THz driven particle acceleration & manipulation

Dr Steven Jamison

Accelerator Science and Technology Centre (ASTeC)
STFC Daresbury National Laboratory
Daresbury, U.K.

Why use THz frequencies?

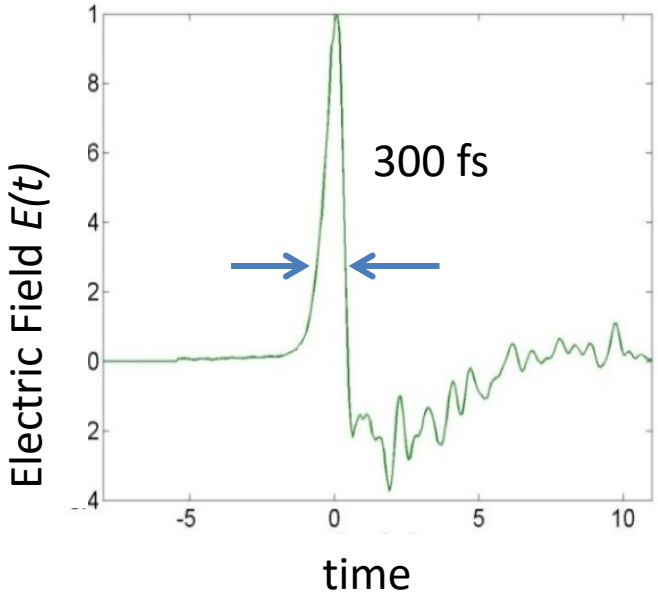
Very high fields strength possible

>> 100 MV/m demonstrated

Direct control of electric field profile

frequency / phase control of THz field

Time structure well matched to <100 fs bunches



Challenges

- Generation & coupling of polarisation states (Longitudinal polarisation)
- Dispersion control
- Velocity matching of THz to particle: $V_\phi = \beta$
- ***Wakefields, beam-loading, ….***

Radio frequency

- Frequency ≈3 GHz
  period ≈ 300ps,
- $\lambda \approx 10$cm
  Cavity aperture ~2 cm
- Eacc ~ 10- 100 MV/m
- Pulse length: 5 ms (superconducting)
  5 μs (normal conducting)
- Energy to cavity: ~10J

Optical Laser

- Frequency ≈300 THz
  period ≈ 3 fs,
- $\lambda \approx 1\mu$m
  Cavity aperture ≈ 1μm
- $E_{acc} \approx$ 100MV/m to >> GV/m
- Pulse length 20fs – 1ps
- Energy to 'cavity': ~1mJ

Laser advantages:

- pulse duration ~ bunch duration (energy efficiency)
- Very high field strengths possible (material breakdown); compact accelerators
- Oscillation period short, in desired femtosecond regime

Laser disadvantages:

- Oscillation period *too short*, below ~ps injection capability
- Small apertures: wakefield perturbations on beam;
  injection & extraction beam transport
  manufacturing of structures (10's nm precision)

Radio frequency

- Frequency ≈3 GHz
  period ≈ 300ps,
- $\lambda \approx$ 10cm
  Cavity aperture ~2 cm
- Eacc ~ 10- 100 MV/m
- Pulse length: 5 ms (superconducting)
  5 μs (normal conducting)
- Energy to cavity: 10's-100's J

THz

- Frequency ≈1 THz
  period ≈ 1 ps,
- $\lambda \approx$ 300μm
  Cavity aperture ≈ 1 mm
- $E_{acc} \approx$ 100MV/m to >> GV/m
- Pulse length 1-5 ps
- Energy to 'cavity': ~10-100 μJ

THz advantages:

- pulse duration ~ bunch duration (energy efficiency)
- Very high field strengths possible (material breakdown); compact accelerators
- Oscillation period short, *but longer than desired pulses*

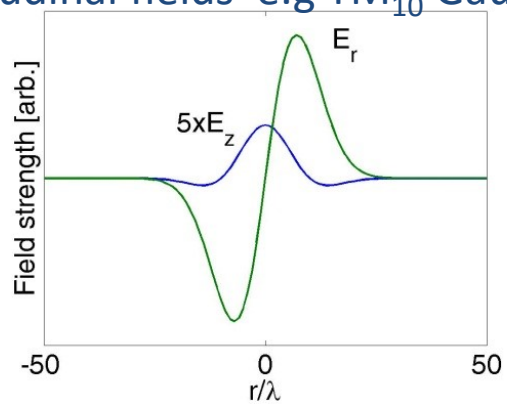
THz disadvantages:

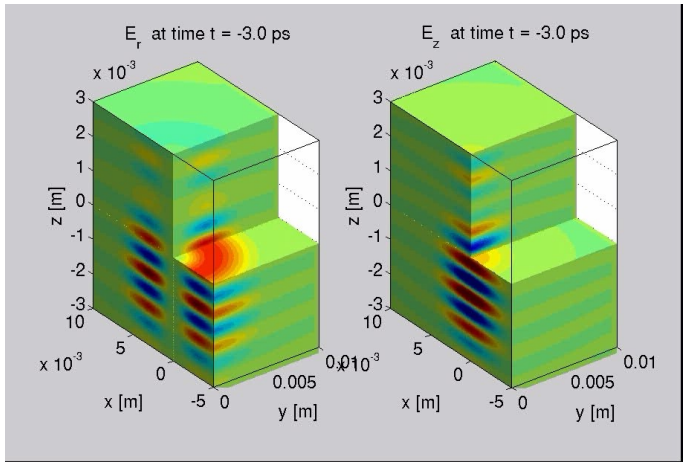
- Broadband pulses – controlling dispersion
- *Small apertures: wakefield perturbations on beam;*
  injection & extraction beam transport

Direct acceleration with THz

- Longitudinal fields, $\underline{E} \parallel \underline{v}_e$ (for linear acceleration)
- Velocity phase matching over interaction length

Longitudinal fields e.g TM_{10} Gaussian

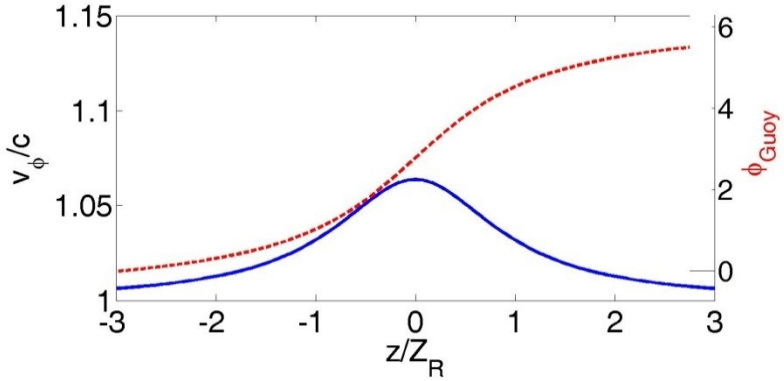




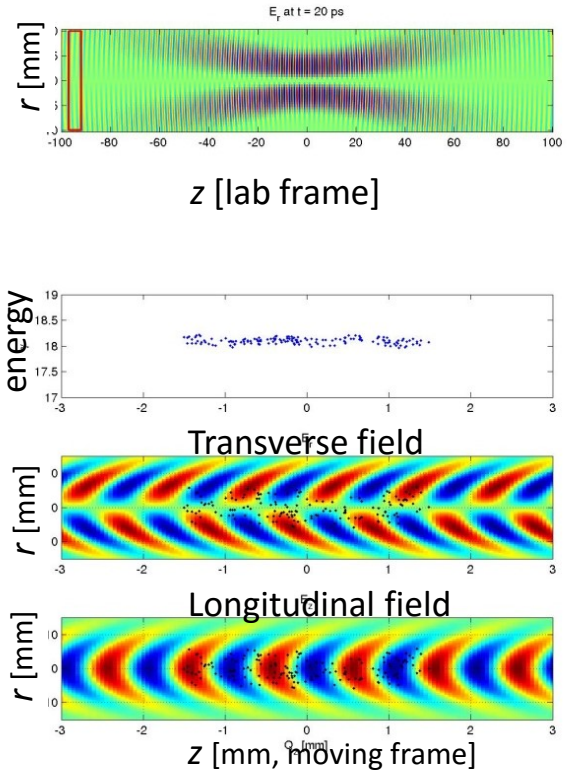
Phase velocity in free-space $v_\phi > c$

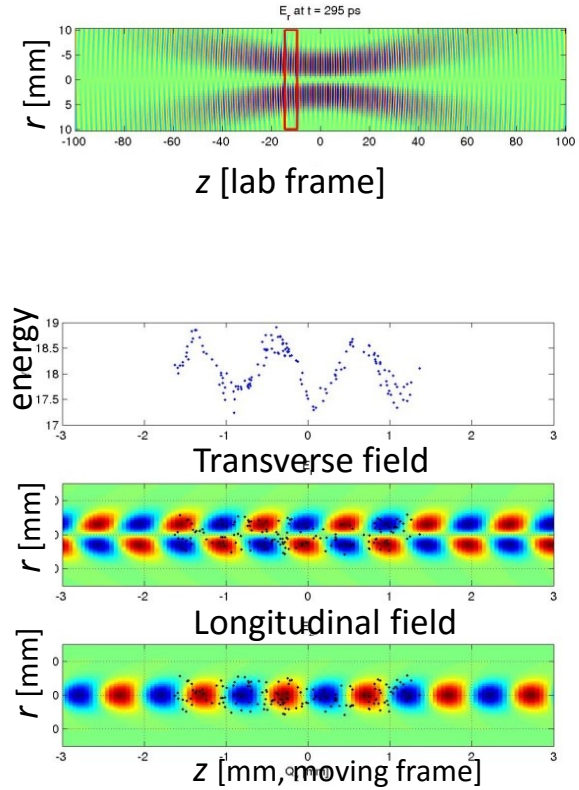
- Guoy phase-shift : interaction limited to Rayeigh length
- Slippage compared to *v=c*

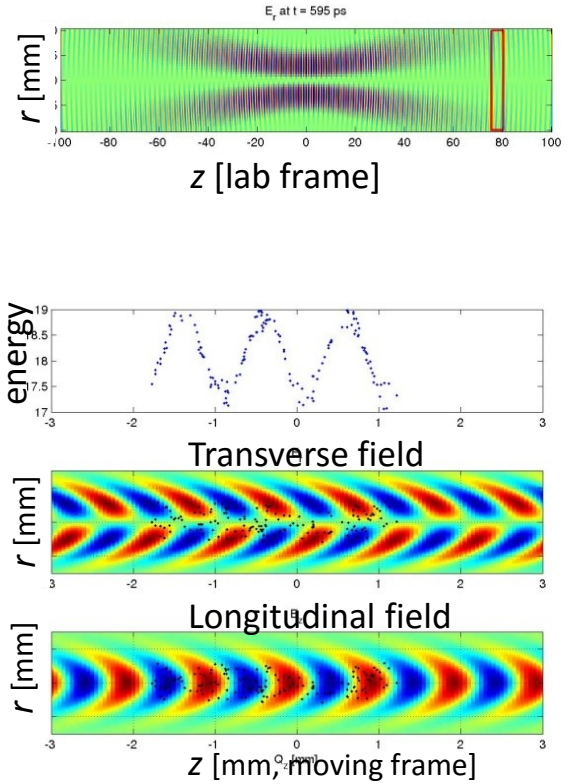
		$L_{slip} = \beta \lambda_{rad} /(1-\beta)$
10 MeV	$\beta = 0.95$	$20 \lambda_{rad}$
1 GeV	$\beta = 1 - 5\times10^{-4}$	$2000 \lambda_{rad}$



Time snap-shots of particle energy and accelerating field



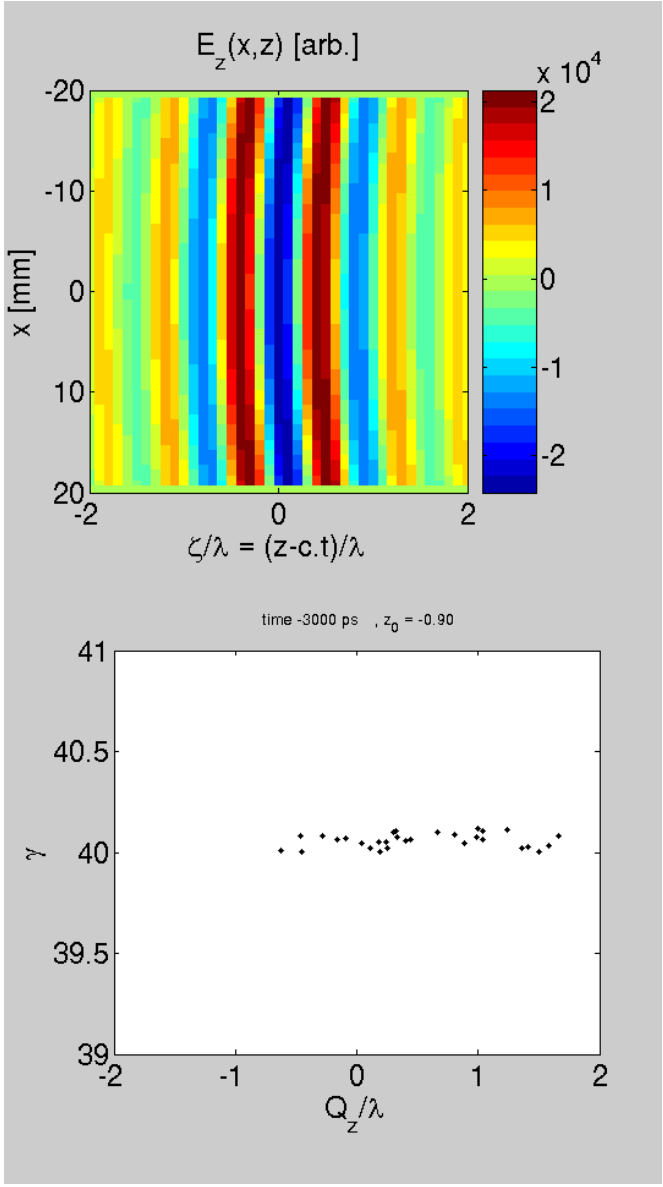




Particle acceleration with TM^*_{10} fields

$$H = \sqrt{(\mathbf{p} - z\frac{q}{c}\mathbf{A})^2c^2 + m^2c^4} + q\phi$$

- Analytic expressions for potentials ***A***(***x***,*t*), *ϕ*(***x***,*t*)
- *Evaluate motion in traveling frame*
  $Q_z = z\text{-}ct$



