THz-based acceleration

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Frontiers in Attosecond X-ray Science: Imaging and Spectroscopy

AXSIS

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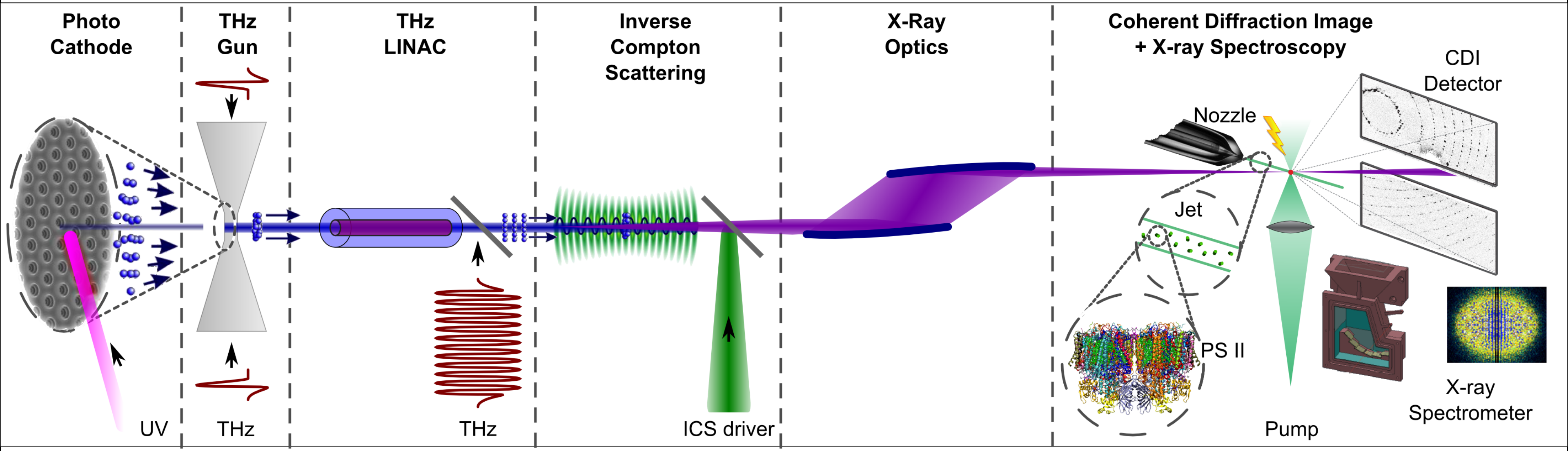
UHH DESY CFEL SCIENCE MSU MIT erc

Attosecond diffraction and spectroscopy of biomolecules

Damage-free structure **Undisturbed electronic structure**



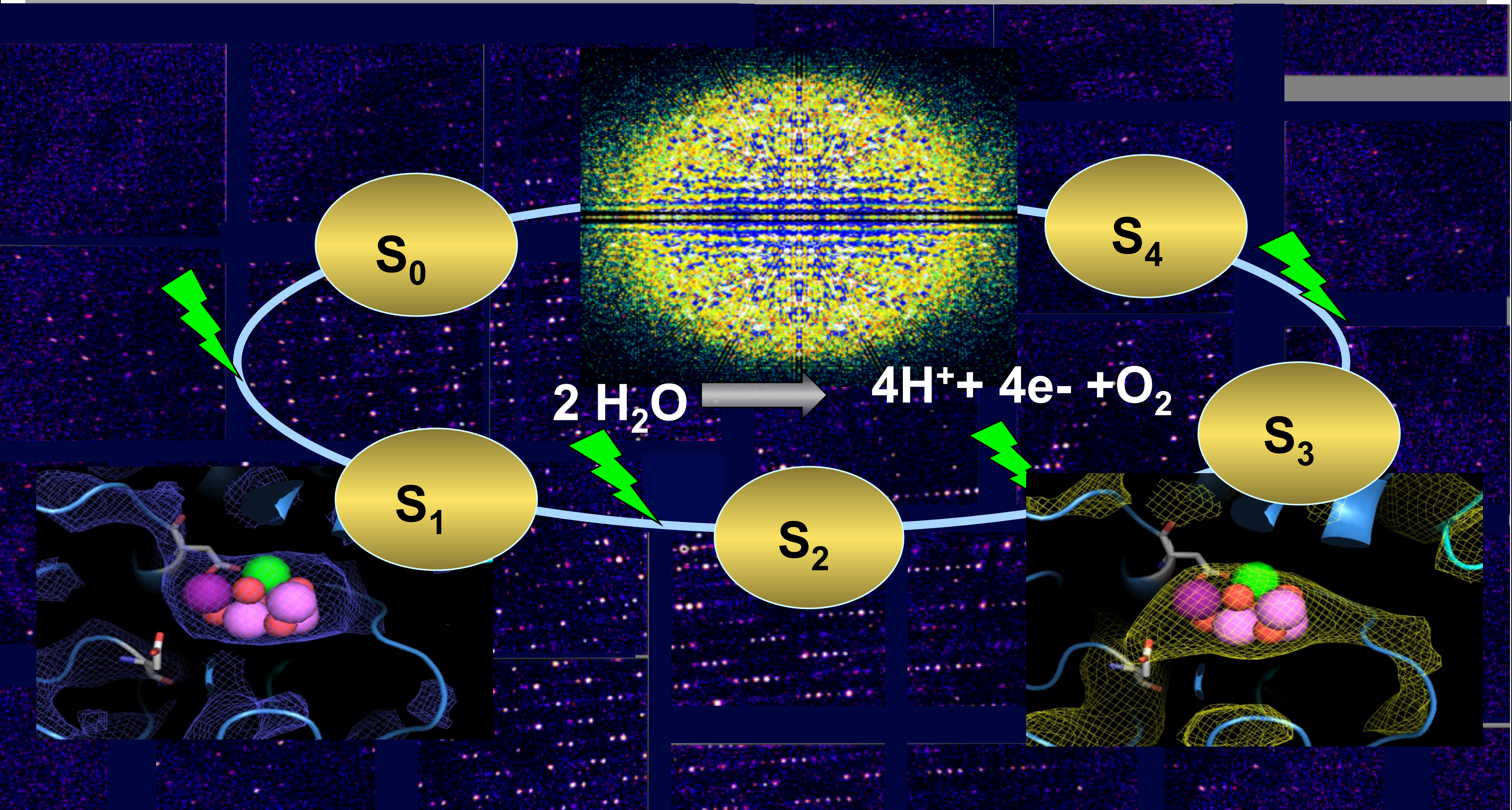
All laser driven, attosecond synchronization simpler

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

→ All optical fully coherent X-ray source, imaging and spectroscopy also seeding of large scale FELs

DESY CFEL SCIENCE UHH MIT

The S-state cycle of water splitting

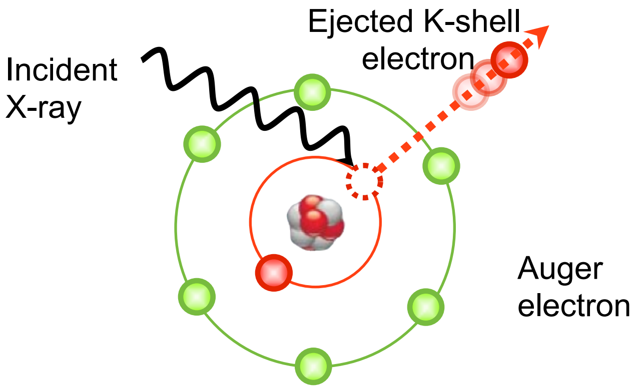


4 electrons & 4 protons extracted from the manganese cluster in 4 light flashes

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

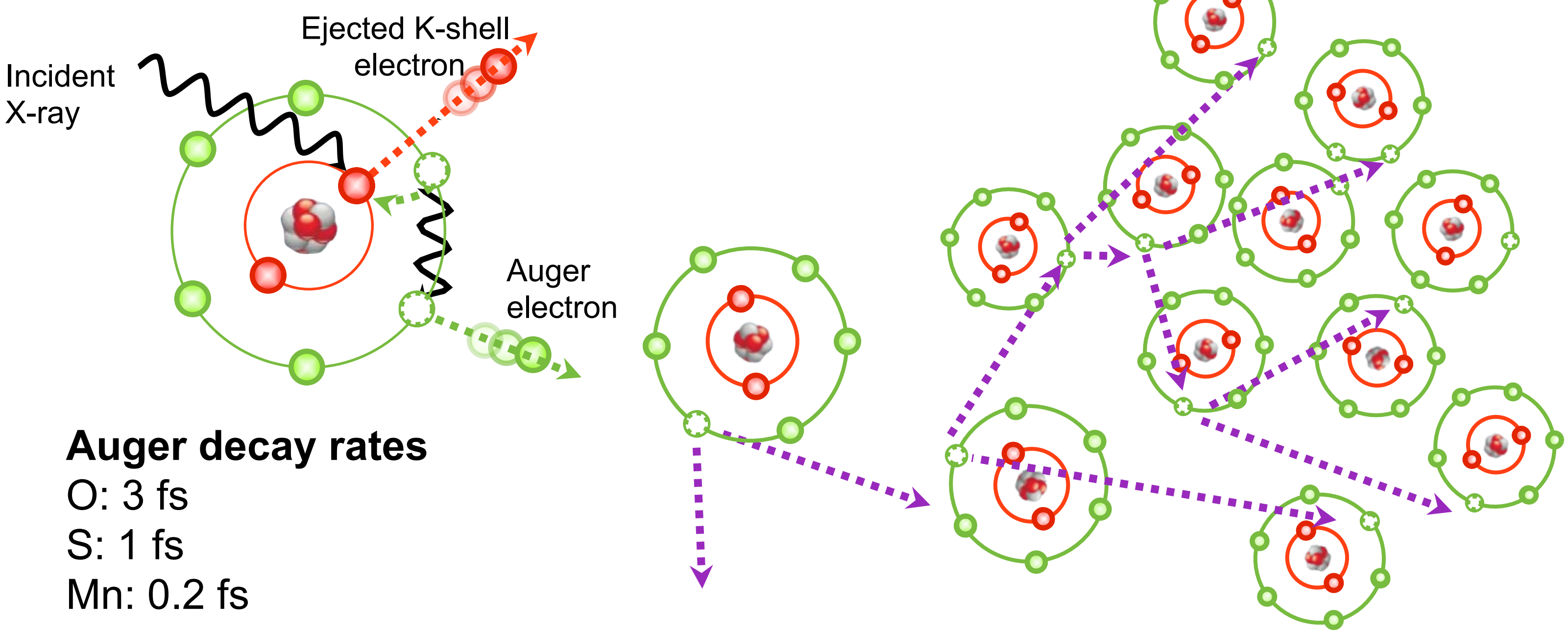
Elucidate electronic and atomic structure to understand the mechanism

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

Outline

- Why THz acceleration?
- Laser driven THz Sources based on optical rectification
- Accelerating Structures
- First results
- Conclusions

THz Acceleration

- **Increasing operational frequency:**

  higher breakdown fields:

$$\boxed{E_s = \frac{f^{1/2}}{\tau^{1/4}}}$$

[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. Tantawi and V. Dolgashev, private Communication.

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

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

  reduced pulsed heating:

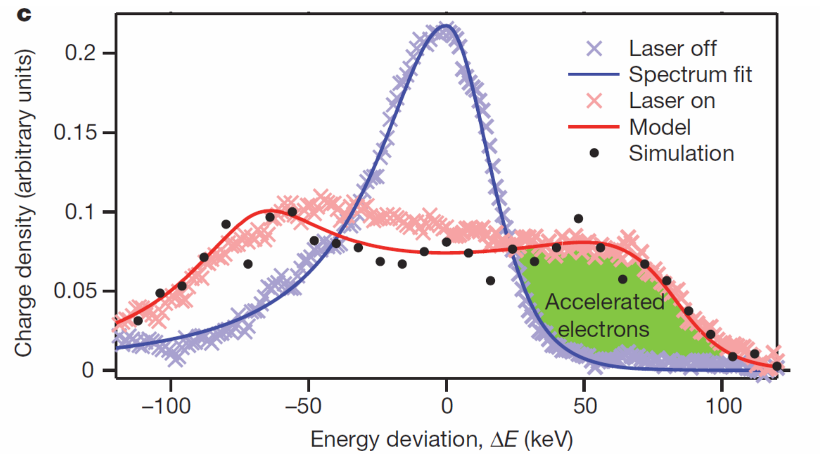
$$\boxed{\Delta T \propto \frac{E_P}{A_{SURFACE}} \propto \frac{V_{CAVITY}}{A_{SURFACE}} \propto R \propto \lambda}$$

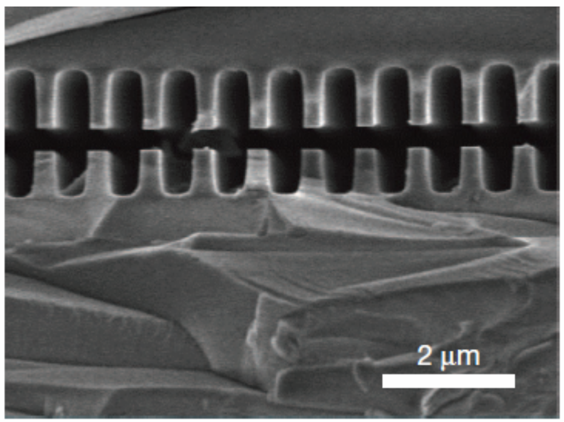
  → high repetition rate operation becomes possible!

- **High-gradient accelerators:** reduced size, short bunches and improved electron beam quality!

Indications for Scaling

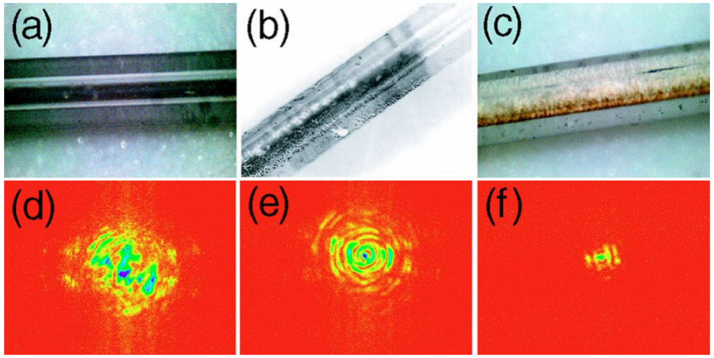
Laser-Driven Acceleration
Demonstrated 190 MV/m

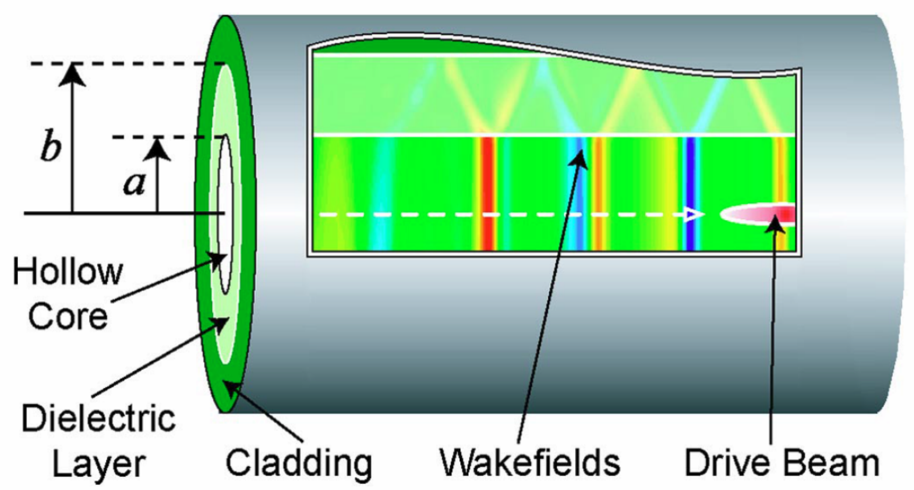




Peralta, E. A., et al., *Nature* 503.7474 (2013): 91-94.

Dielectric Wakefield Acceleration
Demonstrated 5.5 GV/m

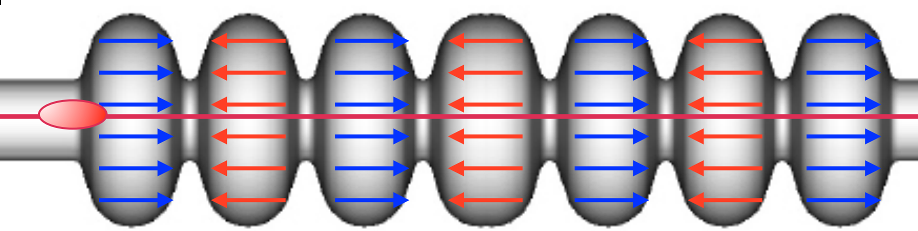




Thompson, M. C., et al., *Phys. Rev. Lett.* 100.21 (2008): 214801.

X-rays are produced from accelerated electrons

Traditional RF accelerator

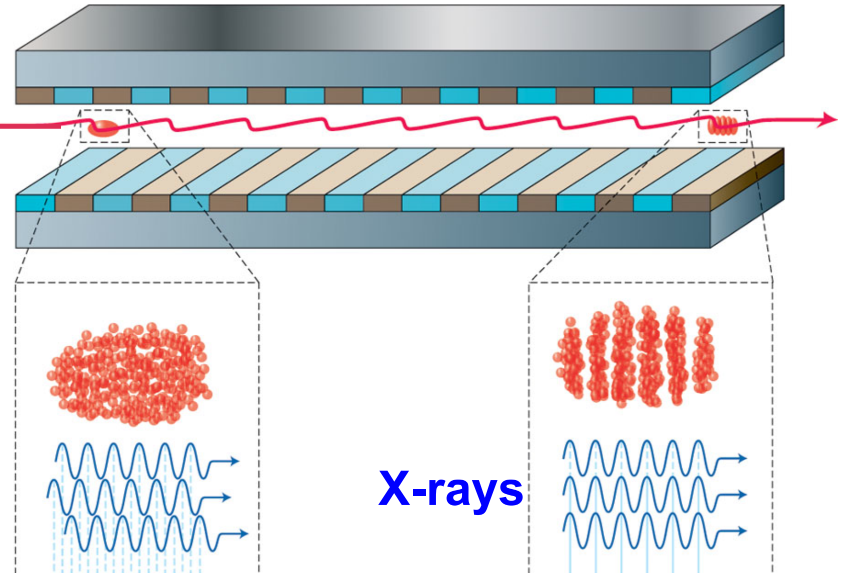


10 cm

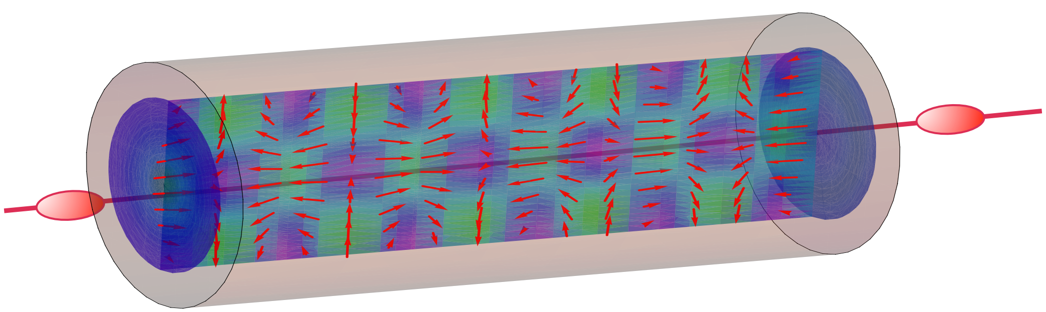
1 km

10 GeV

Magnetic undulator



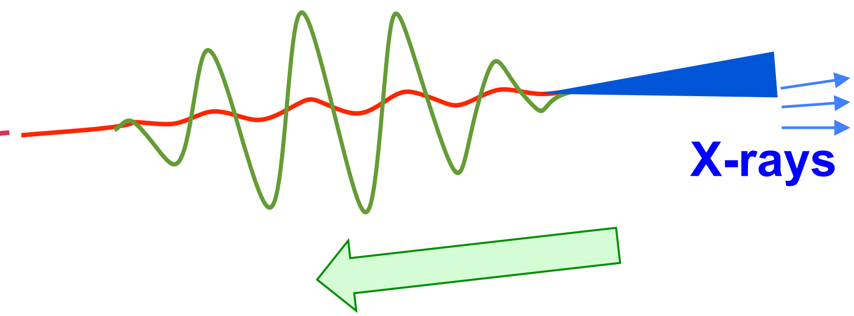
Terahertz cylindrical waveguide



100 µm

10 MeV

20 cm

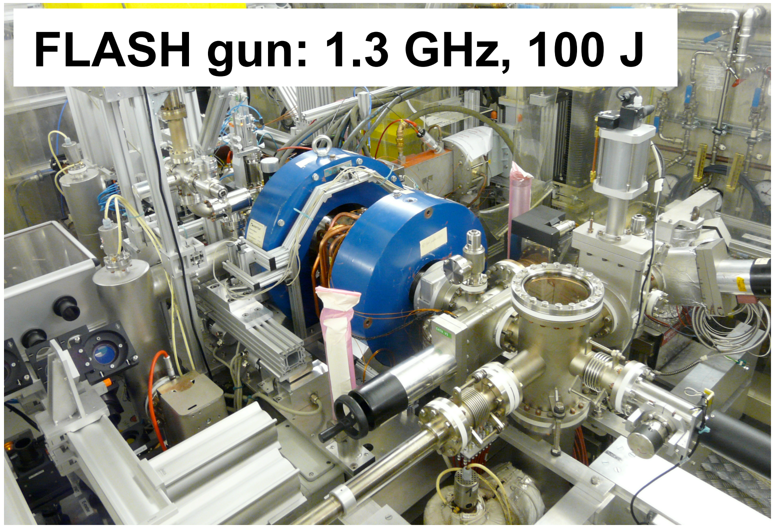


Optical Undulator FEL regime: $E_X \propto N_e^2$

Interesting THz range

- **1-10 pC Charge**
- **0.1 – 1 THz range seems to be optimum (0.3 THz ~ 1 mm)**

Wavelength Scaling

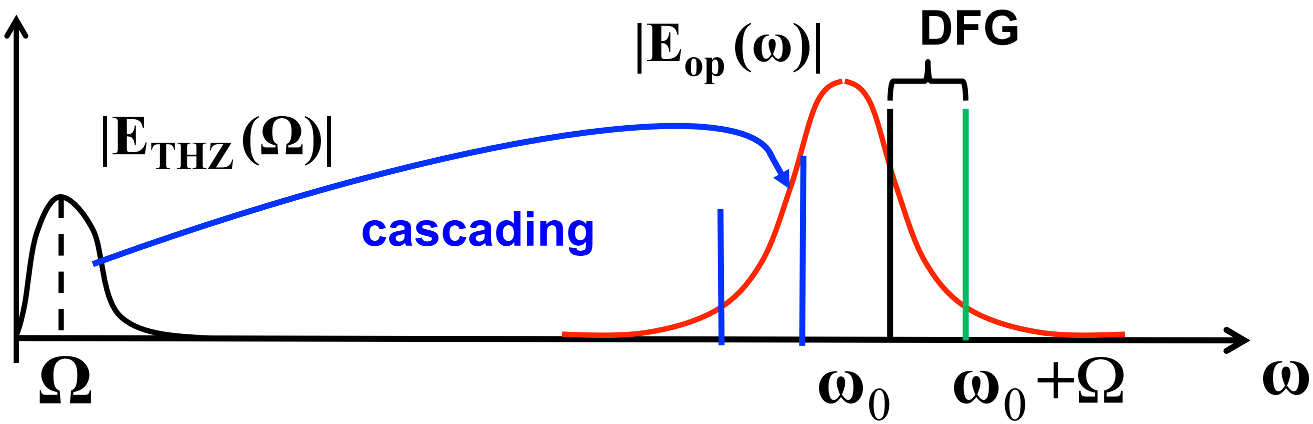


Potential 300 GHz gun

2 mJ, THz Energy

Laser driven THz Sources via optical rectification

- **Most efficient method : ~ 1 % energy conversion efficiency[3], ~ mJ THz pulse energy[4,5]**



- **Intra-pulse difference frequency generation**
- **THz bandwidth proportional to optical pulse bandwidth**
- **Must satisfy phase-matching condition**

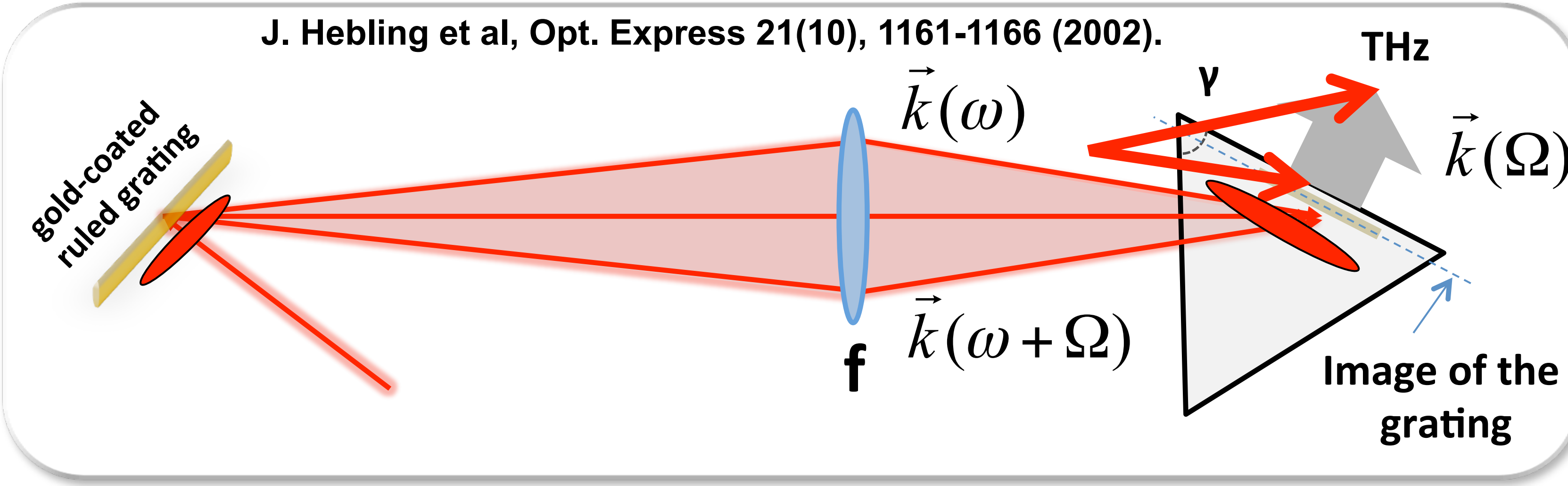
$$\vec{k}(\omega+\Omega)-\vec{k}(\omega)=\vec{k}(\Omega)$$

Lithium Niobate

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

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

Laser driven THz Sources based on optical rectification



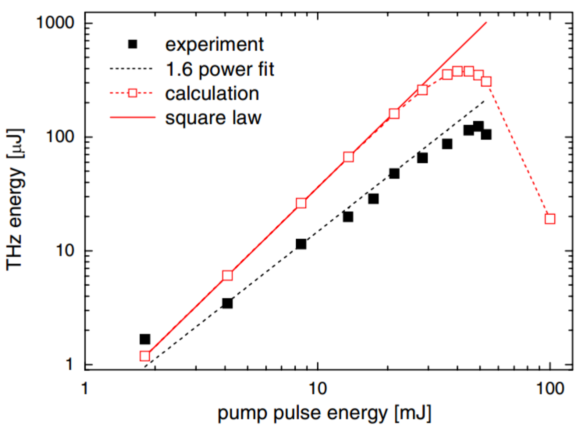


Fig. 1. (Color online) Measured and calculated THz energy versus pump energy.

