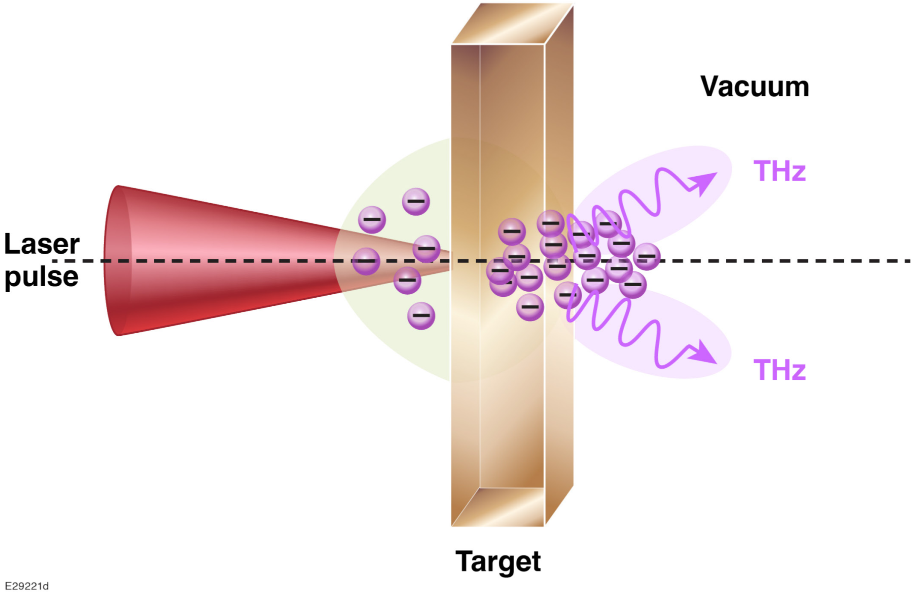
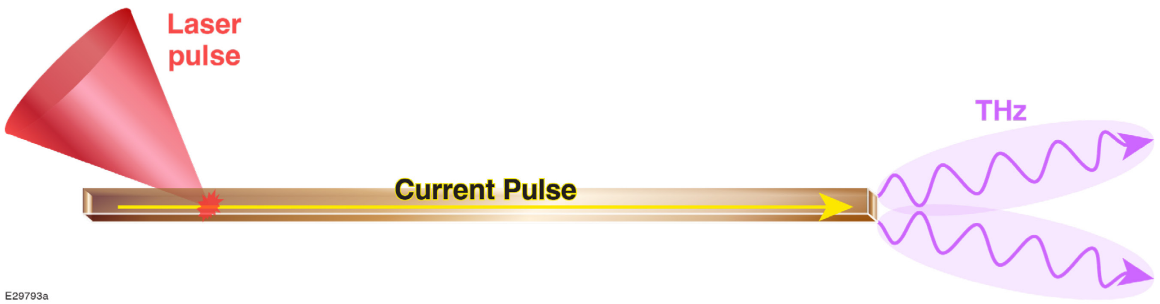
High-Power, High-Energy Laser-Solid THz Generation with Varied Target Geometry





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Spokane, WA
19/10/2022

High-Power, High Energy (HPHE) THz pulses were generated with a wide variety of targets on both the OMEGA EP and MTW lasers

Collaborators

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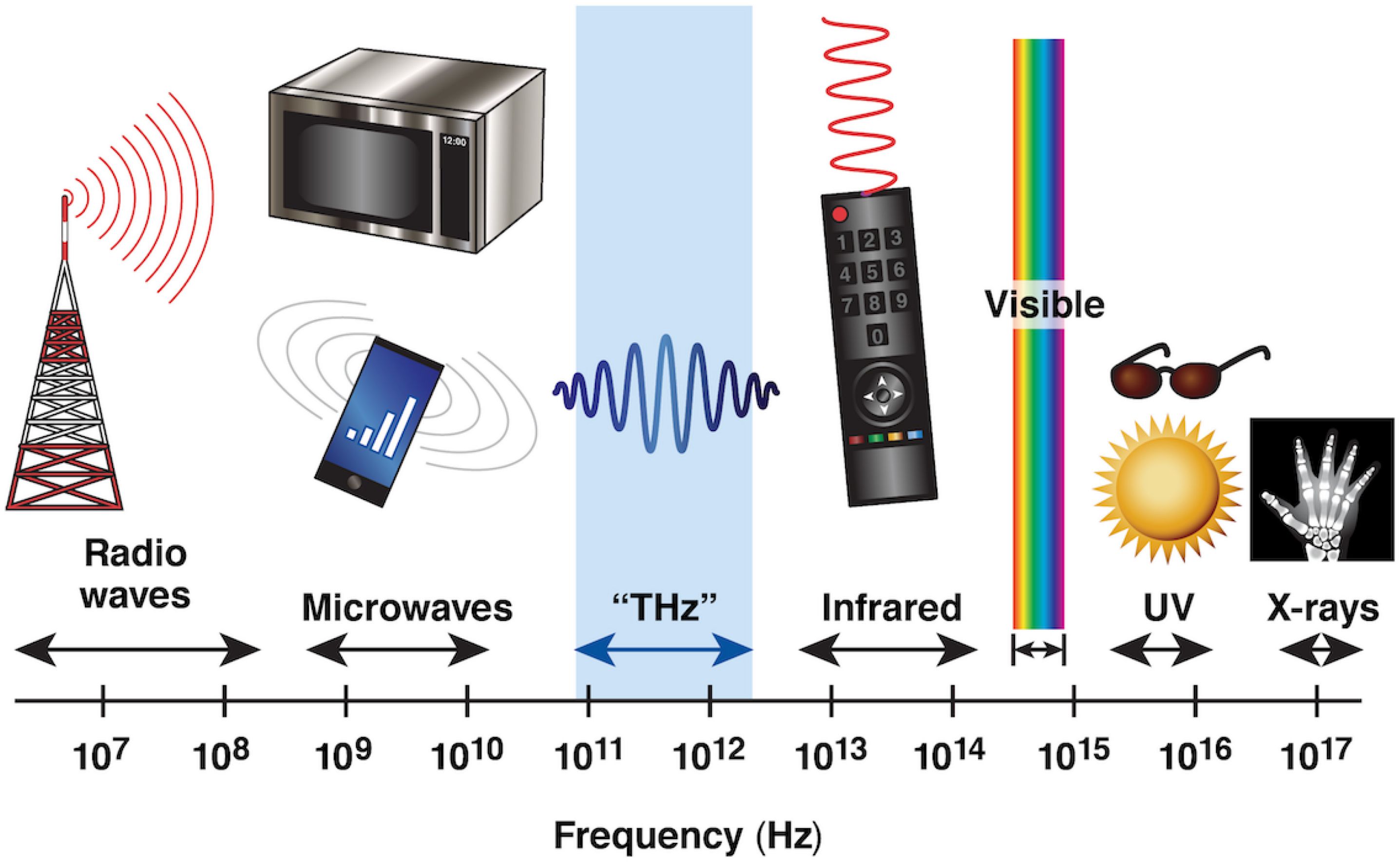
THz radiation is difficult to efficiently generate and detect due to its odd position in the electromagnetic spectrum



0.1-10 THz

$3mm - 30\ \mu m$

3.3 – 334 cm^{-1}

0.414 - 41.36 meV

Not quite electronic or photonic

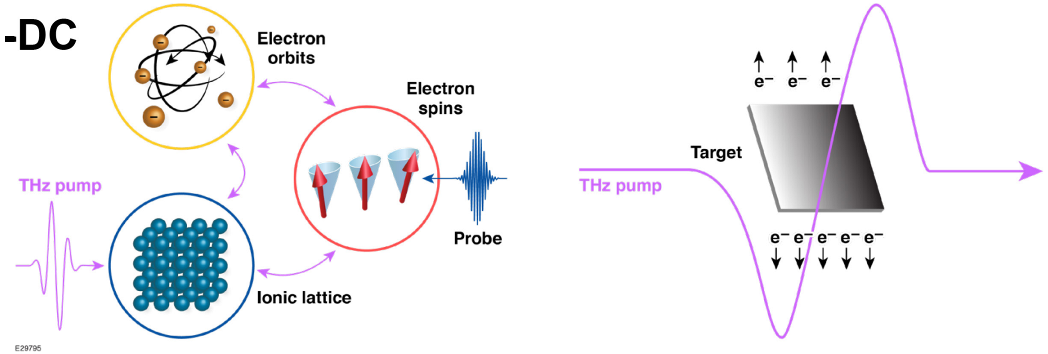
High-Power, High-Energy THz pulses are useful scientific tools as both experimental pumps and probes of materials

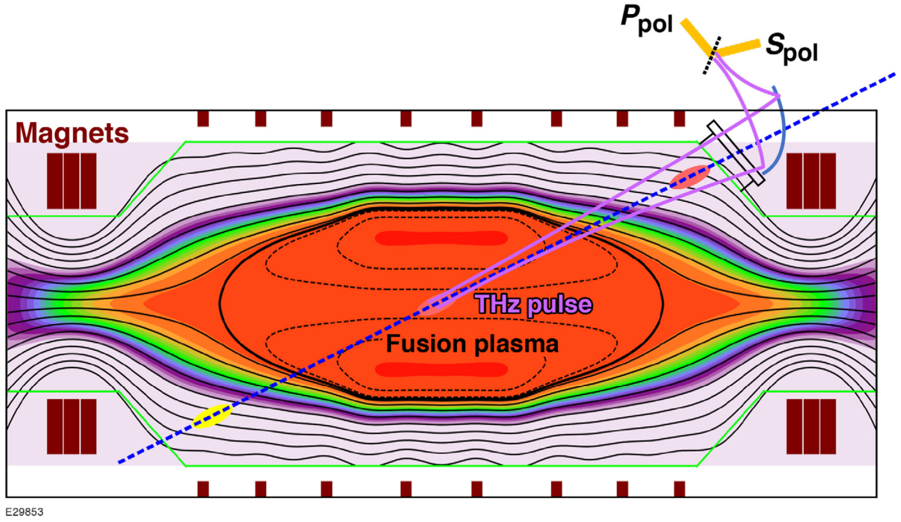
- $\leq$ 1 psec THz pulses act as a source of strong (> 1 MV/cm) quasi-DC electric fields on targets

- 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†

- HPHE THz is a potential diagnostic tool for MFE plasmas
  - Requires ~50 mJ, >1 THz pulses
  - See poster TP11.00016 from A. Necas and poster TP11.00019 from R. Smith for more





* 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

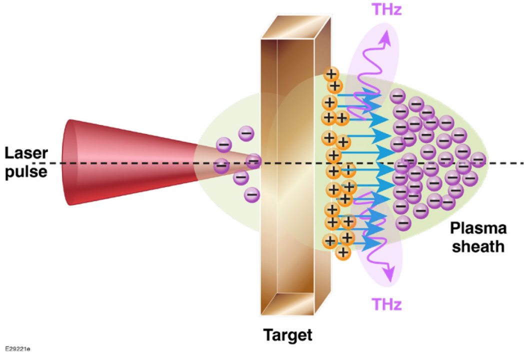
** K. Y. Kim. (2015). *Strong terahertz field generation, detection, and application*.

