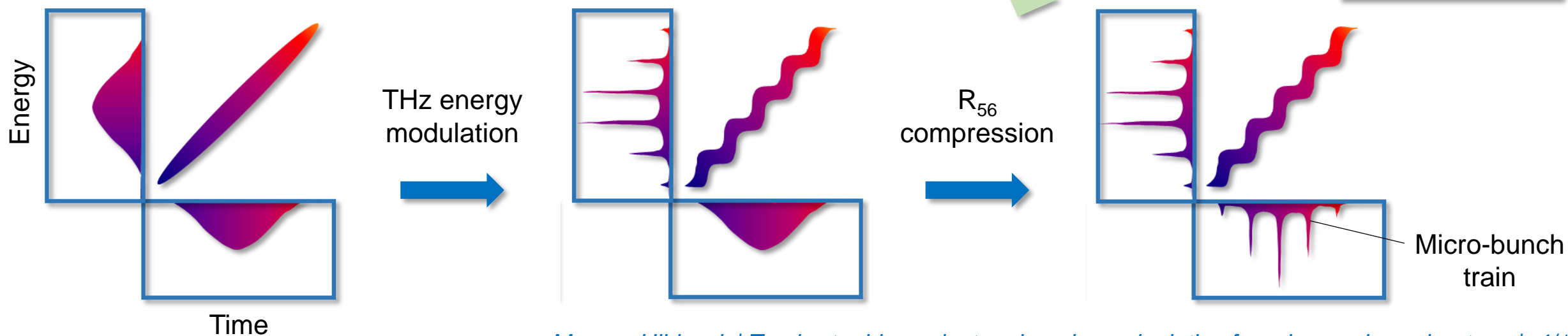
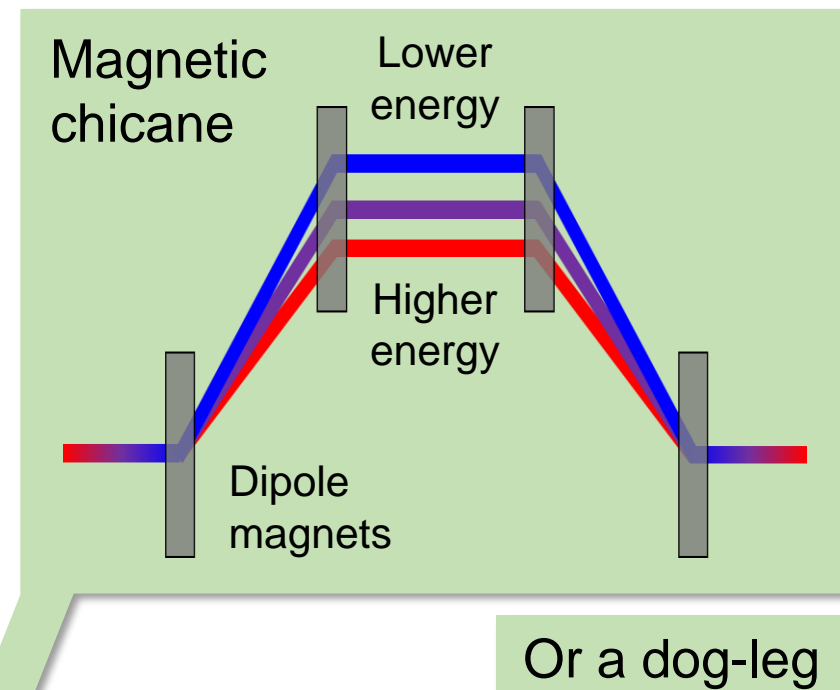
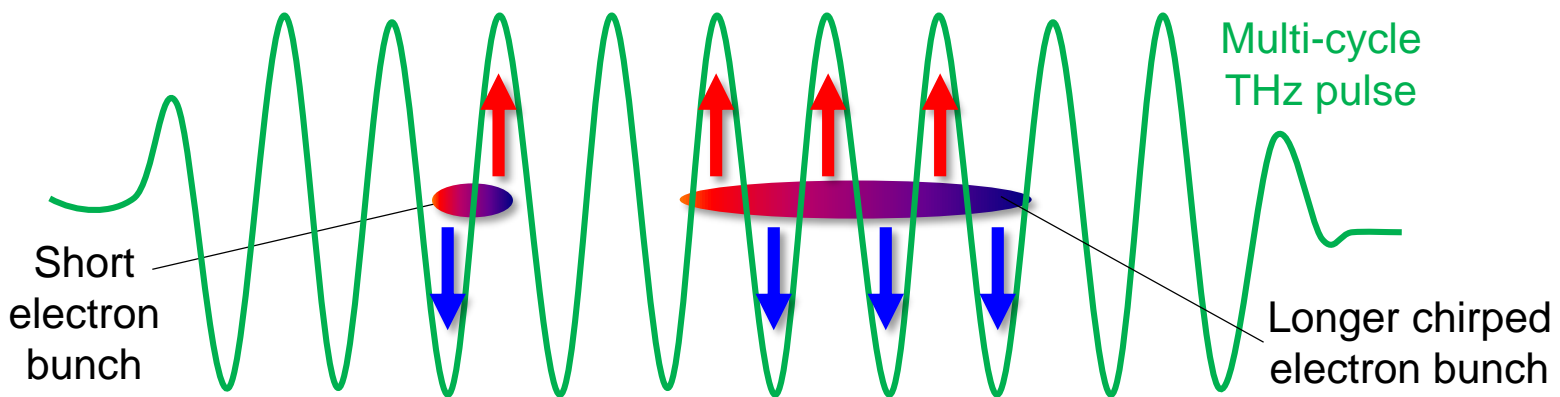
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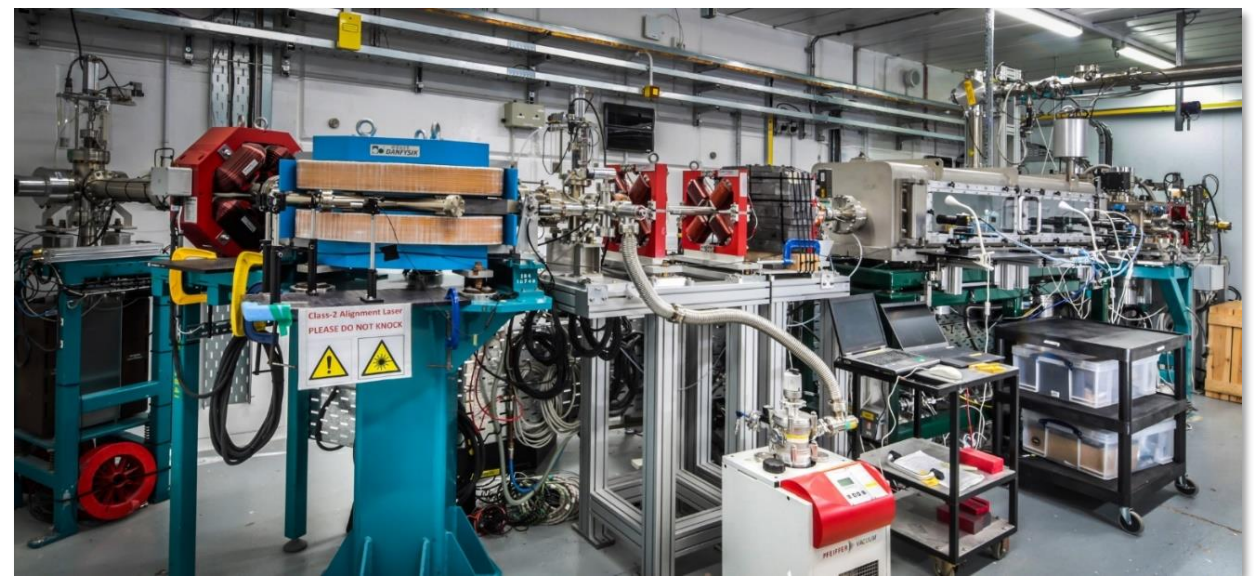
How does terahertz-driven bunching work?

