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Capillary Channel Formation in PMMA and Electrons Acceleration by a Long-Pulse KrF Laser

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Introduction

Two remarkable events in Dec. 2022 proceeded the Channeling 2023:

- **100th Birthday anniversary of academician N. G. Basov on 2022.12.14.**
- **ICF ignition at NIF facility in LLNL on 2022.12.05.**

100th birthday anniversary of academician N. G. Basov

14.12.1922 – 01.07.2001

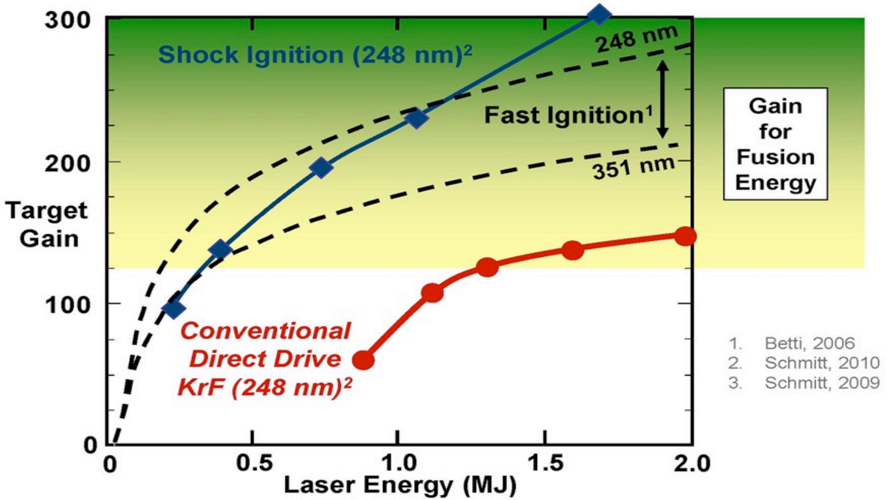
1964

- **1964** – **Basov N.G. and Krokhin O.N.** *Sov. Phys. JETP*, **19**, 123.
  Proposal of the ICF with the laser.
- **1966** – **Basov N.G.** *IEEE J. Quantum Electron.*, **2**, 354.
  Proposal of bound-free transitions in noble gases pumped by electron beams for obtaining laser action in VUV range.
- **1970 – Basov N.G., et al**. *Sov. JETPh Lett.* **12**, 473. *Laser action was obtained in liquid Xe_2 at λ=176 nm.*
- **1975 – Ewing, J., Brau, C.** Appl. Phys. Lett. **27**, 350. *Laser action was obtained in KrF u XeCl in UV spectral range.*
- **2022 –** *ICF ignition (G =1.5) was achieved at NIF Nd: glass laser at LLNL.*

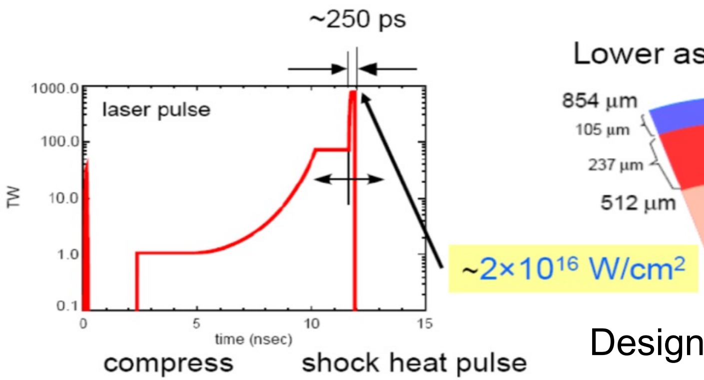
Zvorykin, *Phys Usp* 2023, https://doi.org/10.3367/UFNe.2022.11.039357

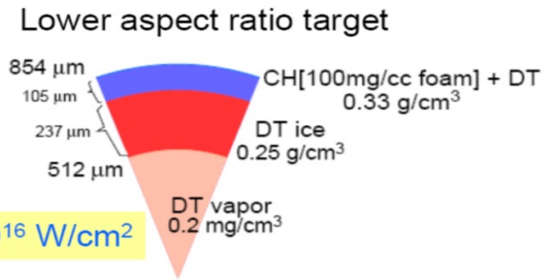
ICF ignition is now achieved, what's the next?

- *G* = 1.5 was demonstrated at 2 MJ NIF Nd: glass laser at LLNL, while hydro instabilities (HI) were limiting the value of *G*.
- IFE power plant should operate at $\eta G \geq 10$
- KrF laser-driven SI ICF allows $G \geq 130$ at sub-MJ pulse energies and efficiency $\eta \approx 7\%$
- Short gain recovery time τ_c = 2 ns is well compatible with SI pulse-form



Compress then shock heat the pellet center for ignition





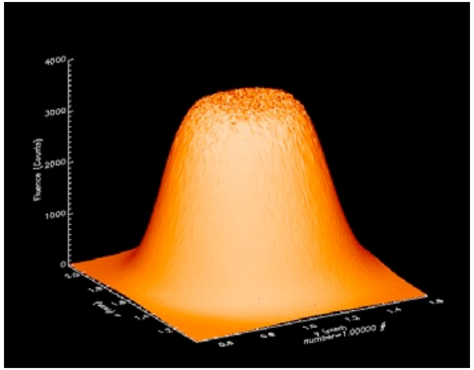
Designed by Schmitt et al. NRL

Shock-ignition ICF was proposed by:
V.A. Sherbakov, *Sov. J. Plasma Physics* 1983, 9, 240.
R. Betti, *et al.*, *Phys. Rev. Lett.* 2007, 98, 155001.
A.J. Schmitt, *et al.*, *Fusion Sci. Technol.* 2009, 56, 377.

