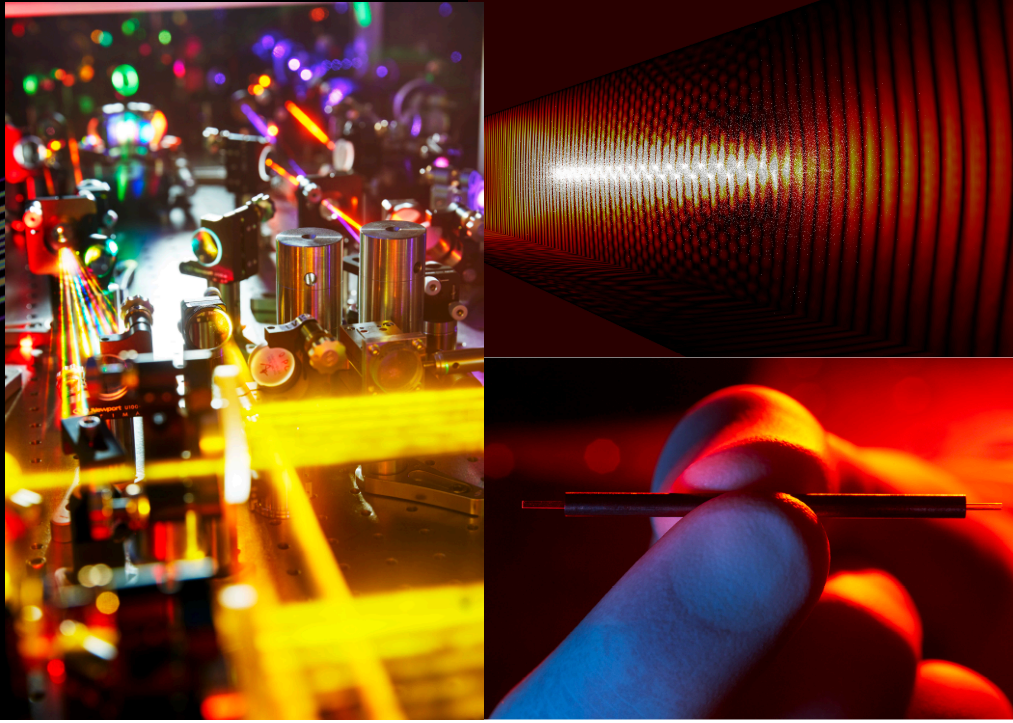
THZ Driven Electron and X-ray Sources



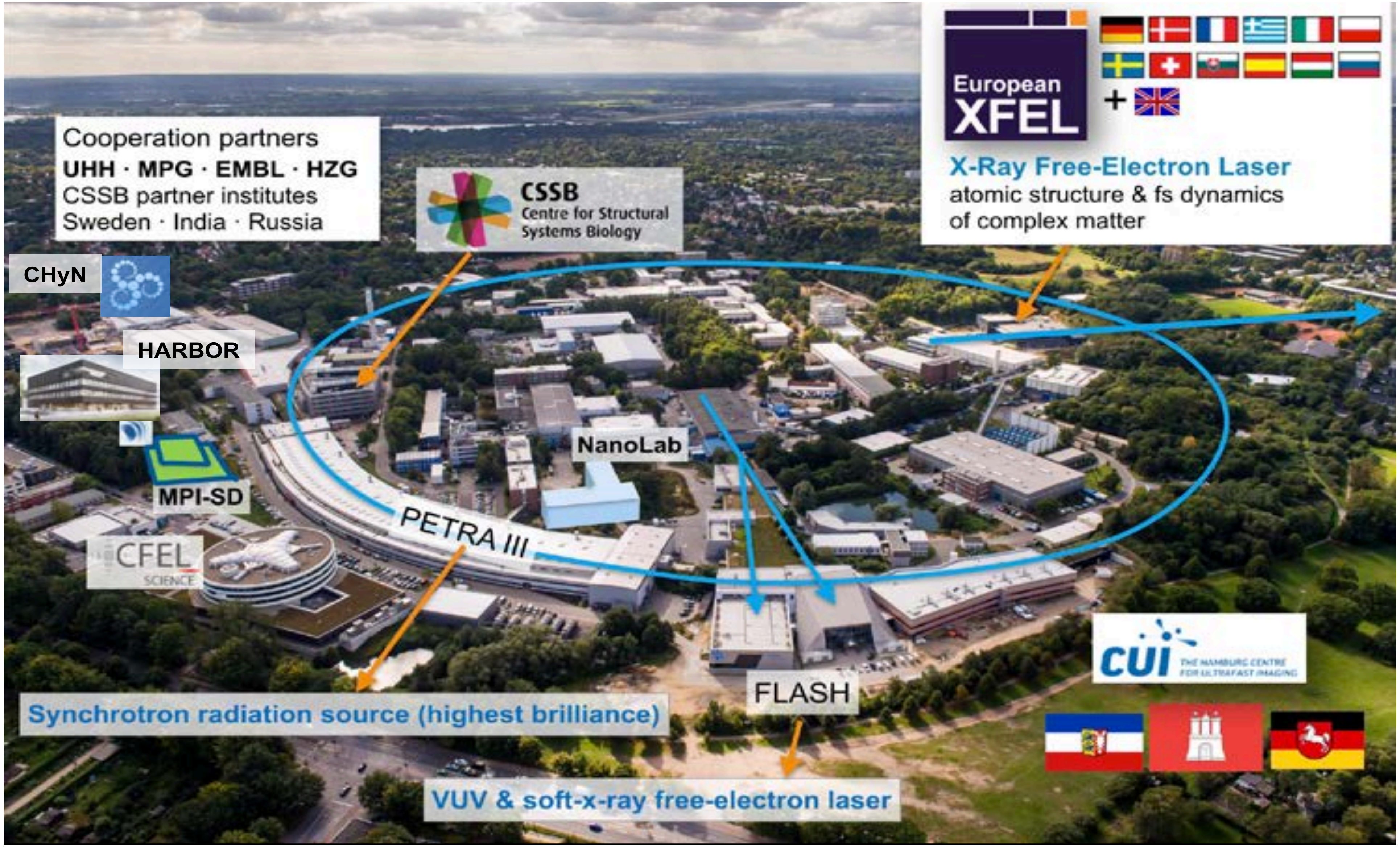
INFN Seminar - November 29, 2018

Franz X. Kärtner

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

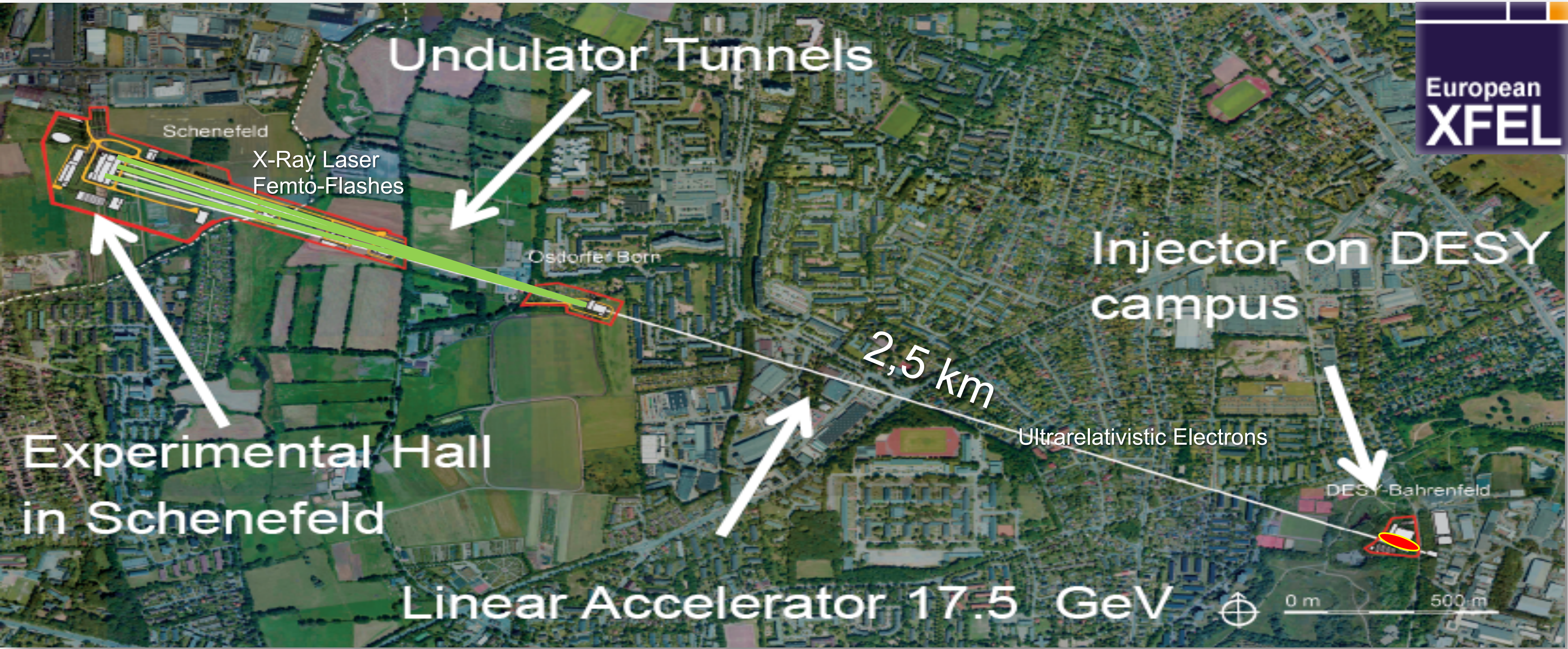
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES · erc · ACHIP Accelerator on a Chip International Program · UHH · cui · CFEL SCIENCE · DESY

Why another Accelerator and X-ray Source?



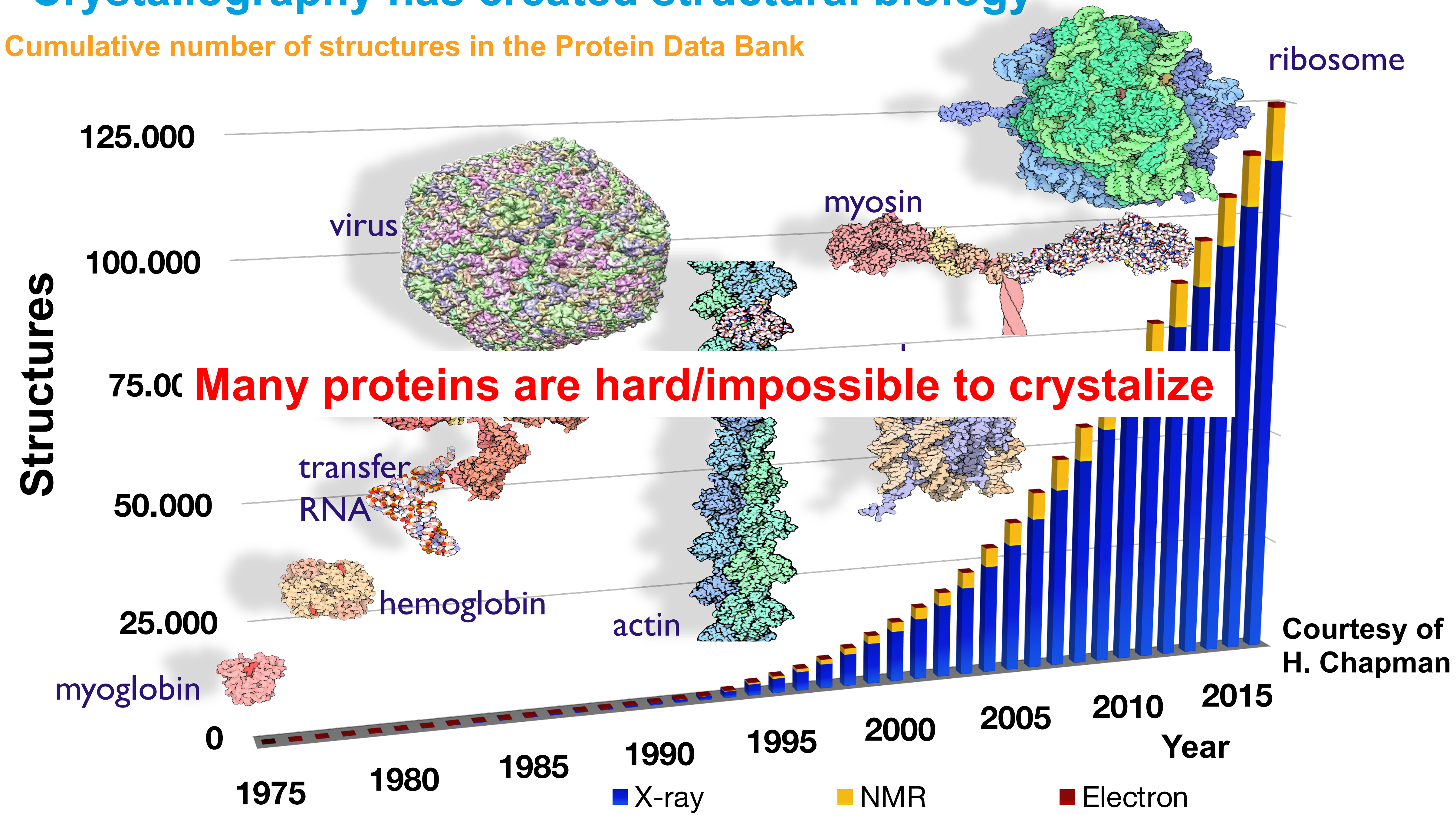
Structure, Dynamics and Function of Matter

European XFEL.



In Operation since May 2017

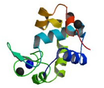
X - Crystallography has created structural biology



Many proteins are hard/impossible to crystalize

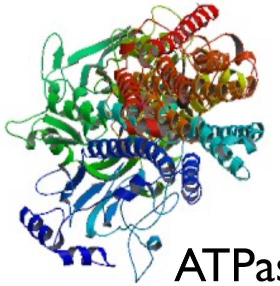
Courtesy of H. Chapman

Over 100 XFEL structures have been solved

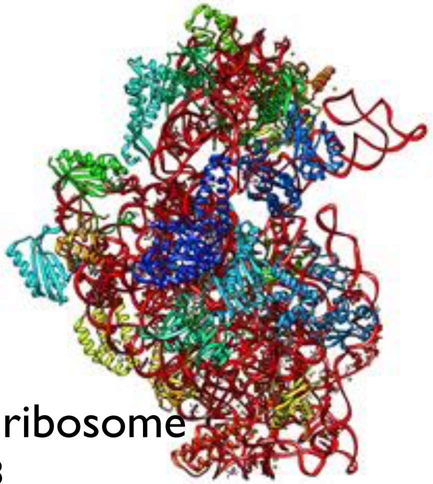


Lysozyme
4ZIX, 5C6I, 5C6J, 5C6L, 4RW1, 4RW2, 4N5R

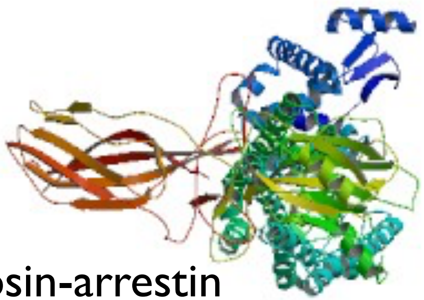
Thermolysin
4OW3, 4TNL, 5DLH



ATPase
4XOU



30s ribosome
5BR8

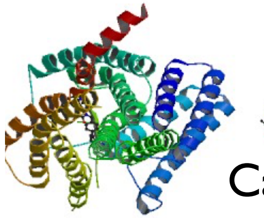


Rhodopsin-arrestin
4ZWJ

A2a
5K2D, 5K2C, 5K2B, 5K2A

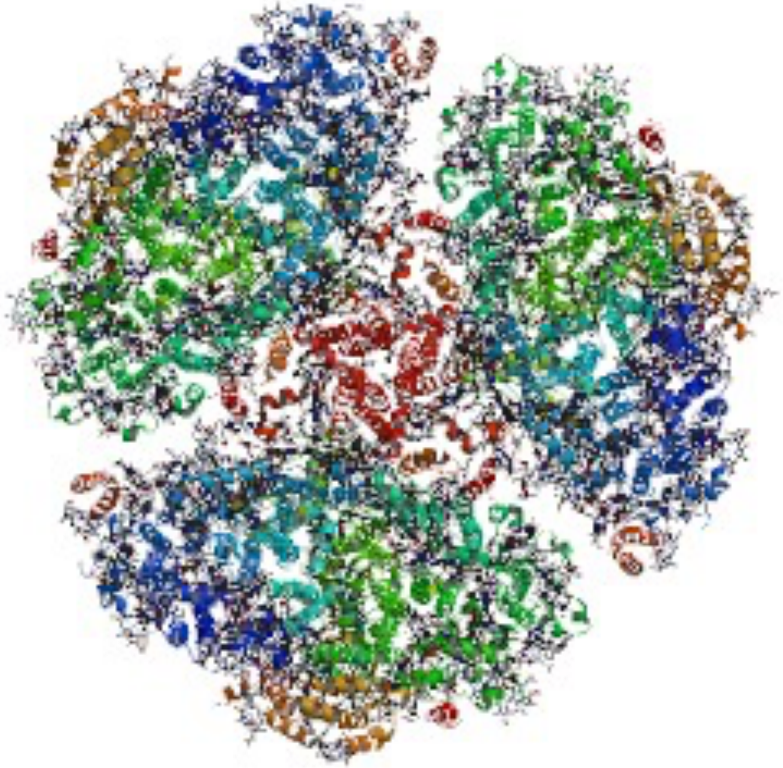
5-HT2B
4NC3

Smoothened
4O9R

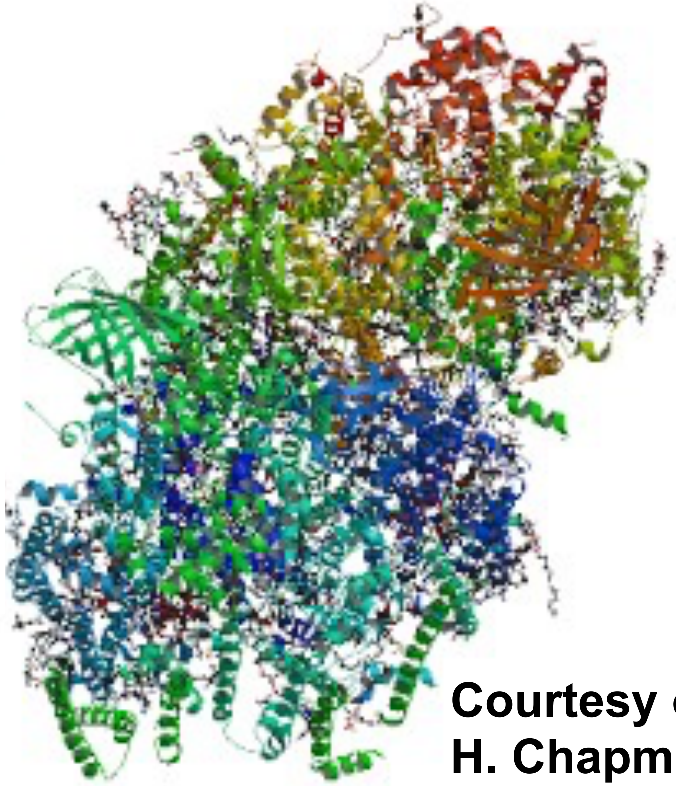


Angiotensin
4YAY

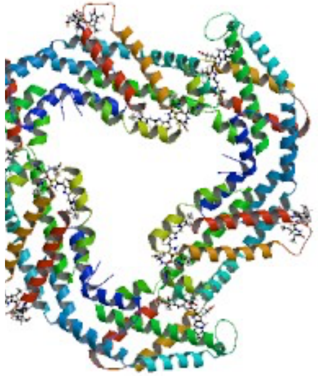
Cath
4HW



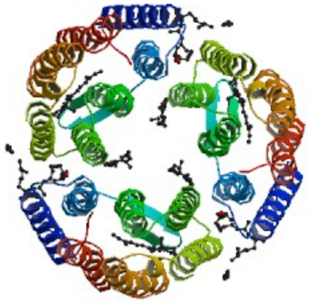
Photosystem I+II
3PCQ, 4FBY, 4IXR, 4IXQ, 4TNK, 4TNJ, 4TNI, 4TNH, 4PBU, 4RVY, 5E7C, 5TIS, 5KAI, 5KAF,