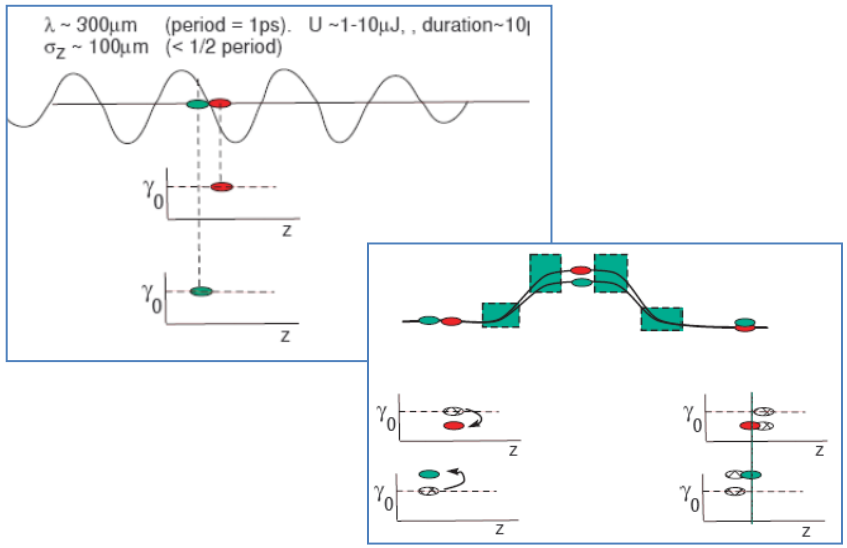
- Net acceleration is possible
- Limited by phase slippage to effective interaction length $z_{Rayleigh}$

THz driven acceleration and synchronisation

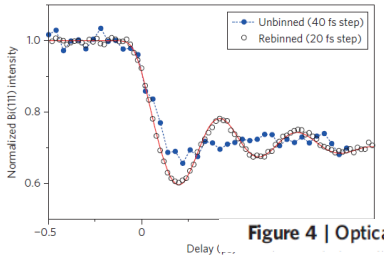
Free-space still has potential application despite acceleration limits

Active synchronisation of particle beams

THz driven synchronisation & bunching



Critical issue for FEL pump-probe science



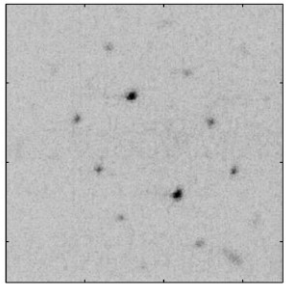
Achieving few-femtosecond time-sorting at hard X-ray free-electron lasers

M. Harmand[†]*, R. Coffee[2], M. R. Bionta[2,3], M. Chollet[2], D. French[2], D. Zhu[2], D. M. Fritz[2], H. T. Lemke[2], N. Medvedev[4], B. Ziaja[4,5], S. Toleikis[1] and M. Cammarata[6]*

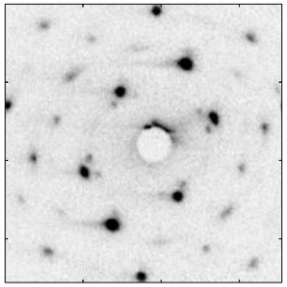
Figure 4 | Optically excited coherent A_{1g} phonon mode of bismuth.

THz driven electron-diffraction

single−shot, single crystal

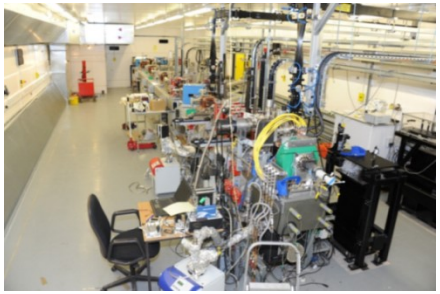


multi−shot, single crystal

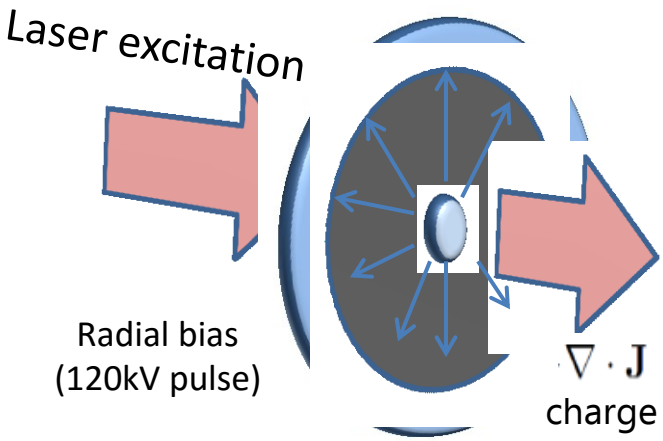


Requirements

- 200 keV – 5 MeV
- Femtosecond laser-electron synchronisation



Generating Longitudinal Polarised THz pulses
I: Photoconductive antenna



Simple & efficient

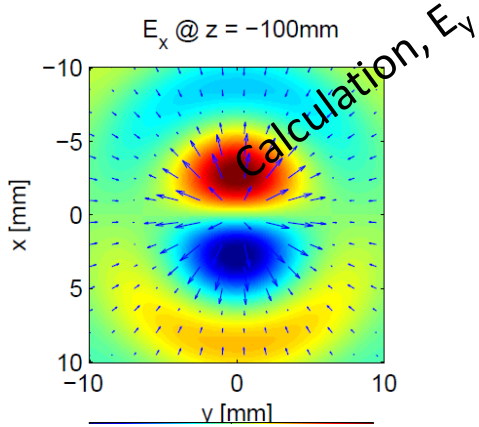
but Lacks temporal shaping capability

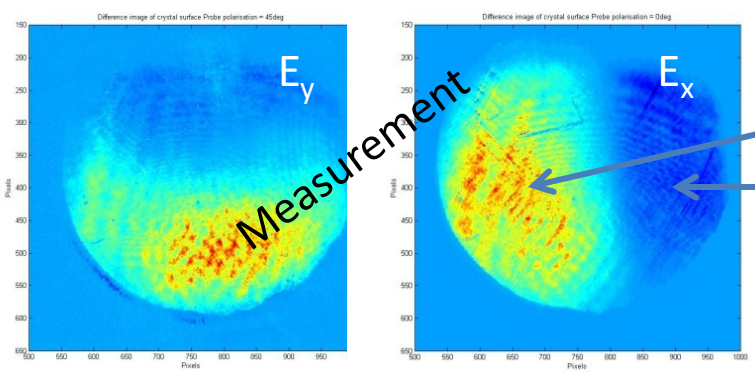
$\nabla \cdot \mathbf{J}$ generates charge separation → origin of longitudinal field

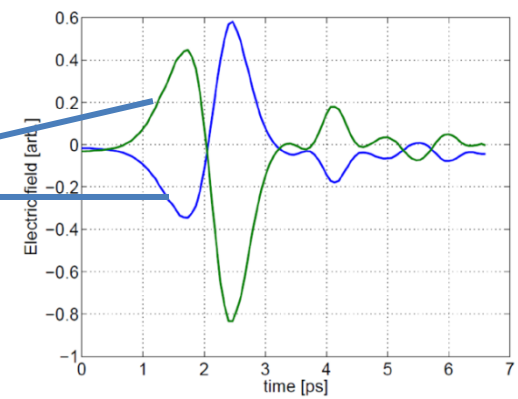
$$\mathbf{E}(\mathbf{x},t) = \frac{1}{4\pi\epsilon_0}\int \mathrm{d}^3\mathbf{x}'\frac{1}{R}\left[\nabla'\rho - \frac{1}{c^2}\frac{\partial \mathbf{J}}{\partial t}\right]_{\mathrm{ret}}$$

Transverse field from current surge

Longitudinal field implicit from □□E = 0

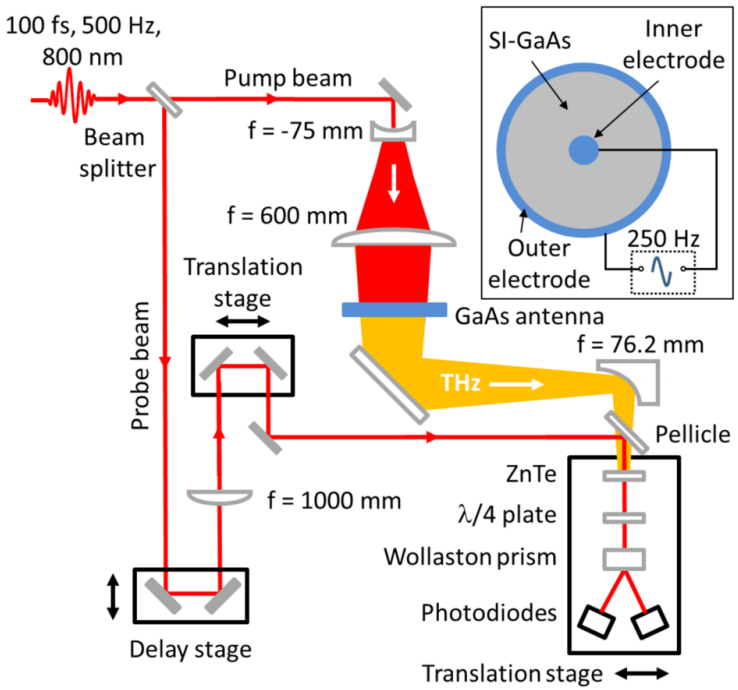




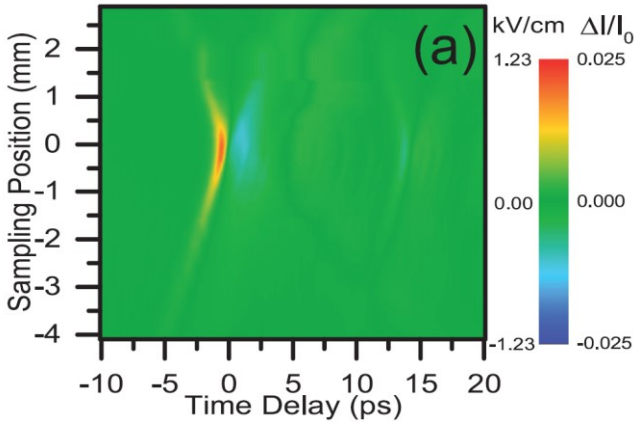


0.2 MV/m longitudinal fields from photoconductive antenna

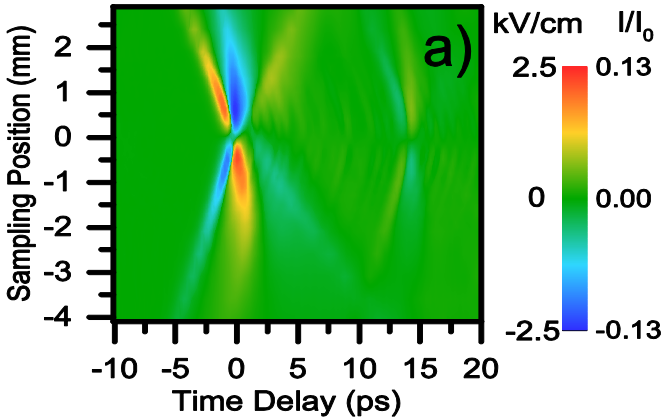
Cliffe et al. Appl. Phys. Lett. **105,** 191112 (2014)



Longitudinally polarised field



Transversely polarised field



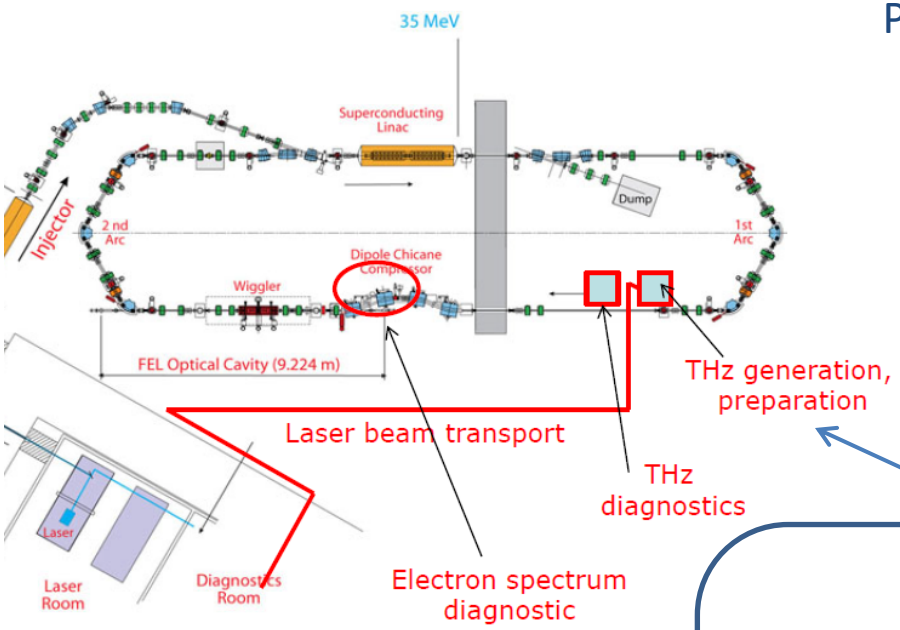
x6 below semiconductor saturation

$\Rightarrow$ capable of >1.2MV/m with more laser energy

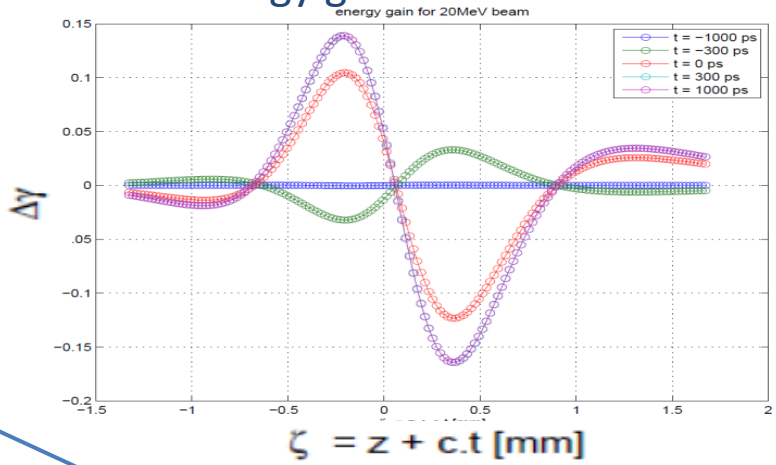
Further increases requires larger antenna

