Institute of Physics
Particle Accelerators and Beams Annual Conference
Liverpool, 25th-26th July 2022

Terahertz-driven acceleration and manipulation of relativistic electron beams

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The Cockcroft Institute & The University of Manchester

Representing the Terahertz Acceleration Group

The Cockcroft Institute
of Accelerator Science and Technology

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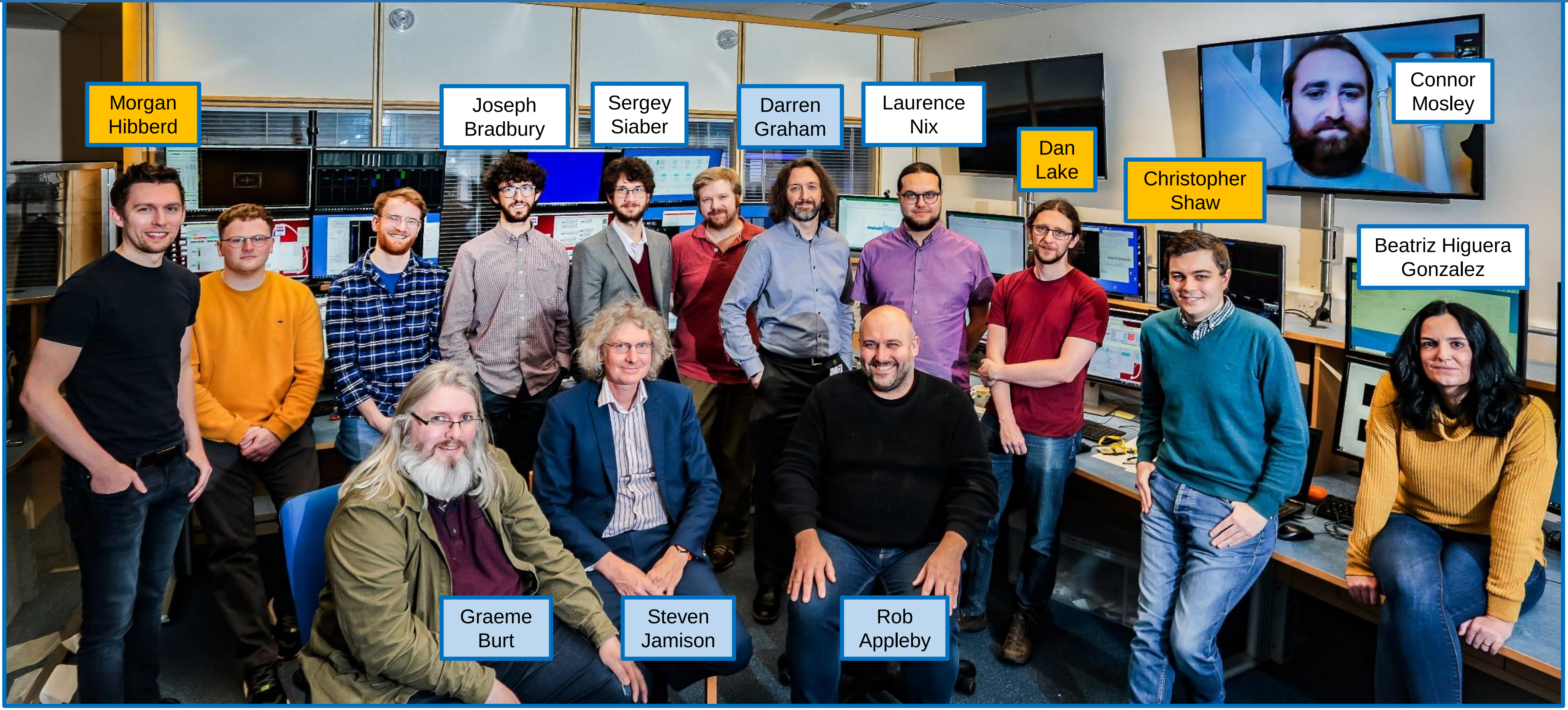
Terahertz acceleration group @ The Cockcroft Institute



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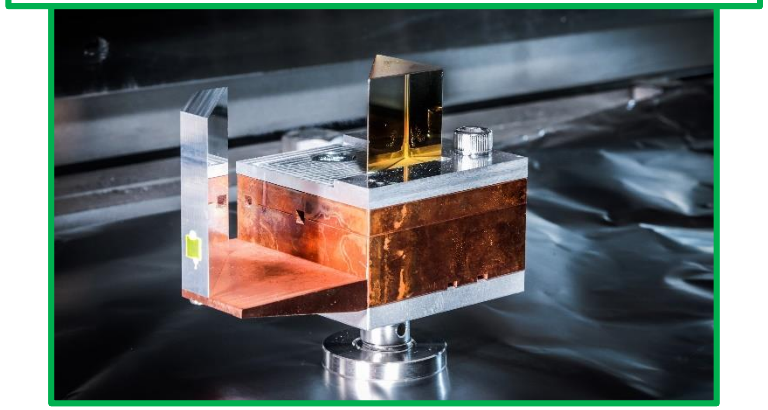
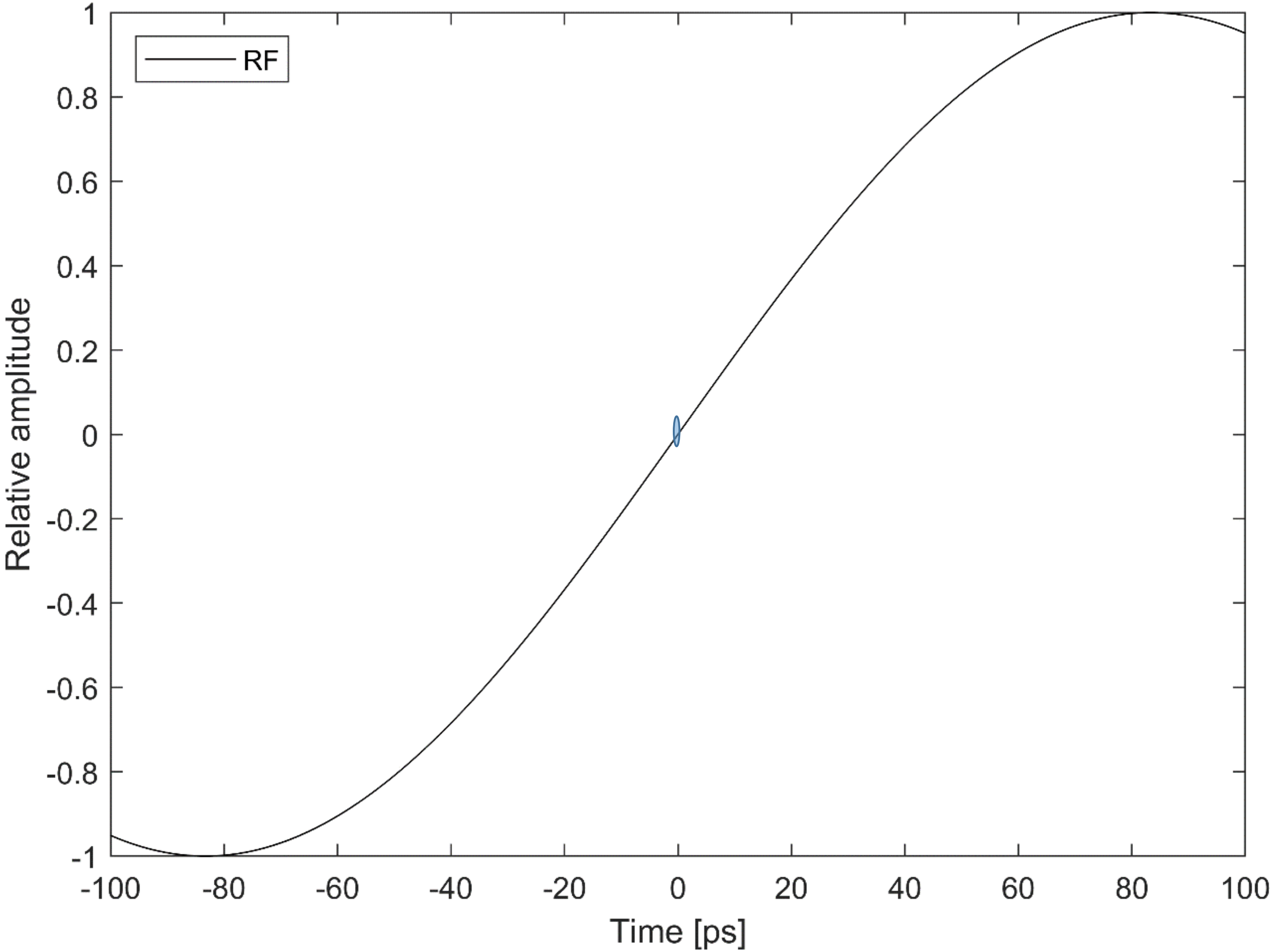
Why use terahertz radiation for particle acceleration and manipulation?

Advantages of THz accelerators

- High field strengths possible (100 MV/m to >GV/m)
- Wavelength allows easy fabrication of structures
- Oscillation period well-matched to typical bunch duration





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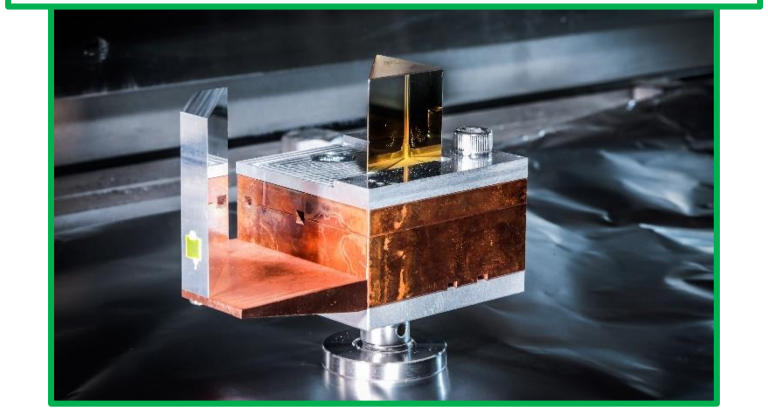