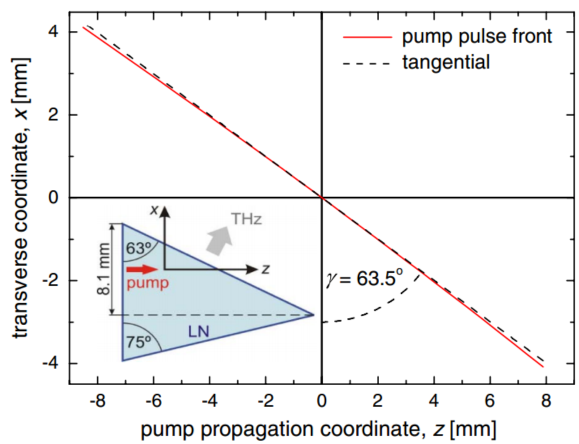


Fig. 3. (Color online) Calculated shape of the tilted pump pulse front inside the LN crystal. Inset: geometry of the LN crystal.

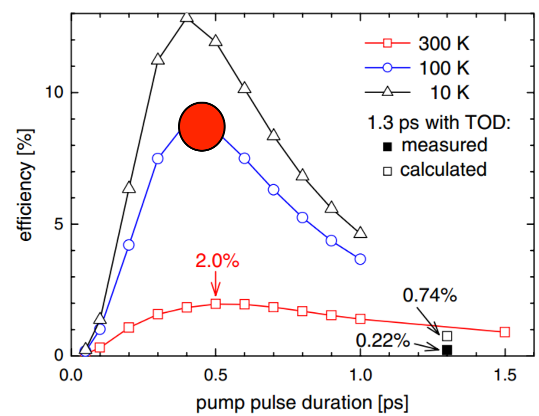
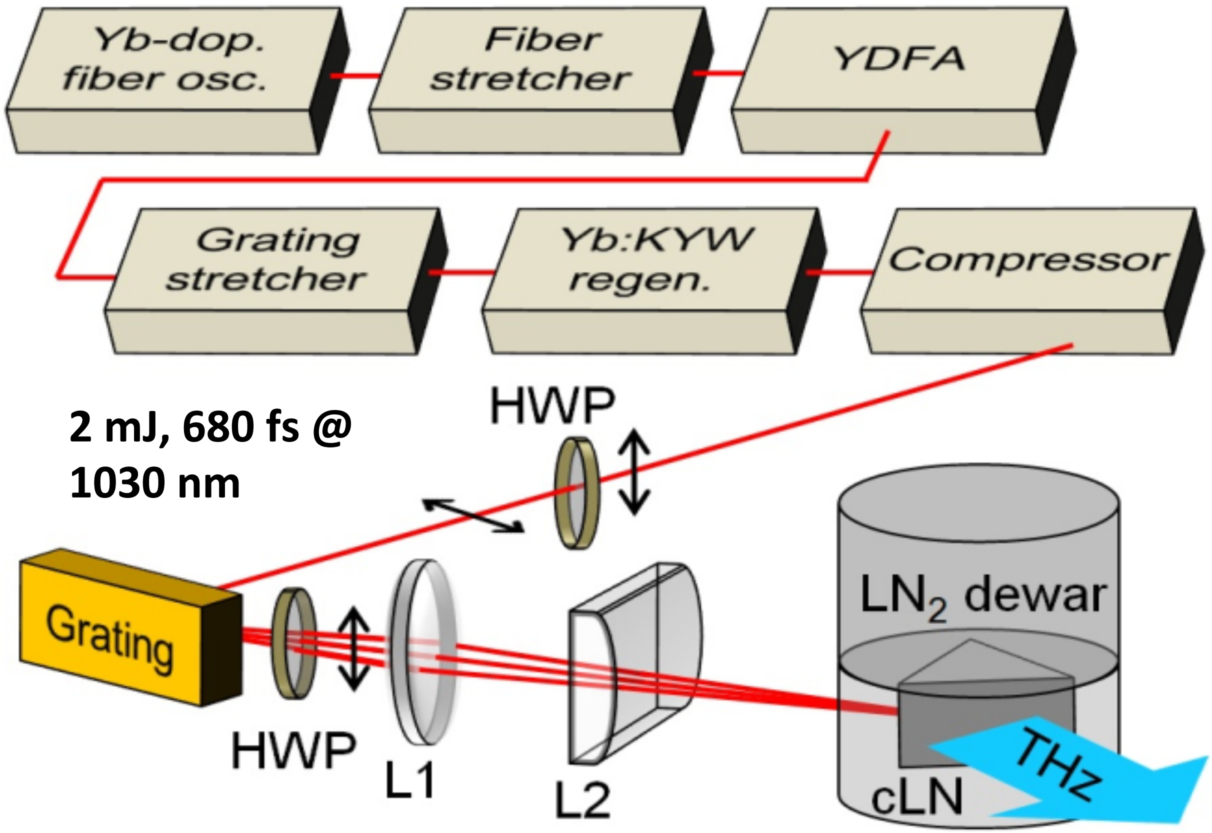


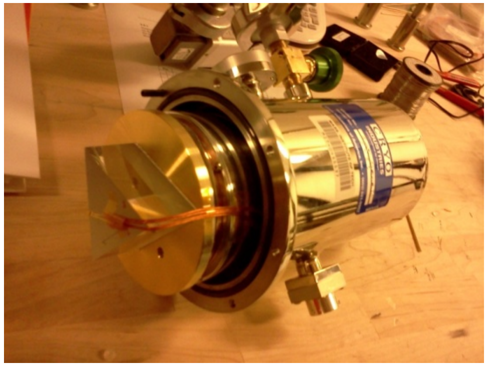
Fig. 4. (Color online) Calculated THz-generation efficiency versus FL pump pulse duration for various crystal temperatures. TOD: third-order phase.

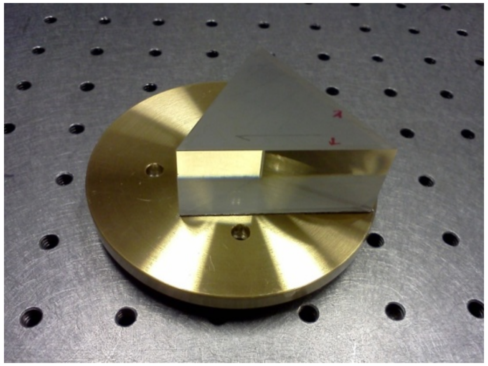
J. A. Fülöp, L. Pálfalvi, S. Klingebiel, G. Almási, F. Krausz, S. Karsch, and J. Hebling, "Generation of sub-mJ terahertz pulses by optical rectification," Opt. Lett. 37, 557-559 (2012)

Experimental Setup

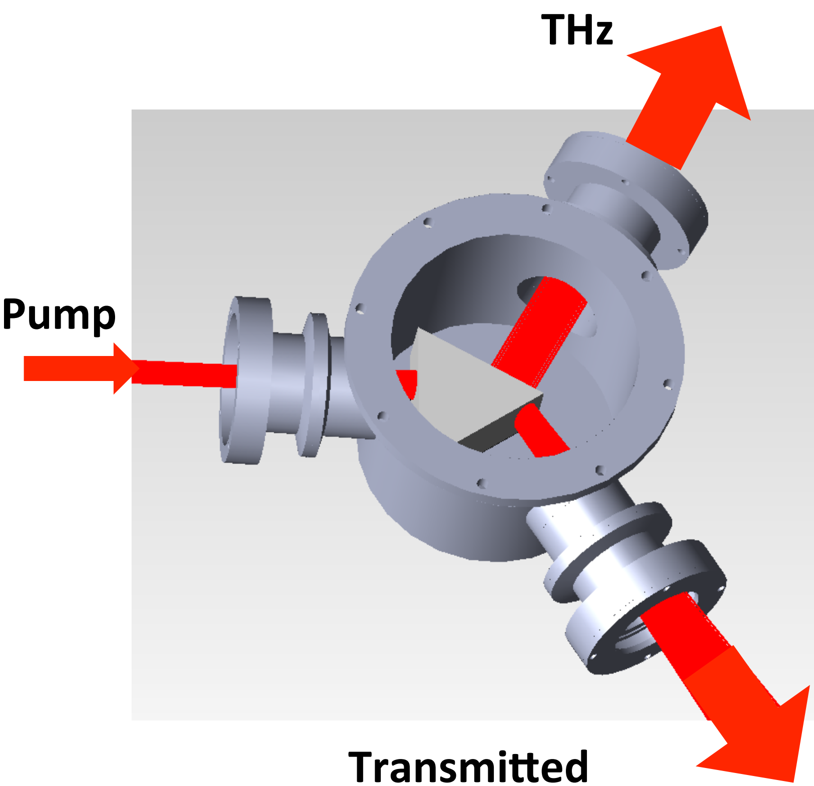


2 mJ, 680 fs @ 1030 nm



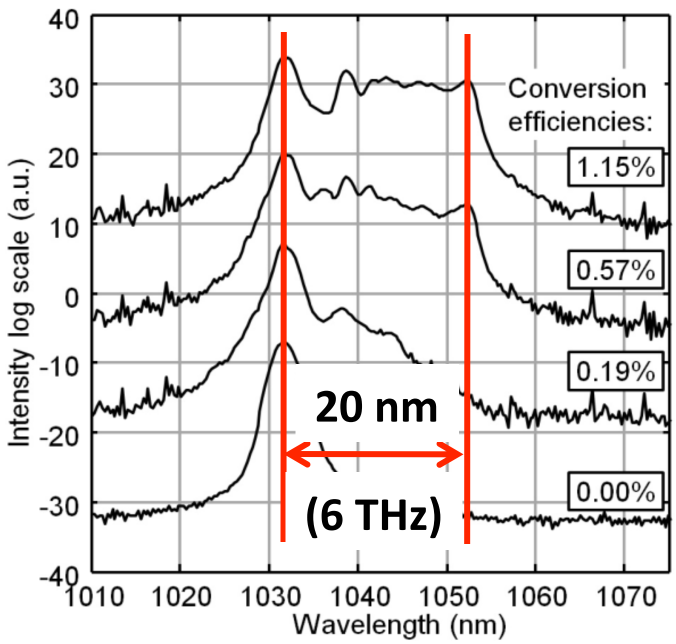


Cascading Effects in Optical Rectification



Spectrum analyzer

Transmitted IR spectrum



Up to 13 cascaded orders at room temperature

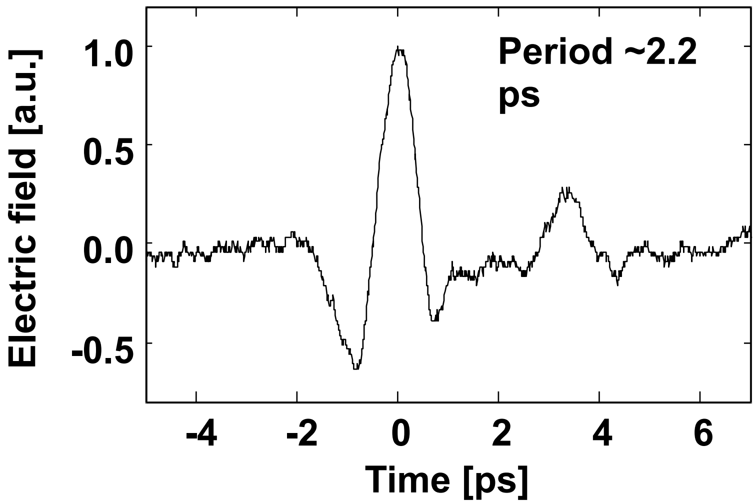
Manley-Rowe limit efficiency = 0.16%

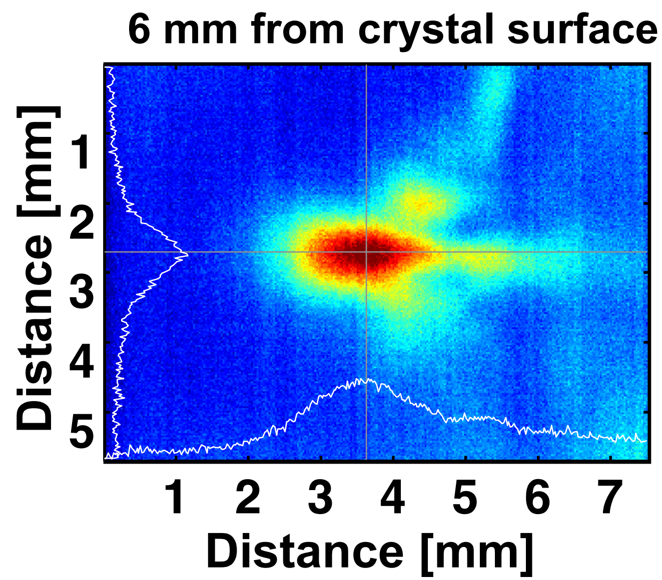
Average photon cascades 7 times

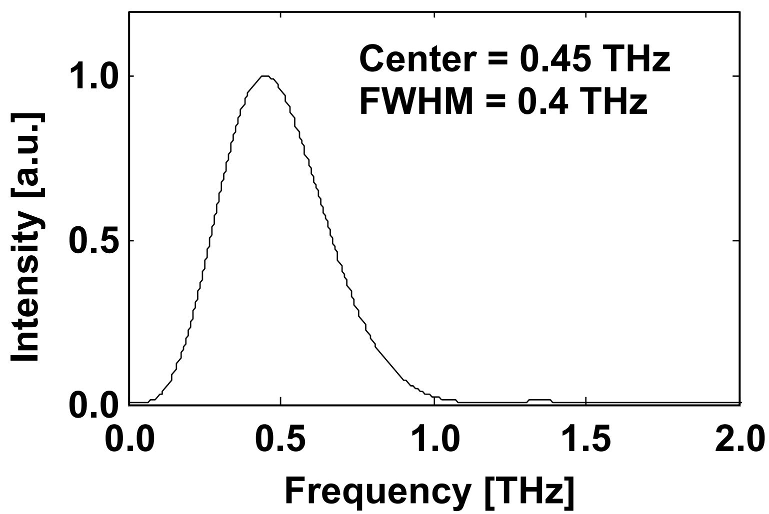
Estimated efficiency from spectrum = 1.12%

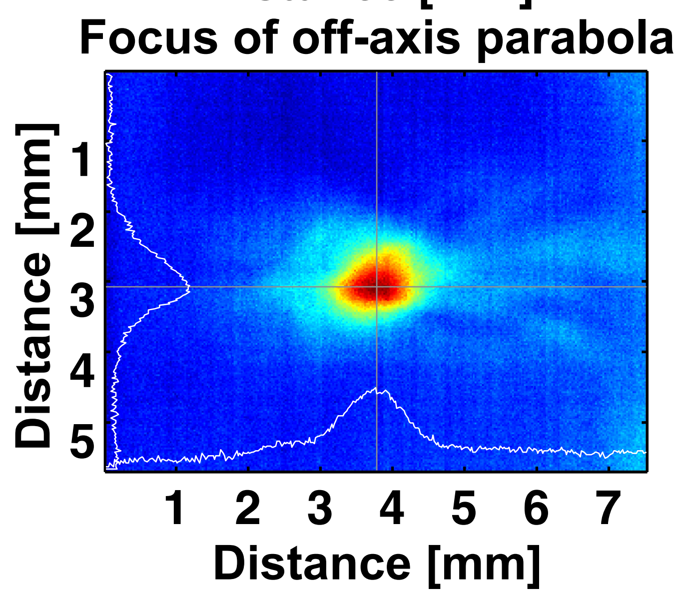
S.-H. Huang, et al. Opt. Lett. 38, 796 (2013)

Spatio-temporal characterization

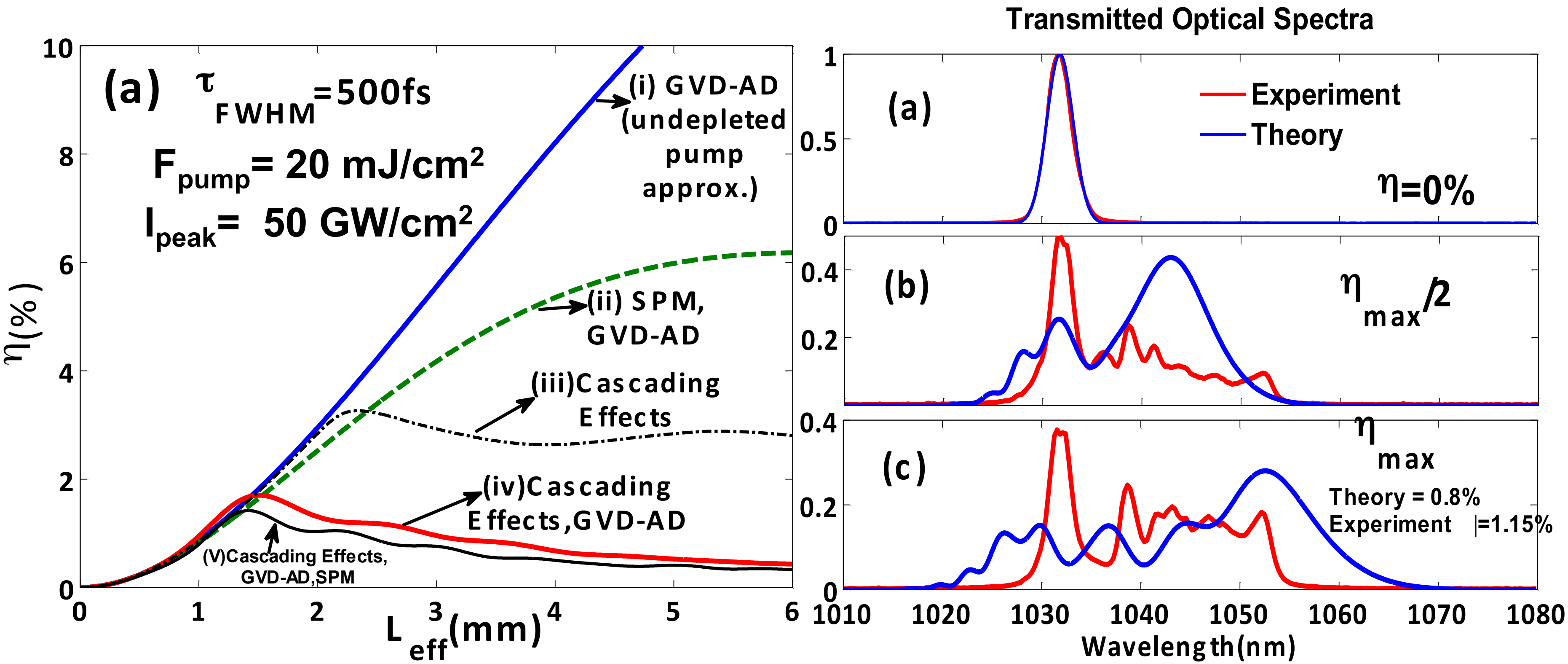








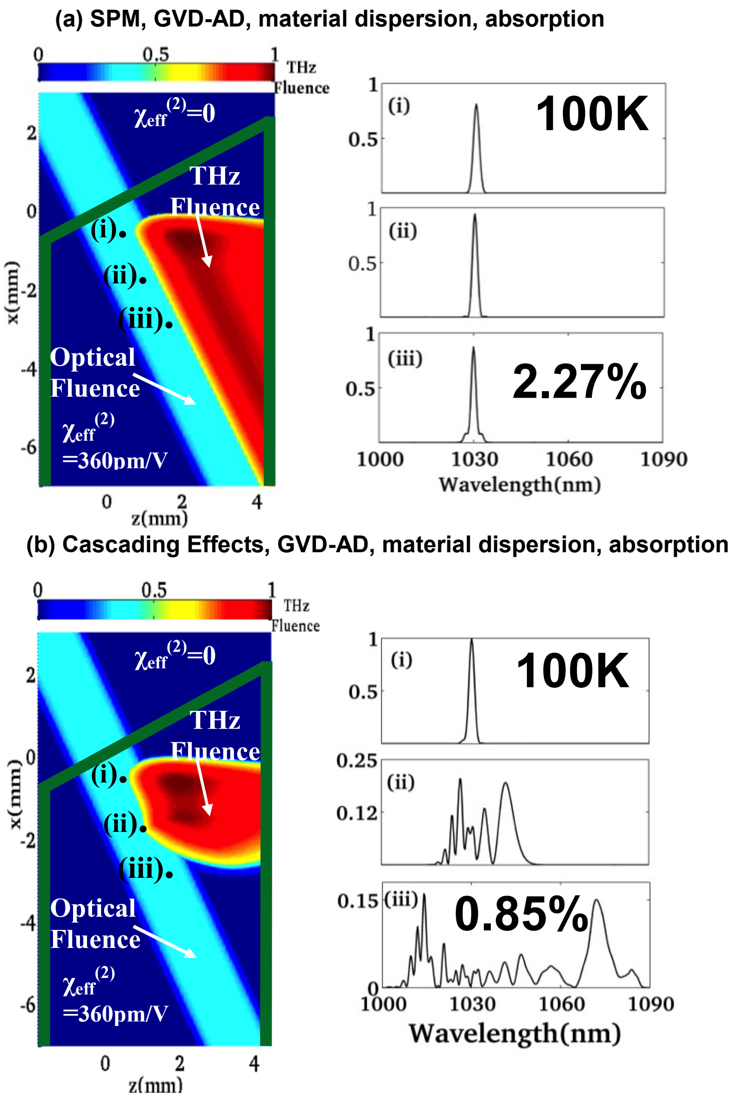
Impact of Cascading : 1-D model



- Cascading + GVD due to angular dispersion -> Strongest limitation
- SPM not important

K. Ravi et al, Optics Express, 22(17), 20239-20251 (2014)

Confirmation with 2-D model



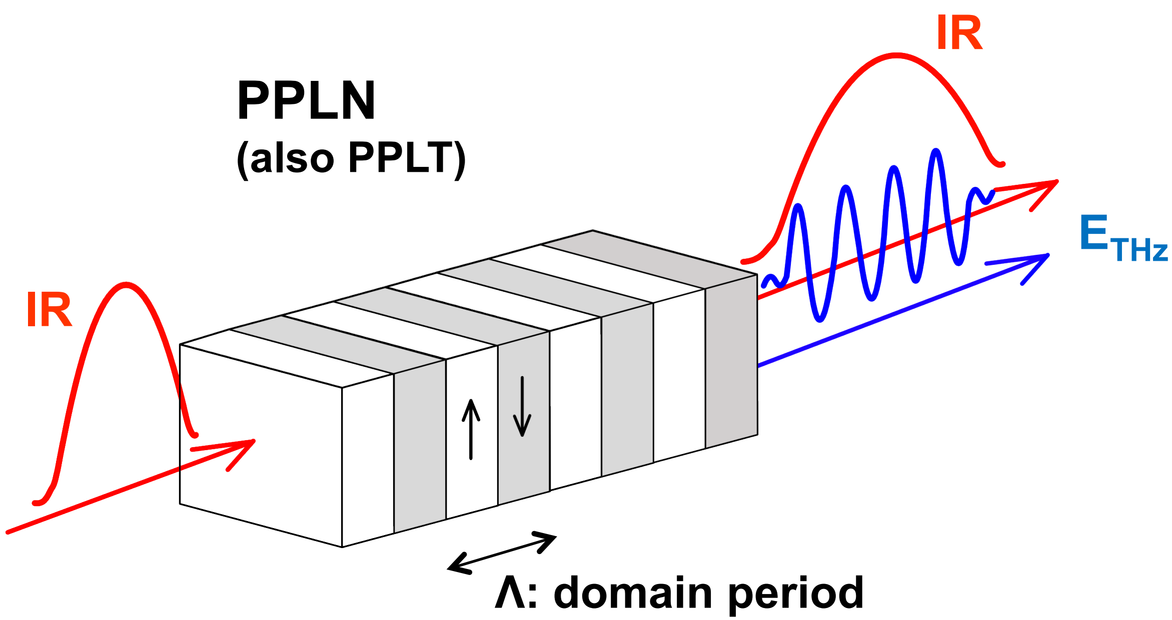
- **Without back action due to cascading**
  - long interaction,
  - higher efficiency

- **With back action due to cascading,**
  - shorter interaction
  - lower efficiency.

