Investigations of dense plasmas created by extreme ultraviolet lasers

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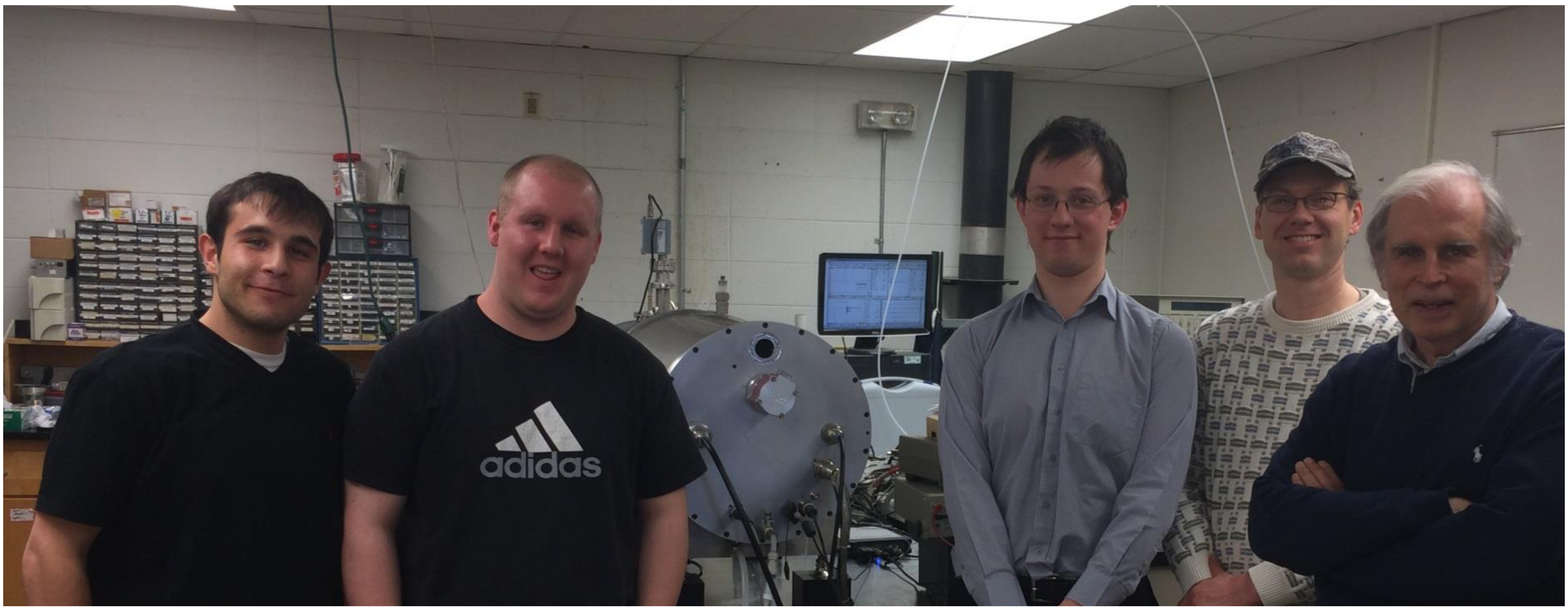
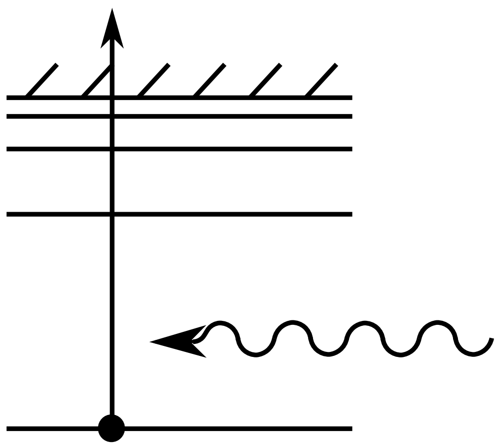
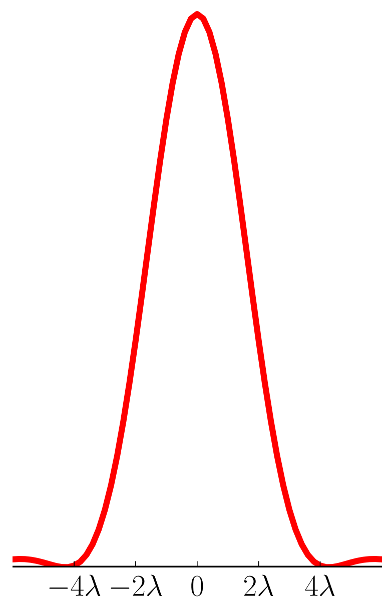


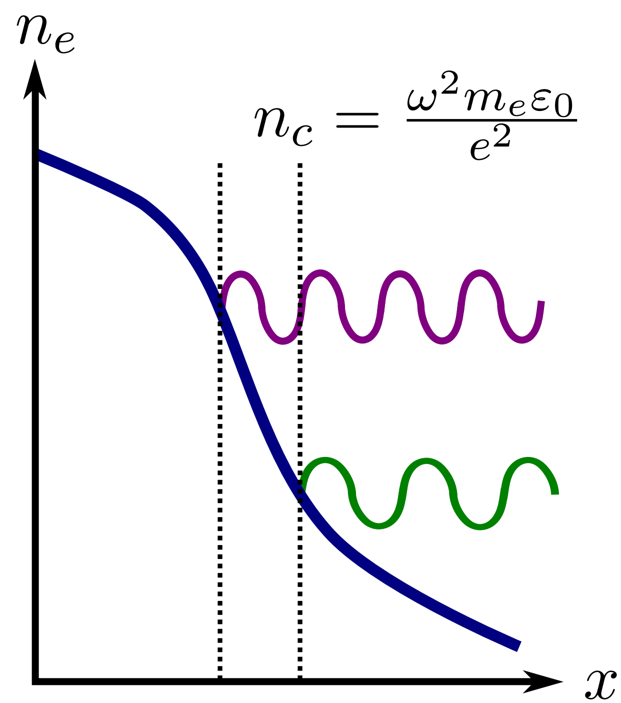
Why short wavelength lasers?



Able to directly photoionize



Focal spot $\gtrsim \lambda$



High critical density

Despite short λ, lasers maintain attractive beam properties

Several challenges to overcome:

- Lack of refractive optics; reflective optics have reflectivities $< 70\%$
- Propagation in vacuum complicates experiments

Atomic states in a plasma

Densities of atomic states in vector $\vec{N}$ evolve through rate matrix:

$$\frac{d\vec{N}}{dt} = R\vec{N} \qquad R_{ij} = \mathrm{Rate}\{i \to j\}$$

Typical collisional rate has the form

$$\int_{E_{\mathrm{th}}}^{\infty} v\sigma(\epsilon) f(\epsilon) d\epsilon$$

Atomic states particularly important for:

- Closure through equation of state for hydrodynamics
- Spectroscopic diagnostics

Steady state may reduce to a thermodynamic relation, such as Local Thermodynamic Equilibrium (LTE), with:

$$\frac{N_{m,l}}{N_{m,l'}} = \frac{g}{g^*} \exp\left(-\frac{\Delta E_{ll'}}{T_e}\right)$$

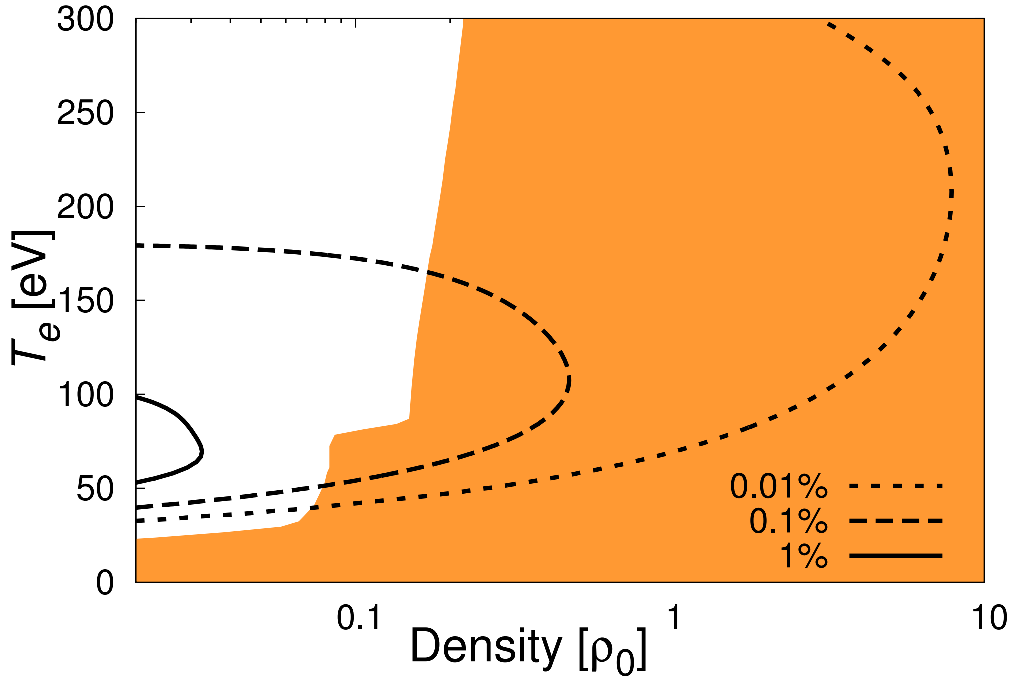
Boltzmann relation

$$\frac{N_{m+1}}{N_m} = n_e \frac{g}{g^*} G \exp\left(-\frac{E_m}{T_e}\right)$$

Saha equation

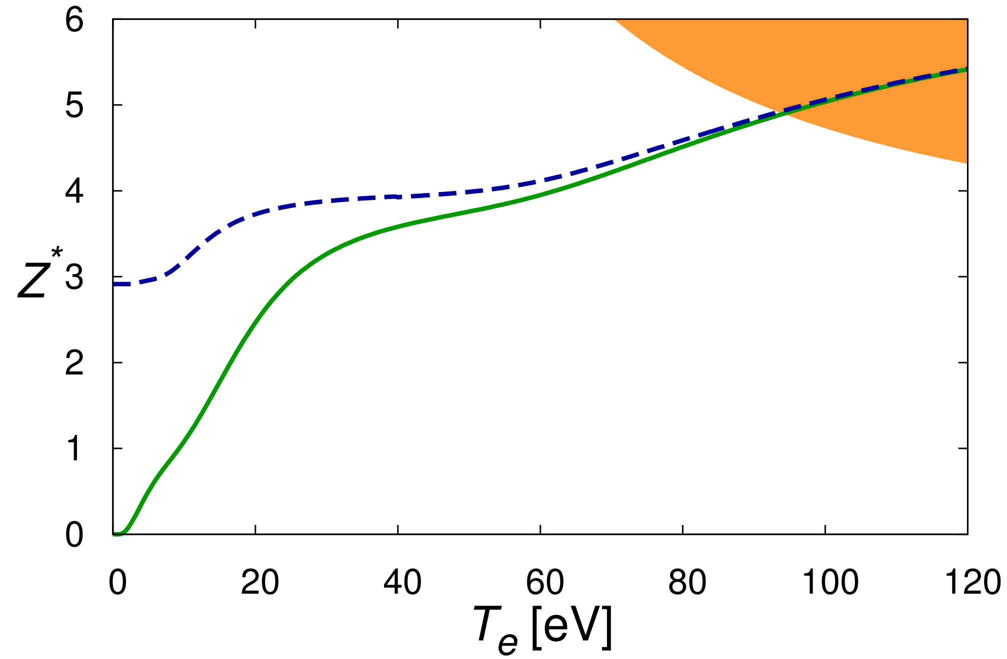
Deviations from LTE

$$n_e > 1.7 \times 10^{14} \sqrt{T_e} (\Delta E_{ll'})^3$$



Deviation from LTE in steady state for carbon, compared to McWhirter's criterion (shaded).

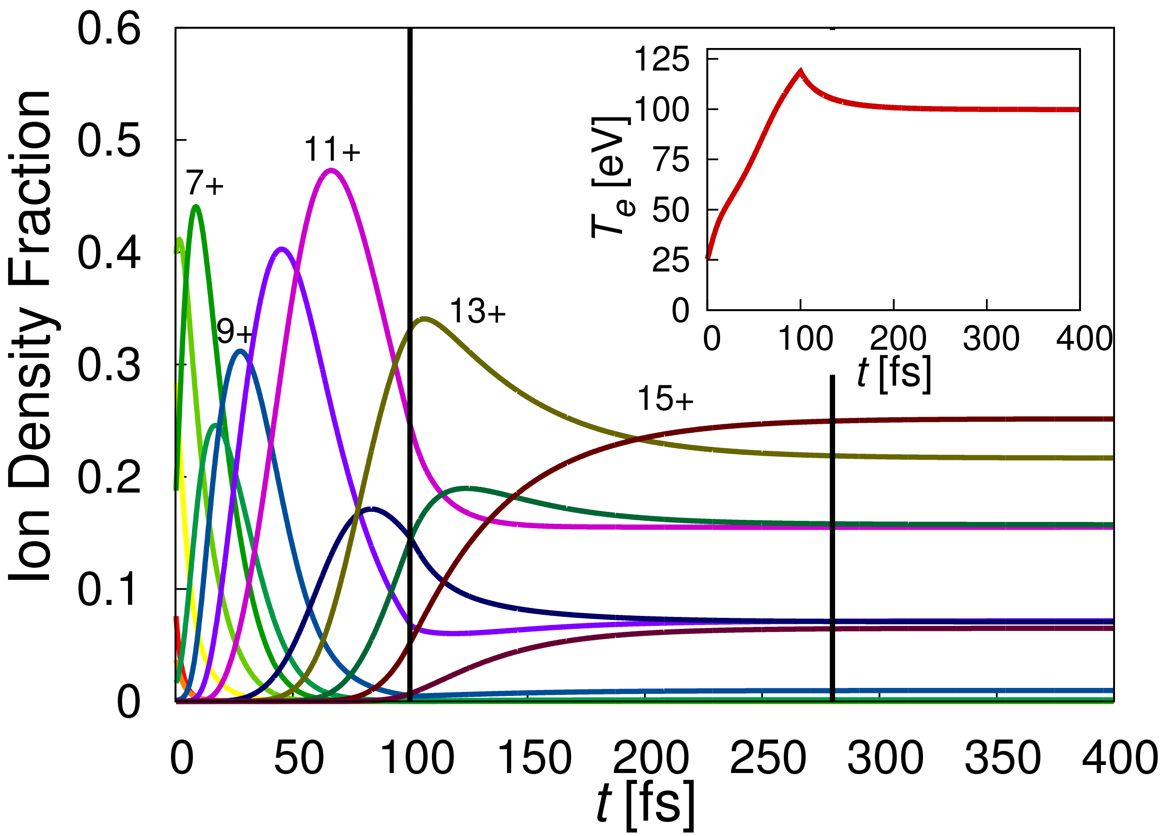
$$n_e > 1.31 \times 10^8 \frac{\sqrt{T_e} I(E_m/E_\gamma)^4}{Z^2 \xi \mathbf{E}_1(E_m/T_e)}$$



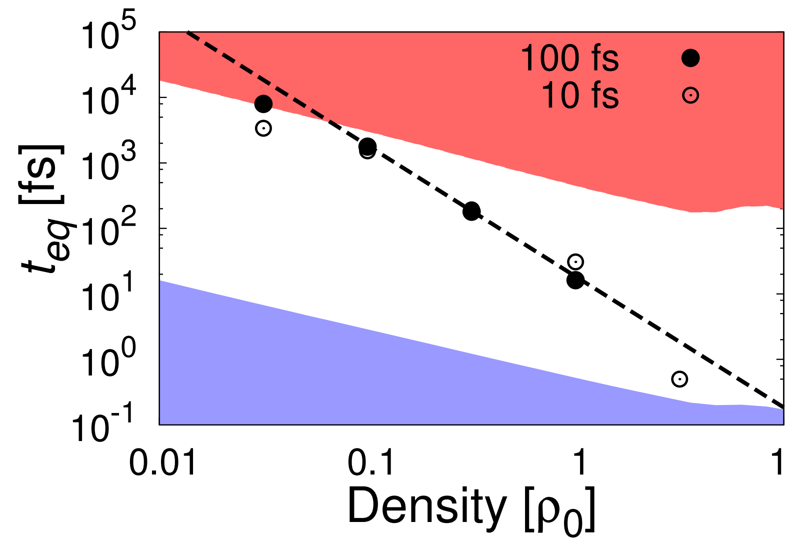
Relative ionization for solid carbon with no photons (solid line), 50 eV photons (dashed) at 10^{15} W cm^{-2}.