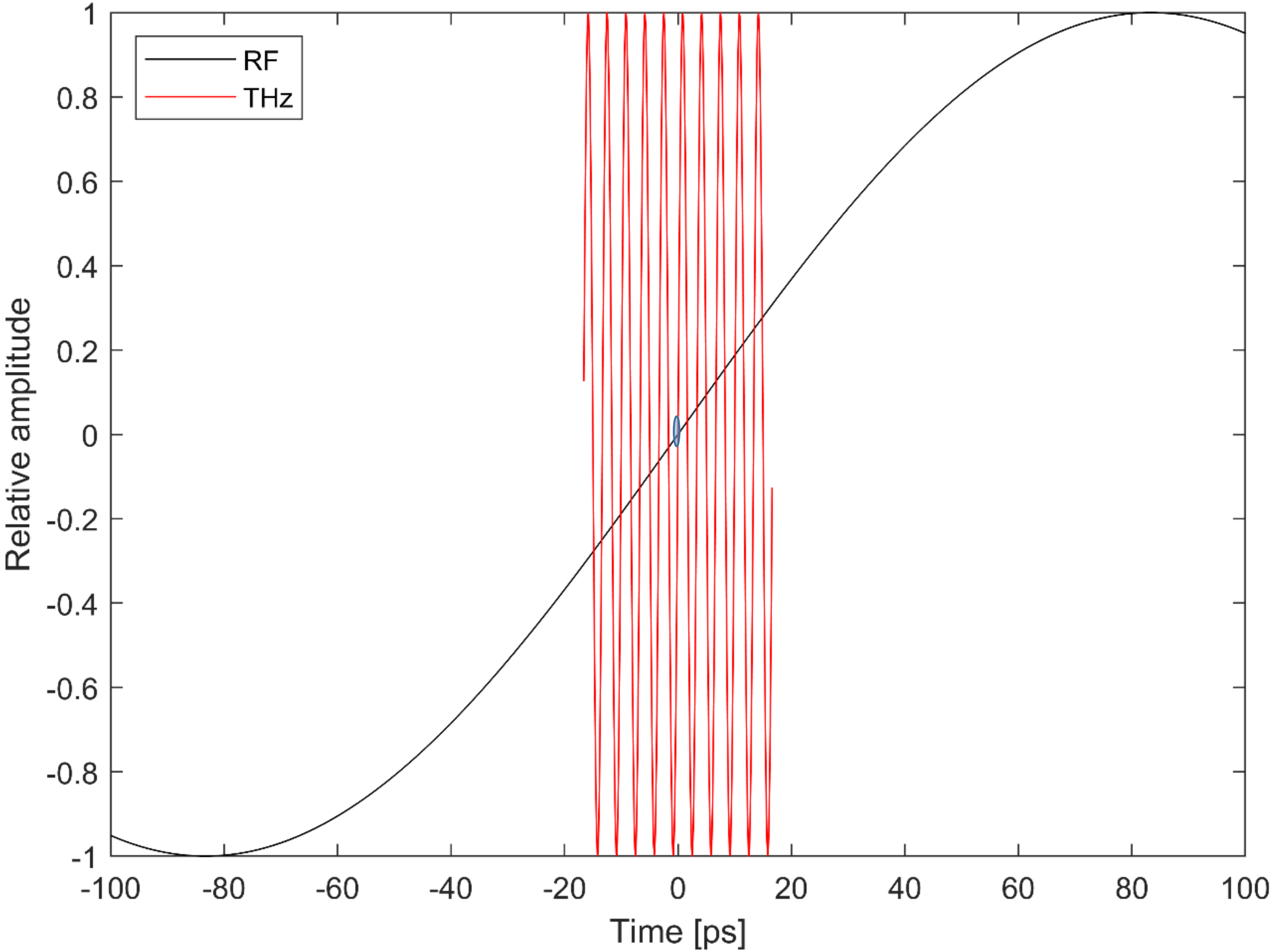

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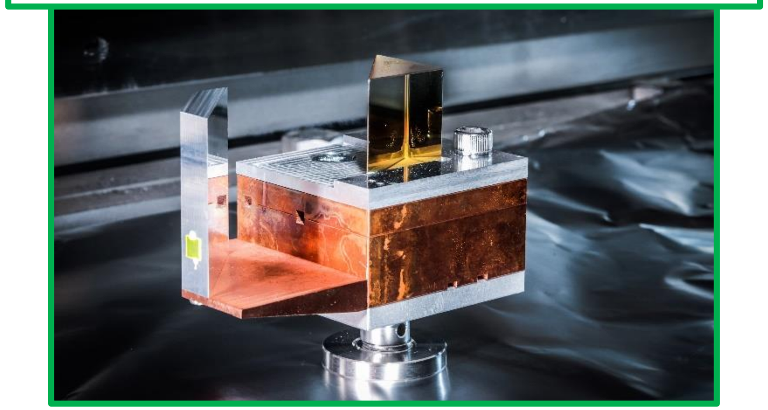

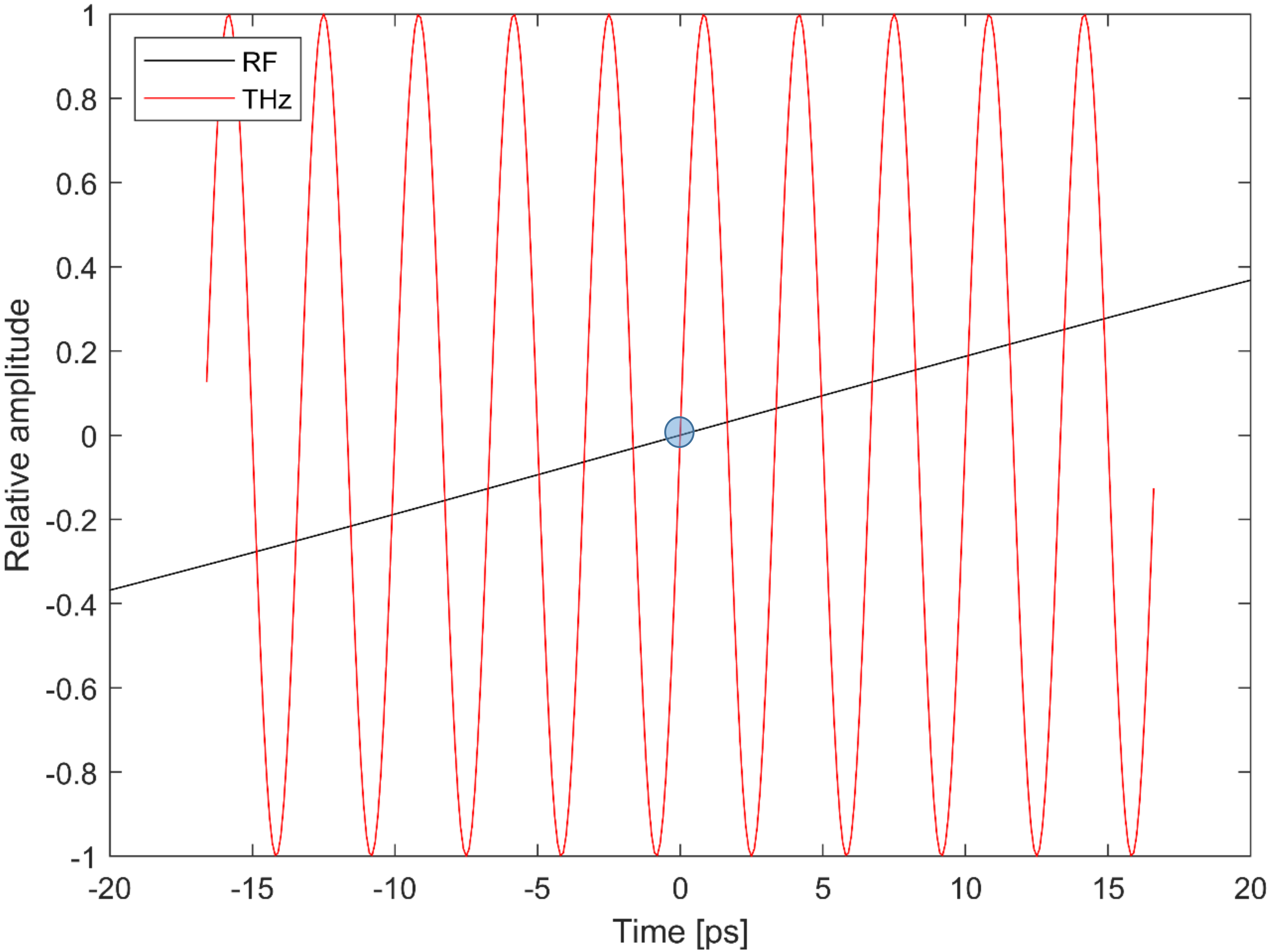

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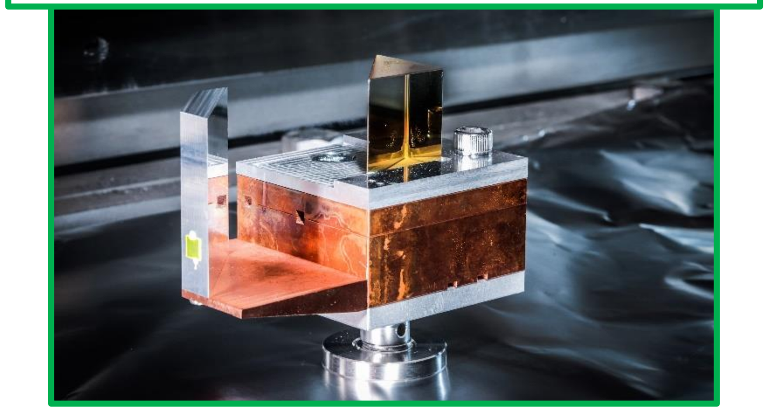
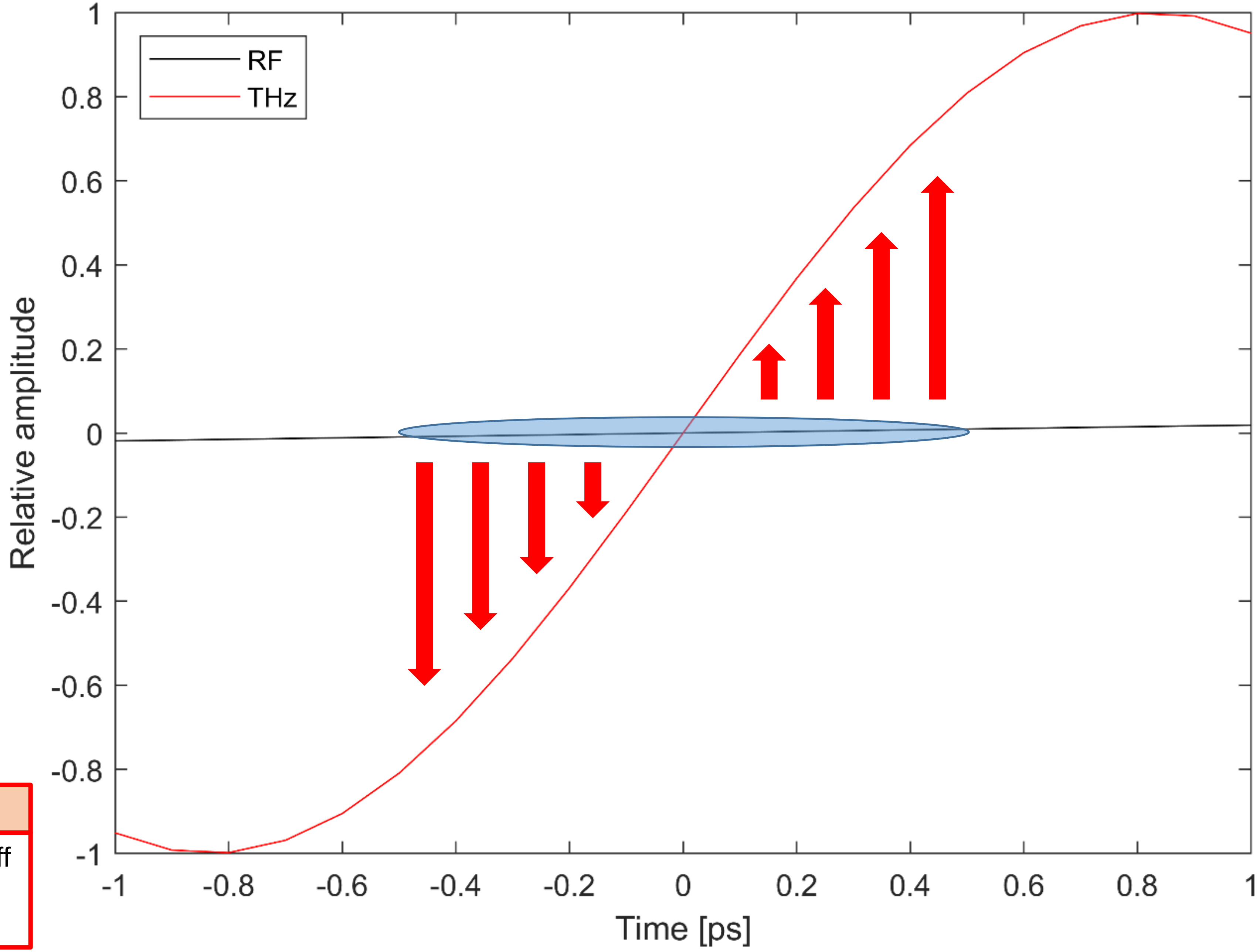