- **OR using TPF in LN max. conv. ~ 1% for single-cycle pulses**

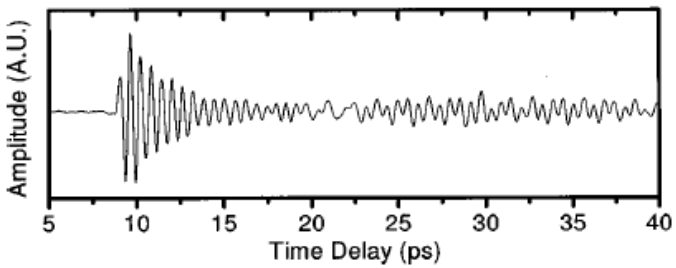
K.Ravi et al, Optics Express, 22(17), 20239-20251 (2014)

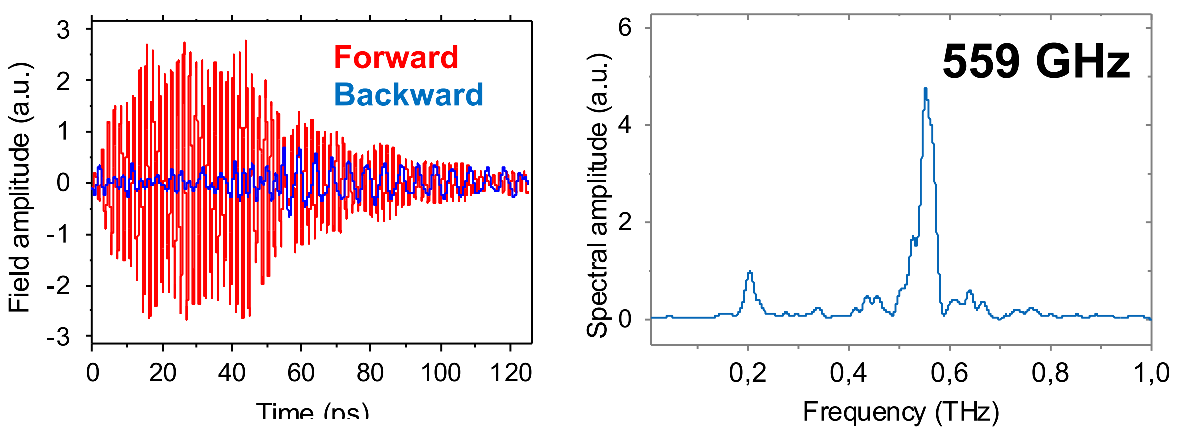
QPM structures for efficient multi-cycle terahertz generation



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

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

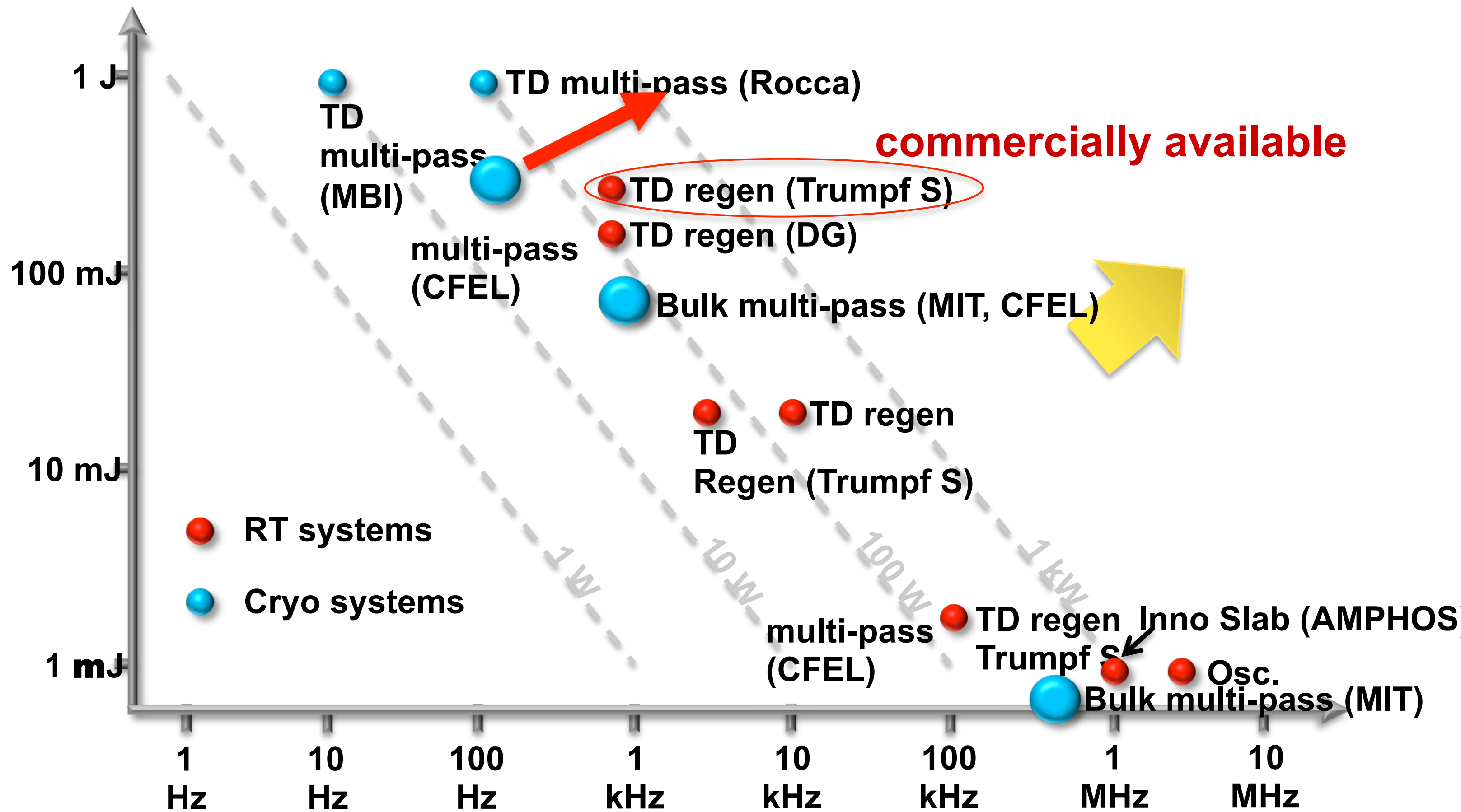




- mJ - level energies → 10^{-3} conversion efficiencies

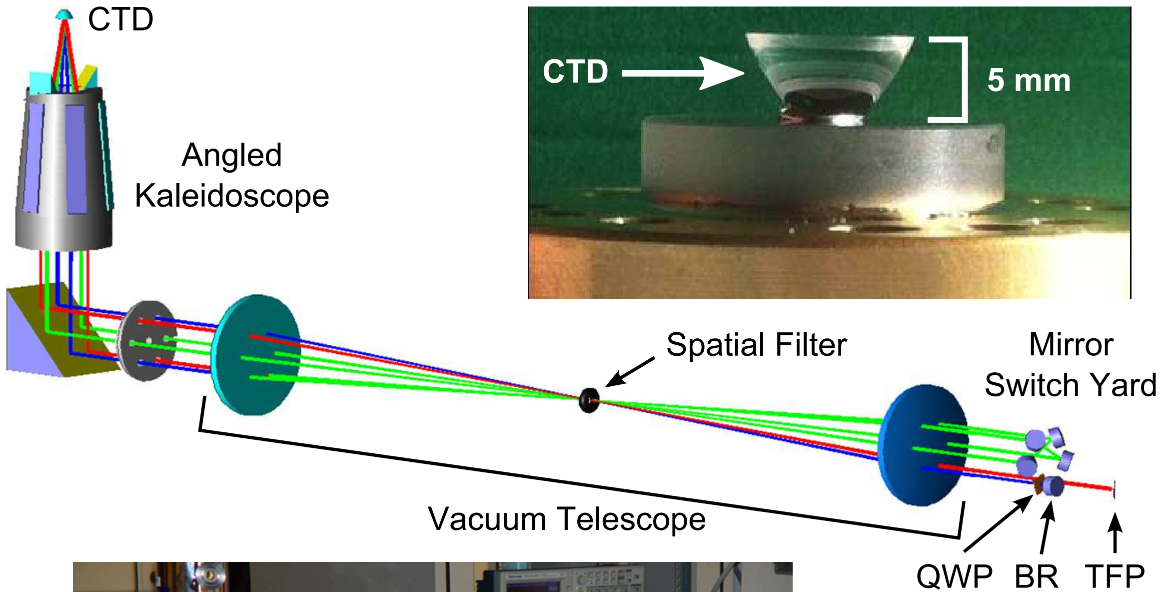
Scalability: sofar only 1 cm x 0.3 cm commercially available.

STATE-OF-THE-ART Yb:YAG PS TECHNOLOGY



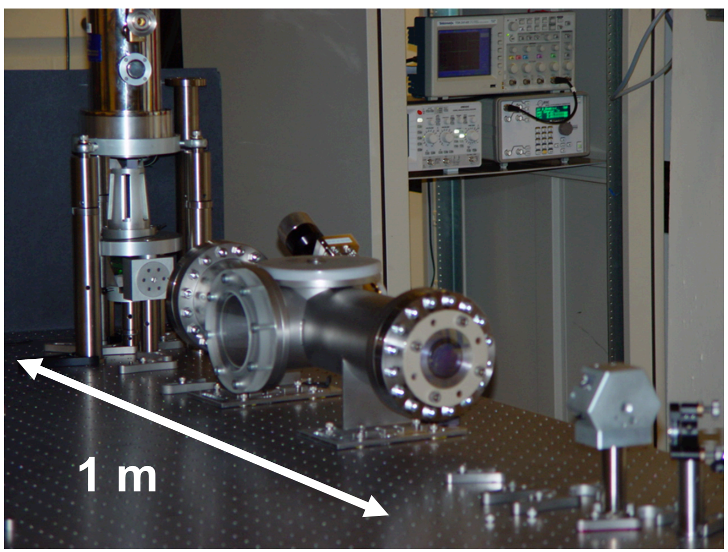
Cryogenic technology can scale energy and repetition rate simultaneously & simplify laser architecture

High energy and power laser development



Gain > 8 dB single pass;
- **160 mJ, 100 Hz,**
- **from 4 mm aperture**

> 1 J, 1 kHz
from 1.5 cm aperture



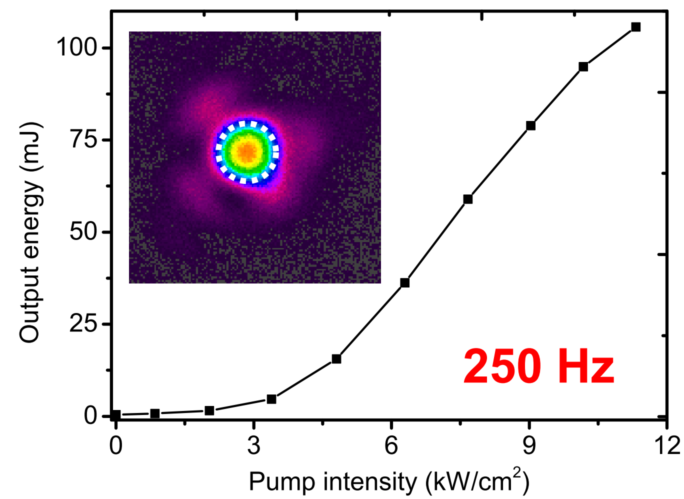
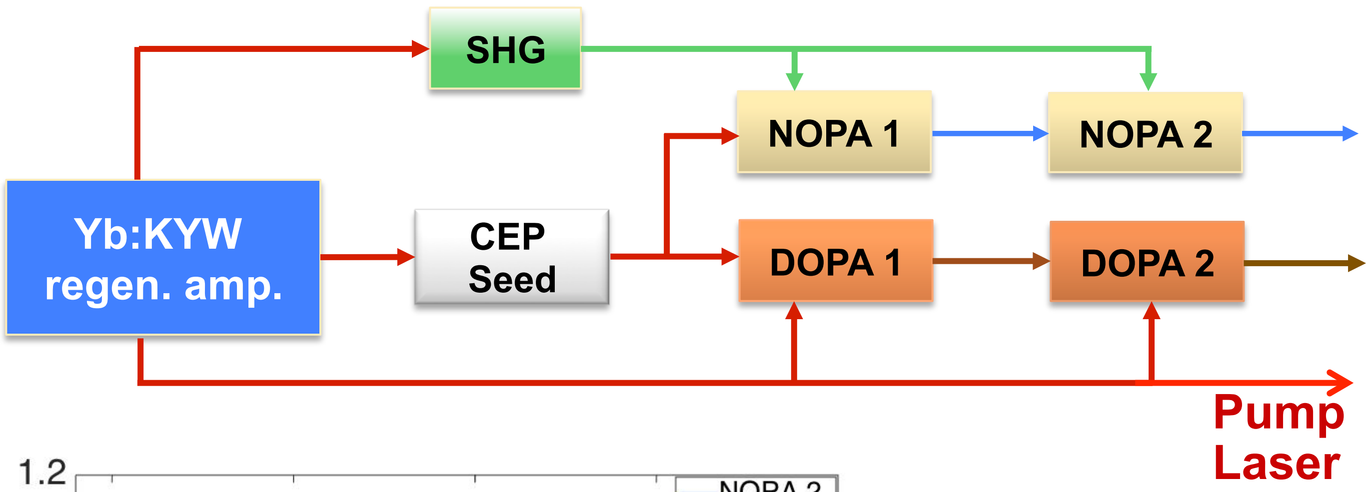


Photo cathode front-end: optical synthesizer

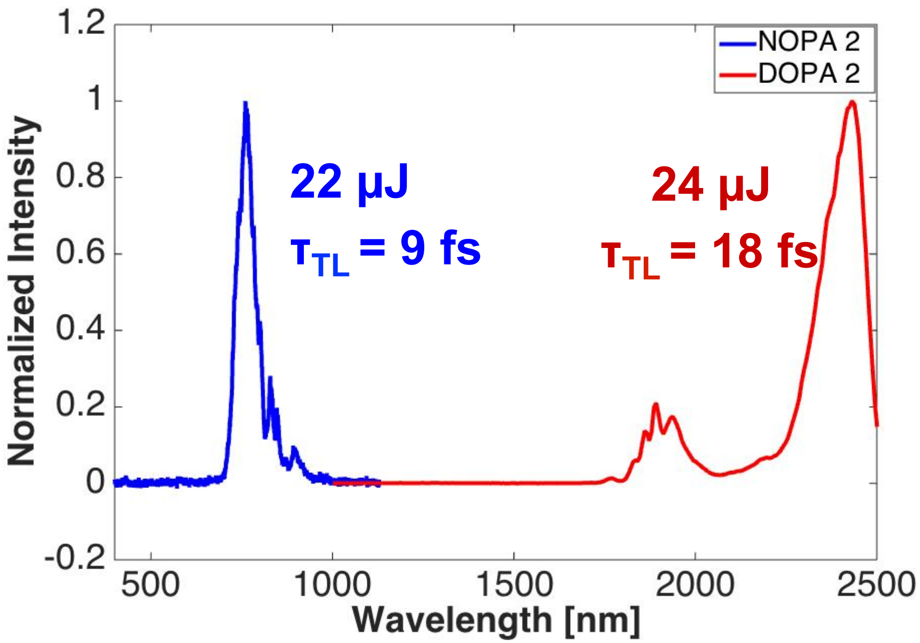


NOPA 2 Parameters:

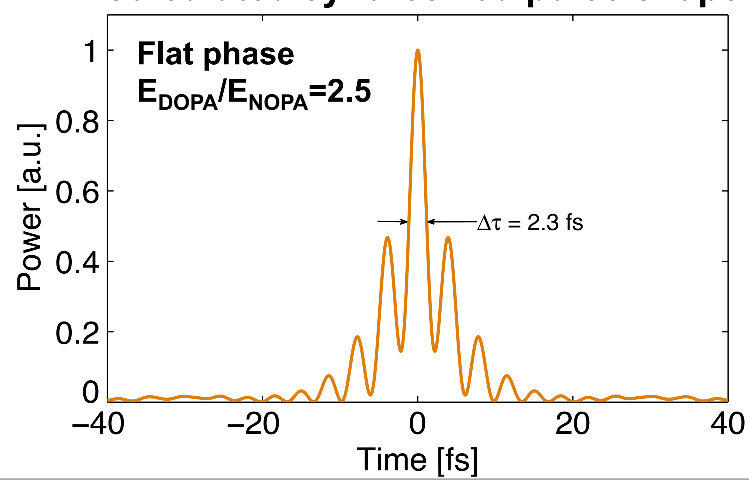
- E_p= 200 µJ
- E_s= 22 µJ
- I_p= 65 GW /cm^2
- λ_s= 700-990 nm

DOPA 2 Parameters:

- E_p= 470 µJ
- E_s= 24 µJ
- I_p= 69 GW /cm^2
- λ_s= 1800-2500 nm

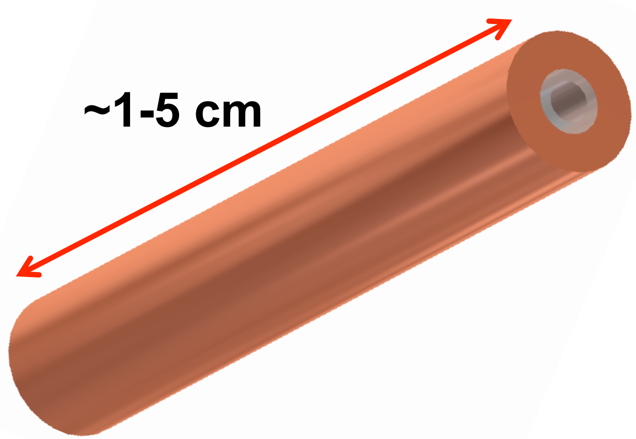


Calculated synthesized pulse shape



Dielectrically Loaded Circular Waveguide

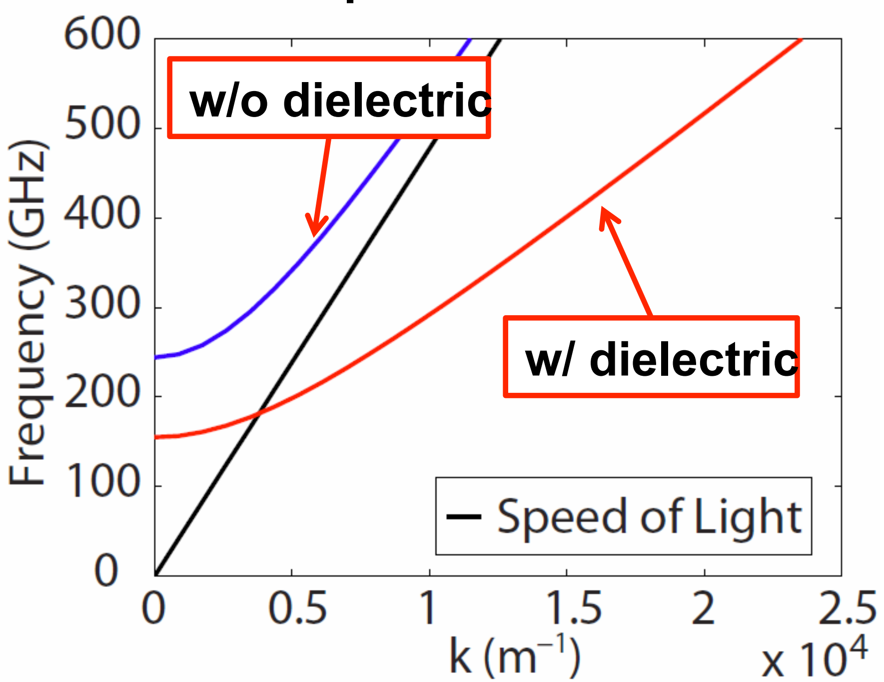
- Traveling wave structure is best for coupling broad-band single cycle pulse
- Phase-velocity matched to electron velocity with thickness of dielectric



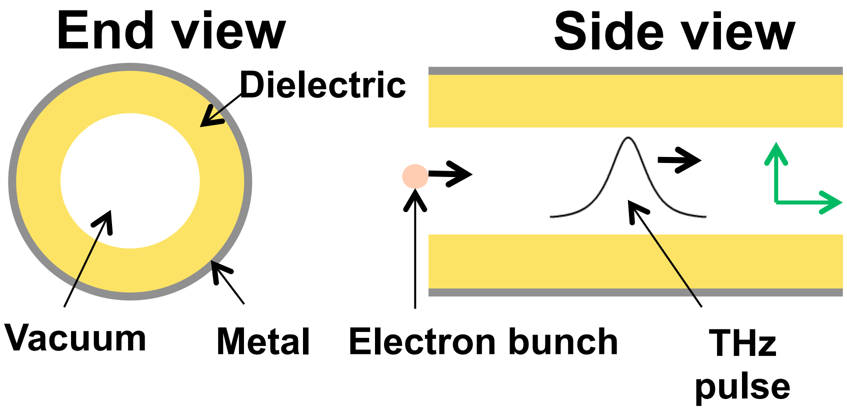
Copper Inner Diameter = 940 μm

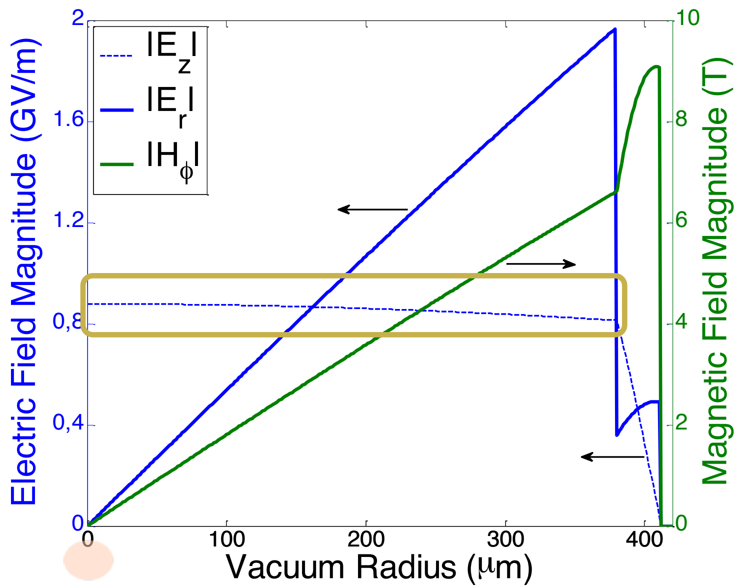
Fused Silica Inner Diameter = 400 μm

Dispersion Relation



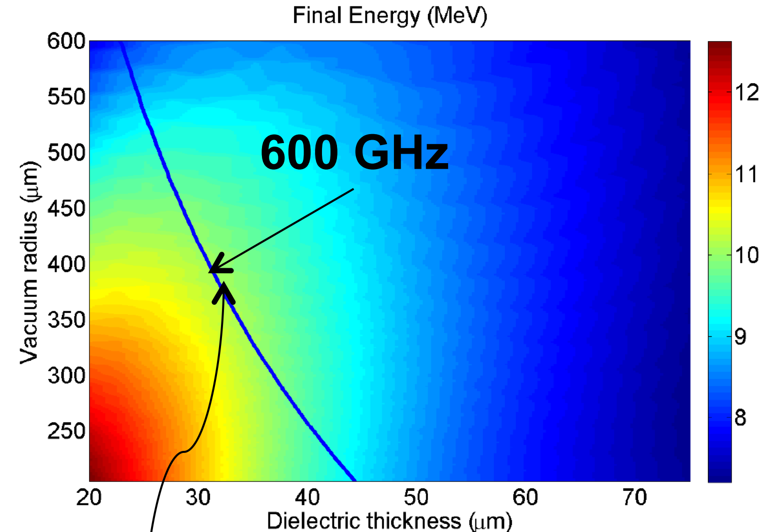
Electron Acceleration using THz Waveguides

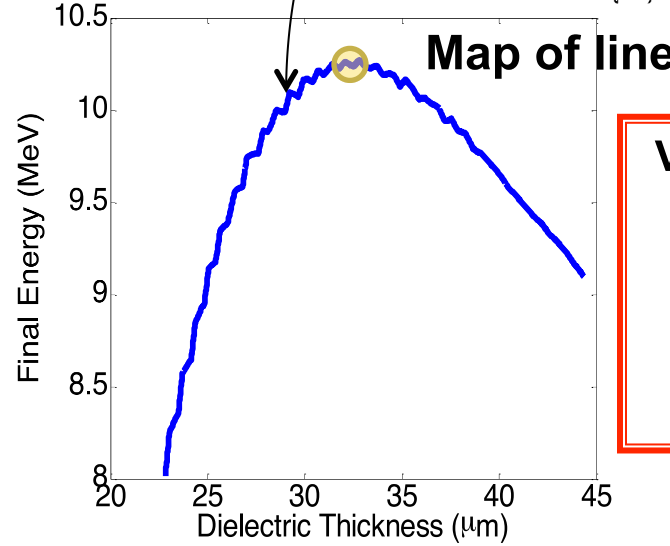




Uniform longitudinal field ideal for bunch acceleration

Optimization (20 mJ, 20 cycles)



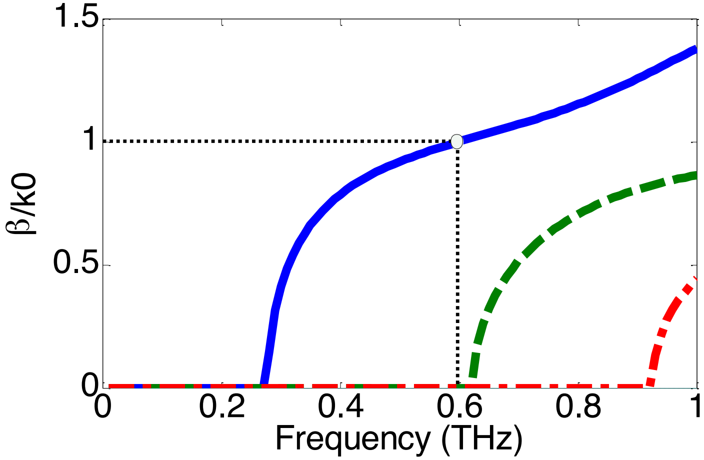


Vacuum radius 380μm

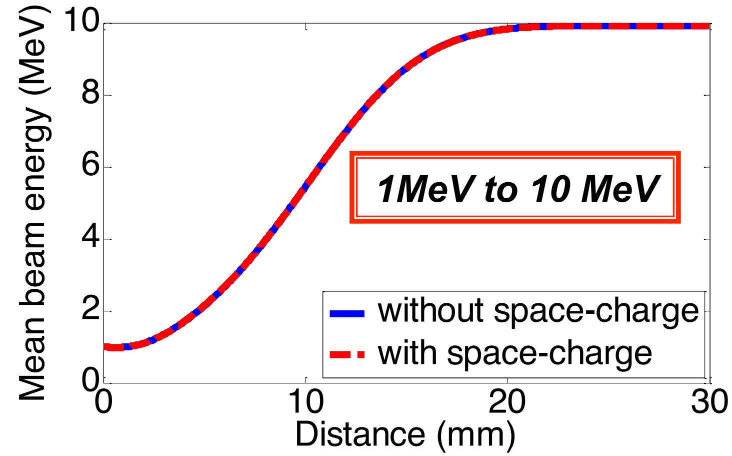
Dielectric thickness 32μm

Electron Acceleration using THz Waveguides

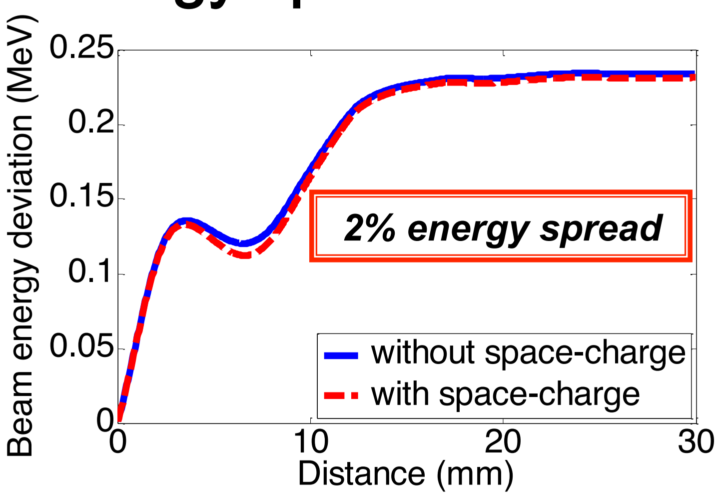
Dispersion curve TM0n



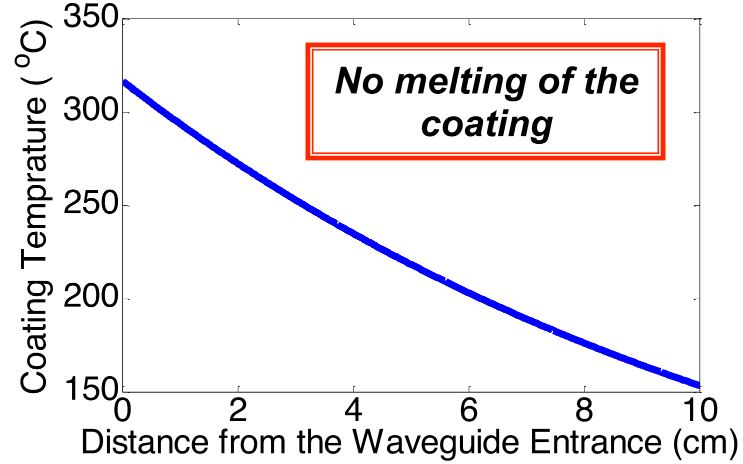
Energy (20 mJ, 10 cycle THz pulse)



