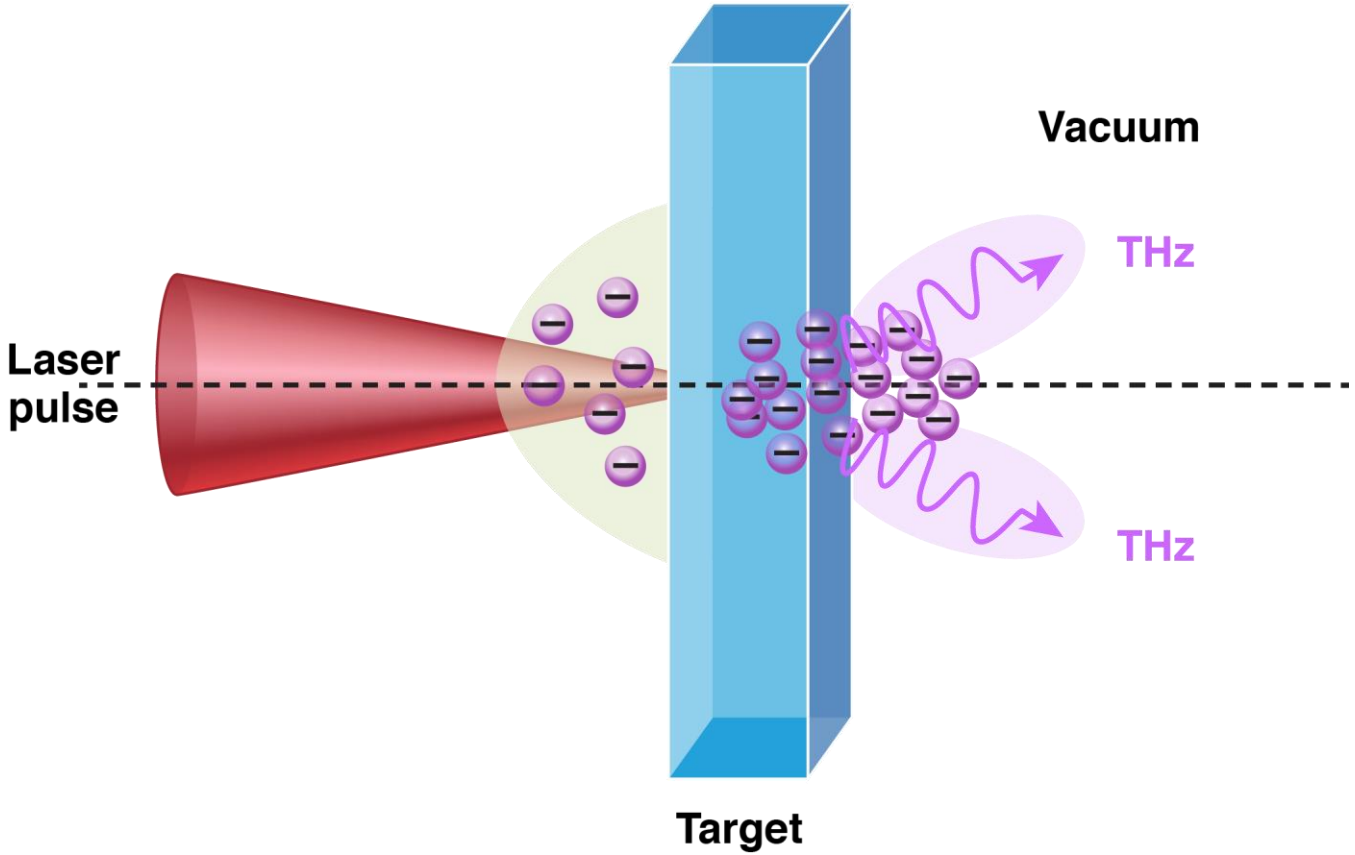
High-Power, High-Energy THz Generation with Joule and Kilojoule-Class Lasers



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Summary

The first HPHE THz experiments were under taken on the OMEGA-EP and MTW lasers, testing THz generation with both J and kJ class lasers

- Low frequency (< 2 THz) High-Power, High-Energy (HPHE) THz pulses were generated and detected on the MTW laser using a variety of targets and laser parameters

- THz experiments were attempted on OMEGA-EP but were swamped with background radiation, detector shielding upgrades are ongoing

- Future experiments will explore uses of HPHE THz pulses and we are collaborating with TAE Technologies on practical uses of HPHE THz pulses as probes for magnetic fusion energy (MFE) plasmas