Induce an energy chirp (or modulation) followed by compression

- Analogous to standard RF-based zero-crossing compression
- Higher THz frequency makes interaction more efficient
- And... makes multi-bunch generation possible



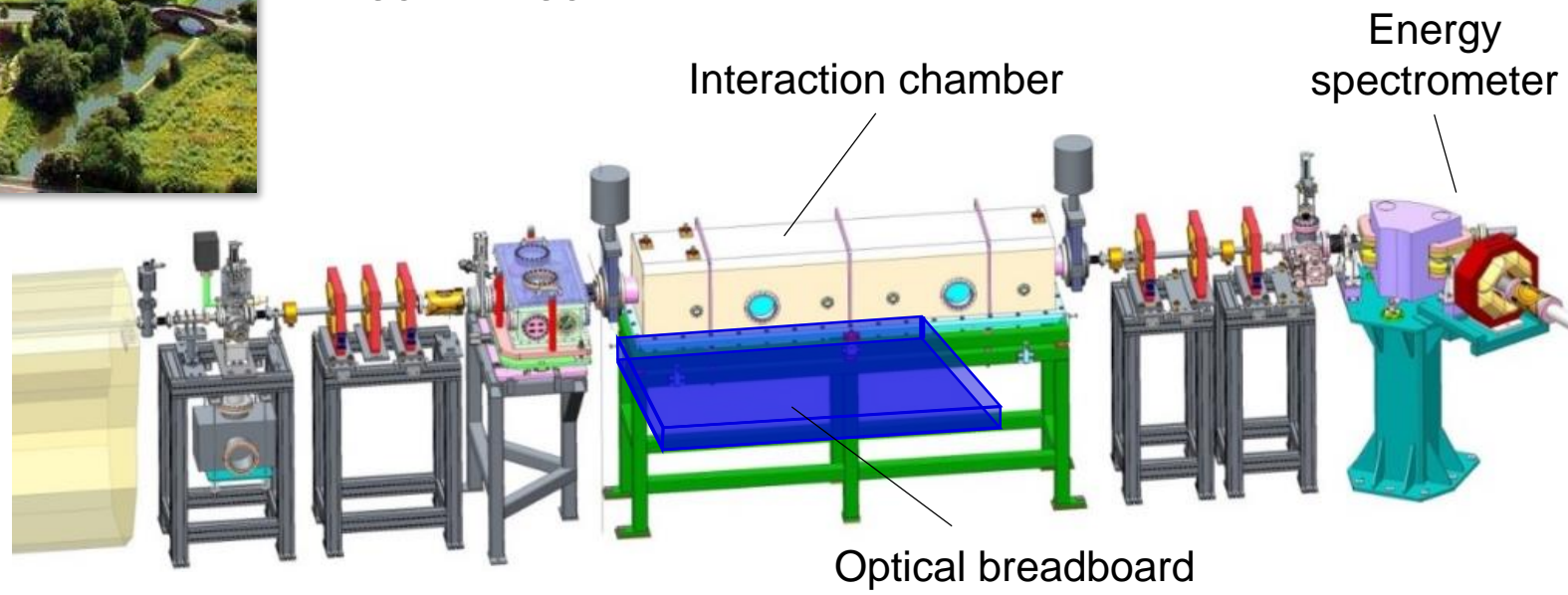
Experiments on CLARA @ Daresbury Laboratory



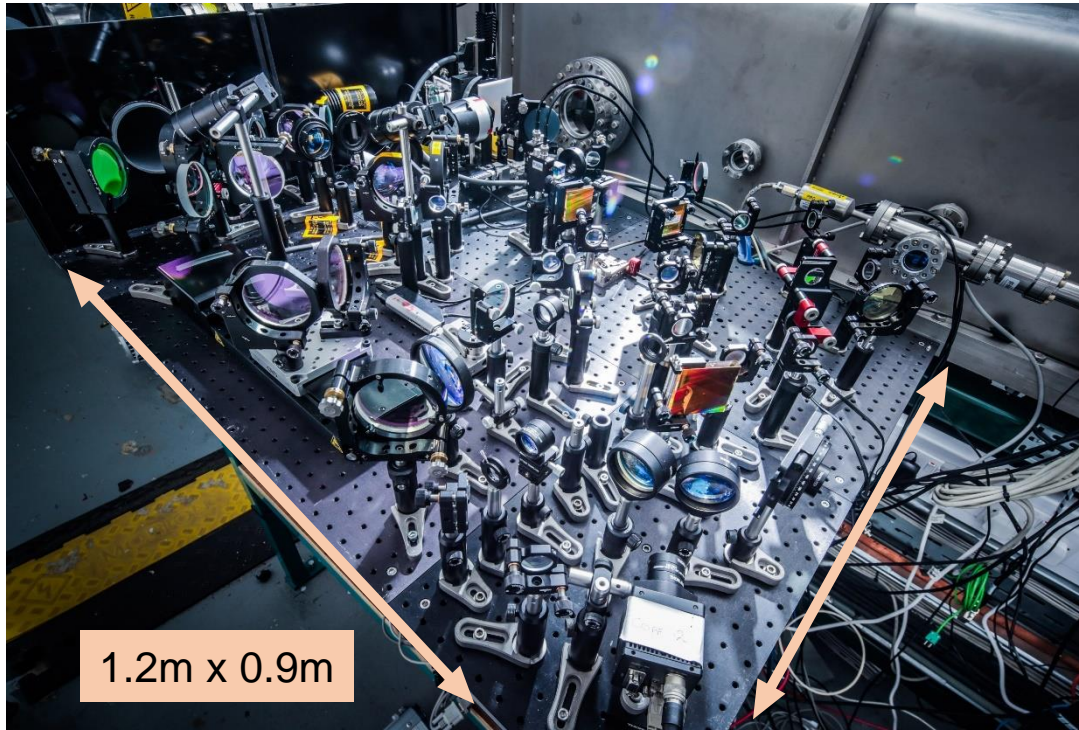
Beam Area 1

Compact
Linear
Accelerator for
Research and
Applications

Bunch parameters	
Energy:	35.5 MeV
Charge:	2 – 100 pC
Duration:	0.2 – 6 ps
Spot size:	100 μ m
Rep. rate:	10 Hz



Experimental setup



Laser and THz optics outside chamber

Laser parameters

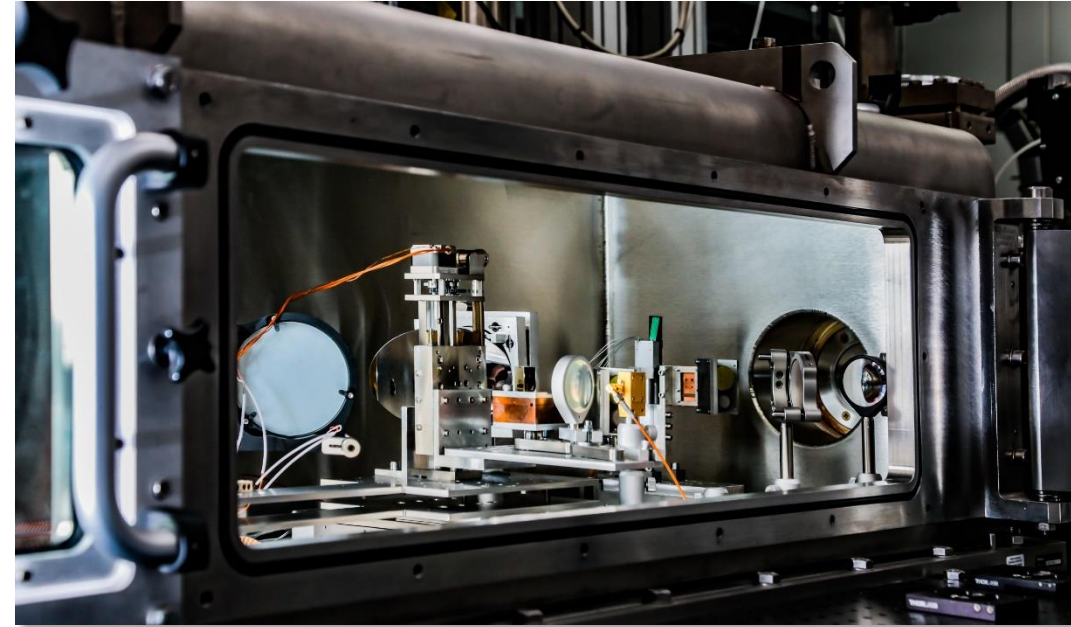
Wavelength: 800 nm
Pulse length: 50 fs
➤ Chirped to 750 fs

