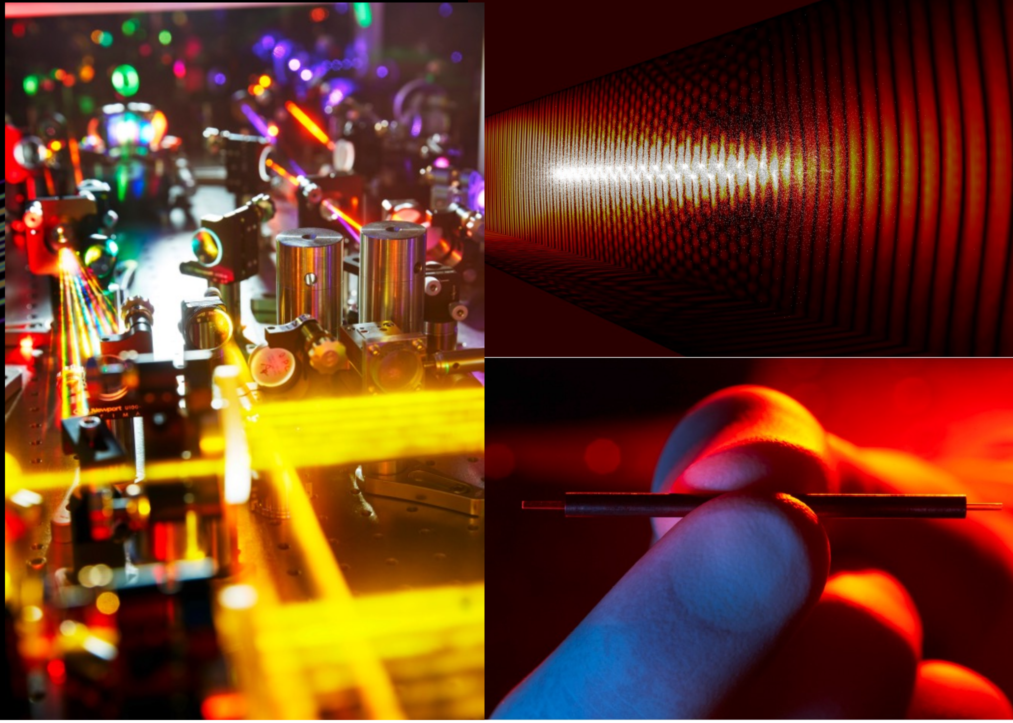
Terahertz and Optical Acceleration Techniques



Cern Accelerator School, June 23, 2023

The CERN Accelerator School

Franz X. Kärtner

Center for Free-Electron Laser Science, DESY, Ultrafast Optics and X-Rays Group, Hamburg, Germany and Department of Physics, The Hamburg Centre for Ultrafast Imaging, Universität Hamburg, Germany

HELMHOLTZ

UHH cui CFEL SCIENCE DESY.

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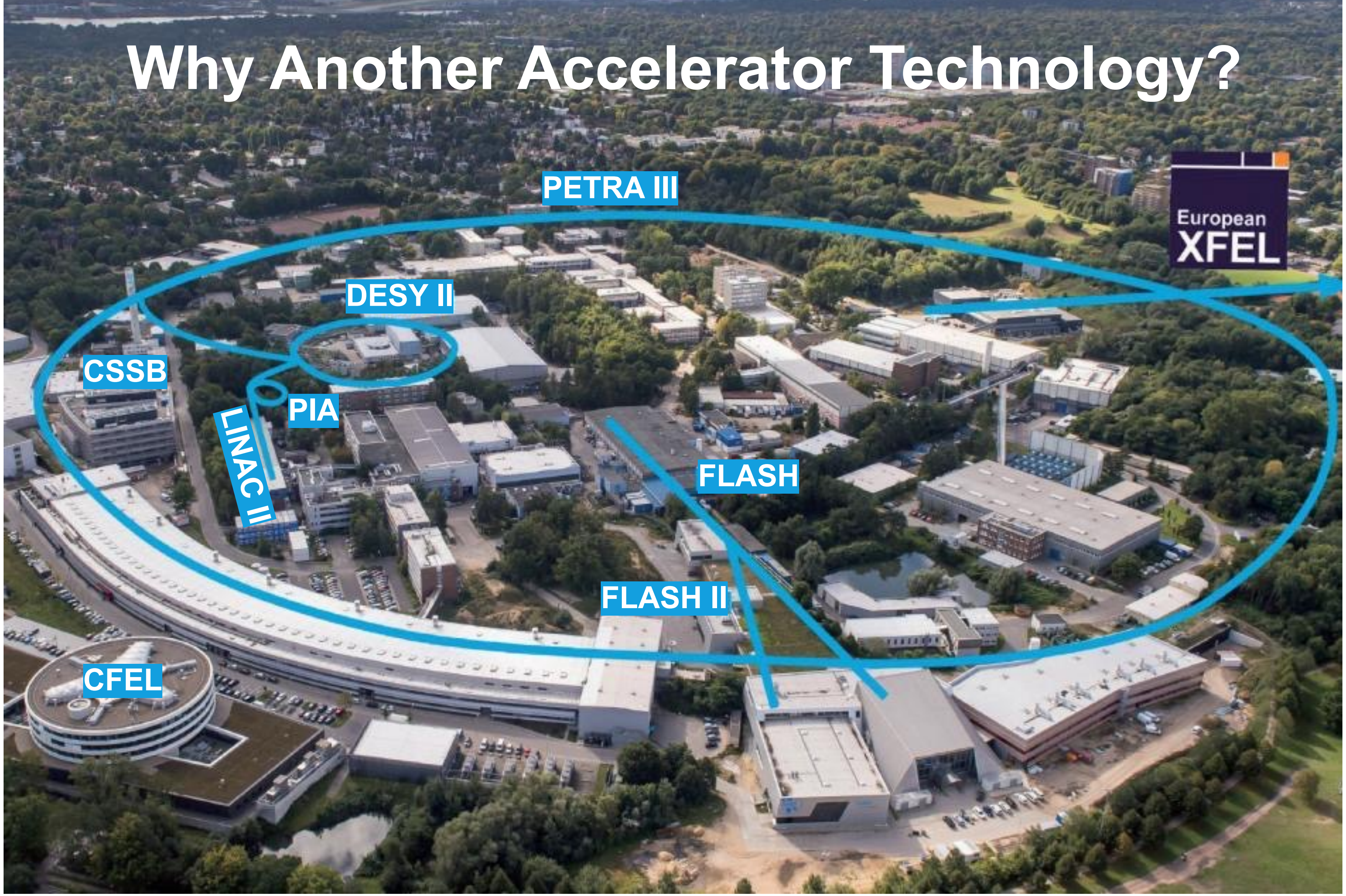
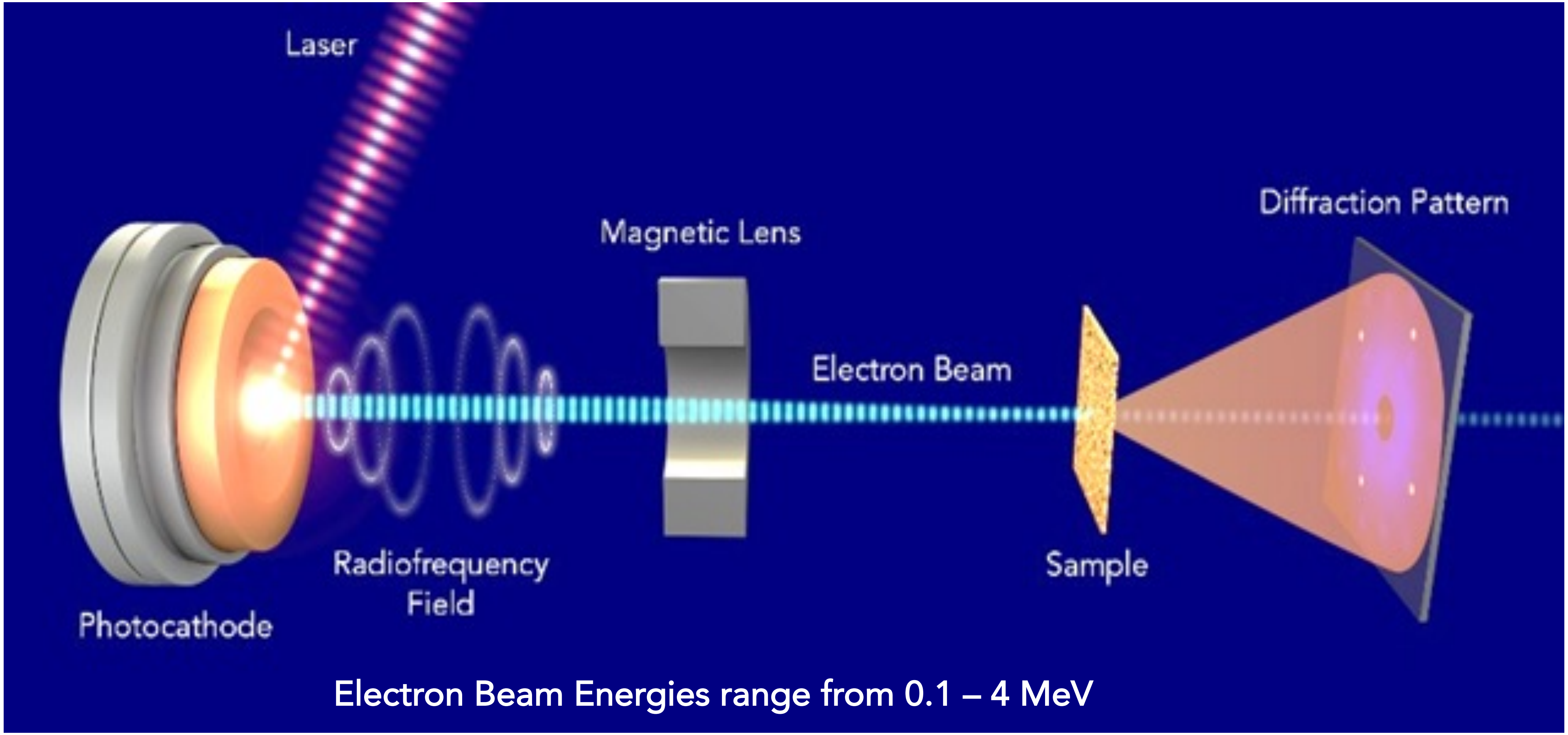
Why Another Accelerator Technology?



Structure, Dynamics and Function of Matter

Ultrafast Electron Diffraction



Schematic UED Setup: SLAC National Accelerator Laboratory

https://www6.slac.stanford.edu/news/2015-08-05-slac-builds-one-of-worlds-fastest-electron-cameras.aspx

Why short wavelength acceleration – THz or Optical?

Increased breakdown fields

- [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] M. D. Forno, et al. PRAB. 19, 011301 (2016).
- [4] W. Wünsch, IPAC (2017)

$$E_{break} \approx \frac{1}{\tau^{1/6}}$$

µs → ps

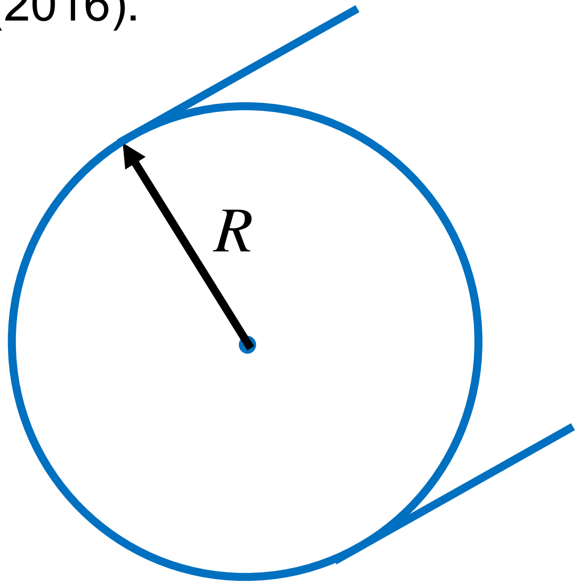
or

0.1 GV/m → 1 GV/m (maybe)

Limited by various Nonlinearities and imperfections!

Reduced pulse energy and heating

- reduced stored energy
- reduced pulsed heating
- high repetition rate possible!



$$E_P \sim \lambda^3$$

$$\Delta T \propto \frac{E_P}{A_{SURFACE}} \propto \frac{V_{CAVITY}}{A_{SURFACE}} \propto R \propto \lambda$$

High gradient acceleration

- reduced size, strong velocity bunching, short bunches – attosecond e$^-$ & X-ray pulses, lower emittance beams
- Short acceleration distances and times: reduced space charge effects
- **But** lower bunch charge: < 1 fC for optical wavelength, and 10 fC – 10 pC for “THz”; ideal for UED

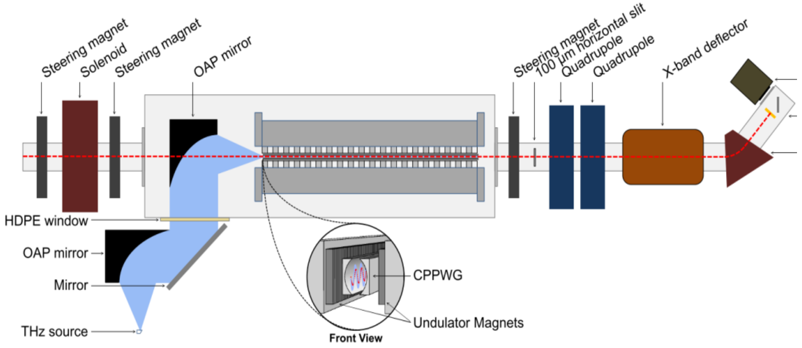
Outline

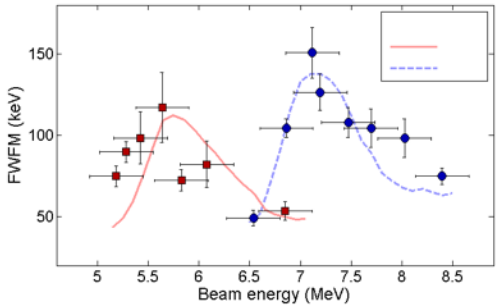
- **Why THz or optical acceleration?**
- **Optical and optically driven THz sources**
- **Laser drivers**
- **THz guns, beam diagnostic and beam manipulations**
- **THz LINACs**
- **First UED applications**
- **Gyrotron sources and THz cavity based acclerators**
- **Optical acceleration**
- **Summary**

THz acceleration and beam manipulation takes up speed!

THz-powered iFEL

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

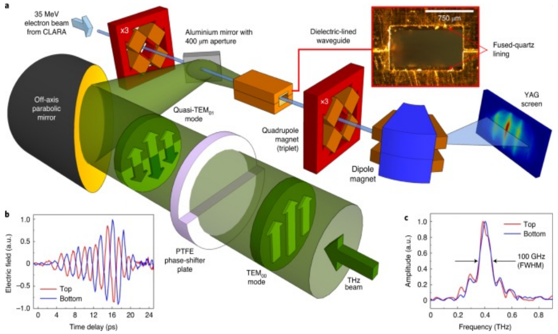


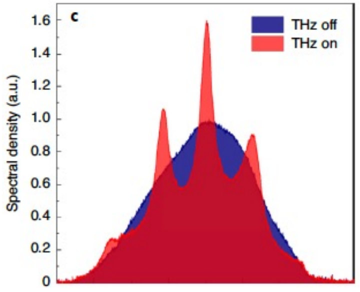


$E_{in} = 5$ MeV
$\Delta E = \pm 75$ keV
$E_{THz} = 1$ µJ

Acceleration

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

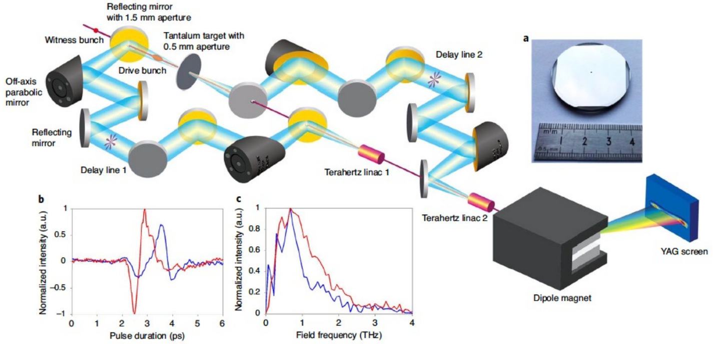


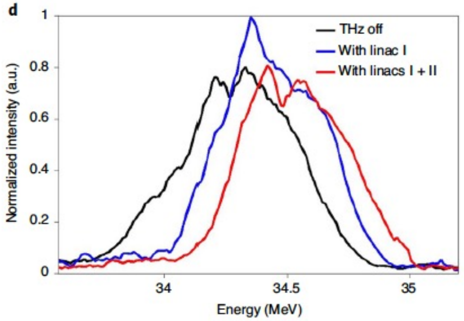


$E_{in} = 35$ MeV
$\Delta E = \pm 10$ keV
$E_{THz} = 2$ µJ

Acceleration & Staging

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



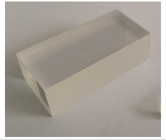


$E_{in} = 34.3$ MeV
$\Delta E = 150$ keV
$E_{THz} = 132$ µJ

Others:

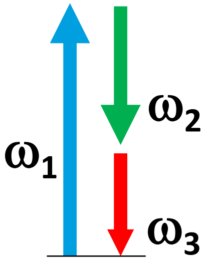
- *Kealhofer et al., Science 359, 459 (2016)*
- *Walsh et al., Nature Comm. 8, 421 (2017)*
- *Zhao et al., PRX 8, 021061 (2018)*
- *Li et al., Phys. Rev. Accel. Beams 22, 012803 (2019)*

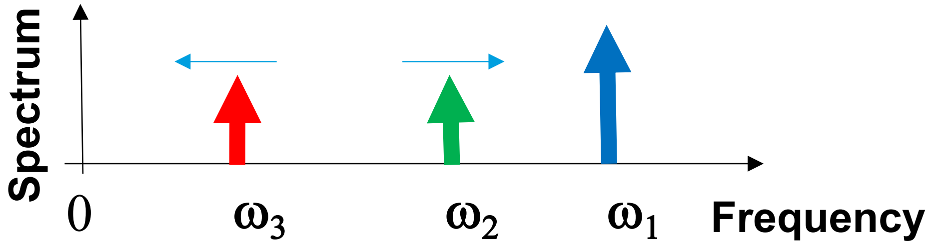
Optical Parametric Amplifiers based on $\chi^{(2)}$



Conservation of energy: $\omega_3 = \omega_1 - \omega_2$

DFG process



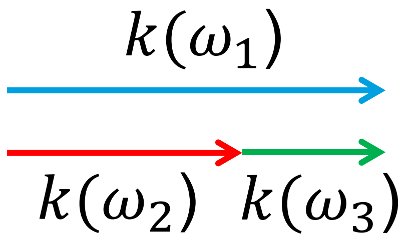


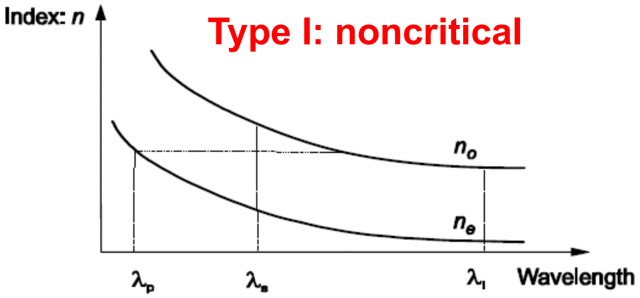
Typically: ω_1 – IR
ω_2, ω_3 – NIR to MIR