Energy spread in bunch



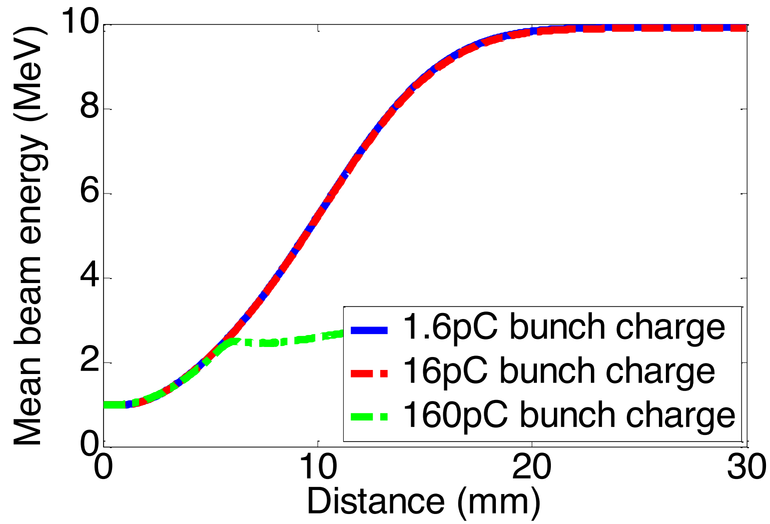
Coating Temperature



Electron Acceleration using THz Waveguides

Space Charge Limit

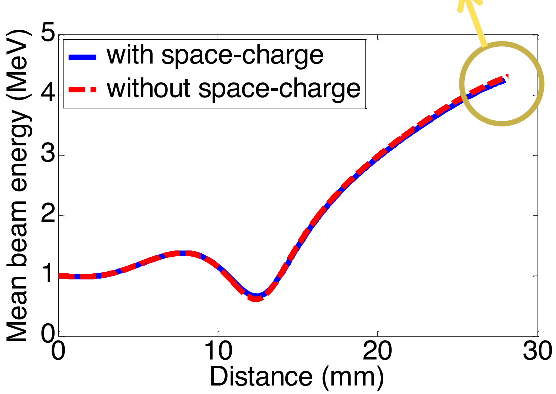
16 pC is easily possible
16 pC x 10 MeV = 160 μJ,
(1% e-beam extraction)

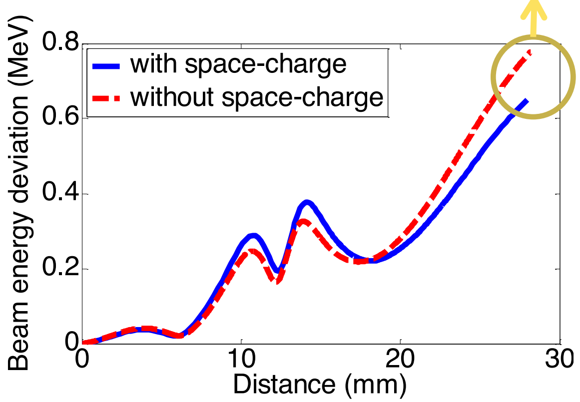


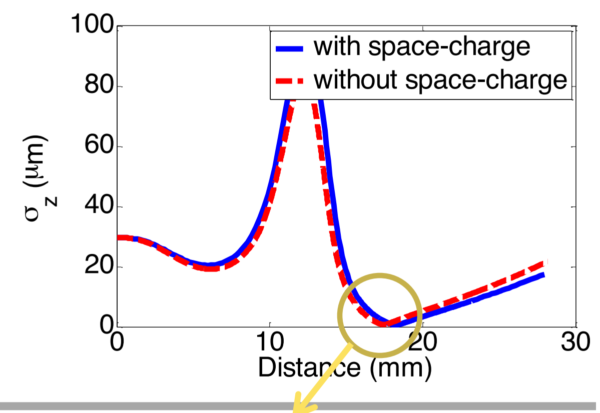
Simultaneous acceleration and compression

Acceleration to 4.5MeV

17% energy spread







DESY CFEL SCIENCE UH MIT

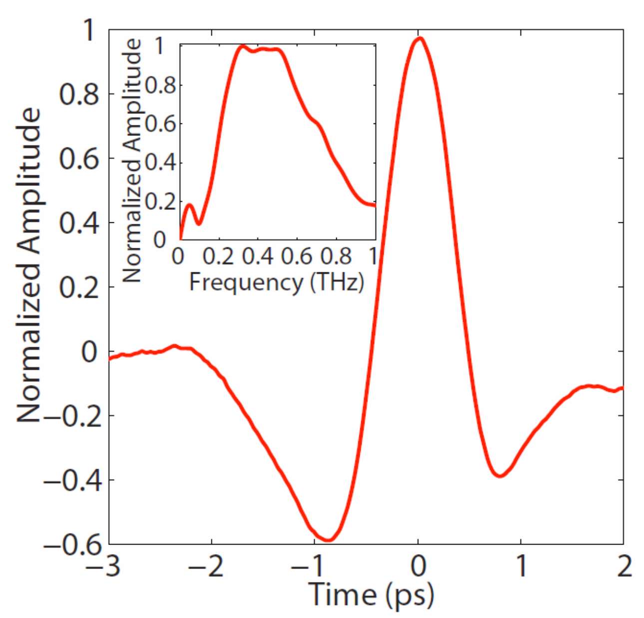
50 times bunch compression

THz Acceleration Experiments with μJ – single-cycle THz pulses

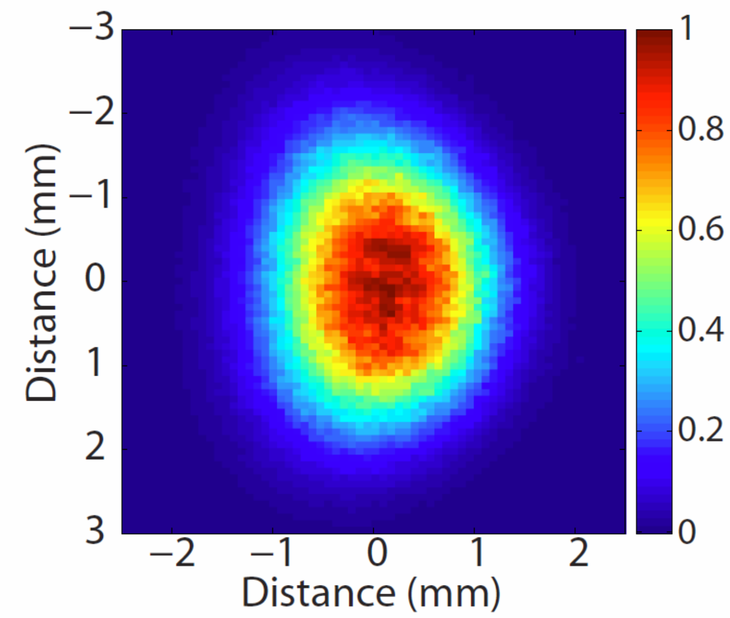
THz Pulse Properties

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

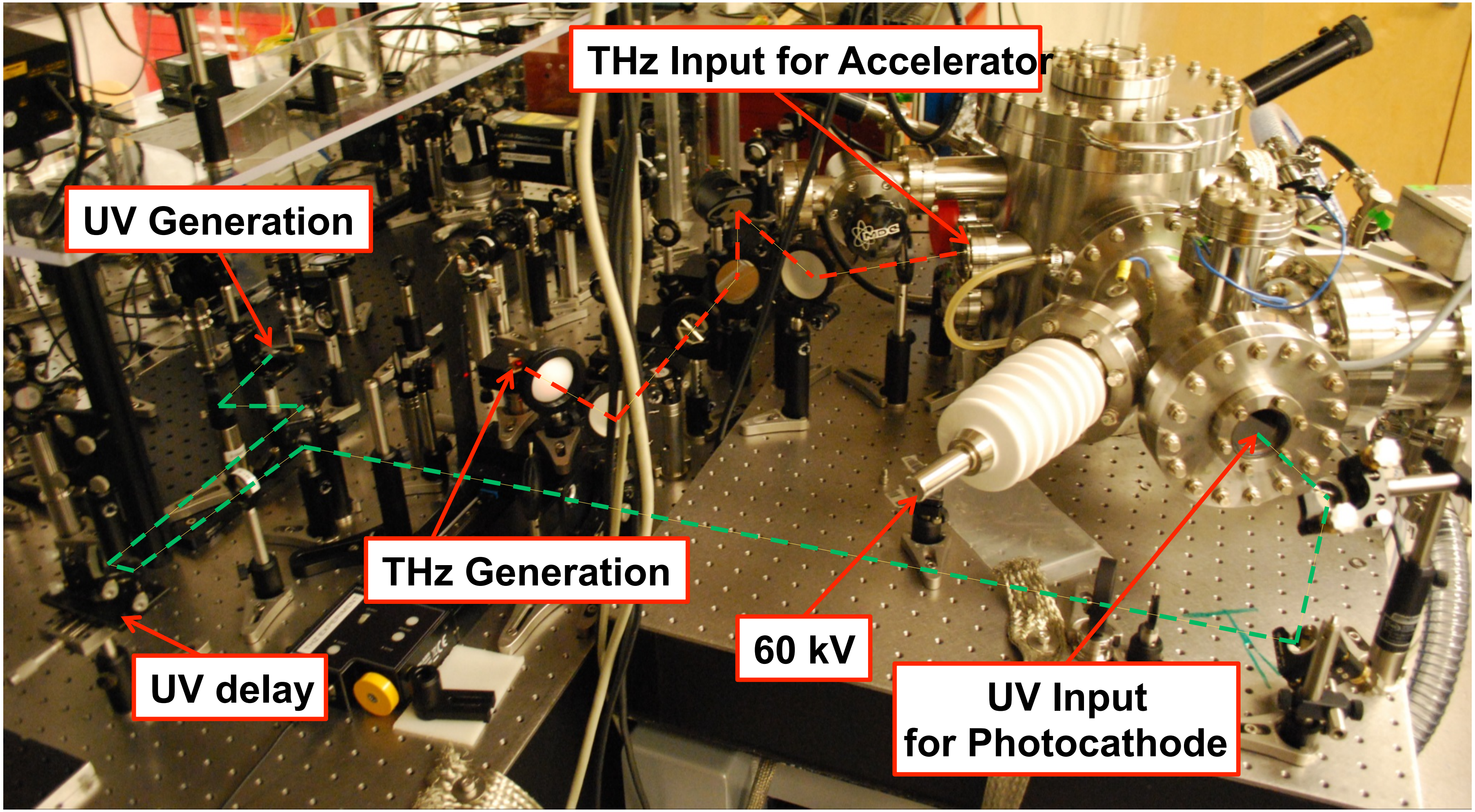
Electric Field from EO Sampling



Transverse Intensity Profile

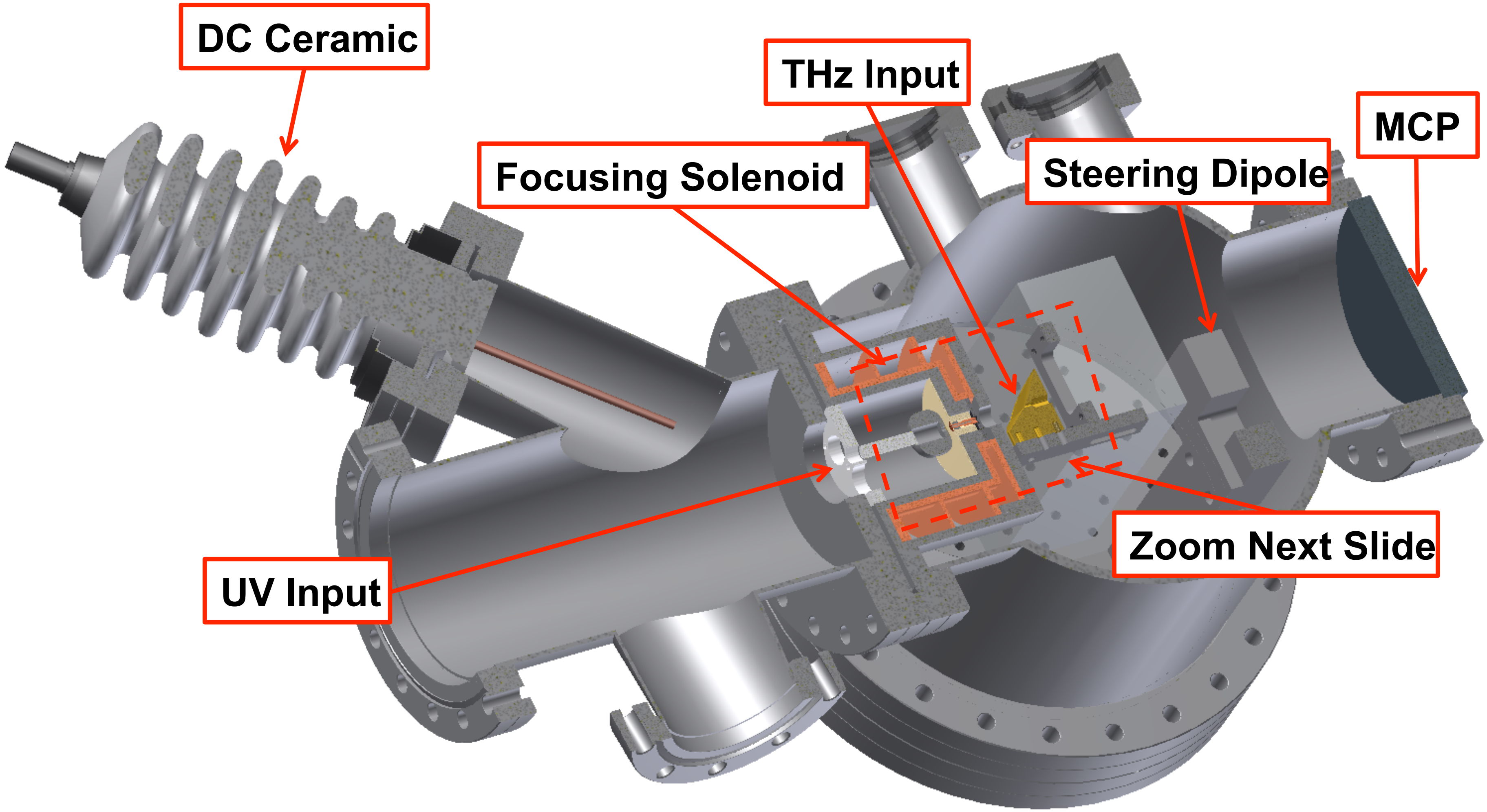


THz Acceleration Chamber

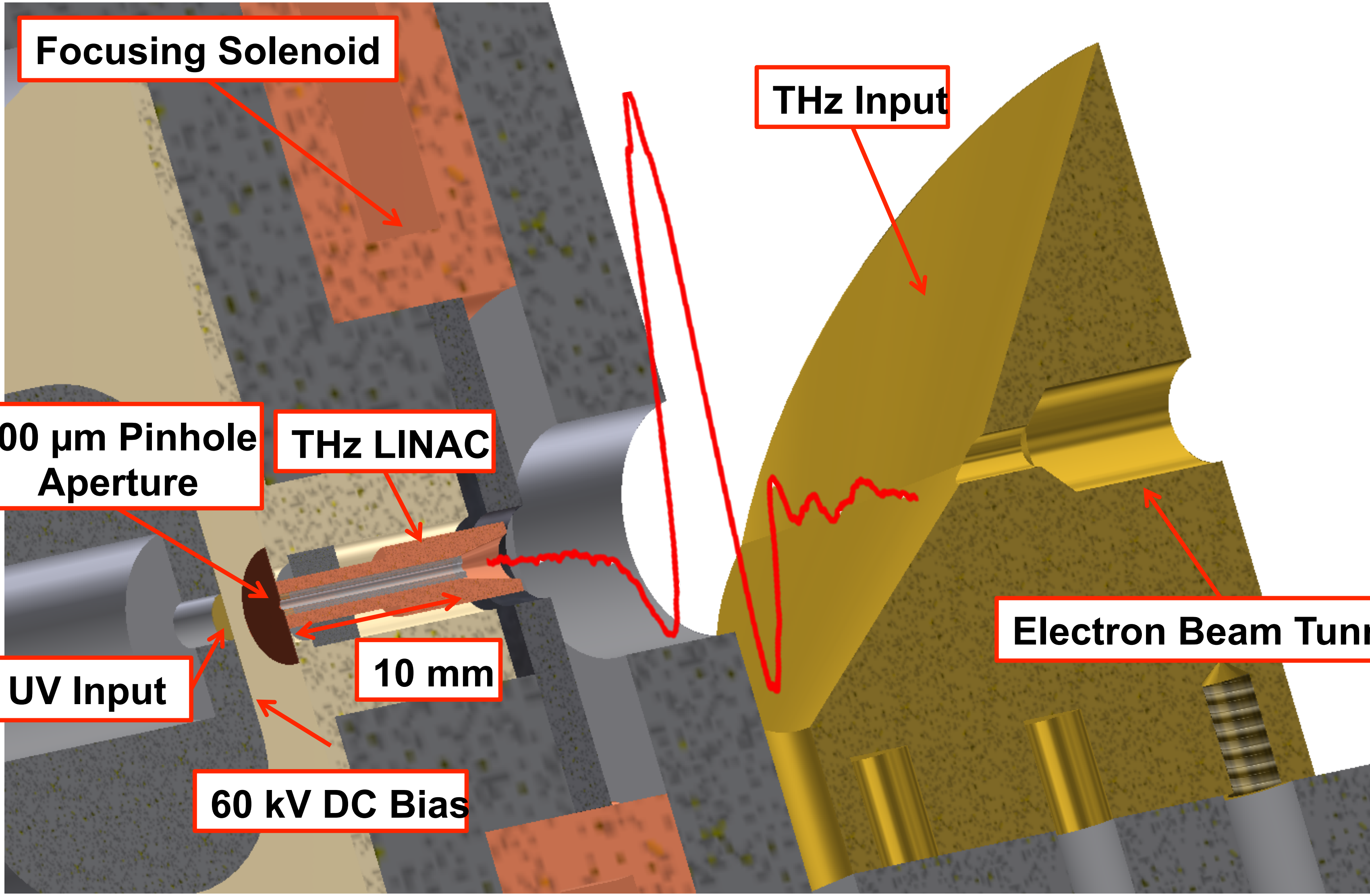


60 keV DC Gun from Dwayne Miller Group

DC Gun and THz LINAC



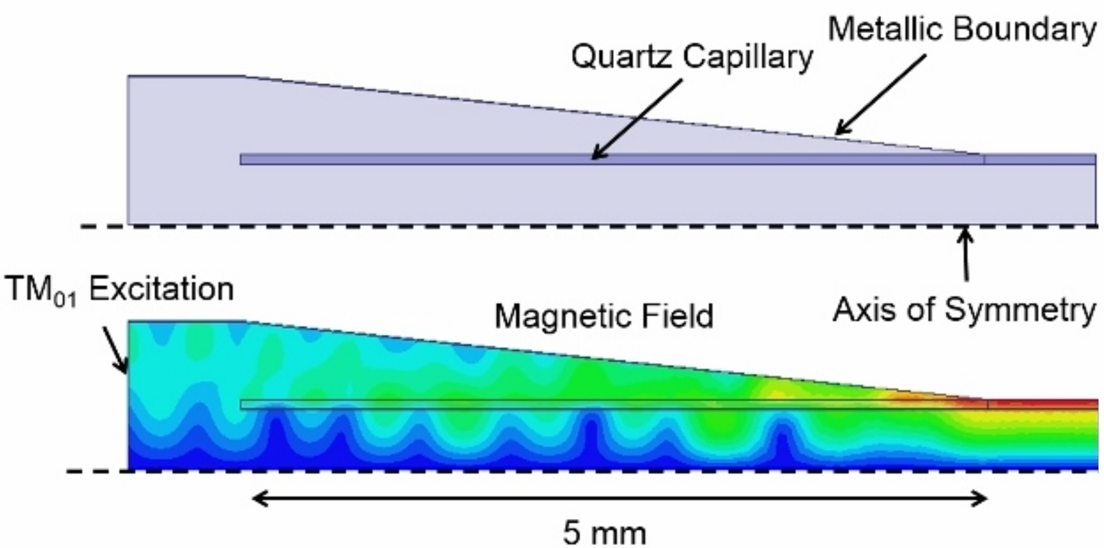
DC Gun and THz LINAC



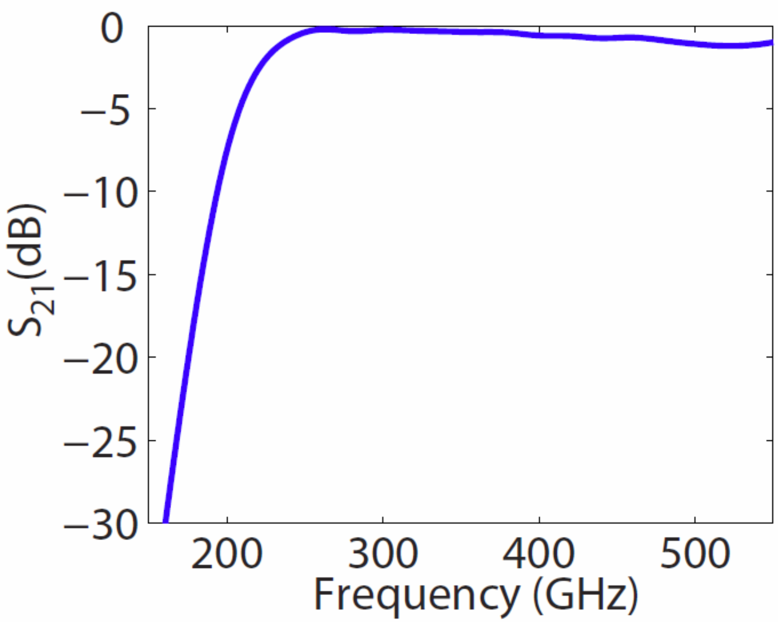
Dielectrically Loaded Horn

- Coupling of THz into waveguides with dielectrically loaded structure that is simple to fabricate

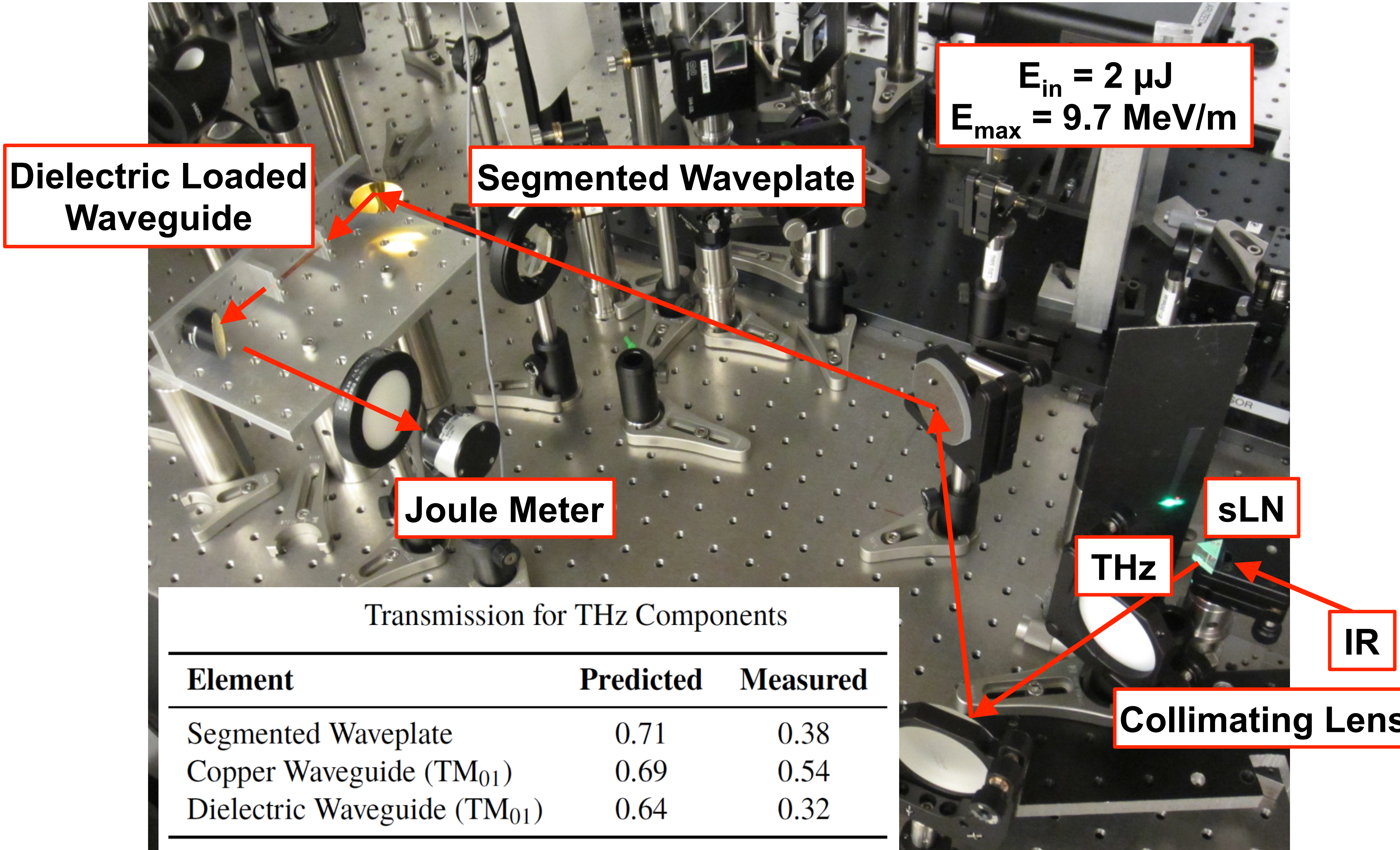
Dielectrically Loaded Horn



Coupling into TM_{01} - HFSS



Transmission Measurements



Transmission for THz Components

Element	Predicted	Measured
Segmented Waveplate	0.71	0.38
Copper Waveguide (TM_{01})	0.69	0.54
Dielectric Waveguide (TM_{01})	0.64	0.32

