THz Acceleration and Sub-Femtosecond X-ray Sources

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Frontiers in Attosecond X-ray Science: Imaging and Spectroscopy

AXSIS

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University of Hamburg

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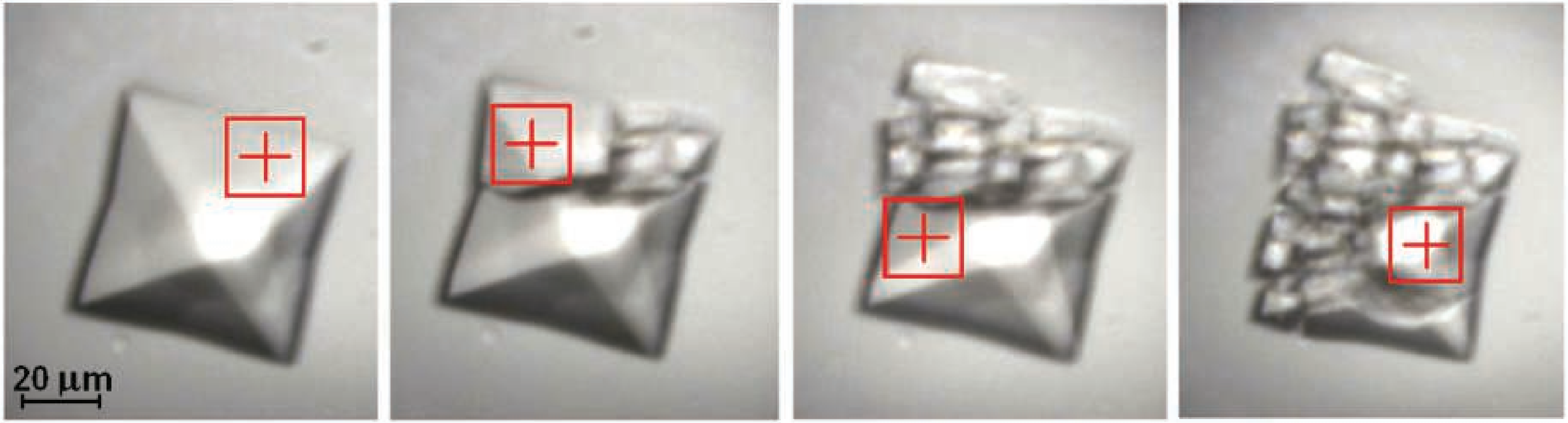
And Associated Scientists from Mid-Sweden University, DESY, and MIT

UHH DESY CFEL SCIENCE MSU MIT erc

Radiation damage requires large crystals

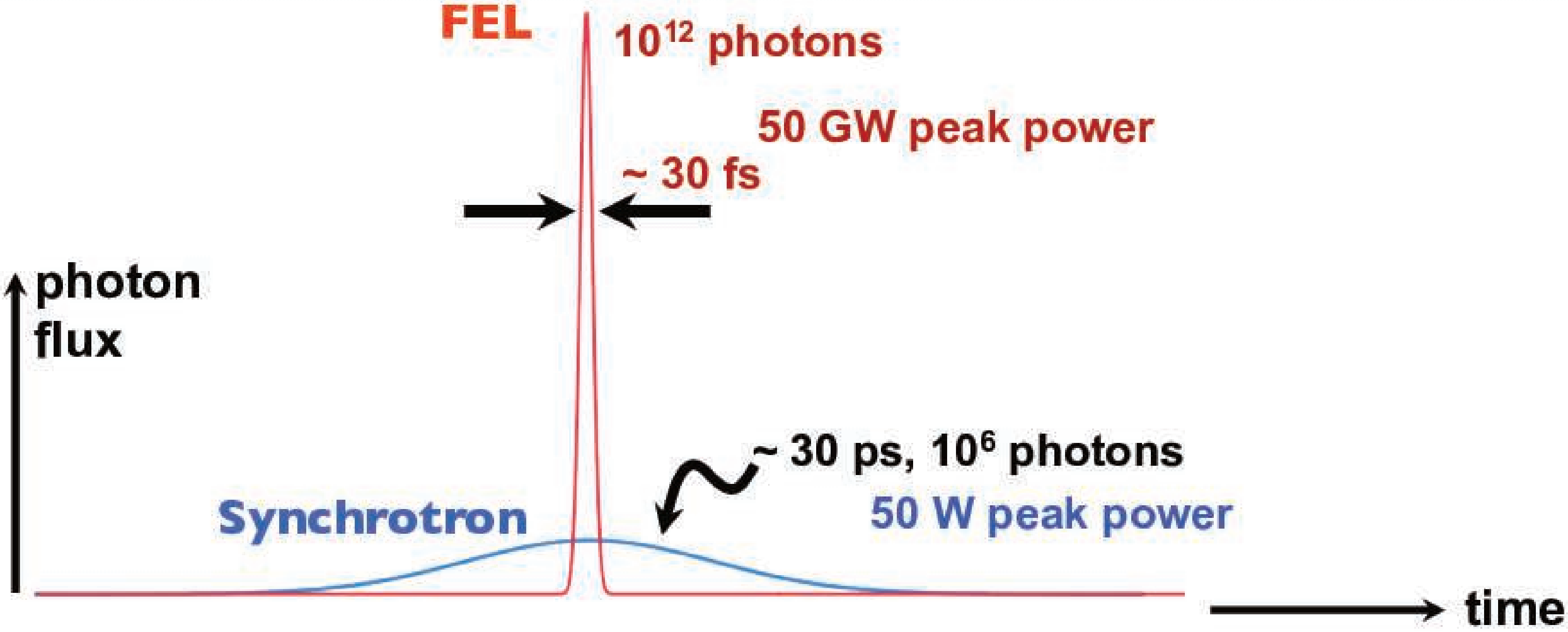


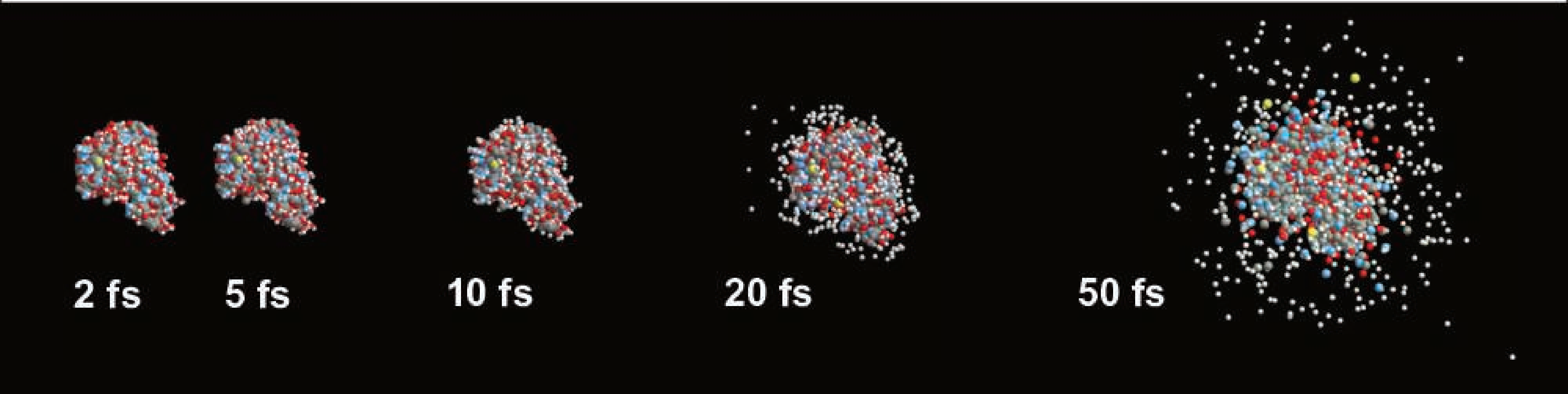
Exposure of a protein crystal to 300 kGy dose (1 second exposures).

The crystal is destroyed, even though this corresponds to less than one X-ray photon scattered per molecule

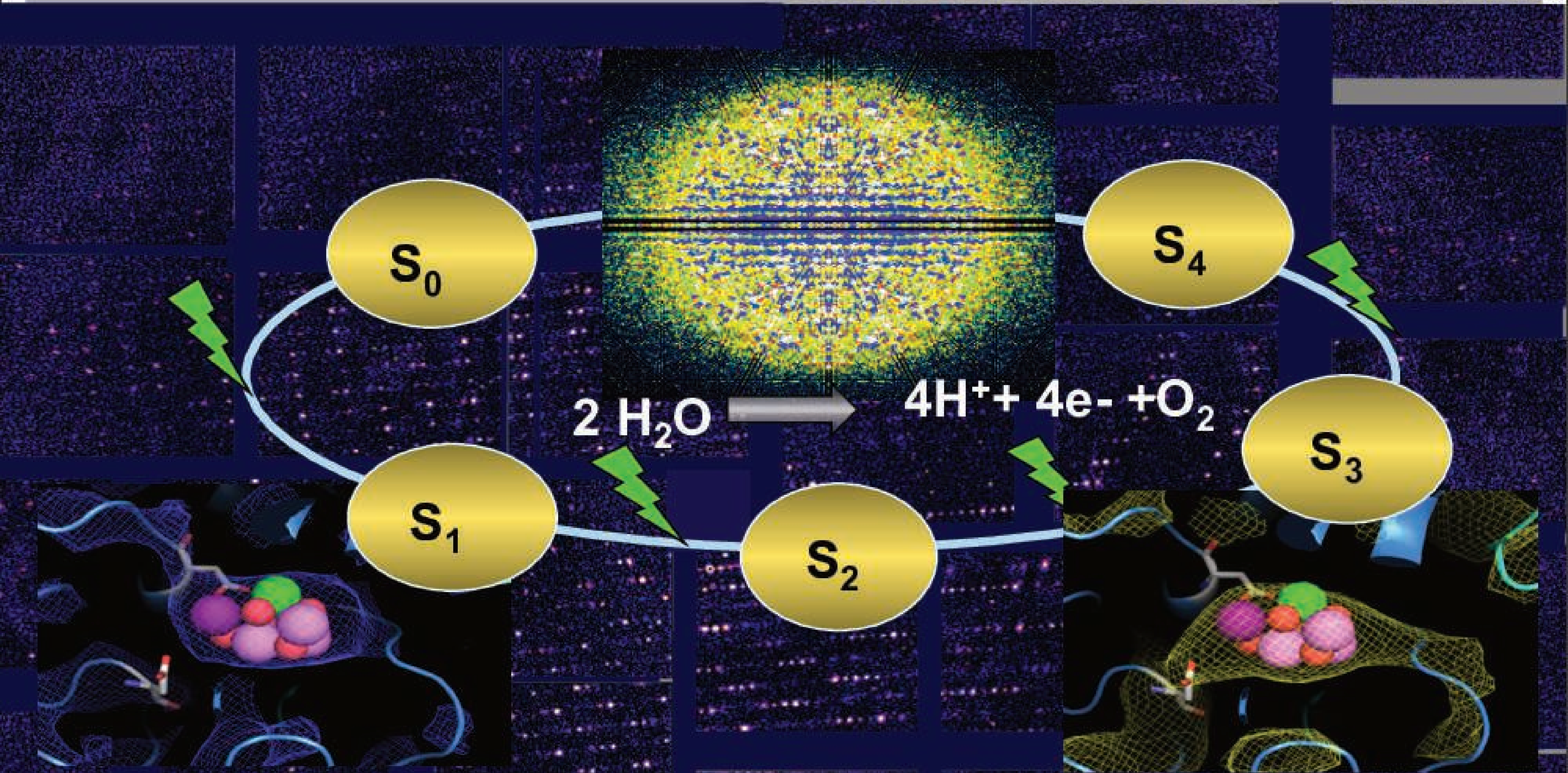
Radiation damage limits X-ray dose, requiring large crystals to obtain measurable signal. These can take years of effort to obtain

X-ray FELs are a billion times brighter than synchrotrons





The S-state cycle of water splitting

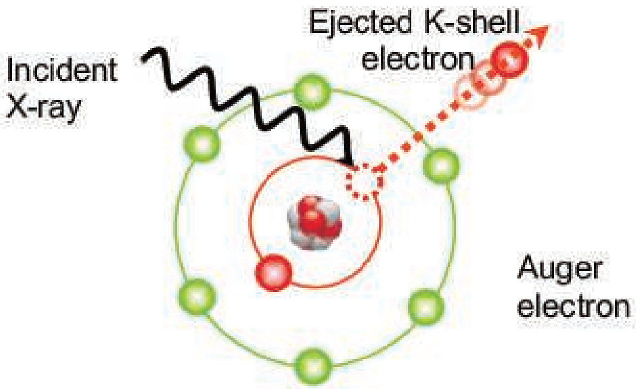


4 electrons & 4 protons extracted from the manganese cluster in 4 light flashes

These coincide with a change of the oxidation states the manganese cluster

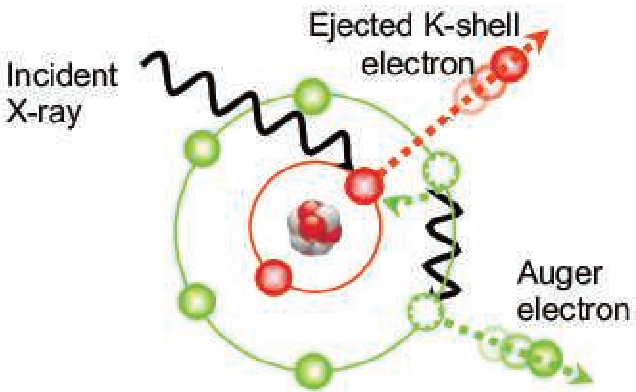
Elucidate electronic and atomic structure to understand the mechanism

