An electron beam-based THz source and the transport of THz radiation over 120-150 meter distances for LCLS-II

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U.S. DEPARTMENT OF ENERGY | Stanford University

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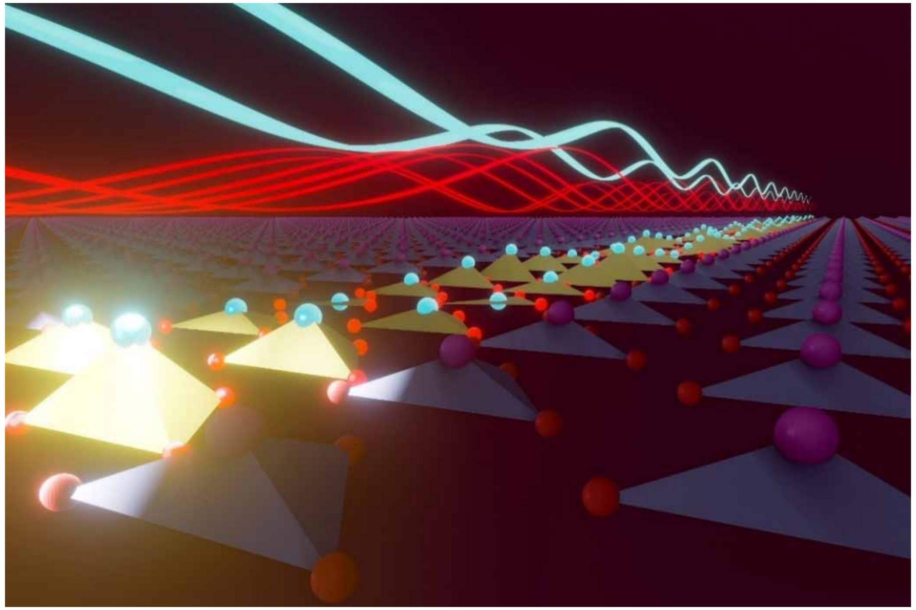
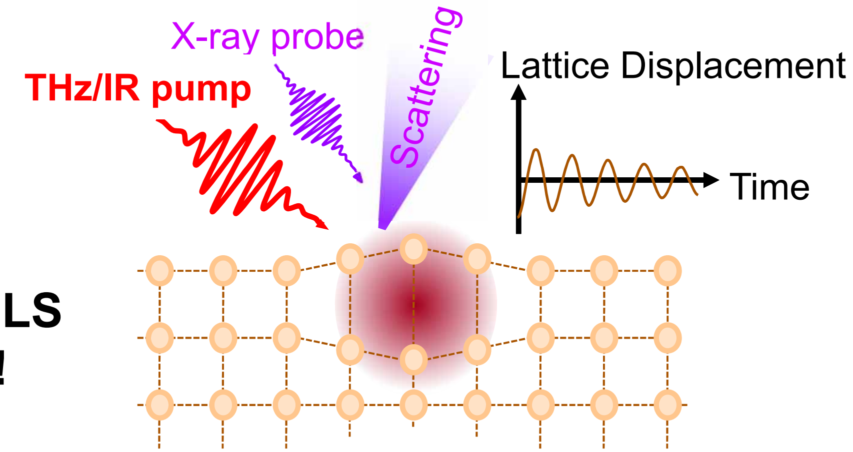
A Scientific Driver

Strong resonant excitation of vibrational modes in the **3 – 30 THz range** has led to the control of functional properties such as superconductivity, ferroelectricity, and magnetism in complex materials…



Which structural pathways and time scales lead to such phenomena?

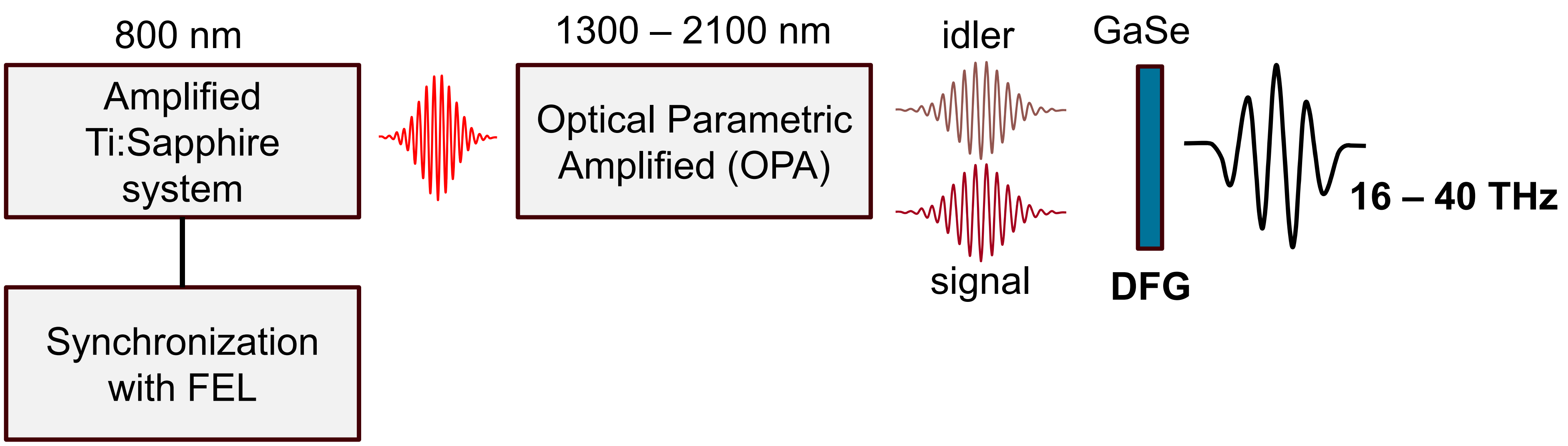


Experiments at LCLS
… and LCLS-II !!

Current laser-based THz sources at LCLS

LCLS THz sources are based on the existing laser infrastructure which operates at a 120 Hz repetition rate.

Difference Frequency Generation (DFG)



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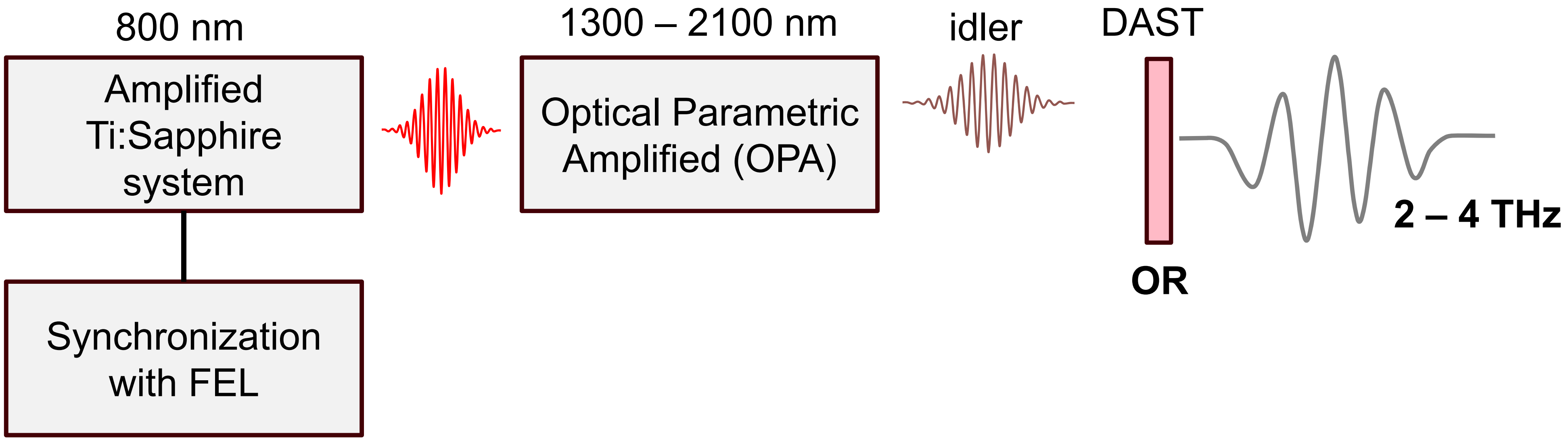
Optical Rectification (OR)