[1] V. Aslanyan, G. J. Tallents, Phys. Plasmas **21**, 062702 (2014)

Transient departure from steady state



Linear energy deposition into free electrons of iron plasma to raise T_e from 25 to 100 eV over 100 fs. Equilibration time $t_{eq} = 168$ fs.

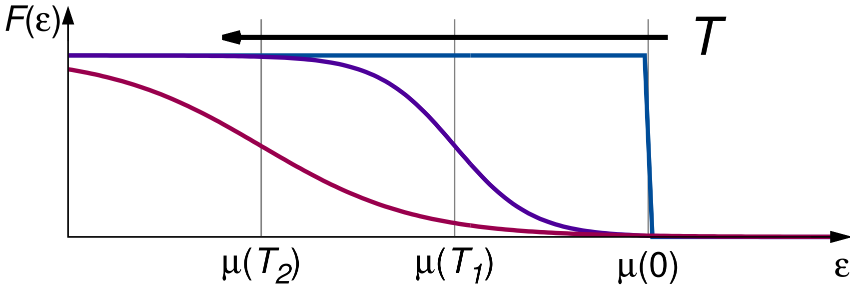


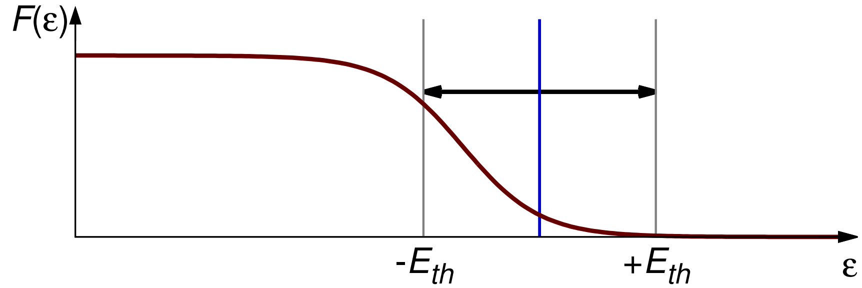
Parameter scan of iron equilibration times for varying densities. Thermalization of electrons (blue region) ions (red region).

$$t_{eq} \propto \rho^{-2}$$

Plasmas from solid density targets typically have < 1 ps equilibration times

Quantum effects: Fermi-Dirac distribution





$$F(\epsilon) = \frac{1}{1+\exp(\frac{\epsilon-\mu}{T_e})}$$

$$\tilde{F}(\epsilon) = 1 - F(\epsilon)$$

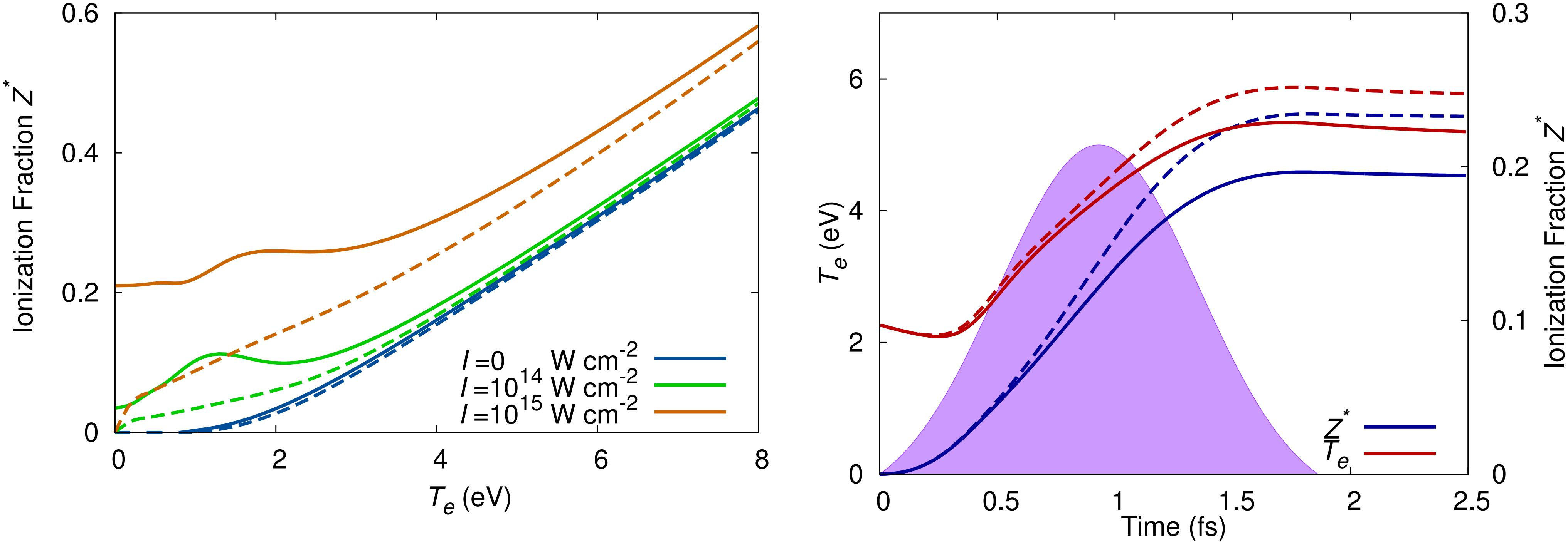
Deviations from Maxwell-Boltzmann occur when T_e is high and n_e is low

Atomic models require many evaluations of non-analytic integrals:

$$K^{\uparrow} = N_i G \sqrt{\frac{2}{m_e}} \int_{E_i}^{\infty} \int_{0}^{\epsilon_0 - E_i} \epsilon_0 \frac{d\sigma^{\uparrow}}{d\epsilon_1} F(\epsilon_0)\tilde{F}(\epsilon_1)\tilde{F}(\epsilon_0-\epsilon_1-E_i)d\epsilon_0 d\epsilon_1$$

A double integral must now be evaluated due to the Pauli exclusion principle

Effects of degeneracy on plasma properties



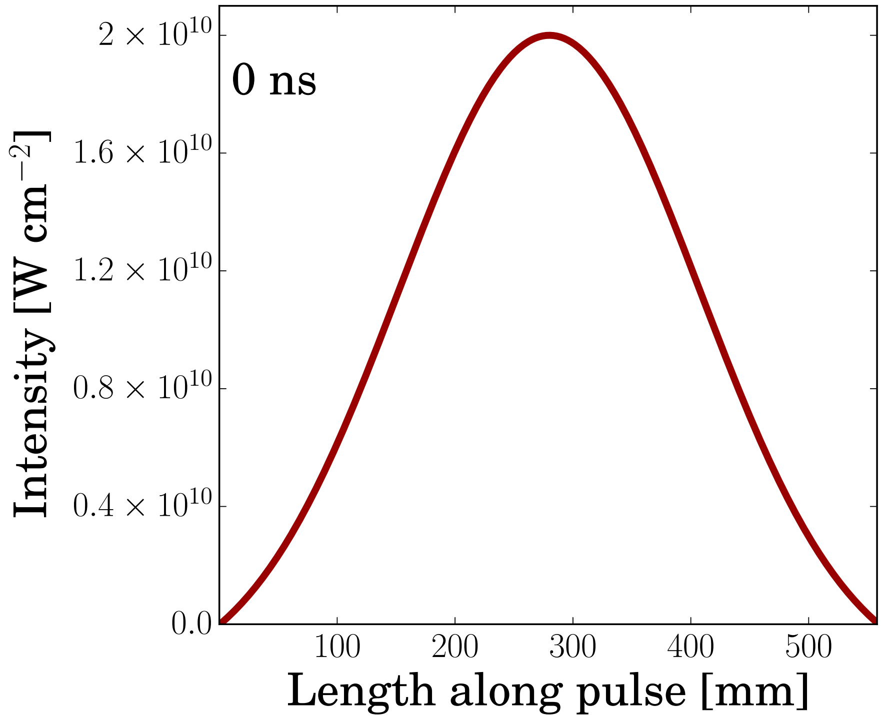
Steady state and time-evolved simulations of carbon with Maxwell-Boltzmann distribution (dahsed) compared to the Fermi-Dirac (solid). Irradiation by a short pulse of 10^{14} W cm^{-2} (right).

Evaluation of multiple integrals is ideally suited to SIMD paradigm of GPUs. Initial results show $> 10\times$ speedup over single CPU.

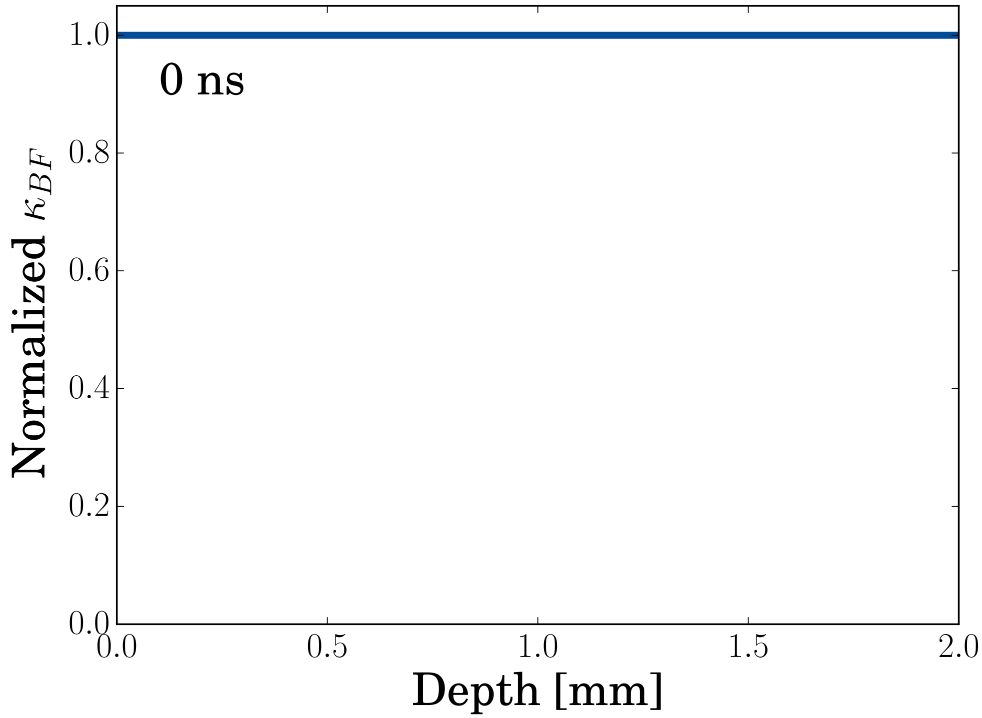
[2] V. Aslanyan, G. J. Tallents, Phys. Rev. E **91**, 063106 (2015)

Going to 1D: bleaching waves

Laser photons: 26.5 eV



Helium ionization energy: 24.6 eV



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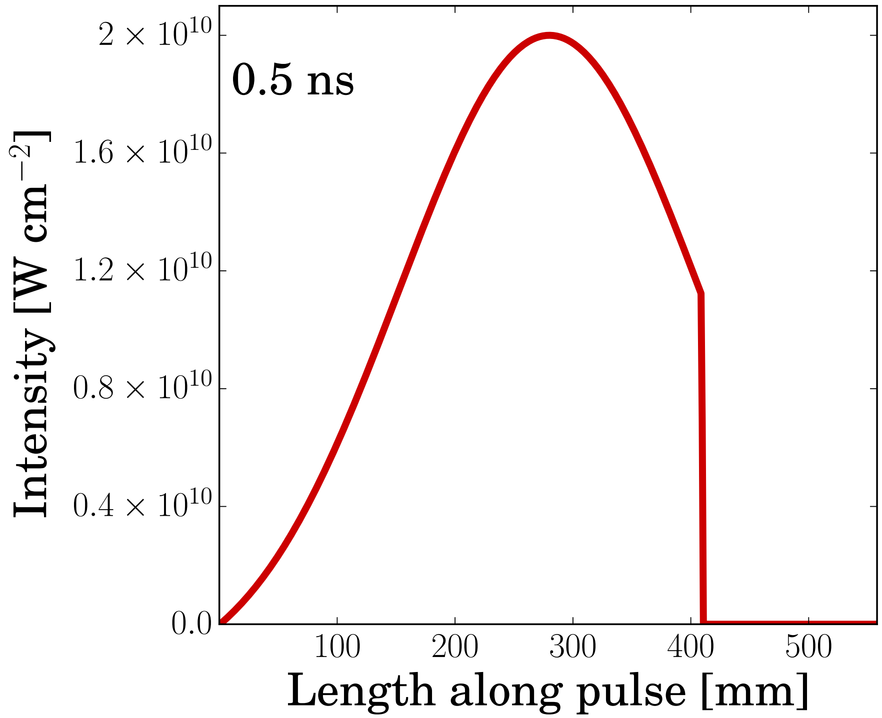

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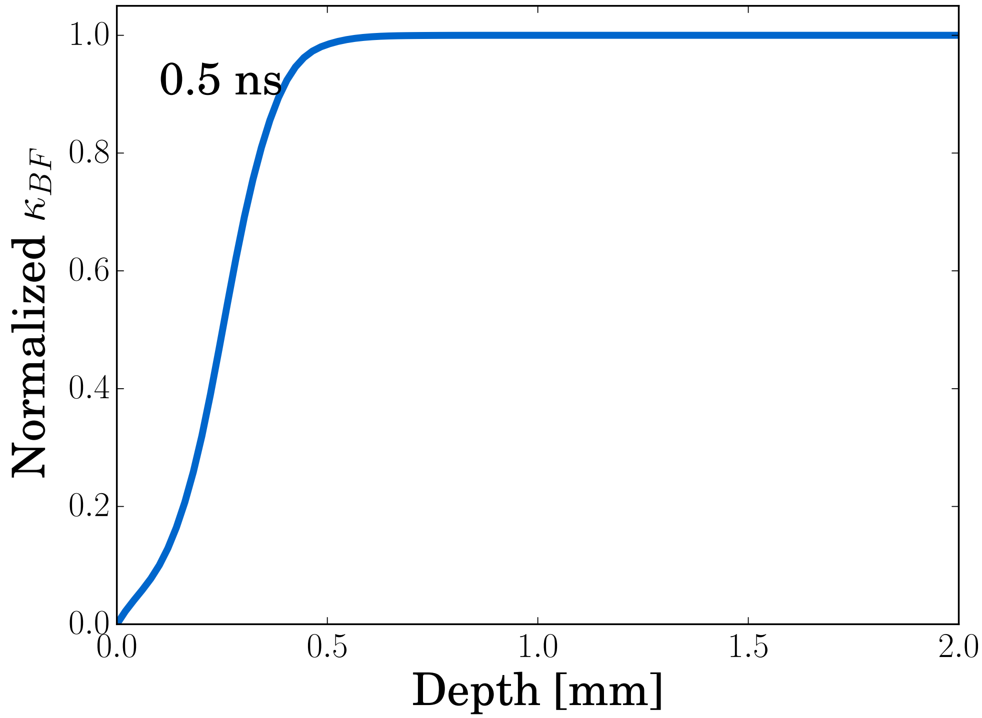