Pulse energy: 300 mJ
➤ ≈ 150 mJ on THz source

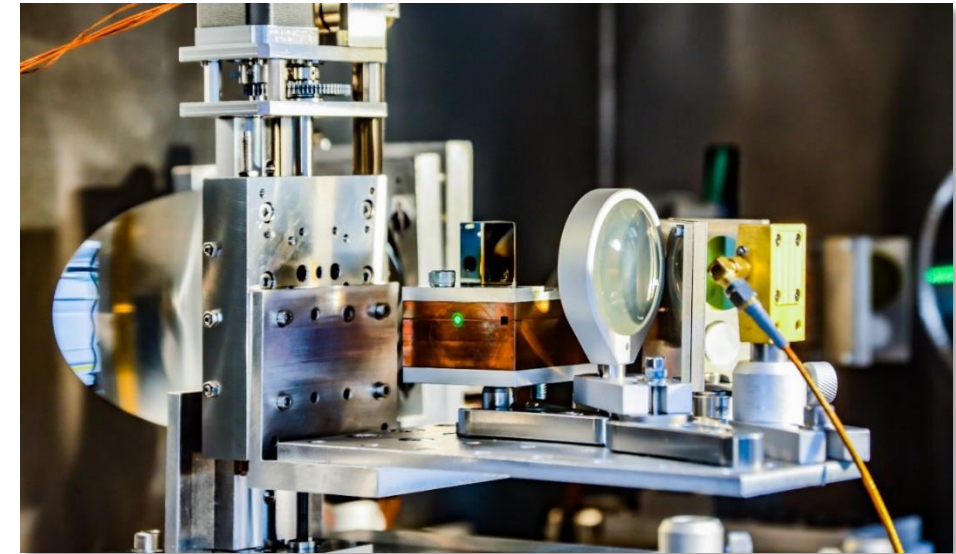
THz parameters

Frequency: 0.4 THz
Bandwidth: 40 GHz
➤ 10 cycles each 2.5 ps

Pulse energy: ≈ 100 μ J
➤ $< 20\%$ coupling



THz-electron interaction point inside vacuum chamber



Terahertz-driven multi-cycle energy modulation

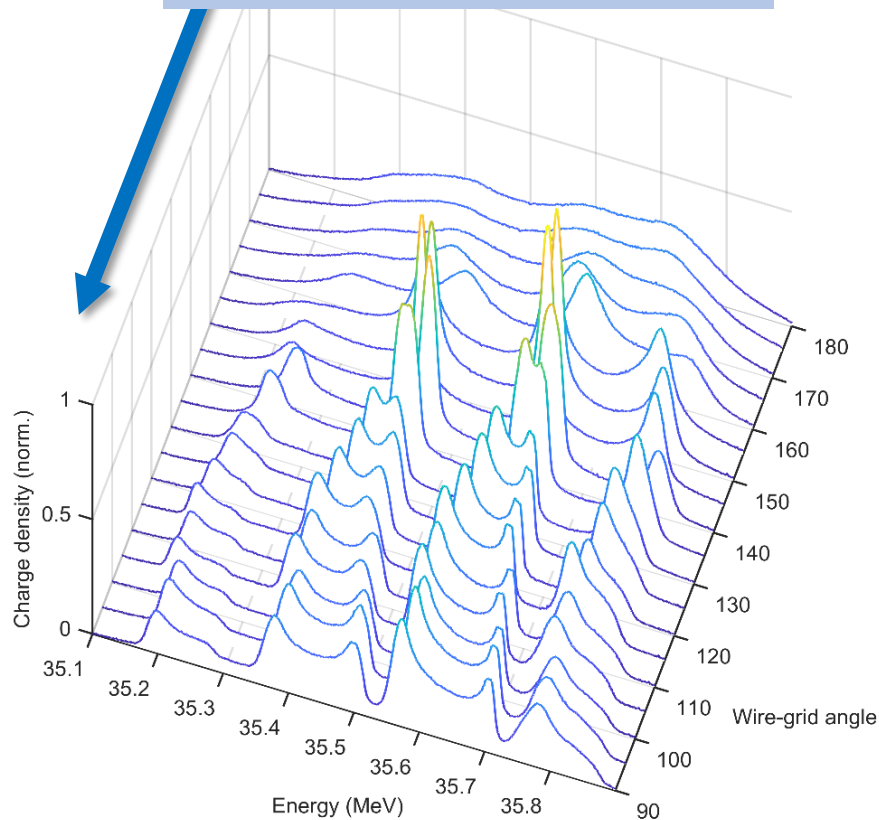
Energy modulation demonstrated experimentally

- Chirped (>4 ps rms) bunches interact with multiple THz field cycles
- Can tune THz field strength and injection timing to control energy modulation

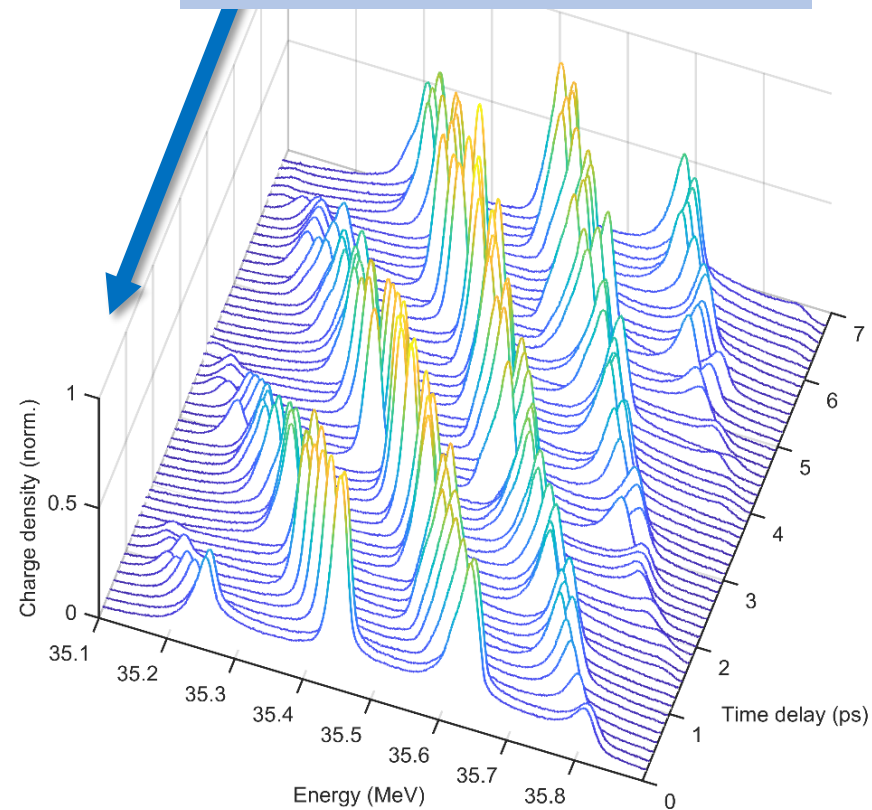
M. T. Hibberd *et al.*
Nature Photonics
14,755-759 (2020)