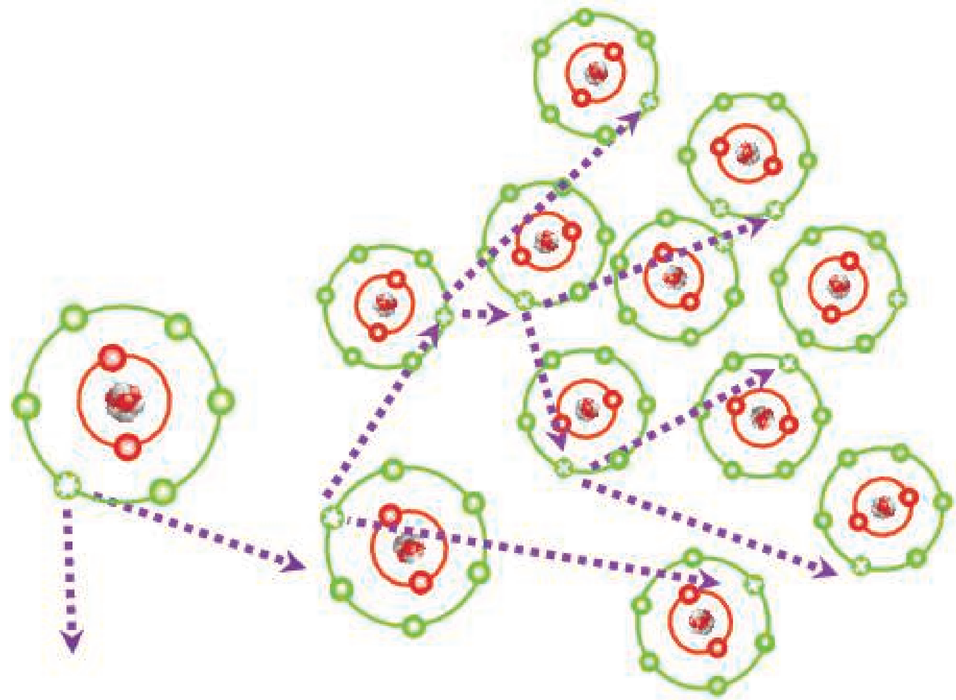
We must outrun electronic processes



We require sub-fs exposures to measure the chemical environment at atomic scale.

Time scale is **Auger decay rate**





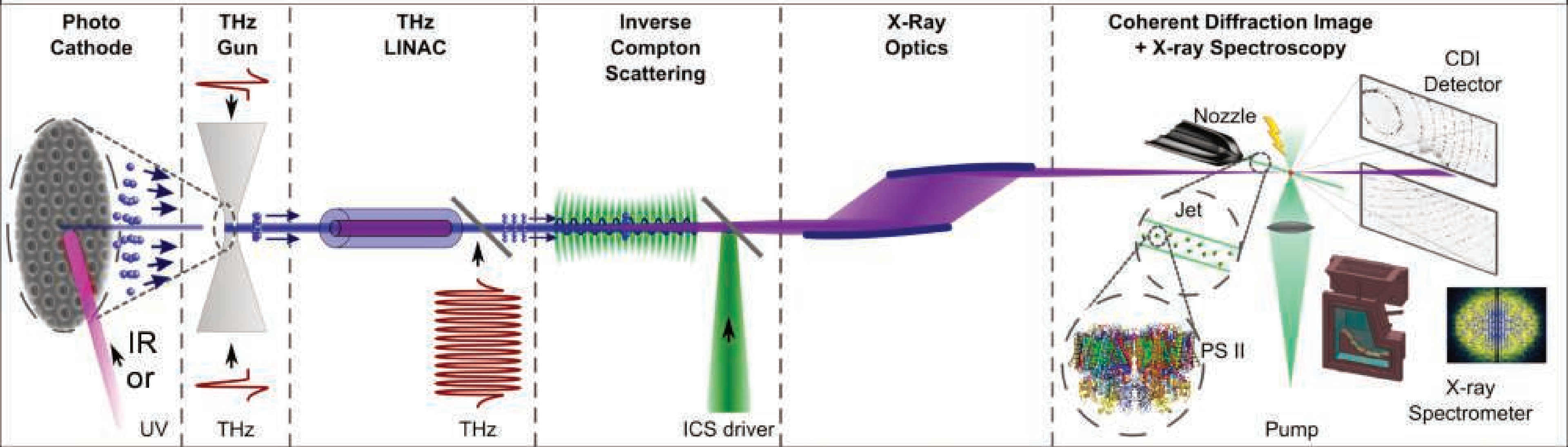
Auger decay rates
O: 3 fs
S: 1 fs
Mn: 0.2 fs

L. Young et al., Nature 466, 56–61 (2010)
S.-K. Son et al., Phys. Rev. Lett. 107, 218102 (2011) and Phys. Rev. A 83, 033402 (2011).

Attosecond CD - imaging and spectroscopy of biomolecules

Damage-free structure

Undisturbed electronic structure



All laser driven, intrinsic attosecond synchr., laser-based THz-accel.

Only pico-second lasers at 1J-level necessary -> kHz operation

→ All optical driven fully coherent attosecond X-ray source:

→ has its own science case

→ seeding of large scale FELs

→ resolve access problem to large facilities

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

Outline

- Why THz acceleration?
- Laser driven THz Sources based on optical rectification and cascaded optical parametric amplification
- Accelerating Structures and Guns
- First results
- Conclusions

Why THz Acceleration?

- **Increasing operational frequency:**

higher breakdown fields: $$\boxed{E_{break} = \frac{1}{\tau} \approx f}$$

Historically:

[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).

- **reduced pulse energy to achieve same electric field in the cavity:**

stored energy: $$\boxed{E_P \sim \lambda^{-3}}$$

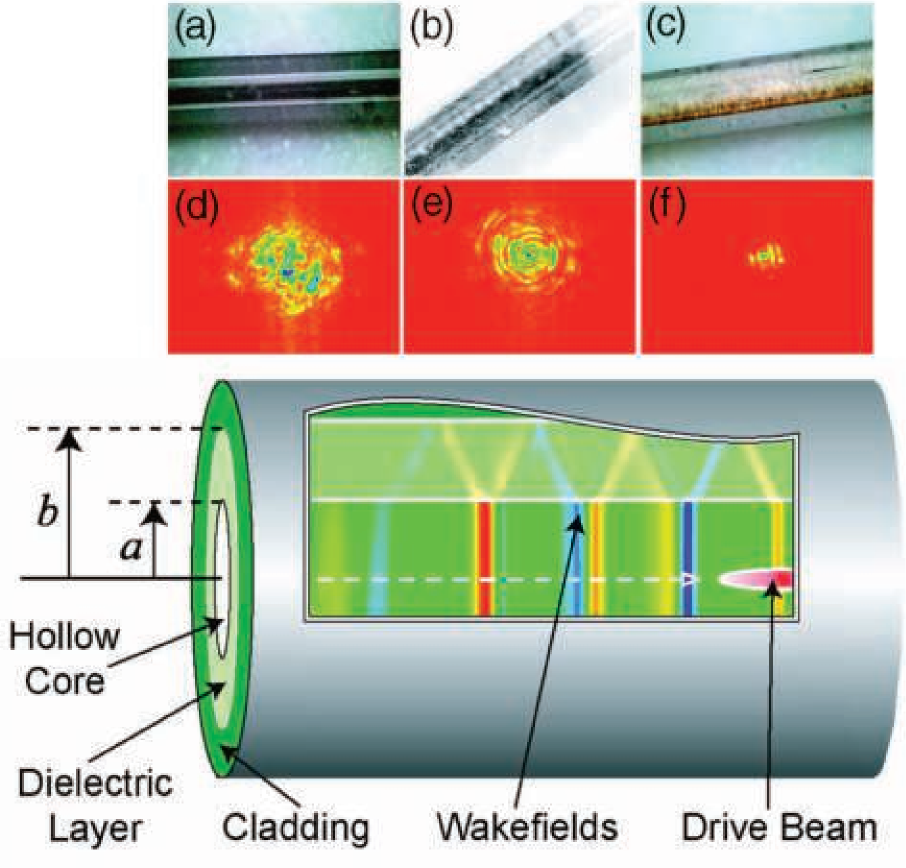
reduced pulsed heating: $$\boxed{\Delta T \propto \frac{E_P}{A_{SURFACE}} \propto \frac{V_{CAVITY}}{A_{SURFACE}} \propto R \propto \lambda}$$

→ high repetition rate operation becomes possible!

- **High-gradient accelerators:** reduced size, short bunches and improved electron beam quality, i.e. lower emittance!

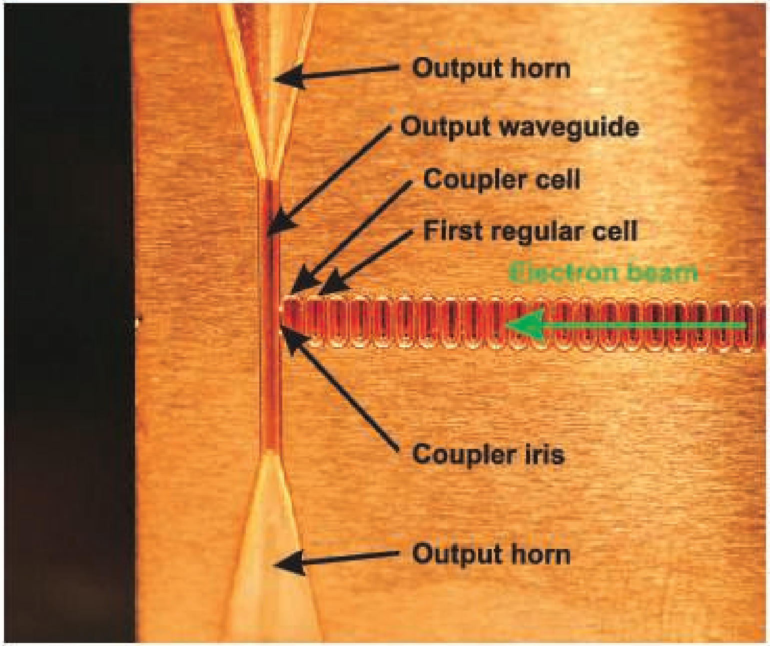
Scaling

Dielectric Wakefield Acceleration: 5.5 GV/m



Thompson, M. C., et al., *PRL* 100.21 (2008): 214801.

115-140 GHz copper structures: 0.3 GV/m accelerating fields with peak surface fields of 1.5 GV/m and 2.4 ns pulses



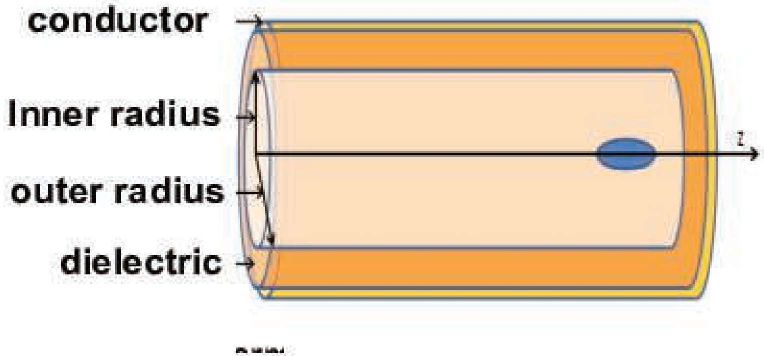
M. D. Forno, et al. PRAB. 19, 011301 (2016).

Interesting THz range

- 1-10 pC Charge
- 0.1 – 1 THz (0.3 THz ~ 1 mm)

Beam Driven Acceleration

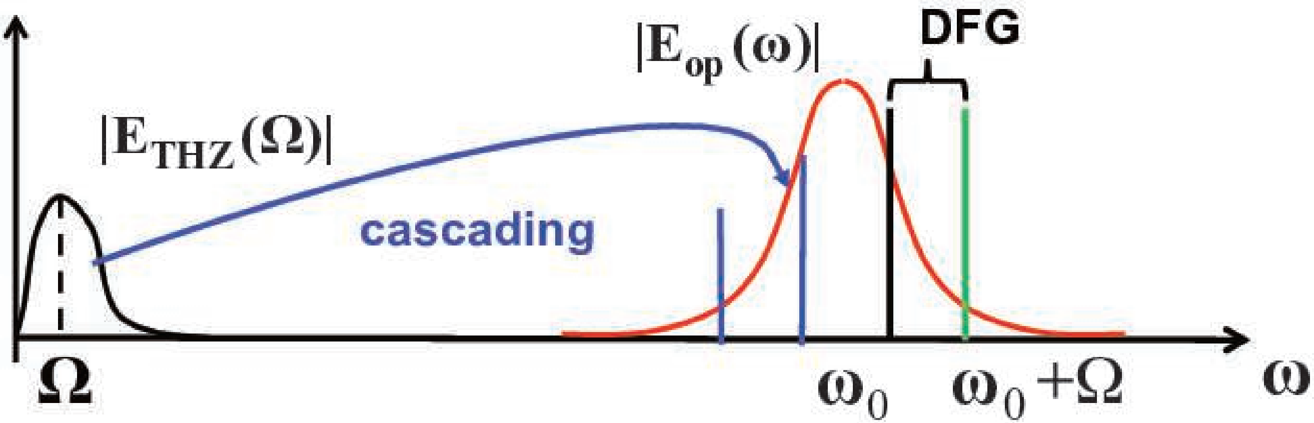
- Voss & Weiland at DESY 1982 – Kinetic energy from bunch to bunch?
- K. L. F. Bane, P. Chen, and P. B. Wilson. Collinear wakefield acceleration. 1985
- Cylindrical DLW theory developed by:
  - K.Y. Ng, Phys. Rev. D42, 1819 (1990).
  - M. Rosing and W. Gai. Phys. Rev. D, 42:1829, 1990.