Electro-Optic (EO) Sampling

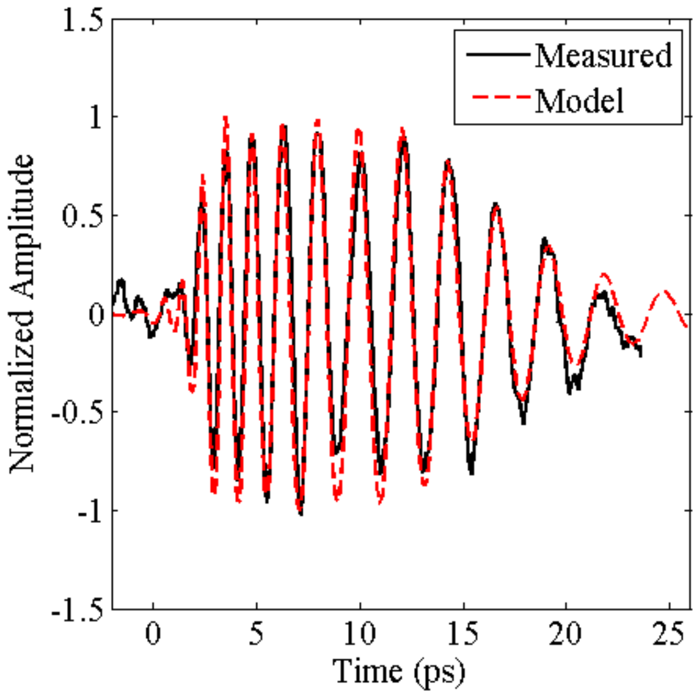
- THz waveguide is highly dispersive over a large bandwidth
- Dispersion in waveguides measured with EO sampling

Waveguide Parameters

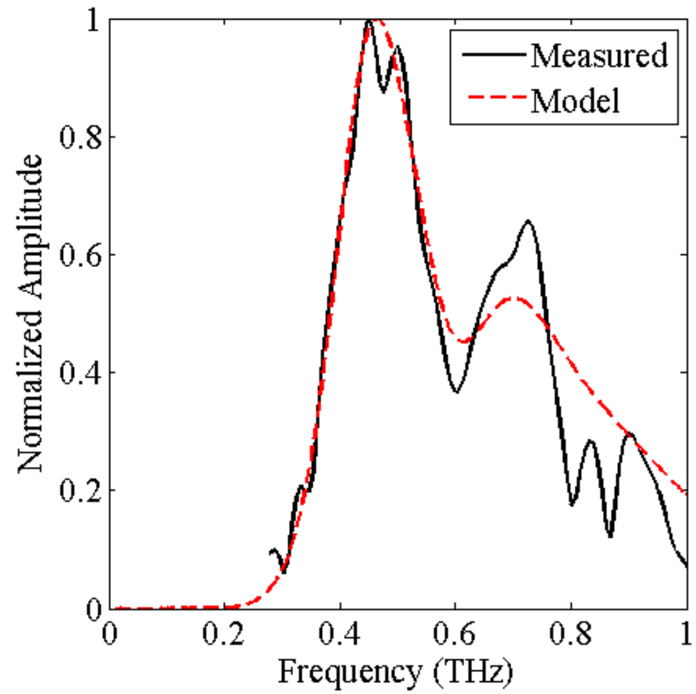
L = 4 cm

r_w = 474 µm

Electric Field



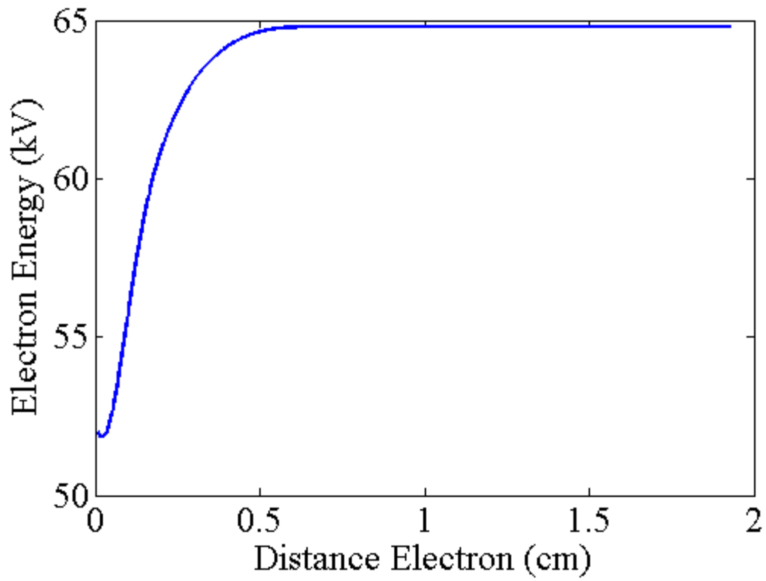
Frequency Spectrum



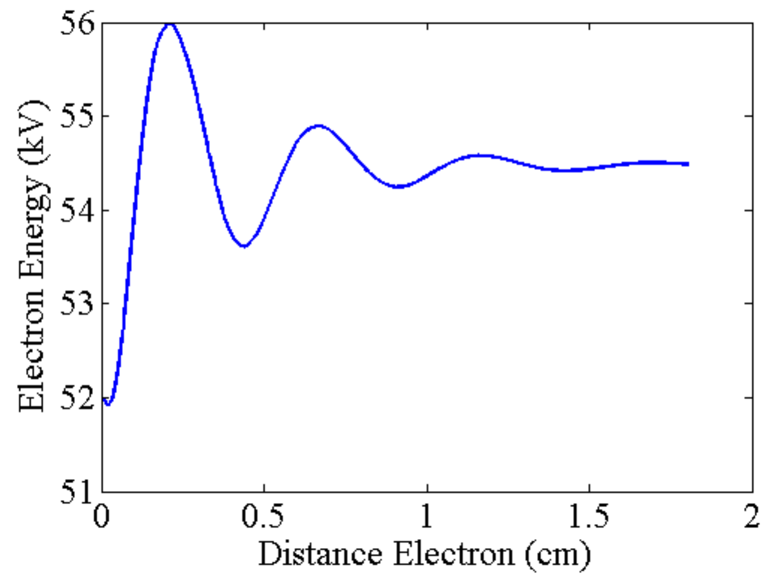
THz Acceleration Modeling

- Time domain acceleration of a single particle
- Small change in field has big impact due to low particle energy

2 μJ THz
10 MeV/m, 13 kV Acceleration

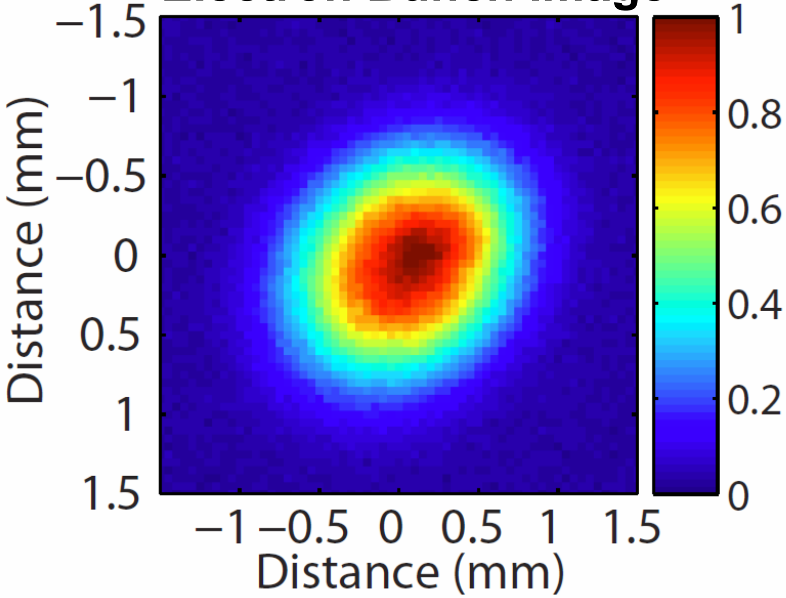


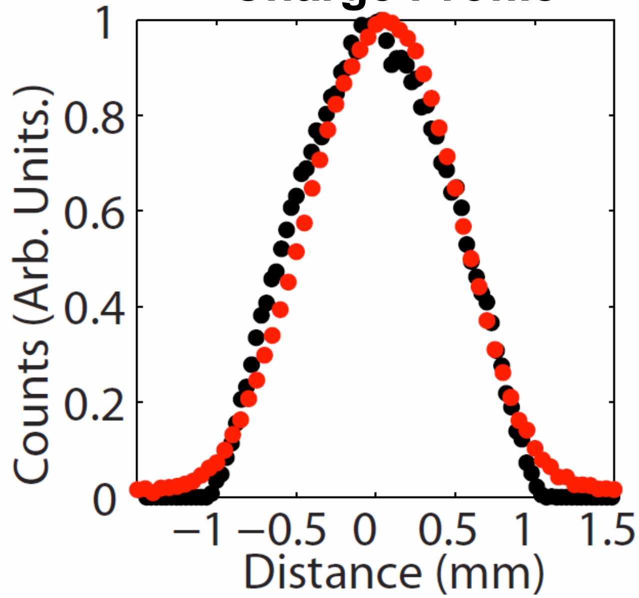
0.5 μJ THz
5 MeV/m, 2.5 kV Acceleration



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**

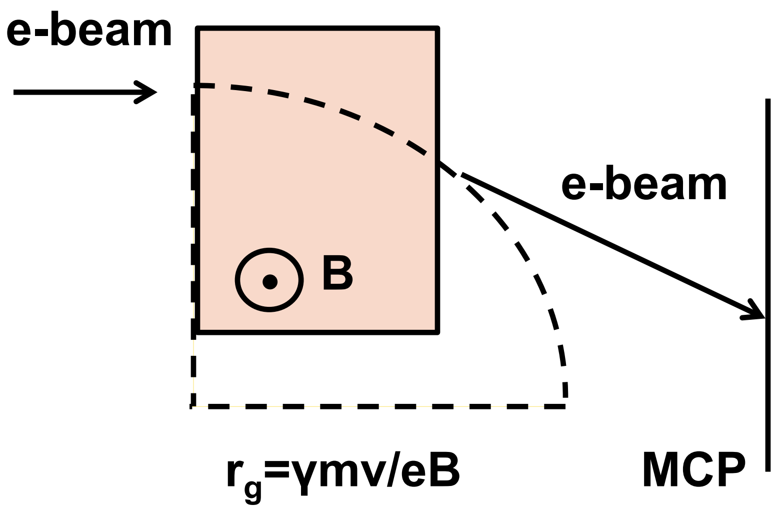


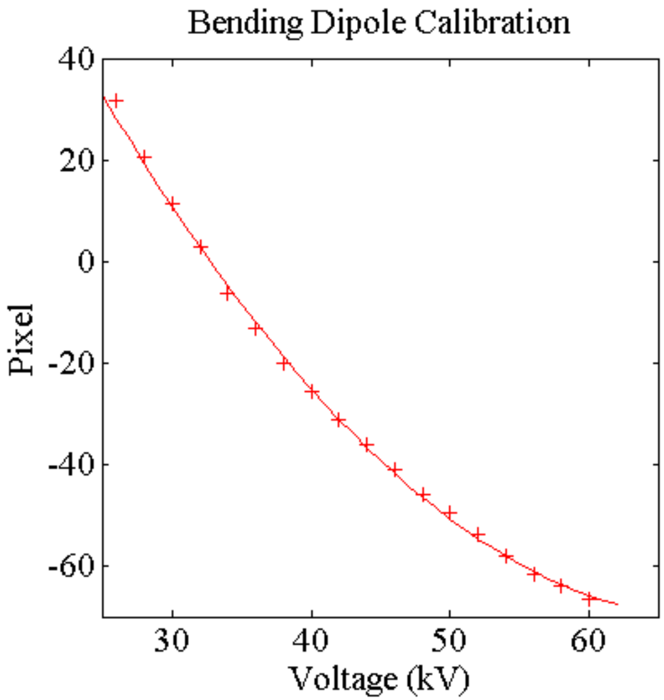


V = 50 kV
Q = 25 fC
Rep Rate = 1 kHz
CCD Exposure = 2 s

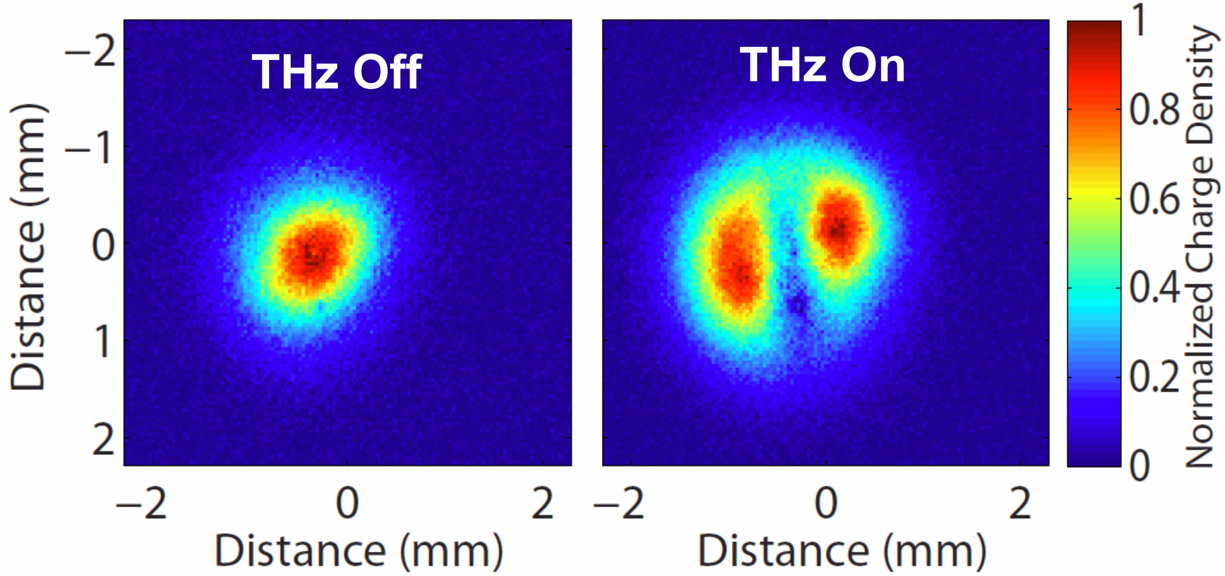
Energy Spectrometer

- A magnetic dipole is used to steer the electron beam in an energy dependent manner
- Resolution limit set by drift distance and pixel size



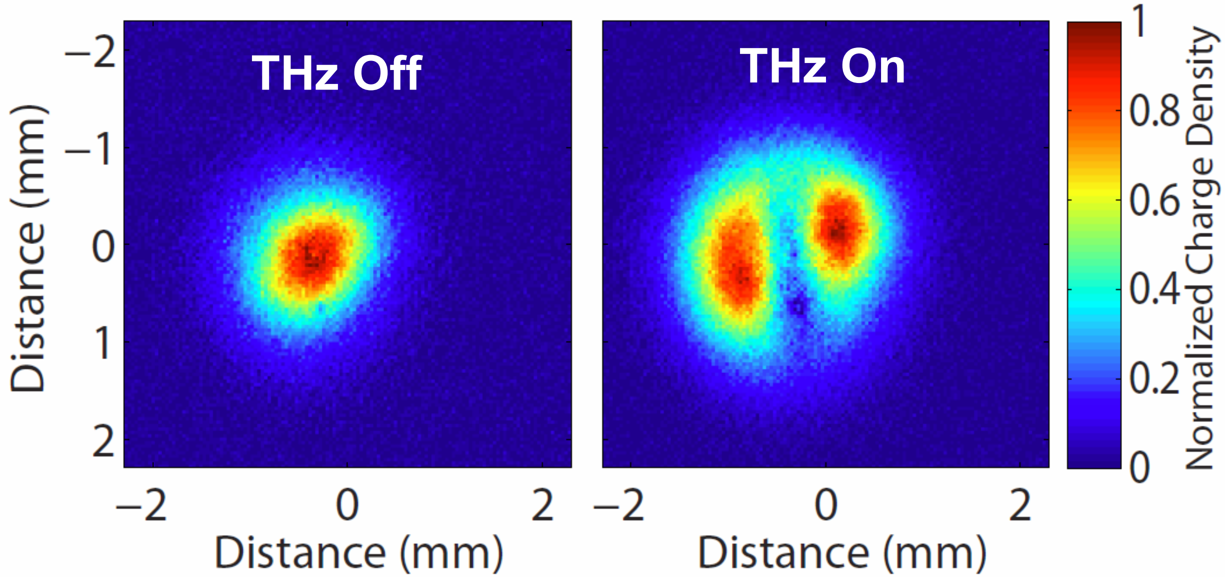


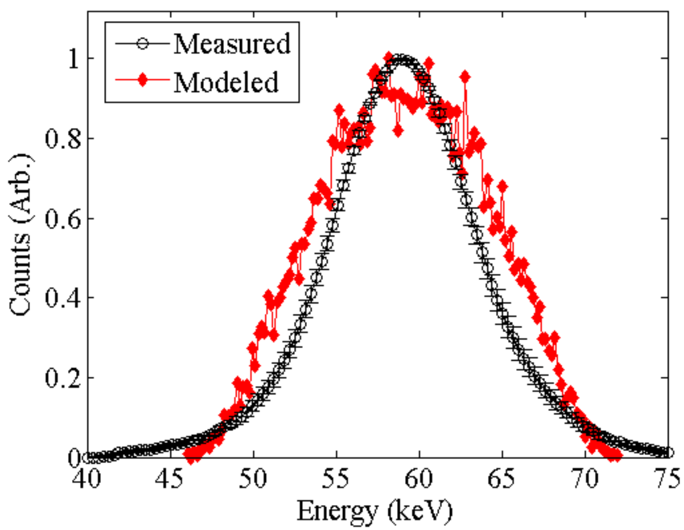
Terahertz-driven Linear Electron Acceleration

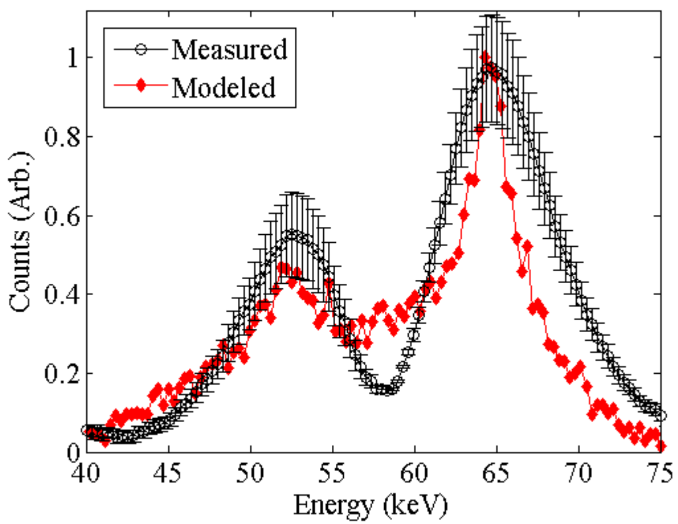


- Signal integrated over 3 seconds with 1 kHz repetition rate
- Measured energy spectrum for 59 keV start energy
- Modeled on-axis gradient of 4.9 MeV/m
- Electron bunch σ_z = 45 µm

Terahertz-driven Linear Electron Acceleration



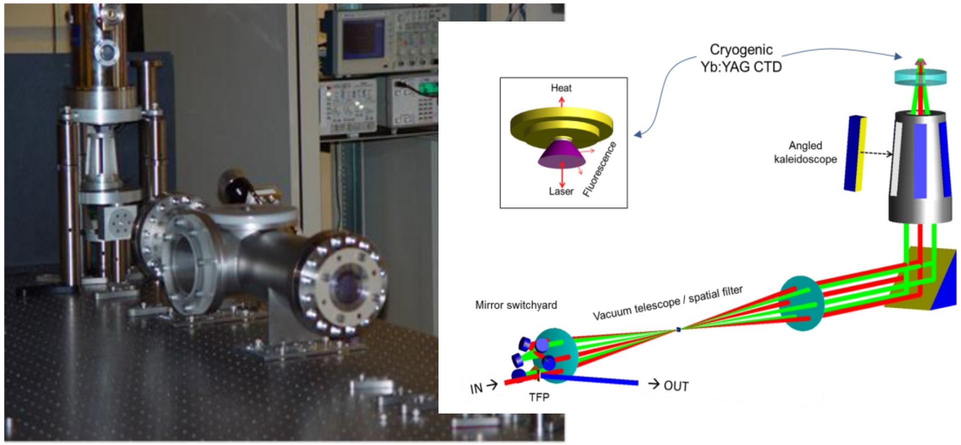




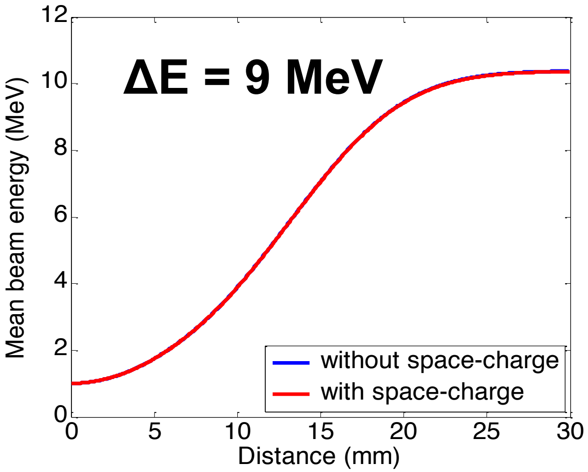
Future Work

- Extending THz acceleration to GeV/m and relativistic energies
  - Improvements to IR laser pulse energy (1 J) with cryo-YAG or cryo-YLF multi-pass amplifiers
  - High energy accelerator development underway using single and multi-cycle pulses

<u>Demonstrated cryo-YAG amplifier</u>
160 mJ IR pulse, uncompressed



<u>Modeling THz Acceleration</u>
10 cycle, 20 mJ pulse, 0.74GeV/m



L. J. Wong, et al., *Optics Express* 21.8 (2013): 9792-9806.

THANK YOU FOR YOUR ATTENTION

European Research Council

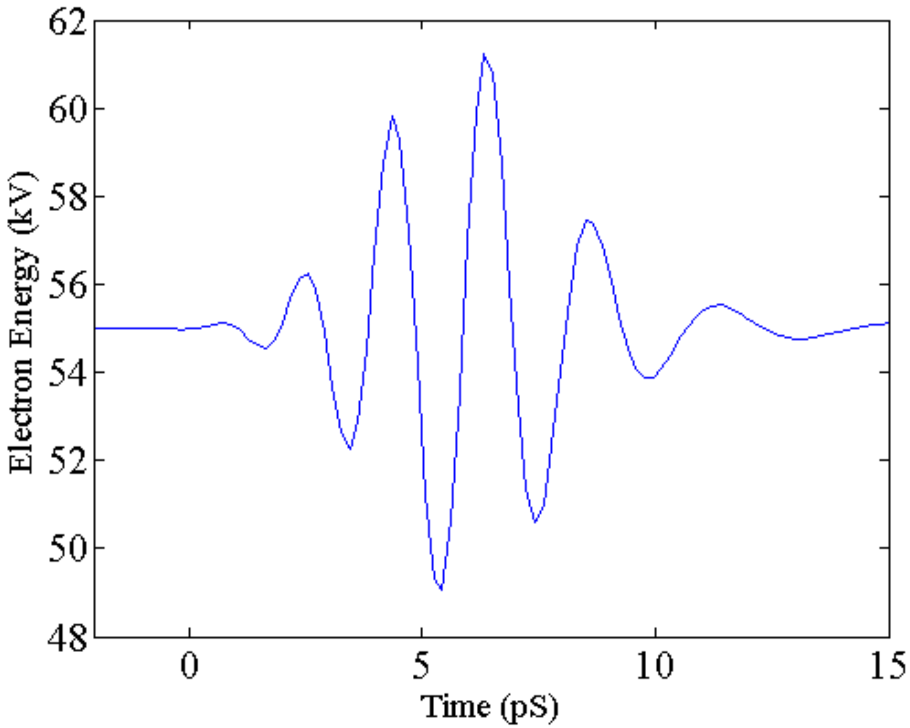
HELMHOLTZ ASSOCIATION

Alexander von Humboldt Stiftung/Foundation

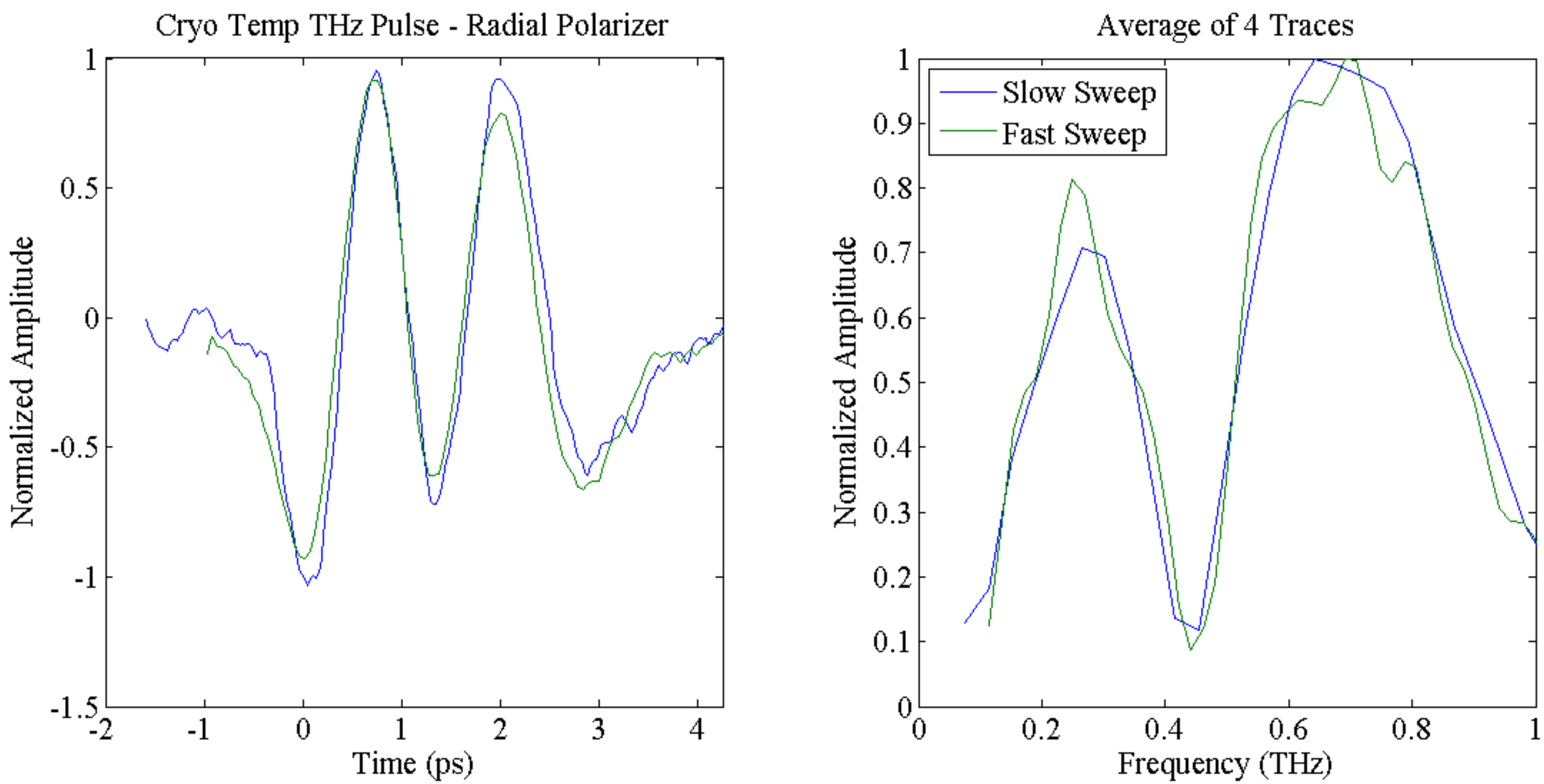
Modeled Acceleration vs UV Delay

- Due to propagation in waveguide THz pulse suffers from dispersion
- Acceleration very sensitive to input spectrum

