Electron beam jitter suppression and diagnostic using terahertz-induced modulation

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The Cockcroft Institute of Accelerator Science and Technology

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THz Acceleration Group @ www.THzAG.uk

Our research group

- Novel terahertz (THz)-based techniques for electron beam acceleration and manipulation.
- Higher driving frequency compared with conventional RF accelerators.
- THz source development.

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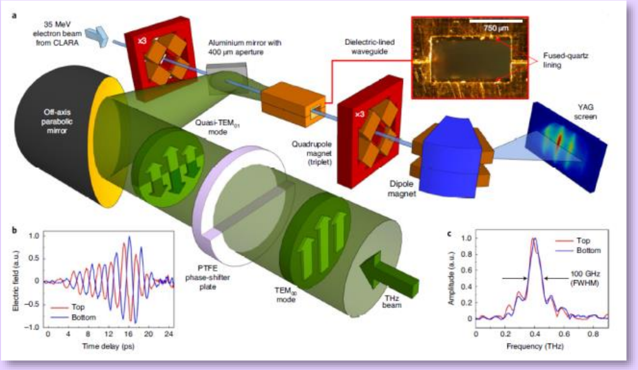
Relativistic acceleration

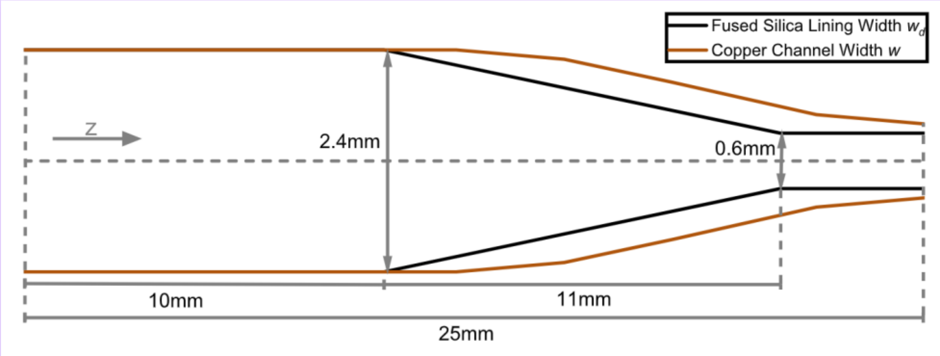


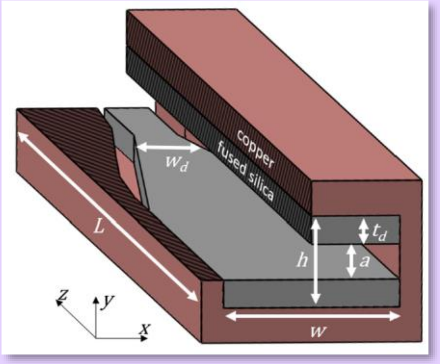
M. T. Hibberd *et al*. "Acceleration of relativistic beams using laser-generated terahertz pulses" *Nature Photonics* **14**,755-759 (2020)

Sub-relativistic acceleration

Poster by me on this topic

Recent publication





L. J. R. Nix *et al. "Terahertz-driven acceleration of subrelativistic electron beams using tapered rectangular dielectric-lined waveguides"* Phys. Rev. Accel. Beams **27** 041302 (2024)

Editors' Suggestion

About this talk

Coming up…

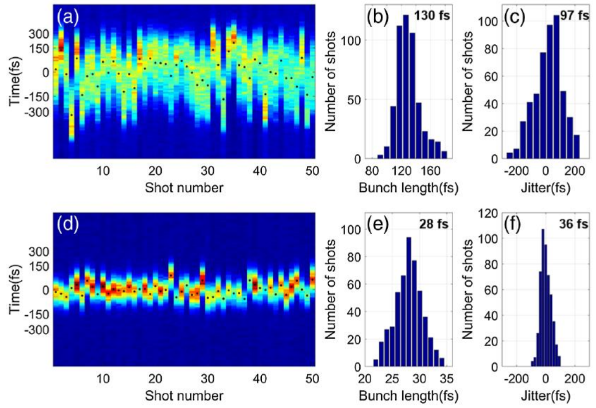
I will present experimental results and supporting simulations showing how THz energy modulation can be used to diagnose and suppress jitter from other accelerator systems.

Content

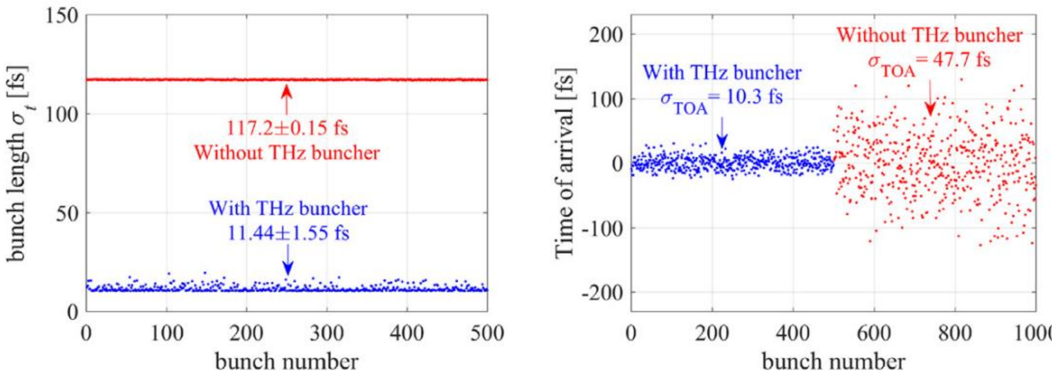
- Longitudinal phase space diagnostic using THz energy modulation
- Compression and bunching
- Jitter modelling and extraction using THz energy modulation
- Jitter suppression

Motivation

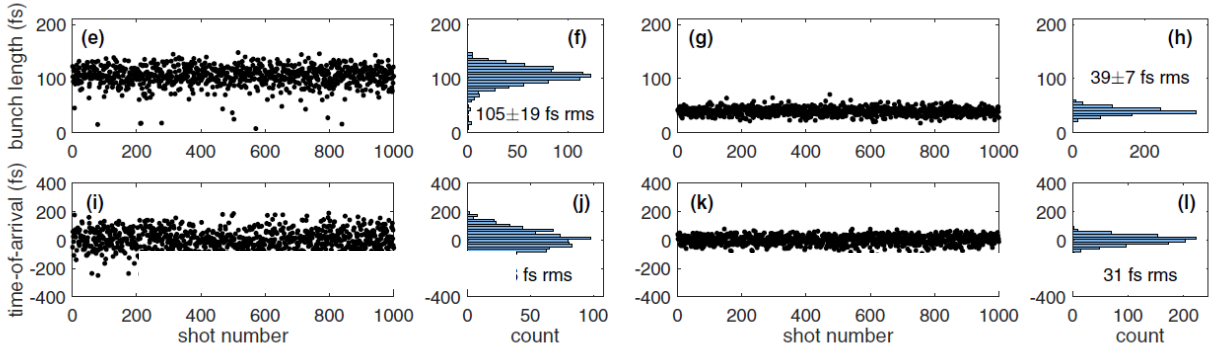
- Diagnosing and suppressing jitter in electron beams using THz is an active research area.
- Using ultra-short fs duration bunches requires excellent timing stability.
- Laser-synchronised bunches with fs-scale jitter are key for
  - Pump-probe experiments.
  - Time-resolved electron diffraction imaging.
  - External injection into e.g. PWFA and FELs.