- HE11 (dipole) mode excitation from small misalignments (Zholents) can lead to beam breakup - PhysRevSTAB.17.091302
- Here: Laser generated THz beams excite single monopole mode.

Laser driven THz Sources

- **Optical rectification: ~ 1 % energy conversion efficiency[1], ~ mJ THz pulse energy[2,3]**



- **Intra-pulse difference frequency generation**
- **THz bandwidth can be as broad as optical pulse bandwidth**
- **Must satisfy phase-matching condition**

$$\vec{k}(\omega+\Omega)-\vec{k}(\omega)=\vec{k}(\Omega)$$

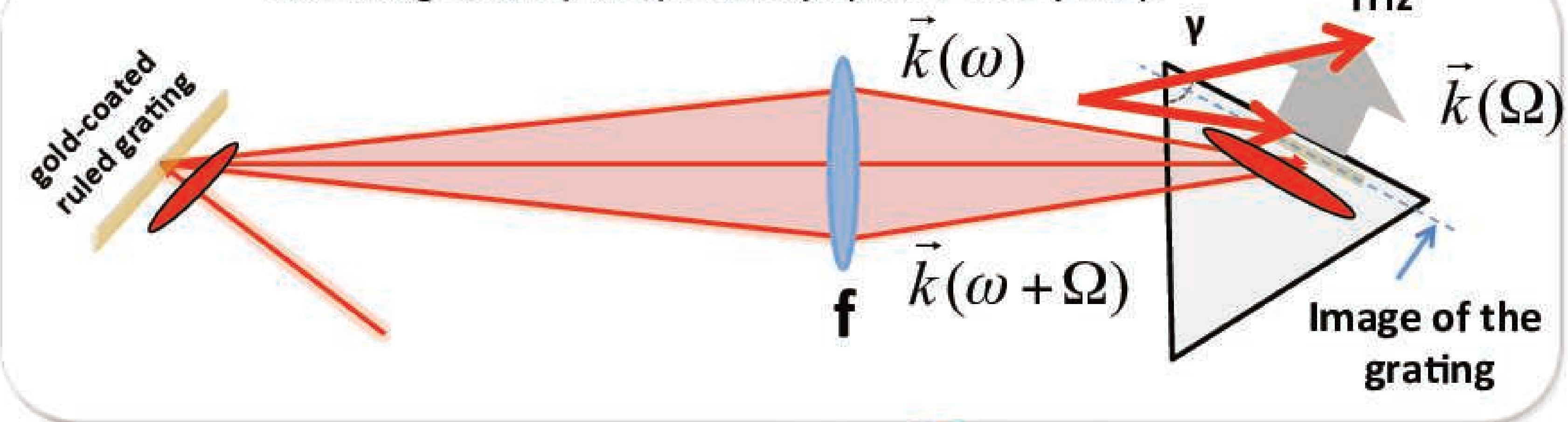
Lithium Niobate

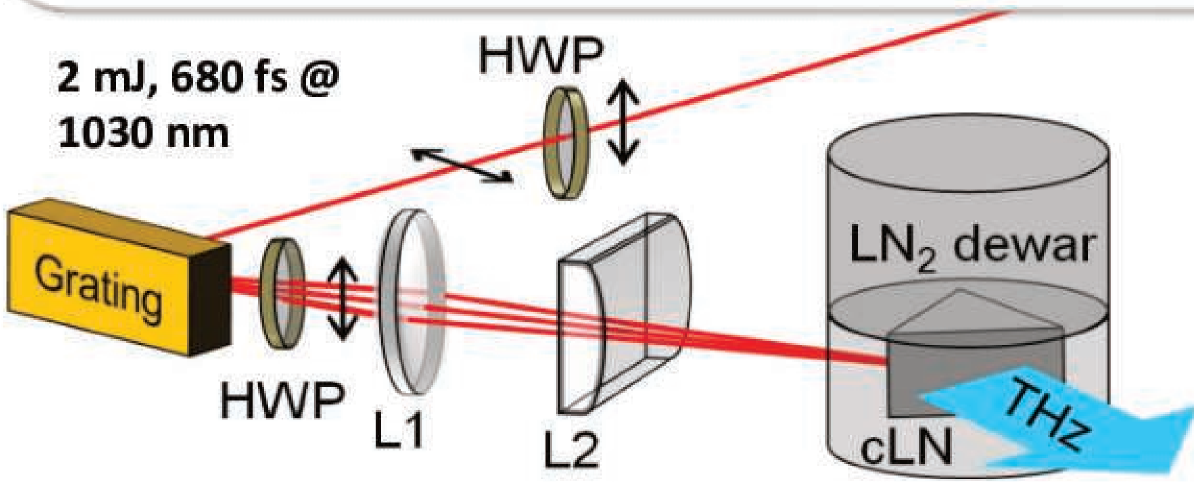
$$\boxed{n_g(\omega)=2, \quad n_p(\Omega)=5}$$

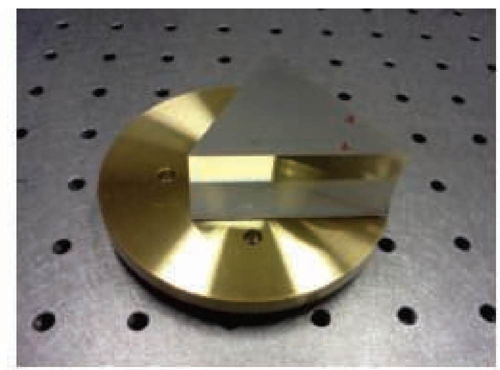
1. S. W. Huang et al Opt. Lett. 38(5), 796-798 (2013).
2. C. Vicario, Opt. Lett., 10.1364/OL.99.09999 (2014).
3. J. A. Fulop et al , Opt. Express 22(17), 20155-20163 (2014).

Optical rectification using Tilted Pulse Fronts

J. Hebling et al, Opt. Express 21(10), 1161-1166 (2002).





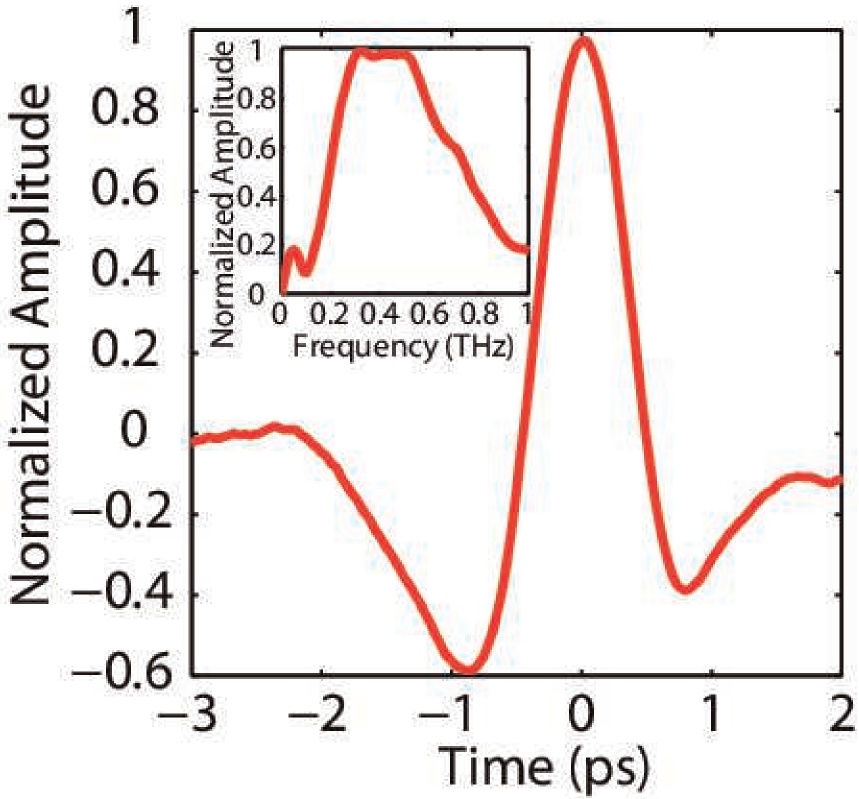


S. W. Huang et al Opt. Lett. 38(5), 796-798 (2013) → **1% optical to THz conv.**

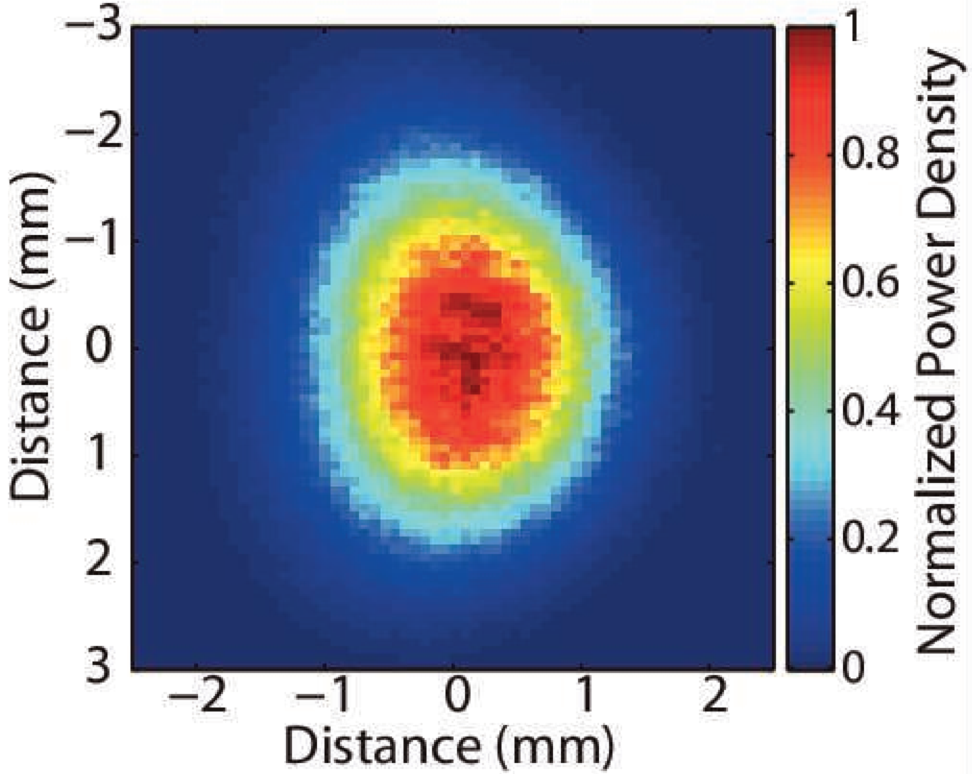
K. Ravi, et al., "Limitations to THz generation by optical rectification using tilted pulse fronts," Opt. Express 22, 20239 (2014).