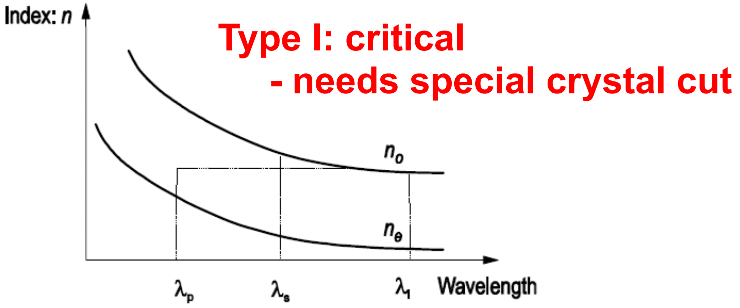
ω_1 – pump
ω_2 – signal
ω_3 – idler

Conservation of momentum:

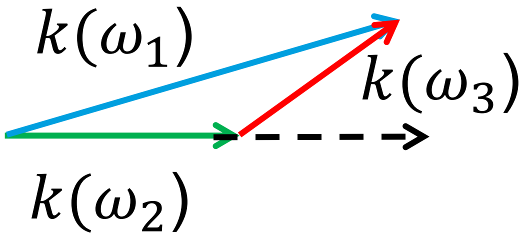
Collinear phase matching – birefringence of materials

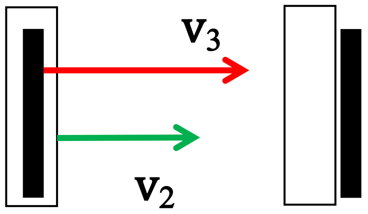


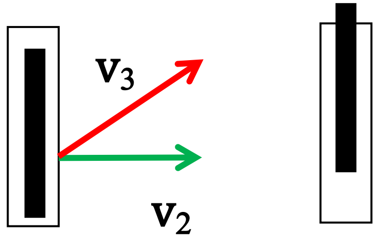




Non-collinear Phase Matching





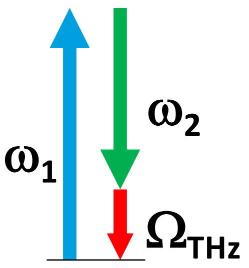


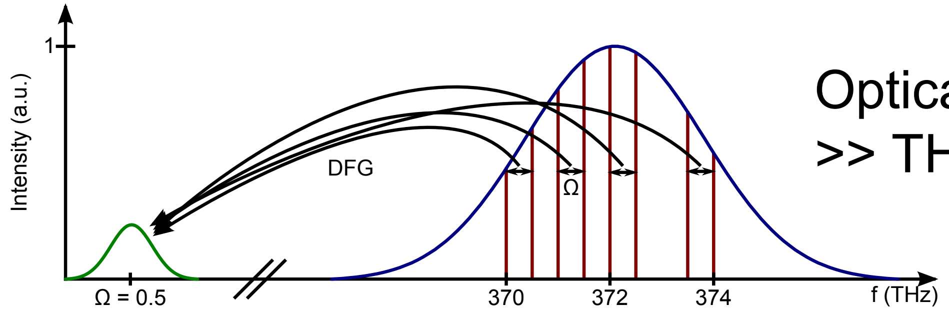
Pulse front tilt in idler

THz Sources

Conservation of energy: $\Delta\omega = \omega_1 - \omega_2 = \Omega_{THz}$

DFG or Optical Rectification

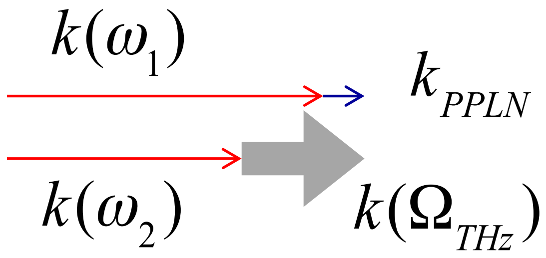




Optical bandwidth >> THz frequency

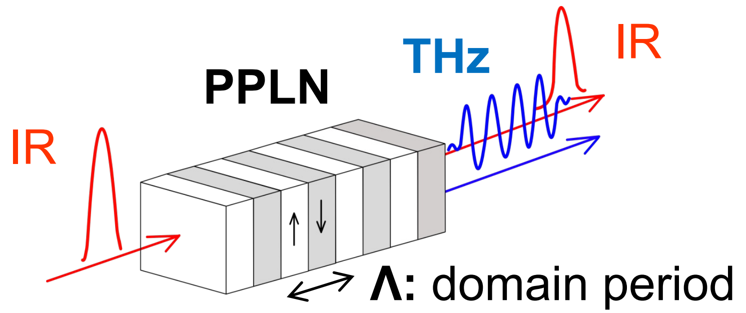
Conservation of momentum:

Collinear Phase Matching

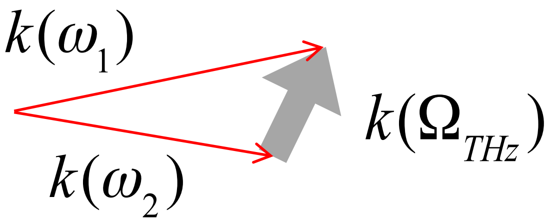


Multi-cycle THz generation using Periodically-Poled Lithium Niobate

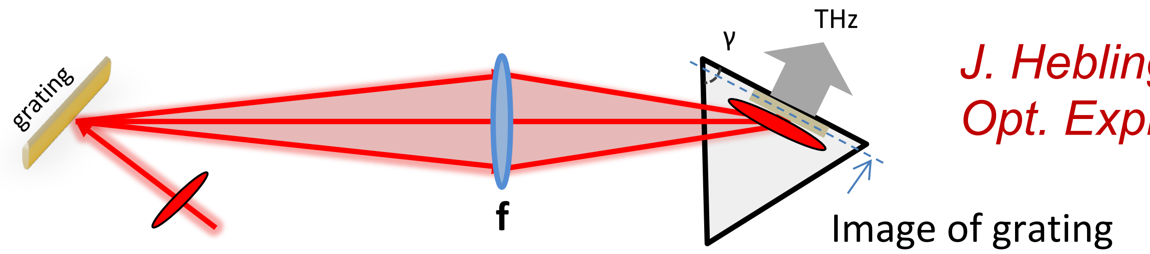
$$n_{opt} \approx 2; \quad n_{THz} \approx 5$$



Non-collinear Phase Matching

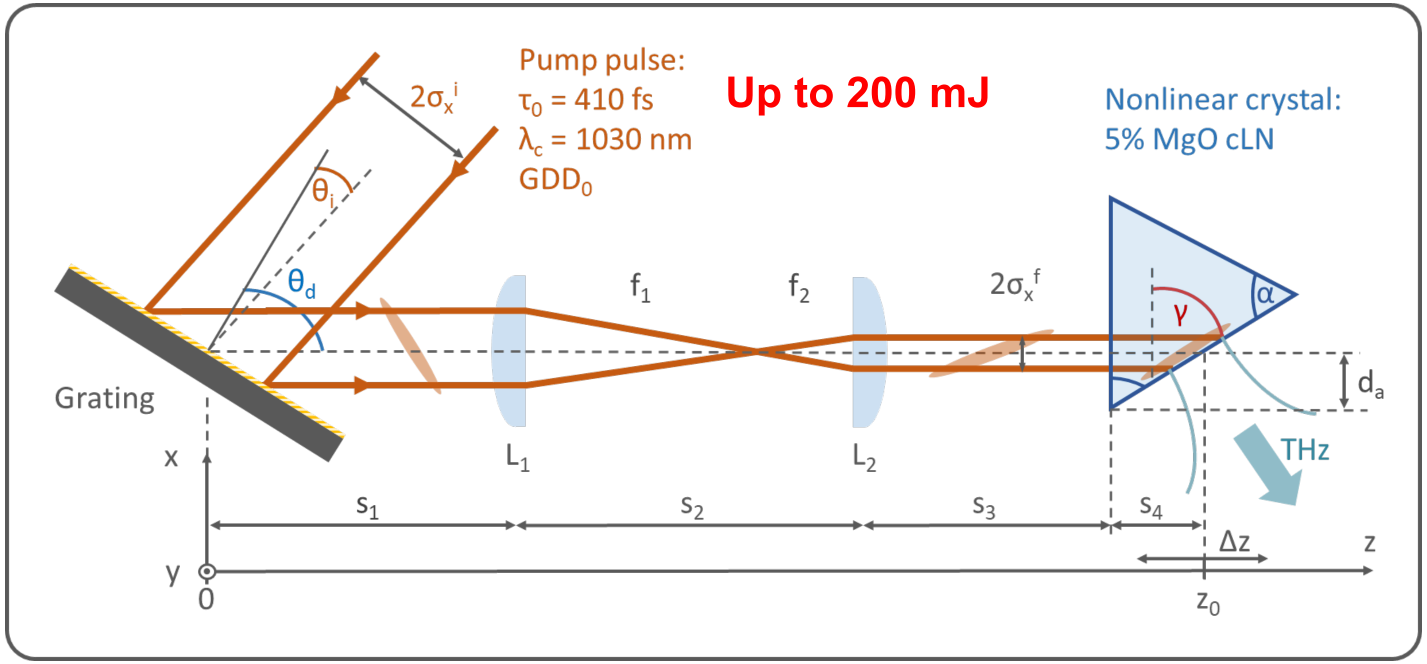


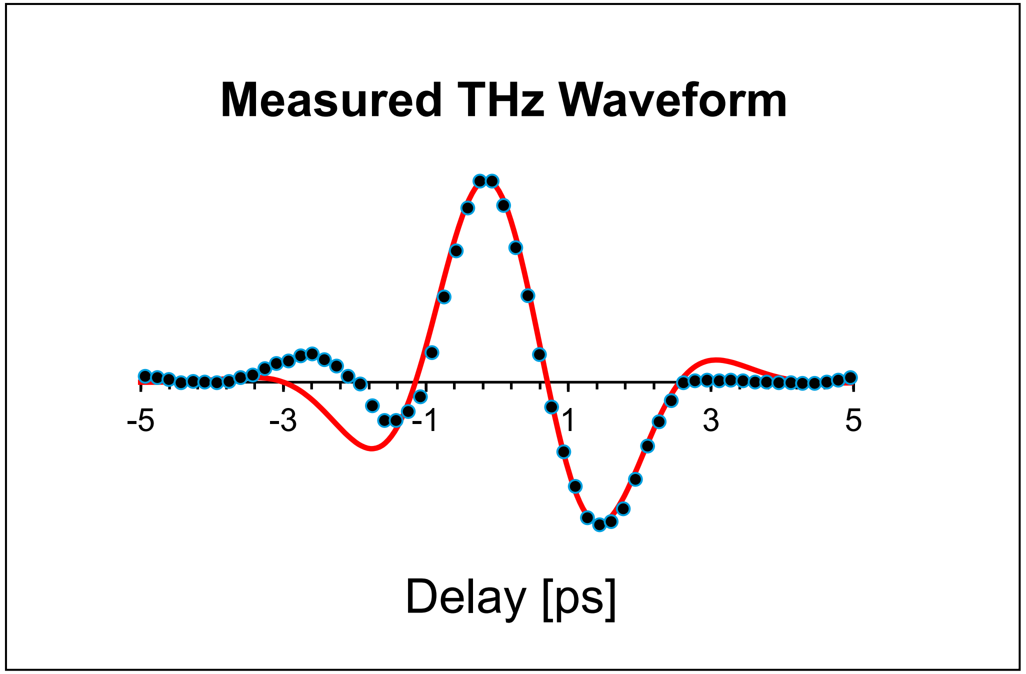
Single-cycle THz generation by Tilted Pulse-Front Technique



J. Hebling et al, Opt. Express ***21****, 1161 (2002)*

Single-Cycle THz Pulses



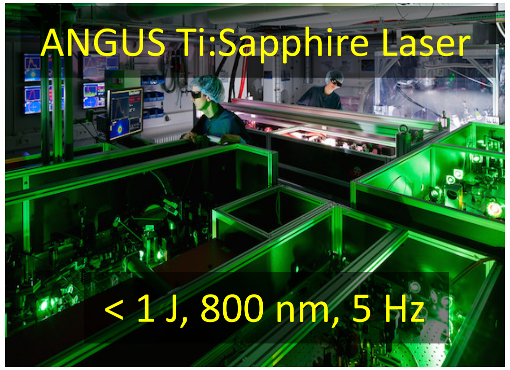


- Single-cycle THz pulses centered **@ 300 GHz** reaching **400 µJ pulse energy → > 1 mJ with THz-AR coating**
- Spatio-temporal manipulation of pump pulse to fine-tune setup performance
- ~ 1% optical to THz conversion should be achieveable with this setup

Xiaojun Wu et al., up to 13.9-mJ @ 200 GHz (Advanced Materials 2023, 2208947),
1.2 J - Ti:Sapphire Laser @ 1 Hz with ~ 1.2% efficiency

K. Ravi et al., “Limitations to THz generation by optical rectification using tilted pulse fronts,” Opt. Express 22, 20239 (2014).

High Energy Multi-Cycle THz from Large Aperture PPLN Crystals

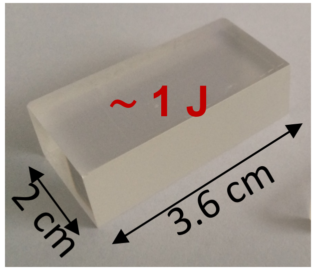


Collaboration @ DESY

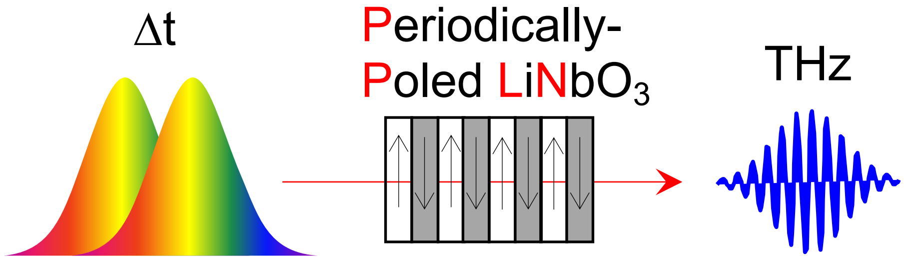
LUX:
- Dr. Andreas Maier
- and Dr. S. Jolly

AXSIS:
- Dr. N. Matlis
- and Dr. F. Ahr

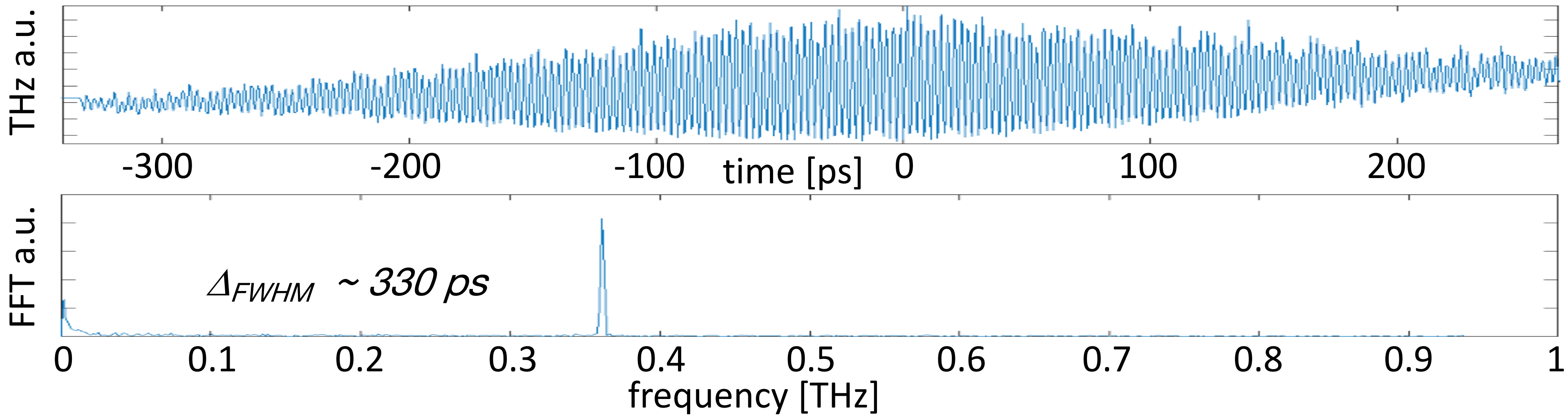
Large PPLN provided by Prof. Taira, IMS, Japan



Chirp & delay difference frequency generation



400 μJ + 200 μJ , 360 GHz multi-cycle THz pulses generated at *5 Hz*



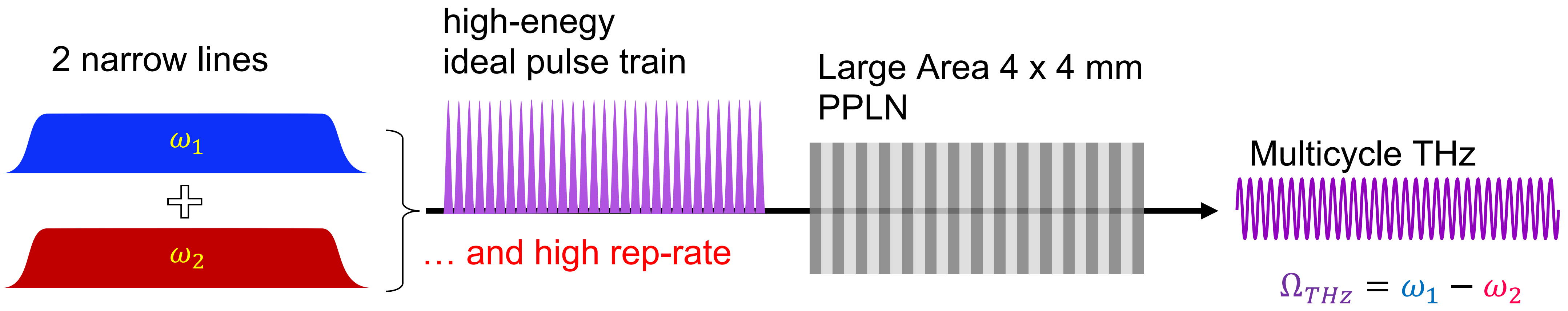
500 x larger than previous record!