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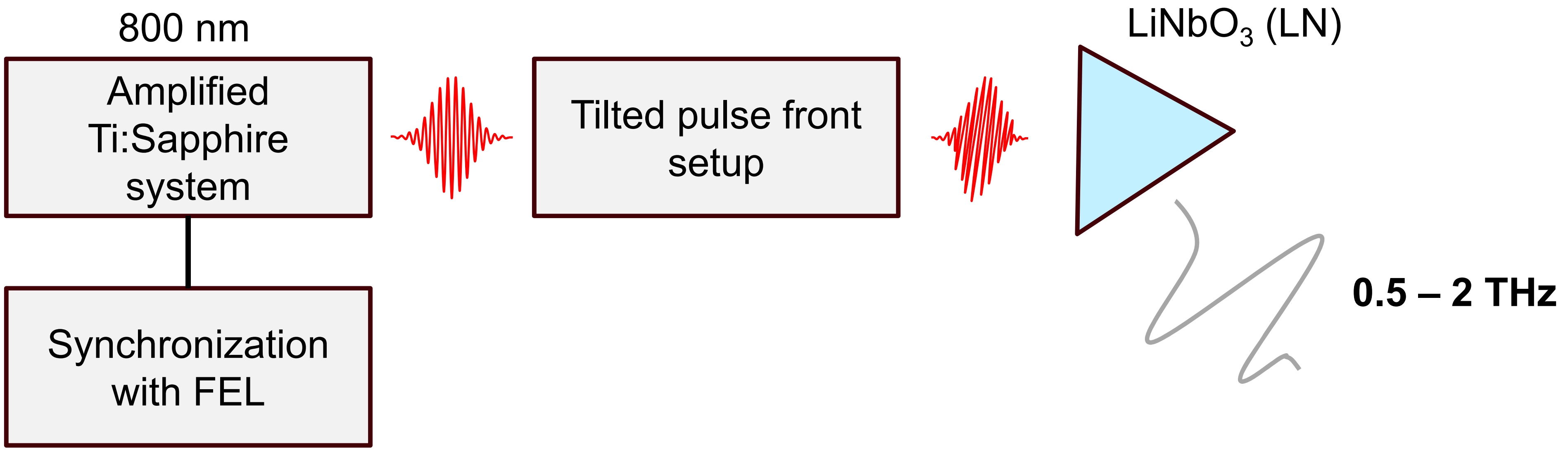
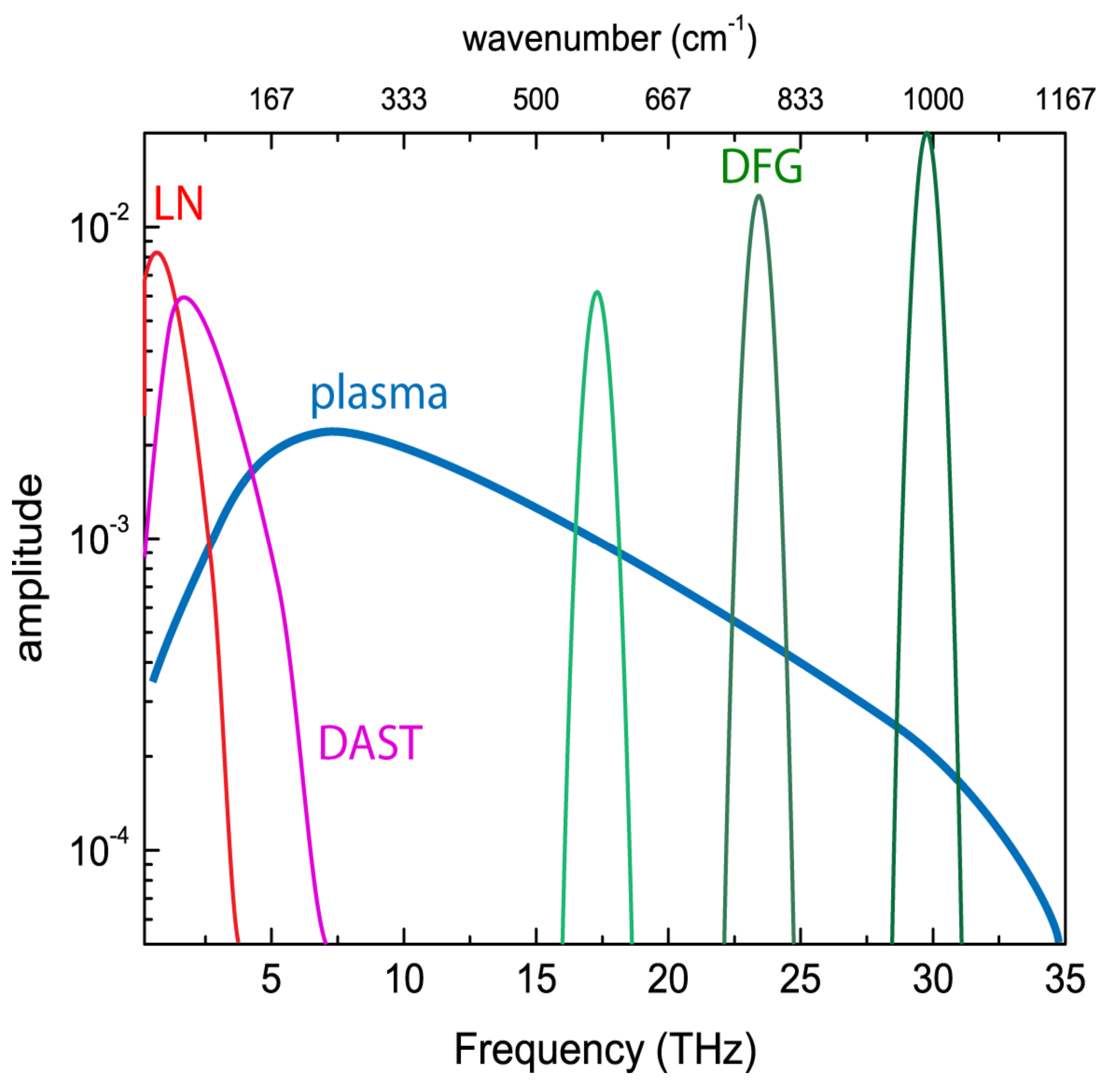
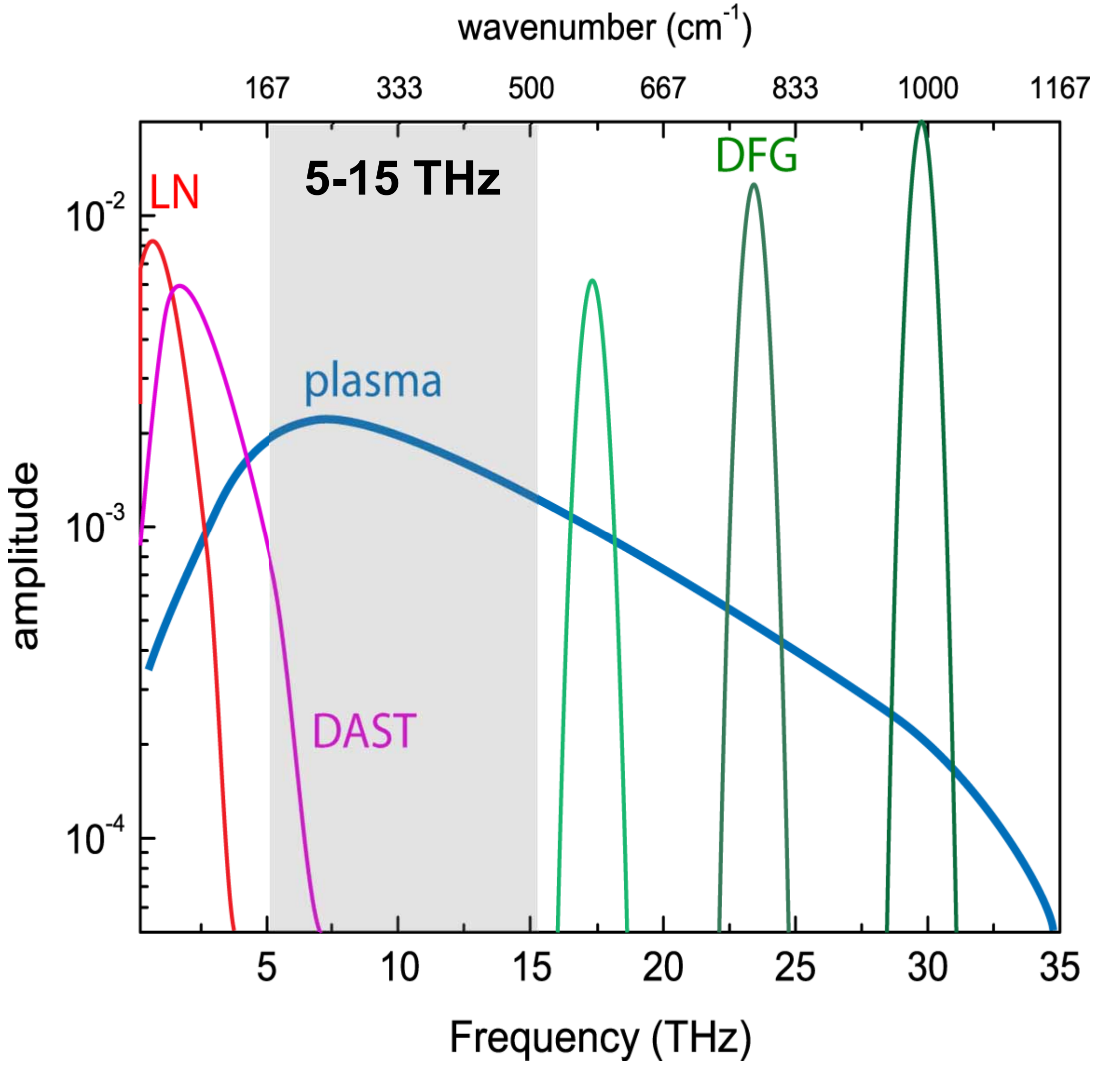
Phase-Matched Optical Rectification