Collaborators

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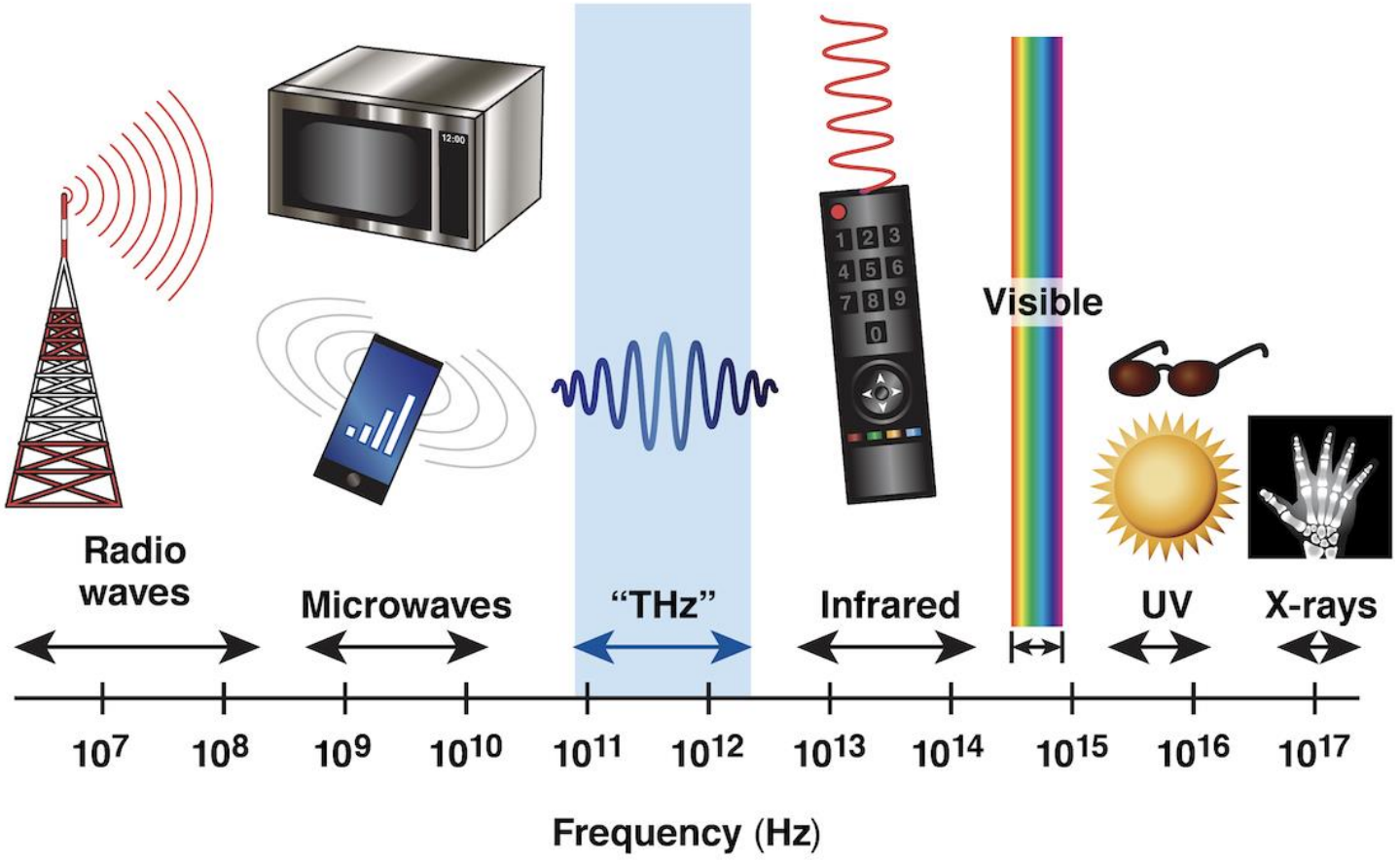
TAE Technologies

THz Radiation can be resonant with phonons, providing unique pump and probe opportunities



0.1-10 THz

$3mm - 30\ \mu m$

3.3 – 334 cm^{-1}

0.414 - 41.36 meV

Not quite electronic or photonic

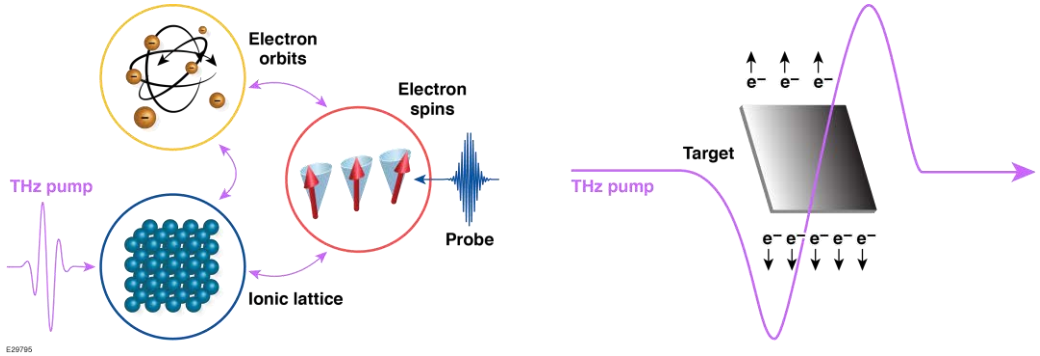
High-Power, High-Energy (HPHE) THz pulses are useful scientific tools as both experimental pumps and probes of materials