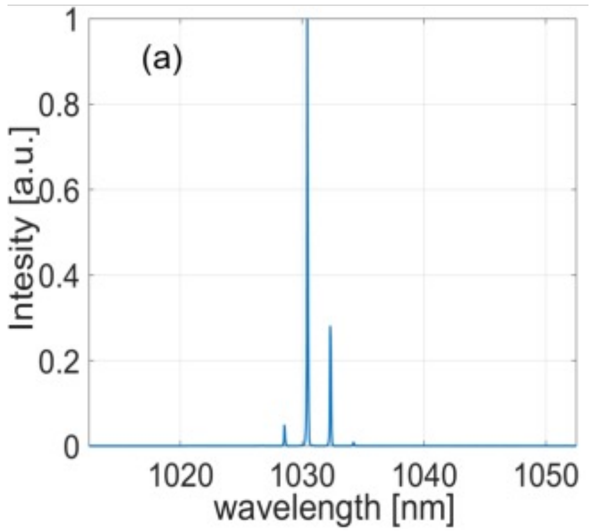
F. Ahr et al., Opt. Lett. *42, 2118 (2017)*

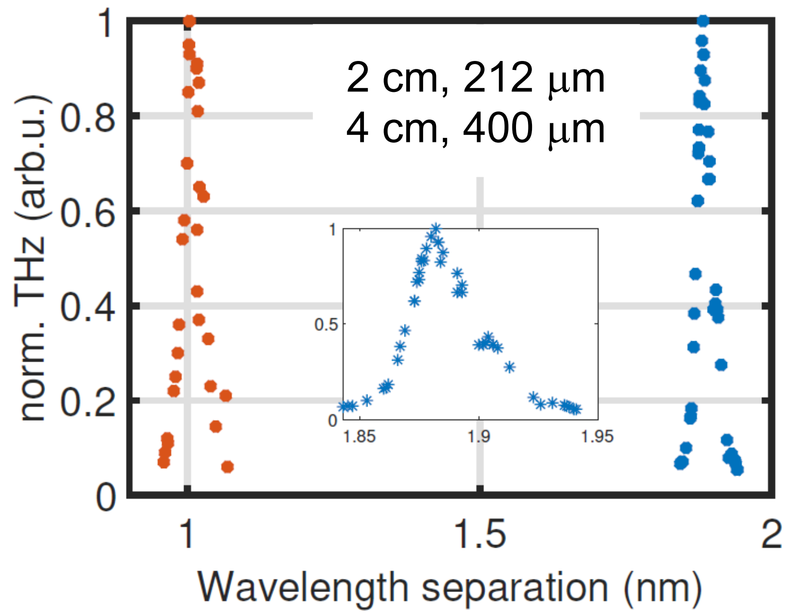
S. Jolly et al., *Nat. Com. 10, 2591 (2019)*

 F. Lemery et al., Nat. Com 3, 150 (2020); 1.3 mJ @ 160 GHz with LN-Stack and 1J Ti:sapphire laser

2-Line Difference Frequency Generation



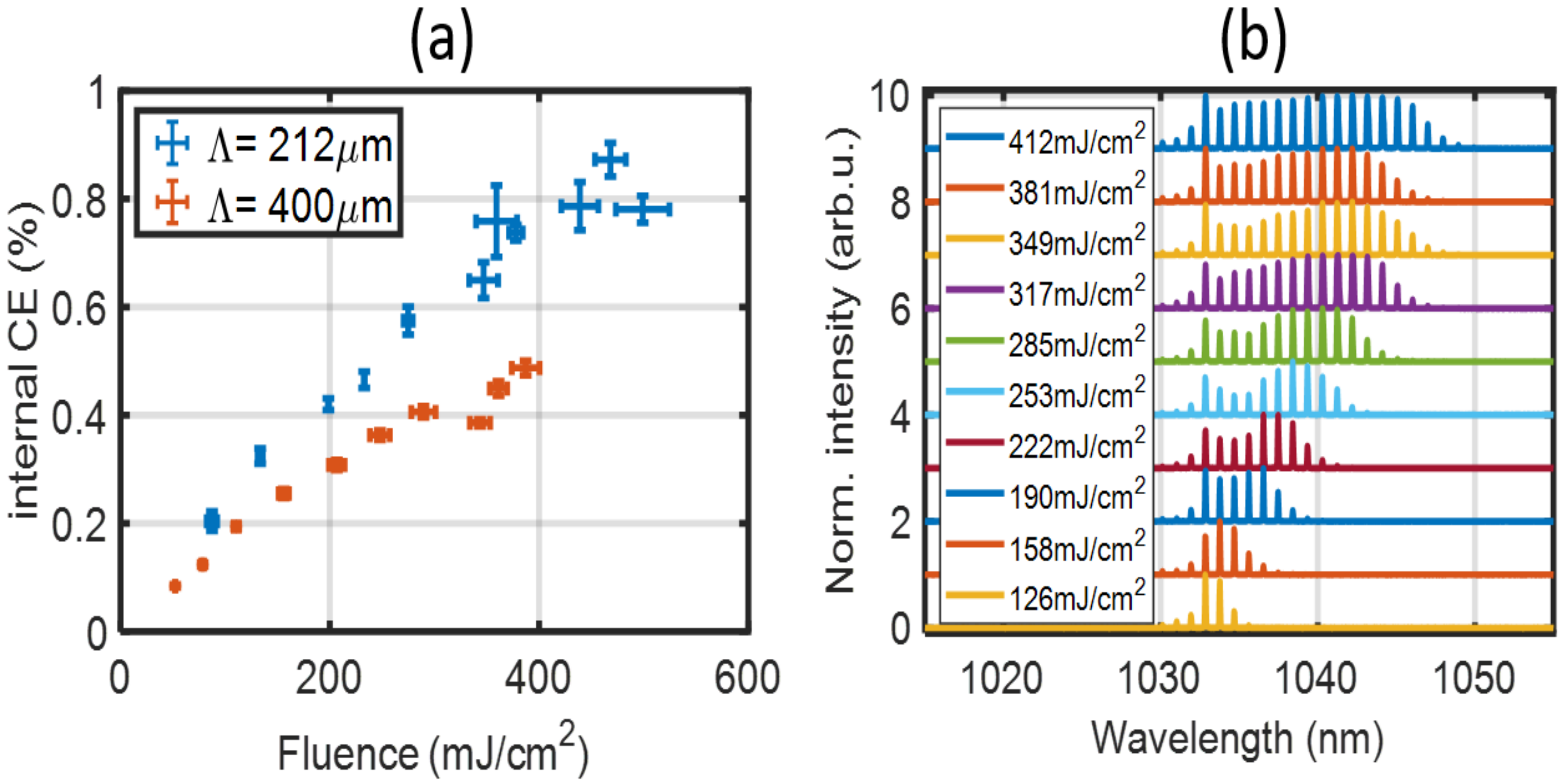




Period	THz frequency	linewidth
212 µm	531 GHz	~3 GHz
400 µm	286 GHz	~1.5 GHz

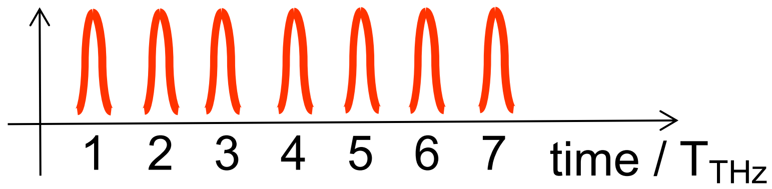
2-Line Difference Frequency Generation:

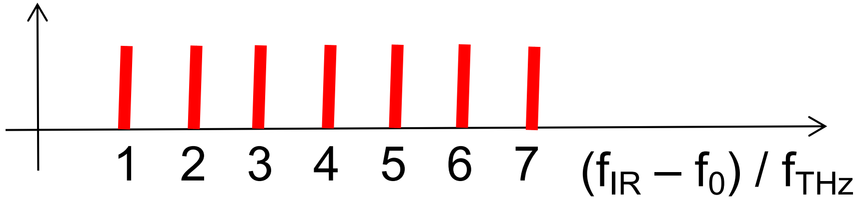
4x4x40mm PPLN @ 77 K

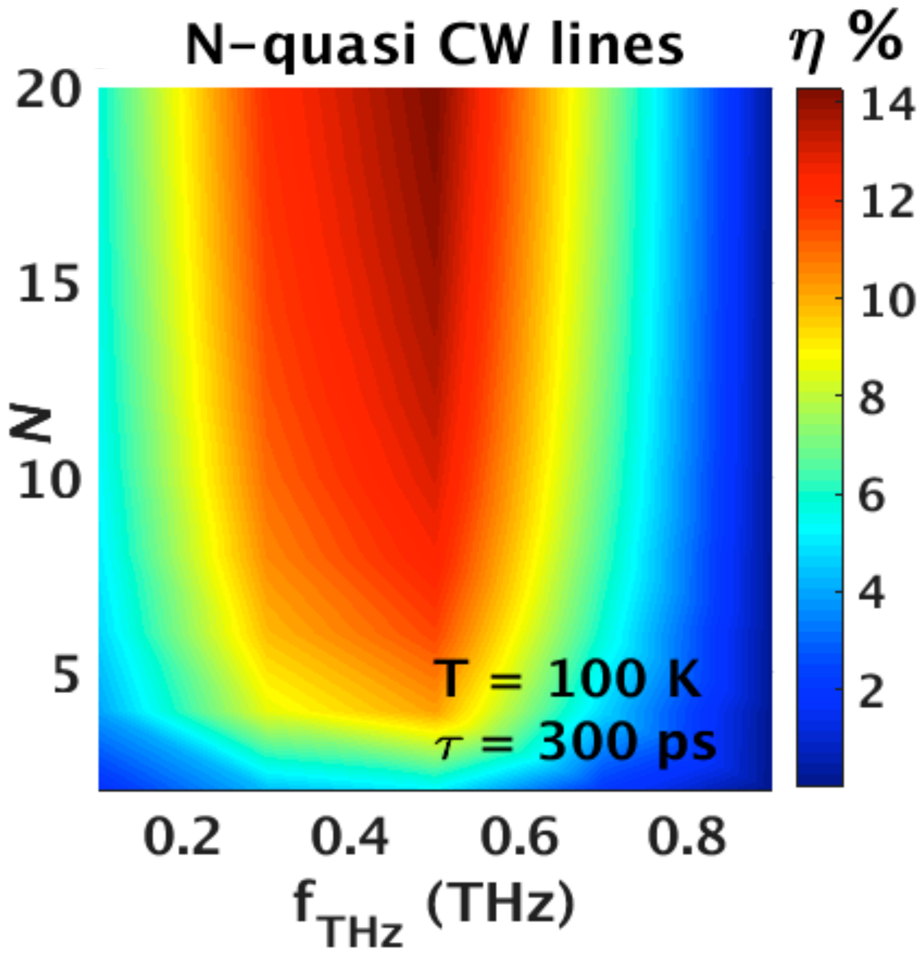


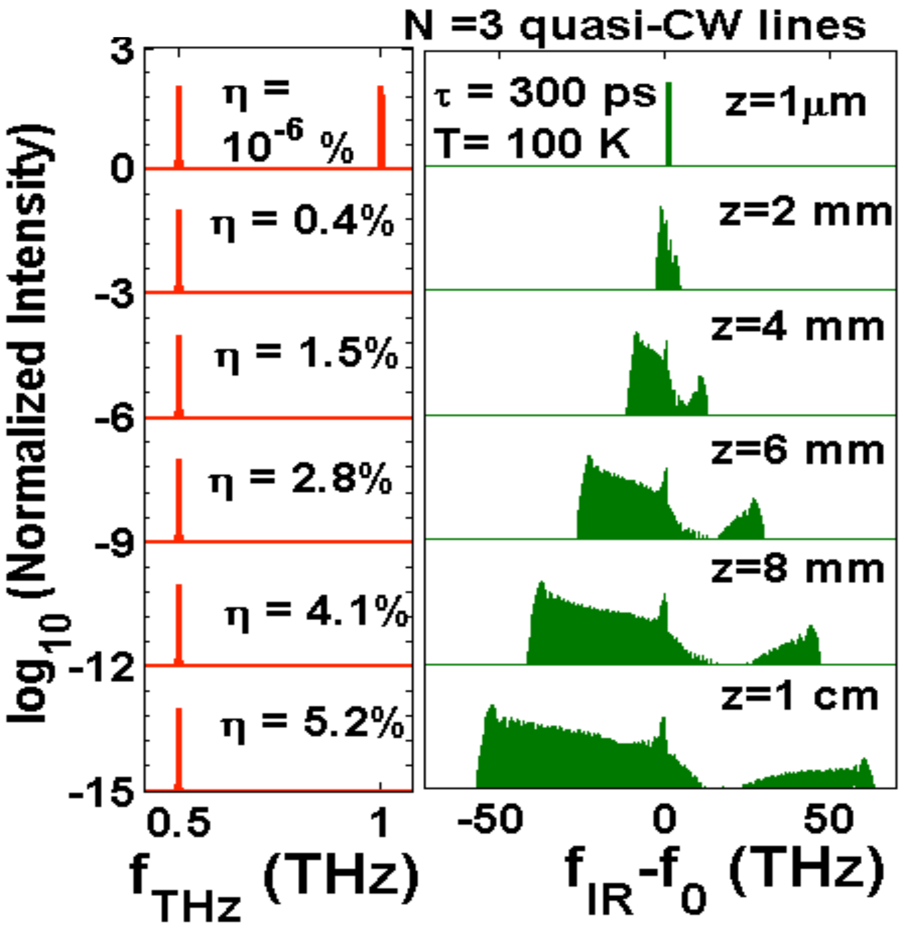
H. T. Olgun et al., Opt. Lett. ***47****, 2374 (2022)*

Multi-line DFG - Highly Efficient THz Generation









K. Ravi et al.,
Opt. Lett. 24, 25582 (2016)

Earlier work by

M. Cronin-Golomb,
Opt. Lett. 29, 2046 (2004)

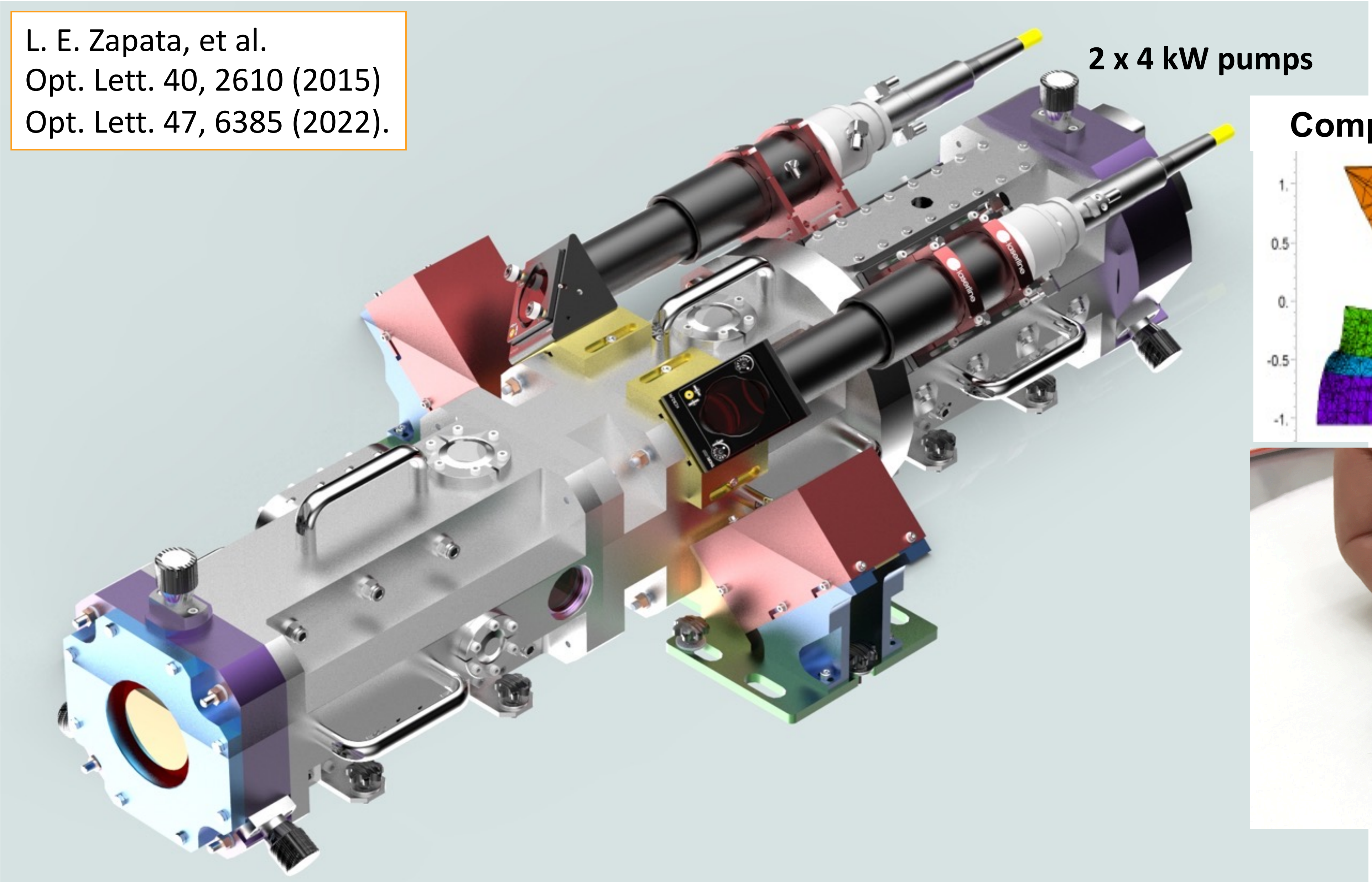
A. G. Stepanov,
JETP Lett., 85, 227(2007)

Limits on MC-THz gen. with pulse trains, see K. Ravi et al. LPR DOI:10.1002/lpor.202000109

Unfortunately, photorefractive effects limit damage threshold

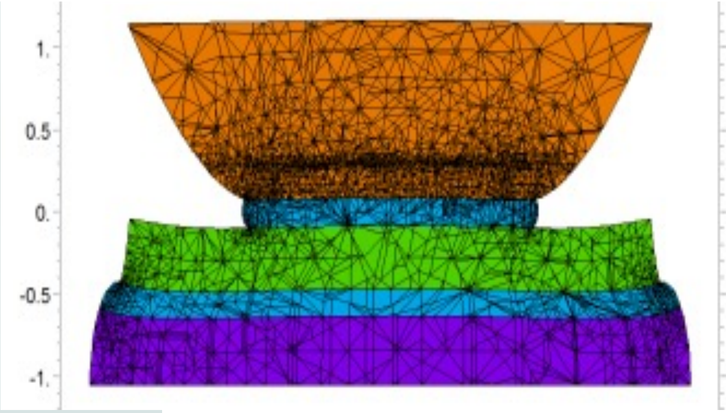
1 J, 1 kHz, 1 kW Cryogenic Composite Thin Disk Laser

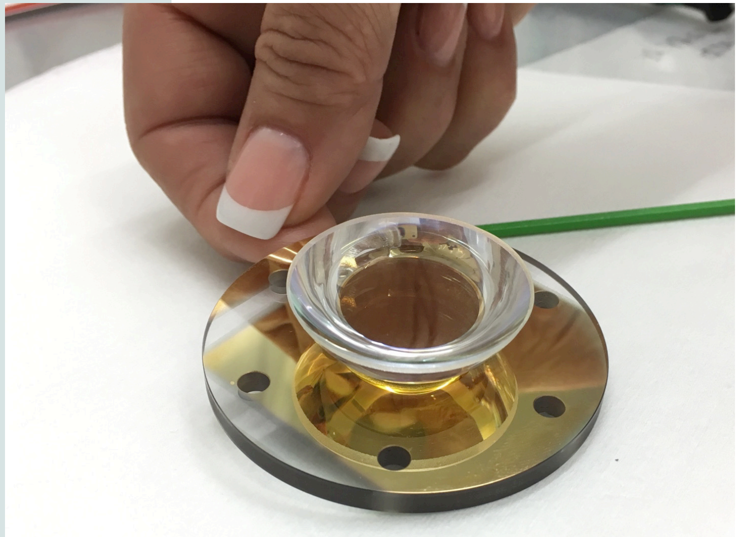
L. E. Zapata, et al.
Opt. Lett. 40, 2610 (2015)
Opt. Lett. 47, 6385 (2022).