Hydro instabilities in KrF laser interaction with plane targets

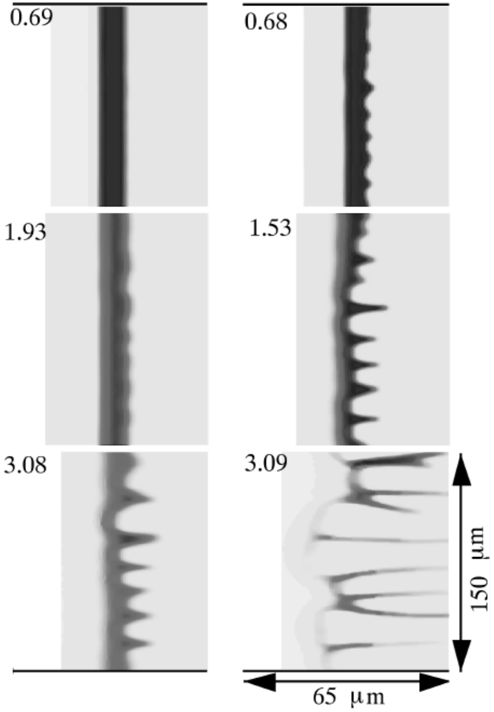
44-beam NIKE (NRL):
2.3 kJ, 4 ns, 10^{14} W/cm^2

Nonuniformity < 0.15% over 500–1000 μm

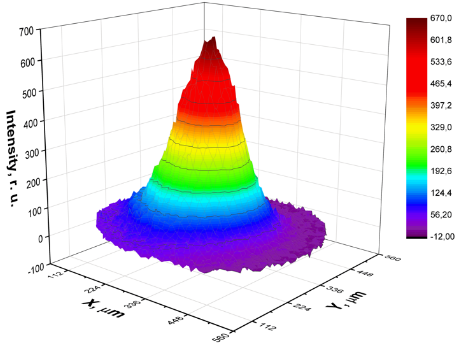


Obenschain, et al, *Appl. Opt.* 2015, **34**, F103

HI development at
0.15% 2.7%

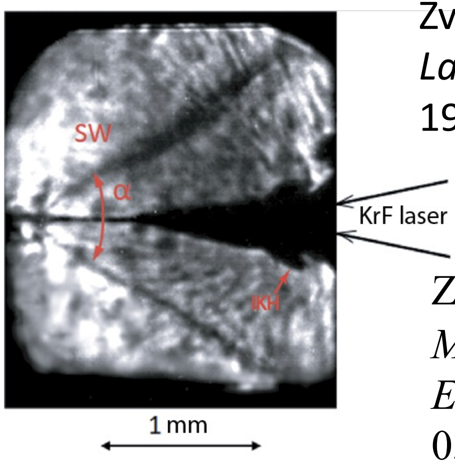


GARPUN (LPI):
100 J, 100 ns, ≤ $5\cdot10^{12}$ W/cm^2



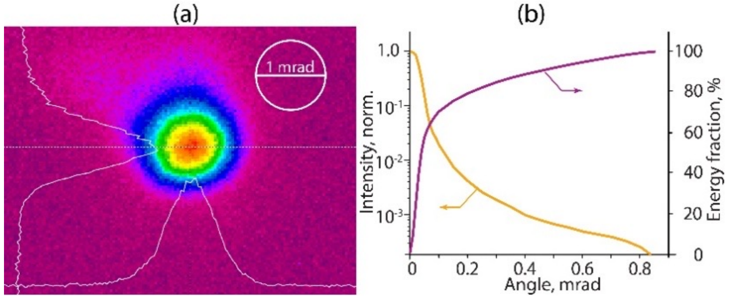
Focal spot 150 μm in dia.

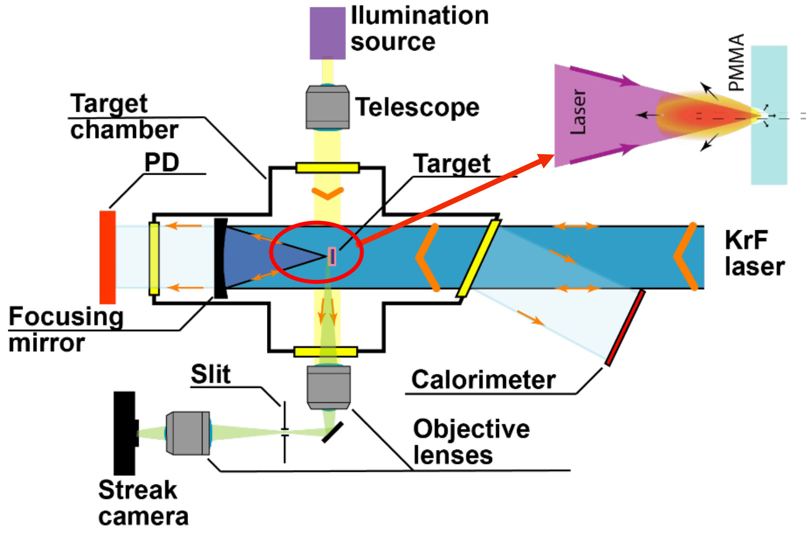
Zvorykin & Lebo, *Laser Part Beams* 1999, **17**, 69

