Terahertz-controlled External Injection

A route to high-quality, stable, plasma acceleration

Steven Jamison

Department of Physics, Lancaster University, UK
The Cockcroft Institute, Scitech Daresbury, UK

High-quality high-gradient acceleration of beams for high-energy physics

H3+BEAMS

HIGH QUALITY HIGH GRADIENT HIGH ENERGY

Exploring the physics of technology of external injection into LWFA

Investigators: S. P. Jamison[1,7] (PI), S. M. Hooker[2,8] (co-PI), R. B. Appleby[3,7], G. Burt[1,7], L. Corner[4,7], R. D'Arcy[2,8], D. M. Graham[3,7], M. T. Hibberd[3,7], J. Jones[5, 7], R. Letizia[1, 7], T. Pacey[5,7], E. Snedden[5,7], and R. Walczak[2,8]

Institutions: [1]Lancaster University, [2]Oxford University, [3]University of Manchester, [4]University of Liverpool, [5]STFC, [7]Cockcroft Institute, [8]John Adams Institute

Terahertz controlled compression and electron-laser temporal-locking

Morgan Hibberd, **Christopher Shaw**, Joseph Bradbury, Daniel Lake, Connor Mosley, Sergey Siaber, Laurence Nix, Beatriz Higuera-Gonzalez, Thomas Pacey, James Jones, David Walsh, Robert Appleby, Graeme Burt, Darren Graham, and Steven P. Jamison

Lancaster University, University of Manchester, STFC, Cockcroft Institute,

THz-controlled external injection into a laser-plasma wakefield accelerator

Aras Amini, Lewis Reid, James Jones, Morgan Hibberd, **Laura Corner**, Darren Graham, Steven Jamison, Graeme Burt, and **Robert Appleby**

University of Manchester, University of Liverpool, STFC, Cockcroft Institute, Lancaster University

External injection: A route to high-quality, stable, plasma acceleration

The opportunity:

Plasma wakefield accelerators provide >10 GeV/m gradients

- *2-3 orders-of-magnitude higher than conventional RF accelerators*
- *High beam energies at significant reduction in accelerator size and cost*
- *Future applications in HEP and beam-driven light sources (X-ray and VUV)*

The plasma acceleration challenge:

Improving beam quality and stability

- *emittance, energy spread, parameter jitter*
- *Stability suitable for facility applications (e.g. HEP, light sources)*
- *Staging… matching of beams*

Injection into the plasma acceleration structure…

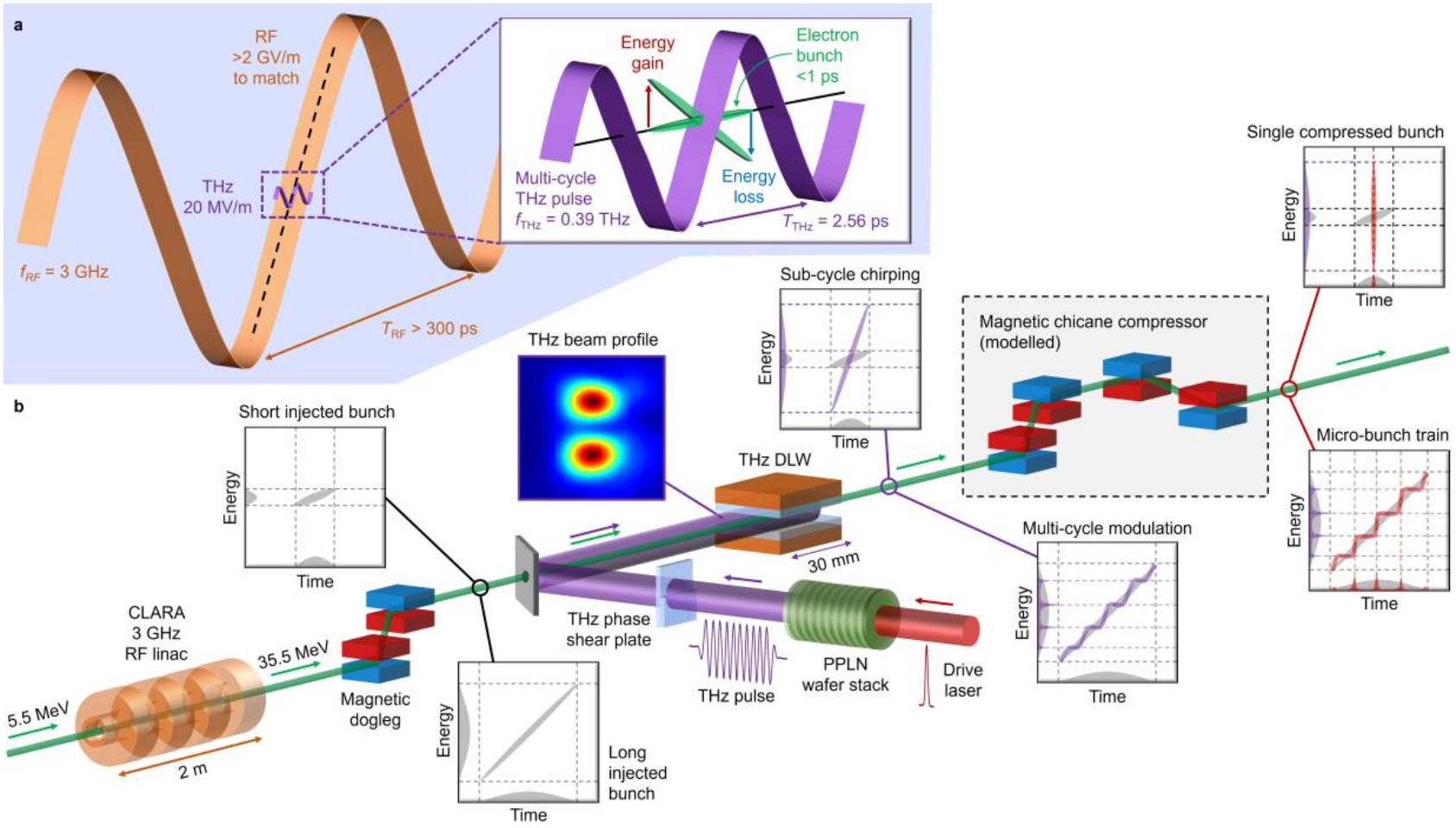
- *Initial bunch is generated from a self-injection process (LWFA)*
- *or constrained to the drive beam properties (PWFA)*

External Injection from RF accelerator injector:

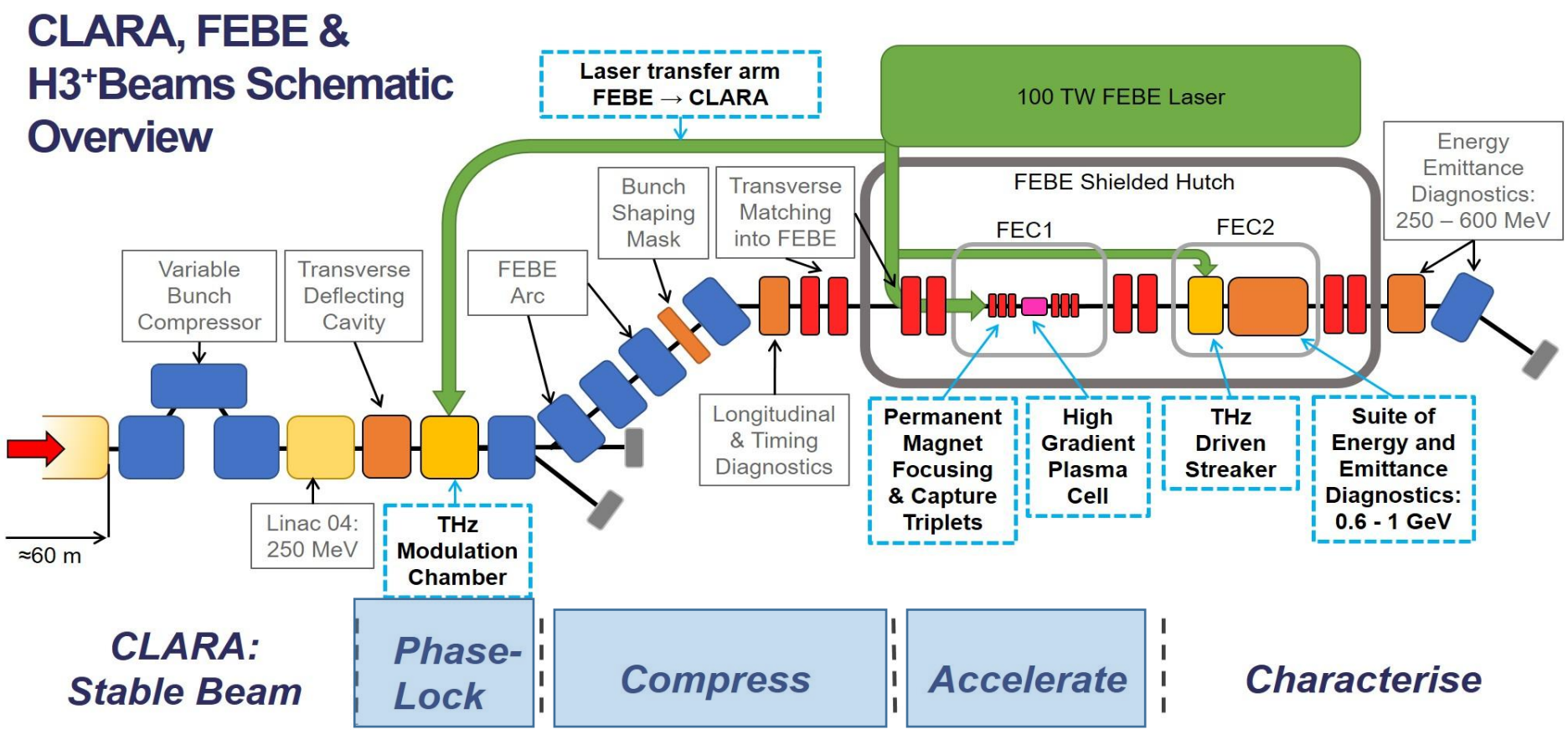
Well controlled, high-quality, stable starting point for acceleration