Varying THz field strength



Varying THz injection timing

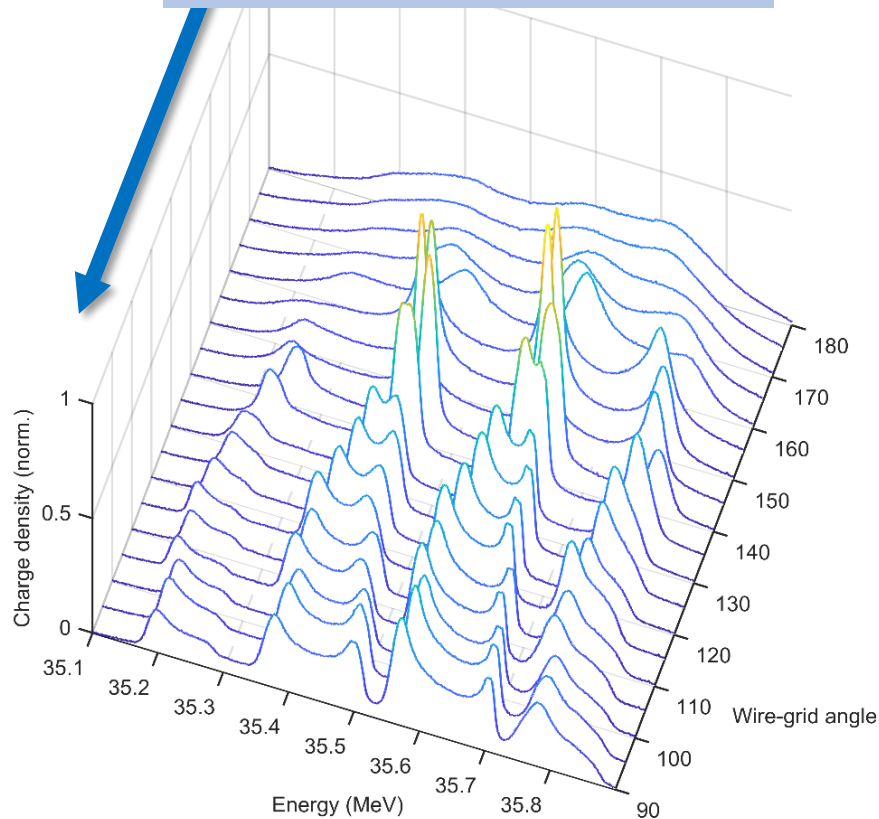


Terahertz-driven multi-cycle energy modulation

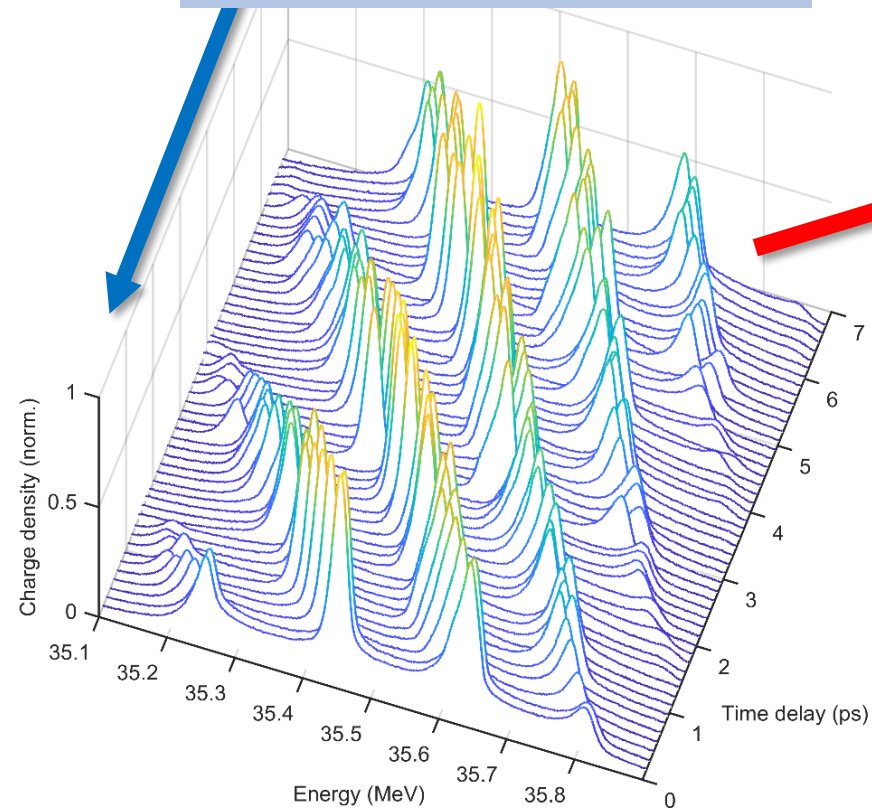
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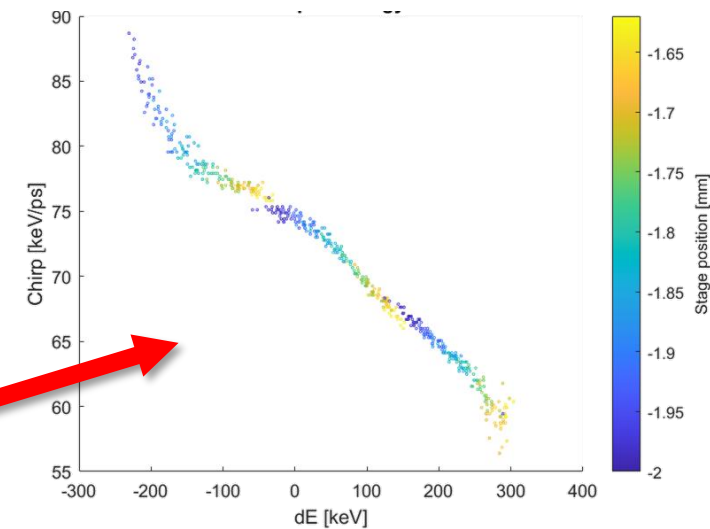
Varying THz field strength



Varying THz injection timing



Longitudinal phase space diagnostic

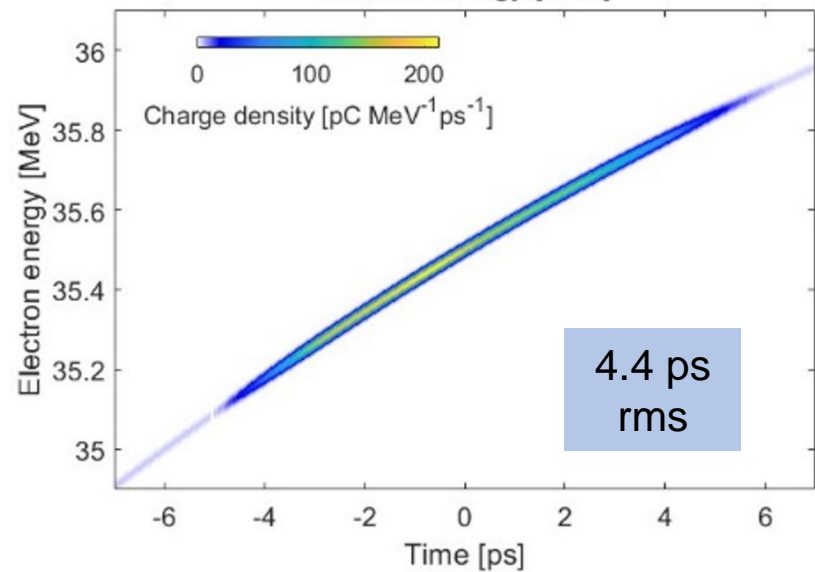
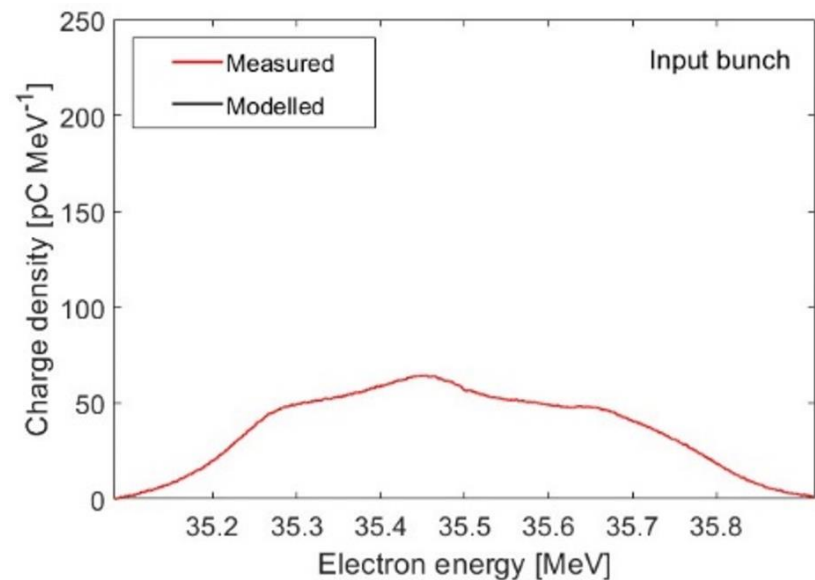


