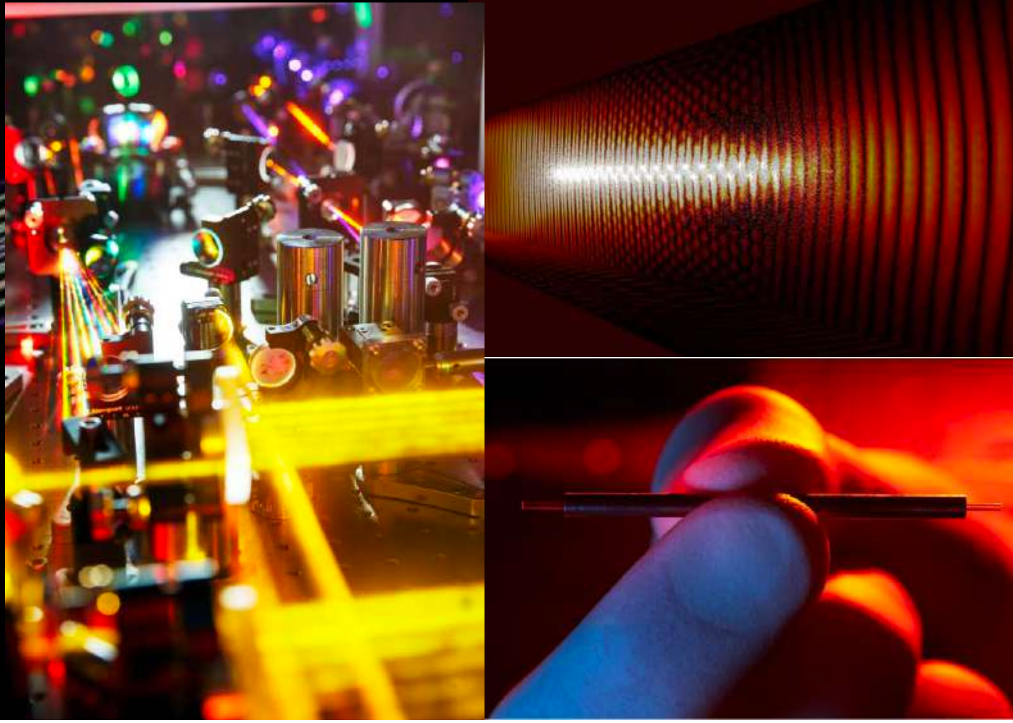
Terahertz Driven Ultrafast Electron and X-ray Sources



11th “Ubiquitous Power Laser”, Technical Committee Meeting, December 17th, 2020

Franz X. Kärtner

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

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

erc

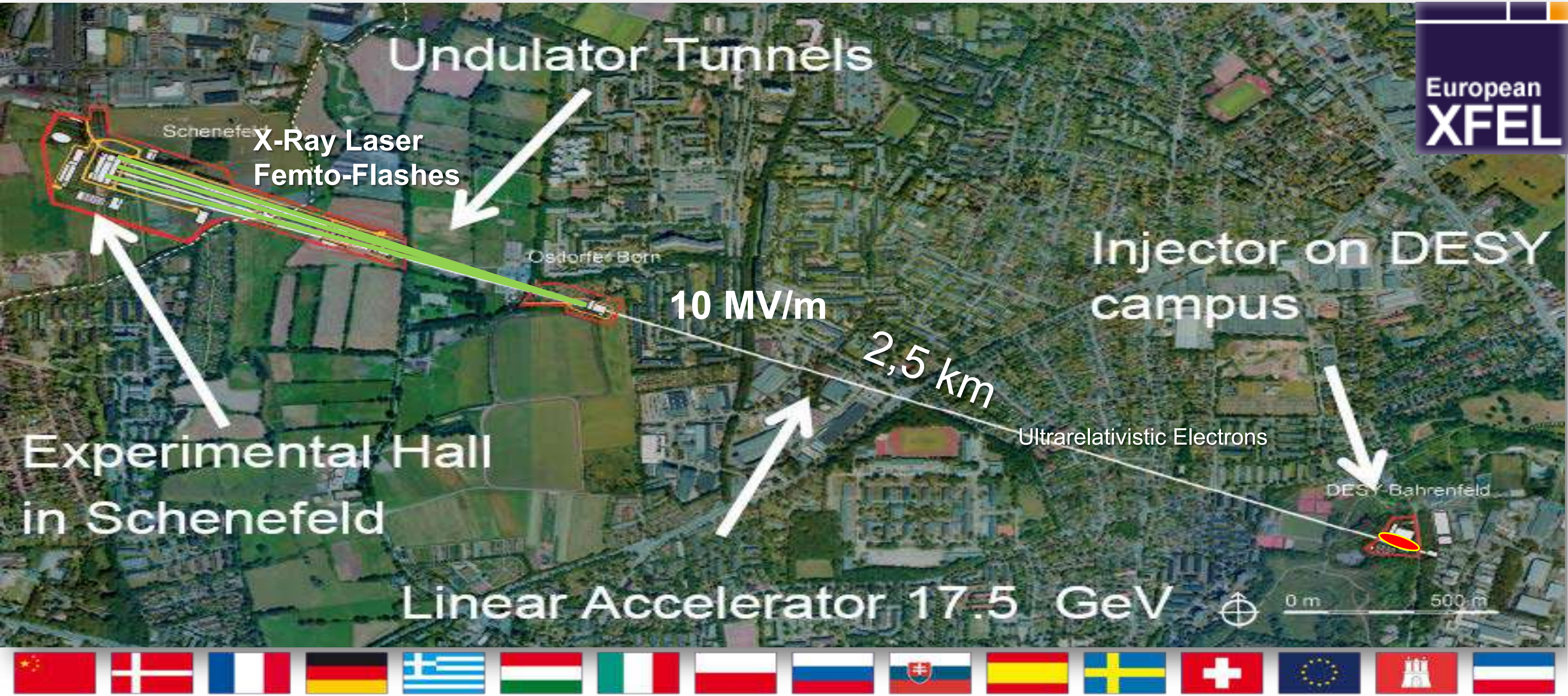
UHH

cui

CFEL SCIENCE

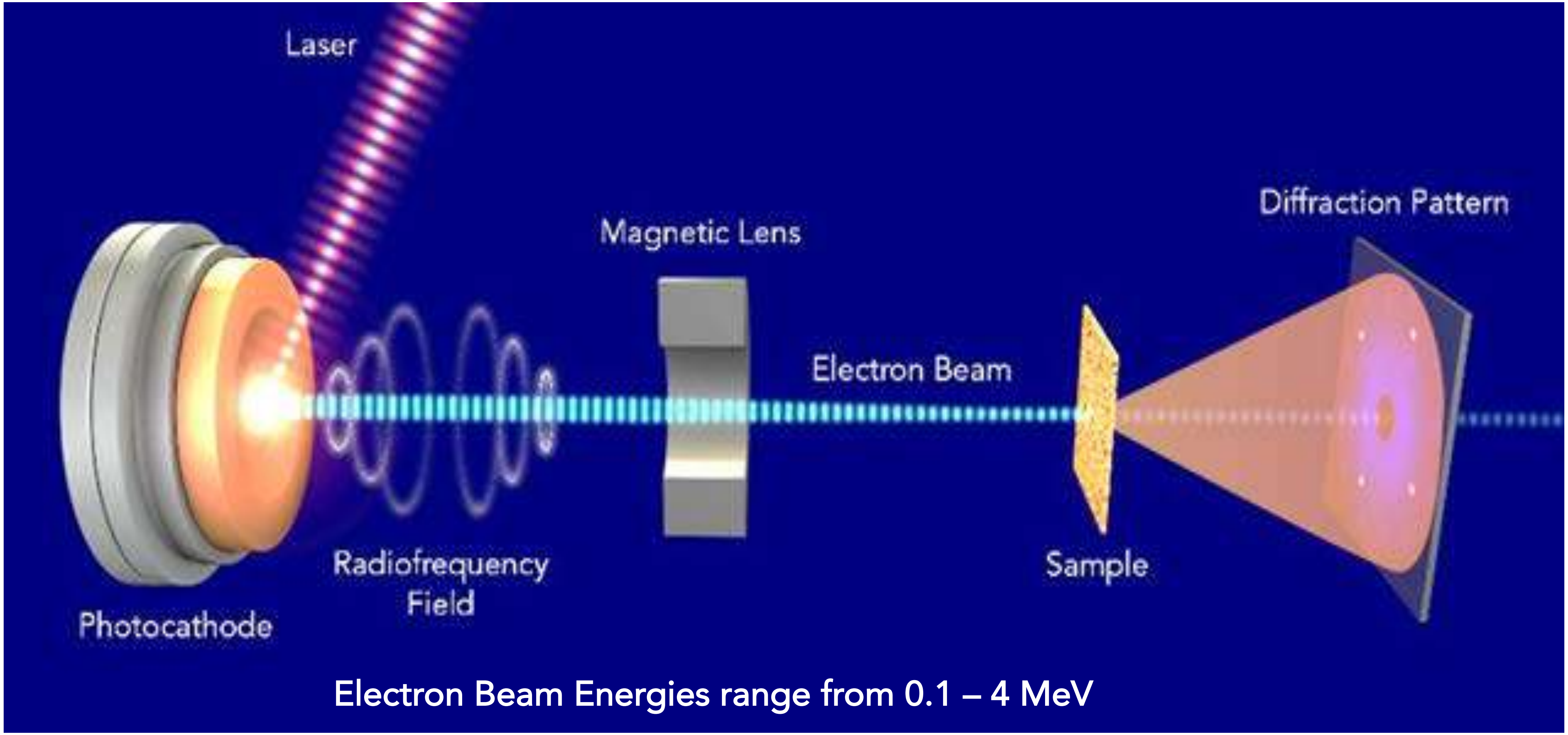
DESY

European XFEL.



In Operation since May 2017

Ultrafast Electron Diffraction

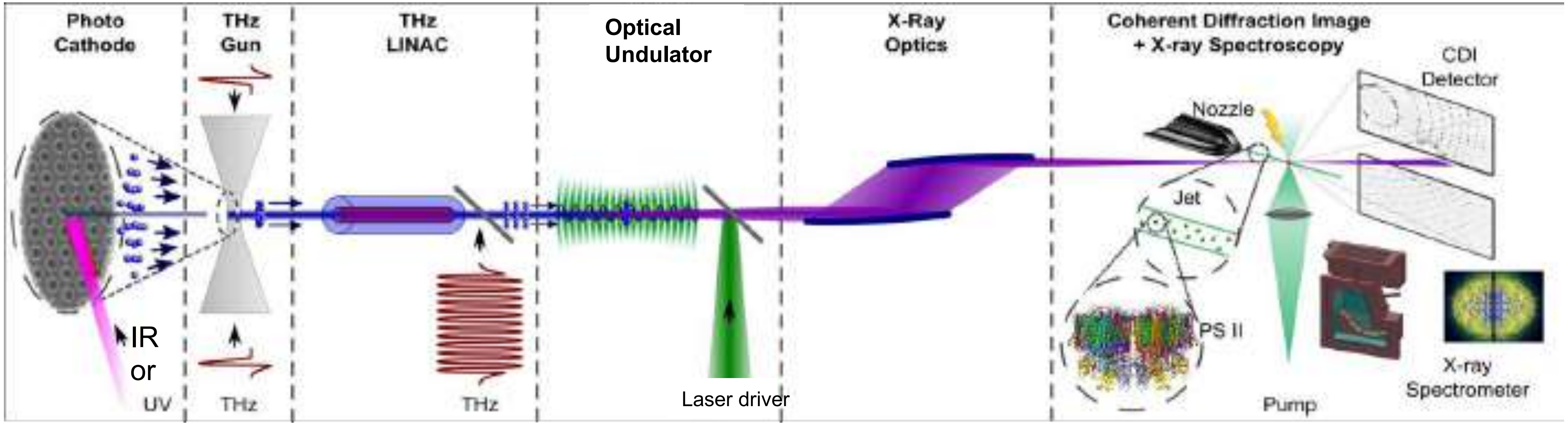


Schematic UED Setup: SLAC National Accelerator Laboratory

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

Attosecond X-ray Science – Imaging and Spectroscopy

The Quest for Compact Coherent X-ray Sources (Sub-fs Pulses)



Laser-based THz-generation, acceleration and optical undulator

ps, 1-J-Lasers,
auto-synchronization
kHz operation

→ has its own science case
→ seeding of large scale FELs
→ solve access to large facilities

Jointly with

Henry Chapman
DESY & U. Hamburg

Ralph Assmann
DESY

Petra Fromme
DESY & Arizona State U.