Courtesy of H. Chapman



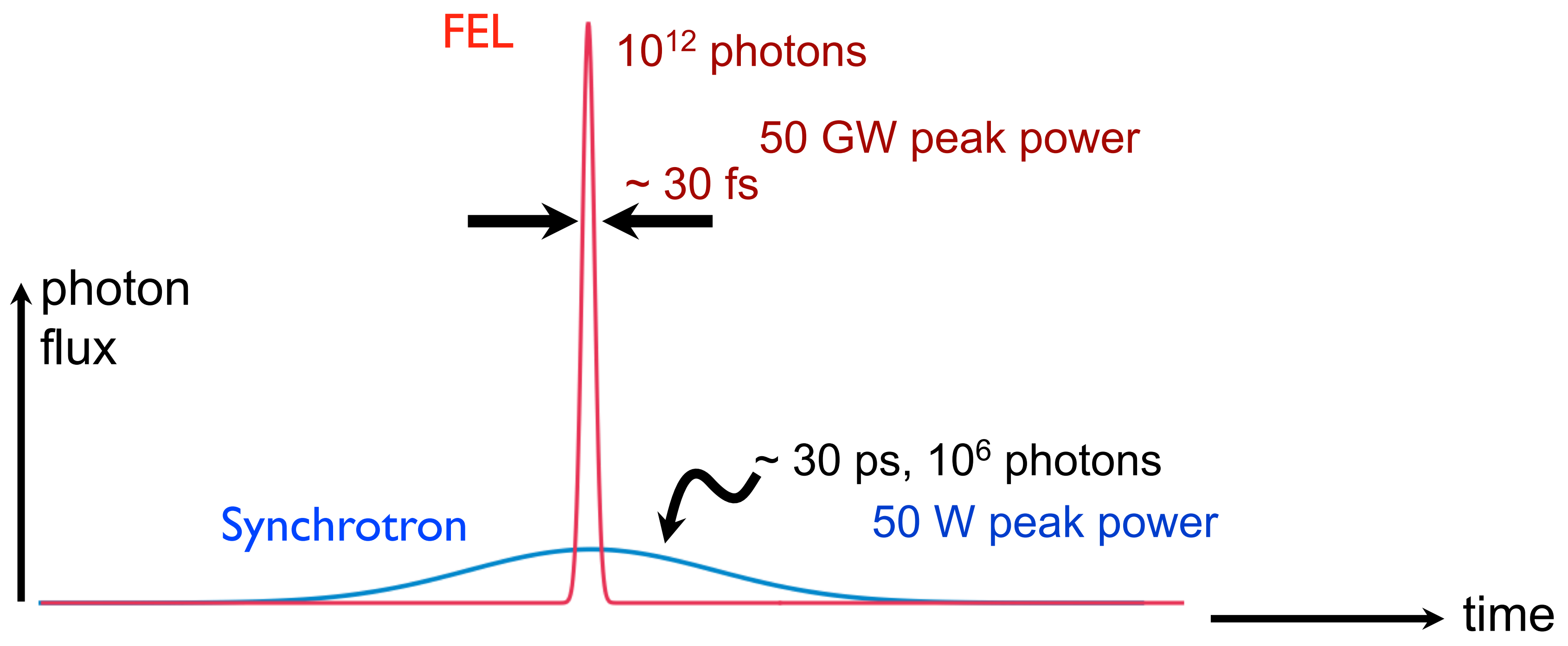
Phycocyanin
4Q70, 4Z8K, 4ZIZ

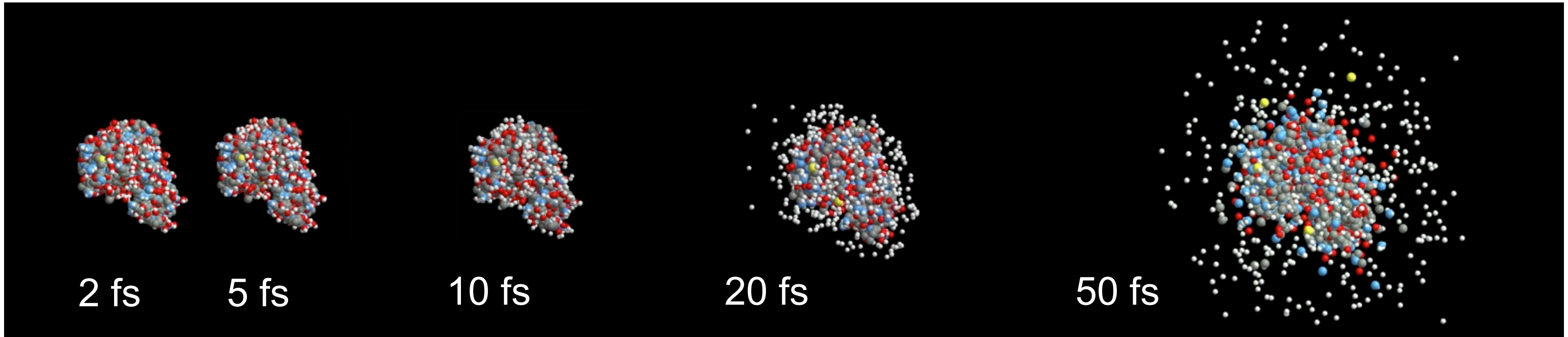


Bacteriorhodopsin
5J7A

Riboswitch
5SWE, 5SWD, 5E54

X-ray FELs are a billion times brighter than synchrotrons

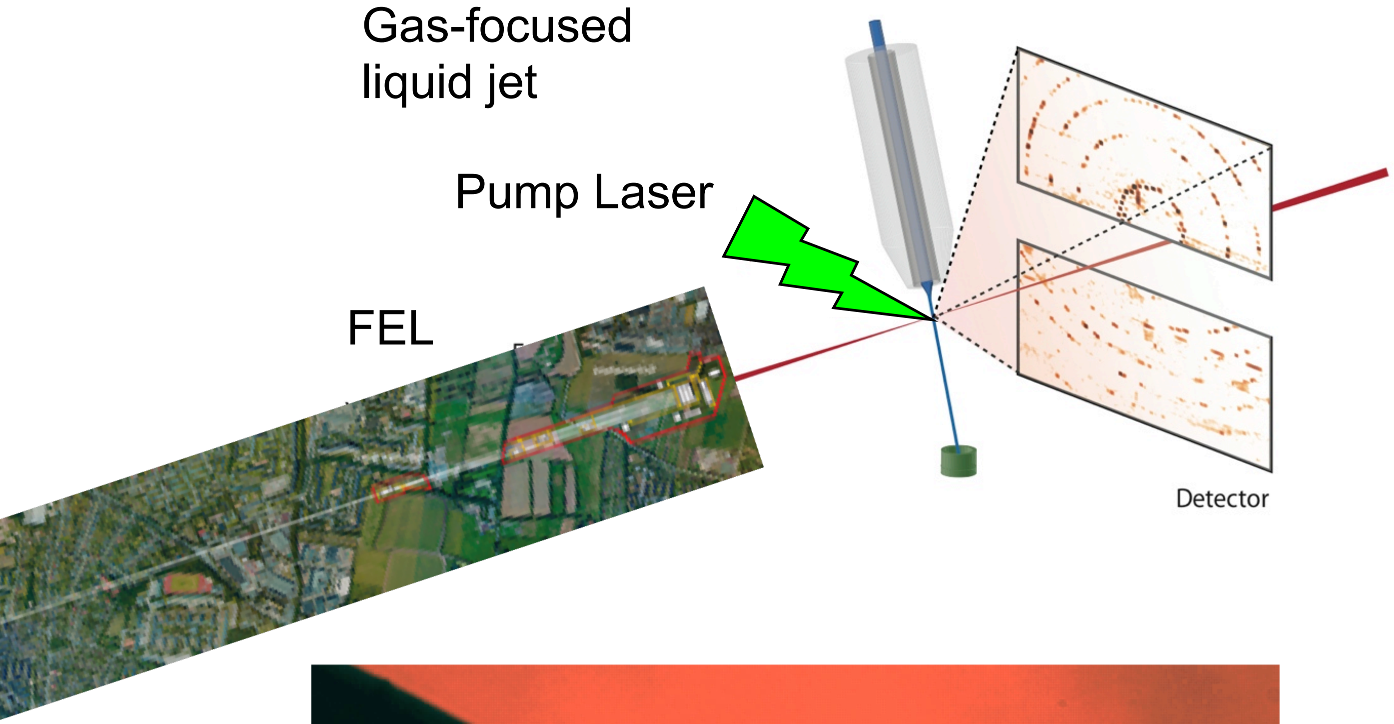


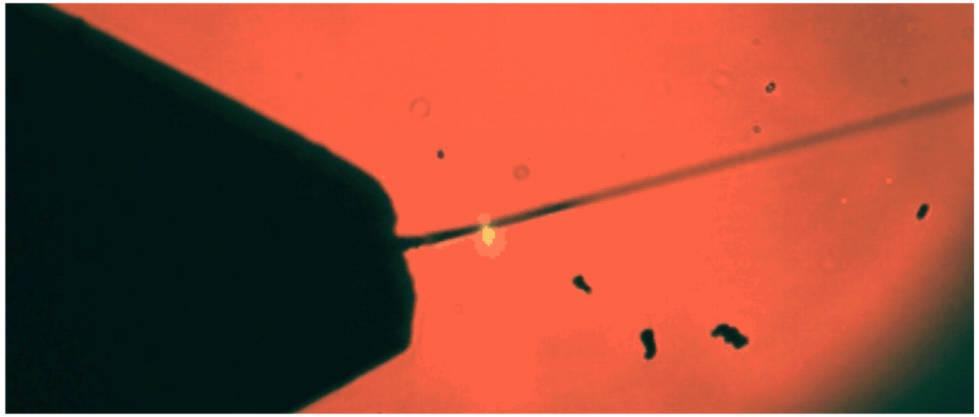


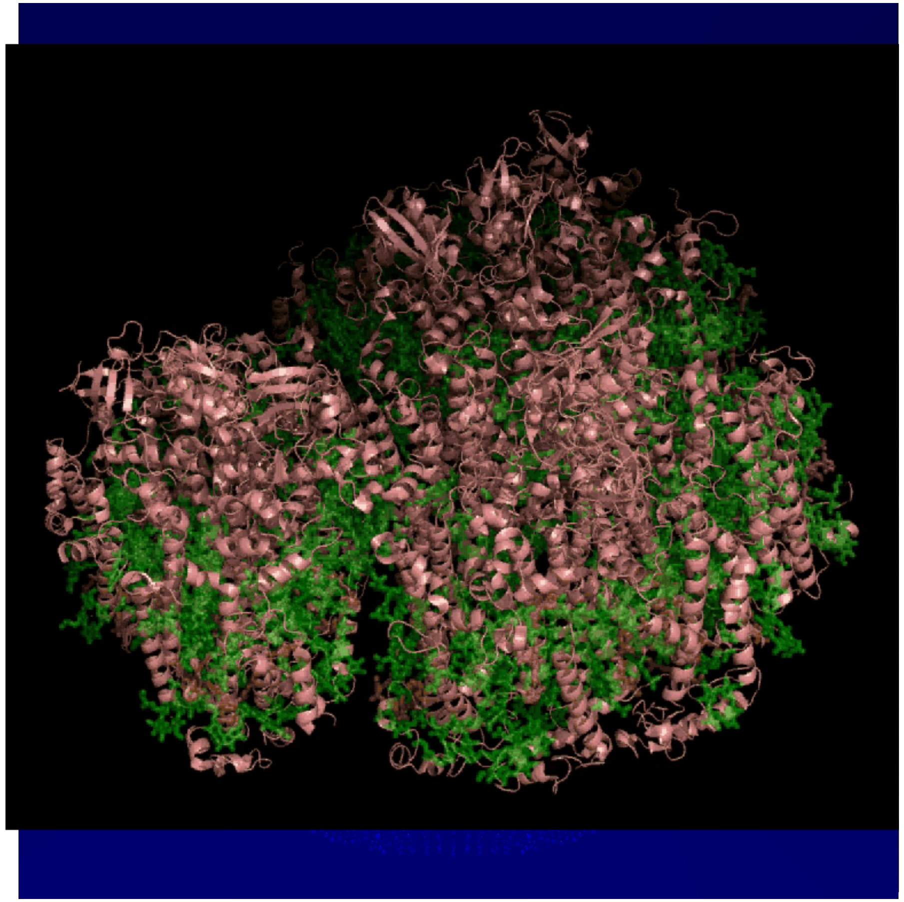
R. Neutze, et al. 406, 752-757 (2000).

Short Pulses Outrun Radiation Damage

Ultrafast X-ray diffraction from a stream of nanocrystals at room temperature
Reaction triggered by optical laser pulses



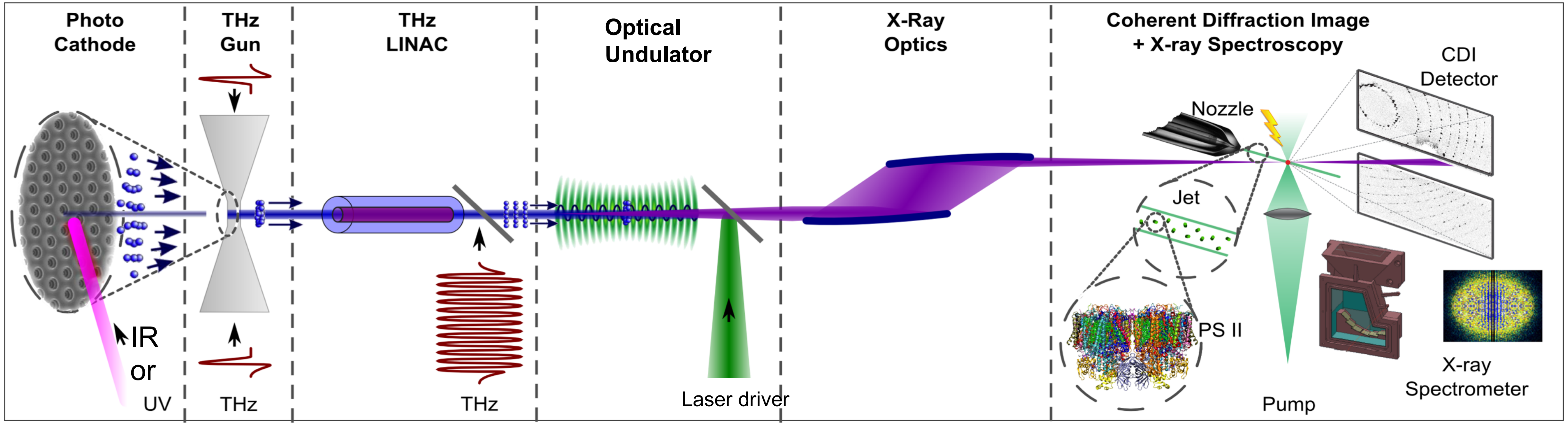




H. Chapman, et al.
Nature 470, 73, 2011

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

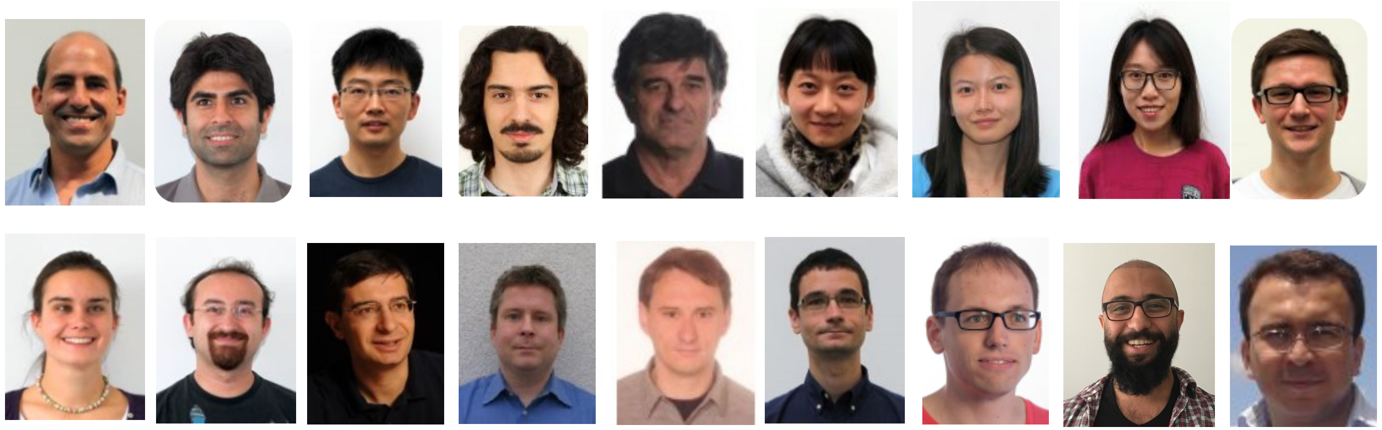
Ralph Assmann
DESY

Petra Fromme
DESY & Arizona State U.

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

AXSIS Team

Ultrafast Optics and X-rays Group



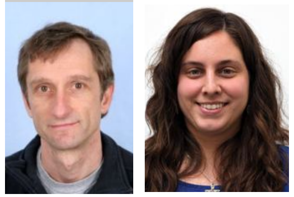
Accelerator Division: DESY

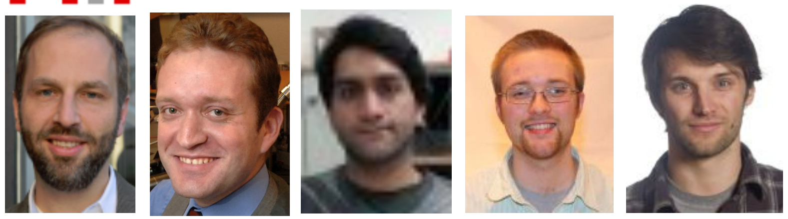
UHH (LUX)

Coherent Diffractive Imaging Group

Bio-Physical-Chemistry Group

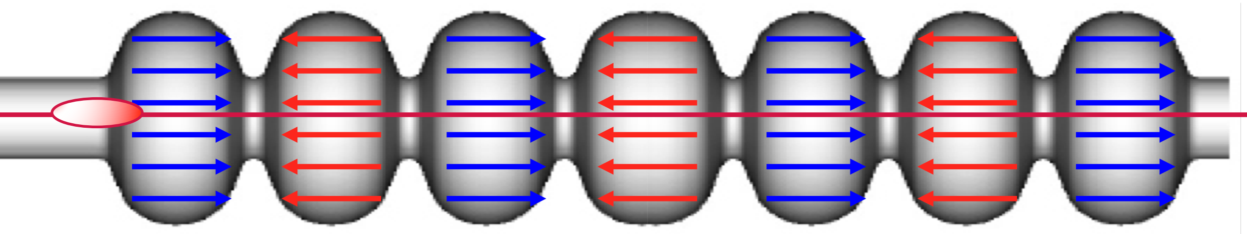
Detector Group





X-rays from Relativistic Electrons

Microwave Accelerator



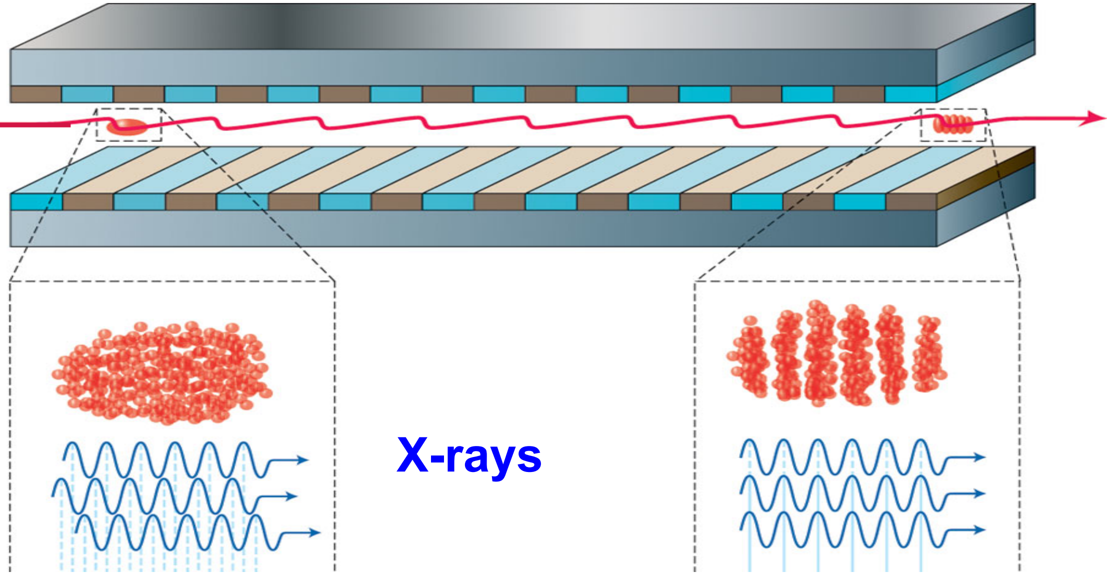
10 cm

10 MV / m

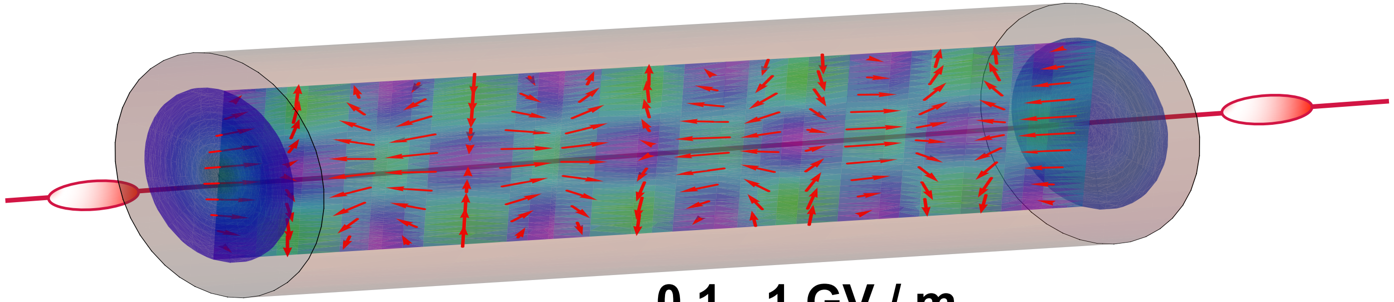
1 km

10 GeV

Magnetic Undulator



Terahertz Waveguide Accelerator

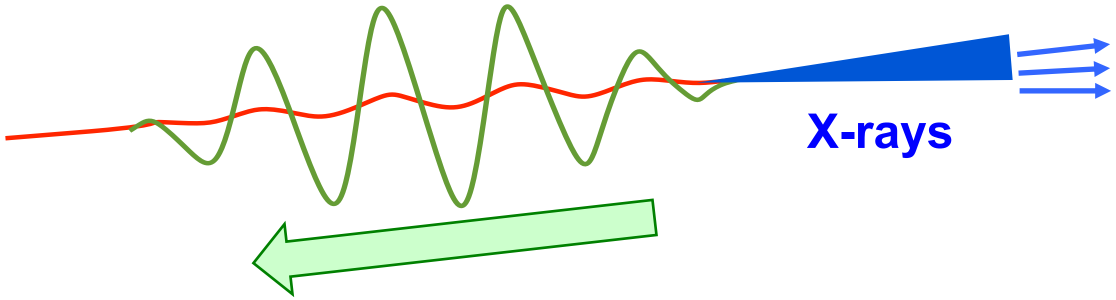


0.1 - 1 GV / m

1 mm

20 cm

20 MeV



Optical Undulator

$$E_X \propto N_e^2$$

→ Sub-fs X-ray Pulses
→ Compact Sources

Outline

- Why THz acceleration?
- THz guns, accelerators and beam manipulation
- Laser driven THz sources based on optical rectification and cascaded optical parametric amplification
- First results with low energy THz pulses
- A first THz driven X-ray source based on Inverse Compton Scattering
- 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 – attosecond X-ray pulses, lower emittance beams
- Short acceleration distances and times: Potential to form crystaline electron pulses at the cathode
- **But** lower bunch charge: 10 fC – 10 pC