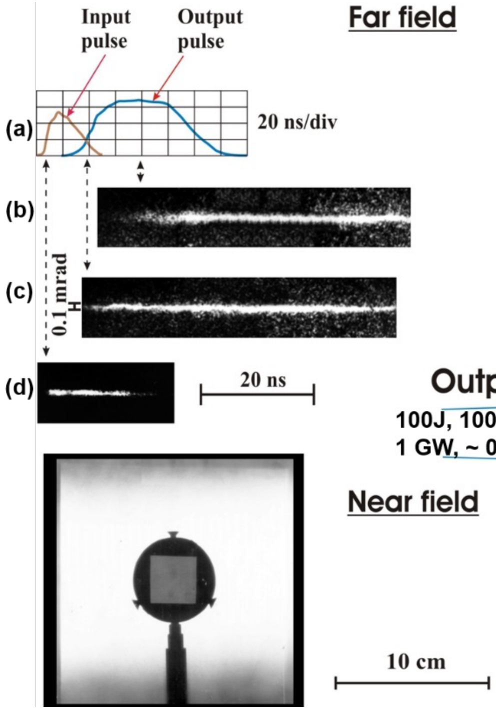


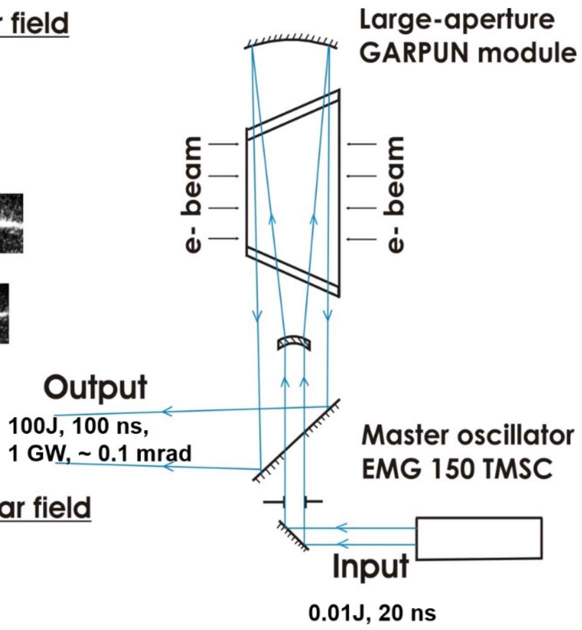
Zvorykin, et al, *Matter Radiat. Extremes* 2020, **5**, 035401

Layout of experiments







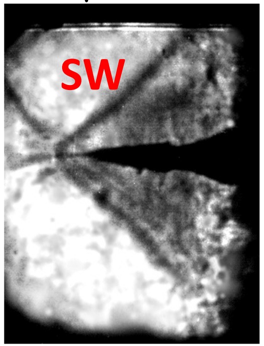


Zvorykin, et al, *Matter Radiat. Extremes* 2020, **5**, 035401

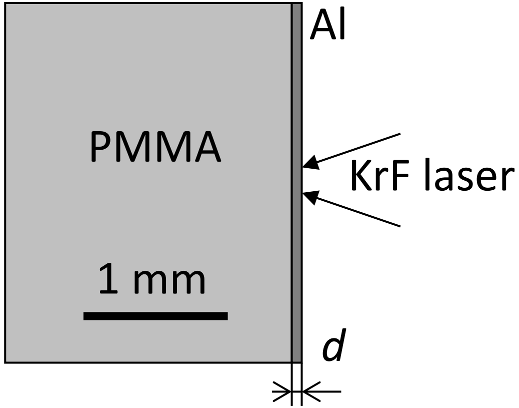
2D hydrodynamics and capillary channel (CC) in PMMA