Short enough for fs-scale control
→ Ultrafast bunch manipulation

Long enough for significant charge capture → 10-100 pC bunch charge

Challenges for THz accelerators

- Phase-velocity matching and group walk-off
- Broadband pulse dispersion
- High-field narrowband sources

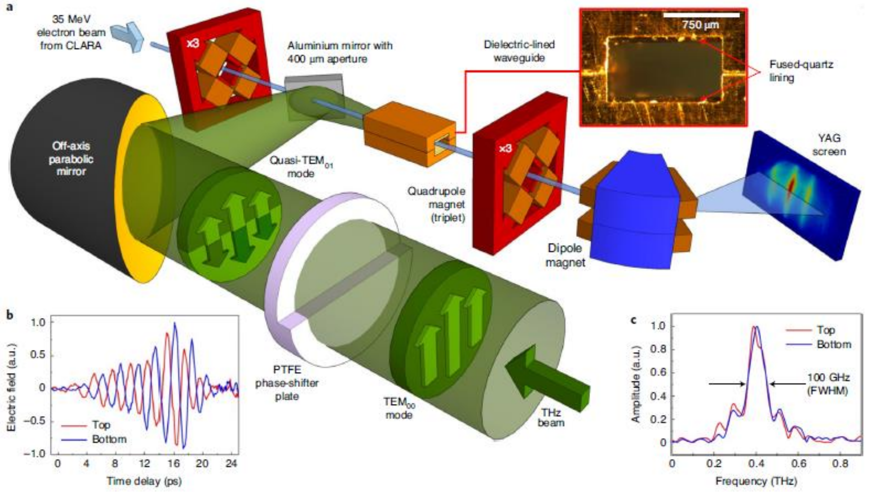


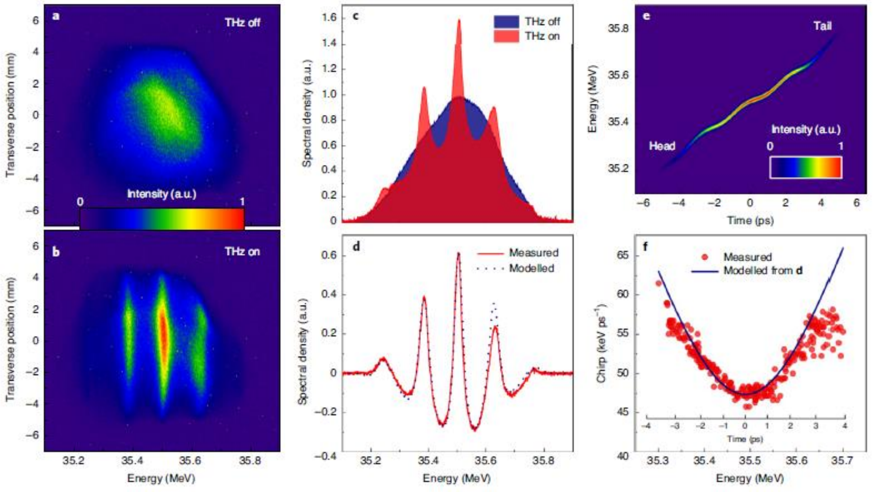
Terahertz-driven interactions: Relativistic electron beams

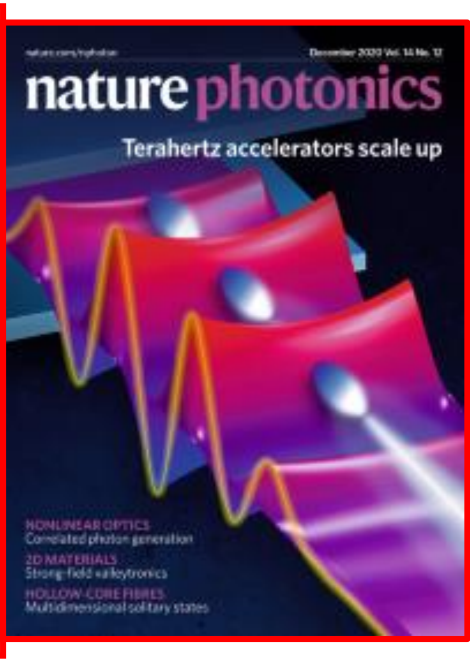
M.T. Hibberd *et al. Nat. Photon.* **14,** 755-759 (2020)

First THz-driven linear acceleration of a relativistic electron beam

Narrowband THz pulse in dielectric-lined waveguide
10 keV peak energy gain

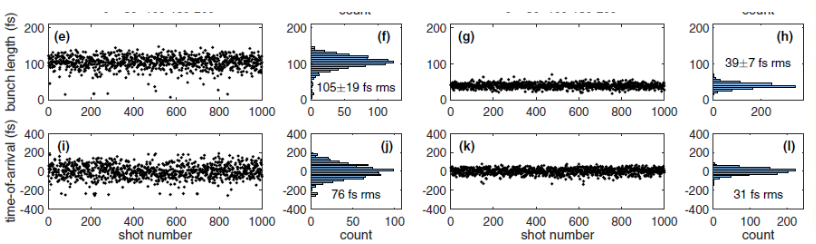


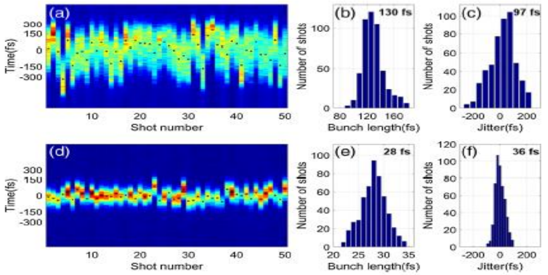




Our group's front-cover publication in Nature Photonics

E. C. Snively *et al. Phys. Rev. Lett*. **124,** 054801 (2020)





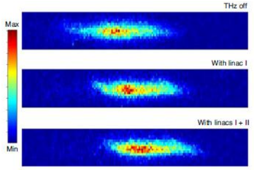
THz-driven compression (3-5x) and jitter-reduction (2-3x) of 3 MeV electron beams

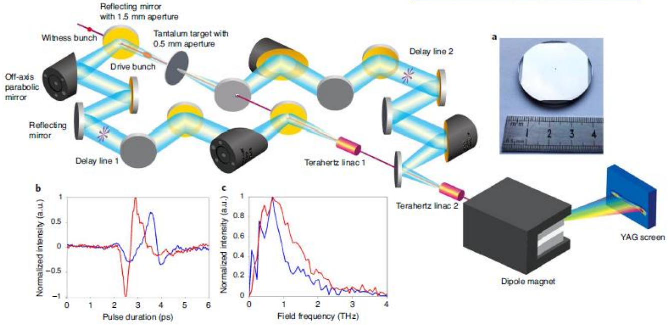
L. Zhao *et al. Phys. Rev. Lett*. **124,** 054802 (2020)

H. Xu *et al. Nat. Photon.* **15,** 426-430 (2021)

Cascaded acceleration using CTR-generated THz pulses

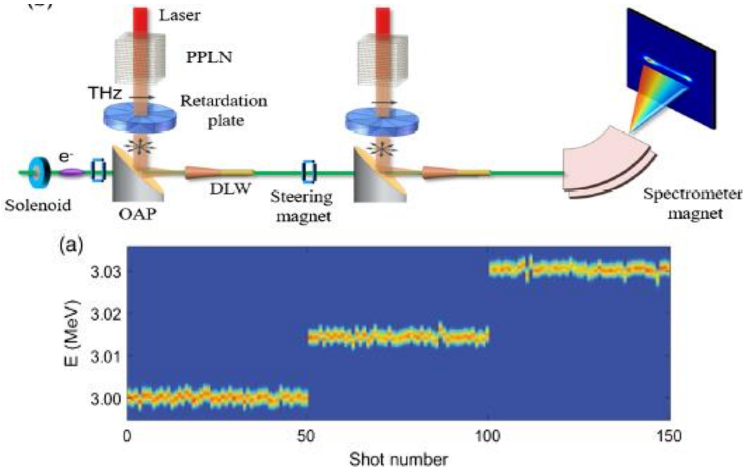
Whole-bunch acceleration
85 MV/m gradient
204 keV energy gain



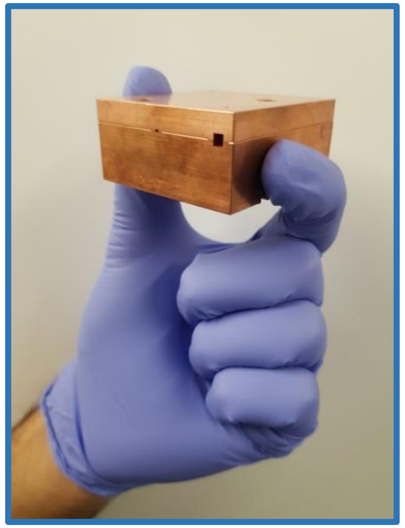


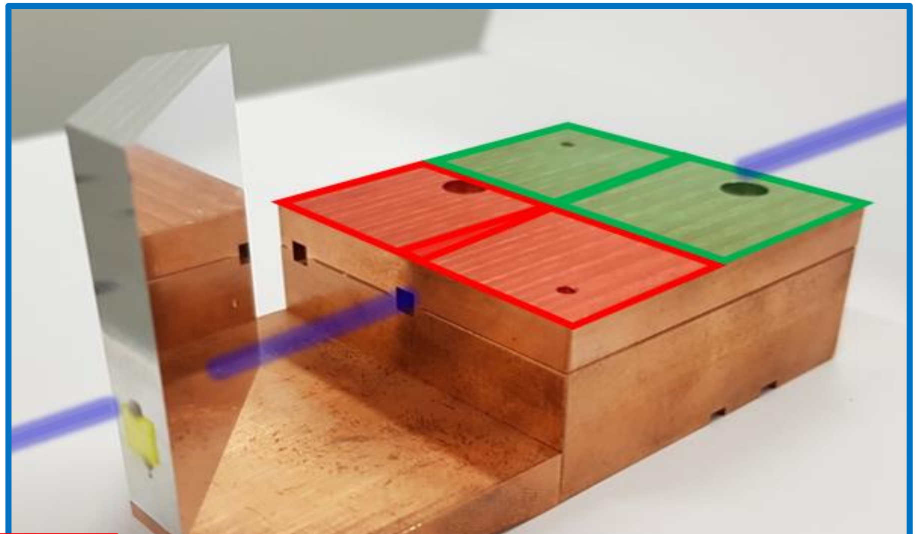
H. Tang *et al. Phys. Rev. Lett.* **127,** 074801 (2021)

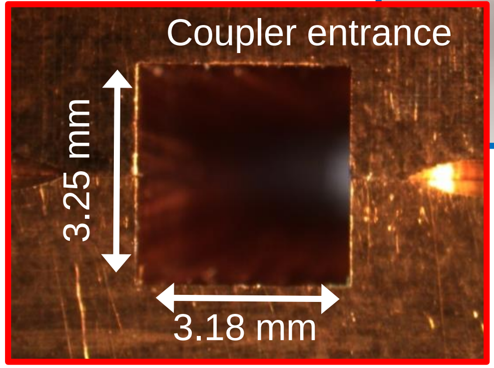
Cascaded acceleration
Unchanged energy spread
30 keV total energy gain