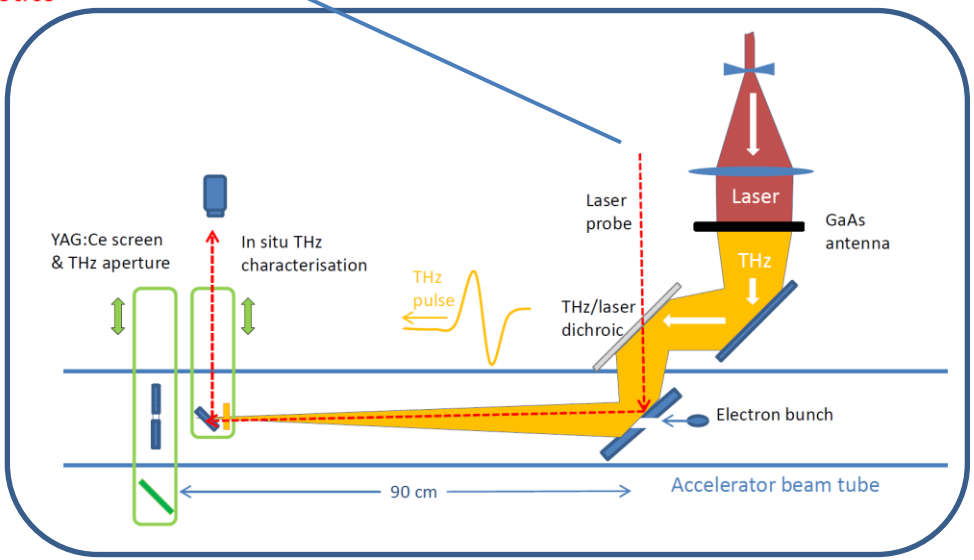
Energy Modulation by Interaction with THz Radiation

An experiment on ALICE energy recovery linac



Predicted energy gain for 20 MeV beam

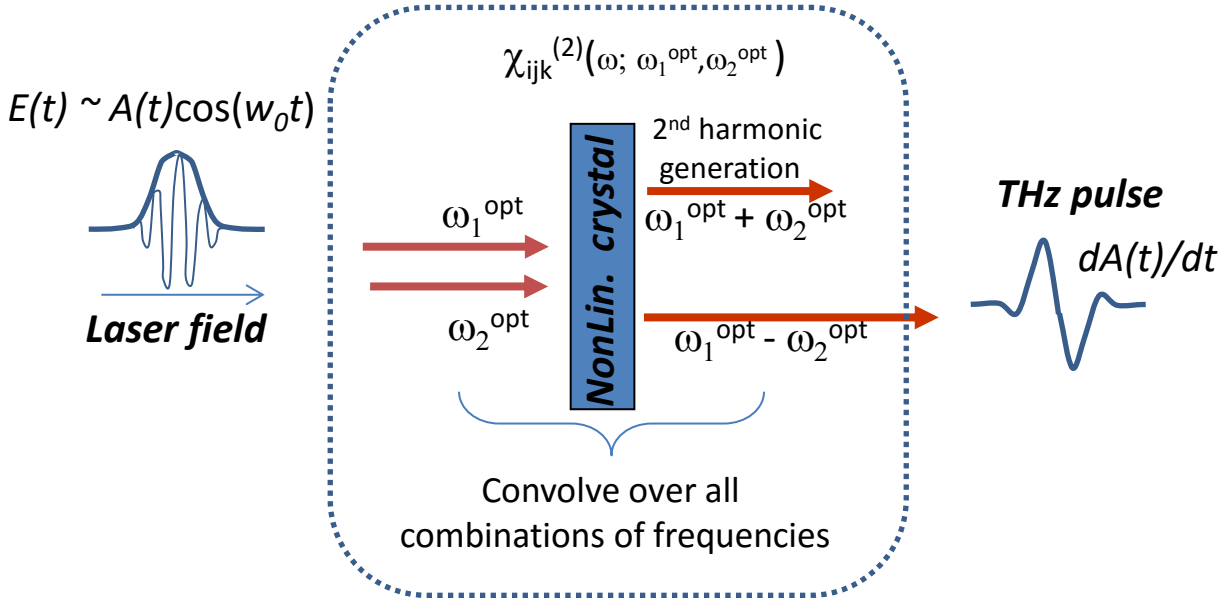




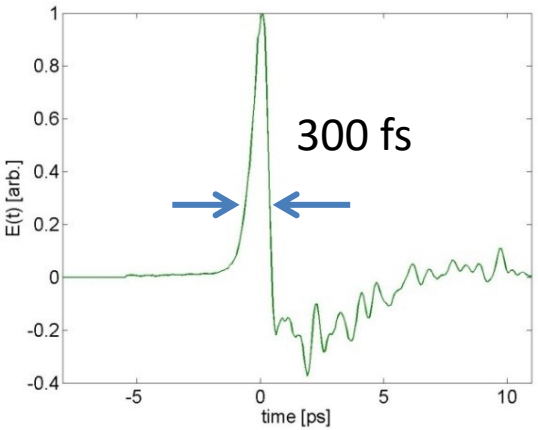
Proceedings of FEL'2012
Jamison et al.

THz generation by Optical Rectification

Difference frequency mixing by broadband ultra-short optical pulse



Typical measured $E(t)$



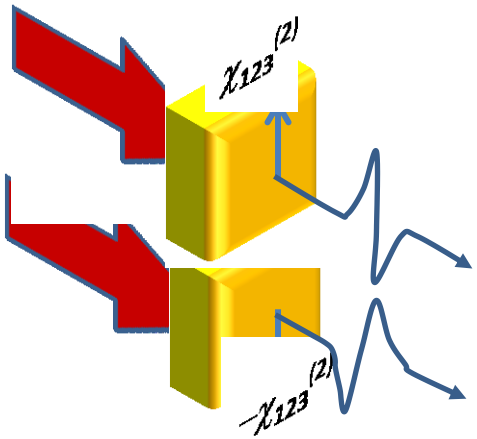
Very high fields strength possible

- > 100 MV/m possible
- 5GV/m reported (at focus)

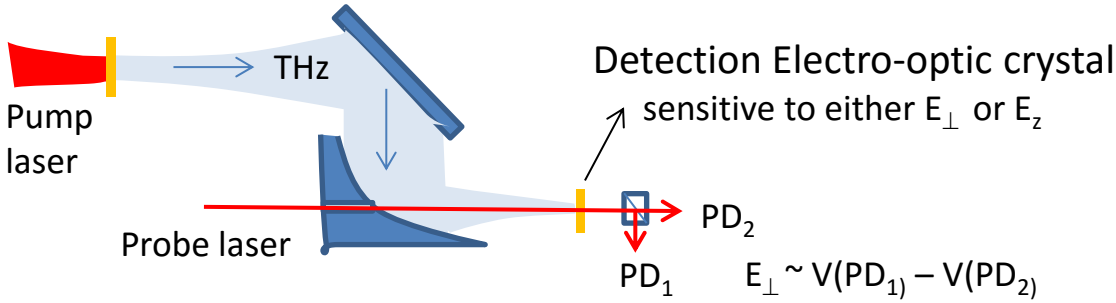
Challenges for application to acceleration

- Available polarisation states restricted by $\chi_{ijk}^{(2)}$ tensor
  plane wave emission → longitudinal polarisation ???
- Velocity matching of THz to particle: $V_\phi < c$ in free-space

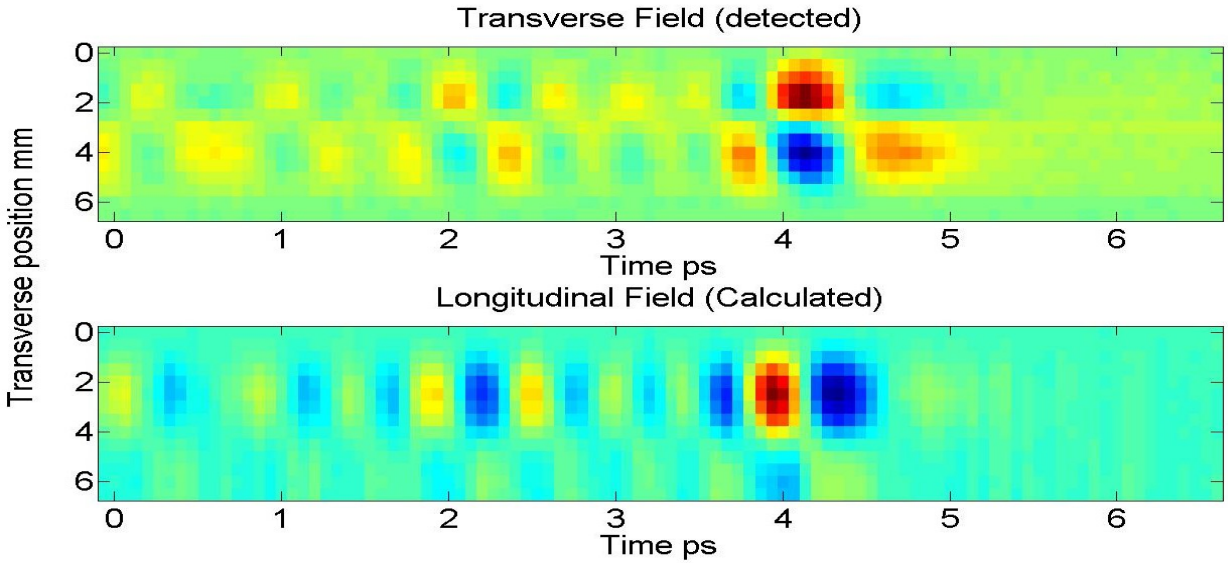
Transverse plane wave → longitudinal polarisation



Paired non-linear polarisation/source for opposite polarity THz fields



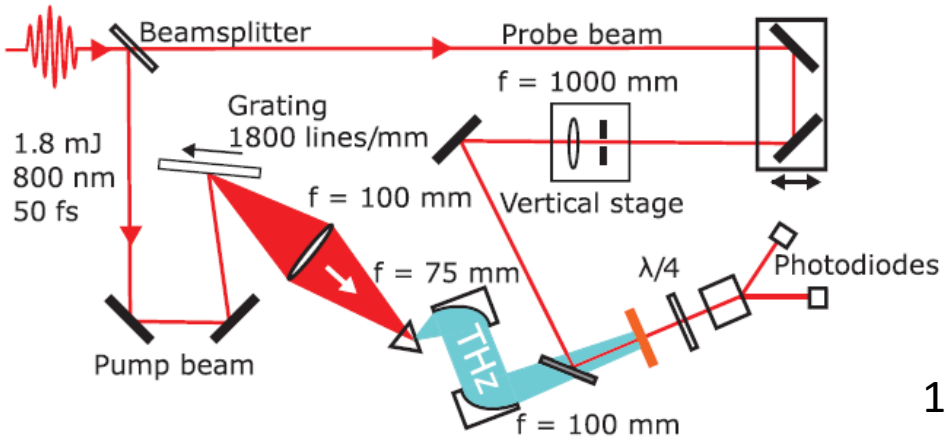
E_z generated from discontinuity $$E_z = \int \partial E_x/\partial x + \partial E_y/\partial y$$



Longitudinal polarisation in $LiNbO_3$

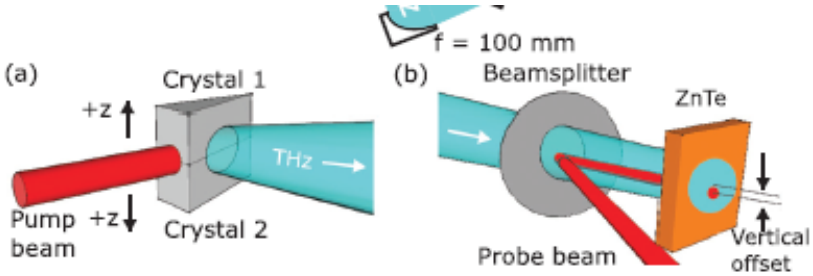
High-field strength non-linear material

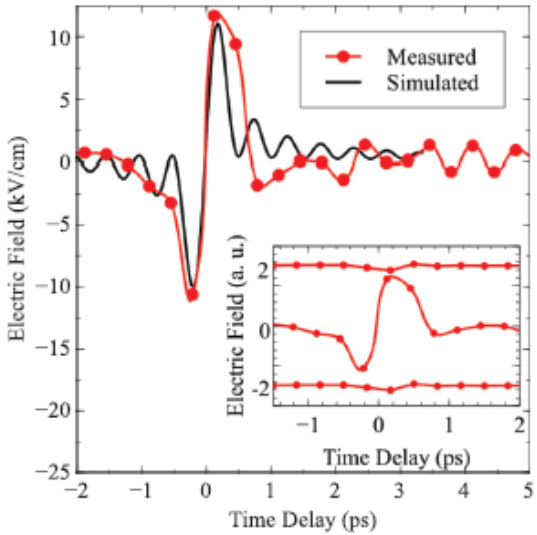
Requires non-collinear & 'tilted pulse front' phase matching



