INSTITUTE FOR RESEARCH IN ELECTRONICS & APPLIED PHYSICS

Simulation of High-Power Tunable Laser Pulse Driven Terahertz Generation in Corrugated Plasma Waveguides*

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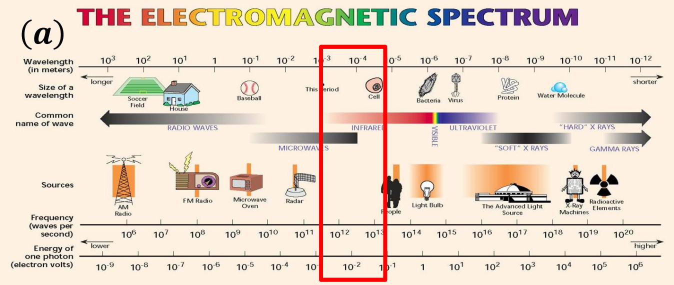
*Supported by DoE and NRL

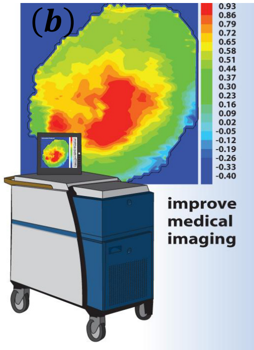
Terahertz radiation and applications

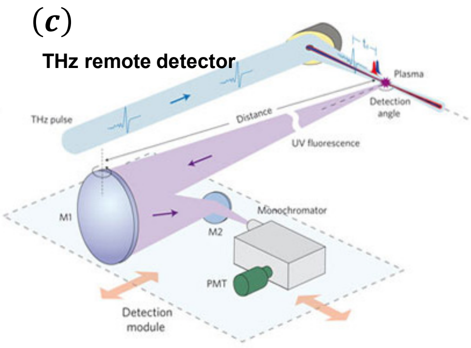
Frequency Range: between microwaves and infrared
300 GHz – 20 THz



Applications:

- ◆ Medical and biological imaging
- ◆ Probe nonlinear effects in materials
- ◆ Induce large transient currents
- ◆ Remote sensing, spectroscopy, etc.





picture (a) and (b) courtesy: Opportunities in THz Science, report of DOE-NSF-NIH workshop, 2004

picture (c) courtesy of J. Liu, Nature Photonics, 2010

Pulsed Terahertz Sources

- Large scale facilities via synchrotron or transition radiation

- Small-scale, table-top sources based on:
  1. Laser-solid interaction, ~ μJ/pulse[1]
  2. Transition radiation electrons passing from plasma to vacuum, ~ 100 μJ/pulse[2]
  3. Ionization by two-color laser pulses, ~ 5 μJ/pulse[3]
  4. Laser driven ion accelerator on thin metal foil targets, >460 μJ/pulse[4]

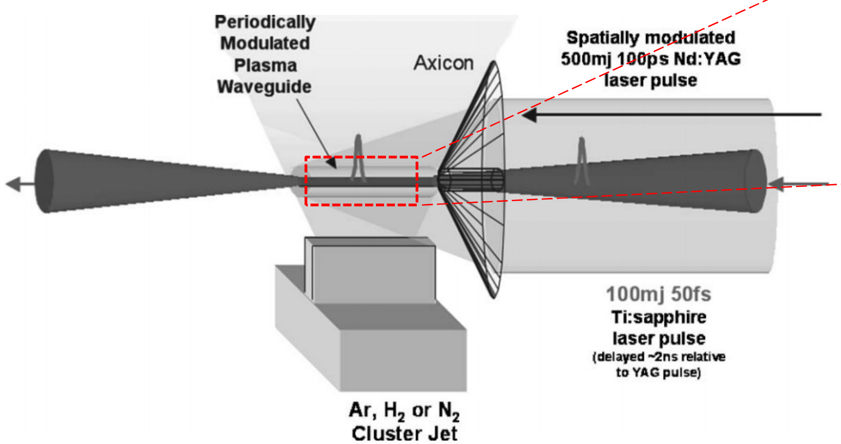
1. E. Budiarto et al. IEEE J. Quantum Electron. **32**, 1839 (1996).
2. W. P. Leemans et al. Phys. Rev. Lett. **91**, 074802 (2003).
3. K. Y. Kim et al. Nat. Photonics **2**, 605 (2008).
4. A. Gopal et al. Phys. Rev. Lett. **111**, 074802 (2013).