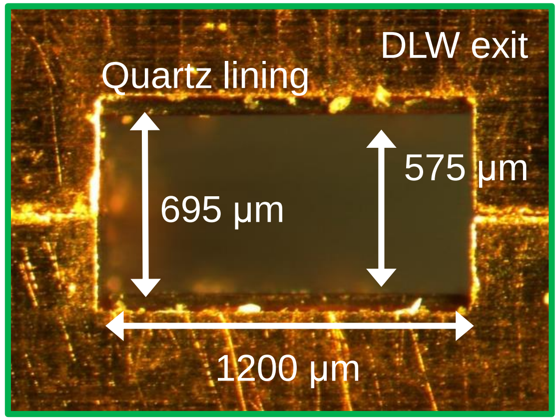


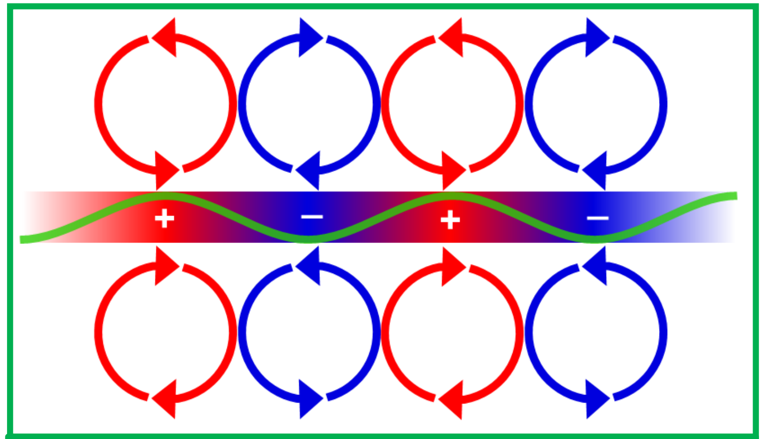
Terahertz dielectric-lined waveguide









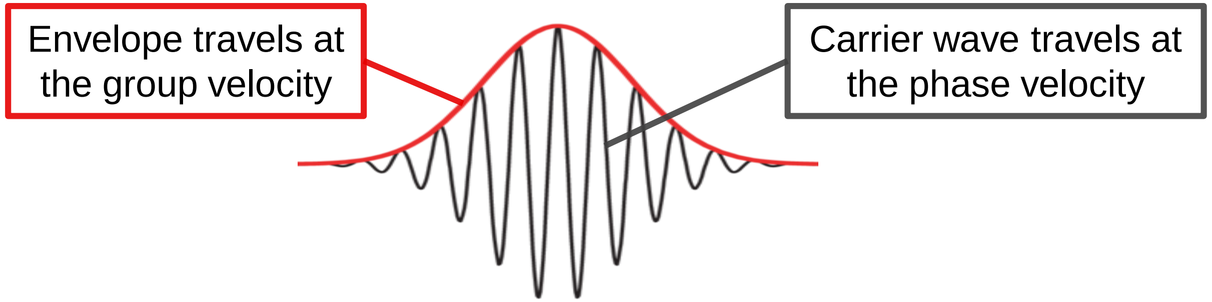


Dielectric lining

→ **L**ongitudinal **S**ection **M**agnetic modes

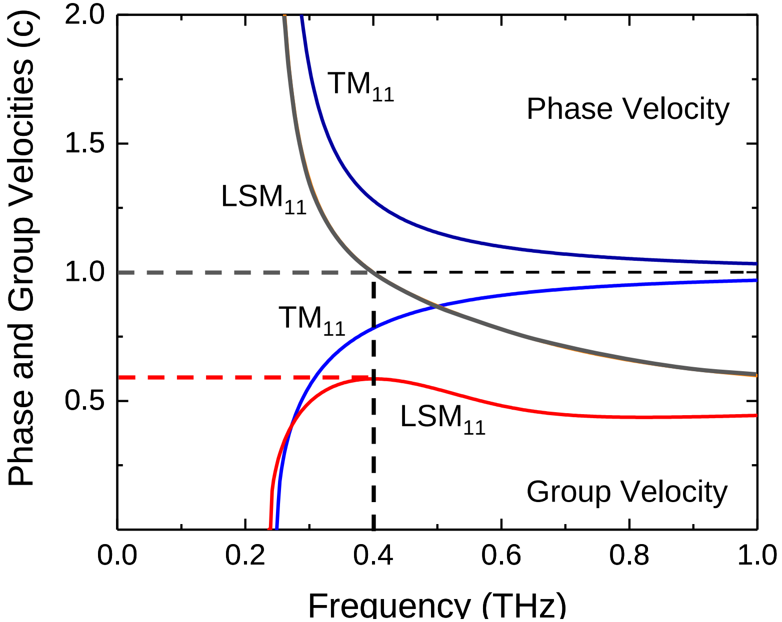
→ LSM_{11} for acceleration

→ Velocity-matching to 35 MeV electrons



Envelope travels at the group velocity

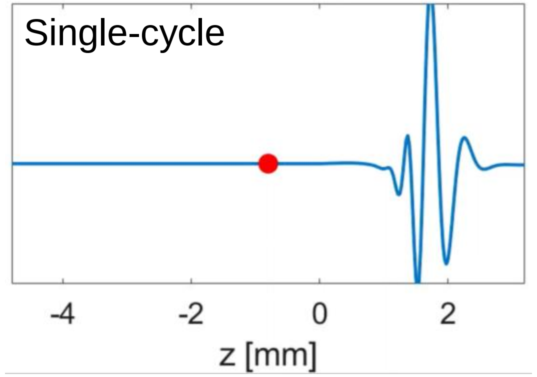
Carrier wave travels at the phase velocity

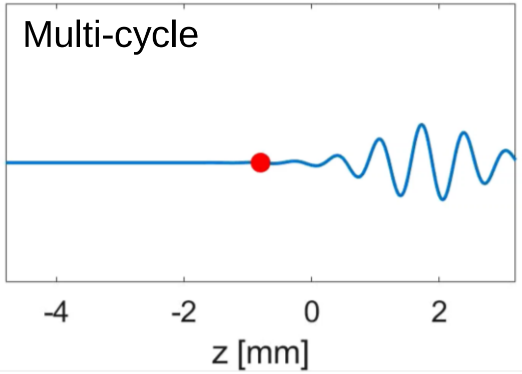


at 0.4 THz

$v_p = 0.9999c = v_e$

$v_g = 0.585c$



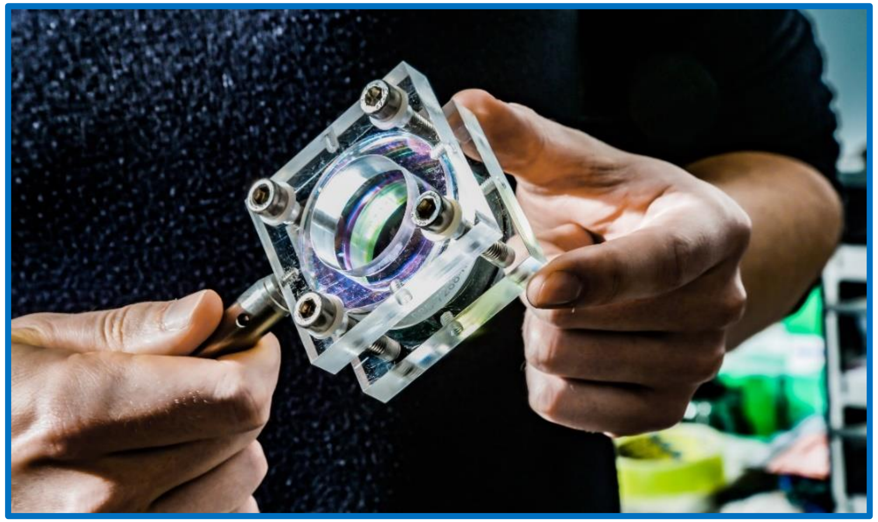


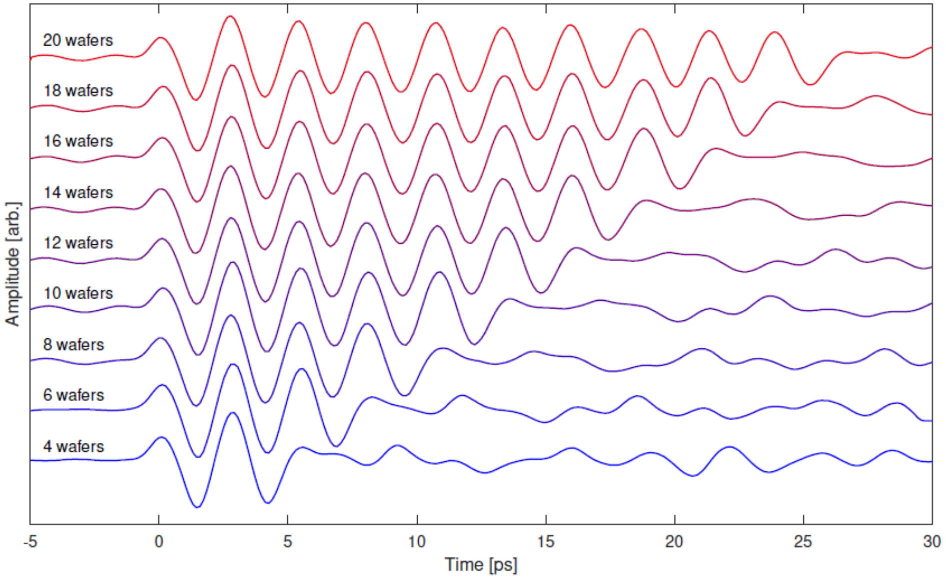
Narrowband terahertz source development

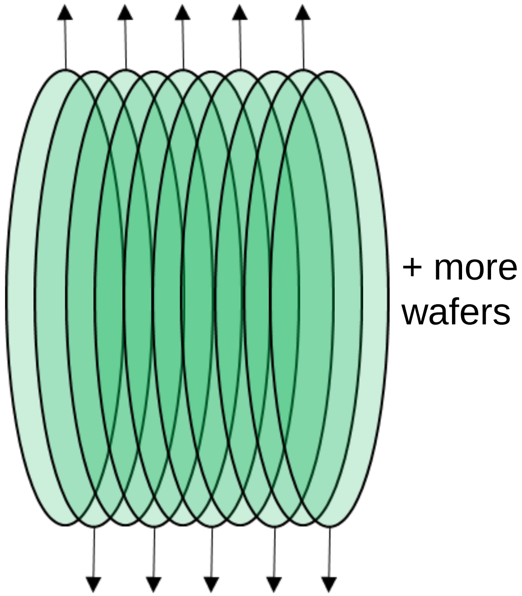
Periodically-poled lithium niobate wafer-stacks

→ Custom-built large-area narrowband THz sources

→ Developed on the concept by:
F. Lemery *et al. Commun. Phys.* 3, 150 (2020)

