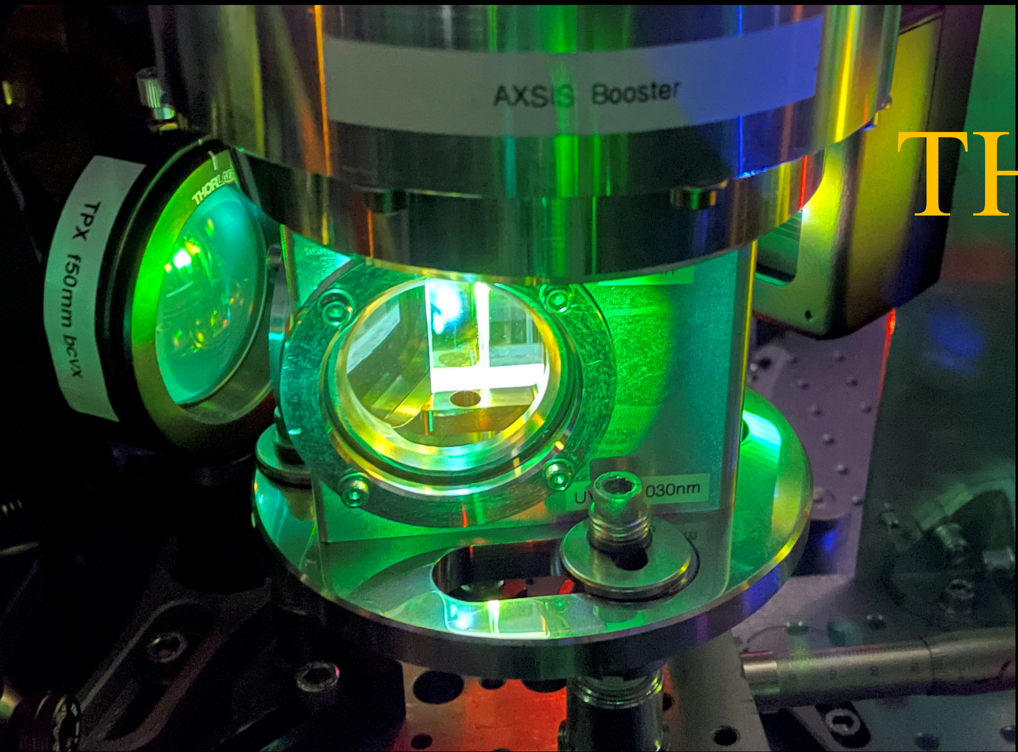



# THz Shaping of Electrons

*Advancing Accelerators with Light*

Dr. Nicholas H. Matlis
Ultrafast Optics & X-Rays Group
CFEL, DESY

June 12$^{th}$, 2023

# Why explore higher frequencies?

## Higher driving frequency allows:

- higher acceleration fields: $\left|\vec{E}\right|_{breakdown} \sim \frac{1}{\tau^{1/6}}$ ➞ smaller accelerator

[1] Kilpatrick, W. D., Rev. Sci. Inst. 28, 824 (1957).
[2] Loew, G.A., et al., 13th Int. Symp. on Discharges and Electr. Insulation in Vacuum, Paris, France. 1988.
[3] S. V. Dolgashev, et al. Appl. Phys. Lett. 97, 171501 2010.
[4] M. D. Forno, et al. PRAB. 19, 011301 (2016).

- lower pulse energy for same E-field in the cavity:

$$U_{Pulse} \sim \left|\vec{E}\right|^2 V_{cavity} \sim \lambda^3 \sim f^{-3}$$

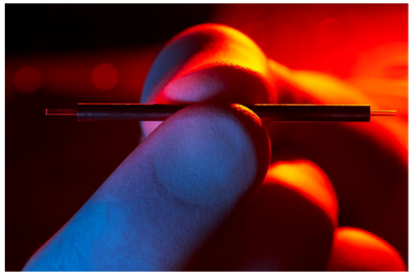
- reduced pulsed heating: $\Delta T \sim \frac{U_{Pulse}}{A_{Surface}} \sim \lambda \sim f^{-1}$ ➞ higher rep rates!

- higher field gradients:
  - stronger compression: $\frac{dF}{dz} \sim \frac{\left|\vec{E}\right|}{\lambda} \sim f^2$ ➞ shorter bunches
  - quicker acceleration ➞ reduce space charge effects

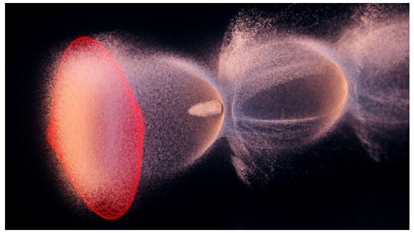
Wavelengths

RF Accelerator
100 mm

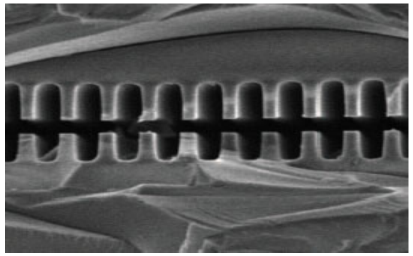
THz
1 mm



Laser-Plasma
0.01 mm



Laser-Dielectric
0.001 mm

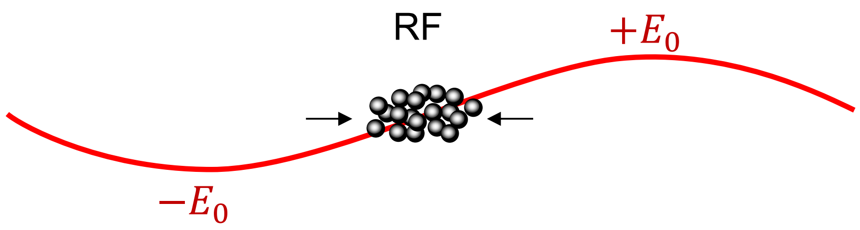


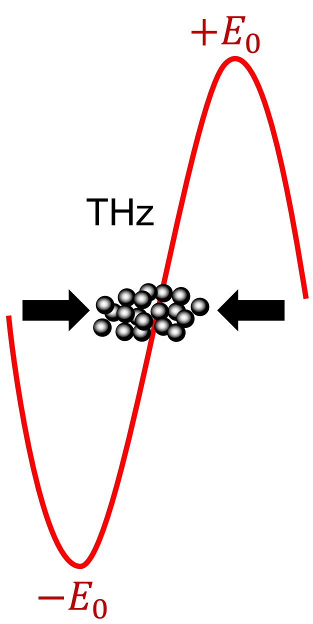
# THz Benefits: shorter waves, higher fields, stronger gradients

| Parameter | RF Accelerators | THz Accelerators | THz Enhancement |
|---|---|---|---|
| Field Strengths, $E_0$ | 10 – 100 MV/m | 100 – 1000 MV/m | ~10x |
| Wavelength, $\lambda$ | 3 – 10 GHz | 100 – 500 GHz | ~100x |
| Field Gradients, $dE_0/dz$ | ~10 GV/m$^2$ | ~10,000 GV/m$^2$ | ~1000x |

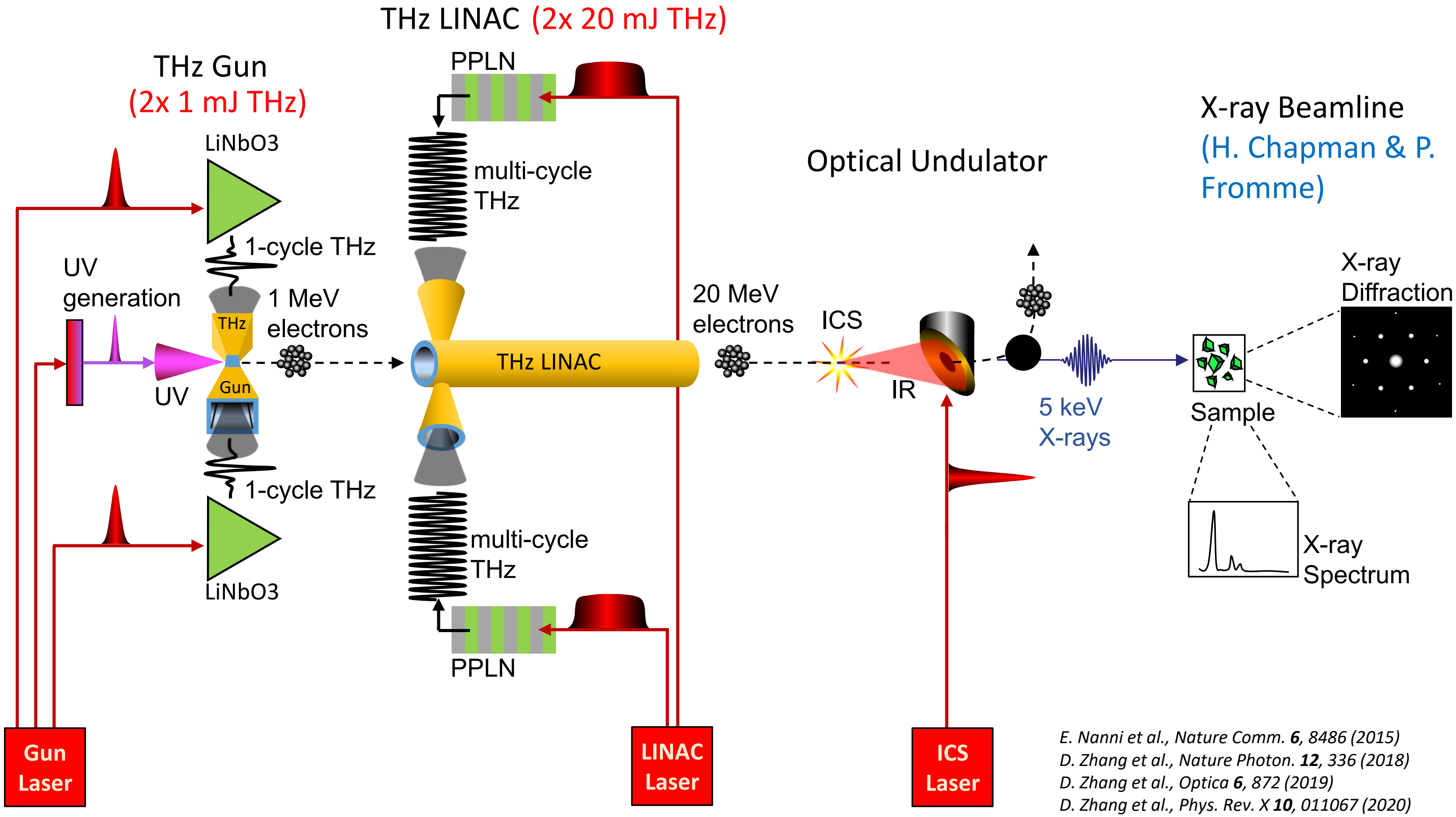
Enhanced Bunch Compression

- ultrahigh field gradients
- intrinsic laser synchronization



# THz-powered electron and X-ray light source: AXSIS



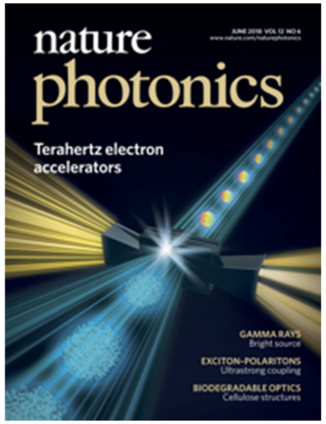

*E. Nanni et al., Nature Comm.* ***6****, 8486 (2015)*
*D. Zhang et al., Nature Photon.* ***12****, 336 (2018)*
*D. Zhang et al., Optica* ***6****, 872 (2019)*
*D. Zhang et al., Phys. Rev. X* ***10****, 011067 (2020)*

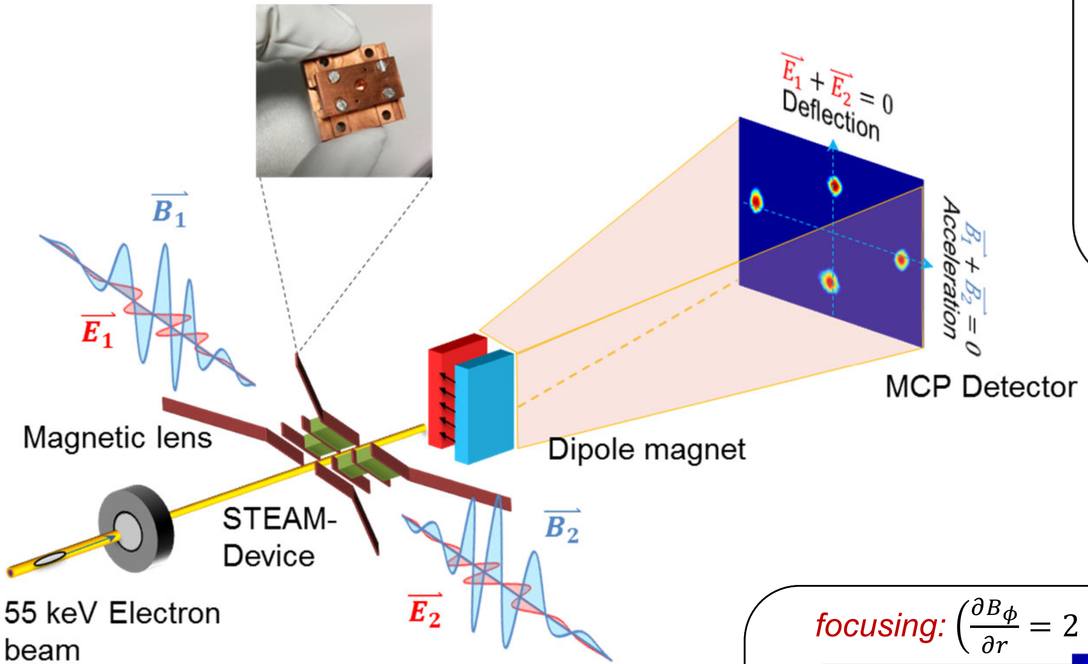
*F.X. Kärtner et al., NIMPRA* ***829****, 24 (2016)*

# STEAM device yields practical beam acceleration & manipulation

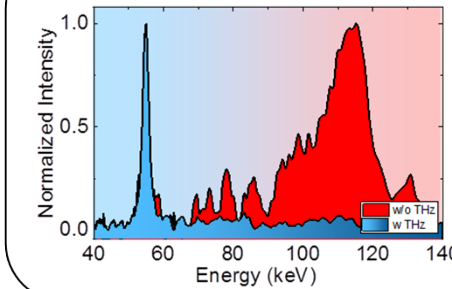
*D. Zhang et al., Nature Photon.* ***12****, 336 (2018)*
*D. Zhang et al., Optica 6, 872 (2019)*

**S**egmented
**T**Hz
**E**lectron
**A**ccelerator &
**M**anipulator

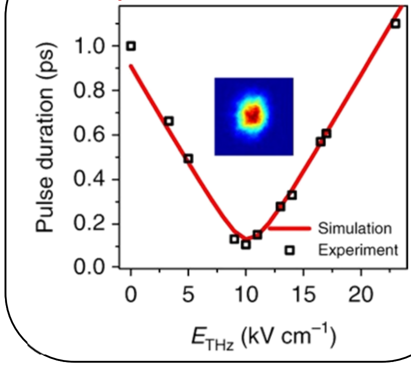


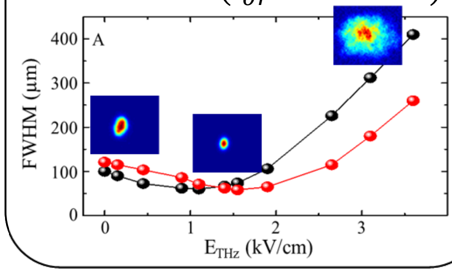

*acceleration:* 65 keV



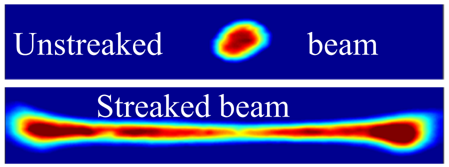

*compression:* $\tau \approx 100$ fs




*focusing:* $\left(\frac{\partial B_\phi}{\partial r} = 2\ k\mathrm{T/m}\right)$



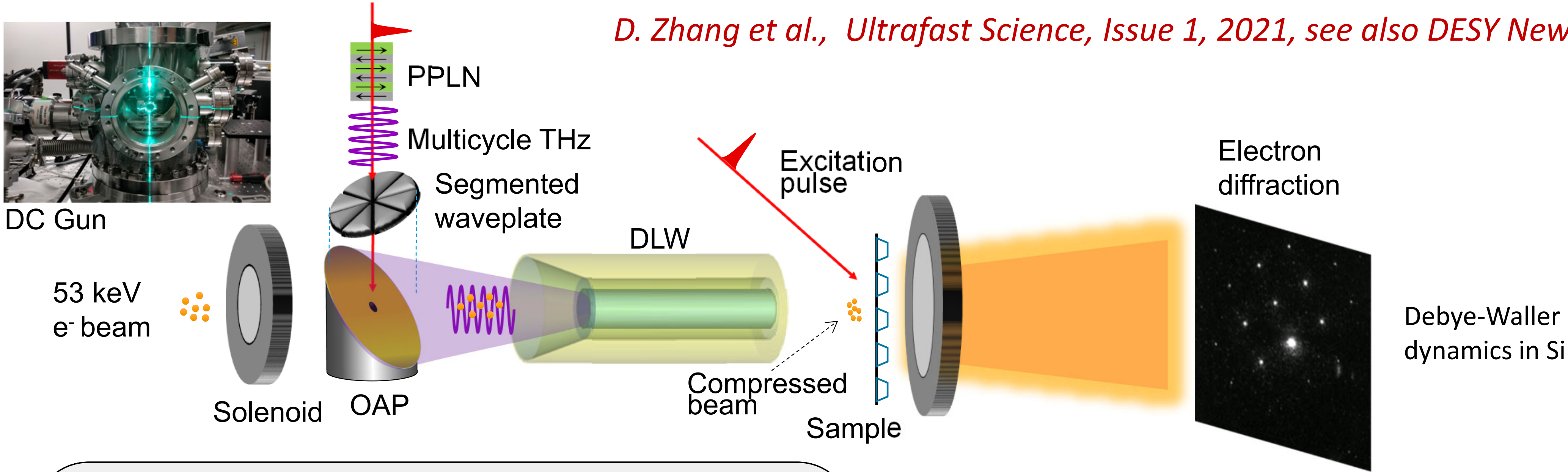

*streaking:* 140 μrad/fs

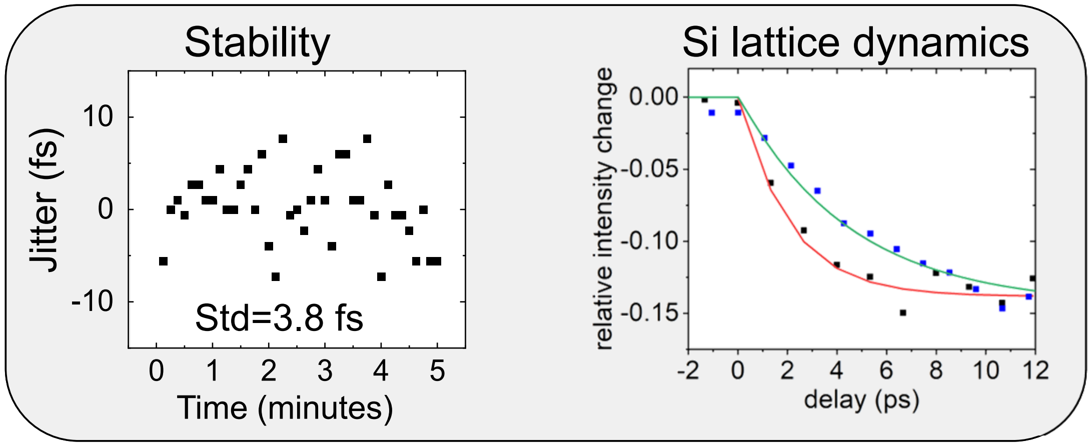



Resolution: sub-10 fs

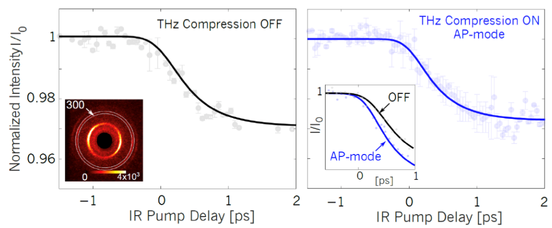
# THz-compression enhances UED temporal resolution