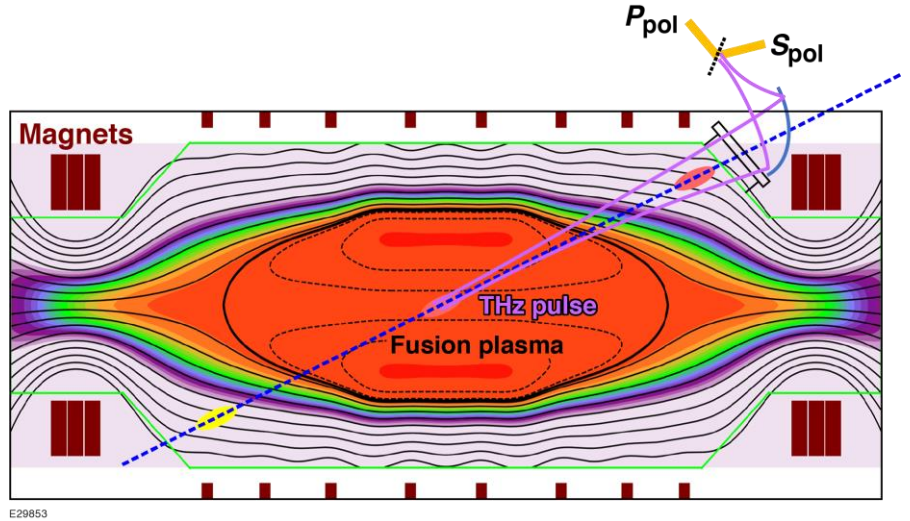
- **≤ 1 psec THz pulses act as a source of strong (MV/cm) quasi-DC electric fields on targets**

- **HPHE THz pulses have been used to study non-linear carrier dynamics in materials (pump and/or probe)***
  - Can be used to constrain EXAFS

- **The next frontier: the interaction of super intense $(a_0 \geq 1)$ THz pulses with matter**
  - - THz tunneling ionization**, MeV scale particle generation†

- **THz are a potential diagnostic tool for MFE plasmas**
  - Requires ~50 mJ THz pulses
  - See poster GP11.00055 from R. Smith and poster GP11.00070 from A. Necas during today's poster session



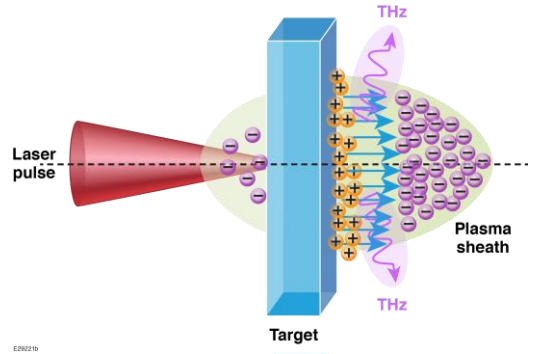


* Hafez, H. A., Chai, X., Ibrahim, A., Mondal, S., Férachou, D., Ropagnol, X., & Ozaki, T. (2016). Intense terahertz radiation and their applications. *Journal of Optics (United Kingdom)*, *18*(9). https://doi.org/10.1088/2040-8978/18/9/093004
** K. Y. Kim. (2015). *Strong terahertz field generation, detection, and application*.
† Salén, P., Basini, M., Bonetti, S., Hebling, J., Krasilnikov, M., Nikitin, A. Y., Shamuilov, G., Tibai, Z., Zhaunerchyk, V., & Goryashko, V. (2019). Matter manipulation with extreme terahertz light: Progress in the enabling THz technology. *Physics Reports*, *836–837*, 1–74. https://doi.org/10.1016/j.physrep.2019.09.002

Laser-plasmas generate THz radiation in a variety of ways depending on laser intensity and target design

$< 10^{18}\ {}^{W}/_{cm^2}$ lasers generate micro-plasmas that act like small dipole antennas emitting THz radiation*

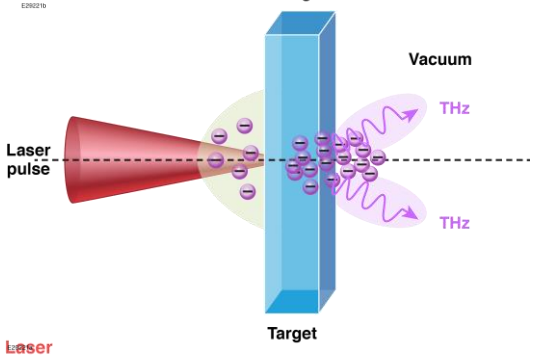
<0.01% generation efficiency typical



Incoherent THz

$\geq 10^{18}\ {}^{W}/_{cm^2}$ THz is primarily Coherent Transition Radiation (CTR)

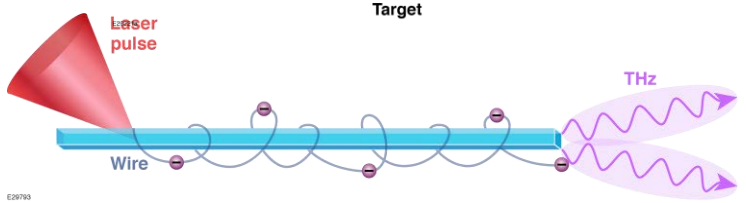
~0.1% generation efficiency has been reported



CTR THz

Structured targets provide new possibilities for THz generation via free electron motion around the structures†

~0.5% generation efficiency has been reported



Structured Target THz

* Yiwen, E., Jin, Q., Tcypkin, A., & Zhang, X. C. (2018). Terahertz wave generation from liquid water films via laser-induced breakdown. *Applied Physics Letters*, *113*(18). https://doi.org/10.1063/1.5054599