1.1 MV/m longitudinal field

(*with only 1mJ laser energy)*



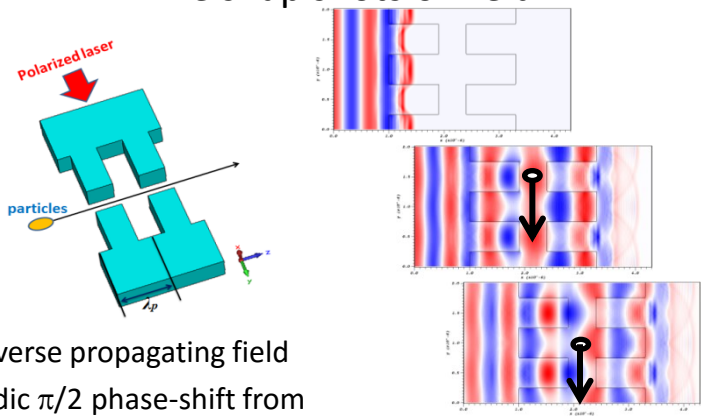


Cliffe et al. Appl. Phys. Lett. **108,** 221102 (2016)

Velocity matching of particle and accelerating field

Dielectric Laser acceleration approach

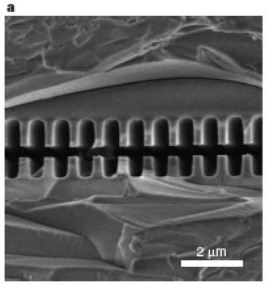
Time snap shots of field

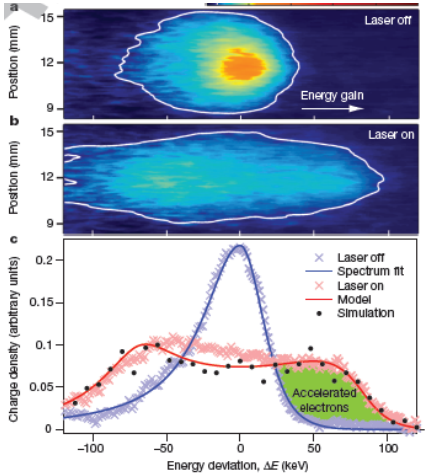


Transverse propagating field

Periodic $\pi/2$ phase-shift from dielectric step

Recent results from SLAC
Peralta et al. Nature **503,** 91 (2013)

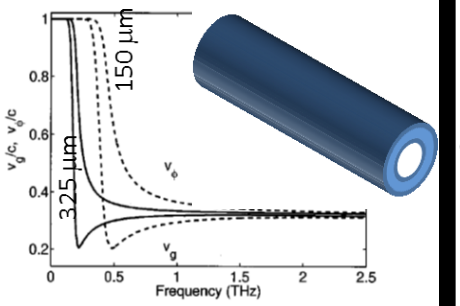


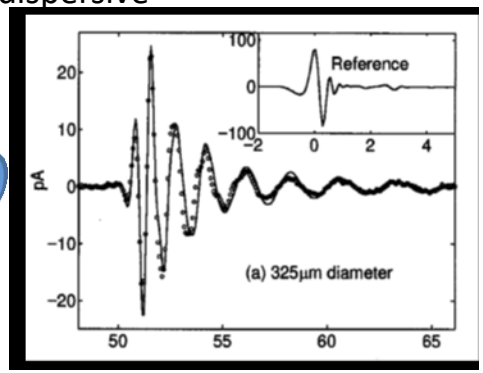


- 20um beams size injected into <10um aperture
- ~1ps duration injected into 3fs period structure

Dielectric Lined waveguide approach

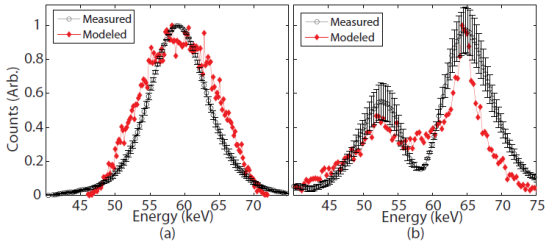
v_ϕ <c possible, but dispersive

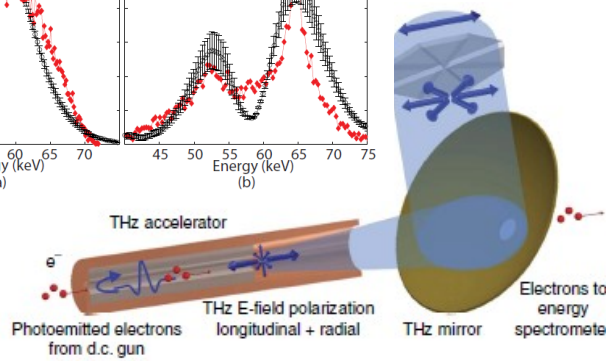




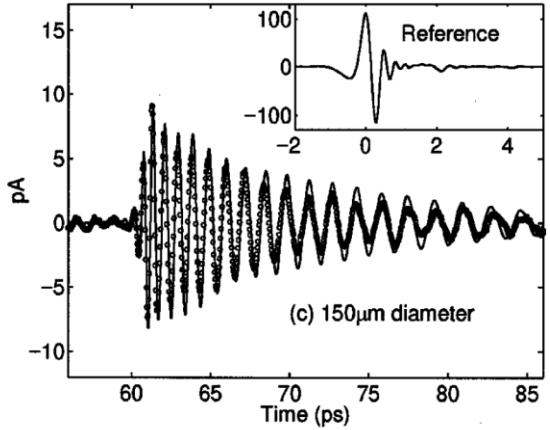
Jamison et al, Appl. Phys. Lett **76** 1987 (2000)

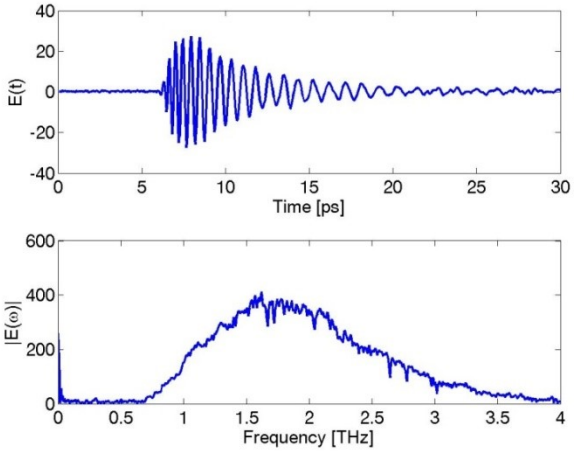
Recent results from MIT/DESY
Nani et al. Nature Comm.6 8486 (2015)

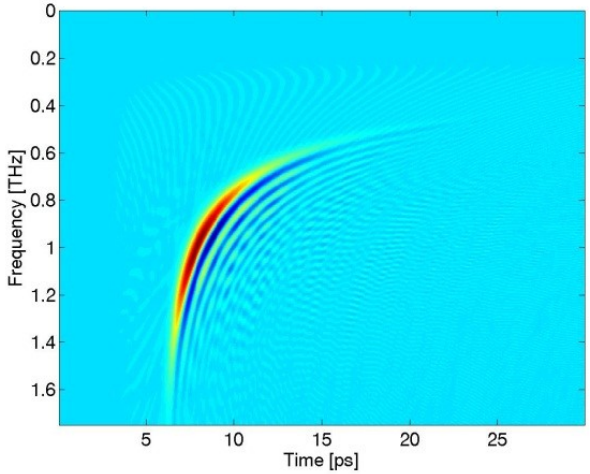




Waveguide Dispersion

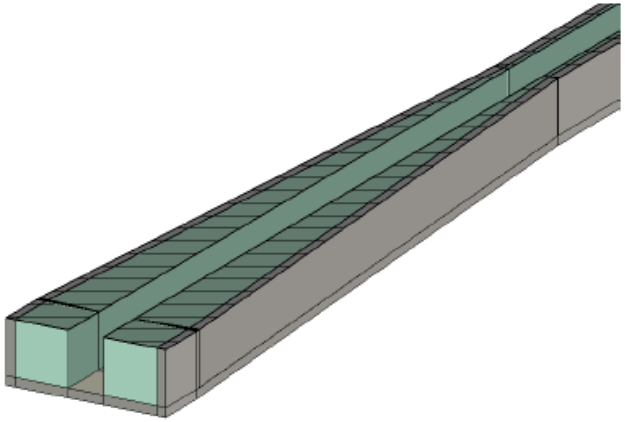






Waveguide Dispersion & coupling

Design, simulation for coupling and velocity matching THz source



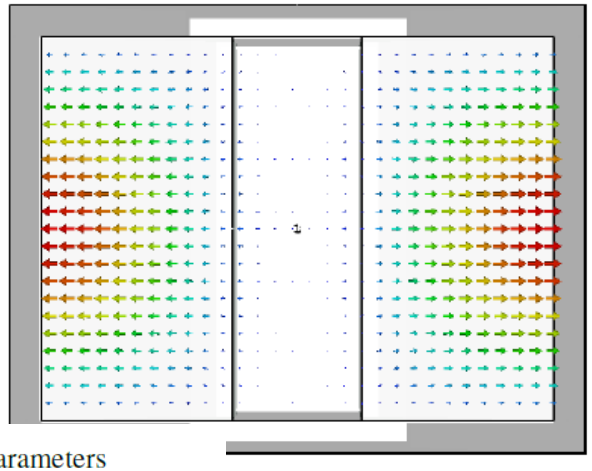


Table 1: Optimised Waveguide Parameters

Operating frequency, f_{op}	0.784 THz
Dielectric slab separation, $2a$	200 μm
Width, w	600 μm
Dielectric slab thickness, t	30 μm
v_p/c	1
v_g/c	0.4
r_s	167 MΩ m^{-1}
r_s/Q	3.28
Δf	5.8 GHz

…. Alisa Healy's presentation

Dispersion-free single-cycle pulse velocity matching

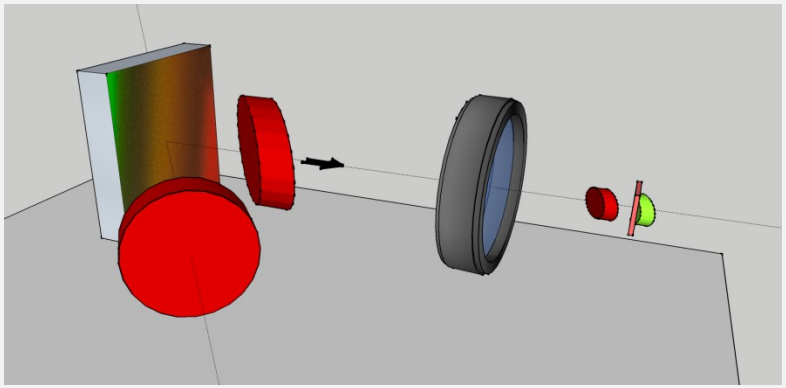
THz pulses have >100MV/m fields ***because*** they are single-cycle

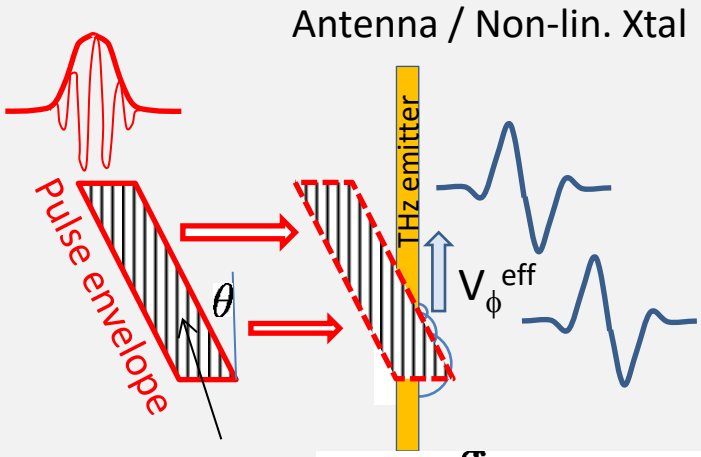
Intrinsically broadband - waveguide propagation can not maintain field strength
Single-cycle - transverse pumping & π-phase jump structure not applicable

Our concept:

Diffraction grating & broadband ultra-short pulses

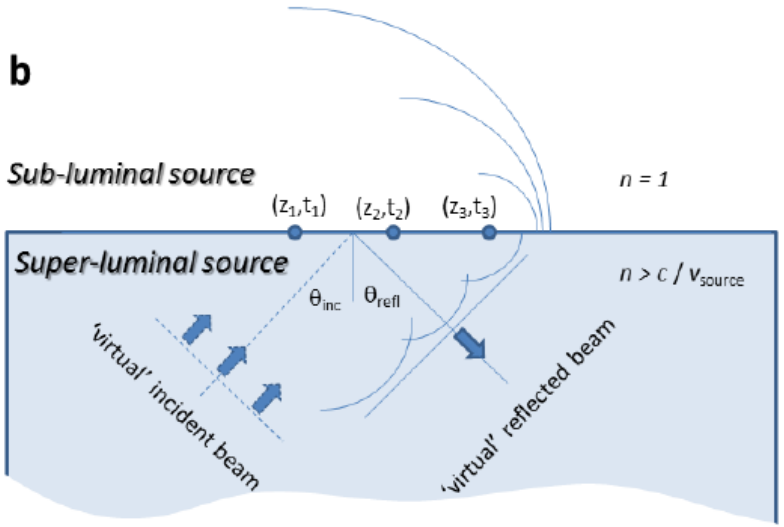
- Phase-fronts remain $\perp$ to propagation
- Pulse (group) front can be arbitrarily tilted w.r.t propagation