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

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

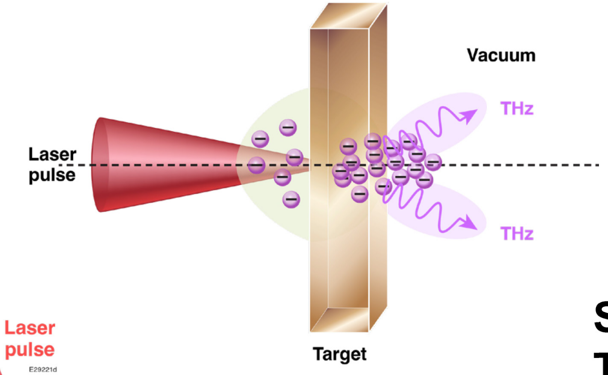
<0.01% generation efficiency typical but higher has been reported



Sheath THz

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

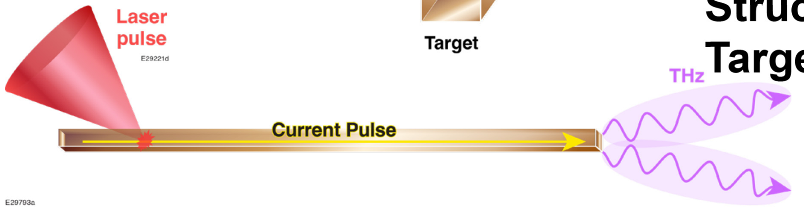
>0.1% generation efficiency has been reported



CTR THz

Structured targets provide new possibilities for THz generation via free electron motion† or micro-antenna action††

>0.5% generation efficiency has been reported



Structured Target THz

* Yiwen, E., et al., Terahertz wave generation from liquid water films via laser-induced breakdown. *Applied Physics Letters*, *113*(18). (2018). 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., et al., Guiding and emission of milijoule single-cycle THz pulse from laser-driven wire-like targets. *Optics Express*, *28*(10), 15258. (2020)., https://doi.org/10.1364/oe.390764

††Zhuo, H.B., et al., Terahertz generation from laser-driven ultrafast current propogation along a wire target. *Phys Rev E*, *95*, (2017). DOI: 10.1103/PhysRevE.95.013201

Previous record HPHE THz experiments generated ~50 mJ of THz using a ~60 J laser and foil targets

UR LLE

- **More recent work has shown >100 mJ multi-cycle THz signals from the same laser††**
- **Our experiments have tested THz generation with up to 12 J using our MTW laser**
- **OMEGA-EP was then used to further push the driver energy beyond 100 J this summer**

Driver for THz	THz Pulse Energy (mJ)	THz Peak Power (GW)
Non-linear crystal†	1	10
Air plasma†	0.1	1
MTW (12 J)	40	57
Vulcan (60 J)*	50	36
OMEGA-EP (300 J)	300	420

Our experiments have generated a near TW class THz source

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

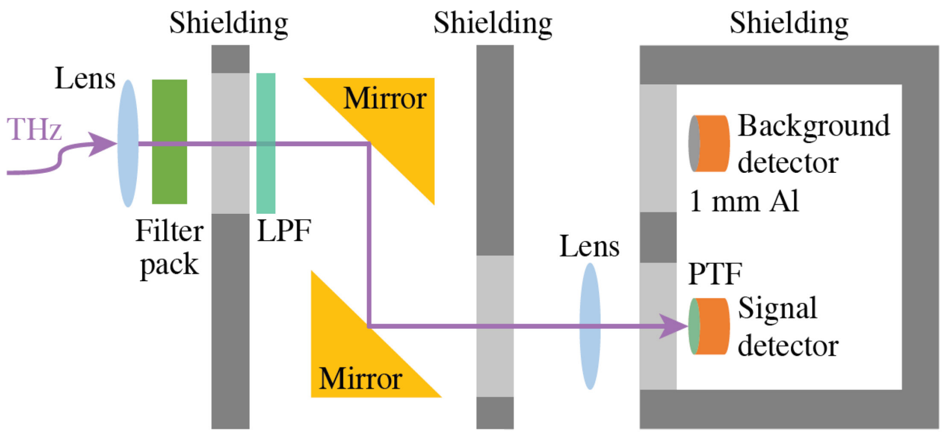
† Koulouklidis, A. D., et al., Observation of extremely efficient terahertz generation from mid-infrared two-color laser filaments. *Nature Communications*, *11*(1), 1–8. (2020). https://doi.org/10.1038/s41467-019-14206-x

††G. Liao, et al., Towards Terawatt-Scale Spectrally Tunable Terahertz Pulses via Relativistic Laser-Foil Interactions. *Phys Rev X*, *10*, DOI: 10.1103/PhysRevX.10.031062

A robust and highly adjustable THz energy meter was developed for use on OMEGA-EP and MTW

- **Uses the comparison of two nJ sensitive pyrometers (Signal – Background)**
  - Called THz Background/Energy Meter (TBEM)*
- **Filters and apertures are used to 'tune' the spectral region detected**
- **~20 kg of tungsten radiation shielding installed in final design**
- **Electro-optical THz detectors are being pursued but are not currently available**

(a)



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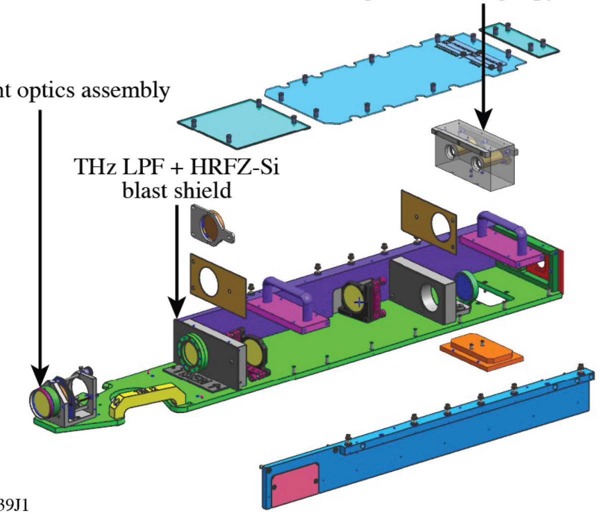
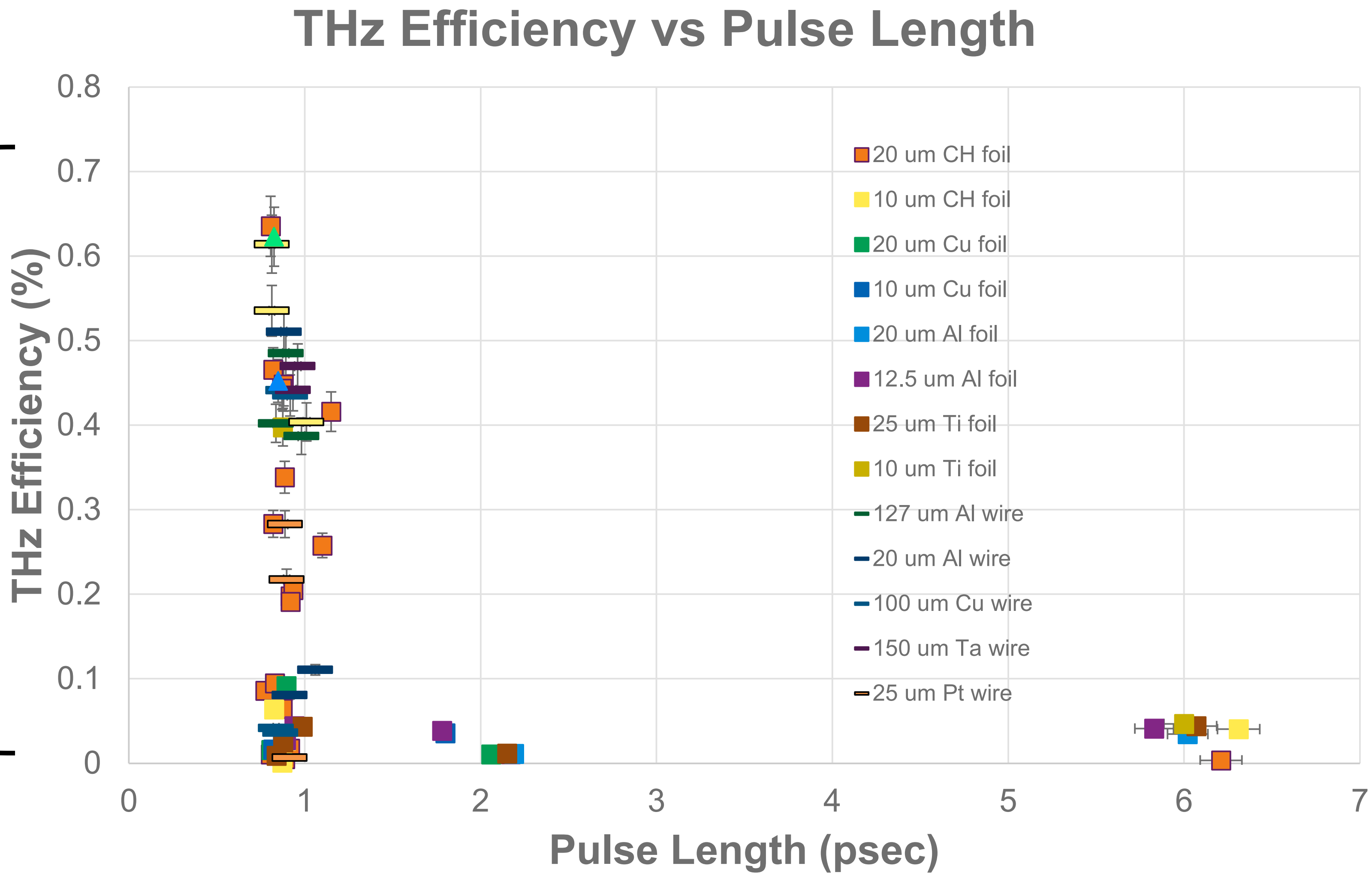