But how to do it!.... Compression to few-fs bunches

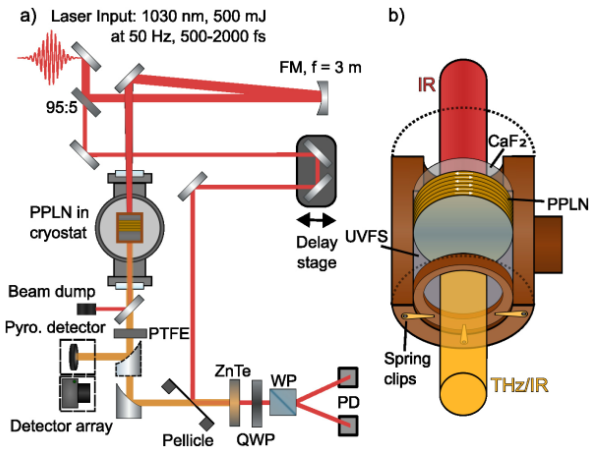
Terahertz Driven Compression & Temporal Locking

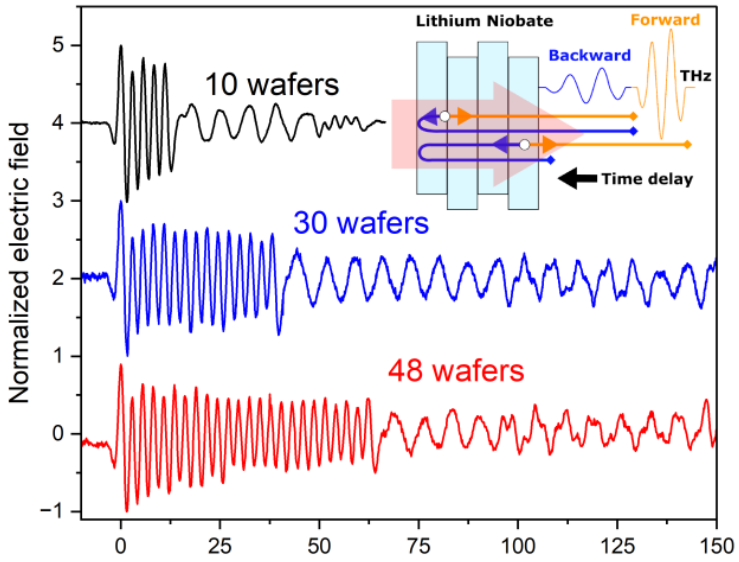


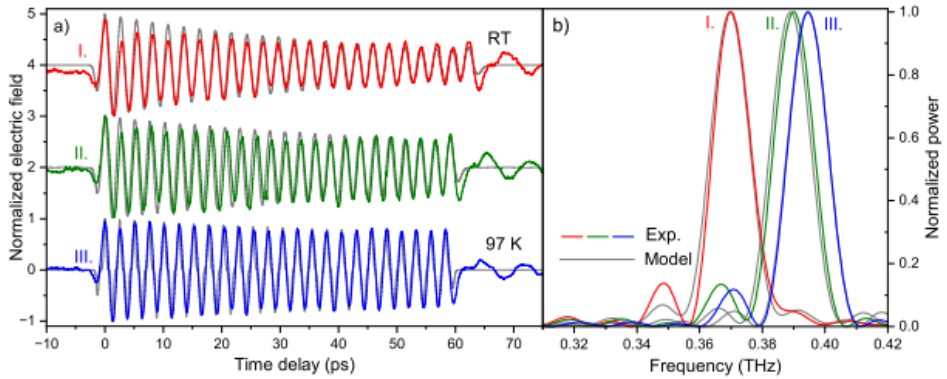
Terahertz Driven Compression & Temporal Locking



Current approach: Periodic Poled $LiNbO_3$ wafer stacks







- > 100uJ THz pulses
- Quasi-monochromatic
- 200GHz - 400GHz (fixed, narrow tunability)

Mosley et al, Opt. Express. 31 4041 (2023)
Dalton et al., Appl. Phys. Lett. 125, 141101 (2024)
Dalton et al., arXiv:2509.13060 . 125, (2025)

Lancaster University

The Cockcroft Institute of Accelerator Science and Technology

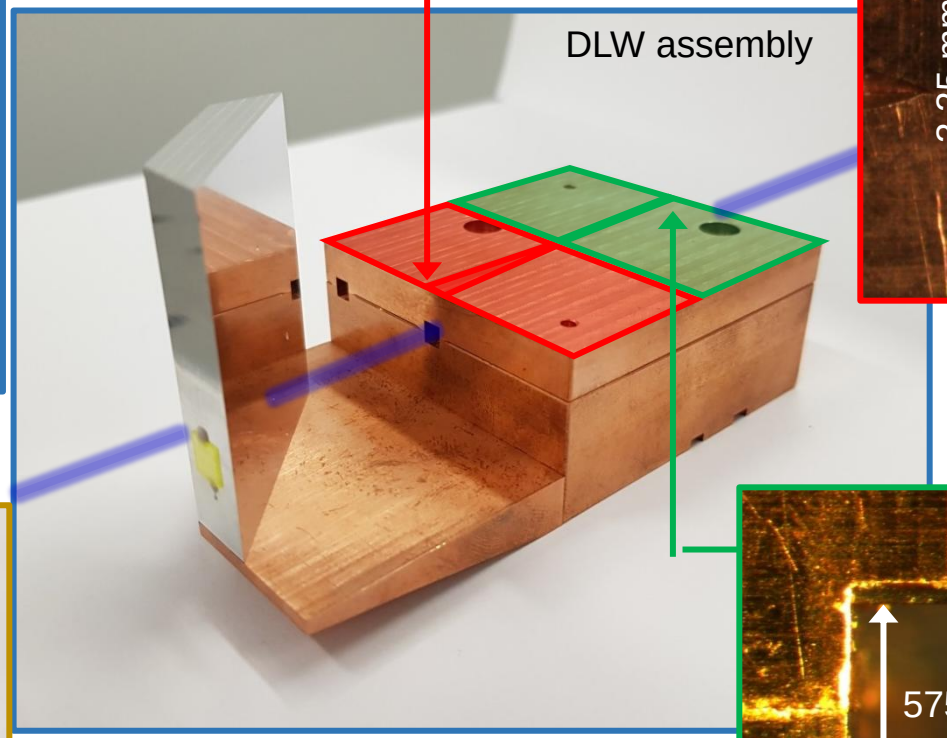
Dielectric lined waveguides

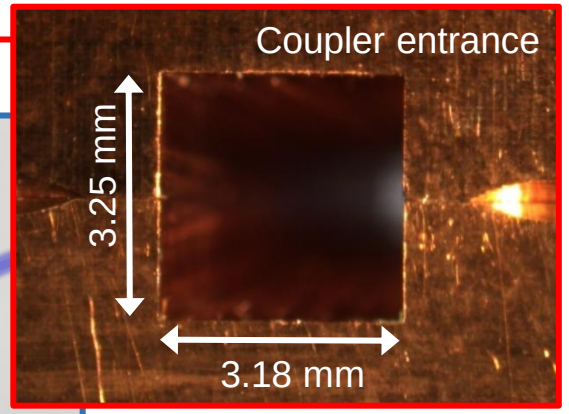
Supports **L**ongitudinal **S**ection **M**agnetic modes

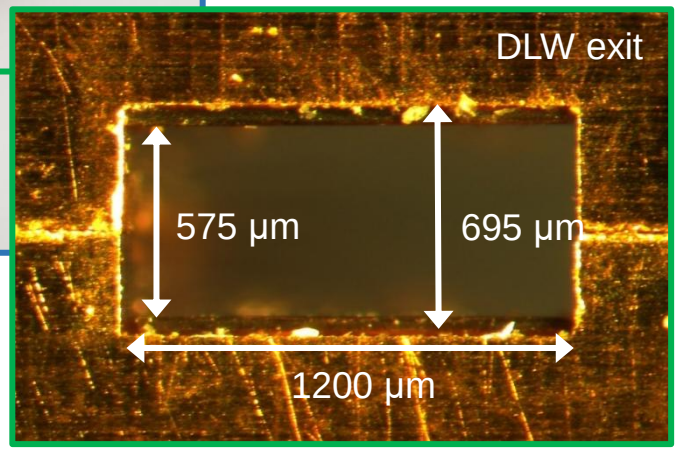
→ Field confinement against diffraction

→ On-axis Longitudinal fields for acceleration (LSM_{11} mode)

