Phase-matched scalable THz generation in two-color filamentation

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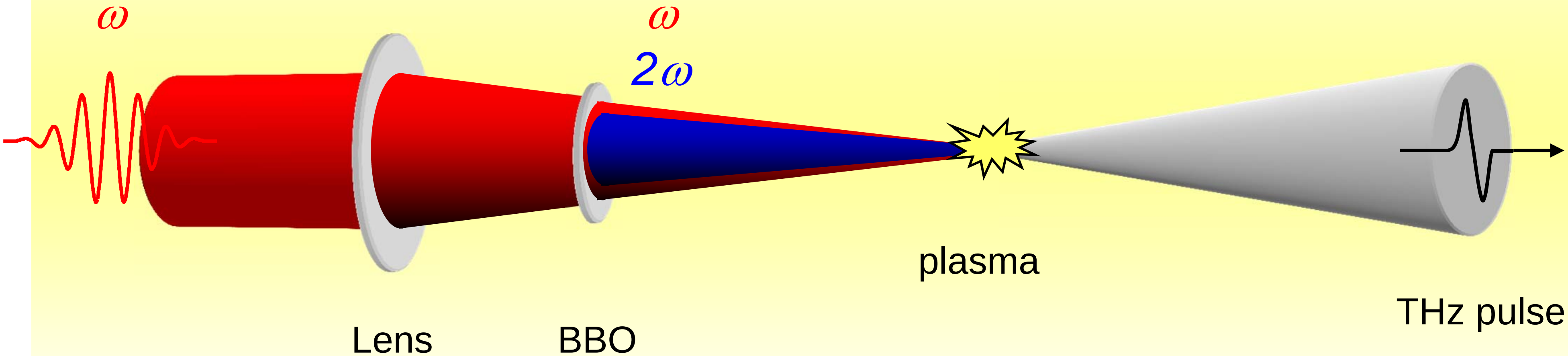
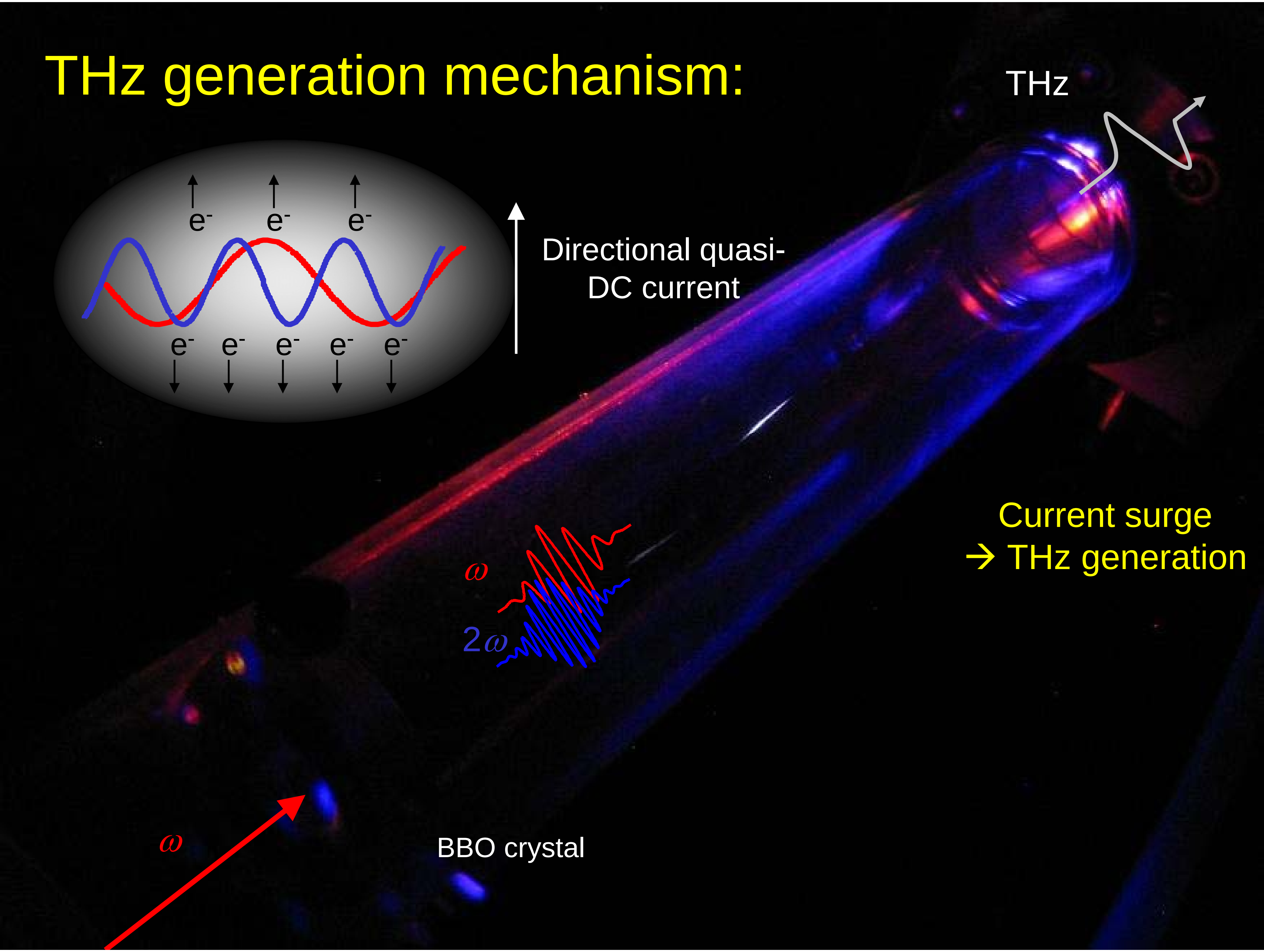
Outline:

- Background
  - THz generation via two-color laser mixing
  - Plasma current model
- THz generation with high-power lasers
- THz phase matching in long filaments
- Summary

Two-color photoionization:



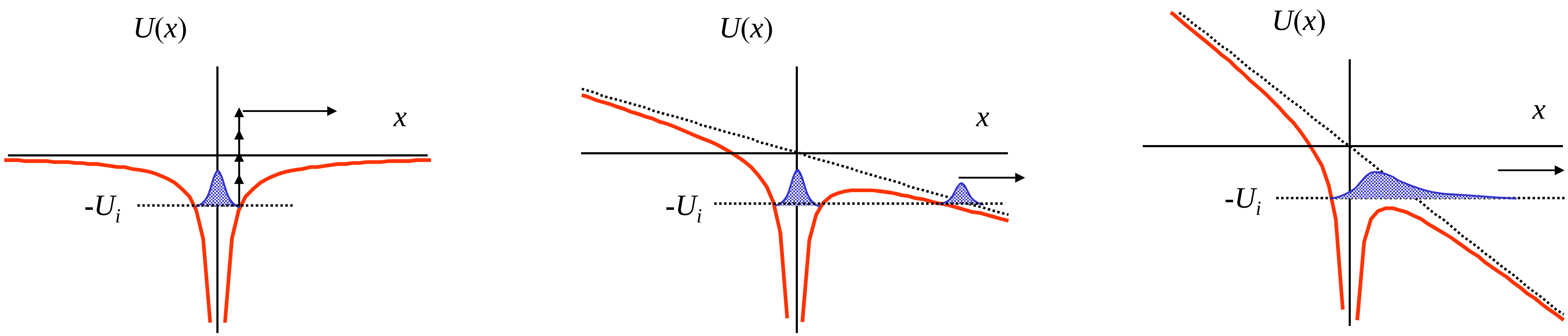
THz generation mechanism:



Tunneling ionization:

The nonlinearity arises from photoionization!

Multiphoton ionization | Tunneling ionization | Over-the-barrier ionization



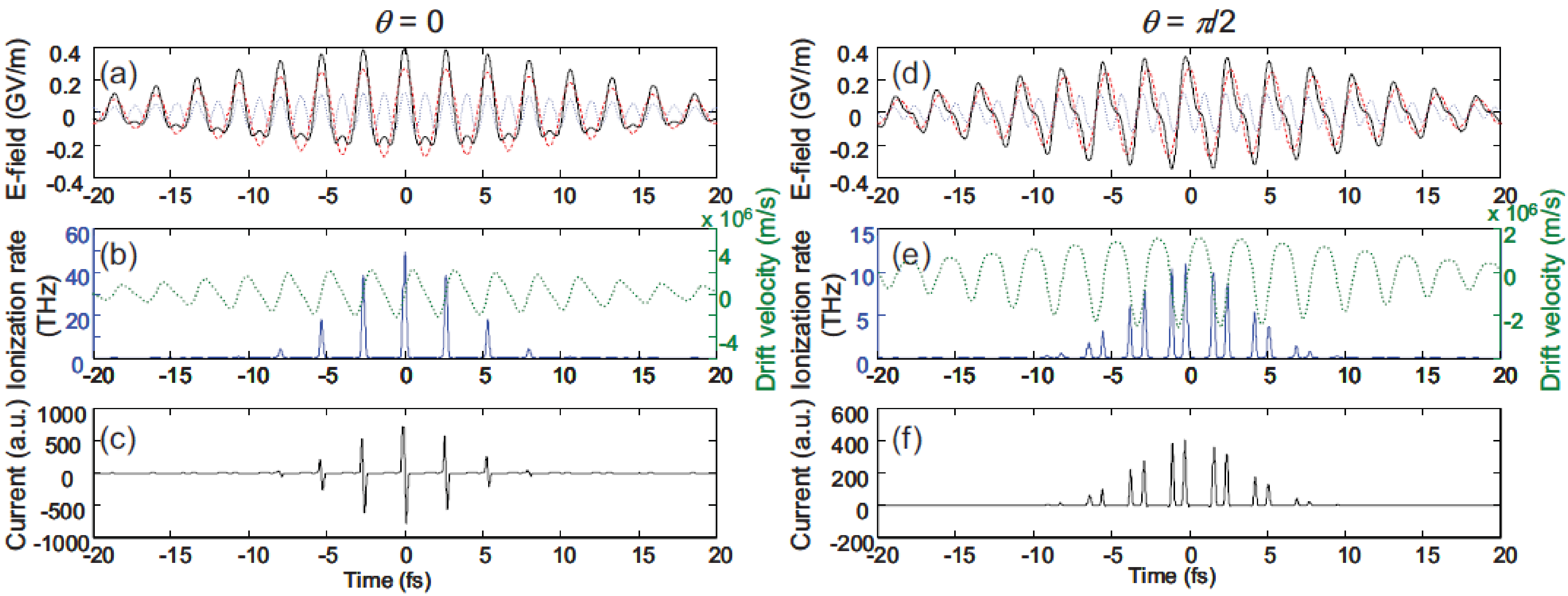
$I < 10^{12}$ W/cm^2 | $I > 10^{14}$ W/cm^2 | $I > 10^{16}$ W/cm^2

However, single-color photoionization can not effectively generate THz radiation.