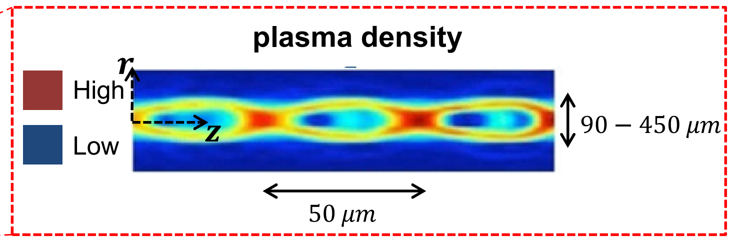
- Our scheme[5]:
  - miniature corrugated plasma channels[6] (period λ_m ~ 50 μm)
  - phase matching
  - possibility of high conversion of optical laser pulse energy to THz.

5. T. M. Antonsen et al. Phys. Plasmas **14**, 033107 (2007).
6. B. Layer et al. Phys. Rev. Lett. **99**, 035001 (2007).

THz generation in corrugated plasma waveguides

Channel Formation





B. Layer et al. Phys. Rev. Lett. **99**, 035001 (2007)
G. Hine et al. Opt. Lett. **41**, 3427 (2016)

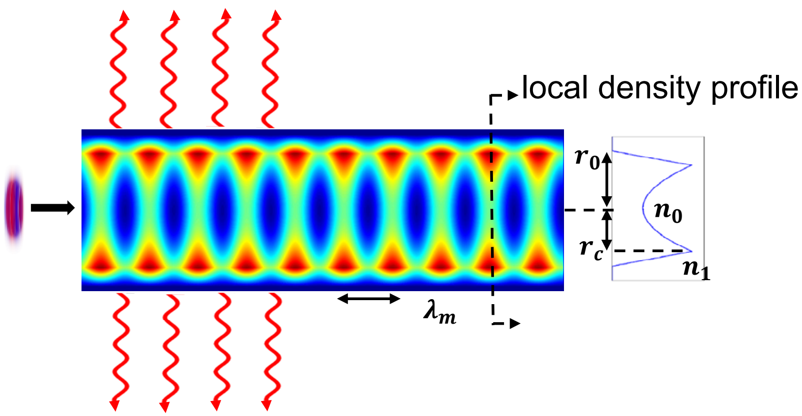
Channel Formation: a radially modulated heater pulse is line focused onto a cluster jet

- ➡ plasma hydrodynamically expands
- ➡ periodic density structure forms by modulating optical heating or neutral gas density

THz Generation: A second laser pulse drives ponderomotive currents which act as a source for the terahertz radiation.

Slow wave phase matching process

corrugated plasma waveguide



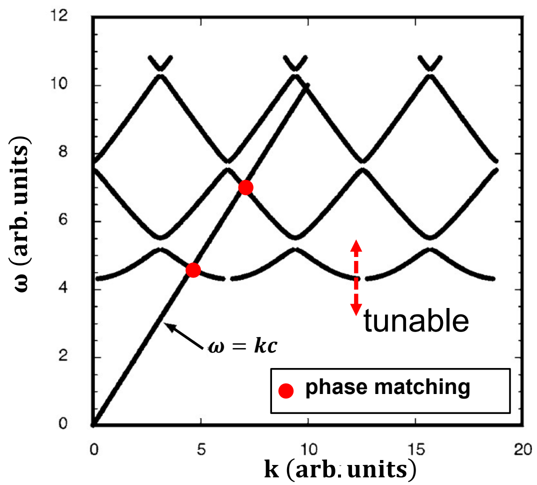
THz radiation

- coherent spectrum with narrow or broad band channel modes depending on laser intensities
- lateral emission, tunable

Why modulated plasma channels?