→ Designed for velocity-matching of relativistic electron beams







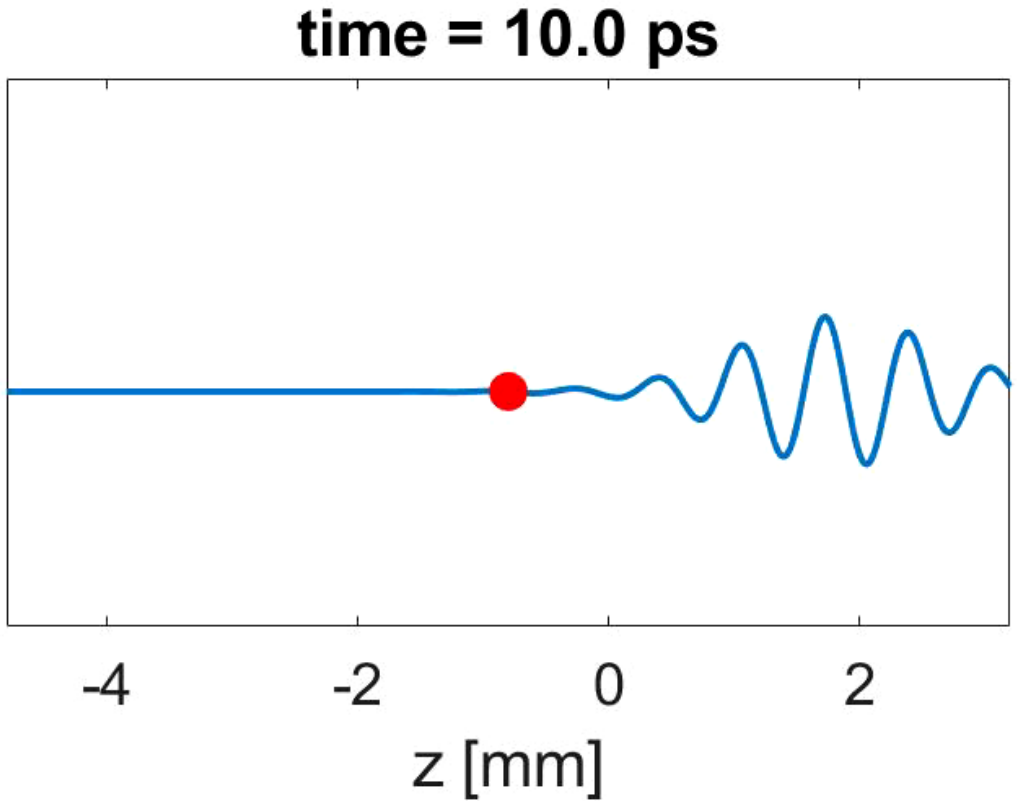
Also developed structures for sub-relativistic beams and deflection modes

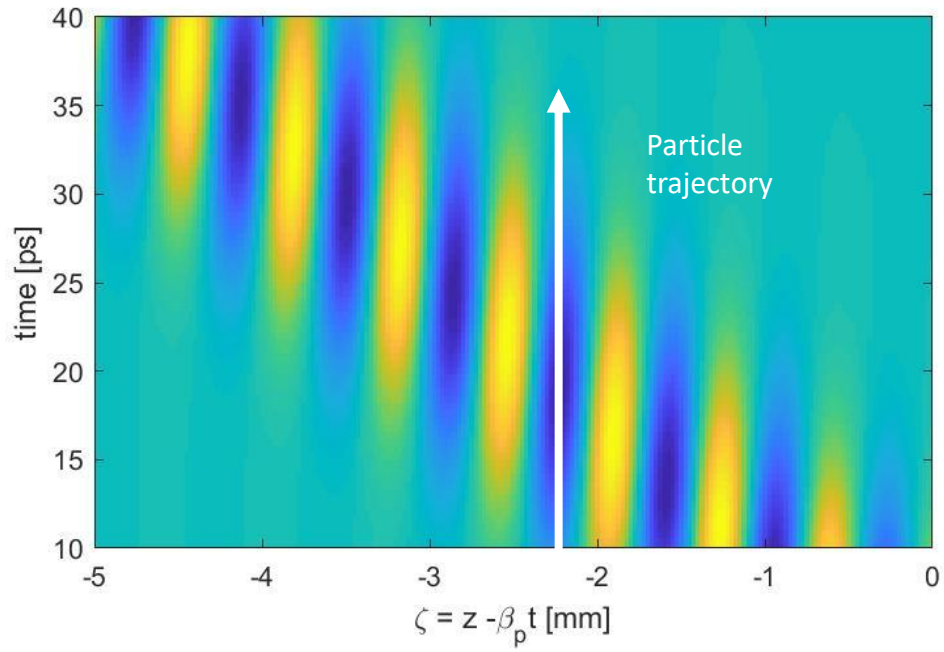
Nix et al., Phys. Rev. Accel. Beams **27**, 041302 (2024)
Apsimon et al. Phys. Rev. Accel. Beams **24**, 121303 (2021)
Georgiadis et al., App. Phys. Lett. 118, 14 (2021)
Hibberd et al., Nat. Photon. 14, (2020)

Relativistic particle & phase-velocity matching

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

Multi-cycle THz input (quasi-monochromatic)

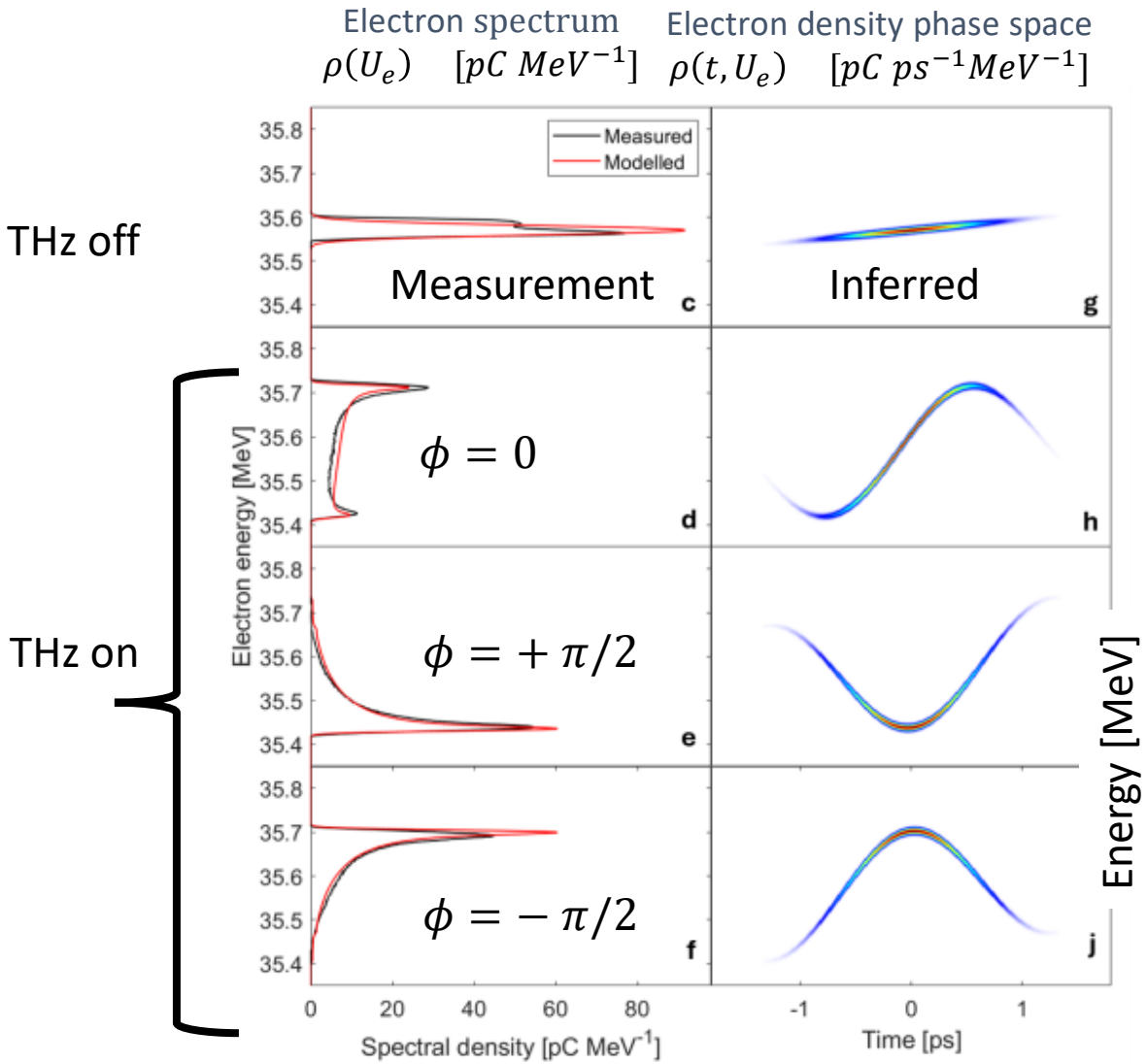




Particle see constant electric field phase (accelerator or decelerating)

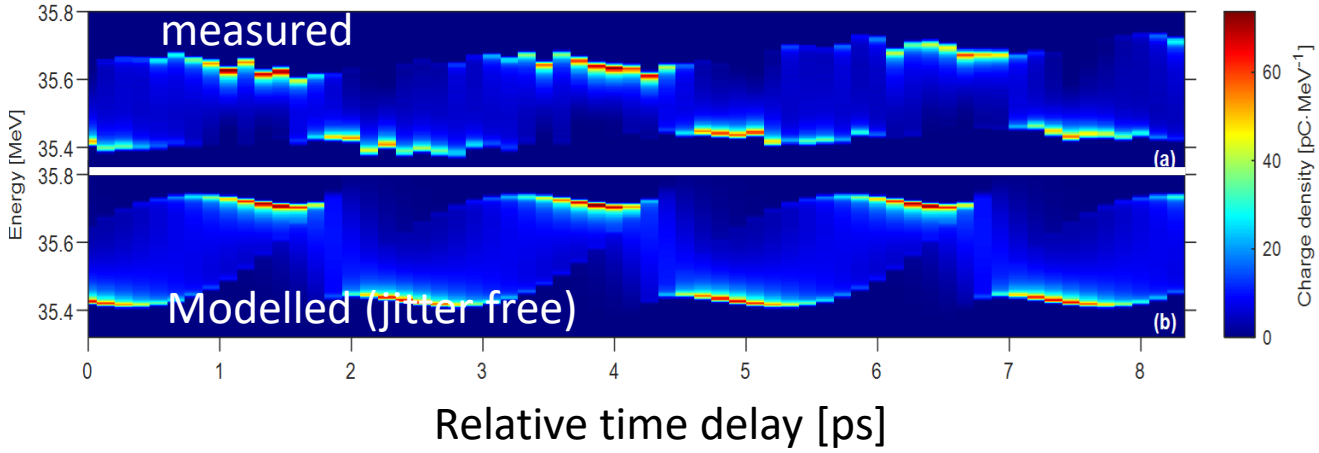
Terahertz Driven Compression, 35 MeV electrons