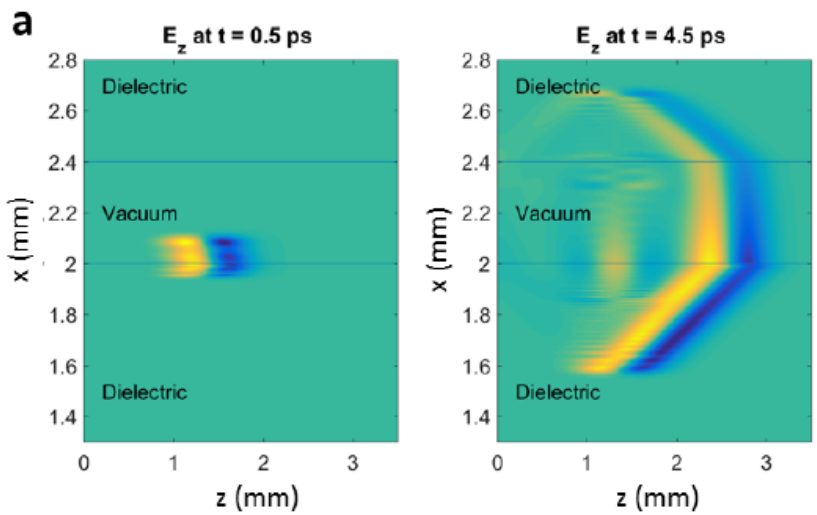


$$0 < v_\phi^{\mathrm{eff}} = c/\tan\theta < \infty$$

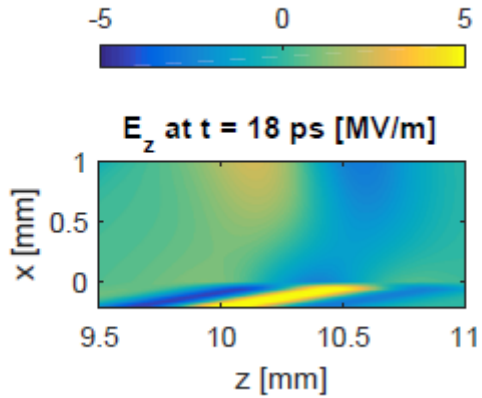
Longitudinal fields generated by subluminal source

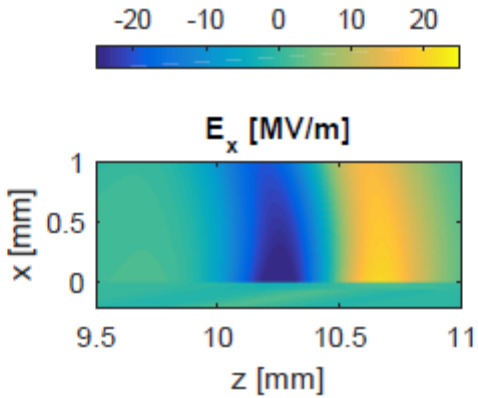


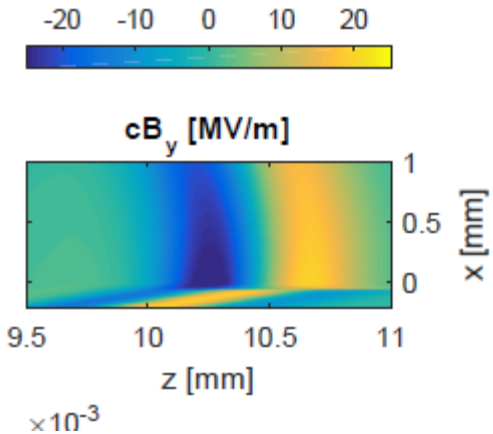
Propagation from boundary extended because of single-cycle structure



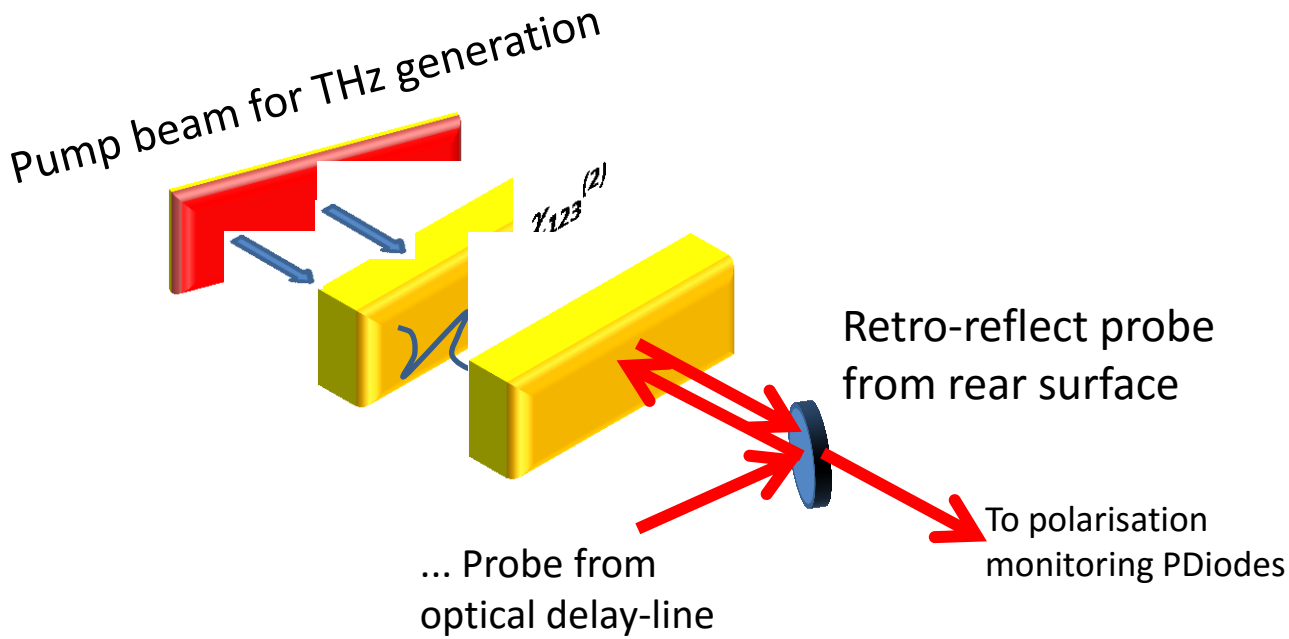
Transverse fields generated by subluminal source



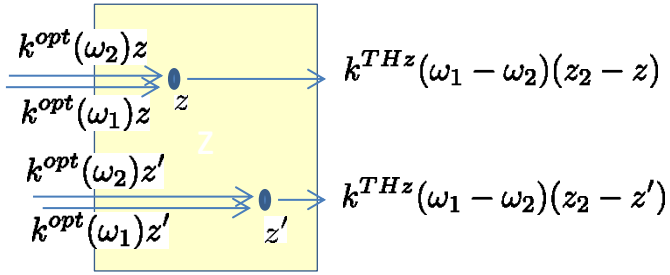




Measuring the propagating wave with EO detection



Phase matching & high-power THz



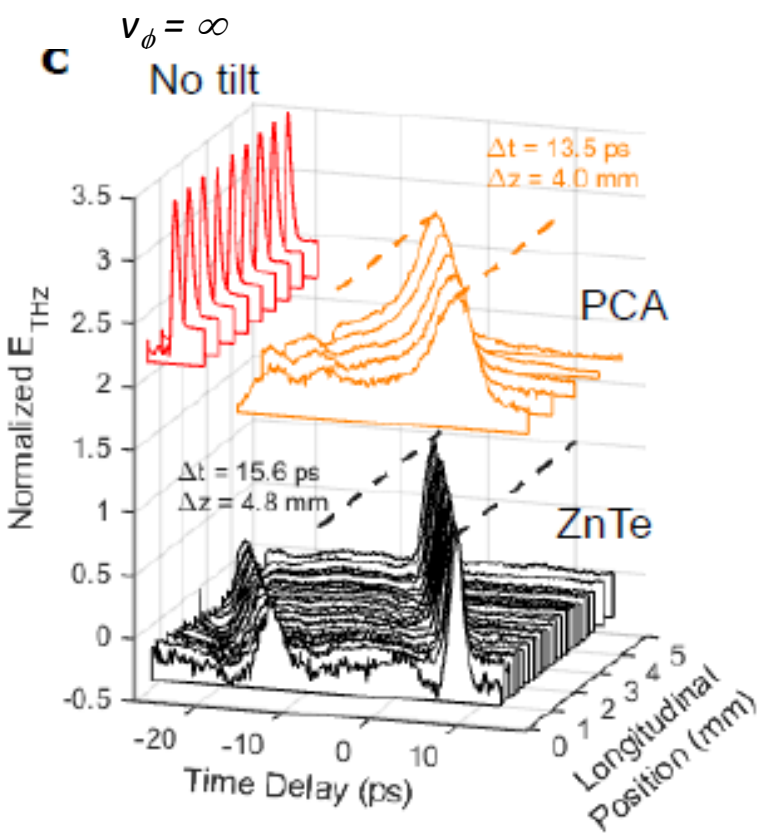
For efficient THz generation require THz generated locally within crystal to add coherently

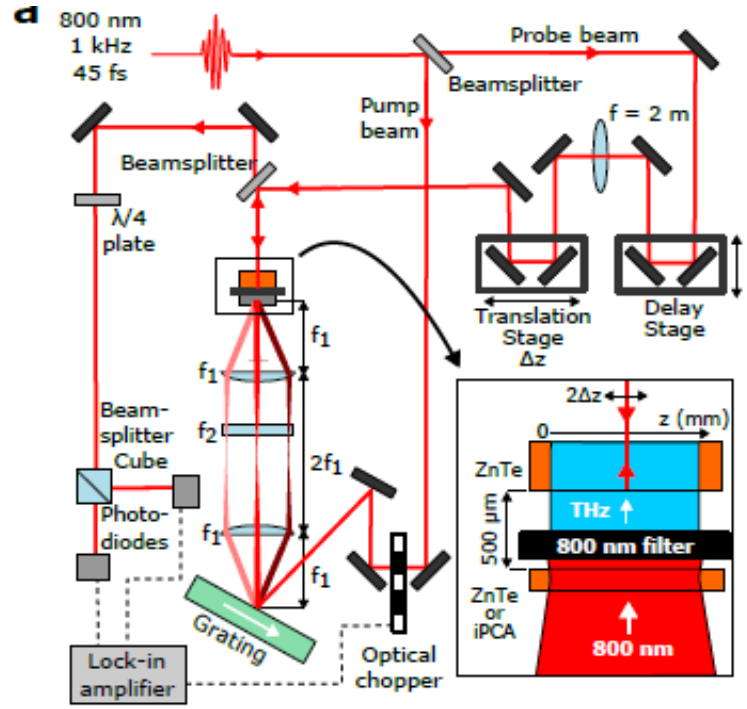
$$v_{\text{group}}^{\text{opt}} \sim v_{\text{phase}}^{\text{THz}}$$

Satisfied for collinear geometry in ZnTe, GaP

Subluminal Dispersionless Source

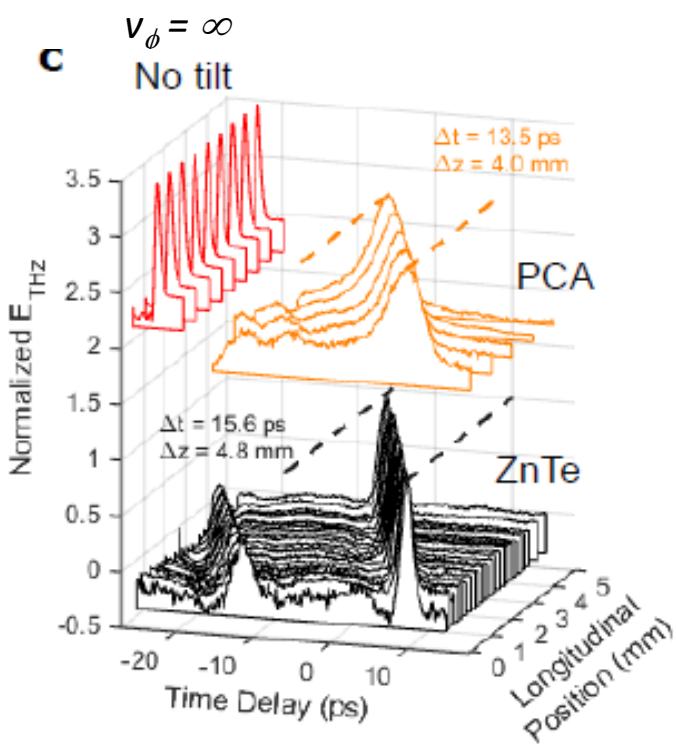
Demonstrating the travelling-wave source concept