FXK. et al., doi:10.1016/j.nima.2016.02.080

Outline

- Why THz acceleration?
- Progress in Single-Cycle and Multi-Cycle THz Sources
- Single-Cycle and Multi-Cycle THz guns
- First results: > 60 keV acceleration
- Summary

Why THz?

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

Reduced pulse energy and heating

- stored energy
- reduced pulsed heating
- high repetition rate operation becomes 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 – lower emittance beams
- Short acceleration distances and times → reduced space charge effects
- **But** lower bunch charge: 10 fC – 10 pC -> typical charge range for Ultrafast Electron Diffraction (UED)

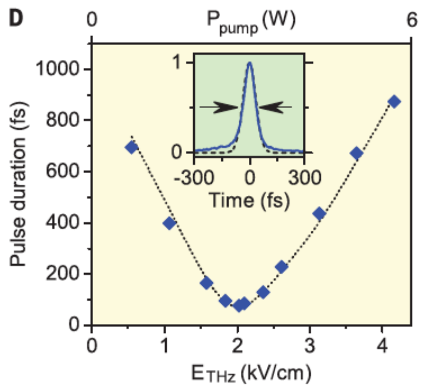
THz Guns Acceleration and Beam Manipulation

THz Compression @ LMU/MPQ

Kealhofer et al., *Science* 359, 459 (2016)

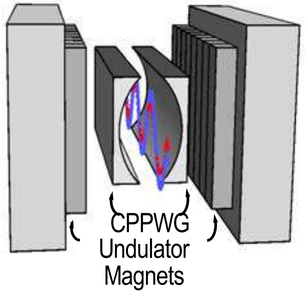
Phase-space control & characterization of electron pulses

- compression from 930 to 75 fs; avg. 1e @ 70 keV per pulse
- see also: SLAC arXiv:1805.03923 [physics.acc-ph]
  Shanghai Jiao Tong University. arXiv:1805.01979 [physics.acc-ph]

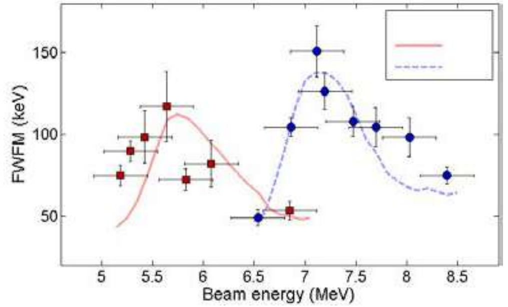


THz IFEL interaction @ Pegasus Lab

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



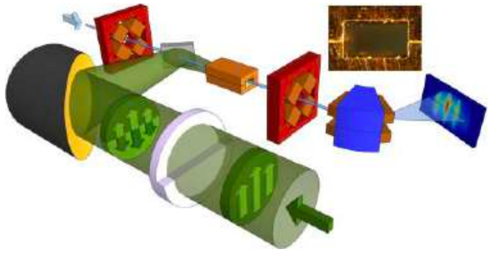
Acceleration with < 1µJ single-cycle 0.8 THz pulses
150 keV energy modulation of 7 MeV beam using
Bunch compression by factor of two



THz sub-luminal free-space fields @ Cockroft Institute (S. Jamison)

Hibberd et al., *Nature Phot. doi.org/10.1038/s41566-020-0674-1*

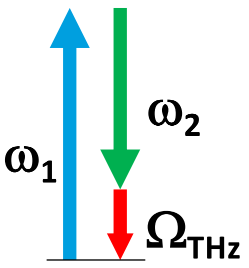
Acceleration of relativistic beams

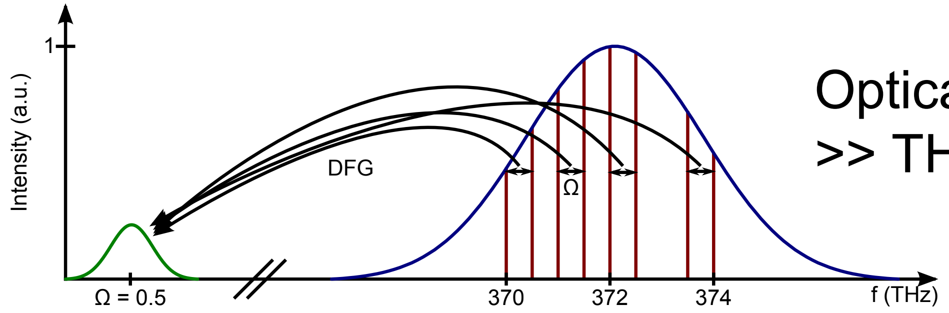


Optical THz Generation based on $\chi^{(2)}$

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

DFG process

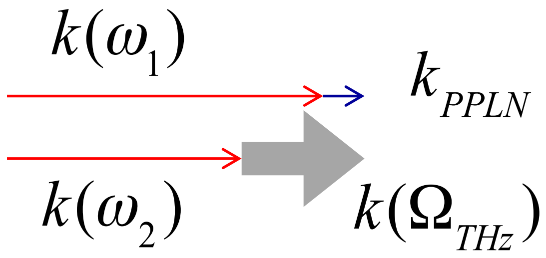




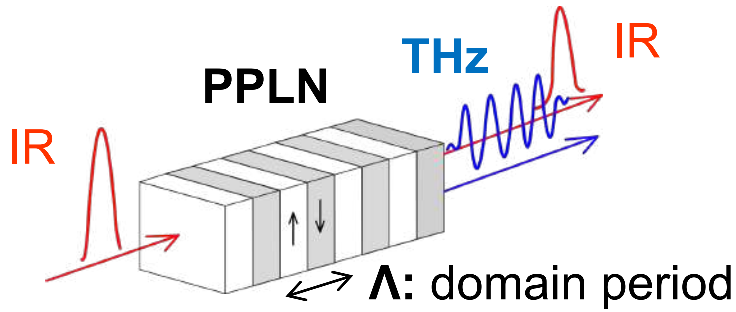
Optical bandwidth
>> THz frequency

Conservation of momentum:

Collinear Phase Matching

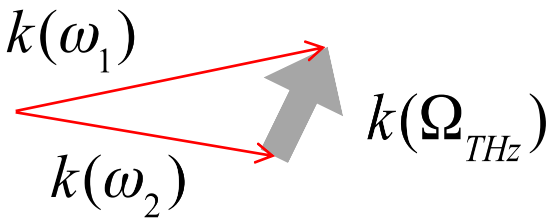


Multi-cycle THz generation using Periodically-Poled Lithium Niobate

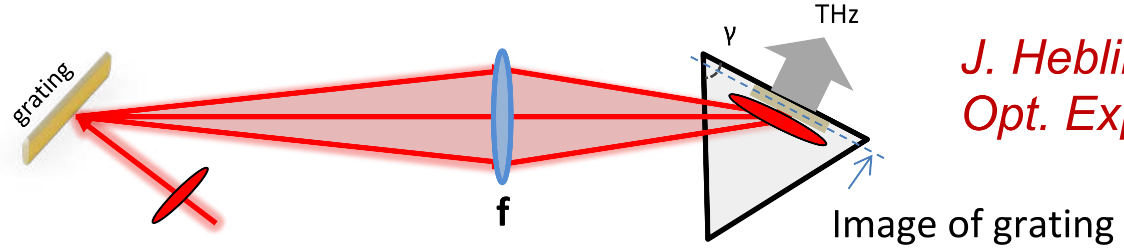


$$n_{opt} \approx 2; \quad n_{THz} \approx 5$$

Non-collinear Phase Matching



Single-cycle THz generation by Tilted Pulse-Front Technique

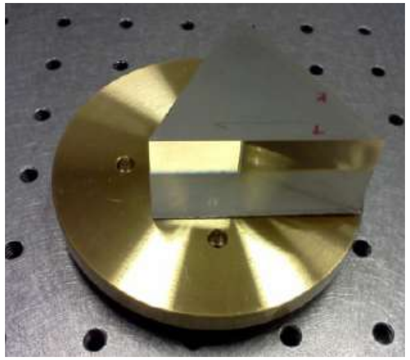


J. Hebling et al,
*Opt. Express **21**, 1161 (2002)*

Single-Cycle THz Pulses

~1% optical to THz conversion

J. Hebling et al., Opt. Express 10, 1161 (2002)
J. A. Fülöp et al., Opt. Express 19, 15090 (2011)



Cryogenic LN prism

Single-cycle THz generation:

E_{THz} ~ 100 μJ

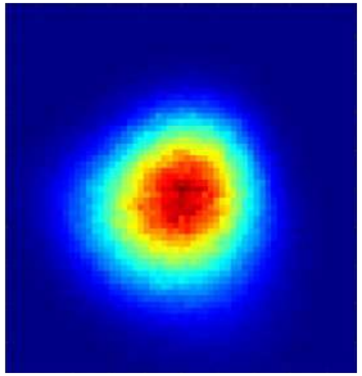
f_{THz} ~ 280 GHz

Δ_{FWHM} ~ 3.3 ps

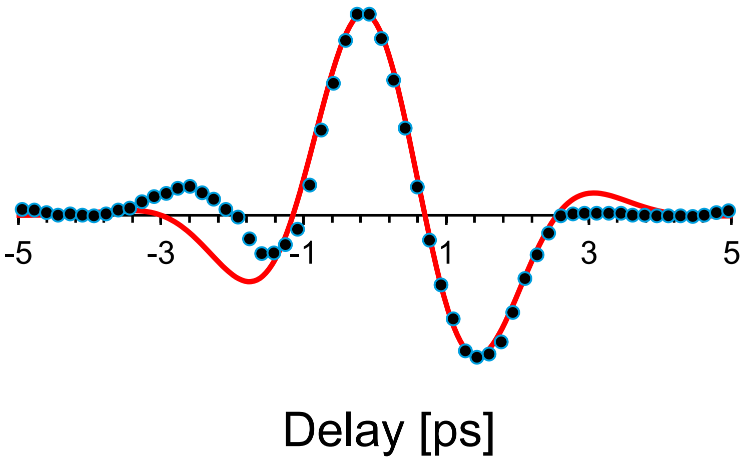
IR laser: 40 mJ, 1020 nm, 1ps

0.5 % internal efficiency

Measured THz mode

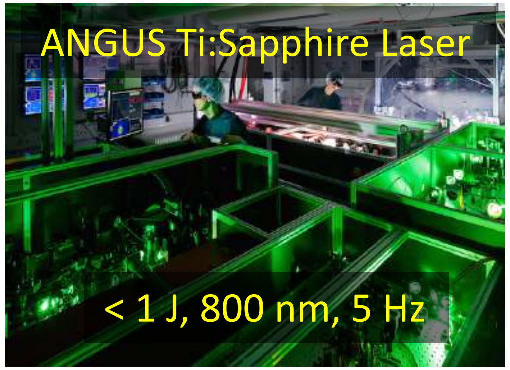


Measured THz Waveform



X. Wu et al., IRMMW 2020 using a 200 mJ, Ti:Sapphire Laser → 1.4 mJ with ~ 0.7% efficiency

High Energy Multi-Cycle THz from Large Aperture PPLN Crystals



Collaboration @ DESY

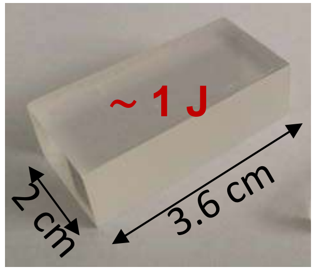
LUX:

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

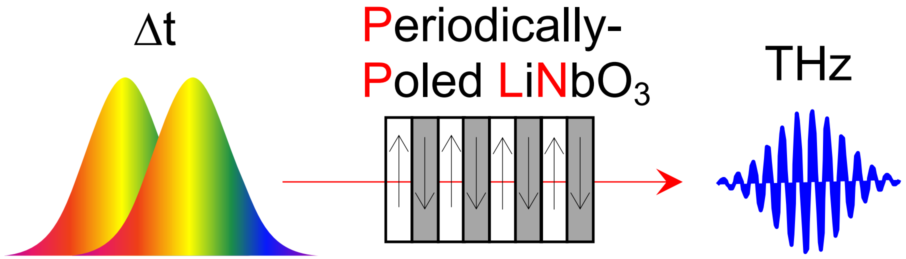
AXSIS:

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

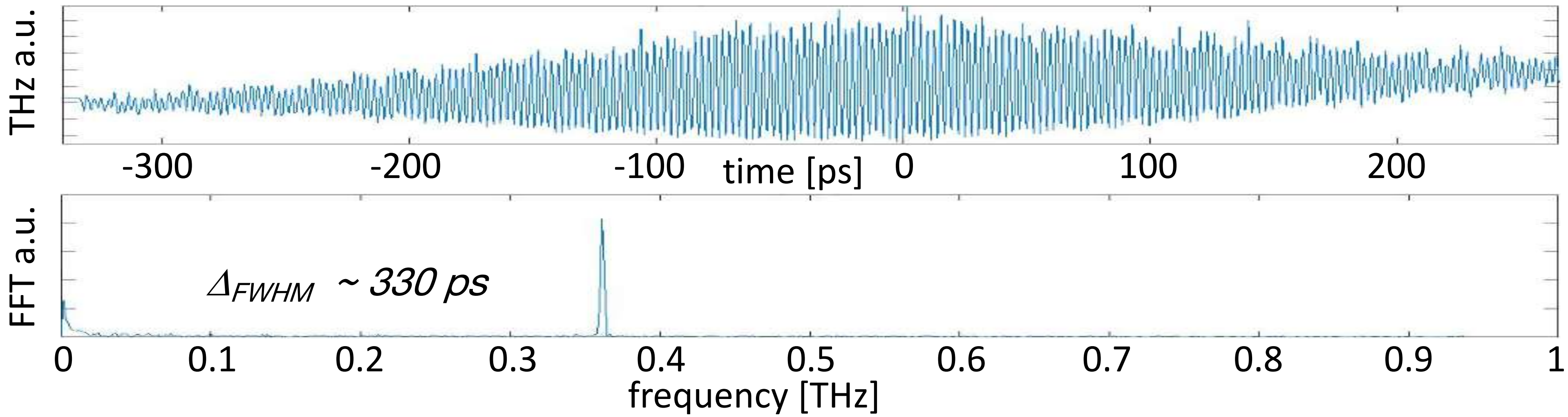
Large PPLN provided by Prof. Taira, IMS, Japan



Chirp & delay difference frequency generation



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



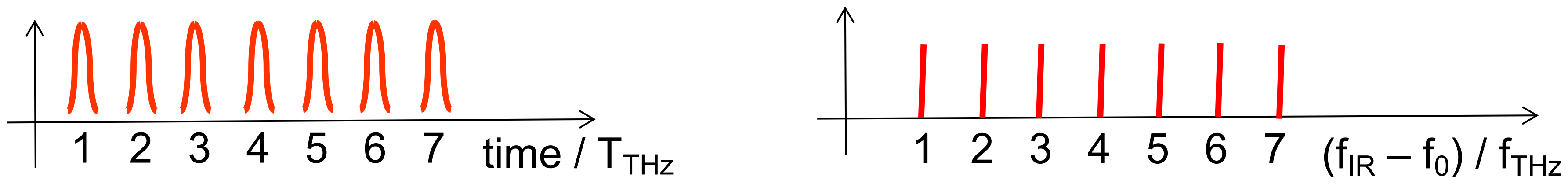
500 x larger than previous record!

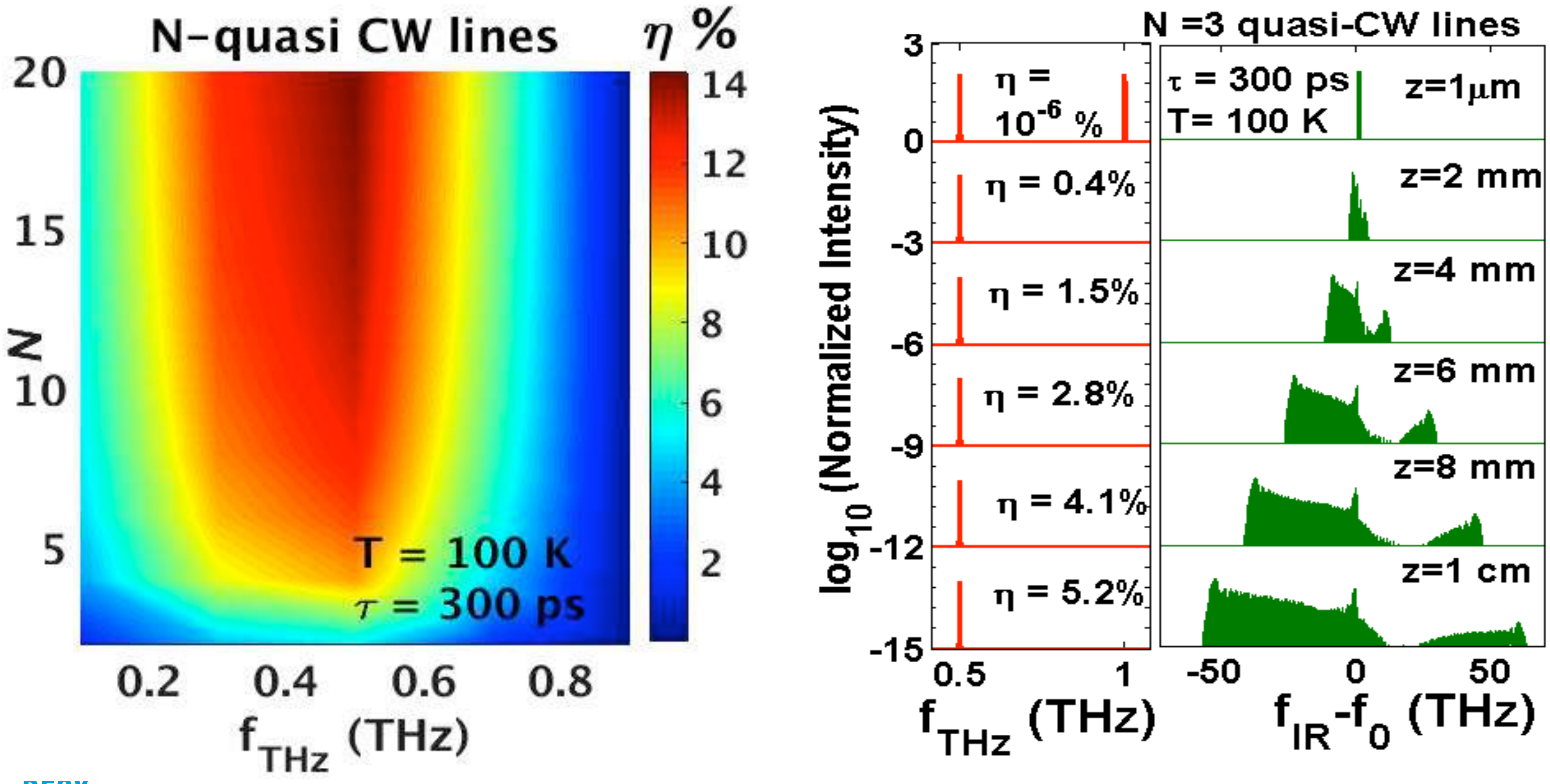
F. Ahr et al., Opt. Lett. *42, 2118 (2017)*

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

Multi-line DFG - Highly Efficient THz Generation





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

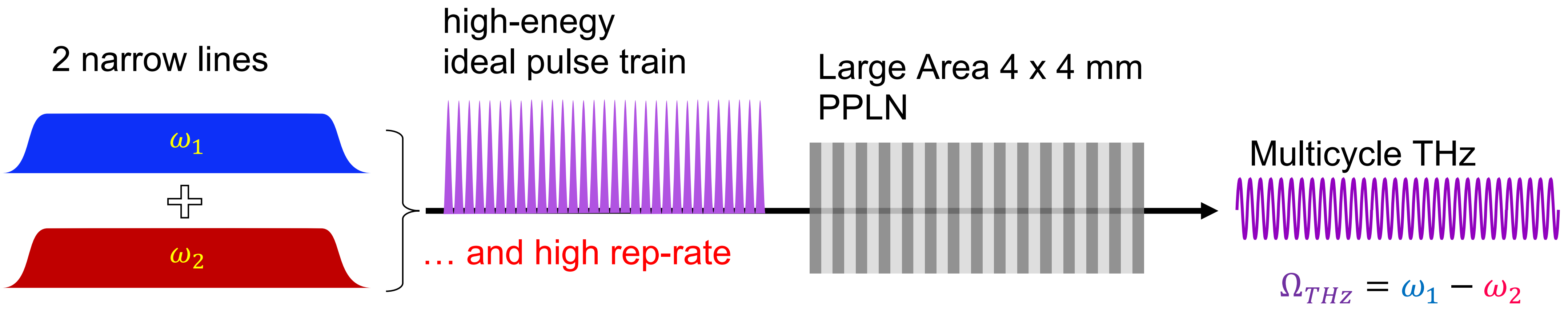
Earlier work by

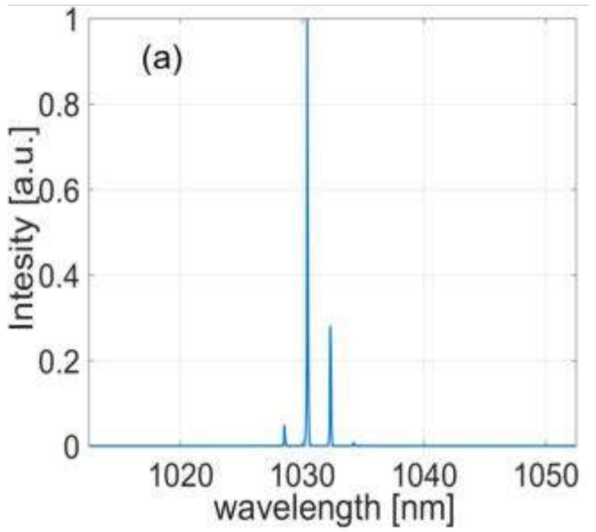
M. Cronin-Golomb,
Opt. Lett. 29, 2046 (2004)

