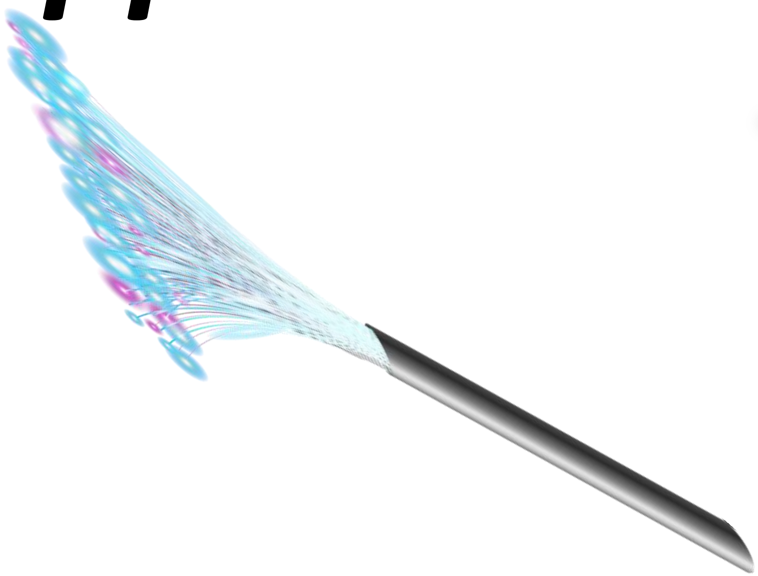
Femtosecond Laser-Induced Plasma for Semiconductors Applications



Dr. Adel Shaaban Awad Elsharkawi

Lecturer, Egyptian Atomic Energy Authority, Cairo 11787, Egypt;

A brief bio.

***Lecturer*, Egyptian Atomic Energy Authority**

Education

- B.Sc., Benha University, Egypt **(2005)**
- M.Sc., Al-Azhar University, Egypt **(2015)**
- Ph.D., Southern Taiwan University of Science and Technology, Taiwan **(2020)**

Fellowships

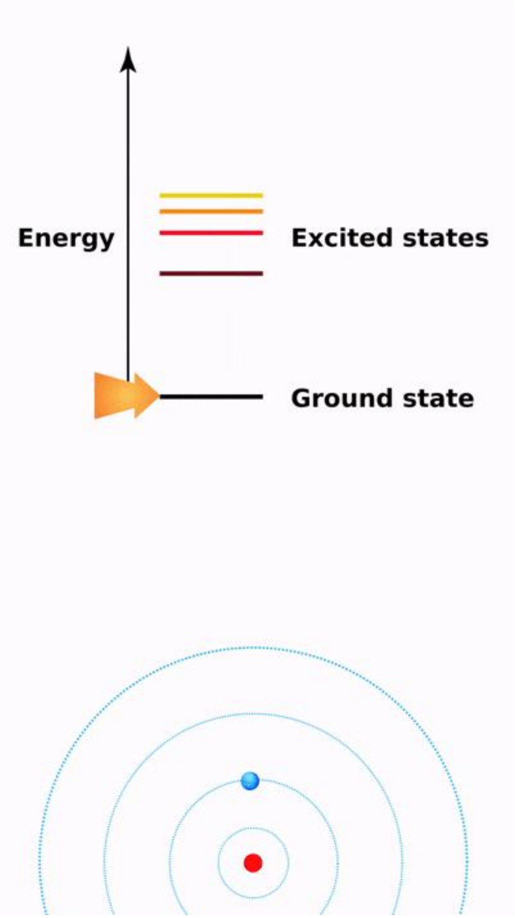
- Postdoctoral Fellowships: National Cheng Kung University, Taiwan.
- Postdoctoral Fellowships: American University in Cairo.

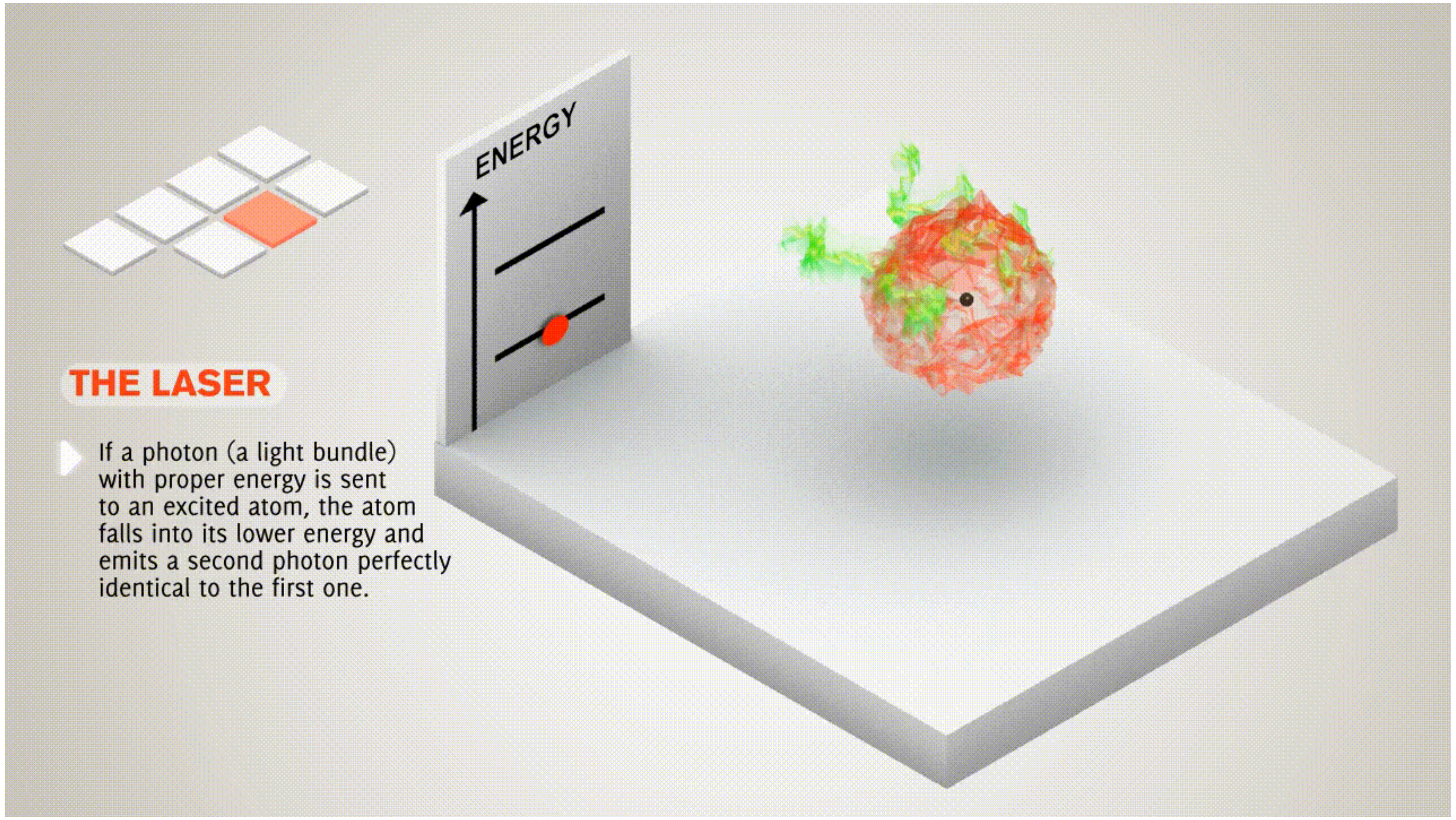
Research Interests

- Ultrafast Laser Modeling and Applications, Through-Glass Vias (TGV) and Semiconductor Packaging
- Biophotonics and Fiber-Optic Dosimetry
- Plasmonic Biosensors and Quantum Optics

6 years as: Engineer Motorola Saudi Arabia, technical support, project manager at Ericsson Egypt

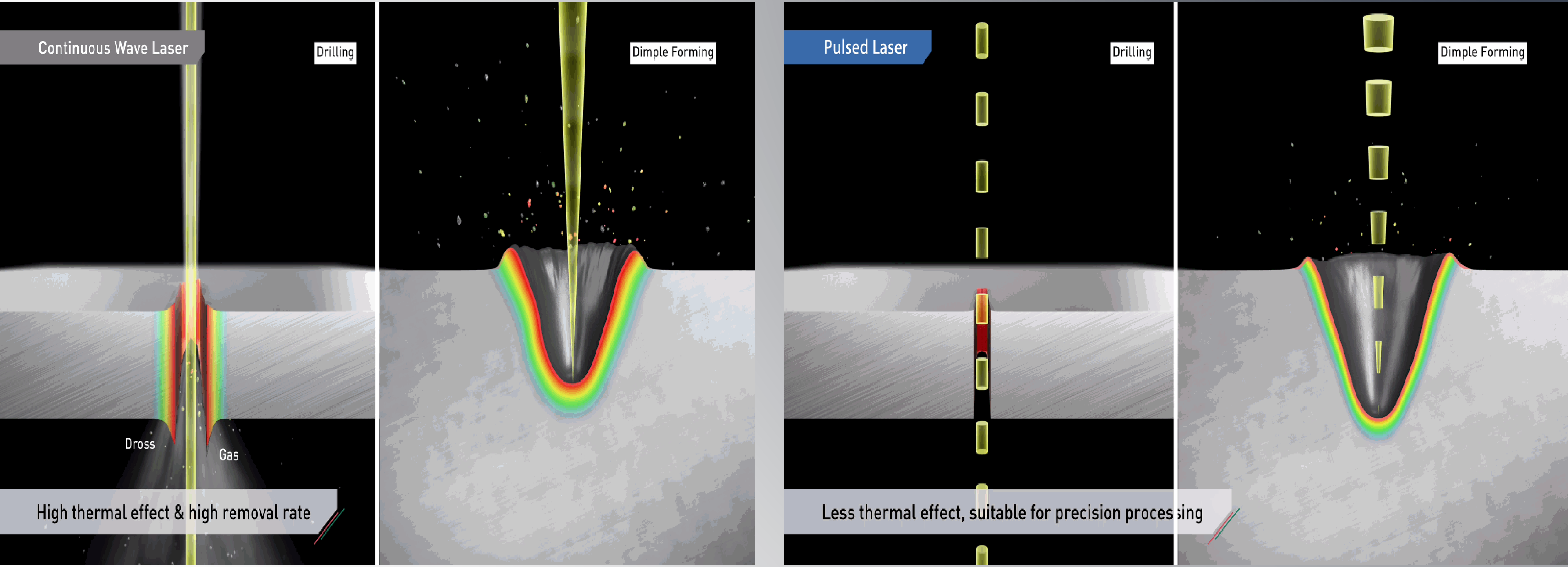
LASER (Light Amplification by Stimulated Emission of Radiation)



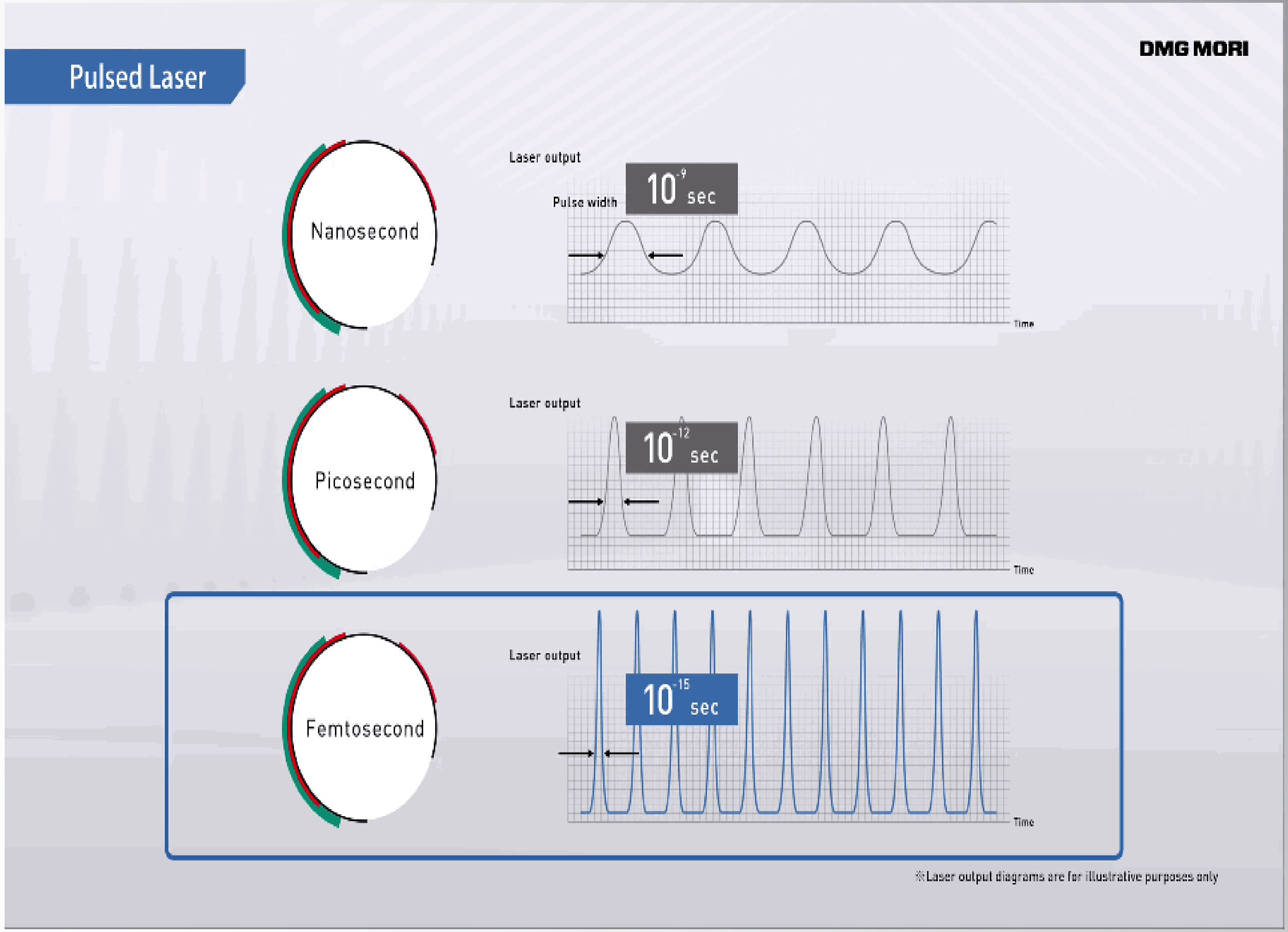


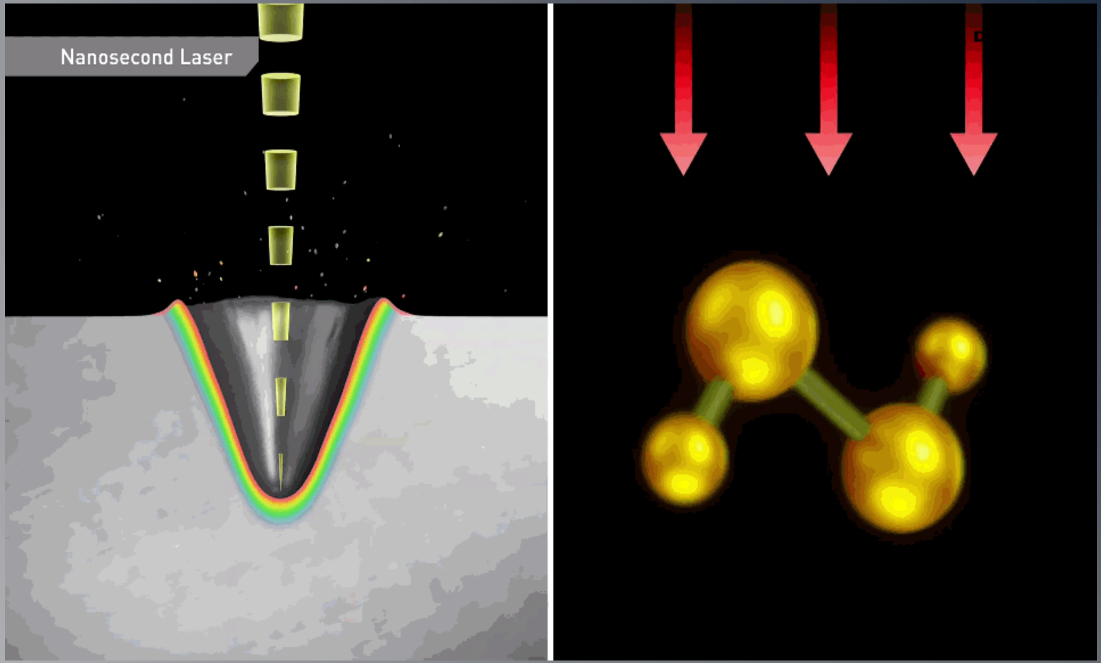
https://www.youtube.com/shorts/Ka7kuISlNSE

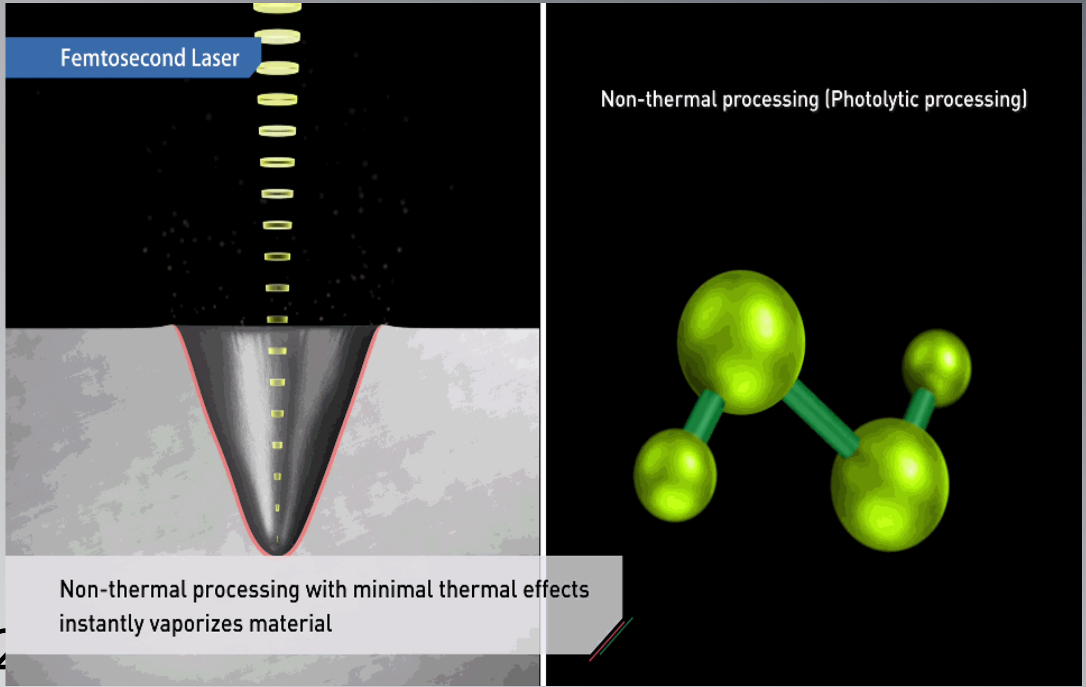
https://www.youtube.com/watch?v=R_QOWbkc7UI



