Fabrication of Submillimetric Dielectric Nozzles using Ultrafast Laser Micromachining for kHz Repetition Rate Laser Electron Acceleration

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Motivation

Compact and cost-effective laser plasma accelerators (LPAs) operating at kHz repletion rates has opened attractive possibilities for practical applications, such as ultrafast electron probing and photon sources. Additionally, the high repetition rate enables active feedback stabilization in these accelerators, enhancing the overall performance and reliability of LPAs.

Multi-MeV electrons can be generated by typical few mJ, kHz laser systems with $a_0 > 1$ and at resonant condition [1, 2]:

$$w_0 \approx c\tau \approx \lambda_P/2$$

- near-diffraction-limit focusing w_0 ~ few μm
- few-cycle τ ~ few fs
- high density plasma waves $n_e \sim 10^{20}$ cm^{-3}

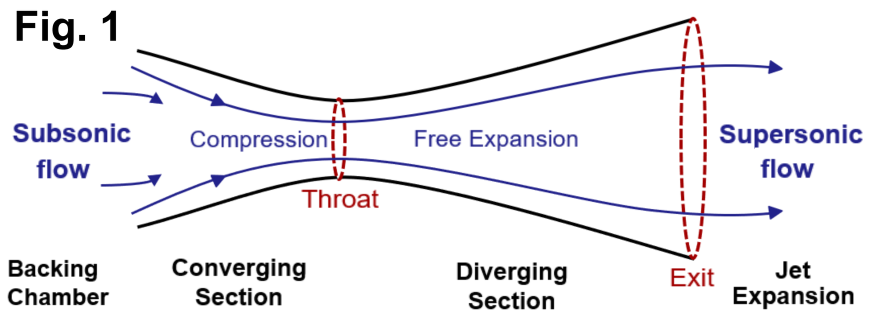
These requirements imply:

- Rayleigh length: w_0~μm → **tens μm**
- Dephasing length: $n_e \sim 0.1 n_{crit}$ → **tens μm**

~100 μm gaseous target is wanted for operating kHz LPA

Moreover, supersonic gas jets with sharp density gradients optimize the coupling of laser pulses into the jet [3]. These jets can be generated from de Laval (coverging-diverging) nozzles, as illustrated in Fig. 1:

Fig. 1



within a quasi-1D model, jet properties such as Mach number (1) and exit density (2) can be described by exit and throat areas [4]:

$$\frac{A_e}{A_t} = \frac{1}{M}\left[\frac{2+(\kappa-1)M^2}{\kappa+1}\right]^{\frac{\kappa+1}{2(\kappa-1)}} \quad (1)$$

$$\frac{n_g}{n_{g,0}} = \frac{1}{M}\left[\frac{\kappa+1}{2+(\kappa-1)M^2}\right]^{\frac{1}{\kappa-1}} \quad (2)$$

Developing submillimetric de Laval Nozzles:

- Not commercially available (COTS) → **must be homebuilt**
- Daily operational durability is a critical → **dielectric materials have higher laser-induced damage threshold (LIDT)**

Our mission:

Design and develop dielectric de Laval nozzles for kHz LPA

References:

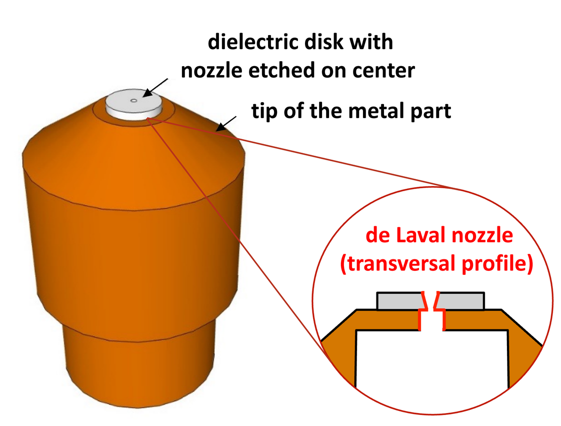
[1] J. Faure, et al., Phys. Plasmas, vol. 26, no. 5 (2019)
[2] F. Salehi, et al., Phys. Rev. X 11, 021055 (2021)
[3] D. Gustas, et al., Phys. Rev. Lett., vol. 120, no. 8 (2018)
[4] K. Schmid, et al., Rev. Sci. Instrum., vol. 83, no. 2 (2012)
[5] A. V. F. Zuffi, et al., SBFoton Conferende Procedings (2022)
[6] O. Zhou, et al., Phys. Plasmas 28, 093107 (2021)
[7] V. Tomkus, et al., Opt. Express, 26(21), 27965-27977 (2018)