*D. Zhang et al., Ultrafast Science, Issue 1, 2021, see also DESY News*



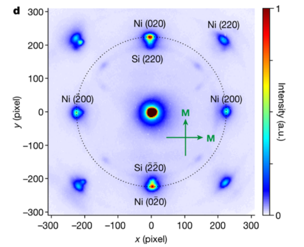




electron-phonon coupling in Bi




*Othman et al., arXiv:2104.05691 (2021)*

ultrafast demagnetization in Ni

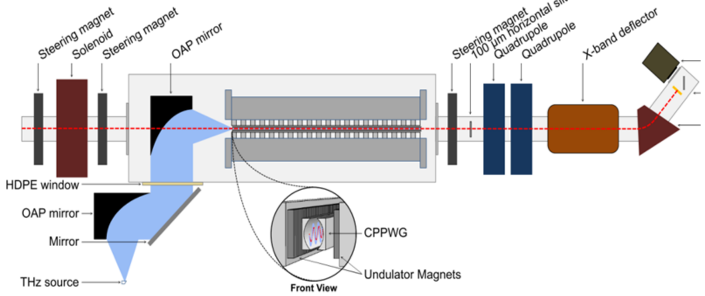


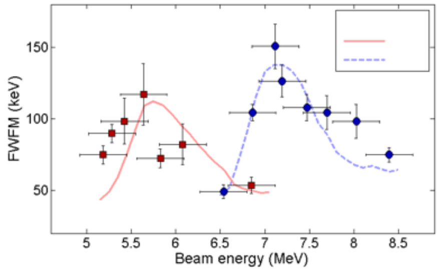

*Tauchert et al., Nature* ***602****, 73 (2022)*

# THz acceleration and beam manipulation takes up speed!

THz-powered iFEL

*E. Curry et al., PRL 120, 094801 (2018)*

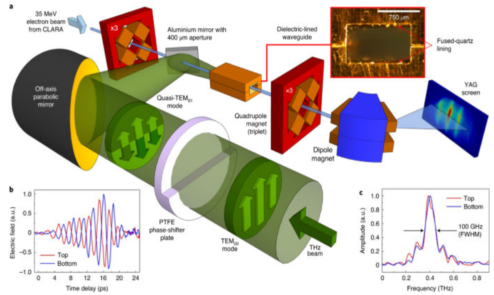


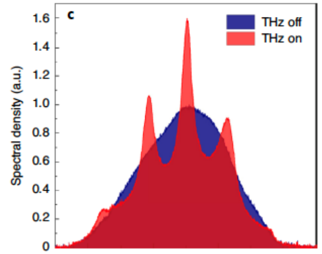




$E_{in} = 5$ MeV
$\Delta E = \pm 75$ keV
$E_{THz} = 1$ µJ

Acceleration

*M. Hibberd et al., Nat. Photon. (2020)*

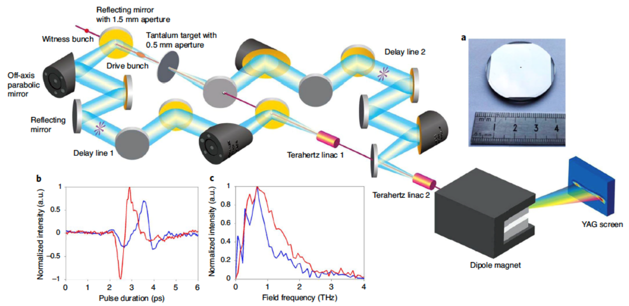


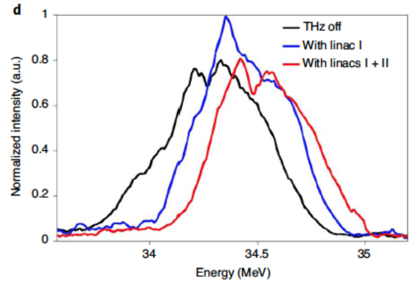



$E_{in} = 35$ MeV
$\Delta E = \pm 10$ keV
$E_{THz} = 2$ µJ

Acceleration & Staging

*H. Xu et al., Nat. Photon. (2021)*




$E_{in} = 34.3$ MeV
$\Delta E = 150$ keV
$E_{THz} = 132$ µJ

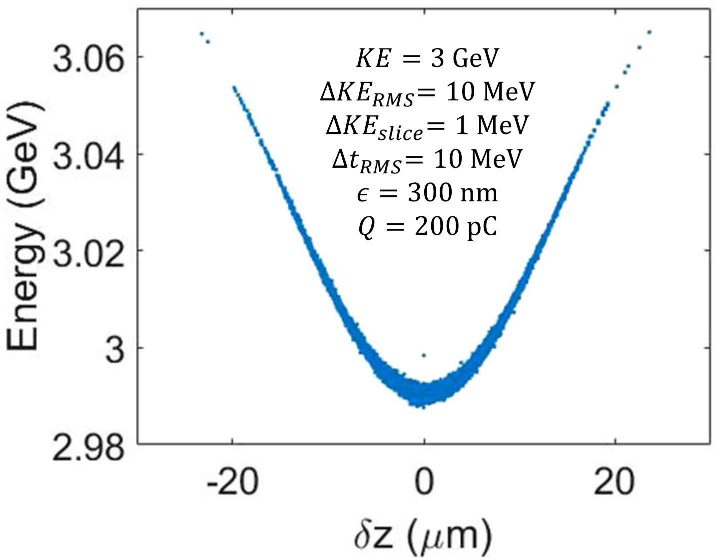
Others:

- *Kealhofer et al., Science 359, 459 (2016)*
- *Walsh et al., Nature Comm. 8, 421 (2017)*
- *Zhao et al., PRX 8, 021061 (2018)*
- *Li et al., Phys. Rev. Accel. Beams 22, 012803 (2019)*

# Applications of THz for LPAs and Conventional Accelerators

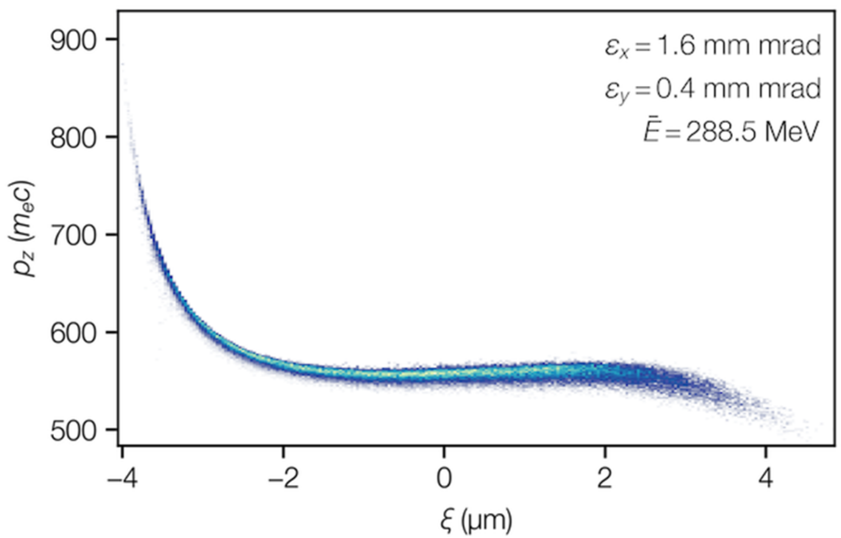
- THz Streaking
- THz Compression
- THz Focusing
- THz Beam Shaping

Output of SwissFEL




*Discussion, R. Ischebeck et al., SwissFEL, PSI*

Output of LPA

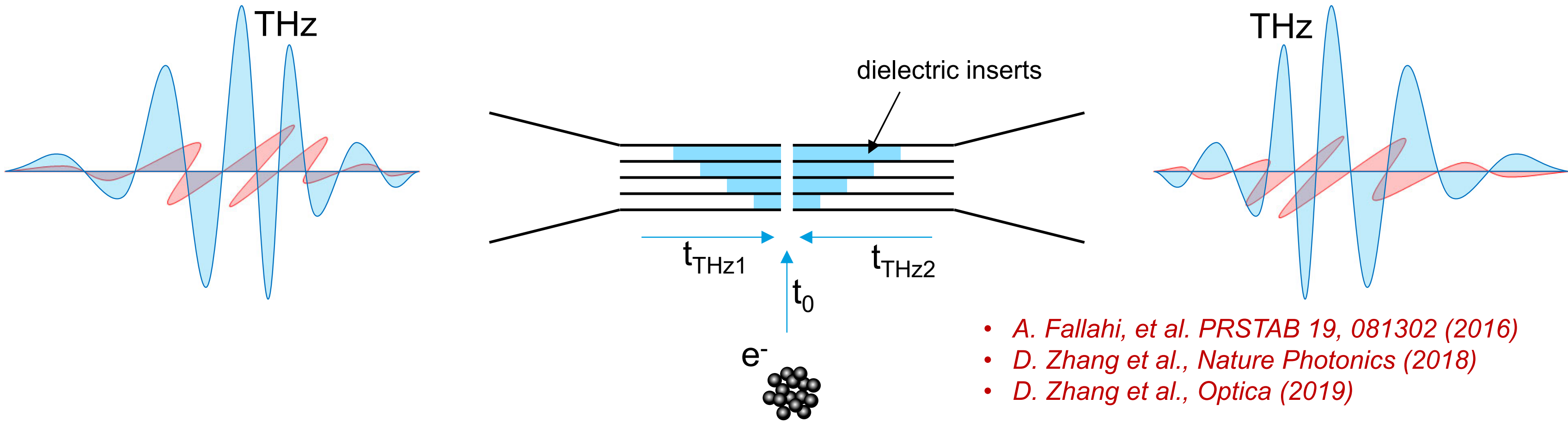



*M. Kirchen et al., Phys. Rev. Lett.* ***126****, 174801 (2021)*

# 2-geometries for THz-electron interaction

Transverse Geometry

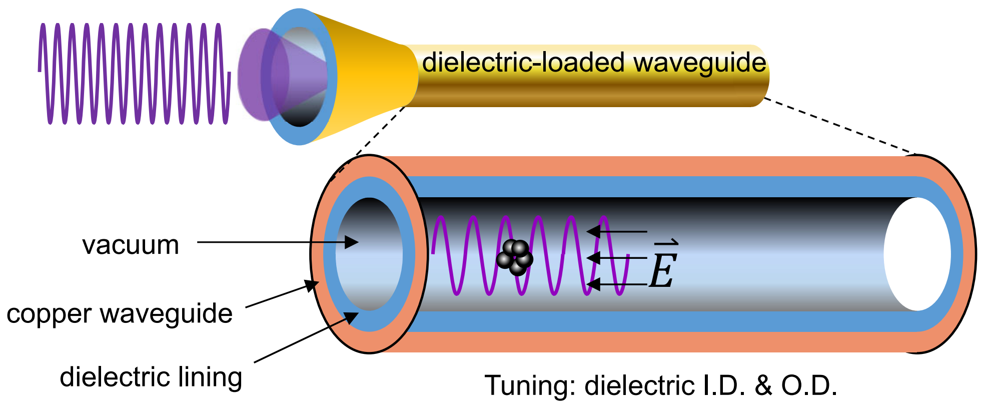
- Single (few)-cycle THz
- Tuning: dielectric $L, h$

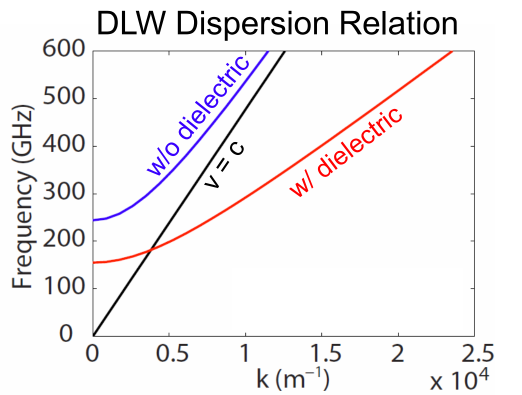



- *A. Fallahi, et al. PRSTAB 19, 081302 (2016)*
- *D. Zhang et al., Nature Photonics (2018)*
- *D. Zhang et al., Optica (2019)*

Co-propagating Geometry

- Narrowband (multicycle) THz
- Tuning: dielectric $R_{I.D.}, R_{O.D.}$




*L.J. Wong et al., Opt. Exp. **21**, 9792 (2013)*

# Benefits and Challenges for Applying THz to High-Energy Beams

## Challenges

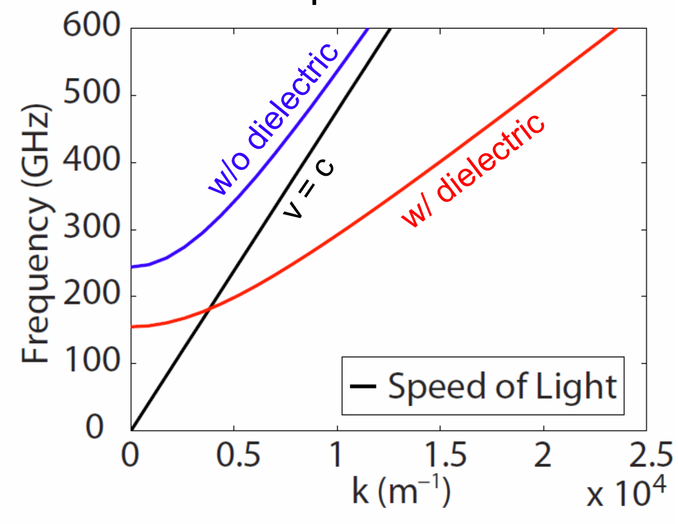
- High-energy requires lots of “umpf”

## Benefits

- Beams are moving really close to c
- Beam velocity doesn’t change with energy
- Long interaction lengths possible
- THz pulse durations can be short
- Waveguide dispersion is minimized

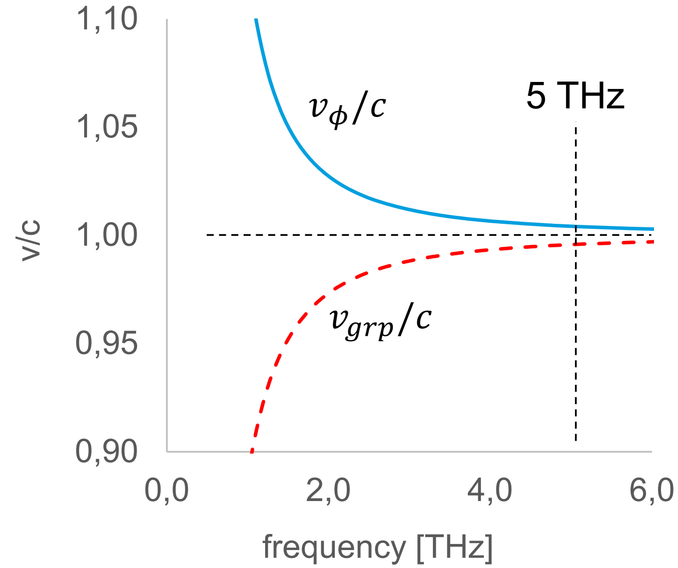
# Near luminal operation brings key advantages