https://www.youtube.com/watch?v=69n4lzw2JUQ







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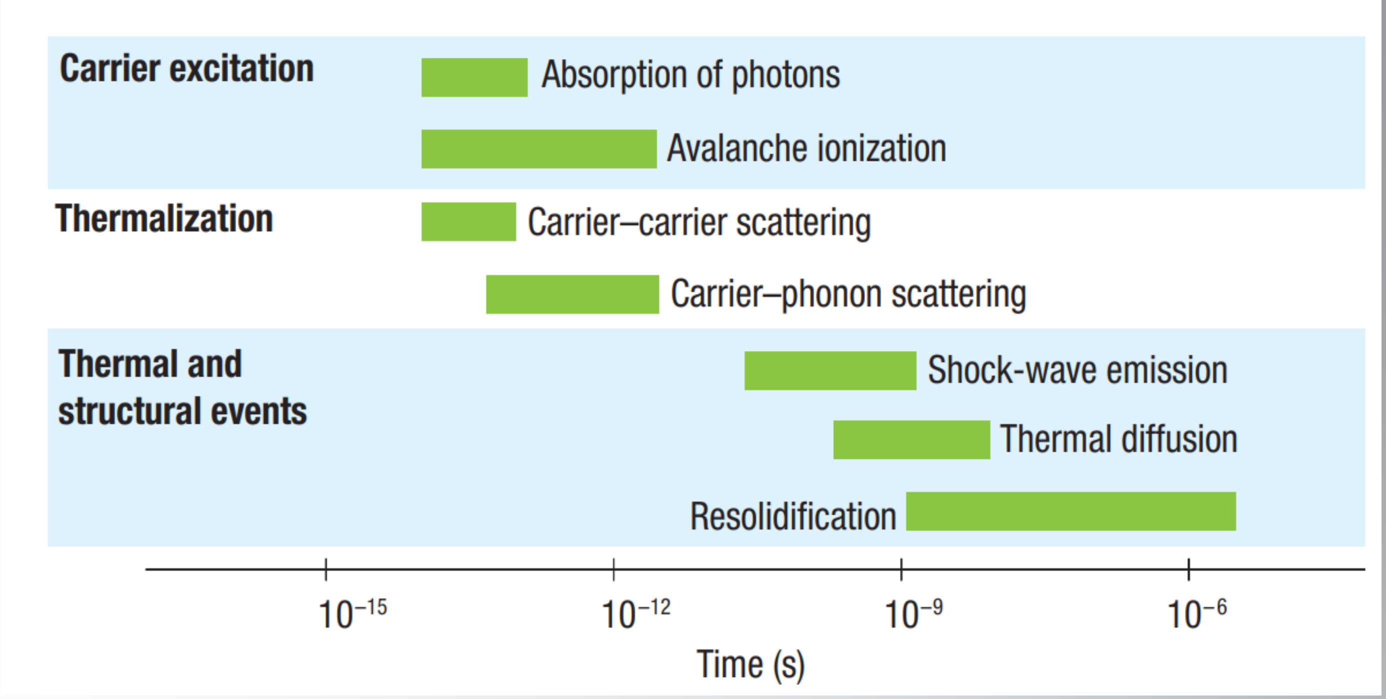
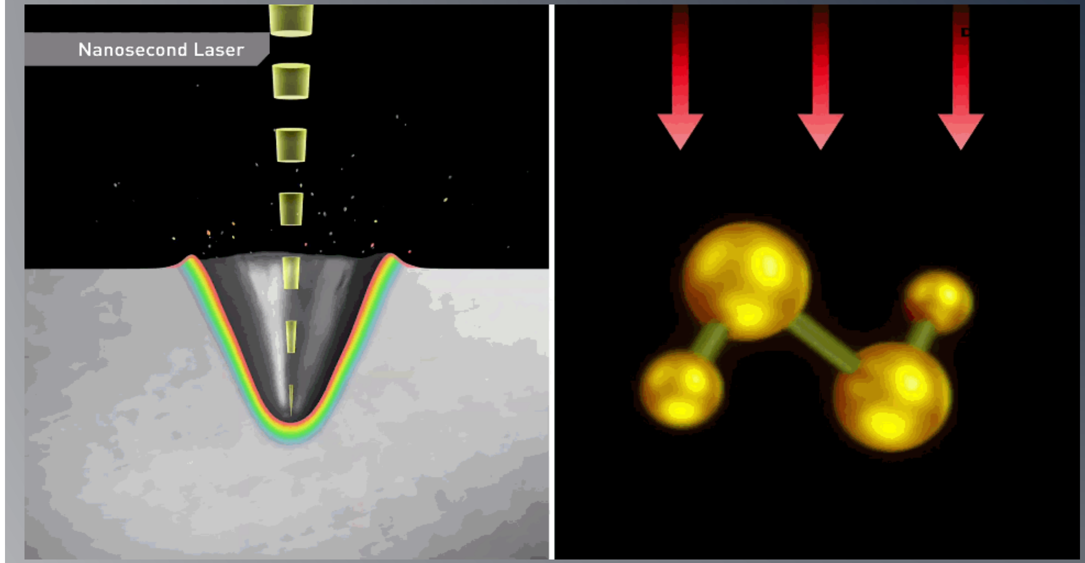
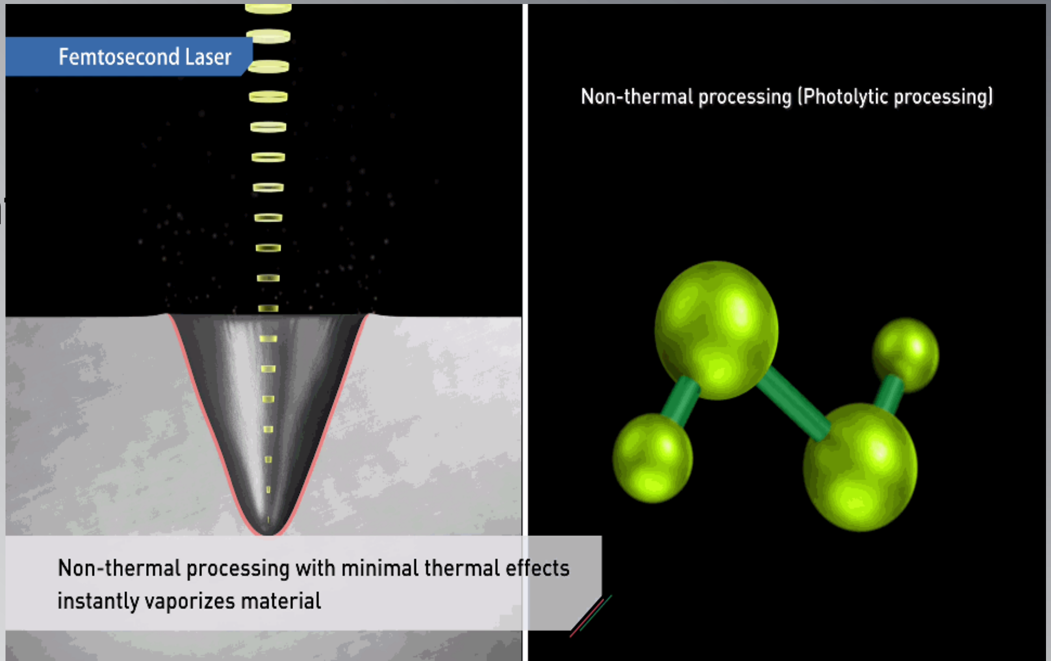


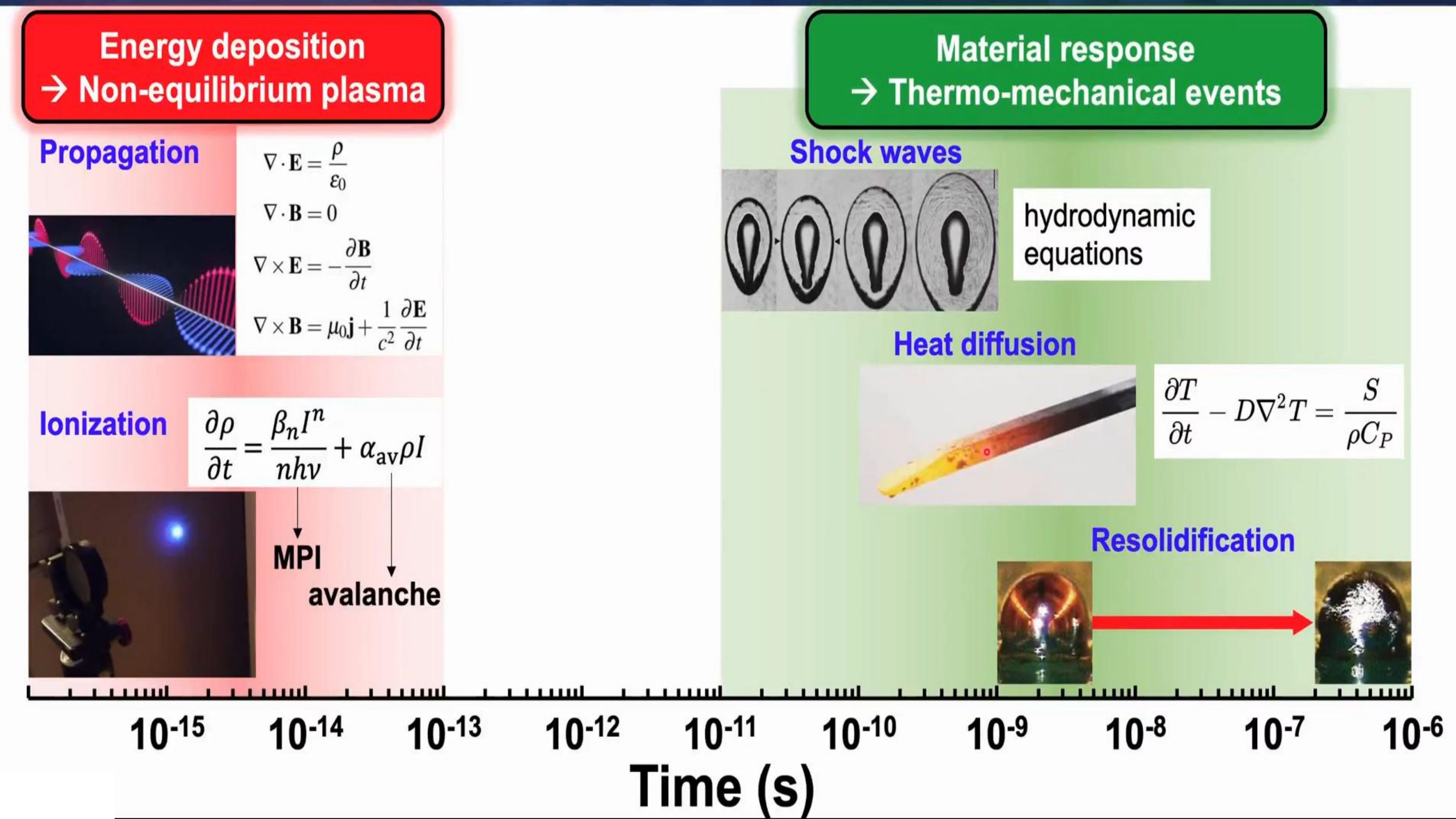




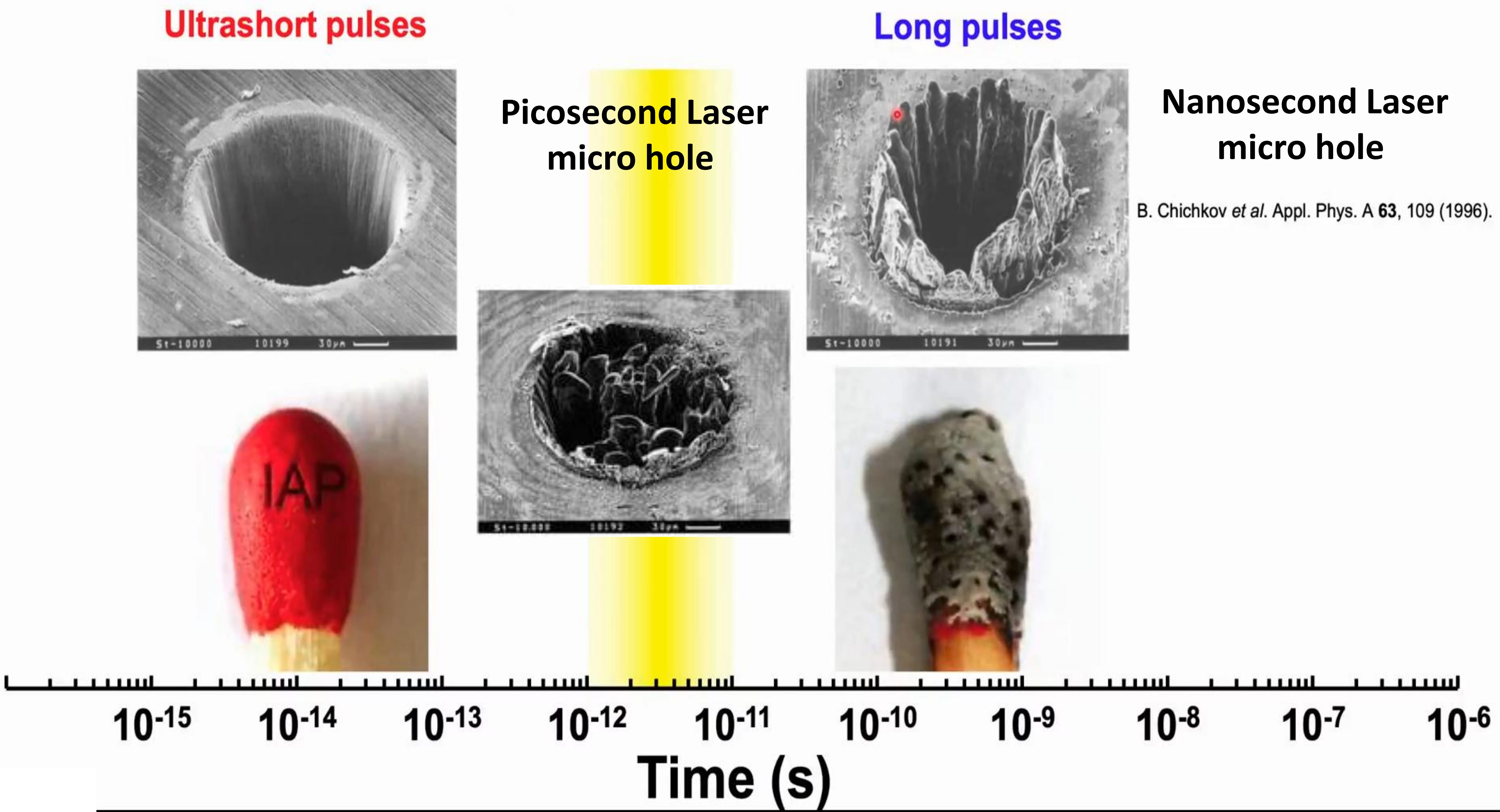
Timescale of the physical phenomena associated with the interaction of a femtosecond laser pulse with transparent materials

Gattass, R., Mazur, E. Femtosecond laser micromachining in transparent materials. *Nature Photon* **2**, 219–225 (2008).

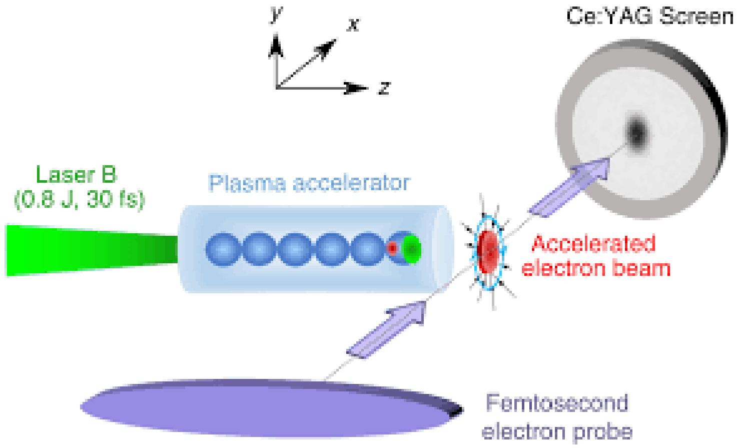
https://www.youtube.com/watch?v=69n4lzw2JUQ

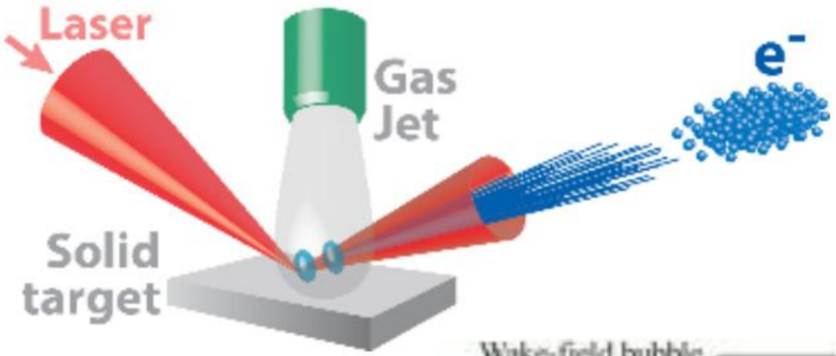


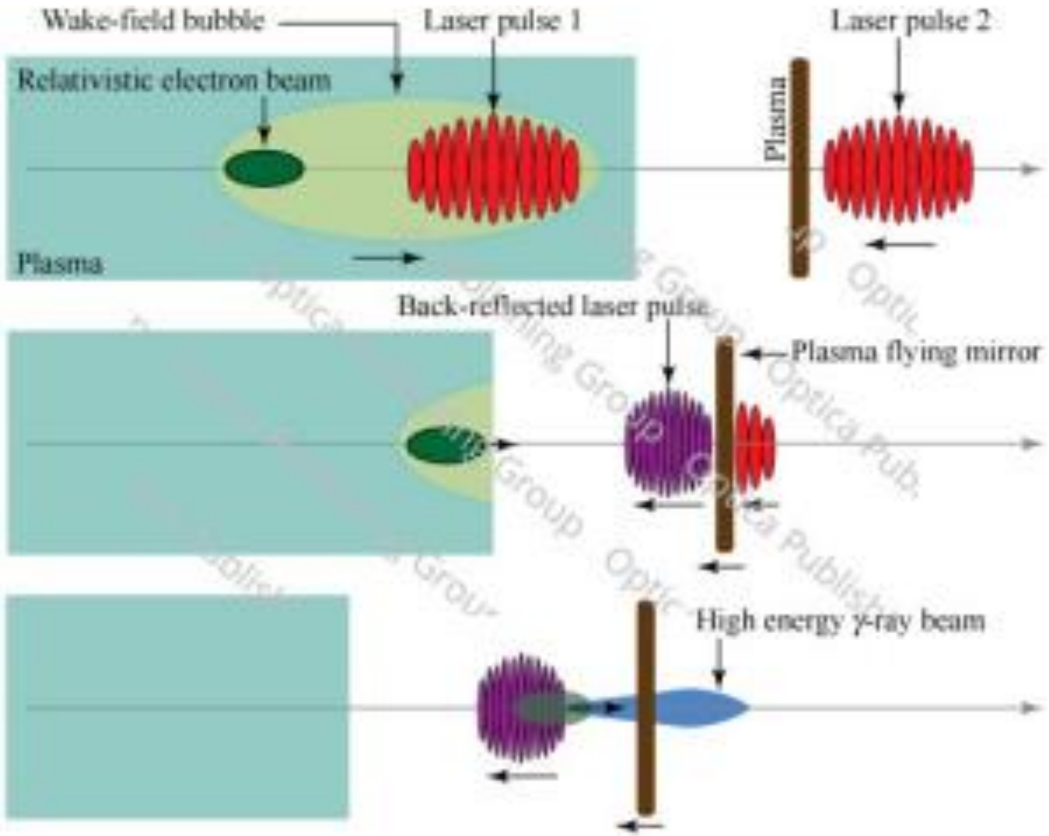
Energy deposition
→ Non-equilibrium plasma
Propagation
$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$
$\nabla \cdot \mathbf{B} = 0$
$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$
Ionization
$\frac{\partial \rho}{\partial t} = \frac{\beta_n I^n}{nh\nu} + \alpha_{av}\rho I$
MPI
avalanche
Material response
→ Thermo-mechanical events
Shock waves
hydrodynamic equations
Heat diffusion
$\frac{\partial T}{\partial t} - D\nabla^2 T = \frac{S}{\rho C_P}$
Resolidification
10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6}
Time (s)

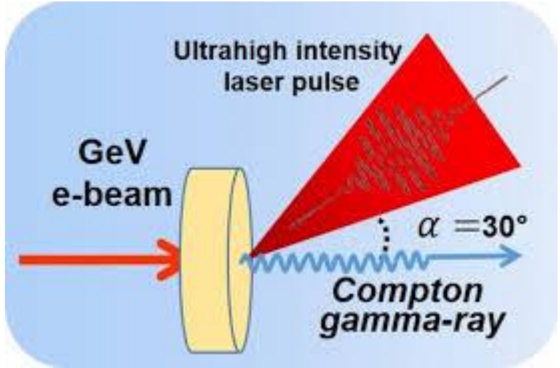

Ultrashort pulses
Long pulses
Picosecond Laser
micro hole
Nanosecond Laser
micro hole
B. Chichkov et al. Appl. Phys. A 63, 109 (1996).
St-10000 10199 30μm
St-10000 10192 30μm
St-10000 10191 30μm
IAP
10^-15 10^-14 10^-13 10^-12 10^-11 10^-10 10^-9 10^-8 10^-7 10^-6
Time (s)

Fs LASER Applications in Nuclear Environments









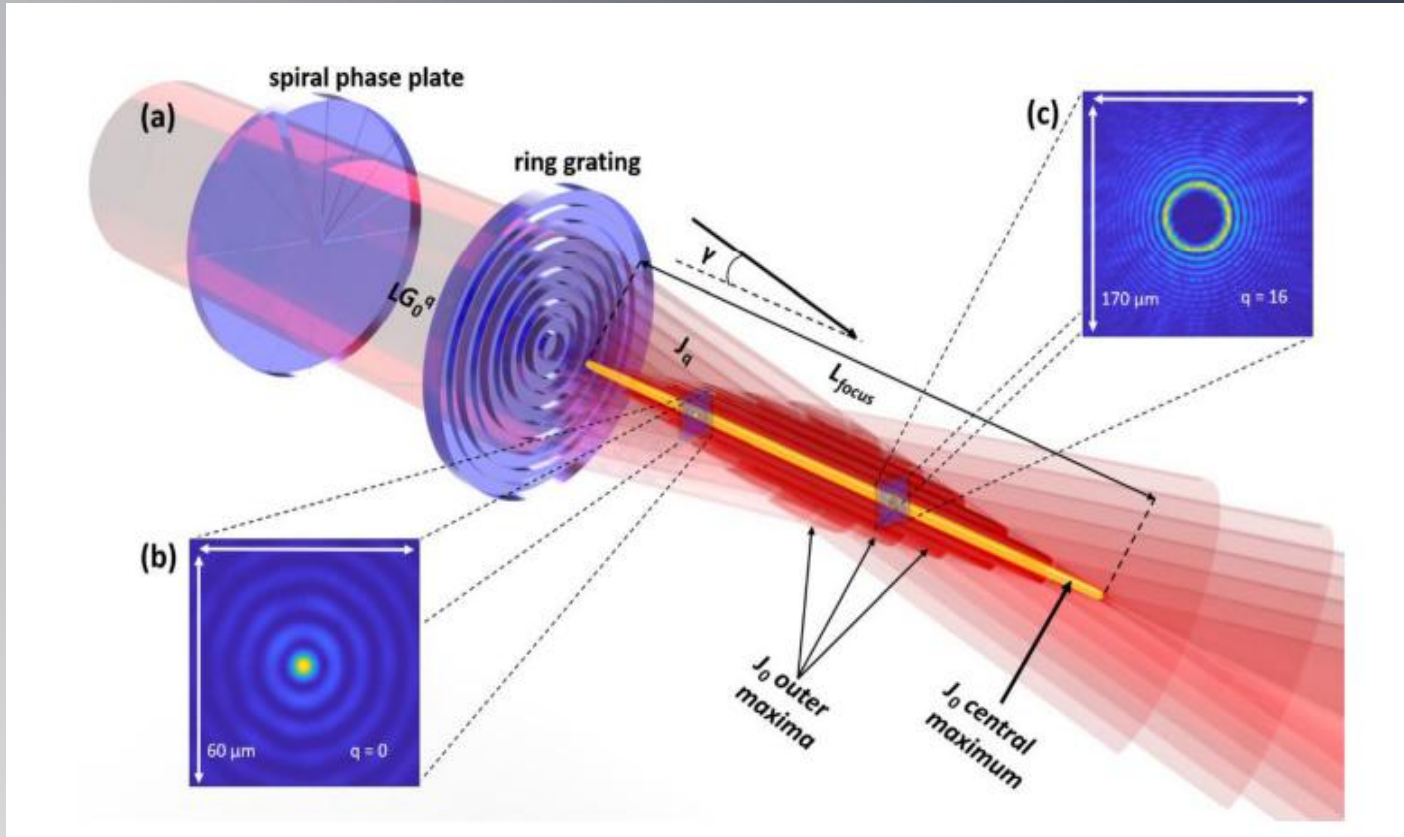
https://www.nature.com/articles/s41377-023-01142-1