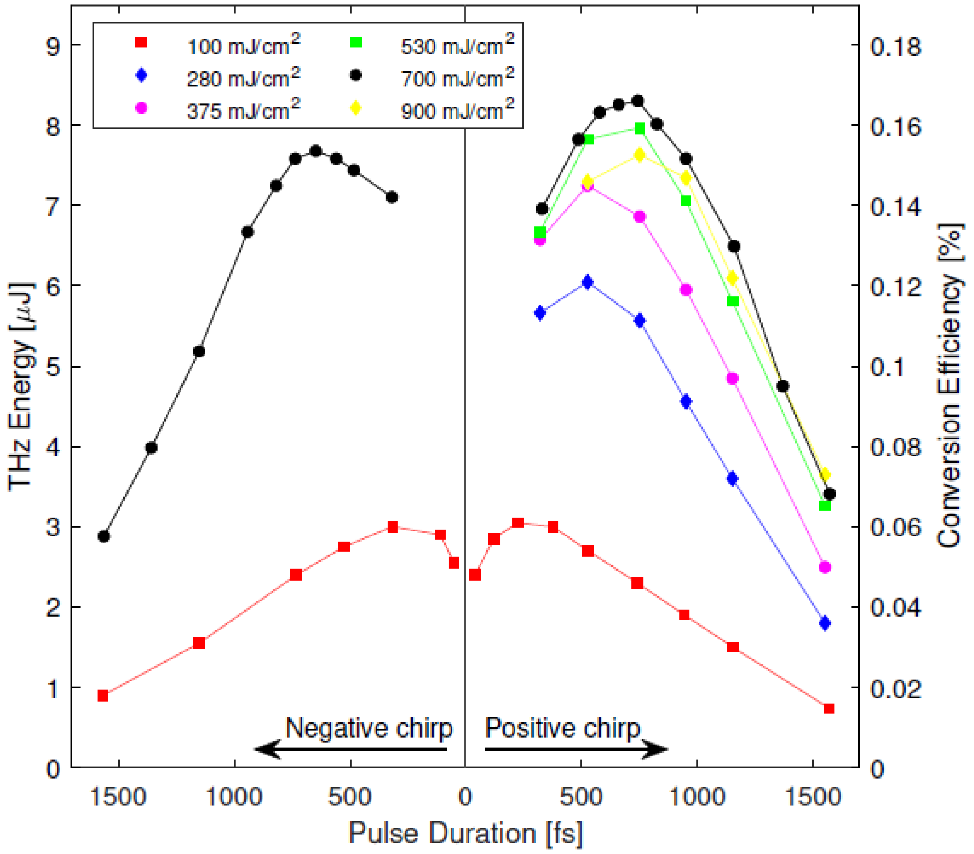






- Large-area wafers are commonly manufactured
- Inexpensive compared to bulk PPLN crystals
- Customisable frequency, bandwidth, pulse-shaping
- High-energy narrowband source up to mJ-level

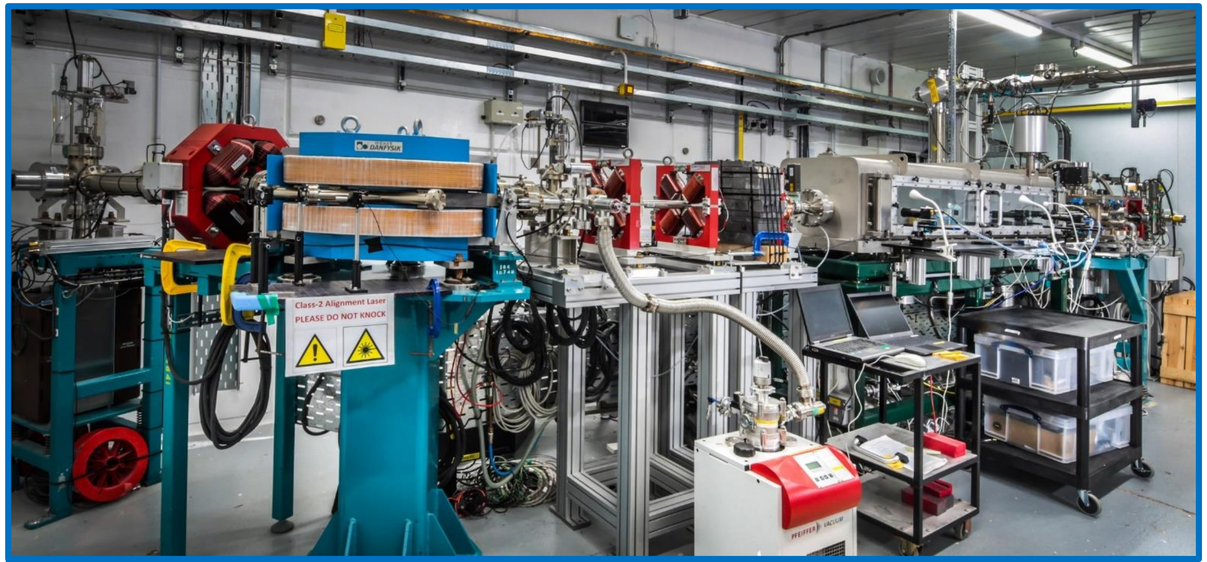
Source optimisation in lab with 5 mJ laser



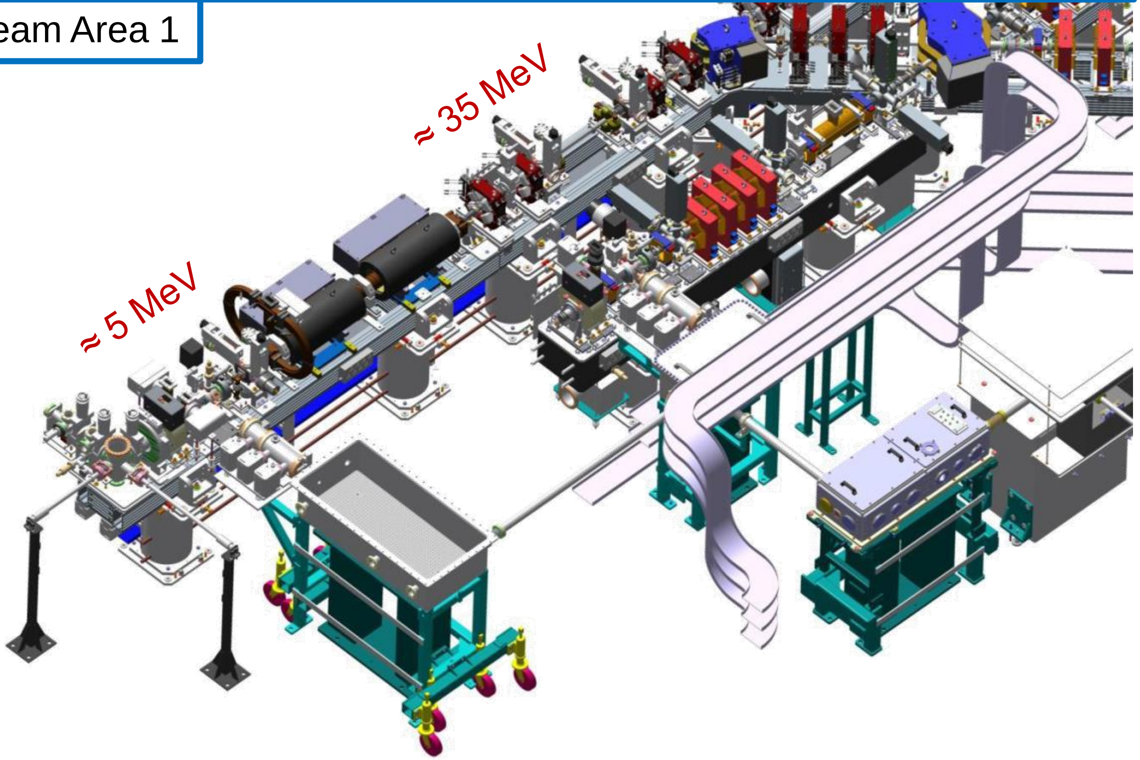
Source developed for CLARA Run 2

- High-power TW laser system
- Up to 1000x more THz pulse energy compared to previous run

CLARA test facility @ Daresbury Laboratory



Beam Area 1



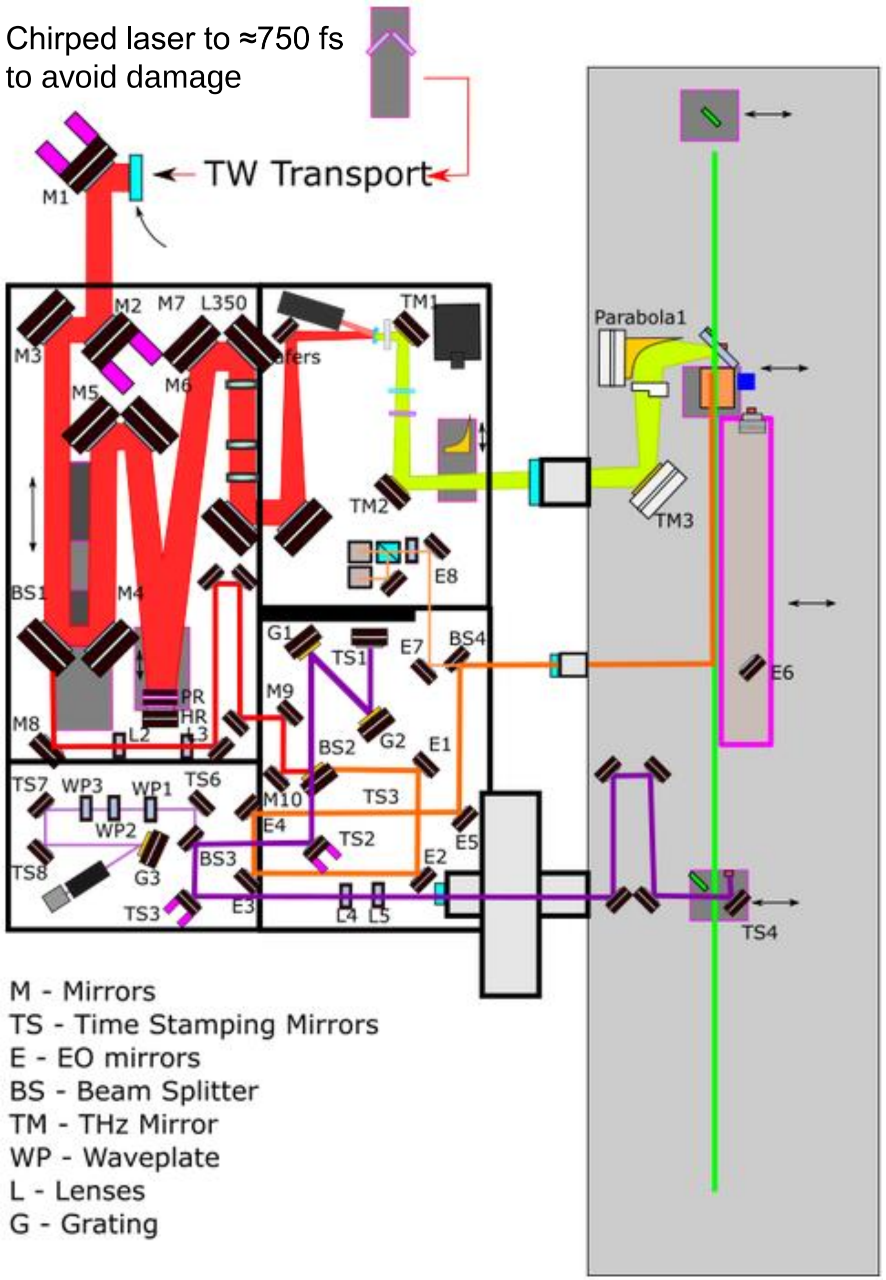
Compact
Linear
Accelerator for
Research and
Applications

<u>Bunch parameters</u>

Energy:	35 MeV
Charge:	2 – 100 pC
Duration:	0.2 – 6 ps
Spot size:	100 µm
Rep. rate:	10 Hz