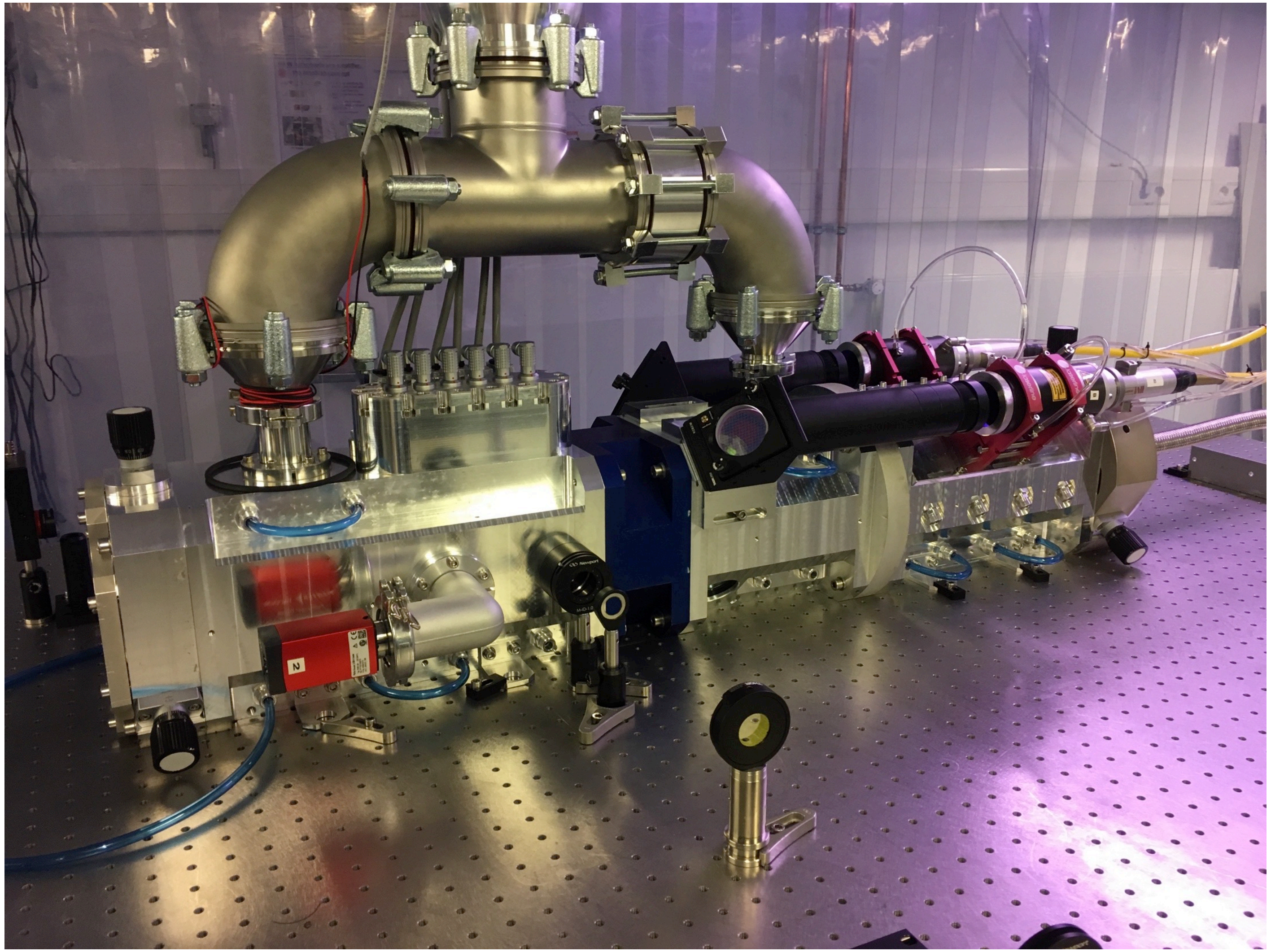
2 x 4 kW pumps

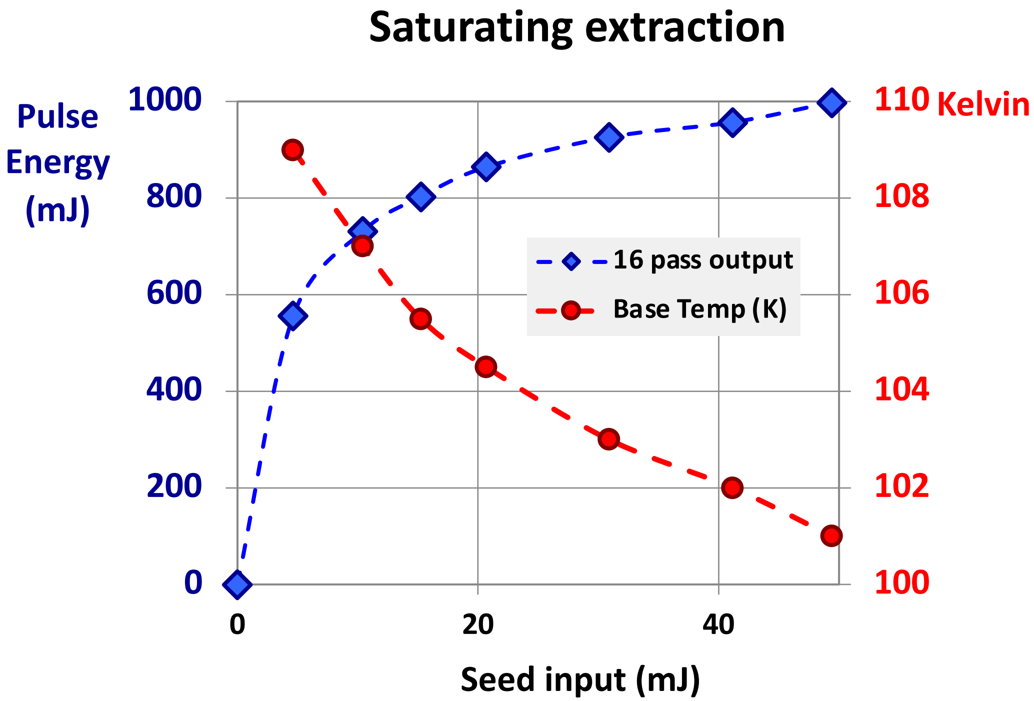
Composite Thin Disk Laser





1 J, 500 Hz, 0.5 kW Cryogenic Composite Thin Disk Yb:YAG Laser





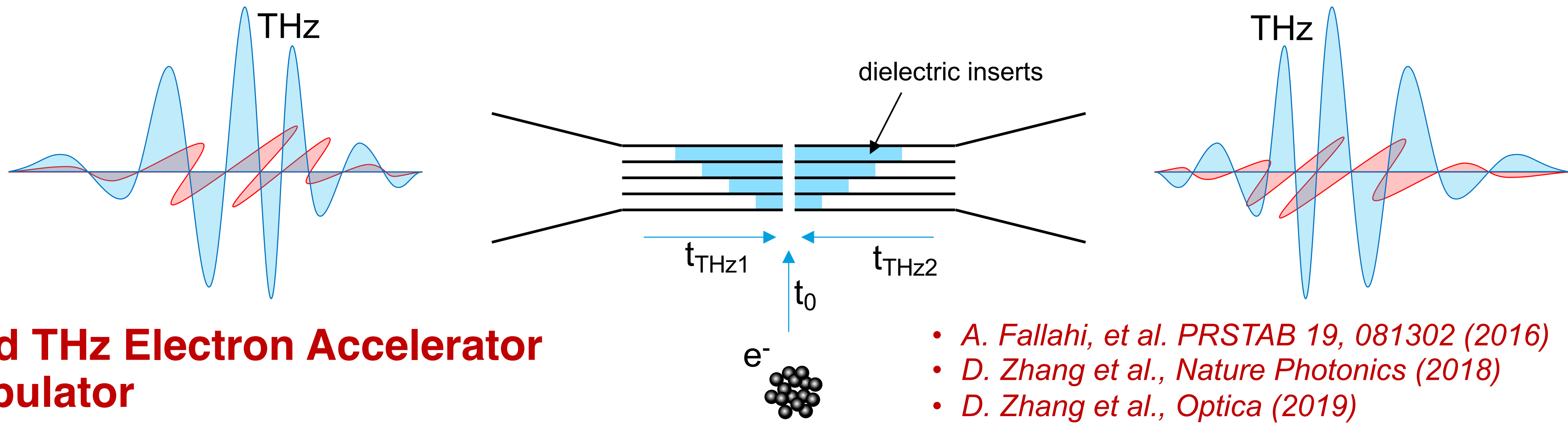
5ps – 10 ns: pulse duration

Also Yb:YLF: < 500 fs, 200 mJ @ 1 kHz soon becomes available.

2-geometries for THz-electron interaction

Transverse Geometry

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



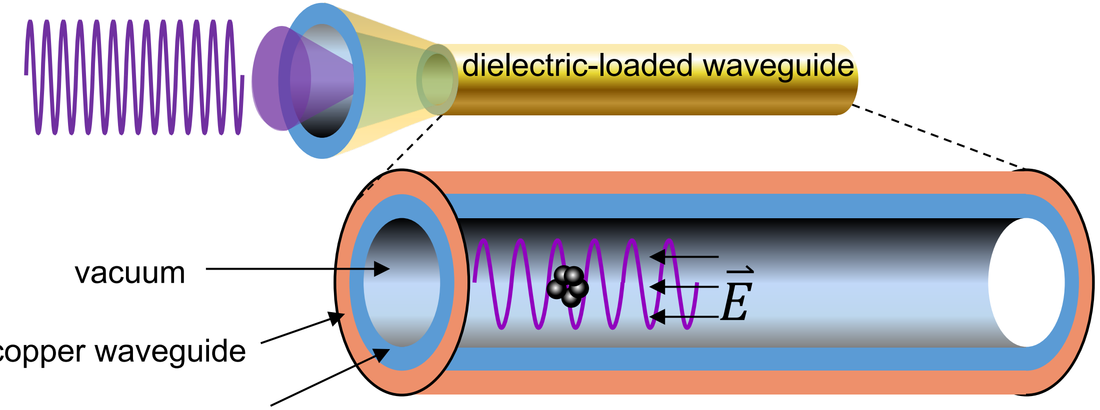
STEAM – Segmented THz Electron Accelerator and Manipulator

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

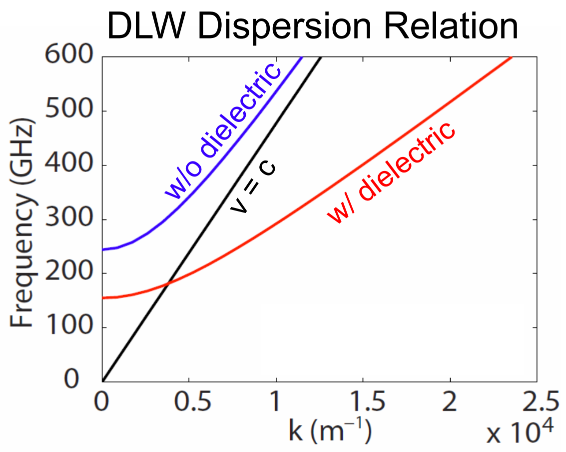
Co-propagating Geometry

- Narrowband (multicycle) THz
- Tuning: dielectric inner and outer diameter

DLW – Dielectrically Loaded Waveguide

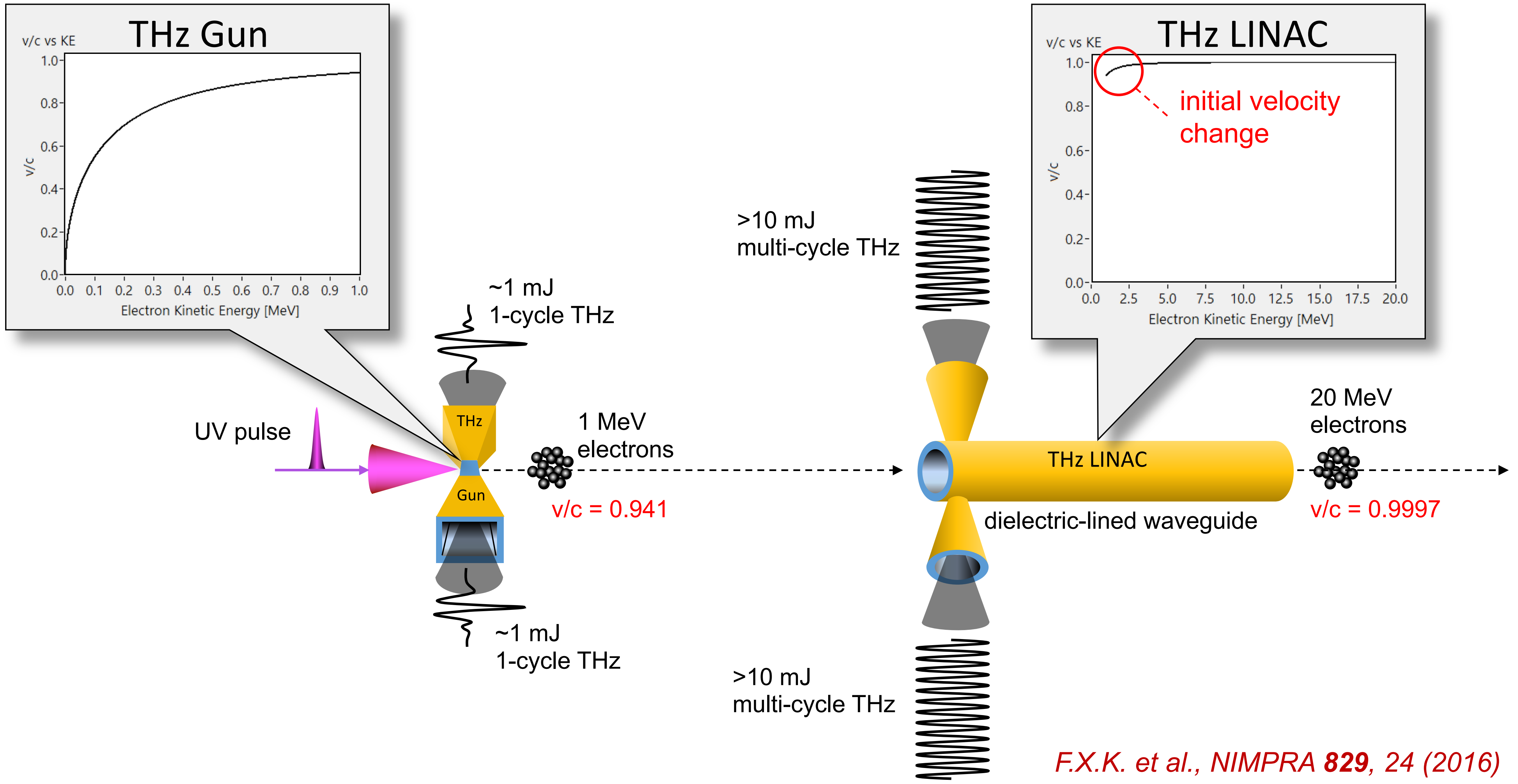


Tuning: dielectric I.D. & O.D.



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

THz Accelerator is composed of THz Gun + THz LINAC

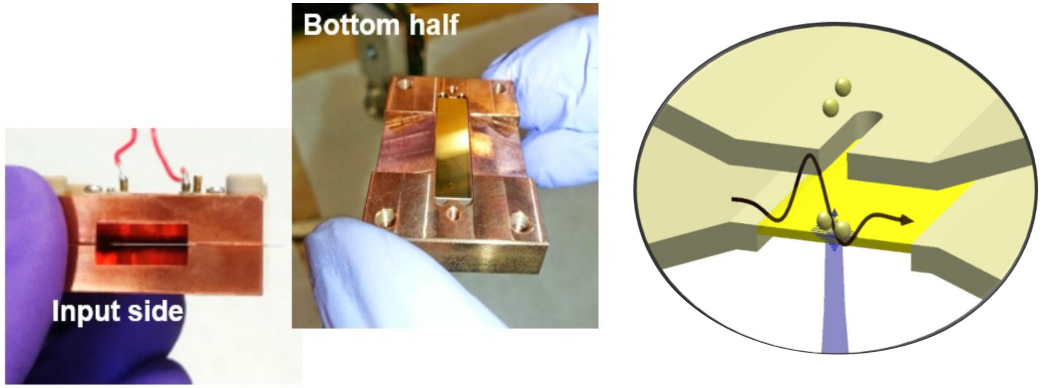


*F.X.K. et al., NIMPRA **829**, 24 (2016)*

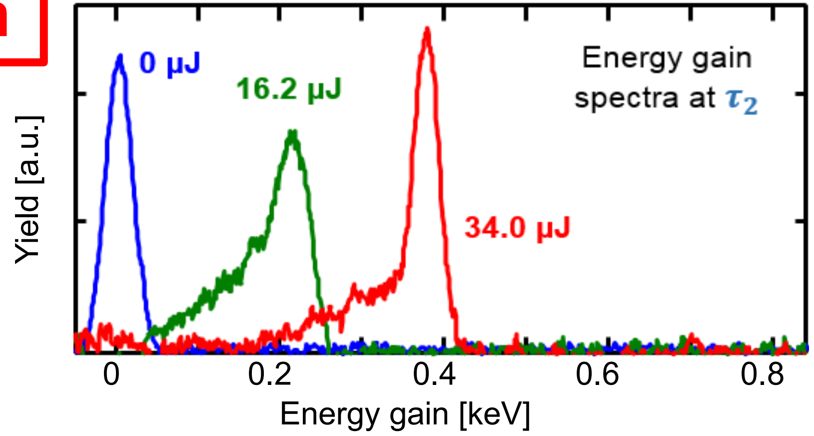
THz Gun & LINAC: Proof of Feasibility

- **THz Gun: 0 ➞ 0.8 keV acceleration**

E_z -> 0.3 GV/m

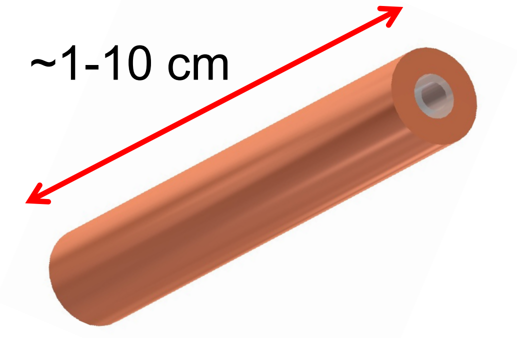


Parallel-Plate structure with 75 μm gap

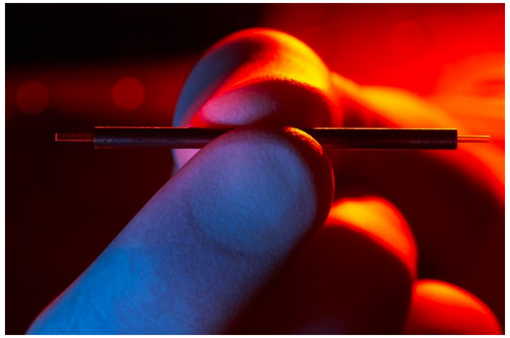


W. Huang, et al., Optica 3, 1209 (2016)
A. Fallahi, et al., PRSTAB 19, 081302 (2016)

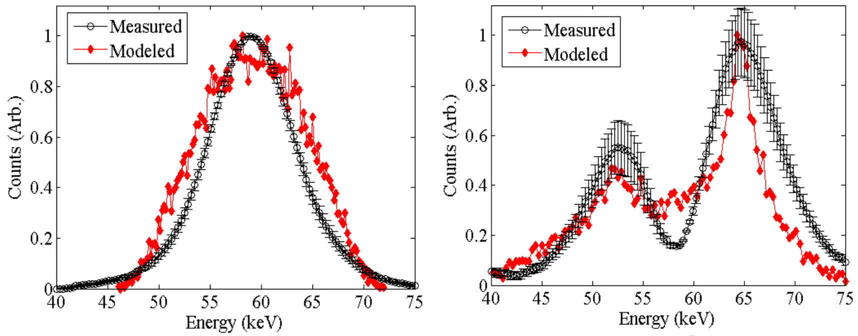
- **THz LINAC: ±7 keV energy modulation**