Other High-Gradient Accelerators

Technology	Wavelength	timing for 0.1%	Fabrication	bunch charge
Conventional	~ 100 mm	~ 300 fs	machining	~ nC
THz-based	~ 1 mm	~ 3 fs	machining	~ pC
Laser-plasma	~ 0.01 mm	~ 0.03 fs	wave excitation	~ pC
Dielectric laser	~ 0.001 mm	~ 0.0003 fs	lithographic	~ fC

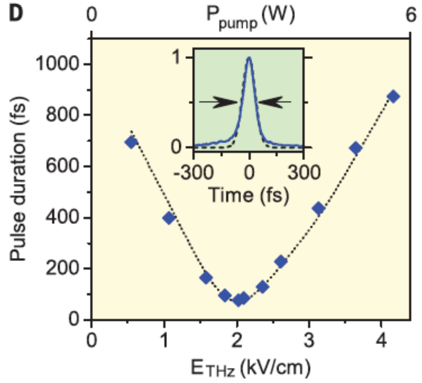
All-optical approach ➞ intrinsic synchronization ➞ important for small scales

THz acceleration and beam manipulation takes up speed

THz Compression @ LMU/MPQ

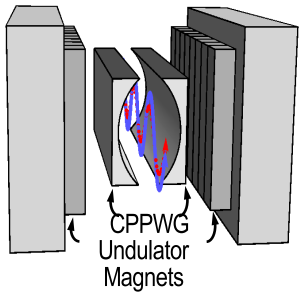
Kealhofer et al., *Science* 359, 459 (2016)

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

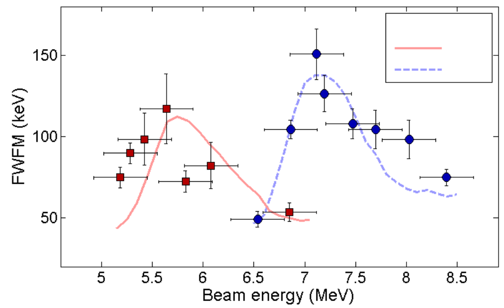


THz IFEL interaction @ Pegasus Lab

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

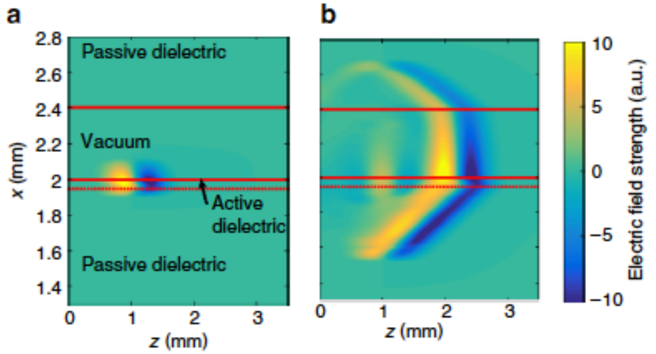


THz sub-luminal free-space fields @ ASTeC in Daresbury

Walsh et al., *Nature Comm.* 8, 421 (2017)

Generation of sub-luminal propagating THz fields in free space

Tunable $v_p = 0.8 - 1.75\,c$ for THz-based acceleration

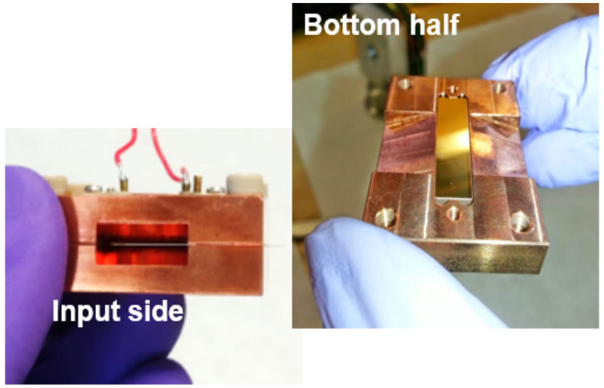


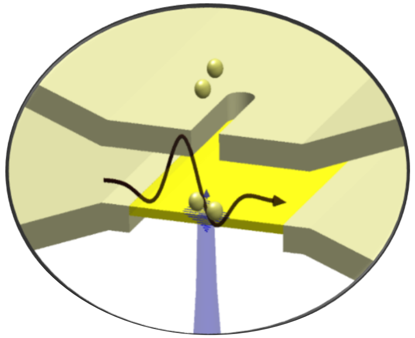
Pecs Group Contributions on THz generation and acceleration

THz Gun & LINAC: Proof of Feasibility

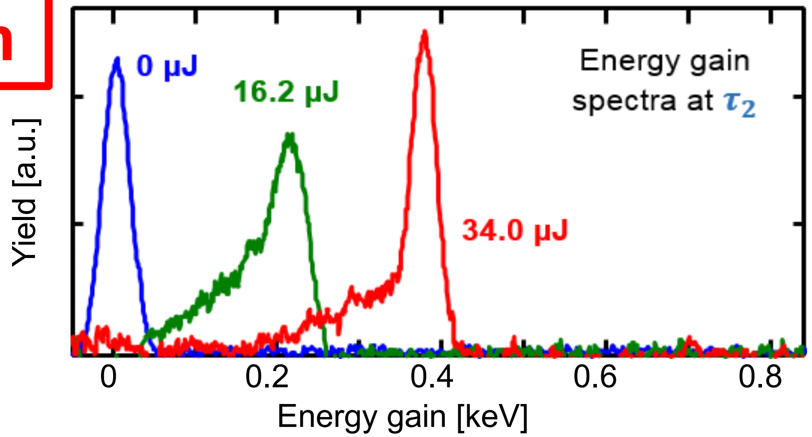
- **THz Gun: 0 ➞ 0.8 keV acceleration**

E_z -> 0.3 GV/m



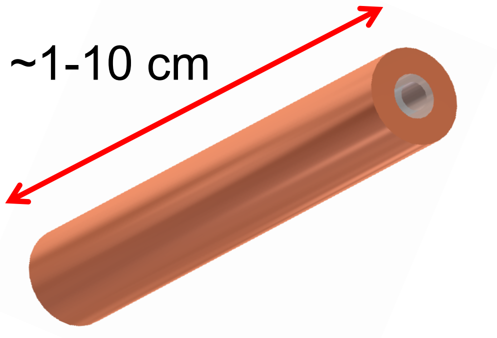


Parallel-Plate structure with 75 μm gap

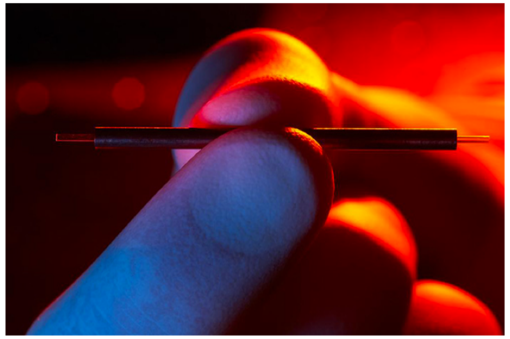


W. Huang, et al., Optica 3, 1209 (2016)
A. Fallahi, et al., PRSTAB 19, 081302 (2016)

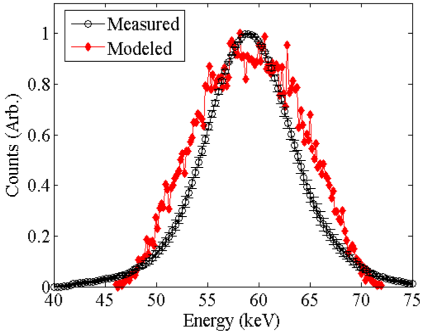
- **THz LINAC: ±7 keV energy modulation**



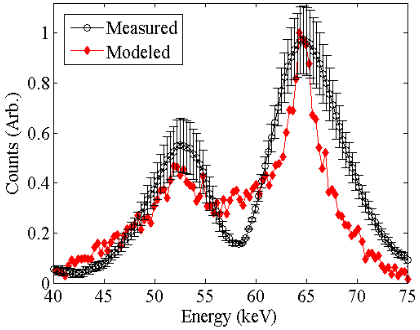
mm-scale THz waveguide



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



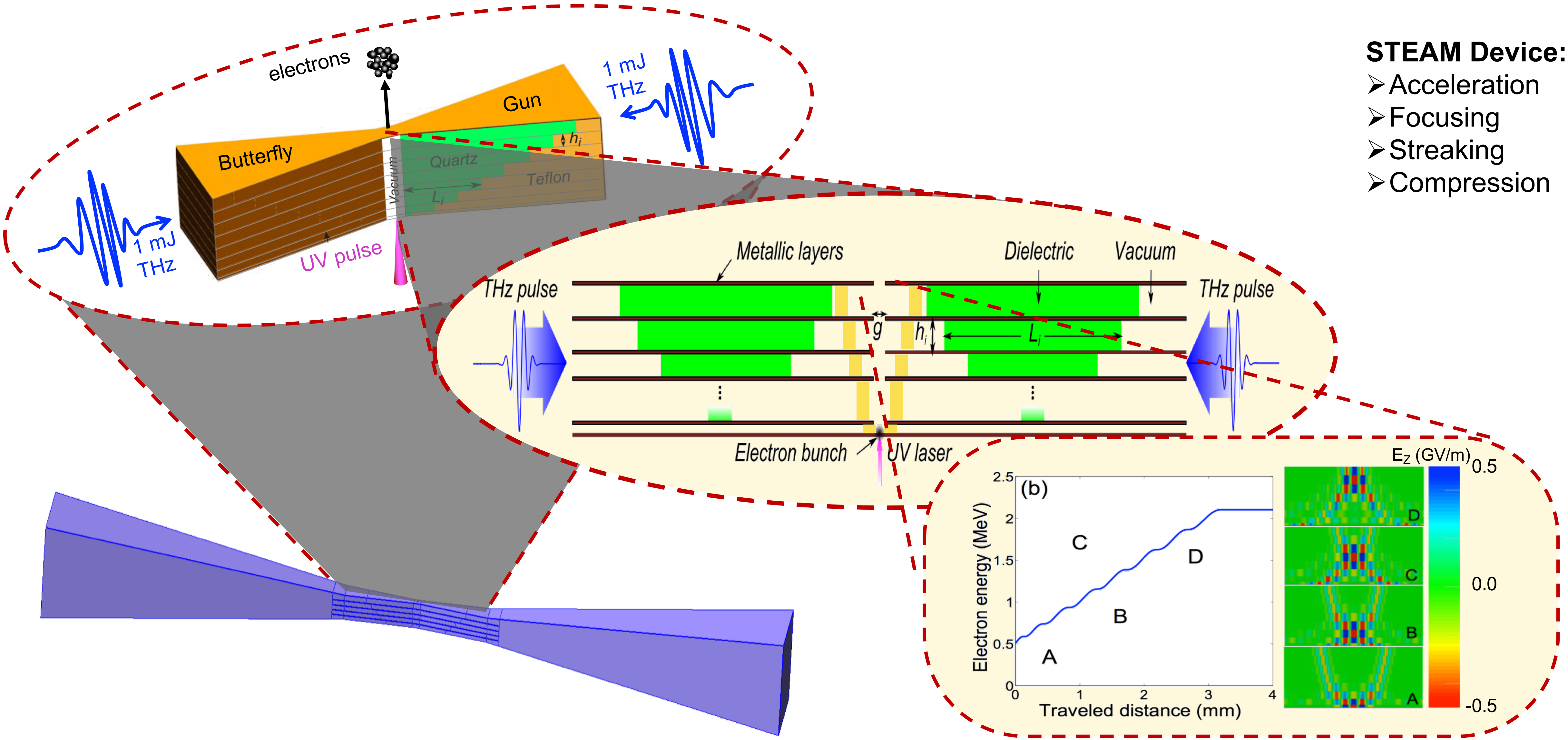
THz Off



THz On

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

Segmented THz Electron Accelerator & Manipulator = STEAM



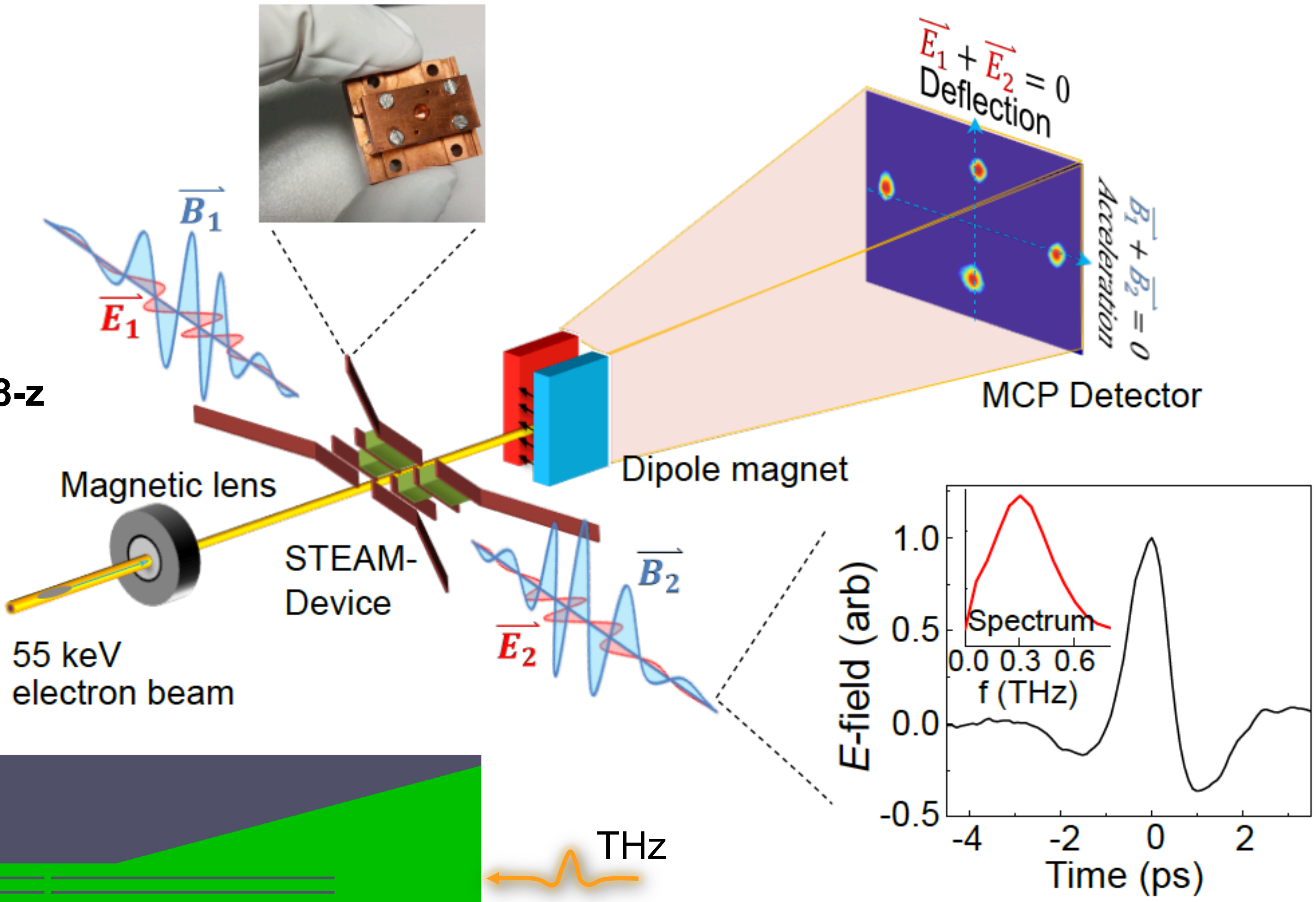
STEAM Device:

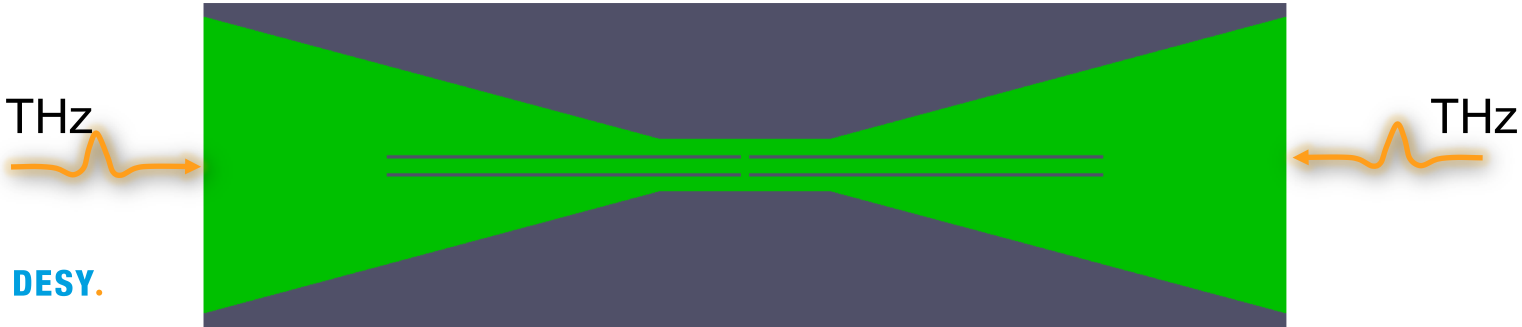
- Acceleration
- Focusing
- Streaking
- Compression