### DLW Dispersion Relation

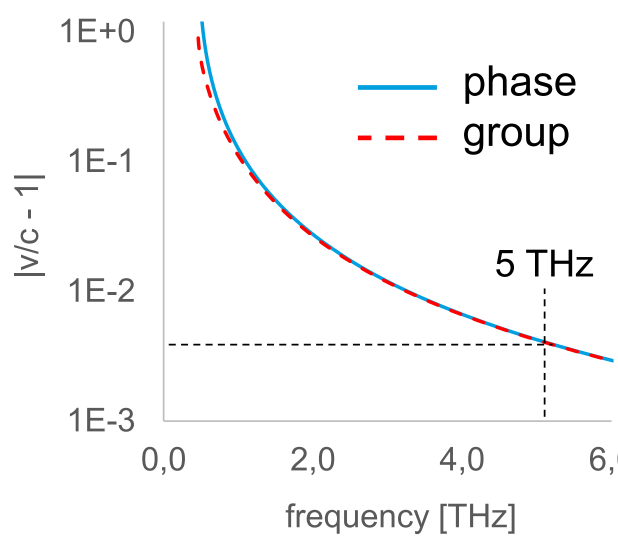



*L.J. Wong et al., Opt. Exp.* ***21****, 9792 (2013)*

### Hollow Metal Waveguide

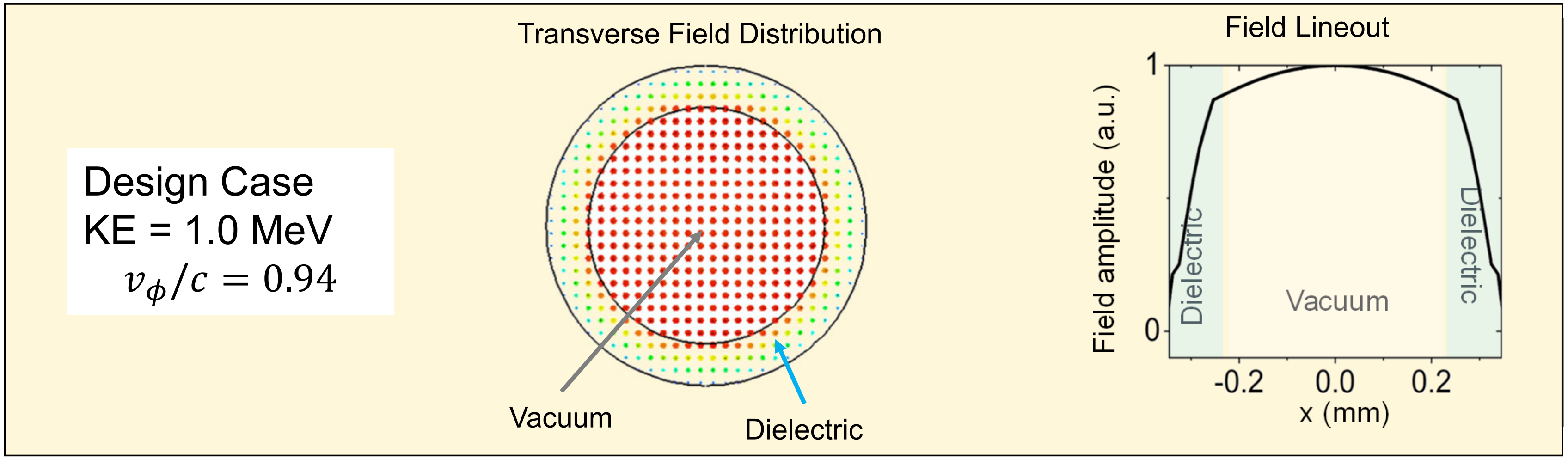


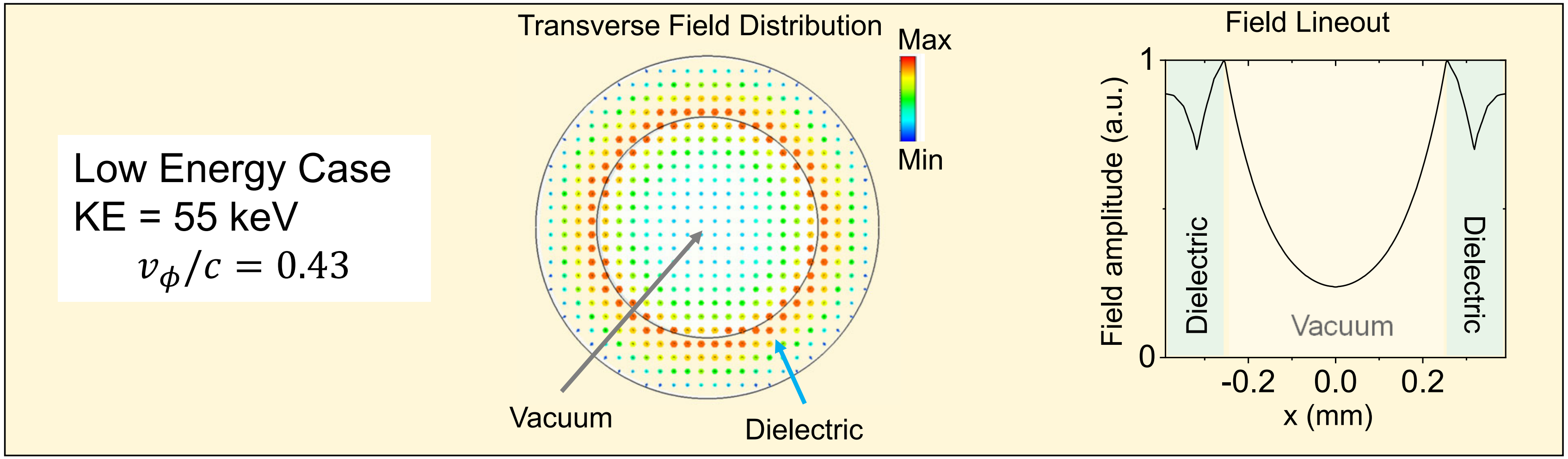

### Velocity deviation from c



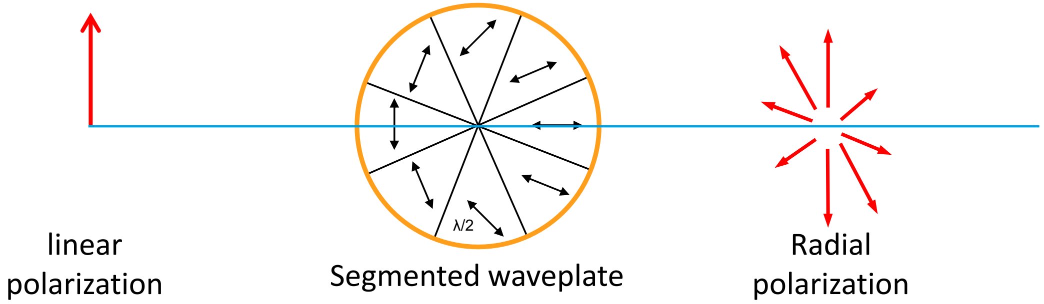

- THz dispersion is very low → can use short pulses
- THz pulse walk-off is very low → can use short pulses

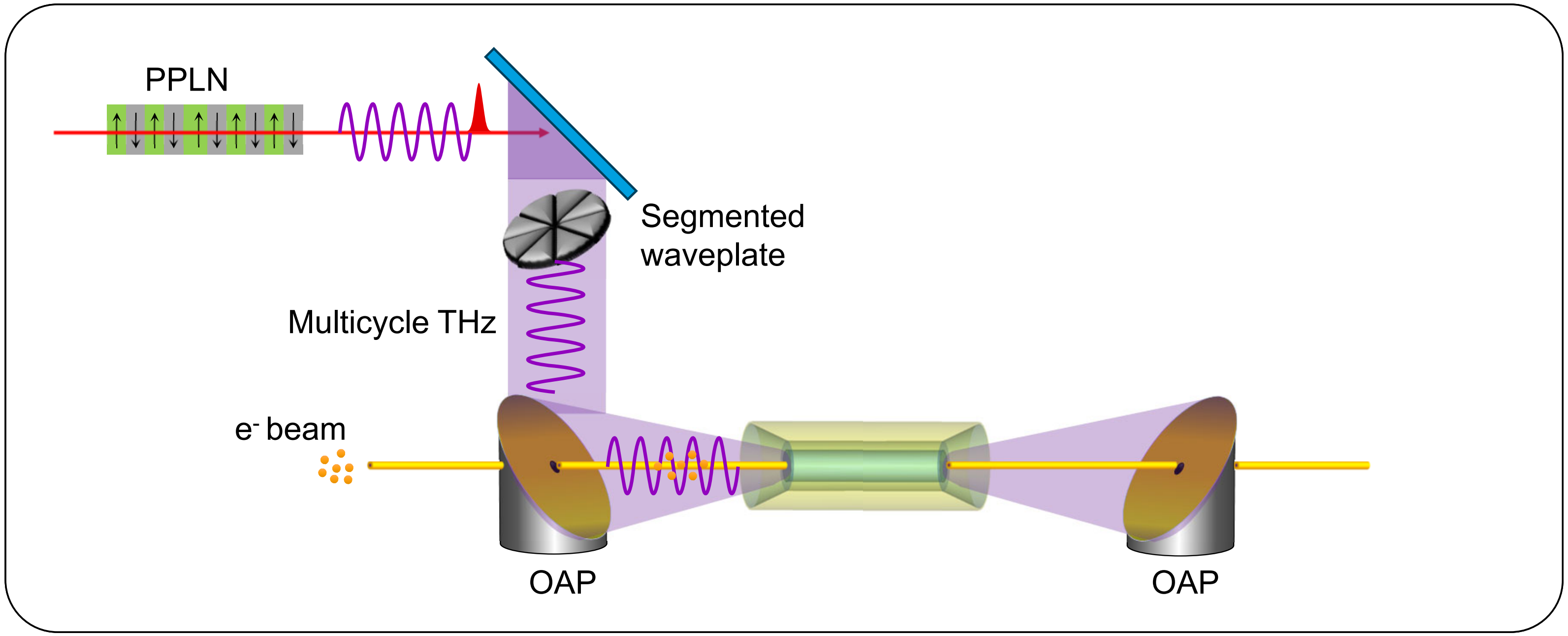
# Benefits of high electron energy: uniform field profile



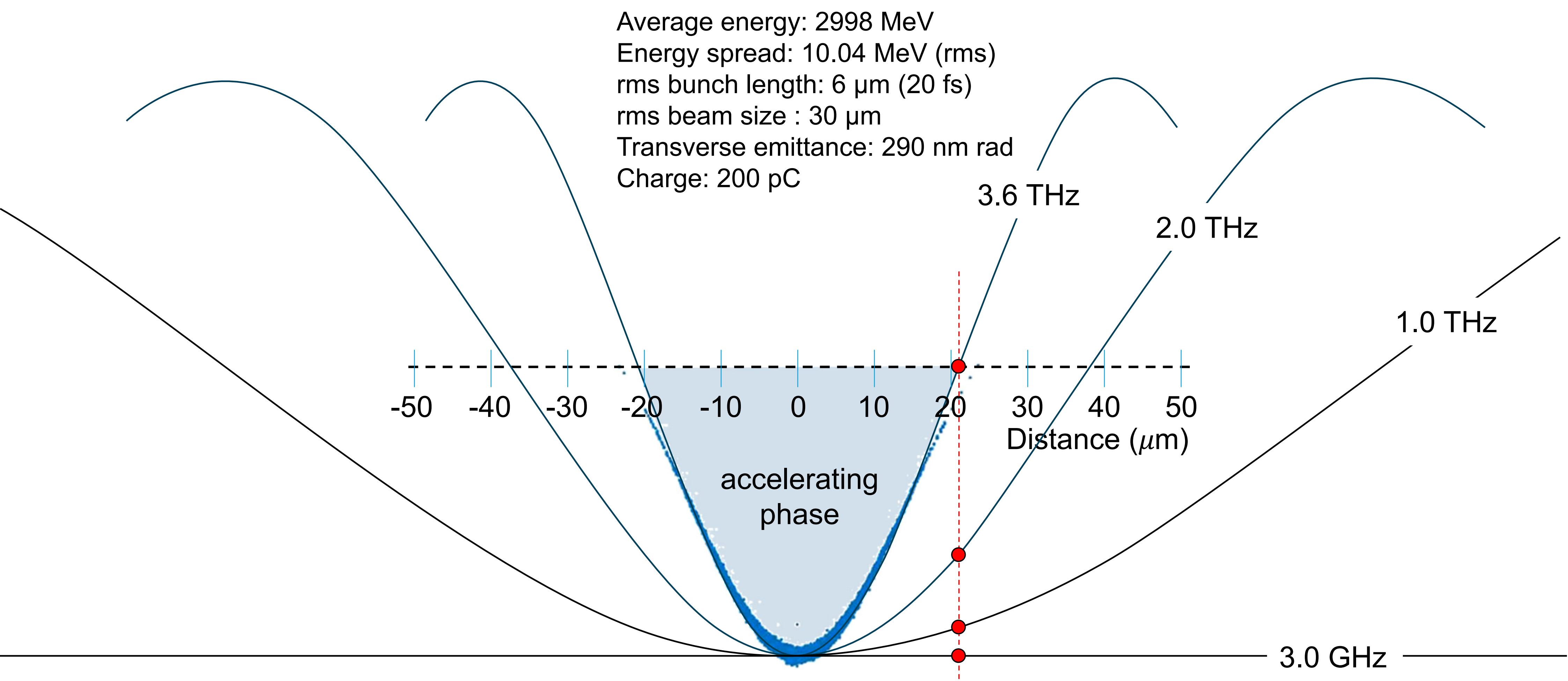



# Acceleration mode $TM_{01}$ in DLW needs radially polarized input



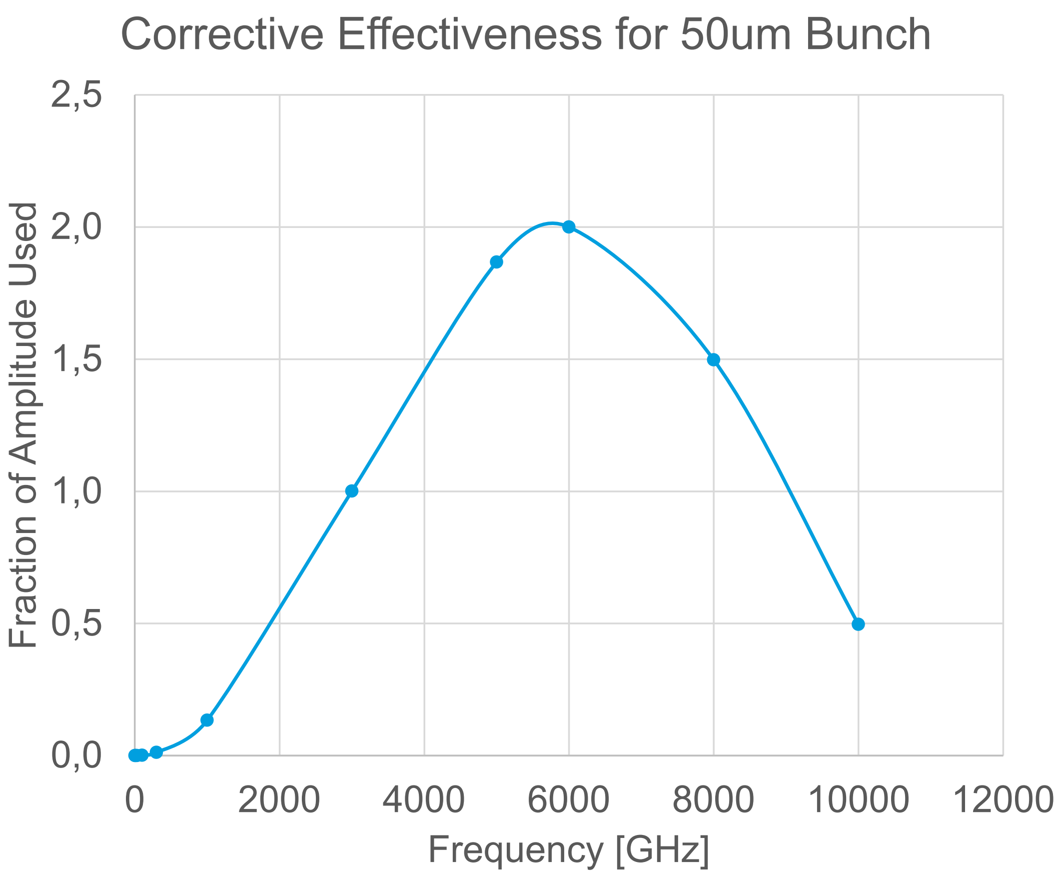



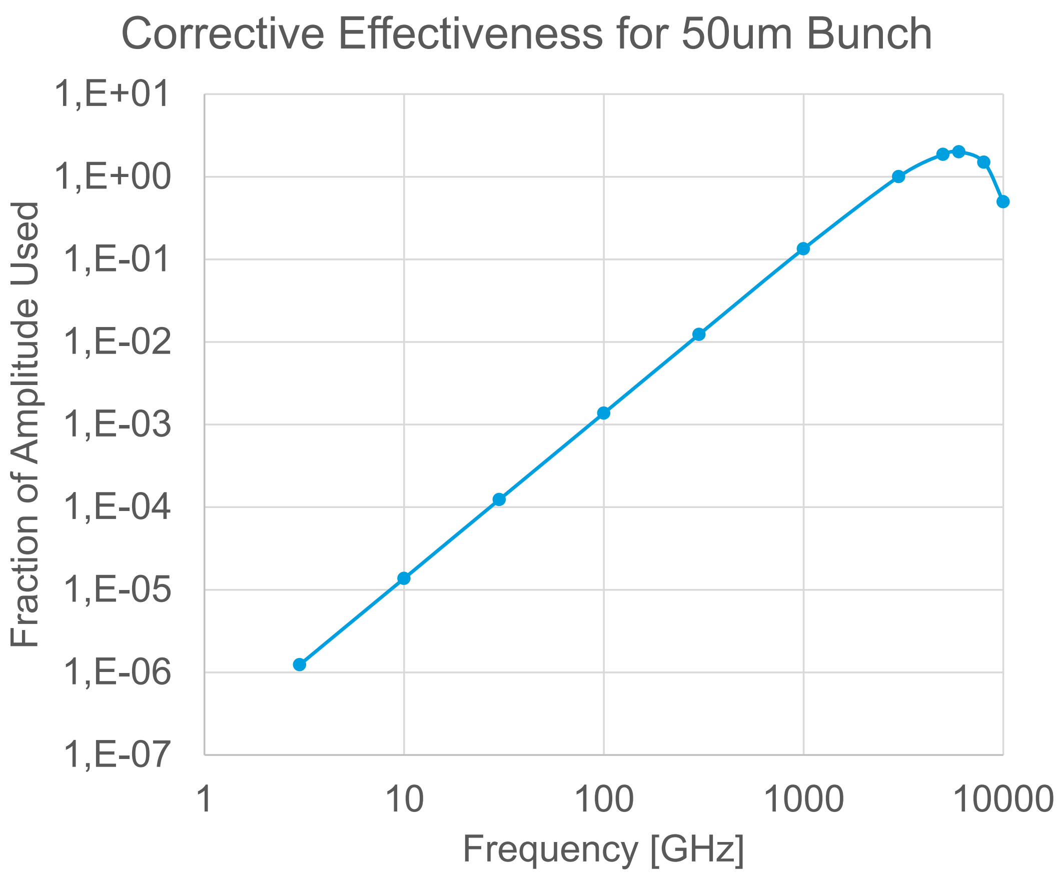
# Tuning the frequency to the length-scale of the feature



# Quantifying the effectiveness vs frequency

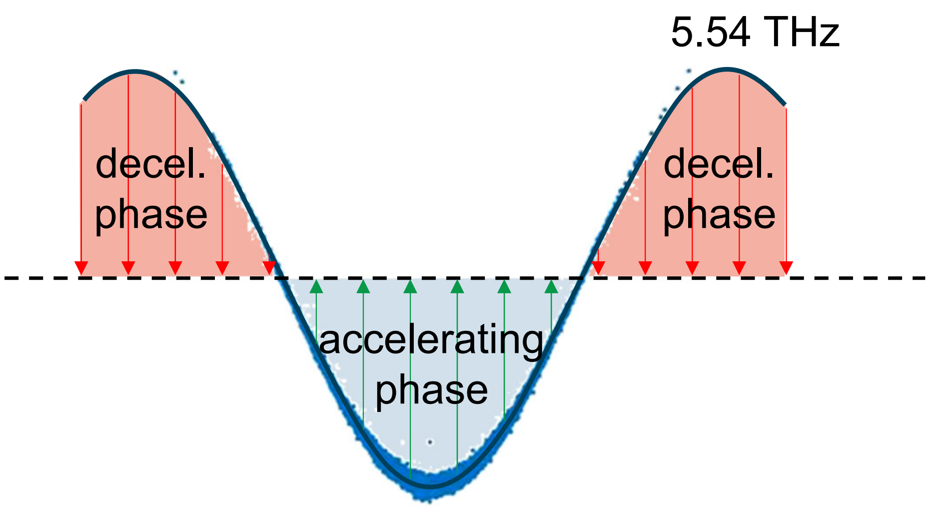
RF is ~1 million times less effective than THz