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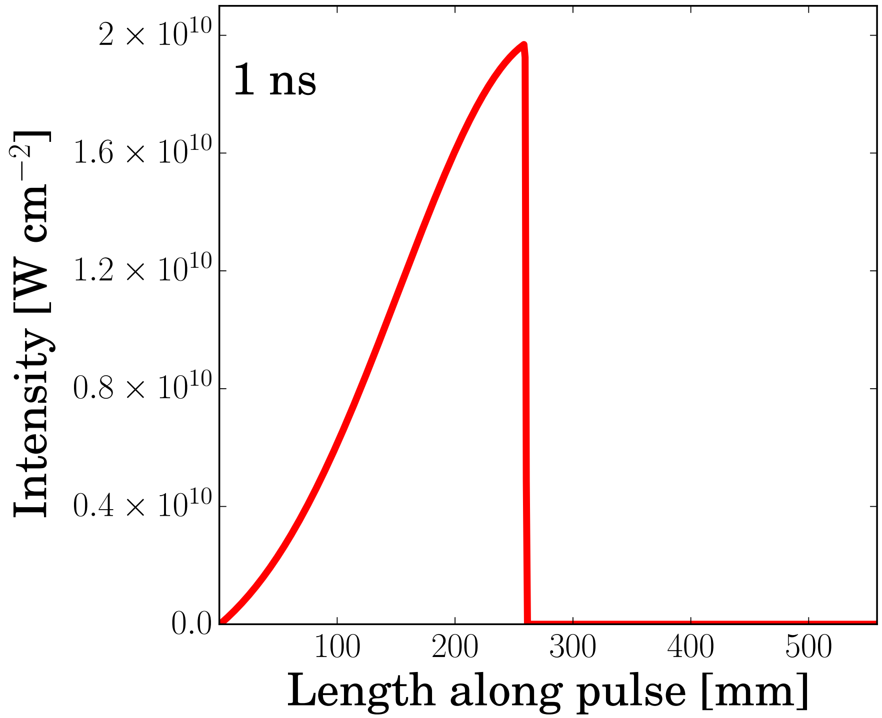

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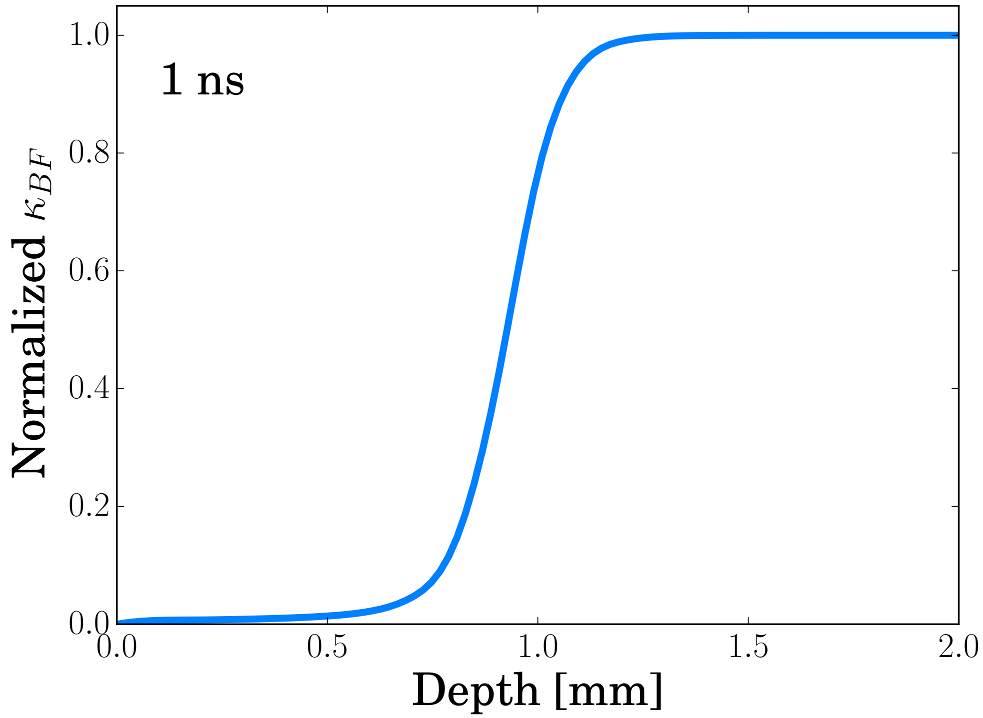

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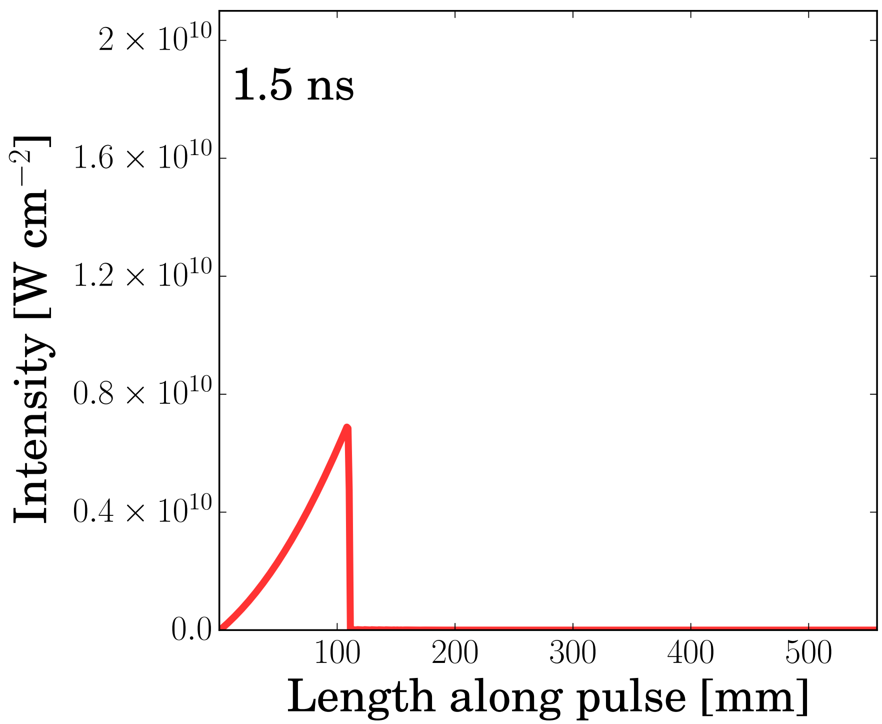

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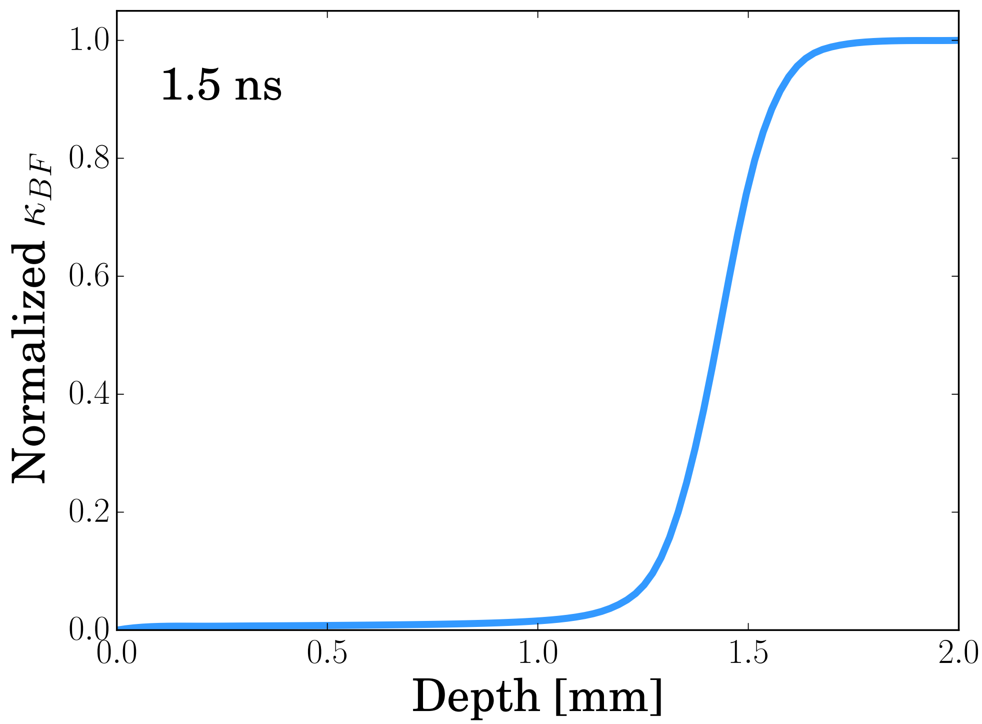

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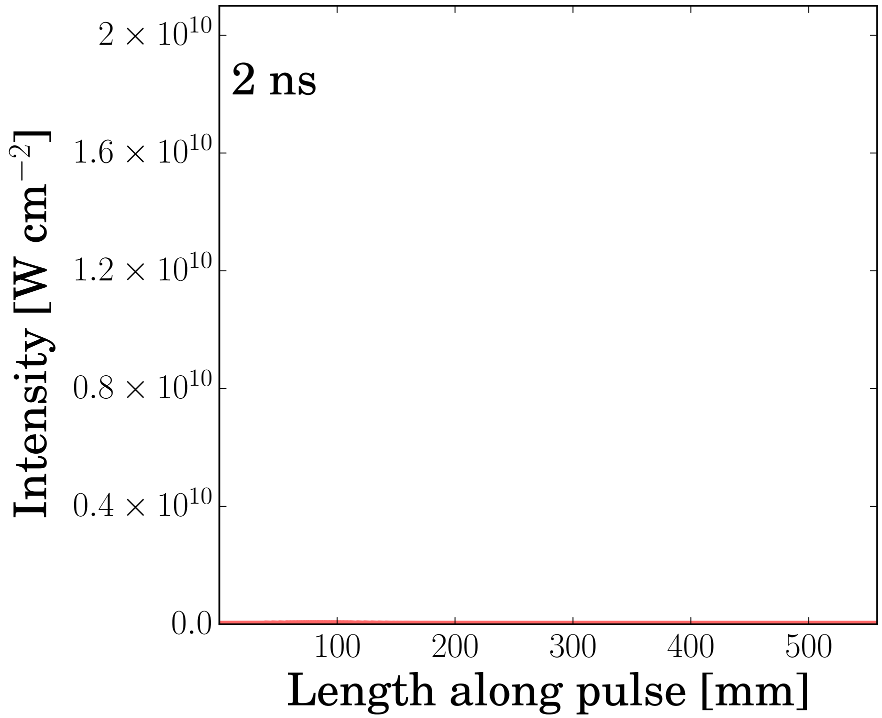

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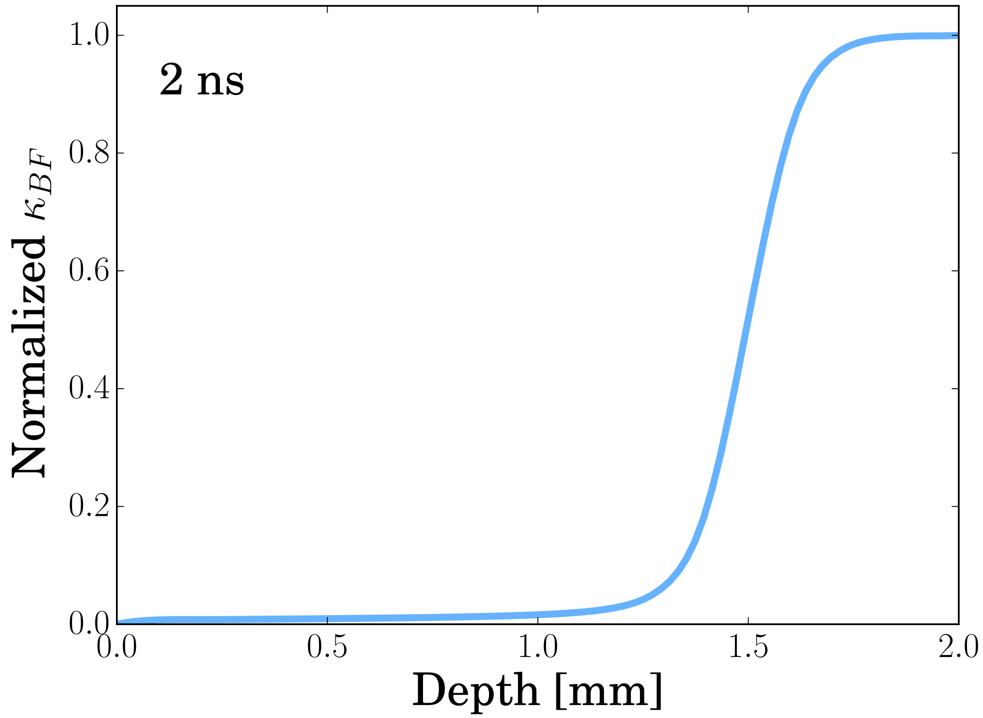

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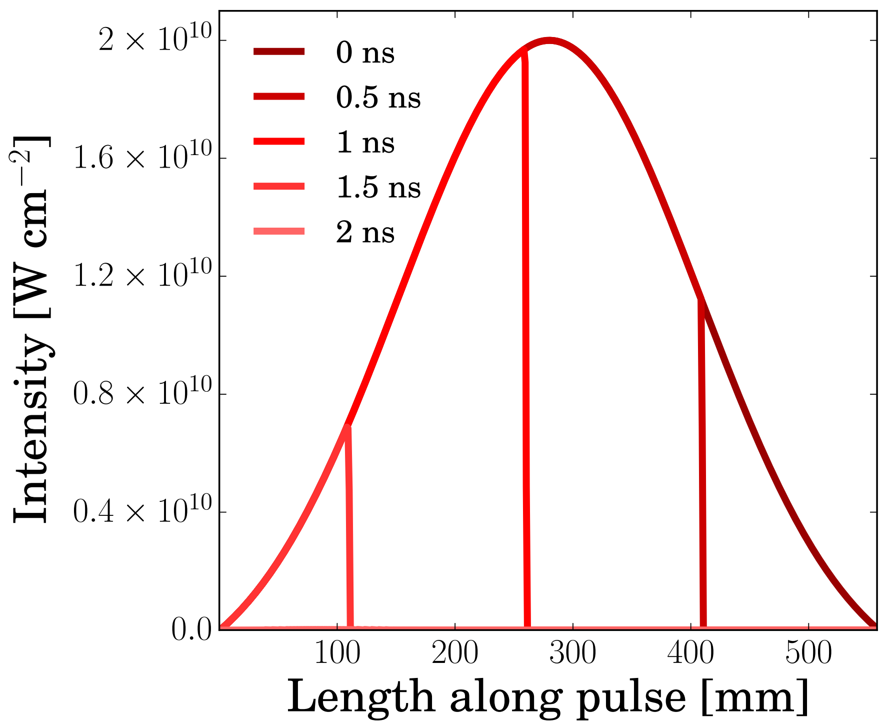