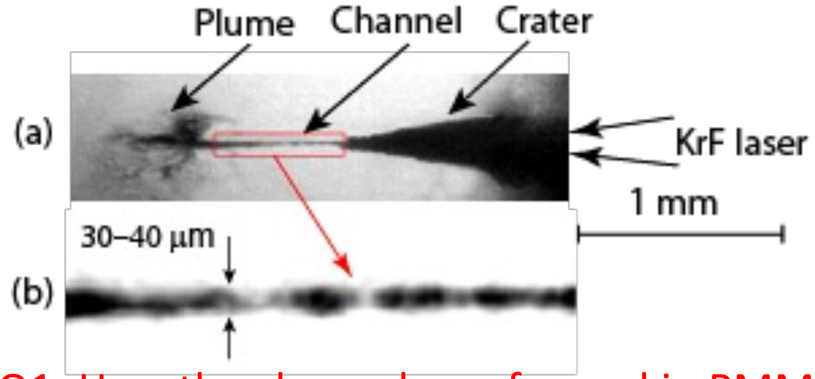
$I = 2.3\cdot10^{12}$ W/cm^2
d=50 μm

$I = 3.8\cdot10^{12}$ W/cm^2
d=200 μm



$I = 3.5\cdot10^{12}$ W/cm^2
d=330 μm

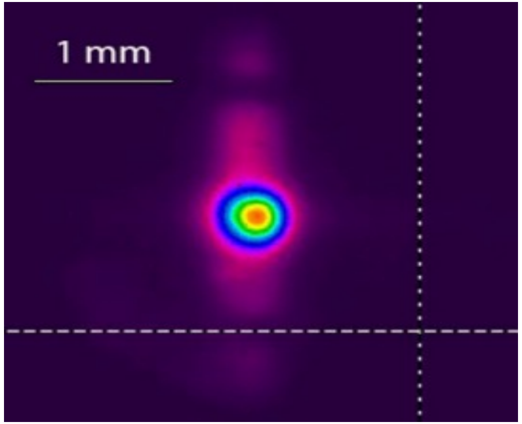


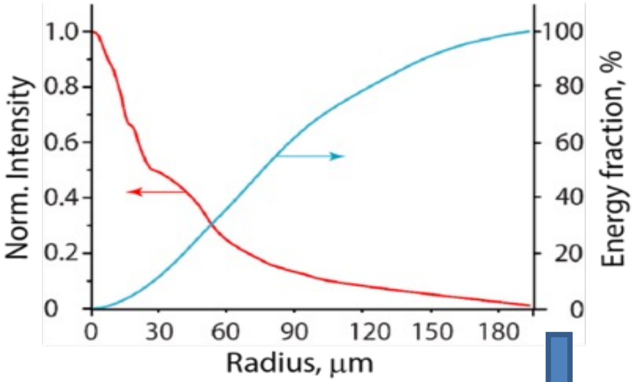


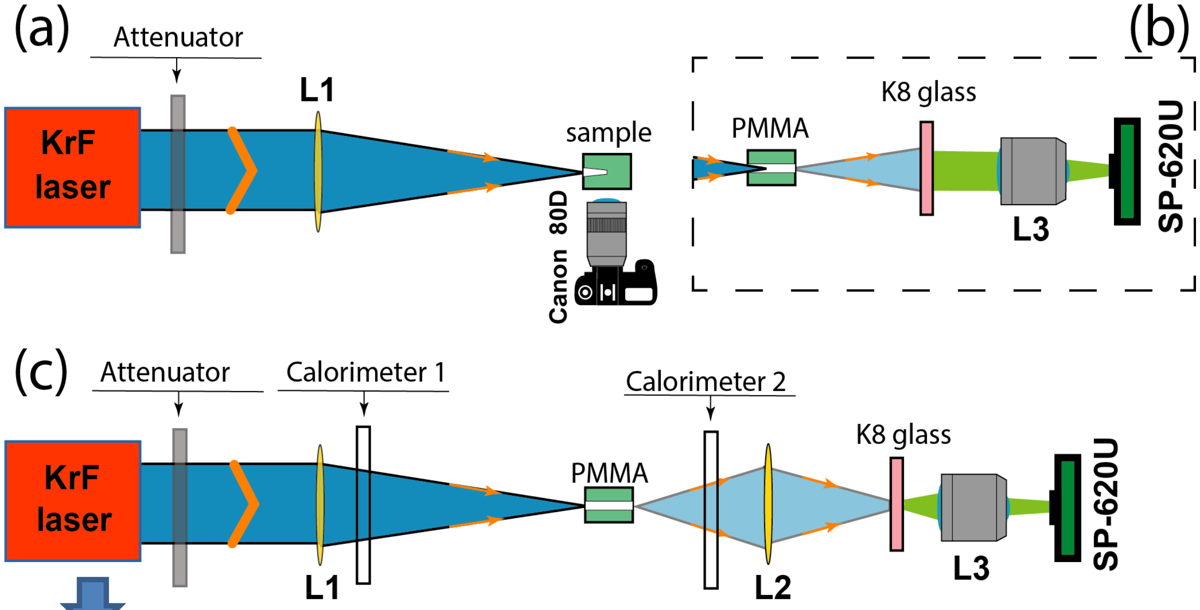
Q1: How the channel was formed in PMMA?
Q2: Was the plume formed by fast e$^-$?

- The ablation front velocity in 2D geometry was tenfold higher than in 1D
- A 1-mm length channel with L / D ~ 300 extended from the top of a conical crater
- Refractive index n was increased in compressed matter behind the SW
- The plume at the channel end looks like e$^-$ tracks during e-beam deceleration