Experimental setup in Beam Area 1

Chirped laser to ≈750 fs to avoid damage

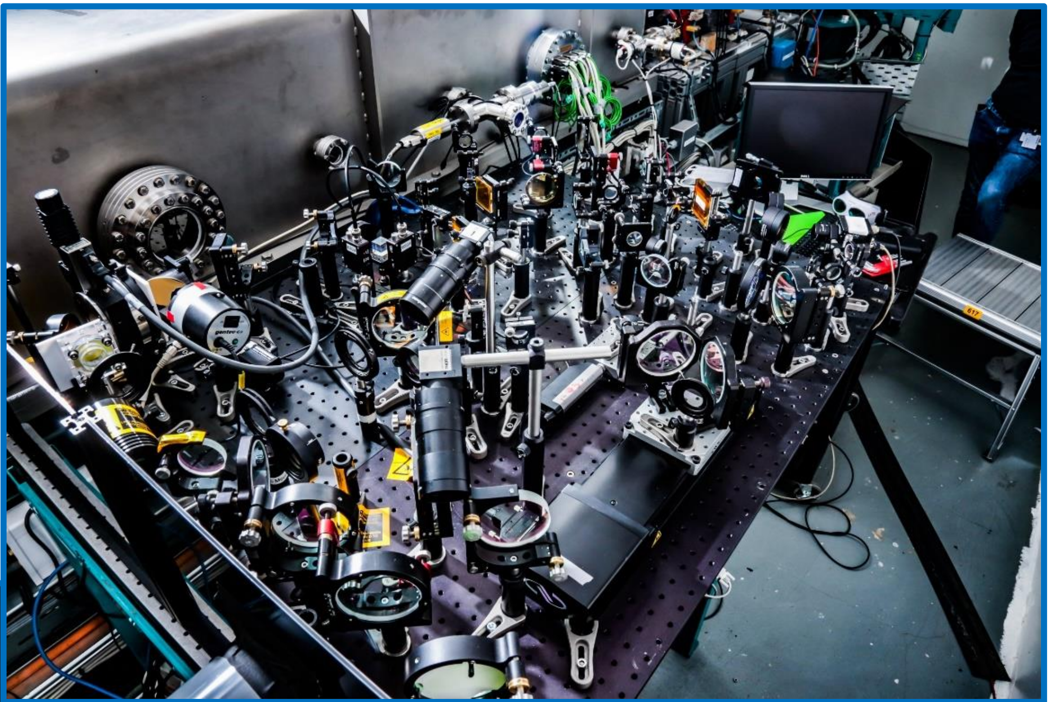


M - Mirrors
TS - Time Stamping Mirrors
E - EO mirrors
BS - Beam Splitter
TM - THz Mirror
WP - Waveplate
L - Lenses
G - Grating

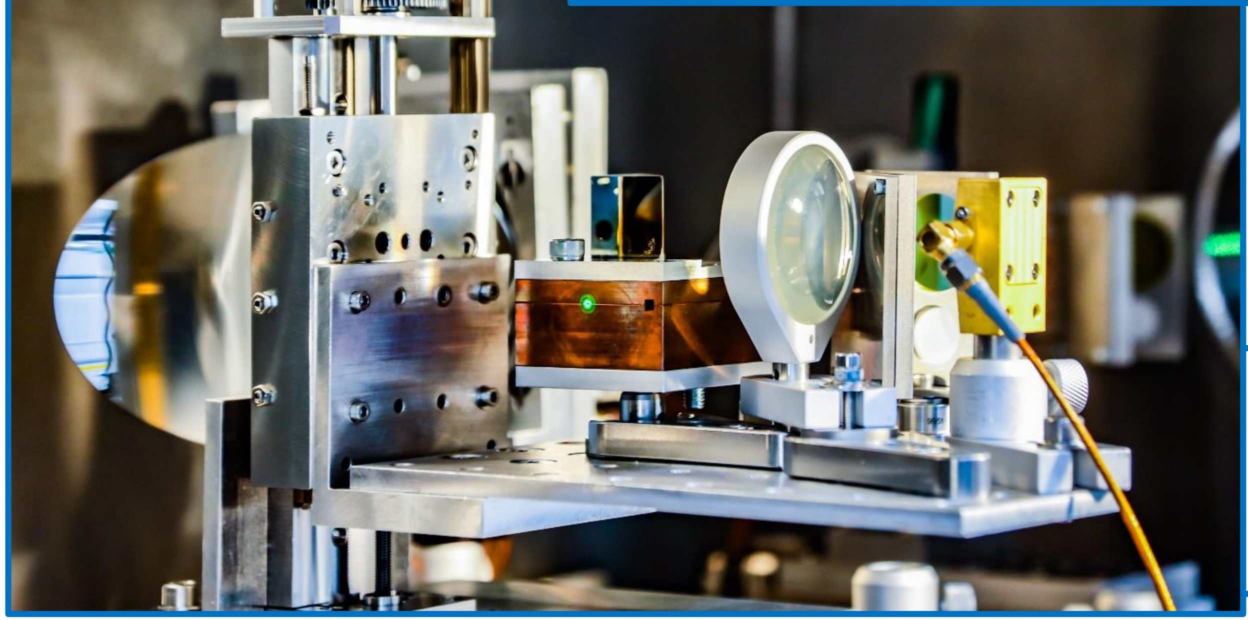
<u>Terawatt laser</u>

Pulse energy: 800 mJ
(max 300 mJ to BA1)

Pulse length: 50 fs
Wavelength: 800 nm
Repetition rate: 10 Hz



Laser and THz optics outside chamber



THz-electron interaction point inside vacuum chamber

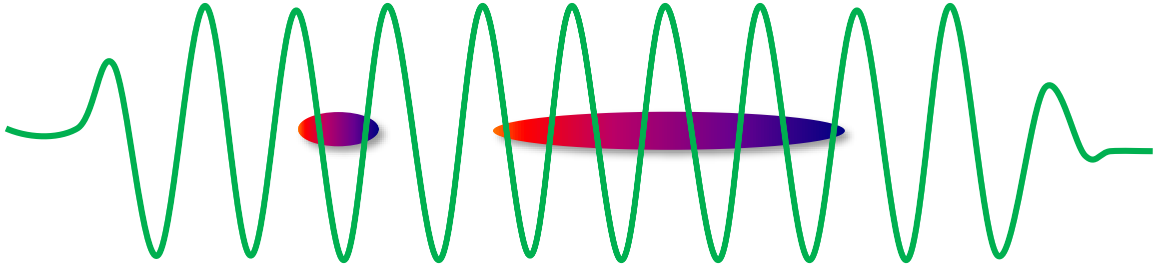
CLARA Run 2 results

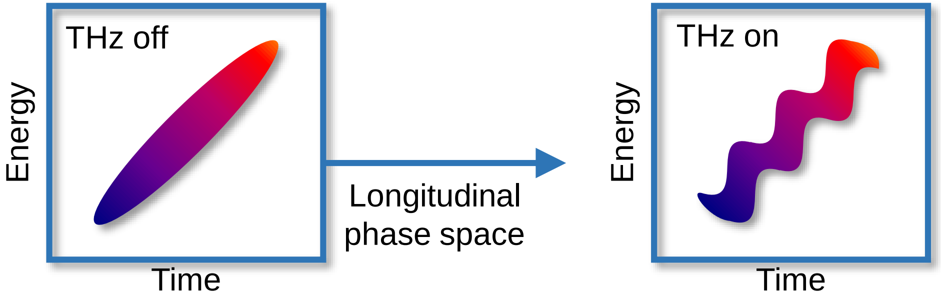
Experimental parameters

CLARA machine operated with different bunch configurations
→ Bunch lengths from 200 fs up to 6 ps (FWHM)
→ With varying chirp and energy spread
→ Bunch charge from 2 – 100 pC

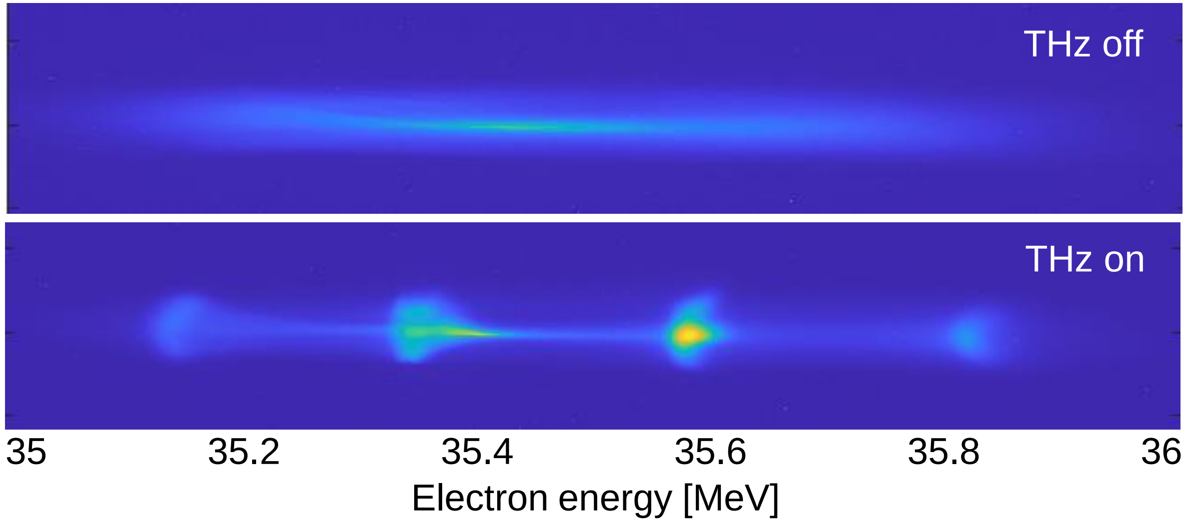
THz source controlled for desired bunch manipulation
→ Pulse energy from 100 nJ to >100 μJ
→ Injection timing
→ Number of cycles (i.e. bandwidth)

THz pulse (*f* = 0.39 THz, *T* = 2.6 ps, 10 cycles)





Electron spectrometer images



Demonstrations of THz-driven bunch manipulation

On-crest acceleration of sub-ps bunches
→ Bunch with single (half) cycle and near-uniformly accelerated