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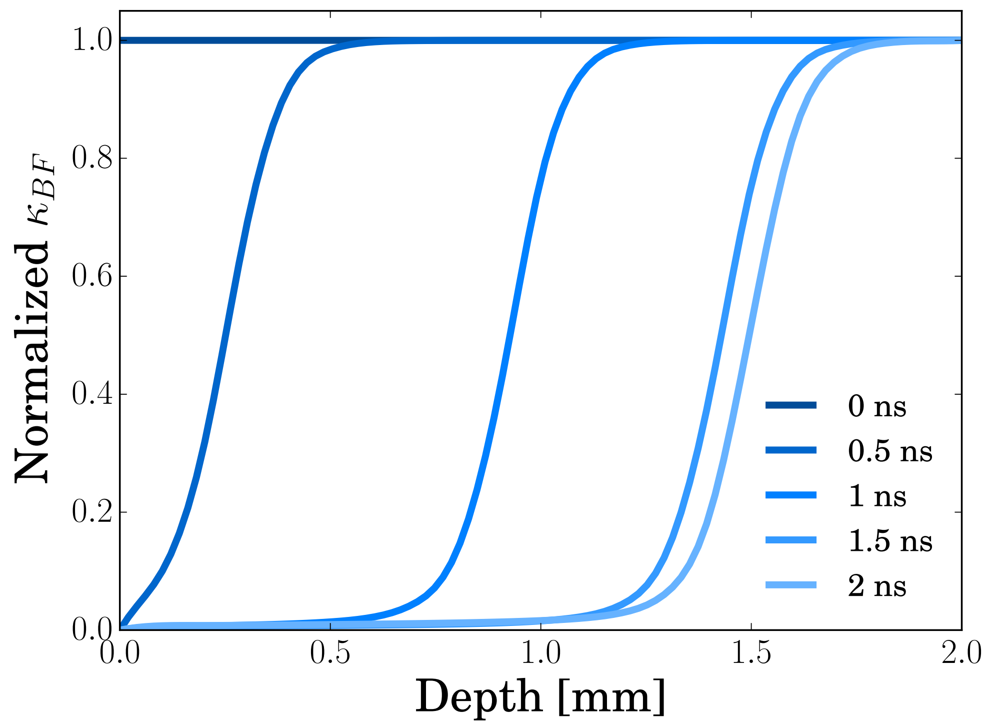

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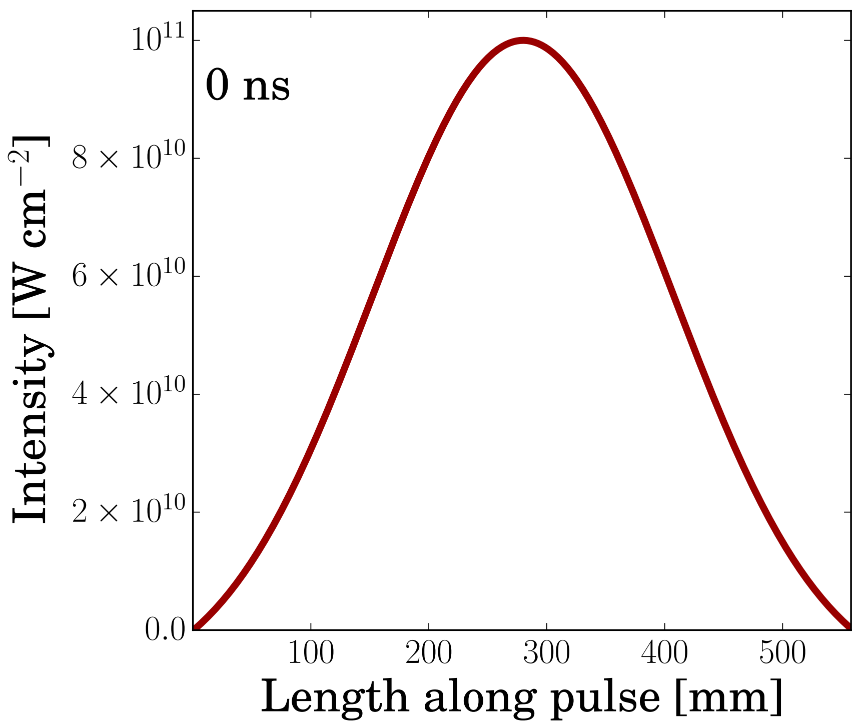

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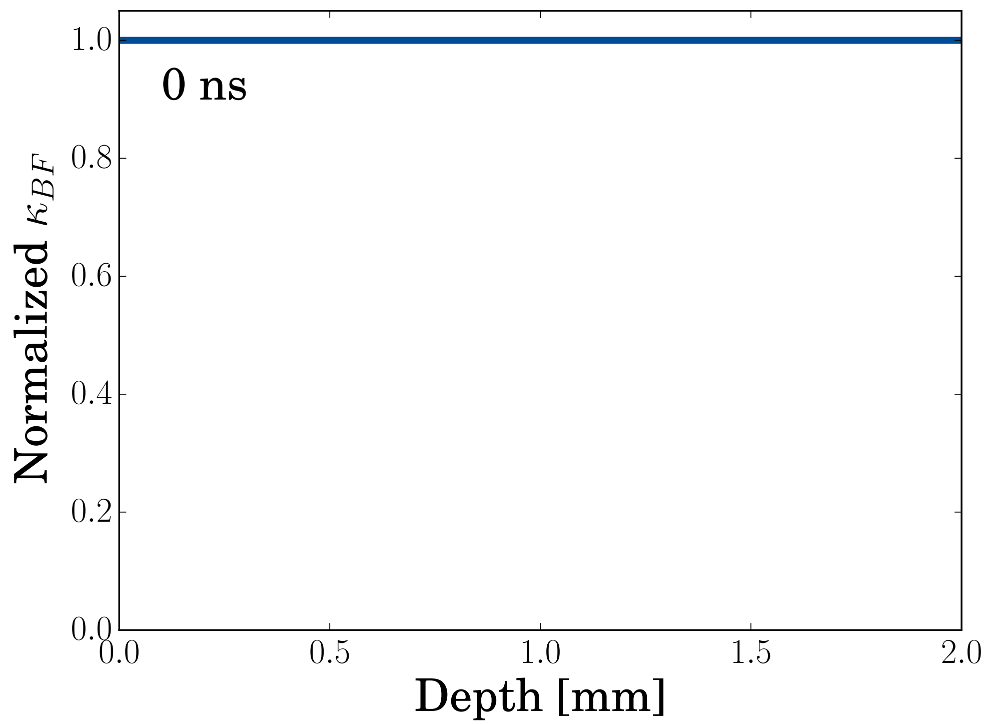

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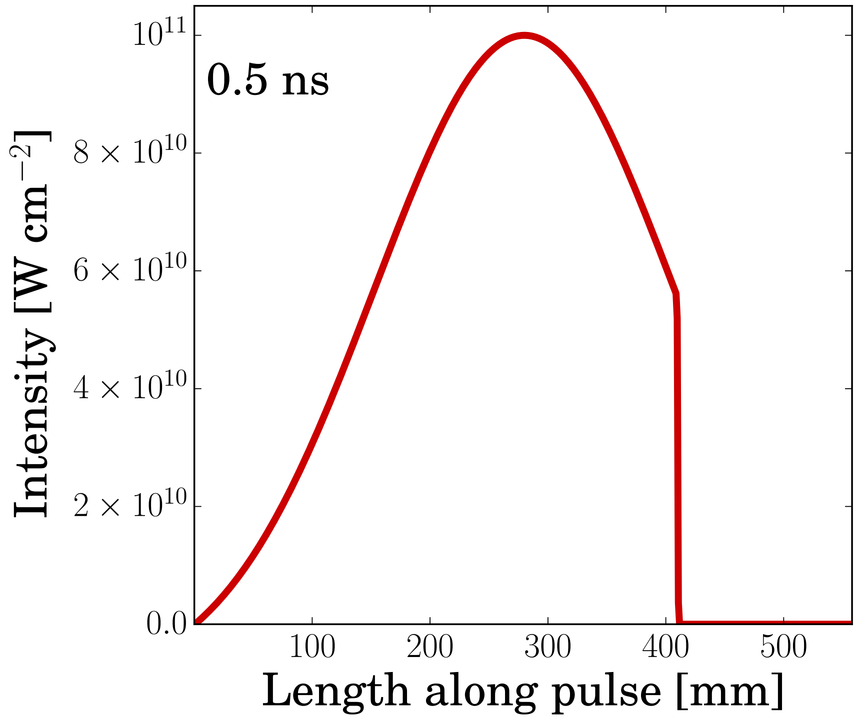

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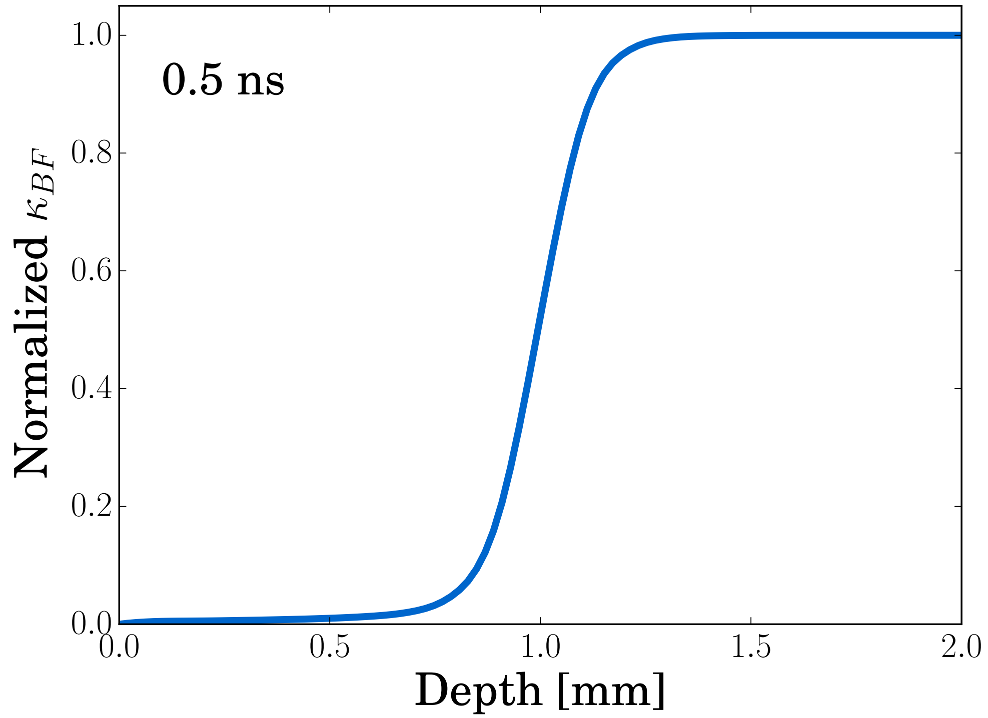

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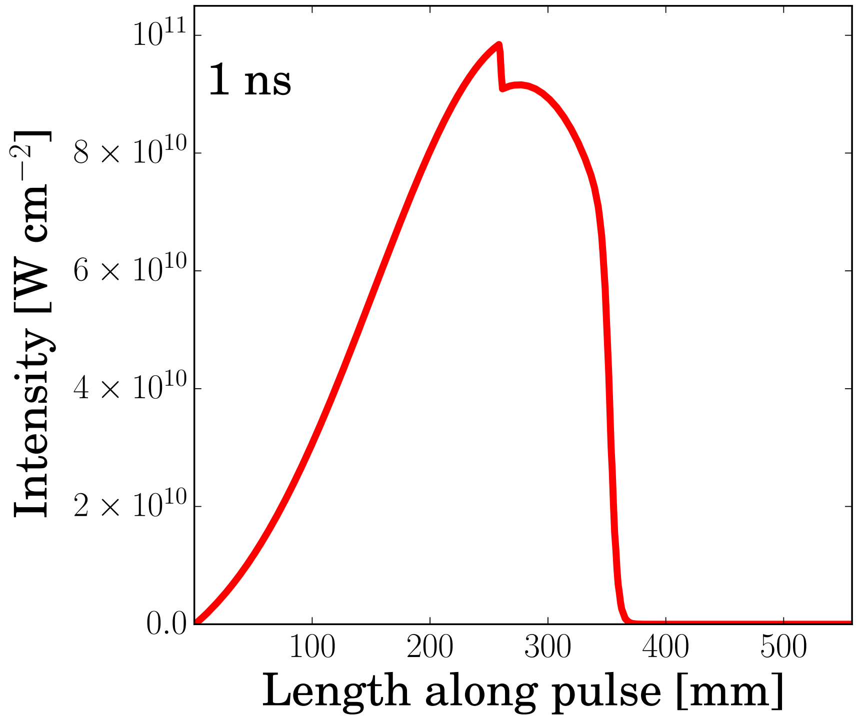

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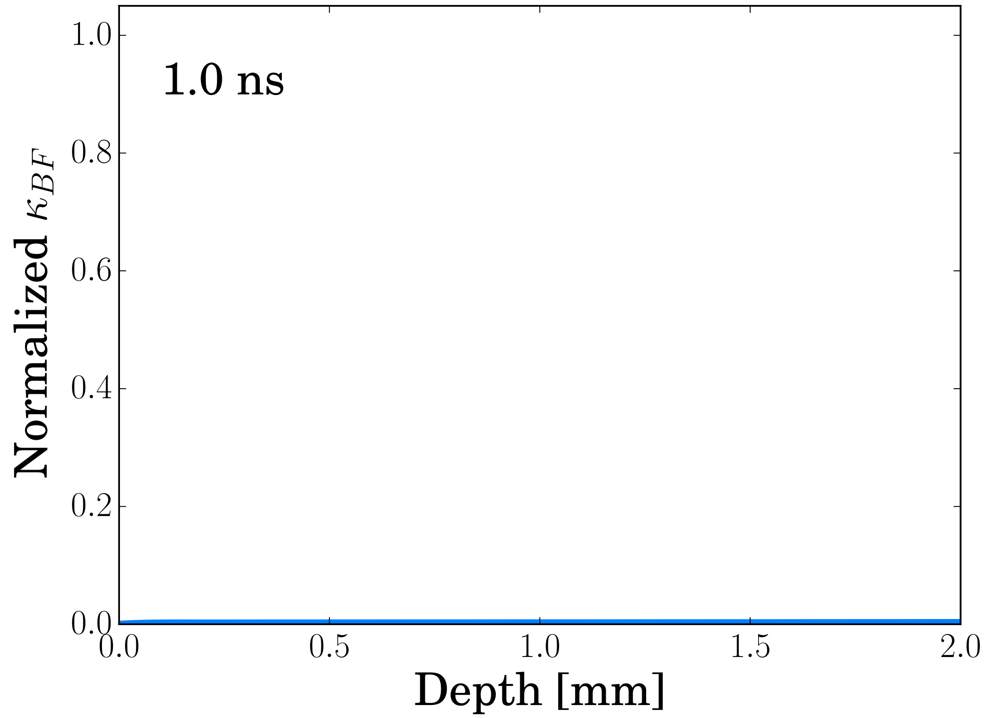