** G. Liao, et al, "THz pulses over 50 millijoules generated from relativistic picosecond laser-plasma interactions", PNAS March 5, 2019 116 (10) 3994-3999

† Zeng, Y., Zhou, C., Song, L., Lu, X., Li, Z., Ding, Y., Bai, Y., Xu, Y., Leng, Y., Tian, Y., Liu, J., Li, R., & Xu, Z. (2020). Guiding and emission of milijoule single-cycle THz pulse from laser-driven wire-like targets. *Optics Express*, *28*(10), 15258. https://doi.org/10.1364/oe.390764

Previous HPHE THz experiments explored up to ~50 mJ of pulse energy using a ~60 J laser as a driver

- **Current record experiment used Vulcan laser (~60 J) to generate ~50 mJ single cycle THz pulses[**]**
- **Our experiments have tested THz generation with up to 18 J using our MTW laser**
- **An attempt was made in July 2021 to use OMEGA-EP (500 J) but background radiation flooded the detectors**
- **Two experiments in FY22 will attempt to generate >1 J, >1 TW of THz radiation using OMEGA-EP**

Driver for THz	THz Pulse Energy (mJ)	THz Peak Power (GW)
Non-linear crystal[†]	1	10
Air plasma[†]	0.1	1
MTW (15 J)	9	10
Vulcan (60 J)[**]	50	36
OMEGA-EP (500 J)[*]	2500	3000

Our experiments aim to drive an order of magnitude above previous HPHE THz experiments

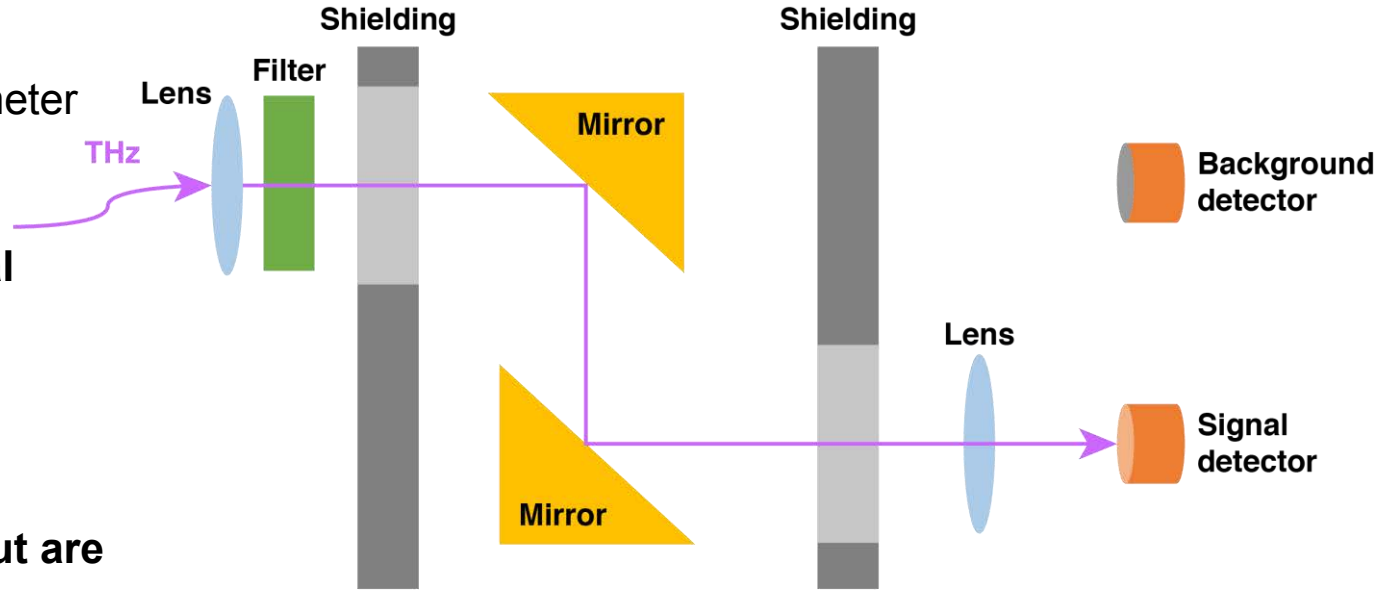
* Estimated based on scaling of previous experiments

** G. Liao, et al, "THz pulses over 50 millijoules generated from relativistic picosecond laser-plasma interactions", PNAS March 5, 2019 116 (10) 3994-3999

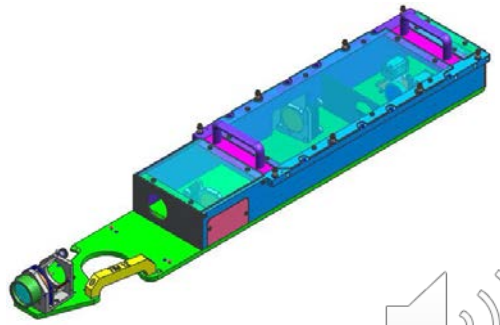
† Koulouklidis, A. D., Gollner, C., Shumakova, V., Fedorov, V. Y., Pugžlys, A., Baltuška, A., & Tzortzakis, S. (2020). Observation of extremely efficient terahertz generation from mid-infrared two-color laser filaments. *Nature Communications*, *11*(1), 1–8. https://doi.org/10.1038/s41467-019-14206-x