E30139J1

* Bruhaug G., et al, Development of a hardened THz energy meter for use on the kilojoule-scale, short-pulse OMEGA EP laser, submitted to the Proceedings of the High Temperature Plasma Diagnostics conference, RSI, 2022

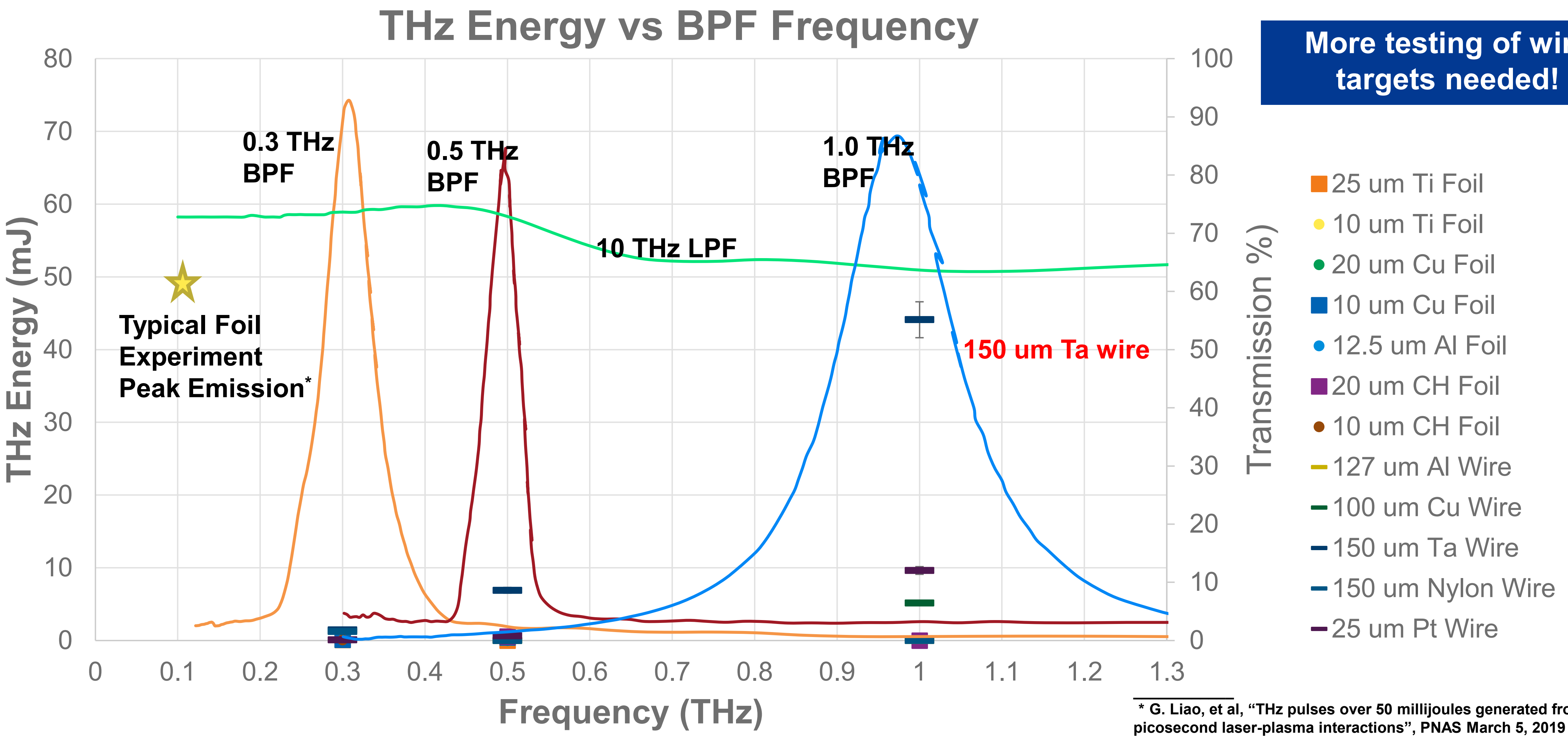
MTW THHz Campaign found <1 ps was best for THz production and that low Z foils and high Z wire targets produced the highest efficiencies of production

Dispersion potentially from alignment errors



Wire targets were shown to generate large amounts of THz radiation above 0.5 THz compared to foil targets

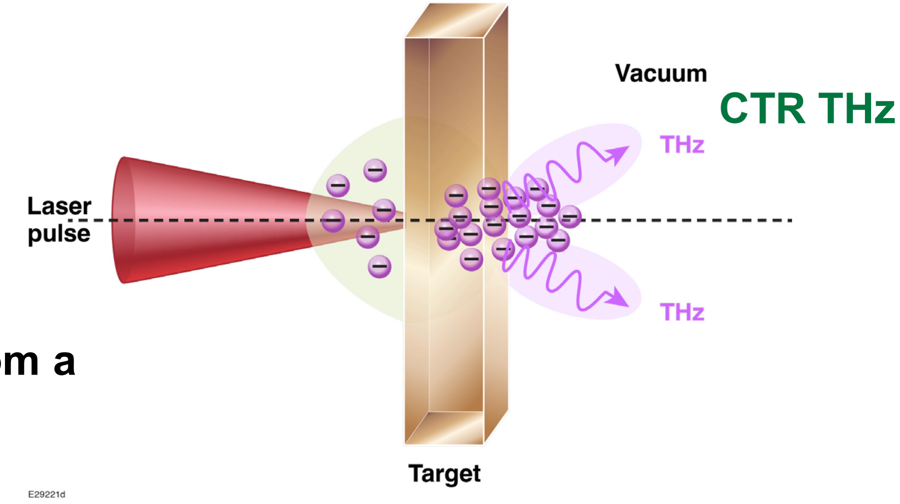
More testing of wire targets needed!



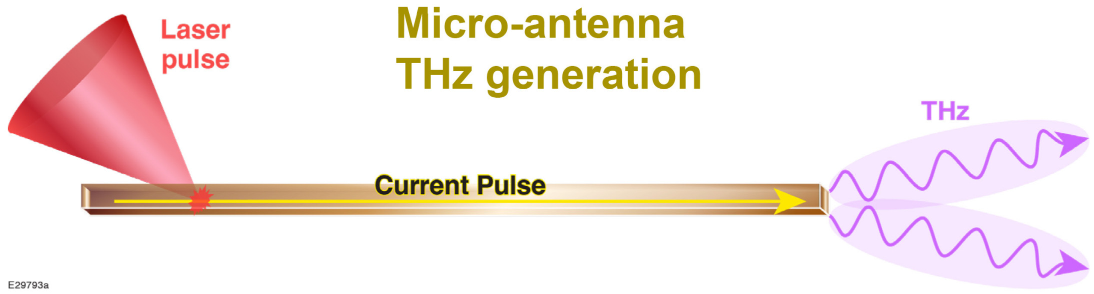
* G. Liao, et al, "THz pulses over 50 millijoules generated from relativistic picosecond laser-plasma interactions", PNAS March 5, 2019 116 (10) 3994-3999

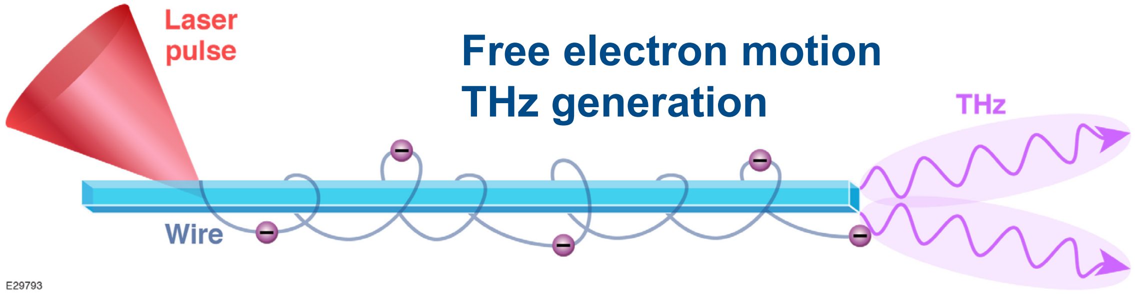
Foil targets generate THz via CTR at these laser intensities, while the wire target THz generation physics is still undetermined

- **CTR from foil targets scales favorably with laser intensity and inversely with Z of the target***
  - The high performance of the CH foils is indicative of this



- **Wire target generation physics is hypothesized to be either from a free electron motion† or micro-antenna action††**
  - Upcoming campaigns will vary wire geometry and utilize more detectors to distinguish between these two models