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

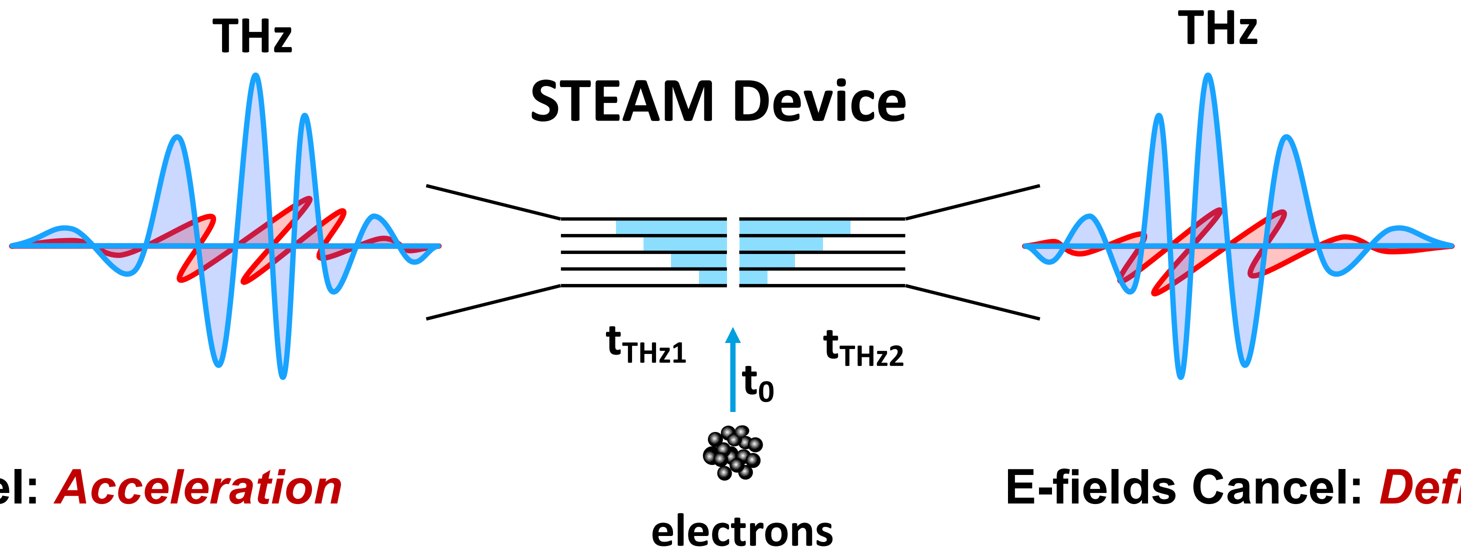
STEAM – Device as Accelerator and Electron Manipulator

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

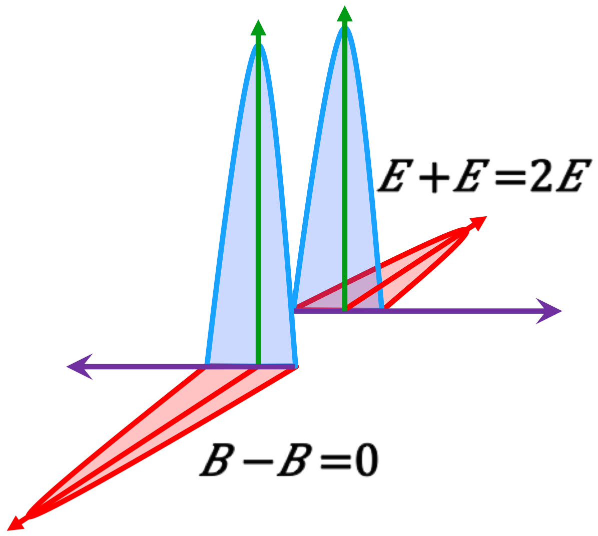




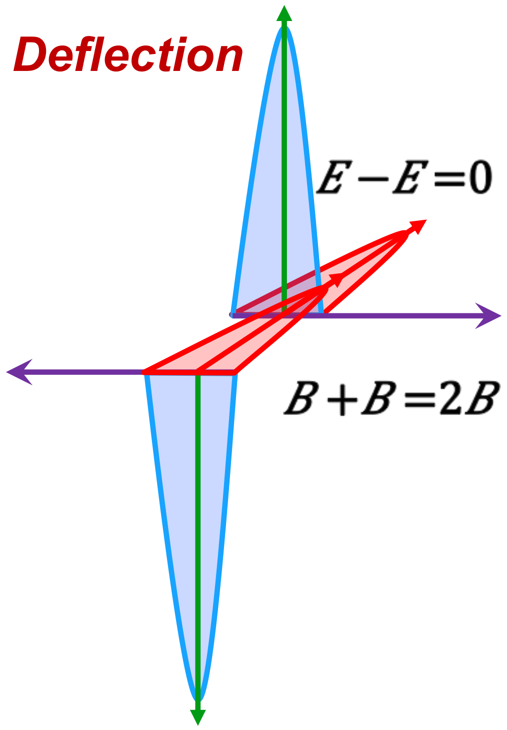
STEAM – Device as Accelerator and Electron Manipulator



B-fields Cancel: *Acceleration*

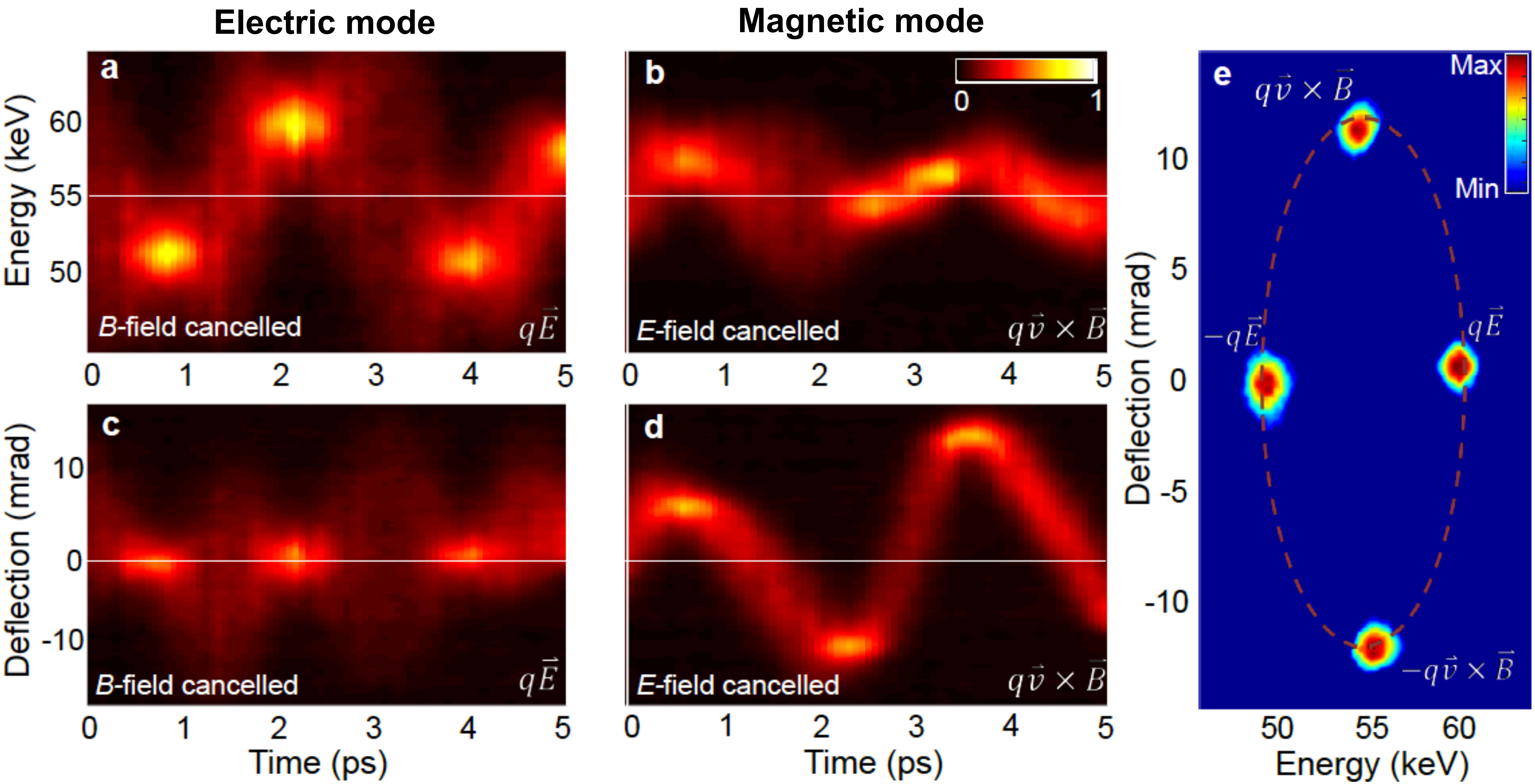


E-fields Cancel: *Deflection*



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

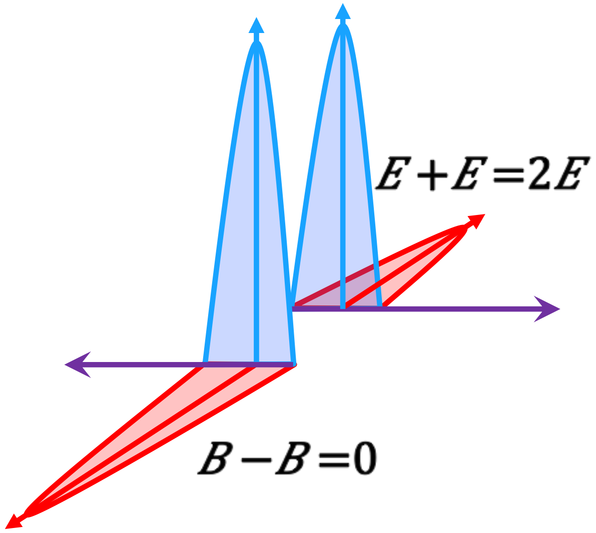
STEAM – Device as Accelerator and Electron Manipulator

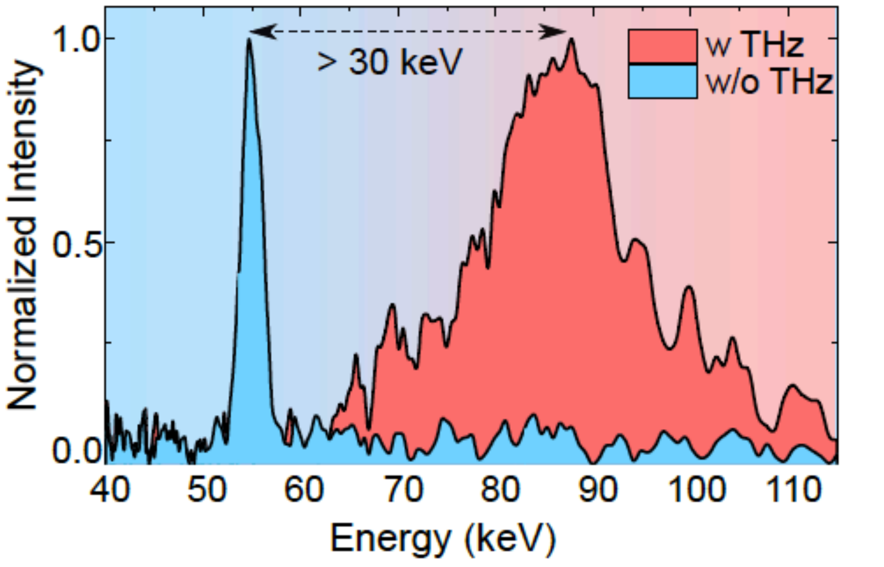


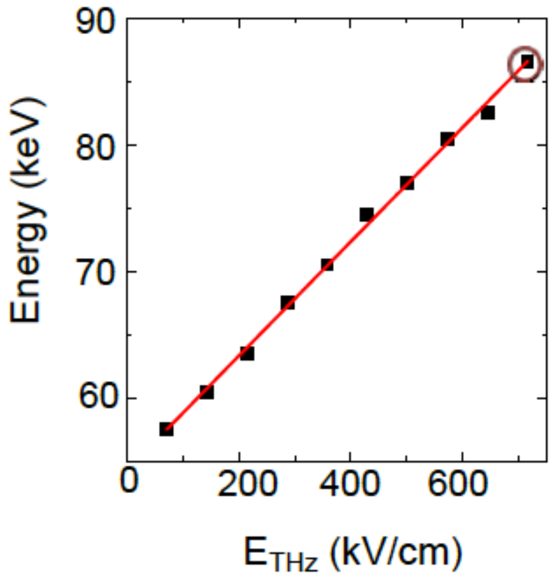
STEAM – Device as Accelerator

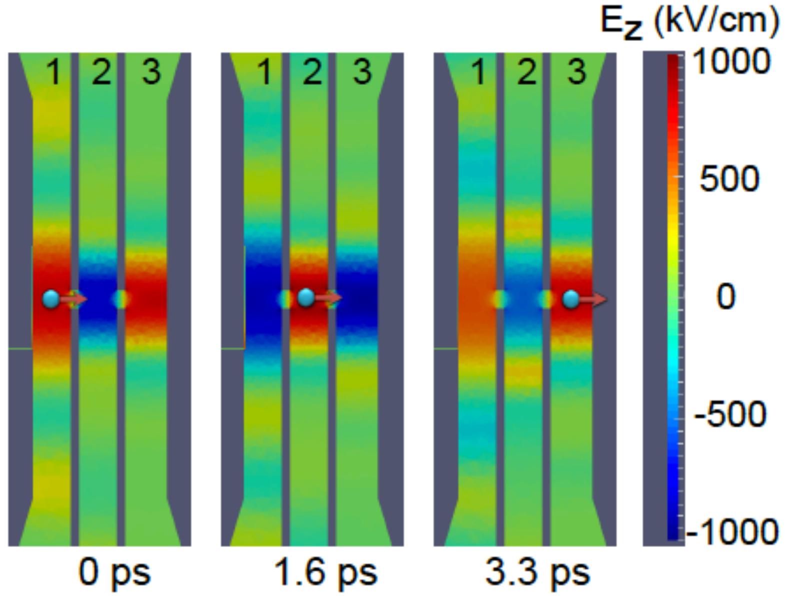
First THz acceleration only!

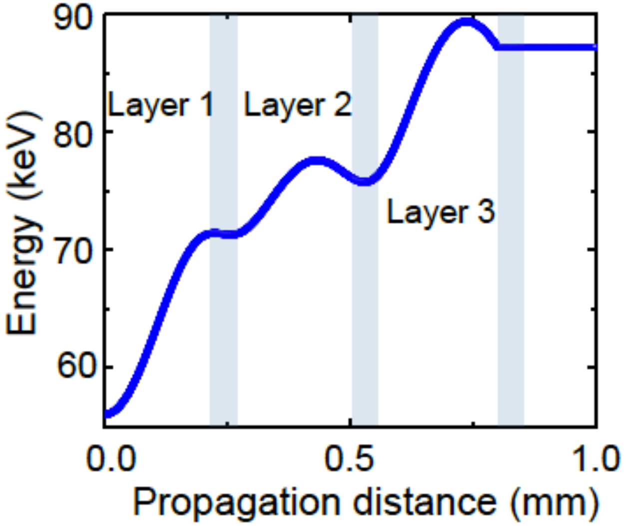
B-fields Cancel: ***Acceleration at maximum E-field***







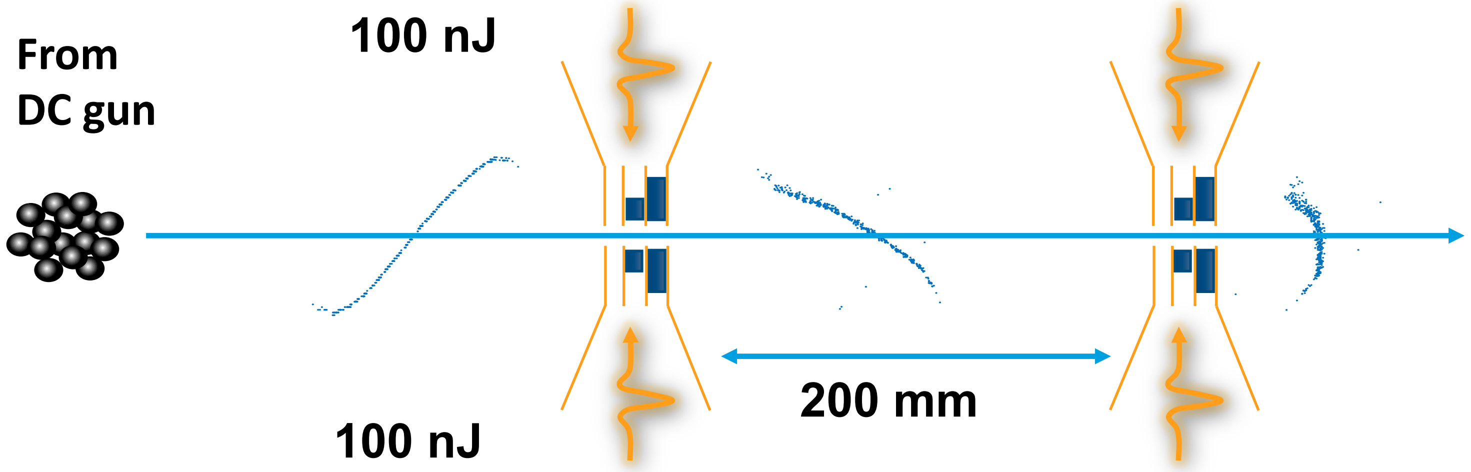




D. Zhang, et al. Nat. Photonics doi.org/10.1038/s41566-018-0138-z

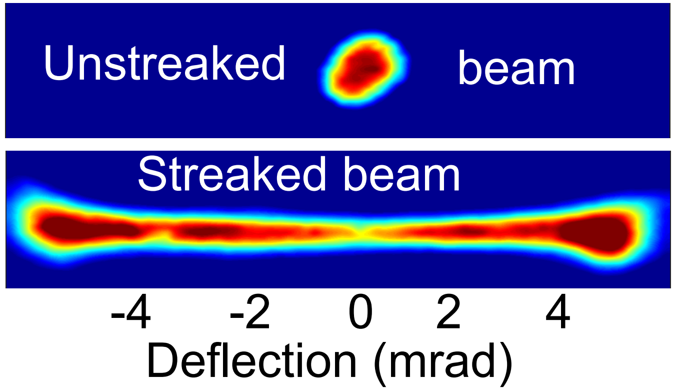
STEAM – Device as Electron Bunch Compressor

STEAM compressor **STEAM streaker**

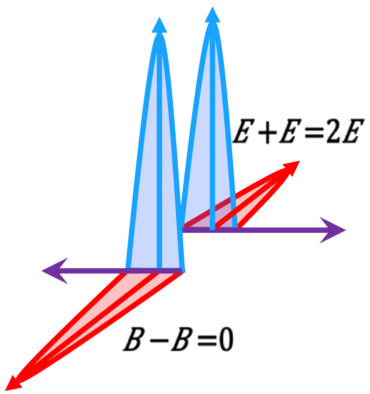


Streaking w. 150 μrad/fs (<10 fs resolution)