THz radiation was detected with highly-sensitive pyrometers

- **Use comparison of two nJ sensitive pyrometers (Signal – Background)**
  - Pyrometers are a form of THz sensitive energy meter
- **Filters and apertures are used to ‘tune’ the spectral region detected**
- **Electro-optical THz detectors are being pursued but are not currently available**

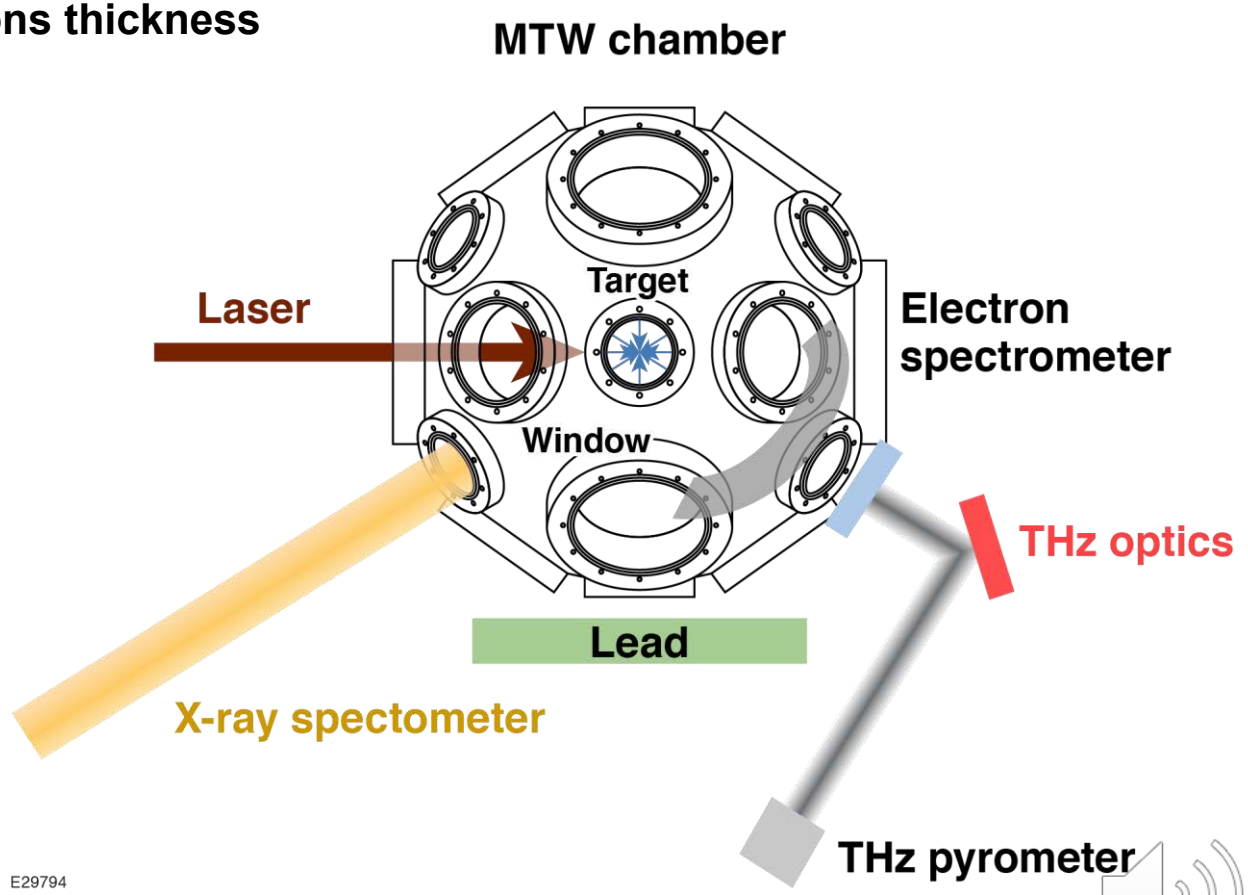


TBEM detector



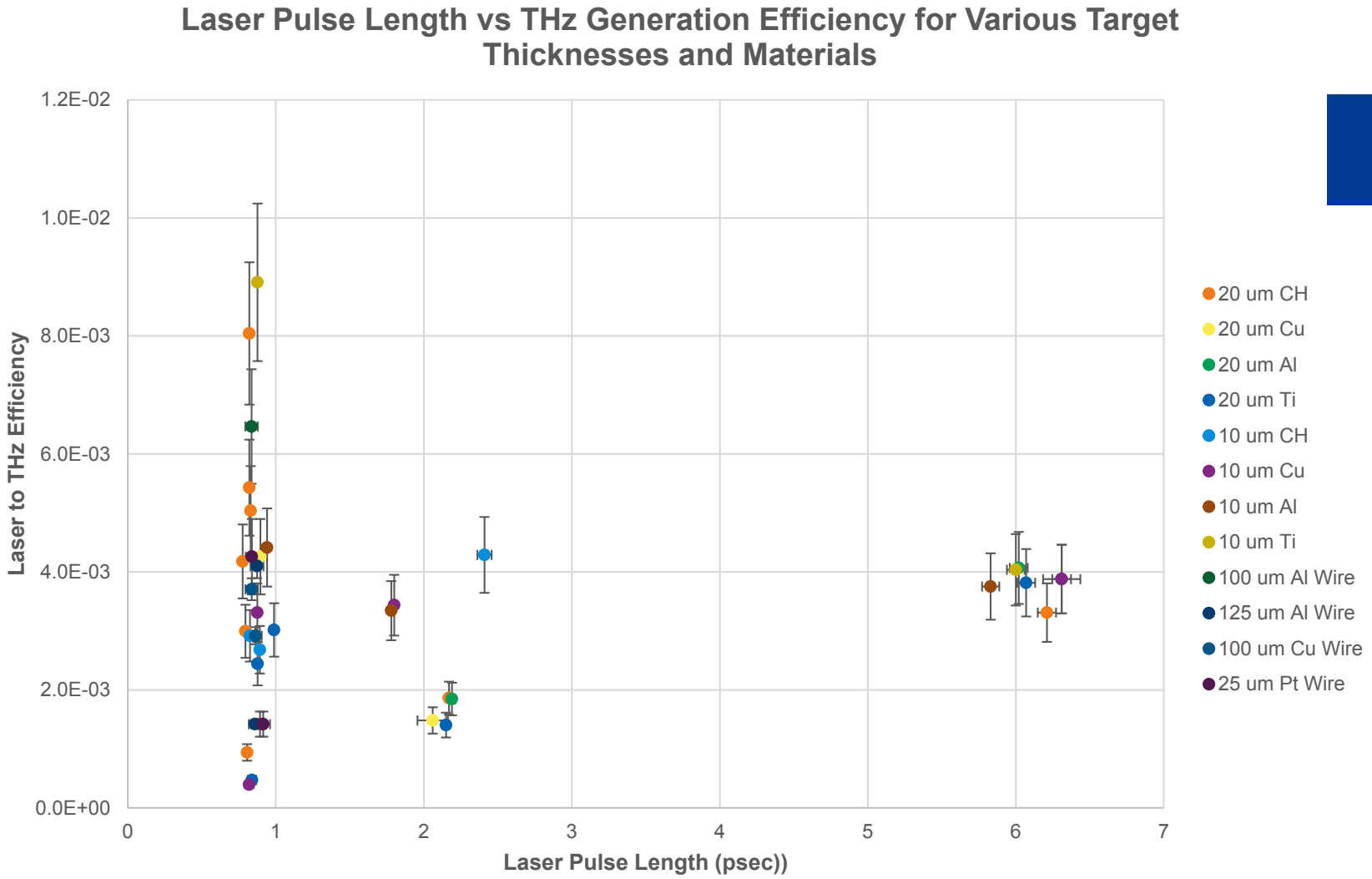
Three campaigns explored optimal target and laser parameters for laser-plasma THz generation using the MTW laser

- **Laser pulse energies between 10-18 Joules at 0.7-6 psec were tested**
- **Foil targets at normal incidence tested at 10-25 microns thickness**
  - CH, Al, Ti, and Cu target materials tested
  - Radiation generated at primarily at <0.3 THz
- **Wire targets at angles were tested**
  - Al, Cu, Pt
  - 25-125 micron diameter
  - Wires show capability to generate 1 THz pulses
- **THz, electron and x-ray diagnostics used**
  - Calibration of THz meter still on-going