https://opg.optica.org/josab/abstract.cfm?uri=josab-40-12-3262

https://iramis.cea.fr/en/anr-femtodose-project-2022-2026/

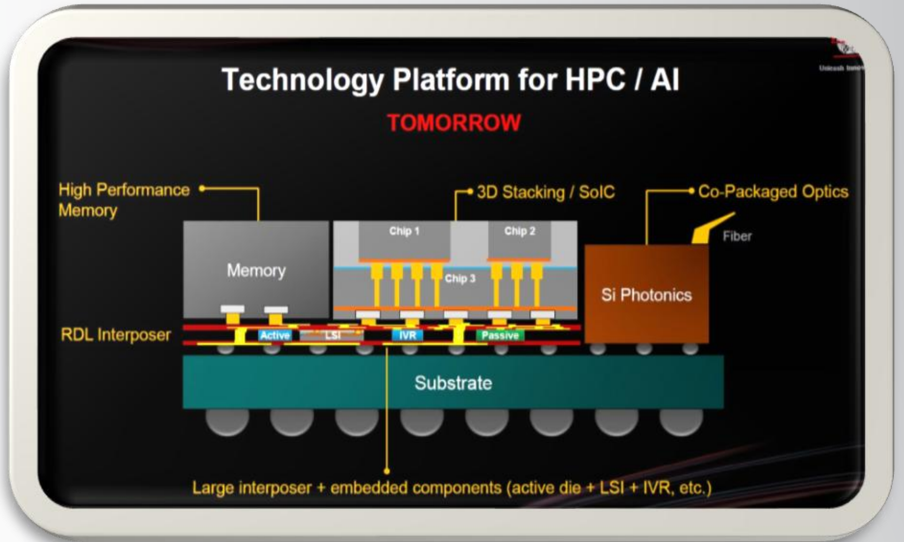
Applications I

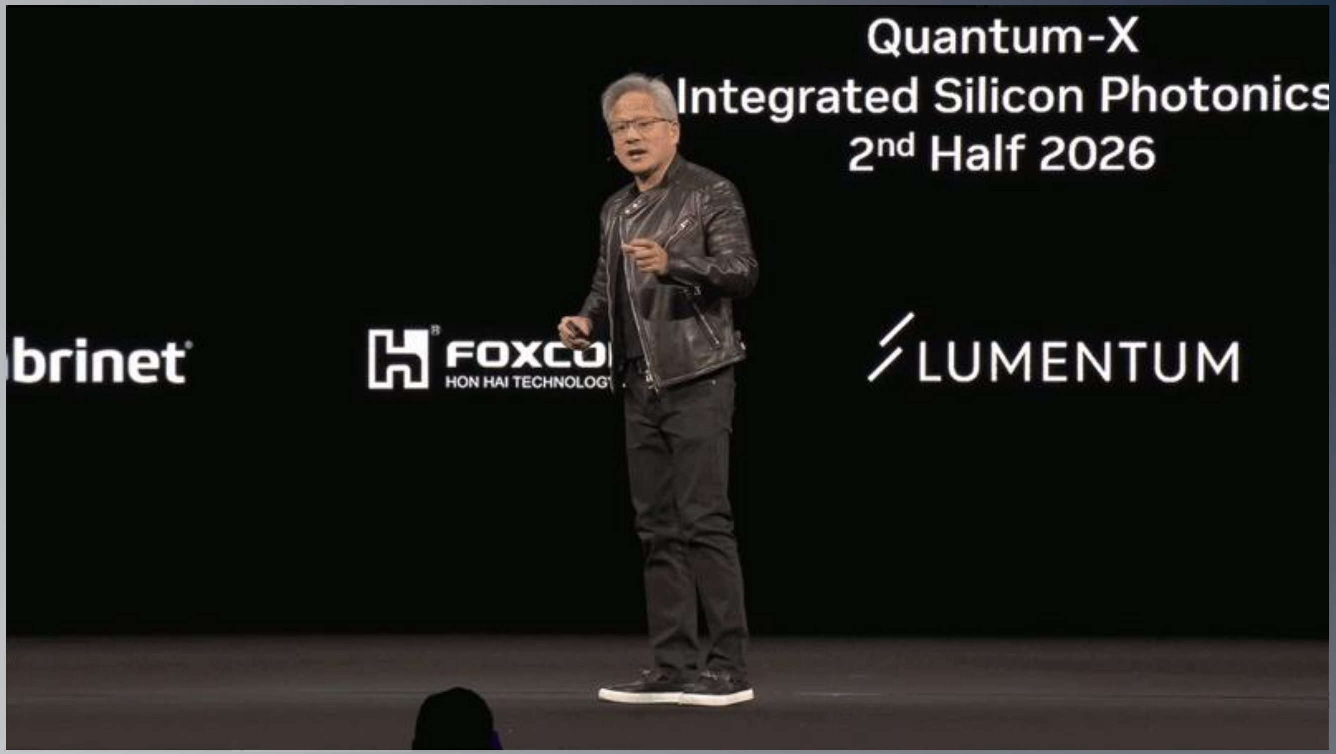
Laser Wakefield acceleration



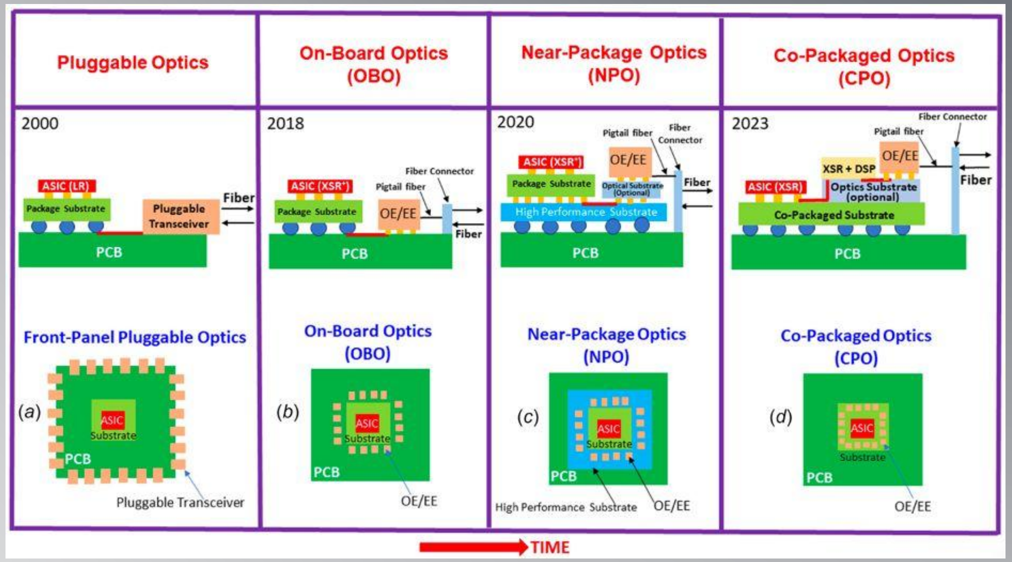
- ✓ **This work could be used in Meter-scale plasma waveguides for multi-GeV laser Wakefield acceleration**

J. E. Shrock, B. Miao, L. Feder, H. M. Milchberg; Meter-scale plasma waveguides for multi-GeV laser wakefield acceleration. *Phys. Plasmas* 1 July 2022; 29 (7): 073101.



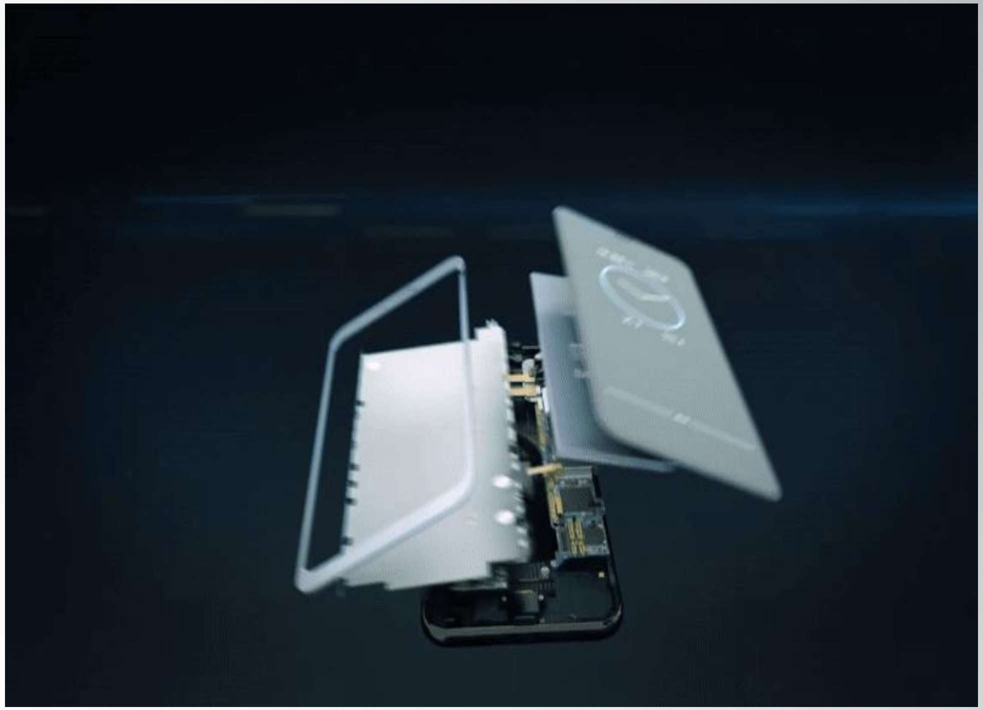


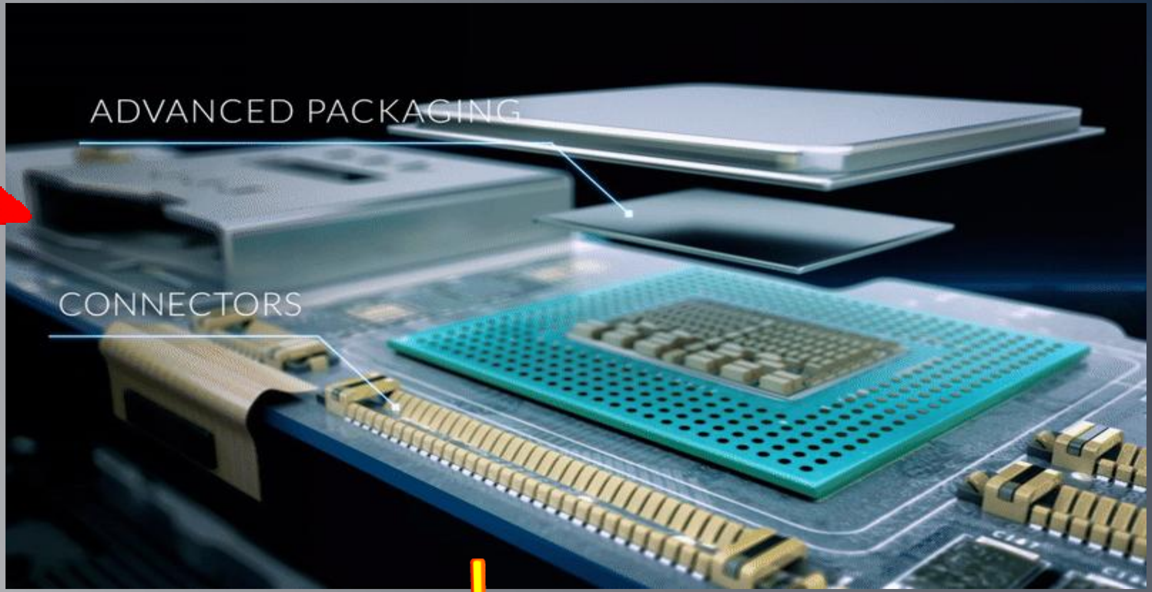
Jensen Huang

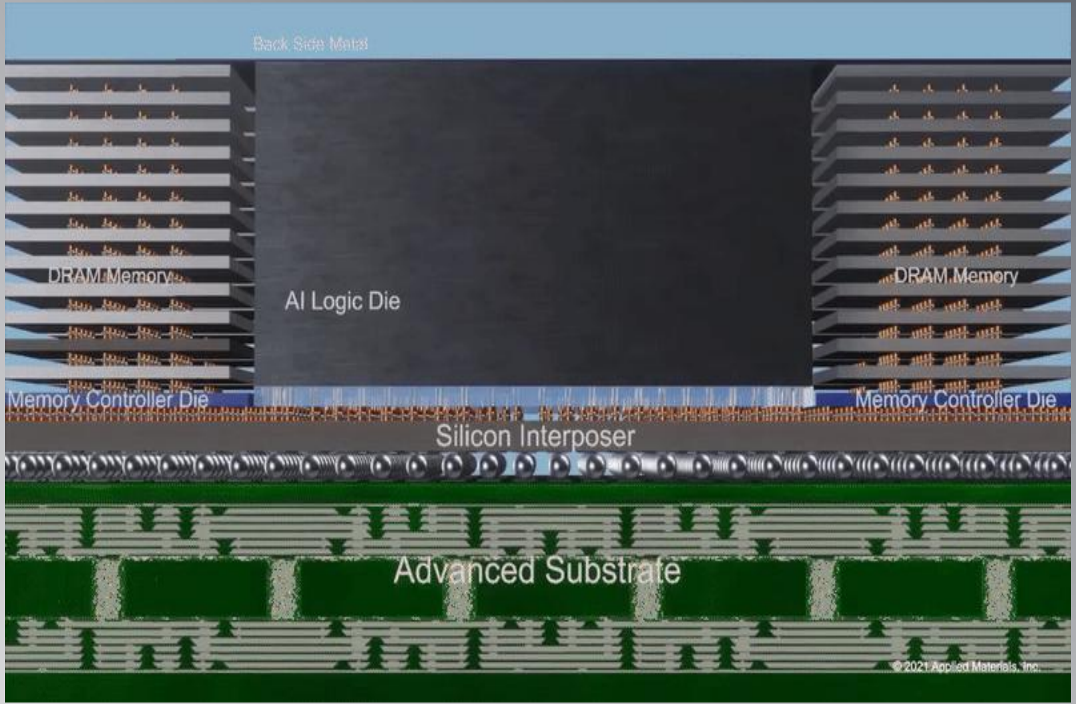


https://www.youtube.com/watch?v=mqJczTBf0nk

The new technology of semiconductors







https://www.youtube.com/watch?v=-egYoxajTz0

SiC for high-speed data transmission and AI technology

Performance Advantages of SiC

- **High Power Density**: Can carry higher voltages and currents in smaller devices.
- **High Temperature Operation**: Works up to 600–1000 °C vs Si's ~150 °C practical limit.
- **High Frequency**: Supports faster switching, reducing size of passive components (like inductors).
- **Better Thermal Management**: Naturally resists overheating, reducing need for bulky cooling.

Application-Level Advantages

- **Power Electronics**: EV inverters, chargers, solar inverters, power supplies — SiC drastically improves efficiency.
- **RF / High-Frequency**: SiC enables compact, efficient 5G base stations and radar.
- **Optical/Photonics Integration**: Its wide bandgap and low optical absorption make SiC attractive for integrated optics.
- **Reliability in Harsh Environments**: Aerospace, defense, and industrial settings benefit from SiC's stability.

https://www.youtube.com/watch?v=aake09AW1D8&t=45s

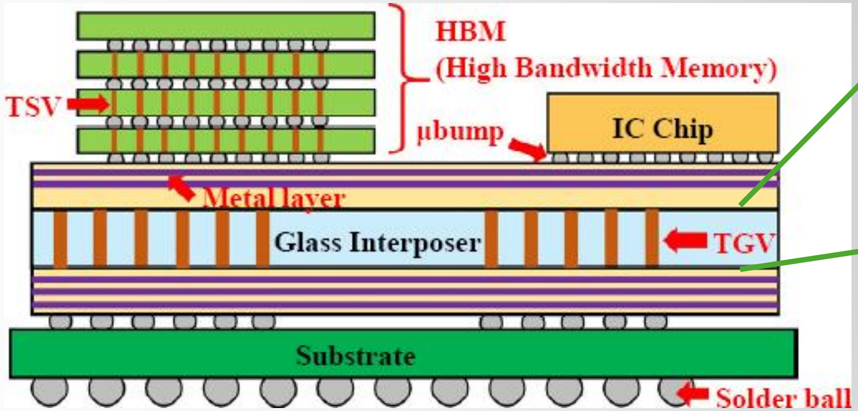
Sic for CPO (Co-packaged Optics) applications

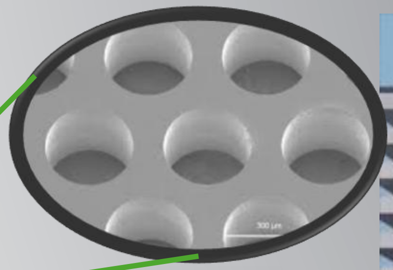
SiC interposers for CPO address the bottleneck — heat. Compared to silicon, SiC improves thermal handling, reliability, and optical integration, making it a strong candidate for next-gen AI datacenter and co-packaged optics systems.

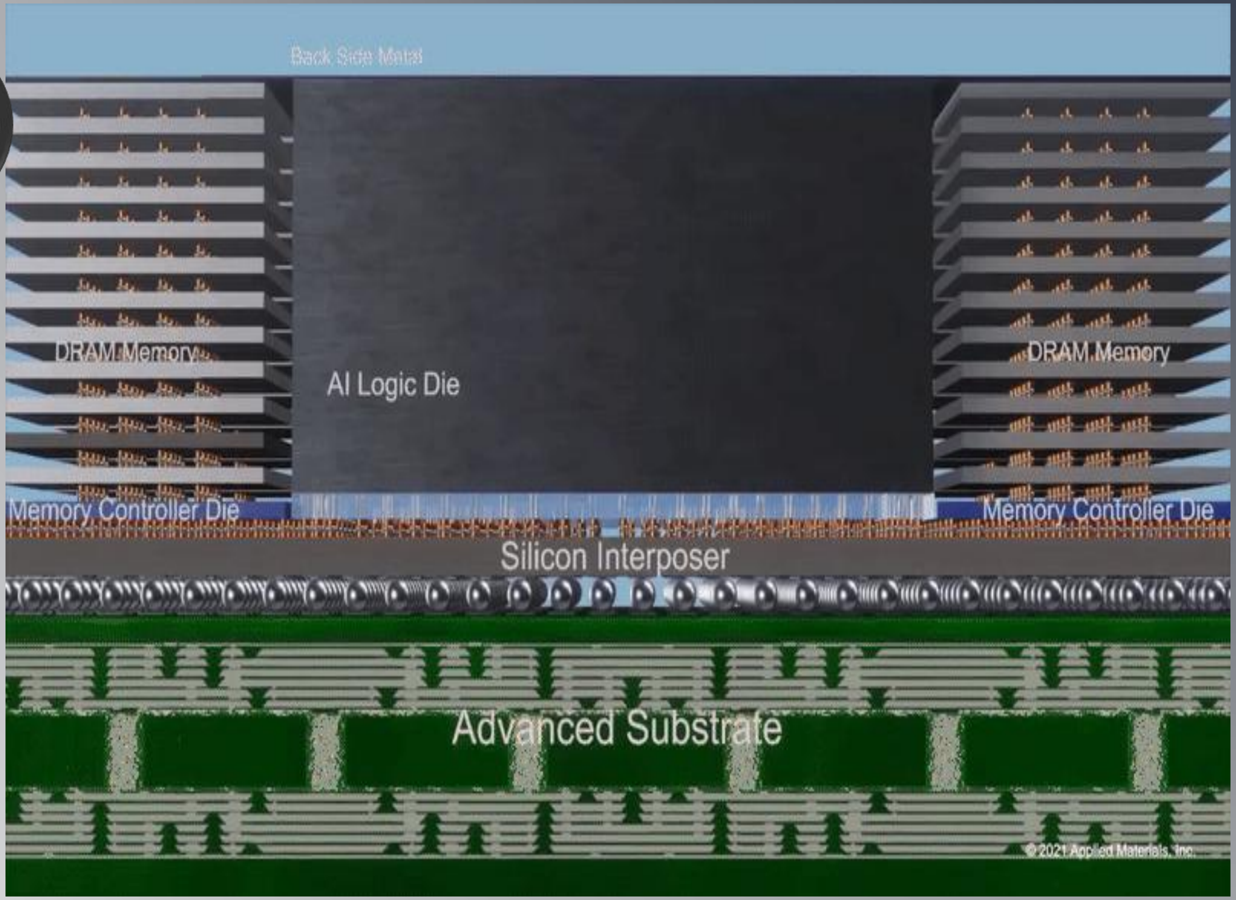
The trade-off is cost and yield, but for high-end applications, SiC could be a game-changer.

https://www.youtube.com/watch?v=PBTt3X2FpqQ

Applications: 3D silicon Packaging



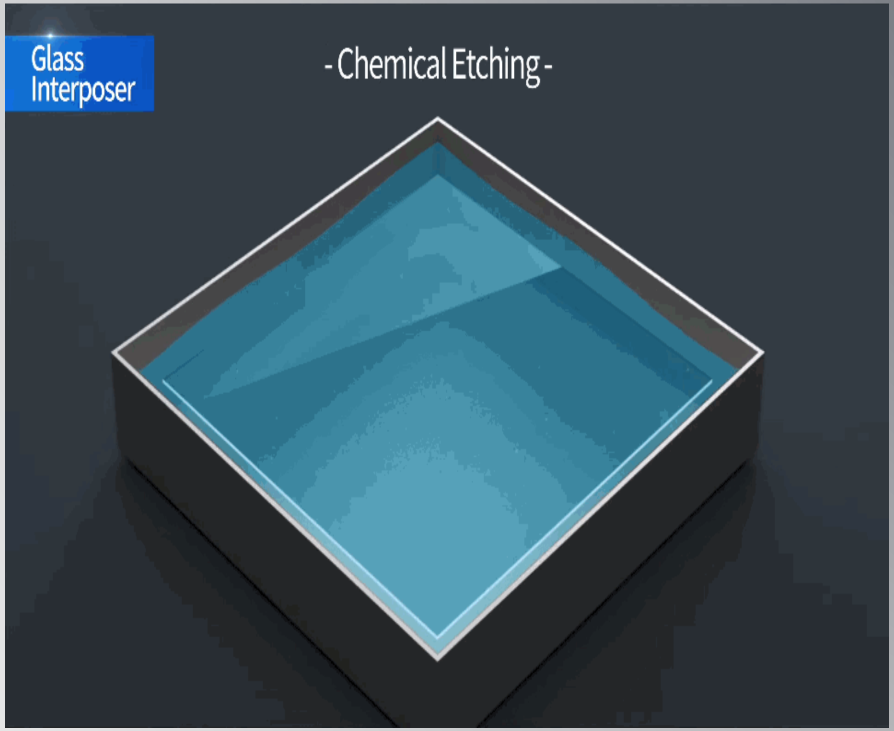


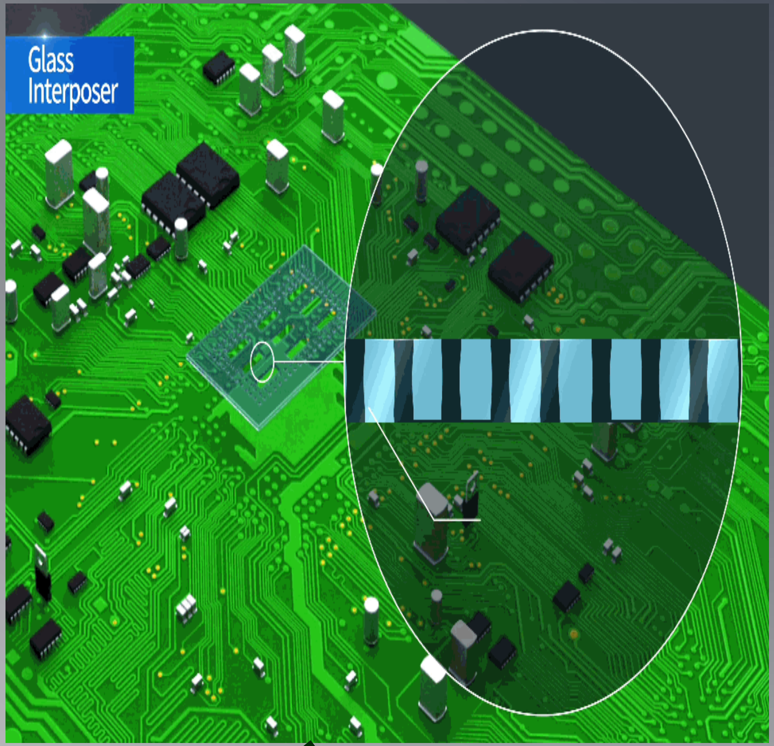


Recent Progress of TGV Technology for High Performance Semiconductor Packaging J Weld Join. 2024;42(2):155-164. Published online April 30, 2024