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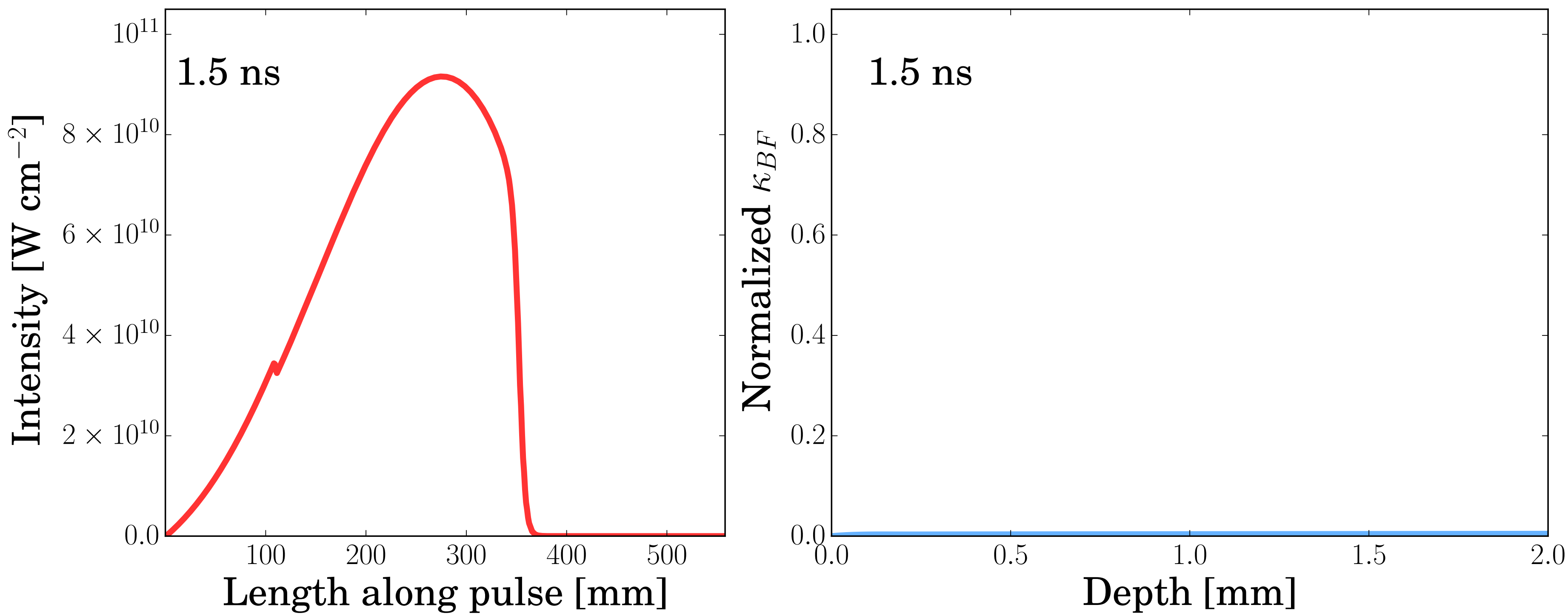
Laser photons: 26.5 eV   Helium ionization energy: 24.6 eV



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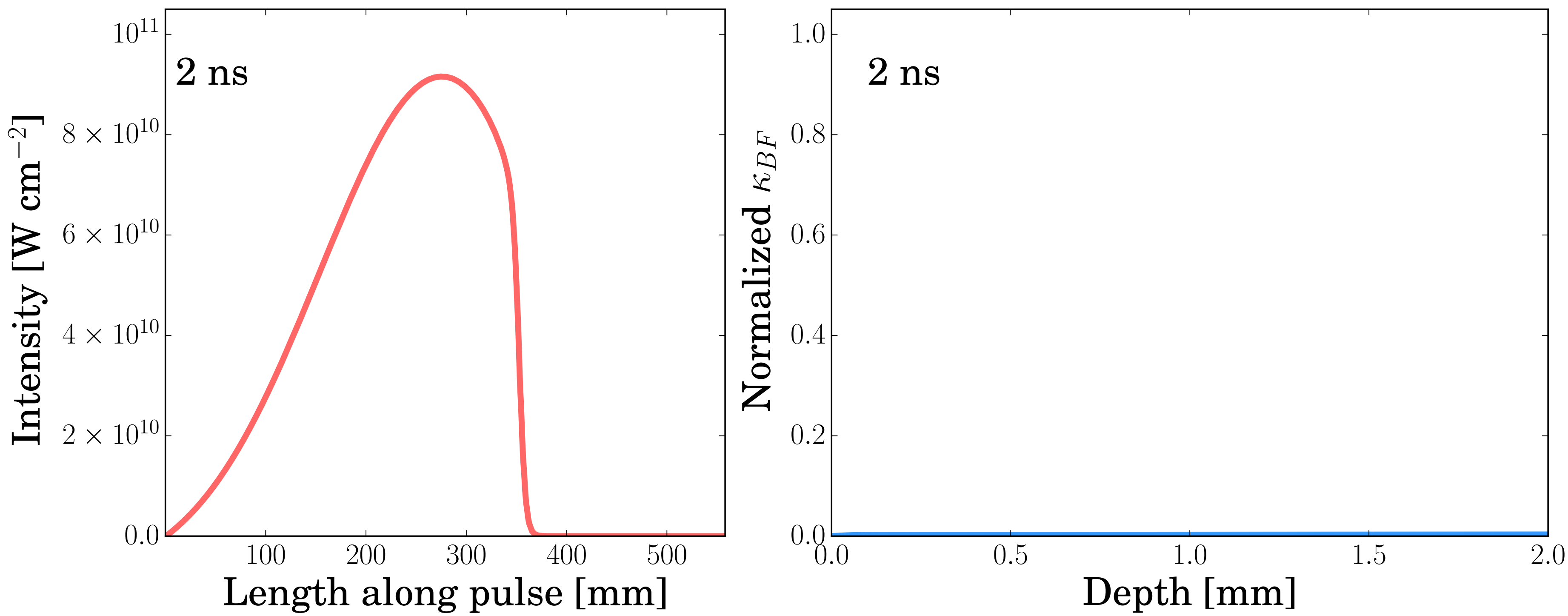

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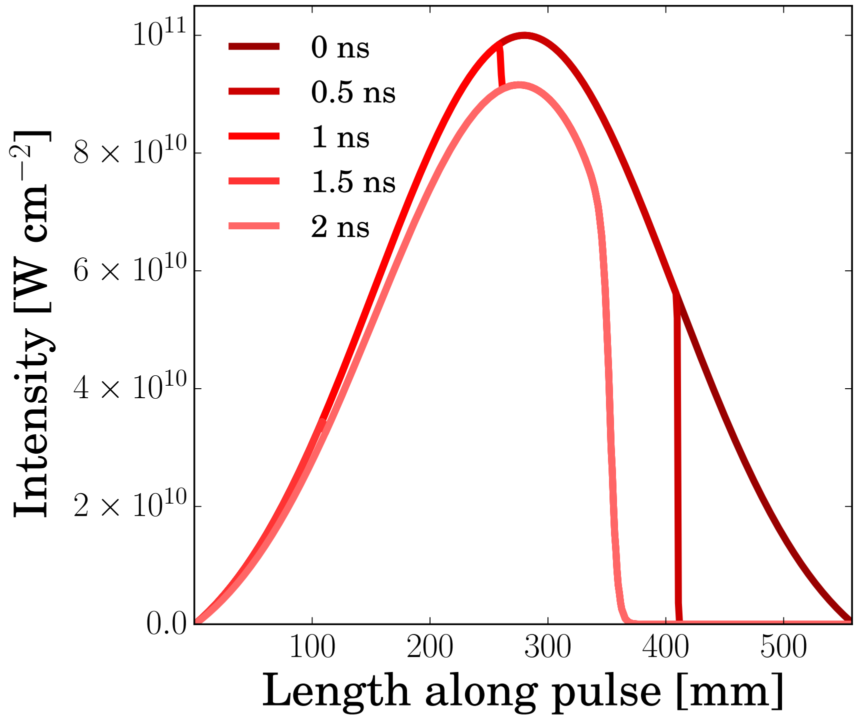

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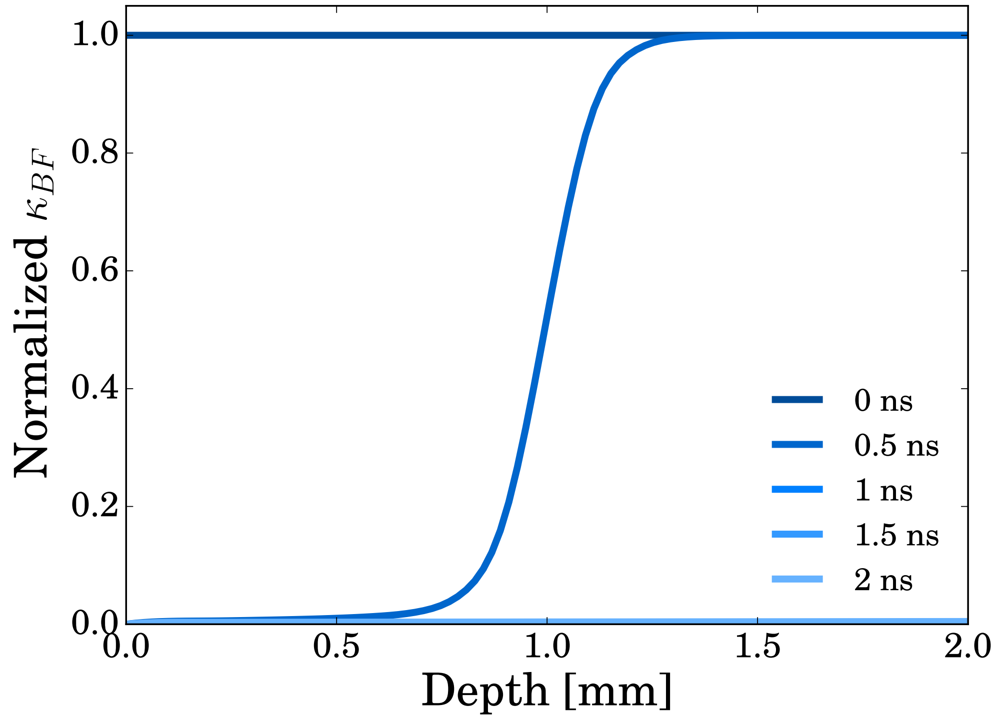

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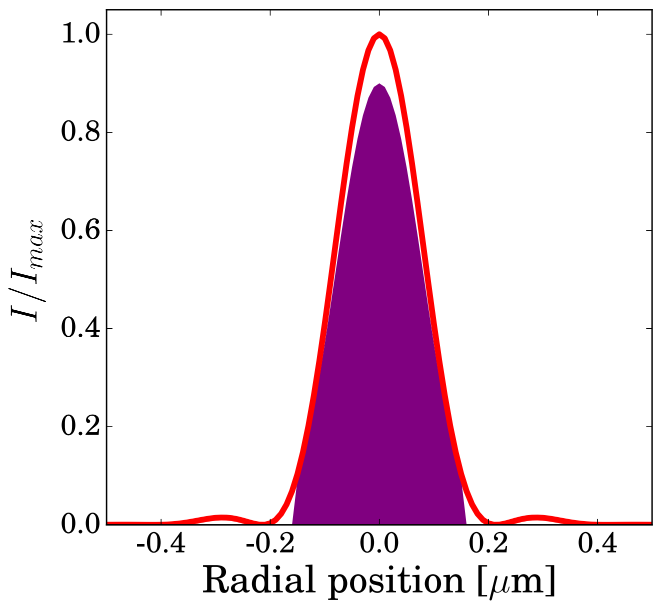
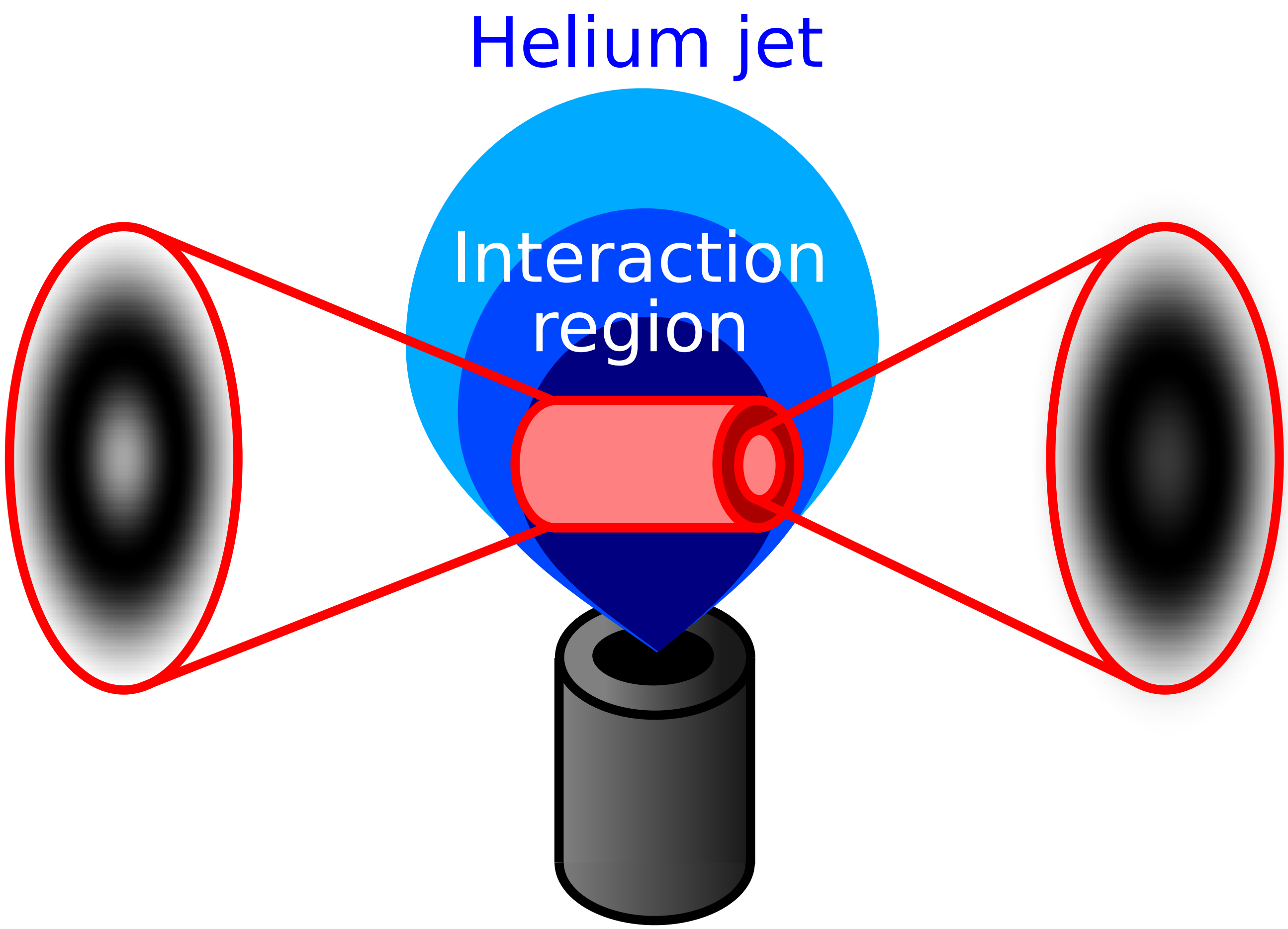
A possible experiment to observe bleaching waves