L. Zhao *et al*. "Femtosecond Relativistic Electron Beam with Reduced Timing Jitter from THz Driven Beam Compression" *Phys. Rev. Letters* ***124***, 054802 (2020)



Y. Song *et al.* "MeV electron bunch compression and timing jitter suppression using a THz driven resonator" *Nucl. Instrum. Methods Phys. Res. Sect. A,* **1047**, 167774 (2023)

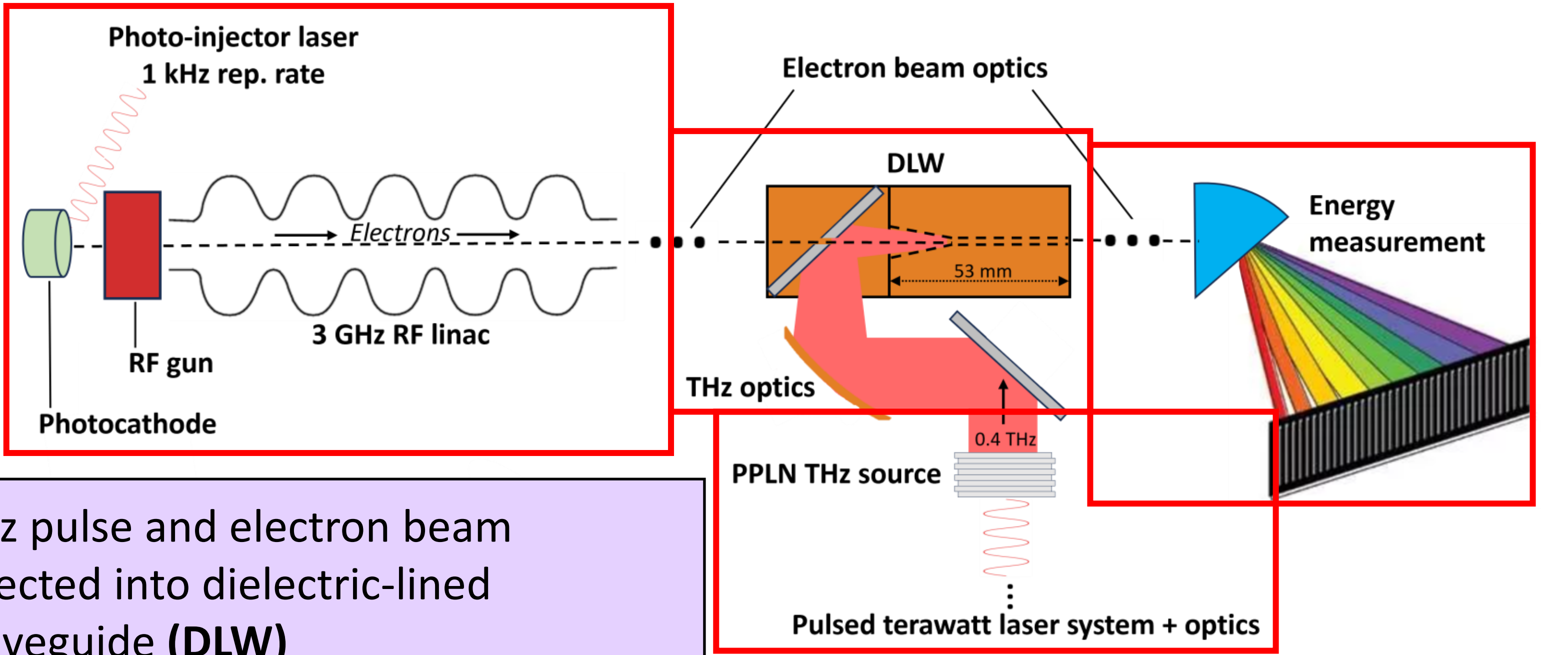


E. C. Snively *et al*. "Femtosecond Compression Dynamics and Timing Jitter Suppression in a THz-driven Electron Bunch Compressor" *Phys. Rev. Letters* ***124***, 054801 (2020)

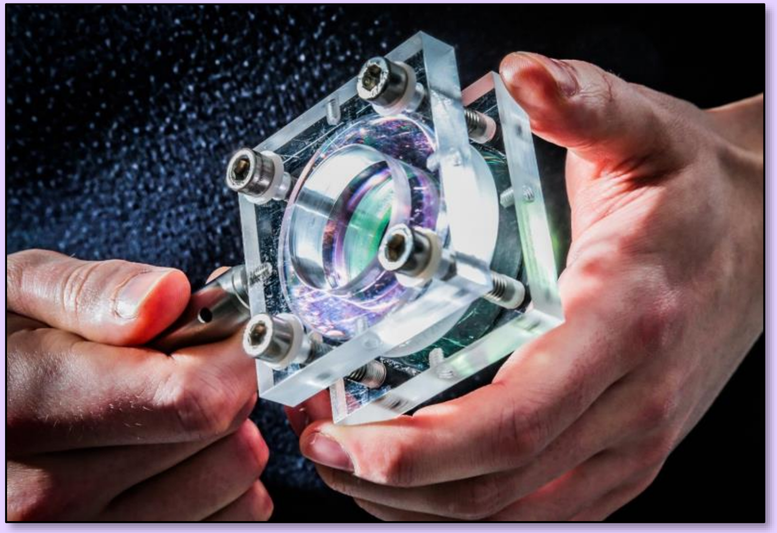
Introduction to the experiment

C ompact
L inear
A ccelerator
R esearch
A pplications

Beam parameters
35.5 MeV
6 ps FWHM
Chirped bunches
100 pC

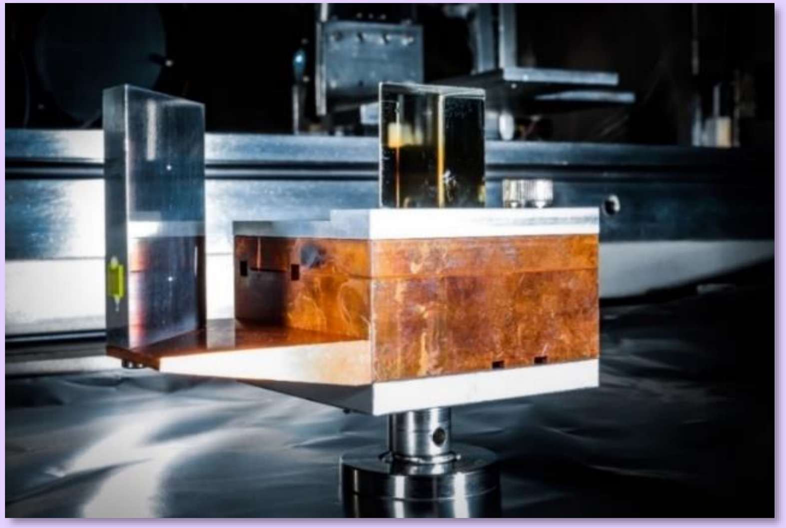


Laser-generated narrowband 0.4 THz pulses using periodically-poled lithium niobate (PPLN) wafers stacks ***(Poster by Patrick Dalton)***



Stack of PPLN wafers for producing laser-generated THz radiation.