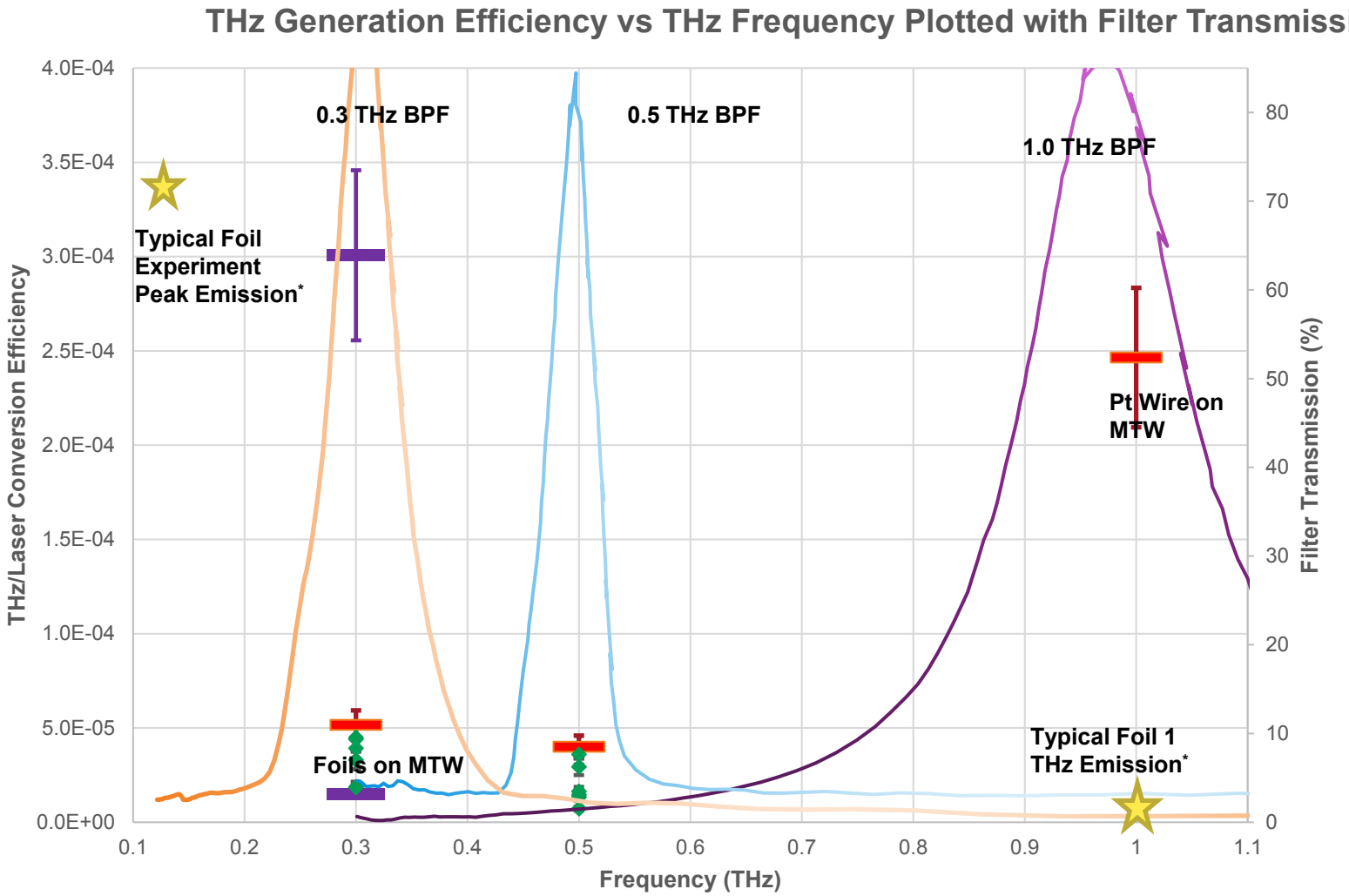
Shortest Pulse Lengths Maximized THz Yield

MTW THz Campaign found <1 psec was best, but THz generation was inconsistent potentially due to variations in target alignment changing intensity



Targets placed by hand and aligned by eye

Wire targets show an ability to generate large amounts of THz radiation above 0.3 THz compared to foil targets



More testing of wire targets needed!

- 25 um Pt Wire
- 125 um Al Wire
- Foil Targets

* G. Liao, et al, "THz pulses over 50 millijoules generated from relativistic picosecond laser-plasma interactions", PNAS March 5, 2019 116 [illegible] 994-1999

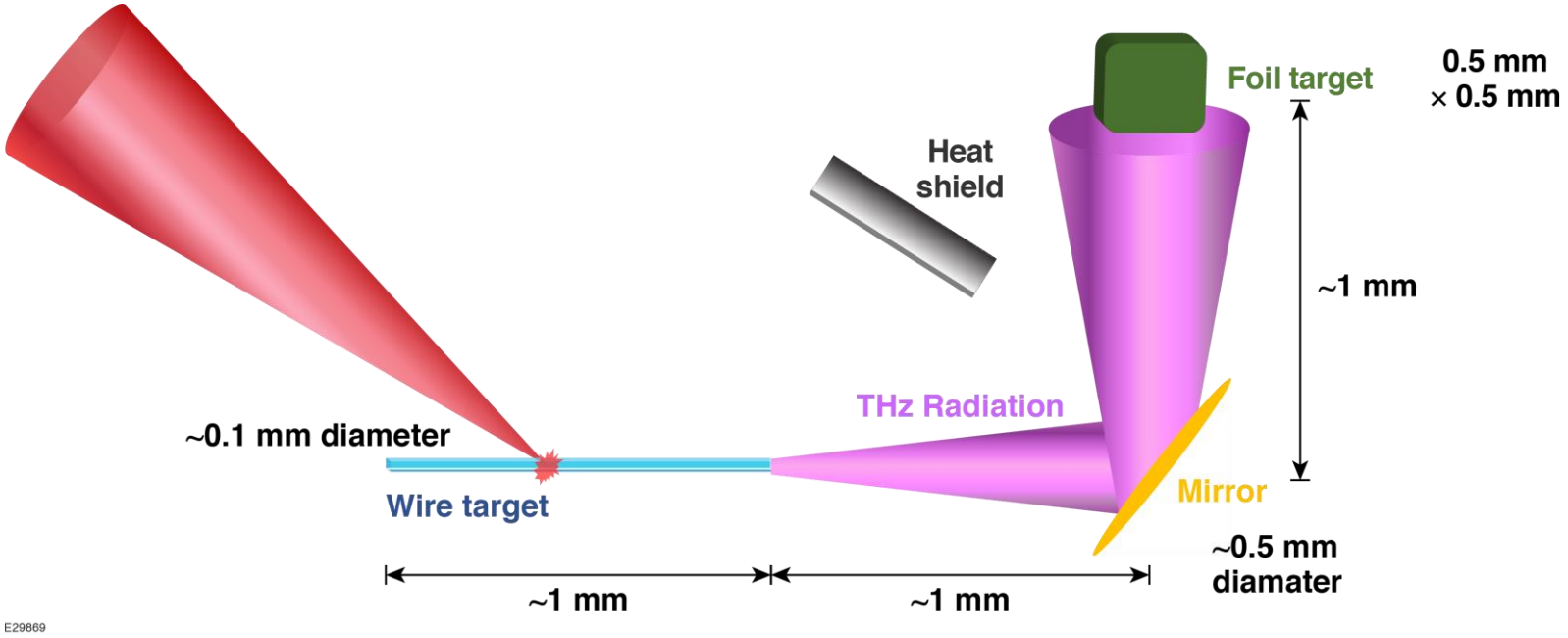
A wide variety of future THz experiments are planned at the LLE