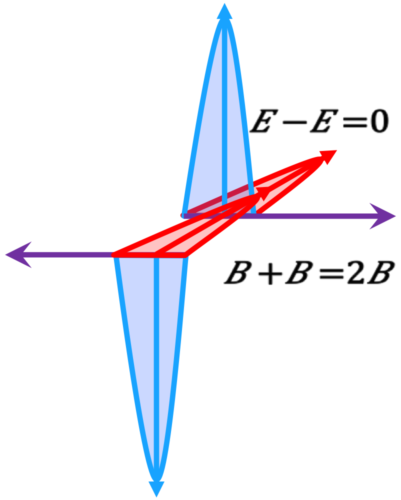
Beam Spatial Mode



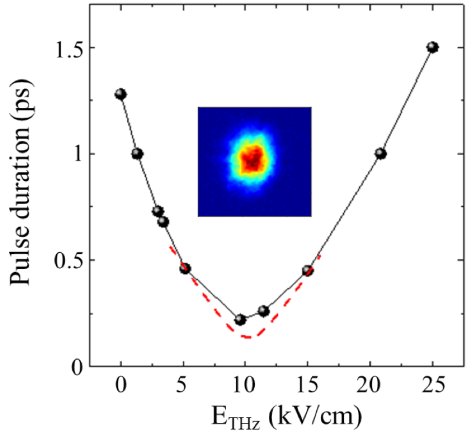
B-fields Cancel: ***Zero E-Field***



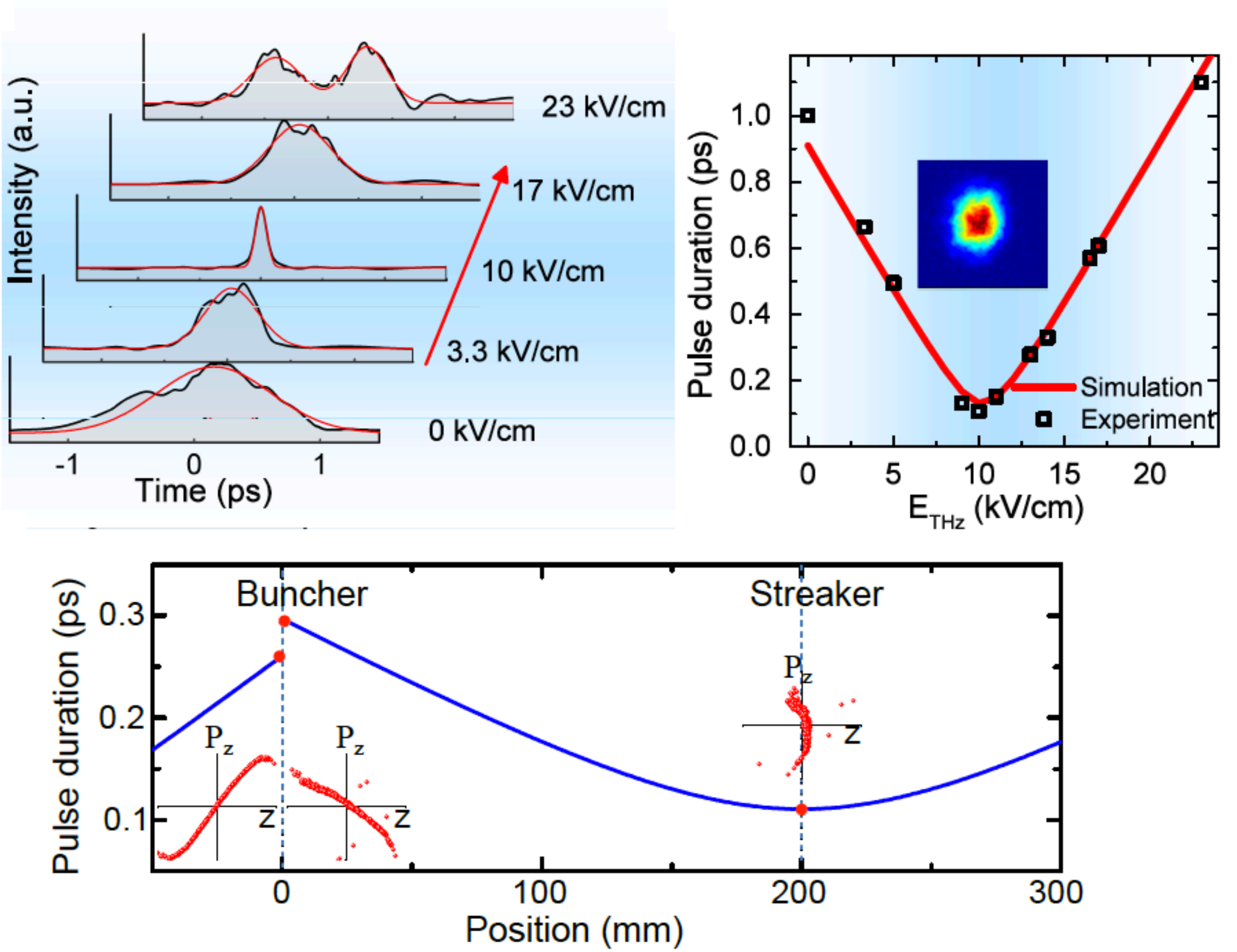
E-fields Cancel: ***Zero B-Field***



Compression < 200 fs



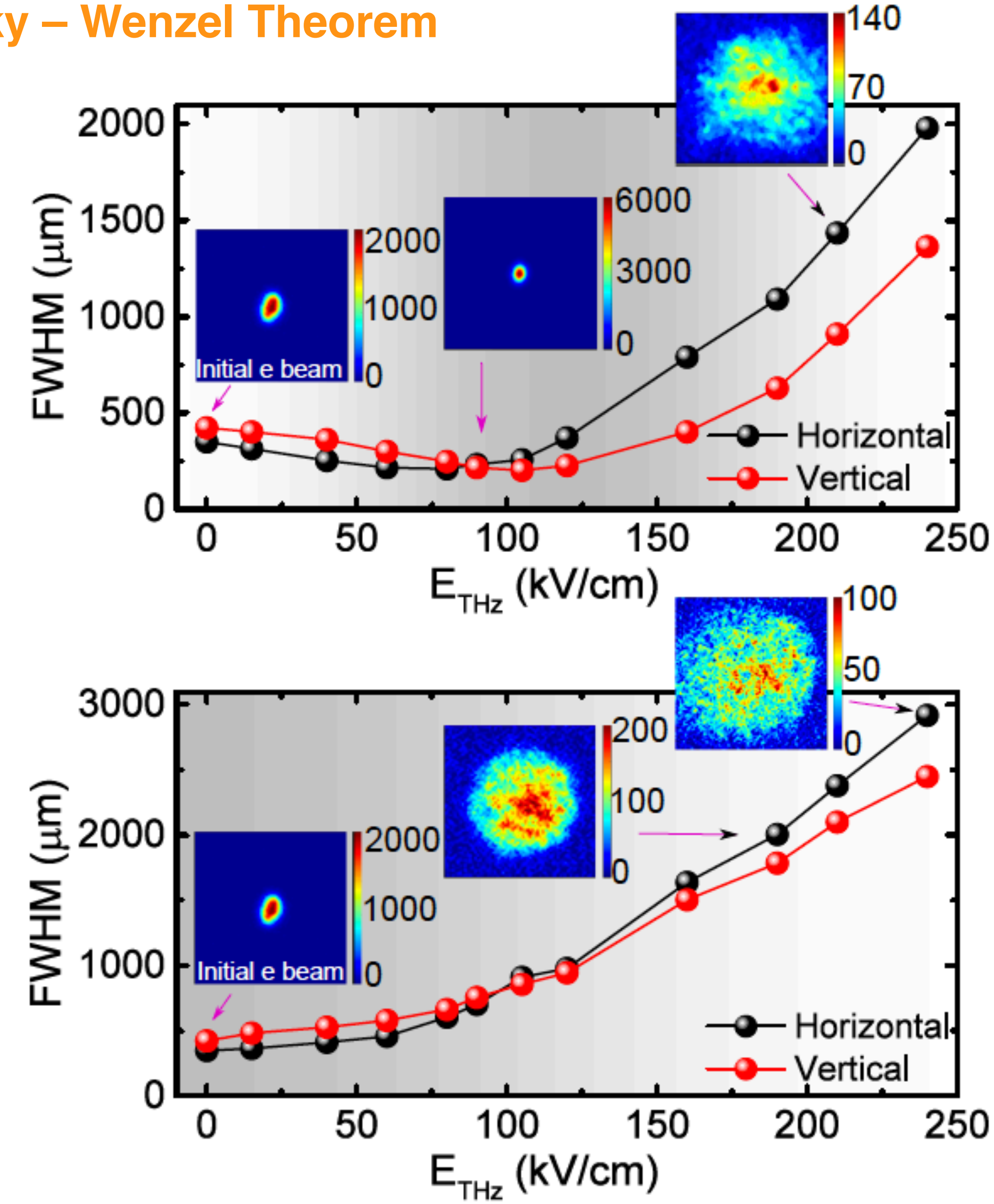
STEAM – Device as Electron Bunch Compressor

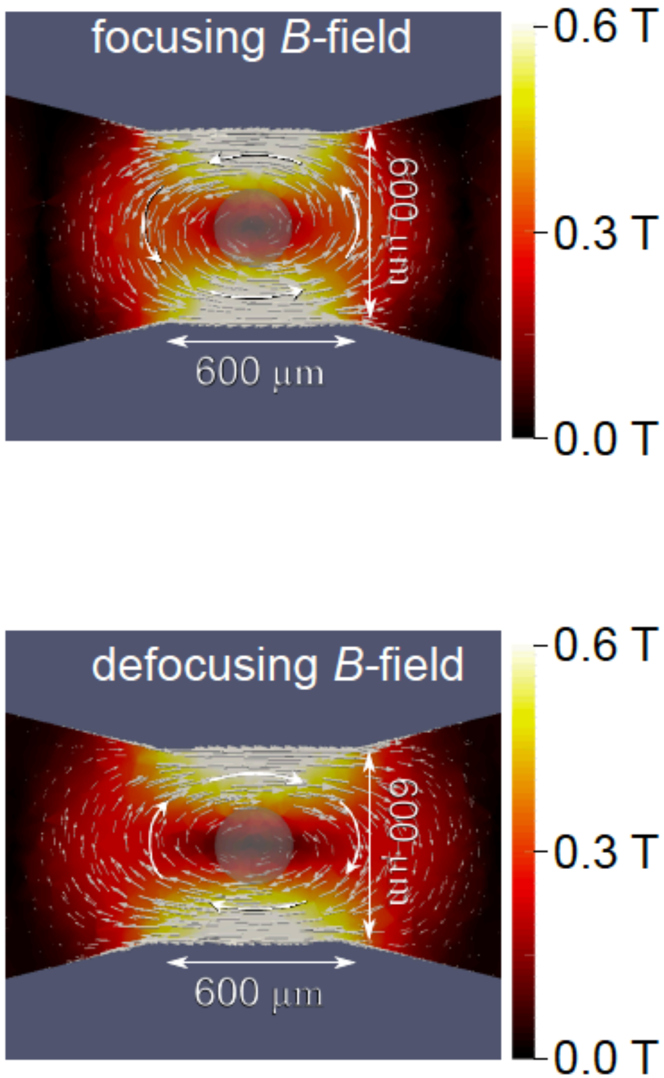


D. Zhang, et al. Nat. Photonics doi.org/10.1038/s41566-018-0138-z

STEAM – Device as Electron Lens

Panofsky – Wenzel Theorem



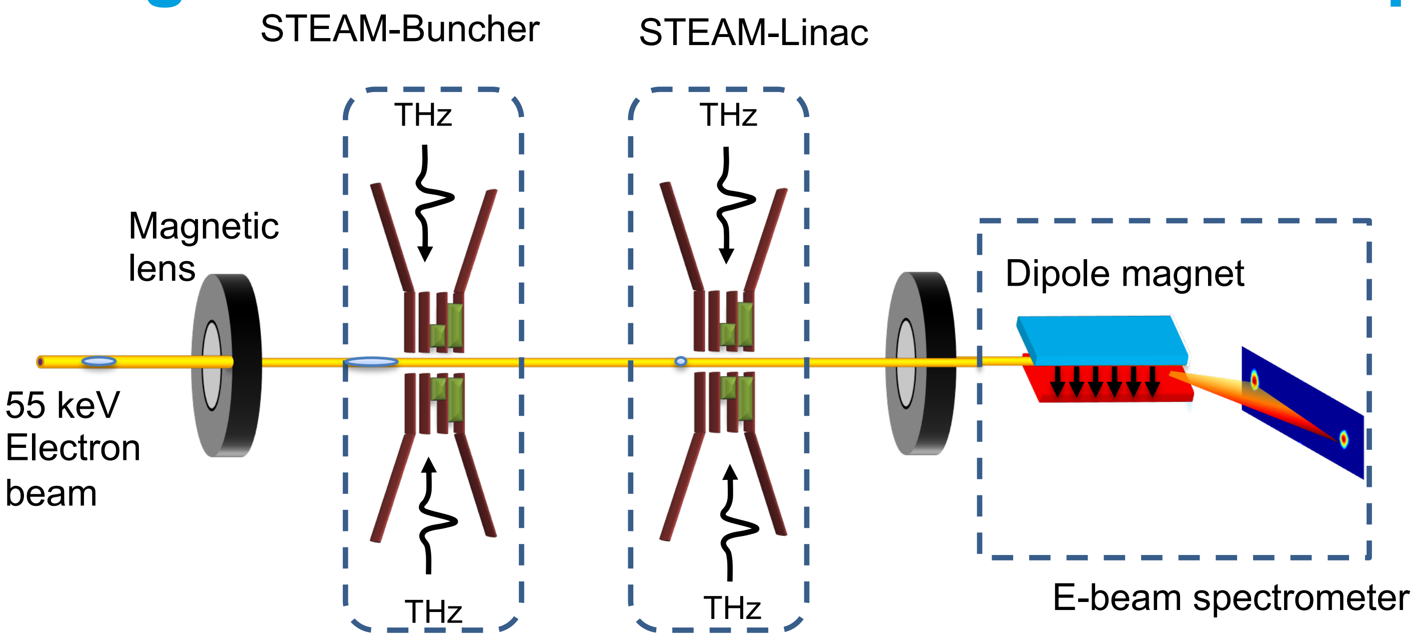


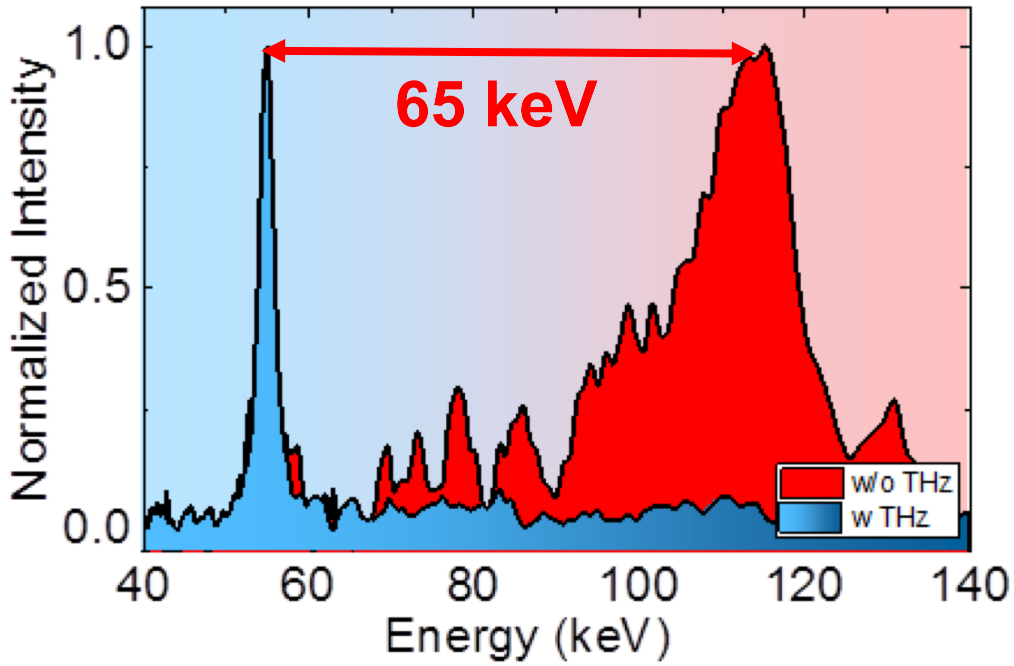
Peak Focussing Strength

- **2 kT/m**

Similar to Plasma Lens

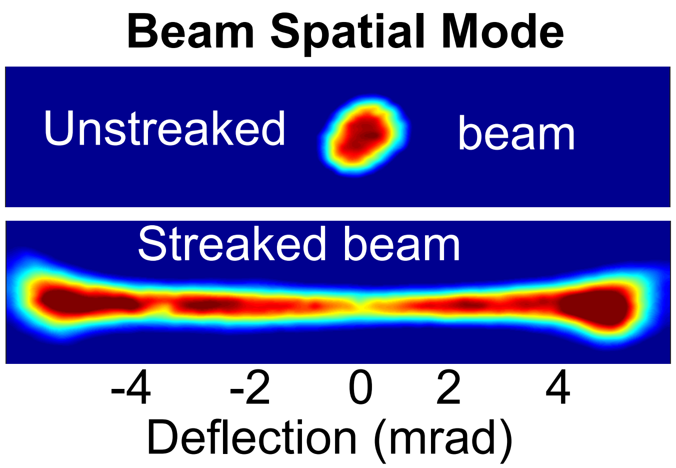
Segmented THz Accelerator and Manipulator

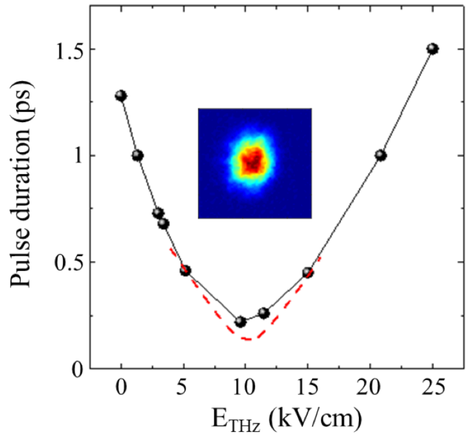




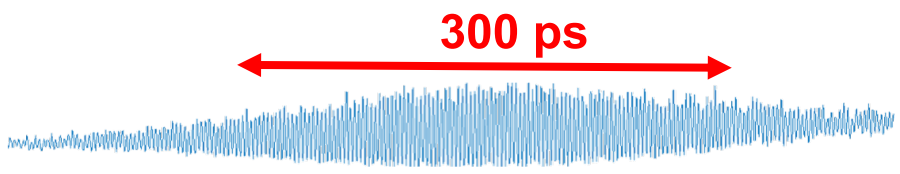
Streaking w. 150 mrad/fs (<10 fs resolution)

Compression < 200 fs





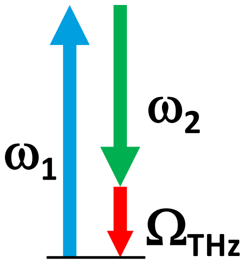
With Maier's LUX-Group
0.6 mJ, 0.5 THz Pulses

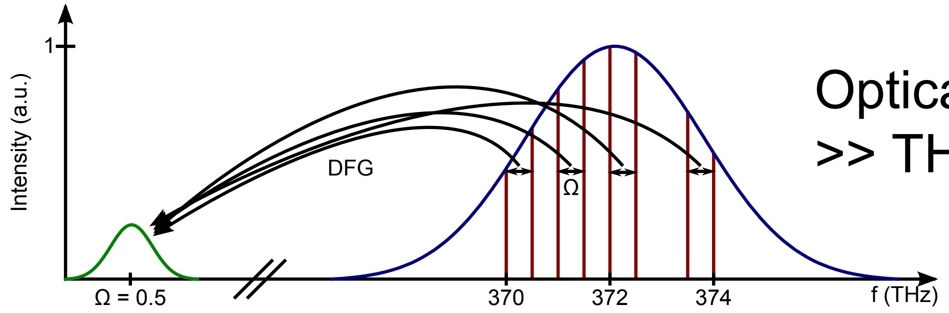


Optical THz Generation based on $\chi^{(2)}$

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

DFG process

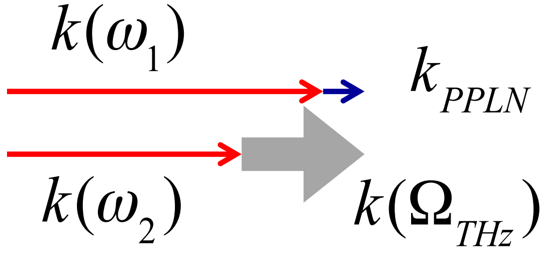




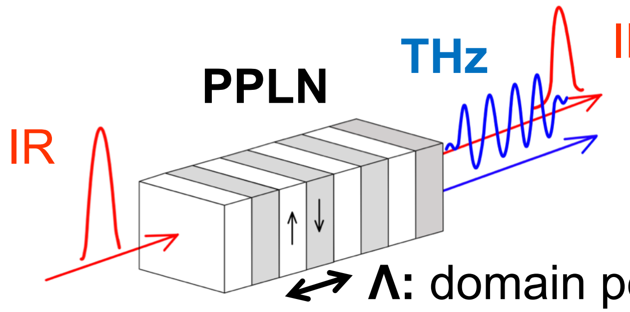
Optical bandwidth >> THz frequency

Conservation of momentum:

Collinear Phase Matching

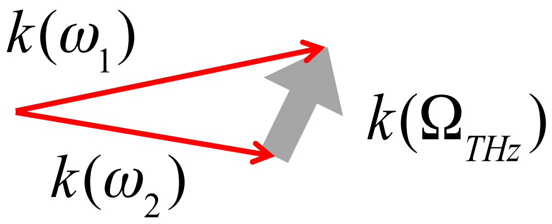


Multi-cycle THz generation using Periodically-Poled Lithium Niobate

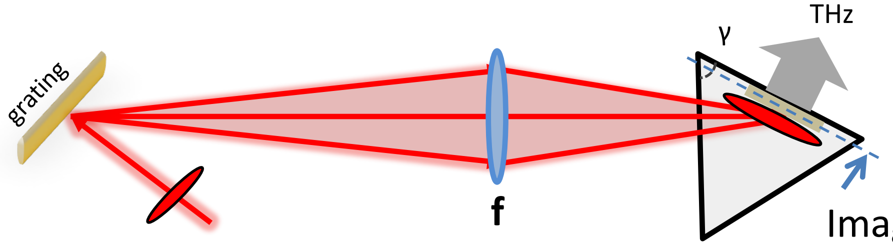


$n_{opt} \approx 2; \quad n_{THz} \approx 5$

Non-collinear Phase Matching



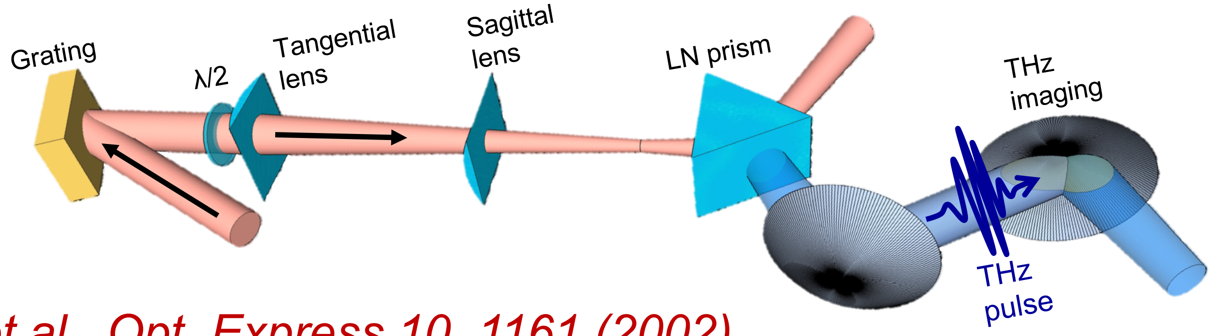
Single-cycle THz generation by Tilted Pulse-Front Technique