Applications

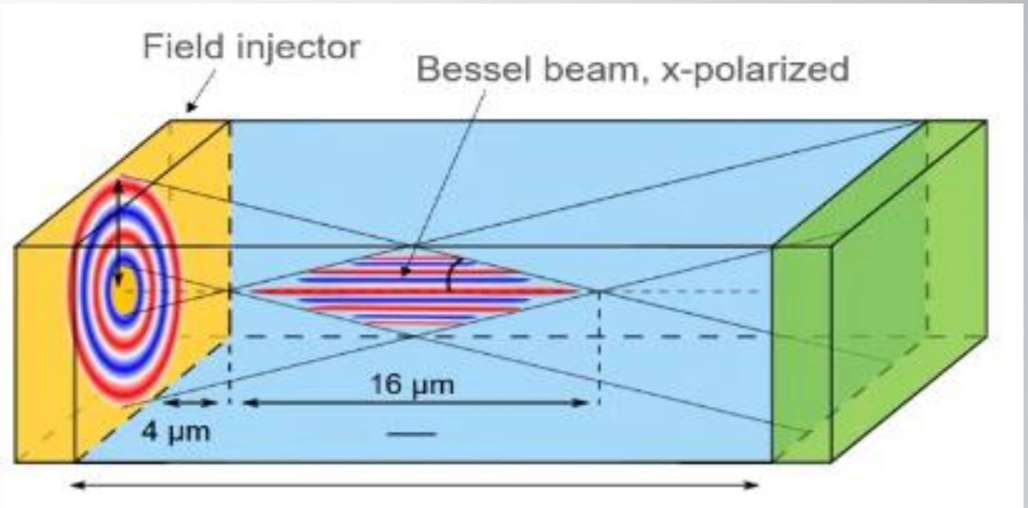
3D silicon Packaging Using TGV

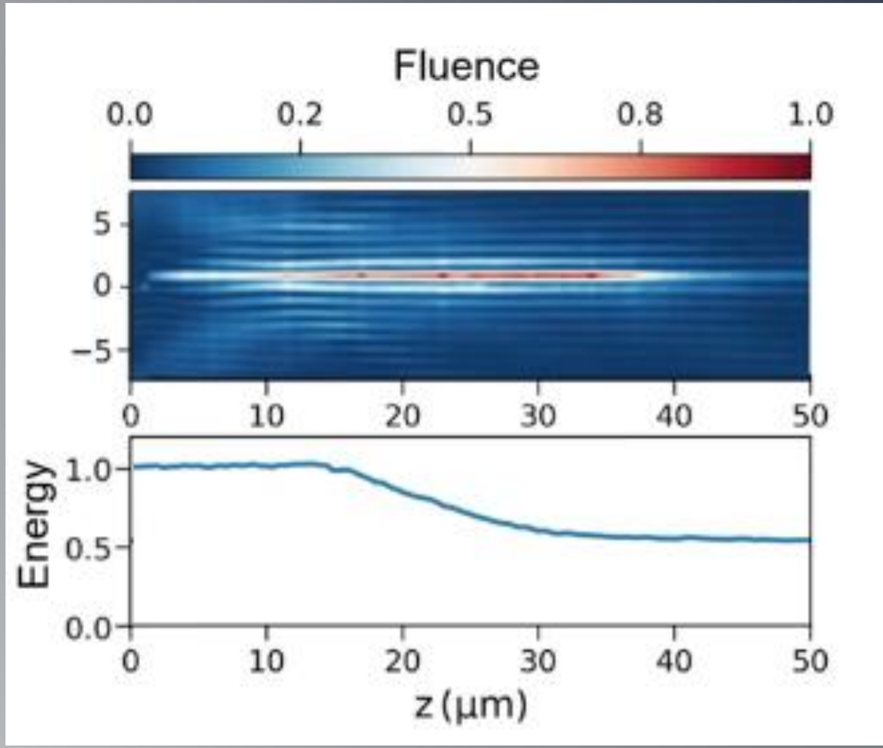


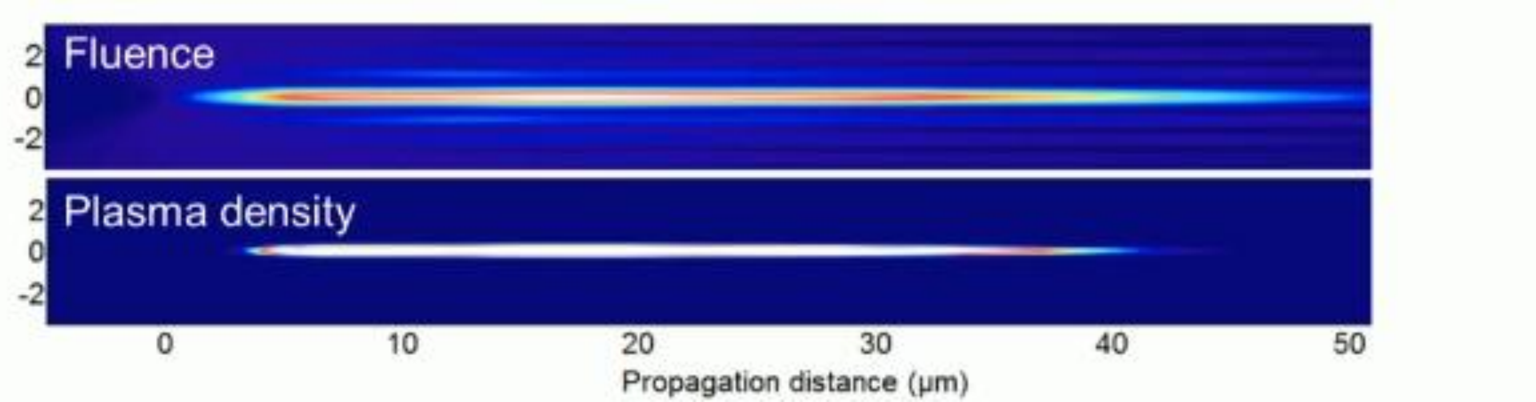


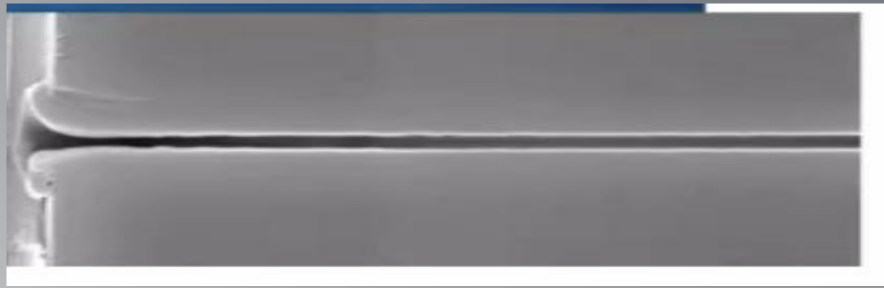
https://www.youtube.com/watch?v=IP39gGR9OVs

Single pulse









P-J Charpin, et al, Optics Express 32, 10175 (2024) "Femtosecond laser-induced sub-wavelength plasma inside dielectrics:

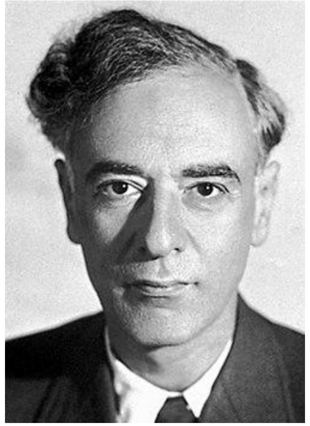
III. Terahertz radiation emission" K. Ardaneh et al, Physics of Plasmas 30, 013301 (2023)

Field Ionization Theory

Field Ionization Theory

Field ionization theory was first quantitatively developed by L. D. Landau in 1934, explaining how a strong electric field can suppress a potential barrier to enable electron tunneling ionization from an atom.

$$\mathbf{E}(\mathbf{r}, t) \approx \mathbf{E}$$



L. D. Landau

1962 Nobel Prize in Physics

Phase I — Atomic Foundation

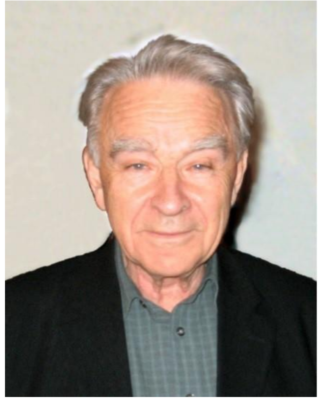
- **Keldysh (1964)** $\mathbf{E}(\mathbf{r}, t) \approx \boldsymbol{cos}(\boldsymbol{wt})$
  Ionization in the field of a strong electromagnetic wave
  → Introduced the **adiabaticity parameter**

$$\gamma = \frac{\omega}{eF}\sqrt{2\mu E_g}$$

Phase II — Atomic Refinements

- **Perelomov–Popov–Terent'ev (1966–1967)**
  → Improved saddle-point evaluation
  → Correct Coulomb corrections (PPT theory)

- **Ammosov–Delone–Krainov (1986)**
  → Practical tunneling limit (ADK)



L. V. Keldysh

Phase III — Modern Femtosecond with Solids

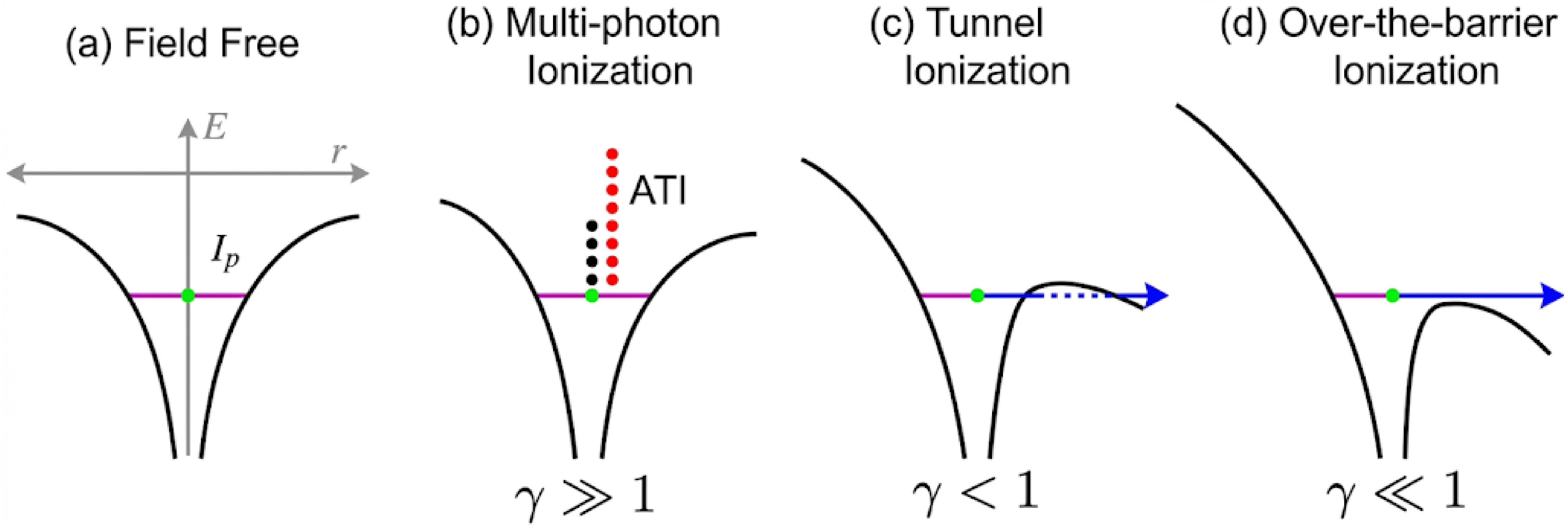
- fs dielectrics (SiO_2, SiC, sapphire), ultrafast breakdown, avalanche coupling
- strong-field intraband motion (Bloch acceleration)

$$\gamma = \frac{T\ (Tuniling\ time)}{\tau\ (Optical\ pulse\ )}$$

DOI 10.1088/0953-4075/47/20/204001

Reiss, H. R. "Complete Keldysh theory and its limiting cases." *Physical Review A* 42.3 (1990): 1476-1486.

Keldysh theory for ionization: depend on keldysh parameter “γ"



$\gamma = \frac{\omega}{eF}\sqrt{2\mu E_g}$

$, \gamma = \frac{T\ (Tuniling\ time)}{\tau\ (Optical\ pulse\ )}$

Keldysh Photoionization Rate:

Assembling all pieces, the ionization rate per unit volume is:

$$w_{PI}(E_0) = \frac{2\omega_0}{9\pi}\left(\frac{\omega_0\mu}{\hbar\gamma_1}\right)^{3/2} Q(\gamma,x)\exp\left[-\pi\lfloor x+1\rfloor\cdot\frac{K(\gamma_1)-E(\gamma_1)}{E(\gamma_2)}\right]$$

with definitions:

$$\gamma = \frac{\omega_0\sqrt{\mu U_g}}{eE_0},\quad \gamma_1 = \frac{\gamma}{\sqrt{1+\gamma^2}},\quad \gamma_2 = \frac{1}{\sqrt{1+\gamma^2}},\quad x = \frac{\tilde{U}}{\hbar\omega_0},\quad \tilde{U} = \frac{2U_g}{\pi\gamma_1}E(\gamma_2)$$

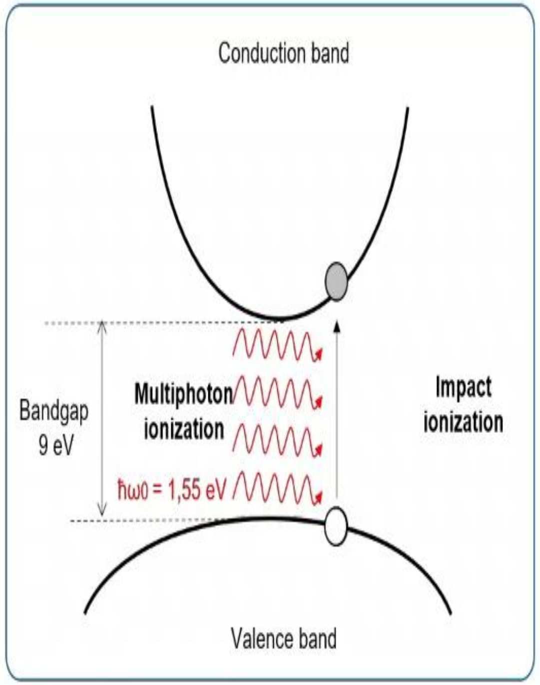
Photon Channels: $Q(\gamma,x)$ Function

Due to periodicity, the total amplitude is a coherent sum over saddles $t_s^{(n)}$. This sum reorganizes into a sum over photon channels $n = 0,1,2,\ldots$, where n counts extra photons beyond $N_{\min}$.

The **channel-sum function** is:

$$Q(\gamma,x) = \sqrt{\frac{\pi}{2K(\gamma_2)}}\sum_{n=0}^{\infty}\exp\left[-\pi n\cdot\frac{K(\gamma_1)-E(\gamma_1)}{E(\gamma_2)}\right]\Phi\left(\frac{\pi}{2}\sqrt{\frac{2\lfloor x+1\rfloor-2x+n}{K(\gamma_2)E(\gamma_2)}}\right)$$

where $\Phi(z) = \int_0^z e^{y^2-z^2}\,dy = \frac{\sqrt{\pi}}{2}e^{-z^2}\mathrm{Im}[\mathrm{Erf}(iz)]$.

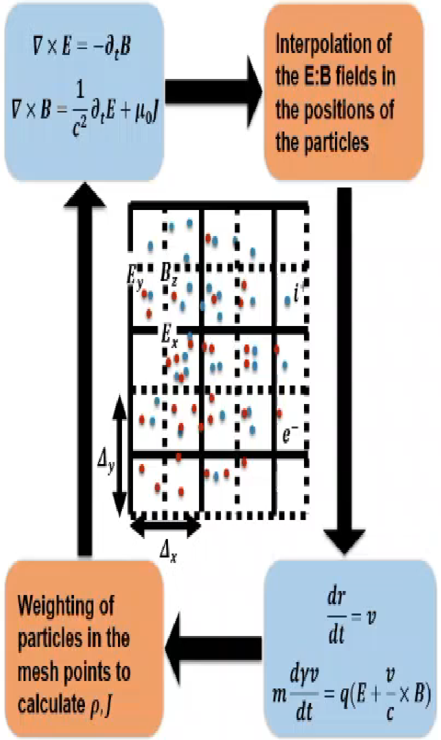


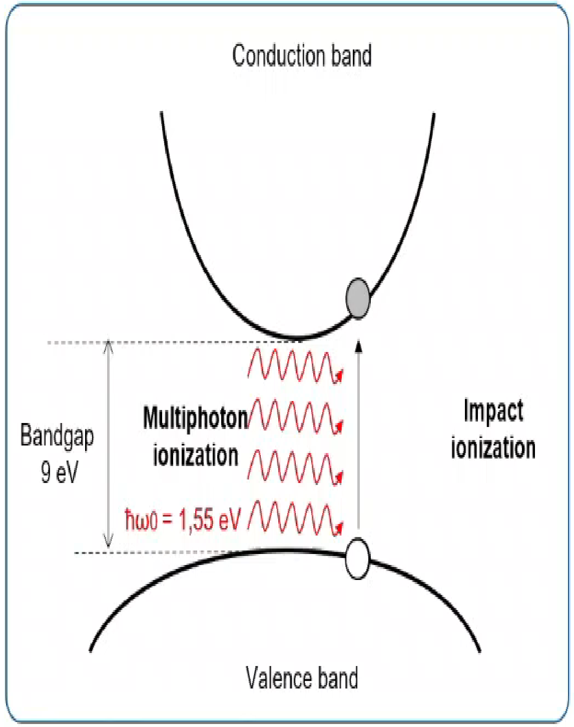
P-J Charpin, et al, *Optics Express* **32**, 10175 (2024)

Can we reproduce the diagnostics with Particle In Cell simulations ?

We included medium permittivity + multiphoton ionization + impact in EPOCH code

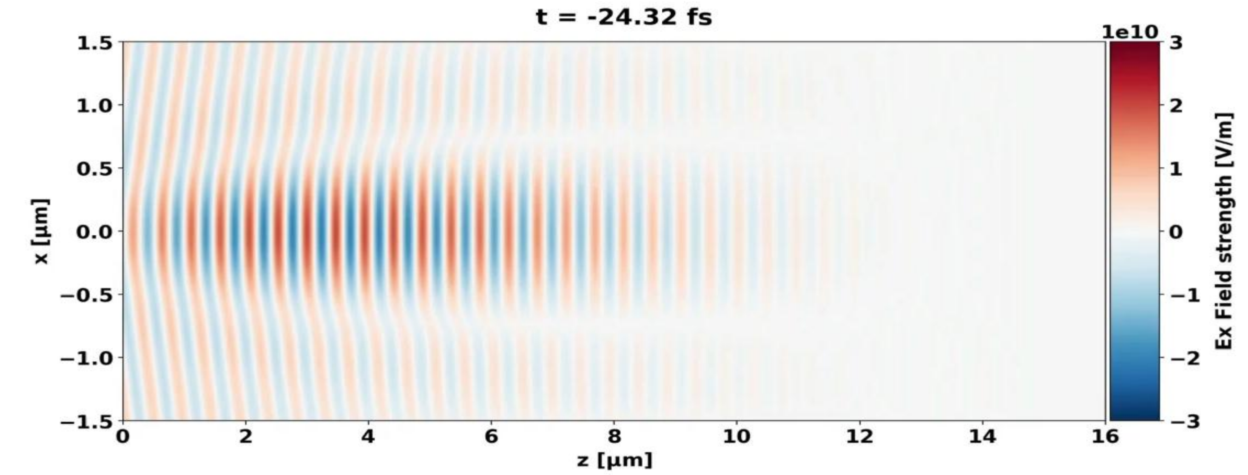
We use Keldysh model.