Plasma current model I:

Laser field: $E_L(t) = E_\omega \cos(\omega t) + E_{2\omega}\cos(2\omega t + \theta)$

θ : relative phase

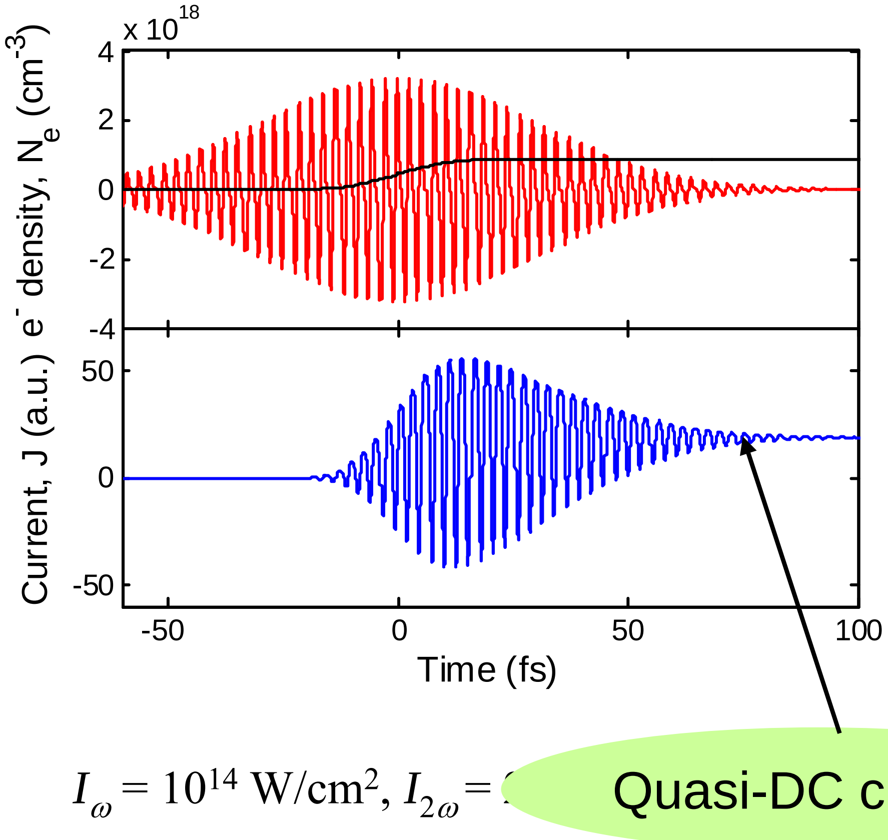


K. Y. Kim *et al*, Opt. Express **15**, 4577 (2007)
K. Y. Kim *et al*, IEEE J. Quantum Electron. **48**, 797 (2012)

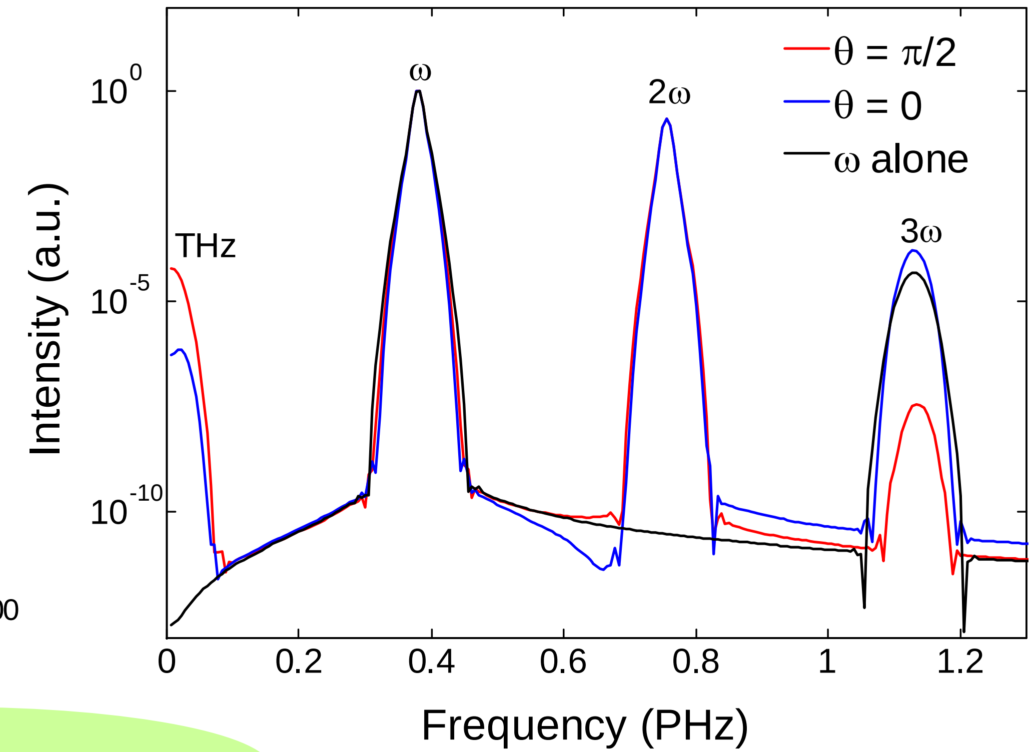
Plasma current model II:

Tunneling ionization and subsequent classical electron motion in the laser field are considered.

θ = π/2



Radiation spectrum



$I_\omega = 10^{14}$ W/cm^2, $I_{2\omega}$ =

Strong field approximation; ignored rescattering, collisional processes, plasma oscillations.

Plasma current model III:

The nonlinearity arises from extremely nonlinear tunneling ionization localized near the laser peaks.*

* Laser field: $E_L(t) = E_\omega \cos \omega t + E_{2\omega} \cos(2\omega t + \theta)$

* Ionization rate: $w(t) = 4\omega_a \left(\frac{E_a}{E_L(t)} \right) \exp\left(-\frac{2}{3} \frac{E_a}{E_L(t)} \right)$

* Plasma current: $J(t) = \left\langle eN_e(t) v(t) \right\rangle$

* THz field:

$$E_{\text{THz}} \propto \frac{dJ(t)}{dt} \propto f(E_\omega) \cdot E_{2\omega} \cdot \sin\theta$$

$$f(E_\omega) = \sqrt{\frac{E_a}{E_\omega}} \exp\left(-\frac{2}{3} \frac{E_a}{E_\omega} - 3\frac{E_\omega}{E_a} \right)$$

* $f(E_\omega)$ is highly nonlinear, not necessarily quadratic dominant.

More effects to consider:

- Ionization model:

  Tunneling vs multiphoton ionization

- Plasma current calculation:

  Semiclassical vs quantum-mechanical calculation

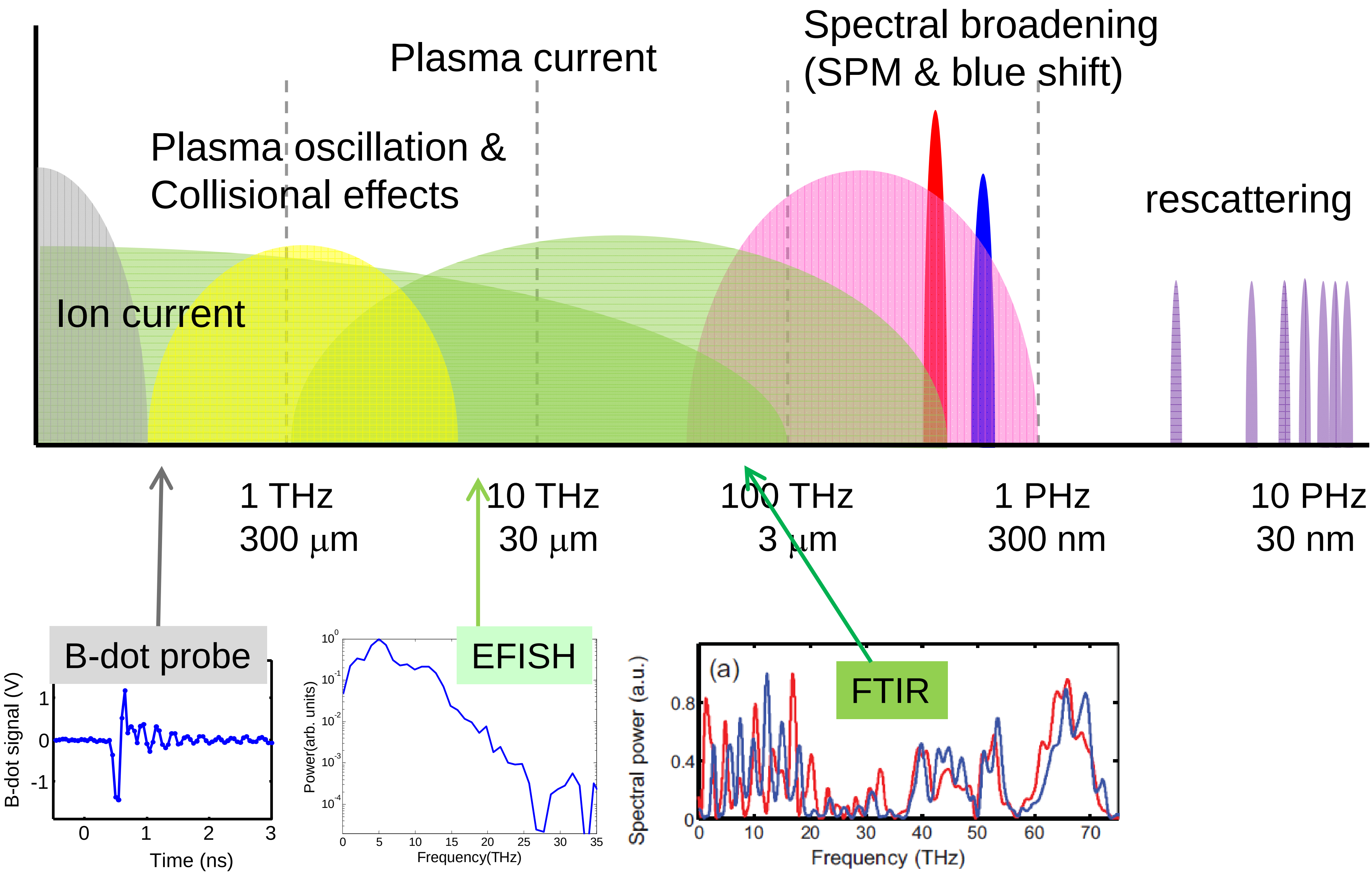
- Additional effects:

  Plasma oscillations, collisional (electron-ion, electron-neutral) effects, rescattering with parents' ions

- Propagation effects:

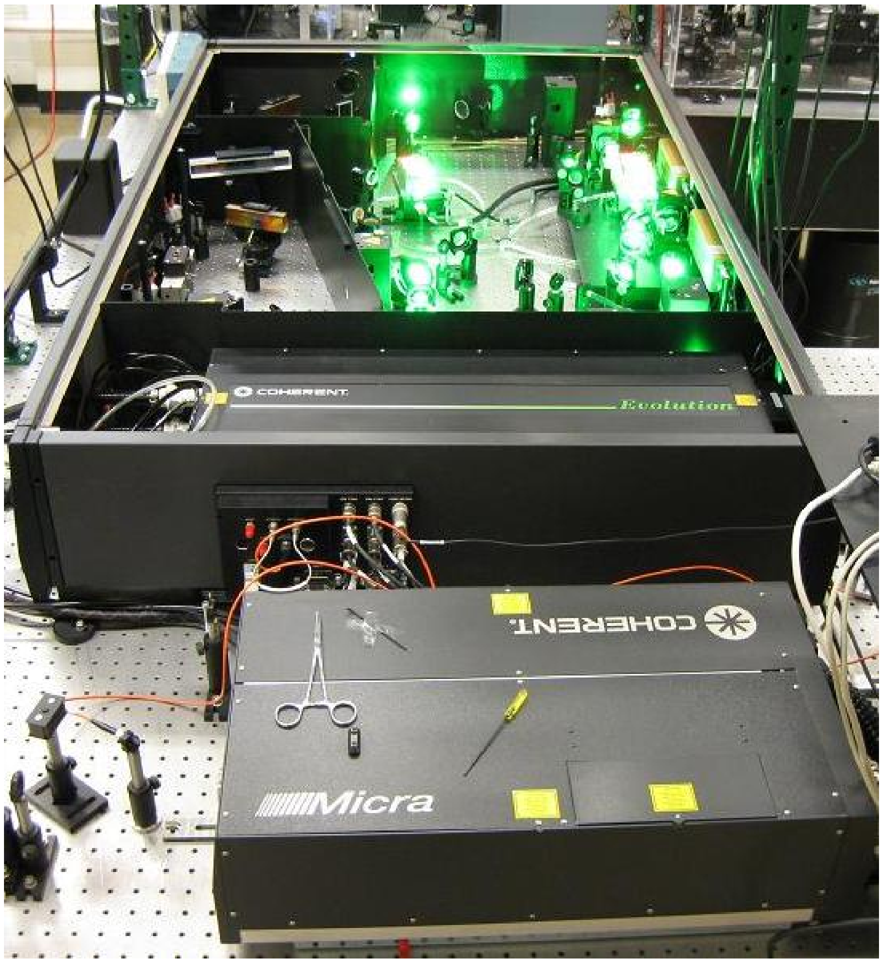
  Self- and cross-phase modulations, spectral shifting and broadening, Kerr-induced polarization rotation, phase- and group velocity walk-offs