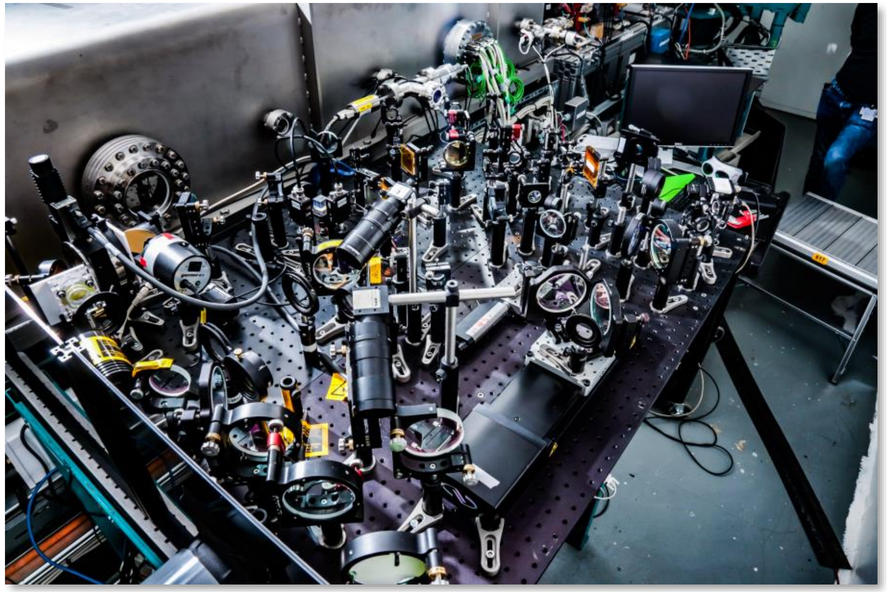
THz pulse and electron beam injected into dielectric-lined waveguide **(DLW)**



DLW installed in the vacuum chamber.

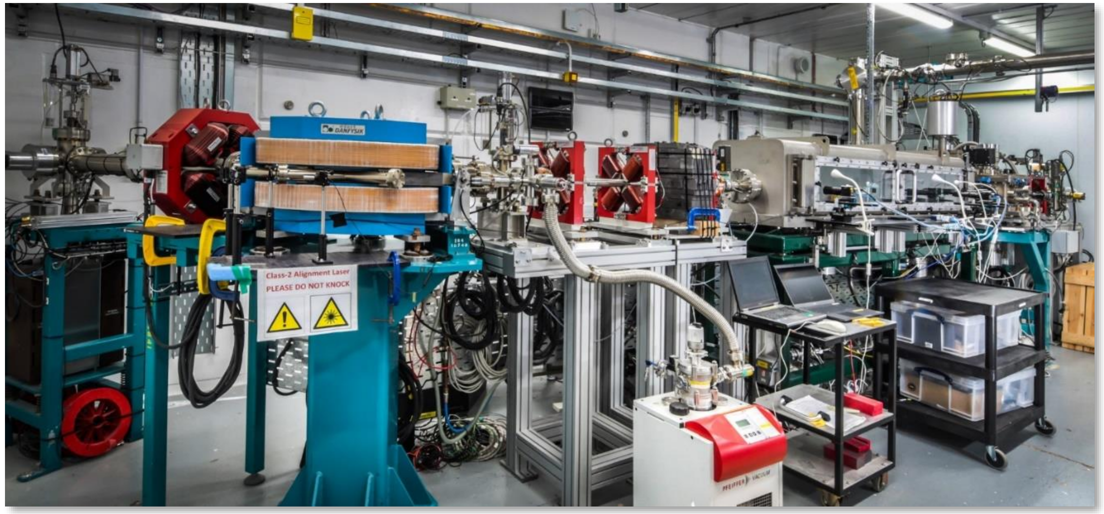
Electron energy measurement using dipole spectrometer