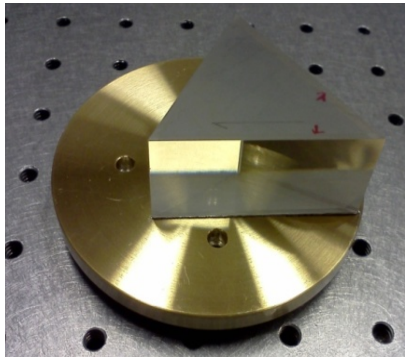


*J. Hebling et al, Opt. Express **21**, 1161 (2002)*

> 200 μJ Single-Cycle THz Pulses

~1% optical to THz conversion





LN prism

J. Hebling et al., Opt. Express 10, 1161 (2002)
J. A. Fülöp et al., Opt. Express 19, 15090 (2011)
S. W. Huang et al Opt. Lett. 38(5), 796-798 (2013)
X. Wu et al., Opt. Express 24, 21059 (2016)

Single-cylce THz generation:

E_{THz} ~ 200 μJ

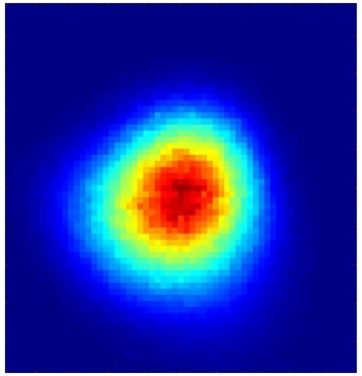
f_{THz} ~ 280 GHz

Δ_{FWHM} ~ 3.3 ps

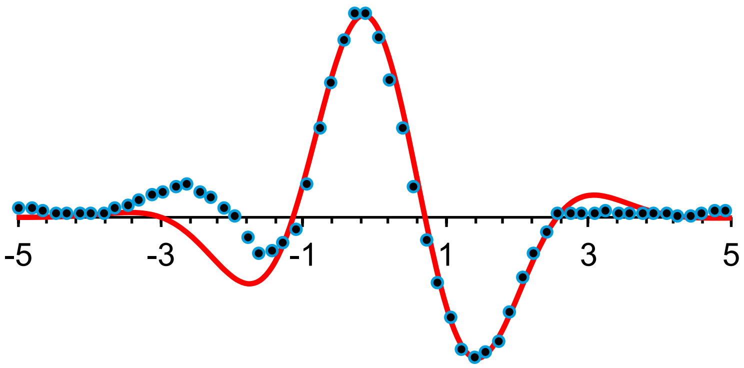
IR laser: 40 mJ, 1020 nm, 1ps

0.5 % efficiency

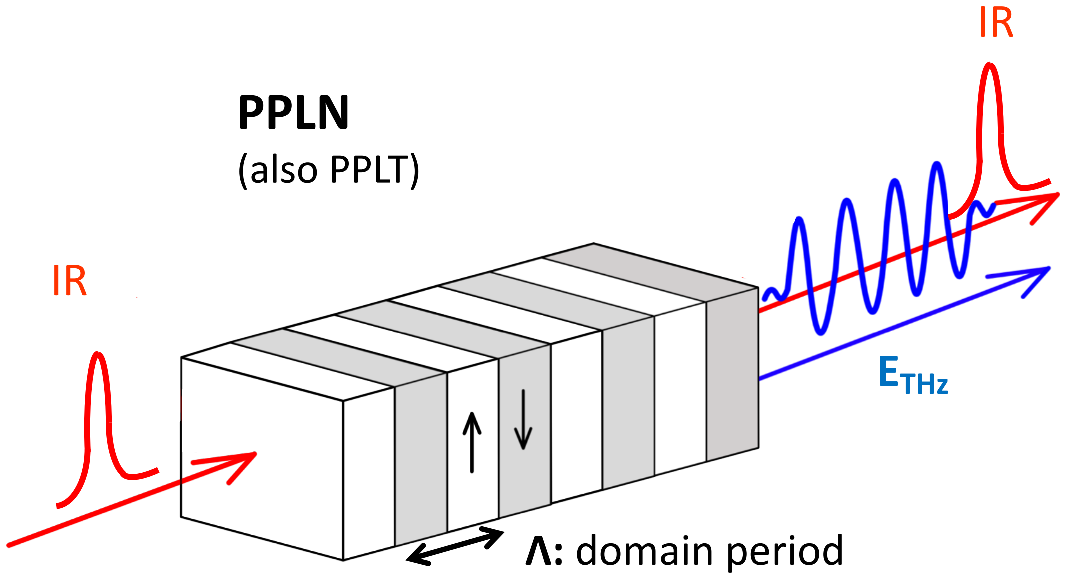
Measured THz mode



Measured THz Waveform

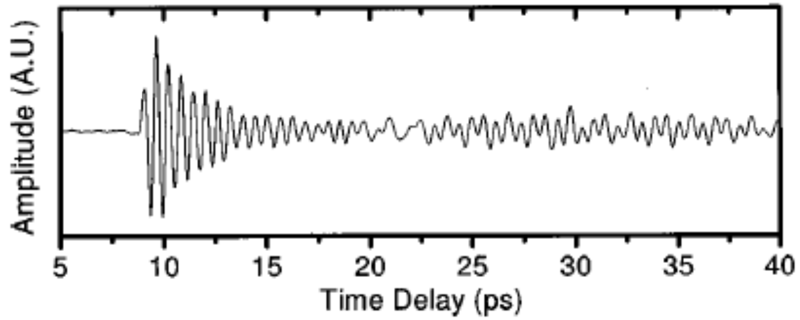


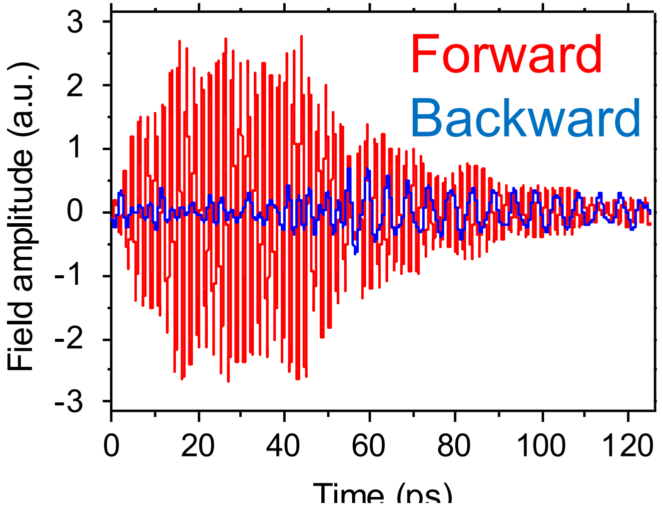
Quasi – Phase Matching for Multi-Cycle Terahertz

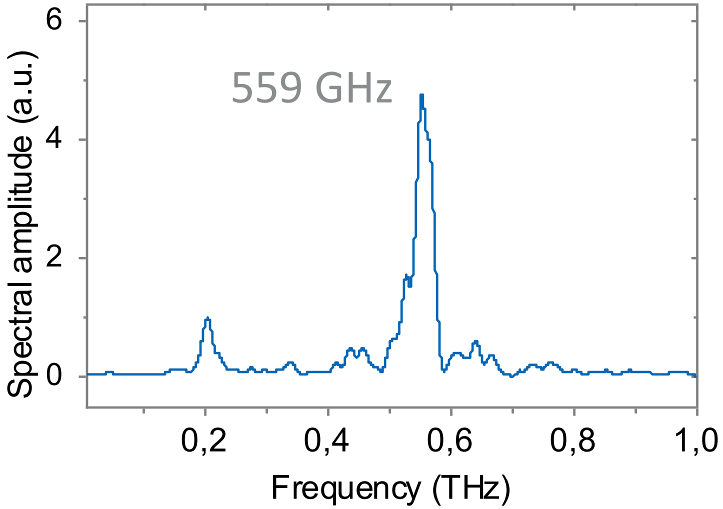


Lee, App. Phys. Lett. 77 (2000)
Lee, App. Phys. Lett. 78 (2001)
Yu, Opt. Comms. 284 (2011)

- µJ-level energies → **10^{-5}** conversion efficiencies







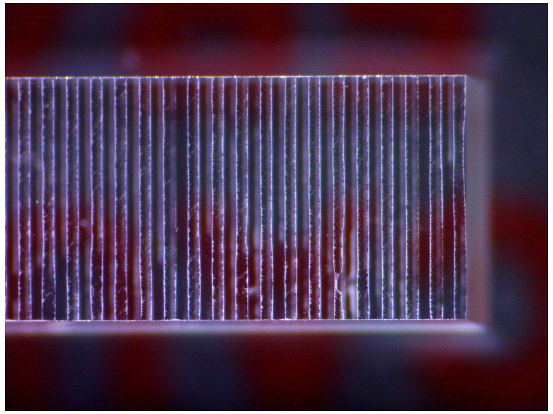
mJ - level energies → **10^{-3}** conversion efficiencies

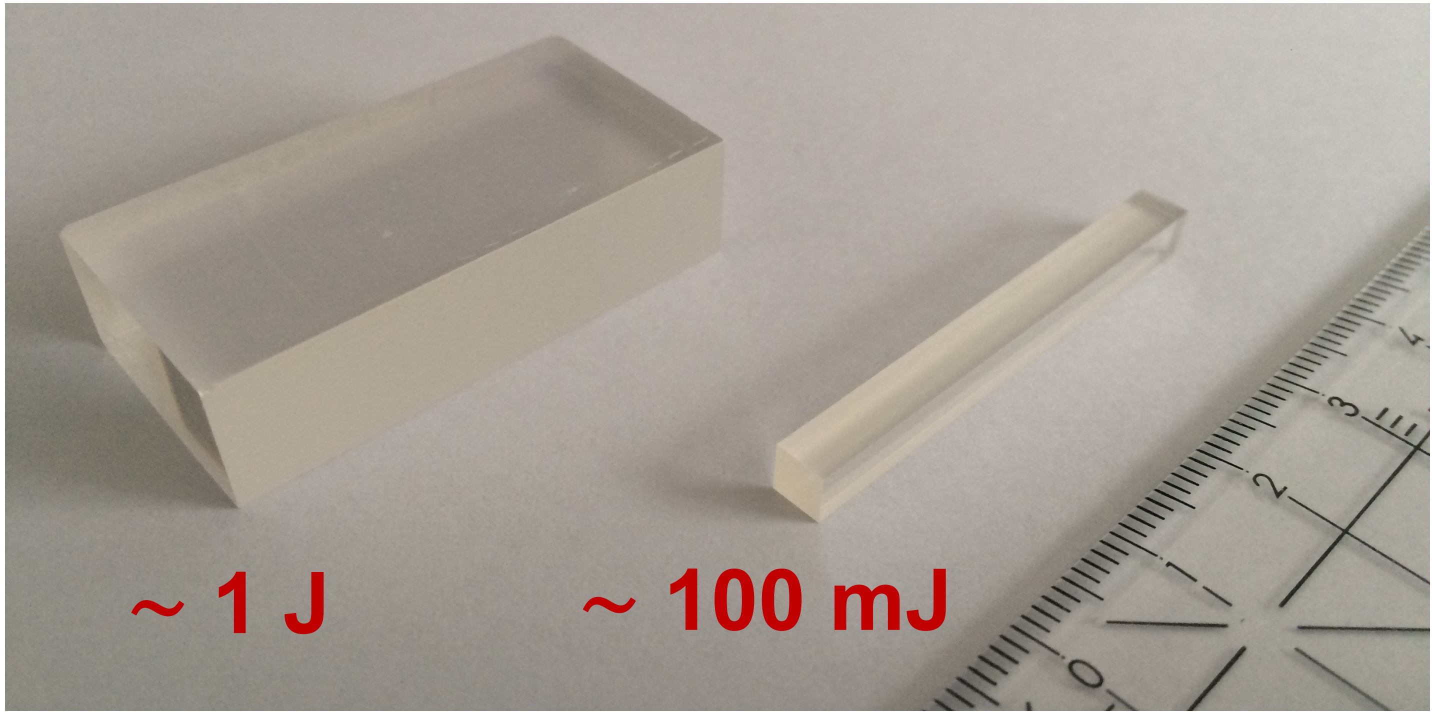
S. Carbajo et al., Opt. Lett. 40, 5762 (2015).

Quasi – Phase Matching for Multi-Cycle Terahertz Waves

PPMg:LN

- Poling period of 125µm – 1200µm feasible
- clear aperture of 10x15 mm^2, 40 mm long
- clear aperture of 4x4 mm^2, 40 mm long

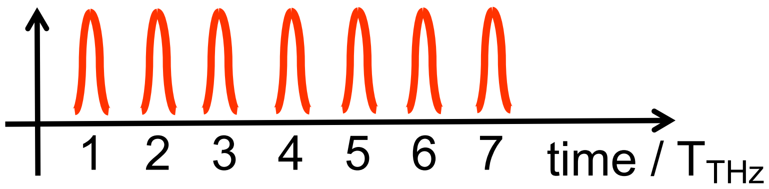


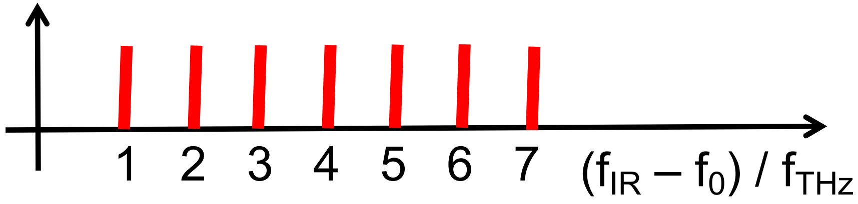


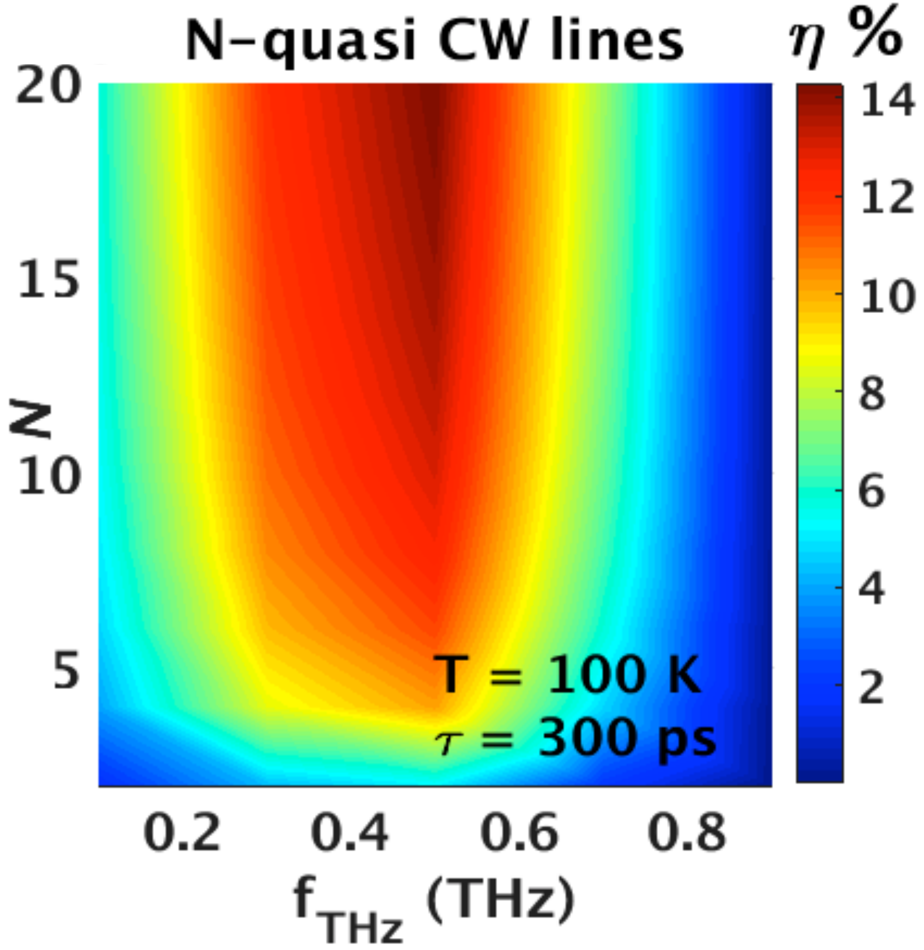
Professor Taira,

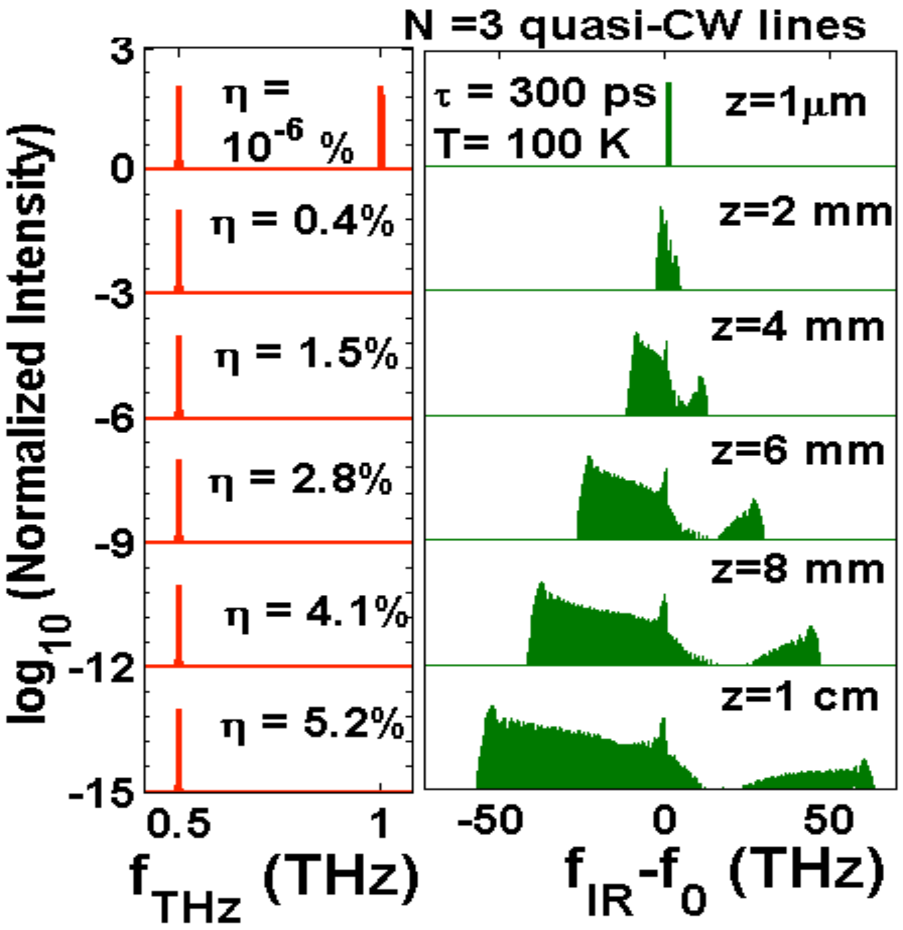
IMS Japan

Multi-line DFG - Highly Efficient THz Generation









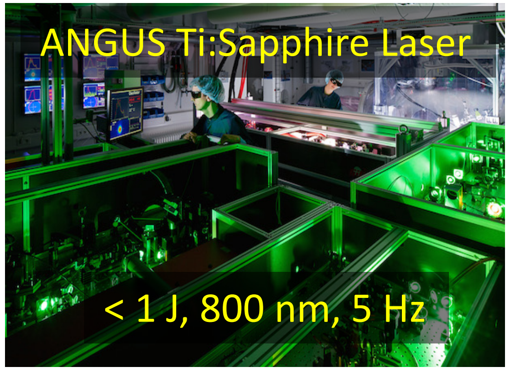
K. Ravi et al.,
Opt. Lett. 24, 25582 (2016)

Earlier work by

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

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

Record Multi-Cycle THz from Large Aperture PPLN Crystals

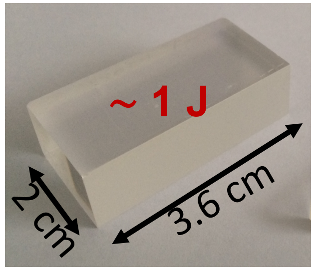


Collaboration @ DESY

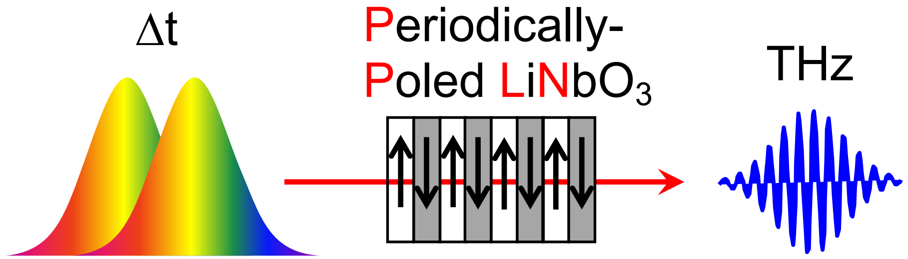
LUX:
- Dr. Andreas Maier
- and Dr. S. Jolly

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

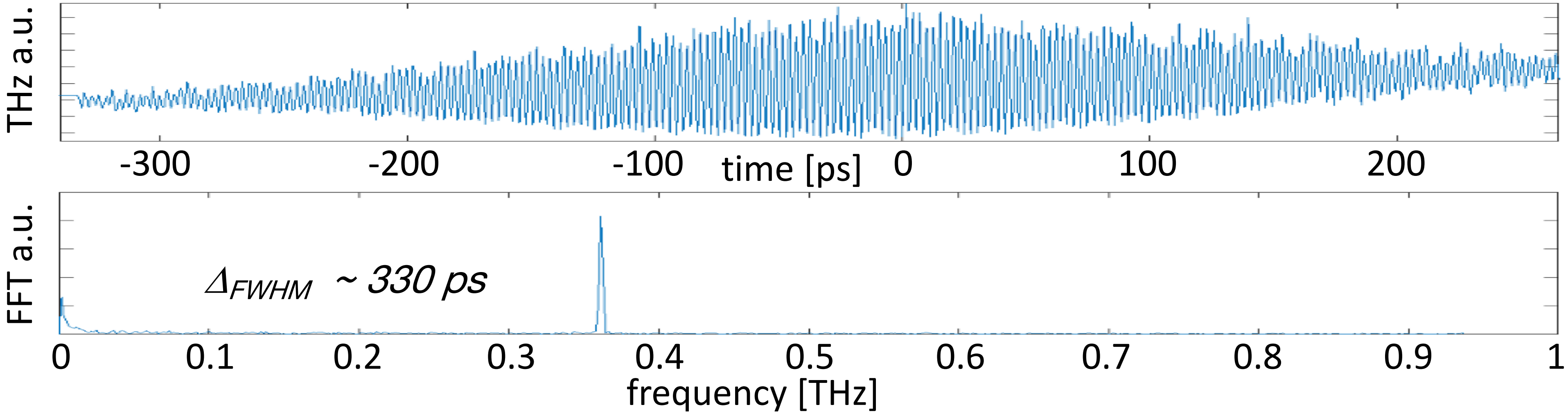
Large PPLN provided by Prof. Taira, IMS, Japan



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!