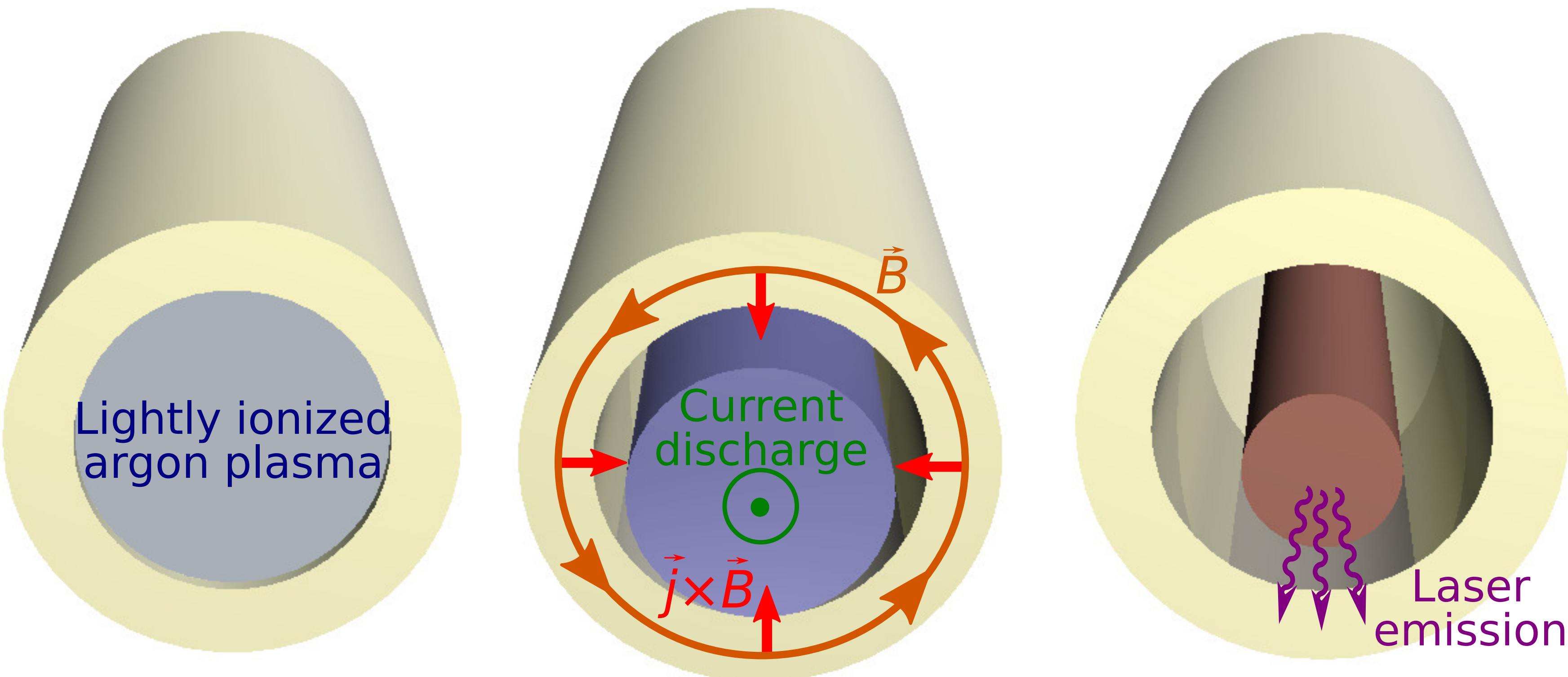
Attenuation of radiation is a strong function of intensity



Intensity profile at focus and after attenuation (shaded)



Capillary discharge laser - operating principle

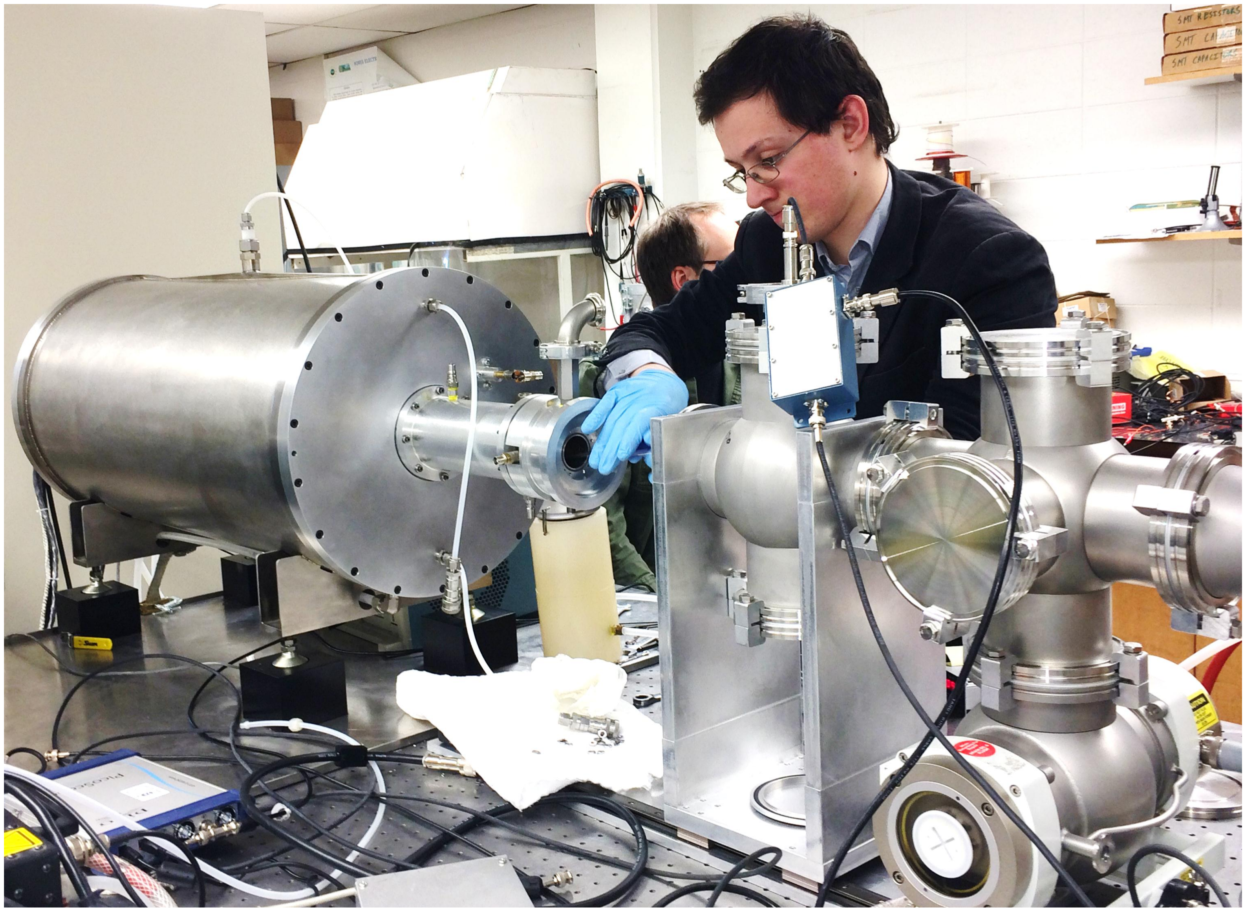


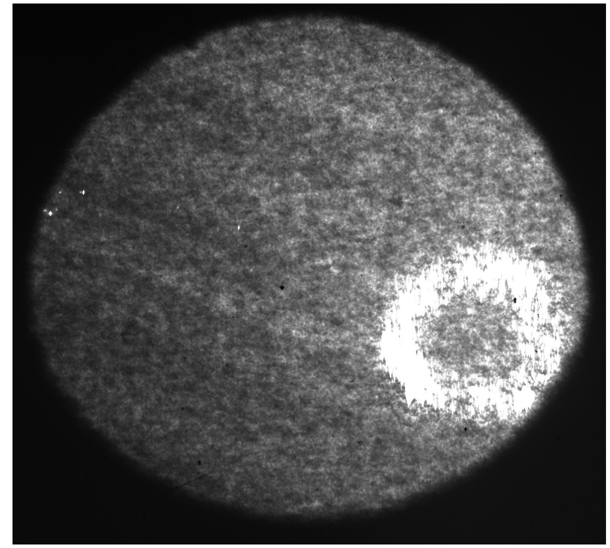
Cycle of a single laser shot in a capillary with 2 mm inner diameter, 200 mm length. Typical peak current rises to ~ 18 kA in 20 ns.

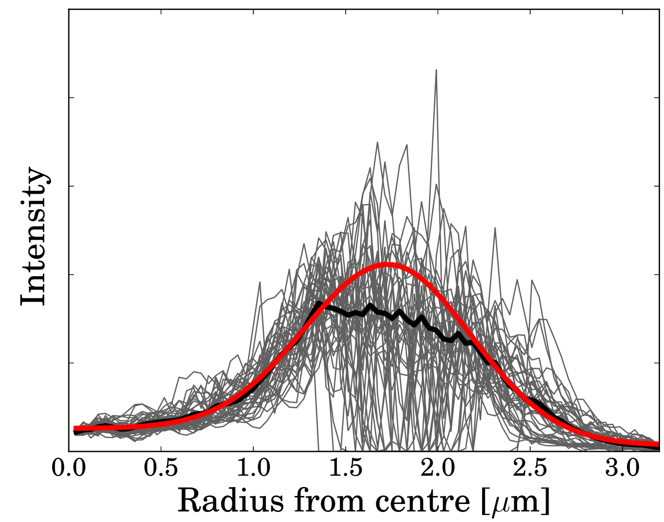
Electrically pumped laser allows:

- Compact size - tabletop
- High repetition rate - up to 10 Hz

Capillary discharge laser at CSU

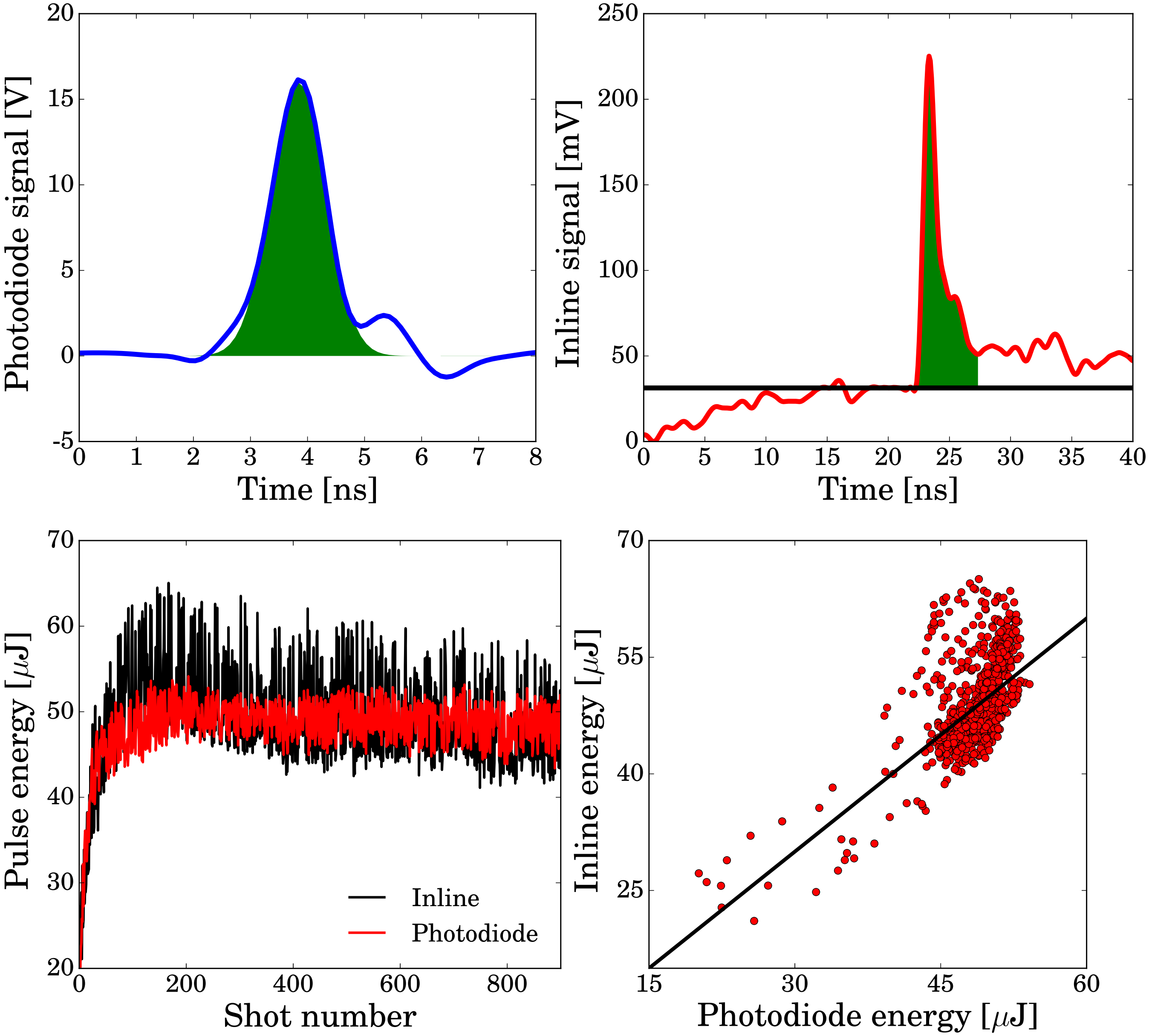






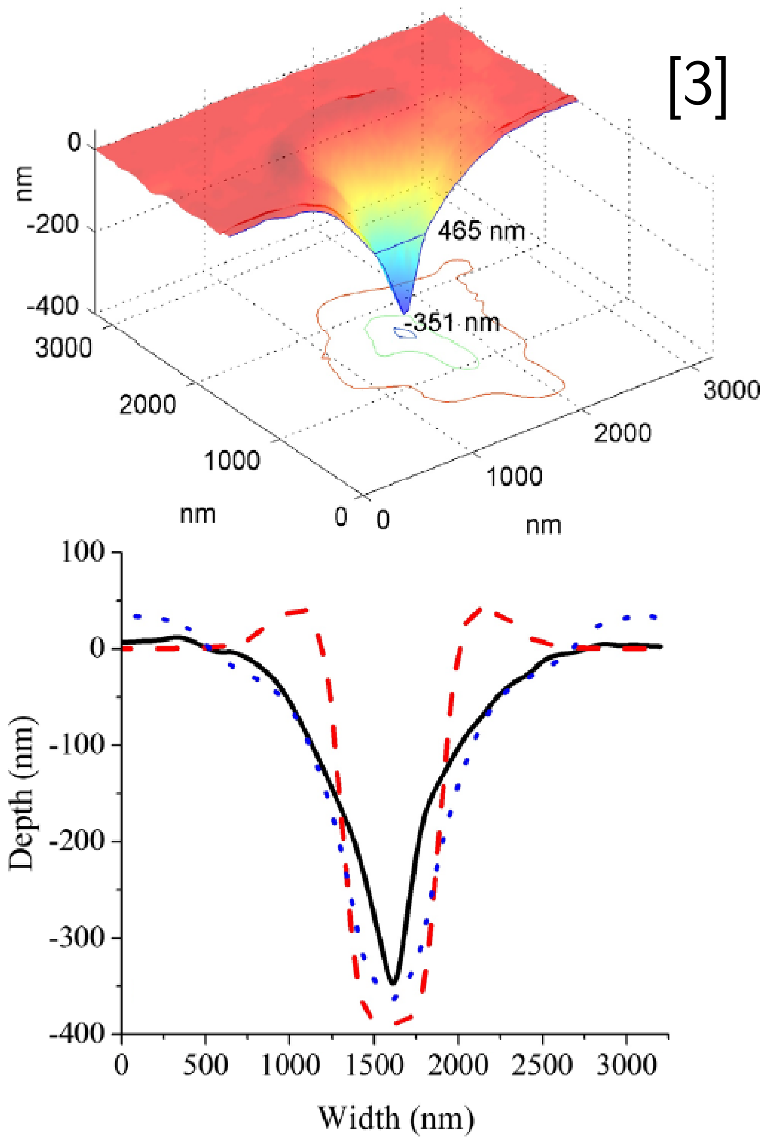
Annular profle of laser beam

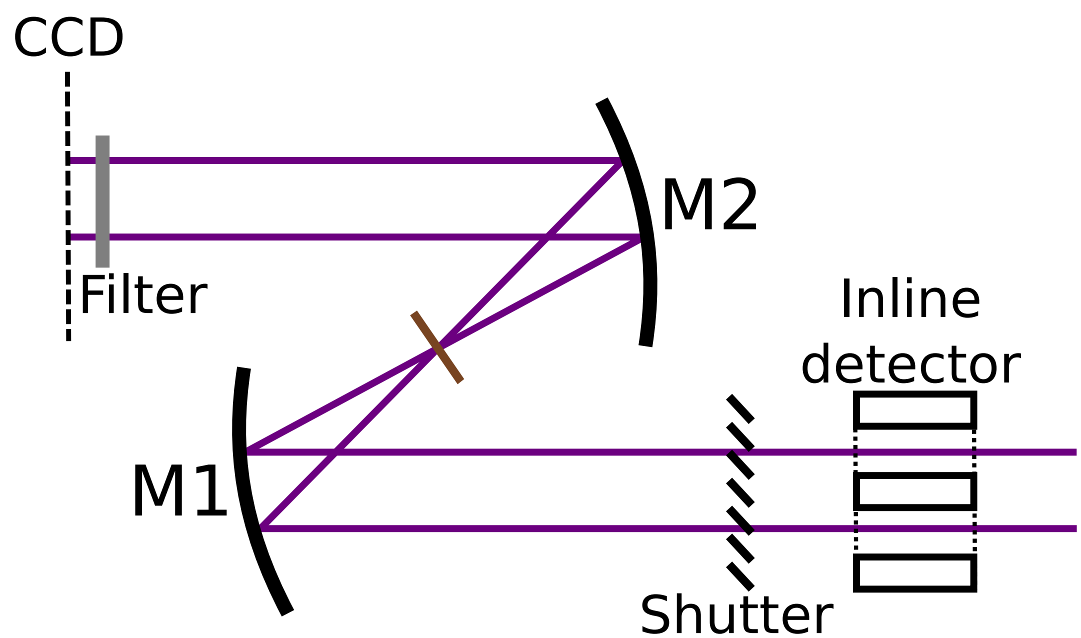
Pulse energy characterization



- Photodiode provides accurate pulse energy - calibrated from first principles
- Inline detector is non-destructive, but noisy - requires calibration at precise experimental conditions

EUV ablation and transmission experiments



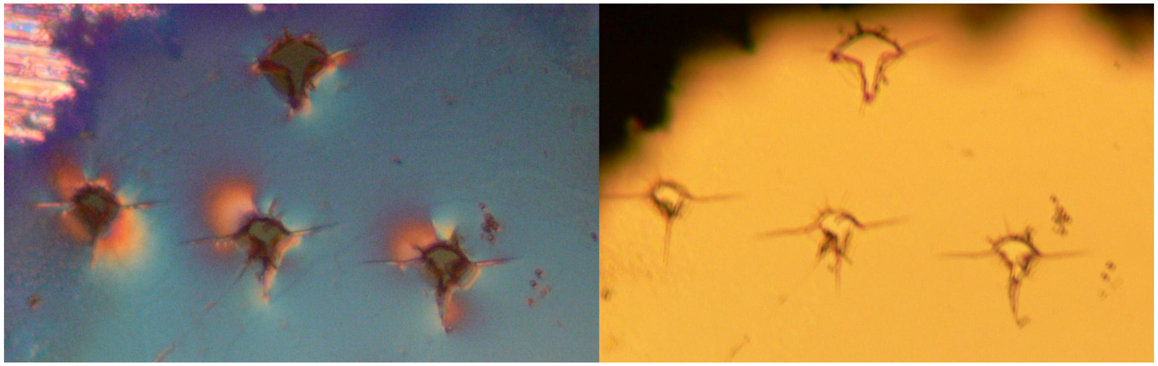


Schematic of transmission experiment

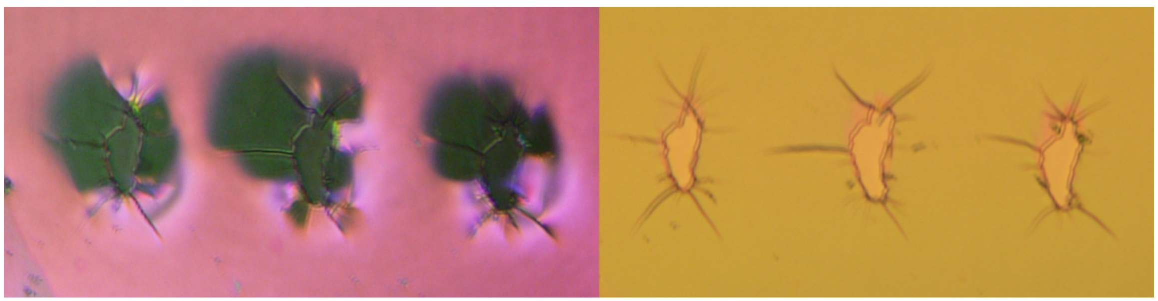
Combination of beam shape and plasma modelling required to match experiments

[3] A. K. Rossall, V. Aslanyan, *et al.* Phys. Rev. Applied **3**, 064013 (2015)

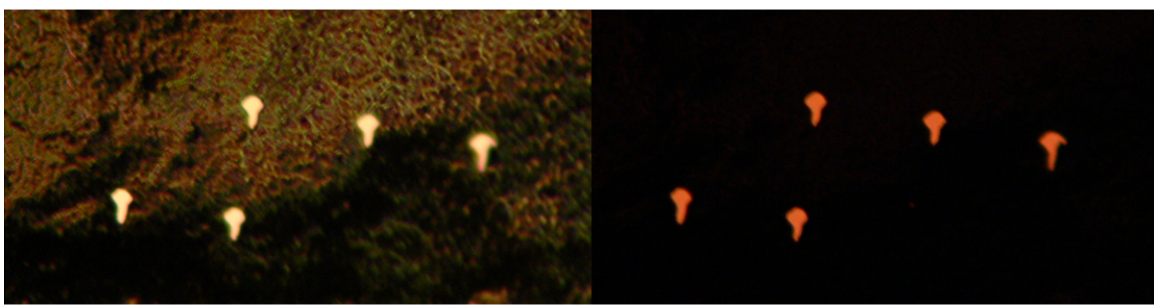
Ablation profiles



Parylene-N 1028 nm



Parylene-N 429 nm

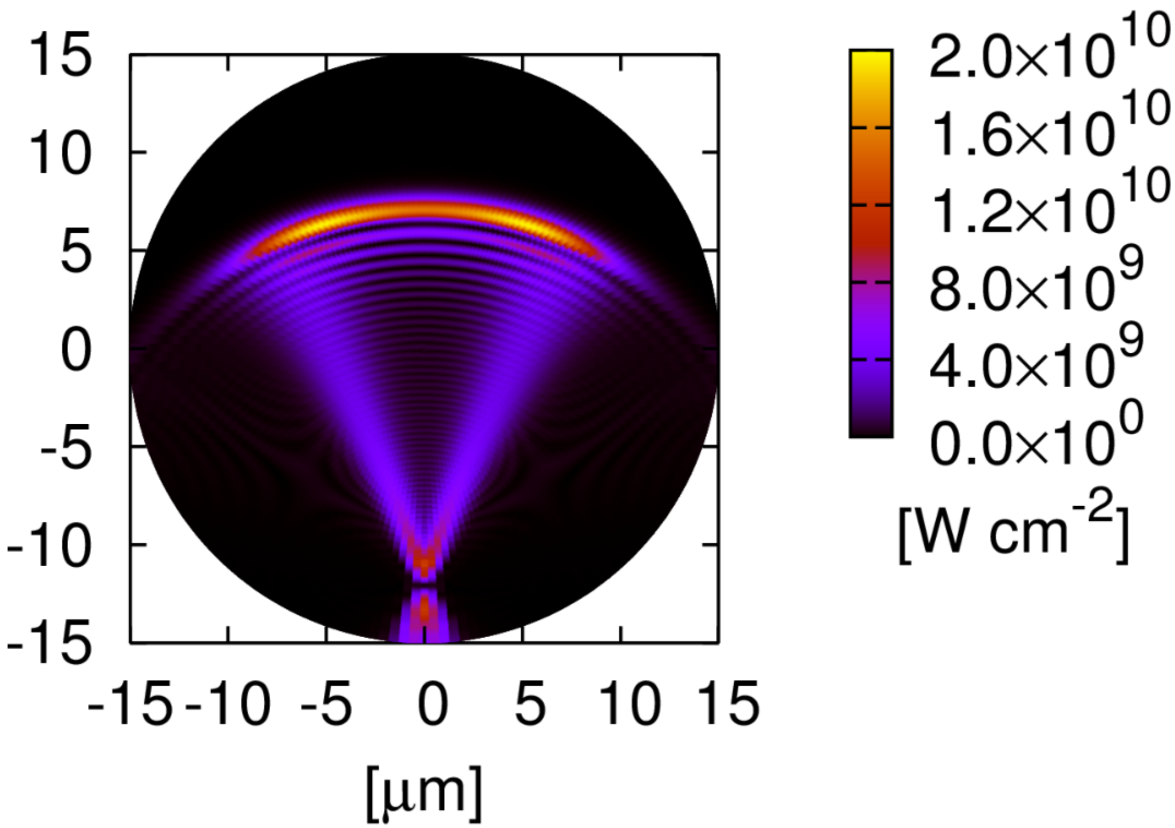


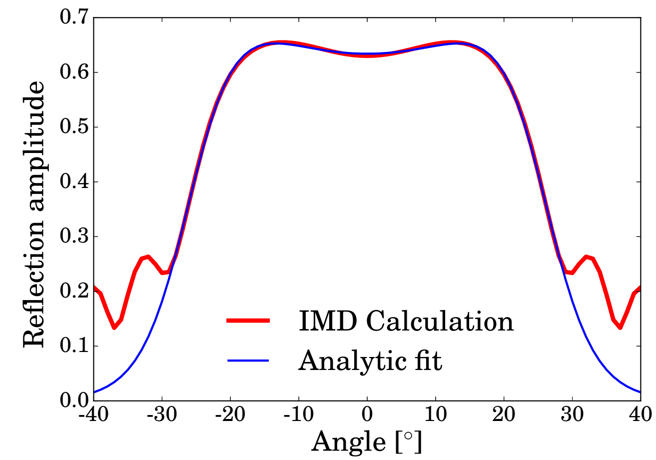
Aluminum 1200 nm

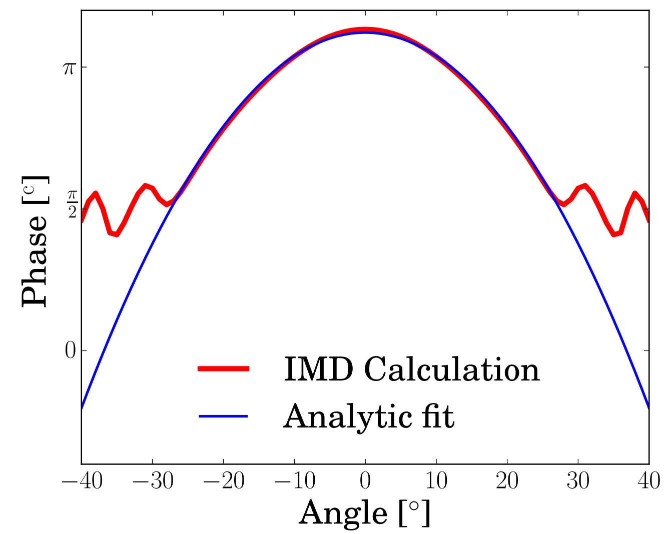
Ablated profiles difficult to describe analytically due to broken symmetry

Fresnel diffraction profiles

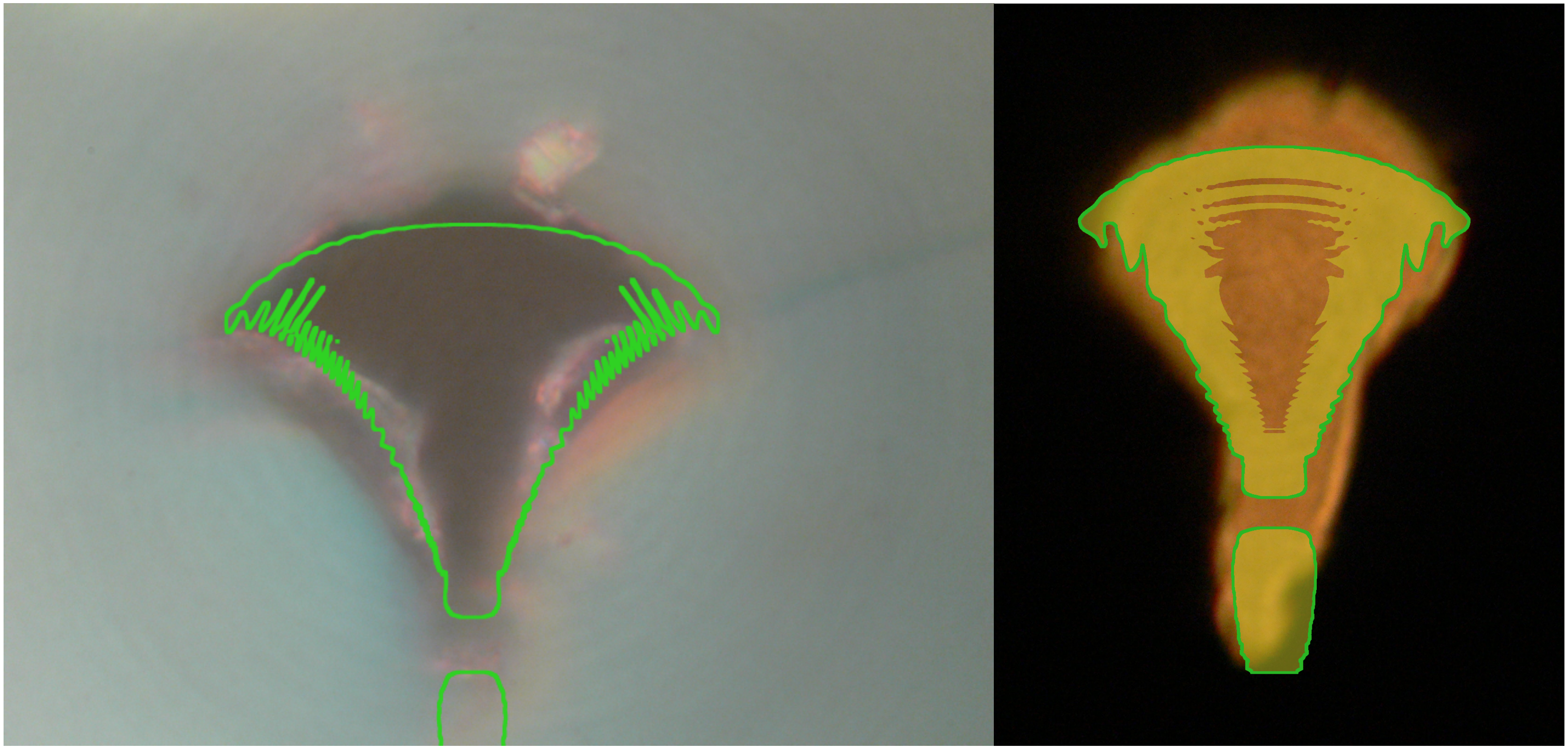
$$\tilde{u}(\tilde{r},\tilde{\theta}) = \mathcal{N}\int_0^{2\pi}\int_0^{\infty} u(r,\theta)\frac{\exp(ik\rho)}{\rho^2} r\,dr\,d\theta$$