mm-scale THz waveguide



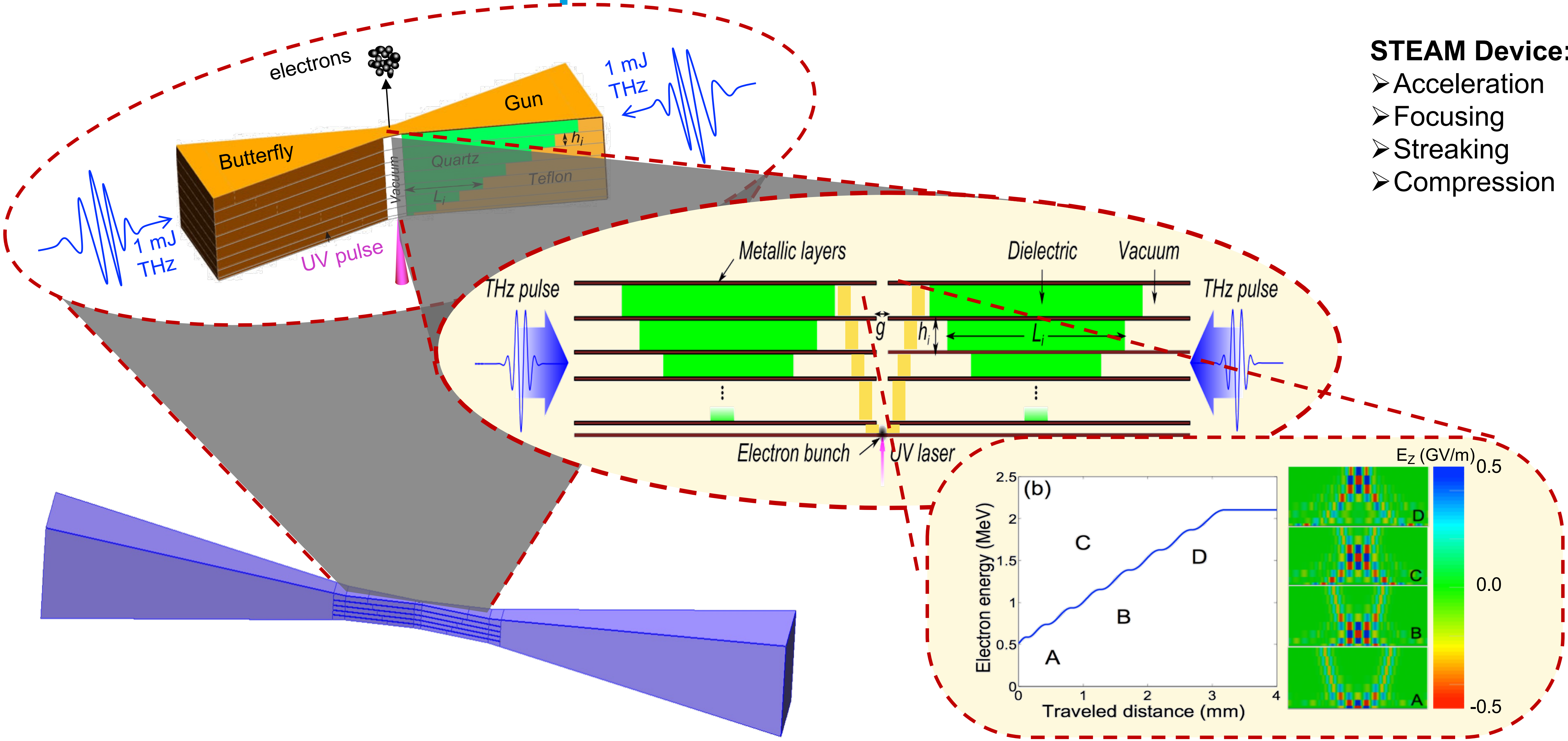
Charge injected from 60 keV
DC-gun from Dwayne Miller group



THz Off **THz On**

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

Single-Cycle THz Electron Guns: Segmented THz Electron Accelerator & Manipulator = STEAM

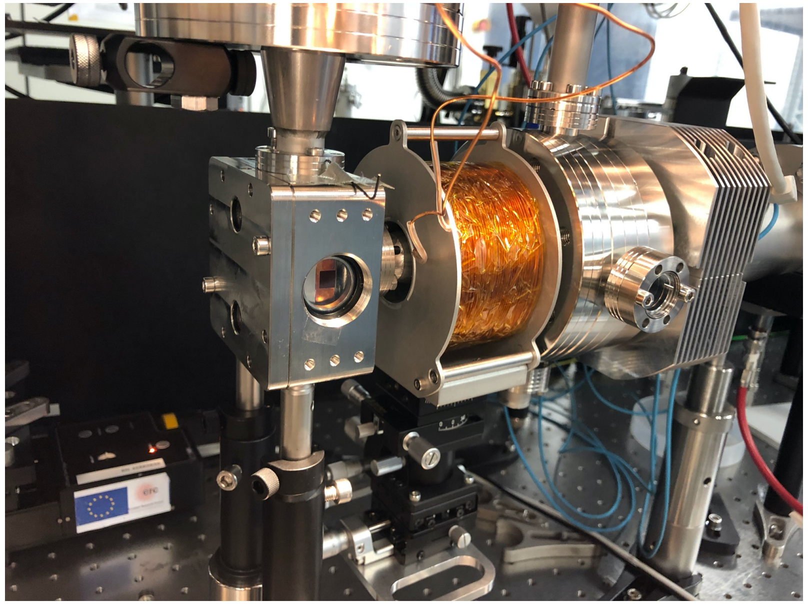


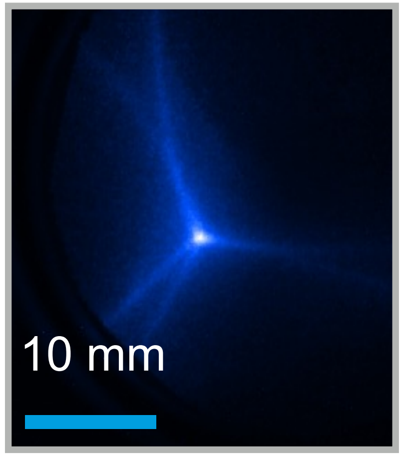
STEAM Device:

- Acceleration
- Focusing
- Streaking
- Compression

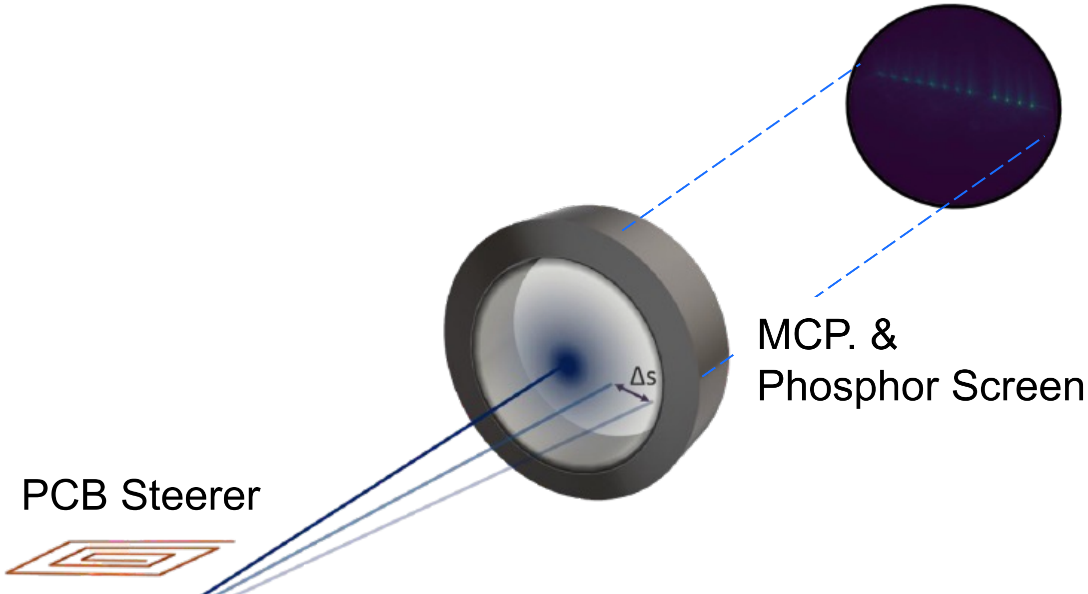
A. Fallahi, et al. PRSTAB 19, 081302 (2016)

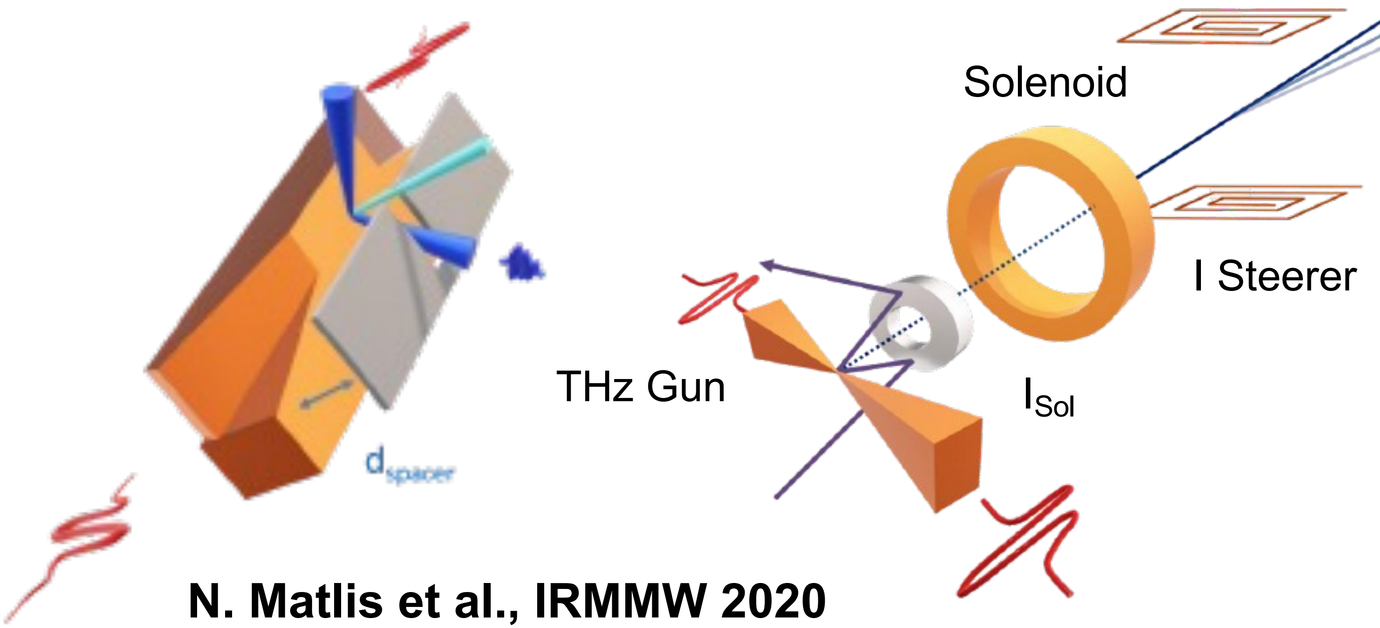
Single-Cycle Driven Single Layer THz Gun (300 GHz)