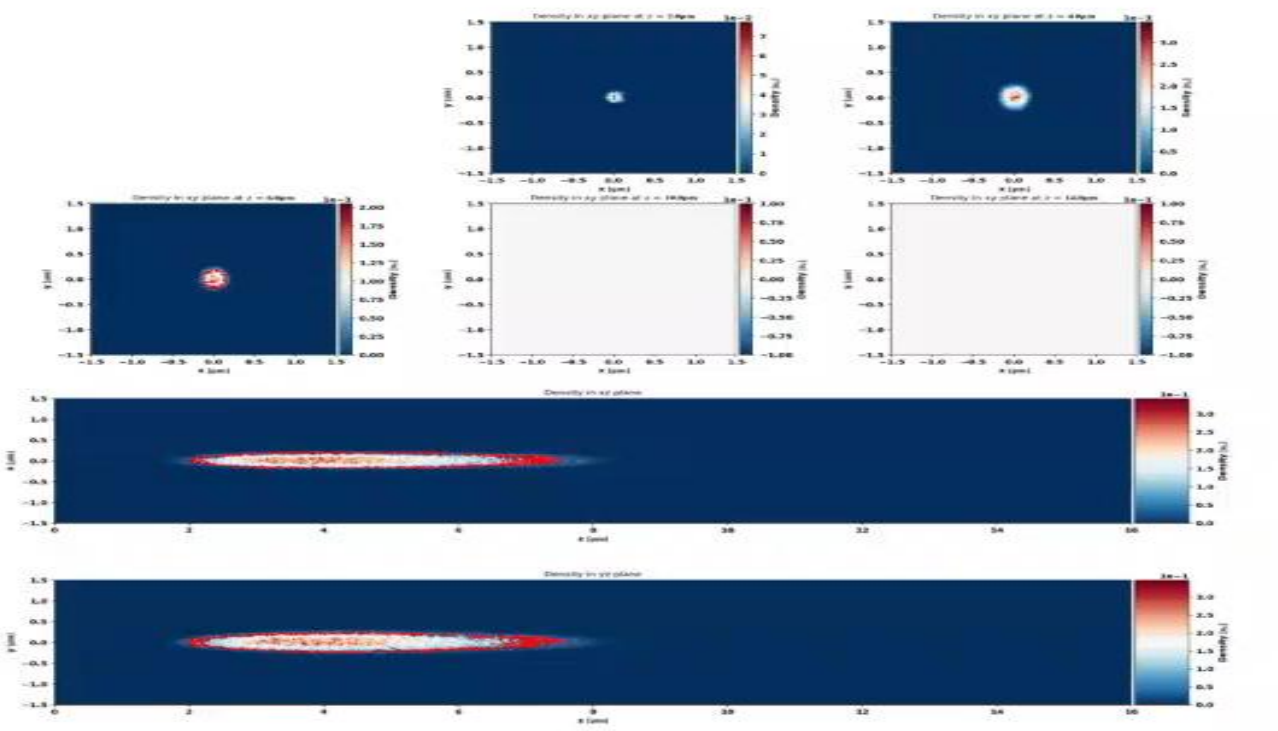




P-J Charpin, et al, *Optics Express* **32**, 10175 (2024)

Pulse propagation in time

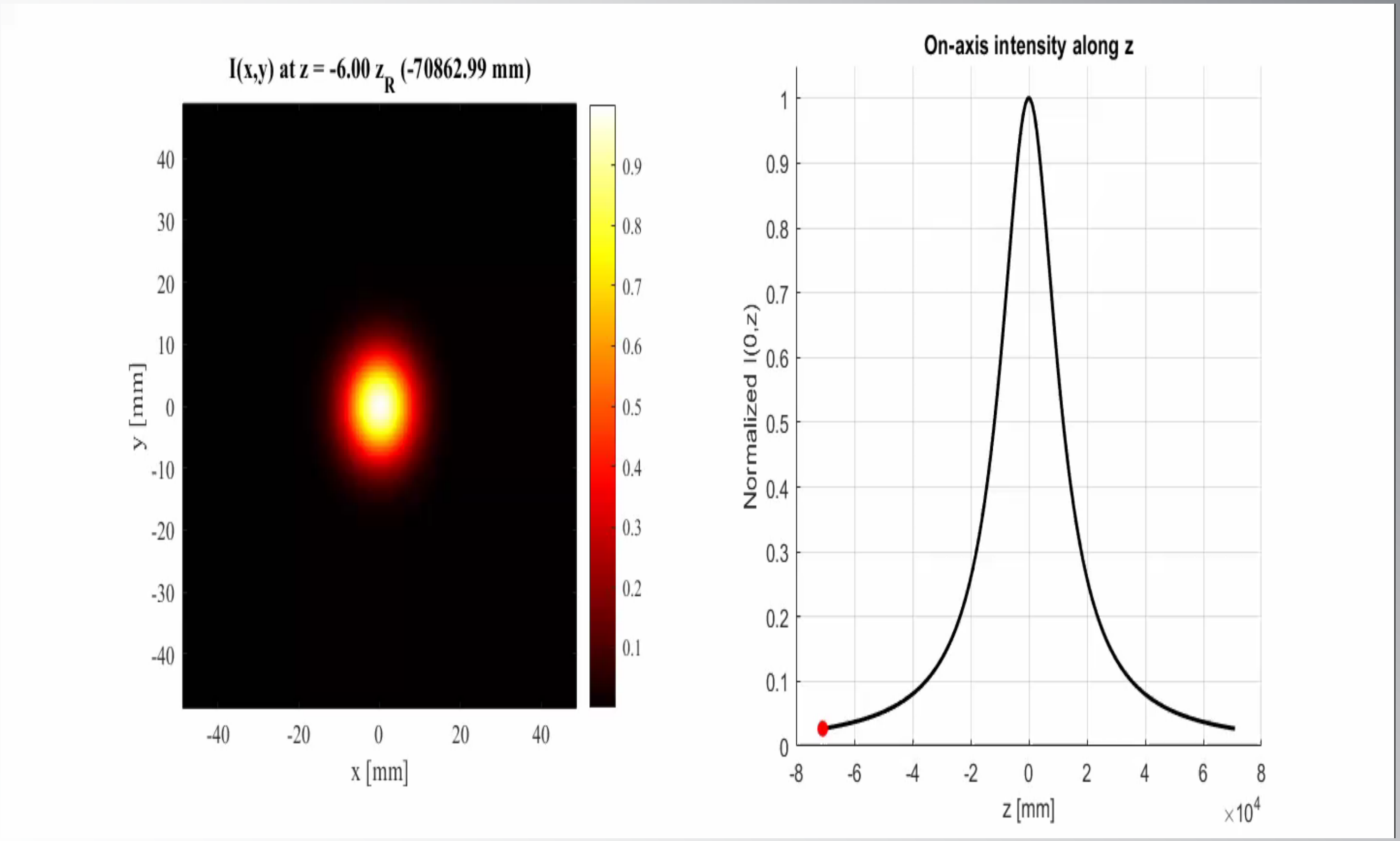


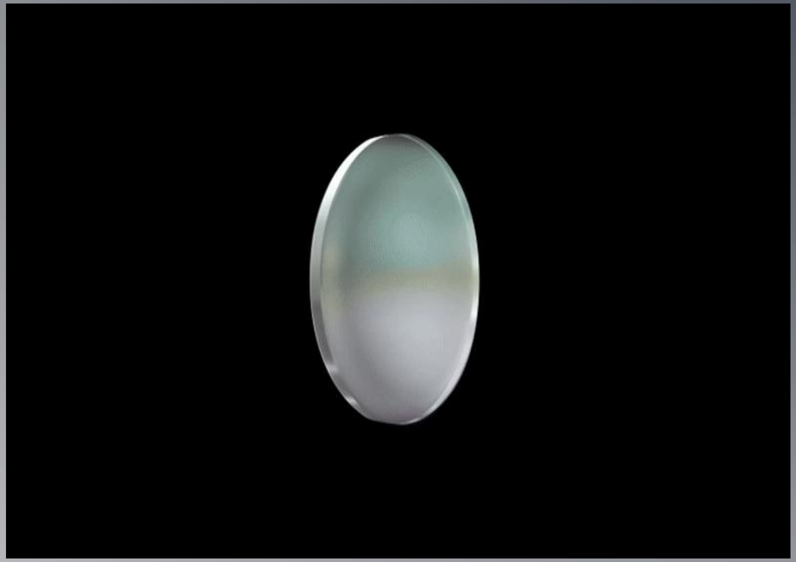


P-J Charpin, et al, Optics Express 32, 10175 (2024) "Femtosecond laser-induced
I. Field enhancement", K. Ardaneh et al, Physics of Plasmas 29, 072715 (2022)
II. Second-harmonic generation", K. Ardaneh et al, Physics of Plasmas 29, 072716 (2022)
III. Terahertz radiation emission" K. Ardaneh et al, Physics of Plasmas 30, 013301 (2023)

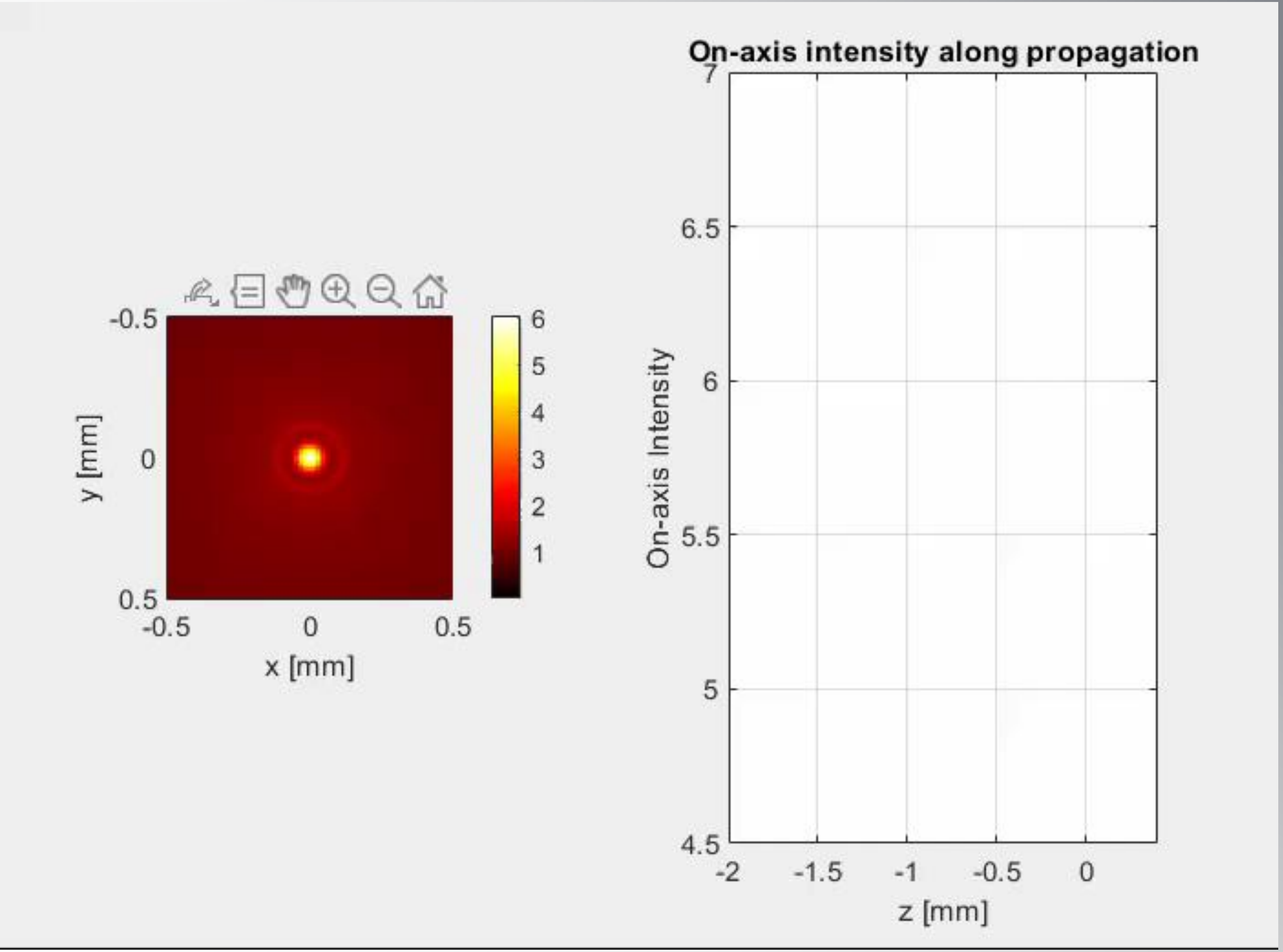
Light Beam Shaping

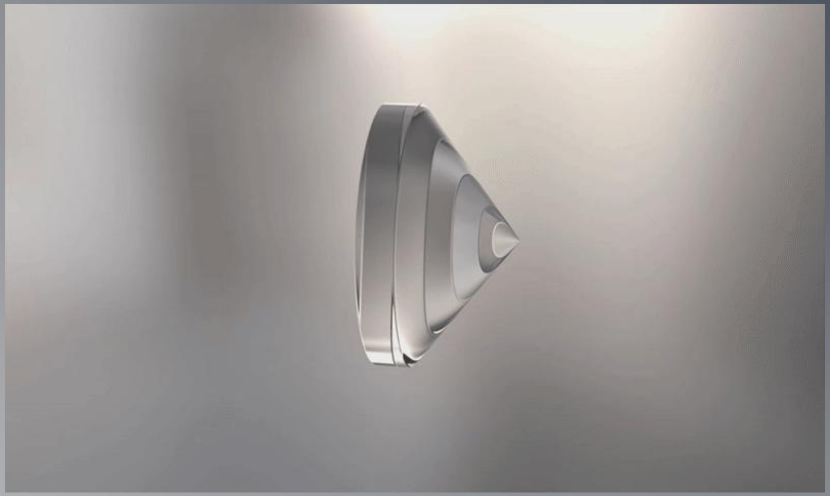
Gaussian Beam



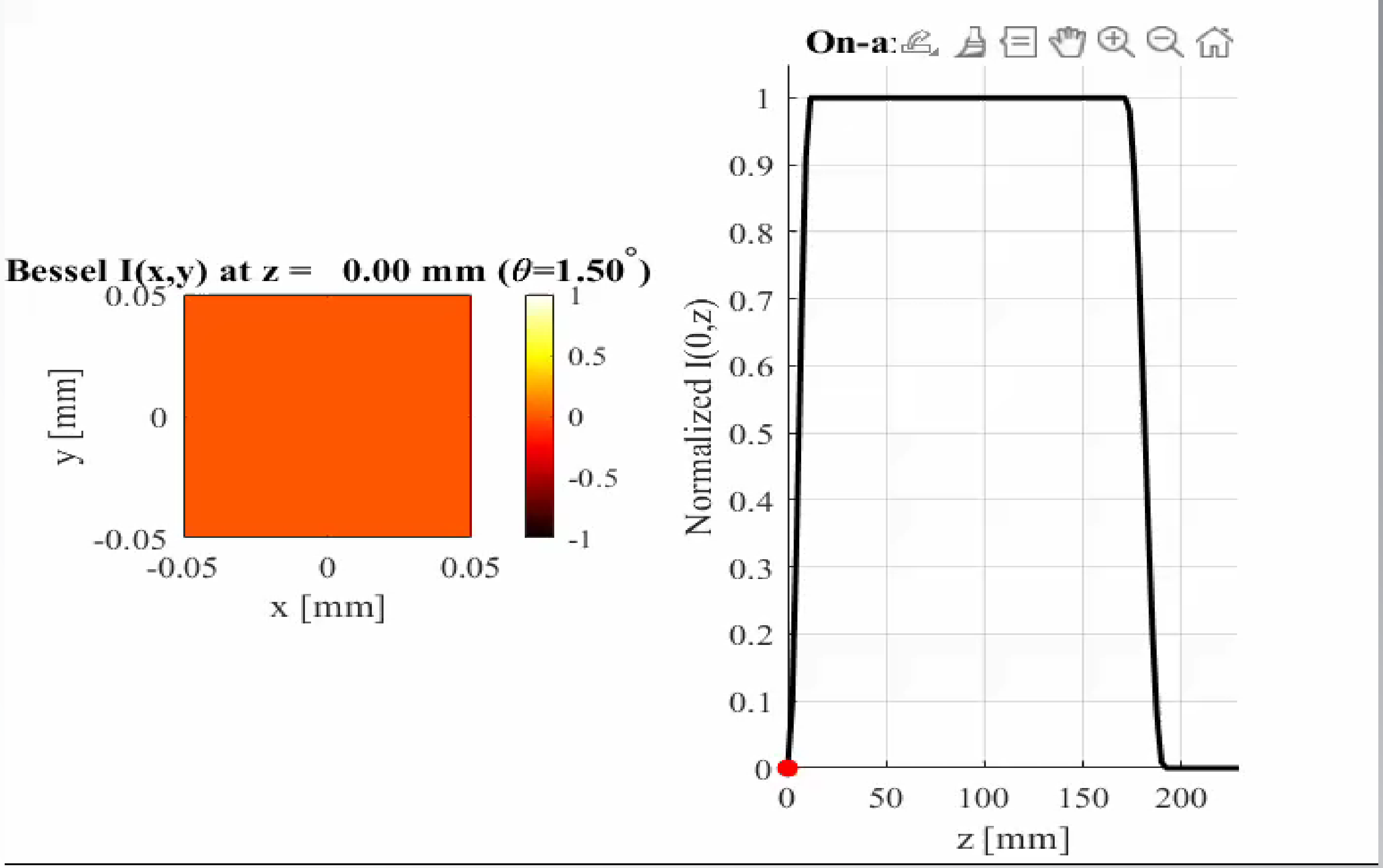


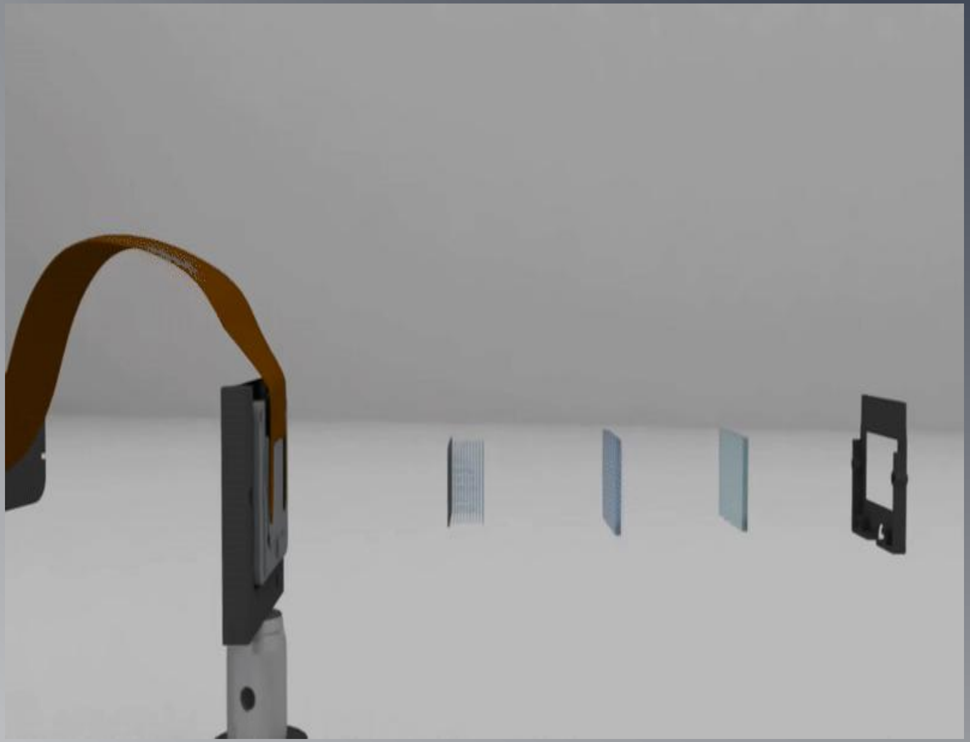
Bessel Beam


On-axis intensity along propagation
y [mm]
x [mm]
On-axis Intensity
z [mm]



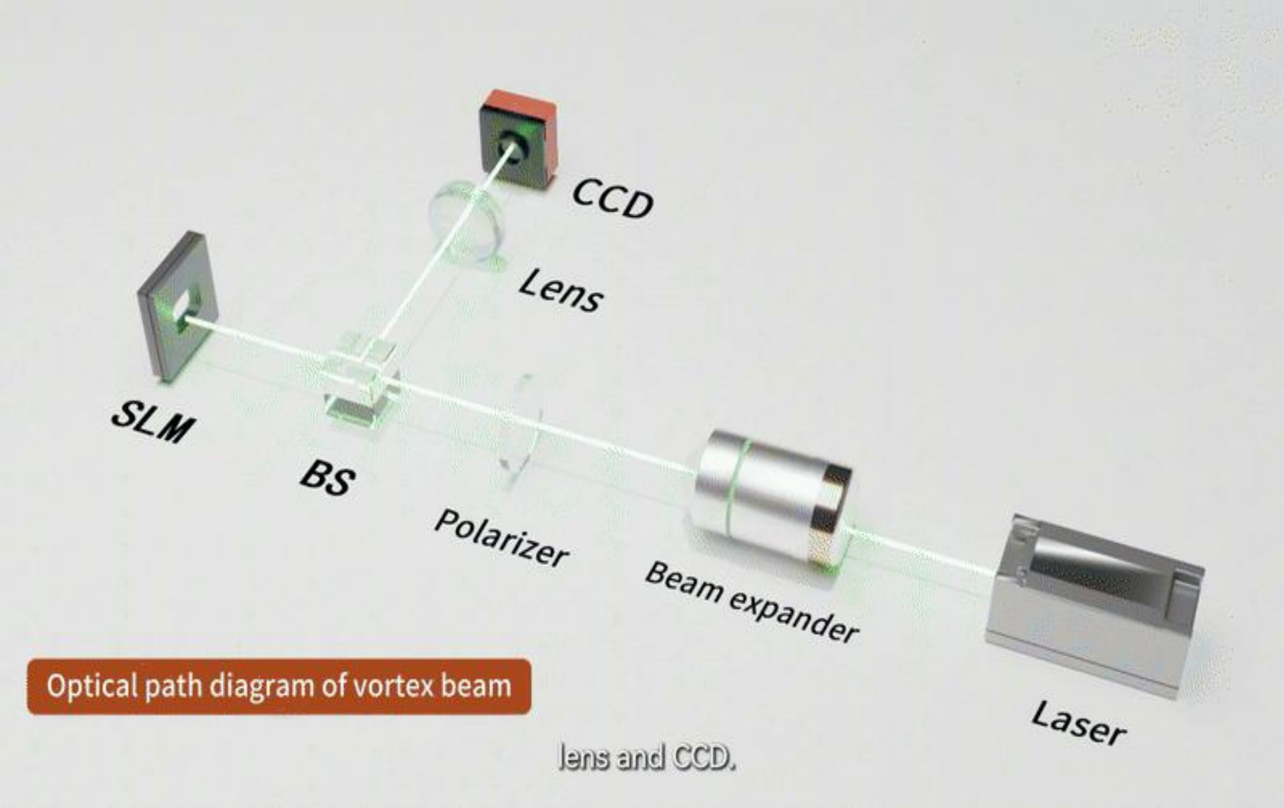
Light Shaping by Spatial light modulator