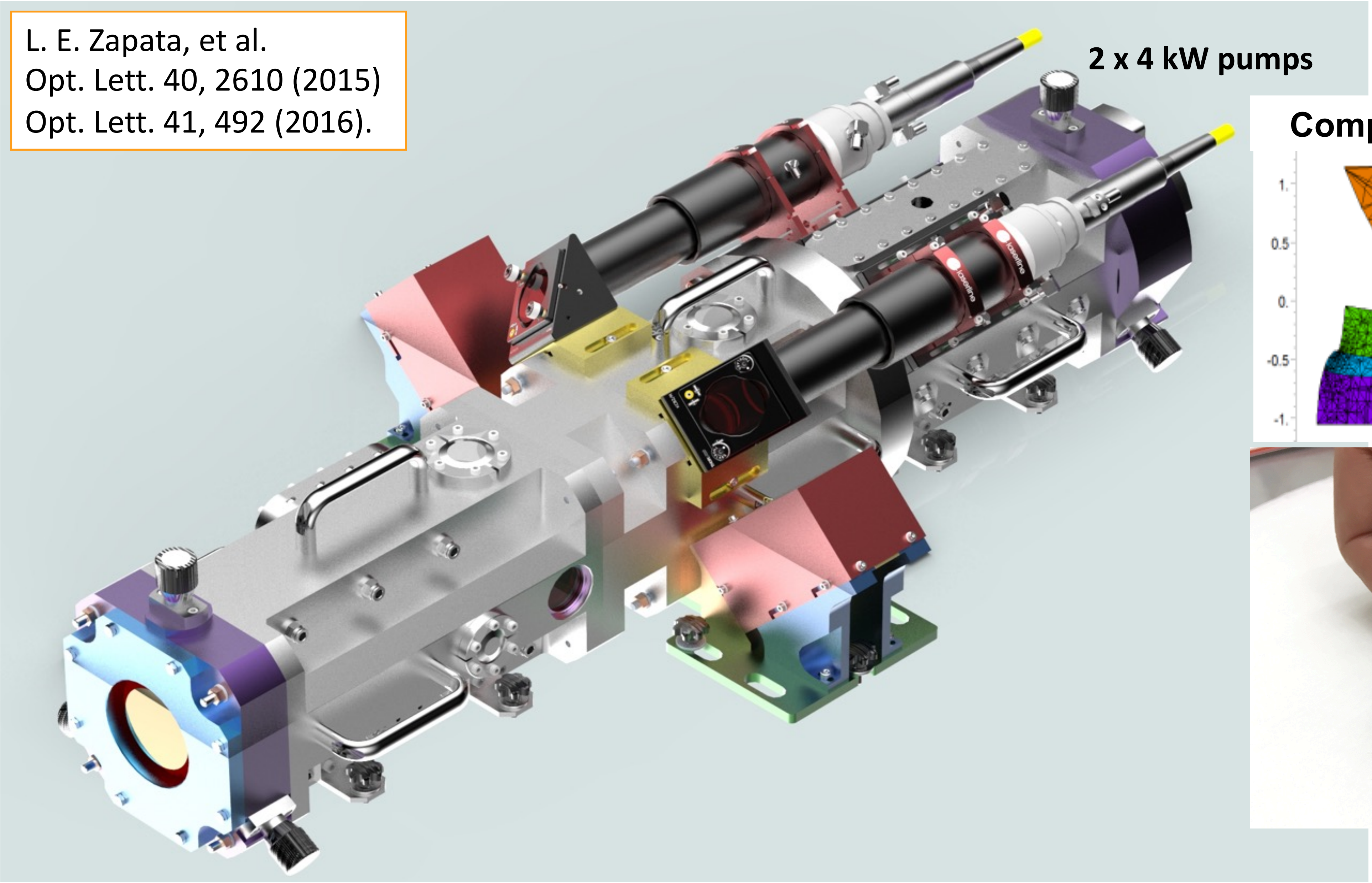
F. Ahr et al., Opt. Lett. *42, 2118 (2017)*

S. Jolly et al., *in preparation*

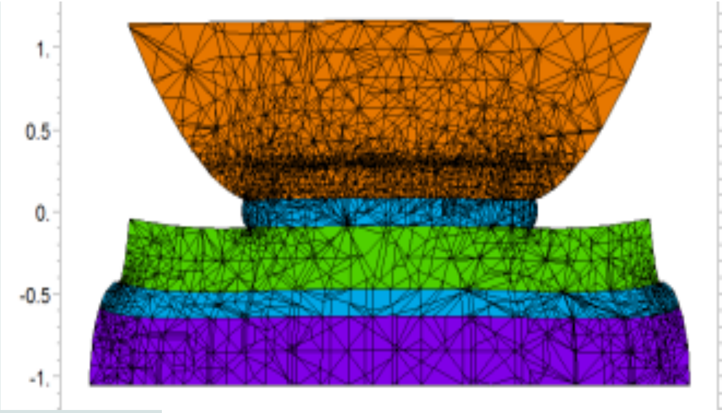
Optimized experiments expected to produce >> 1 mJ (~ 3 MW)

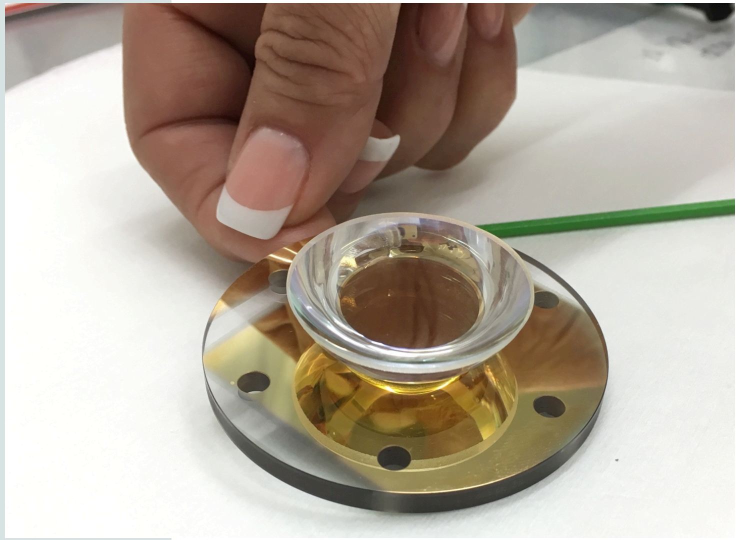
1 J, 1 kHz, 1 kW Cryogenic Composite Thin Disk Laser

L. E. Zapata, et al.
Opt. Lett. 40, 2610 (2015)
Opt. Lett. 41, 492 (2016).

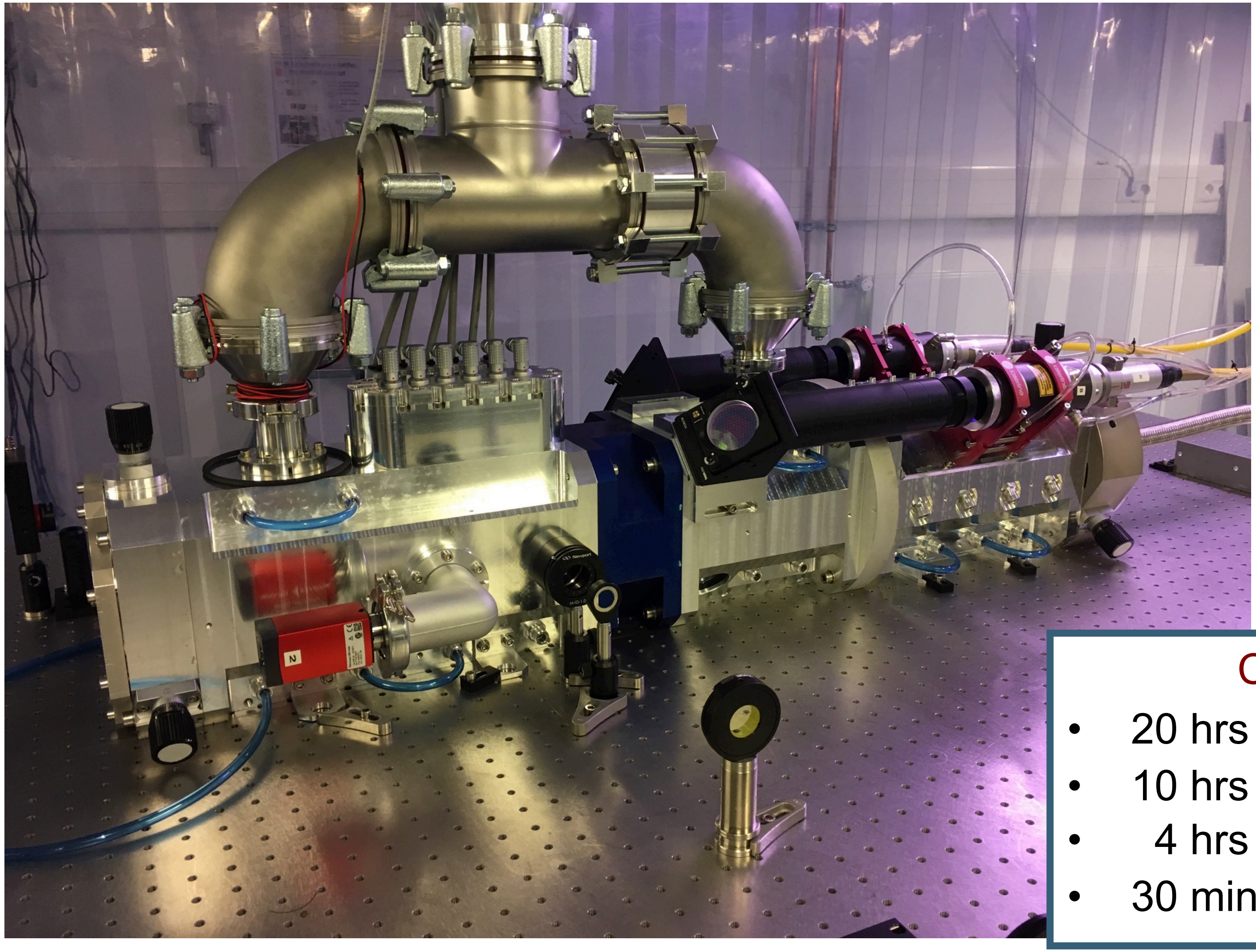


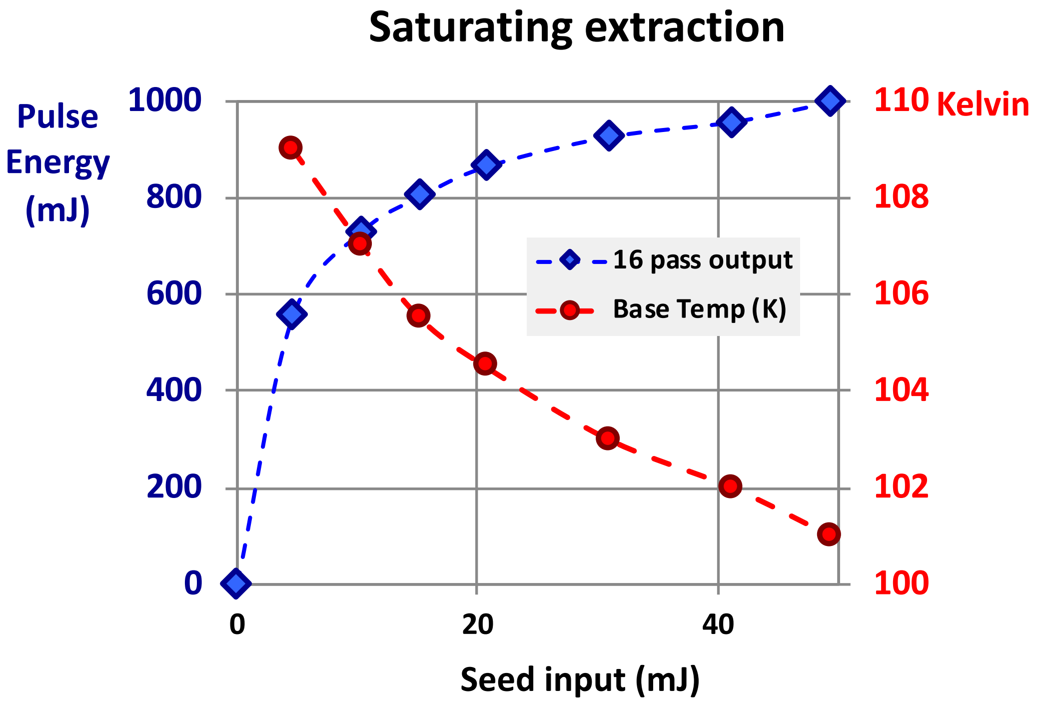
Composite Thin Disk Laser





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



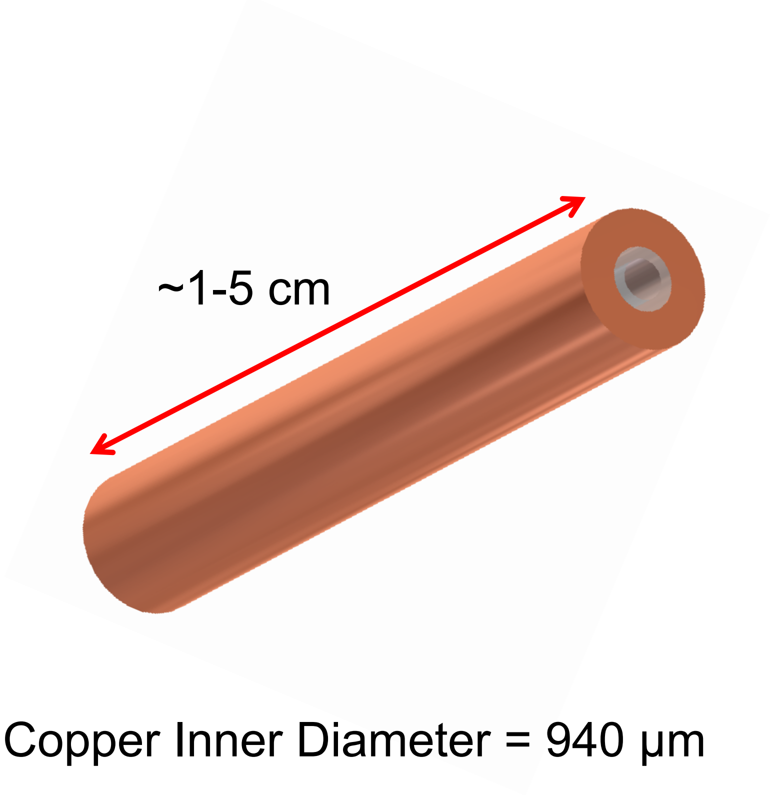


COMPILED OPERATIONS

- 20 hrs at ½ Joule, 100 Hz → 200 W ave pump power
- 10 hrs at 1^{+} Joule, 100 Hz → 200 W ave pump power
- 4 hrs at 1^{+} Joule, 200 Hz → 400 W ave pump power
- 30 min at 1^{-} Joule 500 Hz →1 kW ave pump power

THz Acceleration in Dielectrically Loaded Circular Waveguide

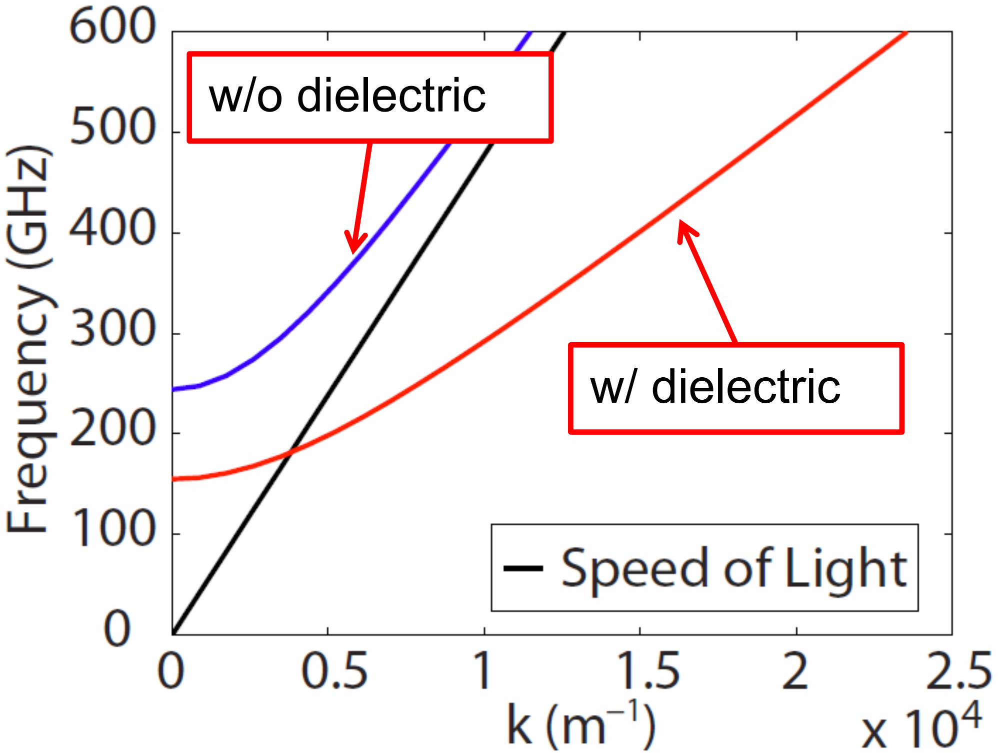
- THz phase-velocity matched to electron speed with thickness of dielectric