Introduction to the experiment

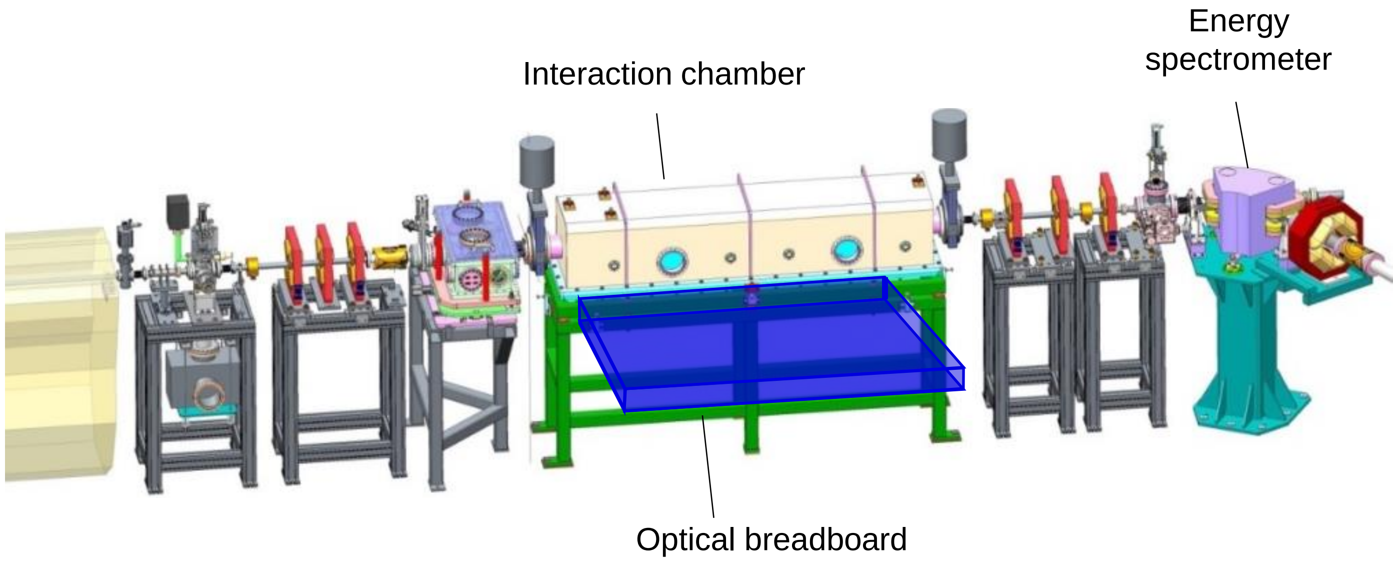


Laser and THz optics outside the vacuum chamber

THz-electron interaction point inside the vacuum chamber



Beam Area 1

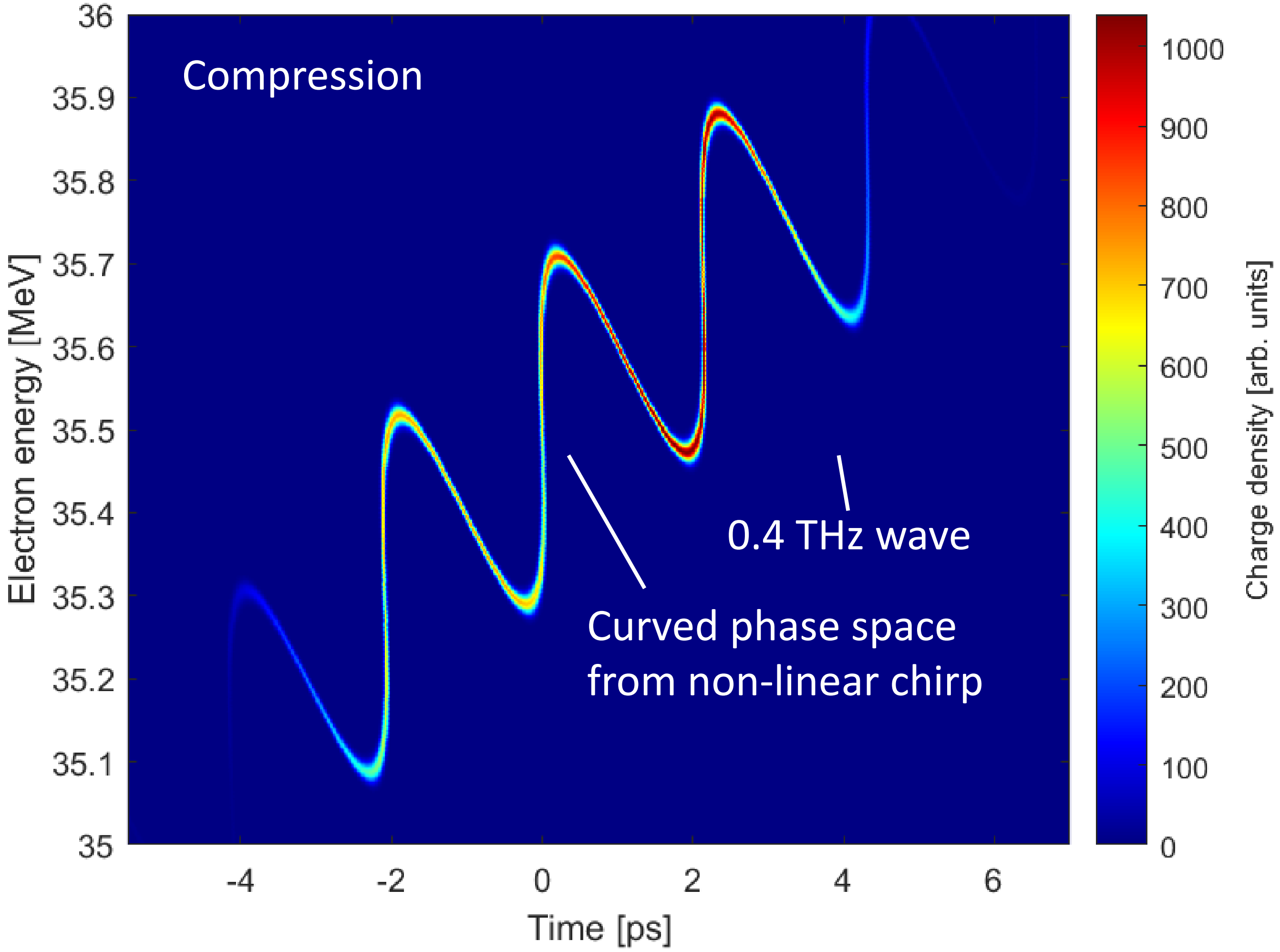


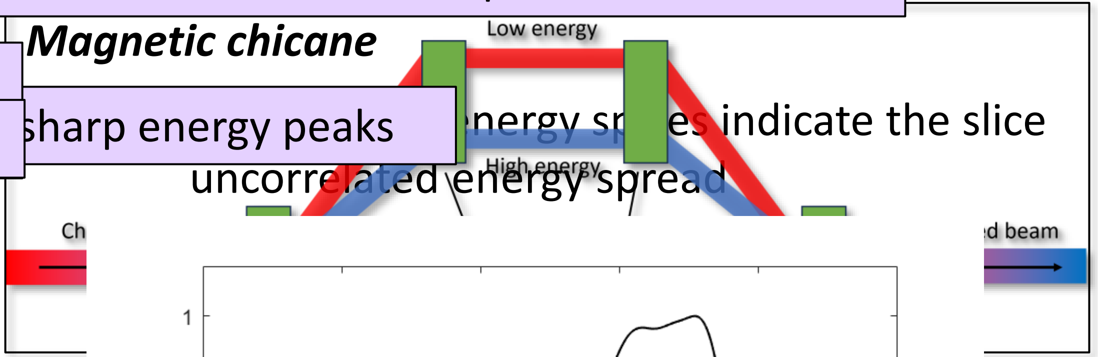
Compression
Accurate longitudinal phase space reconstruction

THz phase scans allow time-slice properties to be diagnosed which are otherwise complex / inaccessible

2.5 ps THz period allows sharp features in the phase space to

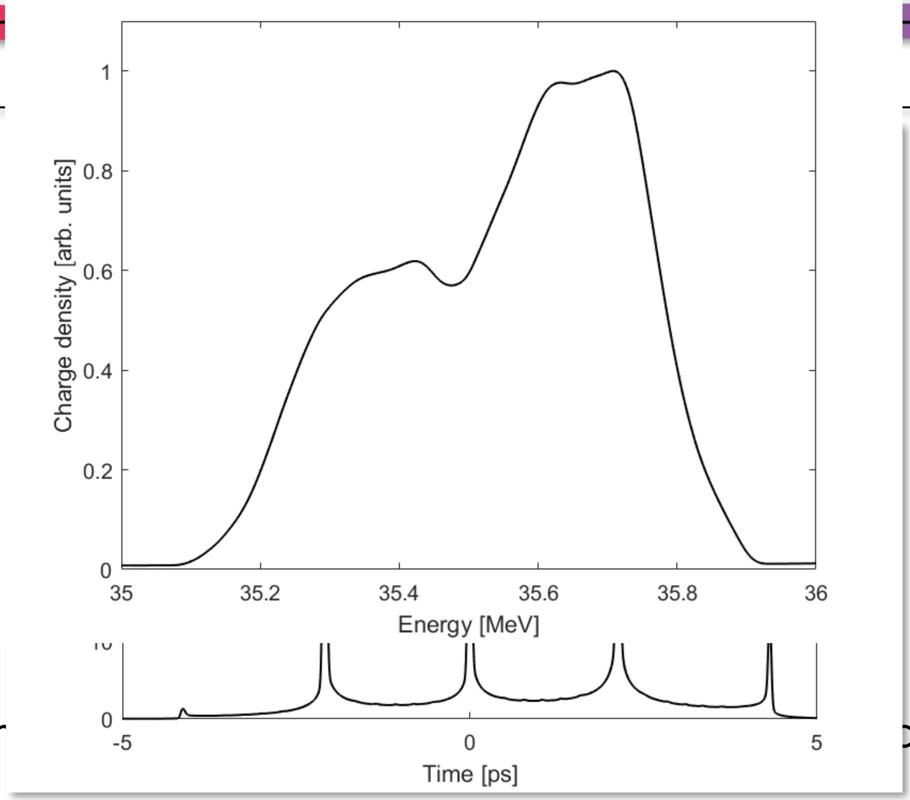
Example compression using moderate THz field