$E_{on\text{-}axis}$ = 2.5 MeV/m
Peak at Input
E_{beam} = 55 keV



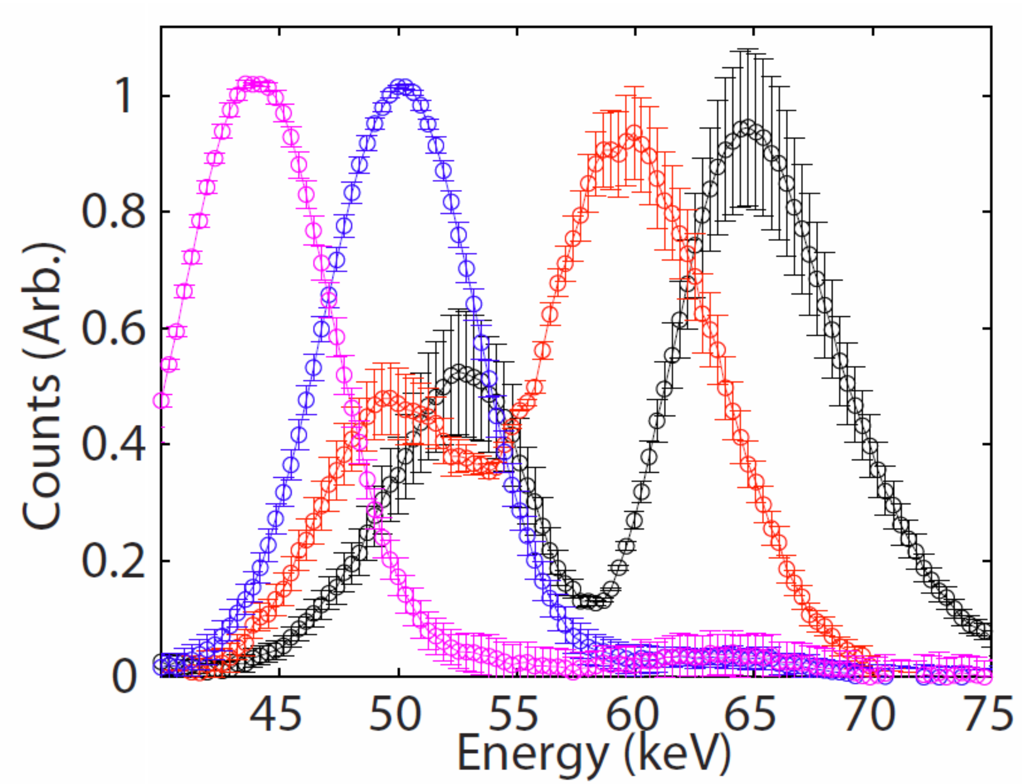
Radial Polarizer w/ Cryo Pulse



EO sampling should be insensitive to radial polarization at 450 GHz

Energy Spectrum vs. Voltage

- Tuning voltage with THz On



Key Laser Parameters

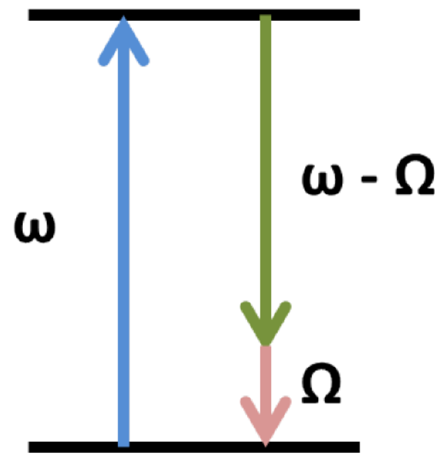
- IP beam waist is 3 microns
- Green pulse length is 2 ps
- Target conversion efficiency – 50%
- IR pulse energy 100 mJ
- Desired repetition rate for cavity is 5 ns or L_{Tot} ~ 1.5 m
- Damage threshold – 0.28 J/cm^2 for 2 ps pulse

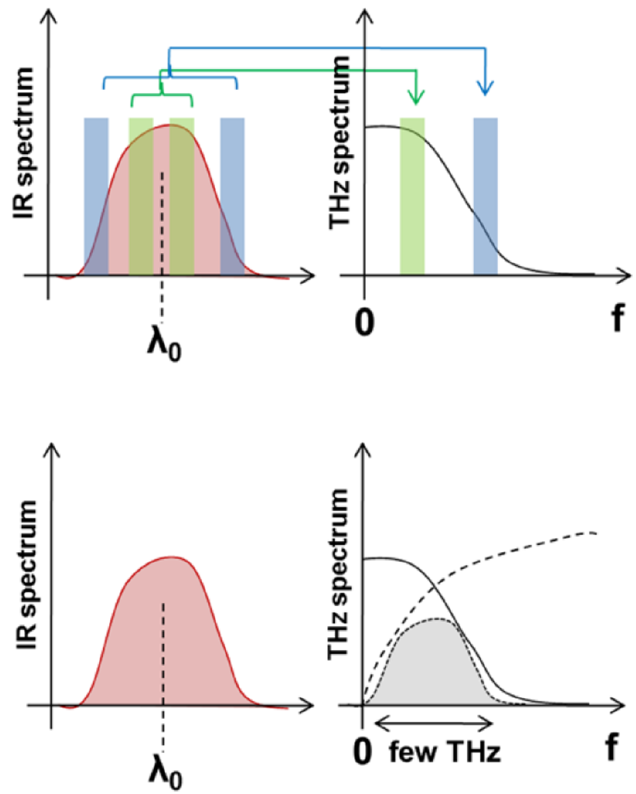
Detailed Parameters

	Cavity Length (m)	1.50
	Focal Length (cm) - f1	34.50
	Focal Length (cm) -f2	3.00
Green	w0 (microns)	3
Green	w1 on Lens (mm)	18.85
Green	w1 on Mirror (mm)	3.28
Green	Peak Surface Intensity (GW/cm^2)	73.9678
Green	Peak Surface Field (GV/m)	0.53
Green	Energy (mJ)	50
Green	Pulse width (ps)	2
Red	w1 (mm)	26.66
Red	Peak Surface Intensity (GW/cm^2)	26.15
Red	Peak Surface Field (GV/m)	0.44
Red	Energy (mJ)	100
Red	Pulse width (ps)	2.83
SiO2	Lens Thickness (mm)	2.8
SHG - LBO	Total Thickness (mm)	3.15
	Surface Safety Factor	1.91
	B-integral (SHG)	2.37
	B-integral (Total)	5.29
	Number of Passes	100
	Loss	1%

THz Generation

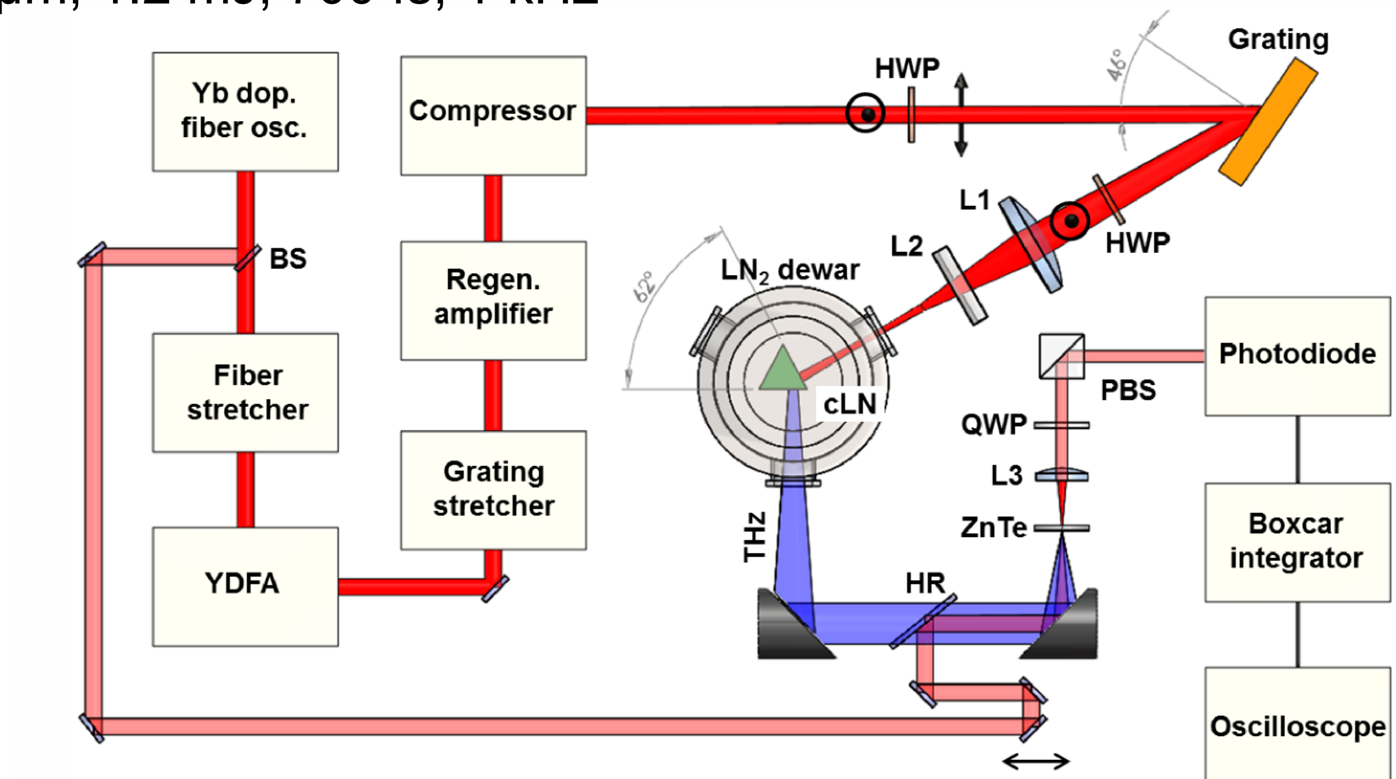
- THz generation via optical rectification of IR pulses
- Optical rectification: intra-pulse difference frequency generation





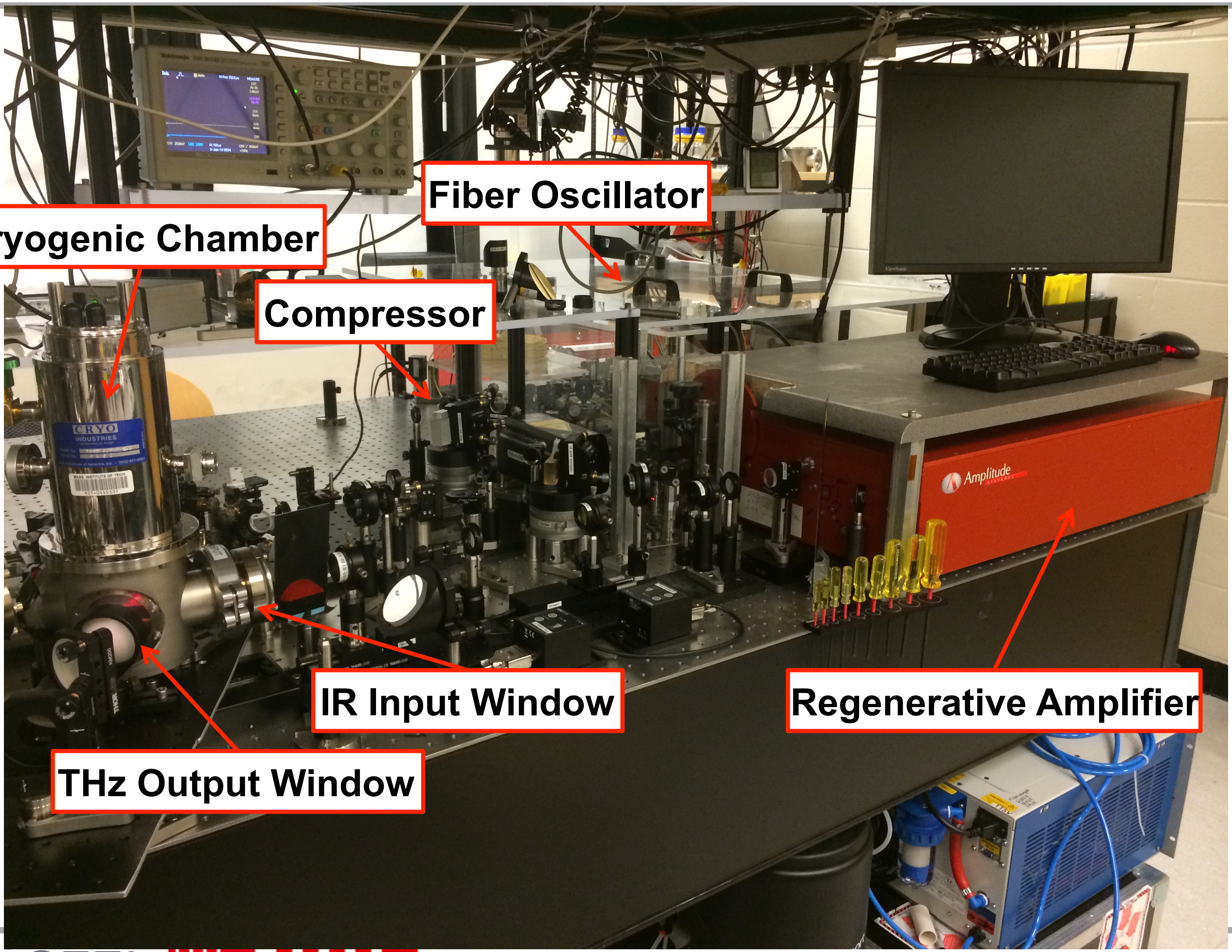
THz Generation Setup

- Yb:KYW regenerative amplifier
  - 1 µm, 1.2 mJ, 700 fs, 1 kHz



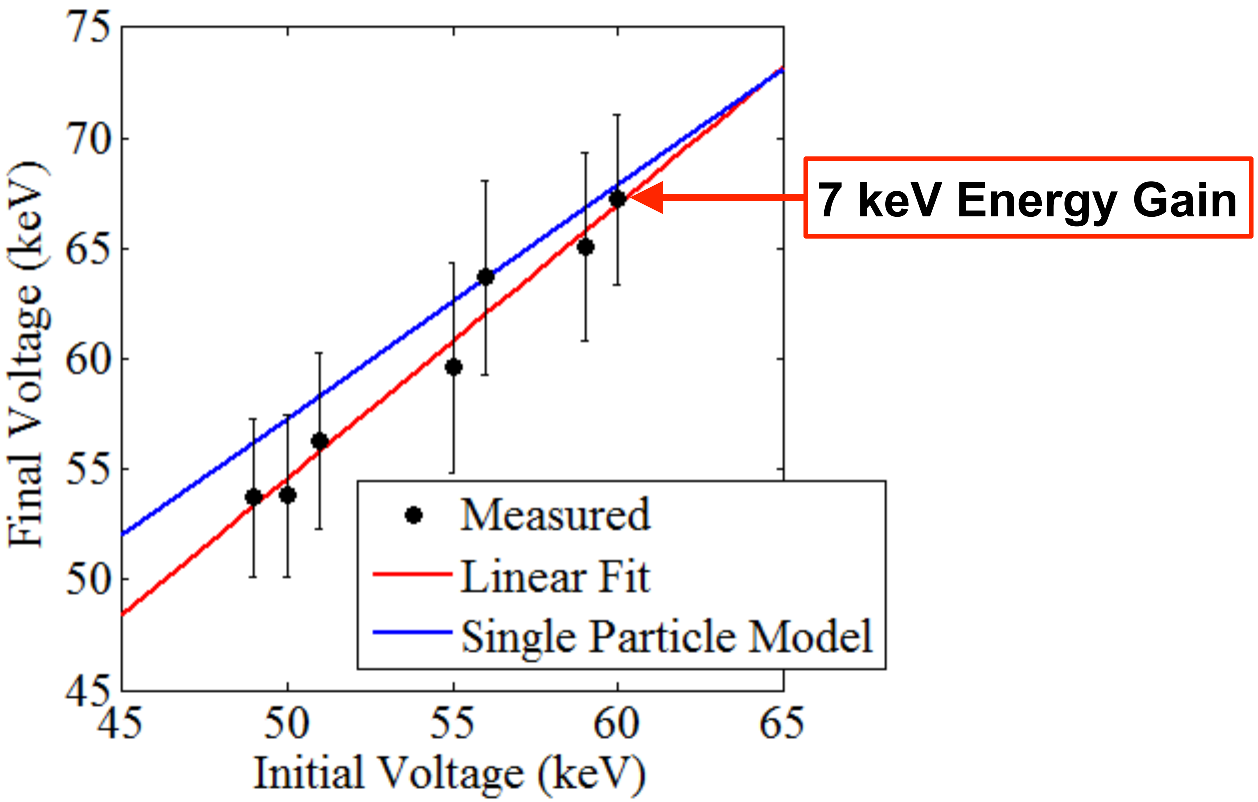
- ~1% THz conversion efficiency with pulse front tilting and cryogenic cooling

THz Generation Setup



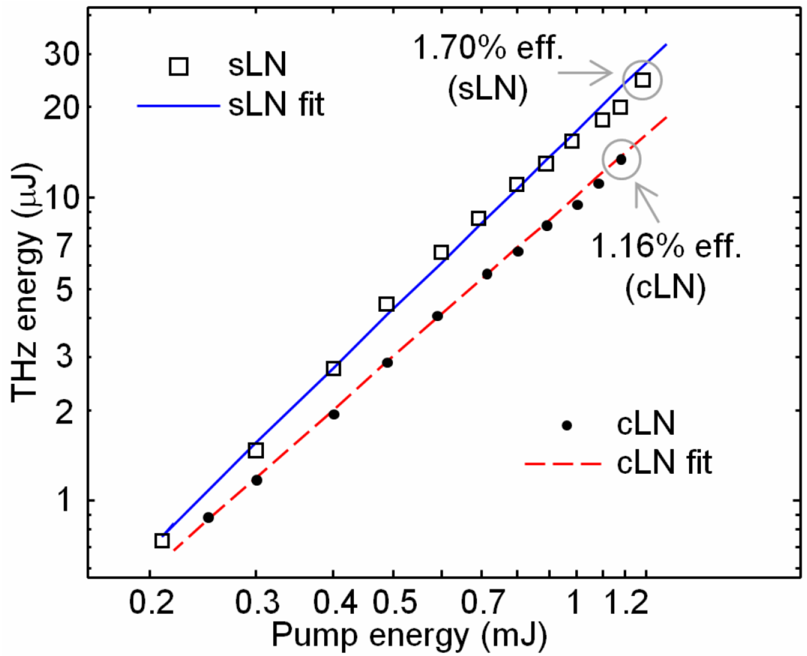
Energy Gain vs Voltage

- Energy gain depends on initial electron energy
- Increase in energy decreases phase slippage
- Single particle model with 5 MeV/m gradient

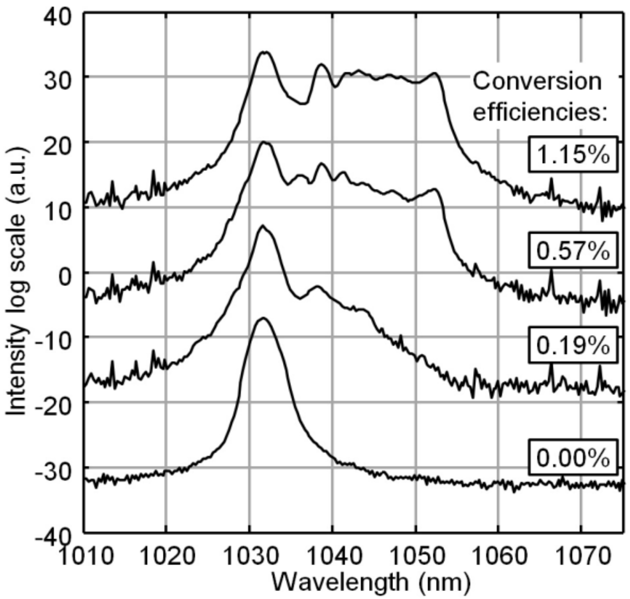


THz Generation Efficiency

- Conversion efficiency of 1.7% in room temperature sLN
- Cascaded IR pulse is associated with high conversion efficiency



Transmitted IR spectrum of room-temp cLN

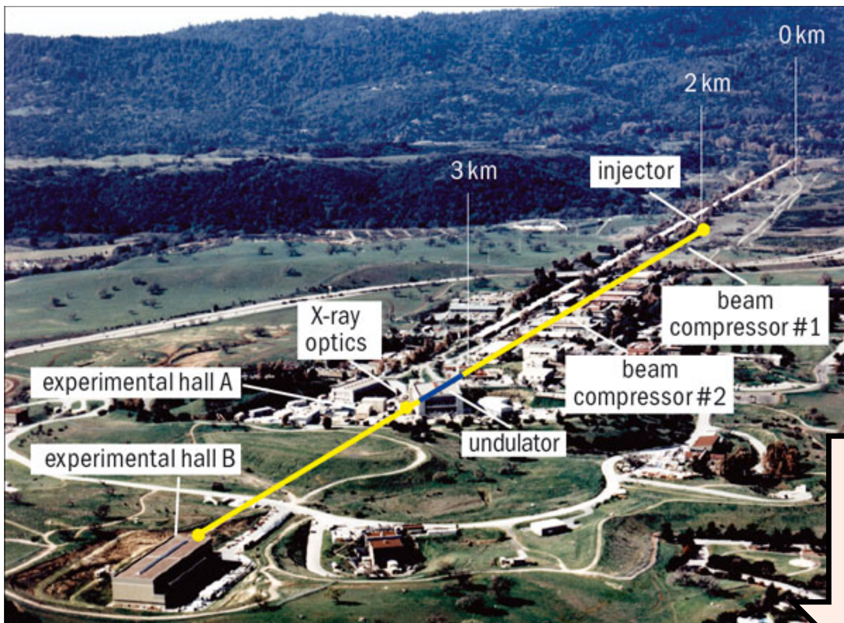


Huang, Shu-Wei, et al., Optics letters 38.5 (2013): 796-798.

X-ray Lasers

- **X-ray FELs provide new opportunities for scientists**
- **Will accessibility remain in issue?**

Coherent emission from LCLS (2009)



European XFEL (2017)

Tabletop X-ray Laser?

Why are X-ray Sources so Big?