- no modulations, superluminal EM modes
- corrugations enable phase matching: slow wave structures

Dispersion Relation

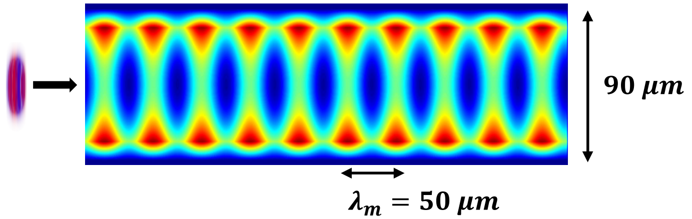


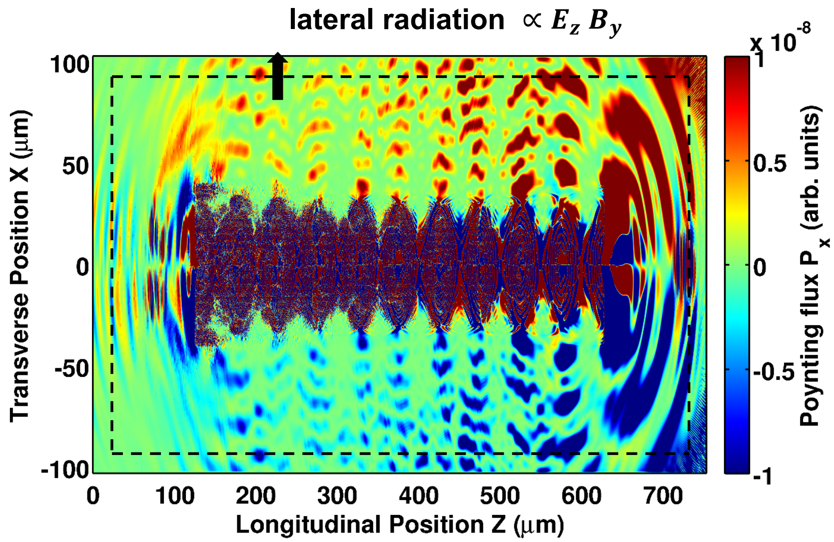
Particle-in-cell (PIC) simulations of THz generation

Full PIC simulations conducted in 2D planar geometry with turboWAVE (D. Gordon, NRL)

Radiated power diagnosed in lab frame:

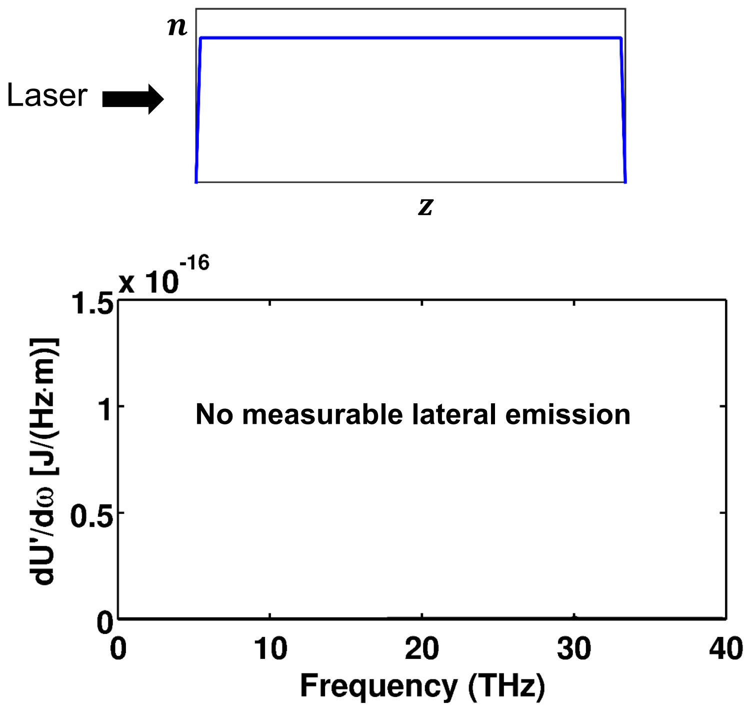
Poynting flux through prescribed surface: forward, backward and lateral radiation