Spatio-temporal characterization

Electro-Optic Sampling Trace



Beam Profile



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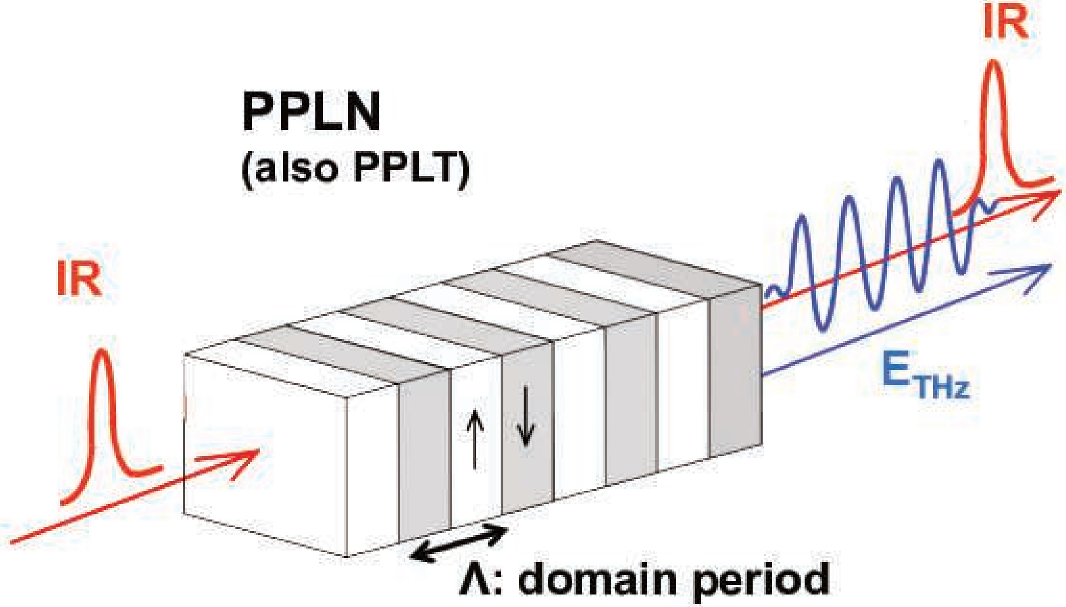
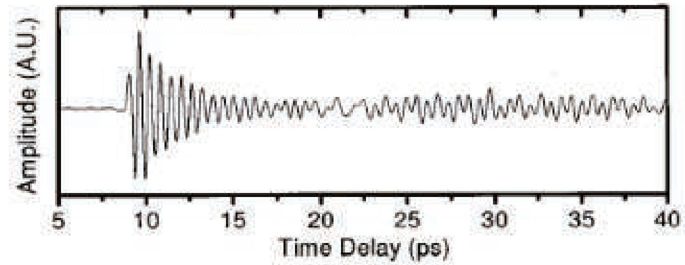
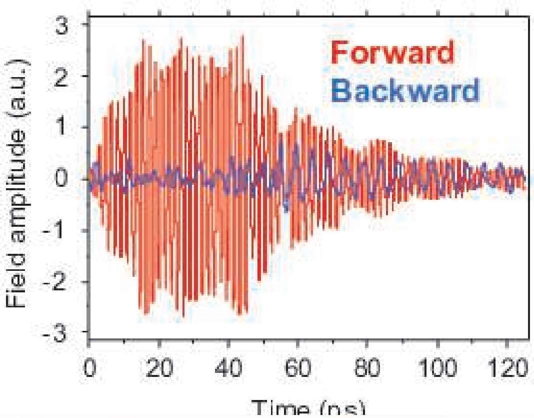
Quasi – phase matching for multi-cycle terahertz generation

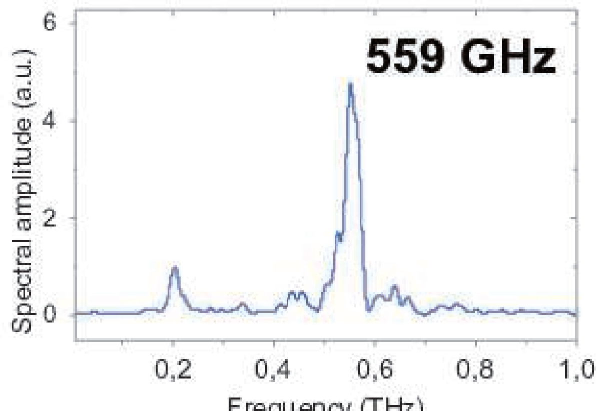


Lee, App. Phys. Lett. 77 (2000)
Lee, App. Phys. Lett. 78 (2001)
Yu, Opt. Comms. 284 (2011)

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



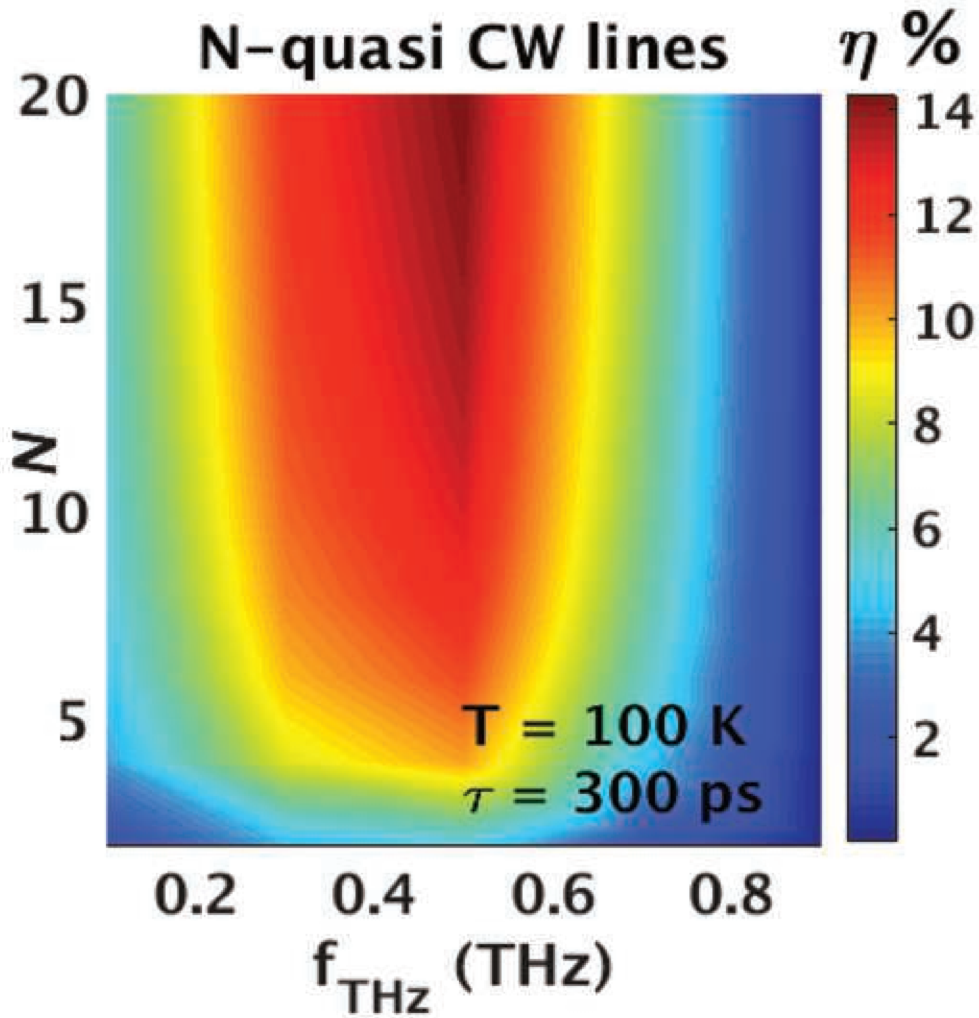


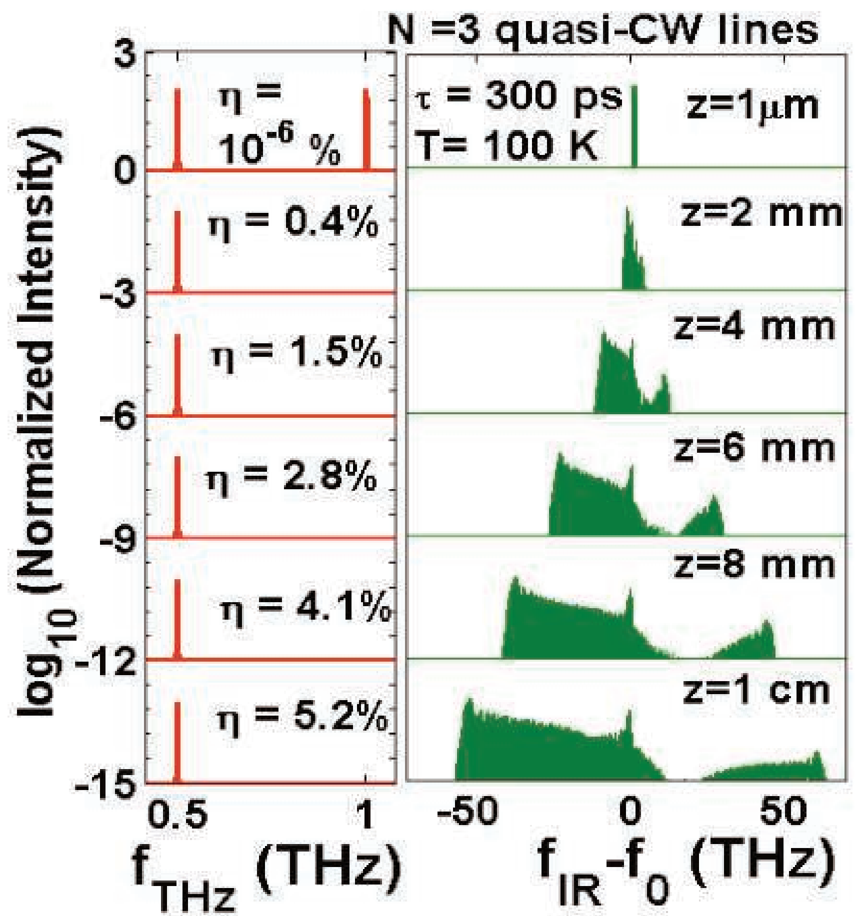


- mJ - level energies
  → 10^{-3} conversion efficiencies

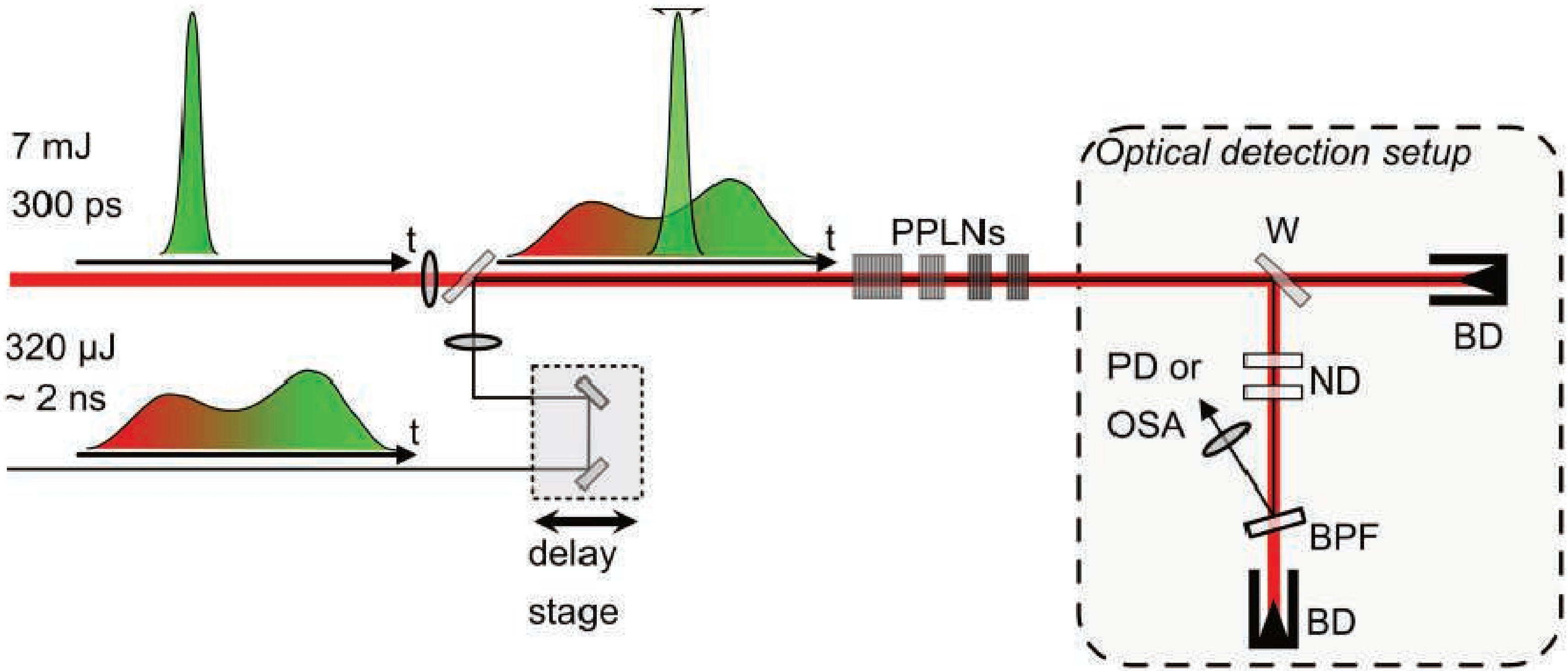
Scalability: sofar only 1 cm x 0.3 cm commercially available.