Now just need magnetic compression to convert into micro-bunches

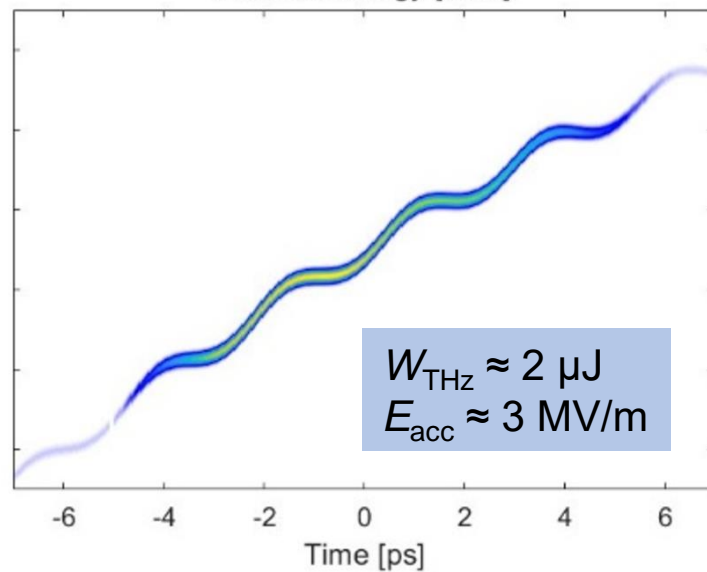
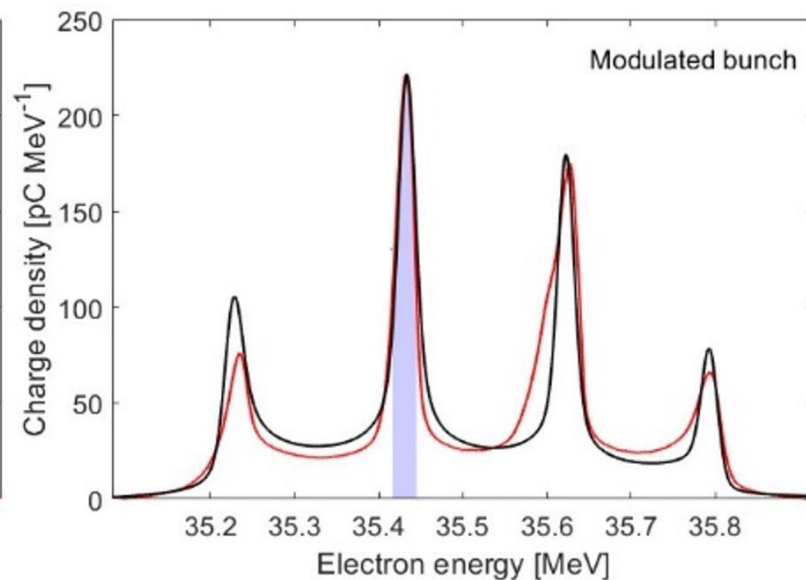
- Can model this using our experimental data for now

Terahertz-driven micro-bunching

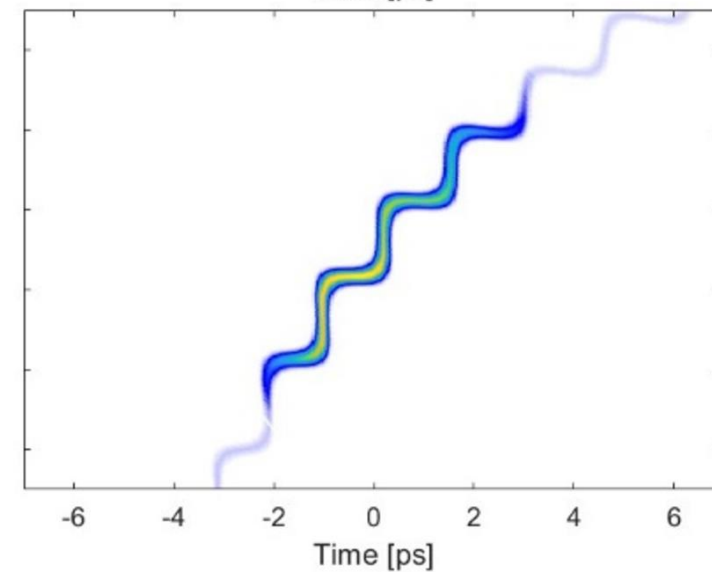
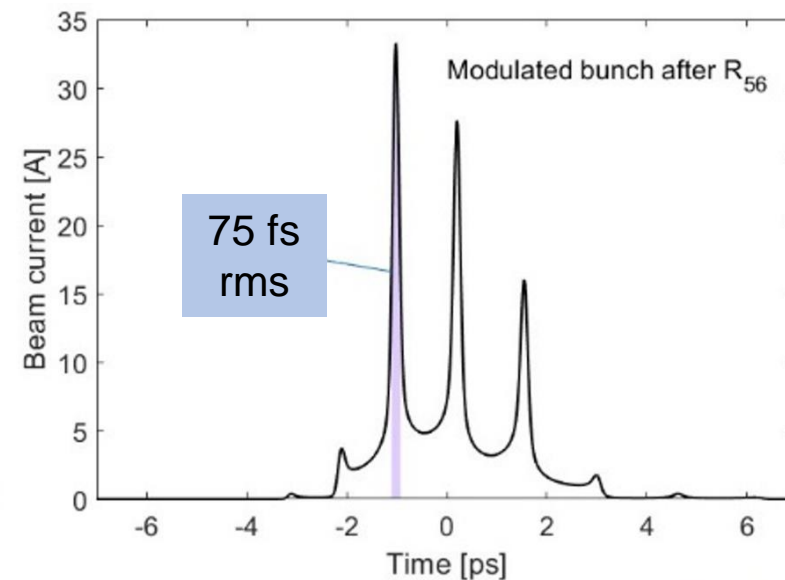
THz off



THz on (sharpest energy peaks)

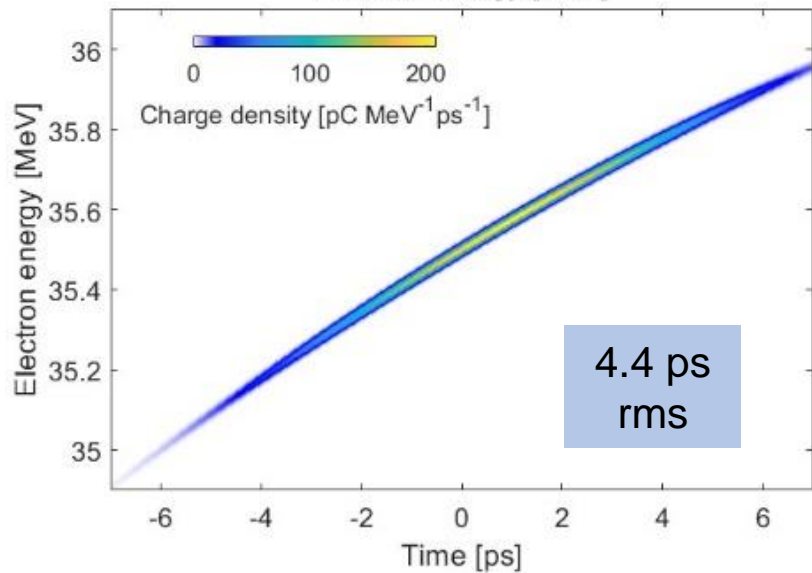
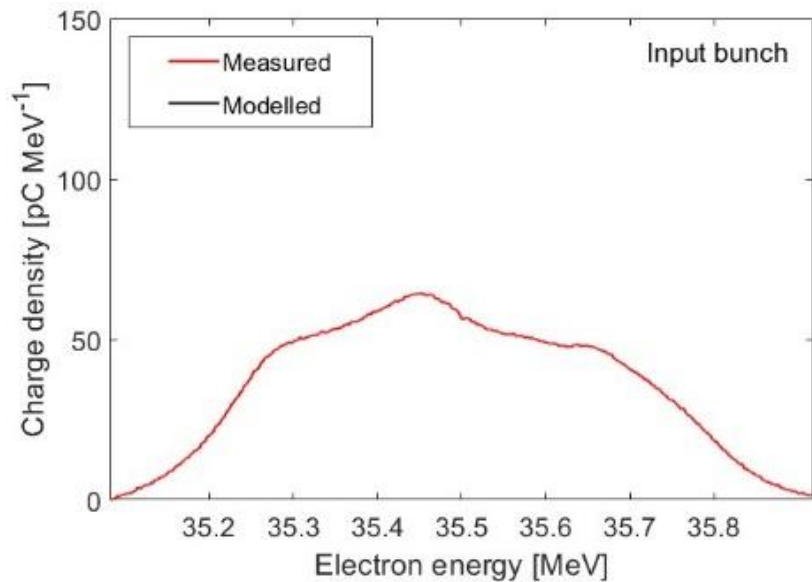