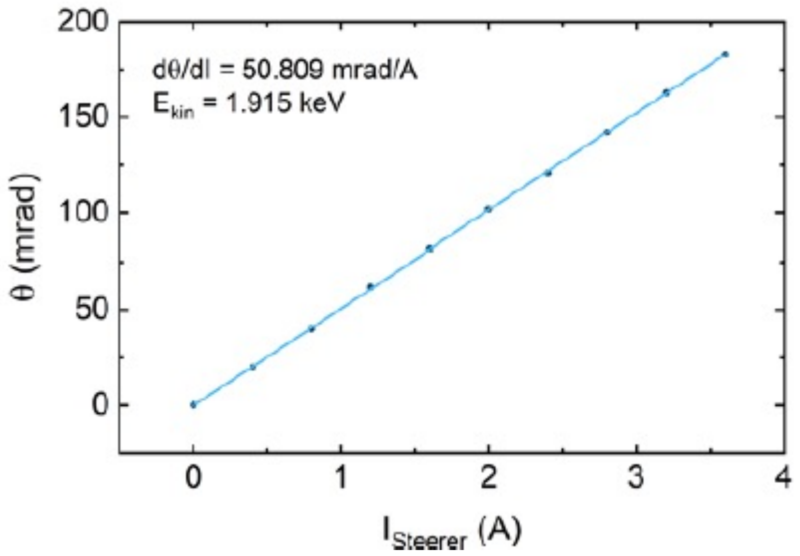




Currently
> 2.7 keV



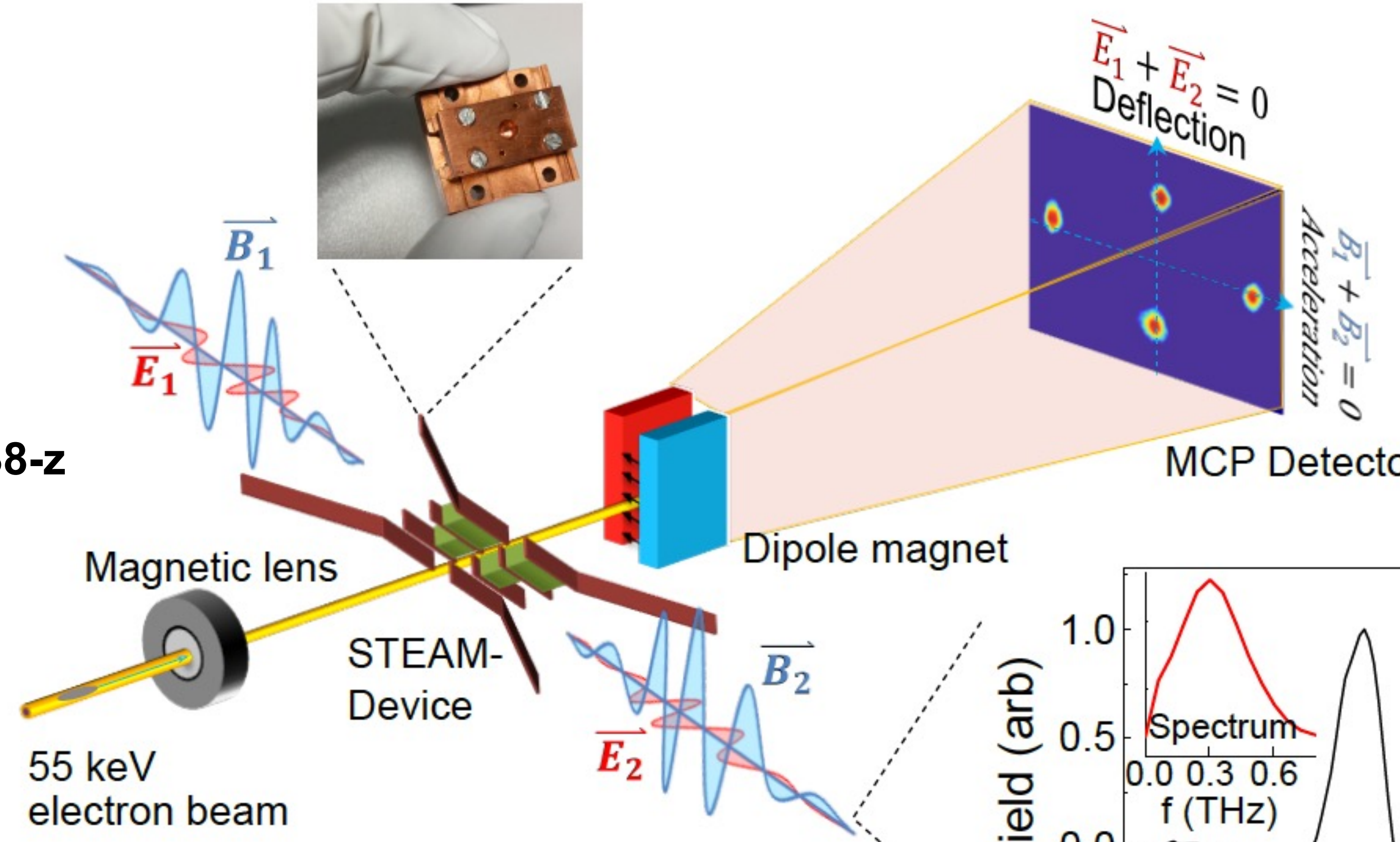


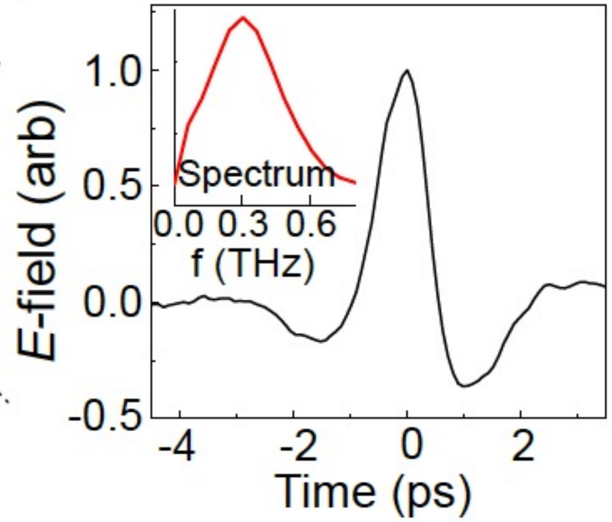


N. Matlis et al., IRMMW 2020

STEAM – Device as Accelerator and Electron Manipulator

D. Zhang, et al.
Nat. Photonics (2018)
doi.org/10.1038/s41566-018-0138-z

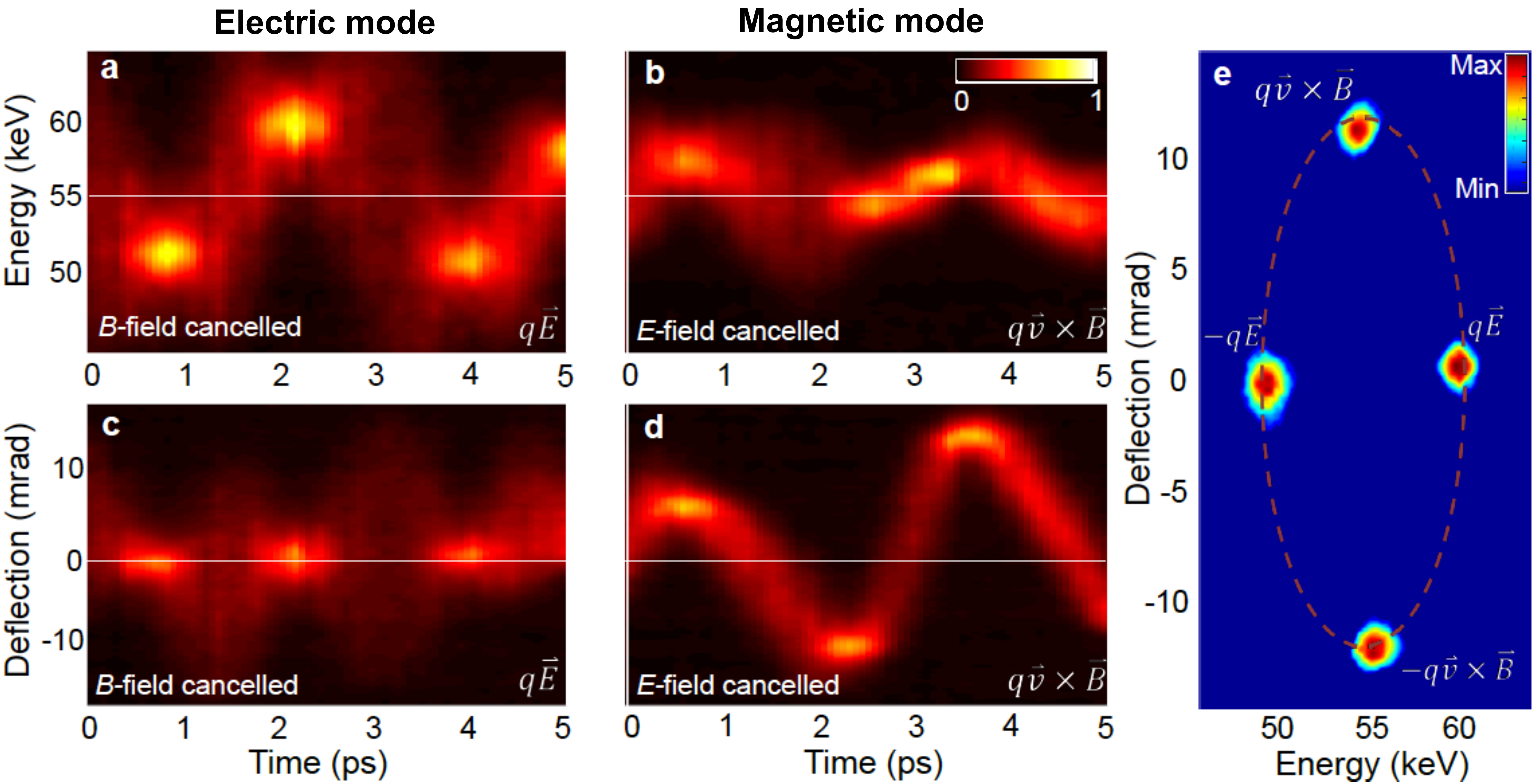




Demonstrated:

- Acceleration
- Compression
- Focussing
- Deflection

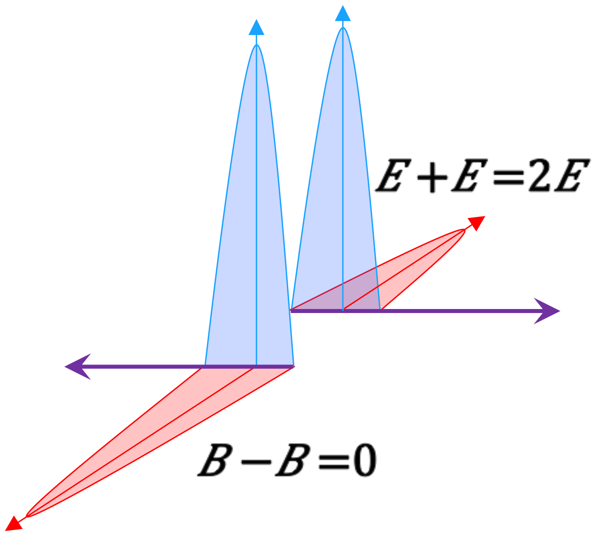
STEAM – Device as Accelerator and Electron Manipulator

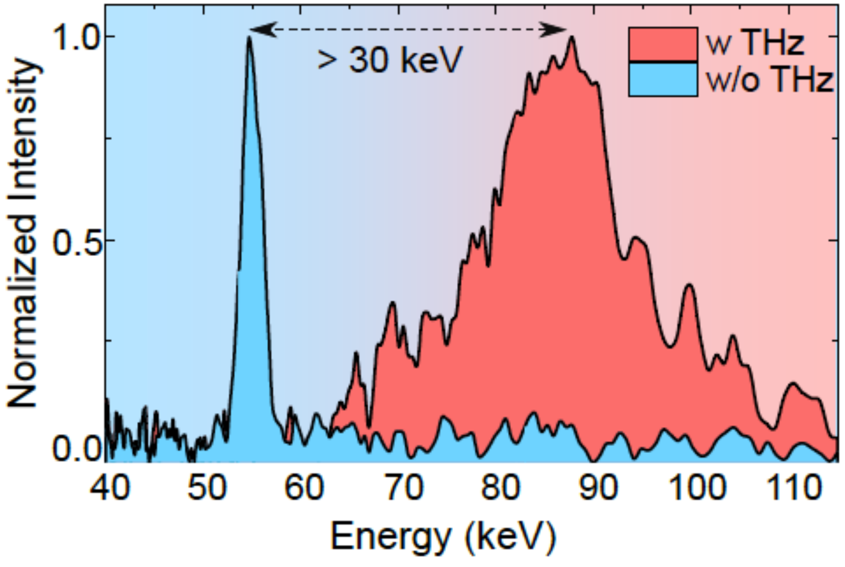


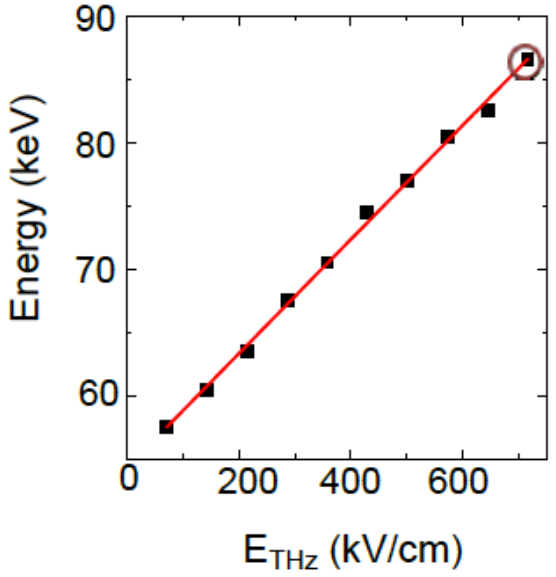
STEAM – Device as Accelerator

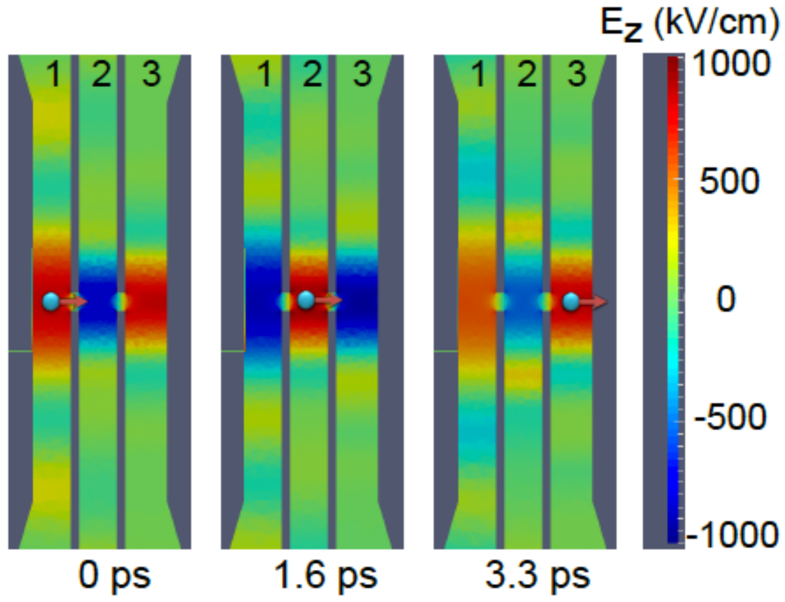
First THz acceleration only!

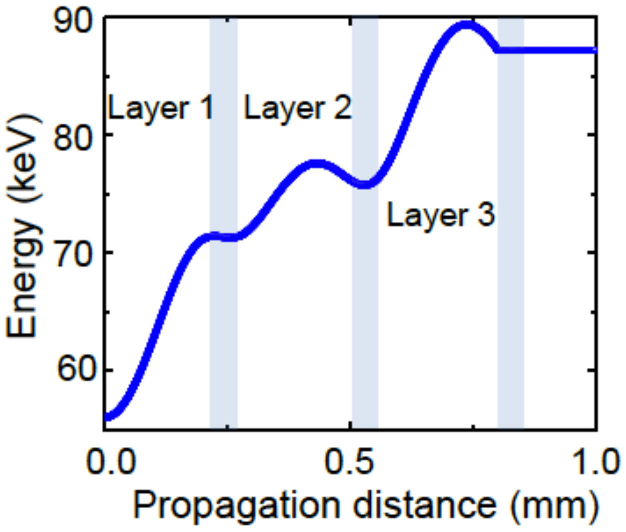
B-fields Cancel: ***Acceleration at maximum E-field***





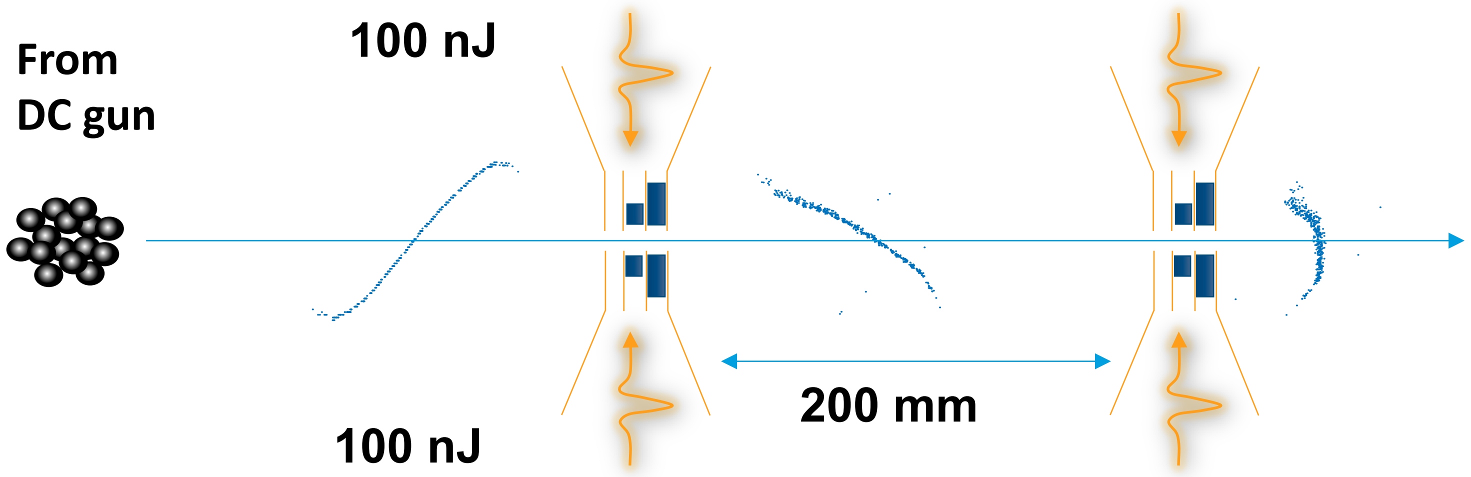






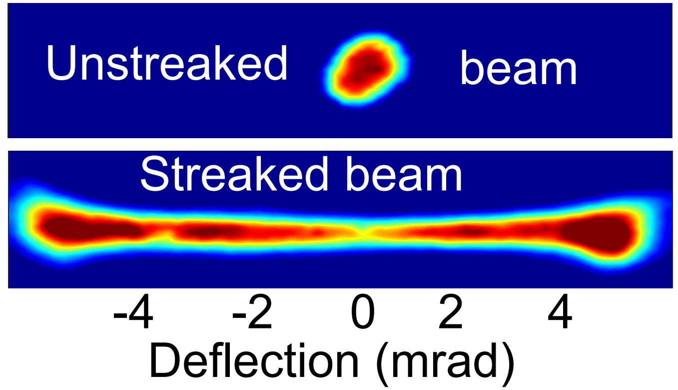
D. Zhang, et al. Nat. Photonics doi.org/10.1038/s41566-018-0138-z

STEAM – Device as Electron Bunch Compressor

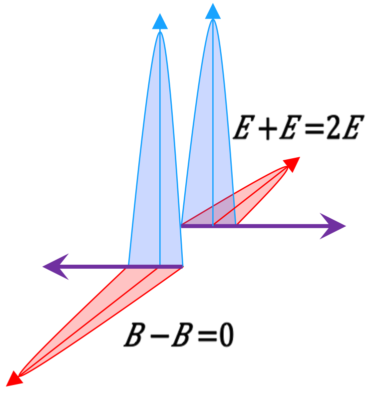


Streaking w. 150 μrad/fs
(<10 fs resolution)