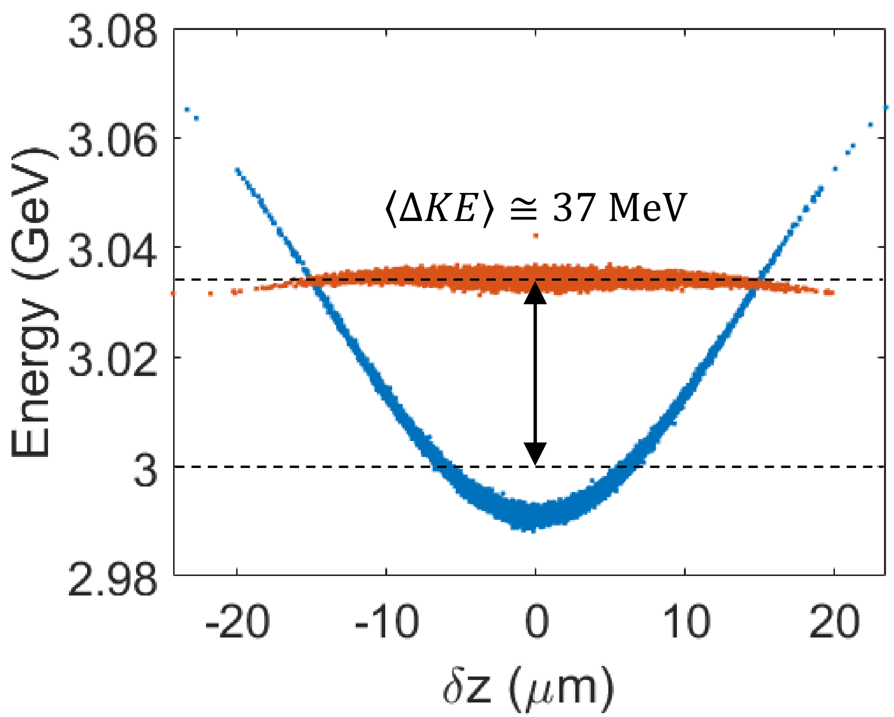
# Optimized frequency minimizes average energy gain

Matched frequency uses full peak to peak amplitude of THz



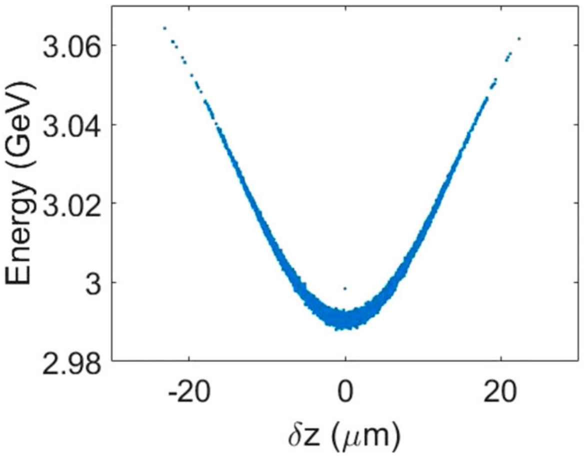

Energy increase of beam:

- $Q = 200 \text{ pC}$
- $\langle \Delta KE \rangle \cong 37 \text{ MeV}$
- $\delta E = 7.4 \text{ mJ}$

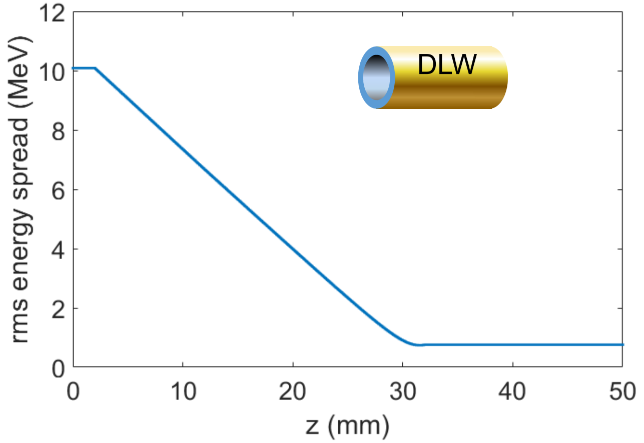


# Near luminal $v_\phi$ and $v_{grp}$ allow long interaction lengths

$E_{THz} = 1.5\ \text{GV/m}$




$L = 3\ \text{cm}$




Parameters

- $d_{waveguide} = 250\ \mu\text{m}$
- $v_\phi \cong c$
- $\phi_{inj} = 135°$
- $\langle \Delta KE \rangle_{RMS} = 0.8\ \text{MeV}$

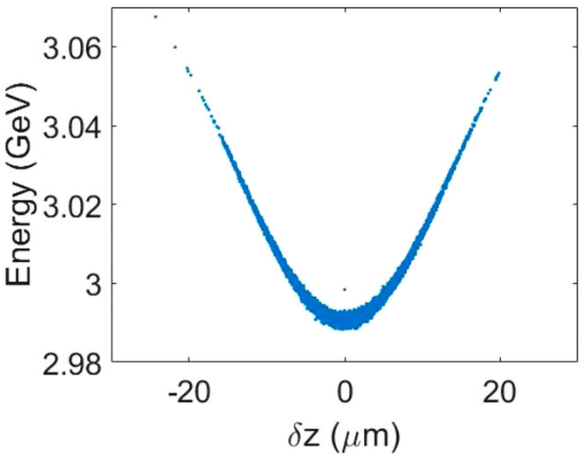
$$E_{pulse} = 1\ \text{mJ}$$

$$u = \epsilon_0 |E_{field}|^2$$

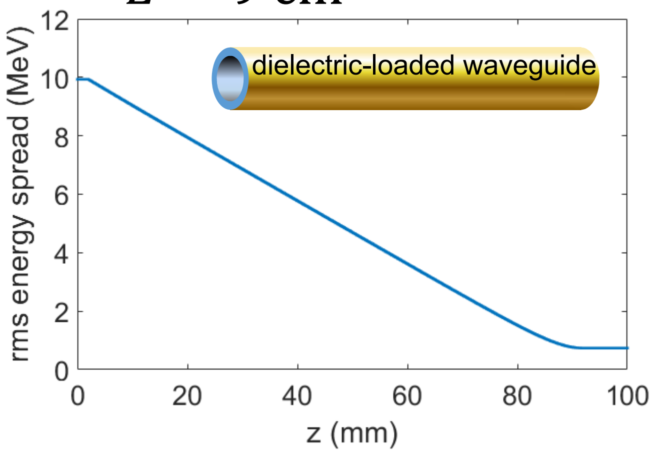
$$V = \frac{1}{4}\pi d^2 N \Lambda_{THz}$$

$$E_{pulse} = uV$$

$E_{THz} = 0.5\ \text{GV/m}$




$L = 9\ \text{cm}$



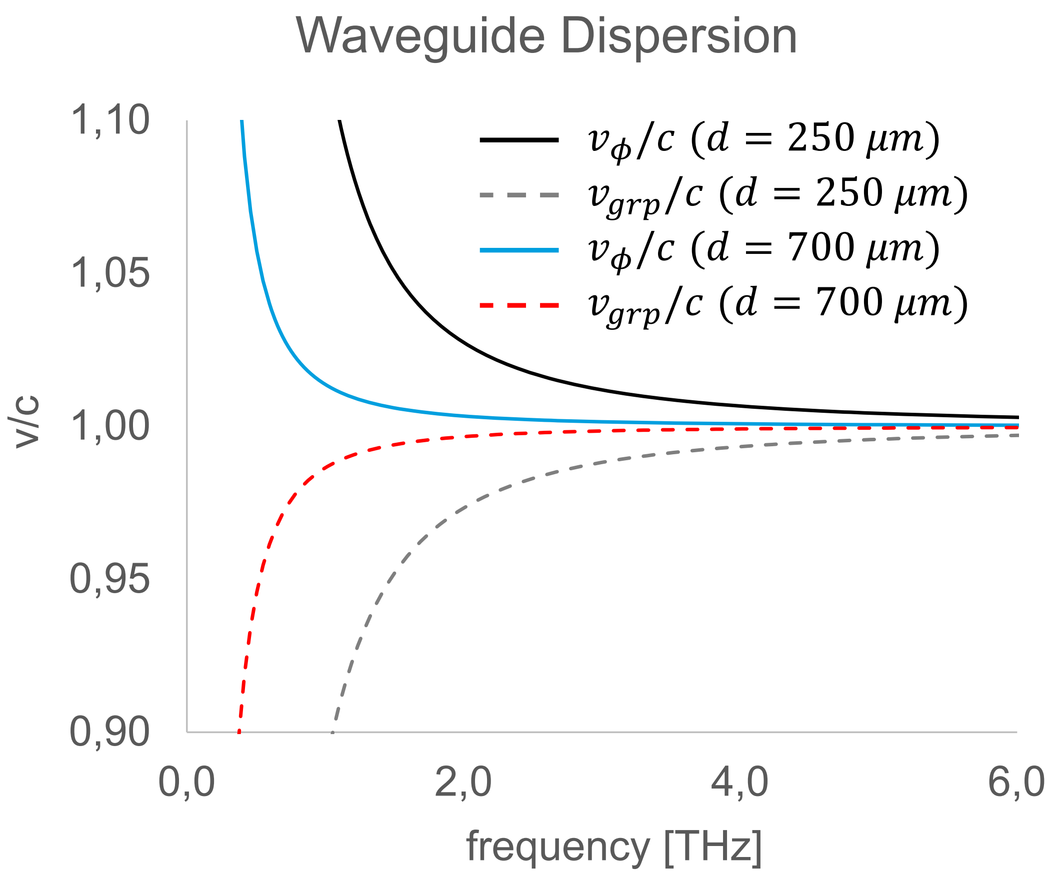

Parameters

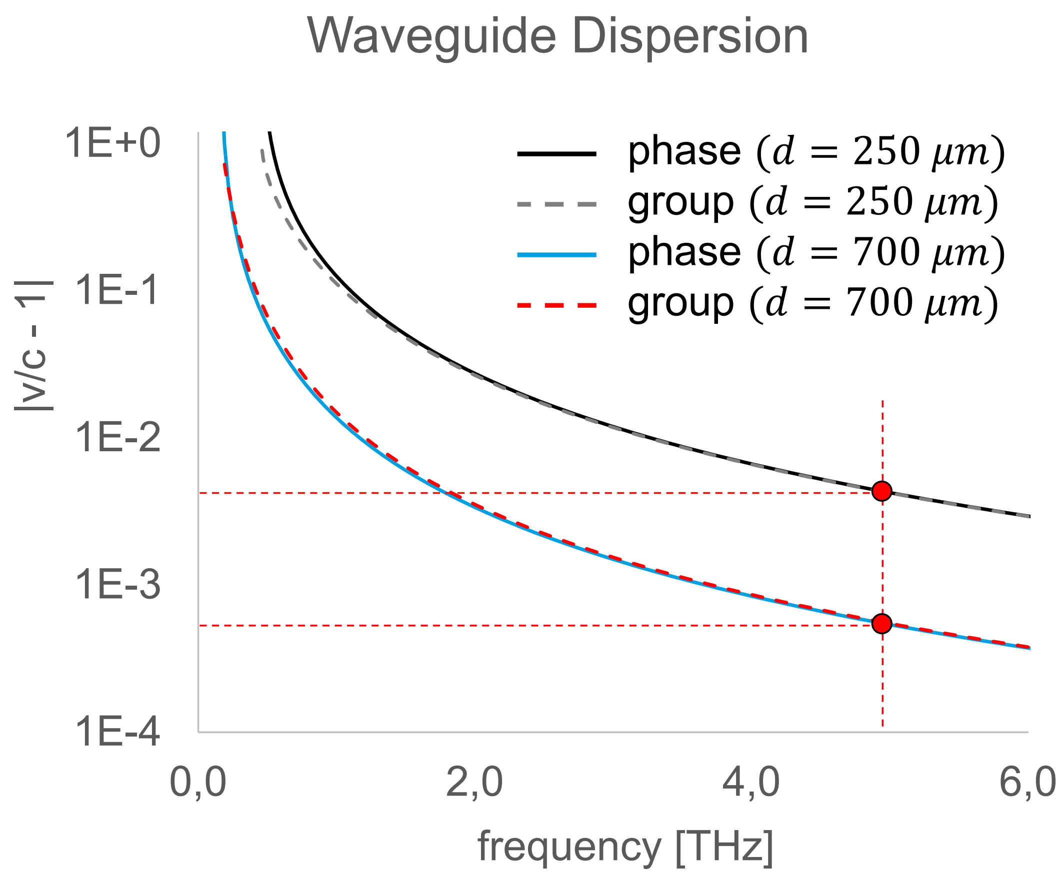
- $d_{waveguide} = 250\ \mu\text{m}$
- $v_\phi \cong c$
- $\phi_{inj} = 135°$
- $\langle \Delta KE \rangle_{RMS} = 0.8\ \text{MeV}$

$$E_{pulse} = 100\ \mu\text{J}$$

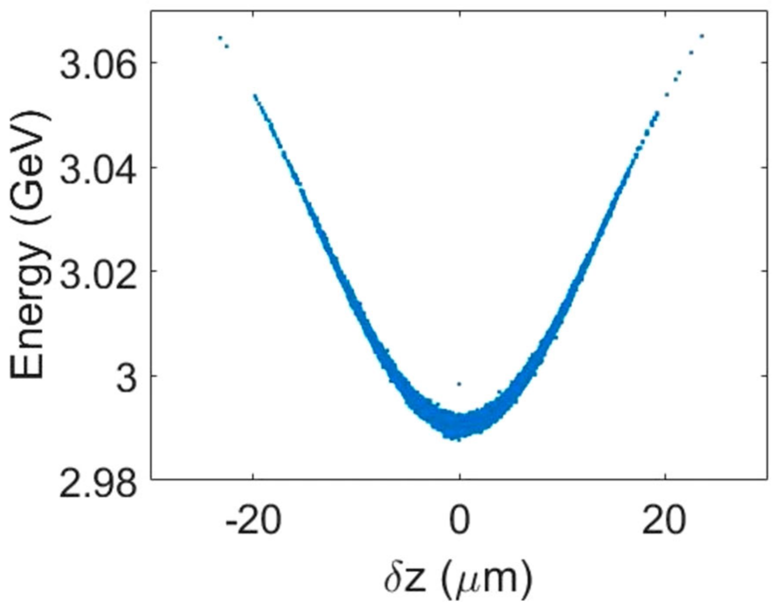
# Phase and group velocities approach zero at higher frequency

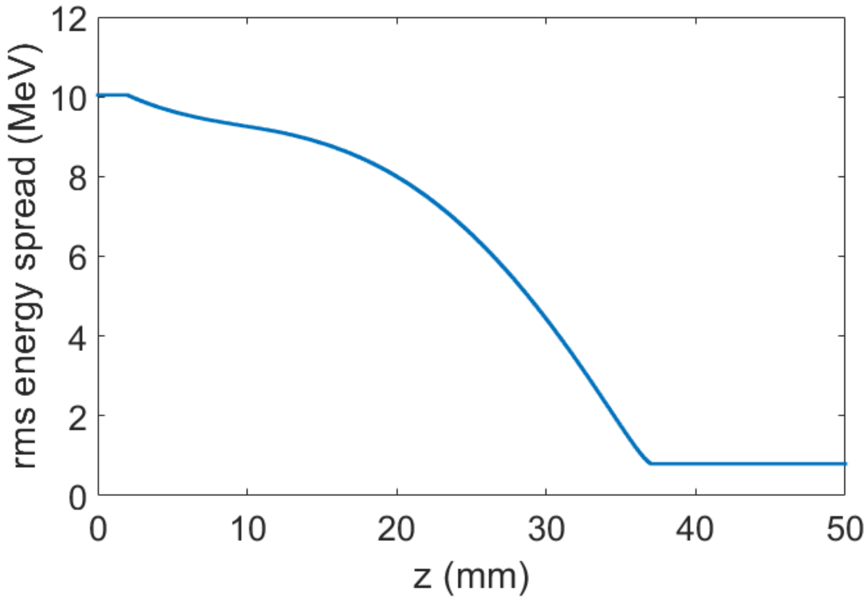
$$\frac{v_\phi}{c} = \frac{f}{\sqrt{f^2 - f_c^2}}$$

# Larger waveguides may work without dielectric


Parameters

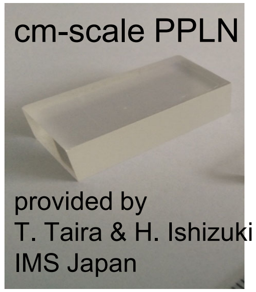
- $d_{waveguide} = 700\ \mu m$
- $E_{field} = 1.5\ GV/m$
- $E_{pulse} \approx 10\ mJ$
- $v_\phi \cong 1.0006\ c$
- $\phi_{inj} = 85°$
- $L = 37\ mm$
- $\langle \Delta KE \rangle_{RMS} = 0.8\ MeV$

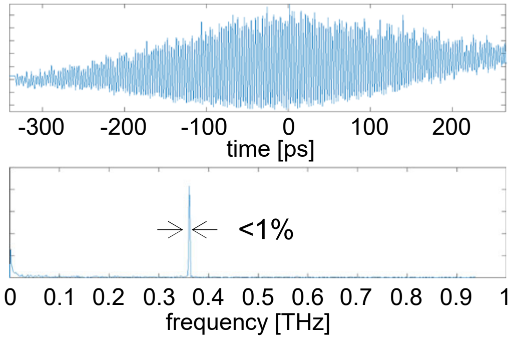
dielectric-loaded waveguide

# Multi-mJ laser-based THz sources now exist

## 600 $\mu$J >100 cycle pulse @ 360 GHz

Laser: 1.2 J Ti:Sapphire @ 5 Hz

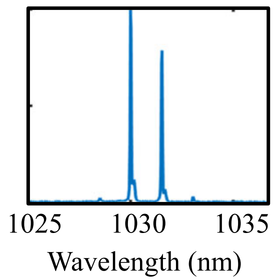


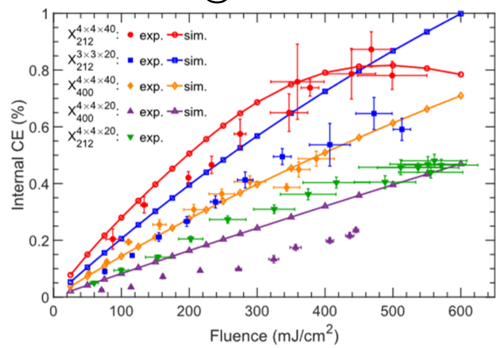




*S. Jolly et al., Nature Commun.* ***10****, 2591 (2019)*

## 45 $\mu$J, 0.9% conv. eff. @ 540 GHz

Laser: 10 mJ Yb:YAG @ 10 Hz

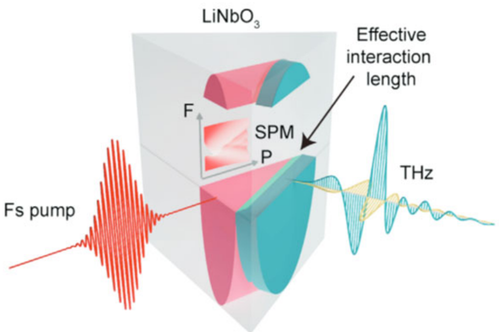



*H. T. Olgun et al., Opt. Lett.* ***47****, 2374 (2022)*

## 13 mJ 1-cycle 180 GHz pulse

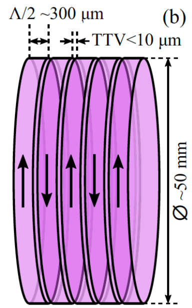
Laser: 1.2 J Ti:Sapphire @ 10 Hz

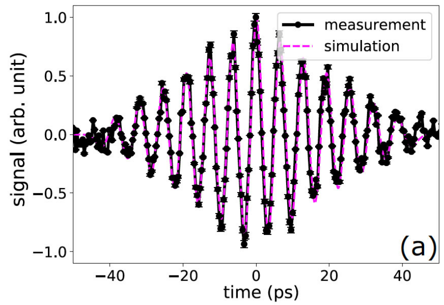



*X. Wu et al., Adv. Mater. 2208947 (2023)*

## 1.3 mJ 6-cycle 160 GHz pulse

Laser: 1.2 J Ti:Sapphire @ 10 Hz

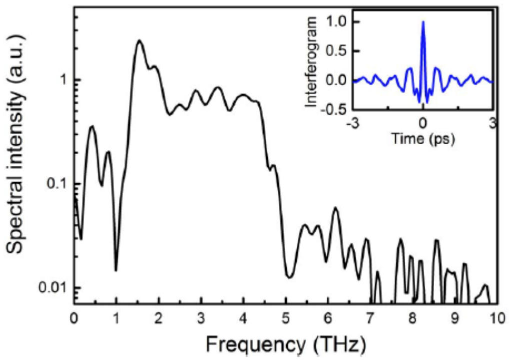


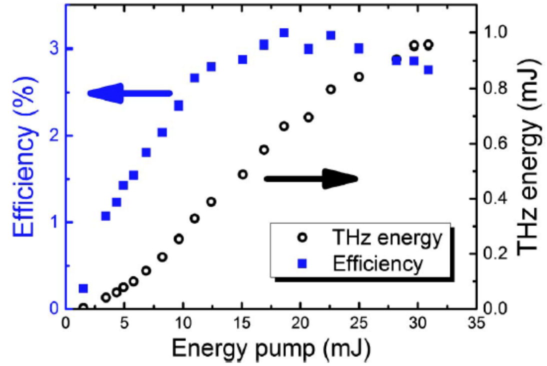




*F. Lemery et al., Commun. Phys.* ***3****, 150 (2020)*

# Organic crystals promising for 5 THz, GV/m fields

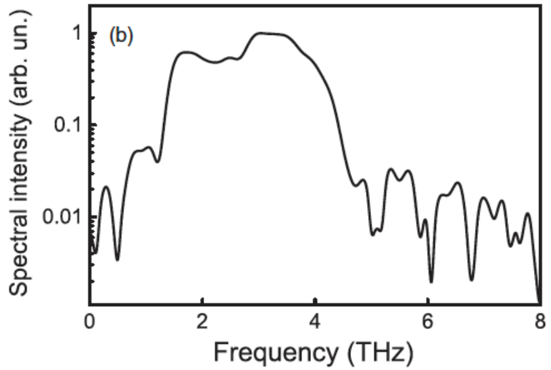
wavelength difference for 5 THz generation: 15 nm