After R_{56} compression

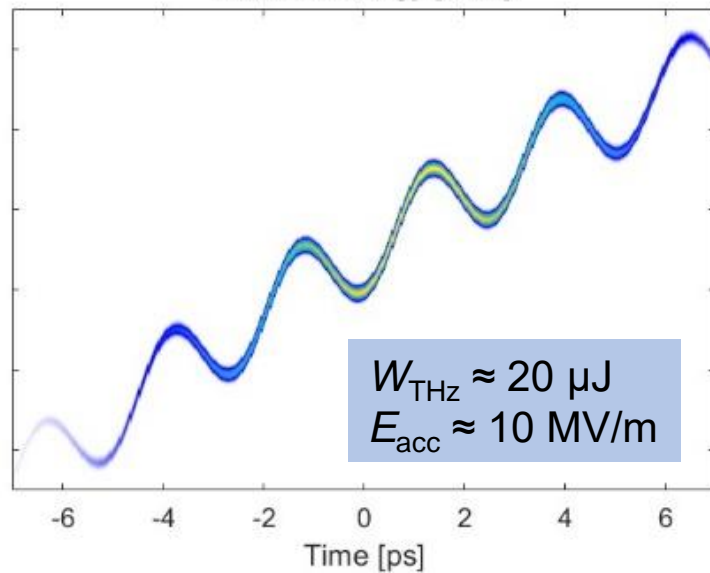
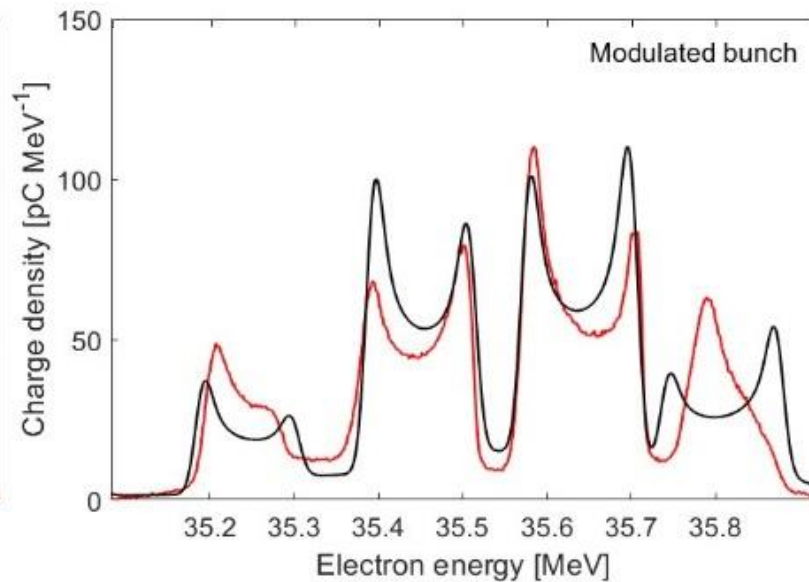


Terahertz-driven micro-bunching

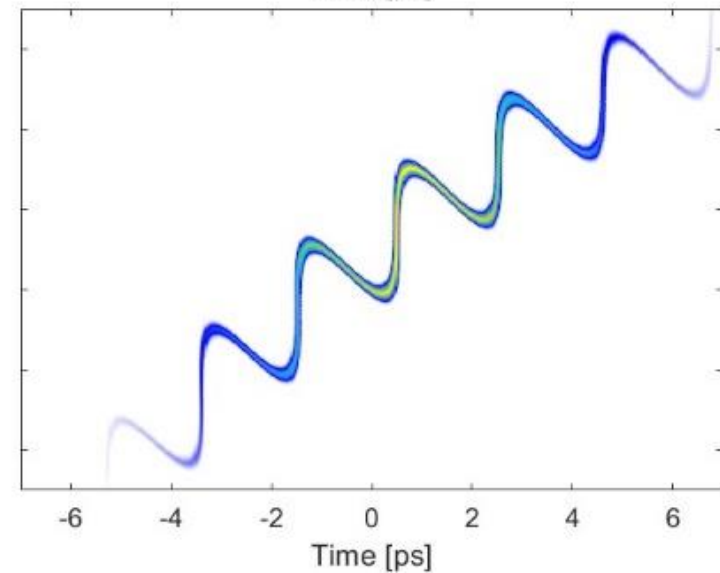
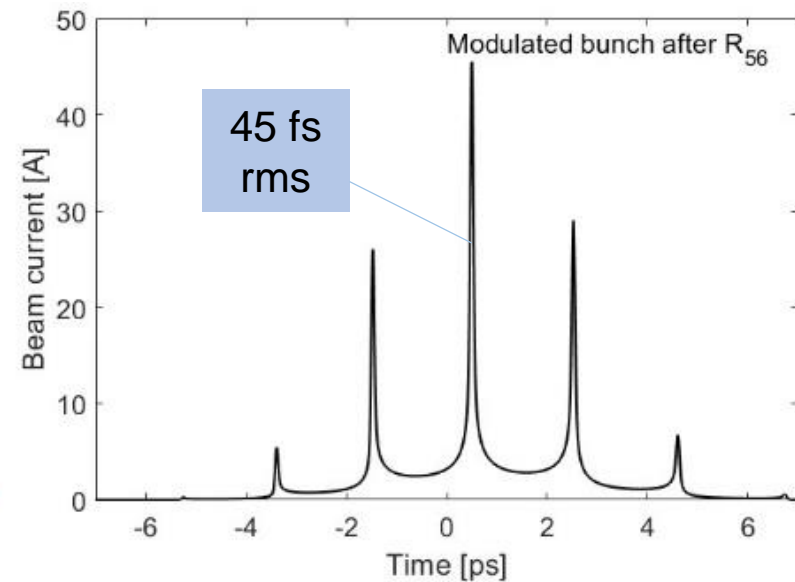
THz off



THz on (largest peak splitting)