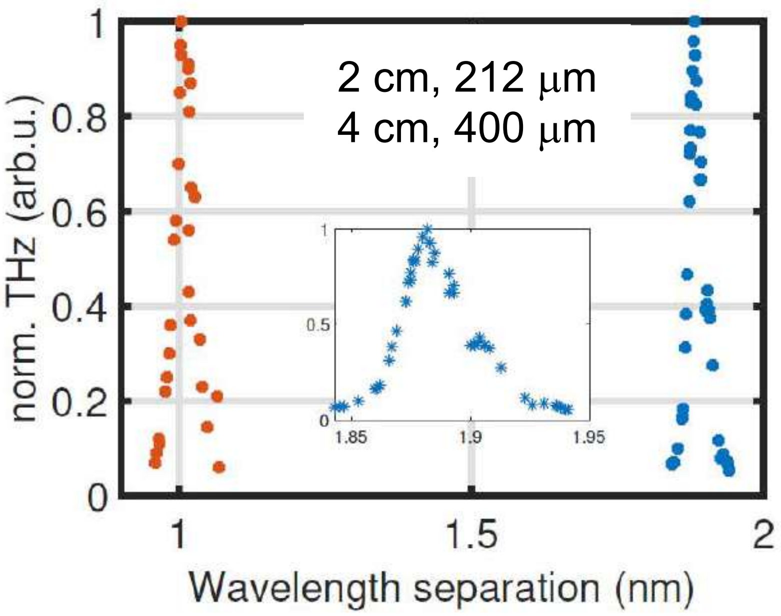
A. G. Stepanov,
JETP Lett., 85, 227(2007)

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

2-Line Difference Frequency Generation

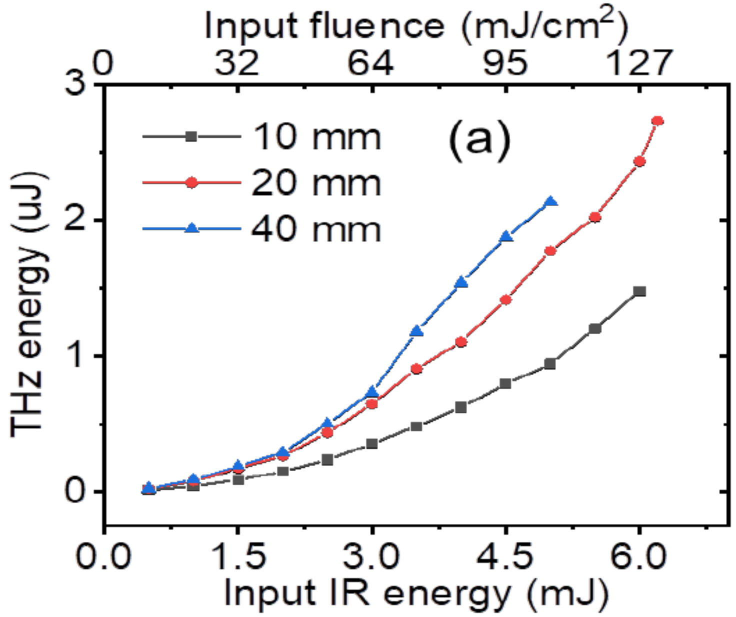


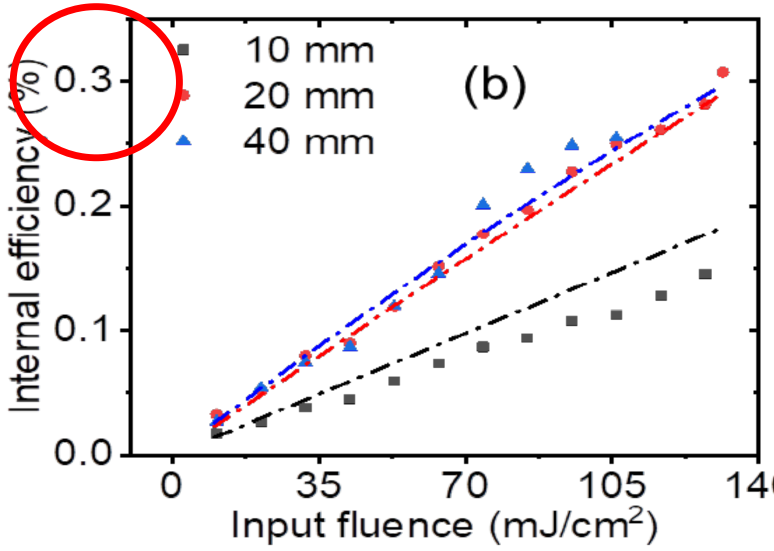


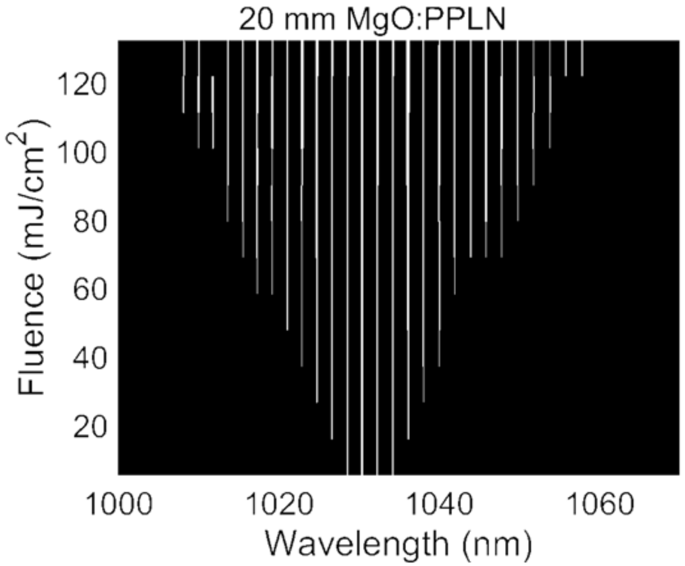


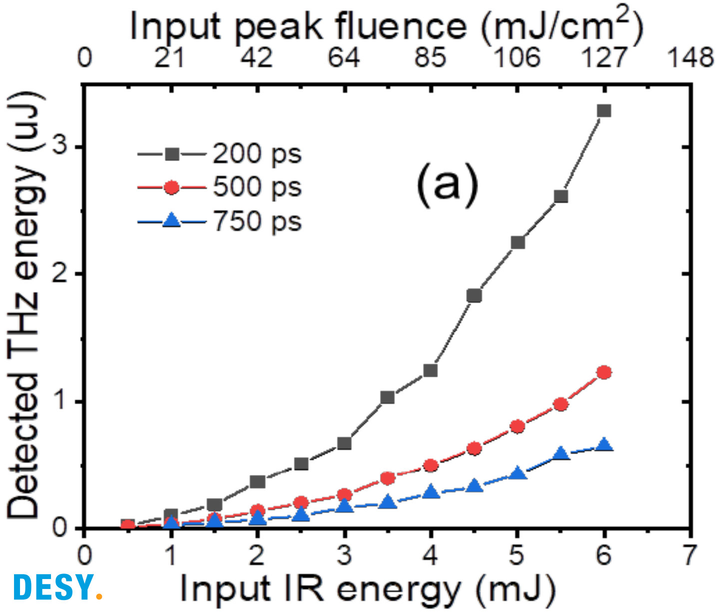
Period	THz frequency	linewidth
212 µm	531 GHz	~3 GHz
400 µm	286 GHz	~1.5 GHz

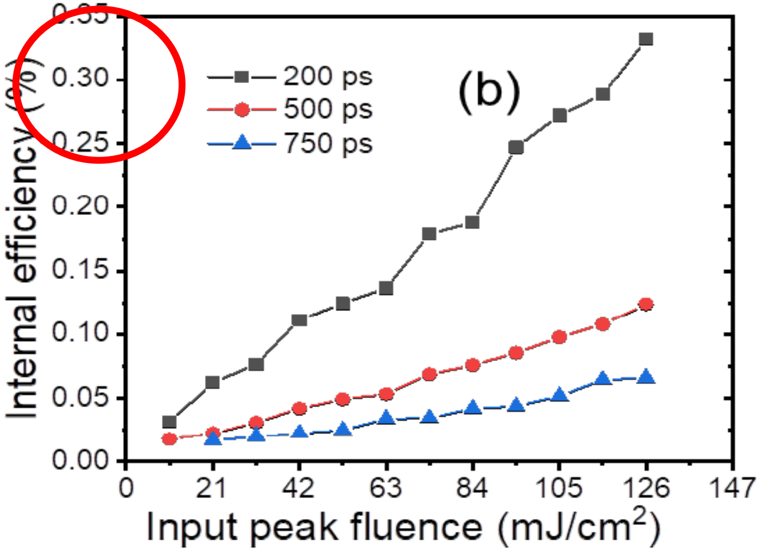
2-Line Results: Variable Crystal Length and Pulse Duration









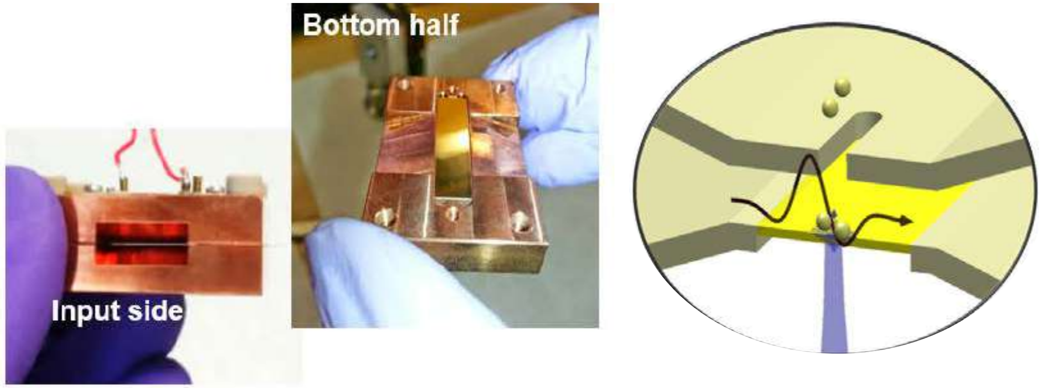


W. Tian et al., to be published

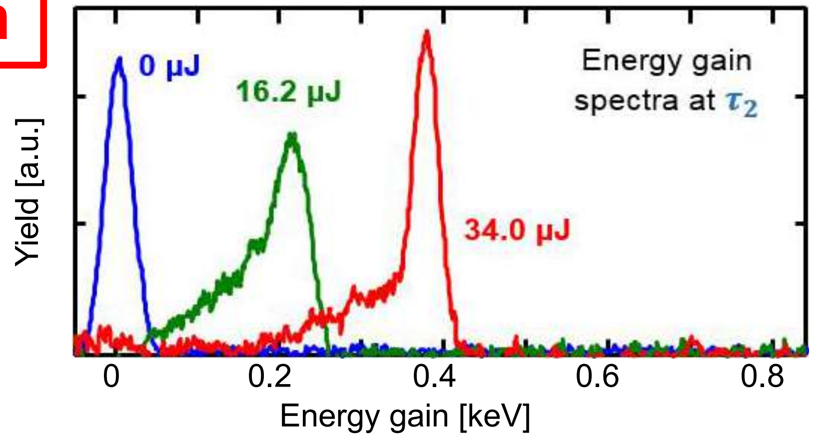
THz Gun & LINAC: Proof of Feasibility

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

E_z -> 0.3 GV/m

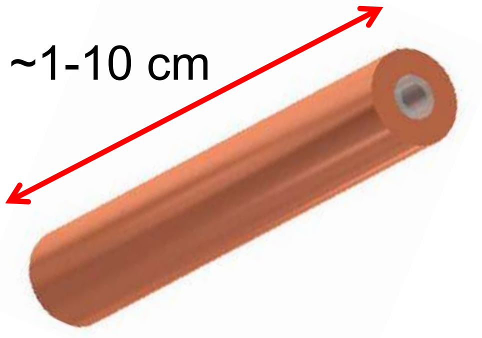


Parallel-Plate structure with 75 μm gap

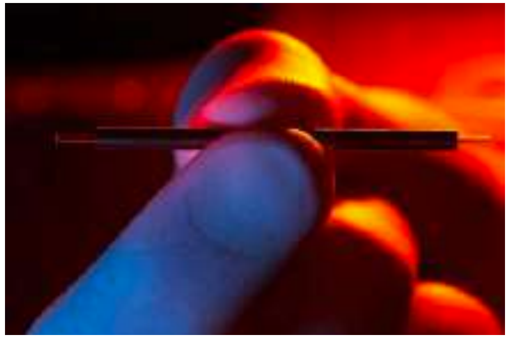


W. Huang, et al., Optica 3, 1209 (2016)
A. Fallahi, et al., PRSTAB 19, 081302 (2016)

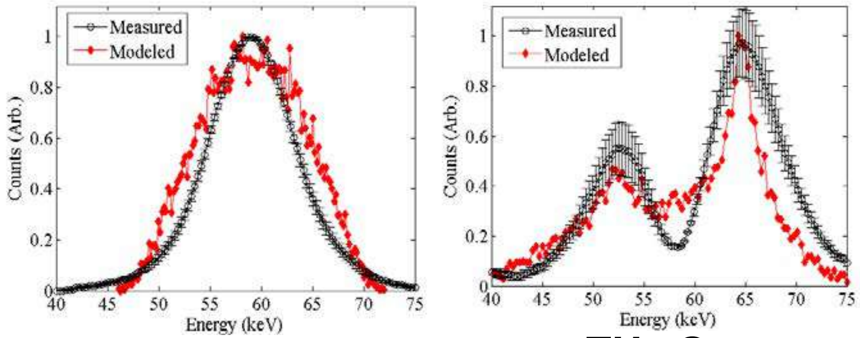
- **THz LINAC: ±7 keV energy modulation**