Low energy-spread, sub-ps bunch injected (2 pC) from CLARA accelerator



- 150 keV energy gain / loss observed in 8 mm interaction length
- Infer the slice energy spread from the time-delay spectrogramme

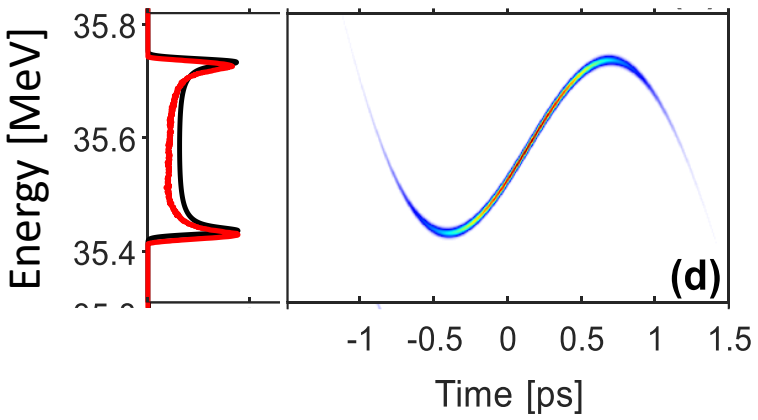
Phase (timing) scans of electron spectrum enables retrieval of electron density phase-space $\rho(t, U_e)$



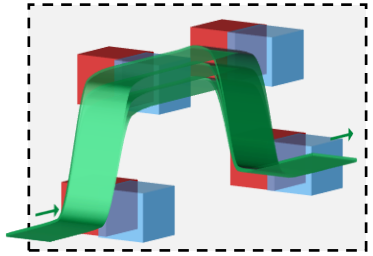
Hibberd et al, arXiv:2508.20685 (2025)

Terahertz Driven Compression, 35 MeV electrons

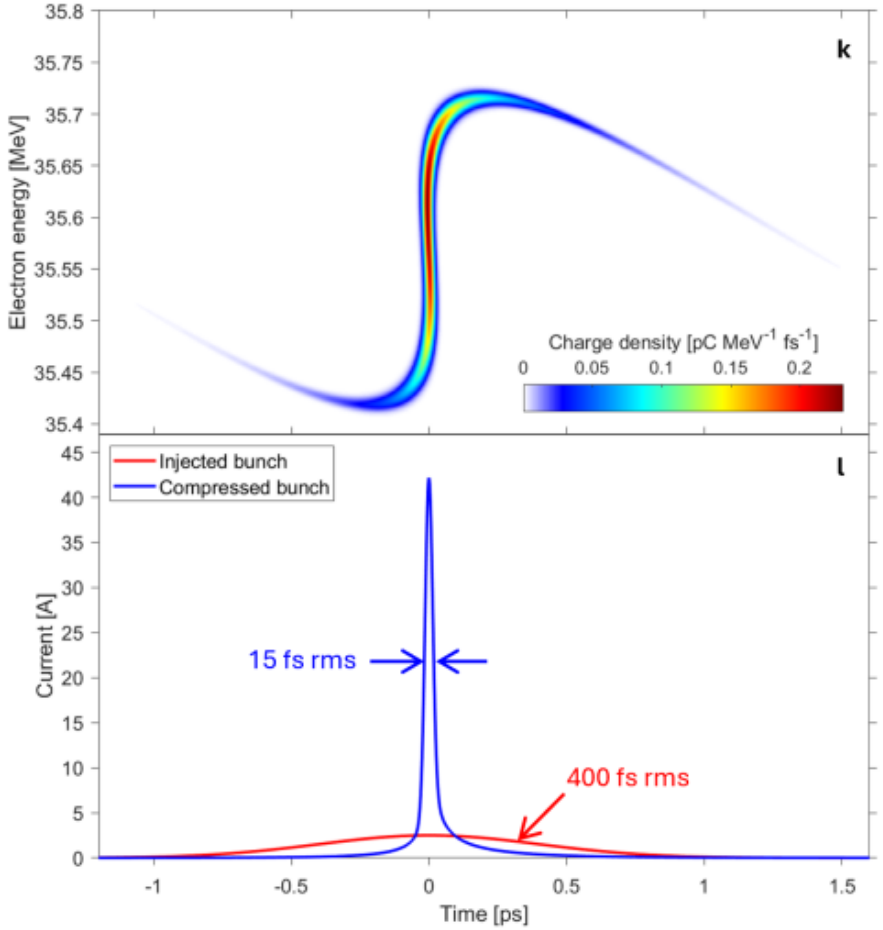
THz-induced energy streaking, as measured



Magnetic chicane



Energy dependent time delay



Higher-order and tunable magnetic compression systems common and well-developed

Compression limit set by 'time slice' energy spread ***& THz energy gain:***

Doubling energy gain would halve the compressed bunch duration

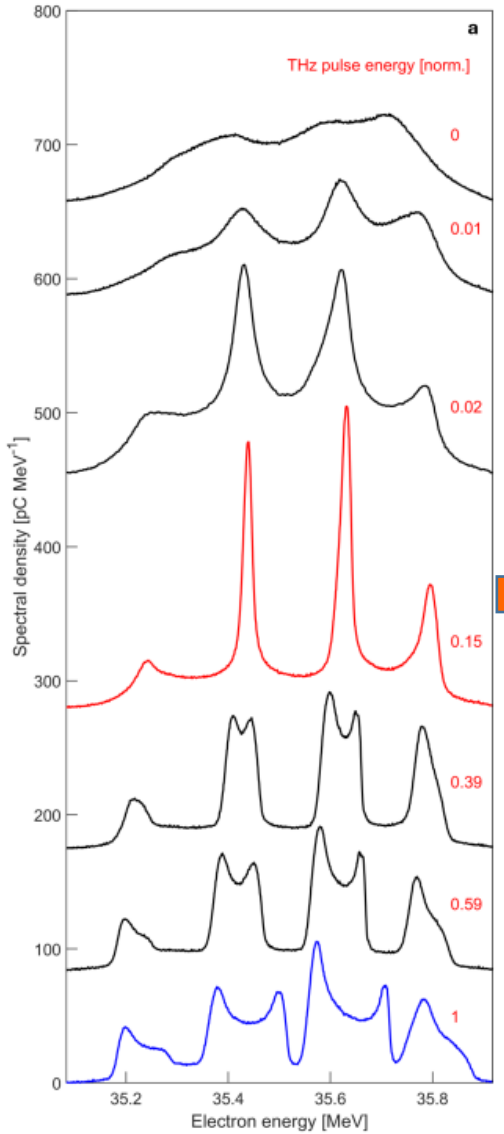
Hibberd et al, arXiv:2508.20685 (2025)

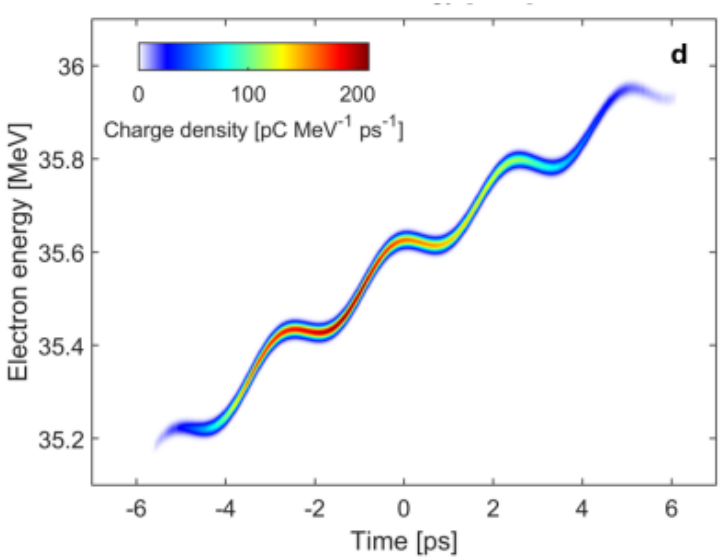
Lancaster University

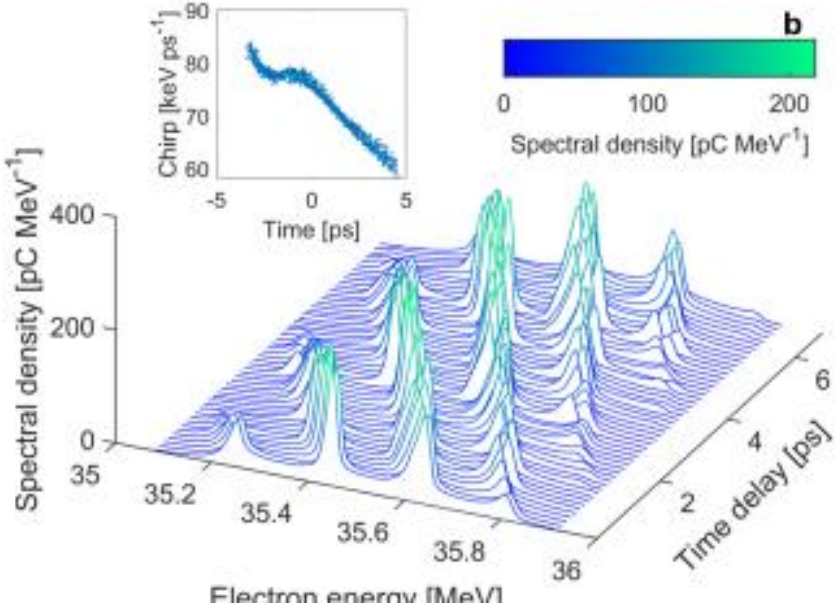
The Cockcroft Institute of Accelerator Science and Technology