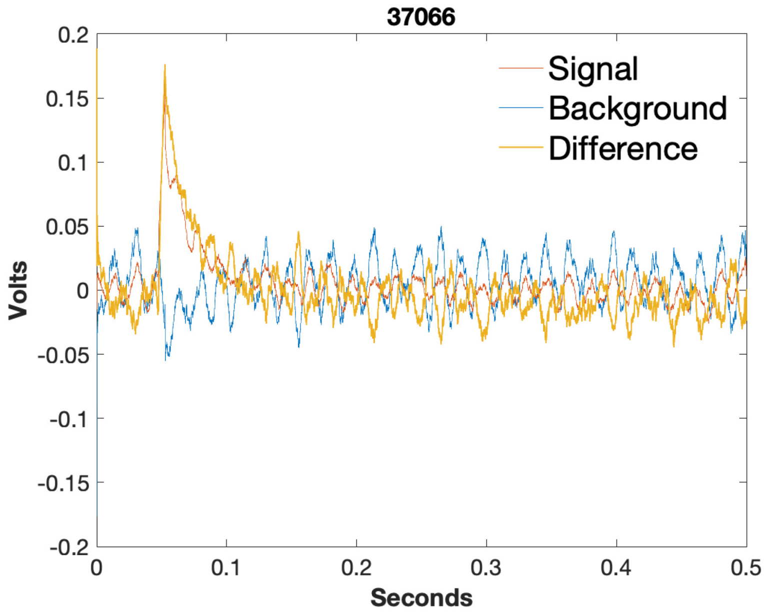




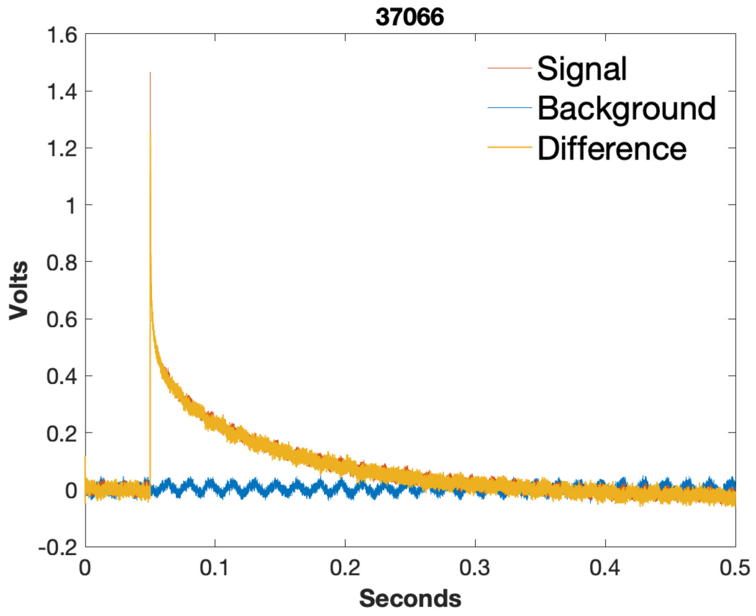
* G. Liao, et al, "THz pulses over 50 millijoules generated from relativistic picosecond laser-plasma interactions", PNAS March 5, 2019 116 (10) 3994-3999
† Zeng, Y., et al., Guiding and emission of milijoule single-cycle THz pulse from laser-driven wire-like targets. *Optics Express*, *28*(10), 15258. (2020)., https://doi.org/10.1364/oe.390764
††Zhuo, H.B., et al., Terahertz generation from laser-driven ultrafast current propogation along a wire target. *Phys Rev E*, *95*, (2017). DOI: 10.1103/PhysRevE.95.013201

>100 mJ THz pulses were also generated via foil targets using OMEGA EP

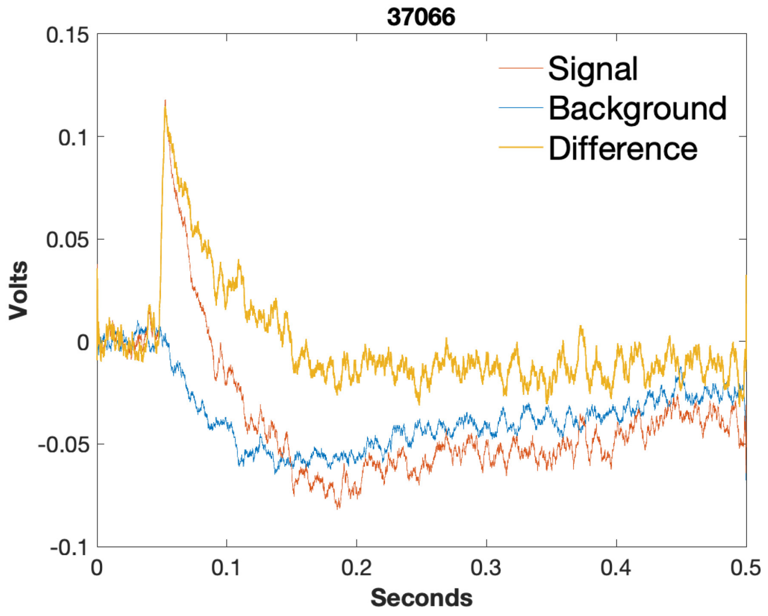
Inserted Detector (TBEM1)



Retracted Detector (TBEM2)



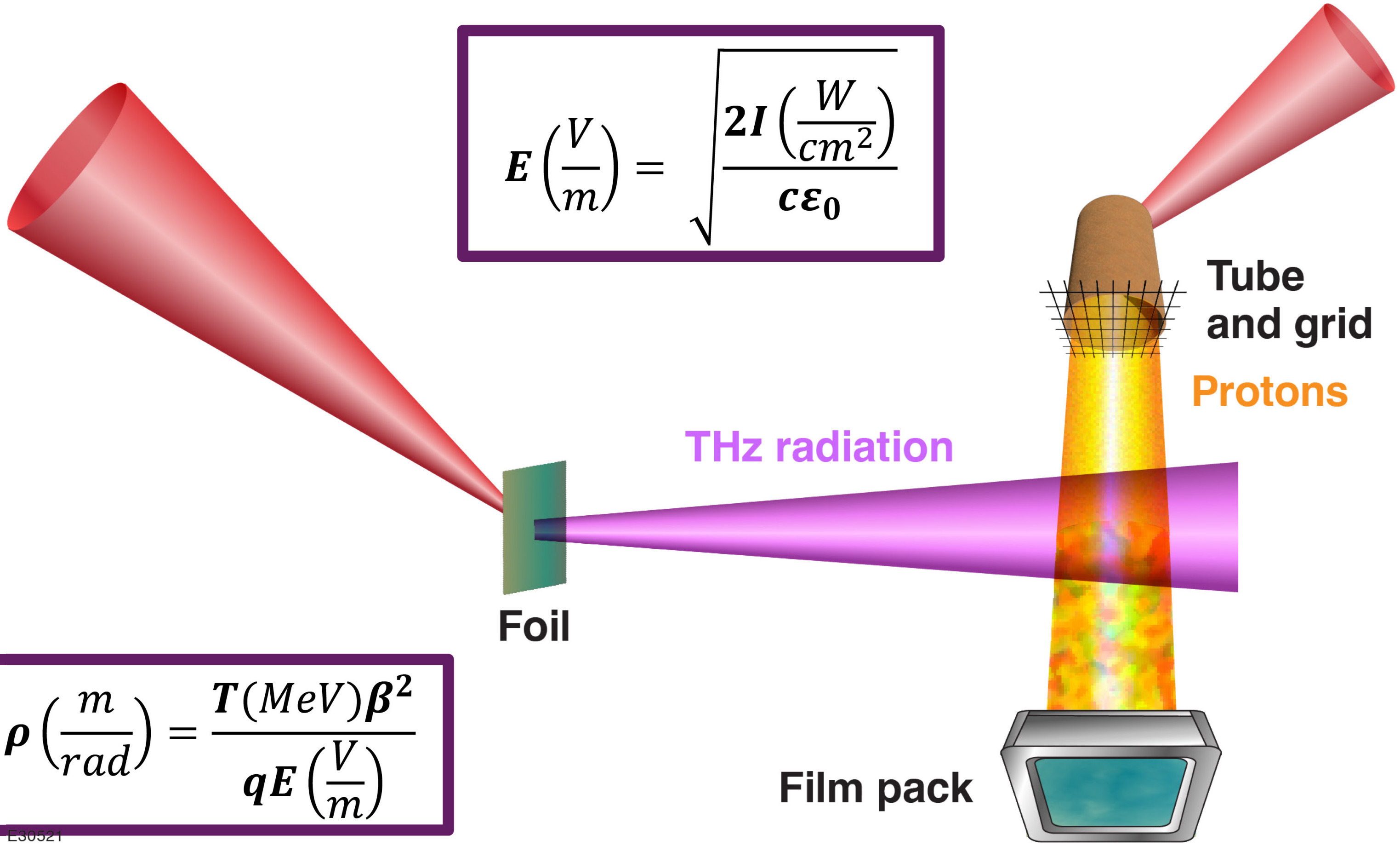
Wall Mounted Detector (MTBEM)



190 J drive laser and THz energy is estimated to be >150 mJ

Proton radiography was also used to directly measure GV/m scale electric fields from the THz emission

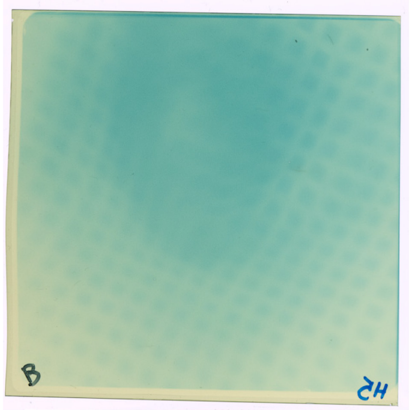
$$E\left(\frac{V}{m}\right) = \sqrt{\frac{2I\left(\frac{W}{cm^2}\right)}{c\varepsilon_0}}$$



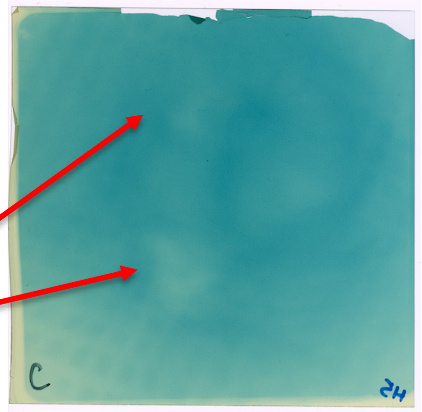
$$\rho\left(\frac{m}{rad}\right) = \frac{T(MeV)\beta^2}{qE\left(\frac{V}{m}\right)}$$