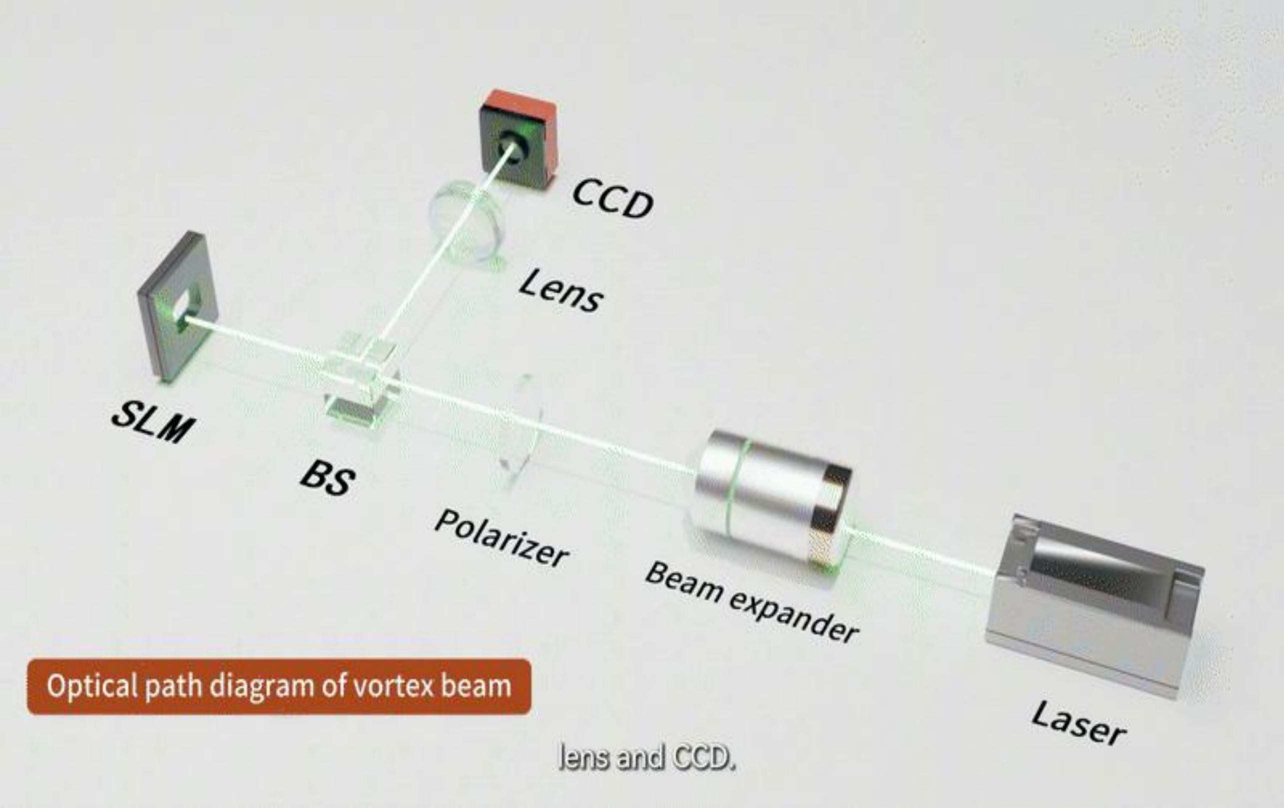
SLM

Light Shaping by SLM

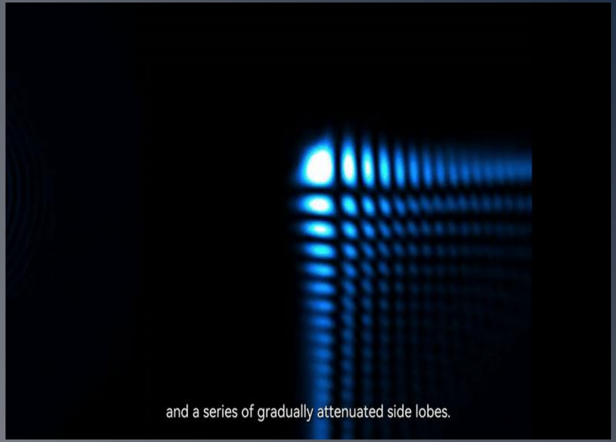


https://www.youtube.com/watch?v=JRqg43GLFSw

Light Shaping by SLM

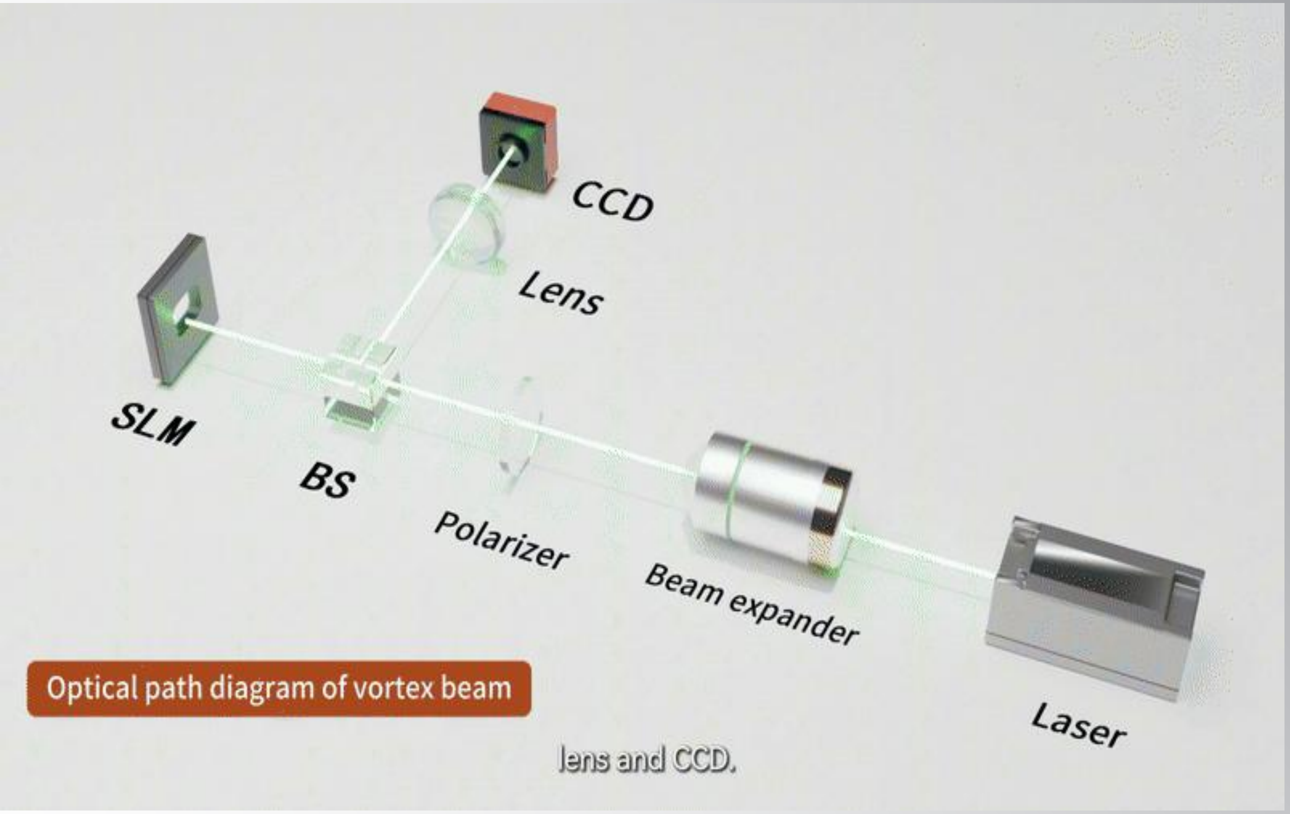


Airy beam

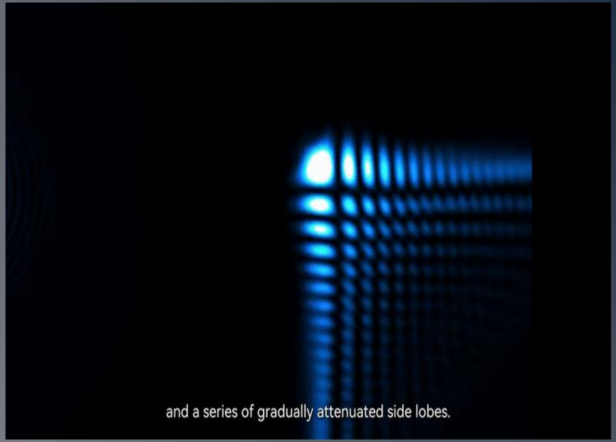


https://www.youtube.com/watch?v=JRqg43GLFSw

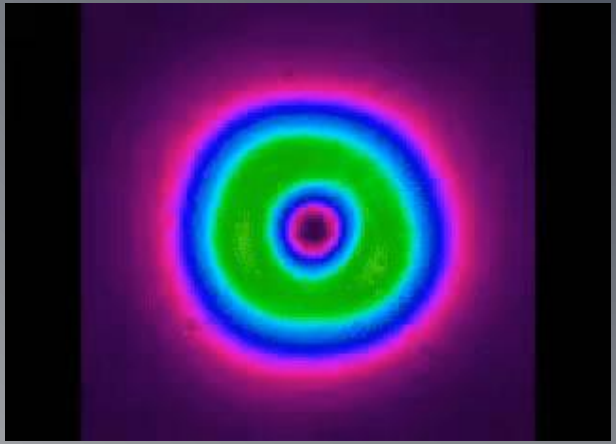
Light Shaping by SLM



Airy beam



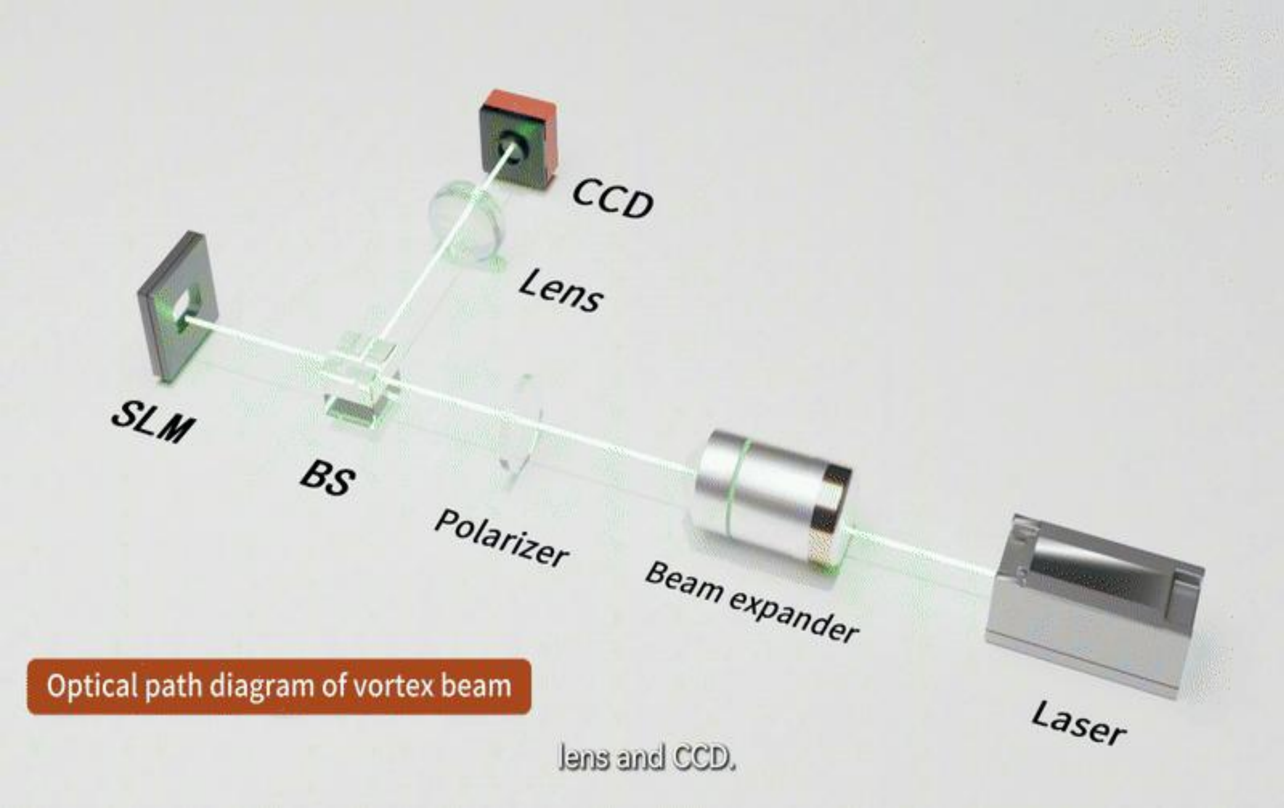
Vortex beam

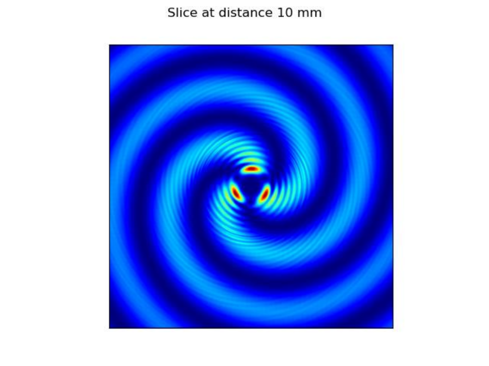


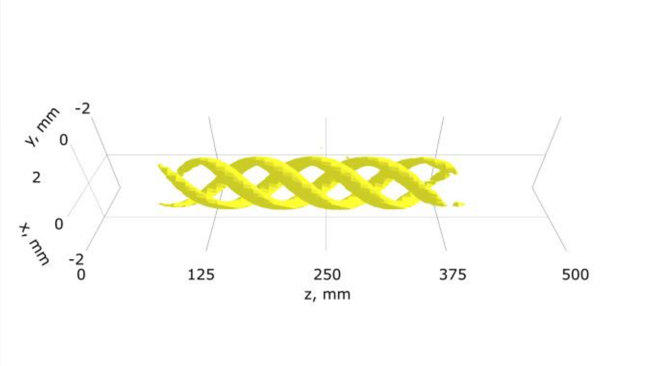
https://www.youtube.com/watch?v=JRqg43GLFSw

https://www.youtube.com/watch?v=2h3FmA6WgGo

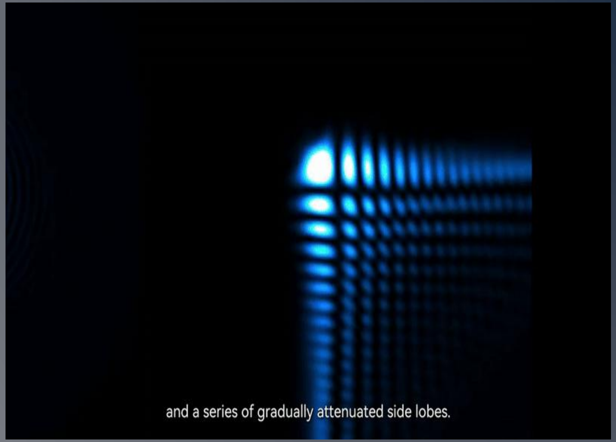
Light Shaping by SLM



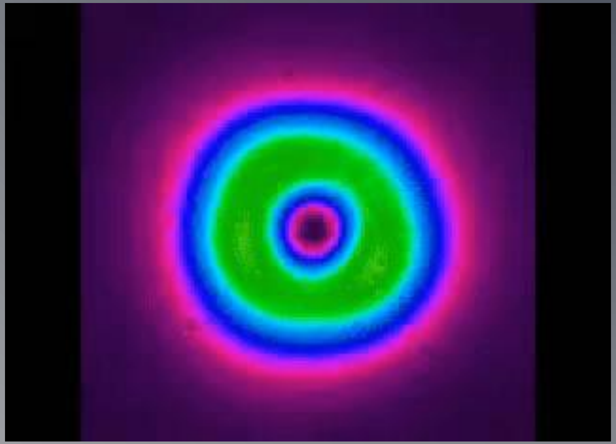




Airy beam



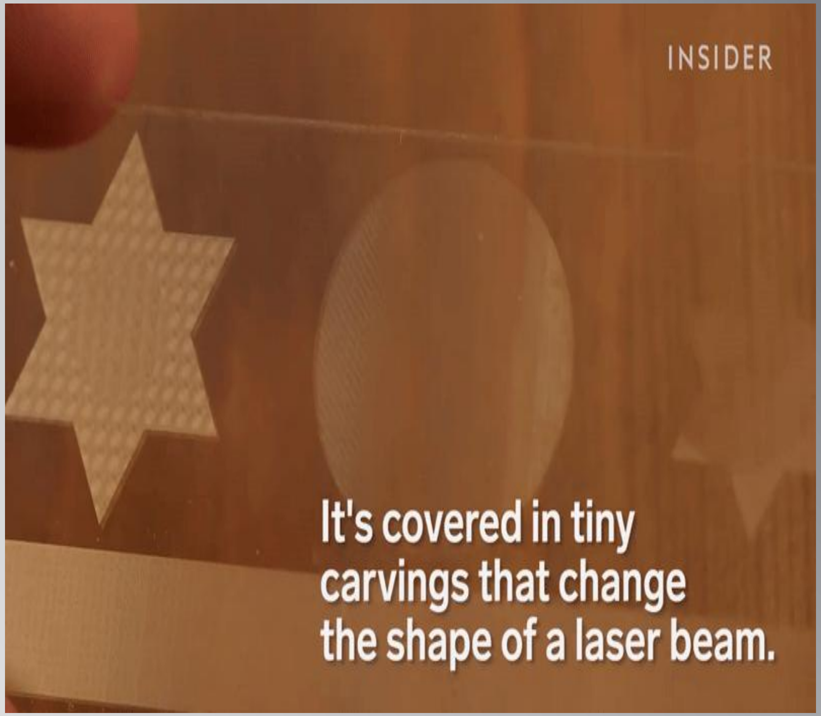
Vortex beam

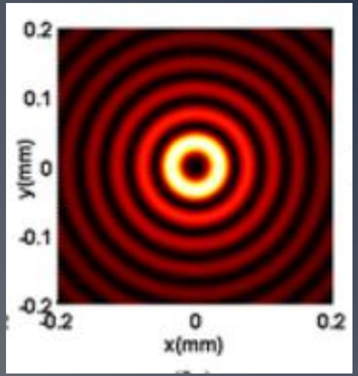


Helical beam

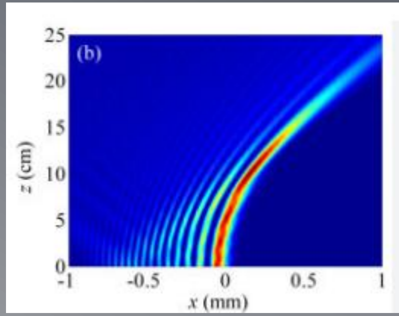
https://www.youtube.com/watch?v=JRqg43GLFSw

Difractive optical element (DOE)





Bessel Beam



Airy Beam

- DOI: 1364/OE.21.018797

https://www.holmarc.com/axicons.php
https://wavelength-oe.com/articles/bessel-beam/

Our Recent Published Work

Letter Vol. 49, No. 19 / 1 October 2024 / *Optics Letters* 5403

Optics Letters

Flattop axial Bessel beam propagation with analytical form of the phase retardation function

ADEL S. A. ELSHARKAWI[1,2,4] AND YU-LUNG LO[2,3,*]

[1] *Department of Radiation Engineering, National Center for Radiation Research and Technology (NCRRT), Egyptian Atomic Energy Authority, Cairo 11787, Egypt*
[2] *Department of Mechanical Engineering, National Cheng Kung University, Tainan 701, Taiwan*
[3] *Academy of Innovative Semiconductor and Sustainable Manufacturing, National Cheng Kung University, Tainan 701, Taiwan*
[4] *11105043@gs.ncku.edu.tw*
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Received 13 June 2024; revised 18 August 2024; accepted 28 August 2024; posted 29 August 2024; published 19 September 2024

Research Article Vol. 32, No. 17 / 12 Aug 2024 / *Optics Express* 30242

Optics EXPRESS

Bessel beam propagation using radial beam propagation method at different propagation scales

ADEL S. A. ELSHARKAWI,[1,2,4] I-CHEN TSAI,[2] XIANG-TING LIN,[2] CHIA-YUAN CHANG,[2] AND YU-LUNG LO[2,3,*]

[1] *Department of Radiation Engineering, National Center for Radiation Research and Technology (NCRRT), Egyptian Atomic Energy Authority, Cairo 11787, Egypt*
[2] *Department of Mechanical Engineering, National Cheng Kung University, Tainan 701, Taiwan*
[3] *Academy of Innovative Semiconductor and Sustainable Manufacturing, National Cheng Kung University, Tainan 701, Taiwan*
[4] *11105043@gs.ncku.edu.tw*
[*] *loyl@ncku.edu.tw*

Letter Vol. 51, No. 2 / 15 January 2026 / *Optics Letters* 341

Optics Letters

Correction of femtosecond laser asymmetric spot size for achieving uniform axial intensity in Bessel beam propagation via GPM

ADEL S. A. ELSHARKAWI[1,2,4] AND YU-LUNG LO[2,3,*]

[1] *Department of Radiation Engineering, National Center for Radiation Research and Technology (NCRRT), Egyptian Atomic Energy Authority, Cairo 11787, Egypt*
[2] *Department of Mechanical Engineering, National Cheng Kung University, Tainan 701, Taiwan*
[3] *Academy of Innovative Semiconductor and Sustainable Manufacturing, National Cheng Kung University, Tainan 701, Taiwan*
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ELSEVIER

Optics and Lasers in Engineering
Volume 201, June 2026, 109713

Beam shaping by nonlinear phase modulation for a femtosecond laser with a spatial light modulator

Adel S.A. Elsharkawi [a b], Amany A. Arafa [a], Amira A.M. Ahmed [c], Shang-Yu Chen [b], Chia-Yuan Chang [b], Yu-Lung Lo [b c]

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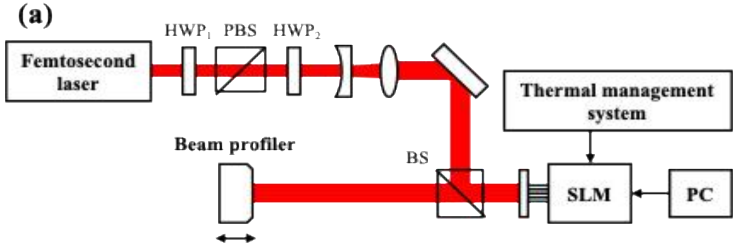
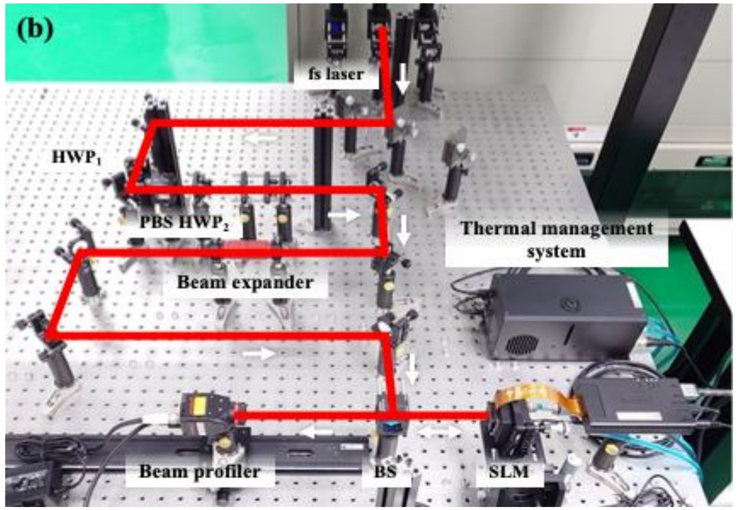
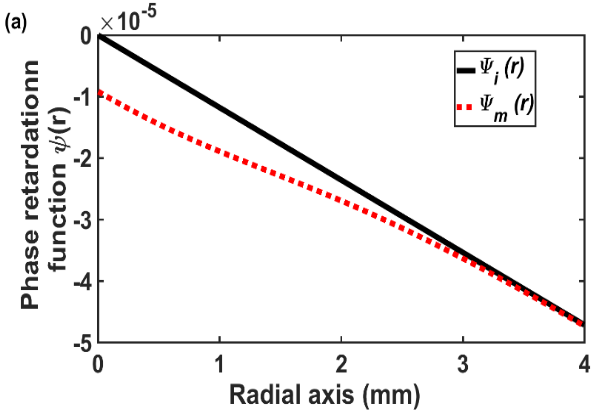
Amplitude SatsumaHP3