sharp energy peaks

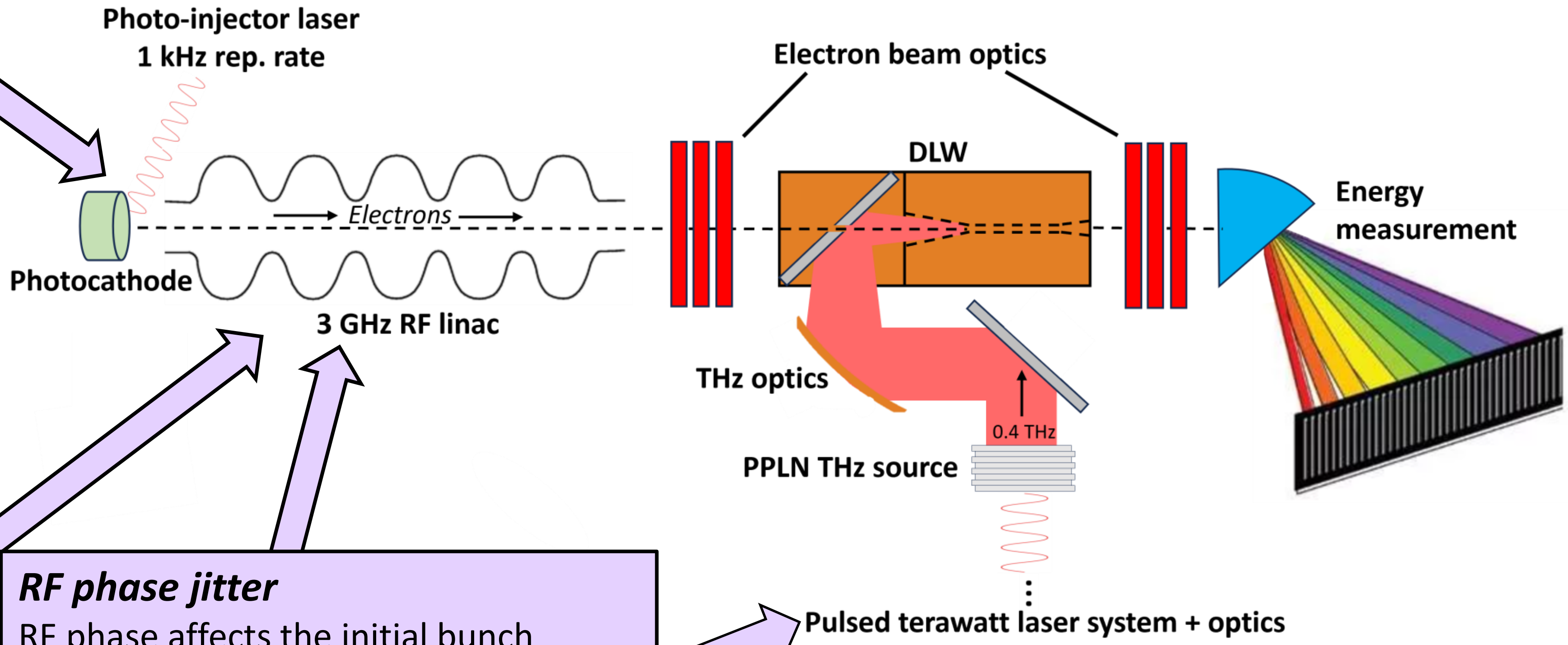
…nergy sp…es indicate the slice uncorrelated energy spread



Er … cycle.

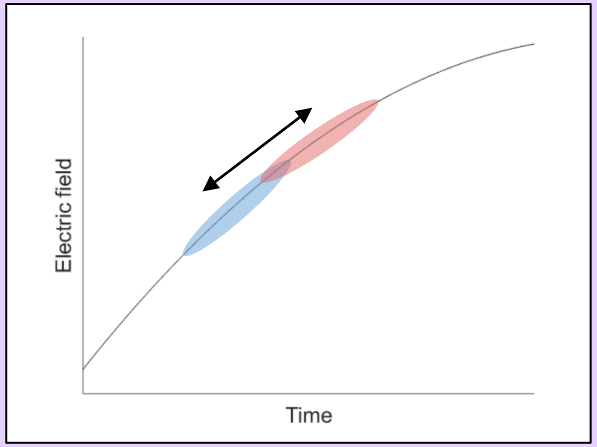
THz-frequency train of < 100 fs, 5 pC micro-bunches.
Short single bunch compression is also possible.

Sources of jitter



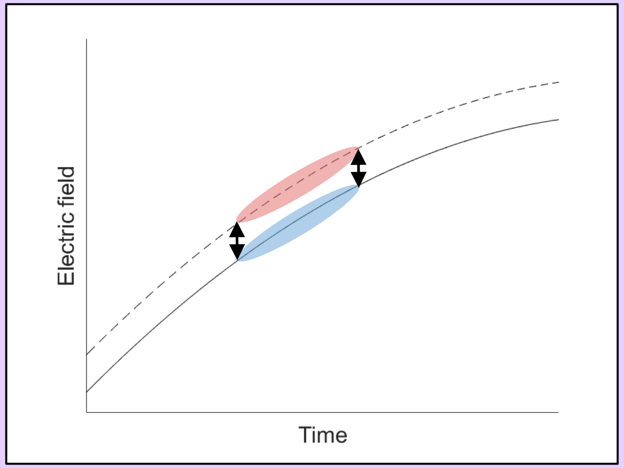
Bunch arrival time jitter

Jitter in injection time into the linac.



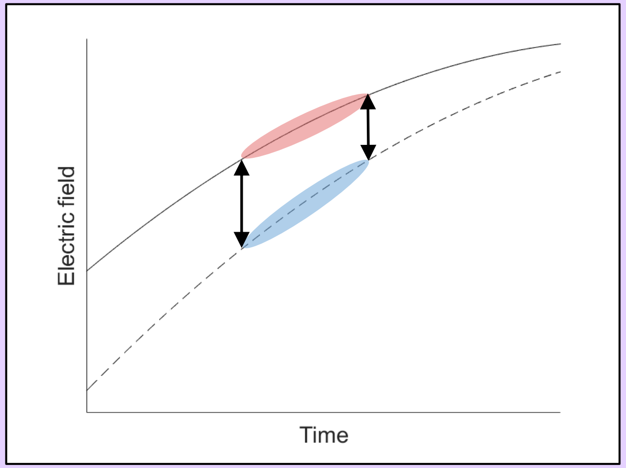
RF amplitude jitter

RF field strength can vary.



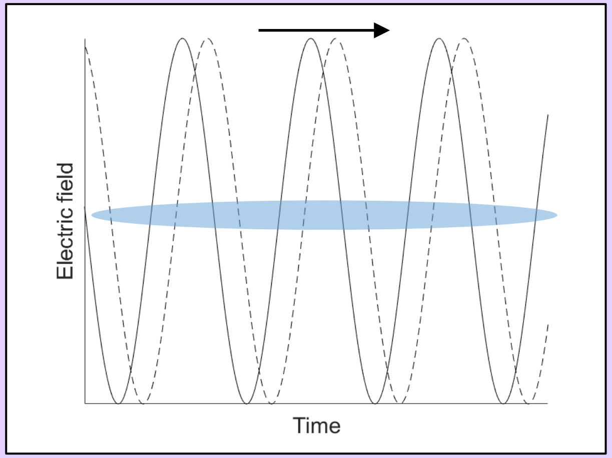
RF phase jitter

RF phase affects the initial bunch energy and chirp.