E30521

15 MeV protons alone



15 MeV protons + THz



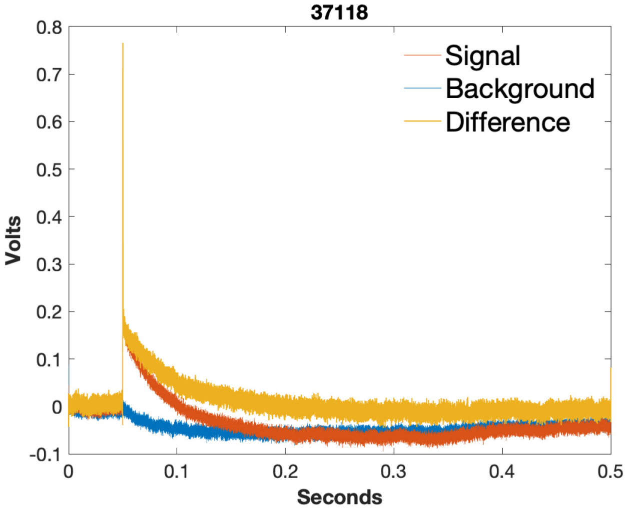
THz Induced Features

>100 mJ THz pulses needed to generate these effects

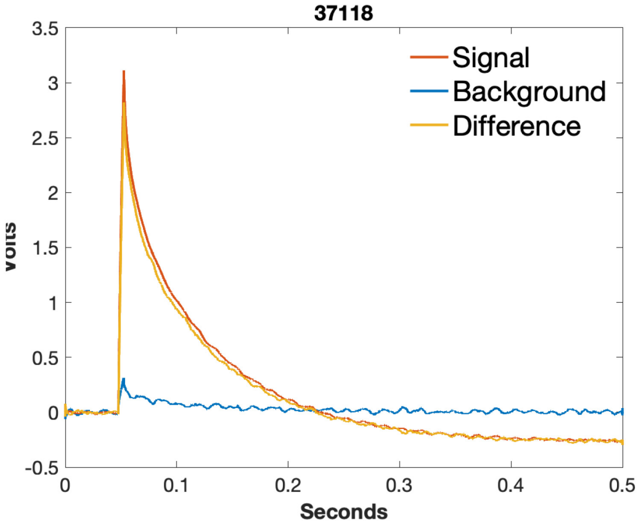
Microchannel targets were then used to generate >300 mJ THz pulses

- **Targets rely on relativistic transparency**
- **Excellent THz results produced**
- **See B08.00012 by H.G. Rinderknecht and JP11.00019 by M.A. VanDusen-Gross for more**

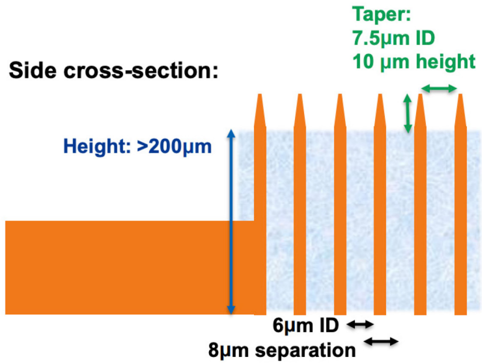
>300 mJ of THz radiation detected!

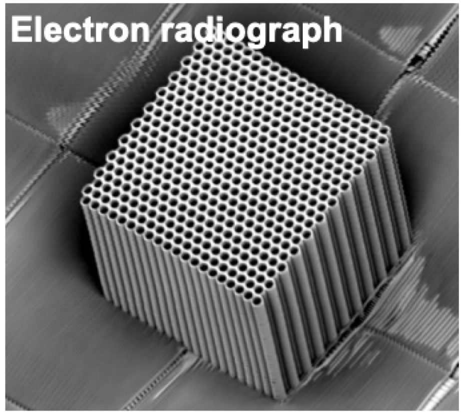


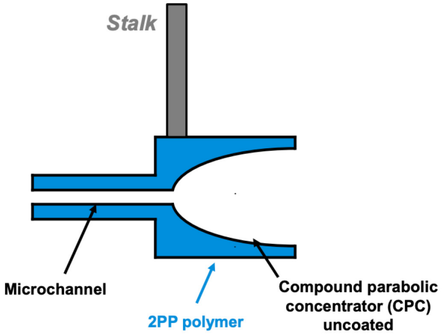
Retracted Detector (TBEM2)

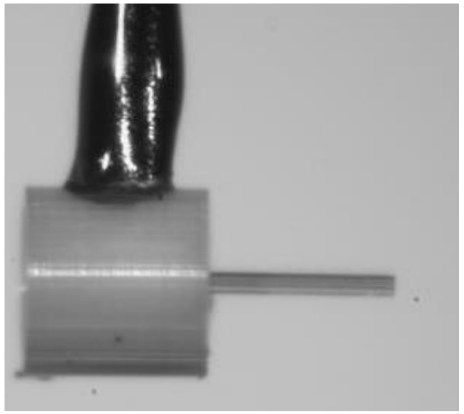


Wall Mounted Detector (MTBEM)





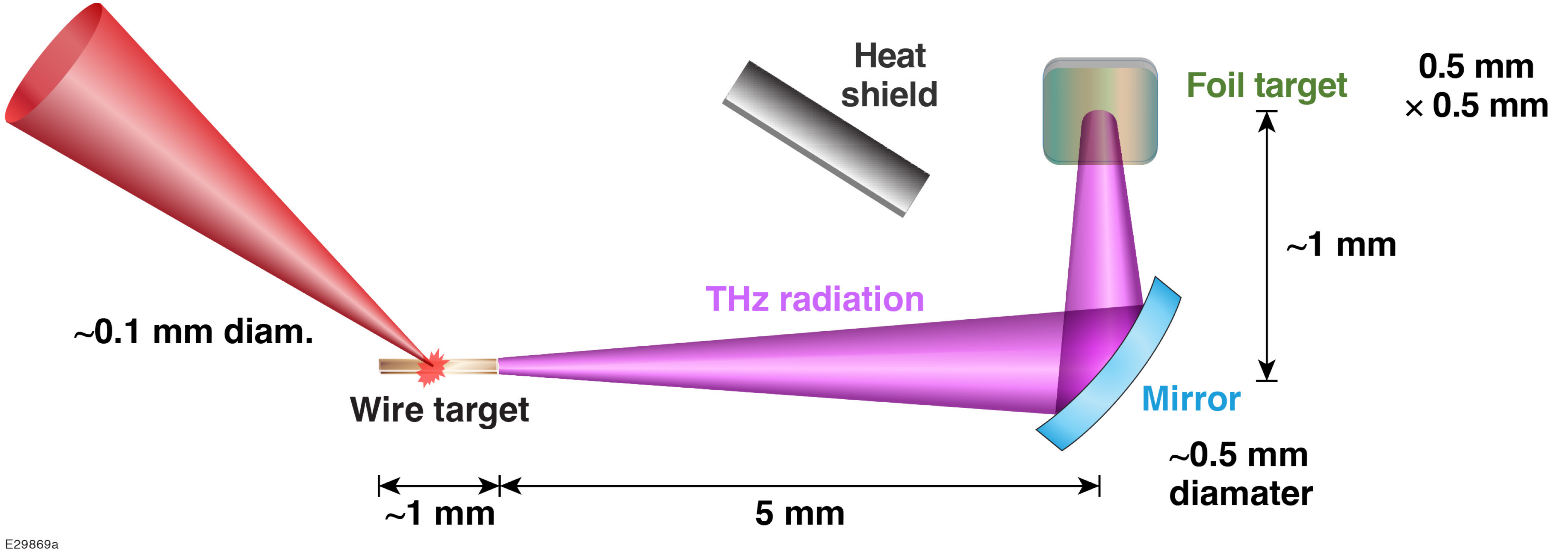




* H. G. Rinderknecht *et al.*, "Relativistically transparent magnetic filaments: Scaling laws, initial results and prospects for strong-field QED studies," *New J. Phys.*, vol. 23, no. 9, 2021, doi: 10.1088/1367-2630/ac22e7.
† L. L. Yi and T. Fülöp, Phys. Rev. Lett. 123, 094801 (2019).

Experiments focused on relativistic THz-matter interactions will take place in early 2023 using OMEGA-EP as the THz source

- Wire THz generation targets will be used to maximize yield
- THz intensities on the order of $\sim 10^{14}\ \mathrm{W}/\mathrm{cm}^2$ will impinge on the target
- Quasi-static electric fields >10 GV/m expected on target
- X-ray, charged particle and THz detectors will be used to monitor the interaction



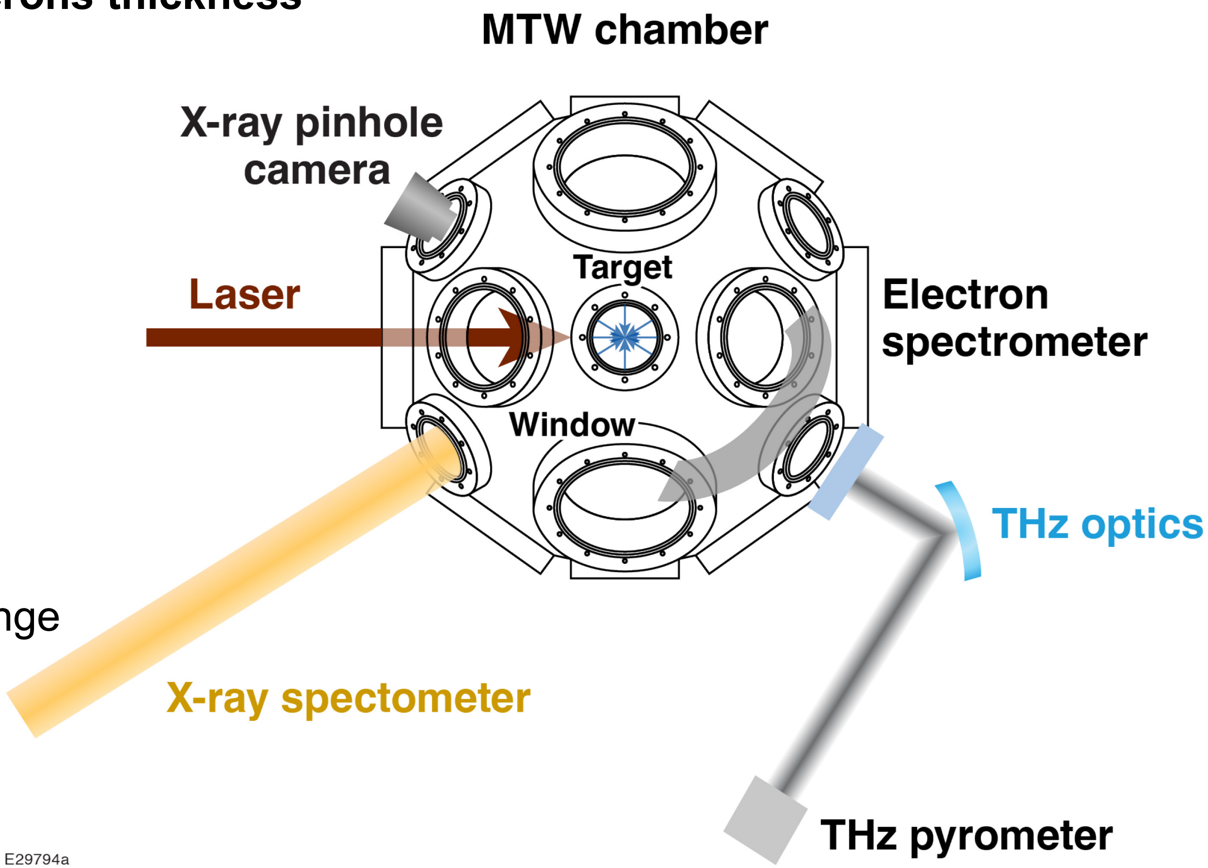
A first of a kind relativistic THz experiment will be attempted