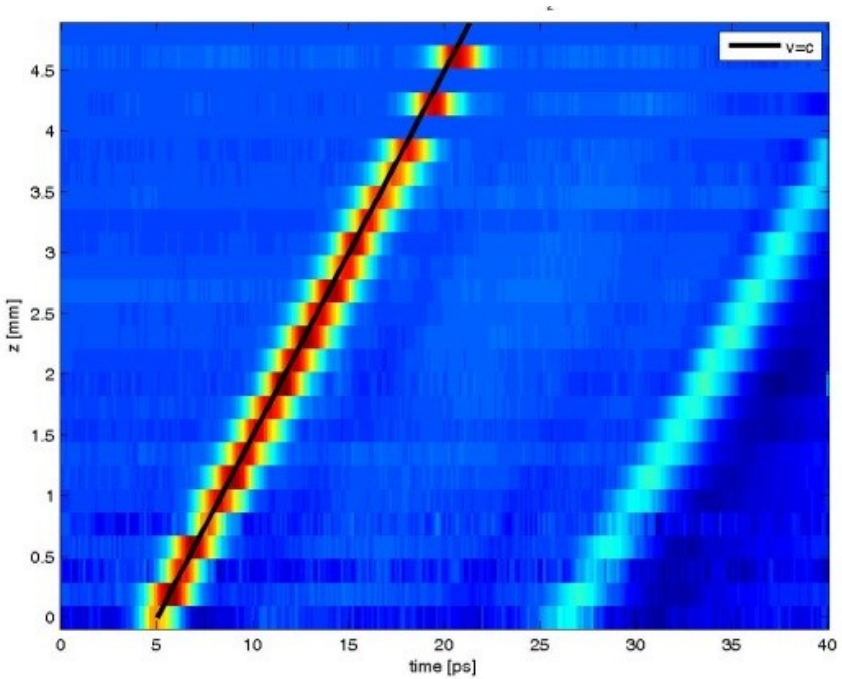


Subluminal Dispersionless Source

Demonstrating the travelling-wave source concept



Longitudinal Electric field E_z

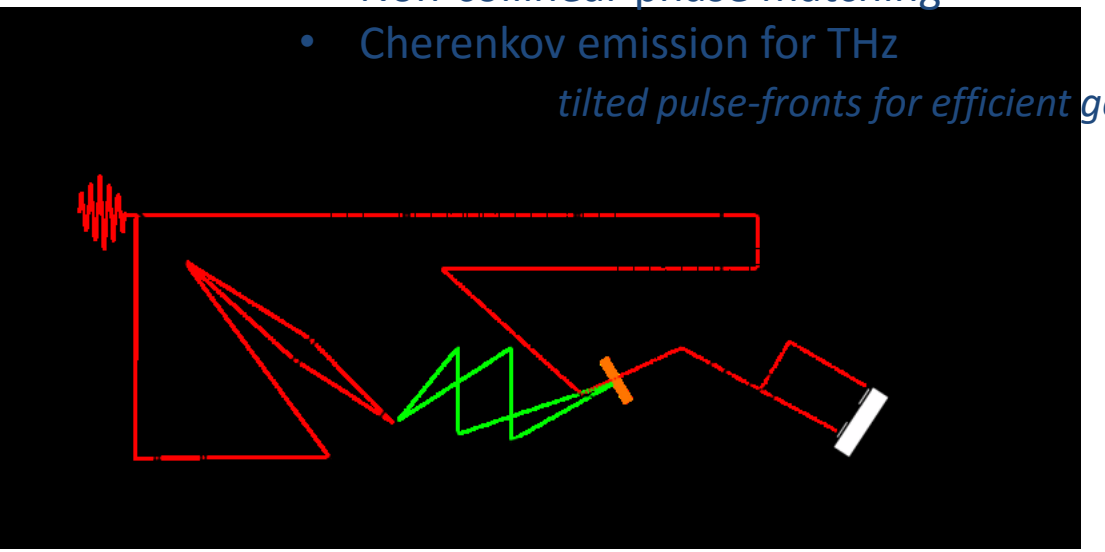


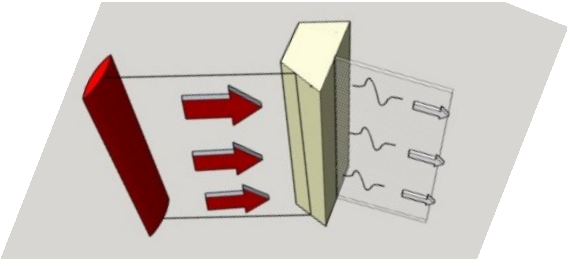
$LiNbO_3$ High-field travelling-wave source

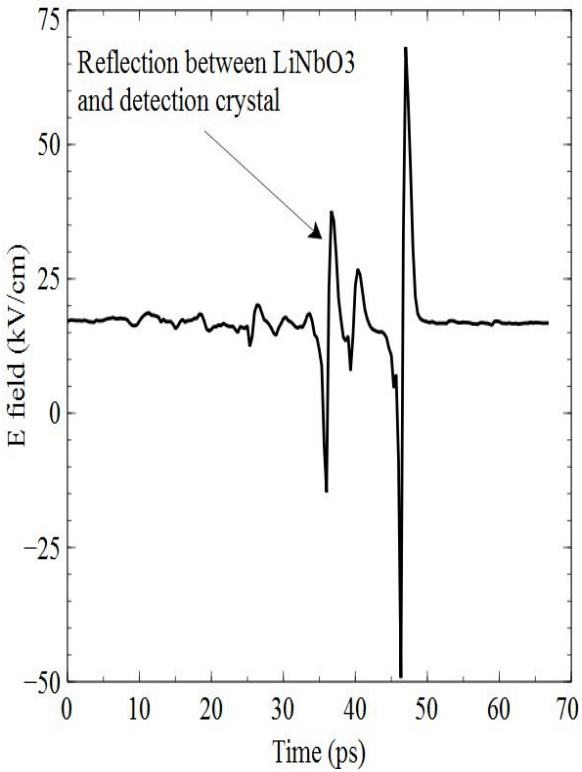
Refractive indices: $n_{THz} \sim 5$; $n_{Opt} \sim 2$

- Non-collinear phase matching
- Cherenkov emission for THz

tilted pulse-fronts for efficient generation





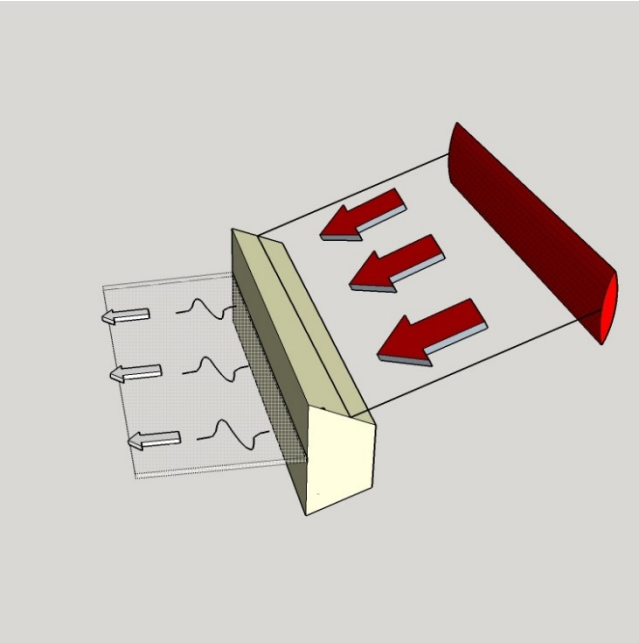


7MV/m measured from LiNbO3

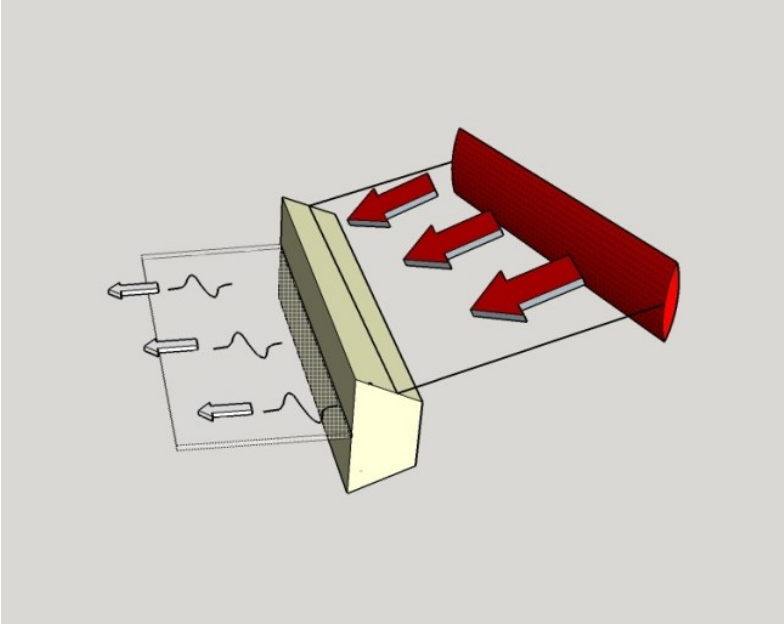
< 2mJ pump energy (>100mJ available)

$LiNbO_3$ High-field travelling-wave source

Standard pulse-front tilt
for efficient THz generation

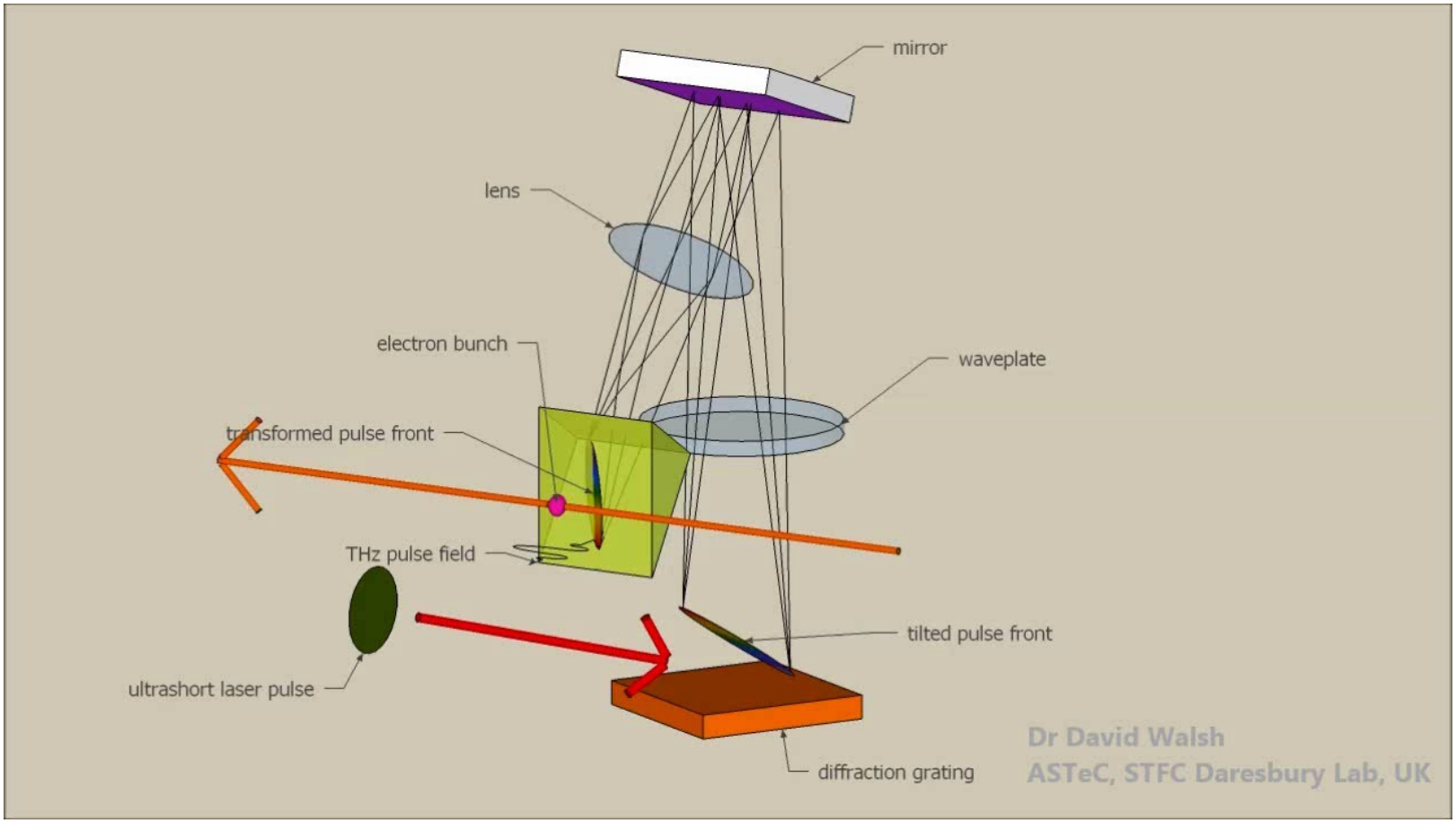


…with additional pulse-front tilt
for source propagation.



Concept to physical implementation

Complicated geometry to match accelerator/injector horizontal plane



THz 'Travelling source' Deflector

20 fs resolution with 1cm structure

Simulation based on laser-lab demonstrated source/structure

10MV/m THz source, travelling wave configuration
200MeV electron beam
1cm interaction, 1 metre drift