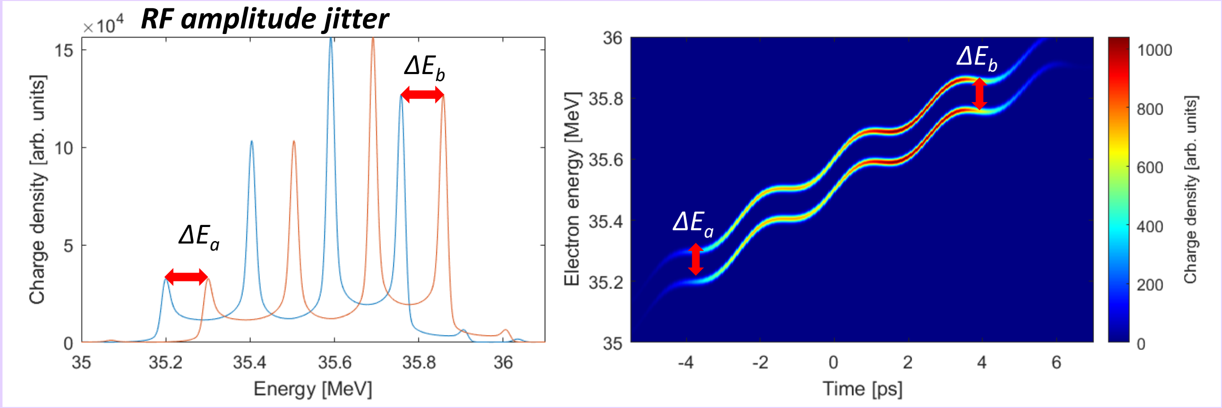
THz arrival time jitter

Alters the phase of the energy modulation imposed on the bunch



Jitter modelling and extraction

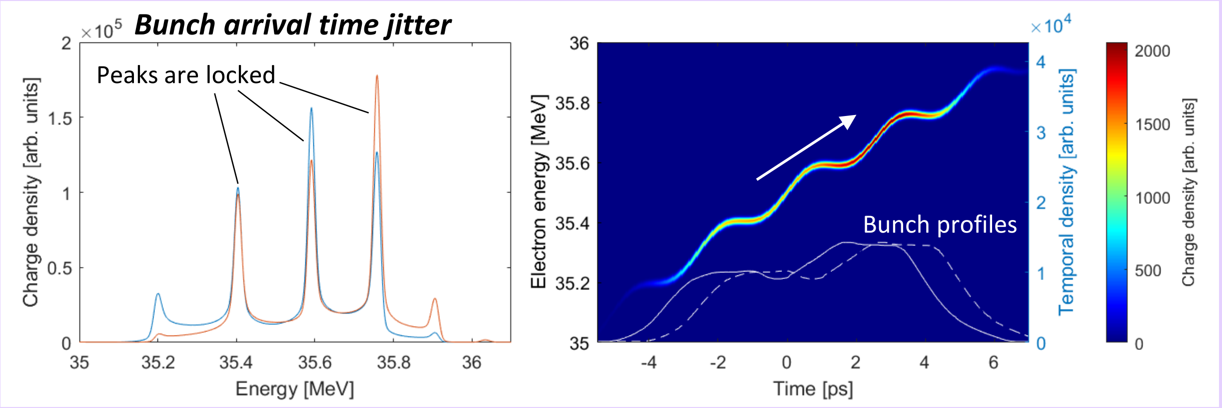
Each source of jitter produces a unique effect in the energy spectrum, and can therefore be extracted independently.



- Pedestal shifted
- Equal energy shift to each peak

$\Delta E_a = \Delta E_b$

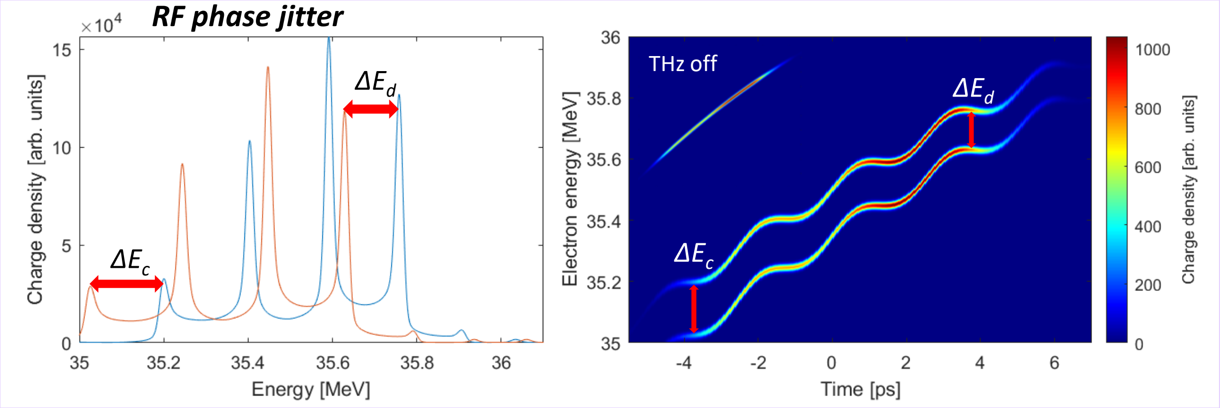
- Phase space moved vertically in energy



- Pedestal is shifted
- Peaks remain at fixed energy

$\Delta E = 0$

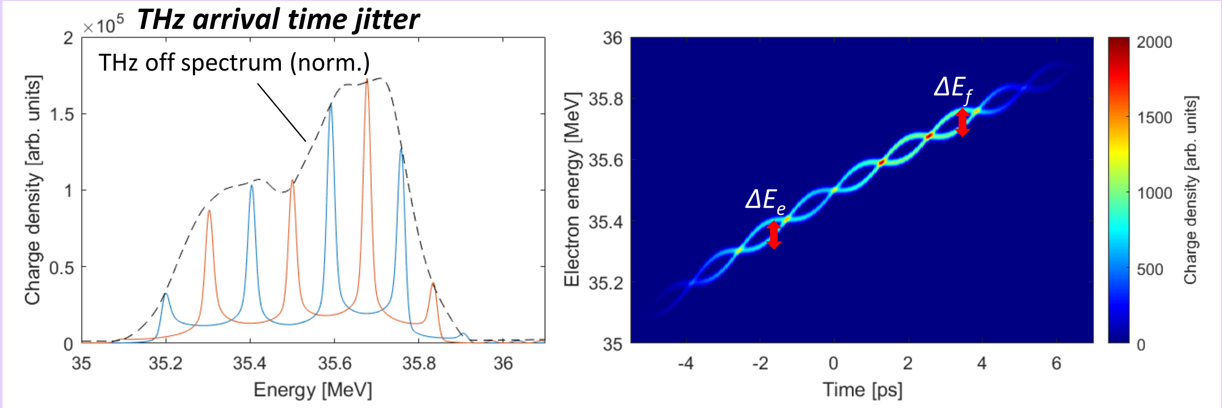
- Phase space remains overlapped
- Bunch profile arrives at a different time



- Energy shift to peaks depends on local chirp

$\Delta E_c > \Delta E_d$

- Chirp profile is of underlying bunch is changed
- THz off LPS has different curvature