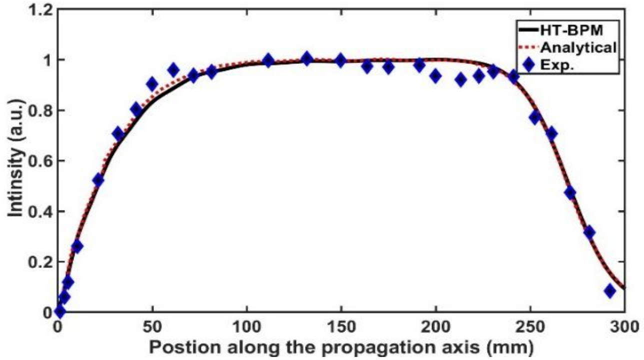


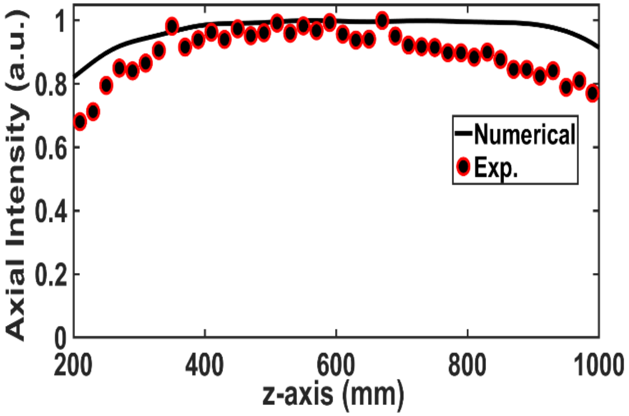


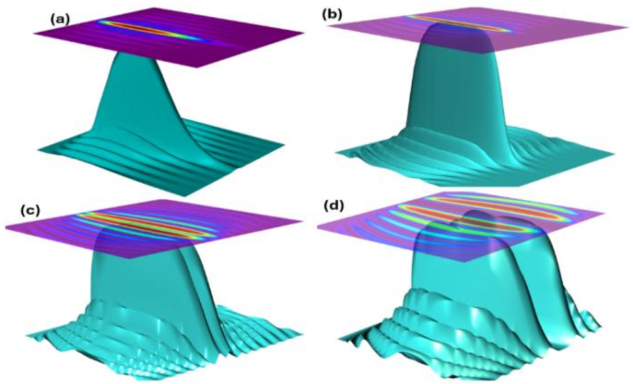
$$\varphi_i(r) = k_o r\,(n-1)\sin\theta,$$

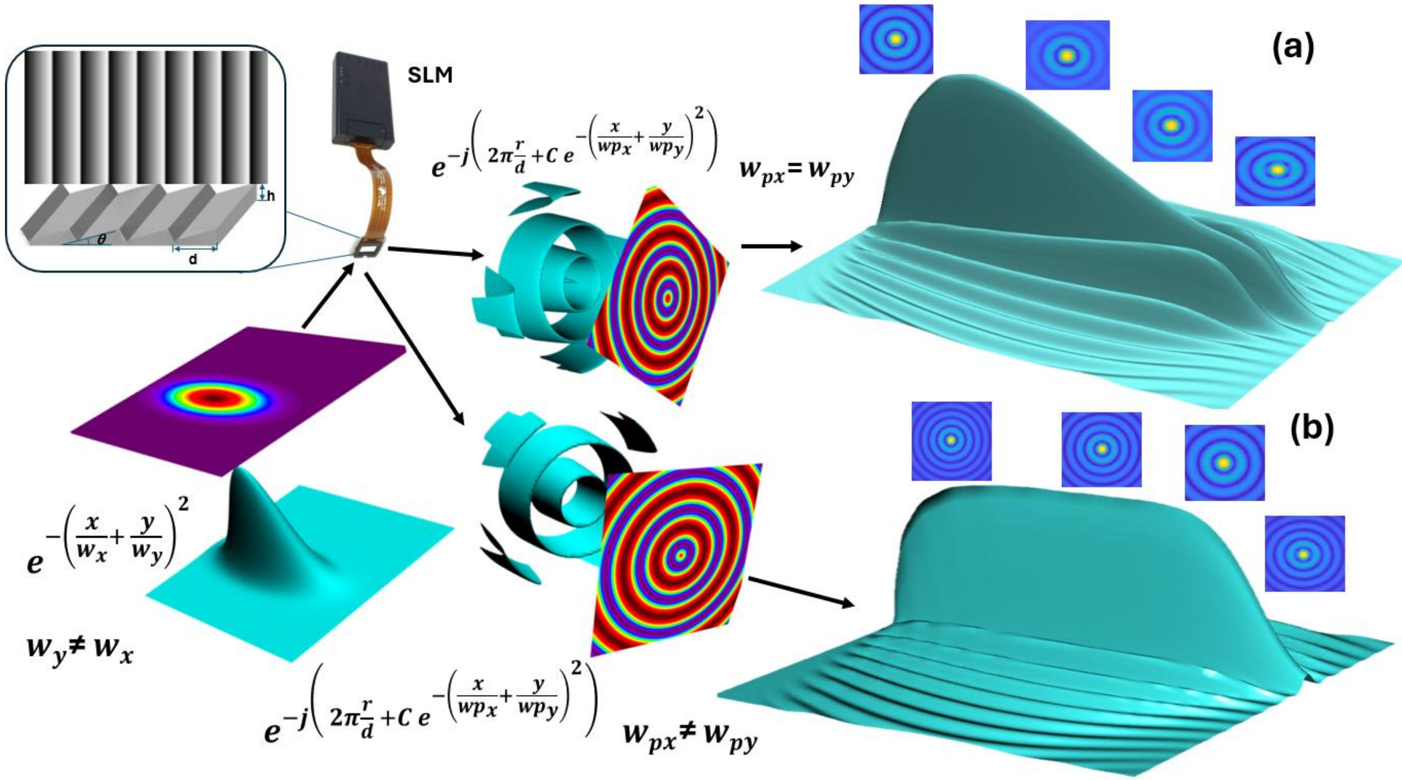
$$\psi_t(r) = \psi_i(r) + \psi_m(r) = k_o r\,(n-1)\sin\theta + C\,e^{-\left(\frac{r}{w_0}\right)^2}$$

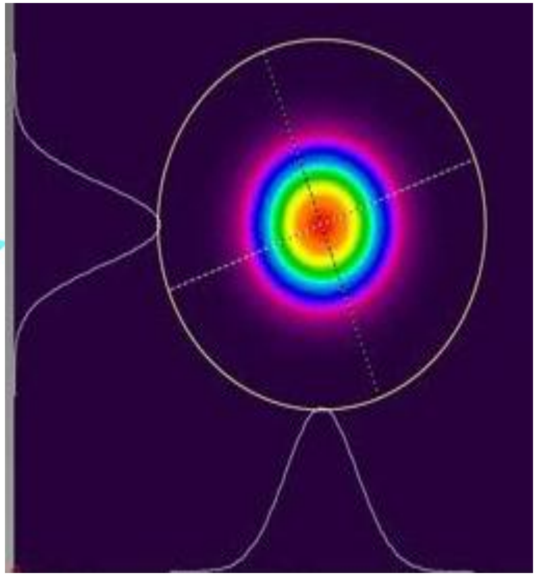
$$\psi(r,\phi) = k_0(n-1)\theta r + \boldsymbol{l\phi} + C\exp\left[-\left(\frac{r}{w_0}\right)^2\right]$$

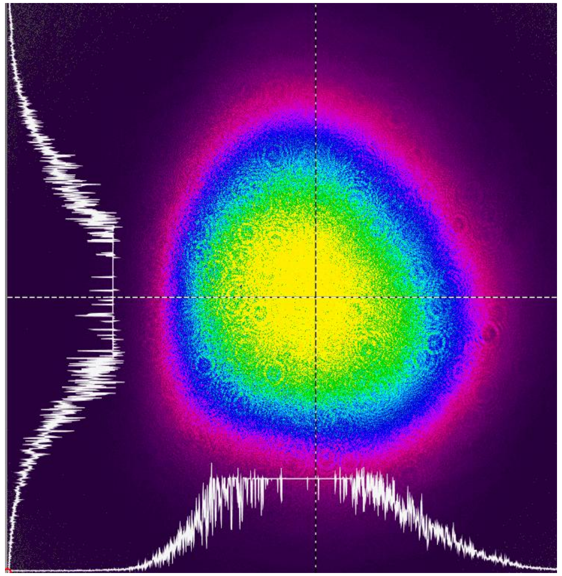


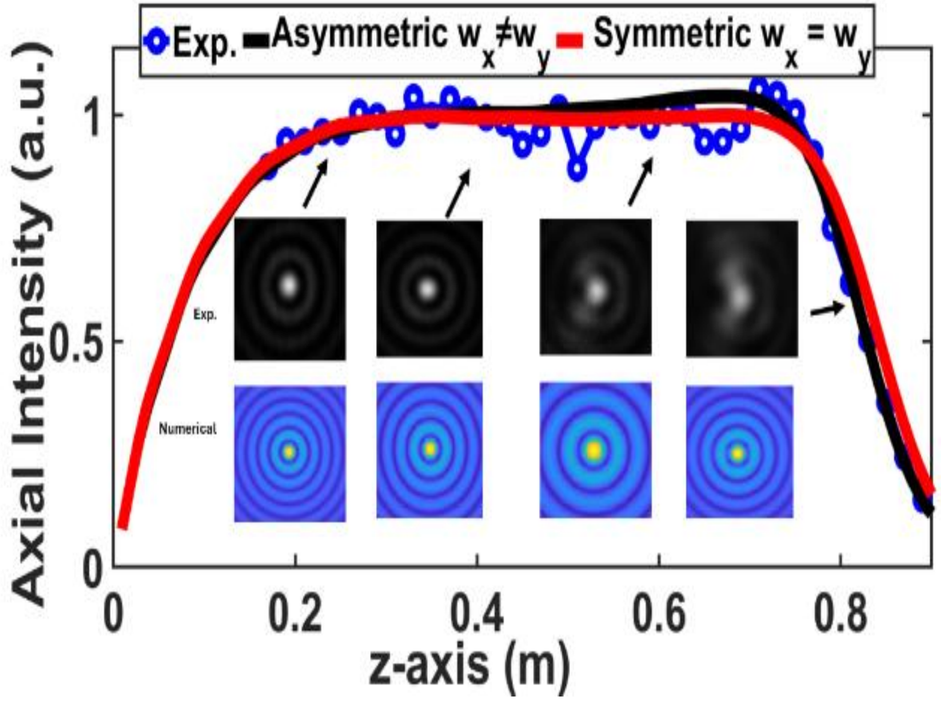


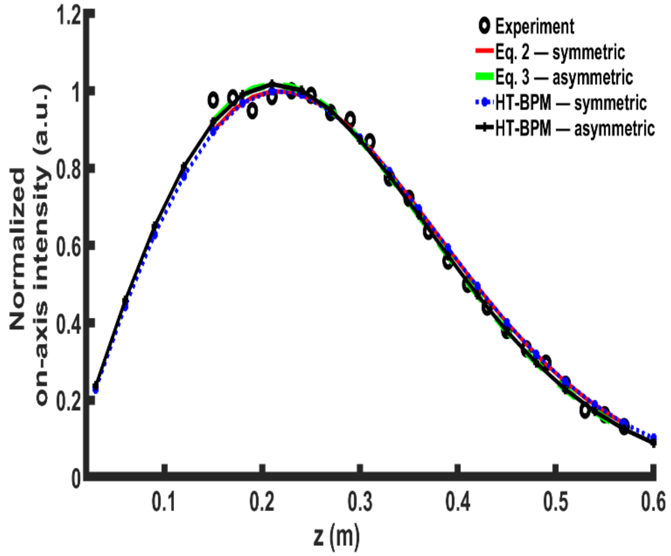


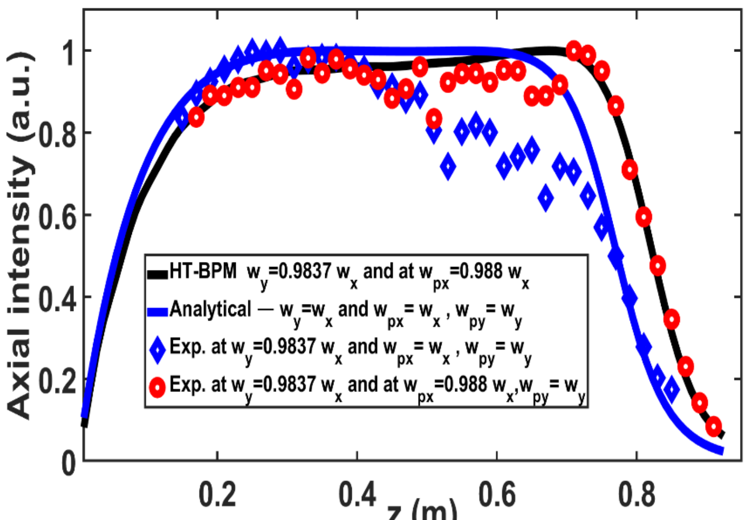

SLM
h
θ
d
(a)
(b)
$e^{-j\left(2\pi\frac{r}{d}+C\,e^{-\left(\frac{x}{wp_x}+\frac{y}{wp_y}\right)^2}\right)}$
$w_{px}=w_{py}$
$e^{-\left(\frac{x}{w_x}+\frac{y}{w_y}\right)^2}$
$w_y \neq w_x$
$e^{-j\left(2\pi\frac{r}{d}+C\,e^{-\left(\frac{x}{wp_x}+\frac{y}{wp_y}\right)^2}\right)}$
$w_{px} \neq w_{py}$






Exp.
Asymmetric $w_x \neq w_y$
Symmetric $w_x = w_y$
Axial Intensity (a.u.)
z-axis (m)
Exp.
Numerical
0
0.5
1
0
0.2
0.4
0.6
0.8

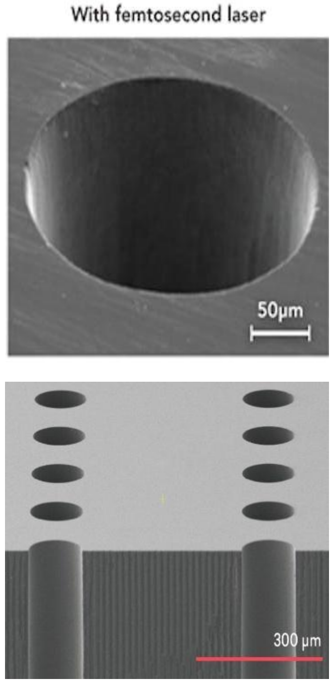

Experiment
Eq. 2 — symmetric
Eq. 3 — asymmetric
HT-BPM — symmetric
HT-BPM — asymmetric
Normalized on-axis intensity (a.u.)
z (m)
0
0.2
0.4
0.6
0.8
1
1.2
0.1
0.2
0.3
0.4
0.5
0.6


HT-BPM w_y=0.9837 w_x and at w_{px}=0.988 w_x
Analytical — w_y=w_x and w_{px} = w_x , w_{py} = w_y
Exp. at w_y=0.9837 w_x and w_{px} = w_x , w_{py} = w_y
Exp. at w_y=0.9837 w_x and at w_{px}=0.988 w_x,w_{py} = w_y
Axial intensity (a.u.)
z (m)
0
0.2
0.4
0.6
0.8
1
0.2
0.4
0.6
0.8

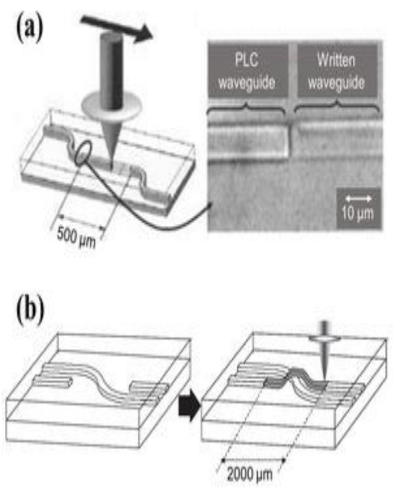
Light beam Shaping applications

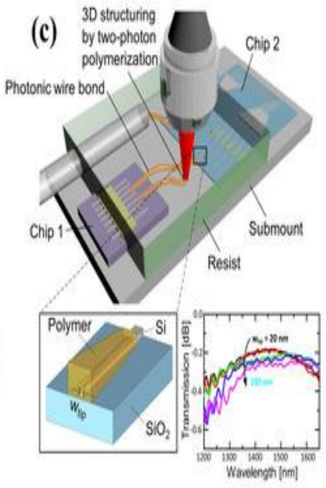
Once the femtosecond (Fs) laser is shaped, it can be applied to a variety of applications, including:

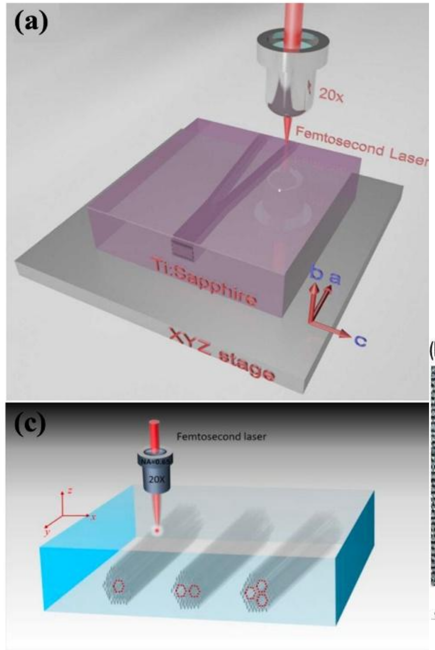
Through Glass/ceramic Vias (TGV) (TCV)



Waveguide writing

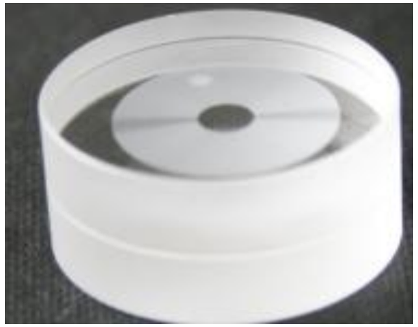


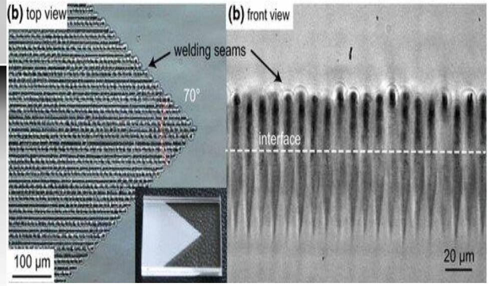




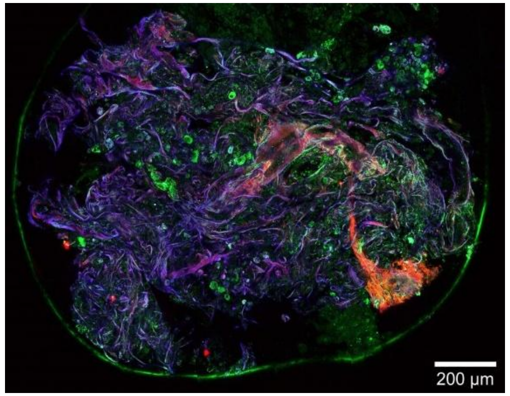
Laser welding

Glass/Glass or Glass/others





Multiphoton Luminance Image



https://www.laserfocusworld.com/industrial-laser-solutions/article/14216407/femtosecond-laser-glass-processing
Niu, S., Wang, W., Liu, P., Zhang, Y., Zhao, X., Li, J., Xiao, M., Wang, Y., Li, J., & Shao, X. (2024). Recent Advances in Applications of Ultrafast Lasers. Photonics, 11(9), 857.
Richter, S., Döring, S., Tünnermann, A. et al. Bonding of glass with femtosecond laser pulses at high repetition rates. Appl. Phys. A 103, 257–261 (2011).
https://hubner-photonics.com/knowledge-bank/femtosecond-lasers-for-multiphoton-microscopy/

Plasma Issues: TTM + MPI

$$\frac{\partial n_e}{\partial t} = \frac{n_v - n_e}{n_v}(w_{PI} + n_e w_{II}) - \frac{n_e}{\tau_r}, \qquad (1)$$

$$C_e \frac{\partial T_e}{\partial t} = -\left.\frac{\partial S_l}{\partial z}\right|_{z=0} - \gamma_{ei}(T_e - T_i) + W_I, \qquad (9)$$

$$C_i \frac{\partial T_i}{\partial t} = \gamma_{ei}(T_e - T_i), \qquad (10)$$

where γ_{ei} is the electron-lattice coupling factor, and C_e and C_i are the electron and lattice heat capacity, respectively. The electron heat capacity is

$$C_e(T_e, n_e) = \rho \int_{-\infty}^{\infty} \frac{\partial f_F(\varepsilon)}{\partial T_e} g(\varepsilon)\, \varepsilon\, d\varepsilon, \qquad (11)$$

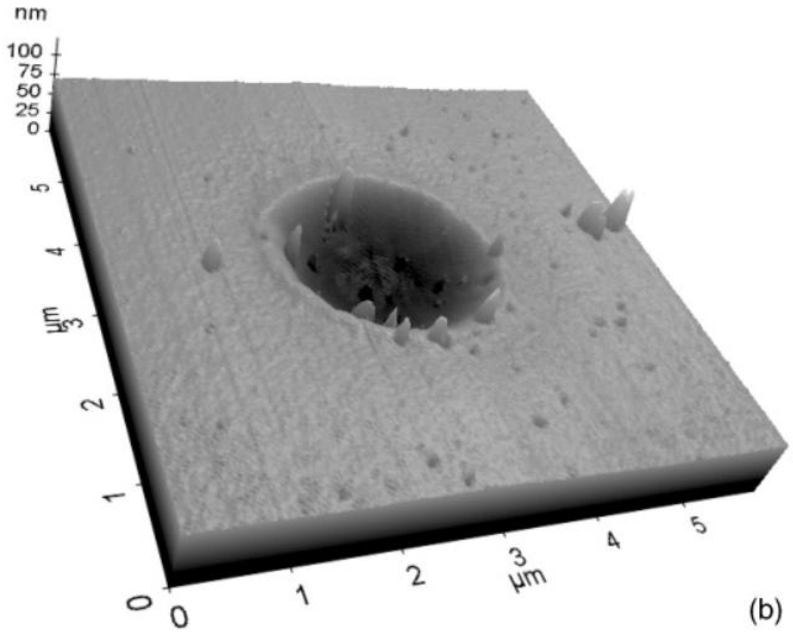
and the lattice heat capacity[3] is $C_i = 1.6\ \mathrm{J/(cm^3 K)}$.