Answer to Q1 was obtained in the multi-pulse PMMA drilling





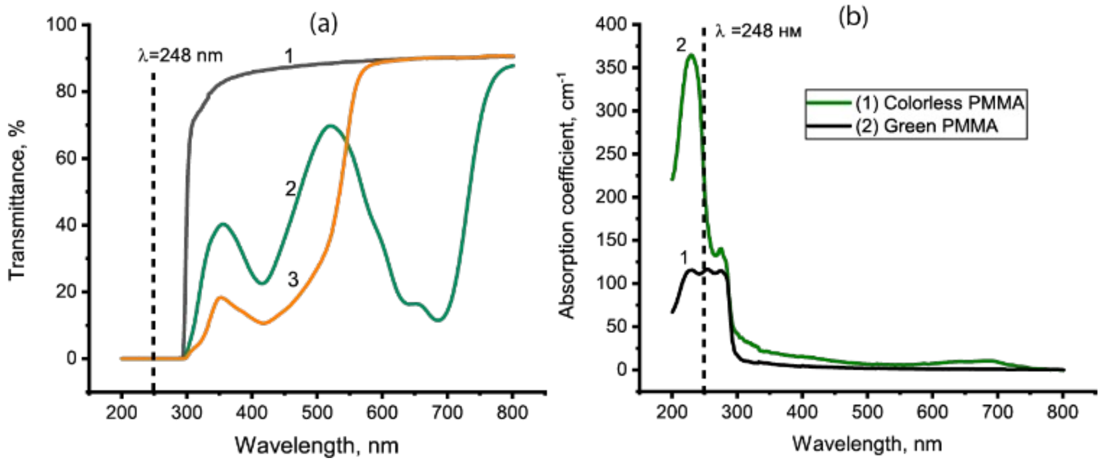


E=0.3÷200 mJ; τ=20 ns, f = 10 Hz

F_0 [J/cm^2] = $5\cdot10^3 E$ [J]=1.5÷1000 J/cm^2
I_0 [W/cm^2] = $2.5\cdot10^{11} E$ [J]=(7.5÷500)·10^7 W/cm^2

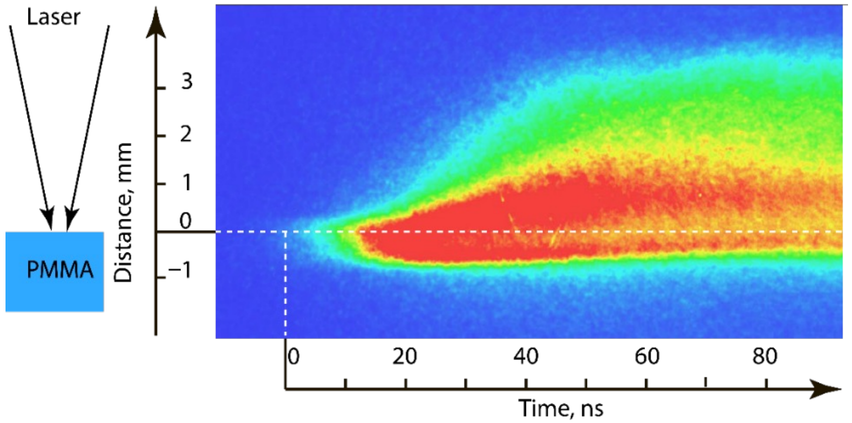
Smetanin, et al, *Materials*, 2022, **15**, 8347

PMMA is partially transparent at KrF laser wavelength λ=248 nm



At λ = 248 nm the absorption coefficient in colorless PMMA α =120 cm^{-1} (radiation penetration depth l=1/ α = 80 µm) is twice less than in the green one

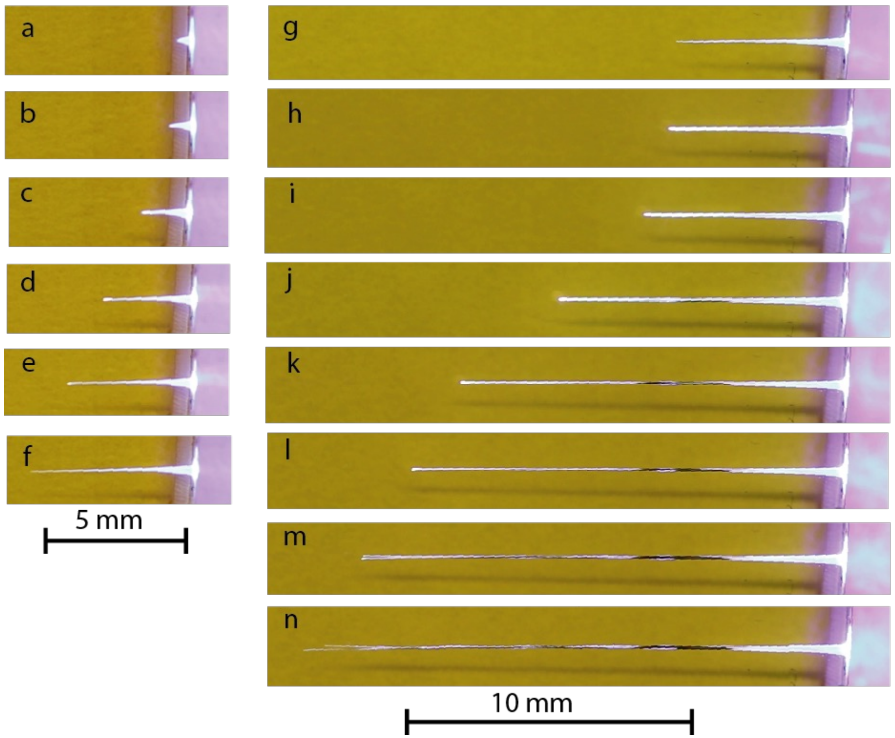
Ablation plasma was rapidly formed at the depth ~1 mm inside PMMA during the first 20 ns, while the rest of 100-ns pulse was interacting with a very long plasma in the channel