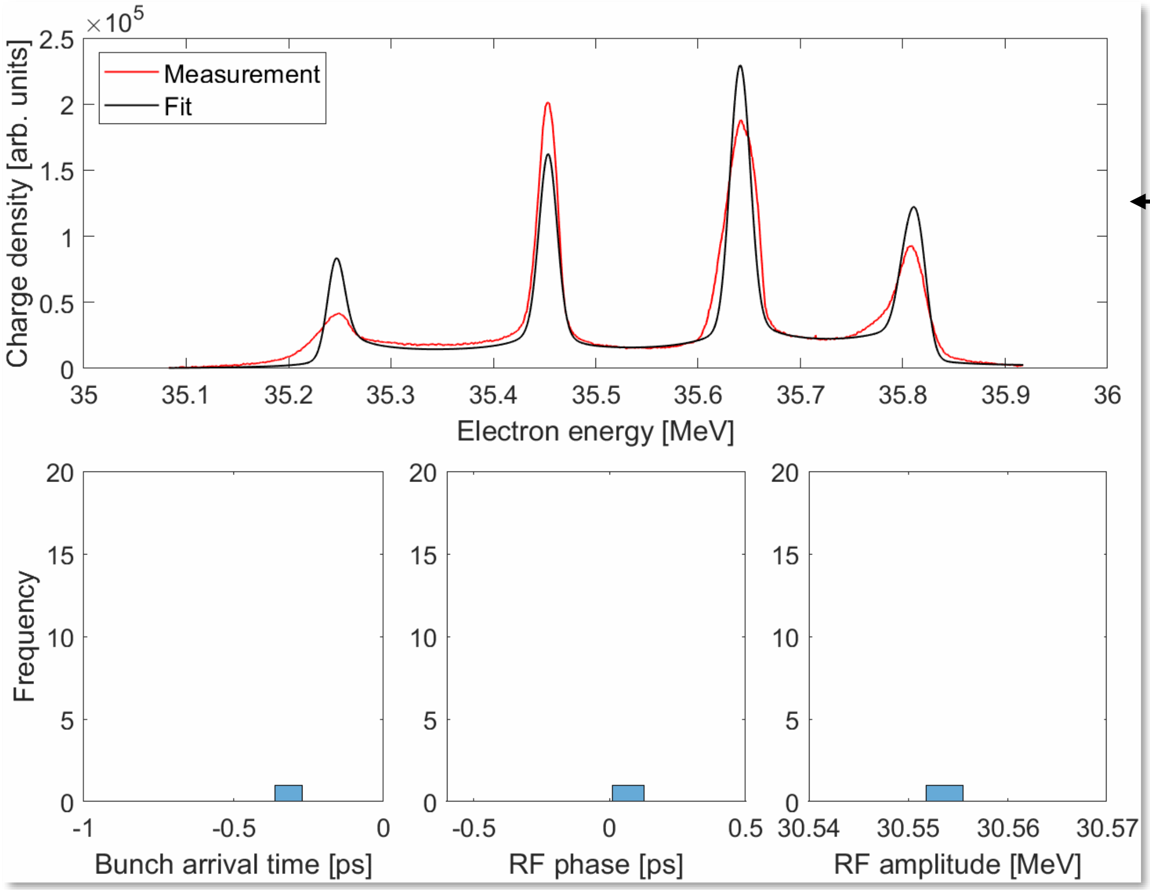


- Peaks are shifted along the underlying phase
- Pedestal is still fixed to the energy of THz off beam

$\Delta E_e \approx \Delta E_f$

- THz phase alters the energies where LPS is flattened
- Chirp profile of underlying bunch unchanged

Jitter modelling and extraction



Measured energy spectra of 50 consecutive THz-modulated bunches.

A best fit to the energy spectrum extracts the phase space.

Values for each source of jitter are found shot-by-shot.

Jitter source	Bunch arrival time	RF phase	RF amplitude
RMS jitter extracted from fitting (rel. to THz drive laser)	157 fs	211 fs	5.3 keV

(Units chosen for convenient simulation)

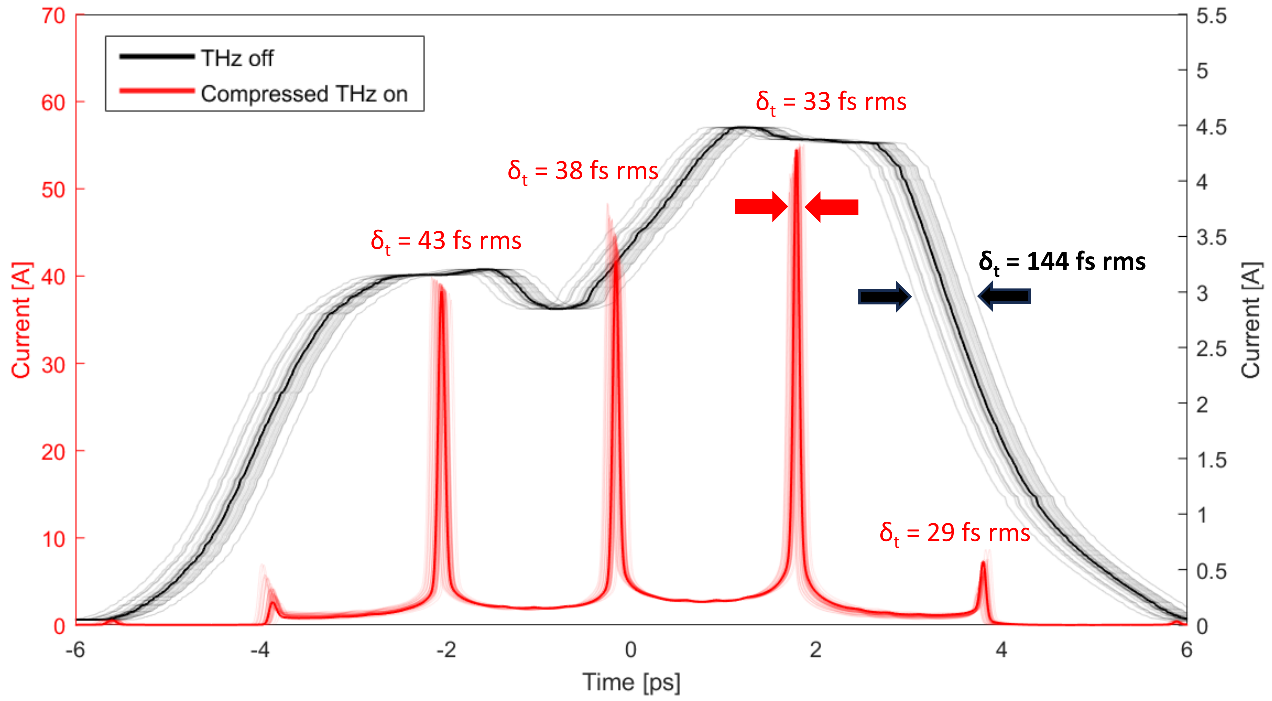
Table 1: Assumed RMS jitter tolerances for each of the machine parameters considered in this study. Values with an asterix are based on measurements with the CLARA FE [3].

Parameter		RMS Jitter
Photoinjector		
Initial bunch charge*		3.4%
Laser spot size		5%
Laser misalignment		100 µm
Laser pulse duration		5%
Laser timing jitter		200 fs
RF Stations	**Voltage**	**Phase**
Gun*	0.035%	0.037°
Linac 1*	0.027%	0.057°
Linacs 2 – 4	0.05%	0.1°
X-band cavity	0.05%	0.3°

By converting the units, we find the extracted jitter compares well with previous work on CLARA.