High-Power, High Energy (HPHE) THz pulses were generated with a wide variety of targets on both the OMEGA EP and MTW lasers

Questions to:
gbru@lle.rochester.edu

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

- **Laser pulse energies between 10-12 Joules at 0.7-6 psec were tested**
- **Foil targets at normal incidence tested at 10-25 microns thickness**
  - CH, Al, Ti, and Cu materials tested
  - Radiation generated at primarily at <0.3 THz
- **Wire targets at angles were tested**
  - Nylon, Al, Cu, Ta, and Pt materials tested
  - 20-150 micron diameter
  - Wires show capability to generate 1 THz pulses
- **THz, electron and x-ray diagnostics used**
  - Electron spectrometer was limited to 5 MeV
  - X-ray spectrometer was limited to Cu emission range



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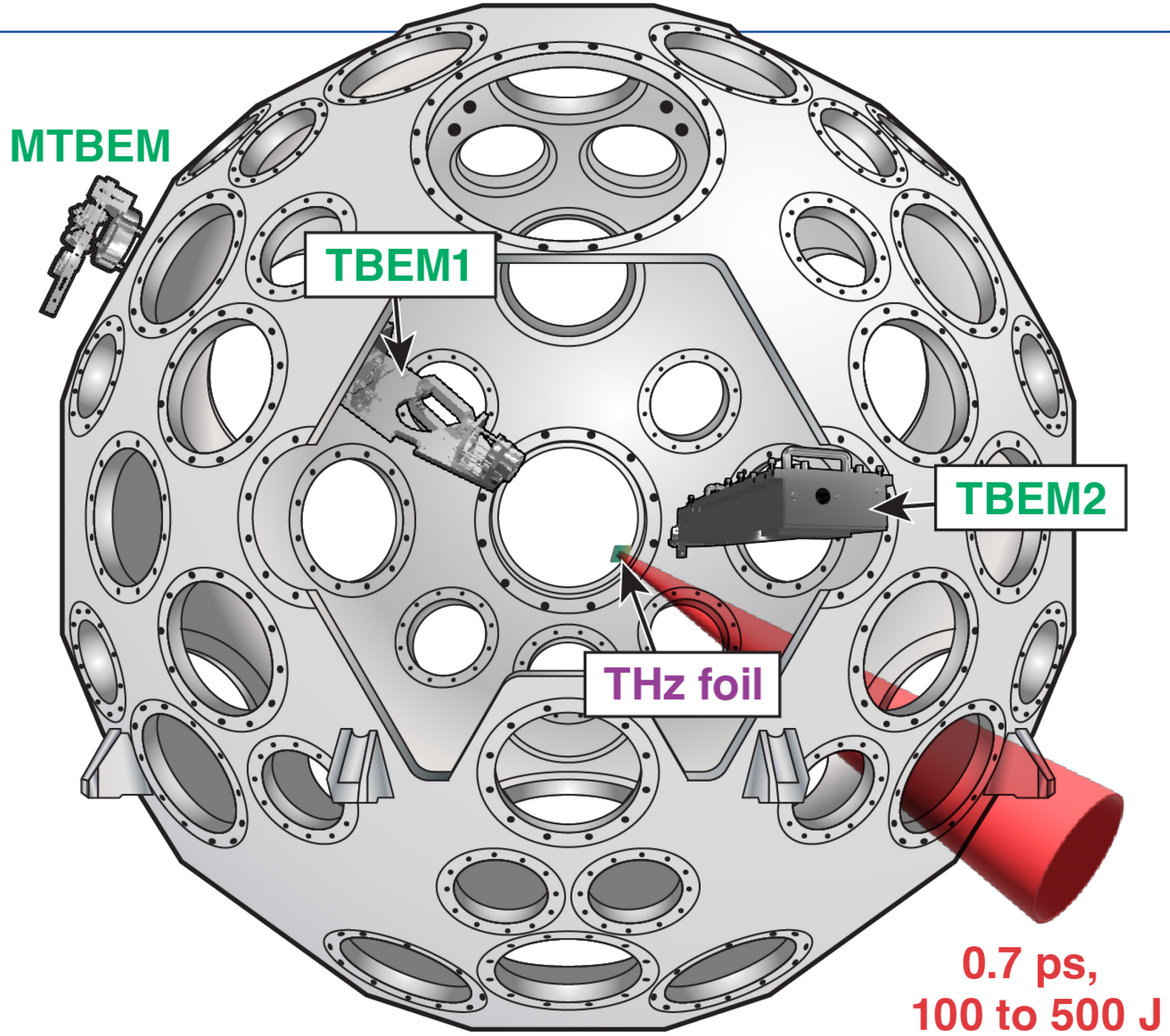
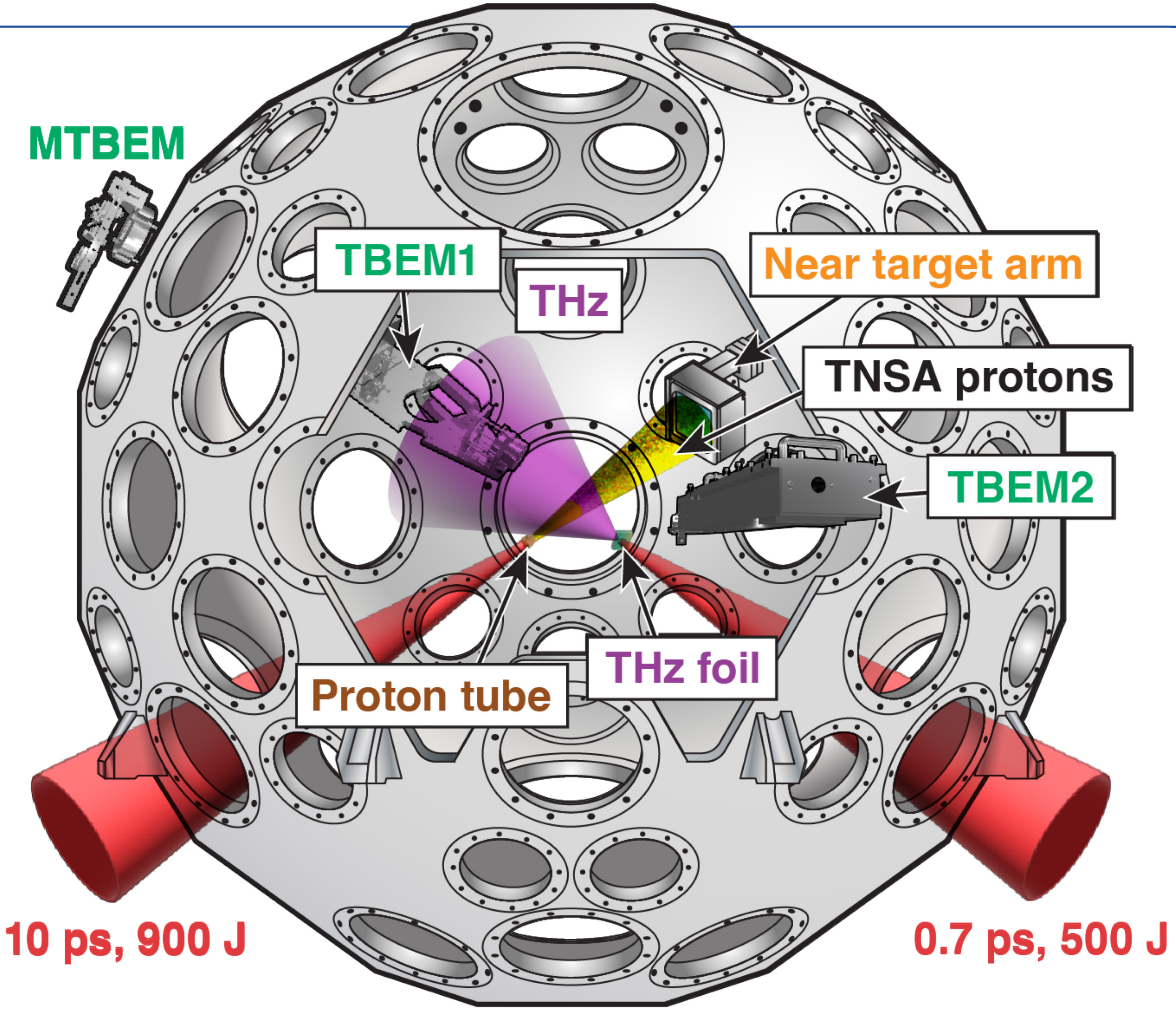
The June 2022 THz campaigns utilized three THz detectors at various positions



The June 8th 2022 THz campaign also interfered THz radiation with a TNSA proton beam to directly measure the electric field