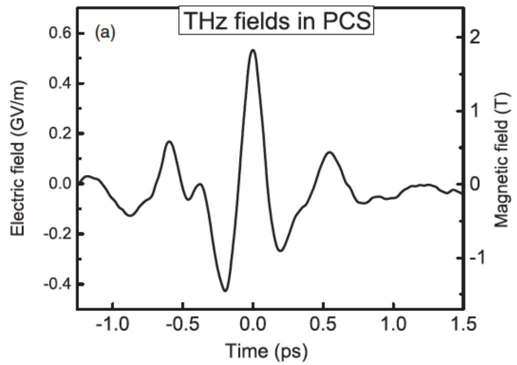



- Laser: Cr:forsterite, 1250 nm, 30 mJ, 10 Hz
- Bandwidth: 20 nm
- Crystal: DSTMS

*C. Vicario et al., Opt. Lett.* ***39****, 6632 (2014)*

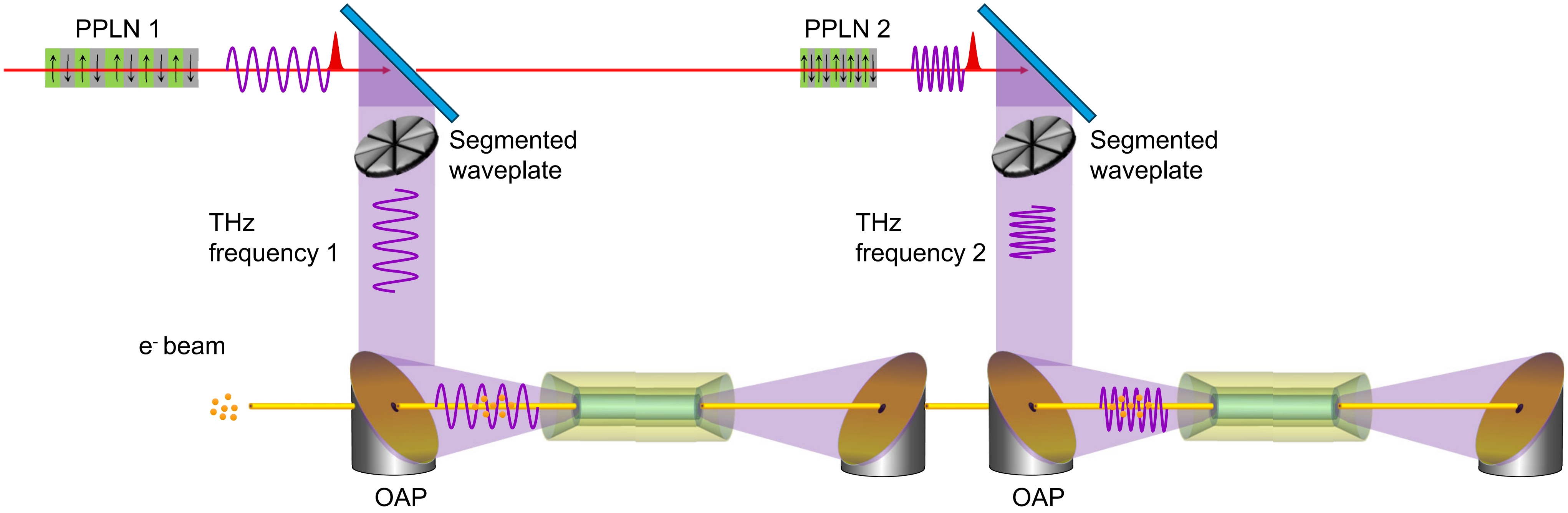



- Laser: Ti:Sapphire, 20 mJ, 100 Hz
- OPA output: 3 mJ, 1500 nm
- Bandwidth: >100 nm
- Crystal: DSTMS

*C. Vicario et al., PRL* ***112****, 213901 (2014)*

# Staged THz interaction with laser recycling (Fourier Concept)




- Cost of insertion is low
- Main cost (laser) can be reused and flexibly repurposed

# Next steps…

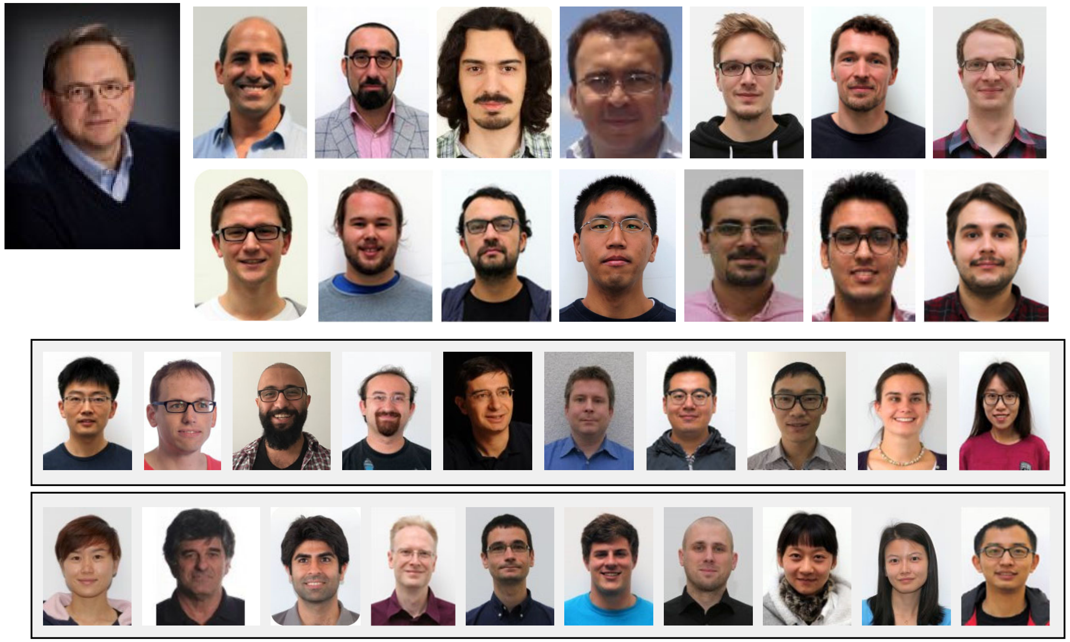
- Explore parameter space for Chirp Correction
  - Ask for sample problems
  - Full-scale simulations
  - Beam loading effects
  - Efficiency optimization
  - Dispersion management
- Apply for funding to do feasibility study
- Look for candidates to do proof-of principle experiments
  - LPAs are good options because of laser

# AXSIS Team and Collaboration

SYNERGY Grant

## Ultrafast Optics and X-rays Group

Alumni



## Coherent Diffractive Imaging Group

## Bio-Physical-Chemistry Group

## Detector Group

## UHH (LUX)

## Accelerator Division: DESY

# Conclusions

- THz waves present unique options for electron acceleration and manipulation
- Energy requirements are reasonable or near reasonable for addressing key problems in plasma and conventional accelerators
- Worthwhile to explore the options
- Vision of the future: Synergy between THz, plasma and conventional accelerators

# AXSIS

erc SYNERGY Grant

## Attosecond X-ray Science: Imaging and Spectroscopy

### THz-driven Accelerator and Light Source

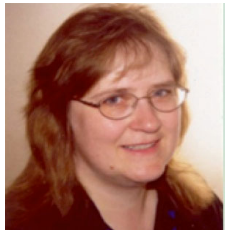
**Ultrafast Optics & X-Rays**

Center for Free-Electron Laser Science

Group Leader:
Dr. Franz X. Kärtner

X-Rays
Henry Chapman
DESY & UHH

Accelerators
Ralph Assmann
DESY



Bio-Phys-Chem
Petra Fromme
DESY & ASU

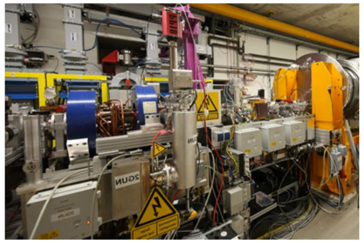
# THz Accelerator Technology: Scaling from cm to mm and below

| Parameter | RF Accelerators | THz Accelerators | THz Enhancement |
|---|---|---|---|
| Field Strengths, $E_0$ | 10 – 100 MV/m | 100 – 1000 MV/m | ~10x |
| Wavelength, $\lambda$ | 3 – 10 GHz | 100 – 500 GHz | ~100x |
| Field Gradients, $dE_0/dz$ | ~10 GV/m$^2$ | ~10,000 GV/m$^2$ | ~1000x |

Compact Devices
- high-field acceleration
- low emittance
- ideal for UED

Eu-XFEL

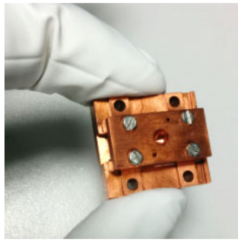
RF Gun



RF LINAC
~ 2 km

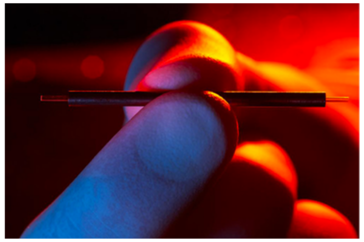
AXSIS

THz Gun



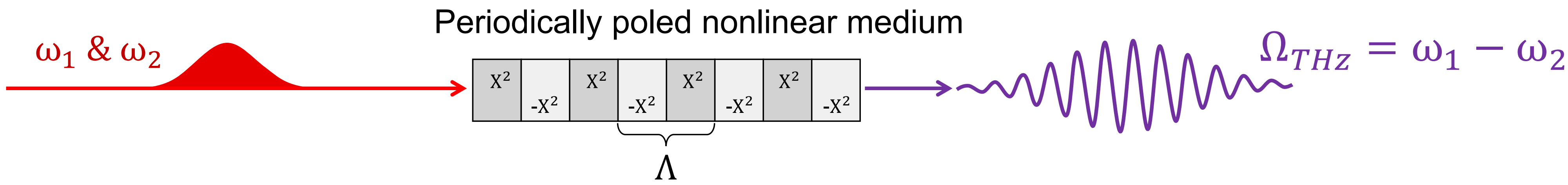
D. Zhang *et al.*, Nature Photonics (2018)

THz LINAC
~ 8 cm



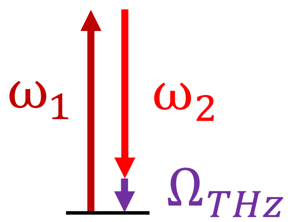
E. Nanni et al., Nat. Comm. 6, 8486 (2015)

# Quasi Phase-Matching Enables Efficient Multicycle THz Generation

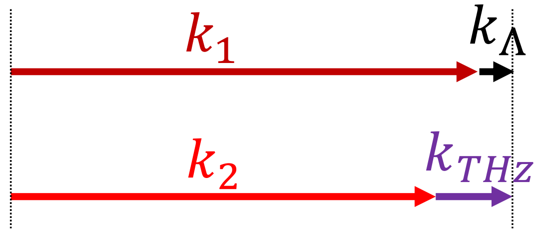



Quasi-phase matching requirements

*Energy conservation:*




*Momentum conservation:*

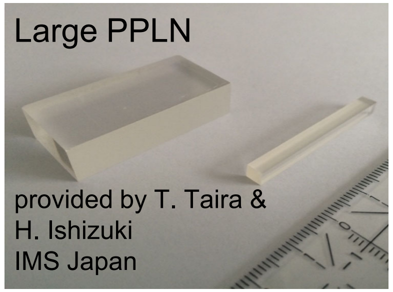



Recent results from our group in THz generation with QPM

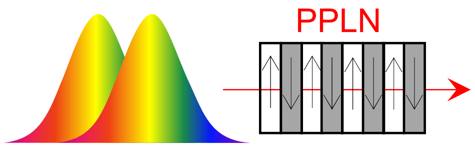
| Record Result | Energy | Material | Conv. Eff. | Article |
|---|---|---|---|---|
| *Energy* | ***1 μJ*** | *LiNbO3* | *0.12%* | *Carbajo et al., Opt. Lett. 40, 5762 (2015)* |
| *Energy* | ***40 μJ*** | *LiNbO3* | *0.13%* | *Ahr et al., Opt. Lett. 42, 2118 (2017)* |
| *Energy* | ***600 μJ*** | *LiNbO3* | *0.24%* | *Jolly et al., Nat. Commun.* ***10,*** *2591 (2019)* |
| *Energy* | ***1,300 μJ*** | *LiNbO3* | *0.14%* | *Lemery, Commun Phys* ***3,*** *150 (2020)* |
| *Material* | *0.7 μJ* | ***KTP*** | *0.16%* | *W. Tian et al., Opt. Lett.* ***46,*** *741 (2021)* |
| *Efficiency* | *45 μJ* | *LiNbO3* | ***0.89%*** | *H. T. Olgun et al., Opt. Lett.* ***47****, 2374 (2022)* |

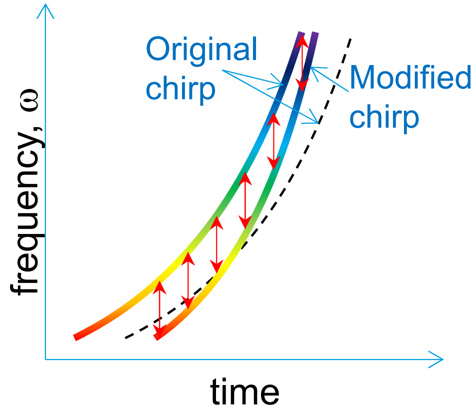
# Record Energy Multicycle THz Generation using Chirp & Delay

*S. Jolly et al., Nature Commun.* ***10****, 2591 (2019)*
*S. Jolly et al., Opt. Express* ***27****, 34769 (2019)*




Chirp & Delay



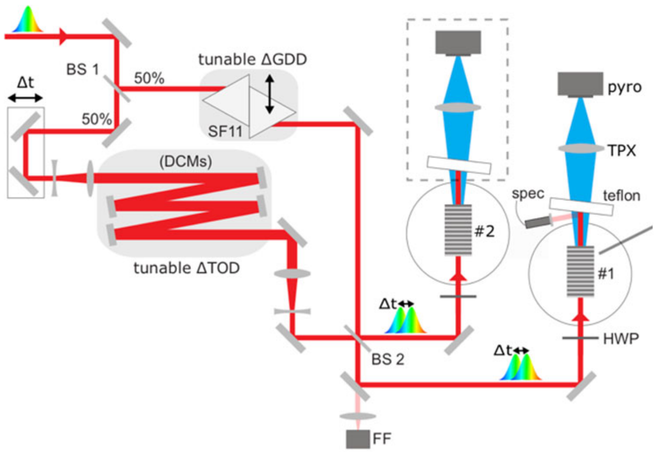




<u>Solution</u>:
Modify chirp of 1 pulse to produce constant $\Delta\omega = \Omega$

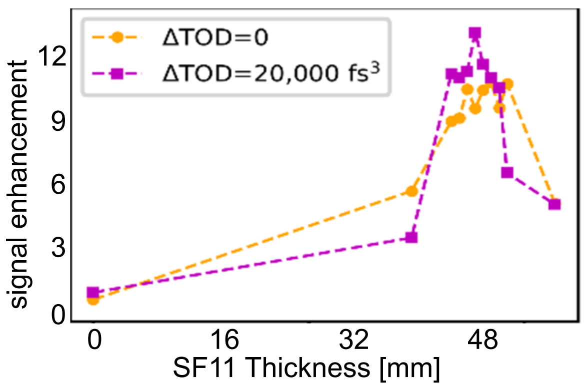
Record Narrowband THz Gen.