Highly Efficient THz Generation: Multi-line DFG

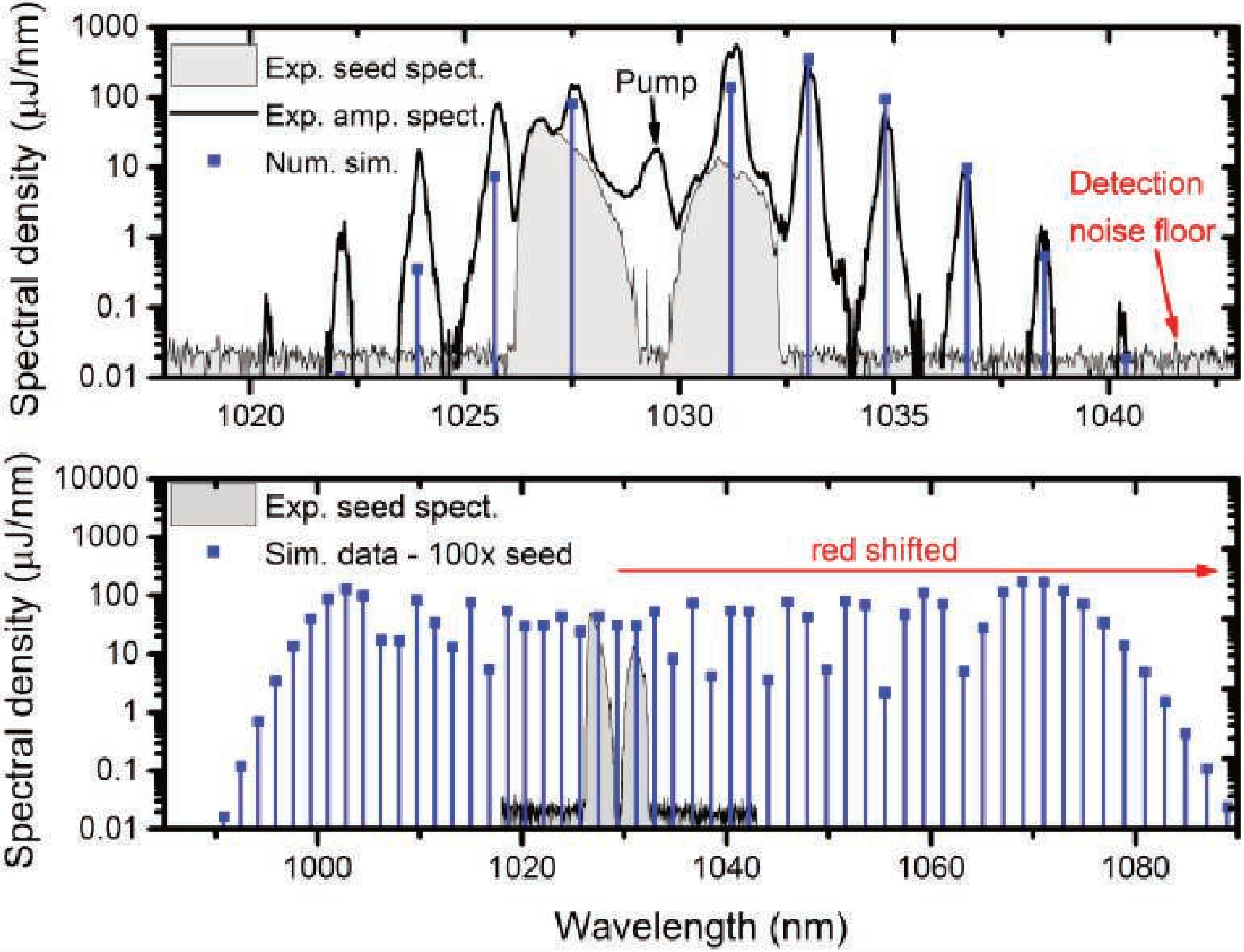




THz – COPA: Experiments



THz – COPA: Experiments



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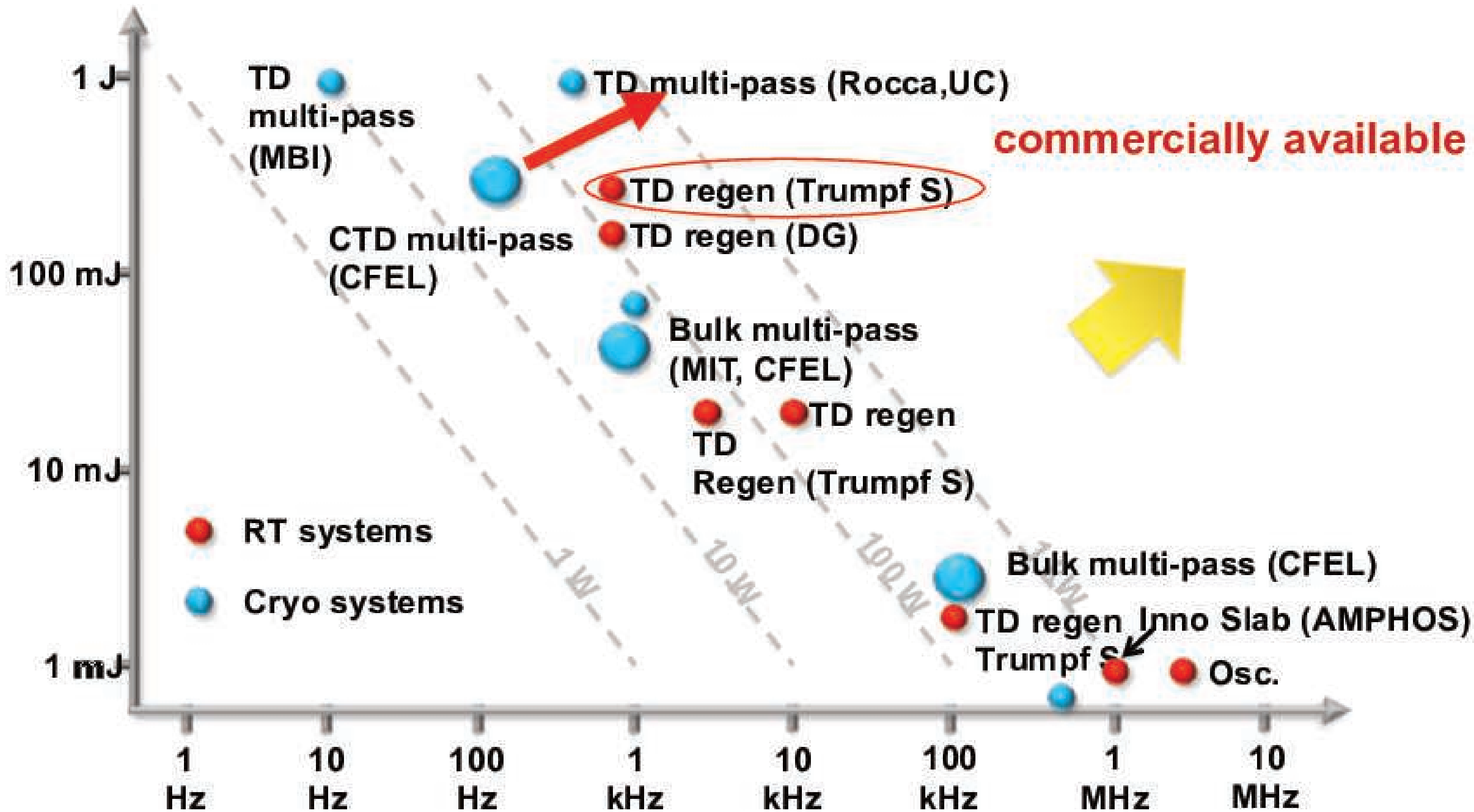
Room temperature!

State of the art Yb:YAG ps-ns laser technology



Cryogenic technology for energy and power scaling with robust laser architecture

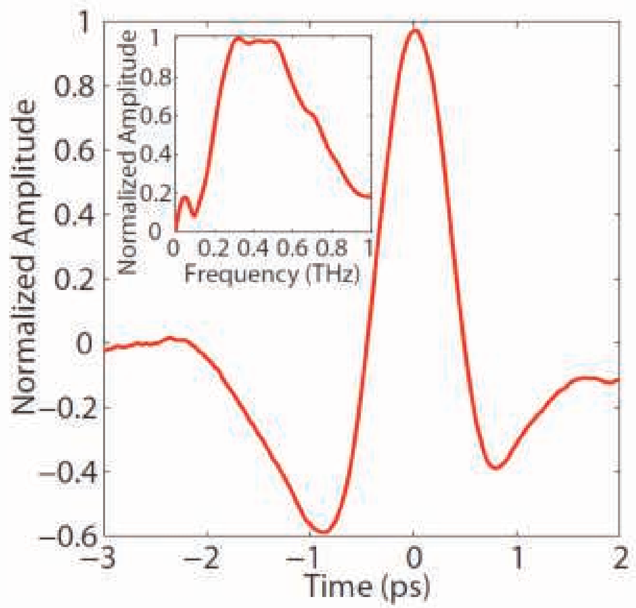
L. Zapata et al.. Opt. Lett. (2015) and (2016).

THz Gun and Acceleration Experiments with μJ – single-cycle THz pulses

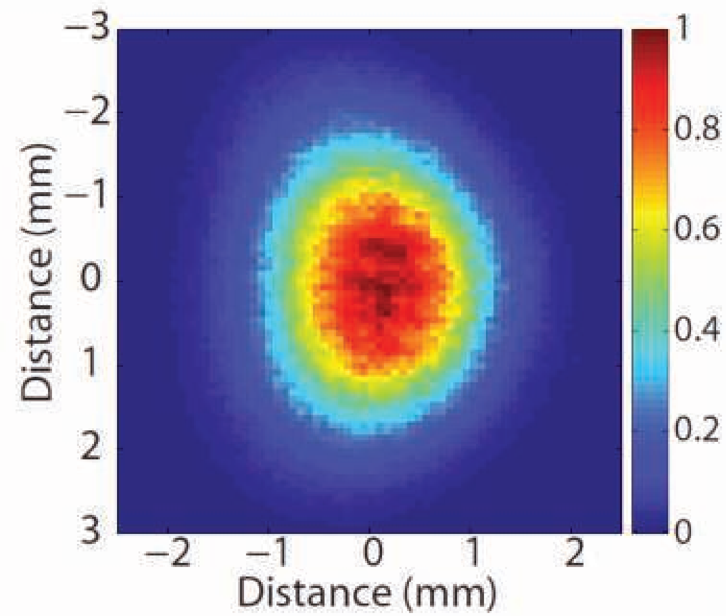
THz Pulse Properties

- Single cycle THz pulse (~2 ps) centered at 0.45 THz
- 10 μJ pulse measured ~1 m from source