Terahertz Driven Compression, 35 MeV bunch trains

few-ps bunch injected (30 pC) from CLARA accelerator



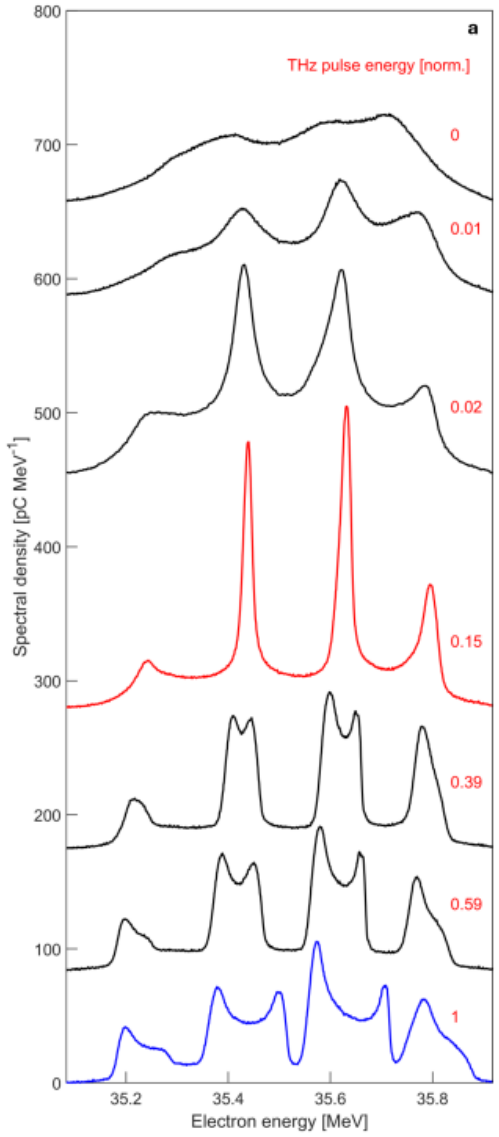


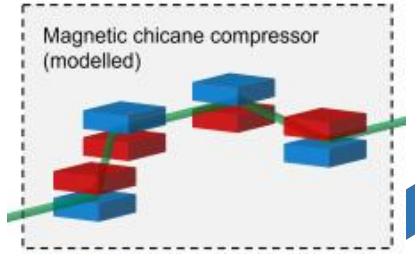


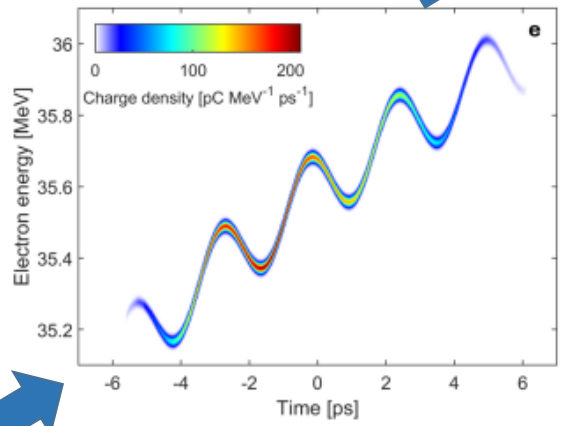
Hibberd et al, arXiv:2508.20685 (2025)

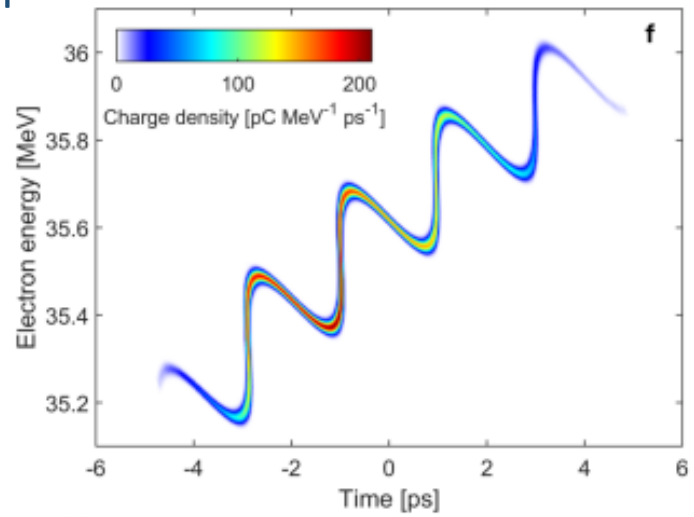
Terahertz Driven Compression, 35 MeV bunch trains

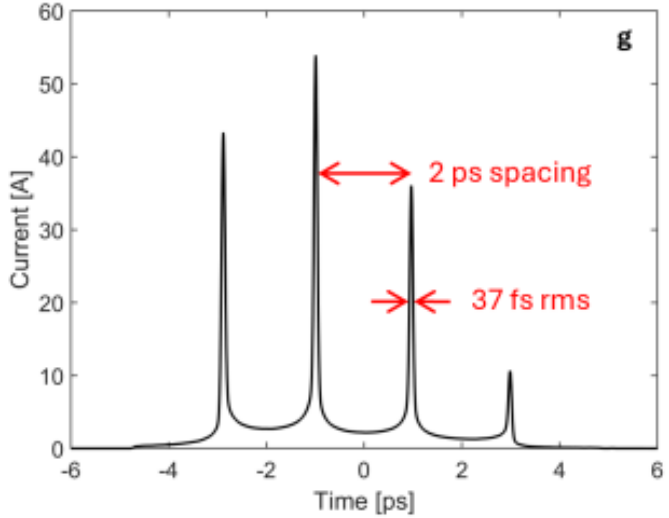
few-ps bunch injected (30 pC) from CLARA accelerator











Trains of compressed bunches
~2 ps spacing (tuneable by chicane or RF phase setting)

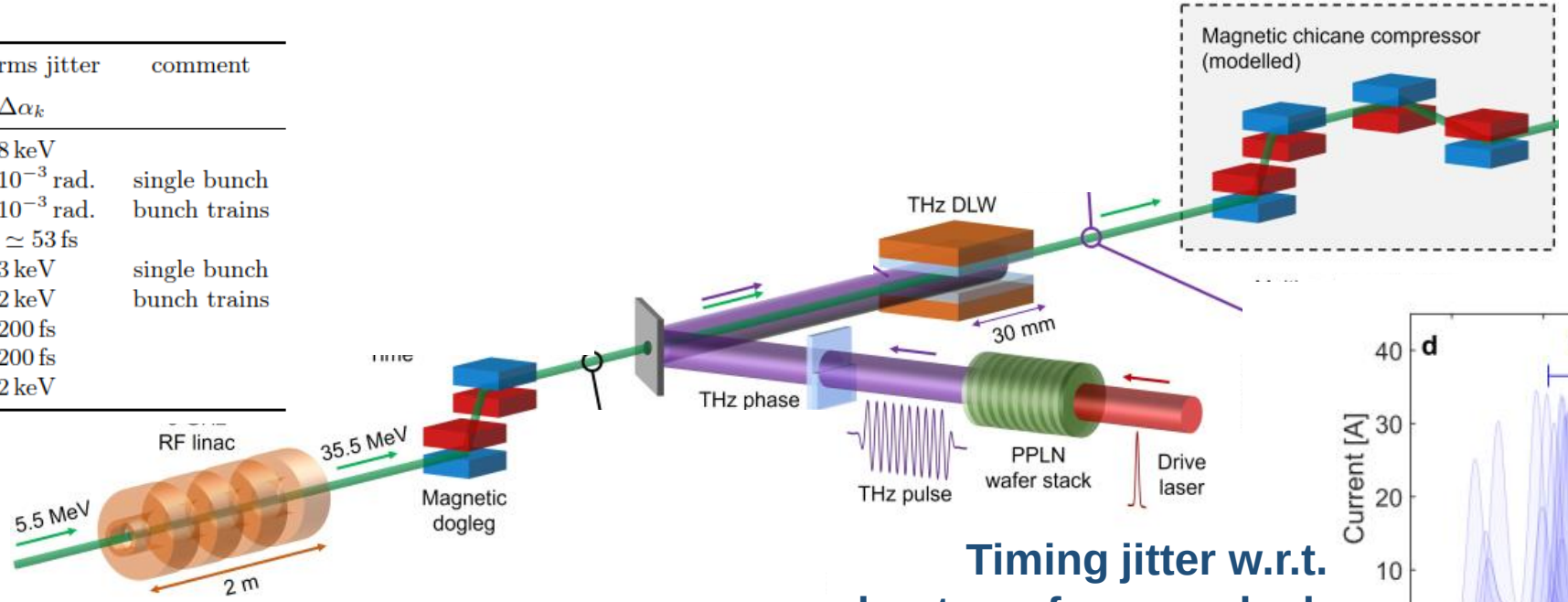
Hibberd et al, arXiv:2508.20685 (2025)