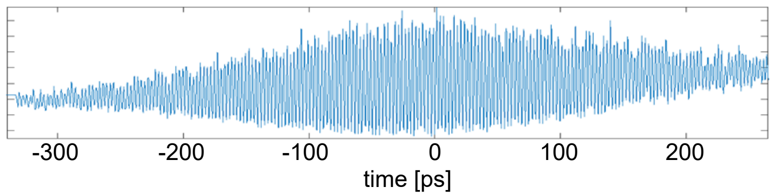
- 0.24% conversion eff.
- 1J Ti:S → **600 $\mu$J THz**

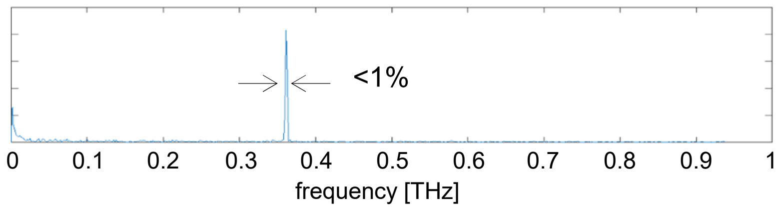
Asymmetric dispersion setup




Enhancement factor



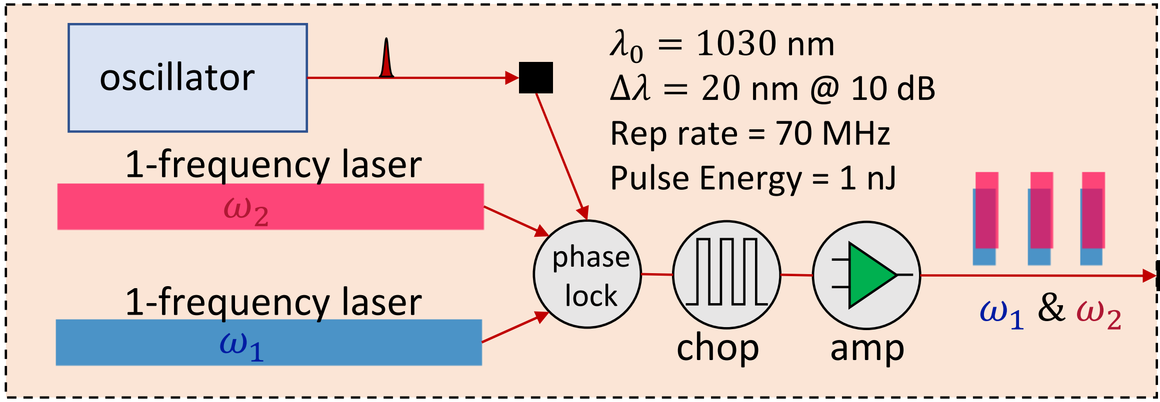



# Record multicycle THz efficiency using 2-line laser

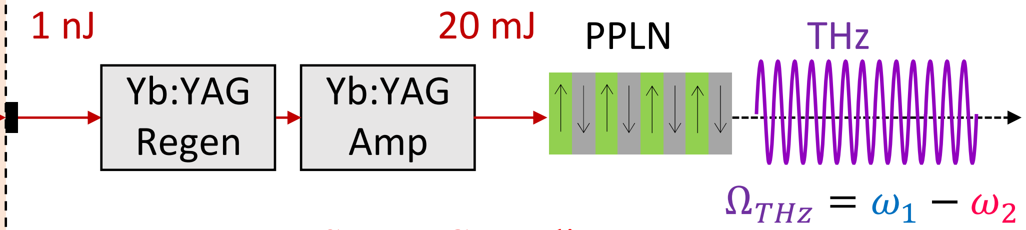
Custom 2-Line Laser

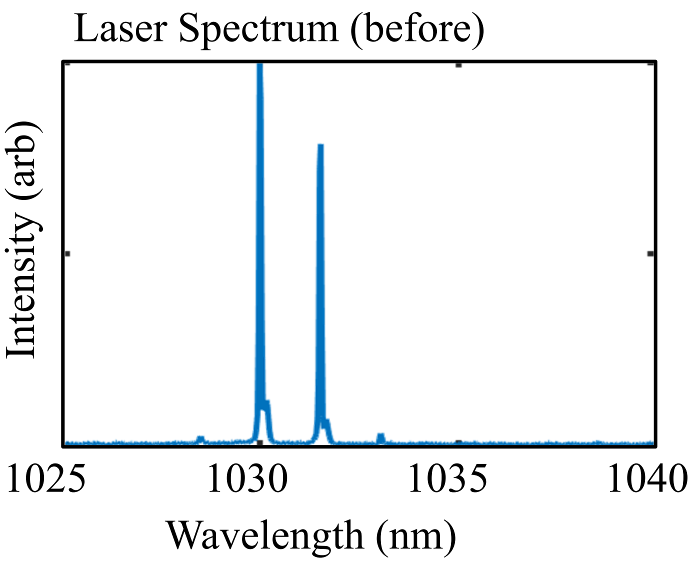
*H. T. Olgun et al., Opt. Lett.* ***47****, 2374 (2022)*

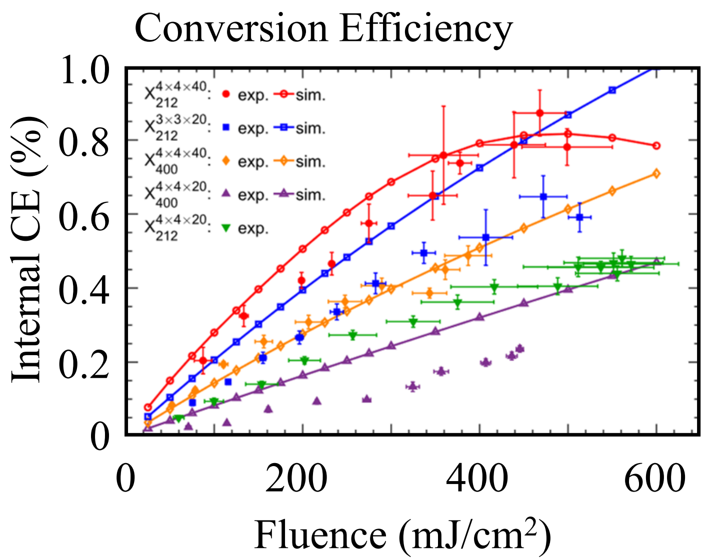



Record Narrowband THz Eff.

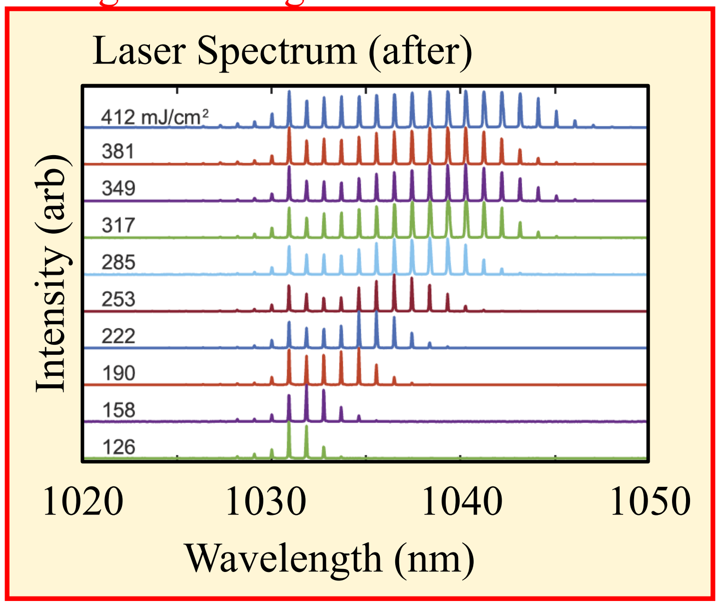
- 0.9% conversion eff.
- 10 mJ Yb:YAG → **45 $\mu$J THz**



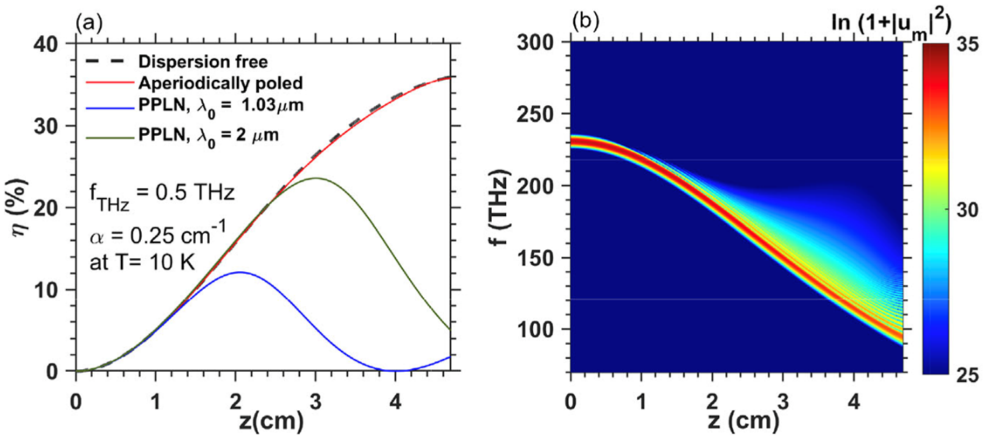




Strong Cascading

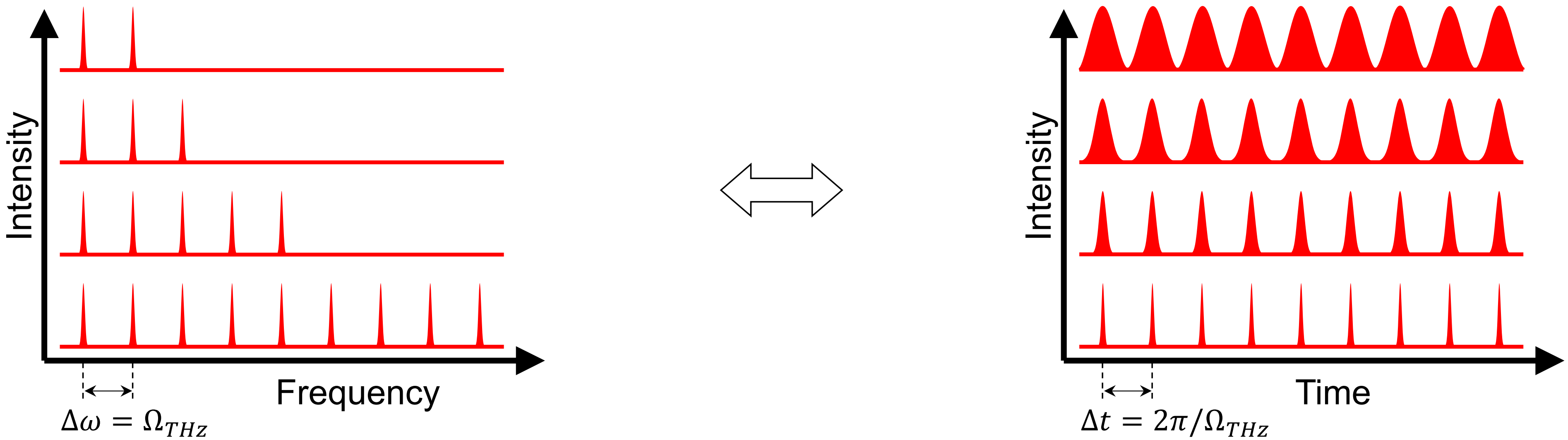


# THz Generation becomes more efficient with more spectral lines

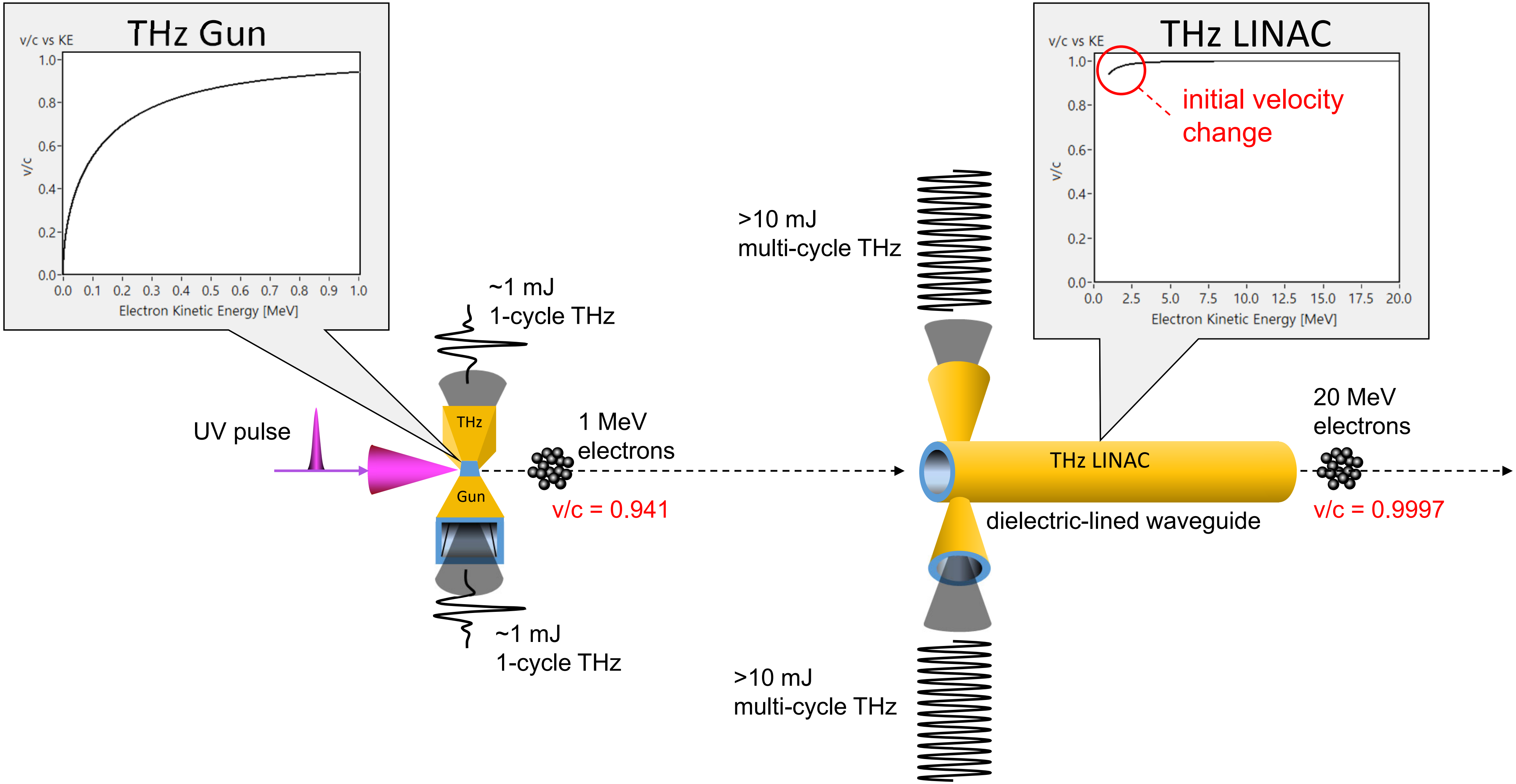



Theory predicts multiple percent efficiency is possible with optimized laser input

K. Ravi & F. X. Kärtner, Laser & Photon. Rev. **14**, 2000109 (2020)
K. Ravi et al., Opt. Lett. 24, 25582 (2016)
A. G. Stepanov, JETP Lett., 85, 227(2007)
M. Cronin-Golomb, Opt. Lett. 29, 2046 (2004)



# THz Accelerator is composed of THz Gun + THz LINAC

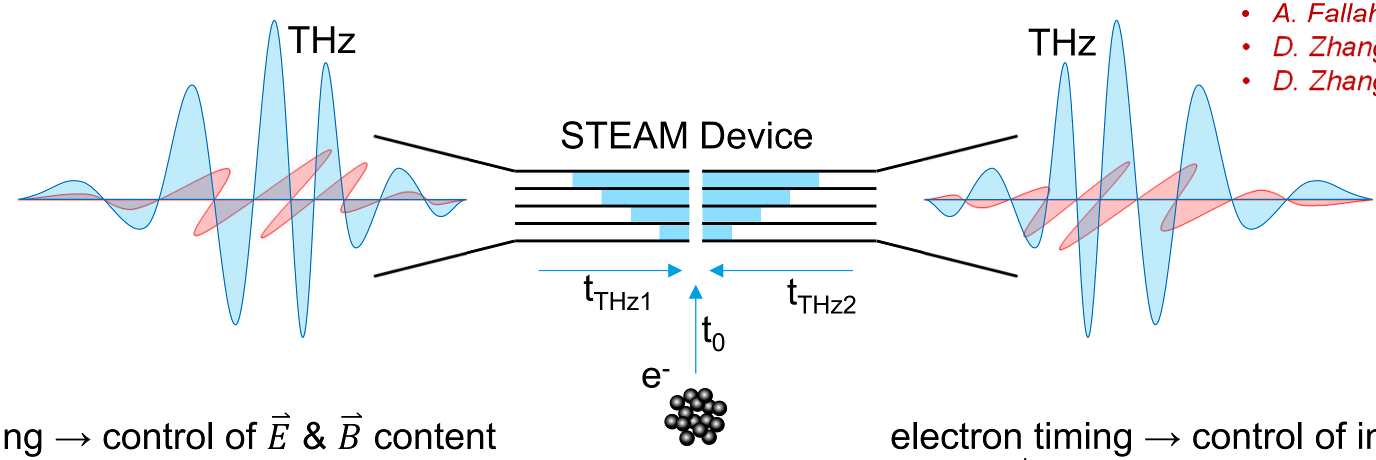



*F.X. Kärtner et al., NIMPRA **829**, 24 (2016)*

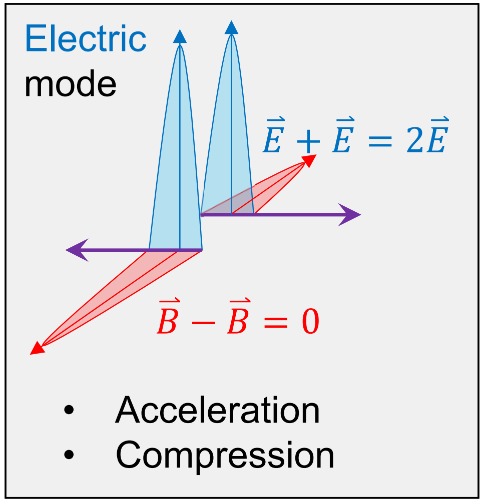
# THz and electron timing controls *STEAM* function

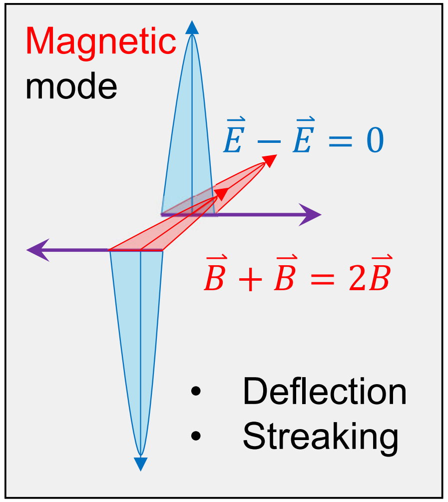
- *A. Fallahi, et al. PRSTAB 19, 081302 (2016)*
- *D. Zhang et al., Nature Photonics (2018)*
- *D. Zhang et al., Optica (2019)*