mm-scale THz waveguide



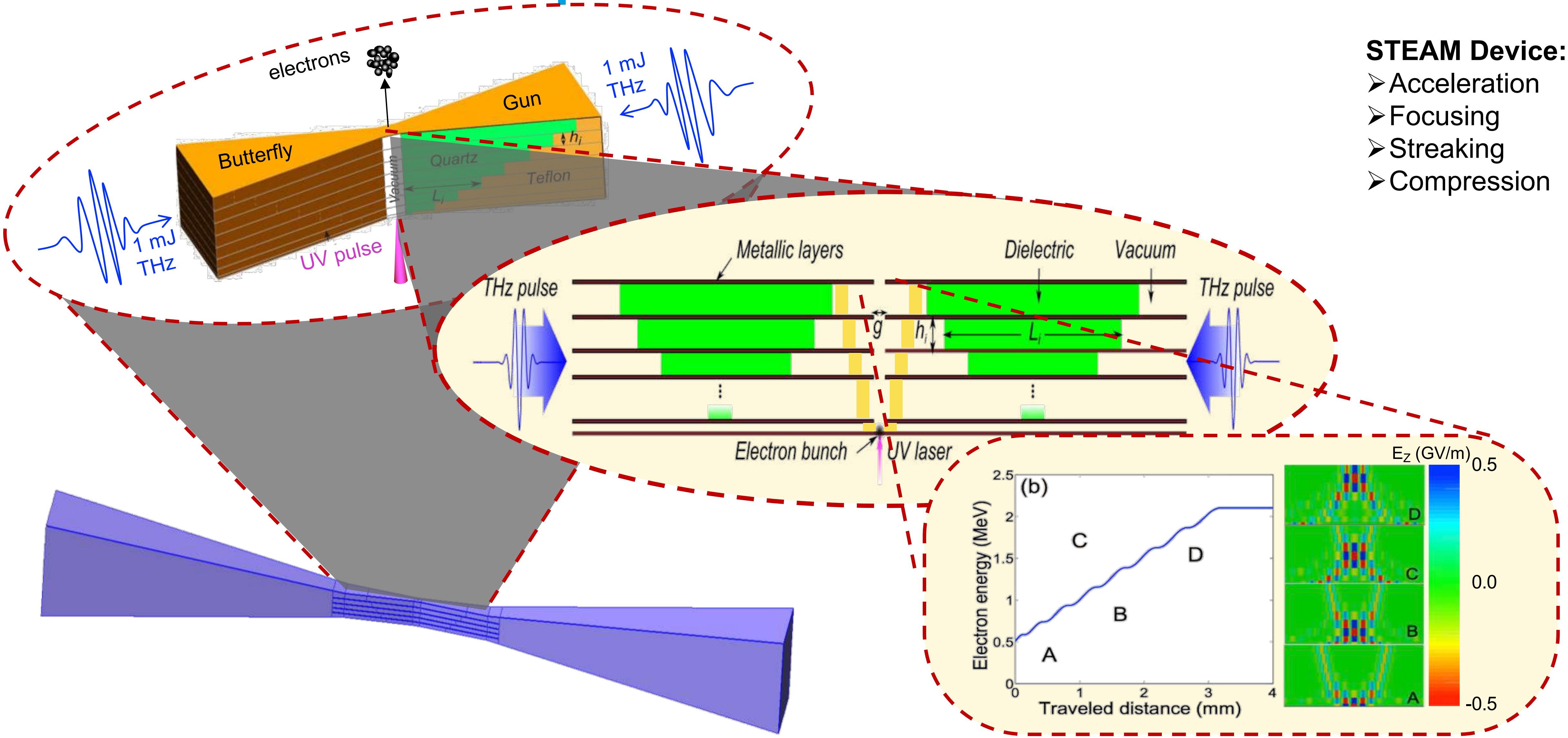
Charge injected from 60 keV DC-gun from Dwayne Miller group



THz Off **THz On**

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

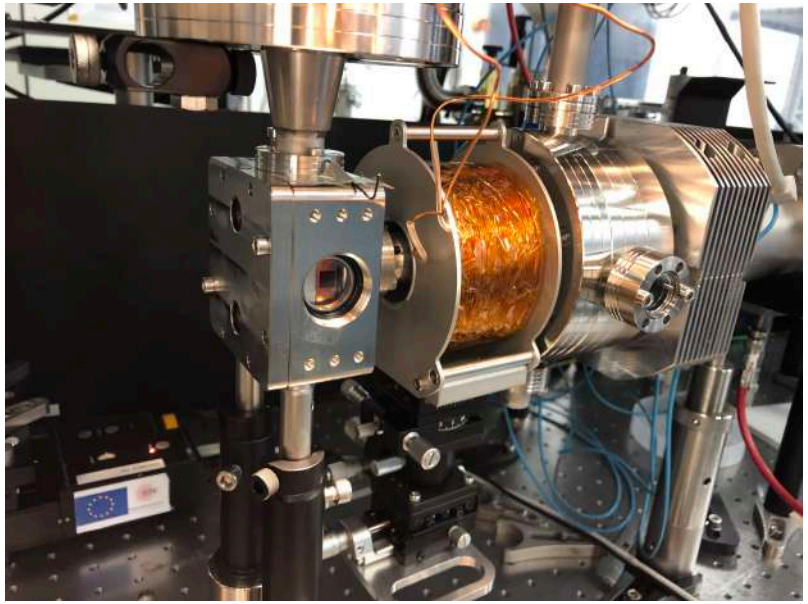
Single-Cycle THz Electron Guns: Segmented THz Electron Accelerator & Manipulator = STEAM

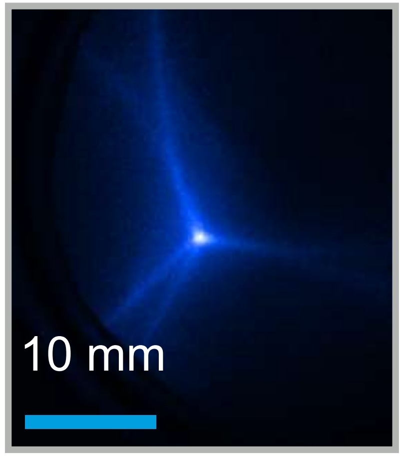


STEAM Device:
- Acceleration
- Focusing
- Streaking
- Compression

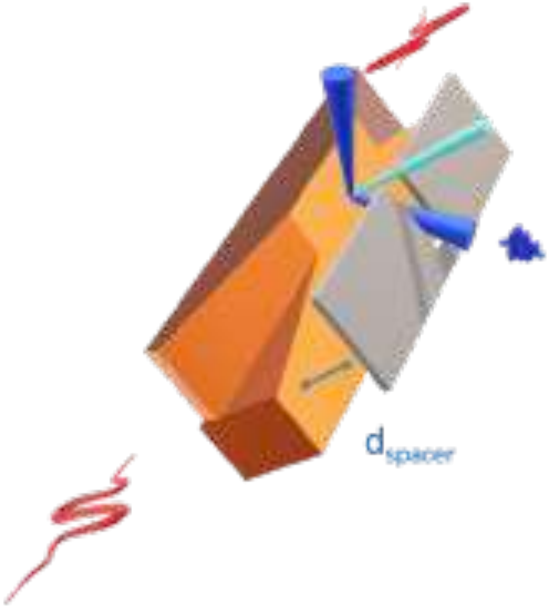
A. Fallahi, et al. PRSTAB 19, 081302 (2016)

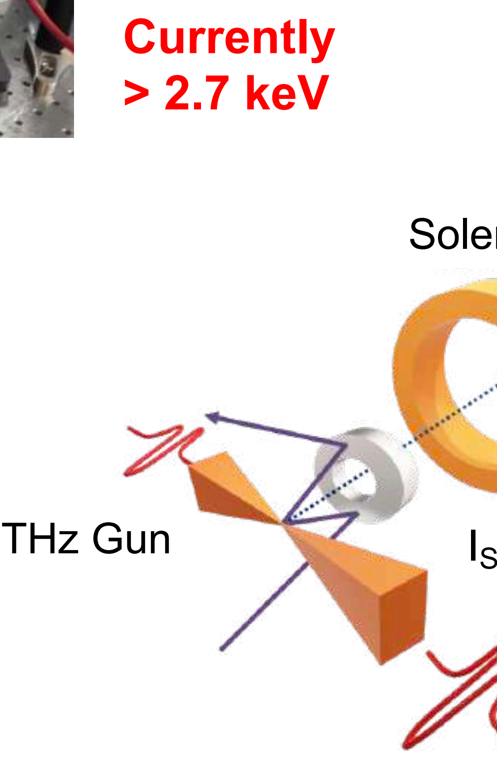
Single-Cycle Driven Single Layer THz Gun (300 GHz)