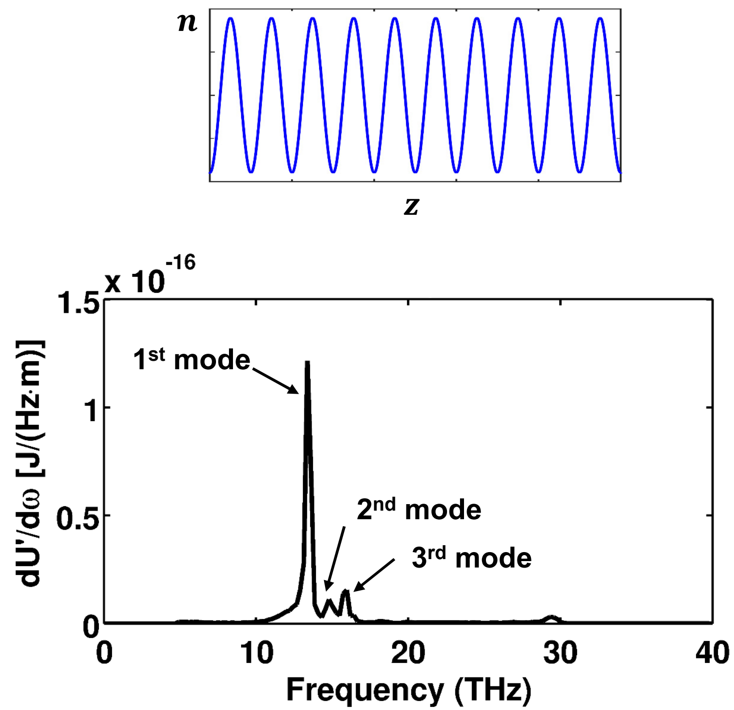


Slow Wave Phase Matching enables lateral THz emission

unmodulated, uniform plasma



axially modulated plasma channel

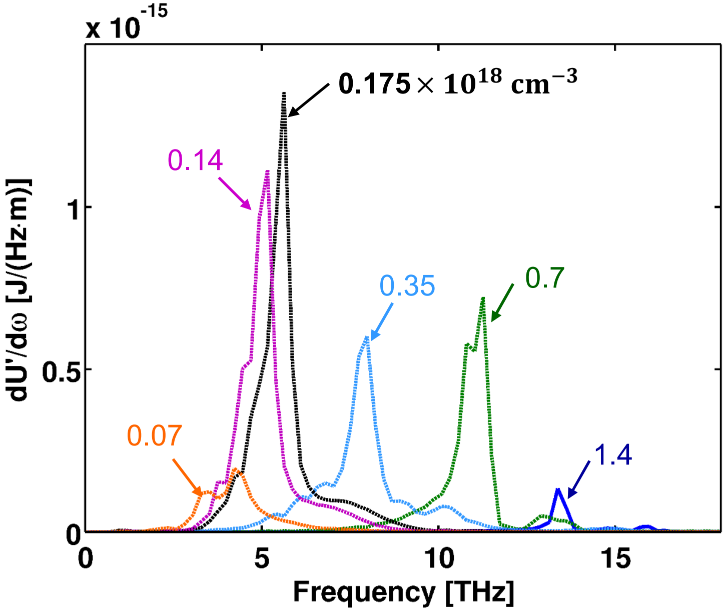


Maximizing THz generation in this mechanism

- vary plasma density
- vary laser intensity
- vary pulse duration
- try different channel structures