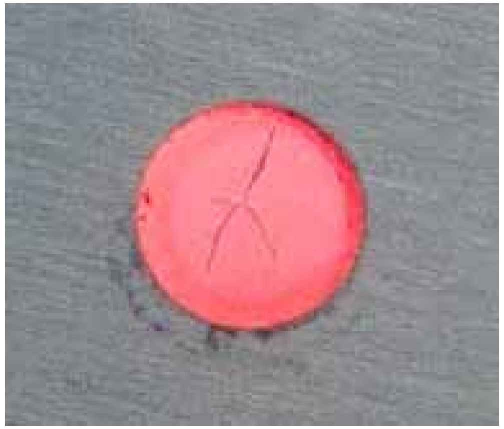
Current laser-based THz sources at LCLS



Current laser-based THz sources at LCLS



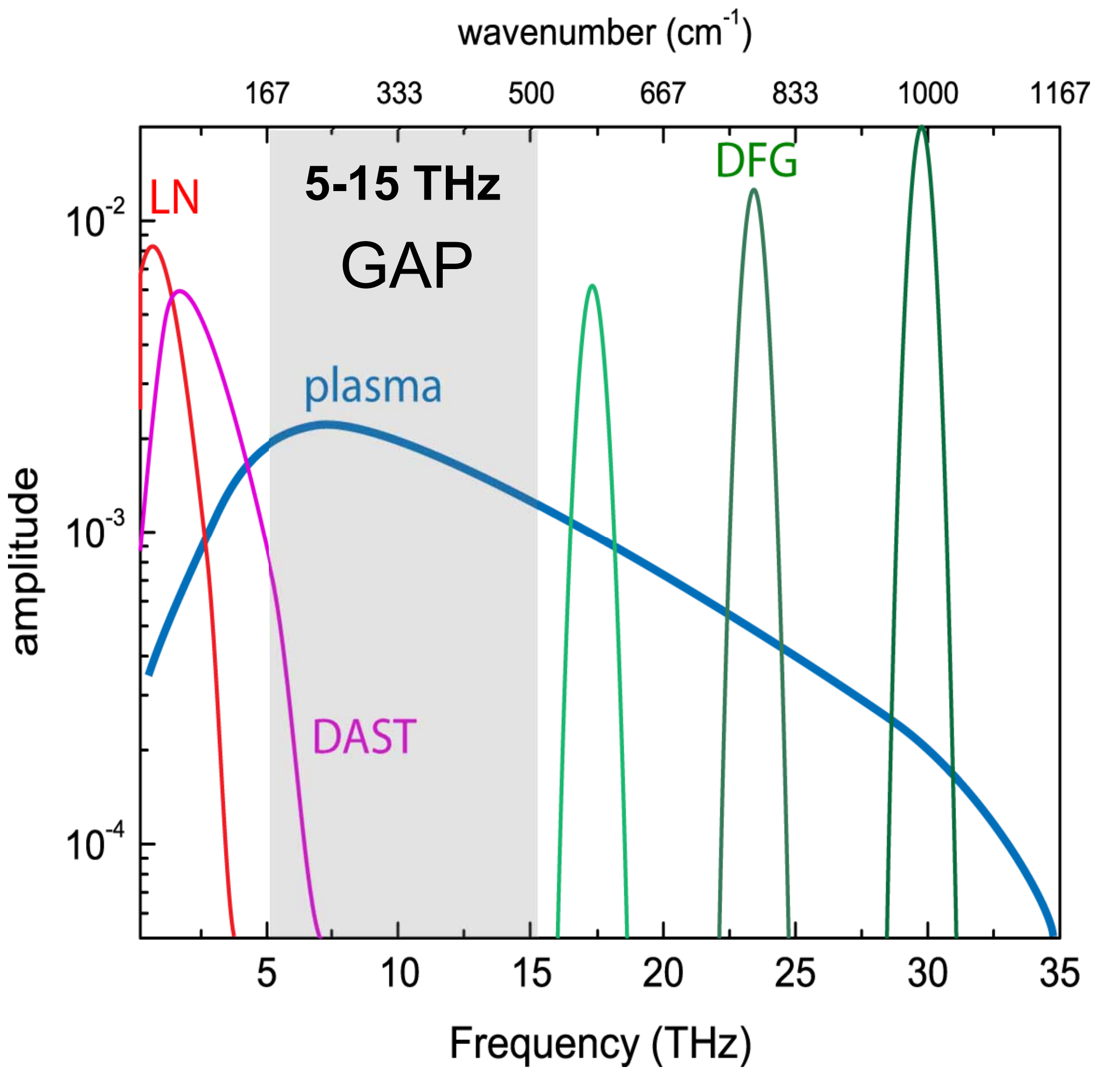
Using a [complicated] double-OPA scheme:
DAST *can* produce radiation in the **5-15 THz** range at 1 KHz repetition rates [1], but this material **damages at > 10 KHz repetition rates.**