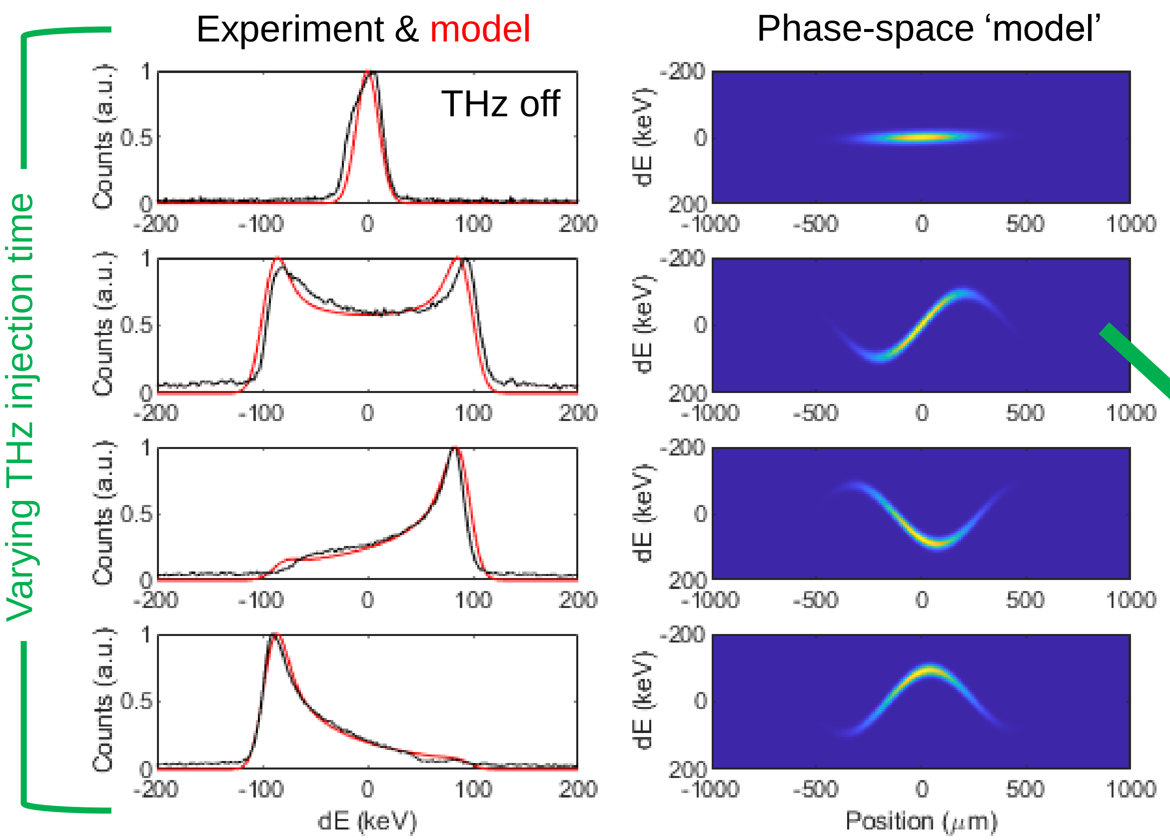
Off-crest de-chirping
→ Control and minimise bunch energy spread

Multi-cycle spectral bunching
→ Pre-cursor to bunch train generation

Staging using a double-pulse structure
→ Two-stage acceleration or Two-stage acceleration and de-chirp

CLARA Run 2 results

High gradients on short(ish) bunches



Experiment & model

Phase-space 'model'

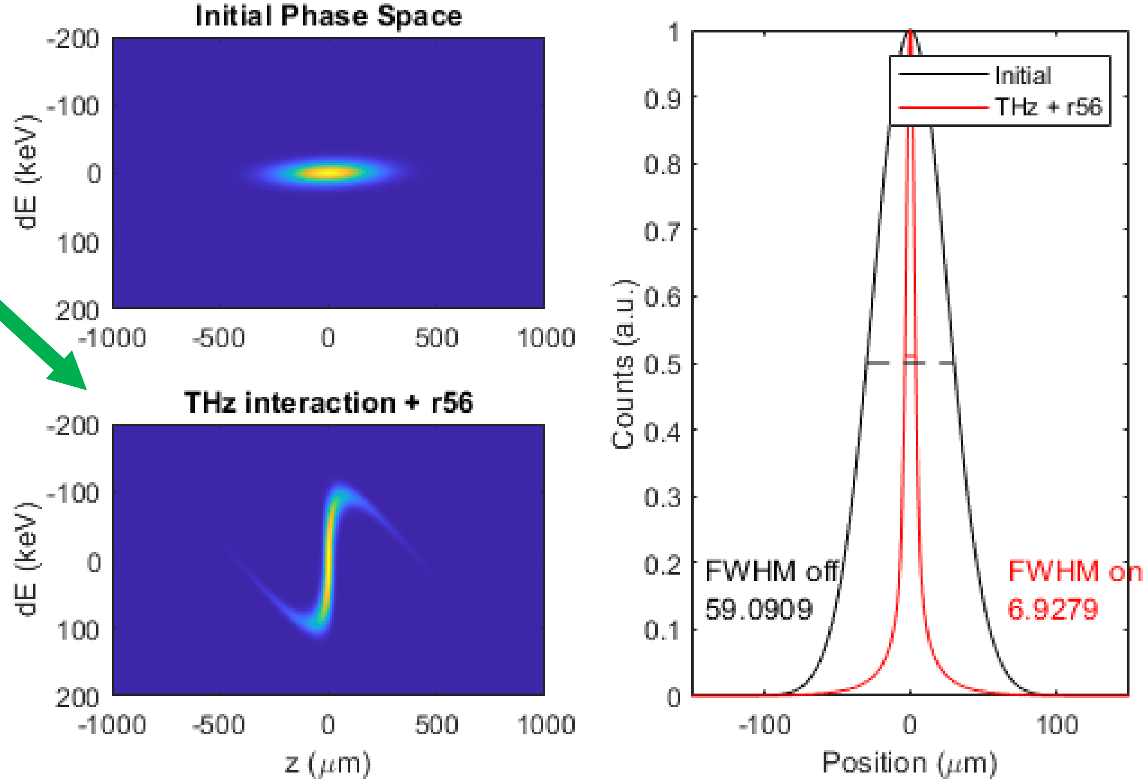
Observed energy spectra with varying THz injection time:

- → Determine the (unknown) bunch energy-time phase-space
- → Residual 'uncorrelated' energy spread of ≈ 20 keV
- → Bunch length ≈ 200 fs FWHM (≈ 60 um)

(Predicted) bunch compression

Standard accelerator technique of magnetic chicane compression

- → Apply chirp (time-energy correlation)
- → Differing path length compresses the bunch length

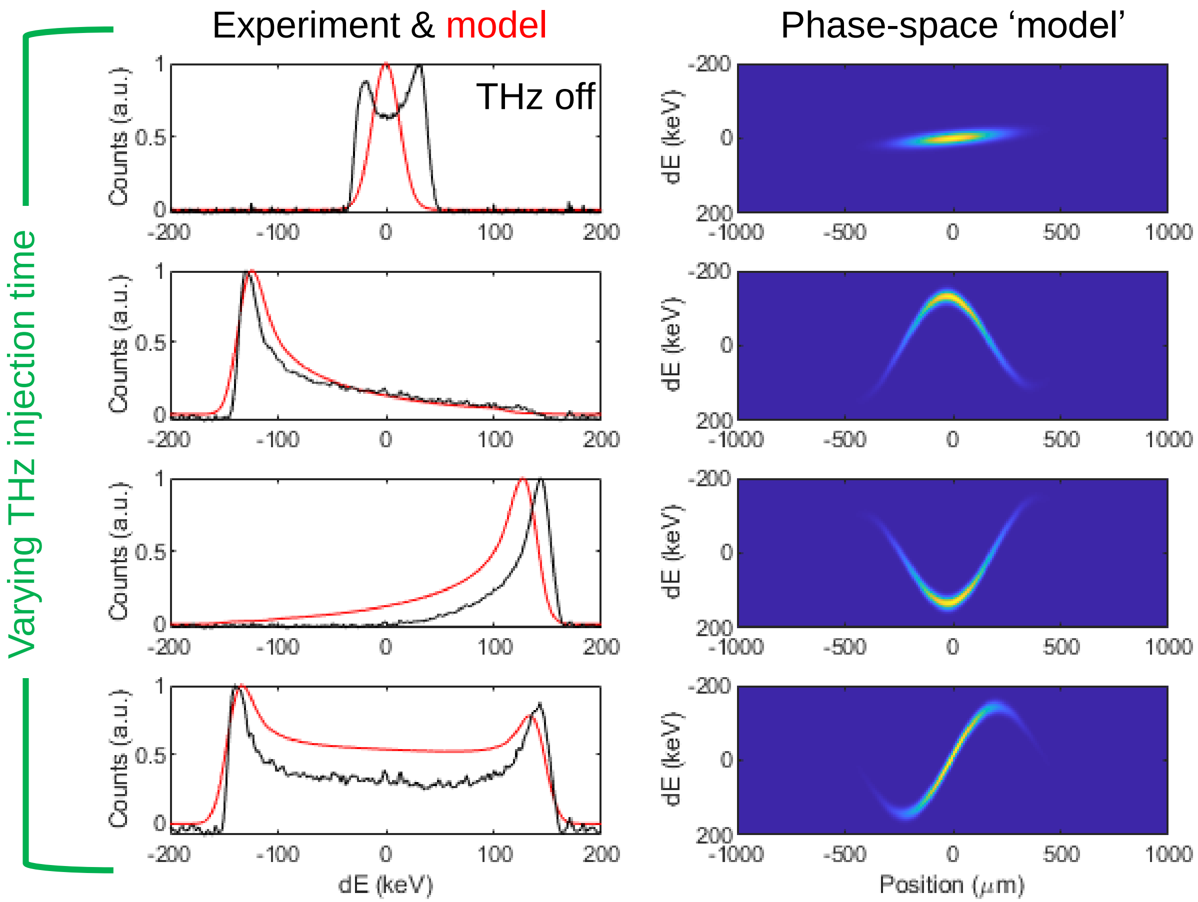


Compression with optimised injection phase and chicane R_{56}

- → Compressed pulse duration ≈ 23 fs FWHM
- → Energy-spread limited so <10 fs feasible

CLARA Run 2 results

High gradients on short(ish) bunches

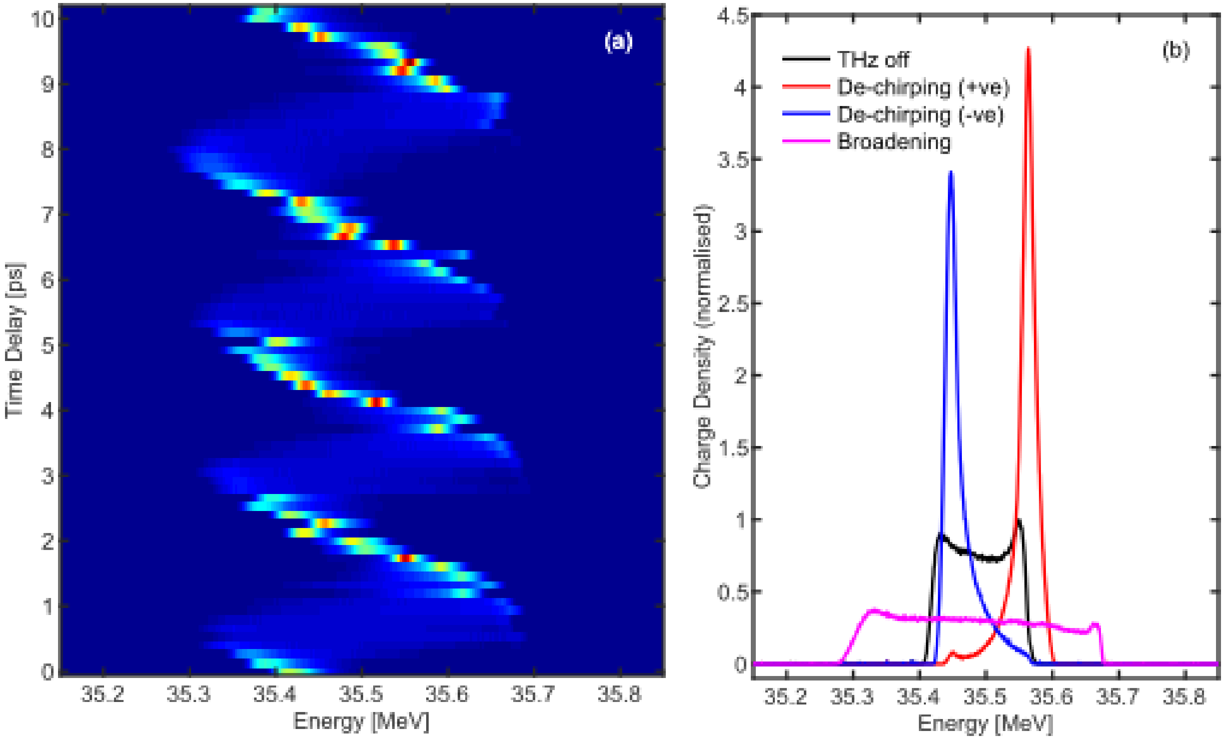


Observed >150keV gain in ≈8 mm interaction length
→ 20 MV/m accelerating gradient, comparable to RF accelerators