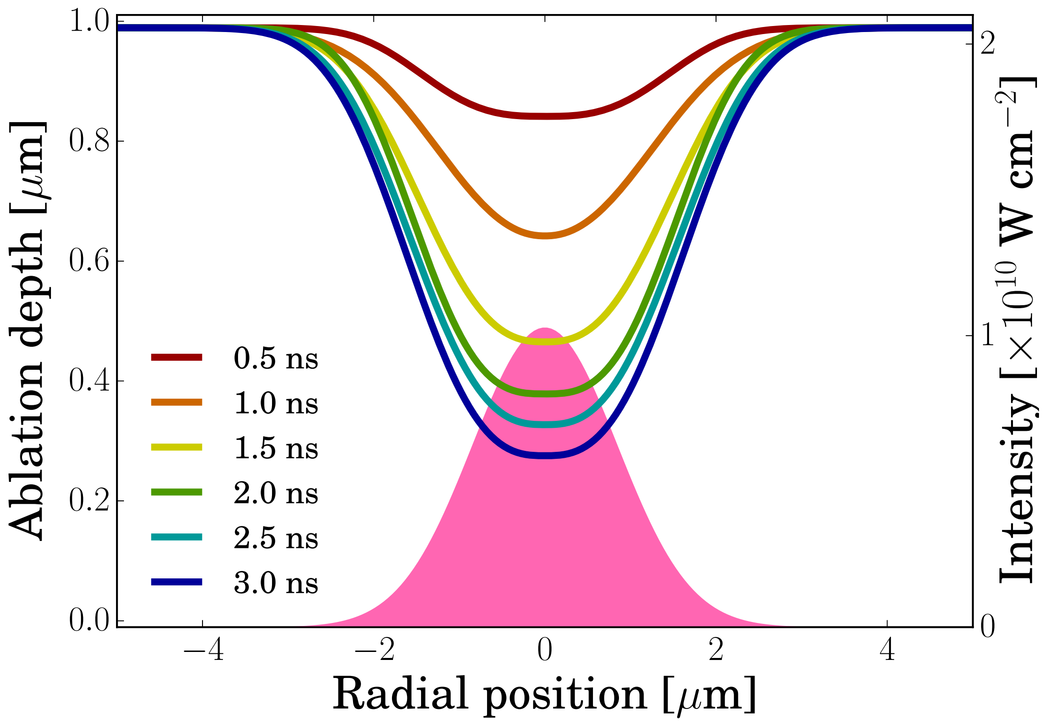


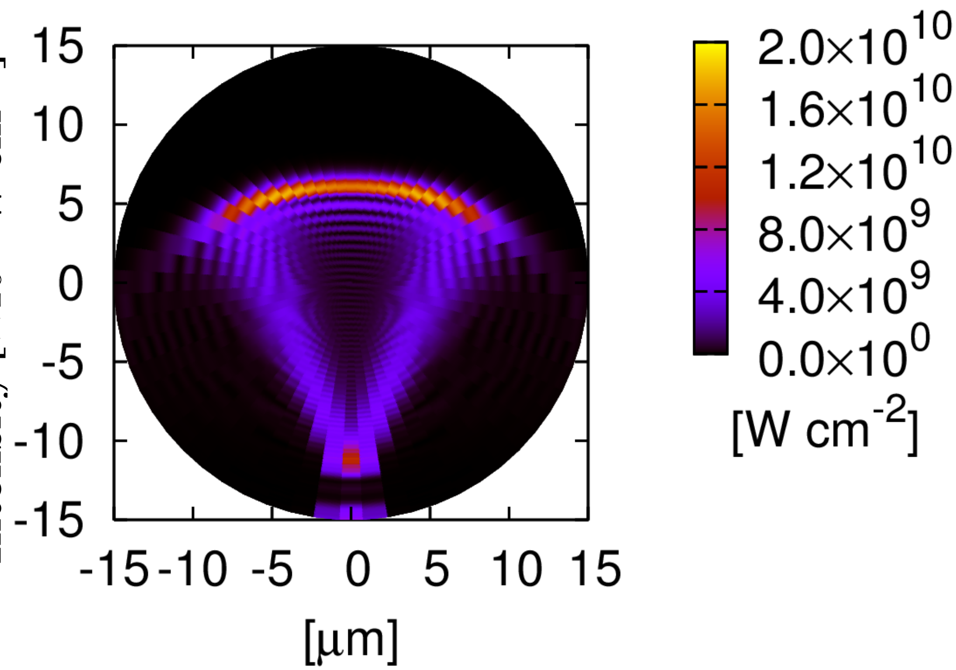
Comparison of diffraction results to target images



Appropriate intensity contours provide reasonably good fits to micrographs

Hydrodynamic simulations





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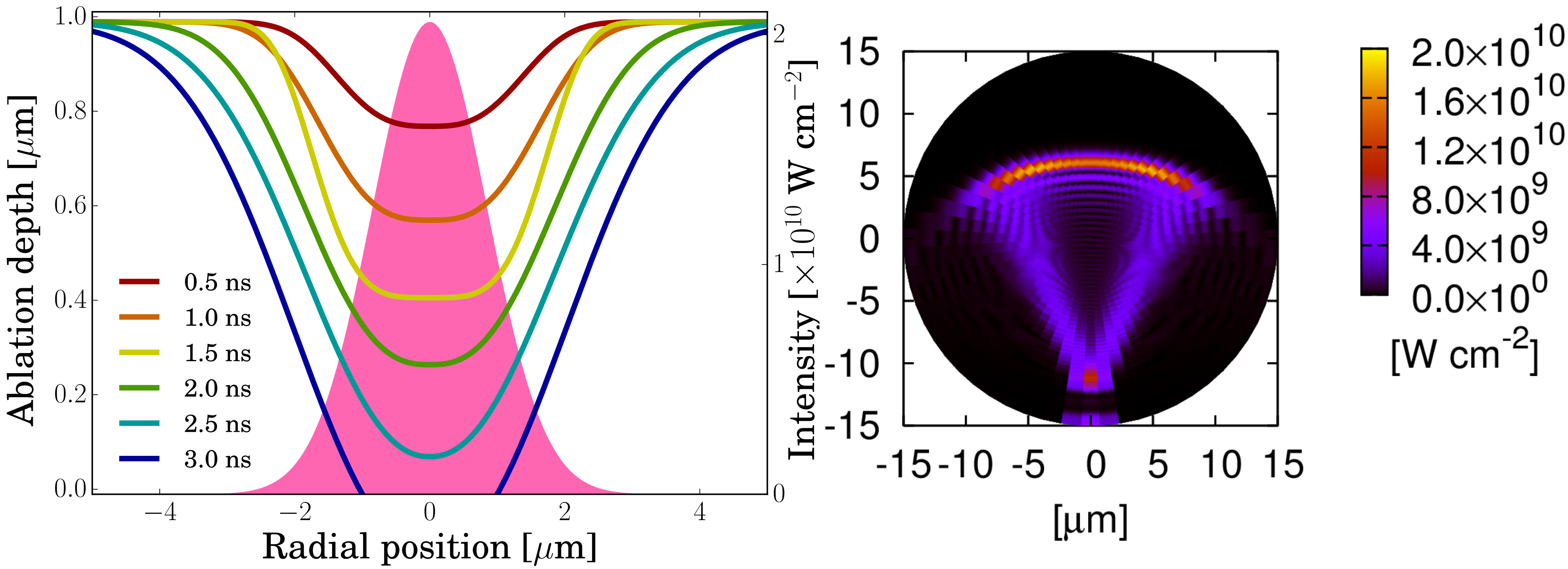

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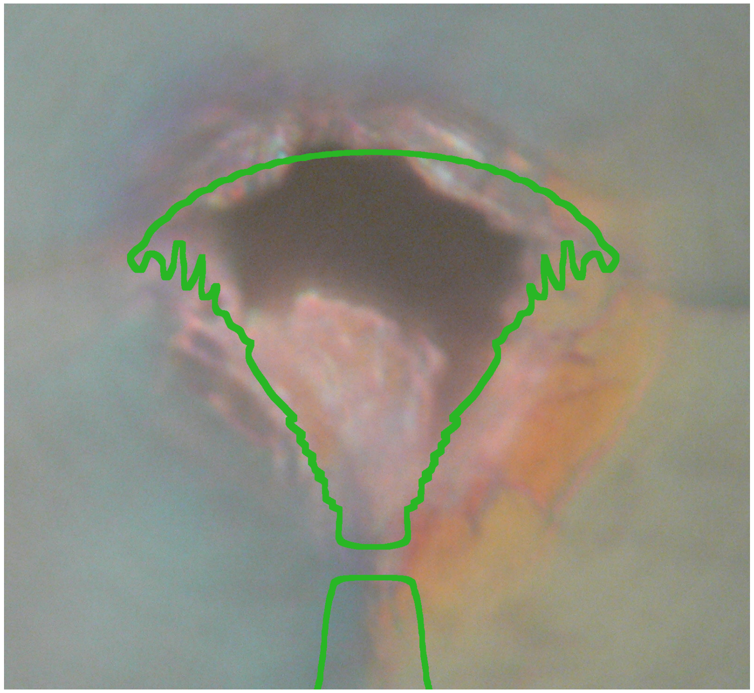

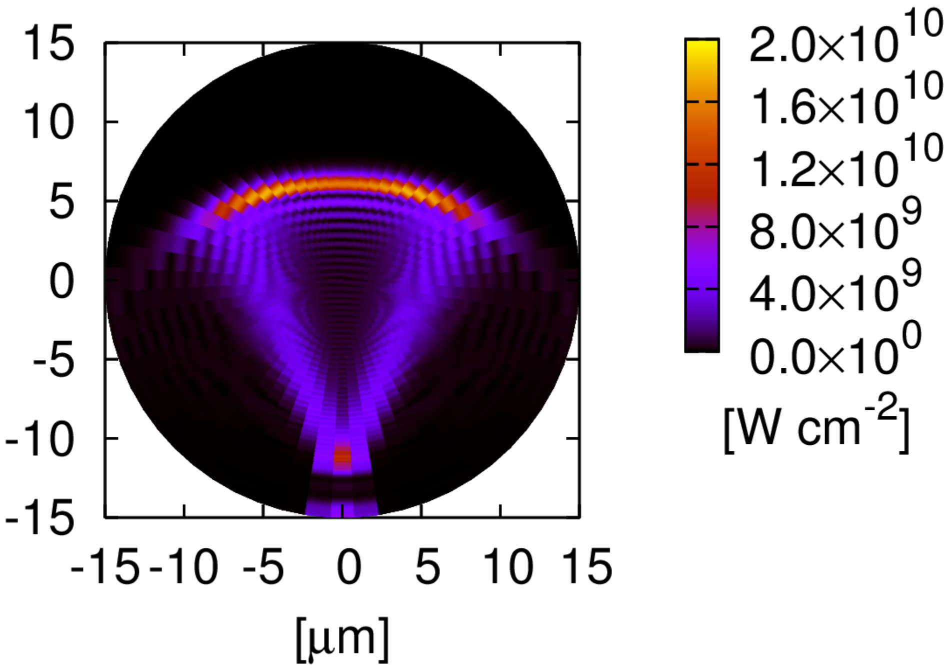

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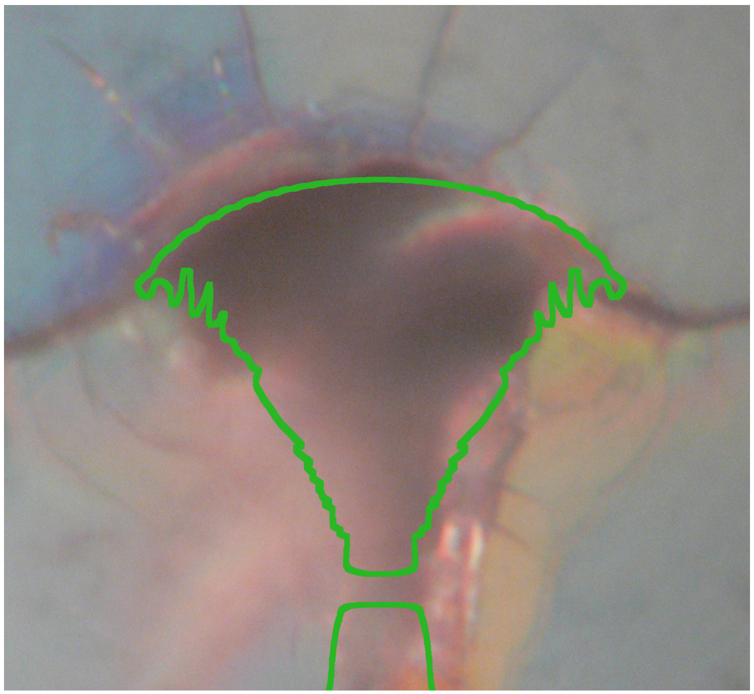

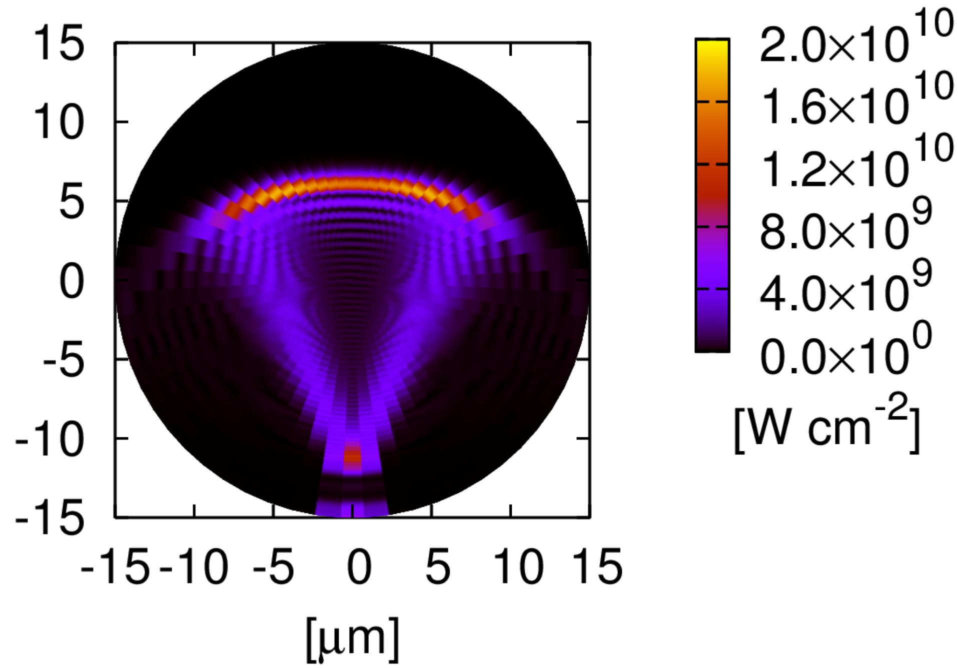

Conclusions from collisional-radiative modelling

- LTE is a useful tool for closure in hydrodynamic simulations and holds under many conditions
- Photoionization can drive plasma out of LTE, especially due to large cross section for EUV radiation
- Strong photoionizing radiation can drive a non-equilibrium opacity bleaching wave, which may be detected through modification of the beam profile

Conclusions from experimental studies

- A compact EUV laser has been characterized and used for the first time to perform experiments
- Its beam shape at focus has been calculated through Fresnel diffraction integrals and matched to experiments
- Hydrodynamic simulations have been benchmarked through microscopy (optical and AFM)