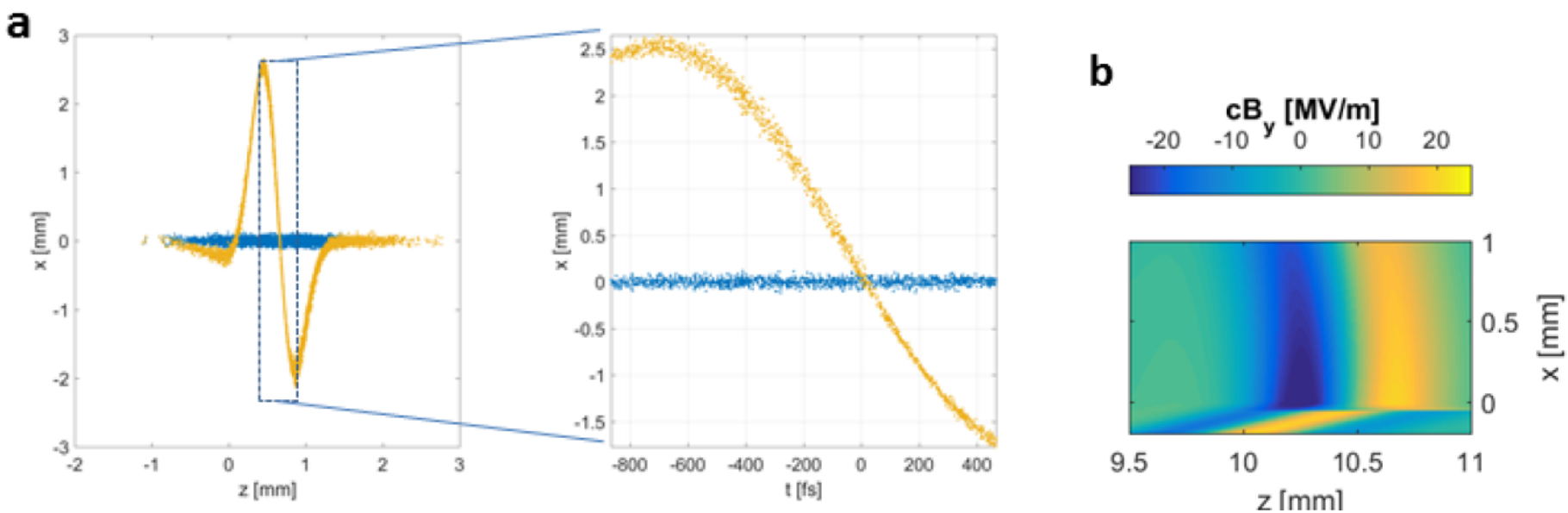


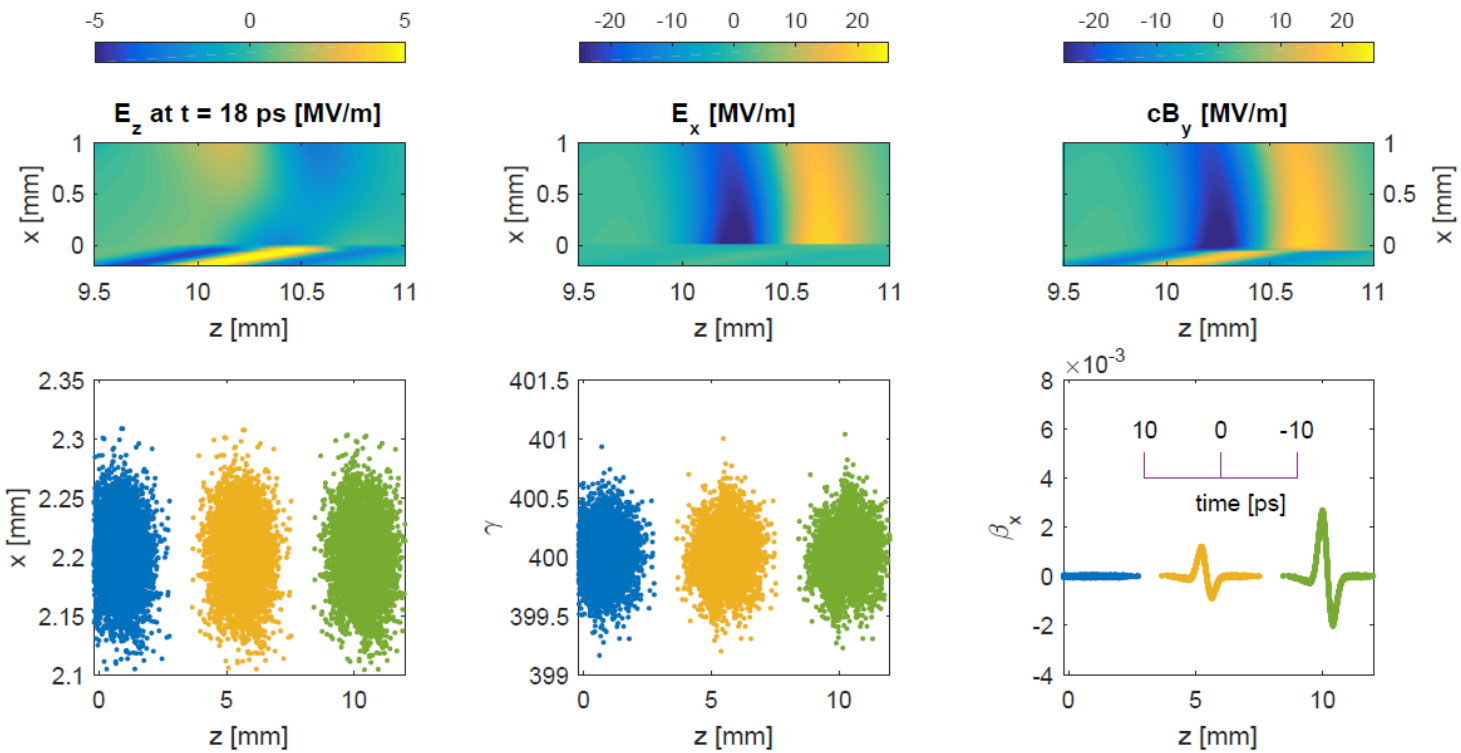
Figure 2: (a) simulated deflection imposed on a 200 MeV, ε = 0.3 mm.mrad beam with a 1 cm interaction region and a 1 metre drift. Blue: without THz pulse. Orange: with a 10 MV/m THz source driving the interaction. (b) FDTD simulations of the magnetic field produced in the vacuum region by a travelling wave THz source.

THz 'Travelling source' Deflector

20 fs resolution with 1cm structure

Simulation based on laser-lab demonstrated source/structure

10MV/m THz source, travelling wave configuration
200MeV electron beam



THz 'Travelling source' Deflector

20 fs resolution with 1cm structure

Simulation based on laser-lab demonstrated source/structure

10MV/m THz source, travelling wave configuration
200MeV electron beam
1cm interaction, 1 metre drift

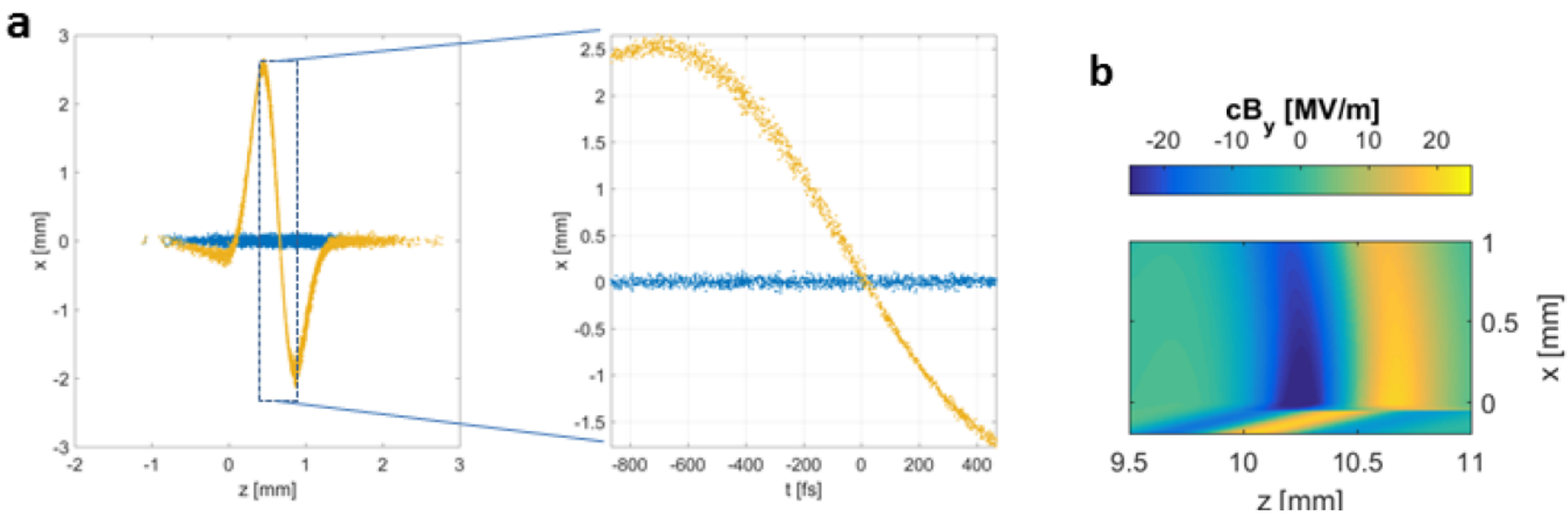


Figure 2: (a) simulated deflection imposed on a 200 MeV, ε = 0.3 mm.mrad beam with a 1 cm interaction region and a 1 metre drift. Blue: without THz pulse. Orange: with a 10 MV/m THz source driving the interaction. (b) FDTD simulations of the magnetic field produced in the vacuum region by a travelling wave THz source.