→ Limited by THz propagation/coupling losses (estimated <20%)
→ Issues with THz source frequency-matching to waveguide

THz-driven energy de-chirper

THz frequency is 100x higher than RF-driven injectors
→ Allows for RF compression followed by THz de-chirping



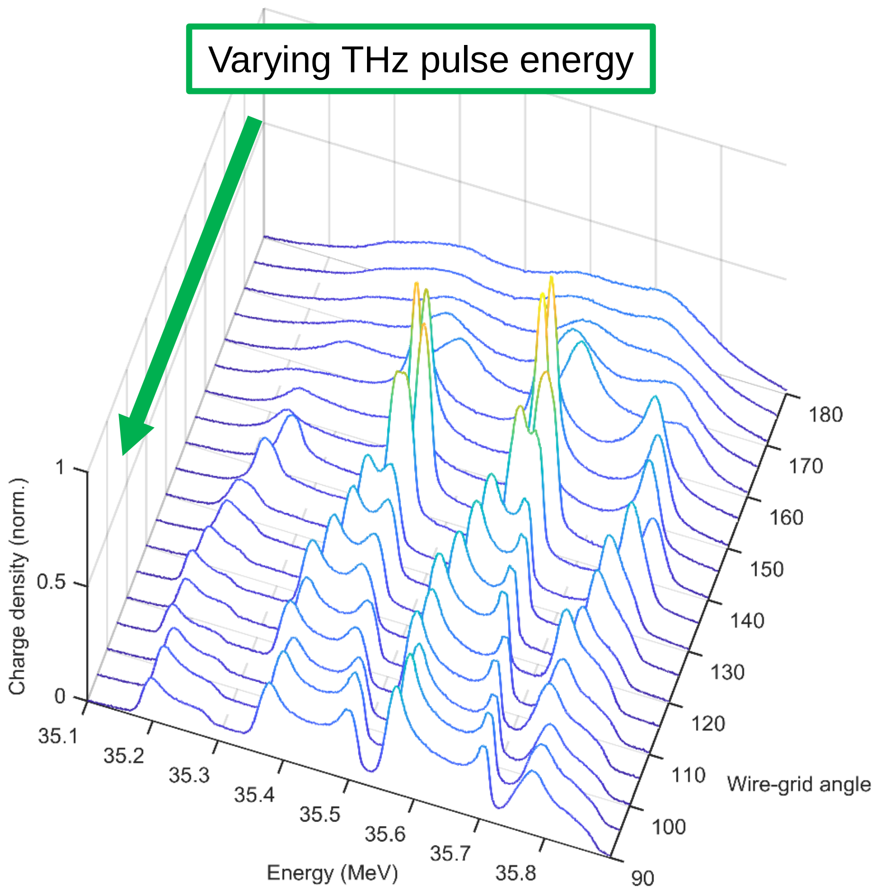
Observed THz-driven de-chirping (and spectral broadening) controlled by THz injection timing

→ Reduce initial spread from 148 keV to 21 keV – factor of 7
→ Final energy spread <0.06% of the 35.5 MeV bunch energy

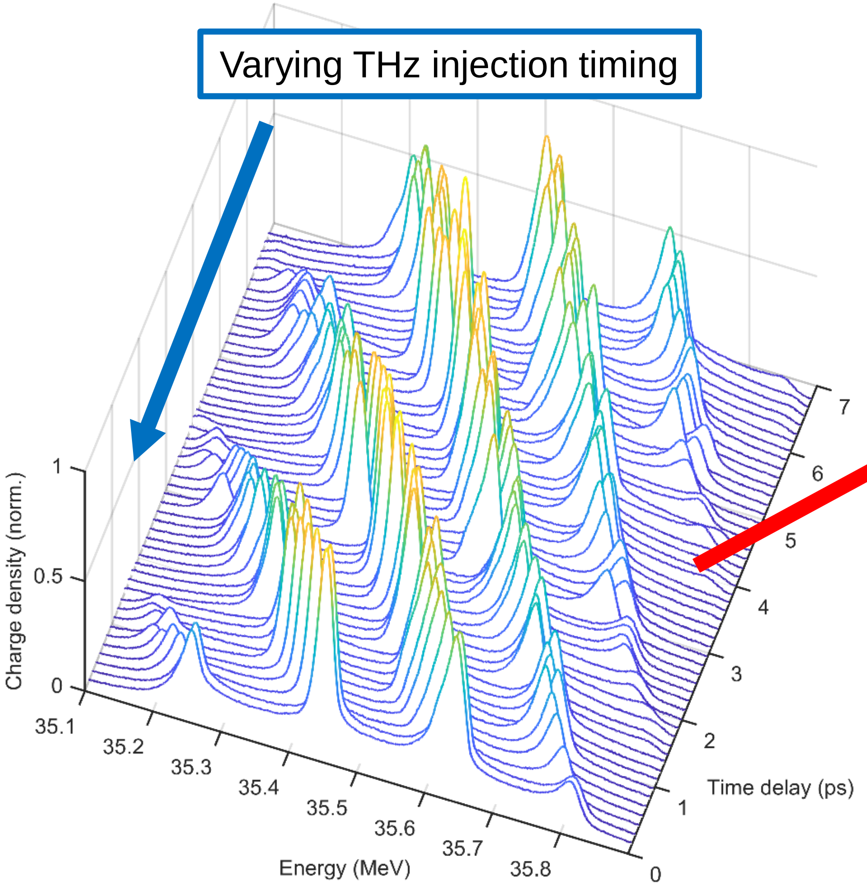
CLARA Run 2 results

Towards micro-bunching with multi-cycle THz pulses

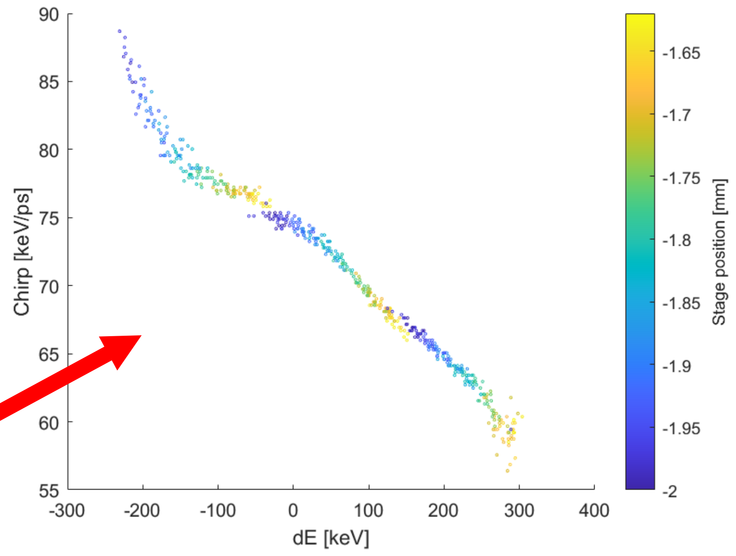
Varying THz pulse energy



Varying THz injection timing



Longitudinal bunch diagnostic



Can use THz frequency and variable injection to “scan” the bunch chirp

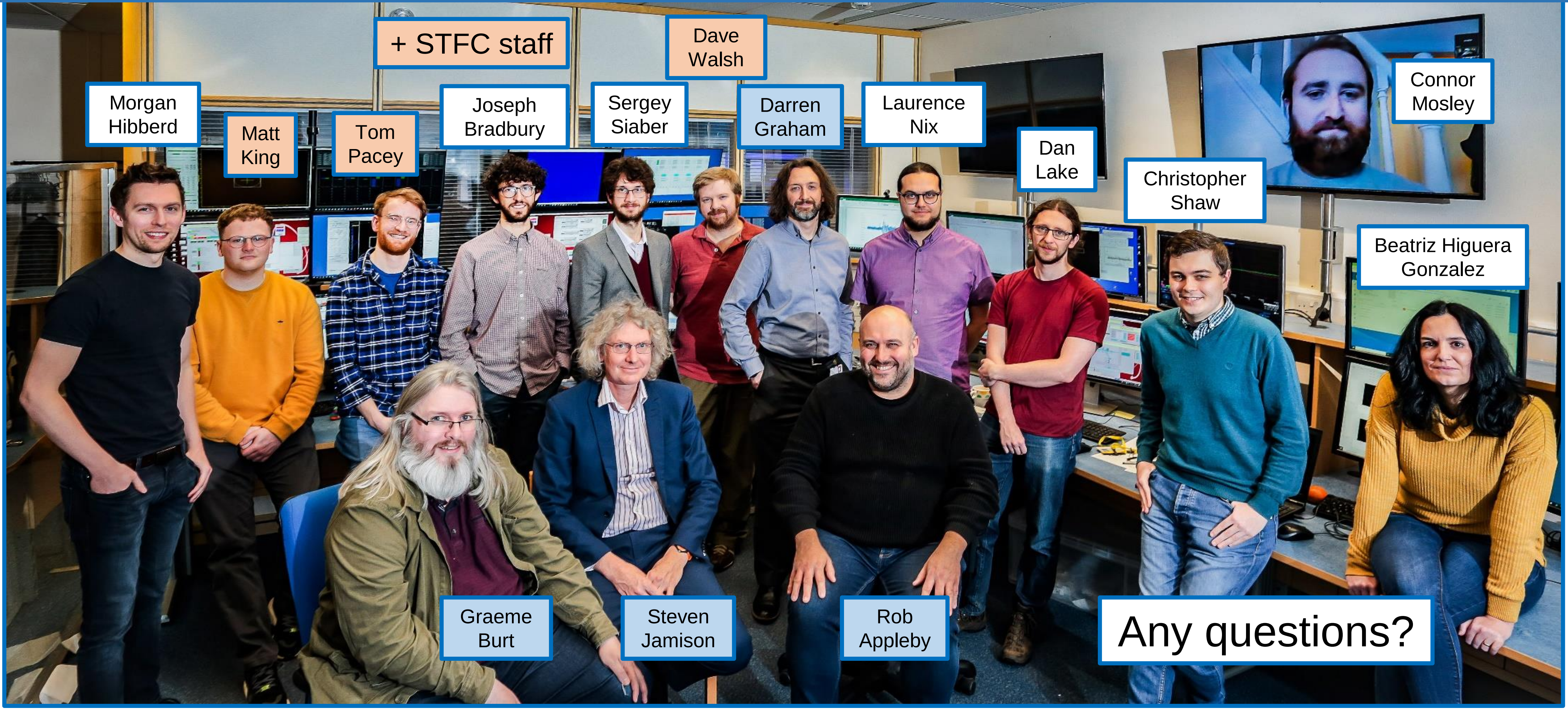
Multi-cycle THz-induced “spectral-bunching”

- → Start with long “linearly”-chirped electron bunch
- → Optimise THz driving field strength
- → Minimum 20 keV peak width observed
- → Non-linear peak-splitting observed beyond that

Magnetic chicane will convert into a train of ultrashort micro-bunches with ps-scale separation

- → Potential for <10 fs bunches with THz-induced fs timing stability
- → Demonstrated with 100 pC charge
- → Capability for 10-100 micro-bunches using narrower bandwidth THz sources

Acknowledgements



Any questions?

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