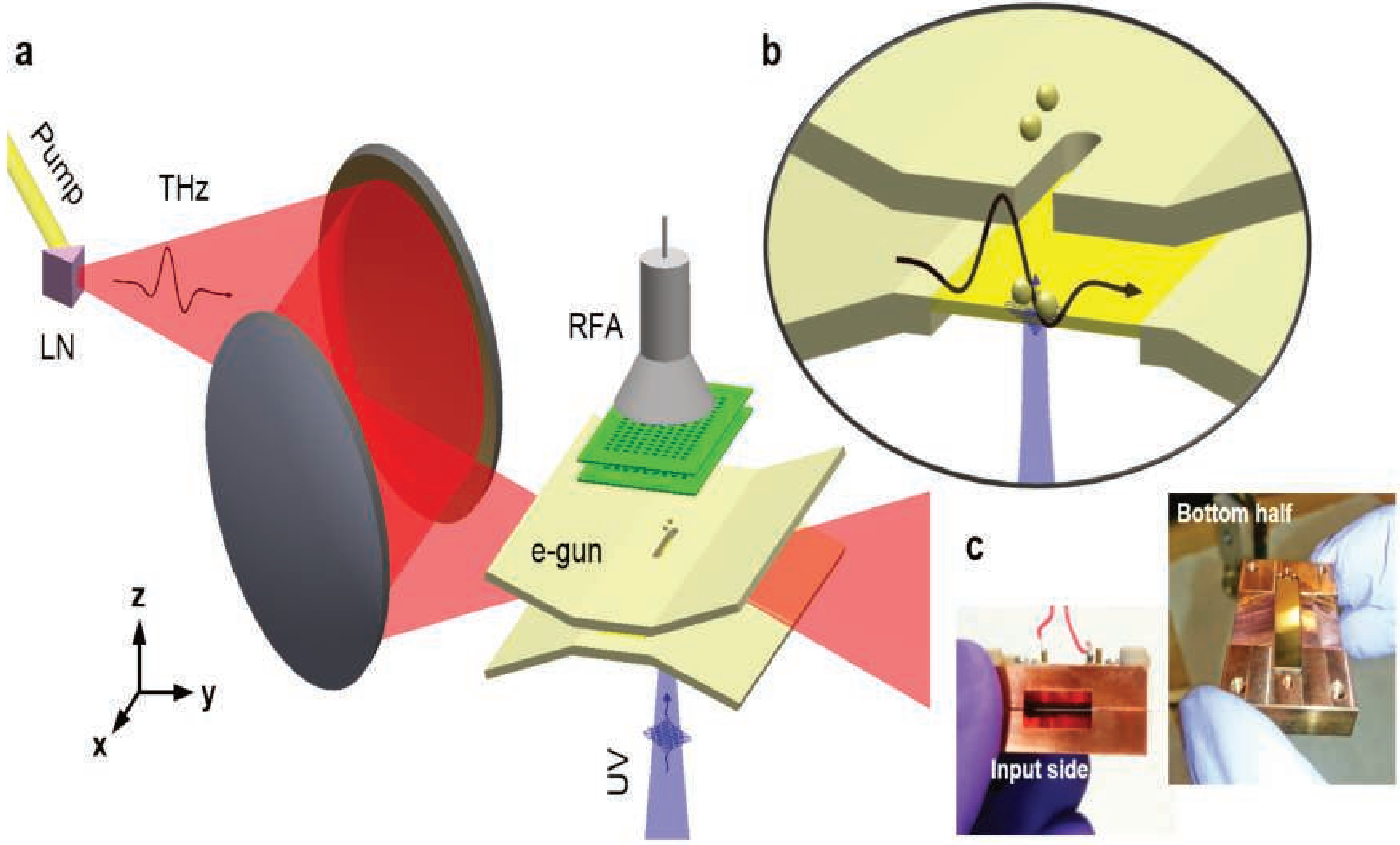
Electric Field from EO Sampling



Transverse Intensity Profile



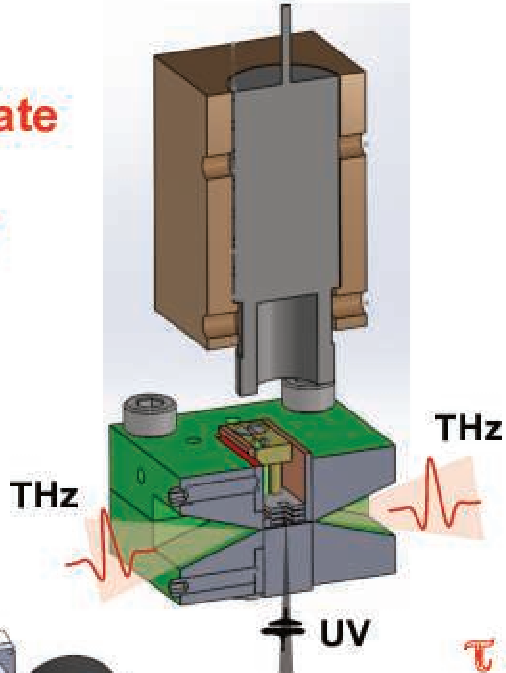
First THz gun results

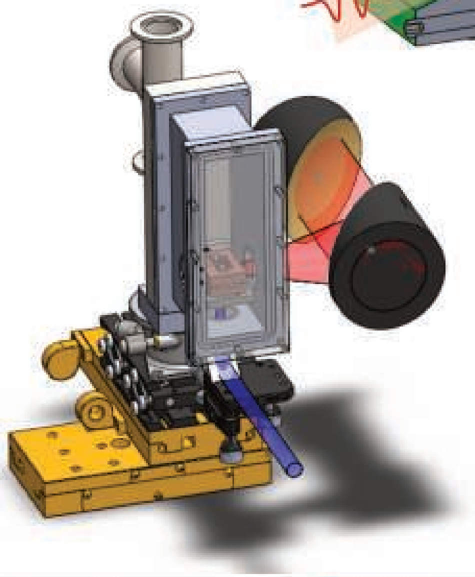


W. Huang, et al. Sci. Rep. 5, 14899 (2015)
and more coming soon

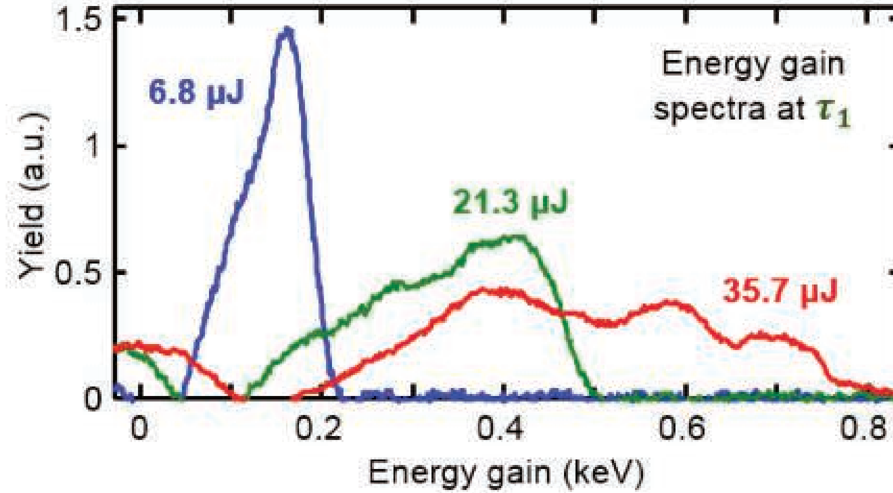
First THz gun results towards 1 keV

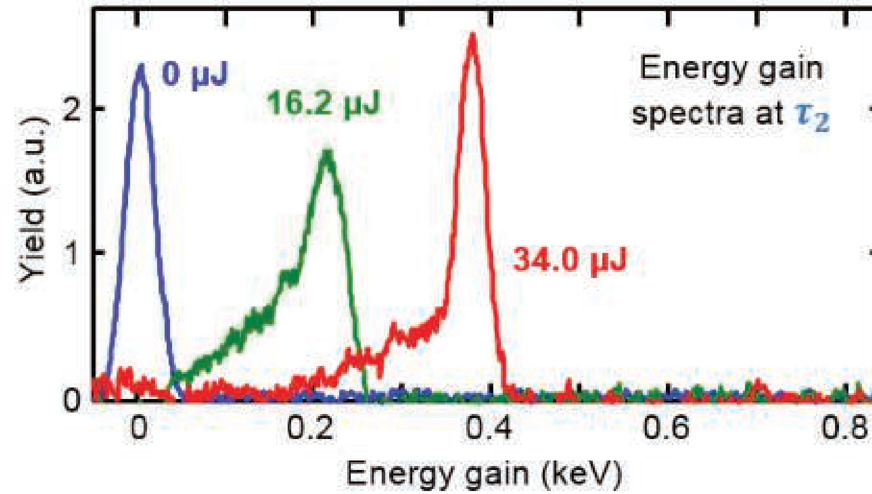
Parallel-Plate Gun with 75 μm gap





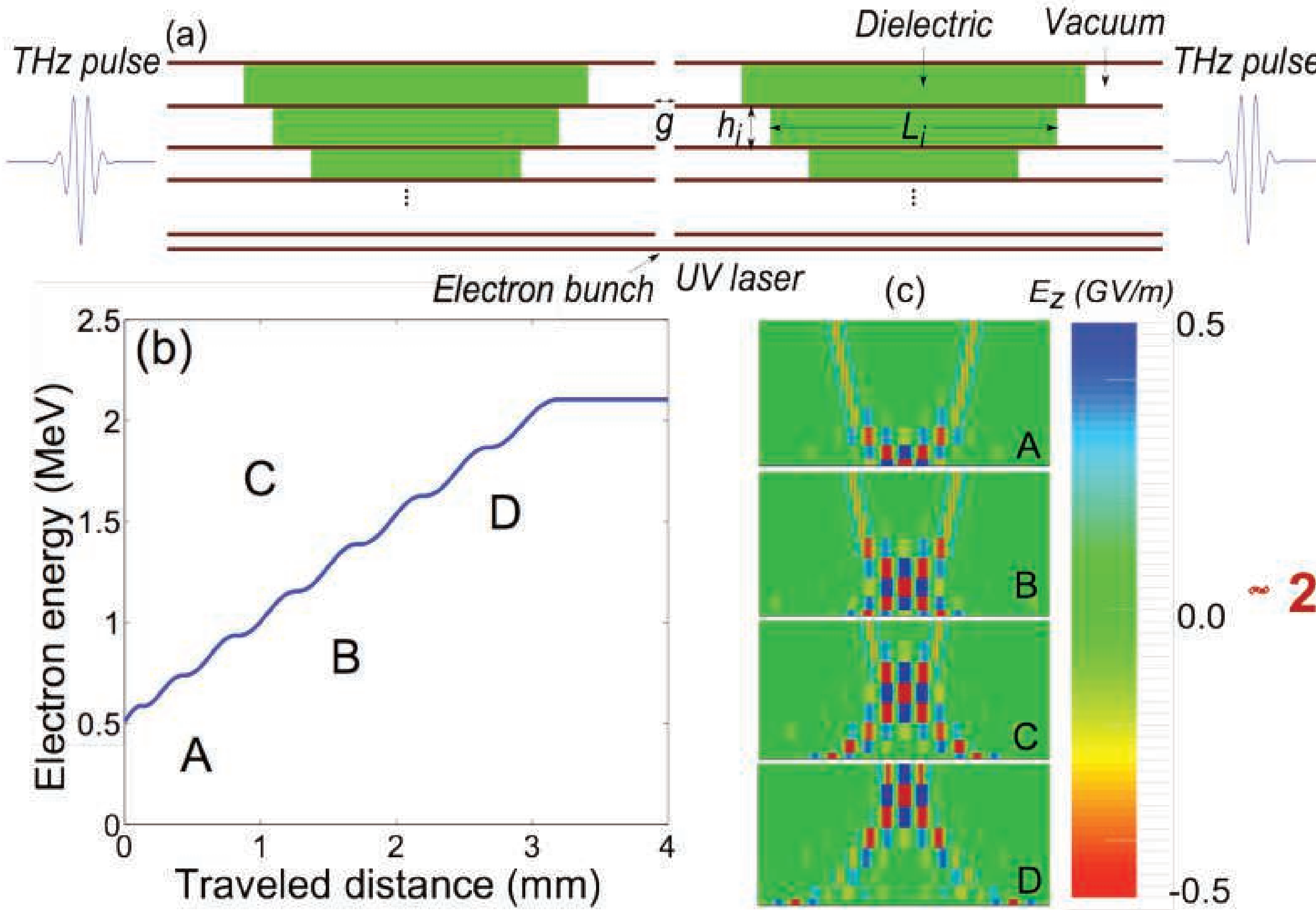
$\tau_{1,2}$





W. Huang, et al. Sci. Rep. 5, 14899 (2015)
and more coming soon

Single-Cycle e-guns and accelerators

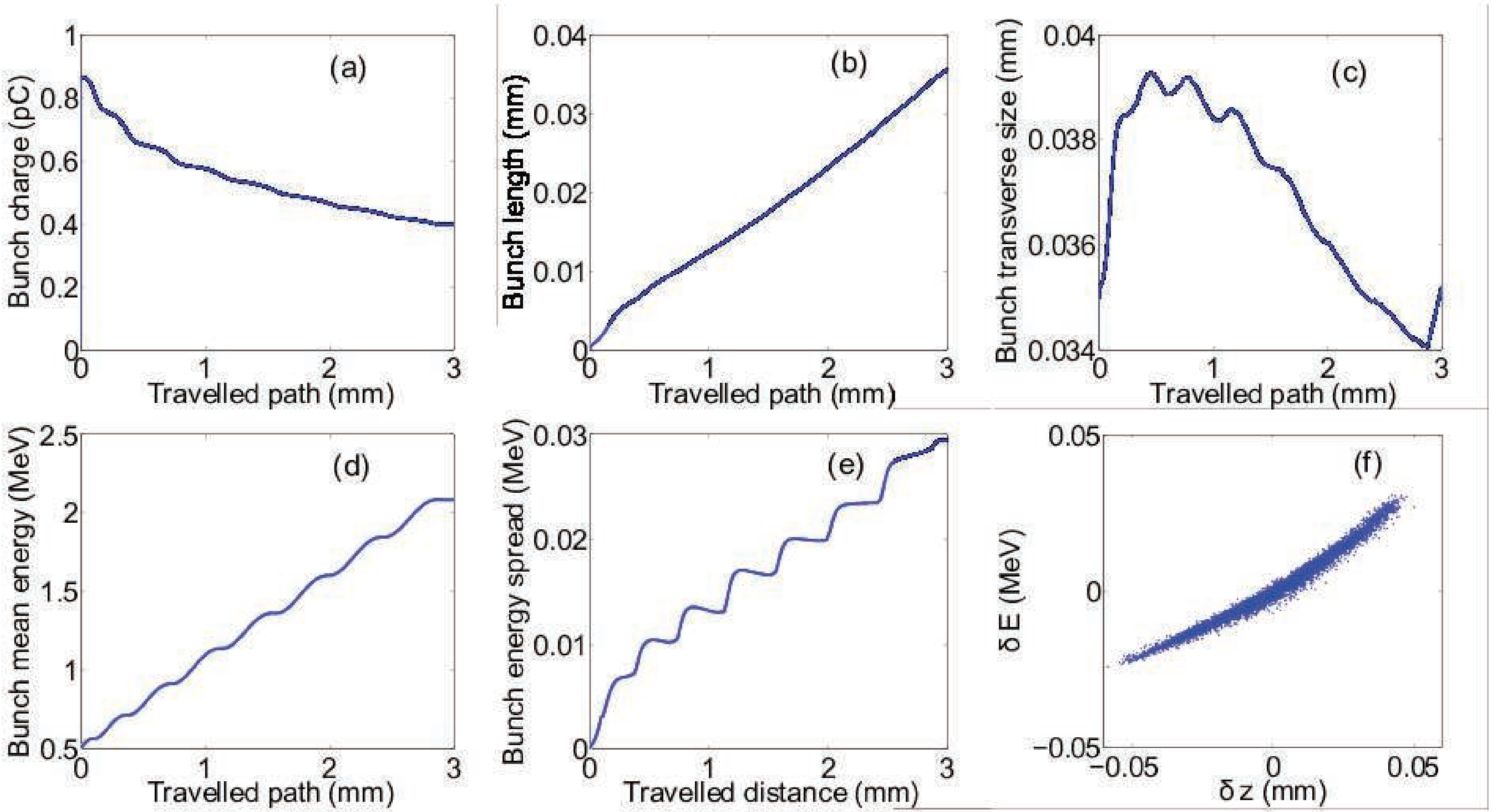


~ 2x1 mJ

A. Fallahi, et al. Submitted

Patent filed

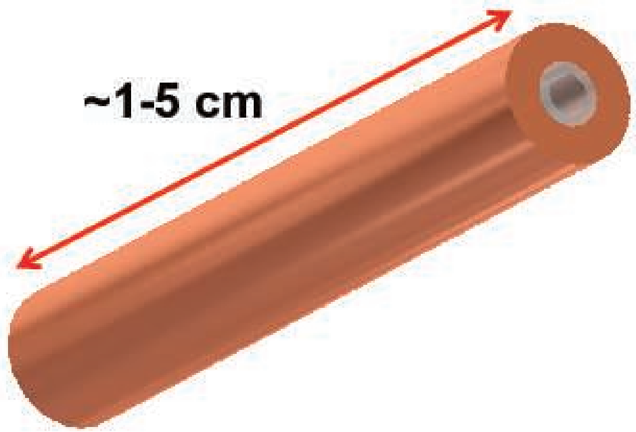
Single-Cycle e-guns and accelerators



THz Acceleration