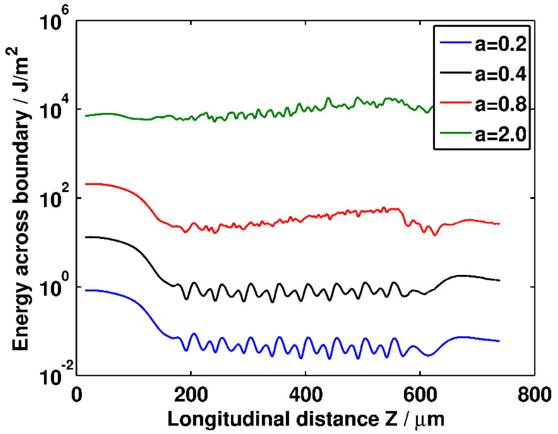
THz dependence on plasma density

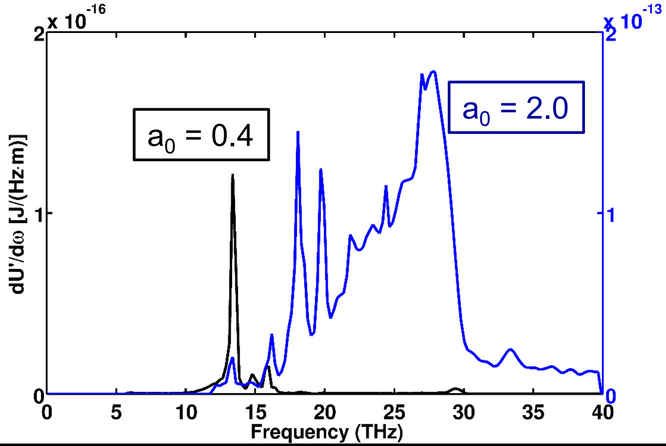
$a = 0.4$



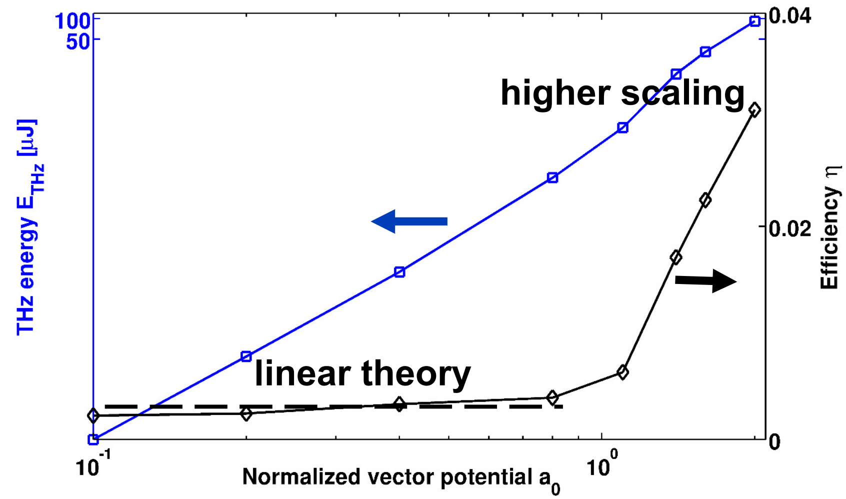
- At an averaged on axis density around 1.75×10^{17} cm^{-3}, the THz generation peaks at the fundamental frequency of 6.6 THz corresponding to the local maxima of coupling.
- More THz radiation escapes channel since the radial density barrier is lower.