- **Size is driven undulator period and need for high energy**

$$\lambda_x \propto \frac{\lambda_u}{2\gamma^2} \qquad \lambda_x = 1\ \mathrm{nm} \qquad \lambda_u = 3\ \mathrm{cm} \qquad E \approx 2\ \mathrm{GeV}$$

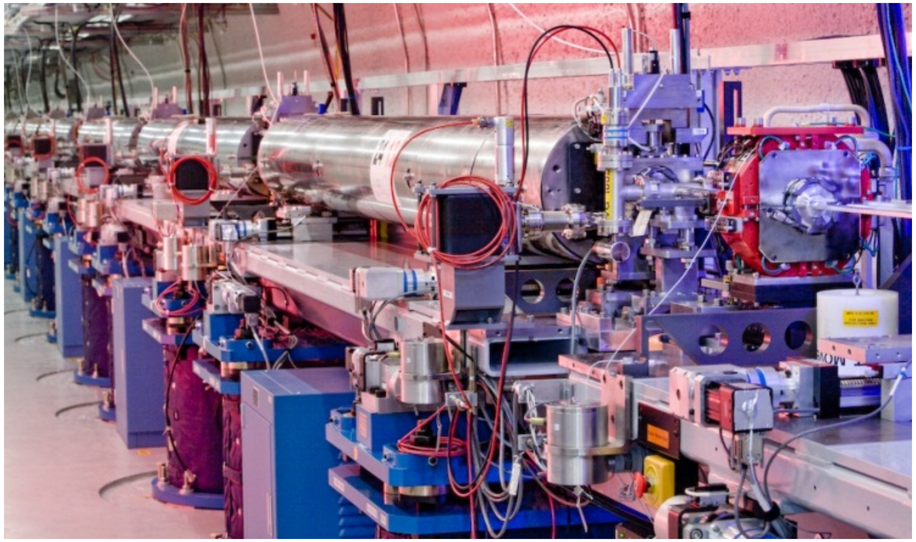
State-of-the-Art

RF Accelerator

Research Instruments GmbH

XFEL SC 1.3 GHz

Static Undulator

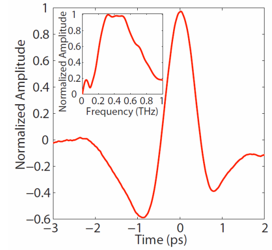


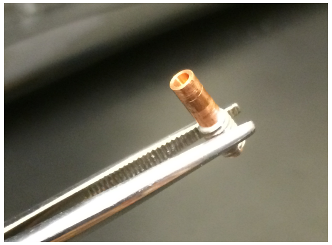
LCLS

Compact X-ray Source Technologies

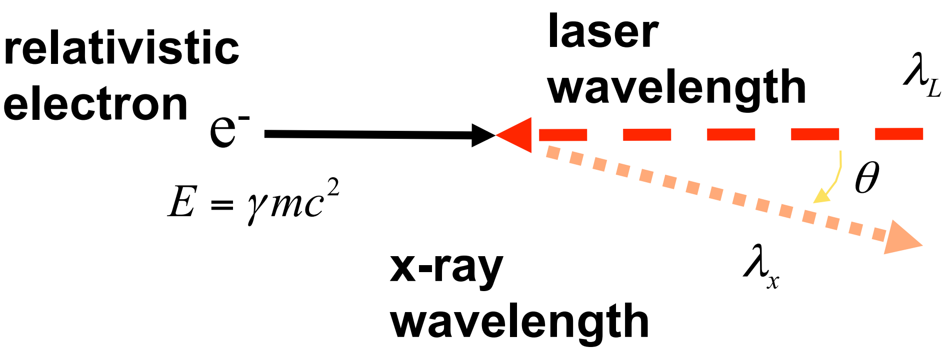
- High Gradient Accelerators
  - 50 MeV/m

Focus of Seminar





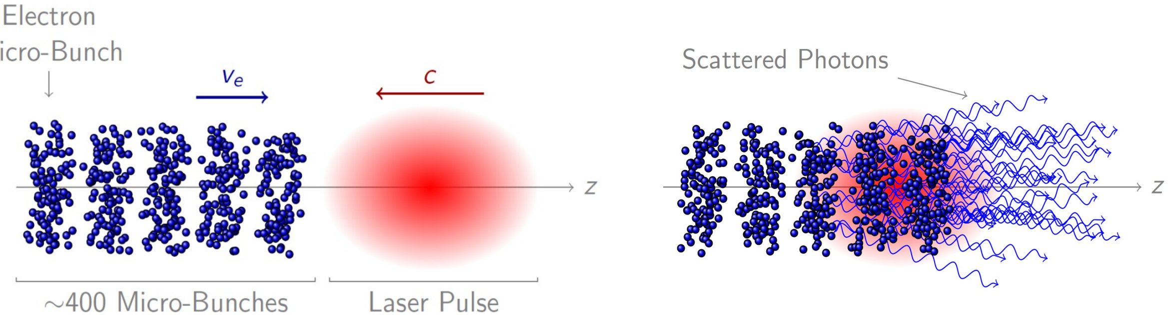
- **Electromagnetic Undulator**



$$\lambda_x = \frac{\lambda_L}{4\gamma^2}\left(1 + a_0^2 + \gamma^2\theta^2\right)$$

***a_0* is laser intensity**

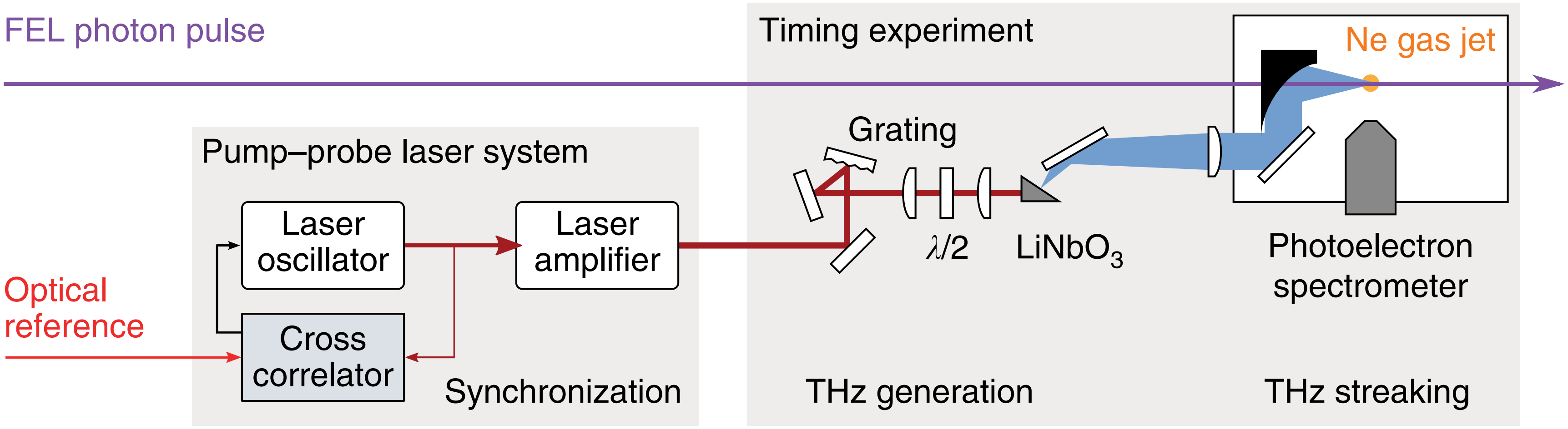
- **Microbunching of Electron Beam**

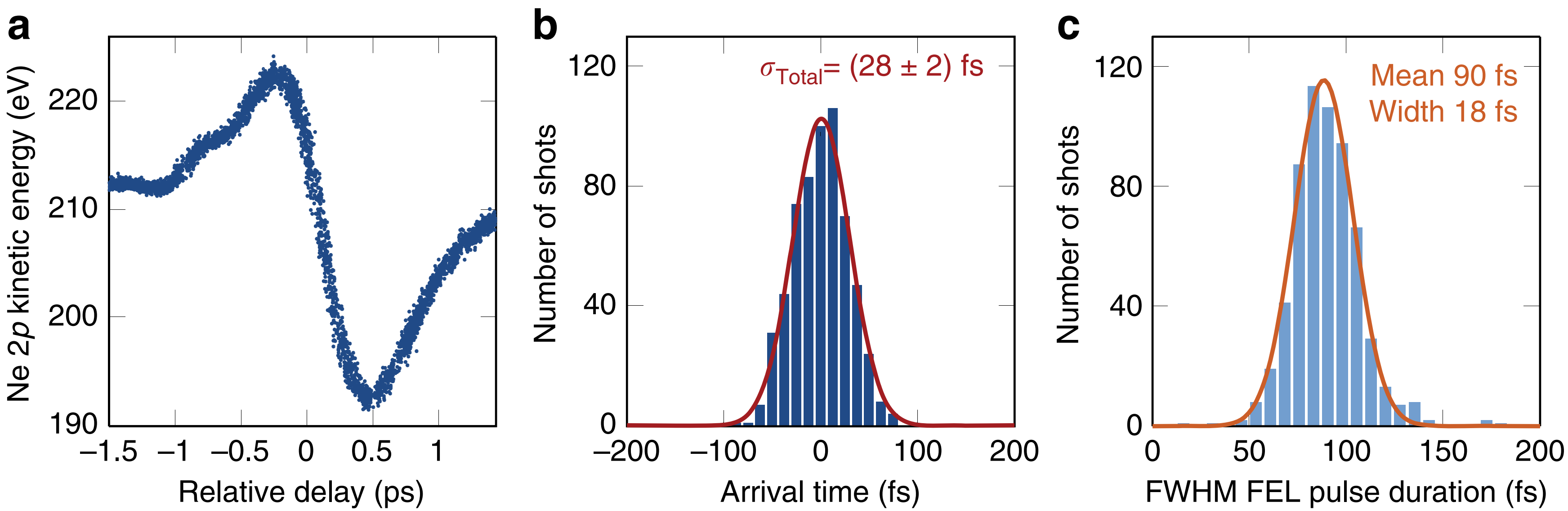


Graves, W. S., et al. *Phys. Rev. Lett.* 108.26 (2012): 263904.

X-Ray FELs operating and under construction

THz streaking of FEL - pulses



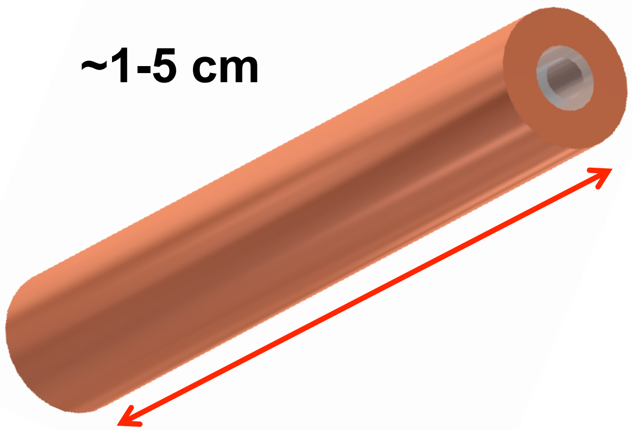


THz Acceleration

• **Increasing operational frequency:** higher breakdown fields, reduced pulse energy ~ λ^{-3}, reduced pulsed heating and average power load

• **High-gradient accelerators:** reduced size, short bunches and improved electron beam quality

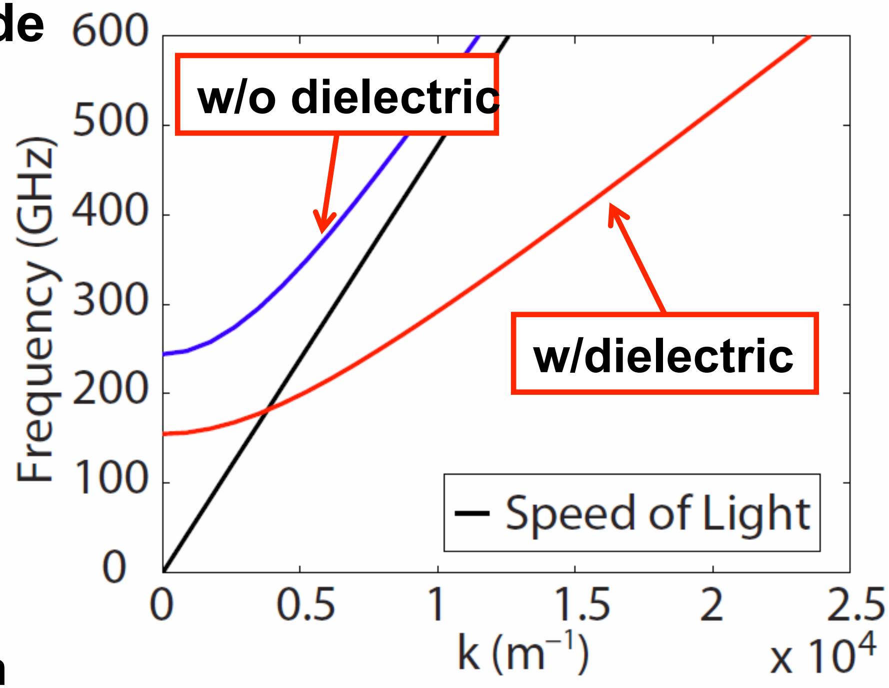
Dielecrically loaded metal waveguide



Copper Inner Diameter = 940 µm

Fused Silica Inner Diameter = 400 µm

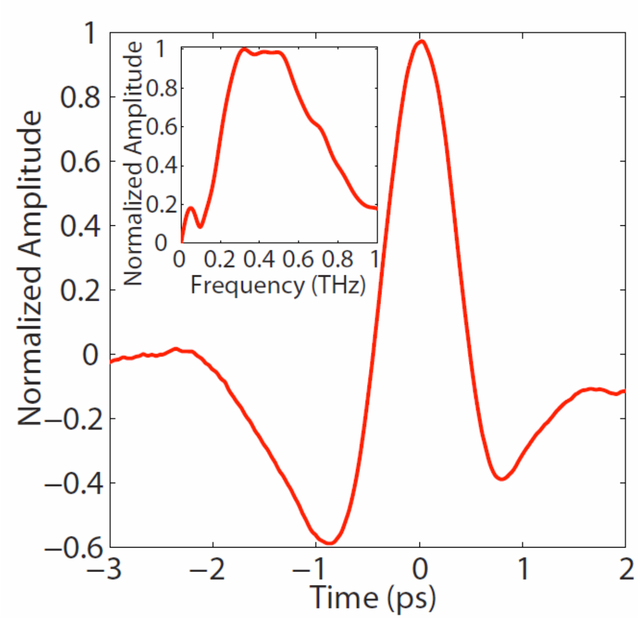
Dispersion Relation



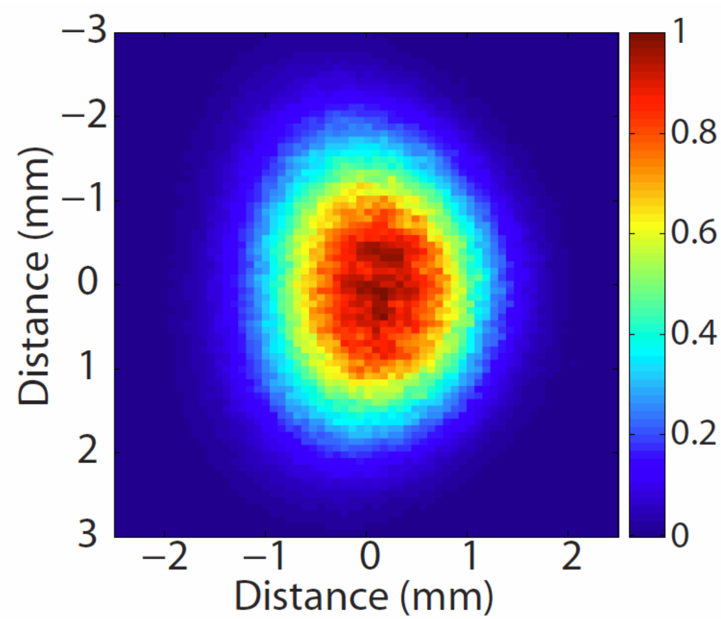
Efficient THz Generation

- Single cycle THz pulse (~2 ps) centered at 0.45 THz
- **J. Hebling et al. Opt. Express 21(10), 1161-1166 (2002).**
- 1mJ → 10 µJ pulse measured ~1 m from source **(1 - 2 %)**

Electric Field from EO Sampling

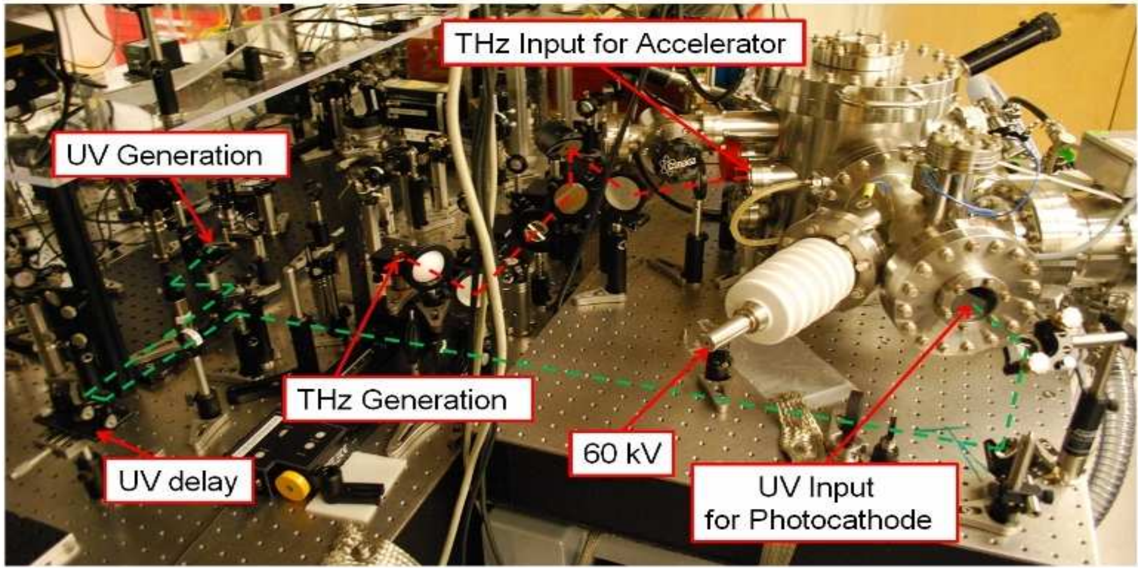


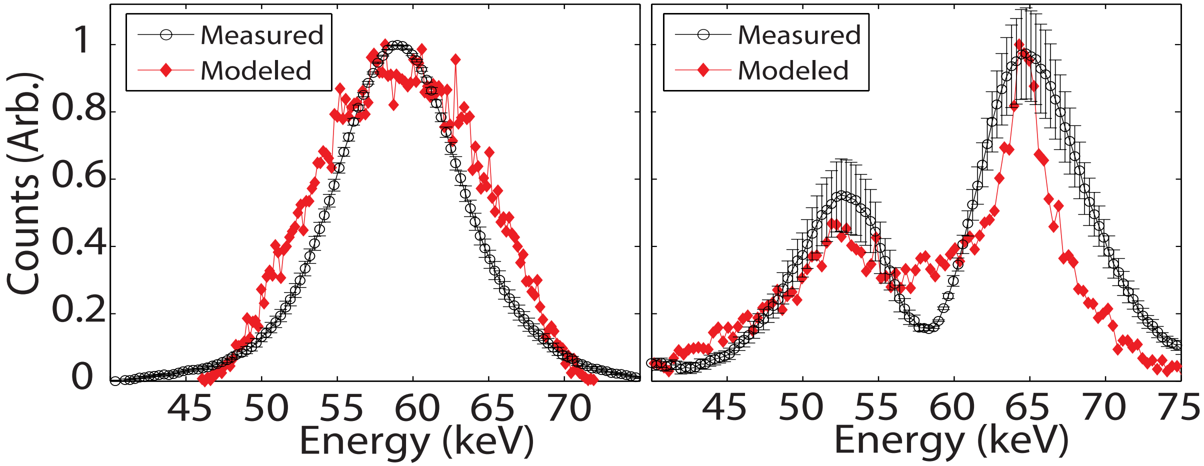
Transverse Intensity Profile



S.-W. Huang et al., Opt. Lett. 38:(5), 796-798 (2013).
S. Carbajo, CLEO US (2015).

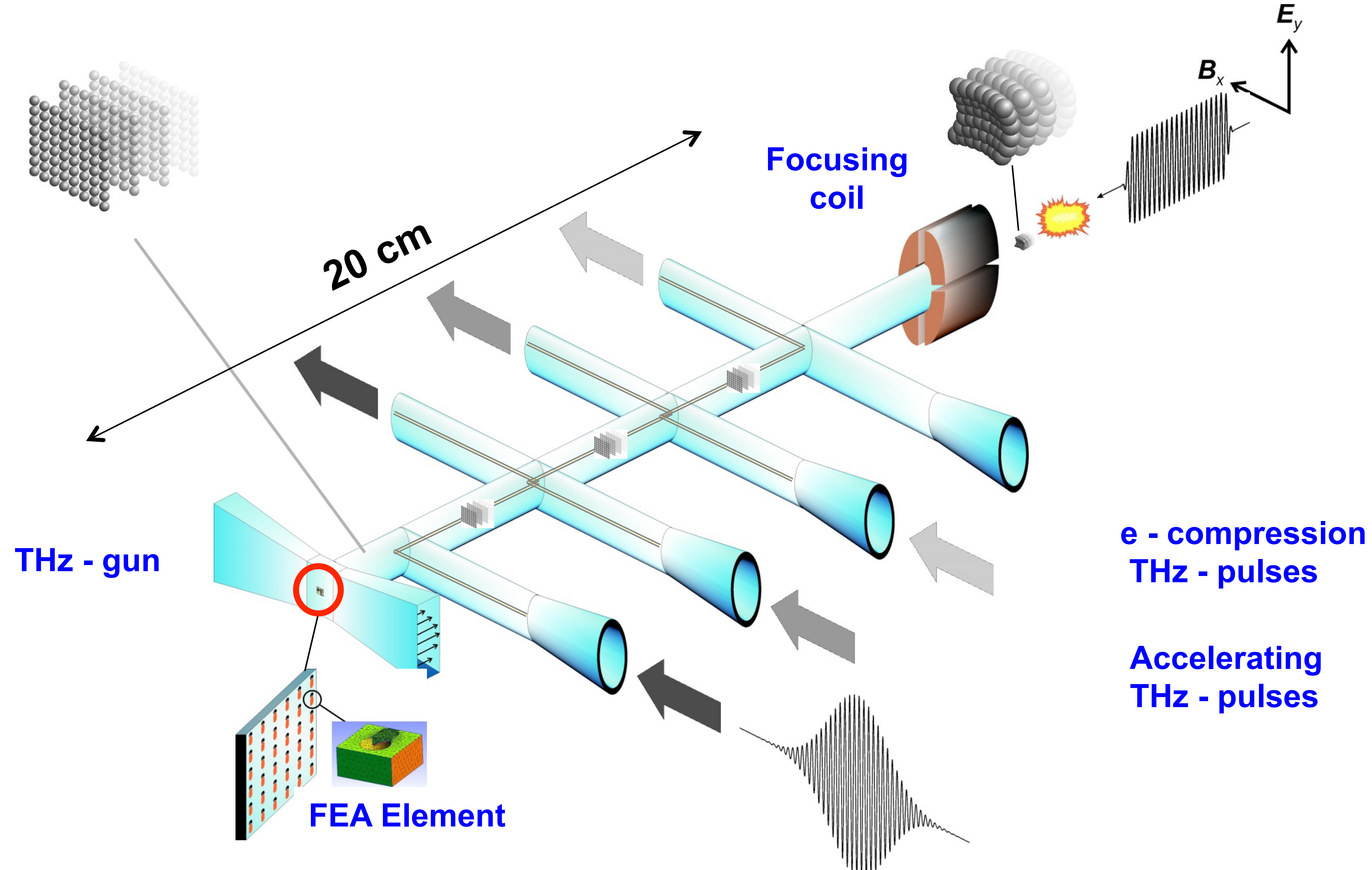
THz Acceleration



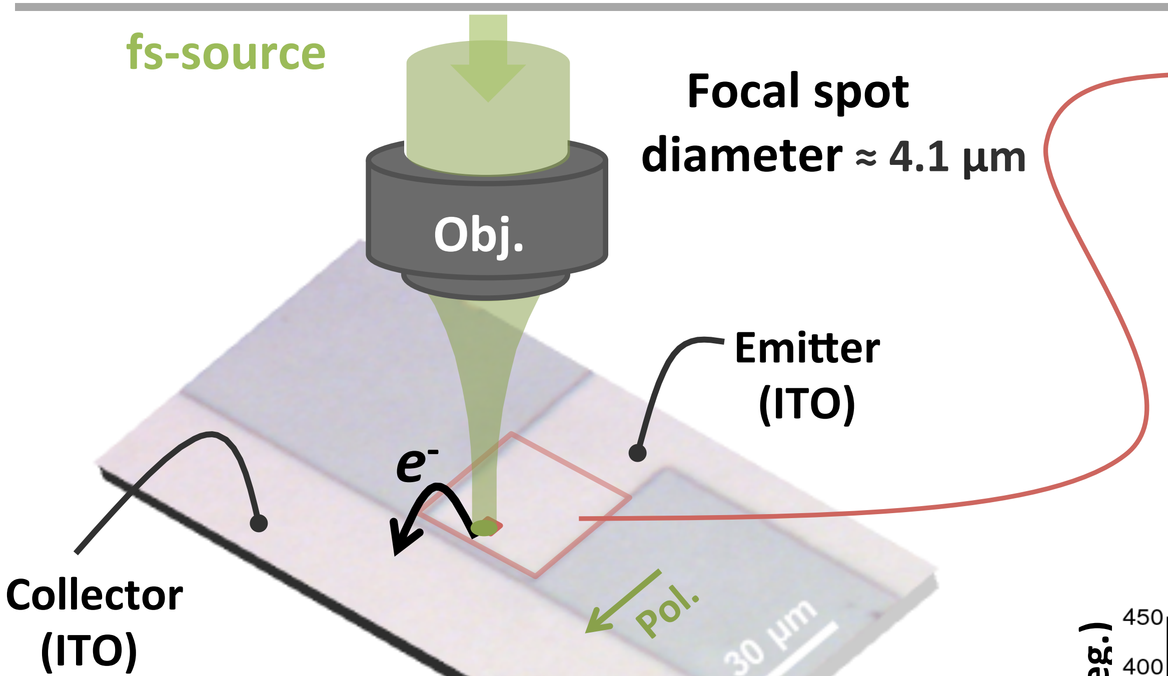


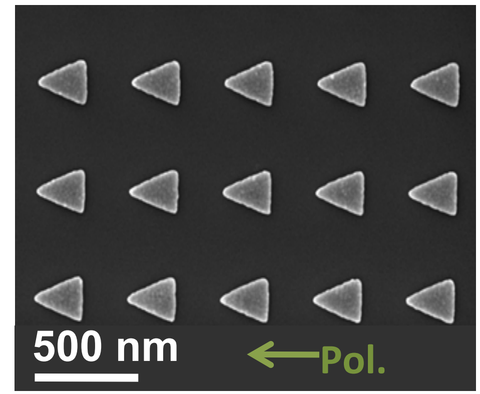
Nanni, E.A., et al. *arXiv :1411.4709* (2014).