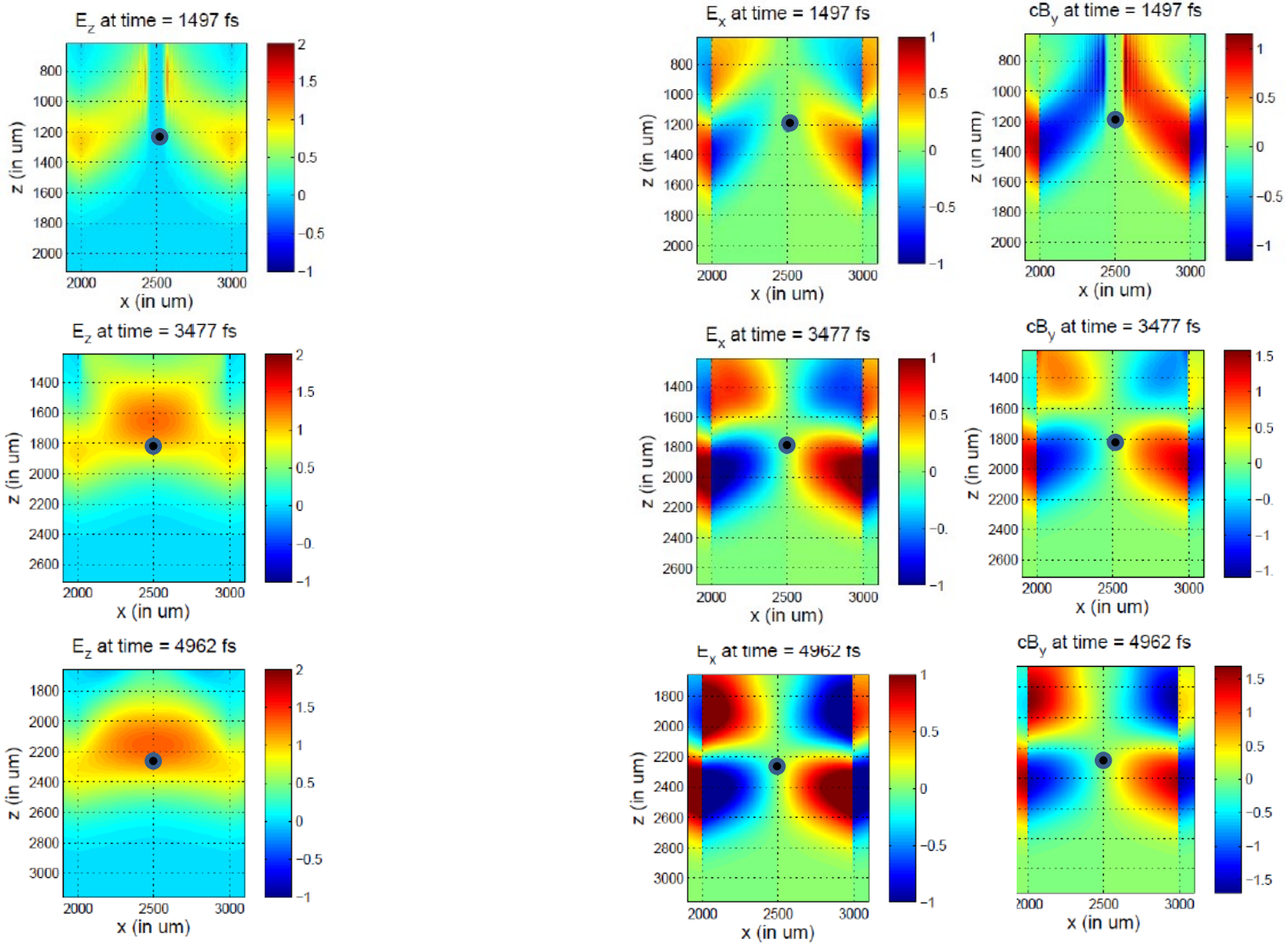
Symmetric structure for Acceleration

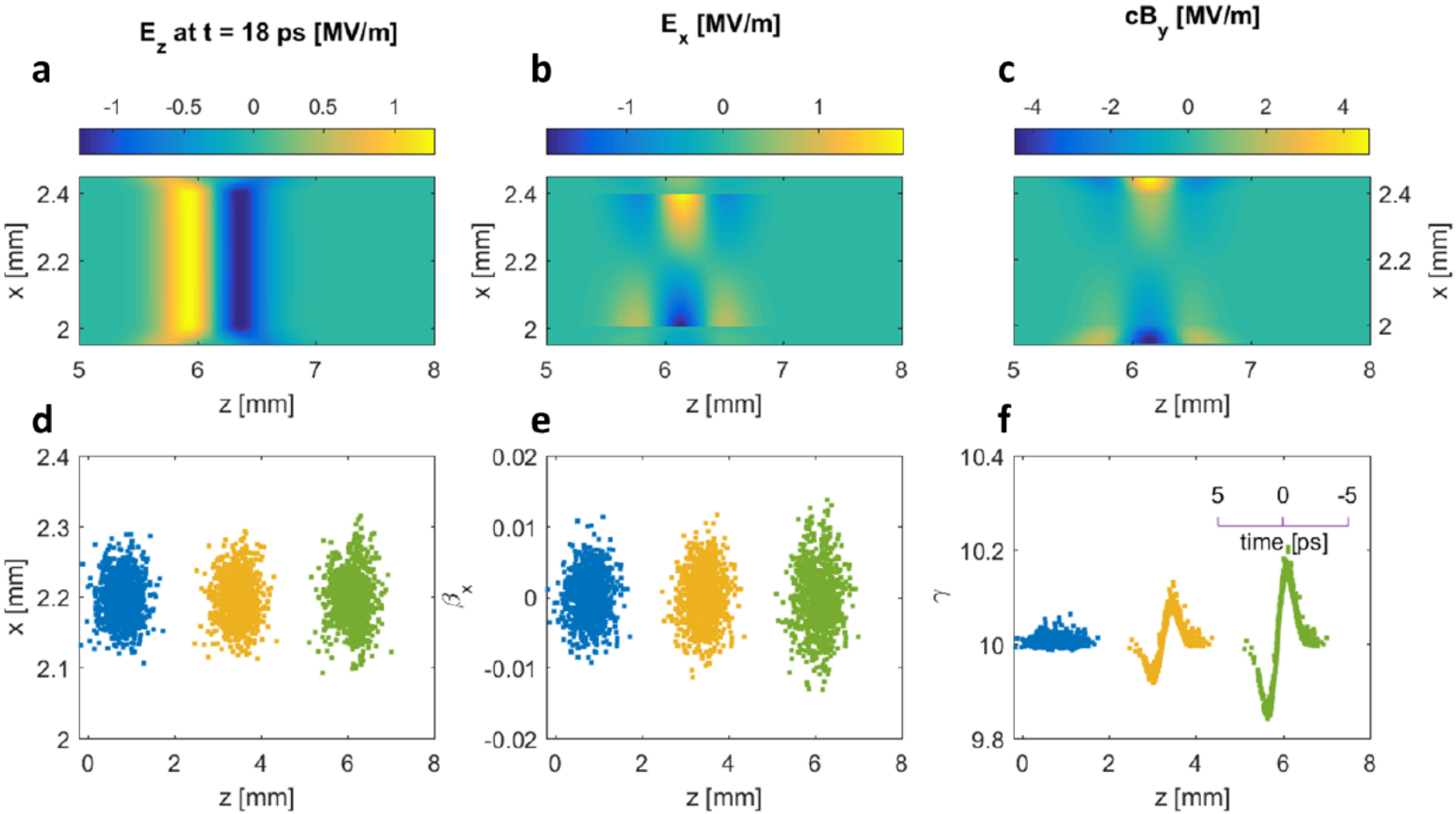
Accelerating fields

Deflecting fields

Time

$\beta_{frame} = c$

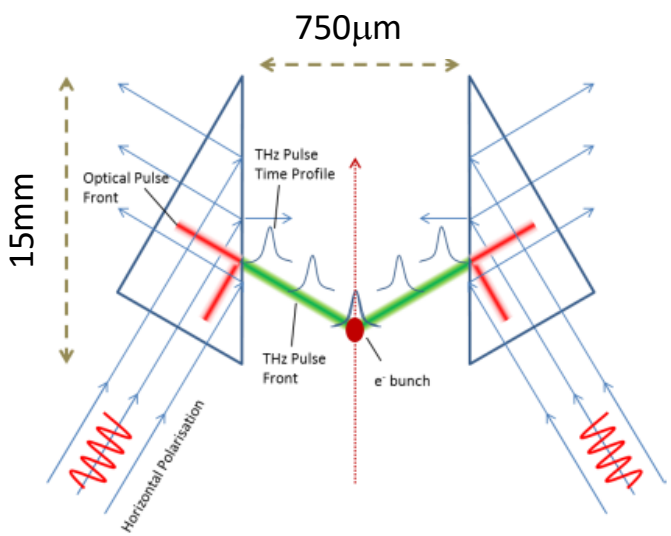


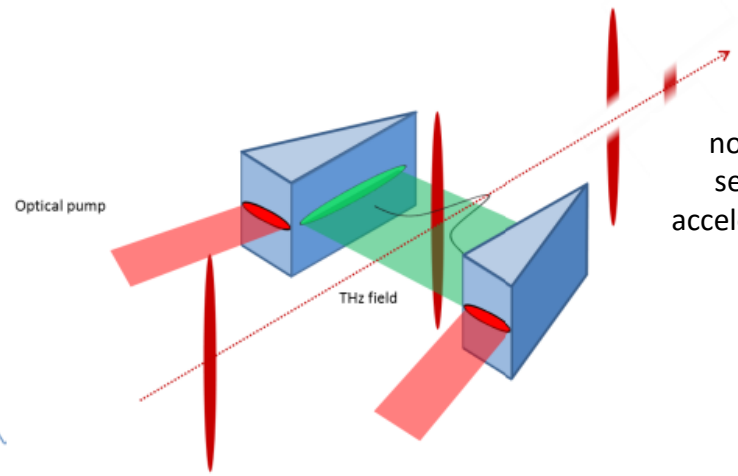


Walsh et al. arXiv :1609.02573 (2016)

Experiment for THz driven Acceleration on VELA

- Symmetric THz excitation – cancels deflection
- Longitudinal velocity β=0.995, matching 4.5MeV
  In-situ velocity measurement for tuning
- Targeting >100keV acceleration in 10mm





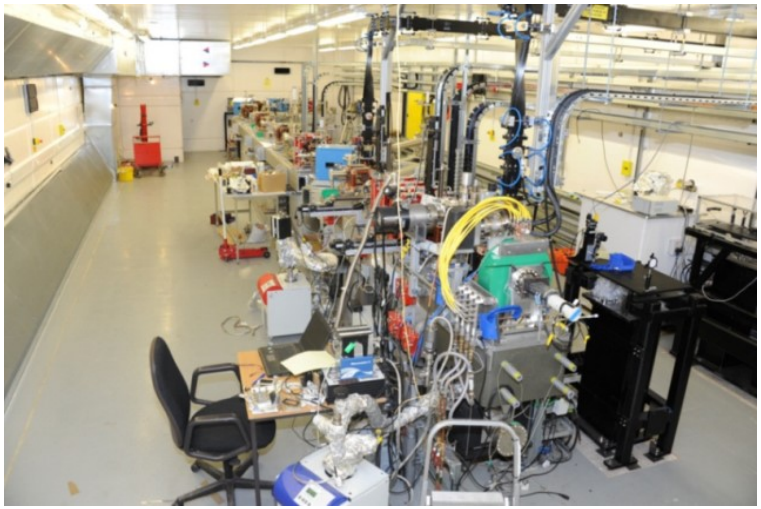
no actual charge separation with acceleration: β = 0.995

Single-shot referencing
mitigating shot-shot jitter

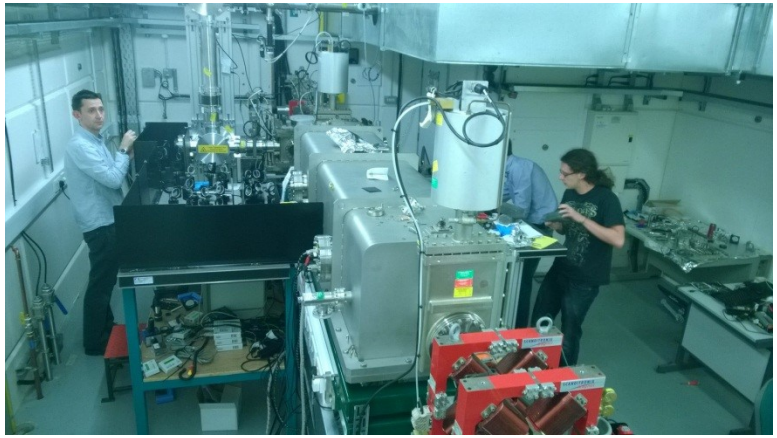
Experiment for THz driven Acceleration on VELA

From demonstration of source to demonstration of particle acceleration

VELA : Versatile Electron Linear Accelerator

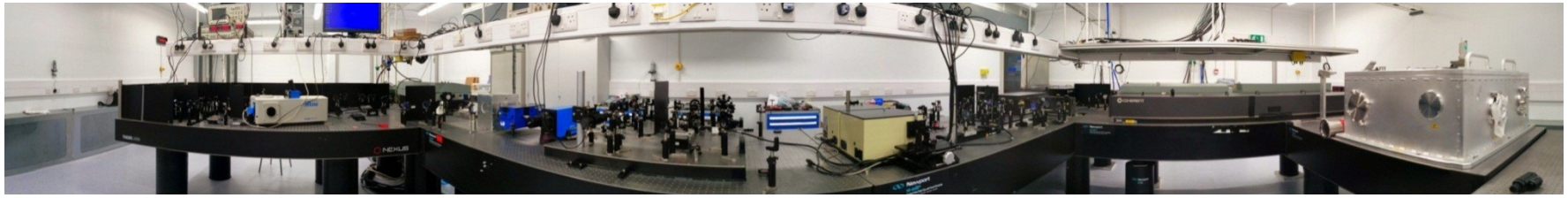


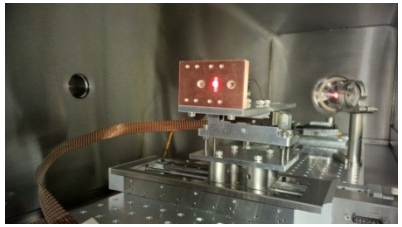
Experimental station

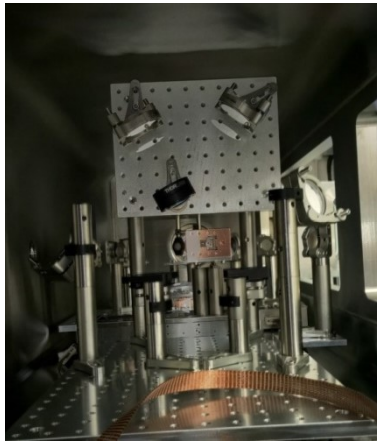


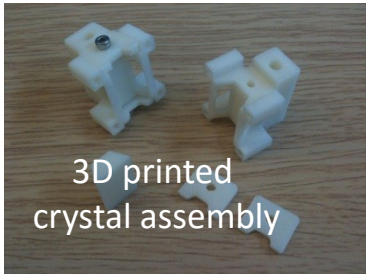
'Latte' lab, coupled to VELA user station

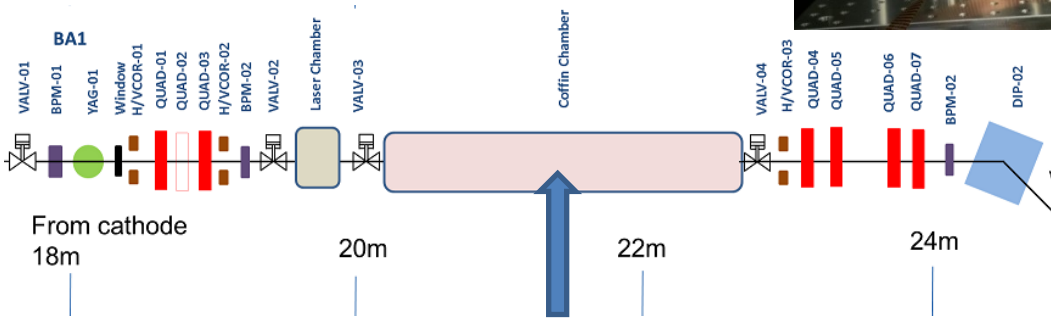
LAser **T**Hz and **T**erawatt **E**xperiments for accelerator applications





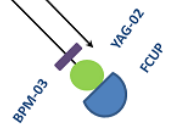






Electron spectrometer

- Vertical imaging of IP
- Horizontal focusing
  + dispersion



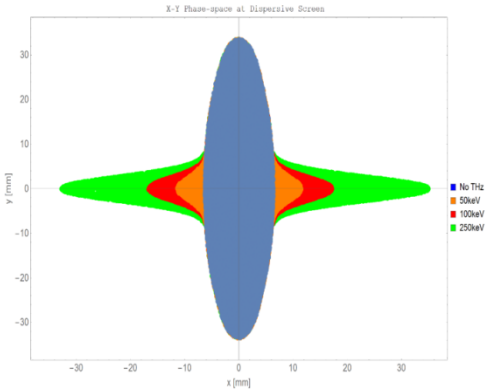
Injected electrons

- 4.5MeV
- 1pC-100pC
- Low emittance, low energy spread
- Short duration
  (space-charge limited, ~2-3ps)

Interaction point (IP)

- 750um crystal spacing
- 500um slit aperture for beam

- Alignment diagnostics/screens
- Laser-electron synchronisation system(s)
- THz spatial imaging (velocity tuning)



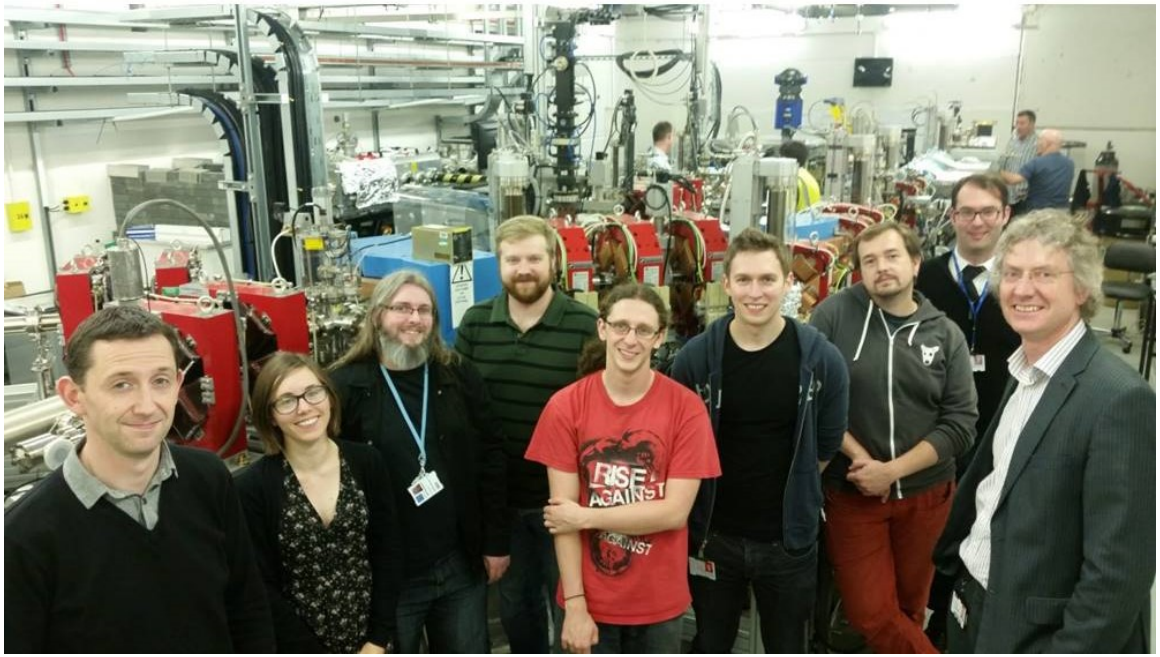
In summary

- High potential for THz acceleration, bunching, deflection of electron bunches
- Velocity matching and dispersion management significant challenges
- real demonstrations happening and in pipe-line

- Novacc:
  THz acceleration & manipulation as injector to DLA structures.
  CLARA/VELA available as test facility.

Acknowledgements

Travelling-wave and waveguide THz acceleration team



David Walsh, Ed Snedden, Darren Graham, Dan Lake, Matt Cliffe, Morgen Hibberd, Graeme Burt, Andrei Gorodetsky, Steven Jamison

Lancaster University

MANCHESTER 1824 The University of Manchester

Science & Technology Facilities Council