Lancaster University

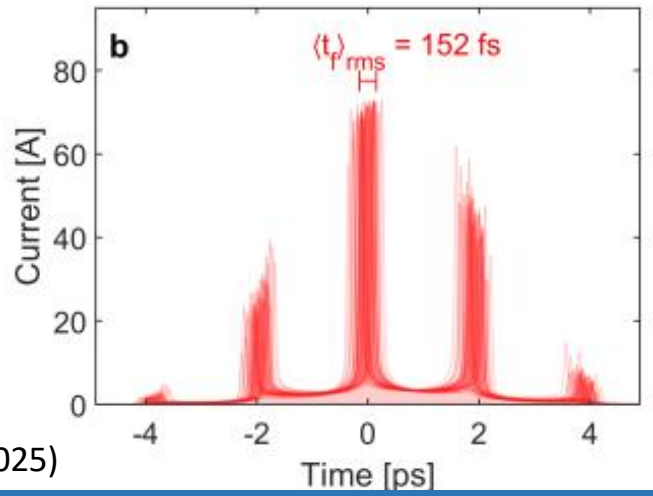
The Cockcroft Institute of Accelerator Science and Technology

Terahertz Driven Temporal Locking

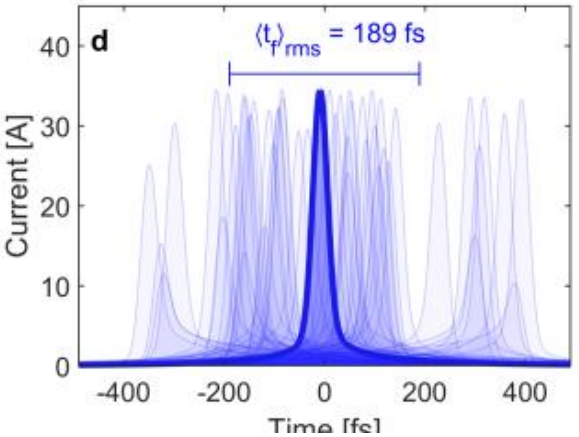
System	set-point $\alpha_{k,\,\mathrm{ref}}$	rms jitter $\Delta\alpha_k$	comment
U_{rf}	30 MeV	8 keV	
ϕ_{rf}	0^o	10^{-3} rad.	single bunch
	-15^o	10^{-3} rad. $\simeq 53$ fs	bunch trains
U_{THz}	133 keV	3 keV	single bunch
	104 keV	2 keV	bunch trains
t_{THz}	0 fs	200 fs	
t_{inj}	0 fs	200 fs	
U_{inj}	5.5 MeV	2 keV	



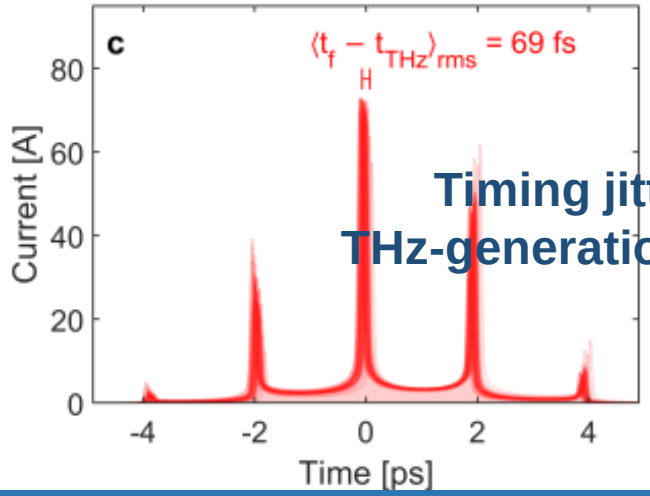
w.r.t. accelerator reference clock



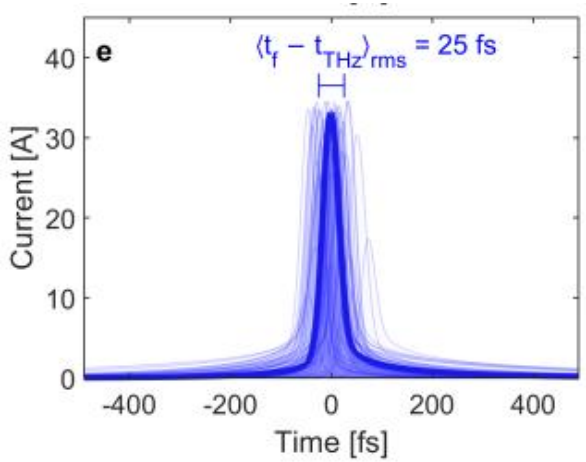
Timing jitter w.r.t. accelerator reference clock



w.r.t. THz-generation laser



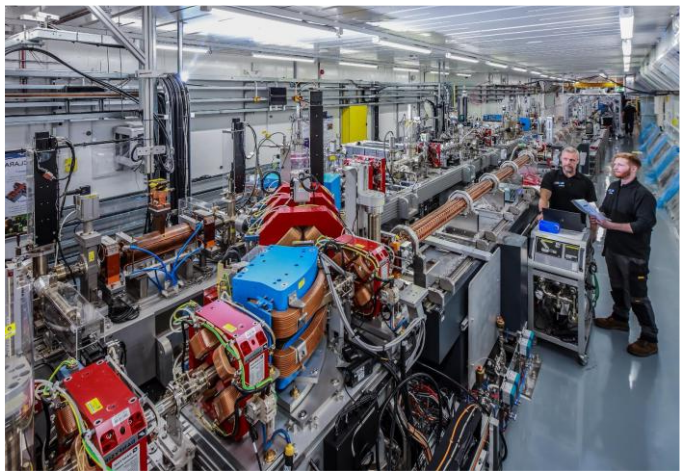
Timing jitter w.r.t. THz-generation laser

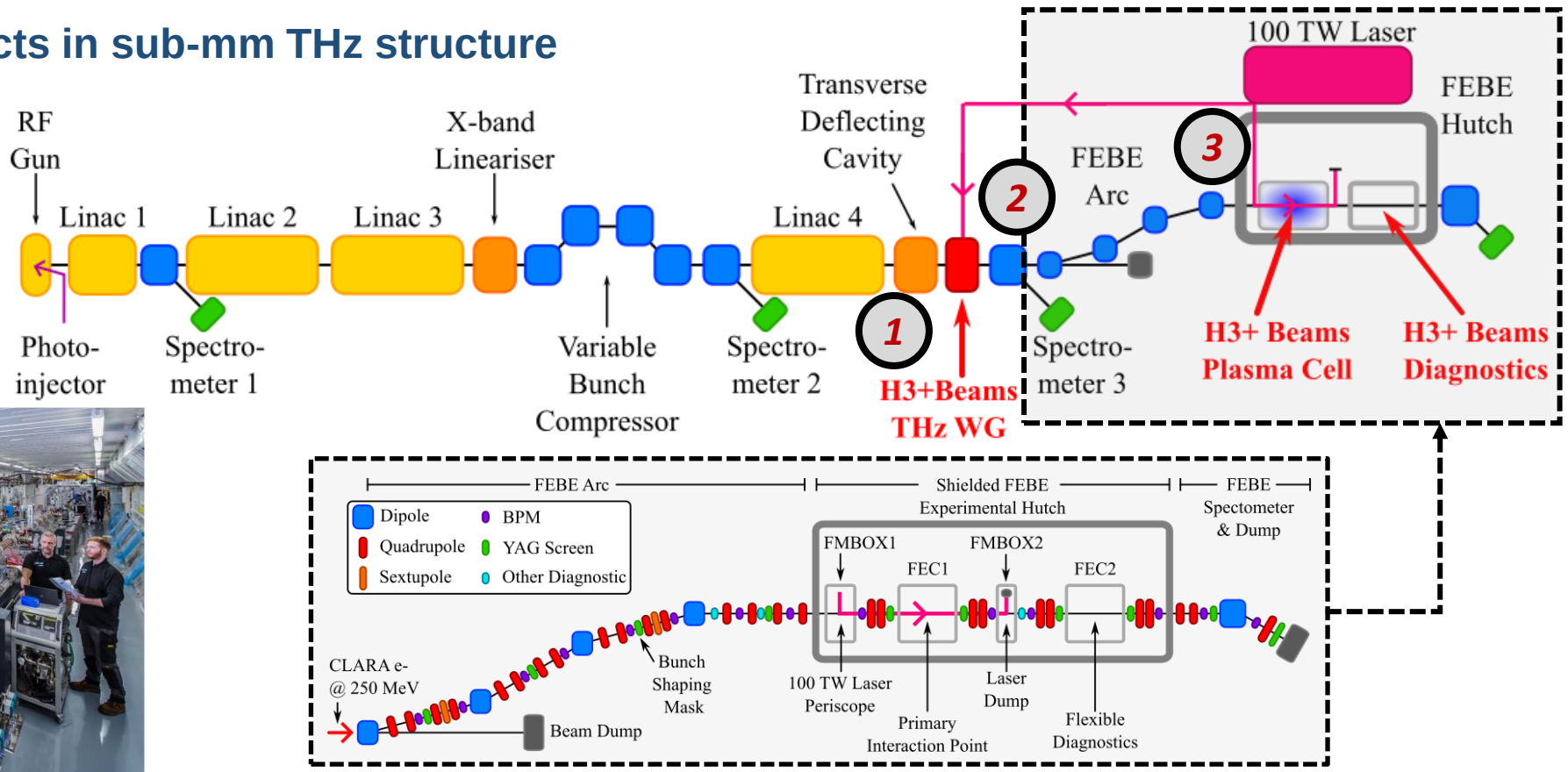


Hibberd et al,
arXiv:2508.20685 (2025)

Injection into a plasma: start-to-end modelling

Start-end simulation of CLARA accelerator (test example)
Including: space-charge
Transverse effects in sub-mm THz structure





Jitter studies:
- Energy and timing jitters sources
- Magnet power supplies

Aras Amini, Rob Appleby, Laura Corner, Lewis Reid
Manuscript in prep.