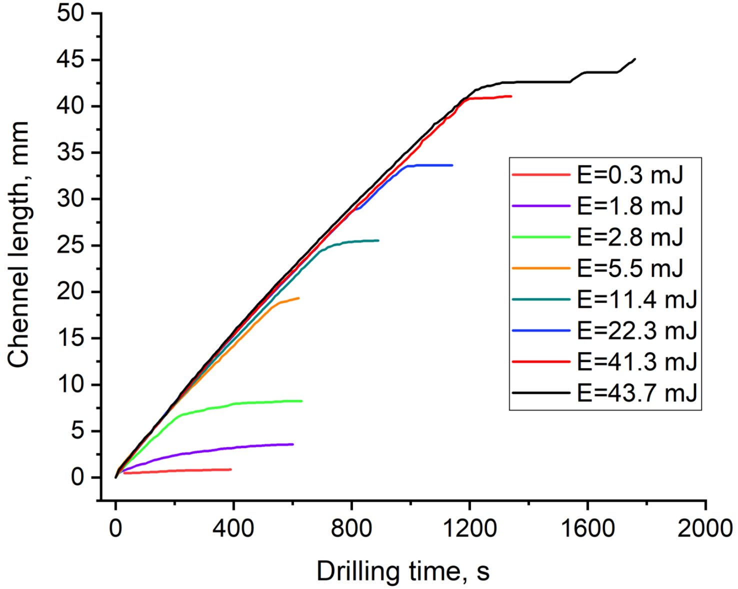


Dynamics of multi-pulse PMMA drilling

Videoframes for 10 Hz rep rate

$E \approx 2.8$ mJ $E \approx 7$ mJ

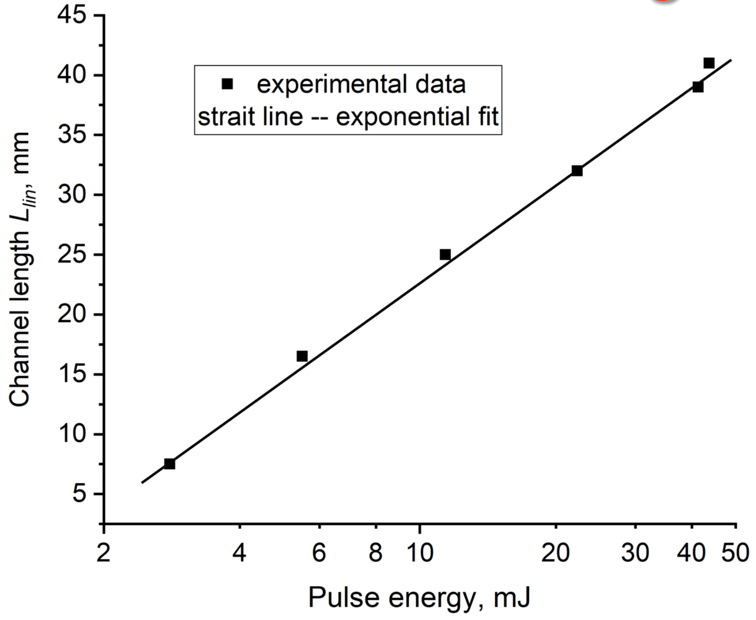


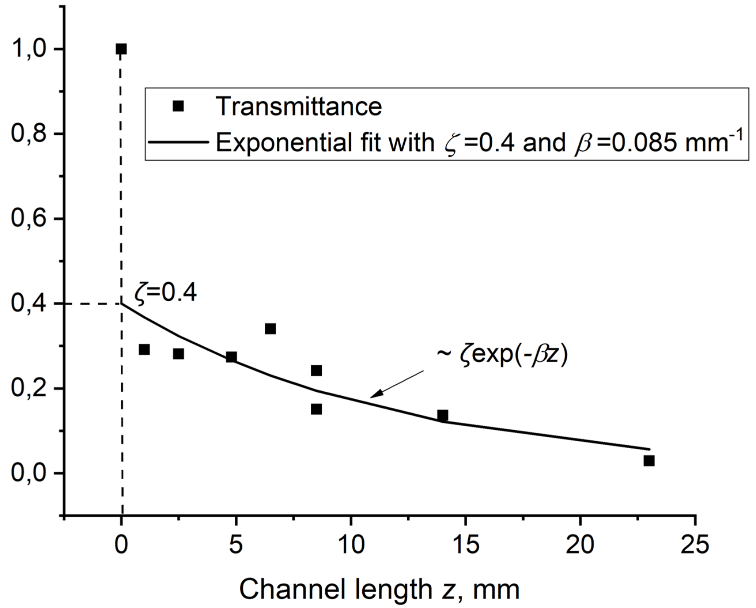


Ablation rate in the channel l_{ab} =3.5–4 μm/pulse does not depend on E and α in contrast to surface polymer ablation described by the formula