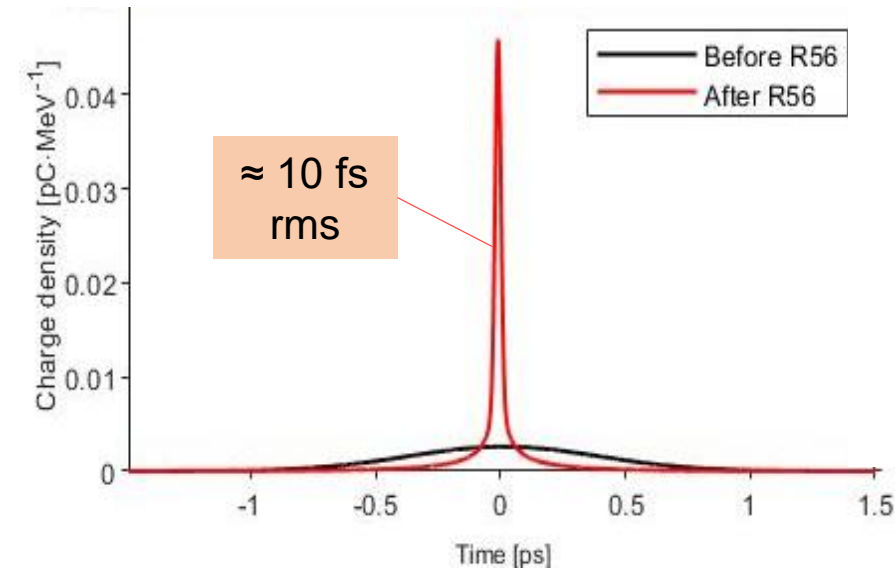


After R_{56} compression



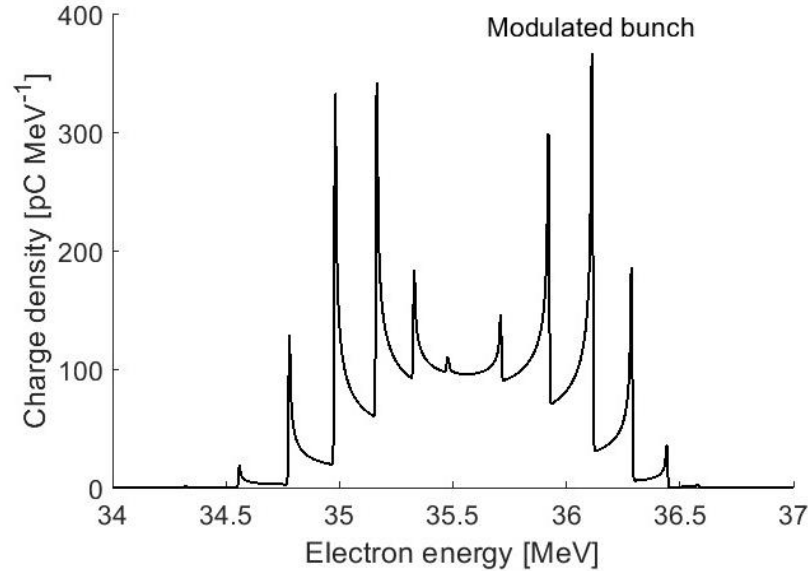
Terahertz-driven bunching

Single bunch compression



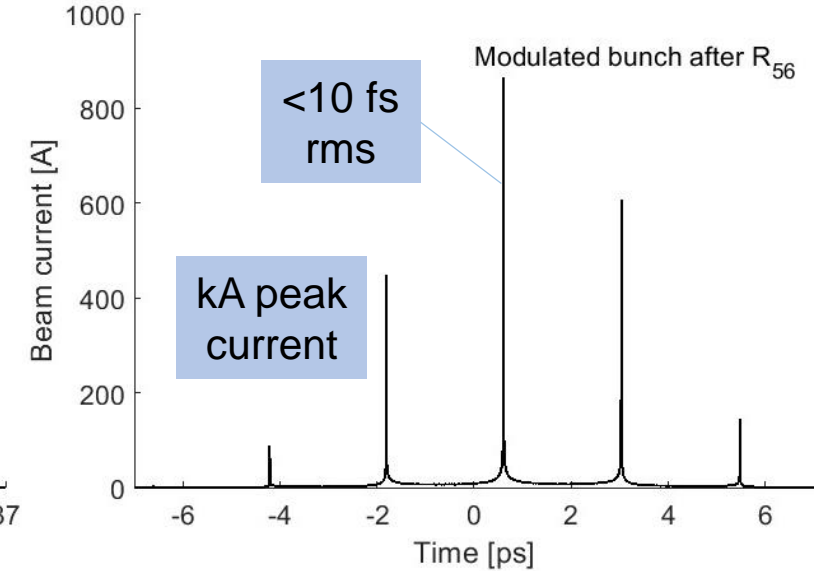
- From experimental measurements
- Shorter (< 1 ps) input bunch
- Injected into a single THz cycle

THz on



- 50 MV/m THz fields
- 4 keV uncorrelated energy spread

After R_{56} compression



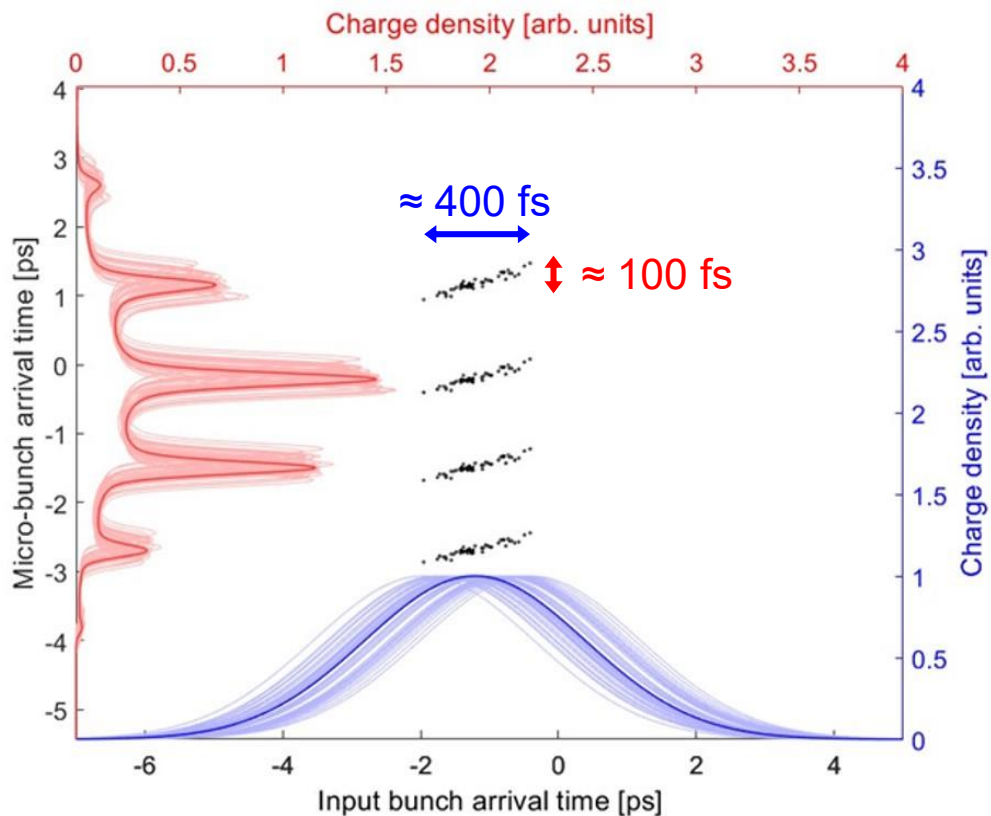
Duration, spacing and number of micro-bunches controlled by:

- THz source frequency
- THz field strength
- Electron bunch chirp
- Electron bunch length
- Magnitude of R_{56} compression

Terahertz-driven bunching – temporal locking

THz-induced energy and timing jitter reduction

- Energy jitter on the initial electron bunch
- THz-induced energy modulation observed to be more stable