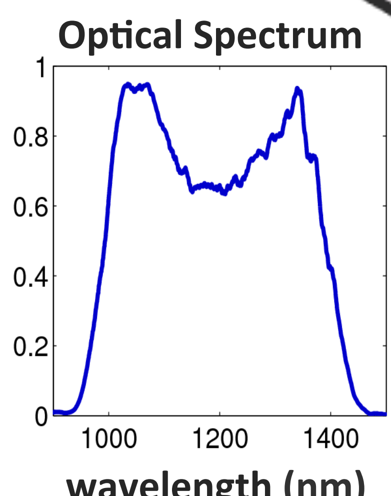
THz driven FEL like source

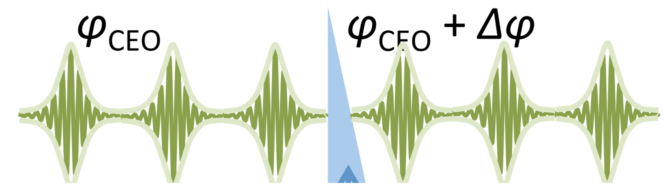


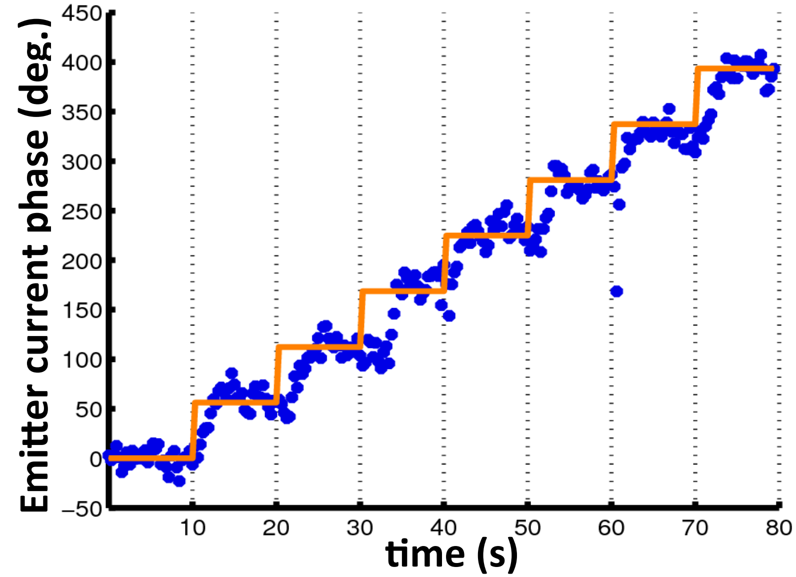
CEP sensitive field emitter array



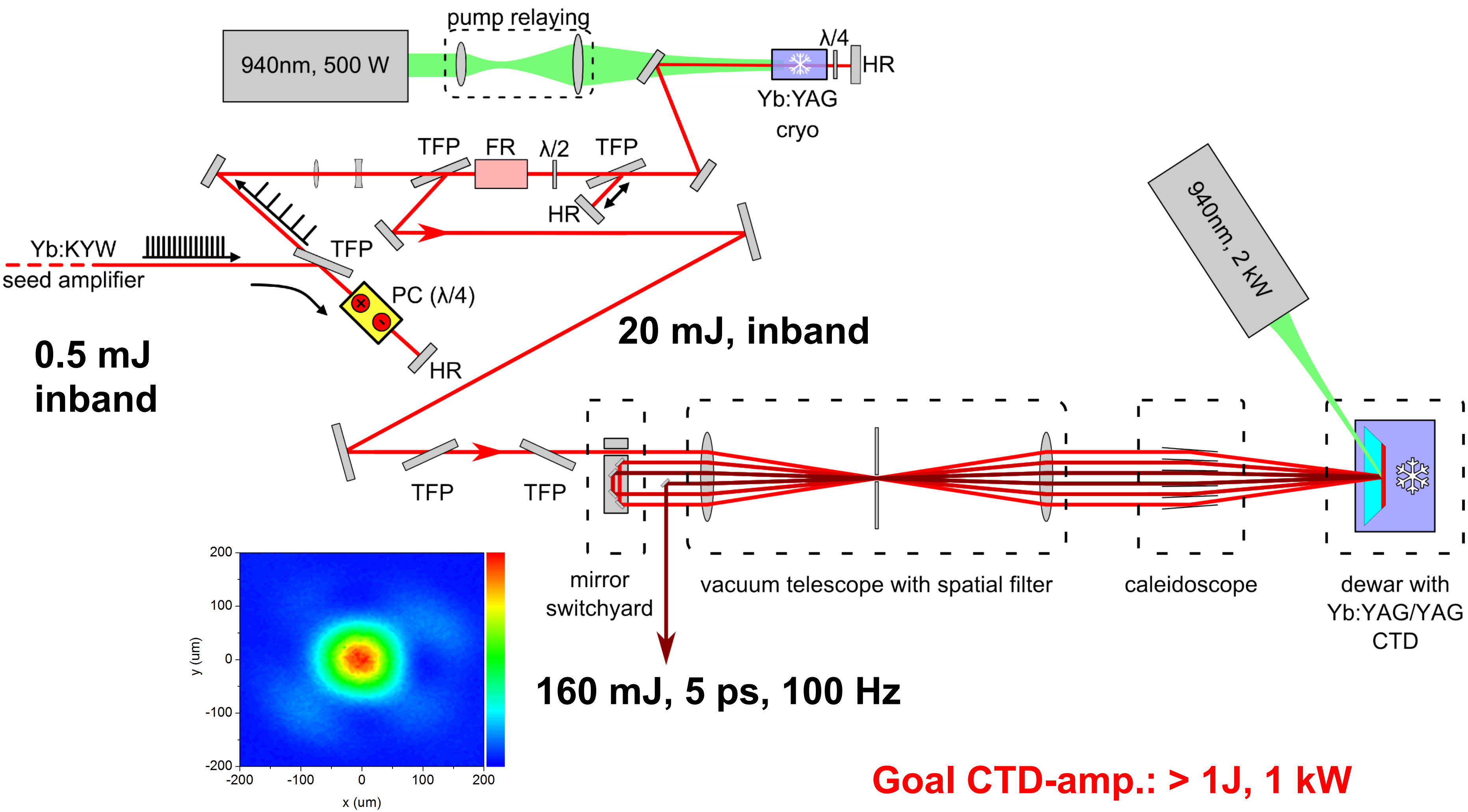








High energy cryogenic lasers

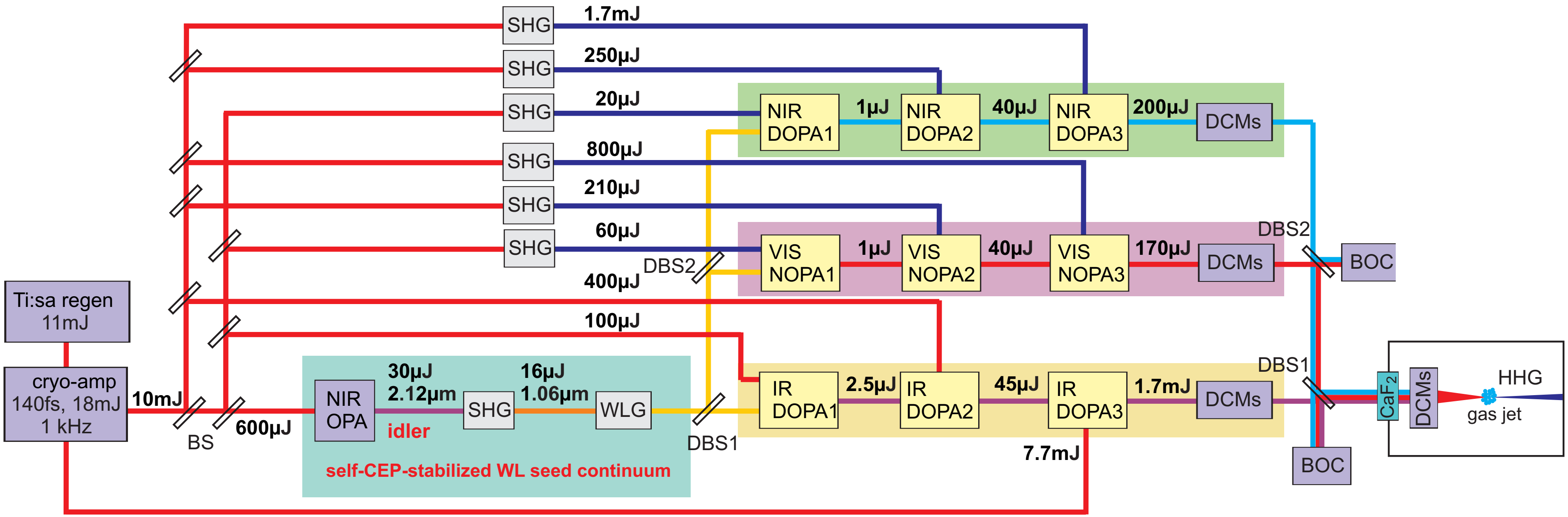


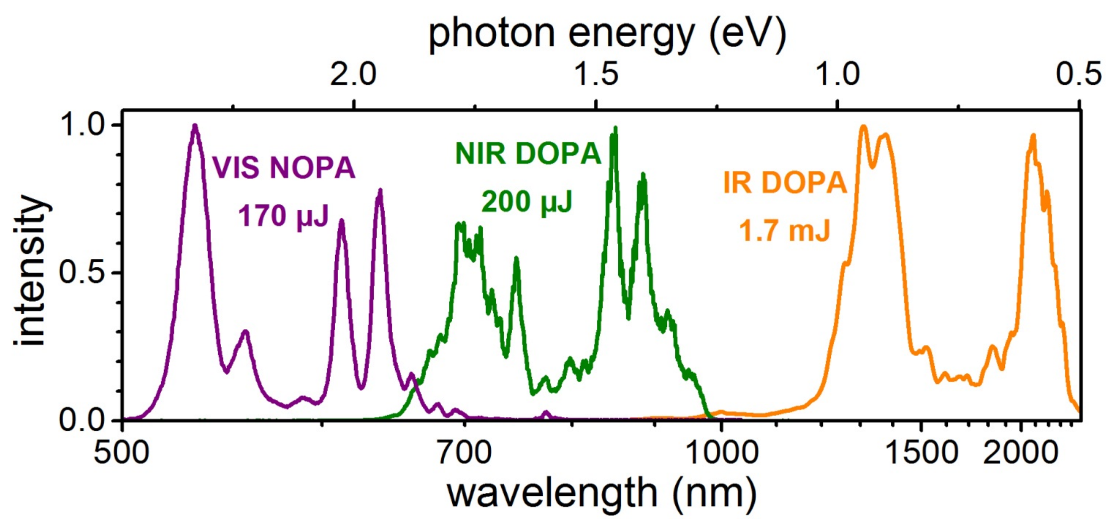
Goal CTD-amp.: > 1J, 1 kW

L. Zapata, et al. Opt. Lett. 40, 2610 (2015).

F. Reichert, et al. CLEO-EU (2015); CA-10.2 THU

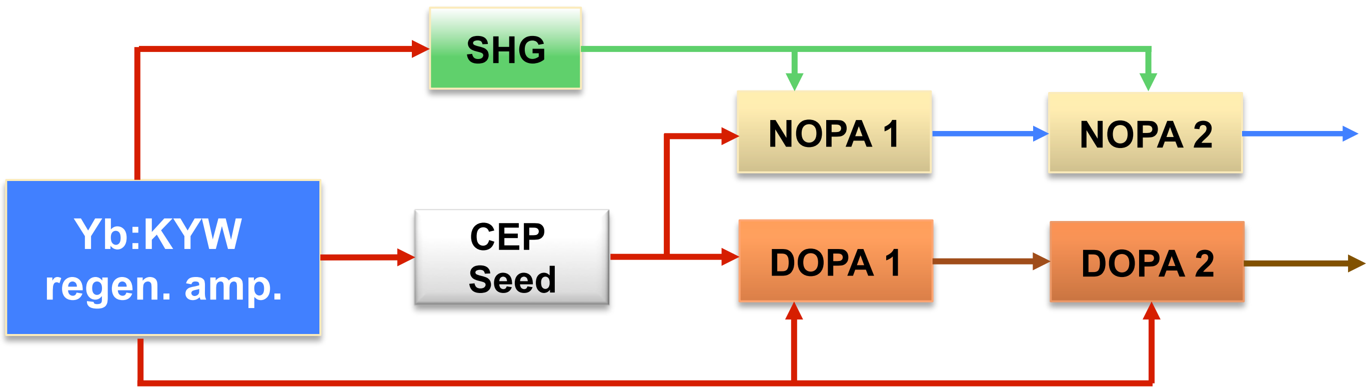
Ti:sapphire Synthesizer





O. D. Mücke, DOI:10.1109/JSTQE.2015.2426653

Yb-based Synthesizers

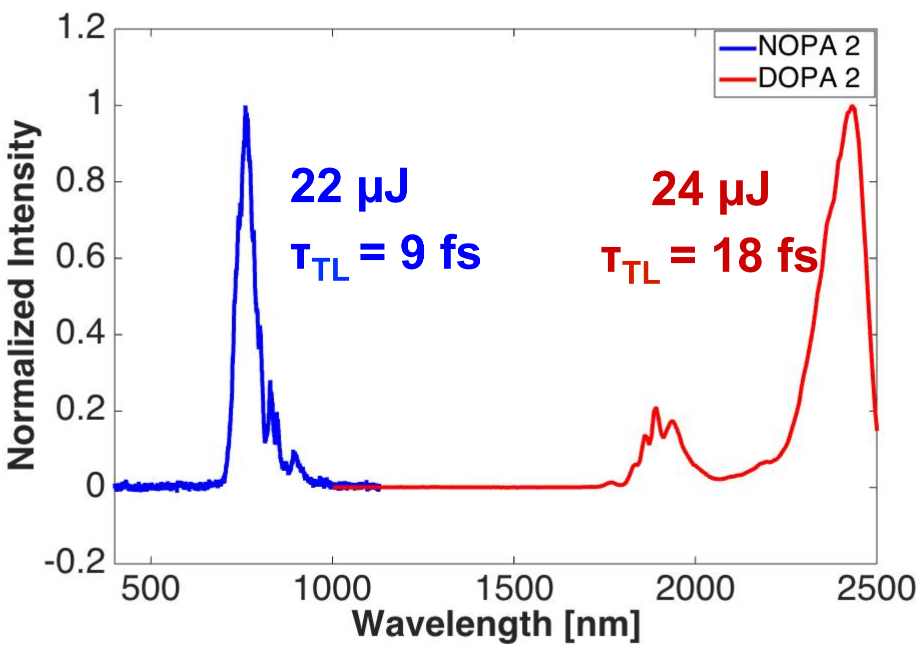


NOPA 2 Parameters:

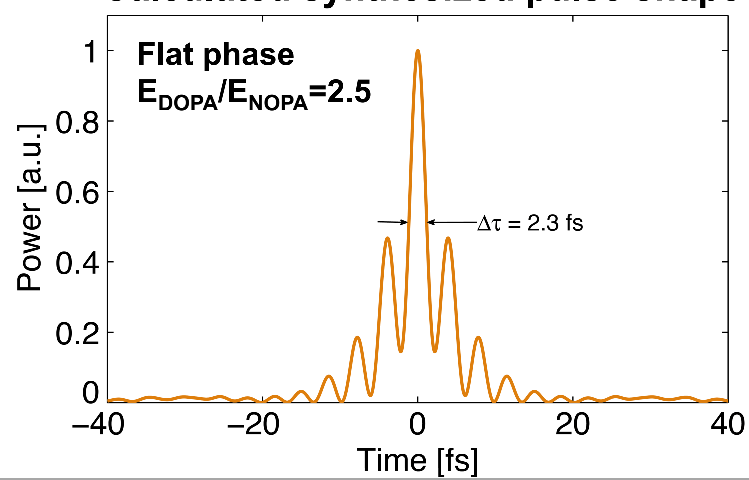
- E_p= 200 μJ
- E_s= 22 μJ
- I_p= 65 GW /cm^2
- λ_s= 700-990 nm

DOPA 2 Parameters:

- E_p= 470 μJ
- E_s= 24 μJ
- I_p= 69 GW /cm^2
- λ_s= 1800-2500 nm



Calculated synthesized pulse shape



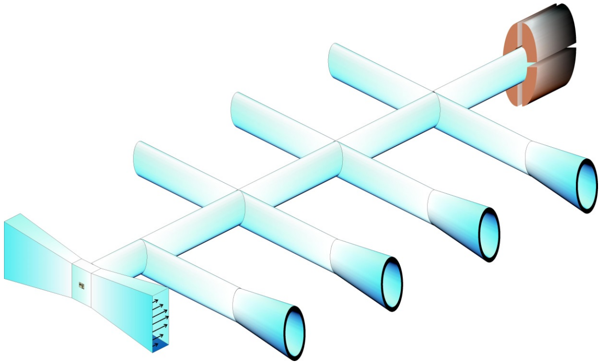
A-L Calendron, et al., CLEO/EU (2015) CF-9.1 THU

Summary

- FELs are combined accelerator and laser facilities with unique challenges to Ultrafast Optics

  - Precision timing
  - High energy and power ultrafast sources

- Laser driven compact coherent FEL source is possible
  - Modulated electron beams source
  - THz generation and & accelerators
  - Joule class picosecond lasers



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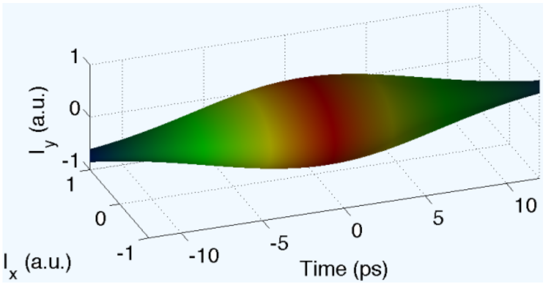
AXSIS - Source Characteristics

Parameter	C-ICS 4 keV	C-ICS 12.4 keV	X-ray FEL 9.6 keV	Units
Bunch charge	3	3	150	pC
e-beam energy	20	35	10,000	MeV
Photon number	10^9	10^9	2.10^{12}	Photons
Pulse length	23	7.5	100,000 (5,000)	as
Peak brightness	6	180	2	10^{22} ph / (s 2% bw mm^2 mrad^2)

Spatio-Temporal Pulse Shaping For Low Emittance

Standard

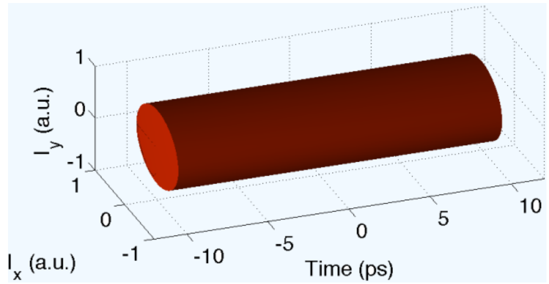


Temporal Gauss, spatial flat-top

Standard config. (non ideal)

Straight forward to obtain

Aim

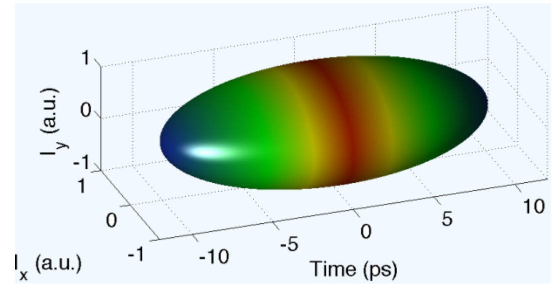


Temporal & spatial flat-top

Better emittance

Requires moderate efforts

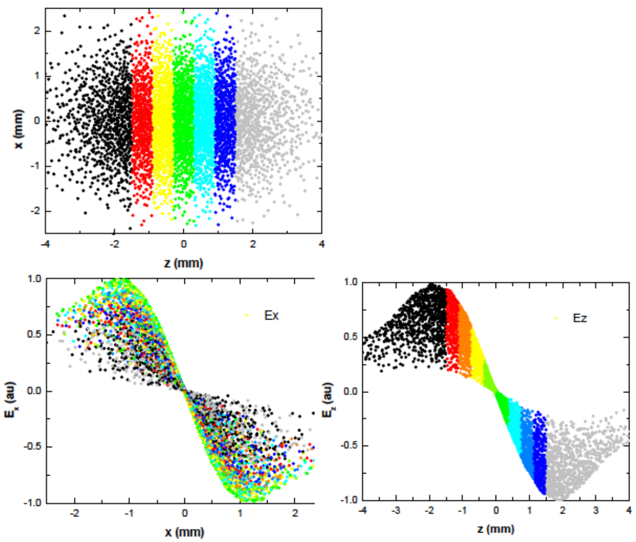
Future

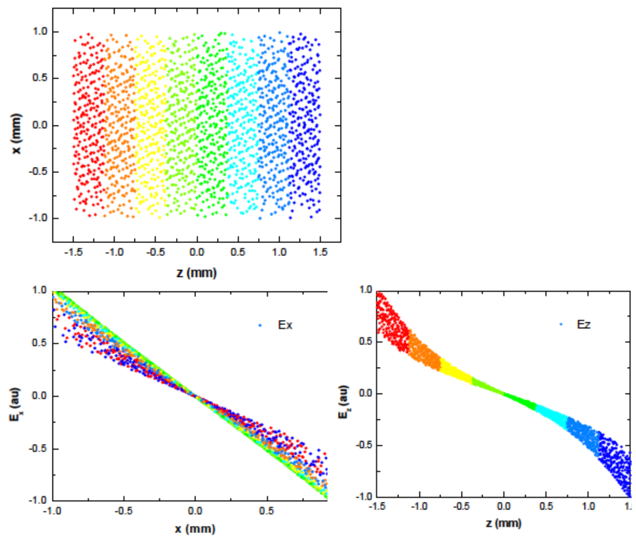


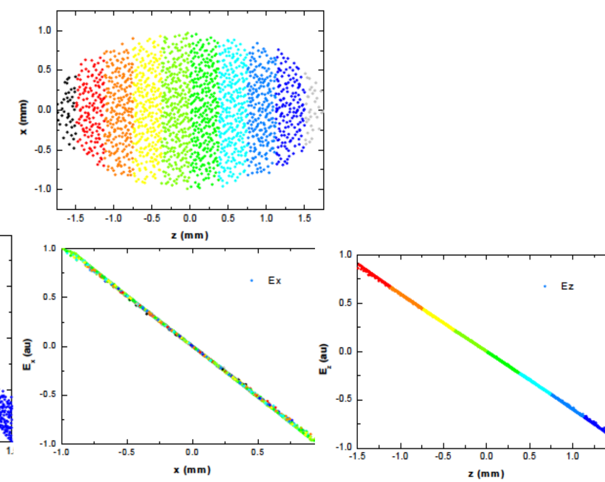
Ellipsoidal / Egg

Lowest emittance

Very hard to obtain





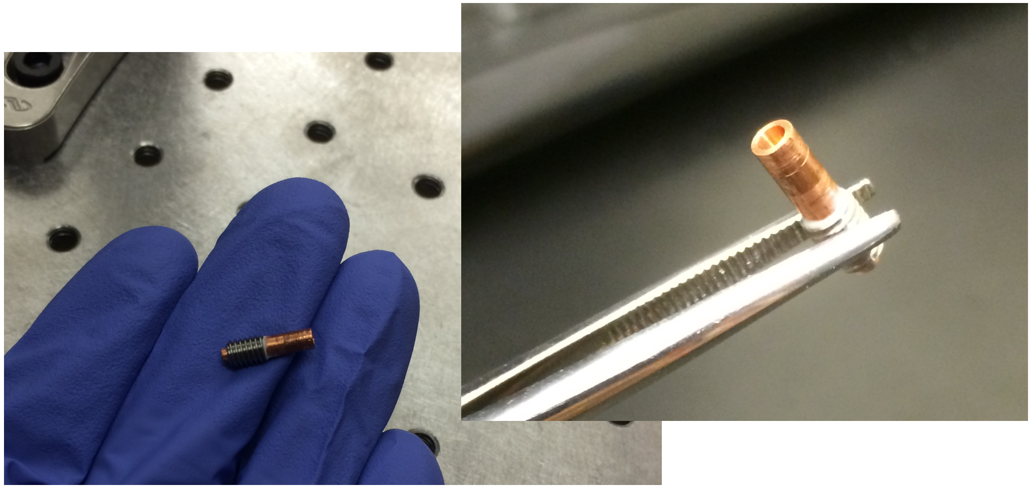


Courtesy: Ingmar Hartl

Motivation for THz Acceleration

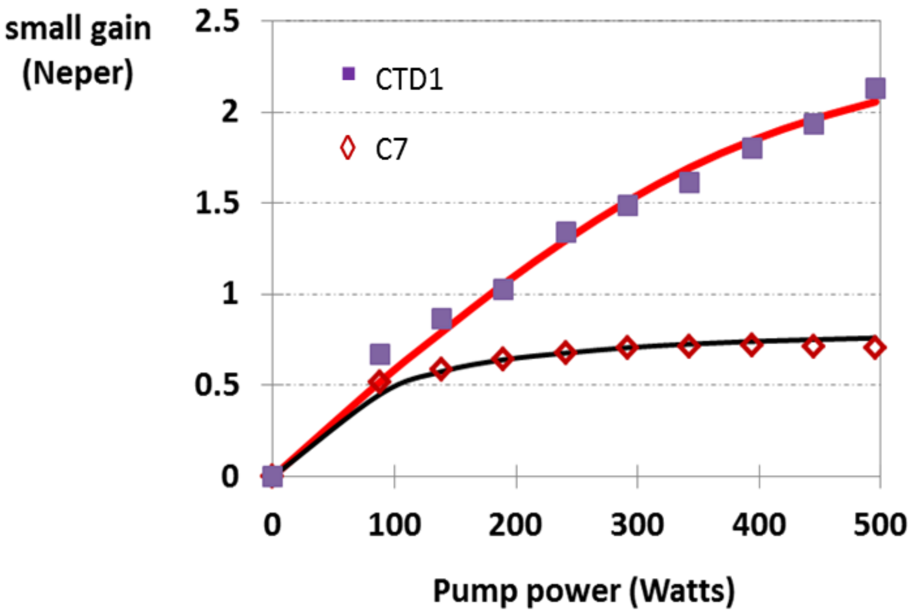
- **High-gradient accelerators are attractive due to reduced size and improved electron beam quality**
- **Increasing operational frequency reduces complications from pulsed heating, breakdown and average power load**
- **Commercial IR laser can generate a 20 MW THz pulse**
- **Proof of concept: accelerate 60 keV electrons with THz pulse**

THz LINAC

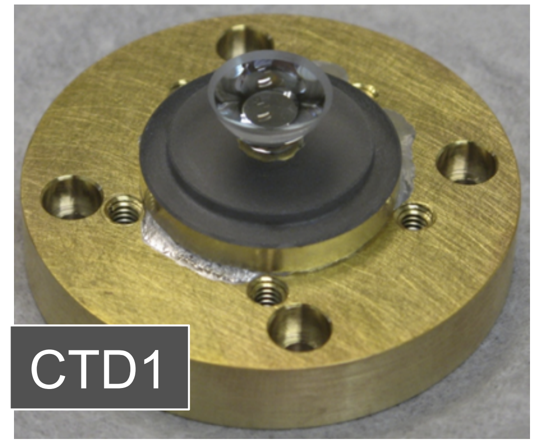


ASE-control and gain hold-off

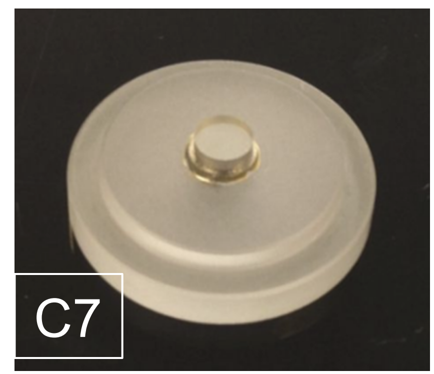
Measured small gain and ASE-code calculation
for disk and composite-disk geometries



Composite disk with fashioned edges



Standard disk



DRAMATIC INCREASE IN GAIN-HOLD REALIZED