DAST crystal cracked after a few seconds of exceeding 60 C locally (500 µm spot size, 200 kHz)

[1] B. Liu, M. Först, M. Fechner, D. Nicoletti, J. Porras, B. Keimer, A. Cavalleri, Phys. Rev. X **10**, 011053 (2020)

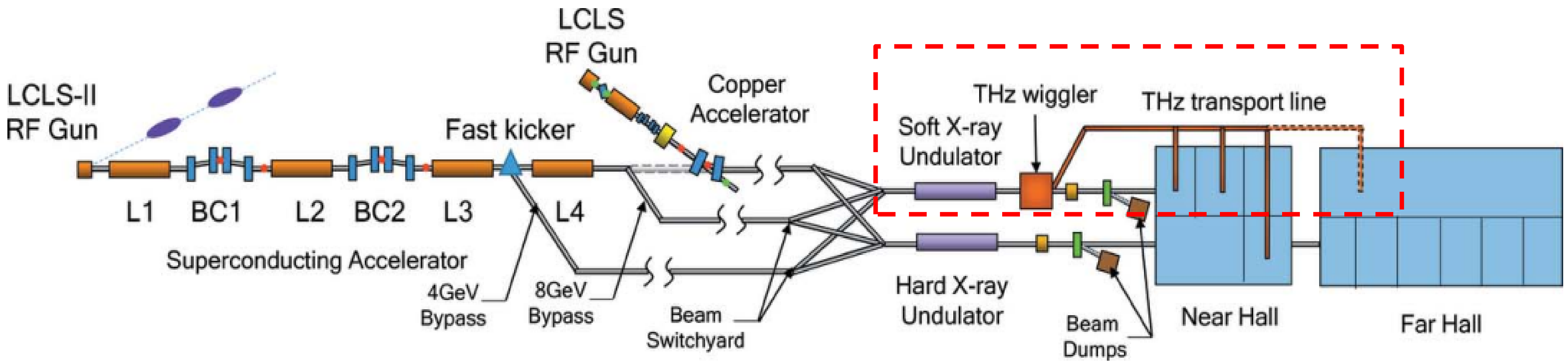
Current laser-based THz sources at LCLS



At the 10 – few 100 KHz repetition rates afforded by LCLS-II, there exists a “**THz gap**” from 5 – 15 THz

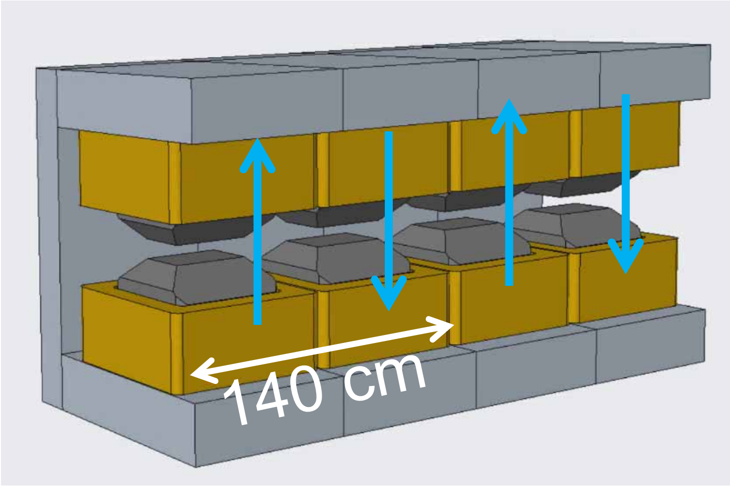
Proposed THz Beamline

Goal: 10 cycles – 10 µJ Energy – 10 THz frequency (3-30 THz tunable)



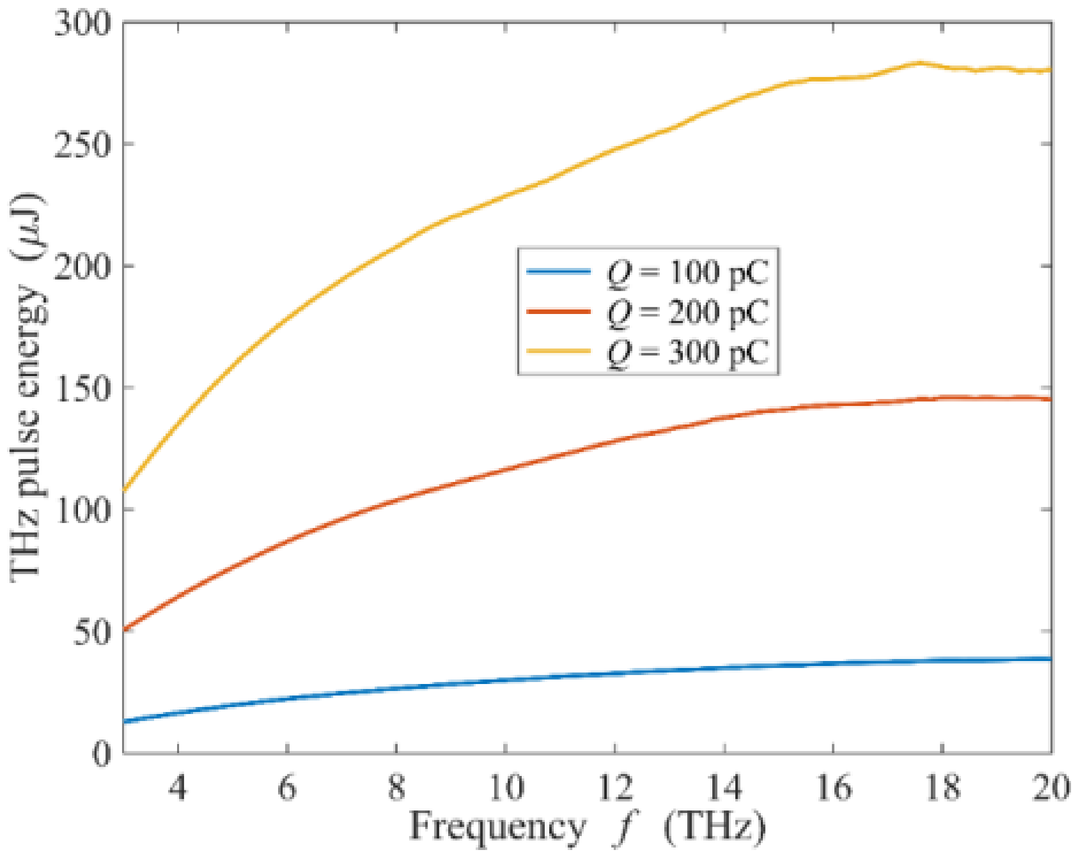
- The THz wiggler is installed **on the soft x-ray beamline**
- LCLS-II RF Gun produces **two bunches** that are delayed by approximately 100 ns
- The first electron bunch is compressed and sent through the THz wiggler.
- The second bunch is optimized for x-ray generation