Copper Inner Diameter = 940 µm

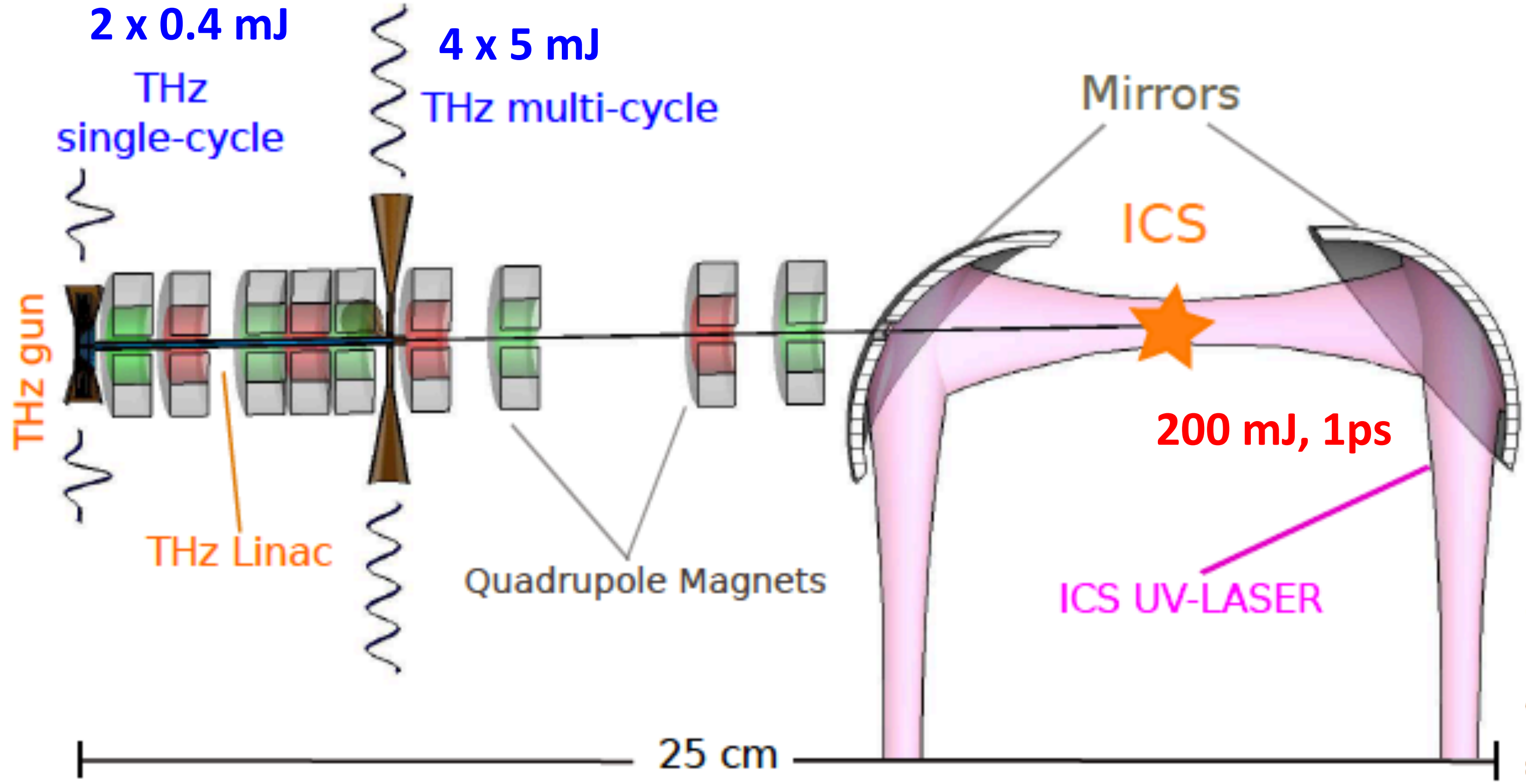
Fused Silica Inner Diameter = 400 µm

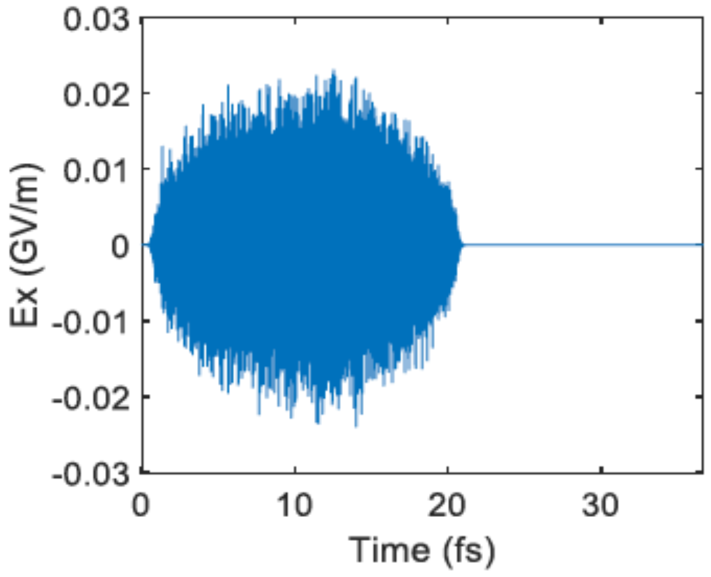
Dispersion Relation

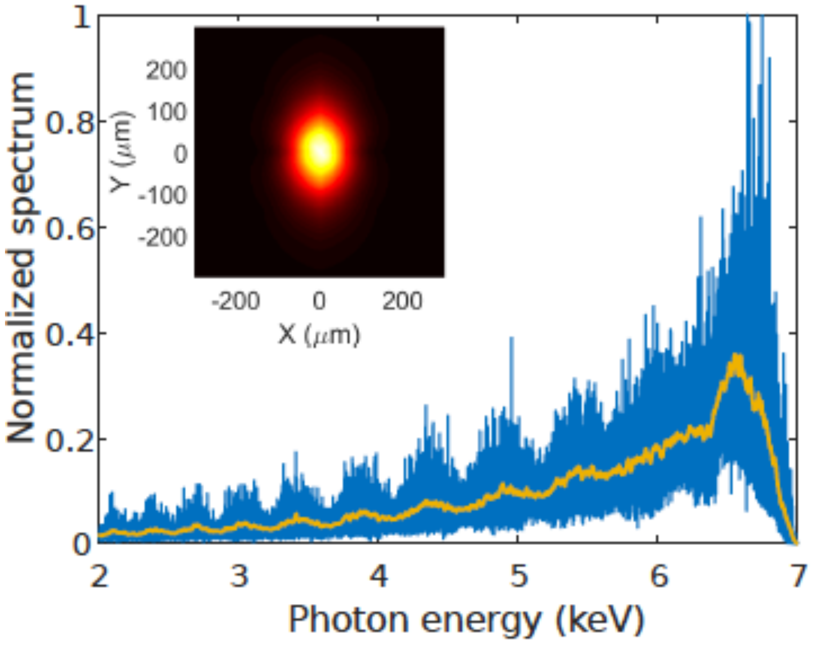


L.J. Wong et al., Opt. Exp. 21, 9792 (2013).

AXSIS I: Start to End Simulations





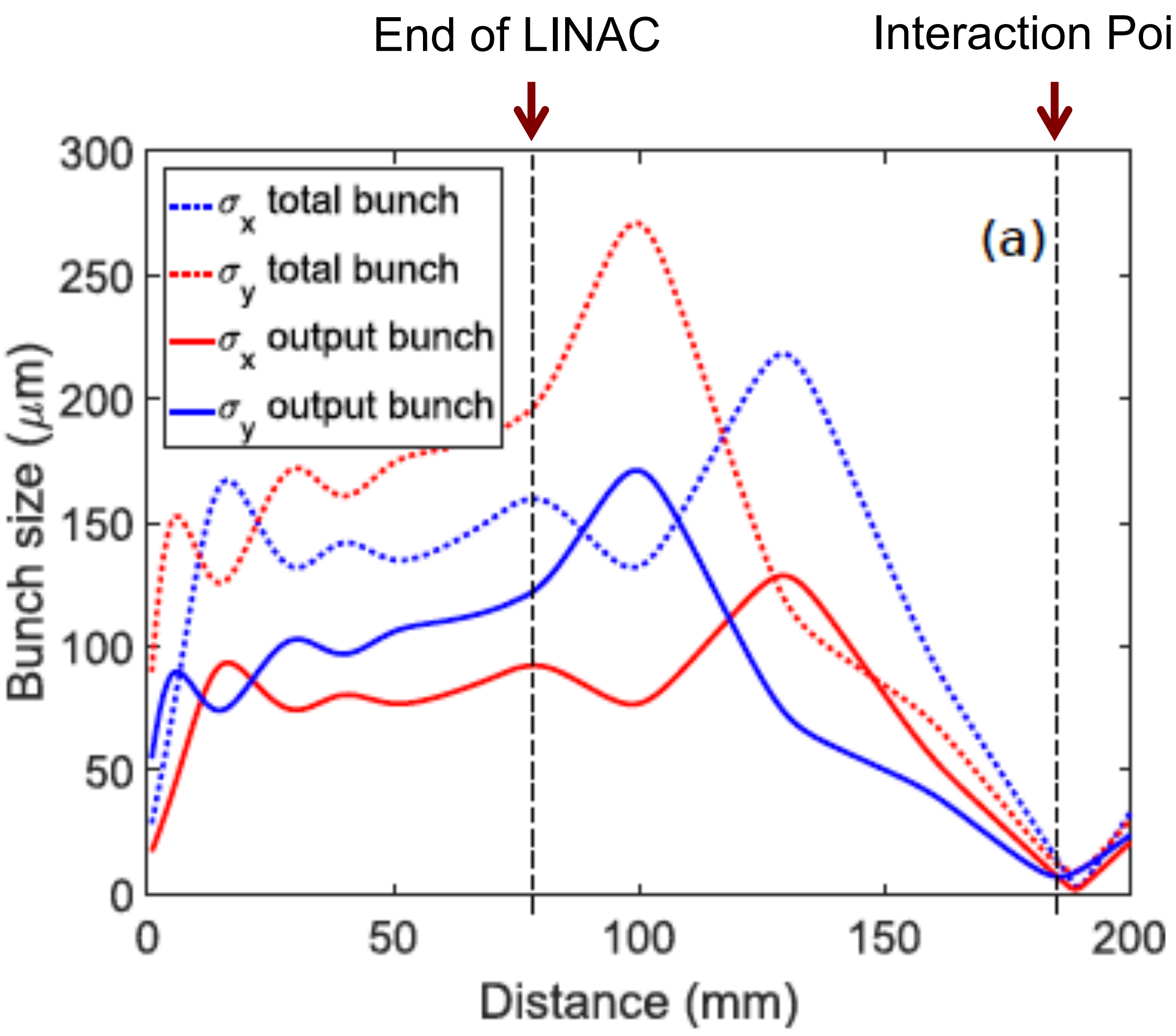


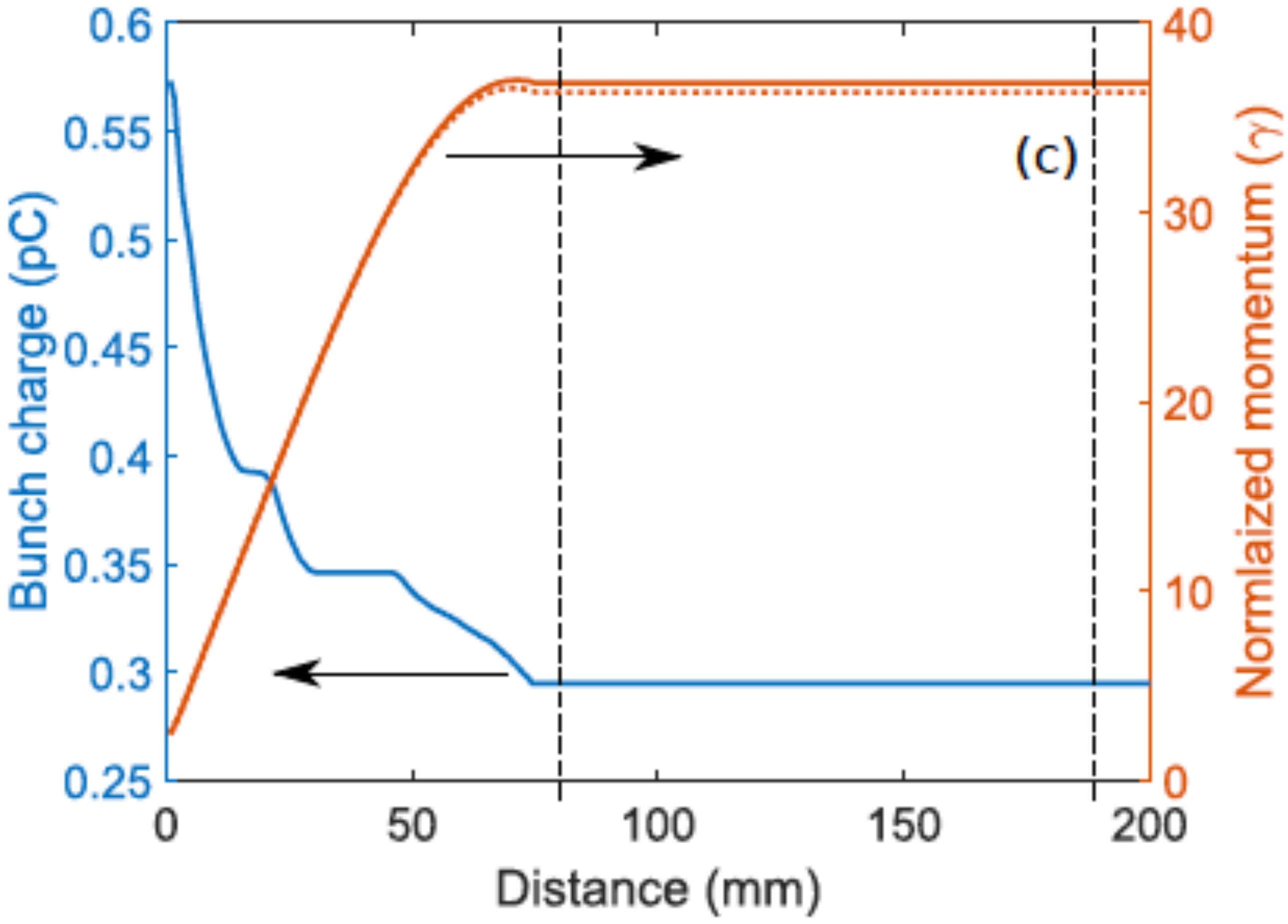
Electrons: 0.3 pC, 18.8 MeV
ICS-Laser: 200 mJ, 1 ps,
20 μm focus

Photon Number: 6 x 10^4 / shot
Pulse length: 10 fs
Photon Energy: 6.5 keV
10 Hz – 1 kHz

M. Fakahri et al., to be published

THz Acceleration in Dielectrically Loaded Circular Waveguide





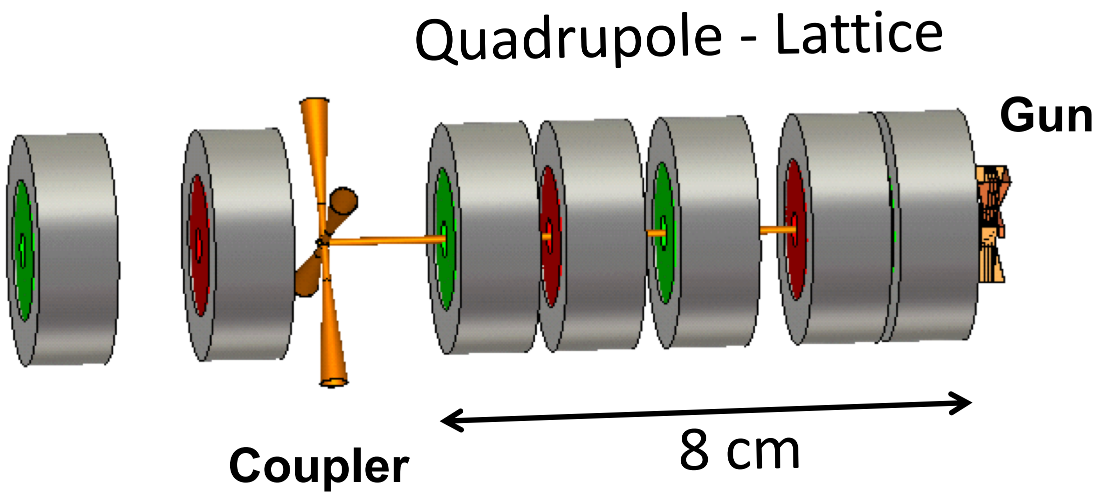
Summary and Outlook

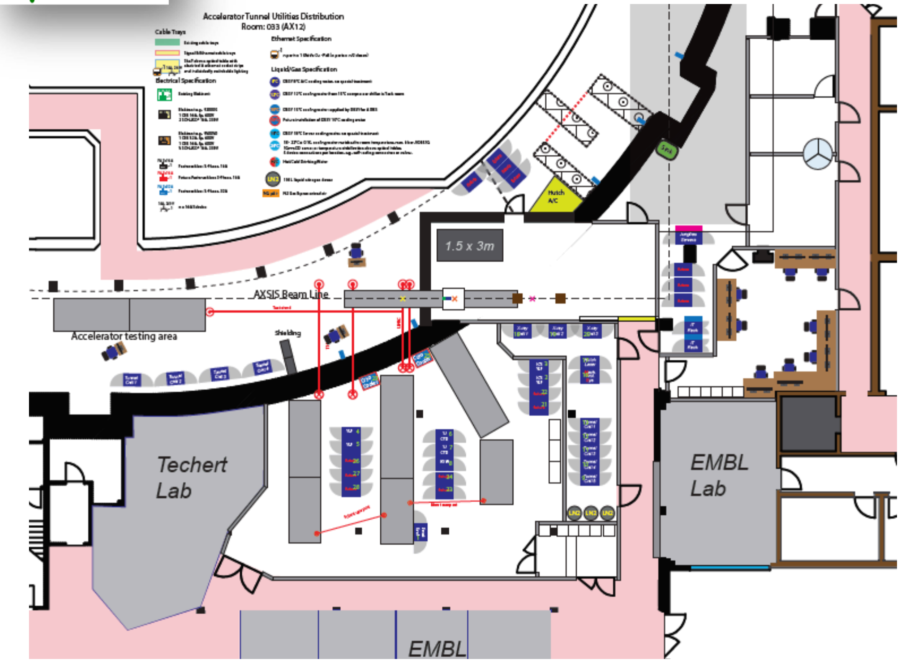
THz fields enable ultra compact guns and accelerators

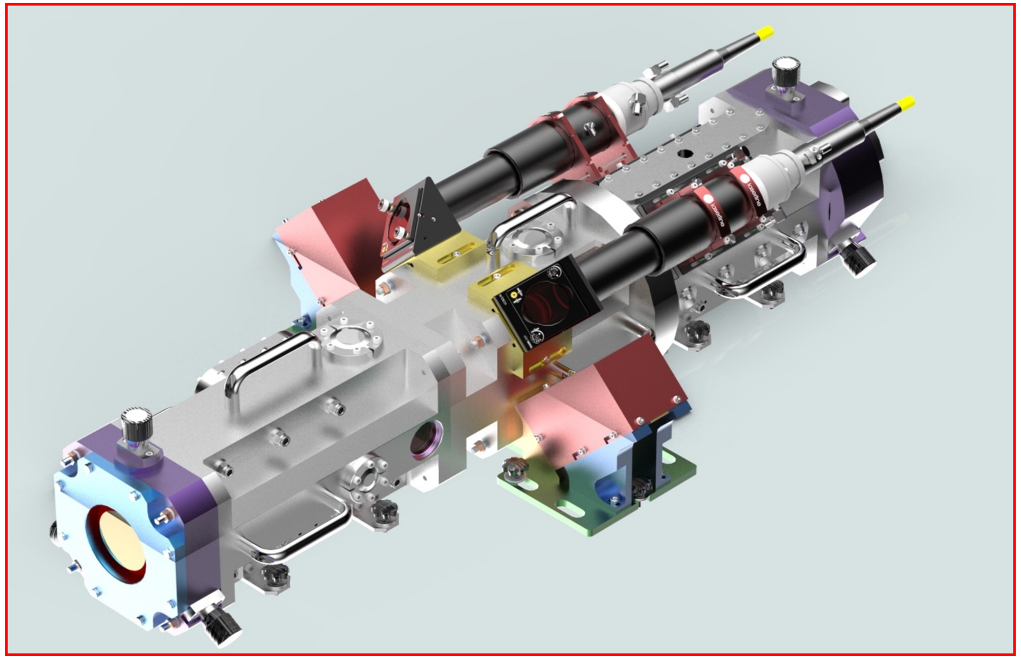
Laser based THz acceleration – tight synchronization

1-J, ps class lasers operating at 1 kHz repetition rate

AXSIS @ SINBAD







Acknowledgement

HELMHOLTZ
ASSOCIATION

erc
European
Research
Council

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
UNITED STATES AIR FORCE

DARPA

Alexander von Humboldt
Stiftung / Foundation

DFG Deutsche Forschungsgemeinschaft

cui

ACHIP
Accelerator on a Chip International Program