Dielectrically Loaded Circular Waveguide

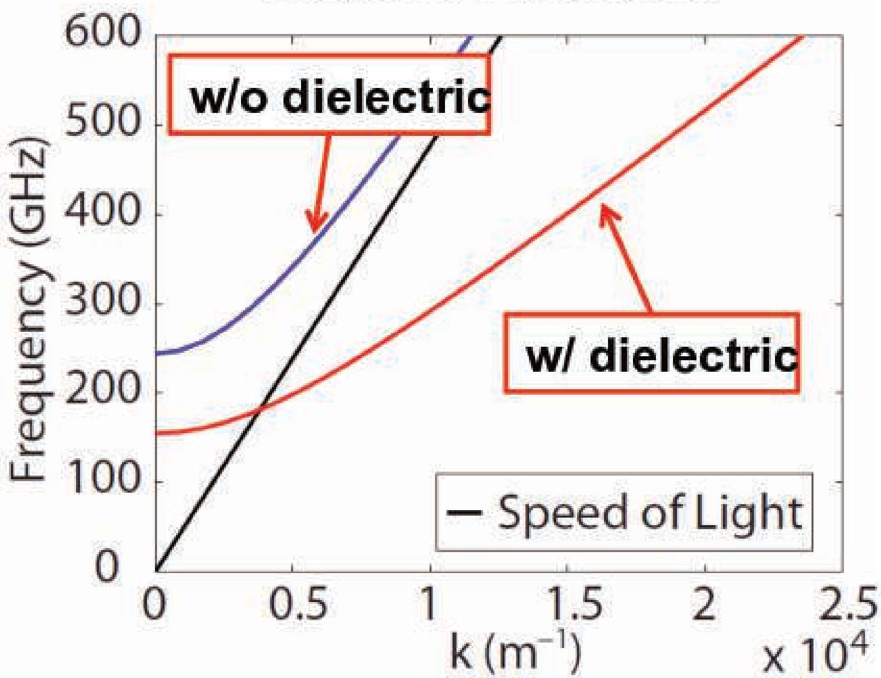
- Traveling wave structure is best for coupling broad-band single cycle pulse
- Phase-velocity matched to electron velocity with thickness of dielectric



Copper Inner Diameter = 940 µm

Fused Silica Inner Diameter = 400 µm

Dispersion Relation

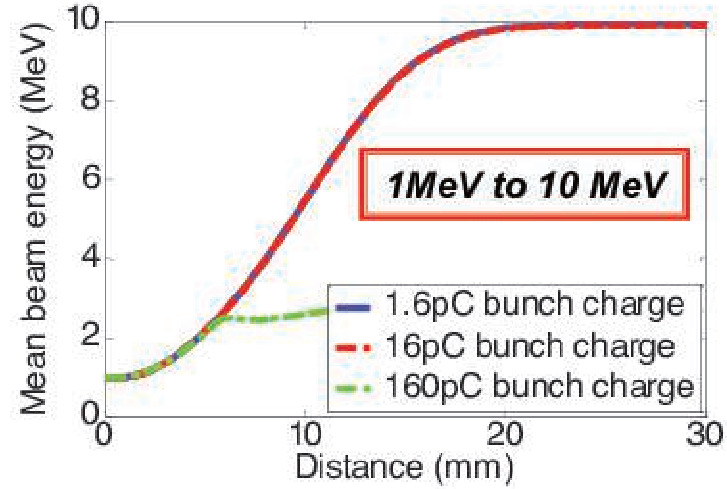


Electron Acceleration using THz Waveguides

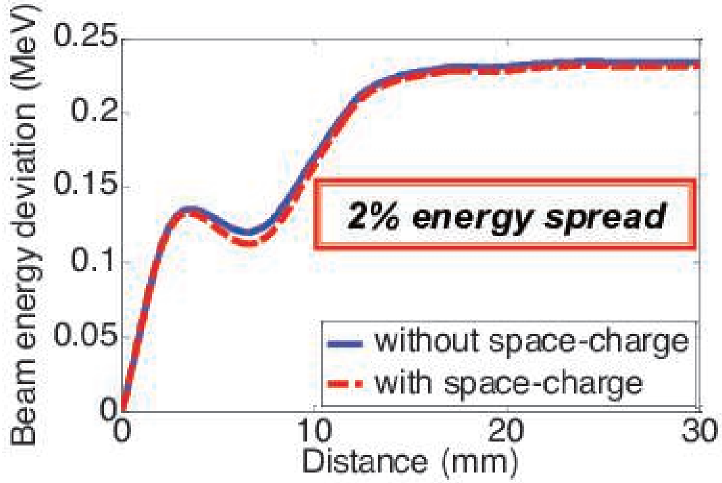
Space Charge Limit

16 pC is easily possible
16 pC x 10 MeV = 160 μJ,
(1% e-beam extraction)

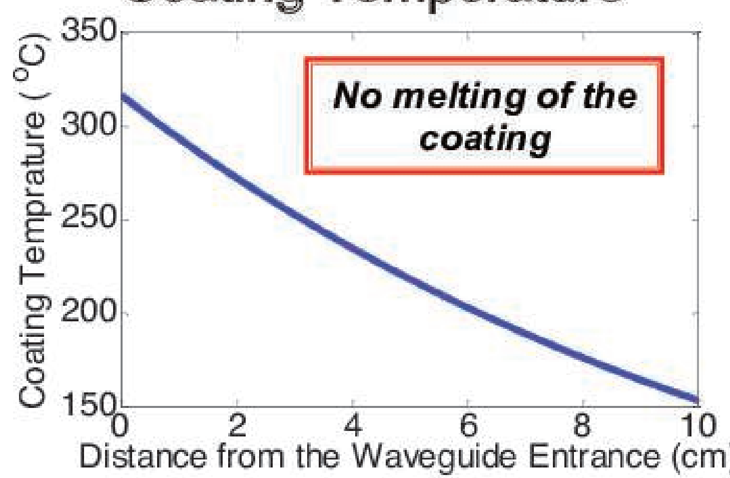
Energy (20 mJ, 10 cycle THz pulse)



Energy spread in bunch

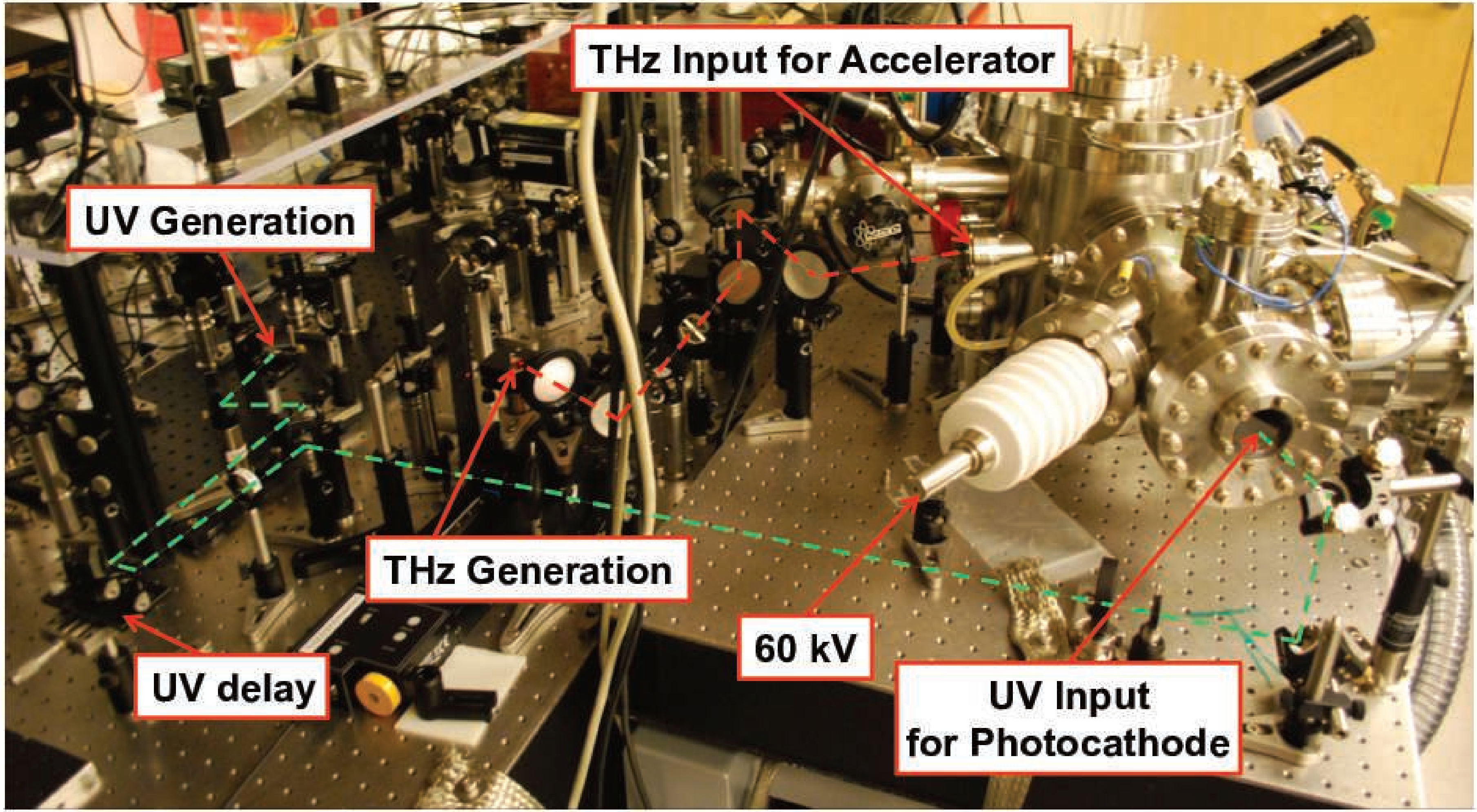


Coating Temperature



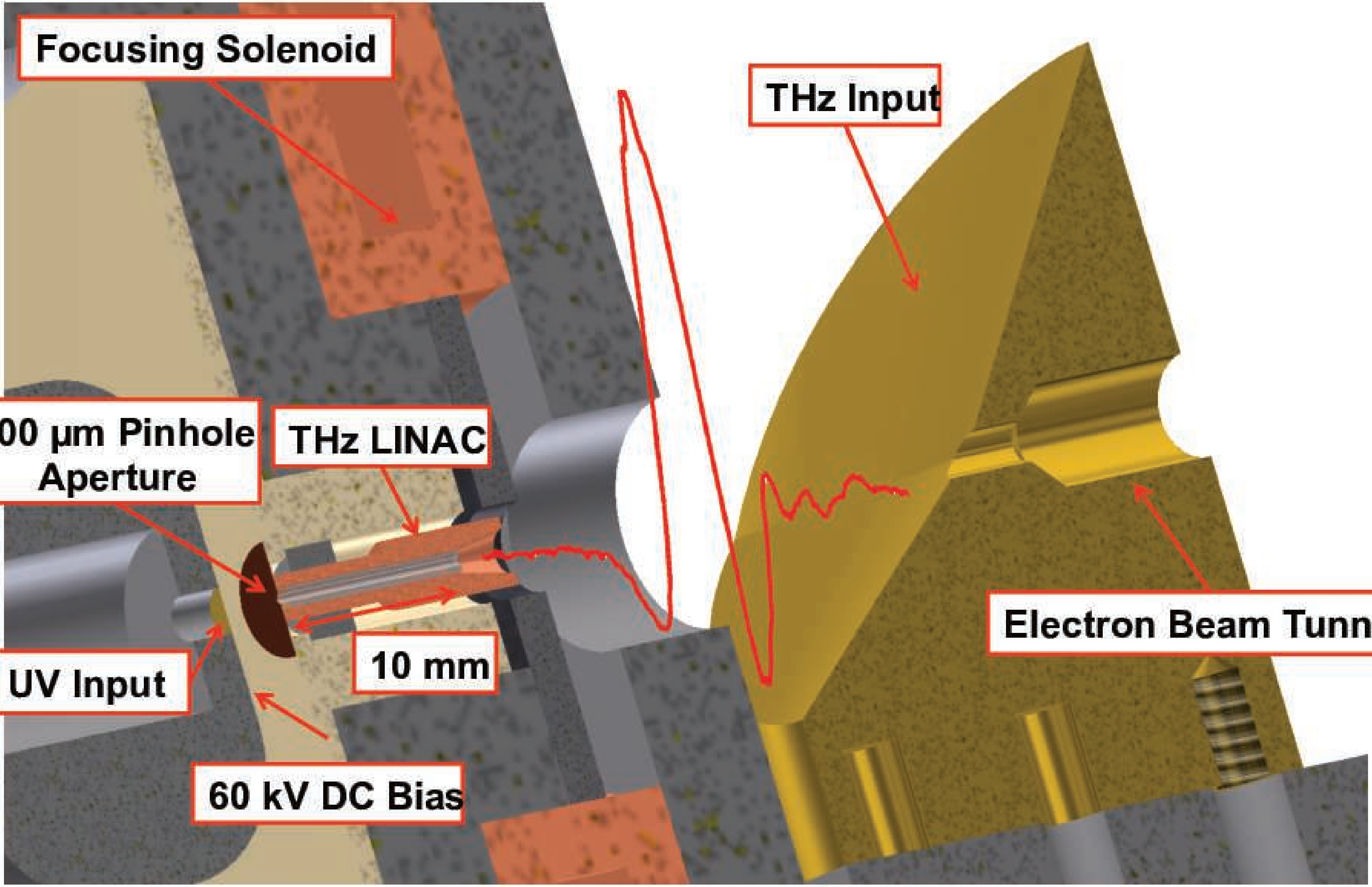
L.J. Wong et al., Opt. Exp. 21, 9792 (2013).