THz Electromagnet Wiggler (Collaboration with ANL)



- Period: 140 cm
- 14 uniform poles, 4 end poles
- Length: 12.11 m
- For **3 THz** with an 8-GeV beam:
  B = 2.03 T, I = 306 A, K = 265
- **10 poles → 10% bandwidth**

Energy v. Resonance Frequency (10% bandwidth)



Z. Zhang, et al. Journ. Synch. Rad. **27**, 890 (2020).
A. Fisher et al., “THz wiggler design for the LCLS-II high-repetition rate facility”, LCLS-II Technical Note, 9/30/2011.

The transport problem

One of the primary challenges to realizing a wiggler-based THz source for LCLS-II:

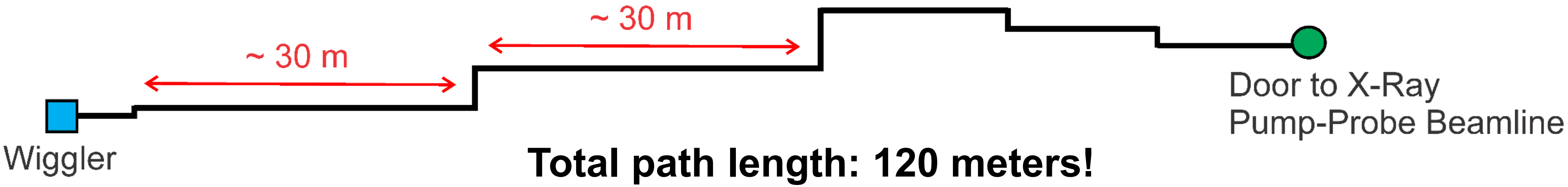
THz radiation must be transported over distances of:

120 – 150 meters to reach the Near Experimental Hall hutches

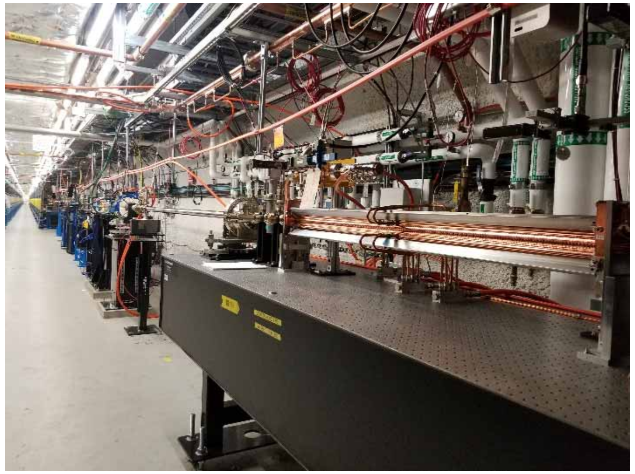
~ 350 meters to reach the Far Experimental Hall hutches

The transport problem

Sketch (to scale) of the path from the Undulator Hall through the “maze” to the X-ray Pump-Probe hutch



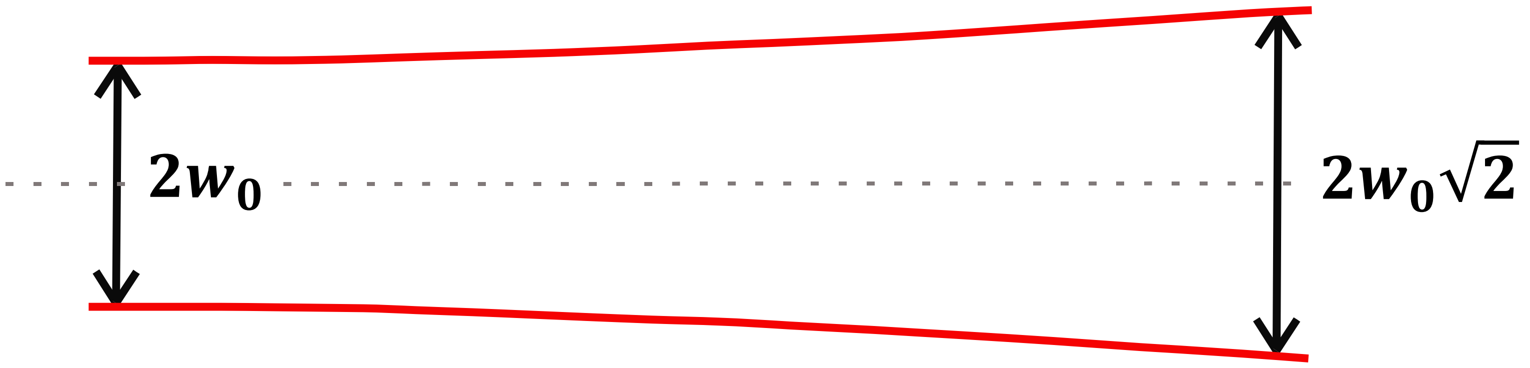
Total path length: 120 meters!



The transport problem

Rayleigh length (z_r): distance after which a Gaussian beam of a given waist (w_0) and wavelength expands by $\sqrt{2}$.

$$z_r = \frac{\pi {w_0}^2}{\lambda}$$



For a beam with $2w_0$ = 5 mm and wavelength:

- **λ = 800 nm (375 THz): z_r = 24.5 meters**
- **λ = 10 um (30 THz): z_r = 1.96 meters**
- **λ = 100 µm (3 THz): z_r = 0.196 meters !!**

The transport problem

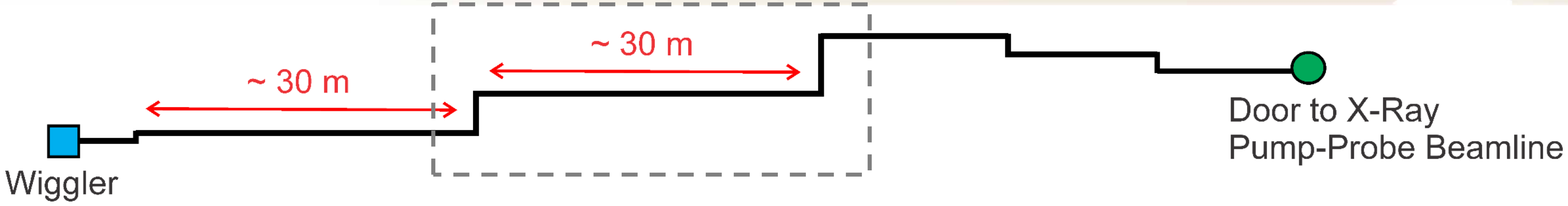
We can eliminate much of the difficulty by simply working with larger beams…

For a beam with $2w_0$ = 100 mm and wavelength:

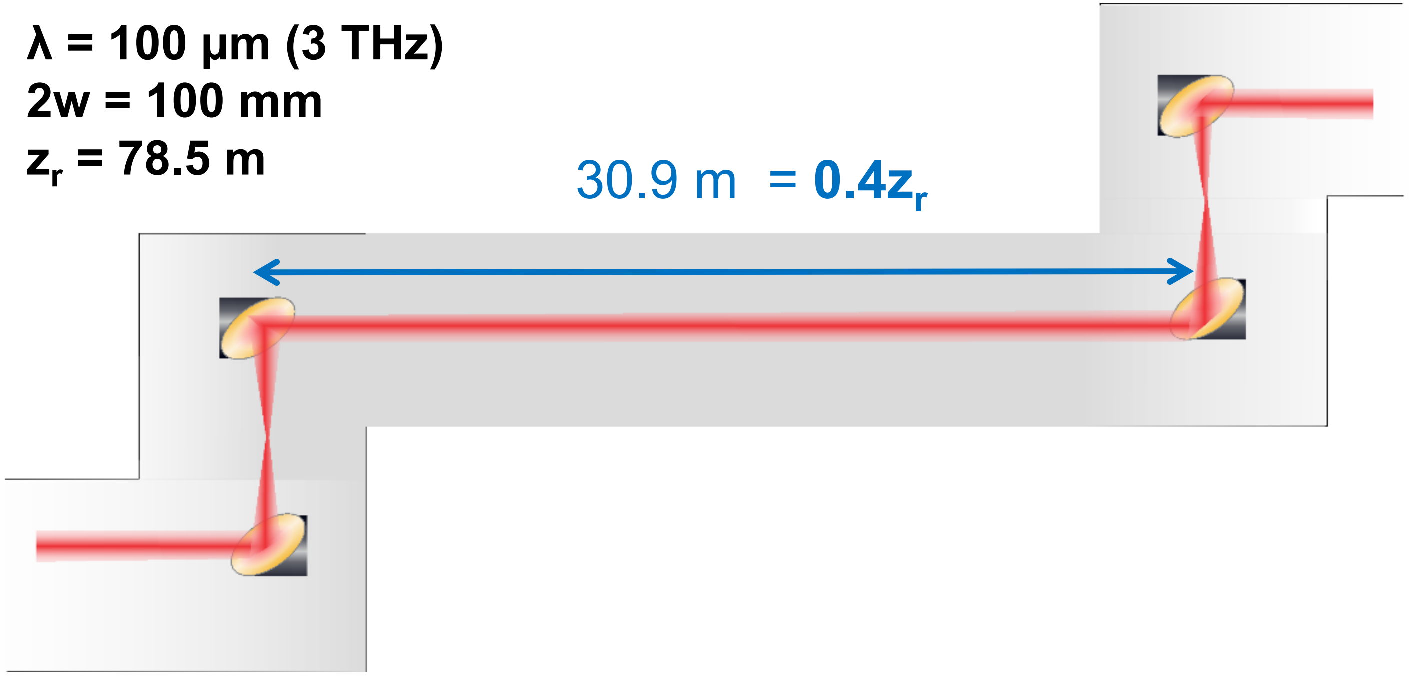
λ = 10 μm (30 THz): z_r = 785 meters

λ = 100 μm (3 THz): z_r = 78.5 meters

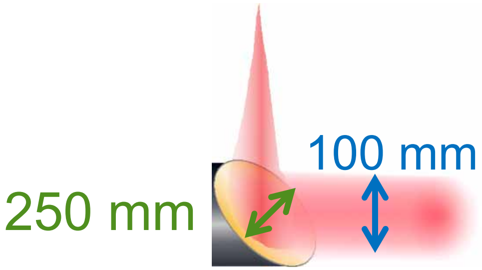
“Stretched” Relay Imaging



λ = 100 μm (3 THz)
2w = 100 mm
z_r = 78.5 m



- Allow the beam to propagate over long straight paths in the maze with minimal diffraction
- Relay-image the beam at 90° degree turns using off-axis parabolic mirrors (OAPs)
- **The beam can be transported over the 120 meter distance using 11 mirrors.**



Effective OAP focal length: **1 – 6 meters**

How can we test this?

SLAC

Currently, we are testing this transport concept over reduced (12 – 25 meter) length scales at the limits of the prospective wiggler spectrum

(3 THz and 30 THz)

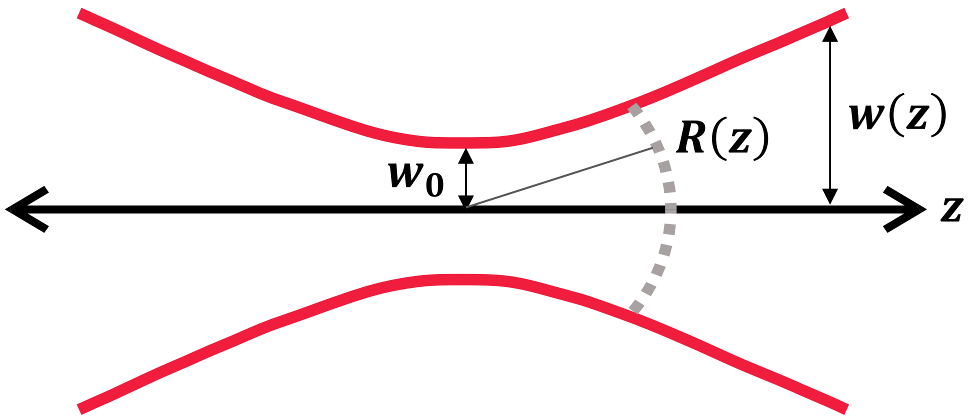
How can we test this?

The diffraction of a Gaussian beam envelope over a distance z is determined solely by the Rayleigh length z_r

[The parameter z/z_r is what matters]