- **Three more MTW HPHE THz source development campaigns planned for 2022**
  - Further explore target design space and test detector technology
- **Two OMEGA-EP THz experiments planned**
  - Plan to explore the potential of OMEGA-EP to generate TW scale THz sources with first experiment
  - Second experiment is planned to test relativistic THz-matter interactions
- **Will learn to use a new single-shot, electro-optical THz spectrometer that we have purchased**
  - This has dual use as a probe for HED matter as well
- **We are also working with TAE to help develop HPHE laser-plasma THz sources for use in their MFE devices**
  - Using MTW data as input on a future laser driven THz pulsed plasma polarimeter

The future is bright for THz work at the LLE!

Experiments focused on relativistic THz-matter interactions will take place in June 2022 using OMEGA-EP as the THz source

- Wire THz generation targets will be used to maximize yield
- THz intensities on the order of $\sim 10^{14}\ {}^{W}/_{cm^2}$ will impinge on the target
- X-ray, charged particle and THz detectors will be used to monitor the interaction



A first of a kind relativistic THz experiment will be attempted

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Questions to:
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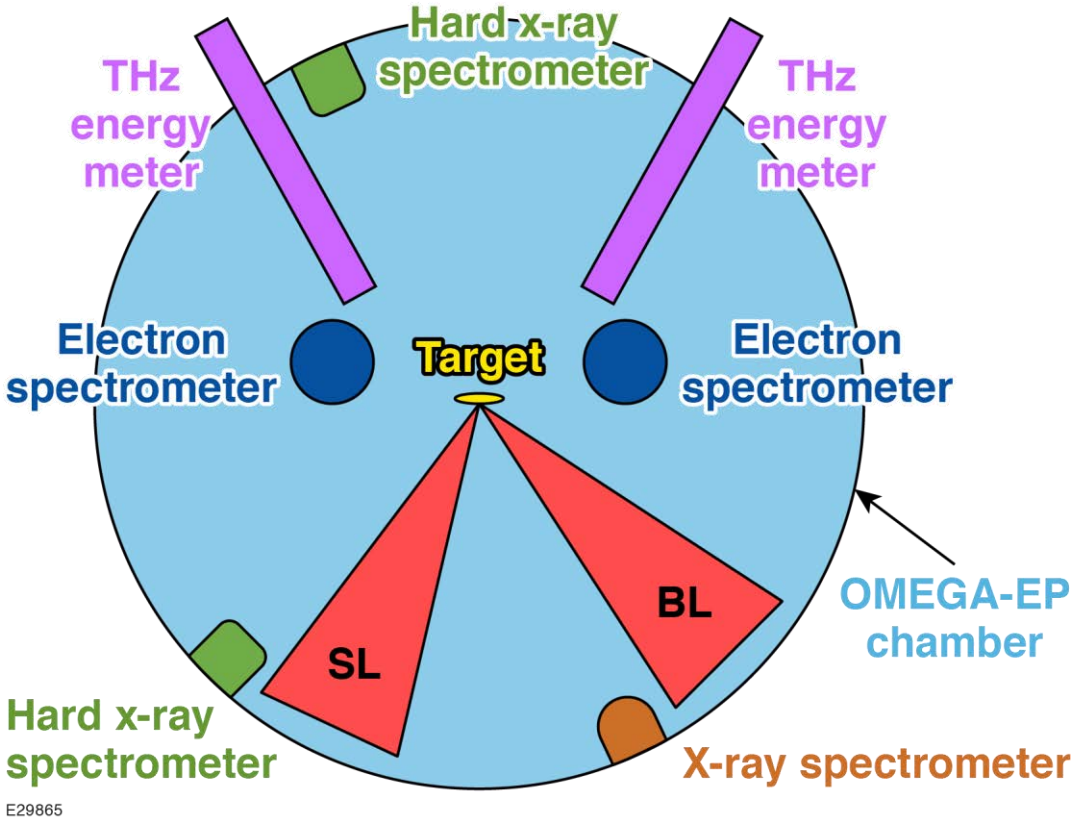
Back-Up Slide

THz generation was tested on OMEGA-EP in July of 2021 but the detectors were flooded with background noise and no definitive detection could be made

- **20 micron CH foils shot with 100-200 Joule laser at ~700 fsec pulse length**
- **THz, x-ray and electron detectors used**
- **Plastic and boron stalks tested**
  - Plastic found to dramatically reduce noise on detectors
  - All future shots will utilize plastic stalks
- **X-ray radiation induced too much background noise on the detectors to reliably separate out a THz signal**
  - Further shielding is needed and is being added now



OMEGA-EP overwhelmed the THz detectors with background signal