The last term in Eq. (9) corresponds to the potential energy transferred to the electrons during the recombination process, and the electron energy losses during the collisional ionization process,

$$W_I = \tilde{U}_s n_e \left[\frac{1}{\tau_r} - \frac{n_s}{n_a} w_{II}(U_s)\right] - \frac{n_v - n_e}{n_v} \tilde{U}_g w_{II}(U_g). \qquad (12)$$

In Eq. (9), S_l is the absorbed energy flux

$$S_l = [1 - R(z=0,t)]\, I_l(t)\, \exp\left(-\frac{2z}{l_p}\right), \qquad (13)$$



Chimier, B., et al. "Damage and ablation thresholds of fused-silica in femtosecond regime." *Physical Review B—Condensed Matter and Materials Physics* 84.9 (2011): 094104.

Recent work:

Prof. Lo group could add the following to Eq. and get new ionization rate:

pupil-plane complex field (SLM/axicon phase mask style):

$$U_{\text{pupil}}(r) = \exp[-\left(\frac{r}{w_p}\right)^2\Big] \exp\left[-j\left(r k_0 \sin\theta + C e^{-(r/w_p)^2}\right)\right], \quad k_0 = \frac{2\pi}{\lambda_0}.$$

Bessel × Gaussian field enters the rate analytically

Local field amplitude and local $\gamma(r,z,t)$

In your experiment/model, E_l is not constant—it depends on (r,z,t):

$$E_l(r,z,t) = E_{\text{pk}}(r,z)\, s(t).$$

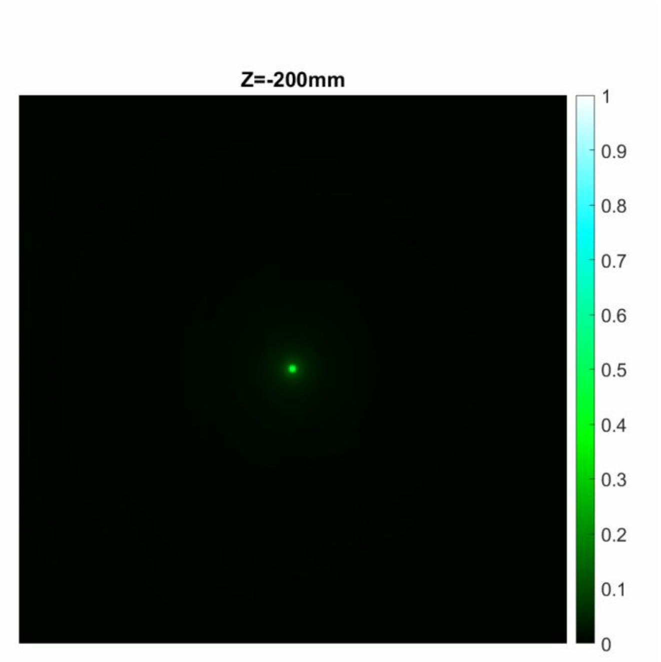
Thus

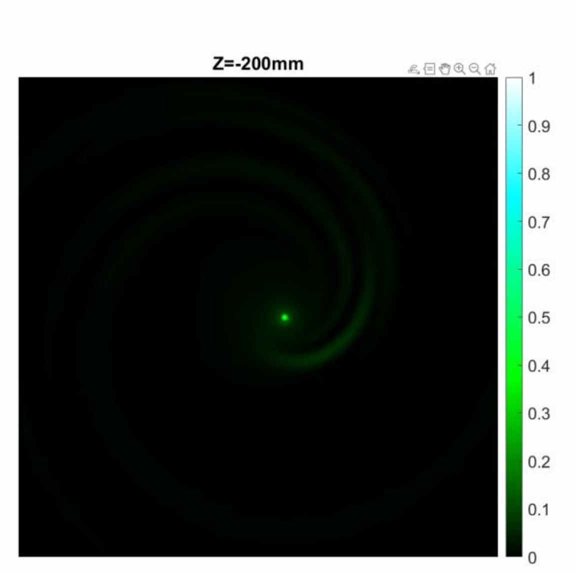
$$\boxed{\gamma(r,z,t) = \frac{\omega\sqrt{m^* U}}{e\, E_{\text{pk}}(r,z)\, s(t)}}.$$

and your **local photoionization rate** is $\boxed{w_{\text{PI}}(r,z,t) = w_{\text{PI}}(\gamma(r,z,t),\ \omega, U, m^*),}$

Recent work:

- Multiphoton Ionization






1494 Vol. 46, No. 7 / 1 April 2021 / Optics Letters
Letter
Optics Letters

Non-diffracting and self-accelerating Bessel beams with on-demand tailored intensity profiles along arbitrary trajectories

Wenxiang Yan,[1,2] Yuan Gao,[1,2] Zheng Yuan,[1,2] Zhuang Wang,[1,2] Zhi-Cheng Ren,[1,2] Xi-Lin Wang,[1,2] Jianping Ding,[1,2,*] and Hui-Tian Wang[1,2]
[1]National Laboratory of Solid State Microstructures and School of Physics, Nanjing University, Nanjing 210093, China
[2]Collaborative Innovation Center of Advanced Microstructures, Nanjing 210093, China
*Corresponding author: jpding@nju.edu.cn

Received 6 January 2021; revised 18 February 2021; accepted 22 February 2021; posted 22 February 2021 (Doc. ID 418928); published 17 March 2021

$$A\left(\sqrt{k^2-k_z^2}\right)=\frac{2}{\mathrm{rect}\left(\frac{k_z}{2k}\right)k_z}\int_{-\infty}^{\infty}\sqrt{I(z)}e^{ik_{z0}z}e^{-ik_z z}\mathrm{d}z, \quad \textbf{(3)}$$

$$A_z\left(\sqrt{k^2-k_z^2}\right)=\frac{2}{\mathrm{rect}\left(\frac{k_z}{2k}\right)k_z}\sqrt{I(z)}e^{i(k_{z0}z+k_x g(z)+k_y h(z))}e^{-ik_z z},$$

(4)

https://doi.org/10.1364/OL.532122

PHYSICAL REVIEW B **73**, 214101 (2006)

Laser-matter interaction in the bulk of a transparent solid: Confined microexplosion and void formation

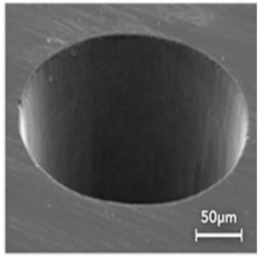
Eugene G. Gamaly*
Laser Physics Centre, Research School of Physical Sciences and Engineering, the Australian National University, Canberra ACT 0200, Australia

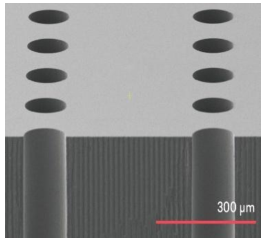
Check for updates
Research Article Vol. 32, No. 6 / 11 Mar 2024 / *Optics Express* 10175
Optics EXPRESS

Simulation of laser-induced ionization in wide bandgap solid dielectrics with a particle-in-cell code

P.-J. Charpin,[1] K. Ardaneh,[1,2] B. Morel,[1] R. Giust,[1] and F. Courvoisier[1,*]
[1]*FEMTO-ST Institute, Université de Franche-Comté, CNRS, 15B avenue des Montboucons, 25030,*

With femtosecond laser





ACS APPLIED ELECTRONIC MATERIALS
pubs.acs.org/acsaelm Article

Internal Nonthermal Melting of 4H-SiC Induced by Femtosecond Laser Pulses

Qianqian Zhang, Yunfan Yue, Zhongle Zeng, Zihan Zhang, Jiakang Zhou, Xiangyu Chen, Niannian Yu, Huan Wang,* and Xuewen Wang*

Cite This: *ACS Appl. Electron. Mater.* 2025, 7, 6402–6410 Read Online

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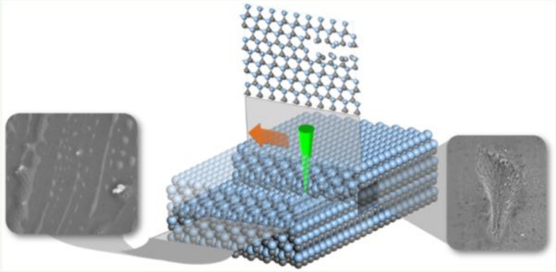
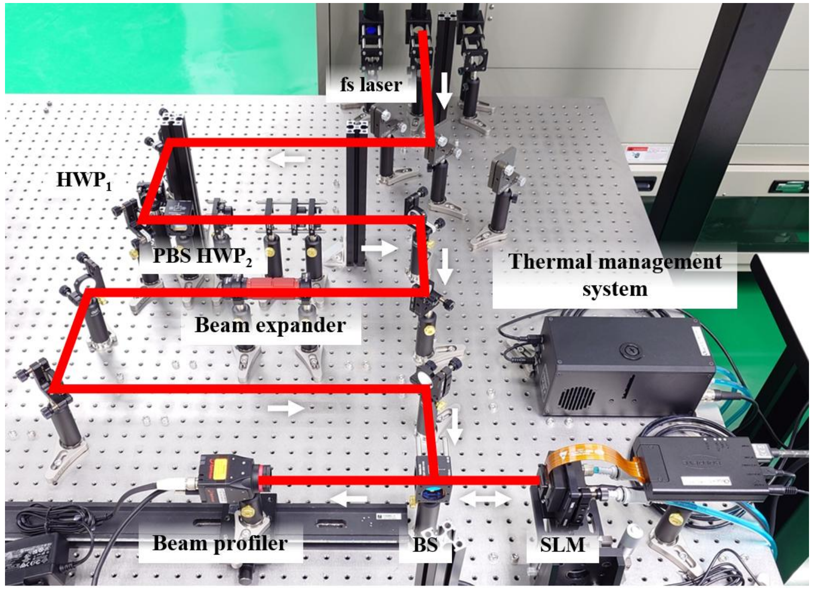
ABSTRACT: As a third-generation semiconductor substrate for high-power electronics, silicon carbide (4H-SiC) faces severe processing challenges, with conventional slicing technologies exhibiting high loss and poor quality. The innovative application of femtosecond laser slicing technology is dedicated to improving the utilization efficiency of 4H-SiC single crystals, significantly reducing damage defects, greatly enhancing the cutting accuracy, and ultimately reducing the loss of 4H-SiC wafers during the slicing process. In this study, femtosecond laser manufacturing technology is used to generate a modified layer inside the 4H-SiC wafer for slicing. The formation mechanism of the modified layers under



PIC → TD-DFT

DOI 10.1070/PU2004v047n09ABEH001812
Photonics **2023**, *10*(5), 515; https://doi.org/10.3390/photonics10050515

Current Work



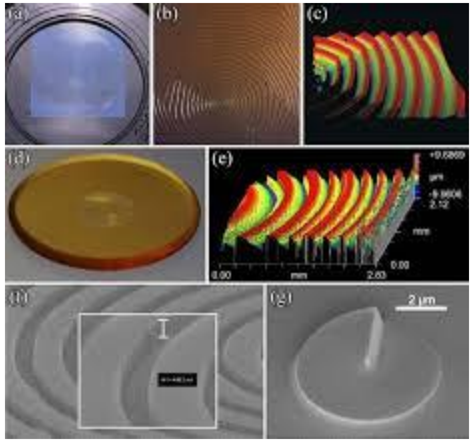
FS laser Experimental setup

Prof. Yu-Lung Lo

Amira

Shang

Department of Mechanical Engineering,
National Cheng Kung University (NCKU), Taiwan

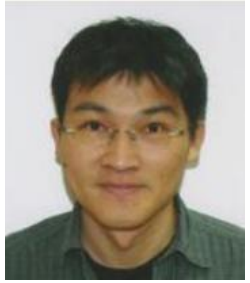


DOE design

The American University in Cairo

Egypt

Plasma Modeling



Kaviya

Prof. Ming-Chieh Lin

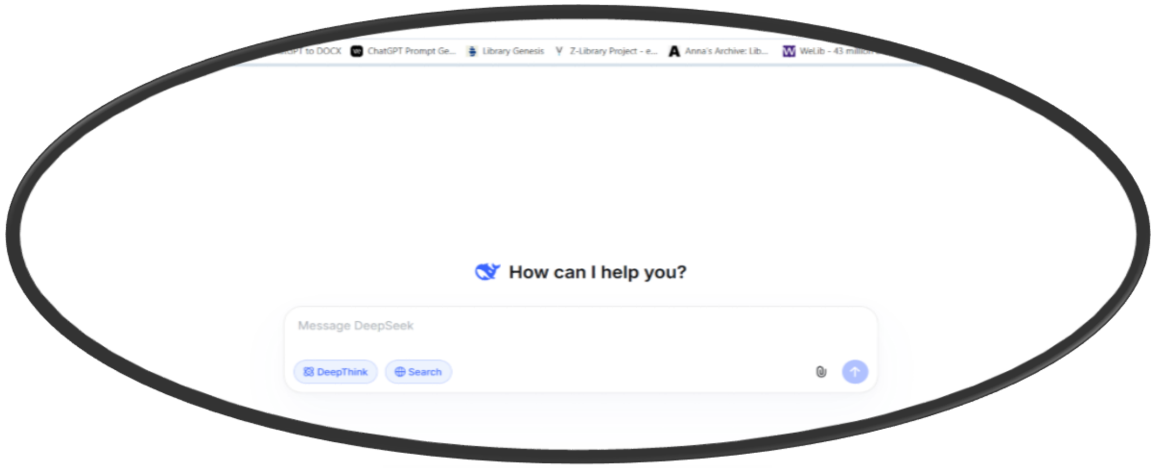
Department of Electrical and Biomedical Engineering,
Hanyang University, Korea

Email: Adel

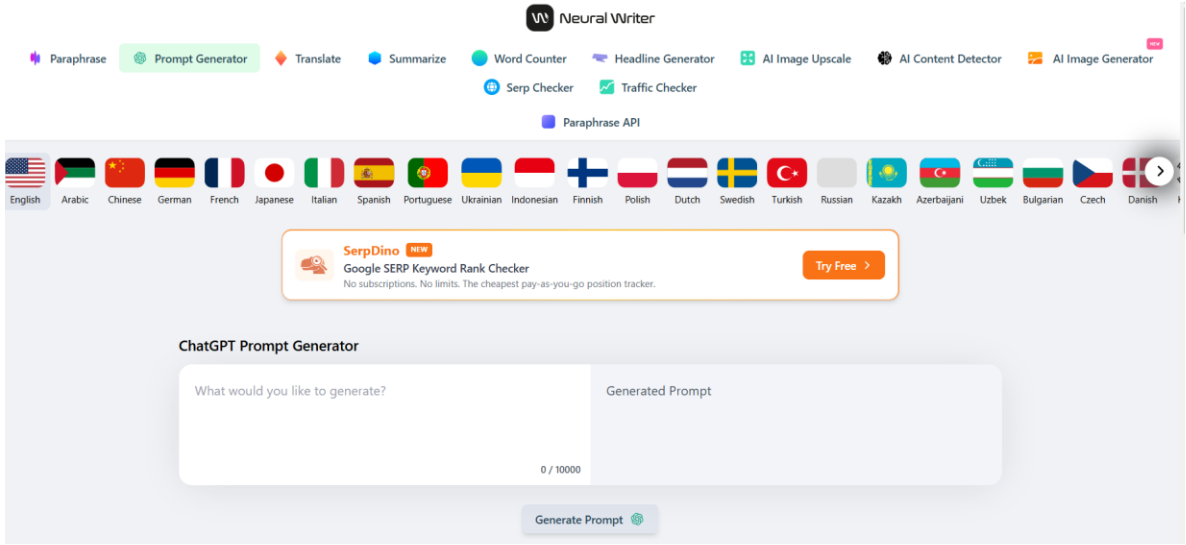
Prof. Lin

Prof. Lo

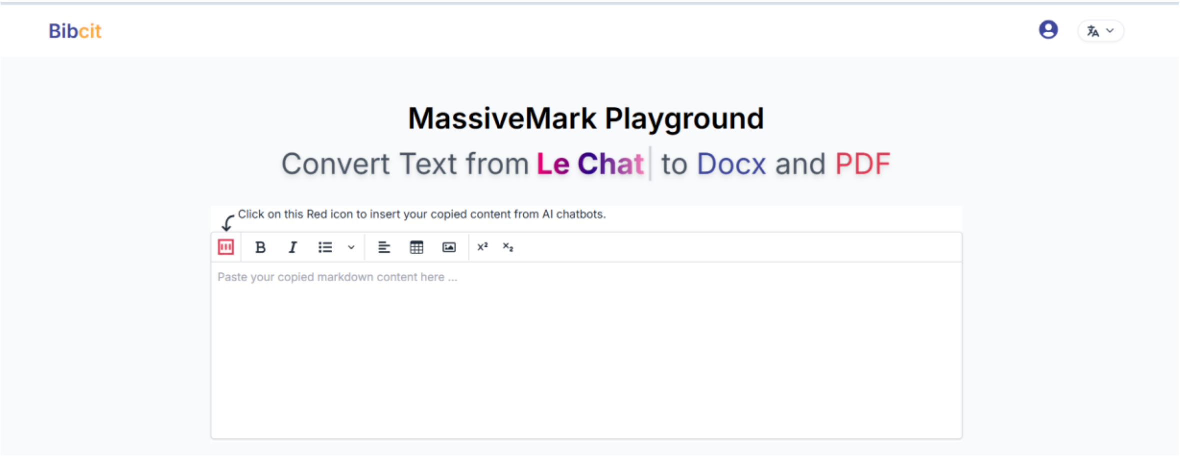
Thank You



https://chat.deepseek.com



https://neuralwriter.com/prompt-tool/#progress=1



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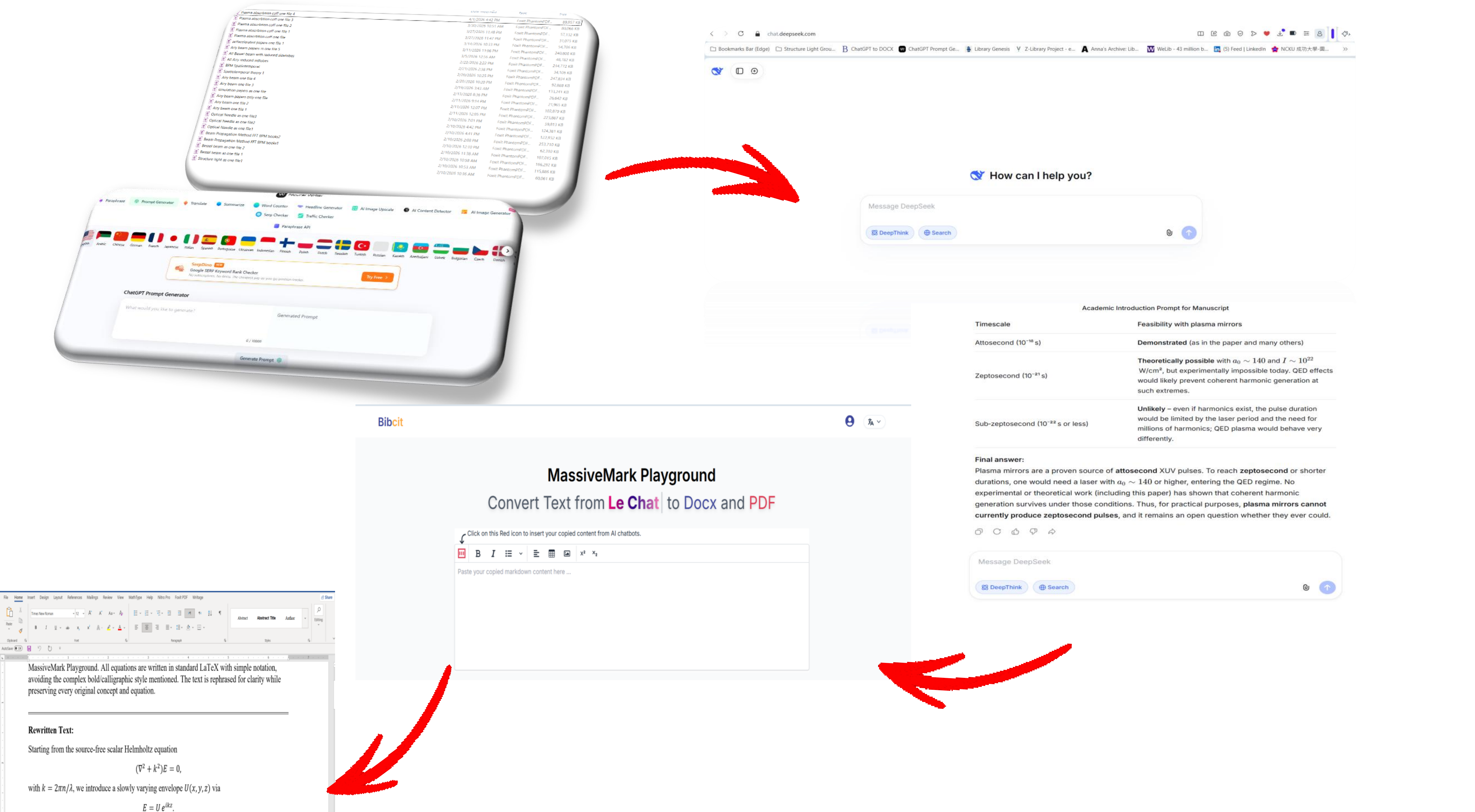

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Timescale
Feasibility with plasma mirrors
Attosecond (10⁻¹⁸ s)
Demonstrated (as in the paper and many others)
Zeptosecond (10⁻²¹ s)
Theoretically possible with $a_0 \sim 140$ and $I \sim 10^{22}$ W/cm², but experimentally impossible today. QED effects would likely prevent coherent harmonic generation at such extremes.
Sub-zeptosecond (10⁻²² s or less)
Unlikely – even if harmonics exist, the pulse duration would be limited by the laser period and the need for millions of harmonics; QED plasma would behave very differently.
Final answer:
Plasma mirrors are a proven source of attosecond XUV pulses. To reach zeptosecond or shorter durations, one would need a laser with $a_0 \sim 140$ or higher, entering the QED regime. No experimental or theoretical work (including this paper) has shown that coherent harmonic generation survives under those conditions. Thus, for practical purposes, plasma mirrors cannot currently produce zeptosecond pulses, and it remains an open question whether they ever could.
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MassiveMark Playground. All equations are written in standard LaTeX with simple notation, avoiding the complex bold/calligraphic style mentioned. The text is rephrased for clarity while preserving every original concept and equation.
Rewritten Text:
Starting from the source-free scalar Helmholtz equation
$(\nabla^2 + k^2)E = 0,$
with $k = 2\pi n/\lambda$, we introduce a slowly varying envelope $U(x, y, z)$ via
$E = U\,e^{ikz}.$