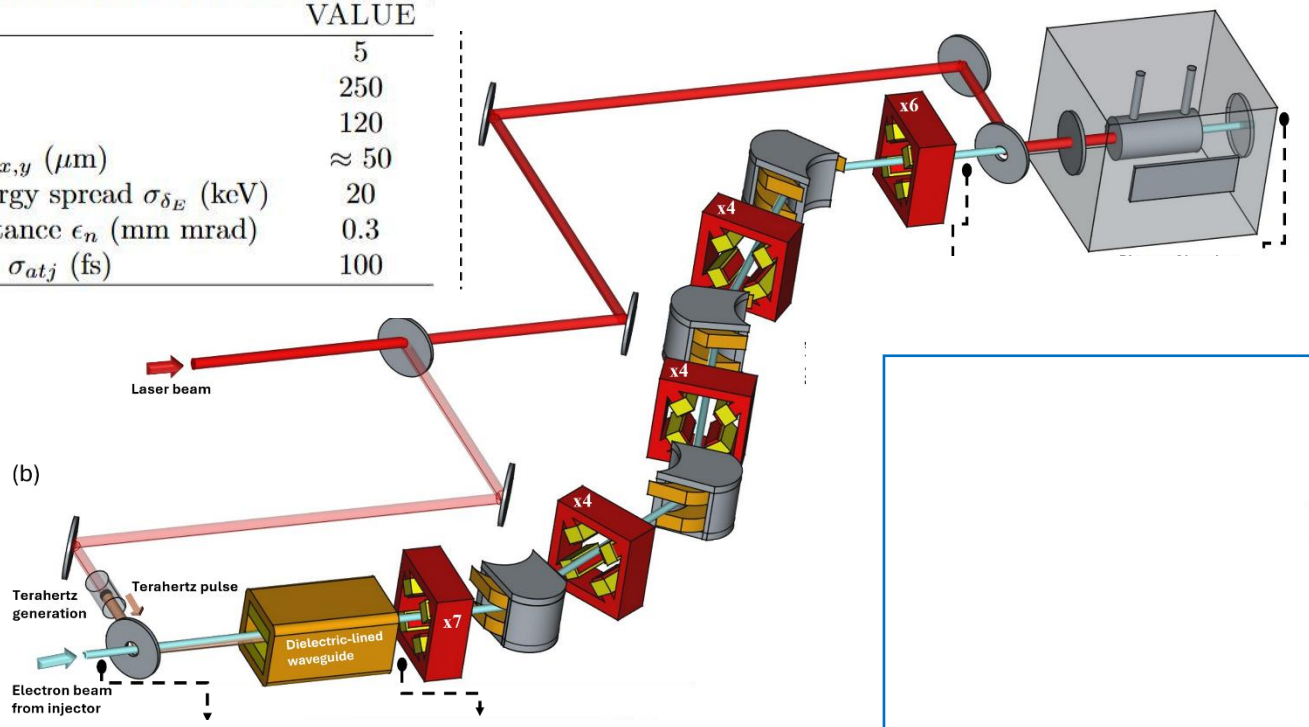
Lancaster University

The Cockcroft Institute of Accelerator Science and Technology

Injection into a plasma: start-to-end modelling

Table 1: Initial Bunch Parameters

PARAMETER	VALUE
Charge Q (pC)	5
Energy (MeV)	250
Length σ_t (fs)	120
Transverse size $\sigma_{x,y}$ (μm)	≈ 50
Uncorrelated energy spread σ_{δ_E} (keV)	20
Normalized emittance ϵ_n (mm mrad)	0.3
Initial time-jitter σ_{atj} (fs)	100



Aras Amini, Rob Appleby, Laura Corner, Lewis Reid
Manuscript in prep.

Lancaster University

The Cockcroft Institute of Accelerator Science and Technology

Injection into a plasma: start-to-end modelling

Aras Amini, Rob Appleby, Laura Corner, Lewis Reid
Manuscript in prep.

Injection into a plasma: start-to-end modelling

Without THz control (RF-manipulated bunches):

Large energy jitter (19.6% rms) dominated by arrival time jitter (> 60 fs rms).

With THz control (S2E beam):

Mean energy ≈ 1066 MeV,
median energy spread ≈ 2.6% rms,
energy jitter reduced to ≈ 2.7% rms;

With THz control (ideal Gaussian beam):

Higher stability: ≈ 1087 MeV mean energy,
0.9% rms spread, 0.9% rms jitter.

Aras Amini, Rob Appleby, Laura Corner, Lewis Reid
Manuscript in prep.

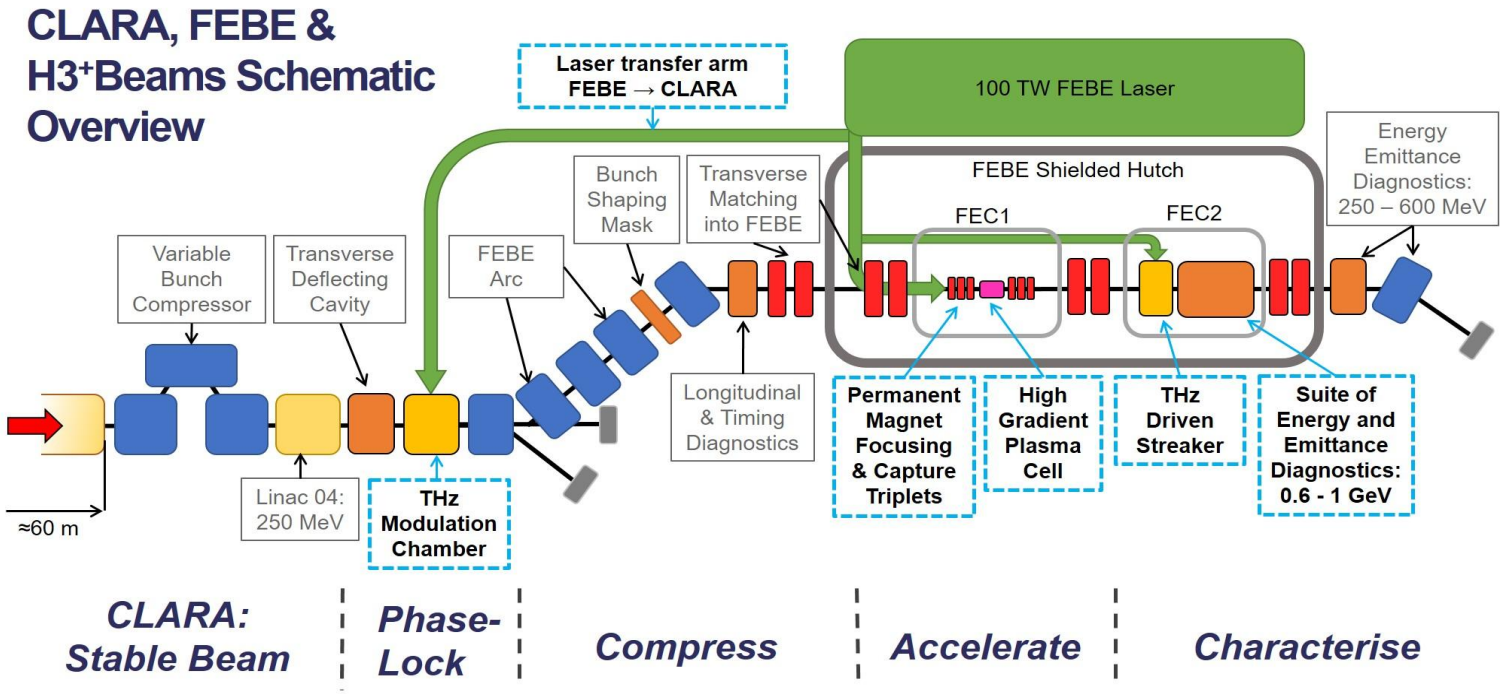
Lancaster University

The Cockcroft Institute of Accelerator Science and Technology

High-quality high-gradient acceleration of beams for high-energy physics

H3+BEAMS
HIGH QUALITY HIGH GRADIENT HIGH ENERGY

Exploring the physics of technology of external injection into LWFA



Project developed to carry-out full concept demonstration, and explore the physics of injection and acceleration.

Based around CLARA 250 MeV accelerator, with 100 TW laser. (both nearing end of commissioning)

Included special-diagnostics (BAM, THz-streaker..), PMQ-systems, suite of experiment-specific systems; THz generation laser beamline….

March 2025: UK research funding crisis, and funding declined after review.