THz dependence on laser intensity





$$\eta = \frac{E_{THz}}{E_{THz} + E_{PW}}$$



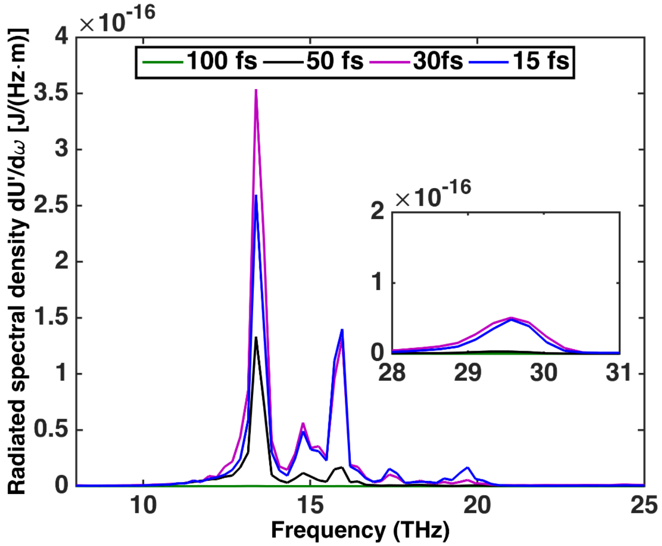
- In the linear regime, ponderomotively driven THz radiation scales as a_0^4.
- Higher modes generation for high laser intensities.
- Interference between higher order modes contributes to radiation enhancement.

THz dependence on laser pulse duration

Suppose the pulse has a temporal Gaussian profile

$$\exp[-(t-z/v_g)^2/\tau_p^2]$$

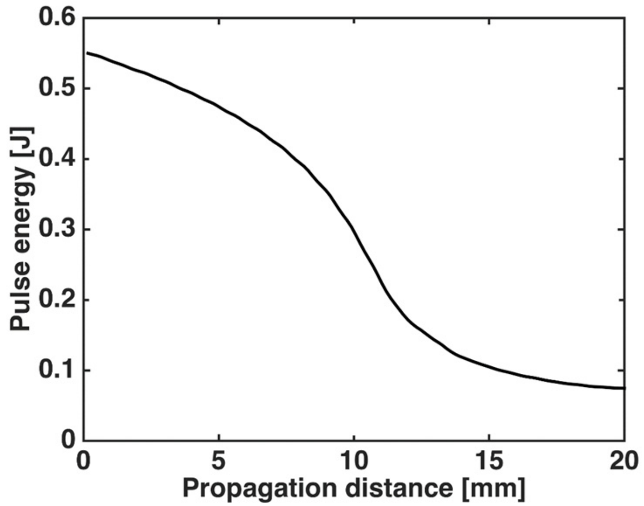
- The ponderomotive driver at a THz mode frequency ω scales as $\tau_p \exp(-\omega^2\tau_p^2/4)$.
- THz with frequency ω can be optimized by $\omega\tau_p \sim \sqrt{2}$, an evident enhancement can be expected by using an optimum pulse duration.

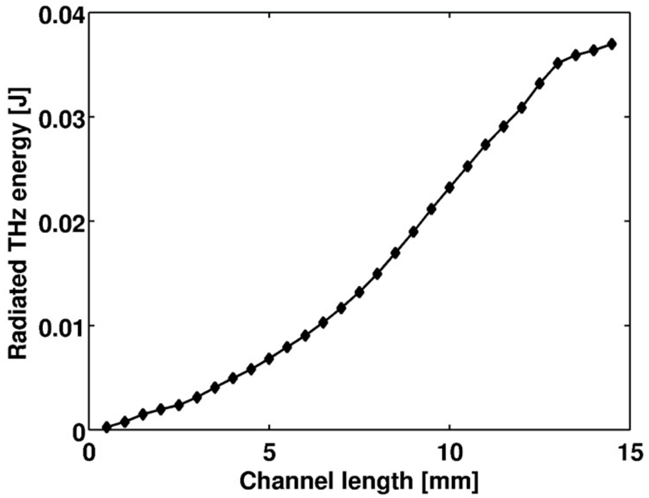


The fundamental mode is enhanced using a optimum pulse duration of 30 fs.
Higher order modes are enhanced using shorter pulse durations.