THz Acceleration Chamber



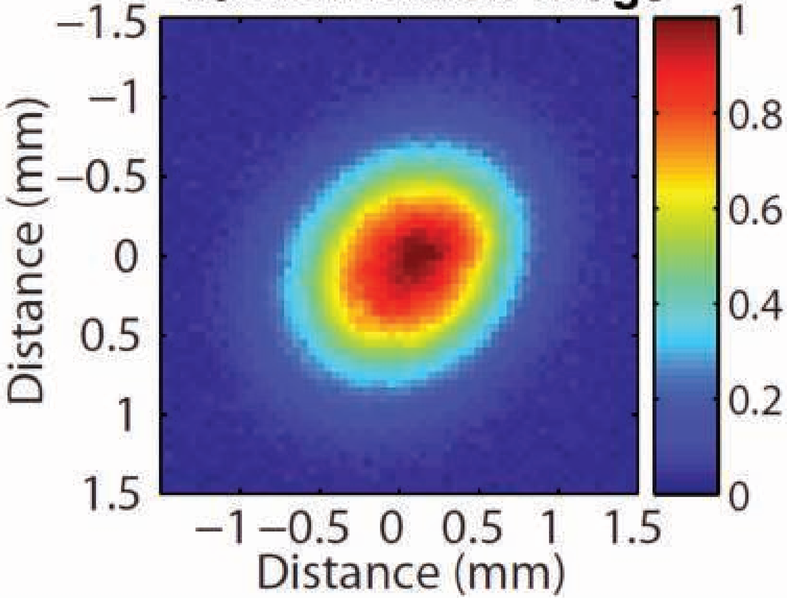
60 keV DC Gun from Dwayne Miller Group

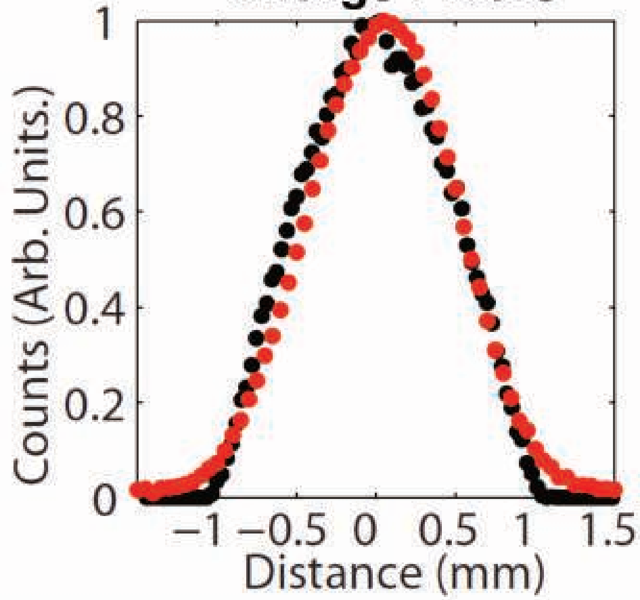
DC Gun and THz LINAC



Electron Beam Parameters

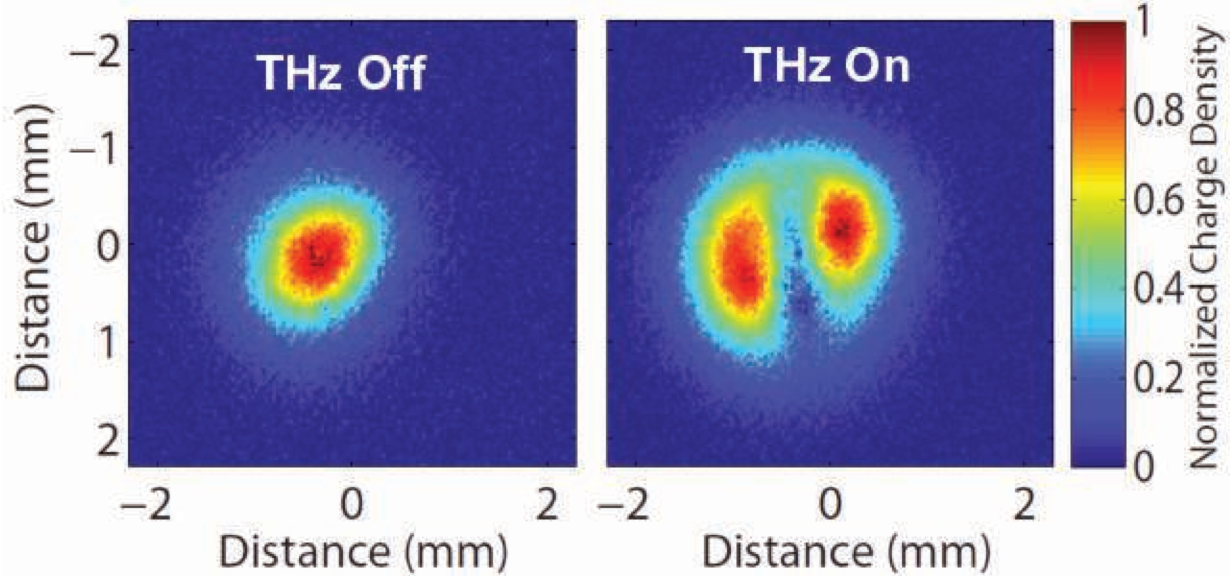
- Electron beam imaged on a microchannel plate (MCP) detector
- Solenoid is optimized to focus electron bunch at MCP
- PARMELA is used to simulate from photo-emission to detection **UV Laser = 0.7 μJ, 250 nm, 350 fs**

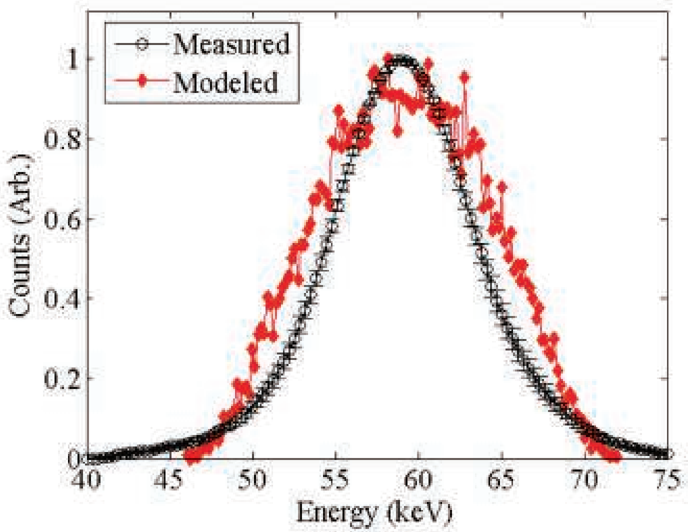


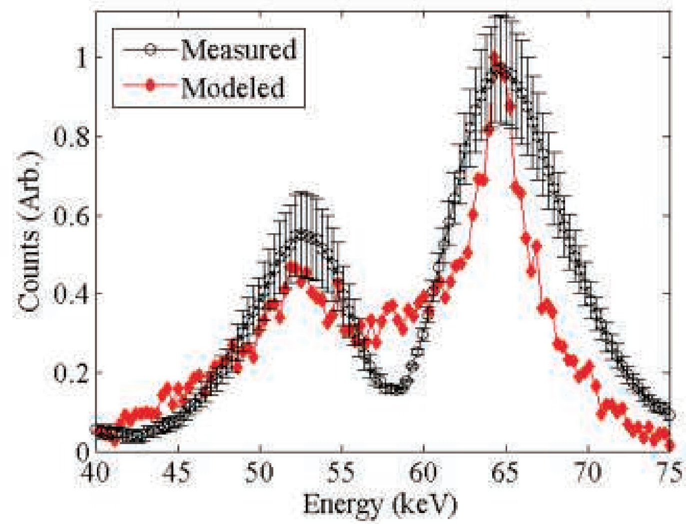


V = 50 kV
Q = 25 fC
Rep Rate = 1 kHz
CCD Exposure = 2 s

Terahertz-driven Linear Electron Acceleration



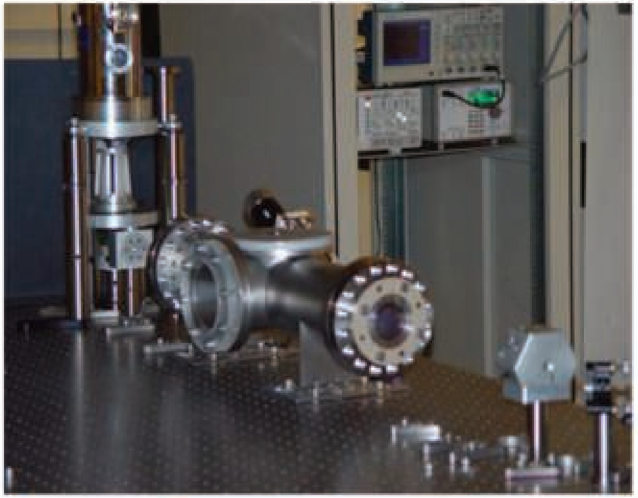




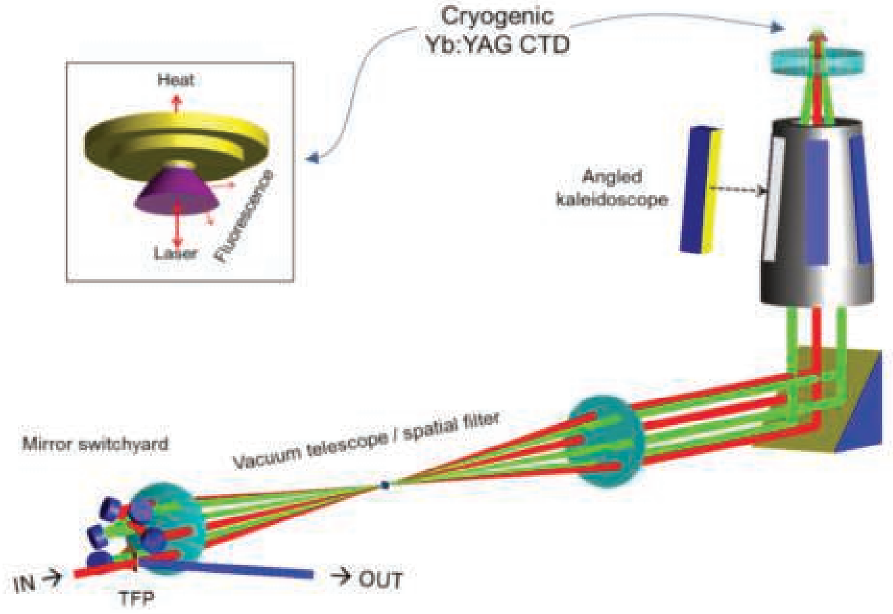
E. Nanni et al., Nat. Com. 6, 8486 (2015).

Future Work

- Demonstrating the THz - COPA to the mJ-level
- Extending THz acceleration to GV/m field range
- Relativistic energies
- Single-cycle gun
- Multi-cycle gun and acceleration
- Acceleration to > 10 MeV



Cryo-Yb:YAG amplifier
160 mJ IR pulses



THANK YOU FOR YOUR ATTENTION

HELMHOLTZ ASSOCIATION

erc European Research Council

Alexander von Humboldt Stiftung / Foundation

DFG Deutsche Forschungsgemeinschaft

Priority Program QUTIF:
Quantum Dynamics in Tailored Intense Fields

cui

GORDON AND BETTY MOORE FOUNDATION

ACHIP