< M. A. Johnson, J. K. Jones, P. H. Williams, 'Jitter Tolerance for the FEBE Beamline on CLARA', IPAC 2023, JaCoW Publishing

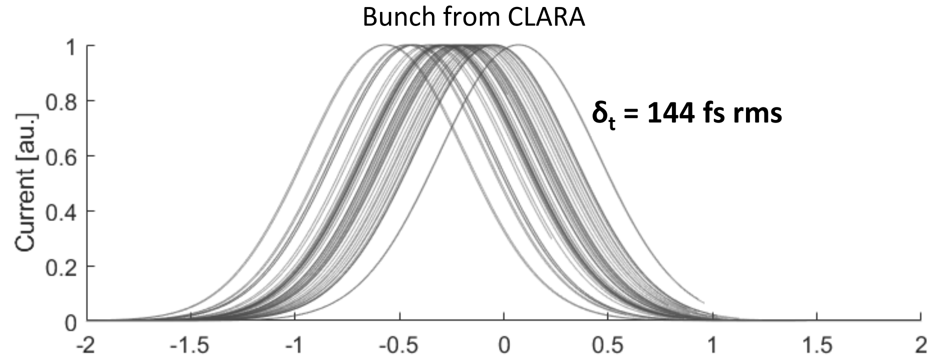
Jitter suppression

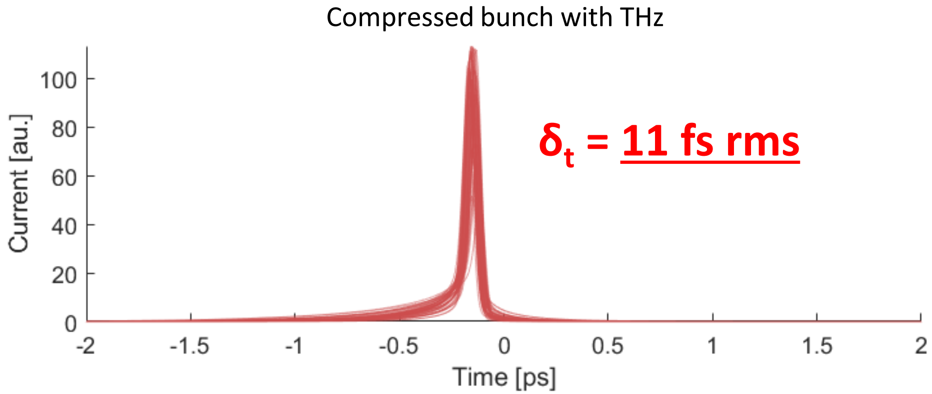


Long bunches for diagnostics, shorter bunches for compression…

- 1.5 ps FHWM
- Lower chirp
- 1.5 x higher THz field
- R_{56} – 2.44 ps/MeV

Jitter relative to the laser is reduced by a factor of **13 x**.



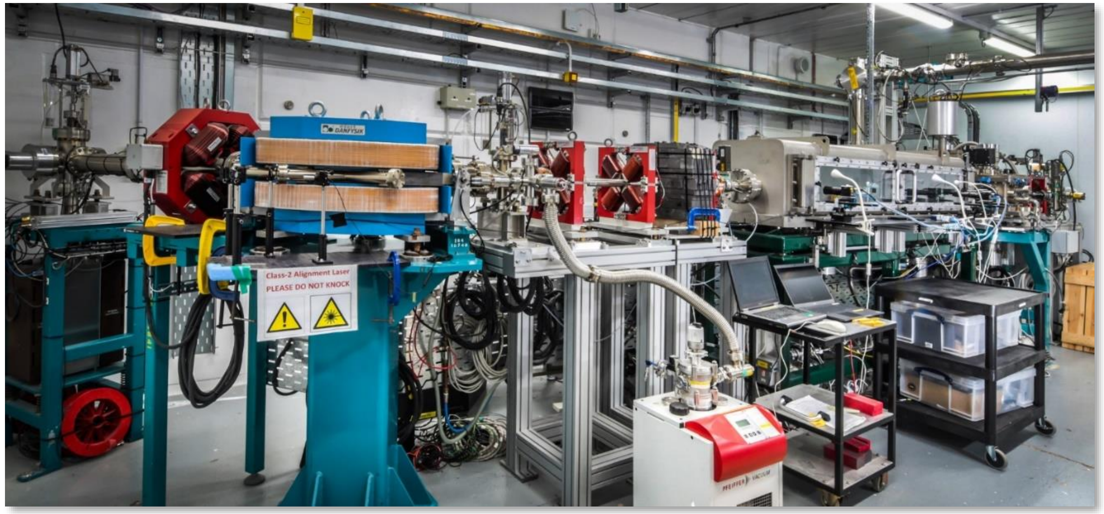


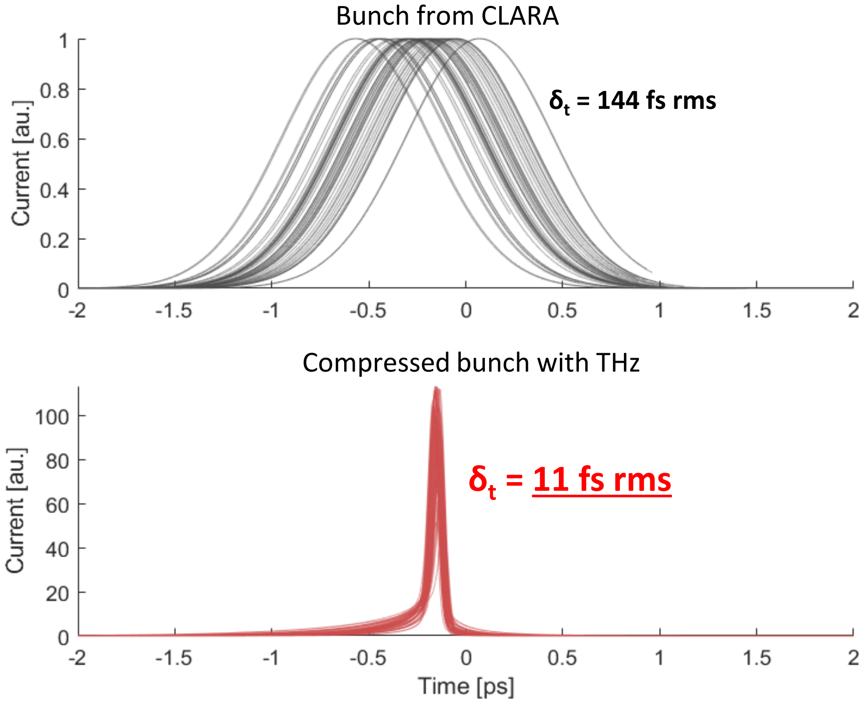
- 50 shots
- Base beam from CLARA (black) - 144 fs rms jitter
- Corresponding compressed bunch trains with THz on (red) - 30 fs rms jitter
- R_{56} – 3.46 ps/MeV

The compressed bunch train becomes locked to the laser.

Timing jitter relative to the laser is reduced by a factor of up to 5.

Summary





THz modulation experiments using CLARA

LPS diagnostic using THz modulation

Jitter from upstream accelerator components can be diagnosed using THz modulation.

THz-modulated / chirped bunches can be compressed into micro-bunch trains or ultra-short single bunches.

The compressed bunches can be locked to the THz drive laser, with rms jitter of 11 – 30 fs.

A directly scalable technique…
Jitter suppression can be readily improved be increasing the THz field and using a lower value of R_{56}, bringing bunches with fs-scale duration and synchronisation within reach.

Thank you for listening!

Thanks for listening! Any questions?

Thanks to all the people involved

Morgan T. Hibberd[1,2], Christopher T. Shaw[1,2], Daniel S. Lake[1,3], Connor D.W. Mosley[1,3], Sergey Siaber[1,3], Beatriz Higuera Gonzalez[1,2], Thomas H. Pacey[1,4], James K. Jones[1,4], David A. Walsh[1,4], Robert B. Appleby[1,2], Graeme Burt[1,3], Darren M. Graham[1,2], and Steven P. Jamison[1,3]

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