E30520b

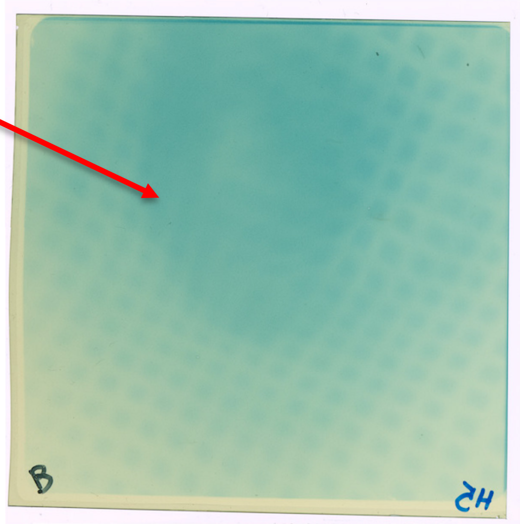
GV/m scale electric fields from HPHE THz emission were seen via proton/THz interactions during these experiments

- This provides an independent measurement of the field strength of the THz emission
- The proton producing target tended to overwhelm the pyrometers with noise, which prevented dual detection

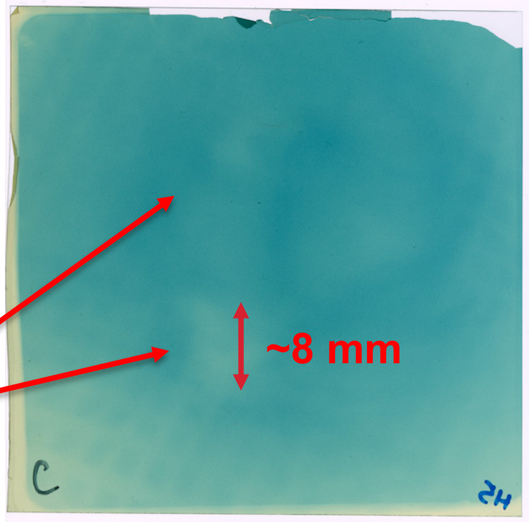
Typical emission ring from proton tube

15 MeV proton RCF

6.35 cm



15 MeV proton + THz RCF



THz Induced Features

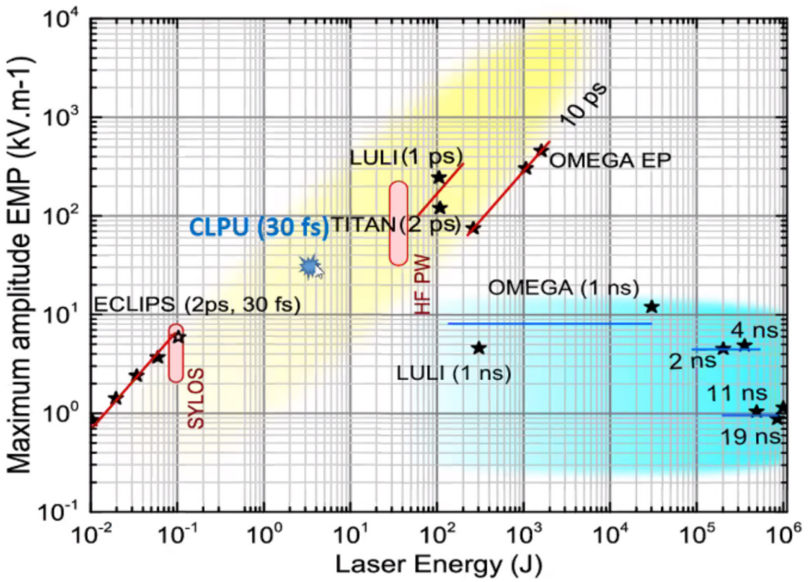
$$E\left(\frac{V}{m}\right) = \sqrt{\frac{2I\left(\frac{W}{cm^2}\right)}{c\varepsilon_0}}$$

$$\rho\left(\frac{m}{rad}\right) = \frac{T(MeV)\beta^2}{qE\left(\frac{V}{m}\right)}$$

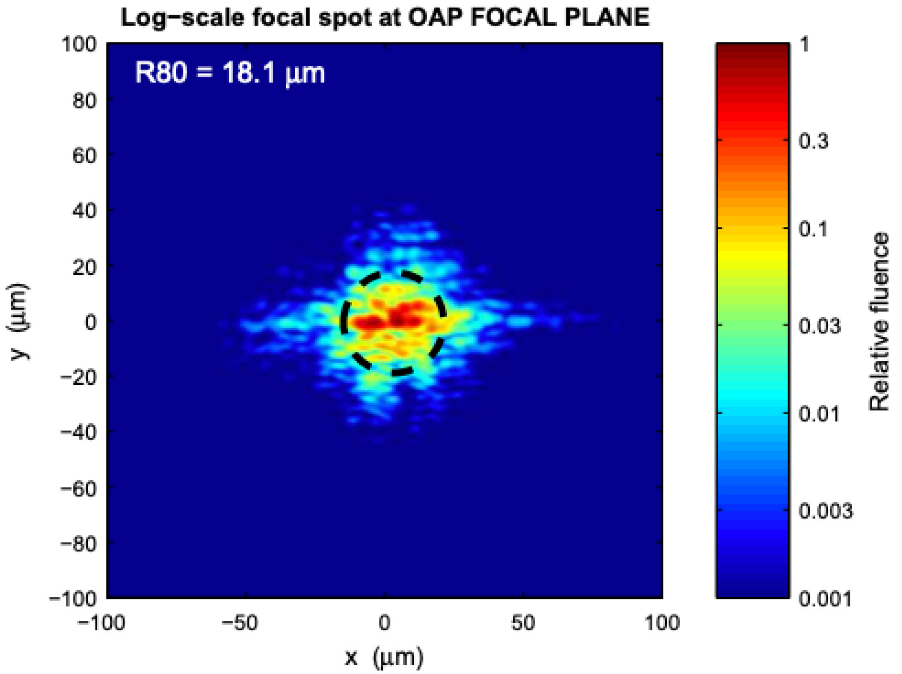
>100 mJ THz pulses needed to generate these effects

Experiments on OMEGA-EP can be extremely challenging

- The EMP environment is one of the worst seen with short pulse lasers*
- Huge fluences of charged particles and x-rays irradiate all detectors**
- The beam spot is often complex and makes simulation and analysis difficult



Sudipta Mondal, Mojtaba Shirozhan, Naveed Ahmed, Maïmouna Bocoum, Frederik Boehle, Aline Vernier, Stefan Haessler, Rodrigo Lopez-Martens, François Sylla, Cedric Sire, Fabien Quéré, Kwinten Nelissen, Katalin Varjú, Dimitris Charalambidis, Subhendu Kahaly, JOSA B, **35**,A93-A102 (2018)



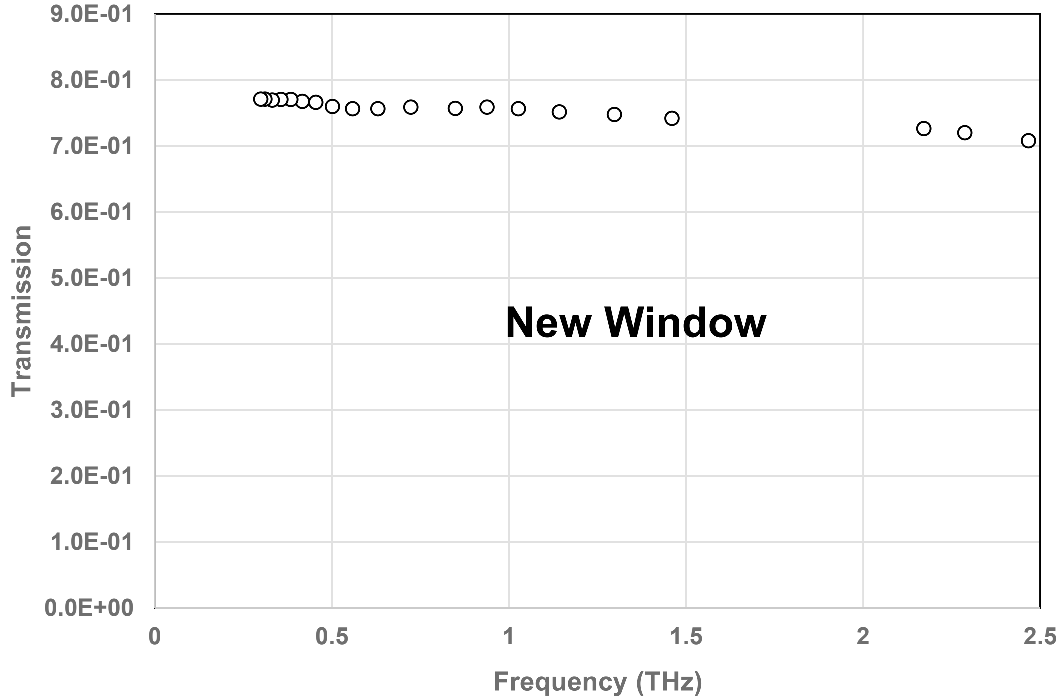
Example OMEGA-EP beam spot for THz experiment

*S. Mondal, et al, "Surface plasma attosource beamlines at ELI-ALPS," J. Opt. Soc. Am. B 35, A93-A102 (2018)

**Shaw, J.L., *et al.* Microcoulomb (0.7 ± 0.40.20.40.2 μC) laser plasma accelerator on OMEGA EP. *Sci Rep* 11, 7498 (2021). https://doi.org/10.1038/s41598-021-86523-5

The window for THz detection is highly attenuating and will be switched out for a crystal quartz window on the next MTW campaign