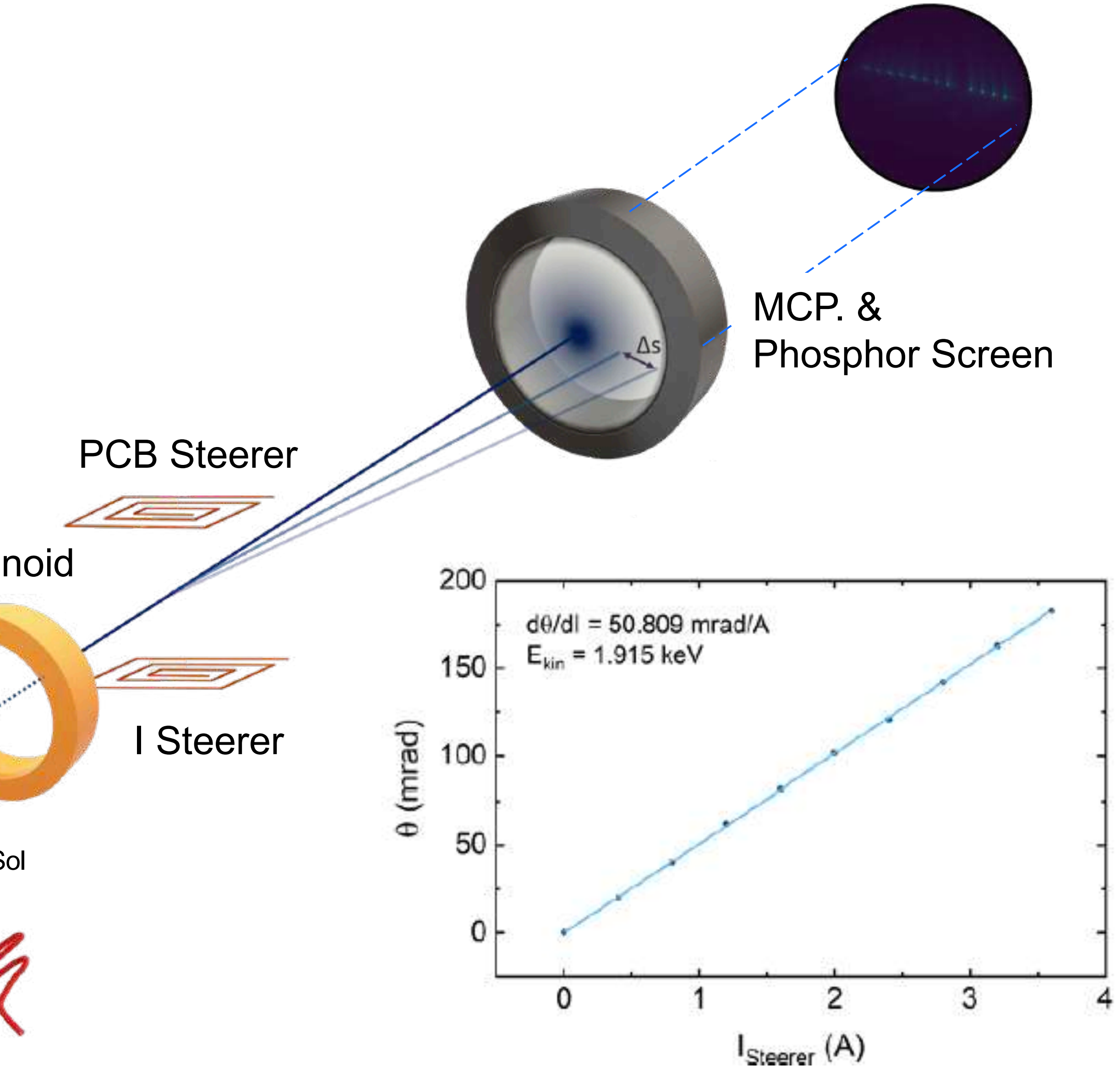




Currently
> 2.7 keV

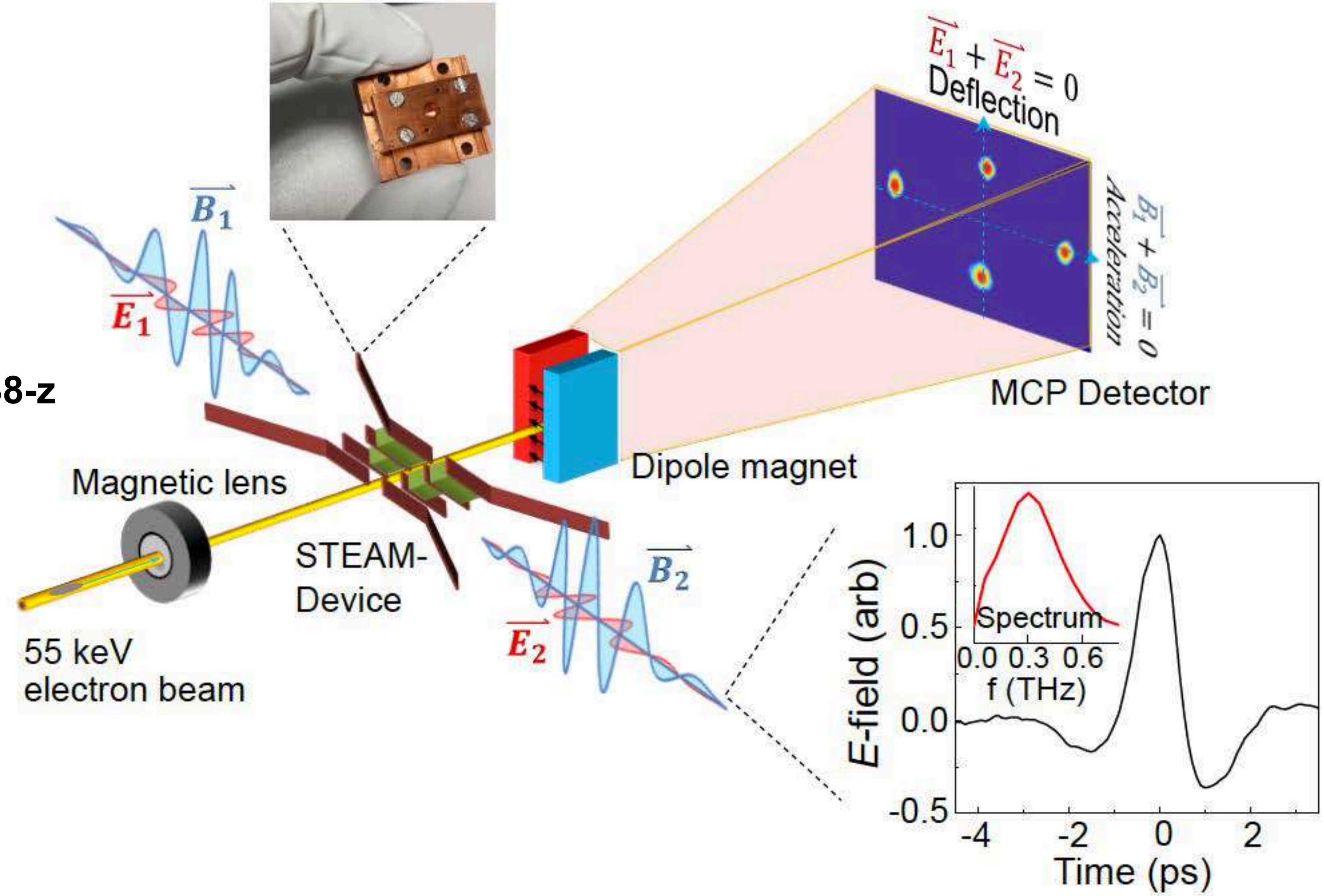






STEAM – Device as Accelerator and Electron Manipulator

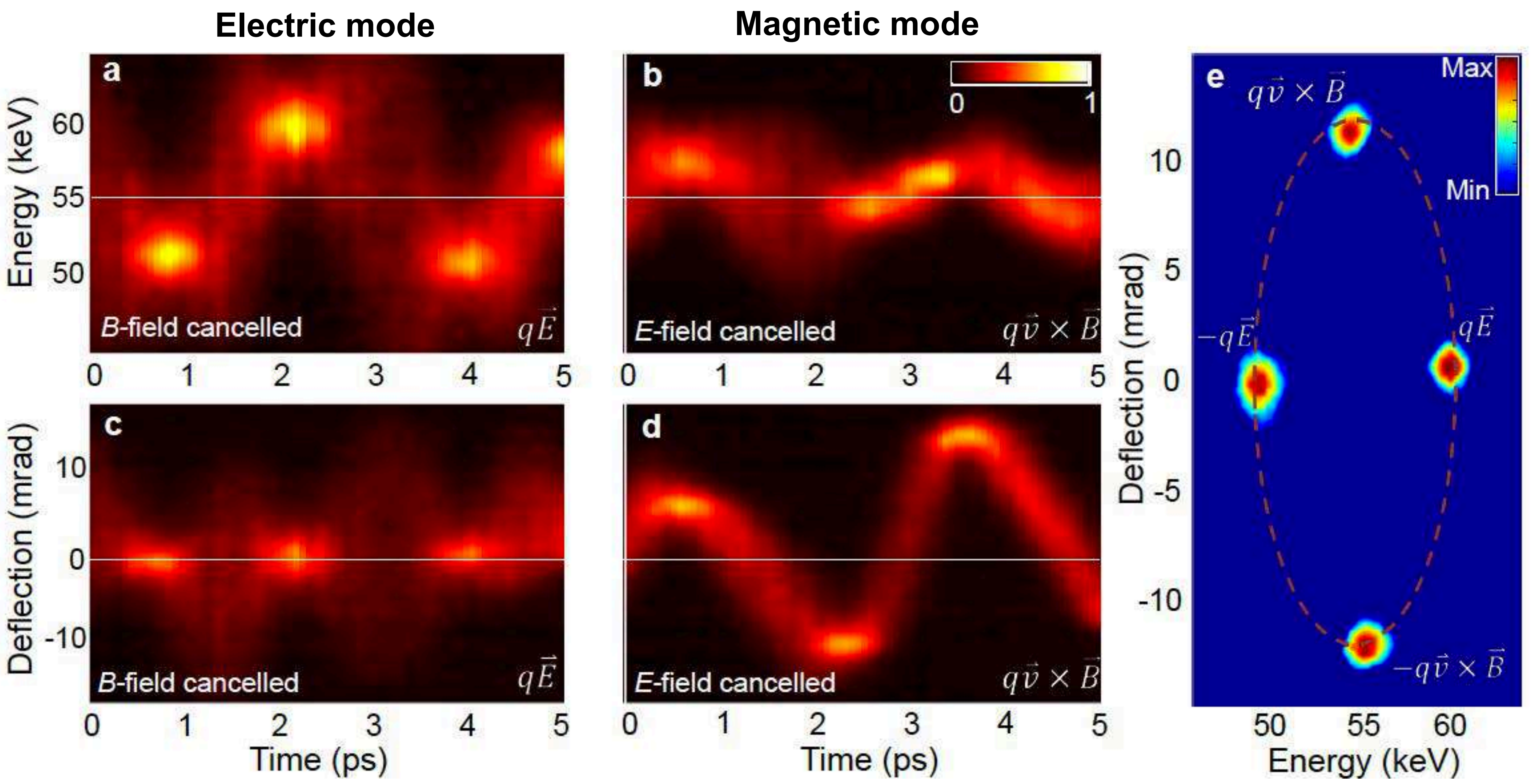
D. Zhang, et al.
Nat. Photonics (2018)
doi.org/10.1038/s41566-018-0138-z



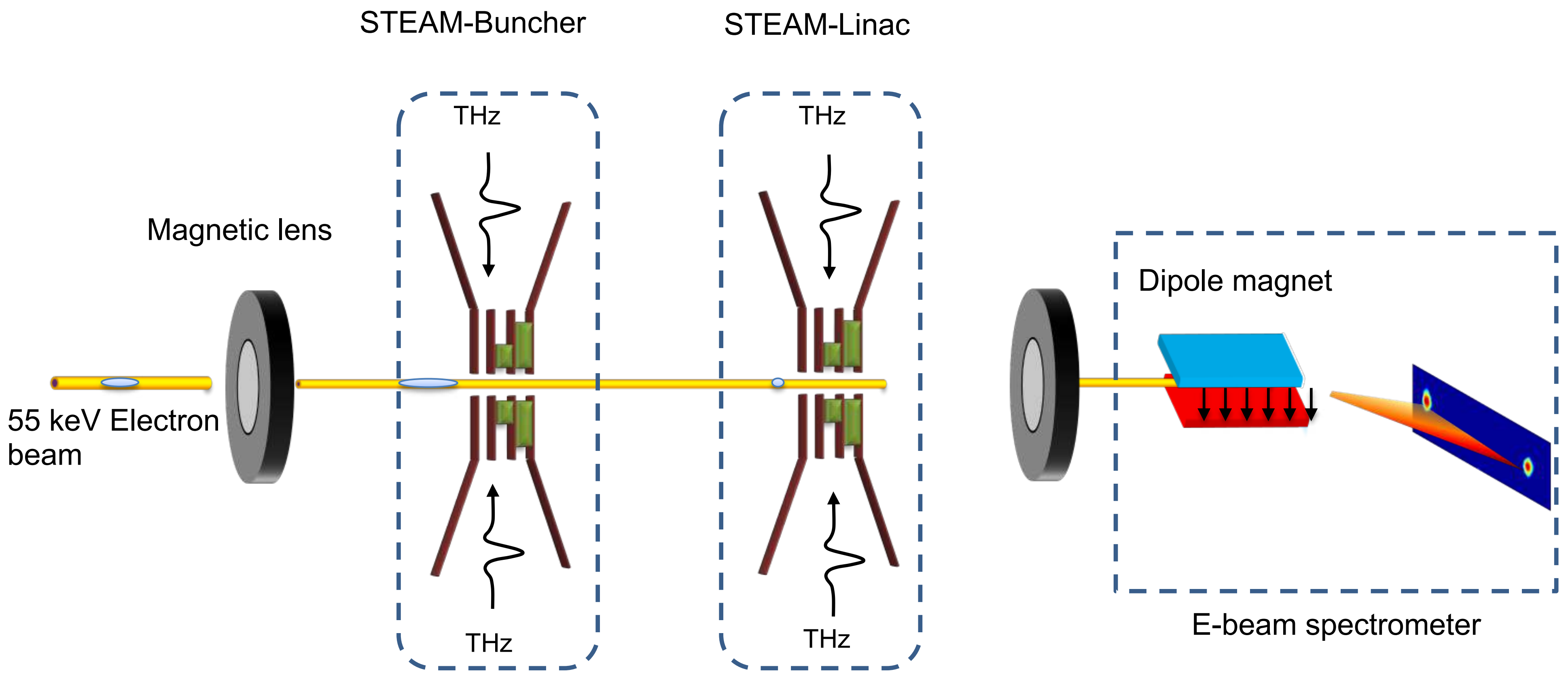
Demonstrated:

- Acceleration
- Compression
- Focussing
- Deflection

STEAM – Device as Accelerator and Electron Manipulator



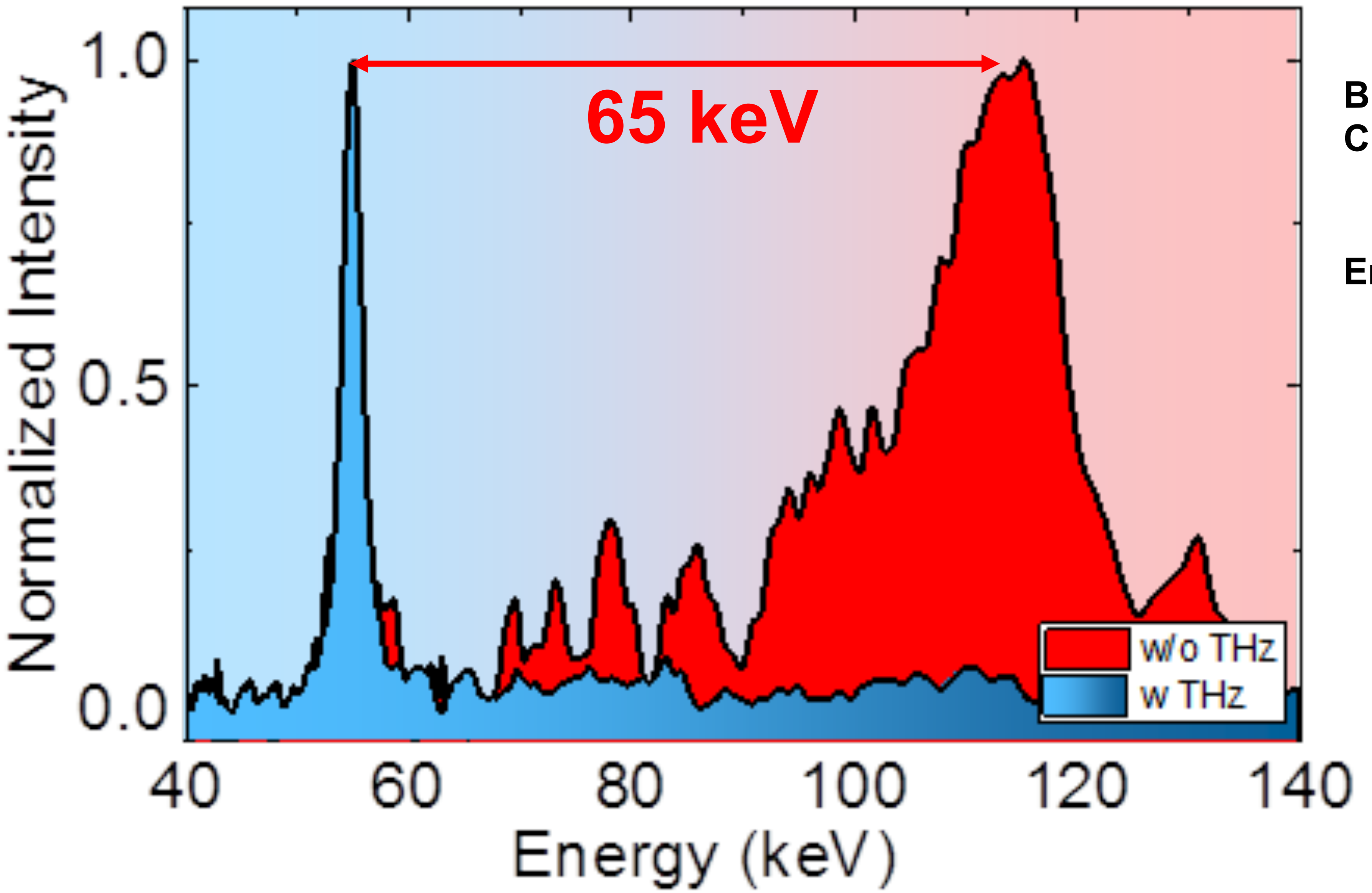
STEAM – Improved Acceleration by Rebunching



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



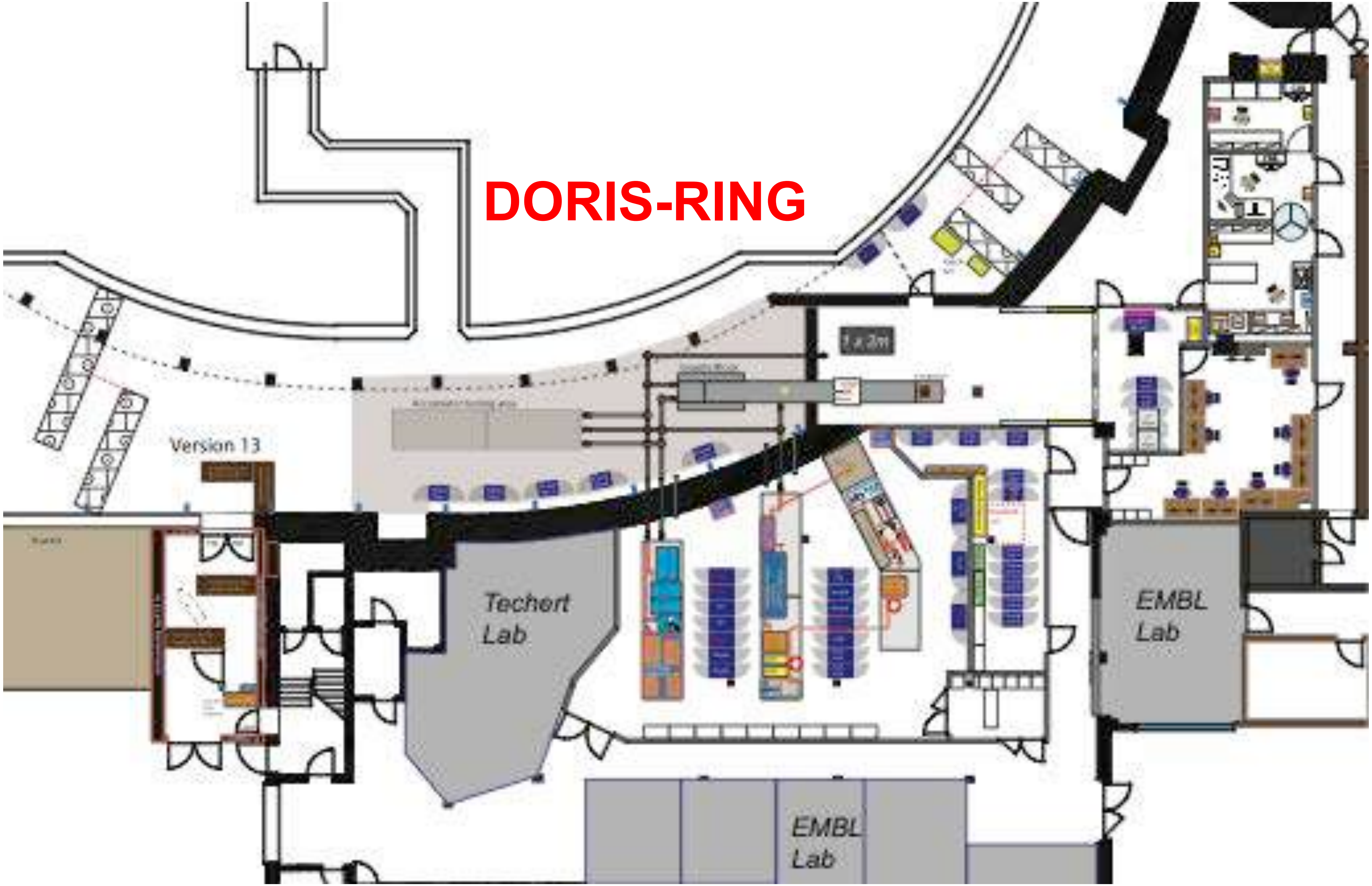
Bunch Charge: ~ *1-5 fJ*

Emittance:

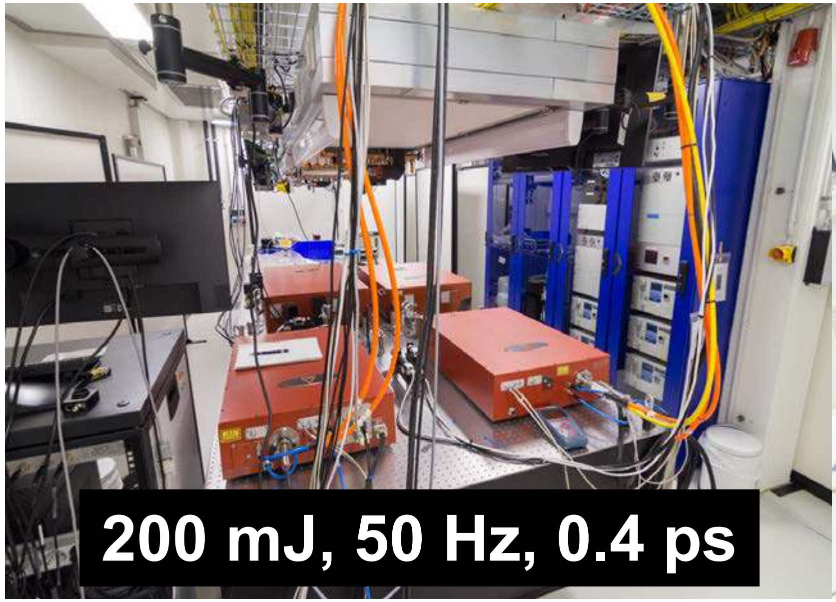
$\varepsilon_{x,y} \sim 0.25\ \mu rad$

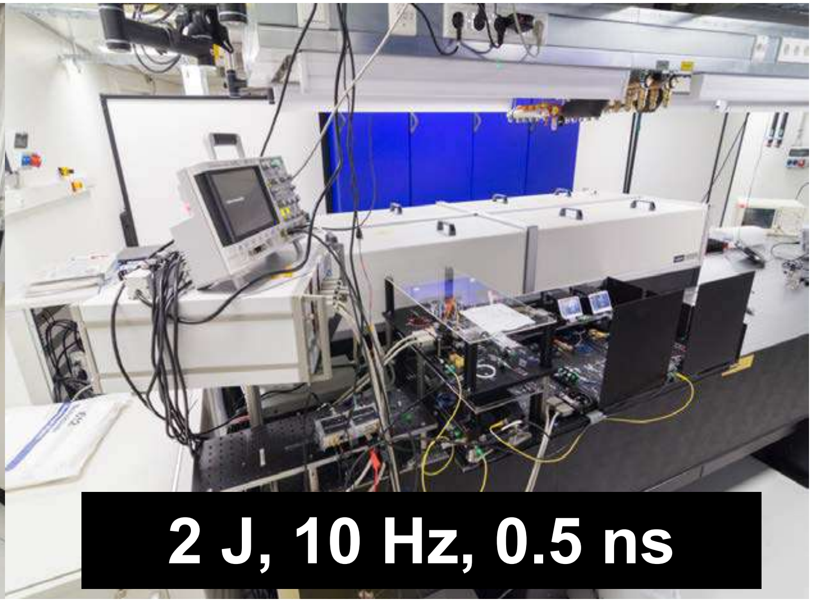
D. Zhang et al., Optica 6, 872 (2019)