$$l_{ab}=\left(\frac{1}{\alpha}\right)\ln\left(\frac{E}{E_{th}}\right)$$

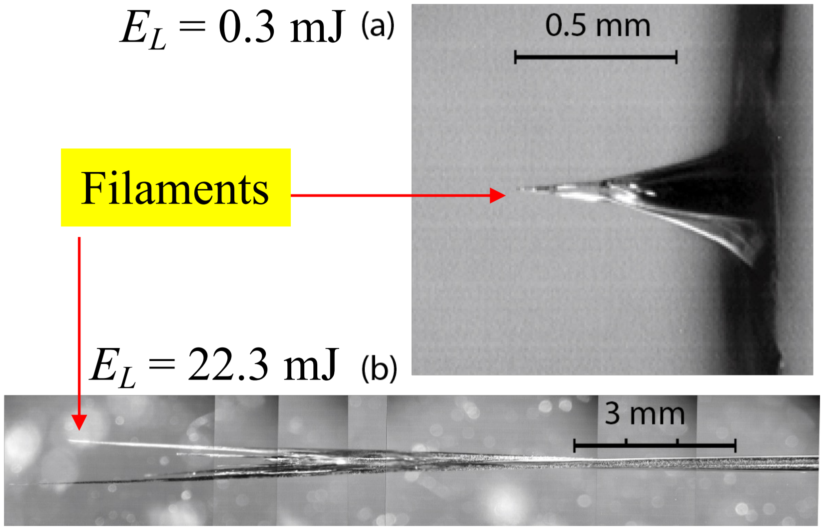
Channel length vs. pulse energy





Channel length L_{lin} logarithmically depends on E which exponentially decrease along the channel length: $E(z) = \zeta E_L exp(-\beta z)$

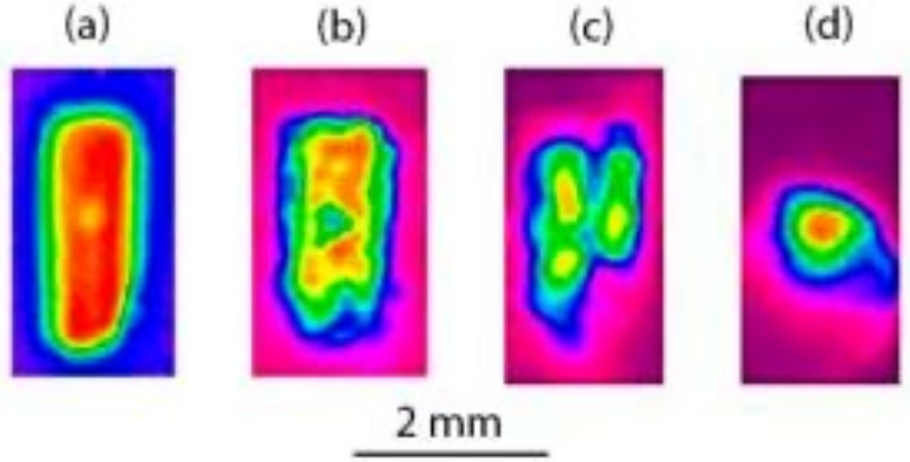
Radiation self-focusing caused filamentation-assisted ablation



- A self-focusing breaks laser beam in PMMA into self-organized filaments with approximately equal power $P_f \sim P_{cr}$
- A bundle of such filaments drill PMMA with the ablation rate independent on E (or P).
- The number of filaments $N_f(z) \approx P(z)/P_{cr}$ decreases gradually along the channel length until $P(z = L_{lin}) \approx P_{cr,}$ when filamentation is turned off.

- For self-focusing onset $B = \frac{2\pi}{\lambda}\int \Delta n dl \geq 1$, where $\Delta n = n(I) - n_0$ is variation of refraction index with laser intensity; Kerr nonlinearity $\Delta n = n_2 I_0 \approx 3 \cdot 10^{-7}$ for $n_2 \approx 4.5 \cdot 10^{-16}$ $cm^2 \cdot W^{-1}$ and $I_0 = 7 \cdot 10^8$ $W \cdot cm^{-2}$ gives $L_{sf} \sim 10$ cm >> $l \sim 100$ µm.
- For UV-induced PMMA defragmentation [Wochnowski et al *Polymer Degradation and Stability* **2005**, *89*, 252] <Δn> ~ $5 \cdot 10^{-3}$ over the UV penetration length $l \sim 100$ µm gives $L_{sf} \sim 8$ µm << l