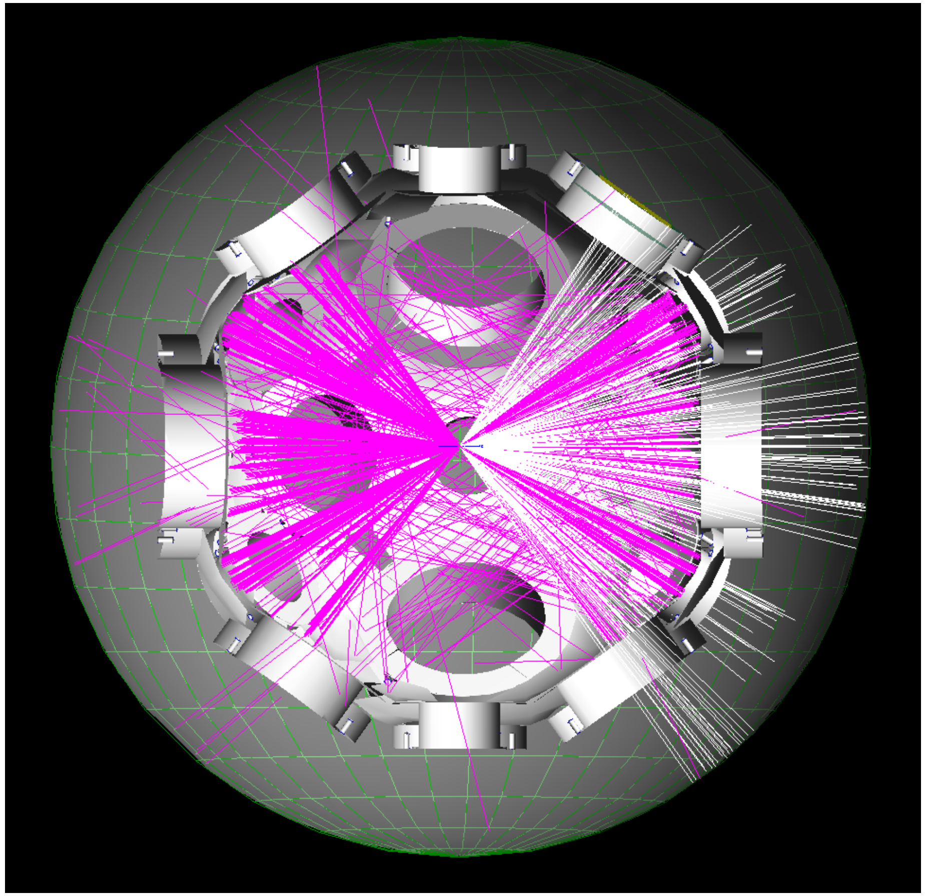
- The results shown all used a LLE standard ”OMEGA” window that is optimized for UV laser transmission
- Two crystal quarts windows will be used to replace this highly absorbing window



This window may make the previous 1 THz claims suspect

Analysis is ongoing to determine portion of THz radiation that the detectors see

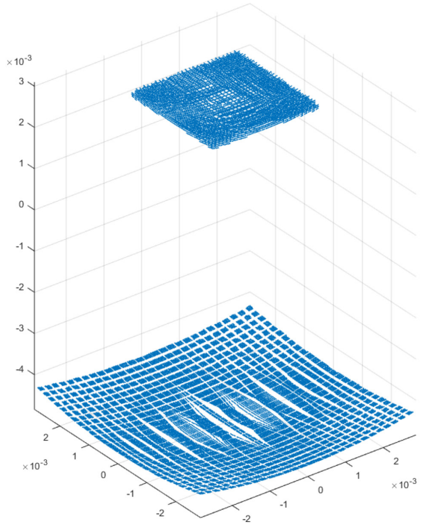
- A preliminary ray trace analysis indicates ~0.3% of emitted THz radiation reaches the detector!
- This would drive the reported emission up nearly an order of magnitude!
- Ray trace of wire target emission is ongoing



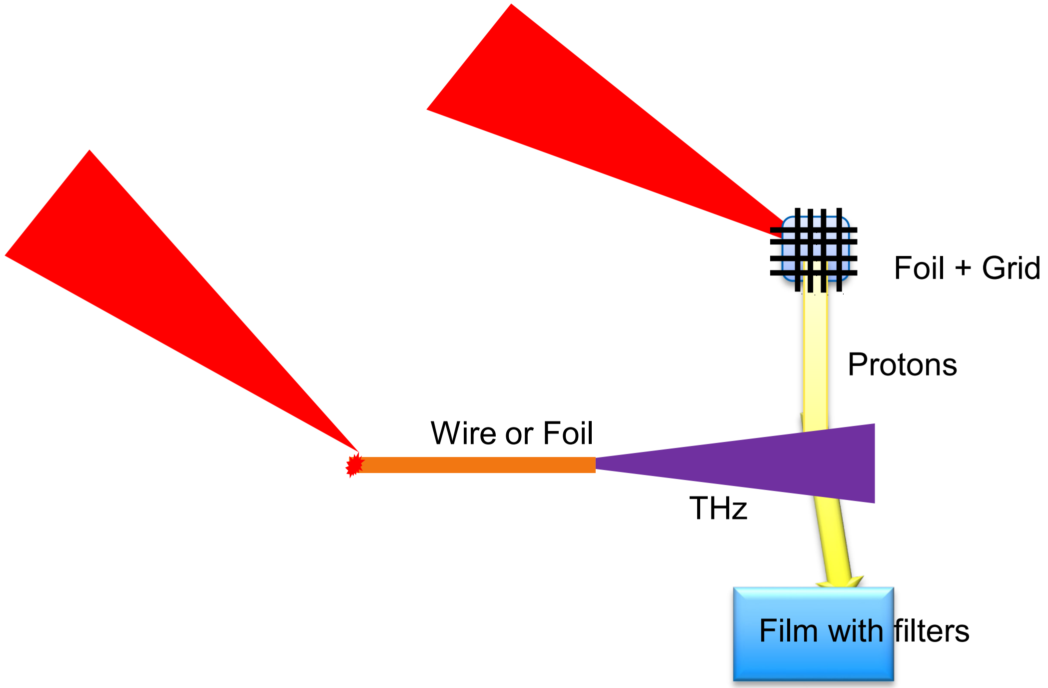
More simulations need to be done!

THz proton deflectometry is based on TNSA measurements of plasma generated fields that are commonly done in fusion experiments

- **Similar experiments have been shown on a tabletop scale with electron beams***
- **Very simple simulations gave credence to the concept, but more will need to be done to full understand the results**



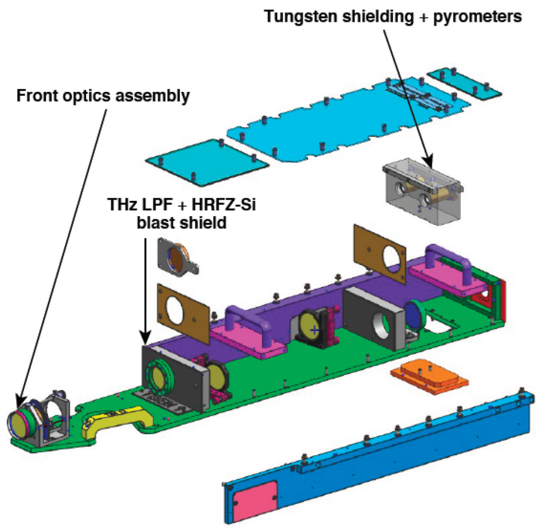
First pass simulation, J. Peebles



* Zhao L., et el, Terahertz Streaking of Few Femotsecond Relativistic Electron Beams, Phys Rev X, 8, 021061, (2018)

We have two purpose built THz detectors for EP called TBEM

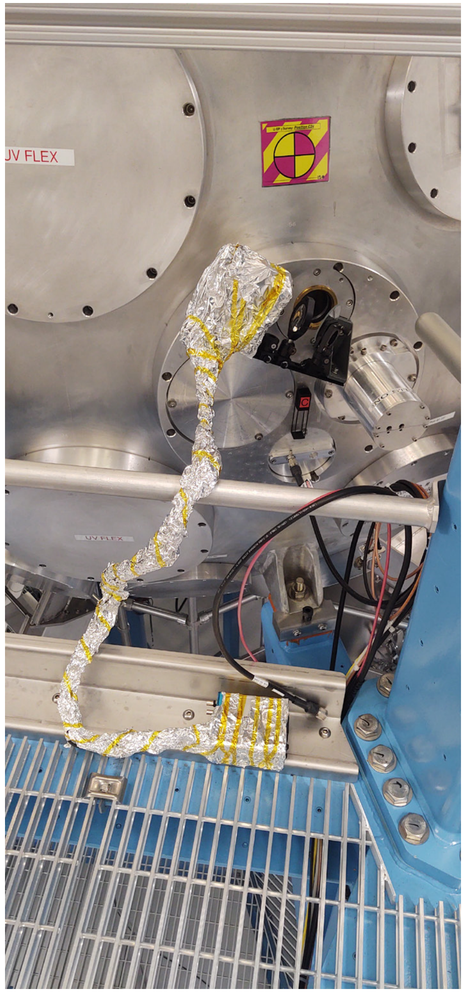
- Two pyros, one in the THz beam path
  - Both are sensitive to ~5 nJ
- 2” TPX lens that is 5.4” from TCC
  - 0.9 transmission per lens
- (2X) HRFZi-Si shield/filters
  - 0.5 transmission per filter
- (1X) Tydex 10 THz LPF
  - 0.7 transmission per filter
- (1X) Teflon LPF on signal detector
  - 0.8 transmission per filter



TBEM Configuration	Steradians Seen	Transmission
Full insertion, no iris	0.0086	0.1134
Full insertion, 0.196” iris	2.07E-5	0.1134
Full insertion, 0.3937” iris	8.3E-5	0.1134
Full insertion, 0.7874” iris	3.32E-4	0.1134
Full insertion, solid iris	0	0
Retracted Operation, no front optics	5.739E-5	0.252

- Option to put iris in
  - 0.196”, 0.3937”, 0.7874” diameter plus a solid block
  - 0.00242X, 0.009688X and 0.03875X reduction respectively
- Detector can also be retracted and operated without front optics
- Has ~50 um pointing accuracy

The MTW prototype of TBEM was also attached to OMEGA-EP for some experiments



Estimates of performance

Laser Energy (J)	Laser-THz Efficiency (%)	Scenario Type	THz on Detector (nJ)	Signal Peak on Pyrometer (mV)
50	0.05	Worst Case	7.28	8.5
300	0.1	Median Case	87.38	430.9
500	1	Best Case	1456	4694.2