**S**egmented
**T**Hz
**E**lectron
**A**ccelerator &
**M**anipulator

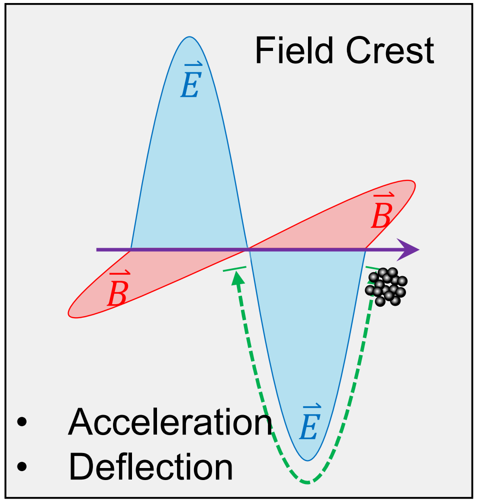


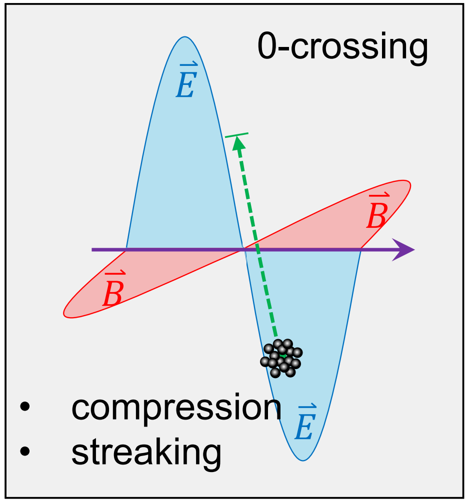

THz timing → control of $\vec{E}$ & $\vec{B}$ content



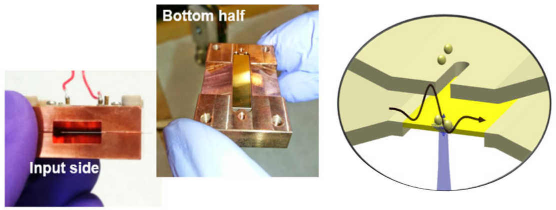

electron timing → control of injection phase



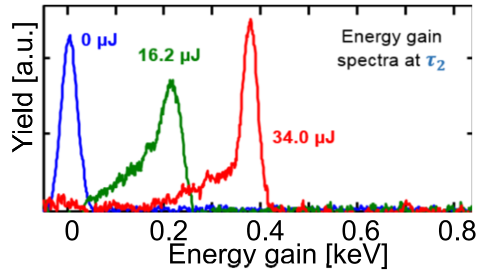



# Preliminary work demonstrates elements required for a THz gun

- THz Gun I: 0 ➞ 0.8 keV acceleration



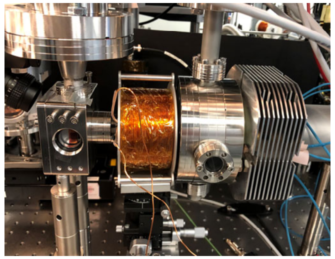

Parallel-Plate structure with 75 μm gap

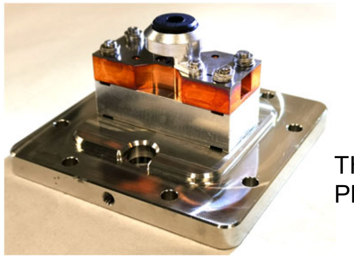


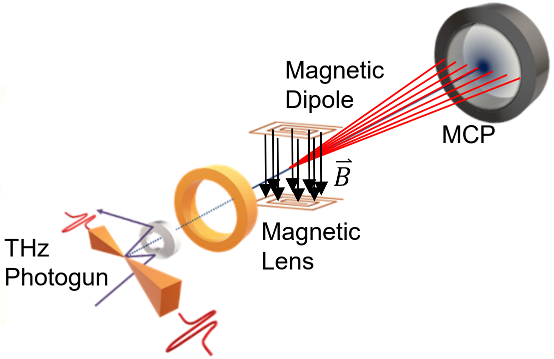

- 1[st] demonstration of THz gun
- Sub-keV electrons demonstrated
- One-side pumped
- 1D THz field concentration

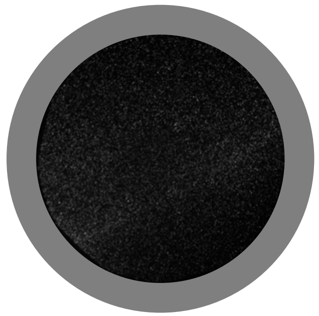
*W. Huang, et al., Optica 3, 1209 (2016)*
*A. Fallahi, et al., PRSTAB 19, 081302 (2016)*

- THz Gun III: 0 ➞ 3 keV acceleration







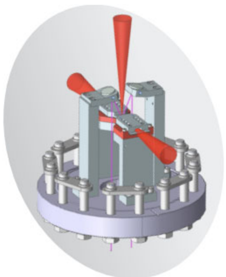



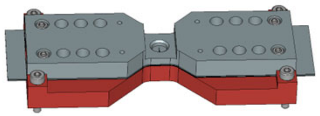
Beam moves with Solenoid current

- $E_{kin} = 2.43$ keV
- Highest energy for THz-driven photogun
- Control over injection demonstrated

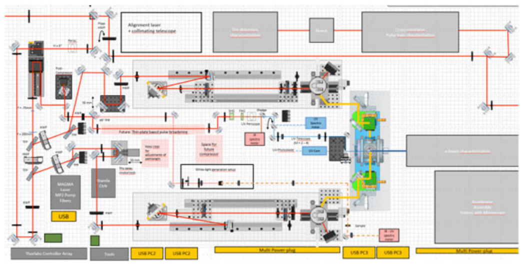
*N. H. Matlis et al. in preparation*

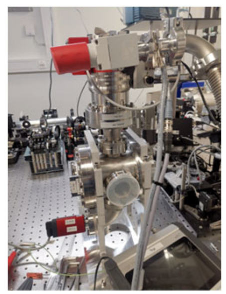
- THz Gun IV: 0 ➞ 200 keV acceleration (in development)





3 – 8 layer device

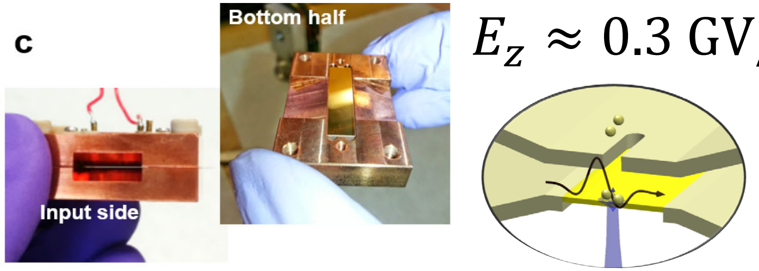




Electron Spec's
- $E_k \sim 190$ keV
- $\Delta E_k / E_k \sim 3.2\%$
- $\Delta t_{RMS} \sim 37$ fs
- $\sigma_x \sim 34\ \mu m$
- $\epsilon_N \sim 0.15$ mm · mrad

# THz acceleration – Nonrelativistic electrons

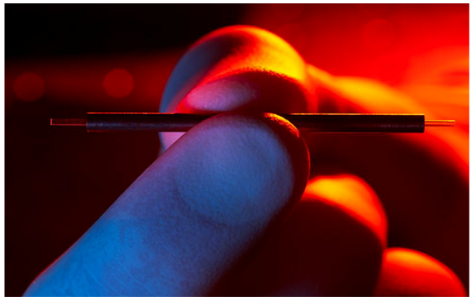
**THz Gun: 0 → 0.8 keV acceleration**




$E_z \approx 0.3 \text{ GV/m}$

W. Huang, *et al.,* Optica 3, 1209 (2016)
A. Fallahi, *et al.,* PRSTAB 19, 081302 (2016)

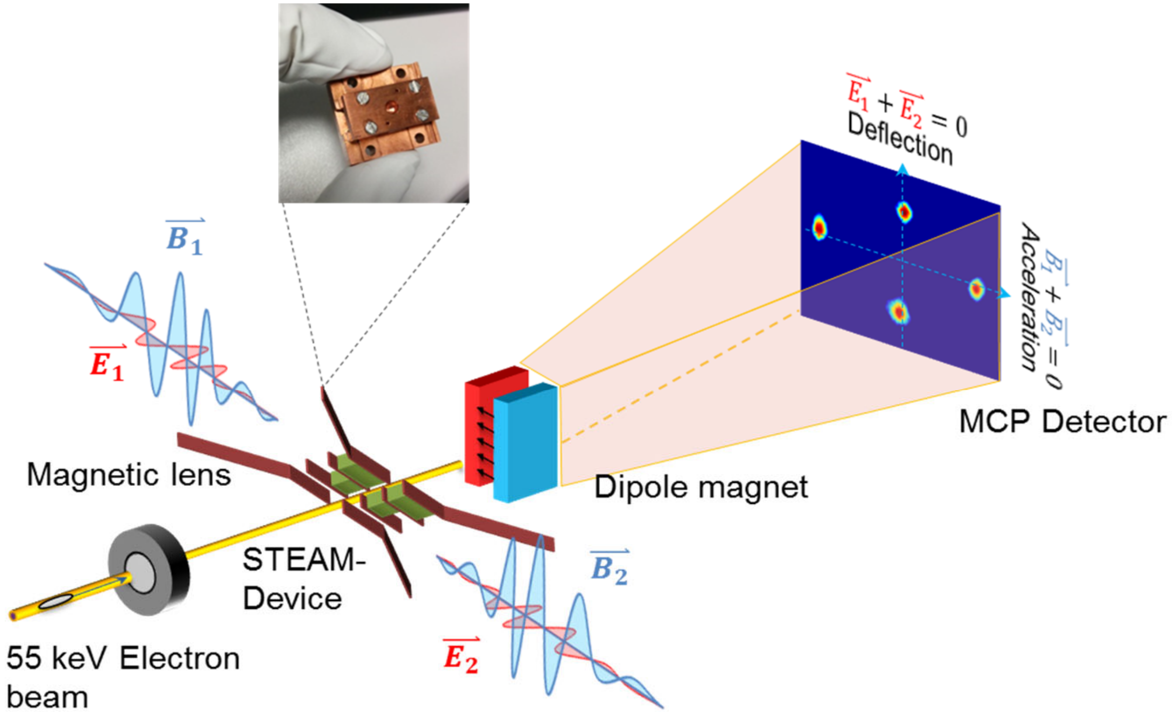
**THz LINAC: ±7 keV energy modulation**



mm-scale THz waveguide

E. Nanni et al., Nature Comm. 6, 8486 (2015)

**THz Manipulator (STEAM): acceleration, compression, focusing and streaking**

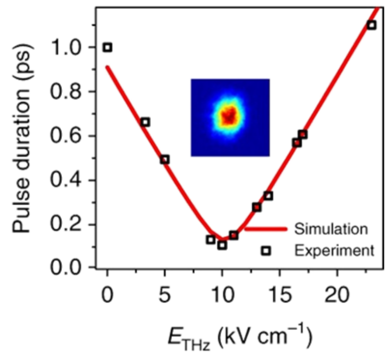


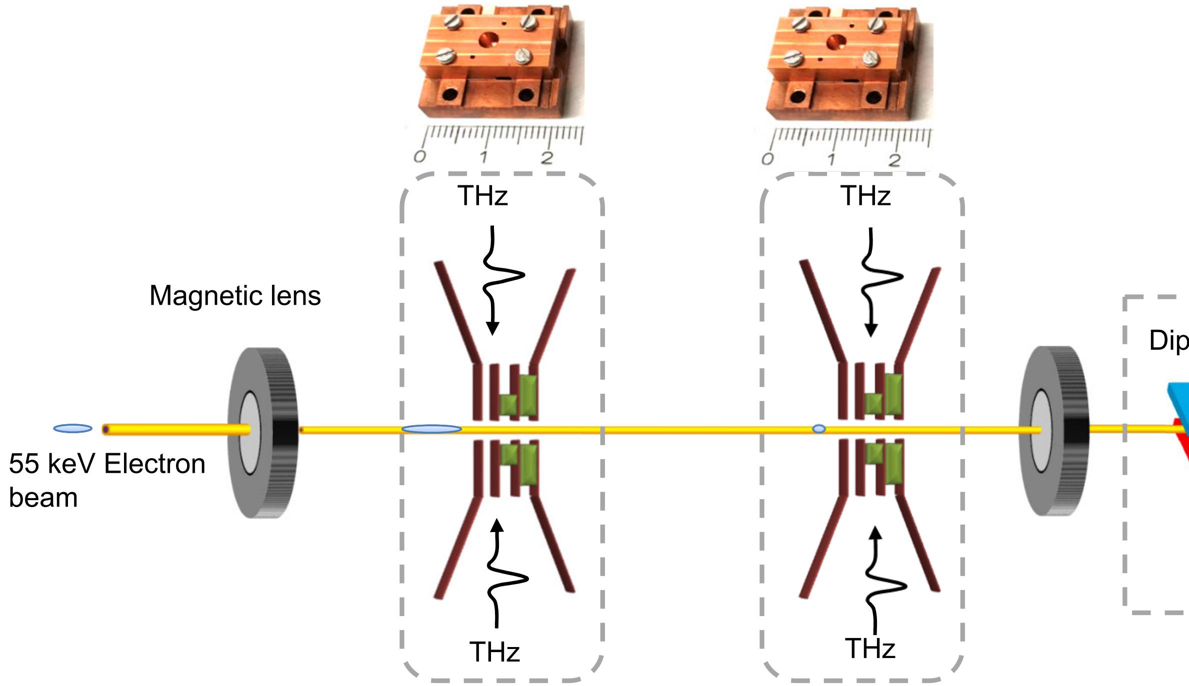

D. Zhang *et al.,* Nature Photonics (2018)
D. Zhang *et al.,* Optica Vol. 6, pp. 872-877 (2019)

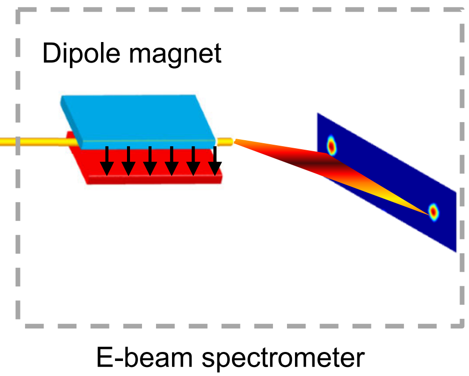
# STEAM devices combined & configured for diverse applications

*D. Zhang et al., Nature Photon.* ***12****, 336 (2018)*
*D. Zhang et al., Optica 6, 872 (2019)*

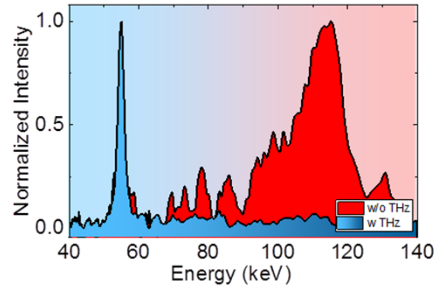
*compression:* $\tau \approx 100$ fs



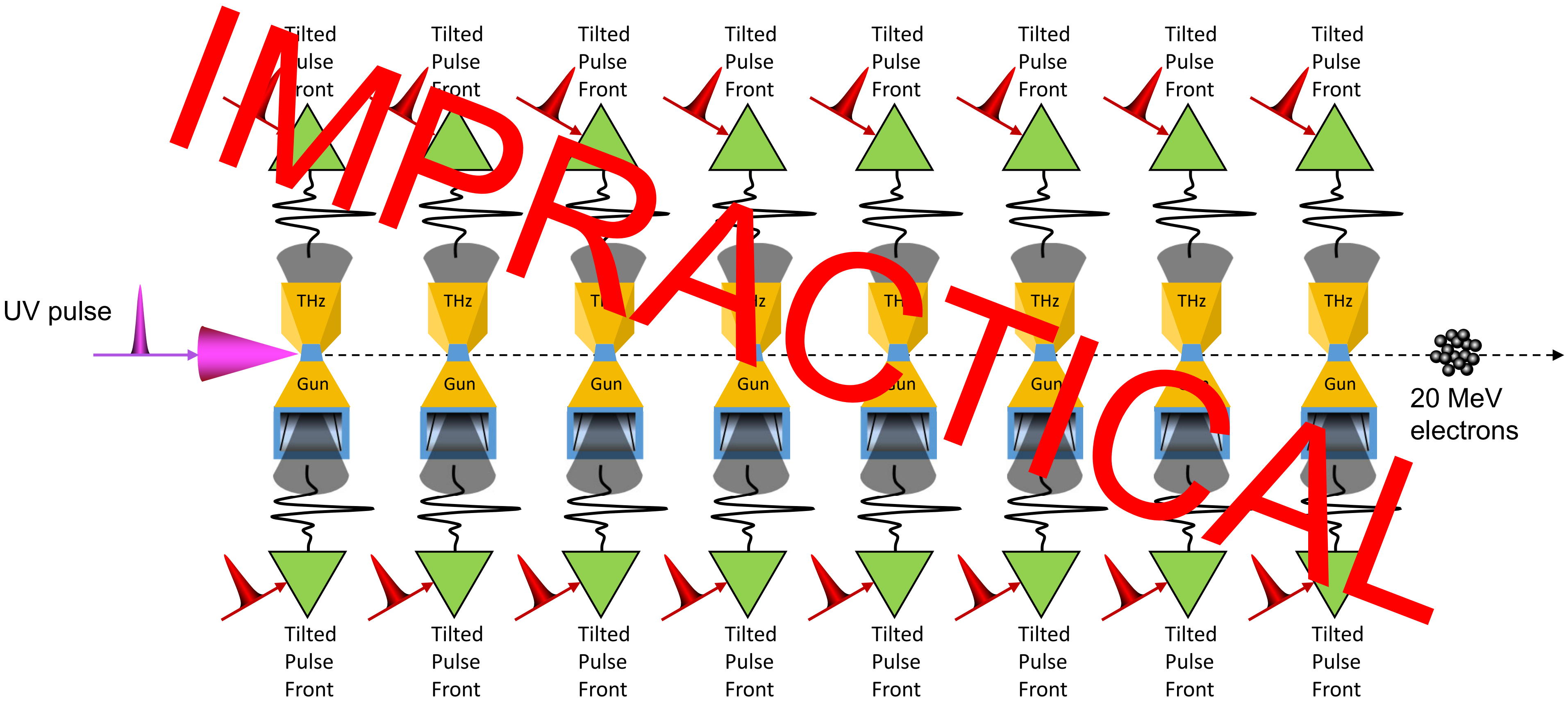




*acceleration:* 65 keV

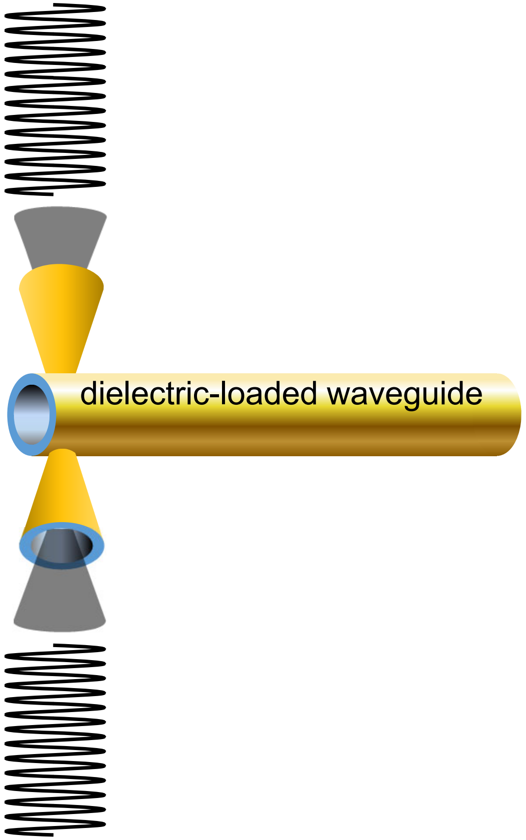



| Pulse duration meas: | Buncher | Streaker |
|---|---|---|
| Electron Acceleration: | Buncher | Accelerator |