Broadband EM generation & control:

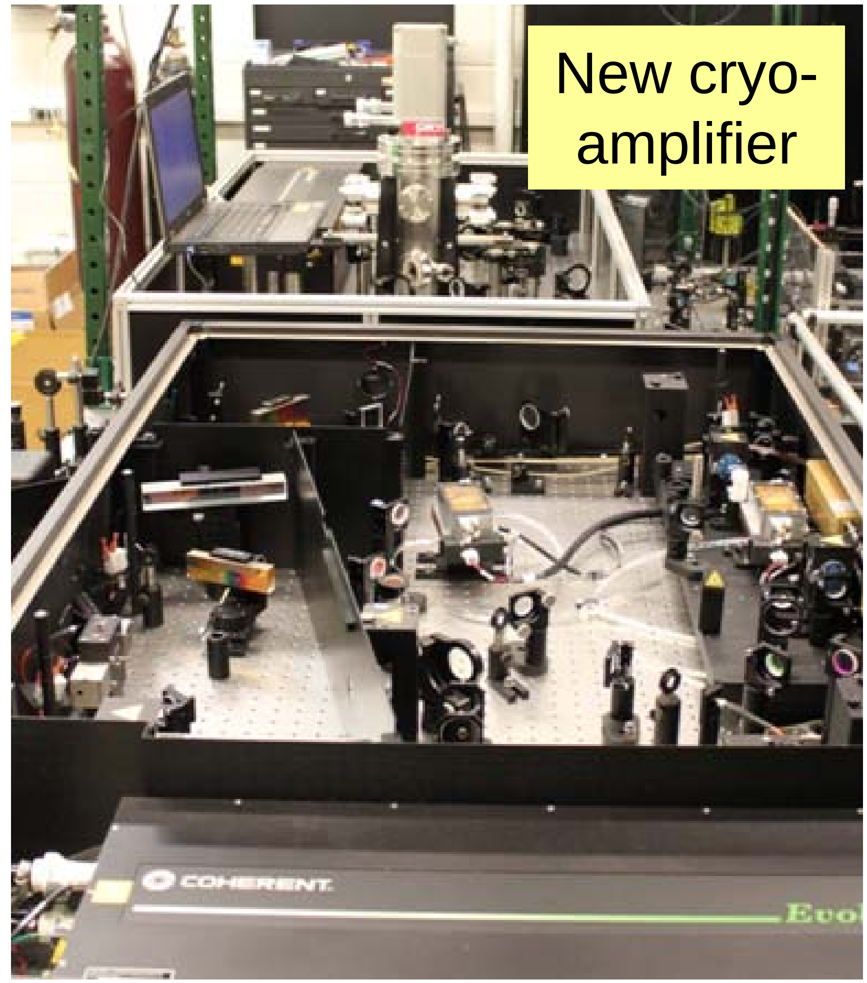


Laser upgrade @ Kim Lab:

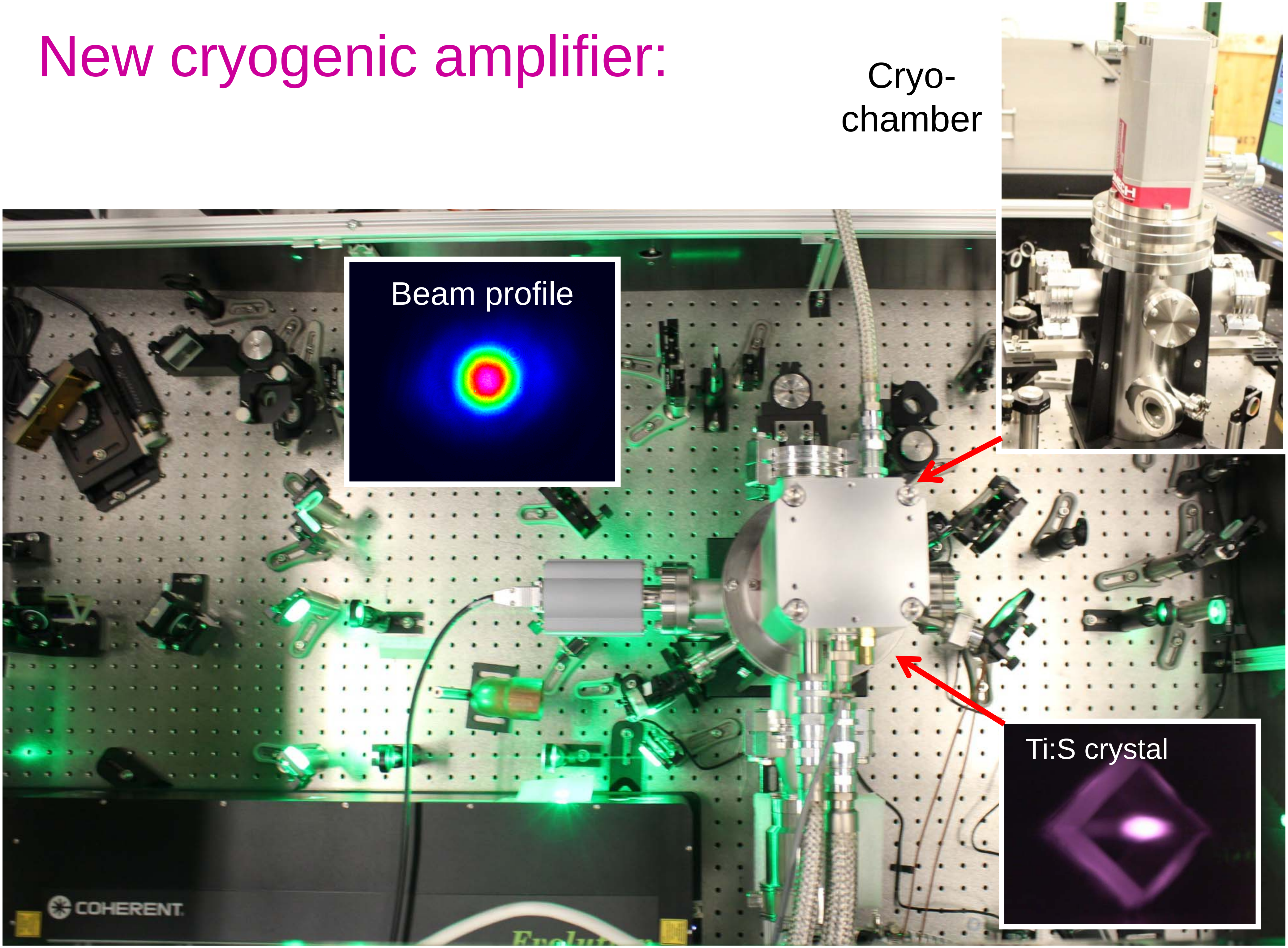
5 mJ, 25 fs, 1 kHz Ti:S laser



15 mJ, 1 kHz Ti:S laser
(Peak power ~0.6 TW)

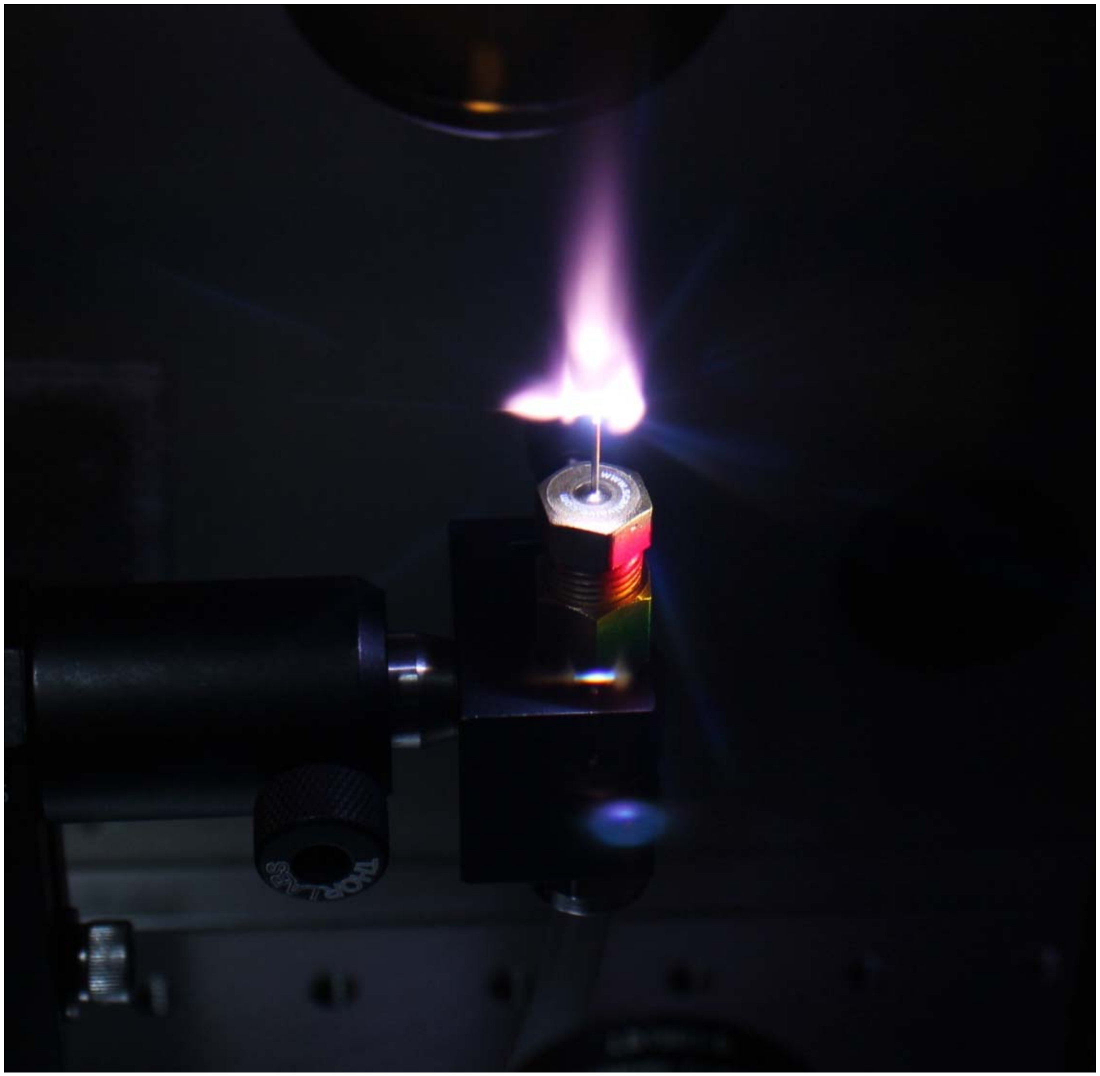


New cryogenic amplifier:

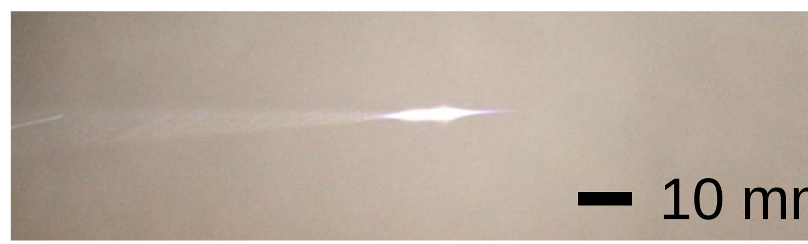


15 mJ laser interaction with gaseous targets

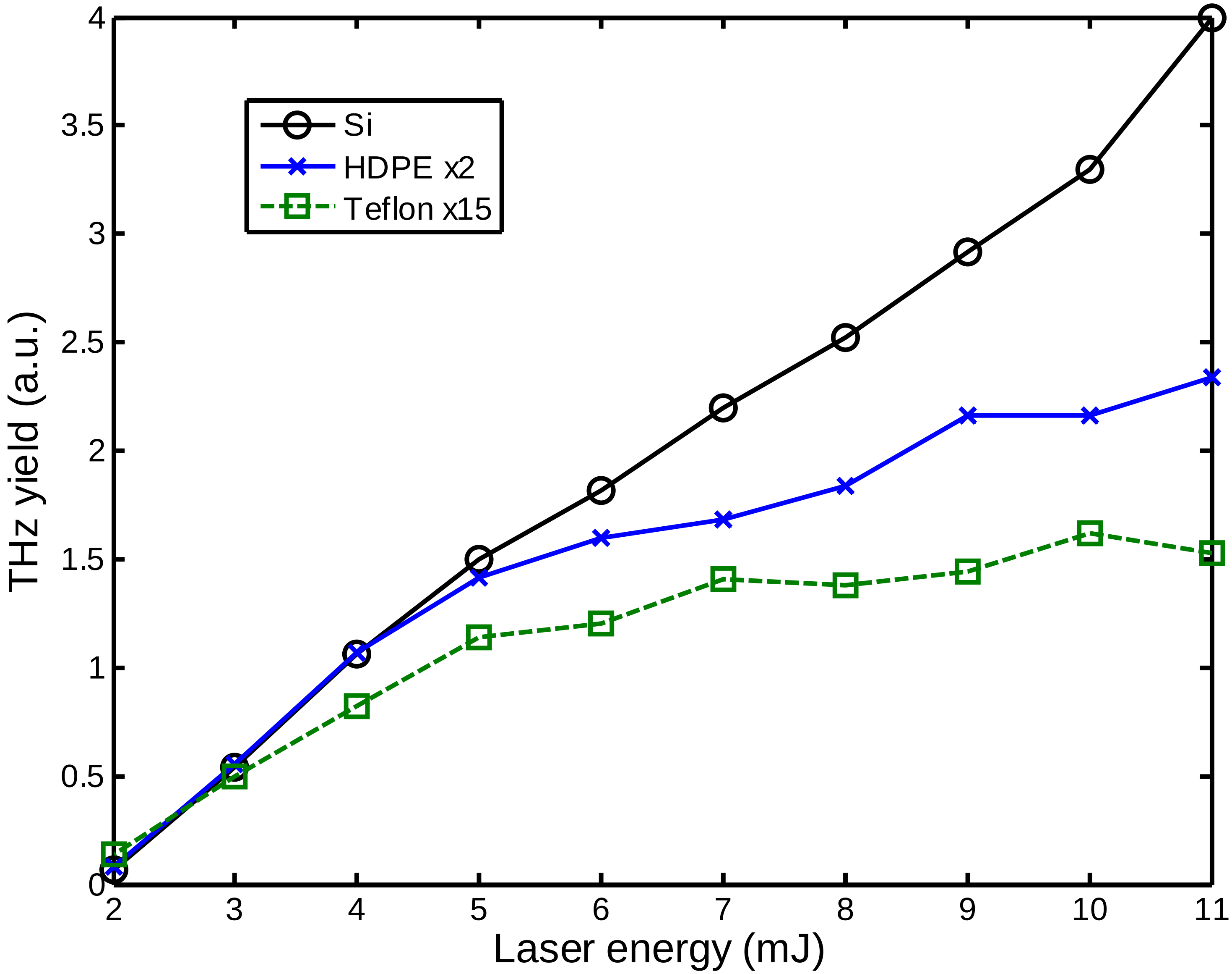
Interaction with Ar cluster gas jets



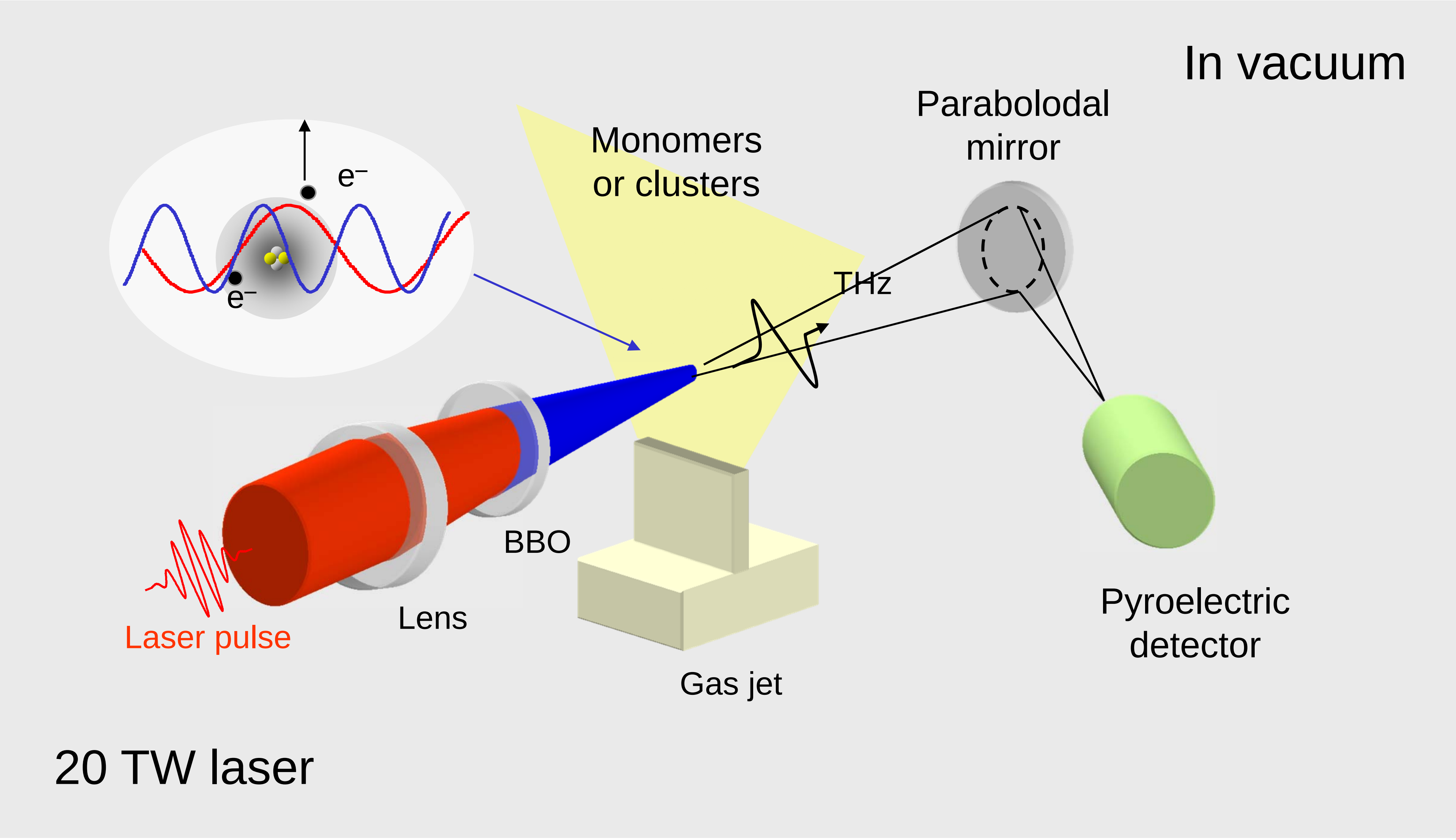
Filamentation in air



THz generation with 15 W laser @1 kHz:

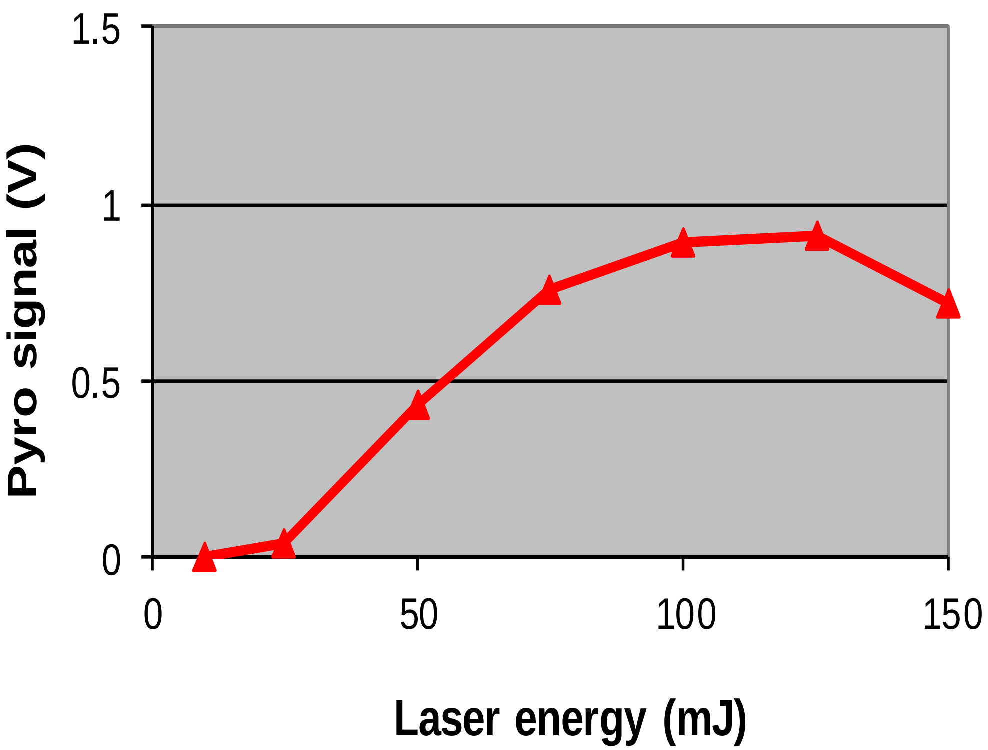


THz generation with 20 TW laser

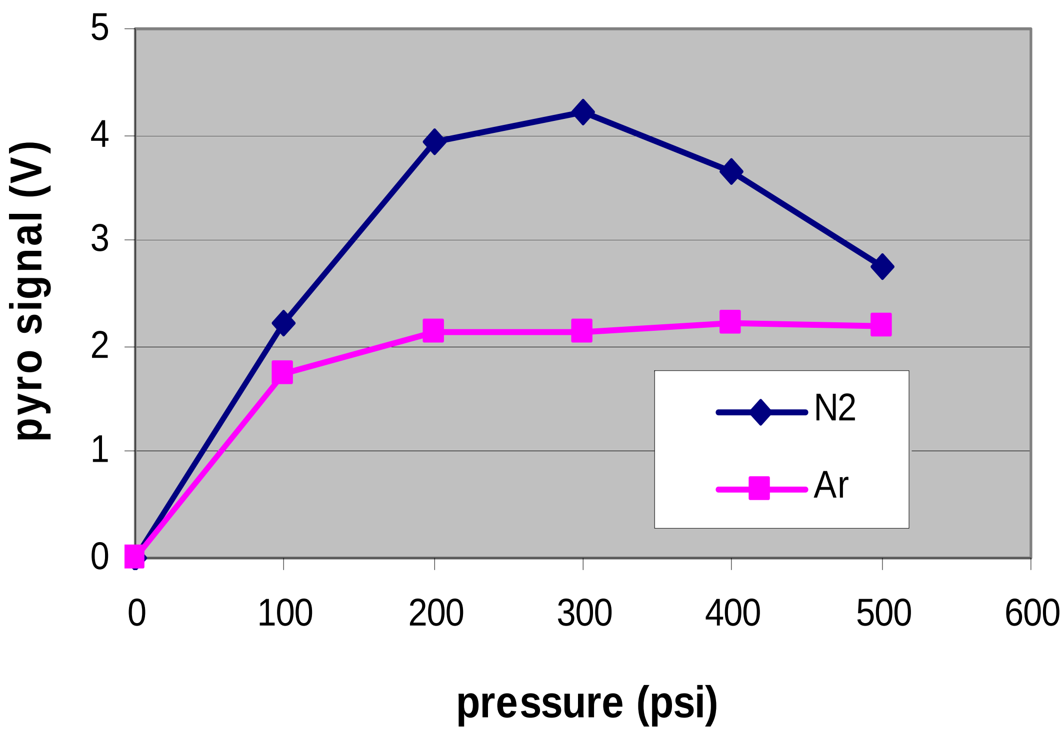


Experimental Result:

THz energy vs laser energy



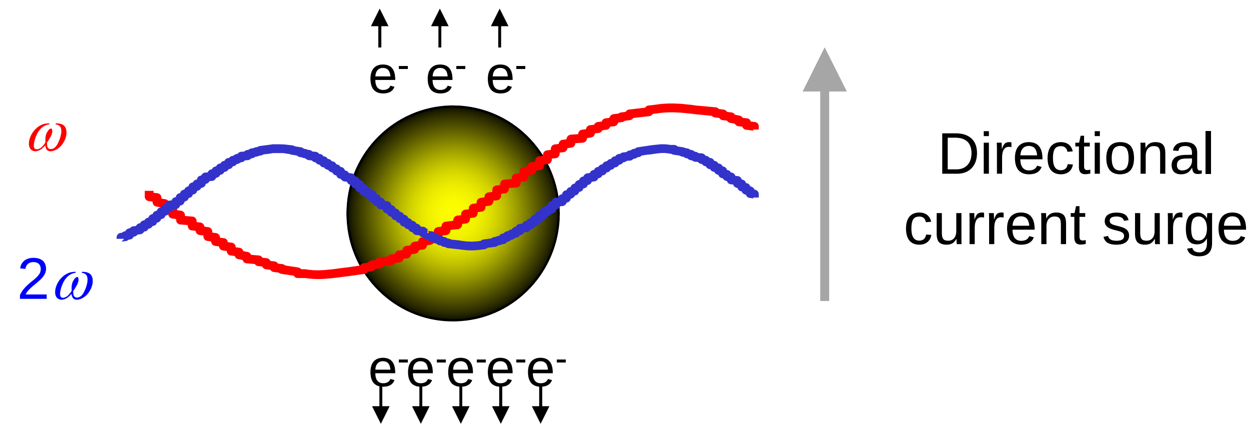
THz energy vs pressure



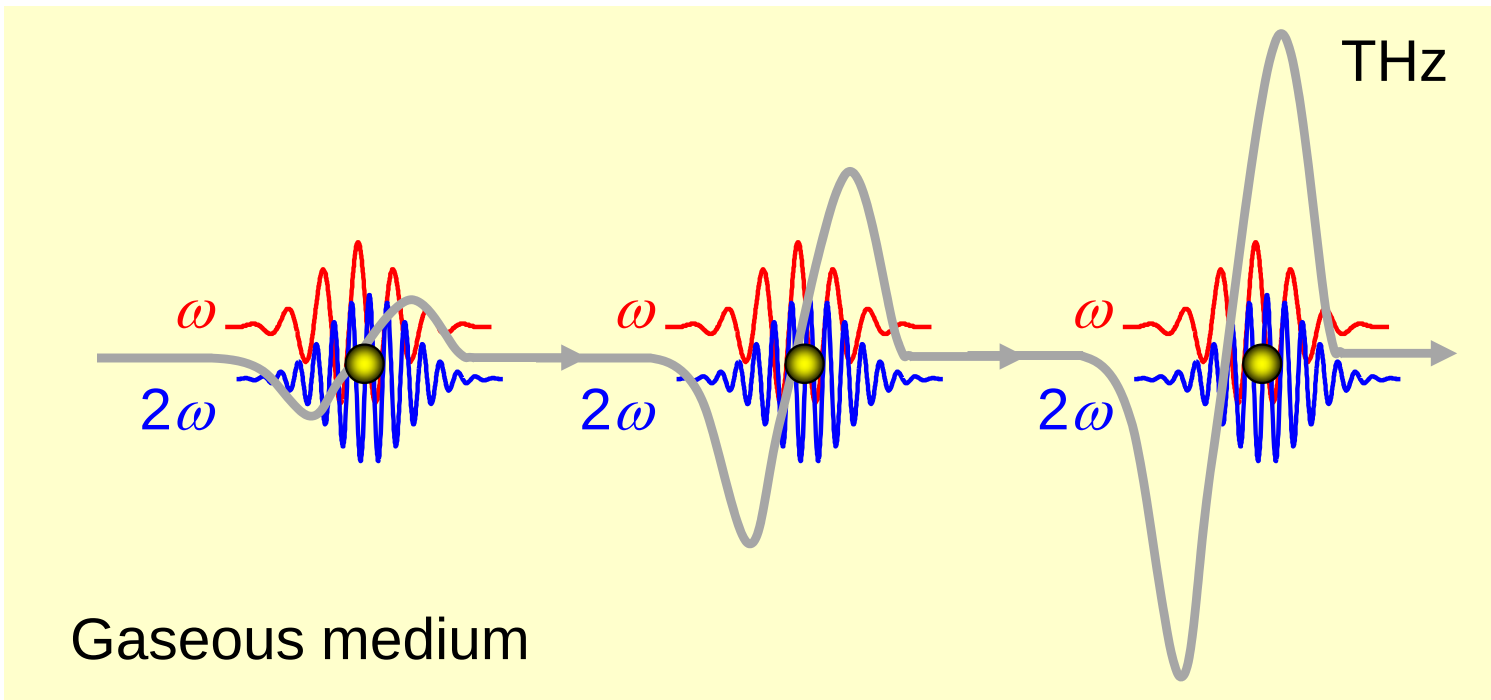
- Several microjoule THz radiation per pulse.
- THz energy saturation.
- Clusters provides less THz output.

Phase matching in THz generation:

Microscopic source



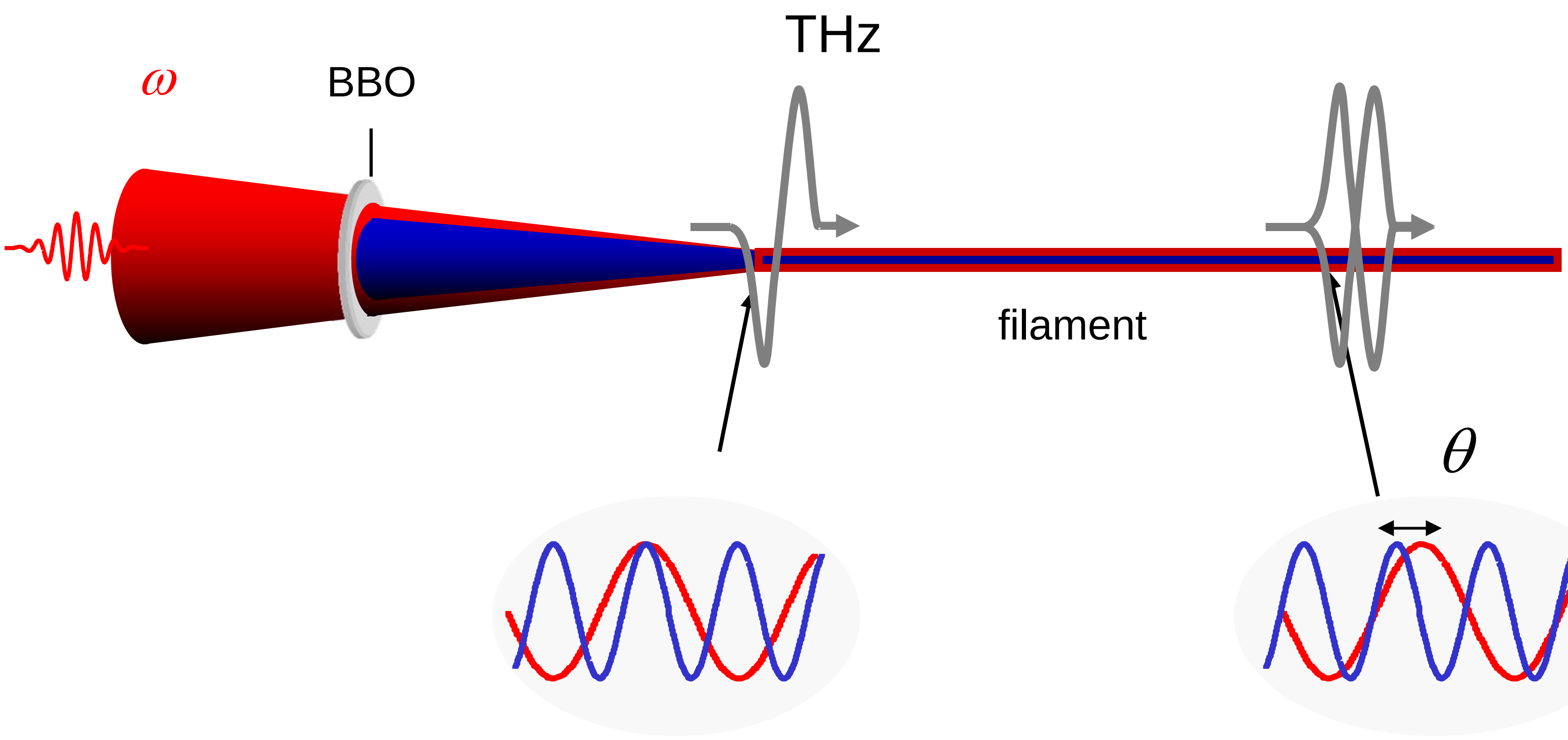
Macroscopic phase matching



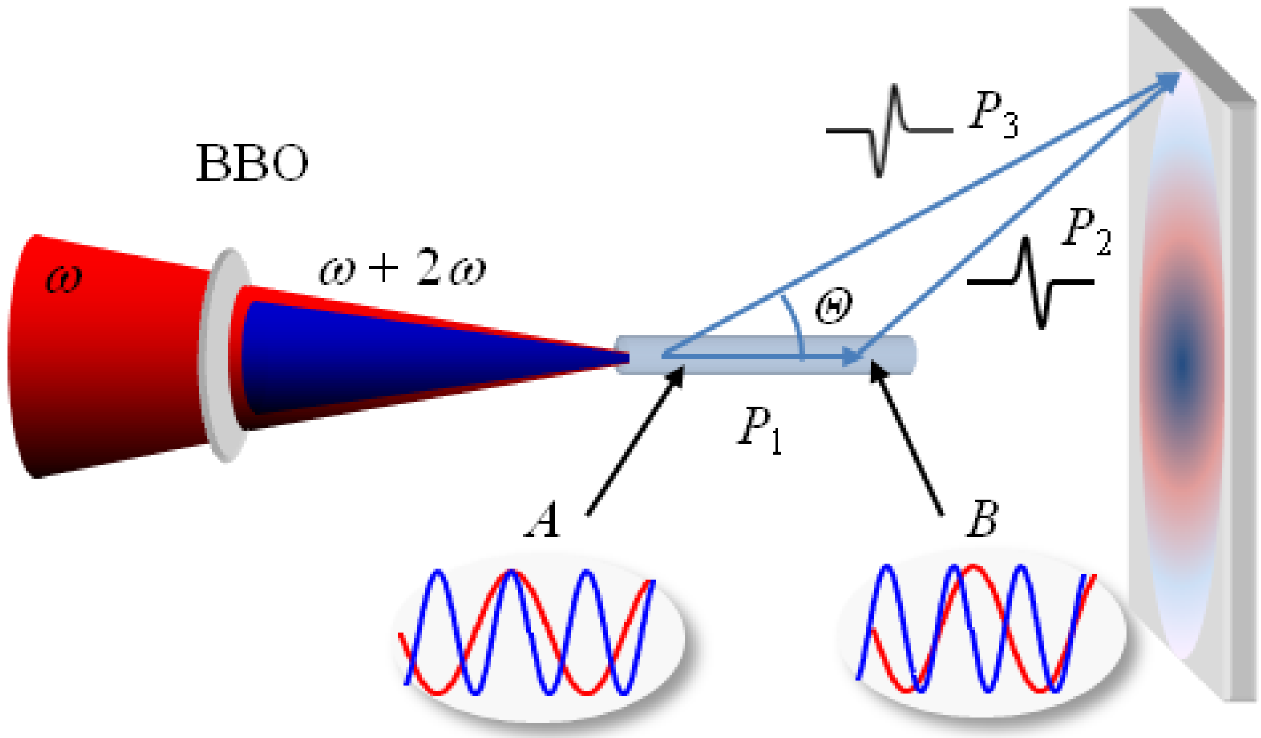
Dephasing between ω and 2ω:

This occurs due to different refractive indices at ω and 2ω in air and plasma

$$\theta = \omega[(n_{air,\omega} - n_{air,2\omega})L_1 + (n_{filament,\omega} - n_{filament,2\omega})L_2]/c + \theta_0$$



Phase matching in a long filament:

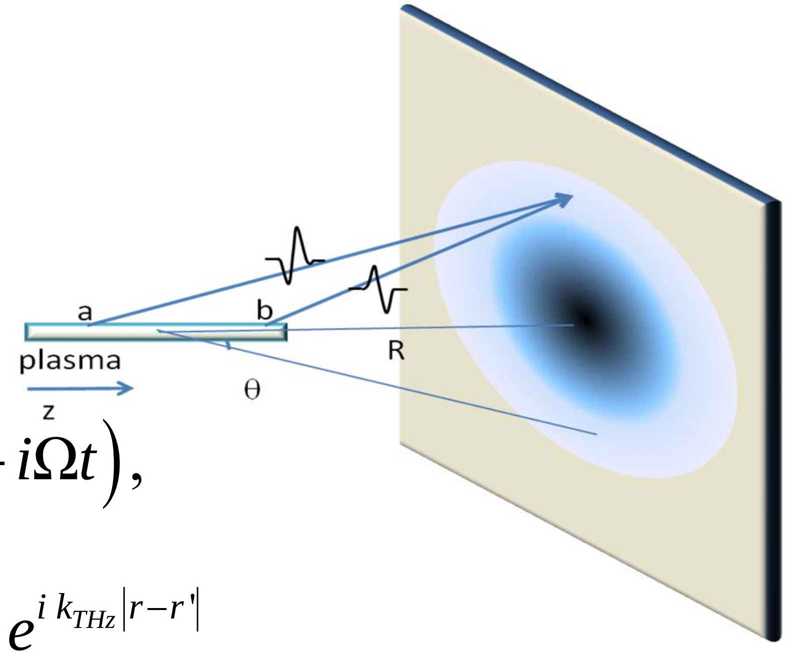


Condition for constructive interference:

$$\Delta l = P_3 - (P_1 + P_2) = (\mathrm{m} + 1/2)\Gamma$$

$$\cos\Theta \approx 1 - \Gamma/(2l_d)$$

THz phase matching:



Source:

$$\tilde{P}\left(r',\Omega\right) \propto \tilde{A}\left(r',\Omega\right)\sin\left(\theta(z')\right)\exp\left(in_g k_{THz} z' - i\Omega t\right),$$

THz far field:

$$E(r,\Omega) \propto \int_V d^3r' \frac{\tilde{P}\left(r',\Omega\right)e^{i\,k_{THz}|r-r'|}}{|r-r'|}$$

THz intensity:

$$\left|E\left(r,\Theta,\Omega\right)\right|^2 \propto \left|\tilde{A}\left(r',\Omega\right)\right|^2 \frac{(\pi a^2)^2 l^2}{r^2}\left(\kappa_1^2+\kappa_2^2+2\kappa_1\kappa_2\cos\left(2\theta_0+\pi\right)\right)\left(\frac{2J_1(\beta)}{\beta}\right)^2$$

$$\kappa_{1,2} = \frac{\sin(\alpha_{1,2})}{\alpha_{1,2}} \qquad \alpha_{1,2} = \frac{k_{THz} l}{2}\left(n_g \pm \frac{\Gamma}{2l_d} - \cos\left(\Theta\right)\right) \qquad \beta = \frac{2\pi a}{\lambda}\sin\left(\Theta\right)$$

$$\cos\left(\Theta_p\right) = 1 - \frac{\lambda}{2l_d}$$

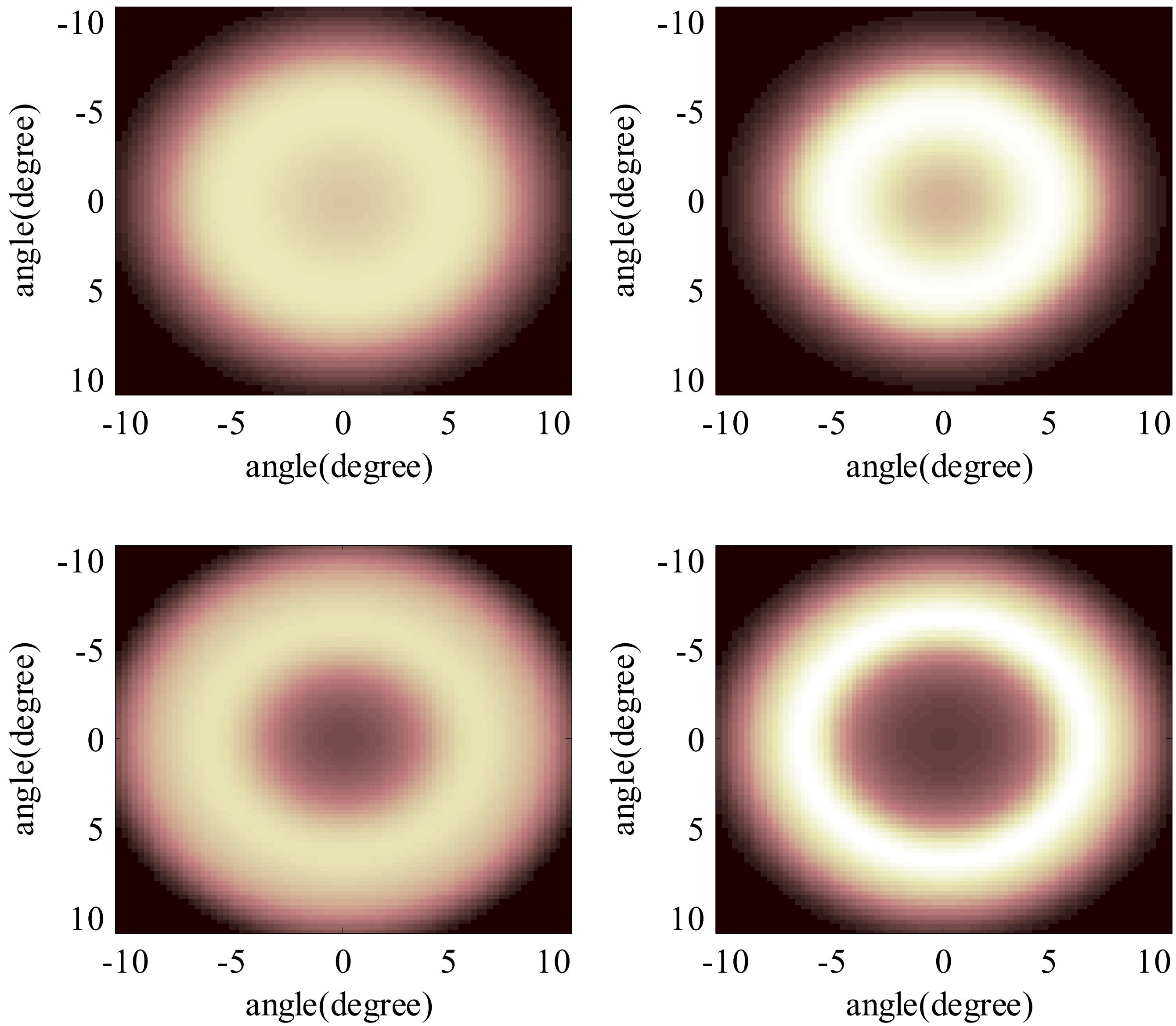
Simulated THz profiles:

0.1 ~ 1 THz

1 ~ 30 THz

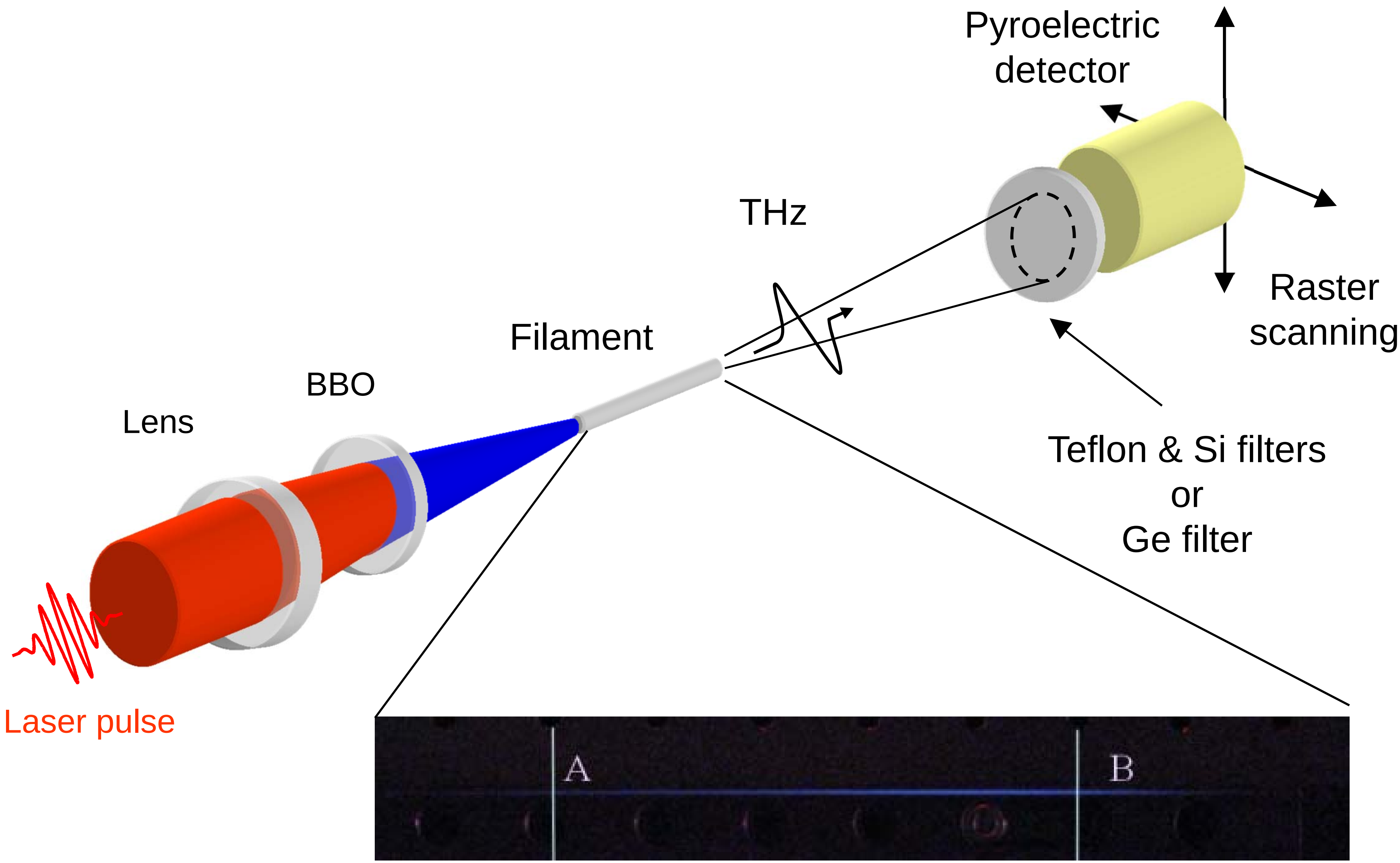
Short (~1 cm) plasma

Long (~3 cm) plasma



N_e ~ 3 ×10^{16} cm^{-3}

THz radiation profile measurement:



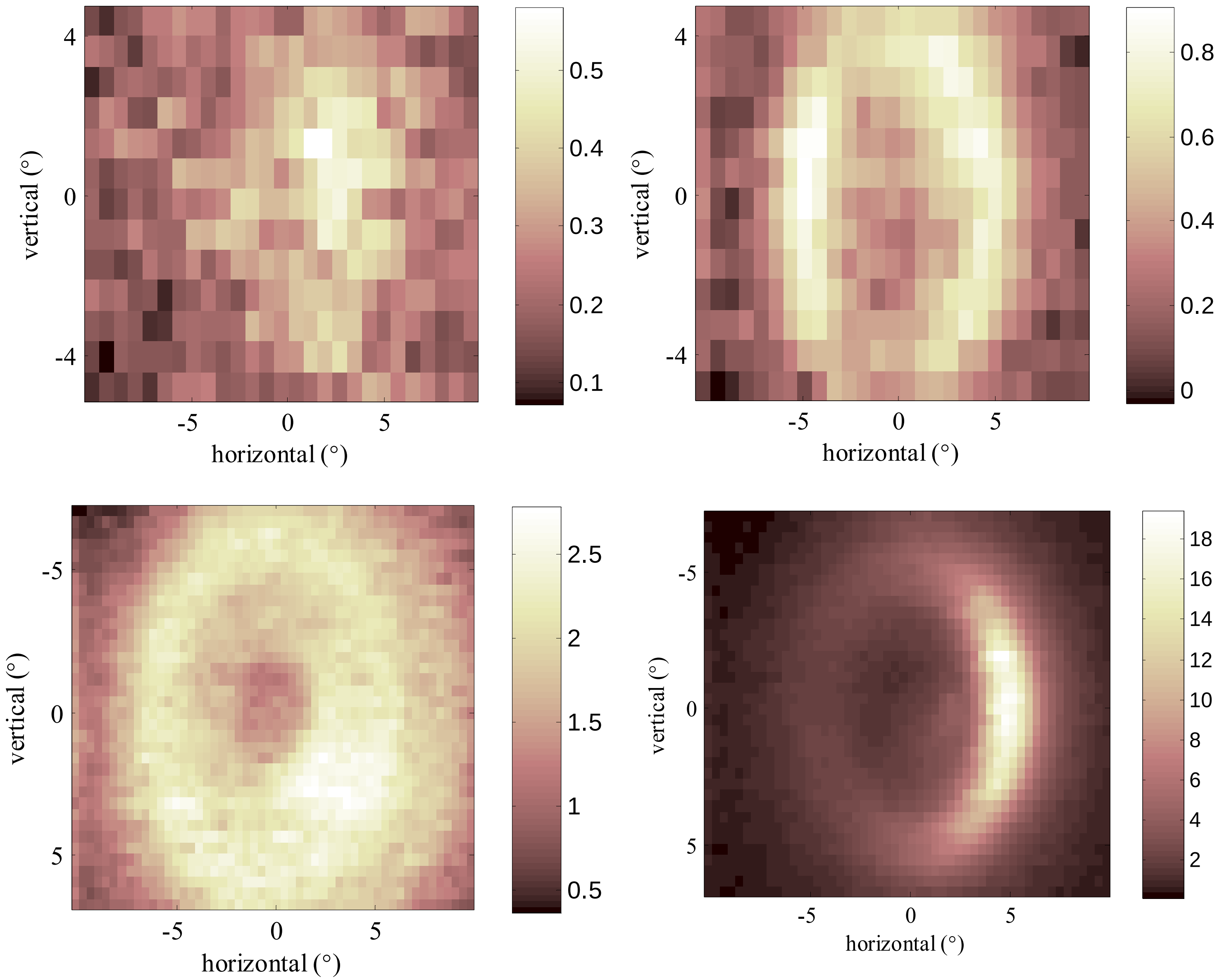
Measured THz profiles:

Low THz

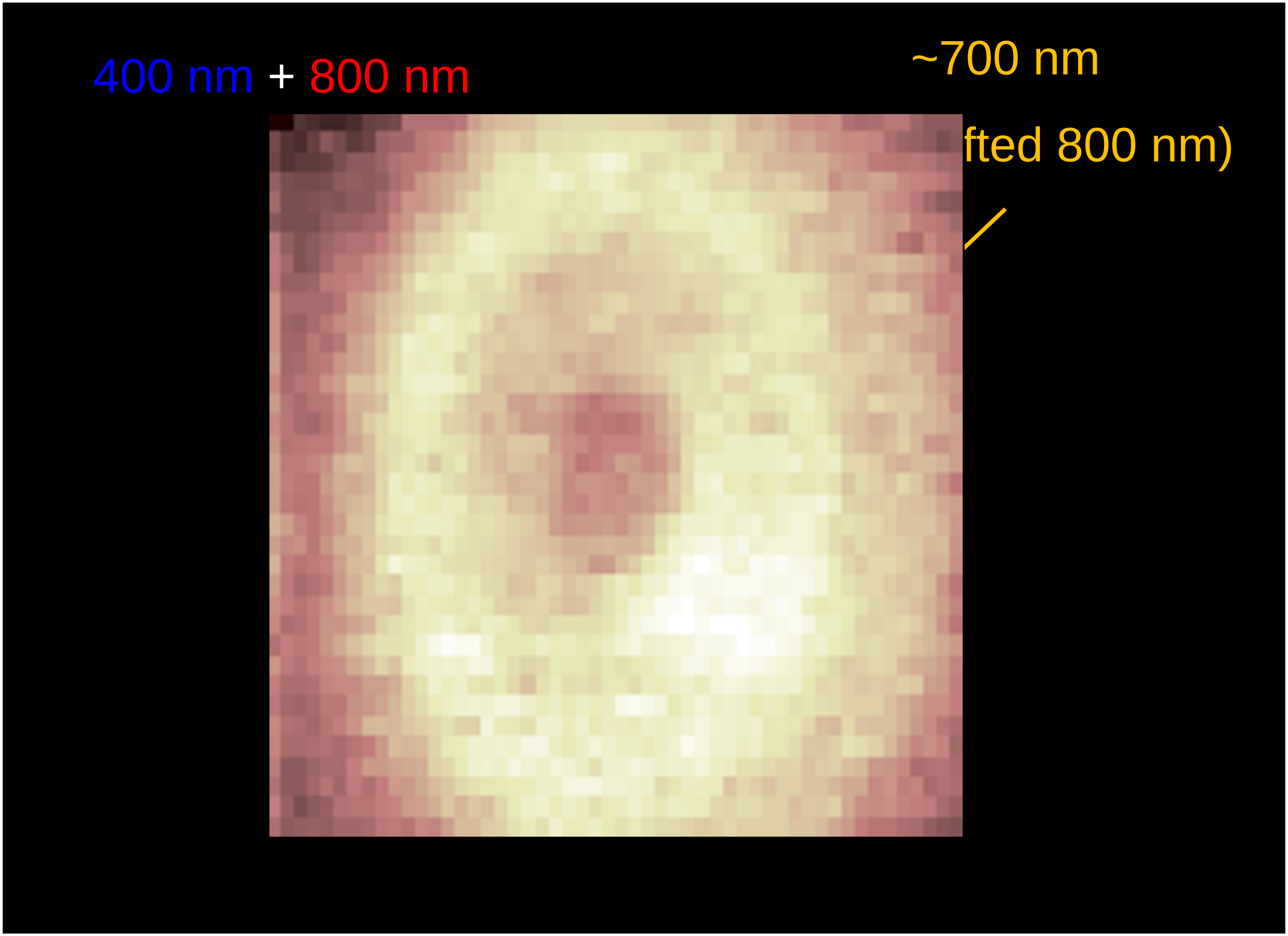
High THz

Short (<1 cm) plasma

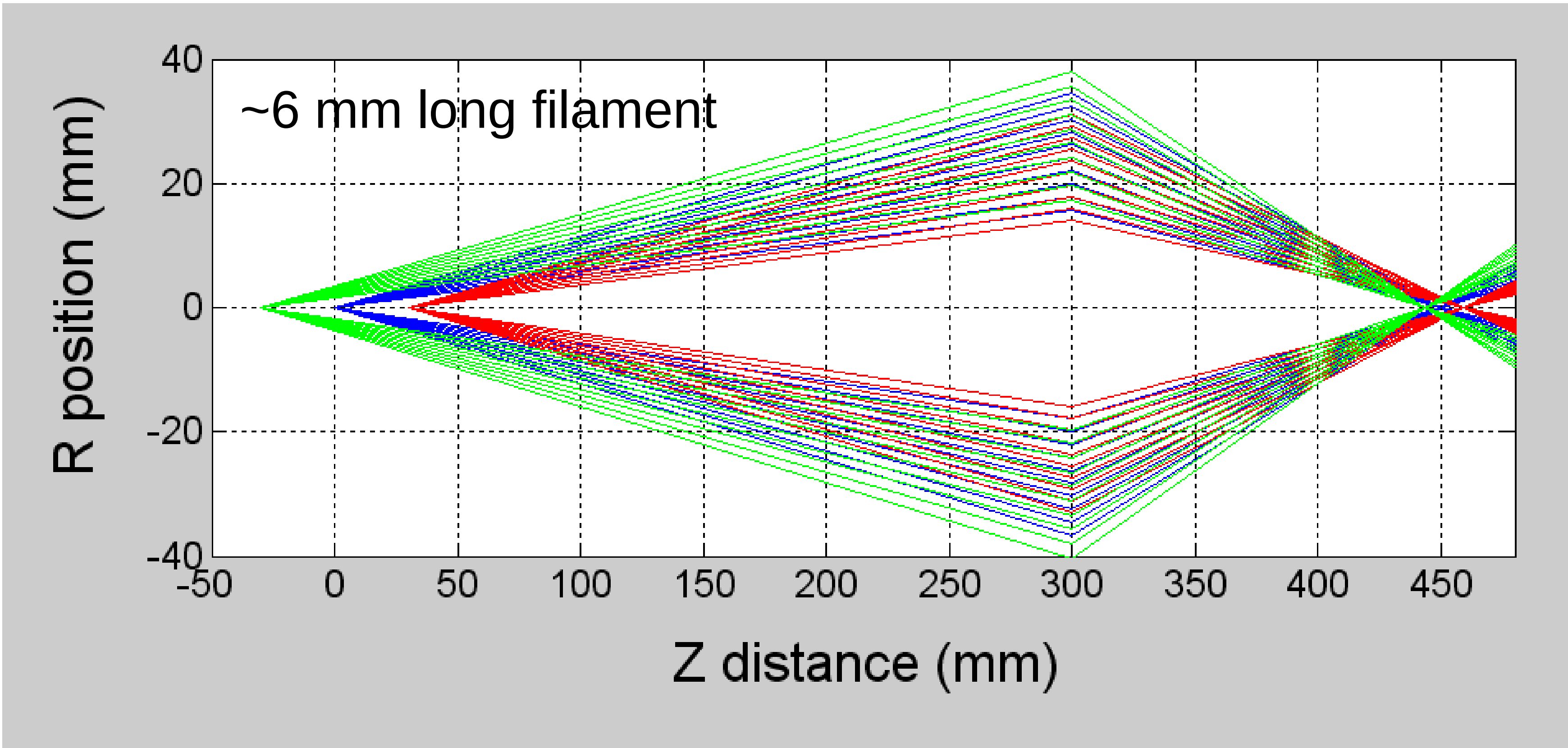
Long (>3 cm) plasma



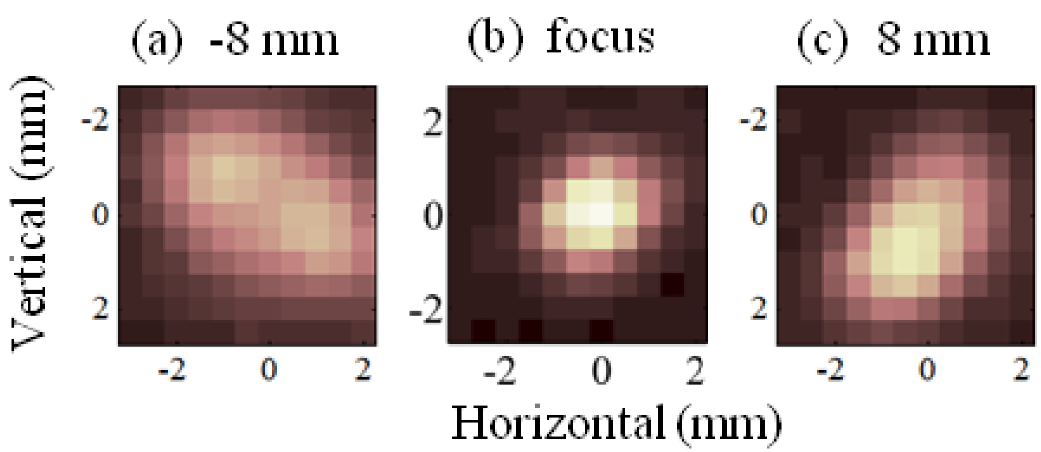
Measured optical and THz profiles:



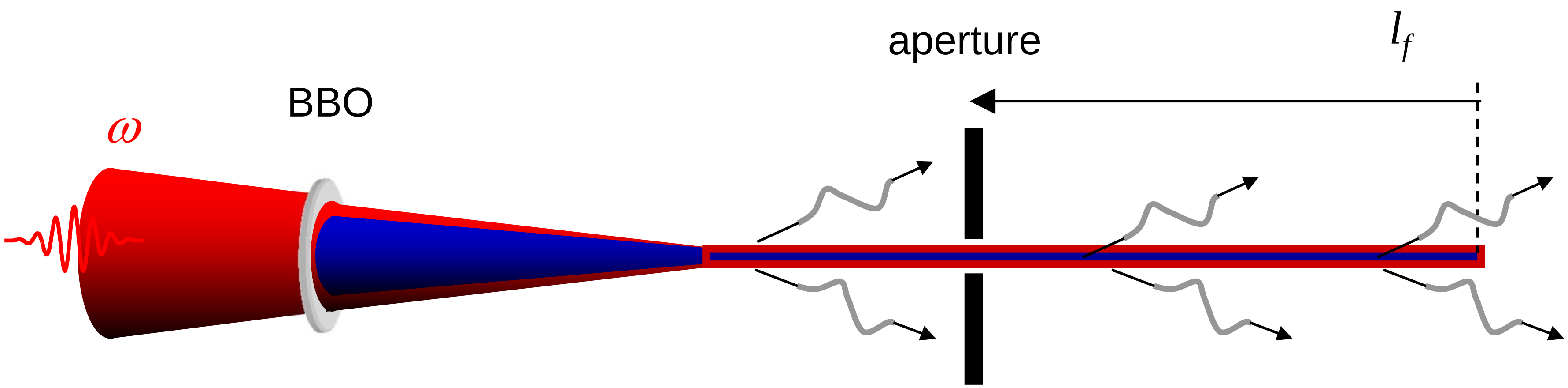
THz focusing issue:

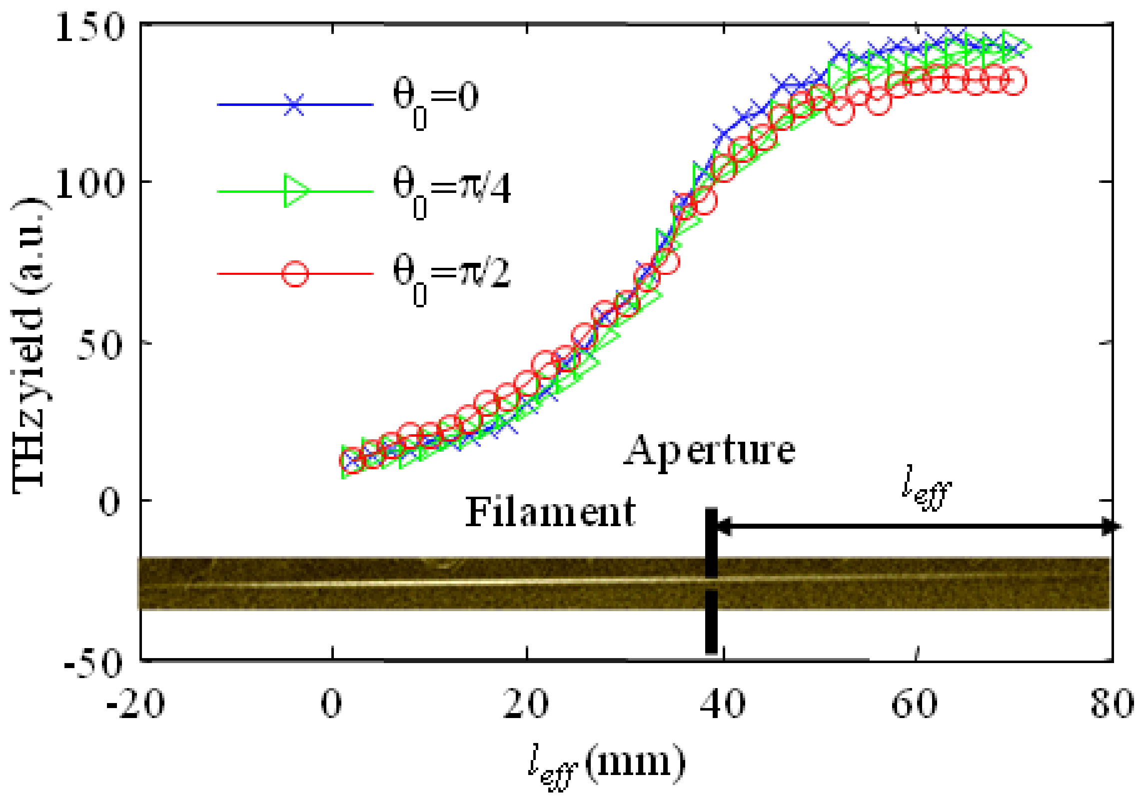


Focused THz profiles



THz yield vs filament length:





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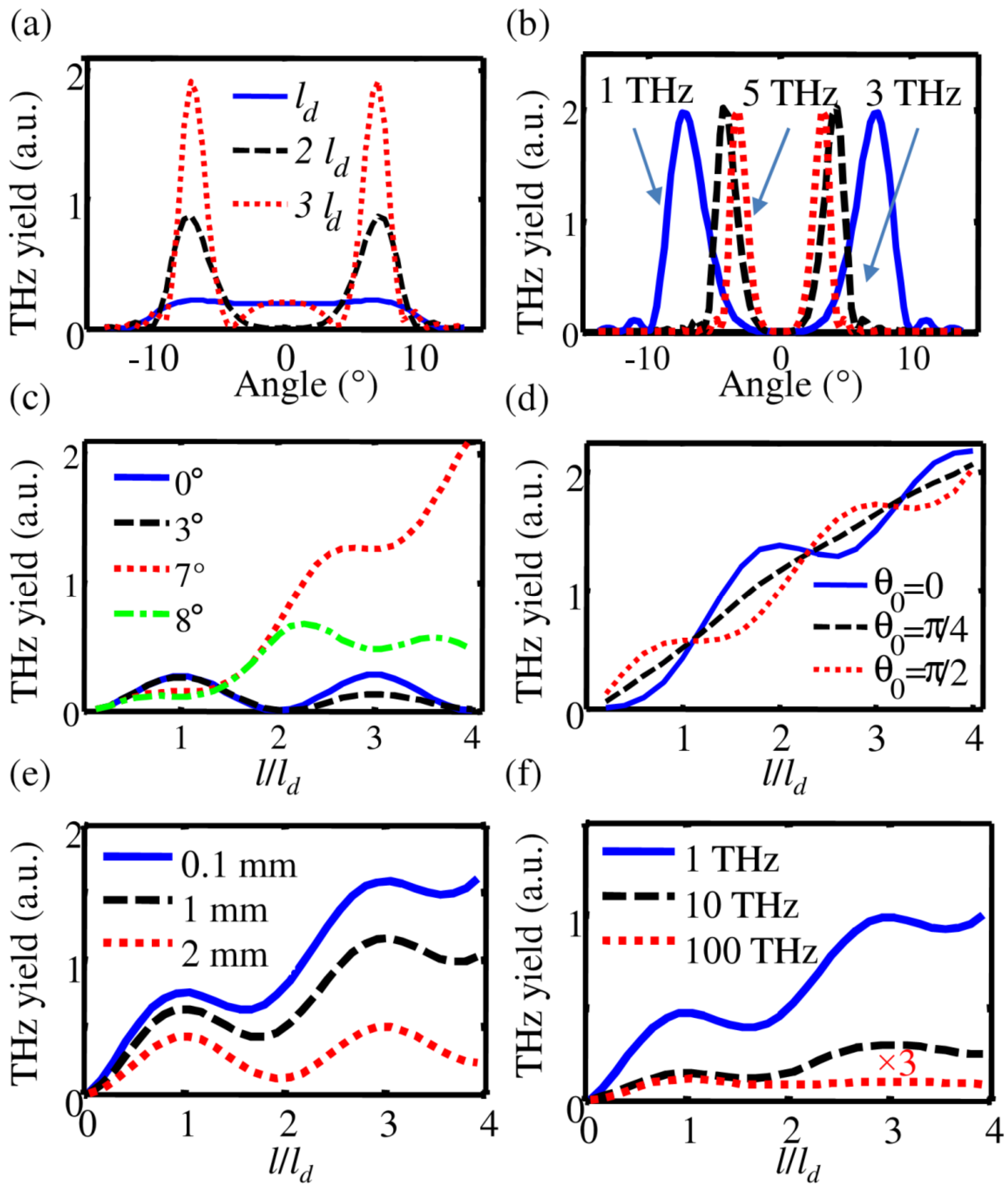

THz output increases almost linearly with the plasma length

Summaries:

- THz generation via two-color laser mixing:
  - Ideal for broadband intense THz spectroscopy
- High-energy THz generation:
  - Used 15 W, 1 kHz and 20 TW, 10 Hz lasers
  - Produced several μJ THz radiation but observed saturation
- Scalable THz generation:
  - Demonstrated THz phase matching in long filaments
  - THz output energy increases with the filament length

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