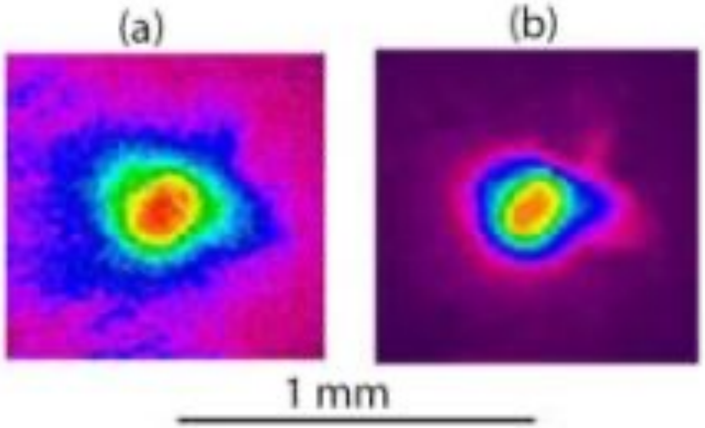
Waveguide features of capillaries



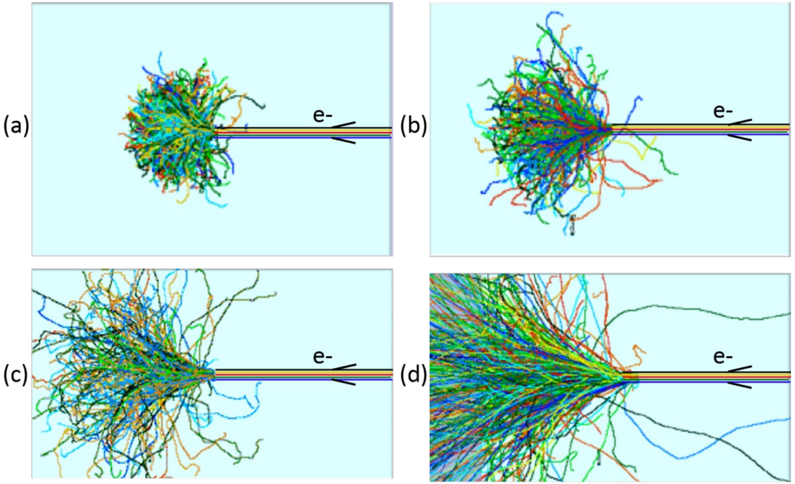
Radiation distributions 10 cm behind focusing lens (a) and at the same distance behind CC of L = 4.8 (b), 6.5 (c) u 23 mm (d); E_L ~15 mJ

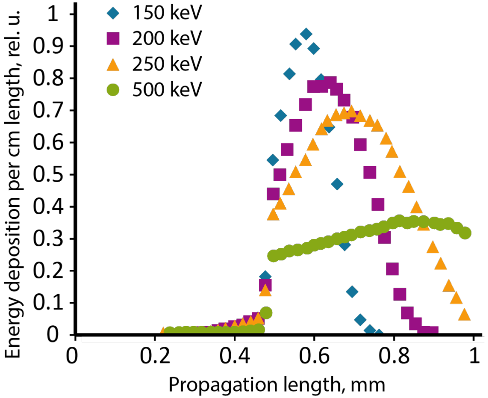
Longer channels produce better mode selection

Radiation distributions at CC exit for L = 23 mm; E_L =110 (a) u 11 mJ (b)

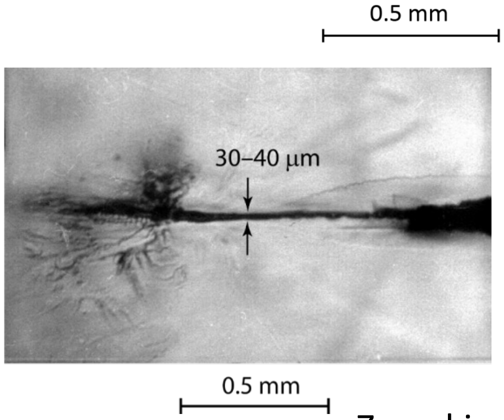


Answer to Q2: Monte-Carlo simulations and experiments proved that the plume was produced by fast electrons accelerated in capillary channel

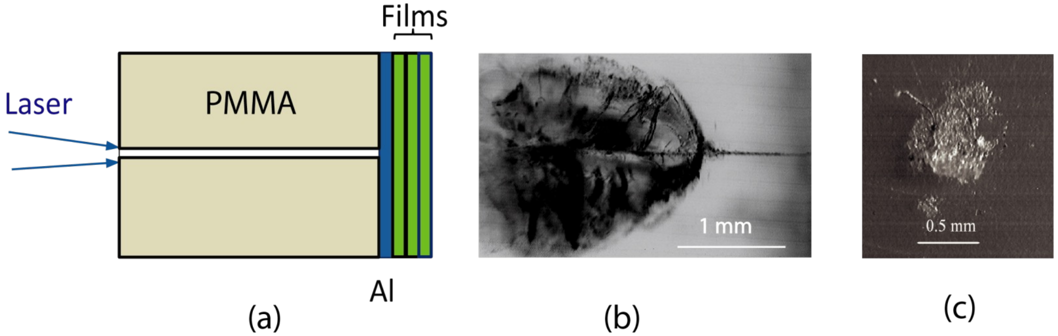




The plume configuration in Monte Carlo simulations corresponds the best to electron energyεe ~ 250 keV



Electron energy ε_e ~ 100 keV was estimated in experiments with preliminary drilled channels



Zvorykin et al, *Symmetry*, 2021, **13**, 1883

Summary

✓ Effective drilling of high-aspect-ratio capillary channels in translucent dielectrics (PMMA, K8 glass) was demonstrated by using a rep-rate KrF laser

✓ The main features of the drilling process were identified:

i. Self-focusing of UV radiation induced in target material by its densification

ii. A bundle of filaments with approximately equal intensity and power provided filamentation-assisted ablation with a rate independent on the incident pulse energy (power).

iii. A waveguide-like propagation of laser radiation was observed in the channels; the single mode with a central maximum was formed in longer channels

✓ Similar processes are responsible for capillary channels production in single-shot high energy laser-target interaction: 2D geometry resulted in rapid propagation of the ablation front and self-sustained long capillary channel formation

✓ Electron acceleration up to a few hundred keV was observed in a corrugated channel via a direct acceleration by an axial component of the laser field

✓ These effects could affect on hydrodynamic instabilities growth in ICF conditions