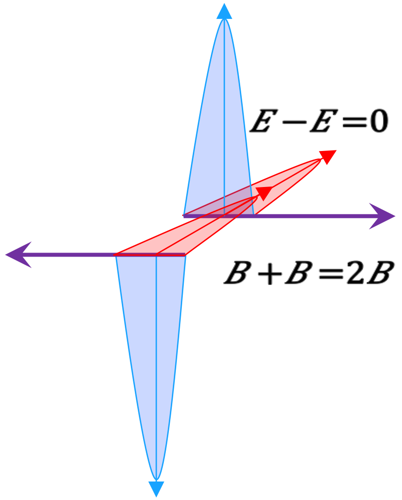
Beam Spatial Mode



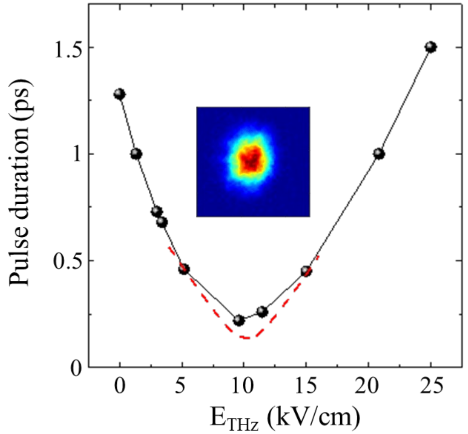
B-fields Cancel: *Zero E-Field*



E-fields Cancel: *Zero B-Field*

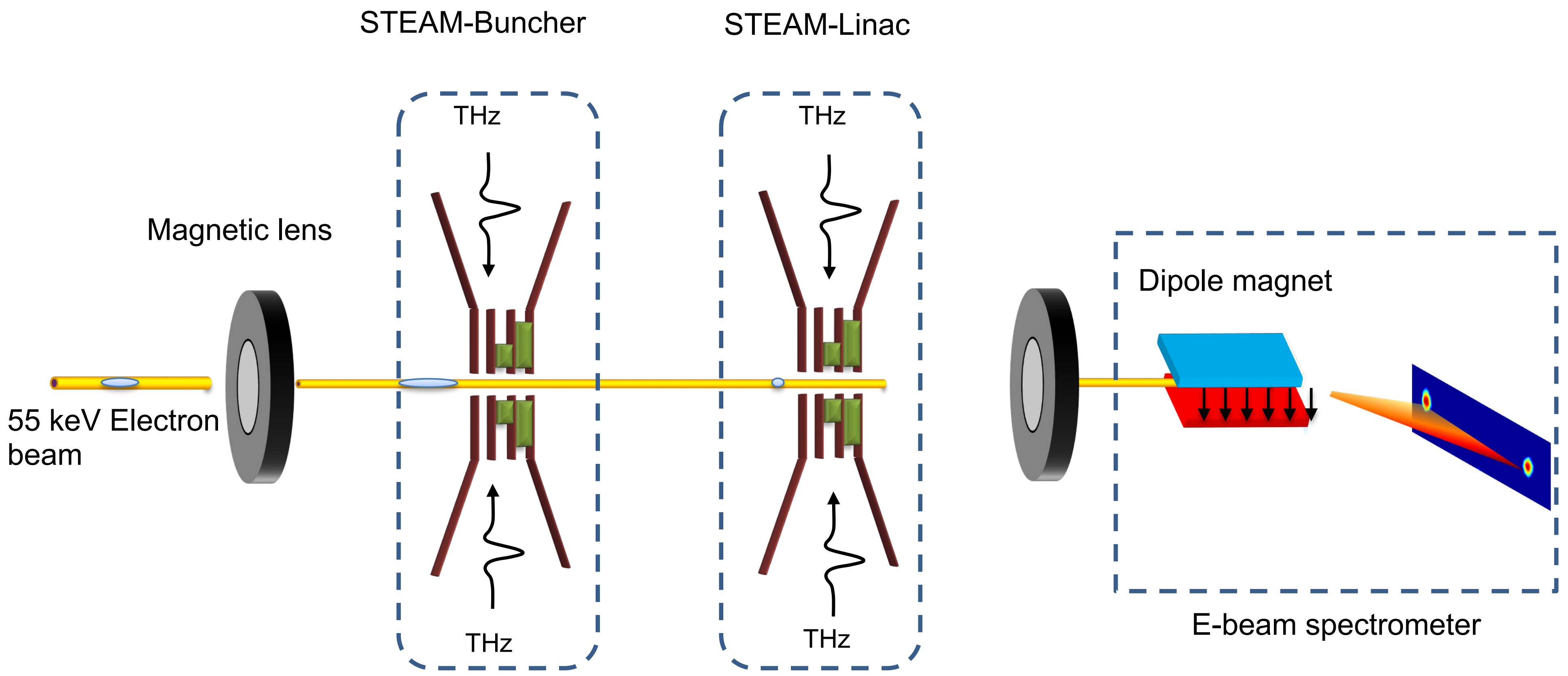


Compression
< 200 fs



Short bunches for UED

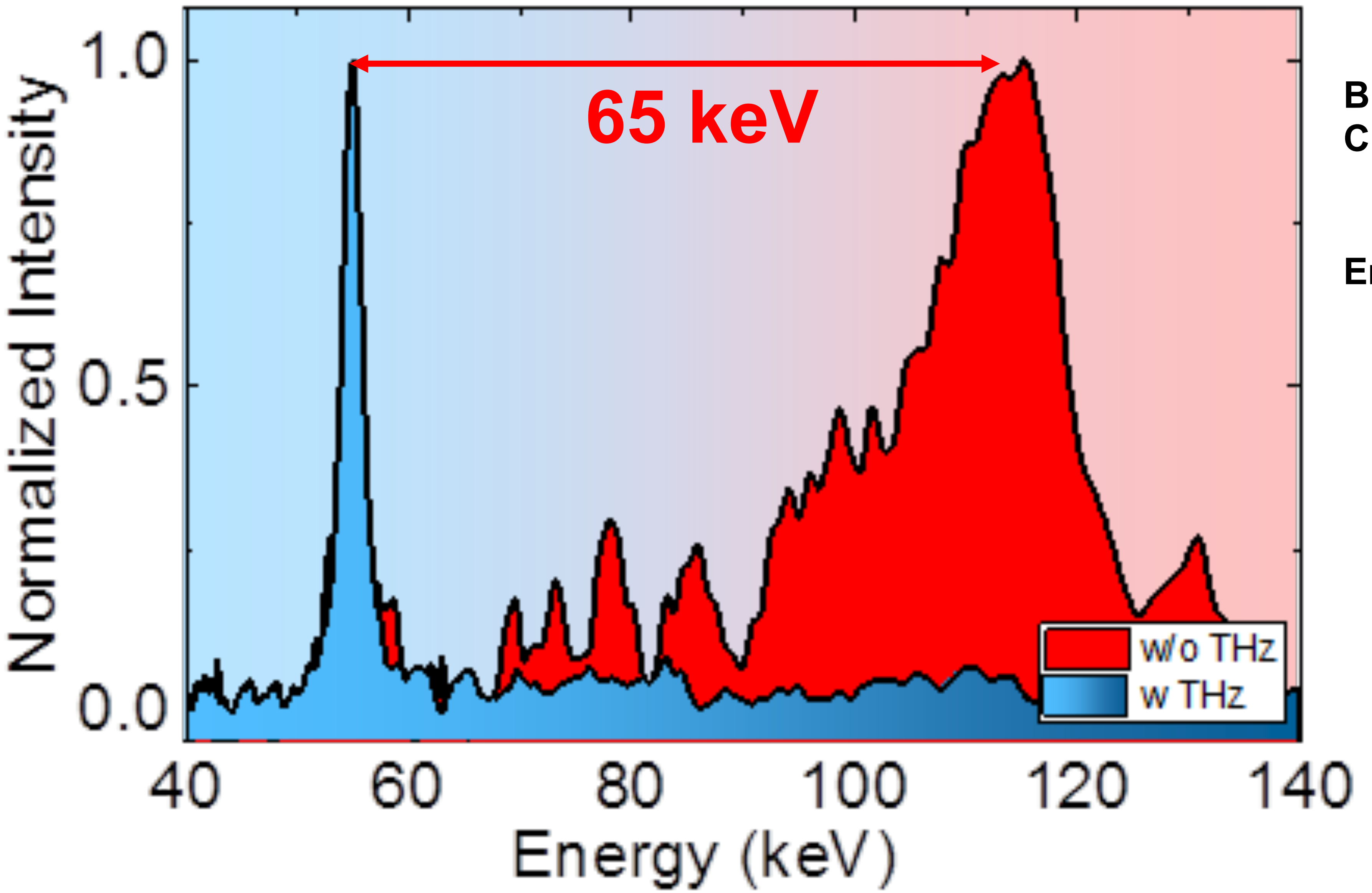
STEAM – Improved Acceleration by Rebunching



2 x 50 nJ coupled in compression to 350 fs (1 ps)

2 x 15 μJ coupled in acc. field = 200 MV/m

STEAM – Acceleration



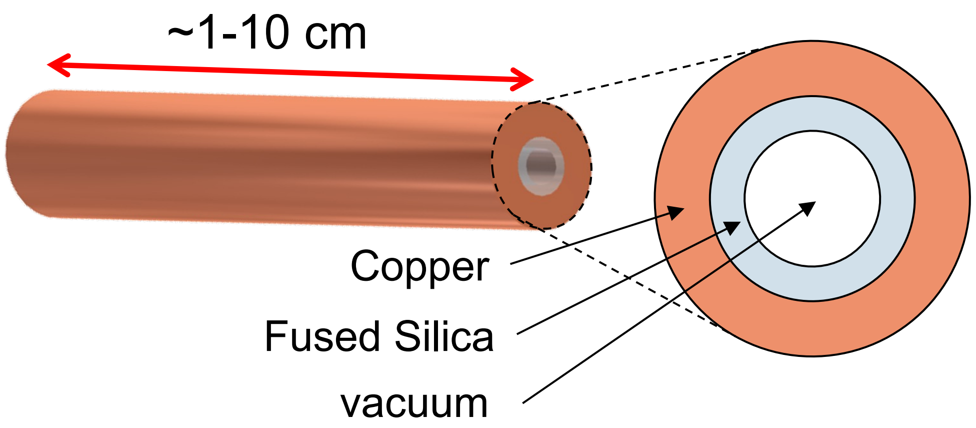
Bunch Charge: ~ *1-5 fC*

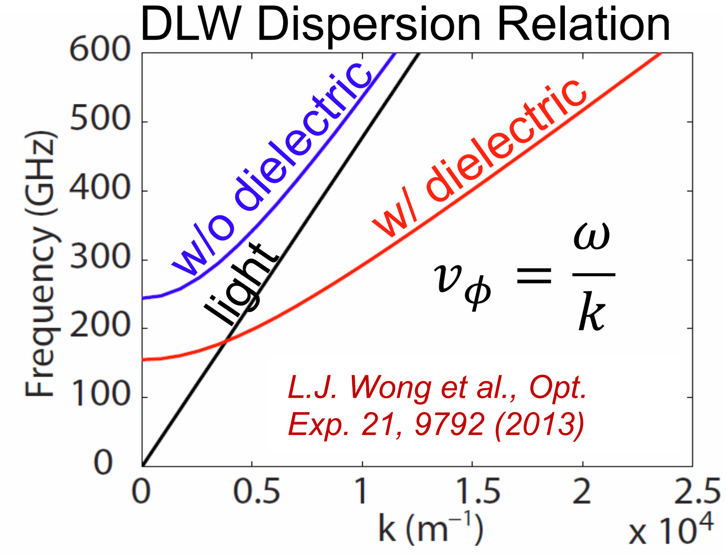
Emittance:
$\varepsilon_{x,y} \sim 0.25\ \mu rad$

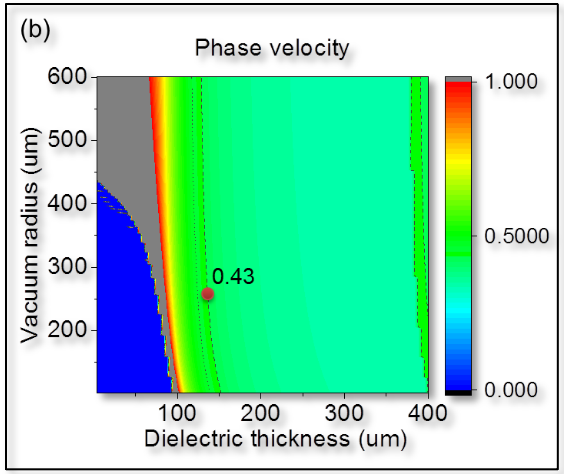
D. Zhang et al., Optica 6, 872 (2019)

THz Acceleration in Dielectrically Lined Waveguide

"Dielectrically-Loaded Waveguide"

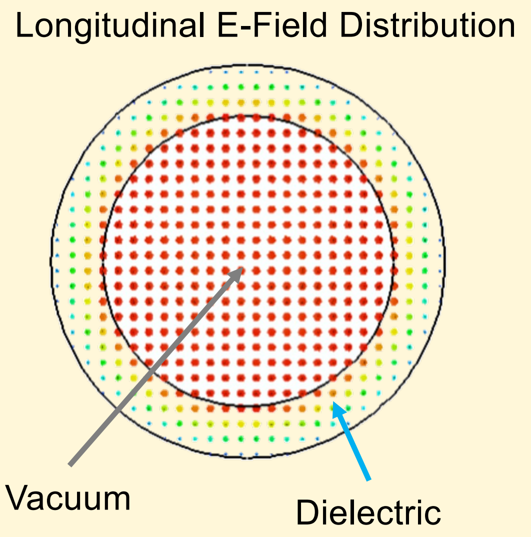


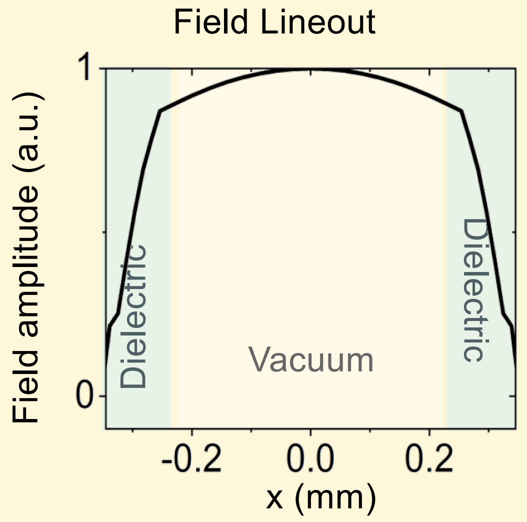




dielectric tunes v_ϕ

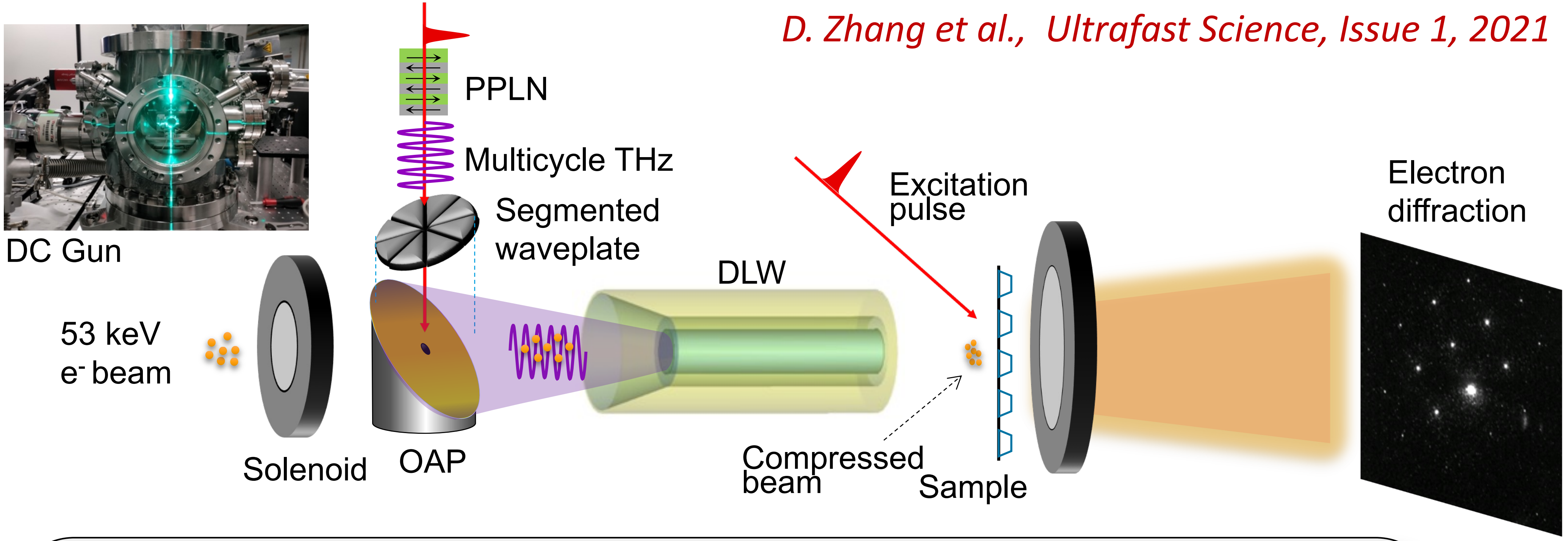
Design Case
KE = 1.0 MeV
$v_\phi/c = 0.94$

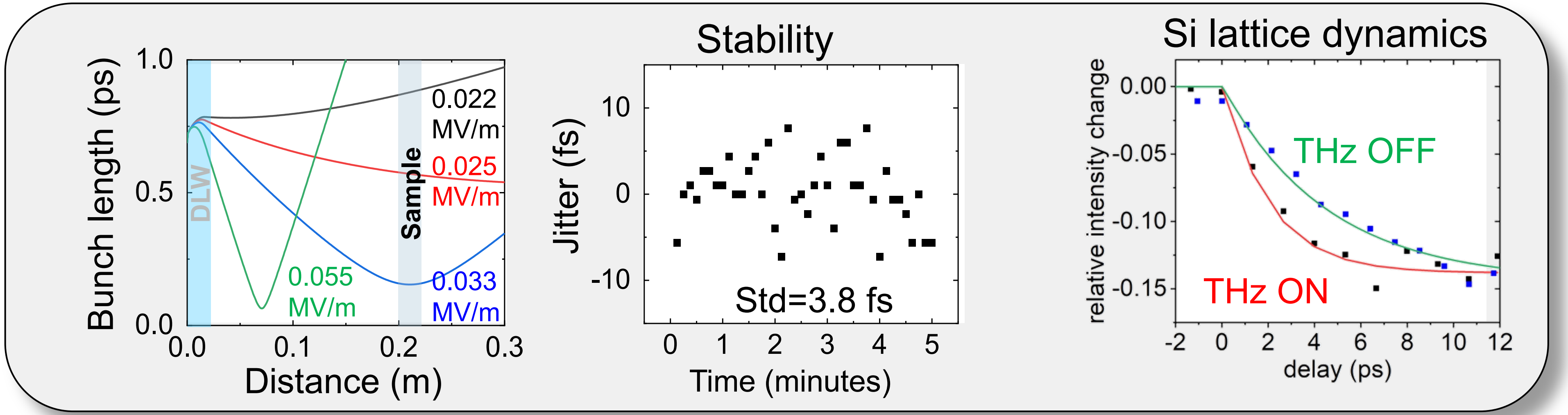




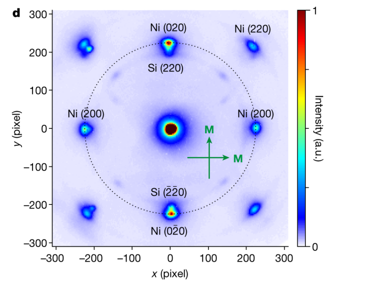
THz-compression enhances UED temporal resolution

D. Zhang et al., Ultrafast Science, Issue 1, 2021



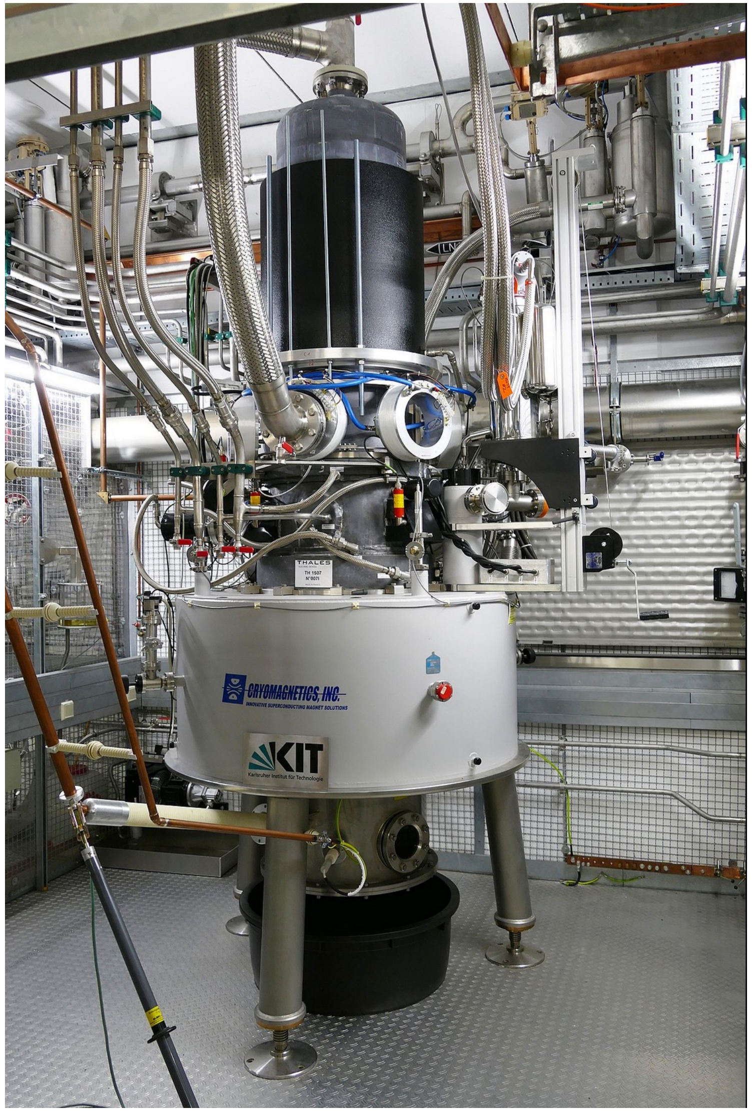


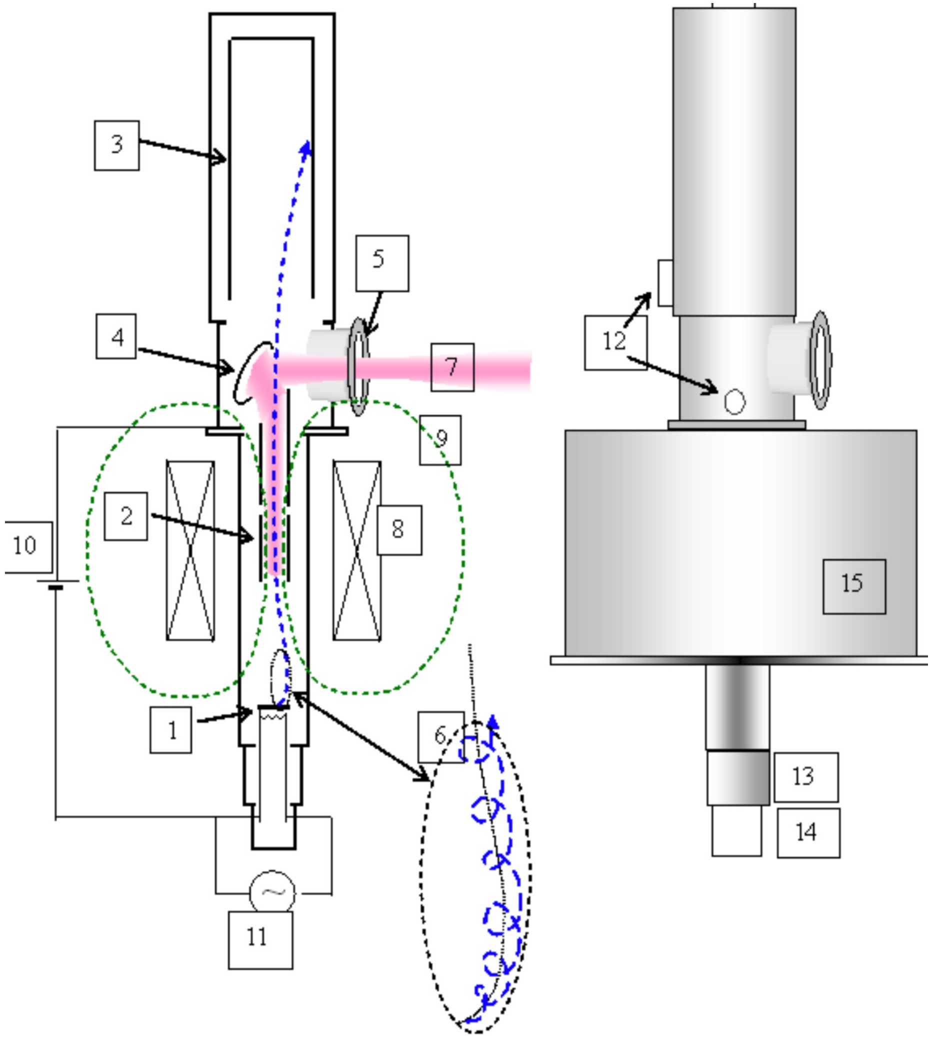
ultrafast demagnetization in Ni



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

Gyrotrons





Wall-plug efficiency:

$\eta = 40 - 50\ \%$

Output Power:

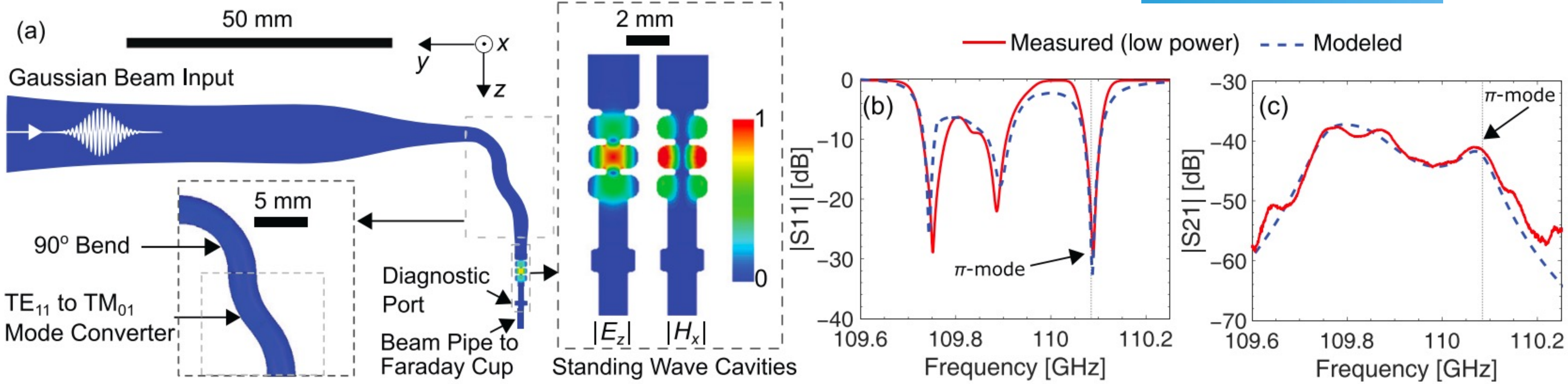
1 - 2.5 MW cw

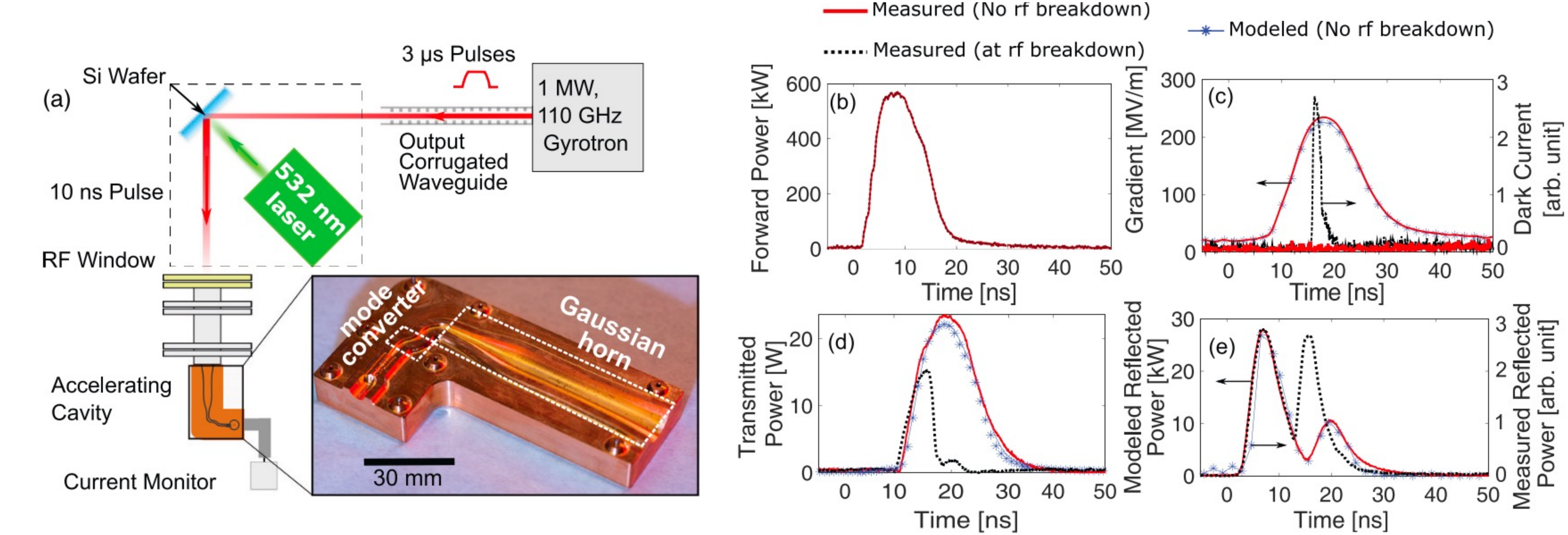
But no high energy short pulses!

High-power **140 GHz** gyrotron for plasma heating in the Wendelstein 7-X fusion experiment, Germany.
https://en.wikipedia.org/wiki/Gyrotron#/media/File:W7-X_gyrotron.jpg

Gyrotron powered THZ-cavity devices

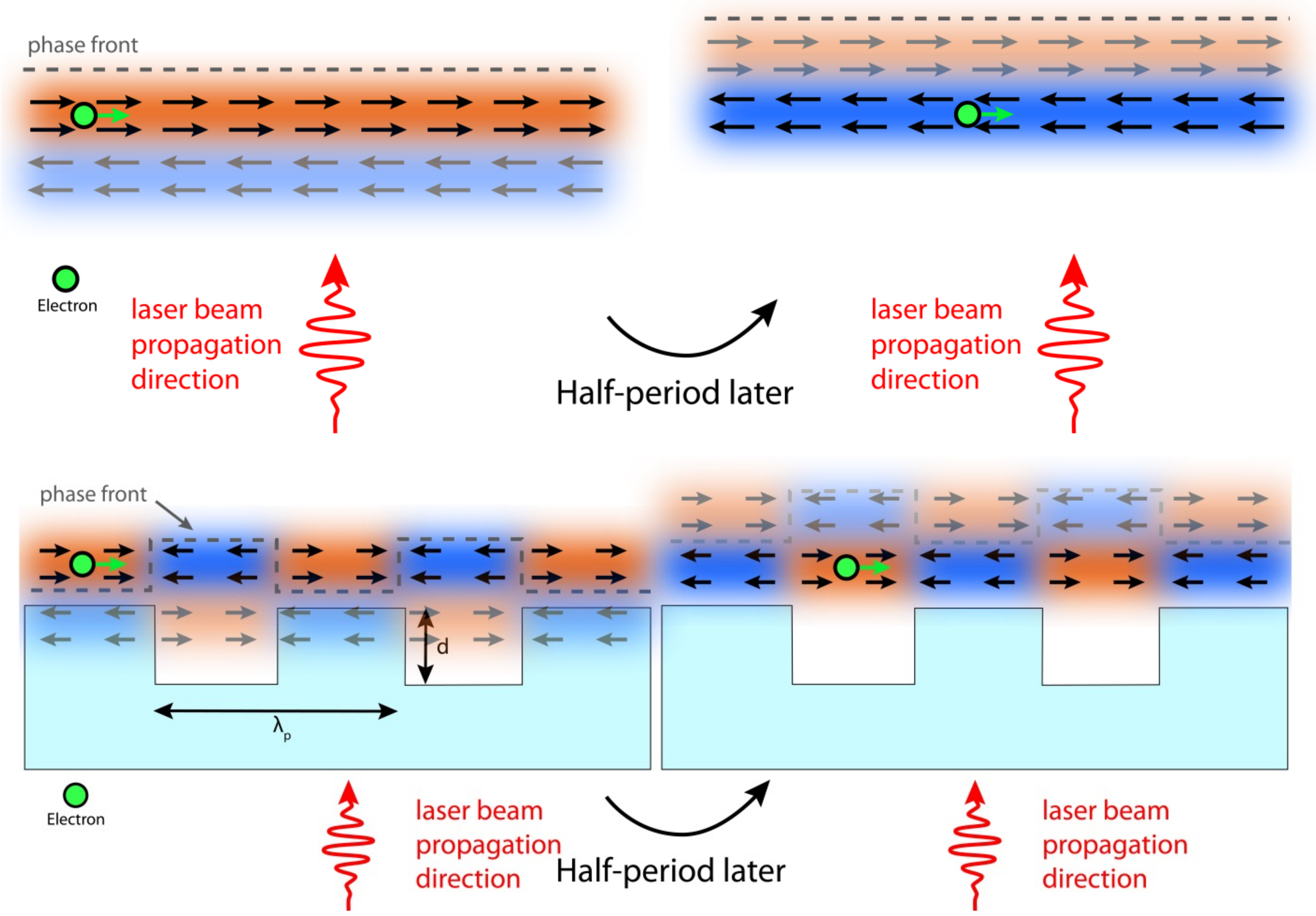
S. Tantawi &
E. Nanni

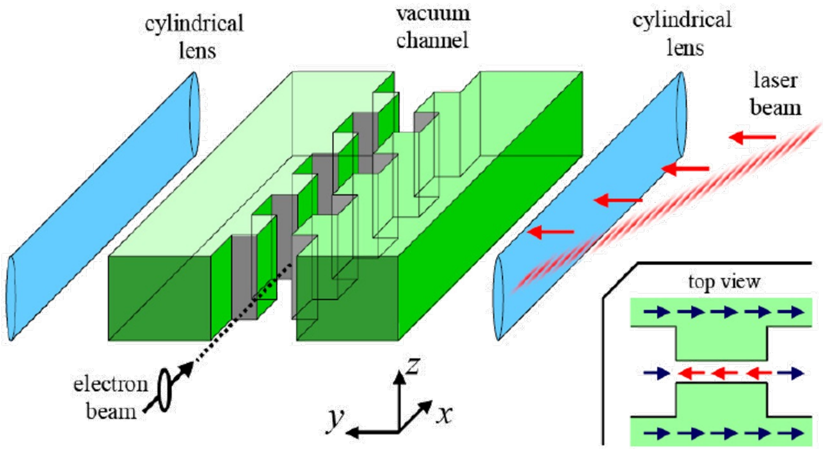




M. A. K. Othman et al., Appl. Phys. Lett. 117, 073502 (2020); doi: 10.1063/5.0011397

Direct optical-field acceleration with dielectric structure





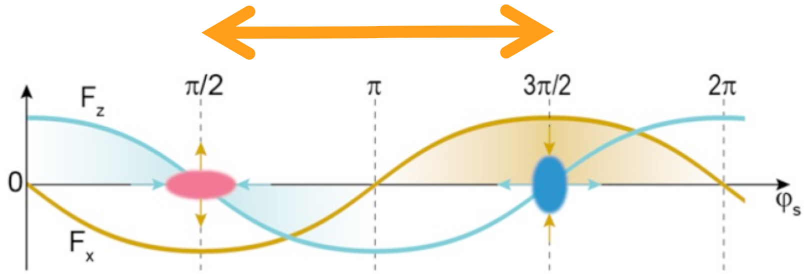
Plettner, Lu, Byer, 2006

… and variants

- Goal: generate a mode that allows momentum transfer from laser field to electrons
- Use first order effect (efficient!)
- Second order effects (ponderomotive) too power costly
- Can be fabricated by modern nanofabrication facilities, same as electronics

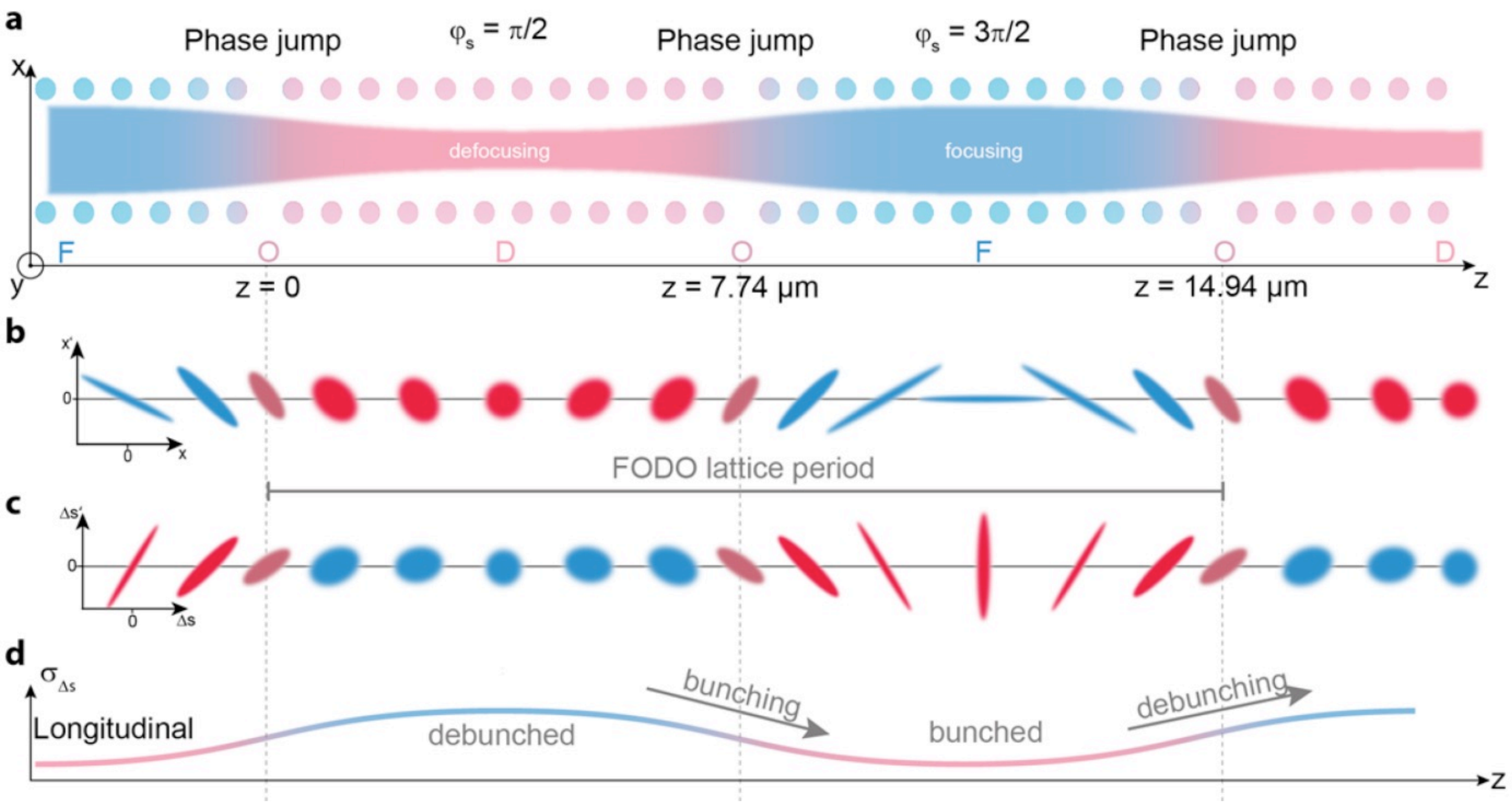
Peter Hommelhoff, Laser Physics, FAU Erlangen - Nürnberg

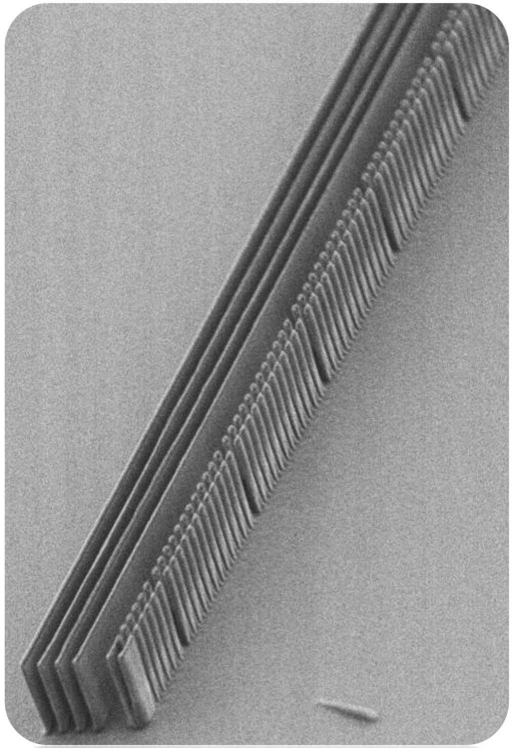
Alternating phase focusing: jump btw. phases



Jump between phases!
Net stable
Hard? Dial into structure

ACHIP
Accelerator on a Chip International Program



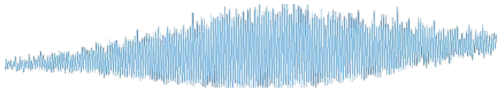


R. Shiloh, J. Illmer, T. Chlouba, P. Yousefi, N. Schönenberger, U. Niedermayer, A. Mittelbach, P. Hommelhoff, Nature 597, 498 (2021)

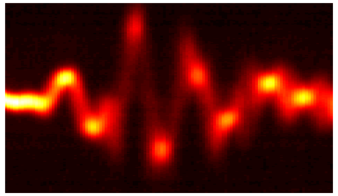
Peter Hommelhoff, Laser Physics, FAU Erlangen - Nürnberg

Summary

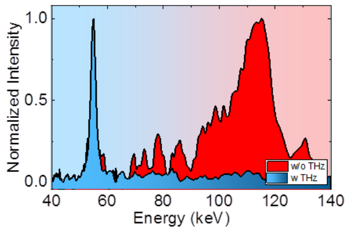
- THz and optical accelerators benefit from increased breakdown fields
- THz-accelerators can be powered by (multi)-mJ-level pulses



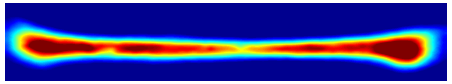
- 1 GV/m gradients should be possible



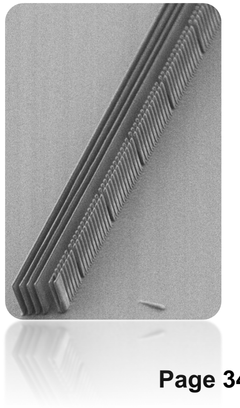
- Electron manipulation with segmented THz waveguide devices and DLW-devices
- > 60 keV THz acceleration demonstrated (starting from 55 keV)



- Optical accelerator structures operating at 2 μm wavelength



- Alternate phase focusing structures demonstrated
- Enables compact electron guns (as - fs) and devices
- Dielectric accelerators can use semiconductor fabrication processes
- Compact accelerators for UED and X-ray sources



Acknowledgement

- THz accelerator team at DESY

AXSIS – ERC Synergy Grant

Prof. Taira, IMS and SACLA, Japan for PPLN material.

- Peter Hommelhoff, Laser Physics, FAU Erlangen – Nürnberg and ACHIP team