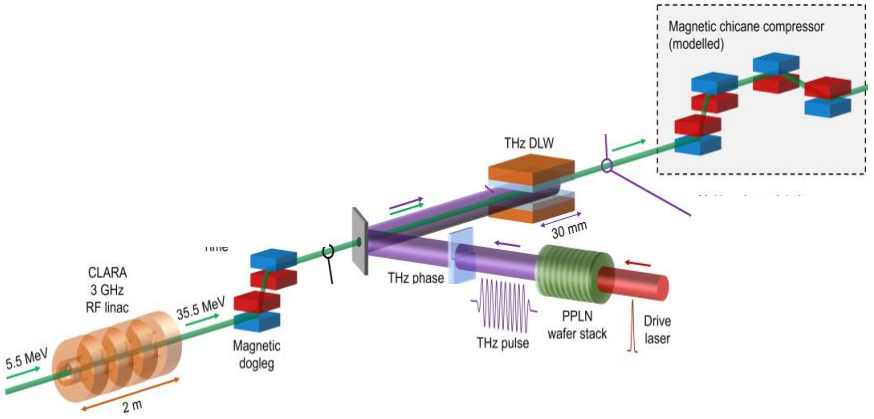
Exploring reframing of project

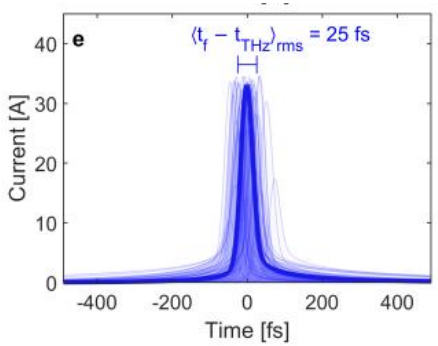
open to new partners, new emphasis or goals to move concepts forward to reality

Terahertz controlled Compression & Temporal Locking

Summary

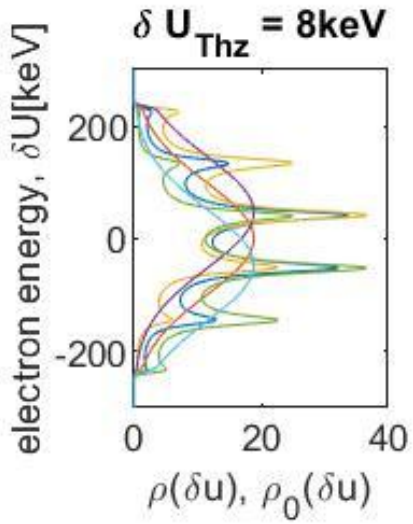
- THz-controlled compression and temporal locking a potential route to enabling external injection.
- Coupled to plasma HOFI channel, with density ramps offers emittance preservation…
- …shot-shot narrow energy spread,
- and central energy stability.
- Component concepts demonstrated, awaiting an integrated demonstration

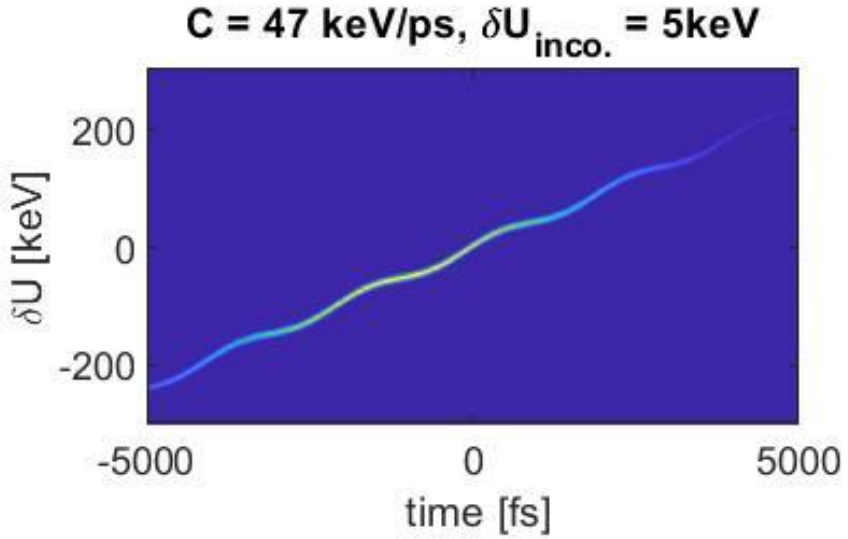


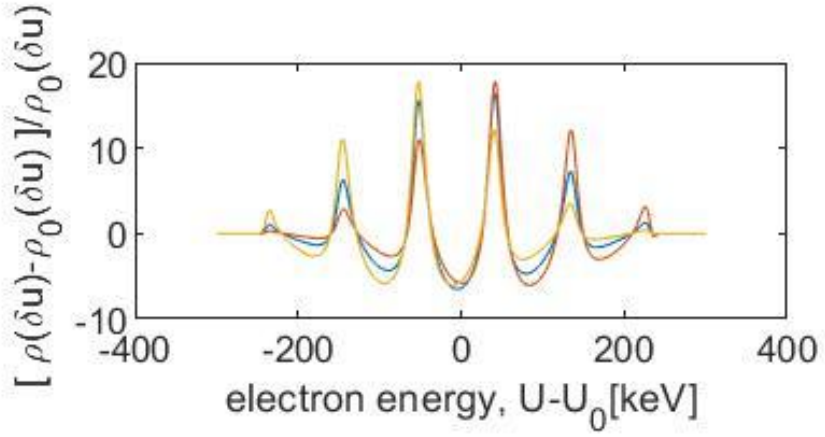


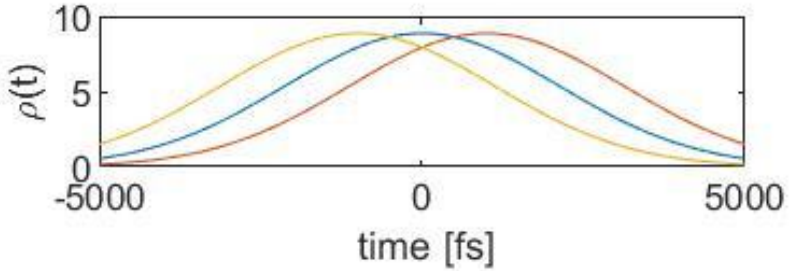
THz-induced energy and timing stabilization

Approximately linear chirp $\Rightarrow$ $E_{central}$ proportional to $t_{arrival}$

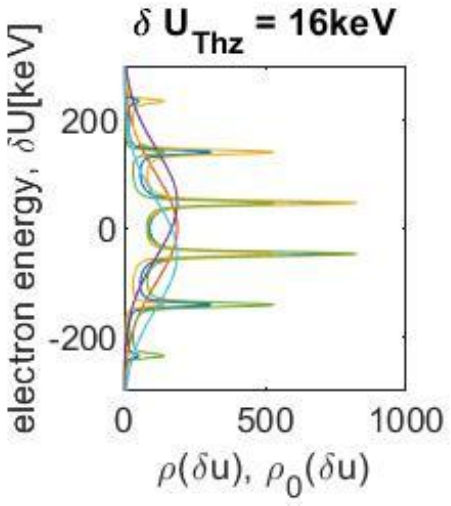


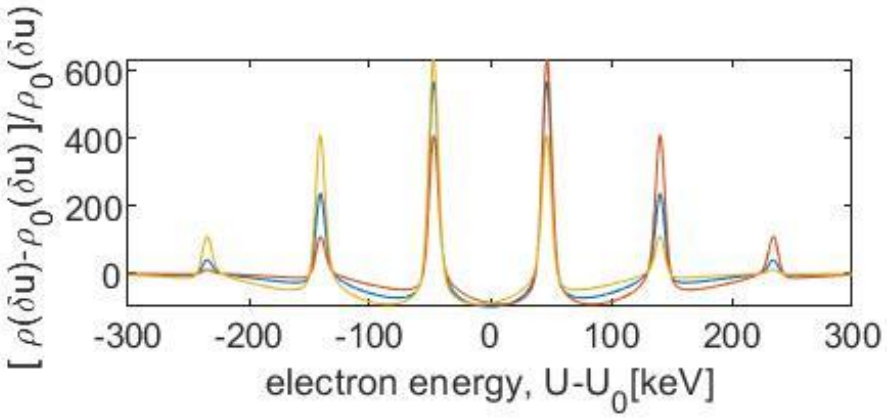




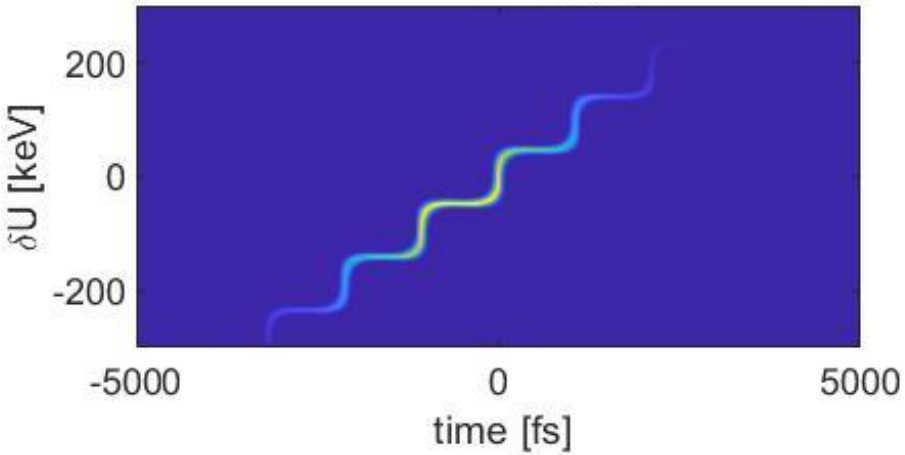


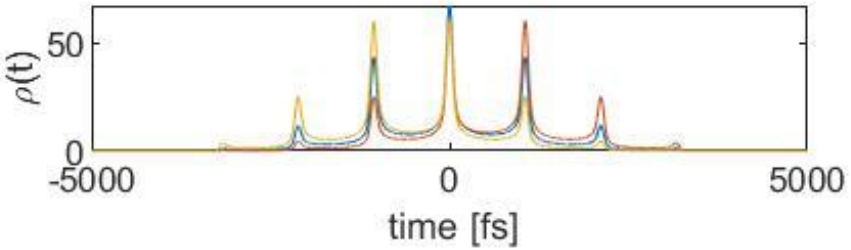
THz-induced energy and timing stabilization





Addition of R56 for compression





- Compression : sub-10fs for realistic parameters
- Active timing stabilization

  Micro-bunches locked to THz timing &
  THz timing locked to laser envelope