Beam waist $$\boldsymbol{w(z) = w_0\sqrt{(1 + (z/z_r)^2)}}$$

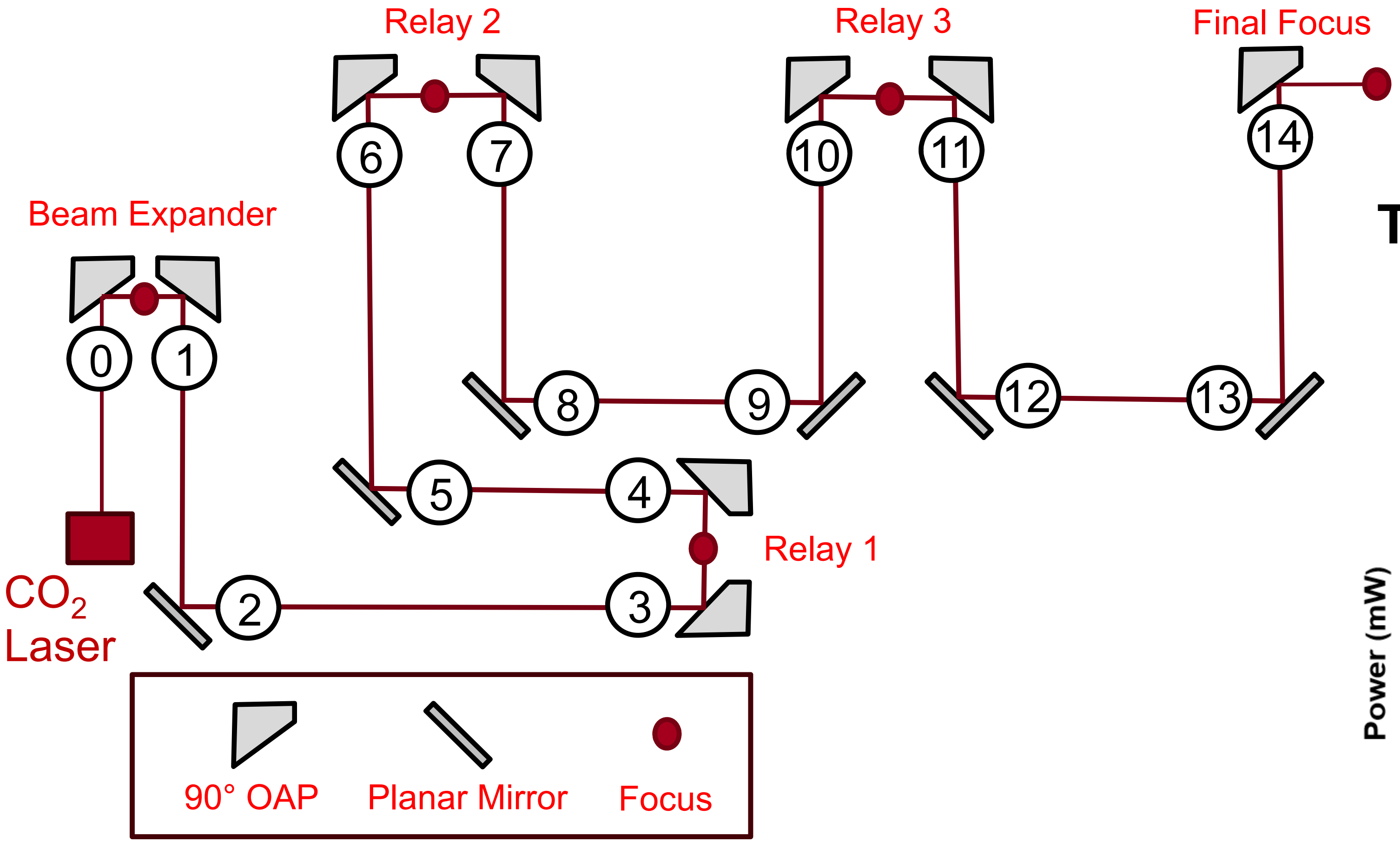
Radius of curvature $$\boldsymbol{R(z) = z\left(1 + (z_r/z)^2\right)}$$



We can develop transport / alignment strategies over reduced length scales [10 – 20 meters] in the laboratory…

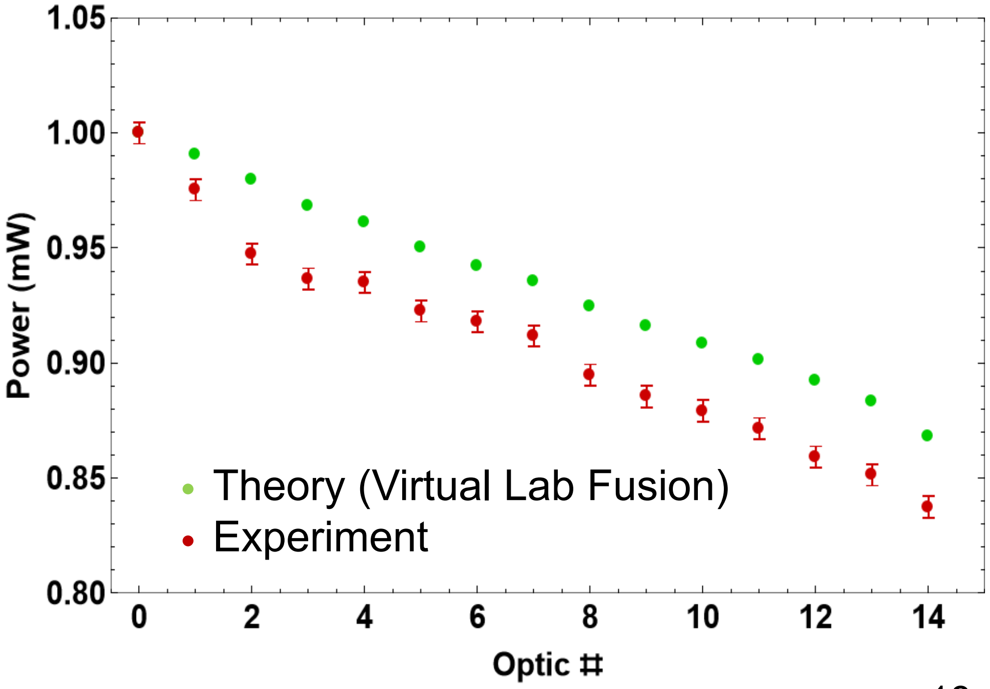
…and they should work equivalently for longer (120+ meters) distances.