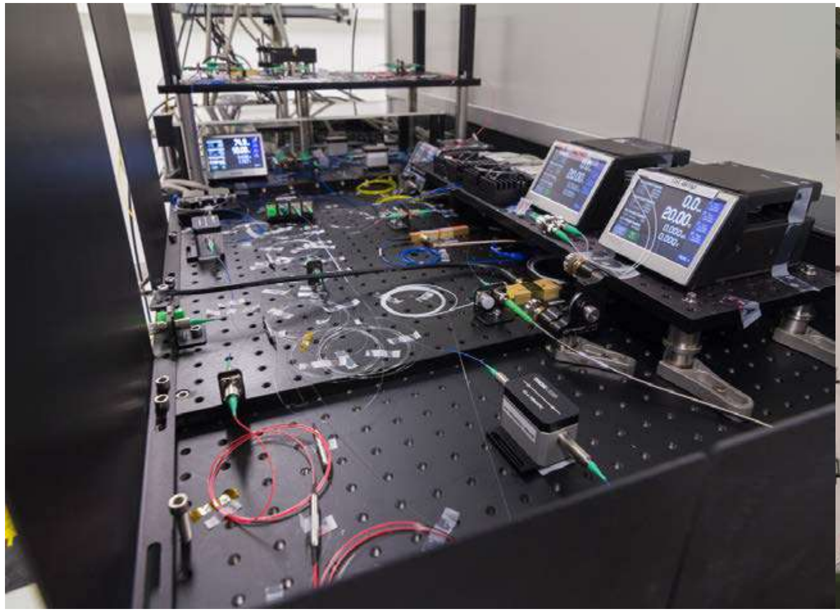
AXSIS Lab



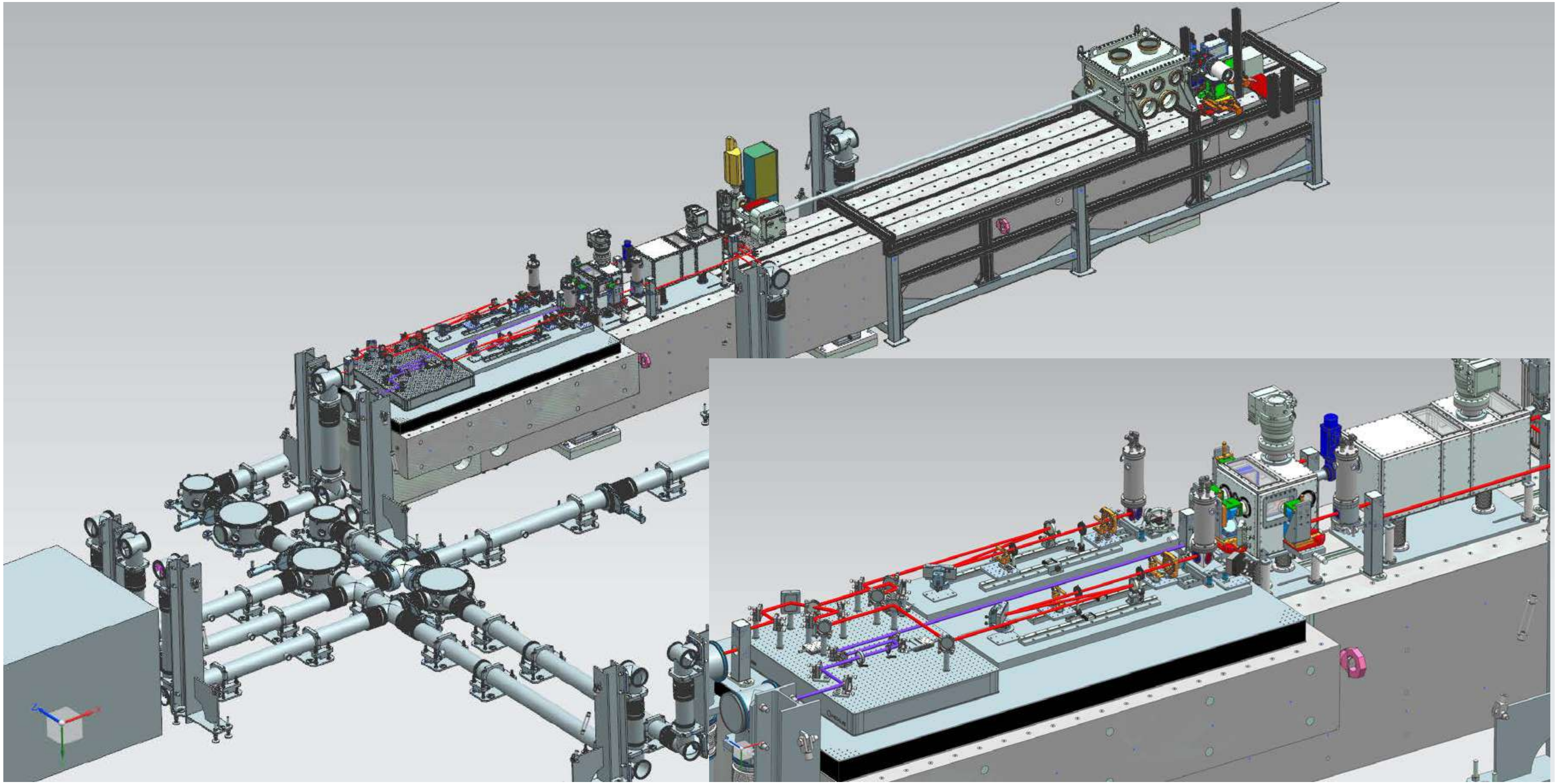
AXSIS Laboratory





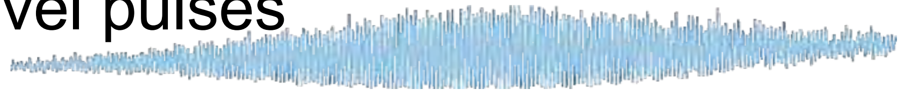


AXSIS Accelerator and X-ray Source

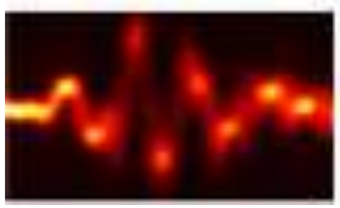


Summary

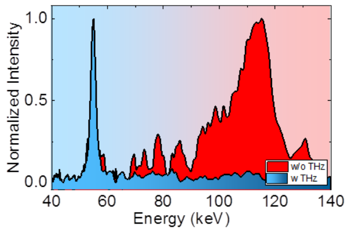
- THz-accelerators can be powered by (multi)-mJ-level pulses



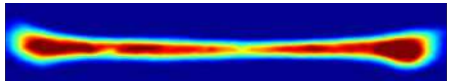
- Close to 1 GV/m gradients possible
- Enables compact ultrafast relativistic electron guns (10 fs)



- > 100 μJ single-cycle THz pulses generated
- > 600 μJ multi-cycle THz pulses generated



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



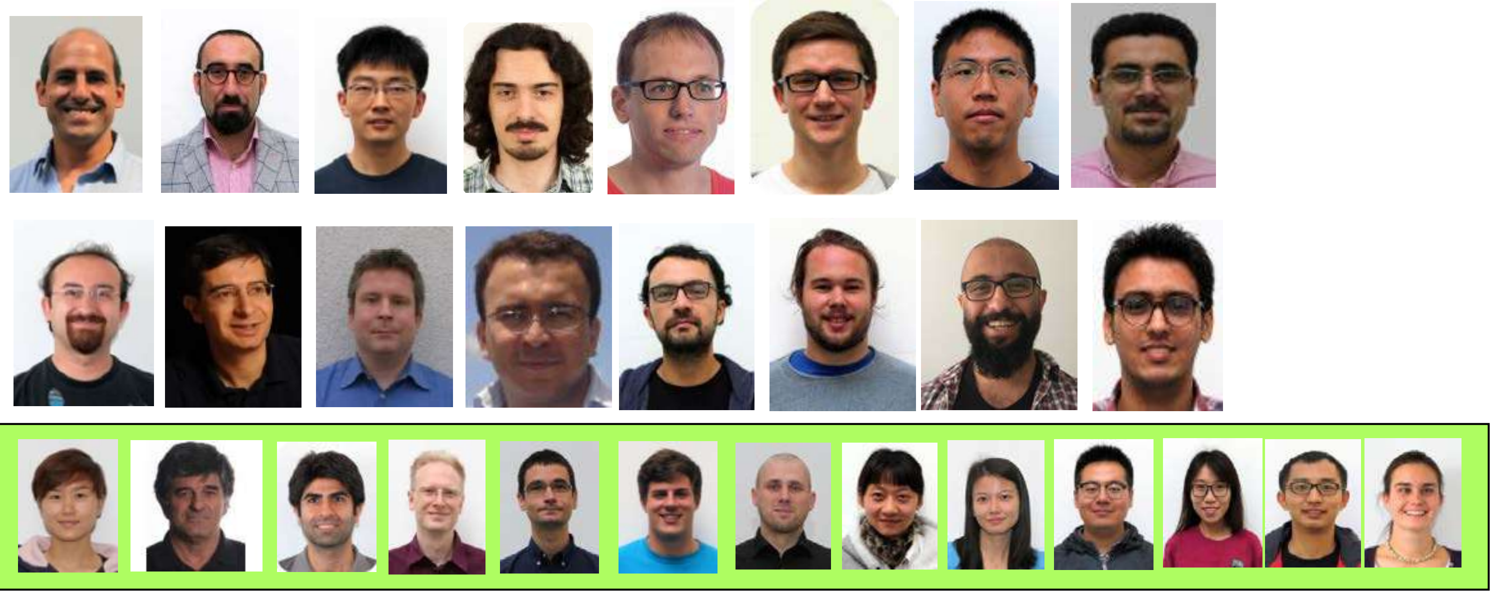
- Cascaded DFG with J-level @ 1 μm pulses → > 20 mJ MC-THz
- Compact Accelerators for UED and X-ray sources

1 J @
500 Hz

AXSIS Team and Collaboration

Ultrafast Optics and X-rays Group

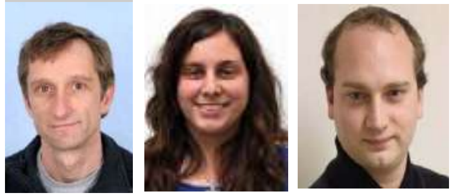
Alumni



Coherent Diffractive Imaging Group

Bio-Physical-Chemistry Group

Detector Group



Accelerator Division: DESY

UHH (LUX)

MIT

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