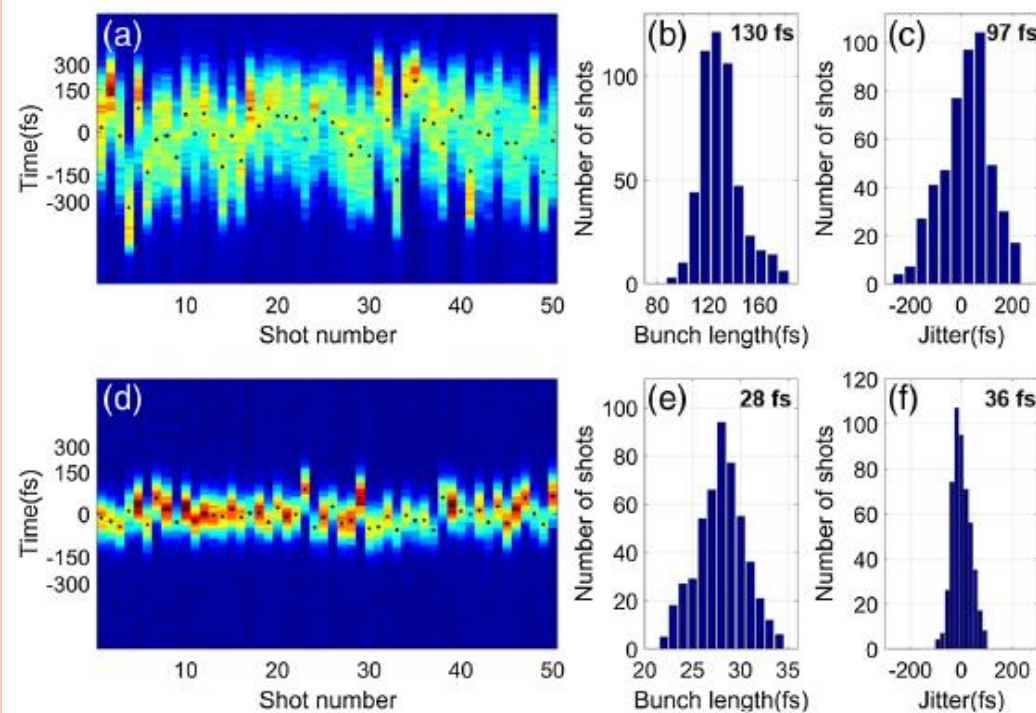


- Micro-bunches locked to the THz pulse (laser) timing
- Experimental data indicates 4x reduction in timing jitter

Energy spectrometer with THz on and off

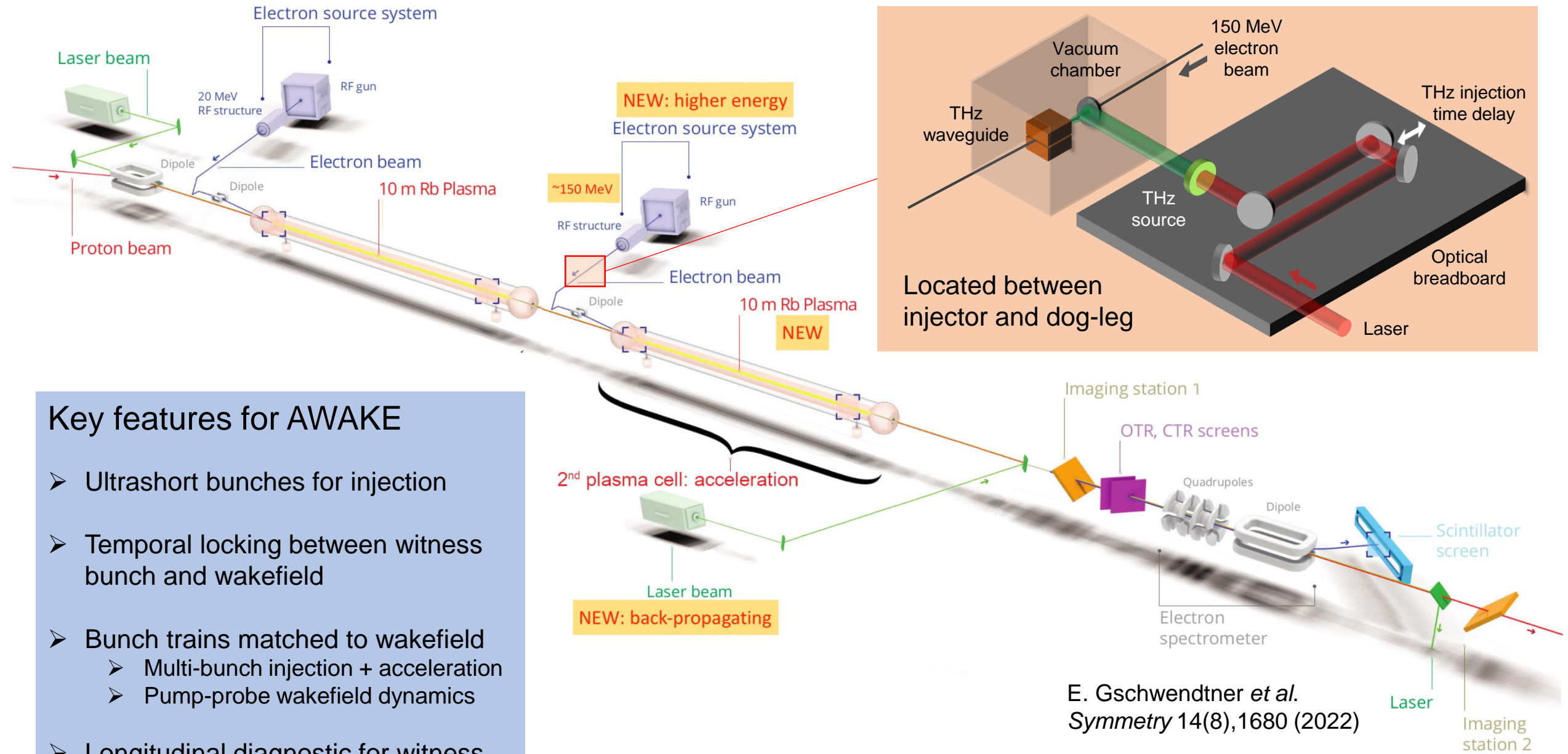


Shanghai group – compression and timing jitter reduction



L. Zhao *et al.* *Phys. Rev. Lett.* 124,054802 (2020)

Opportunities at AWAKE



Key features for AWAKE

- Ultrashort bunches for injection
- Temporal locking between witness bunch and wakefield
- Bunch trains matched to wakefield
 - Multi-bunch injection + acceleration
 - Pump-probe wakefield dynamics
- Longitudinal diagnostic for witness

E. Gschwendtner *et al.*
Symmetry 14(8),1680 (2022)

THz-driven electron bunch manipulation

Ultrashort bunches with phase-locked timing jitter

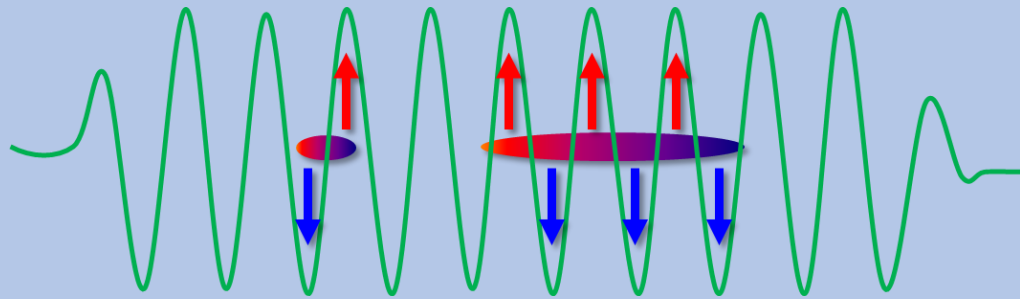
- **Optimised injection**

Bunch trains at THz repetition rates

- **Multi-bunch injection**
- **Pump-probe wakefield dynamics**

Energy-modulation for longitudinal bunch diagnostics

- **Measure bunch length and chirp**



Further advanced accelerator applications

- **Wakefield drivers**
- **Free-electron lasers**
- **Ultrafast electron diffraction**

Acknowledgements

➤ **Terahertz Acceleration Group**

Steven Jamison

Darren Graham

Graeme Burt

Rob Appleby

Connor Mosley

Daniel Lake

Sergey Siaber

Laurence Nix

Christopher Shaw

Joseph Bradbury

Beatriz Higuera-Gonzalez

➤ **STFC staff**

Thomas Pacey

James Jones

David Walsh

+ CLARA

operators

Job advert!

- **2x PDRA positions** in the Terahertz Acceleration Group
- Links can be found at: www.THzAG.uk
- Deadlines 10th and 14th July

Thank you for listening!
Any questions?