Laboratory tests at 10.6 μm Wavelengths



Rayleigh Length: ~ **7 meters**
Distance between relays: **3 meters**

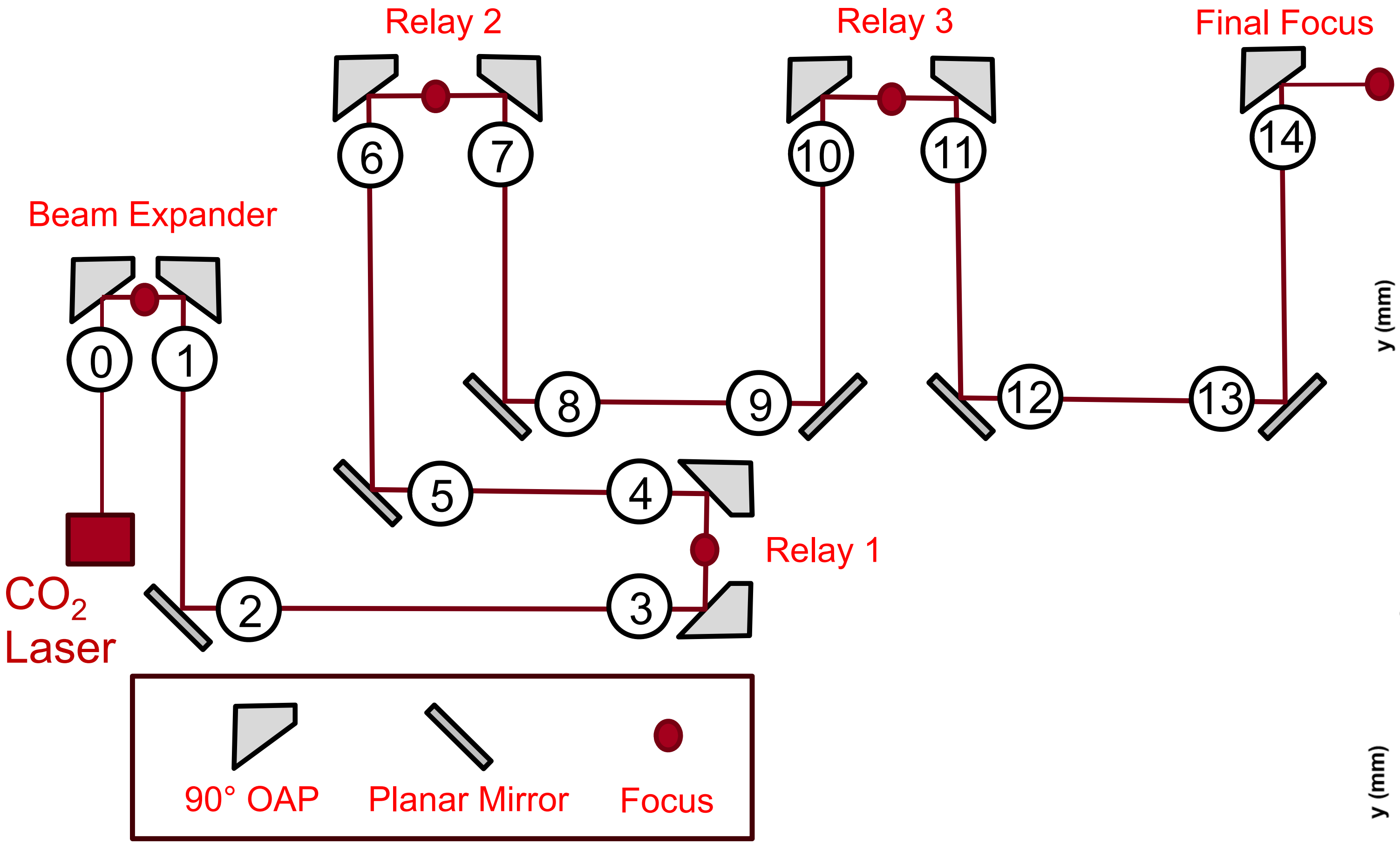
Total transport distance: 12 meters

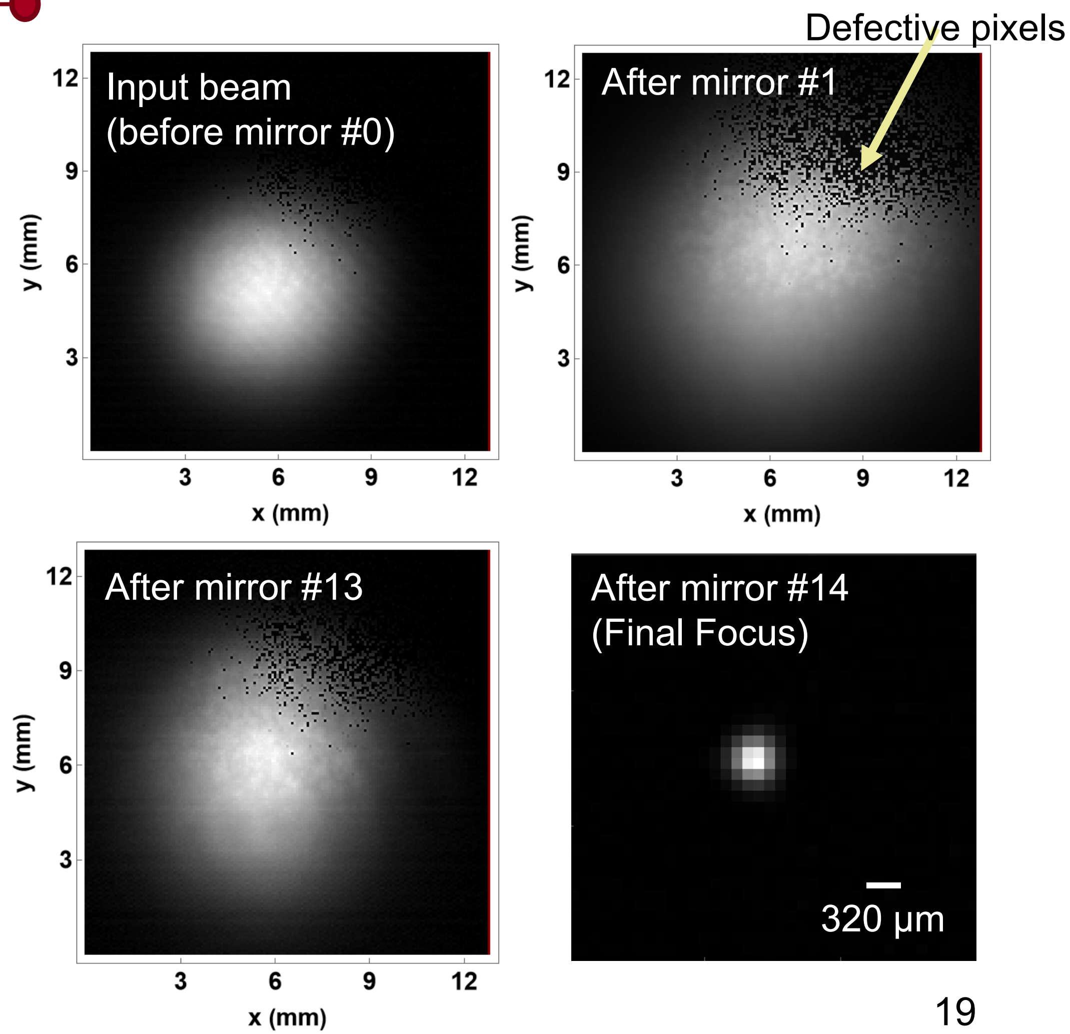


Loss is predominantly ohmic: ~ 1% per optic

120-m transport line: 11 optics → 89% efficiency

Laboratory tests at 10.6 μm Wavelengths





Summary

- **We propose a mirror-guide system to route THz radiation in the 3 – 30 THz range over the 120 – 150 meter distance to the near hall hutches.**

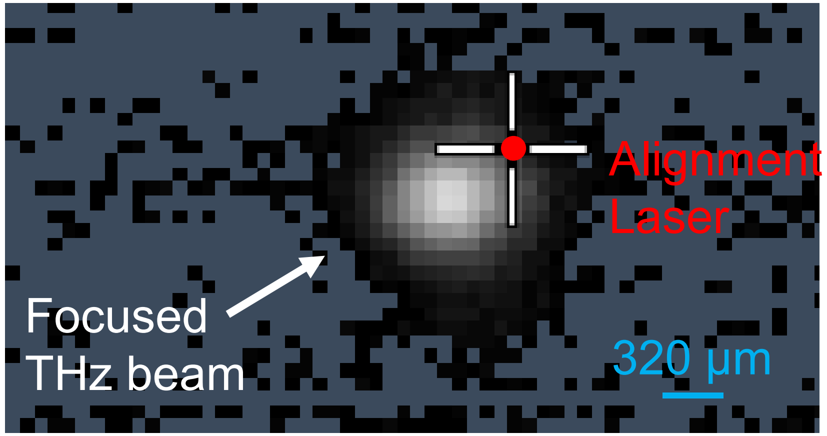
  - We minimize the number of mirrors needed for transport by exploiting the long Rayleigh length associated with large (100 mm diameter) beams

- **12-meter reduced-scale transport experiments confirm negligible diffraction losses and that ohmic losses are on the order of 1% per mirror at 30 THz.**

  - Transport to the NEH with **efficiency as high as 89%** is feasible!

Current and Future Directions

- **Currently, we are conducting a similar 12-m test at 3 THz wavelengths using a THz quantum cascade laser.**



3 THz beam focused after 4 meters of transport

(further transport requires enclosed / dry-air purged system)

- **Future tests: Transport the 3 THz beam over a 25 meter distance using 4" custom parabolic mirrors with 3 meter focal lengths in a purged environment.**

- **Further numerical studies:**
  - Considerations beyond 10% bandwidth
  - Model transport using theoretical THz emission profile from wiggler

Acknowledgments

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Alternate waveguide strategy for extended transport to the Far Experimental Hall:
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