THz scaling with plasma channel length

$a_0 = 2.0$





Around 80% of the energy stored in the laser pulse is depleted within the propagation distance of 1.5 cm*

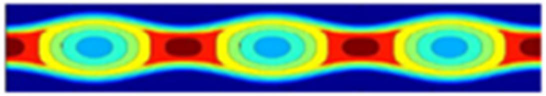
THz energy of 38 mJ is generated, more than 8% of the depleted pulse energy is converted into THz radiation.

THz exceeds the linear scaling with channel length.

*on NERSC, 1024 cores for 2 days

Different channel types

A new channel with maximum density in the center instead of at lateral edges

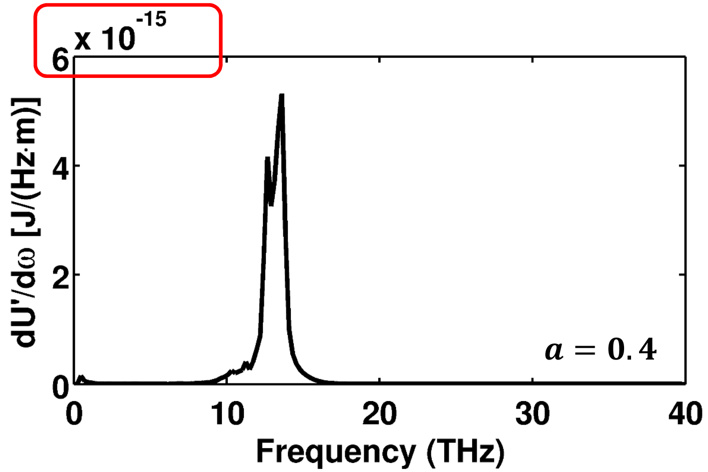


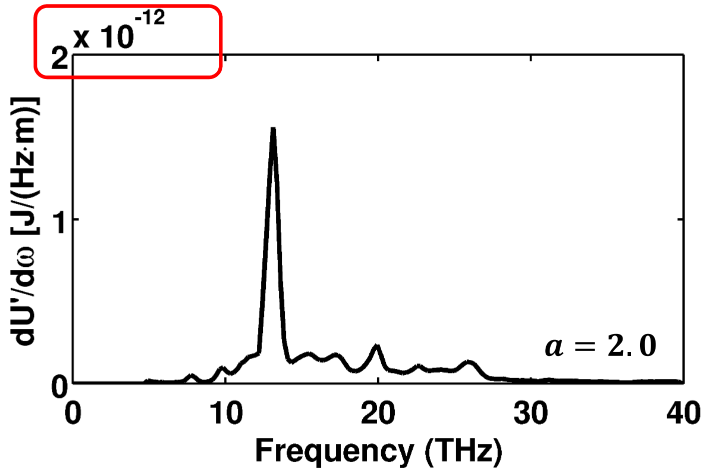
Pros:

- the spectrum is confined in a narrow band fundamental frequency even for the relativistic case
- a higher optical conversion efficiency can be achieved due to the excitation of a higher electron current

Cons:

- channel no longer remains a transverse parabolic structure for optical guiding (laser energy leaking)





Summary and conclusions

- Lateral THz emission is generated in corrugated plasma waveguides.
- THz spectrum is easily tunable.
- As an example, a fixed driver pulse (0.55 J) with spot size of 15 μm and pulse duration of 15 fs excites approximately 37.8 mJ of THz radiation in a 1.5 cm corrugated plasma waveguide with on axis average density of 1.4×10^{18} cm^{-3}.

Thank you!