# Why not use a series of transversely-pumped boosters?



# Benefits and Challenges of Dielectric-Loaded Waveguide LINACs




## Benefits

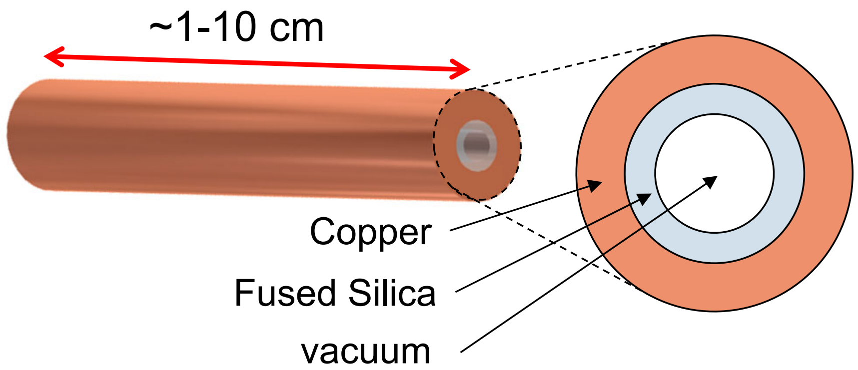
- Simple fabrication
- Tunable by varying the dimensions
- Travelling-wave nature allow efficient driving with pulses
- Dielectric sustains higher fields

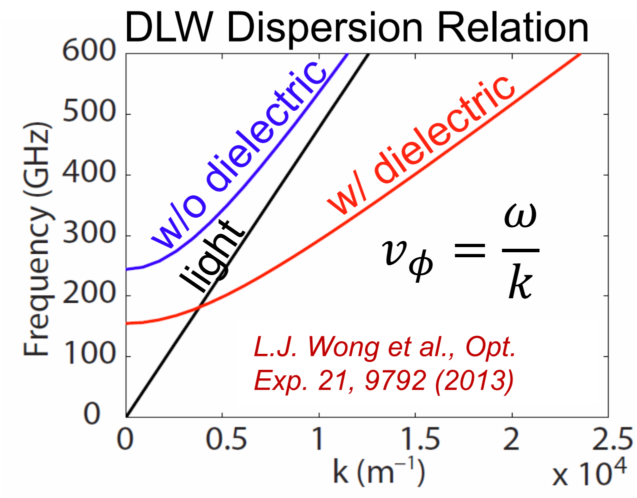
## Critical Issues

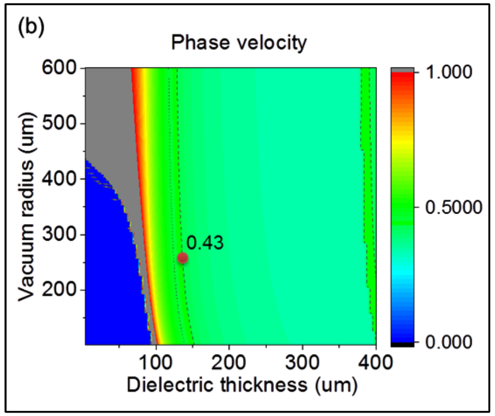
- **Tuning:** adjusting the speed of the wave
- **Dispersion** causes the THz pulse evolves
- **Dephasing:** electrons to move relative to wave crests
- **Walk-off:** electrons move relative to pulse envelope)
- **Inefficient** for low electron energies
- **Coupling** requires mode conversion to $TM_{01}$

# Phase velocity tuned using dielectric layer thickness

"Dielectrically-Loaded Waveguide"



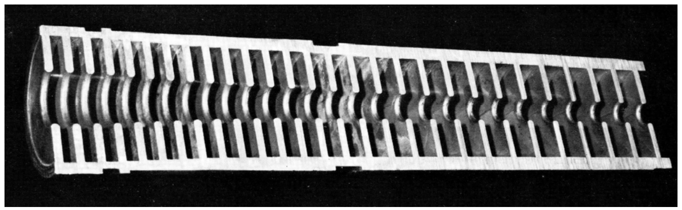




dielectric tunes $v_\phi$

"Cavity Waveguide"

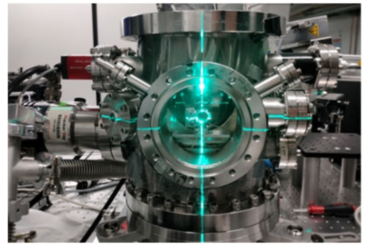
"Disk-Loaded Waveguide"

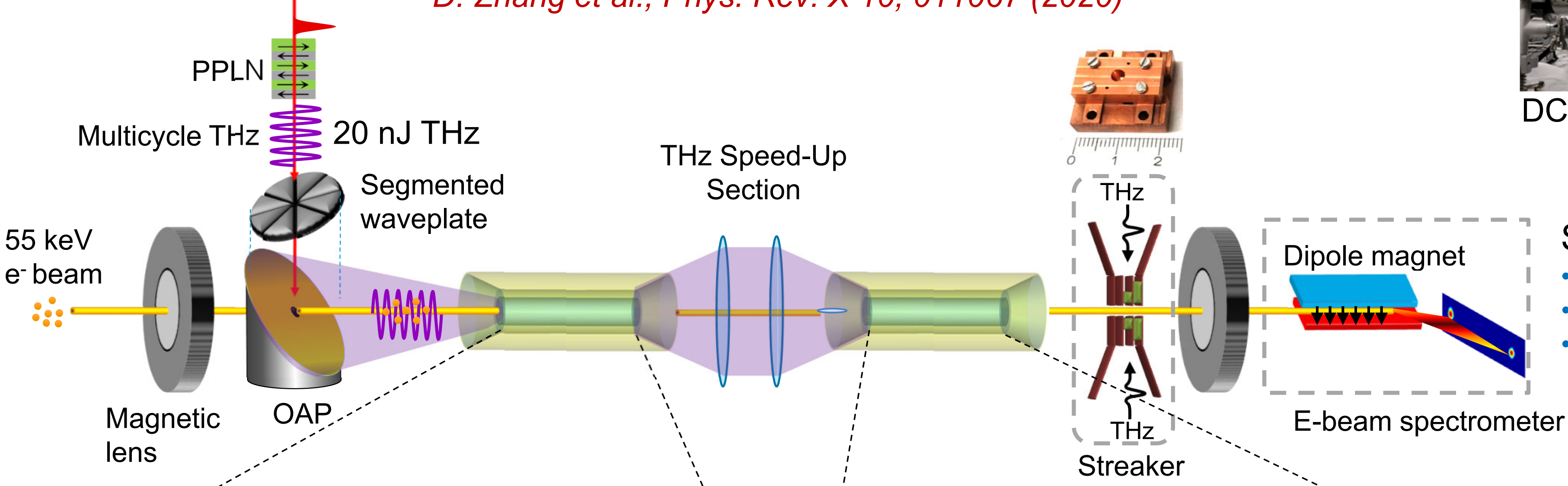


Restrictions used to tune phase velocity

# Staged THz acceleration with energy recycling

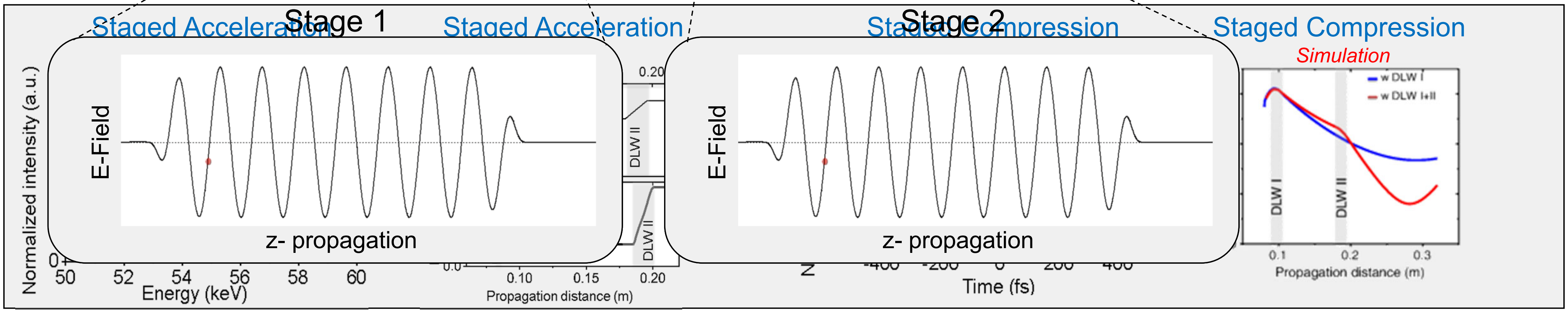
*D. Zhang et al., Phys. Rev. X 10, 011067 (2020)*


DC Gun

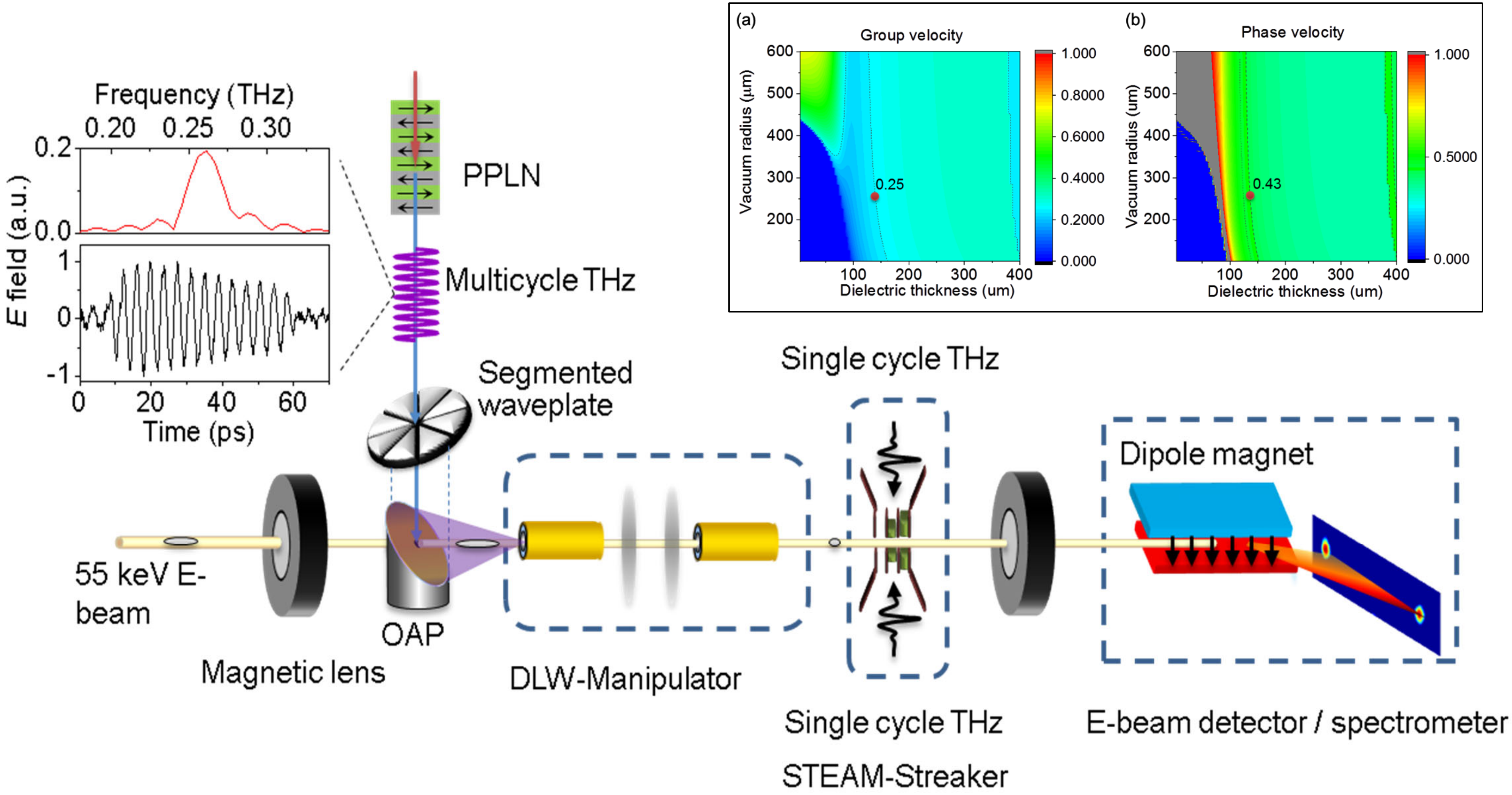



**Staged Acceleration**

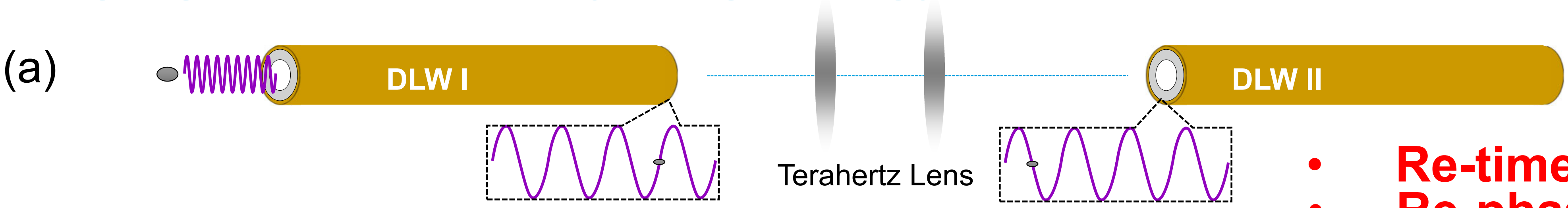
- Retiming & rephasing
- Longer interaction
- Improved efficiency



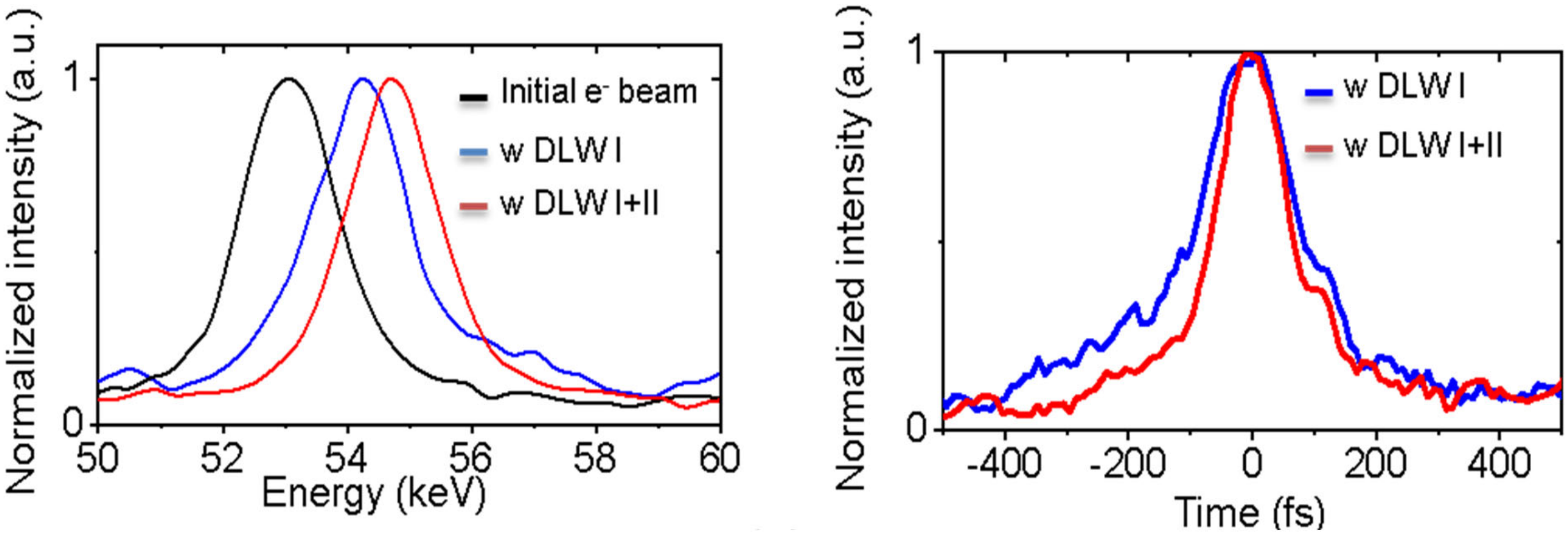
# Solution for low injection $v_e$: staged DLWs & energy recycling



# Staging DLWs and recycling energy improves LINAC performance




- **Re-time**
- **Re-phase**

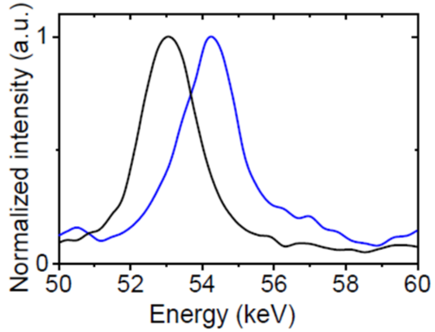



v/c (53 keV) = 0.423 v/c (54.2 keV) = 0.427

*D. Zhang et al., Phys. Rev. X 10, 011067 (2020)*

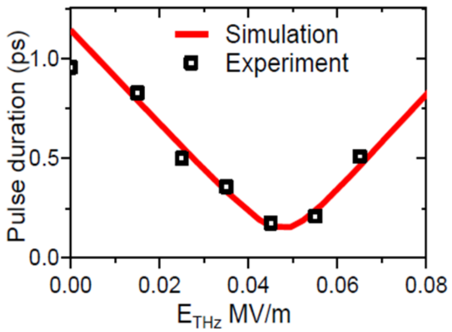
# Electron acceleration, compression and focusing with DLW

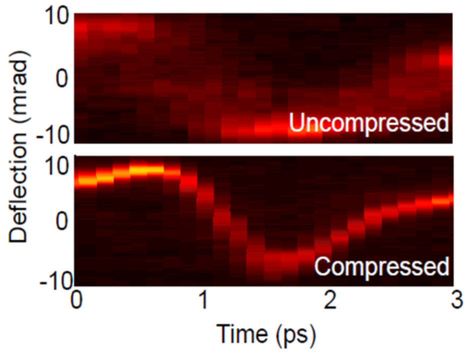
Electron acceleration



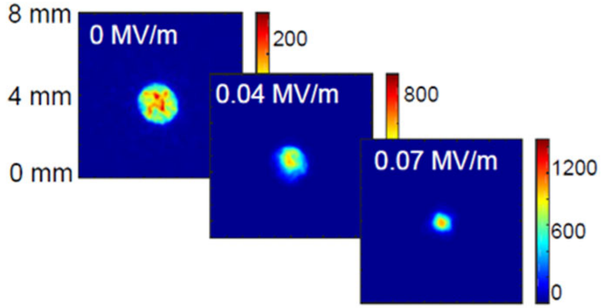

- THz energy ~ 20 nJ
- electron energy gain ~ 1 keV
- minimal dephasing

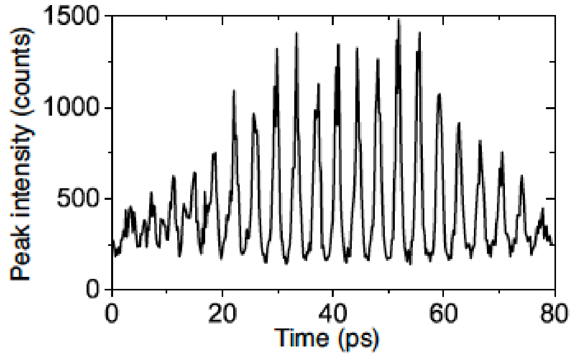
Electron compression




Electron focusing



# $TM_{01}$ - mode of DLW Group and Phase velocity