Nozzle fabrication by ultrafast laser micromachining

Nozzles with exit diameters from 100 to 500 μm were fabricated by ultrafast laser machining using a Ti:Sapphire laser (25 fs, ≤650μJ, ≤4kHz)

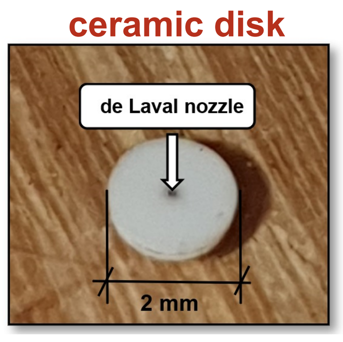
- **Design:** de Laval nozzle (or diverging section) is etched on a dielectric disk, then it is glued to a metallic part to gas line connection, see Fig. 2
- **Etching:** trepanning method by utilizing a rotating electric motor, as shown in Fig. 3. The nozzle diameters of the exit and throat could be controlled by tuning the machining parameters, which also influences the supersonic jet Mach number and its density profile

Fig. 2

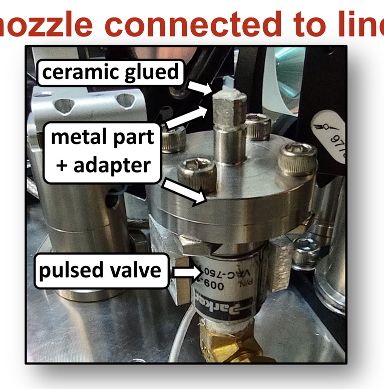


2mm ceramic disk with 0.6mm thickness + tip of the metal part

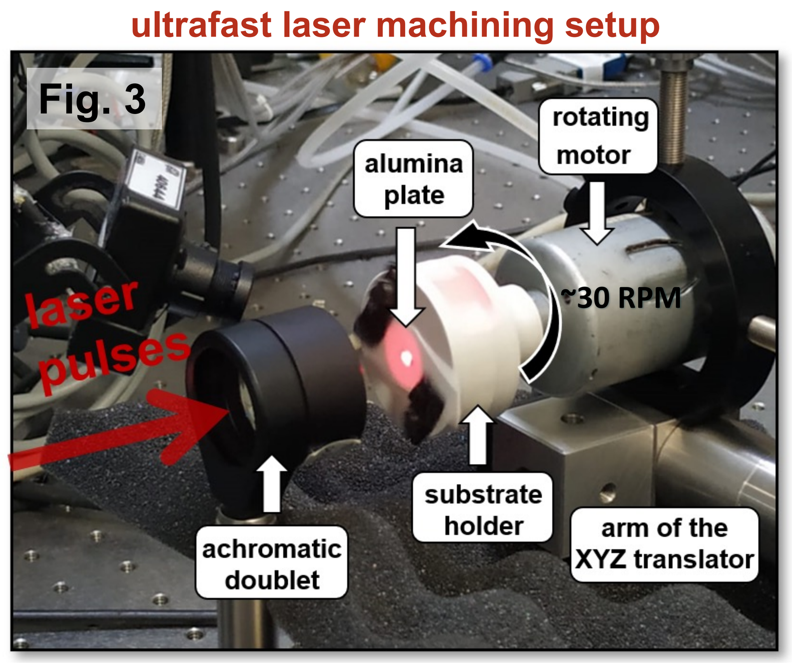
ceramic disk



nozzle connected to line



ultrafast laser machining setup



Machining Parameters:

Investigated in this study:

- **Laser energy ($\mathcal{E}$):** 250-600 μJ
- **Achromatic doublet focal length (f):** 30, 50, 75, 150, and 250 mm
- **Focus position into ceramic (pos):** at surfaces, or center the substrate
- **Exposure time after boring the substrate (t):** 1-60 s

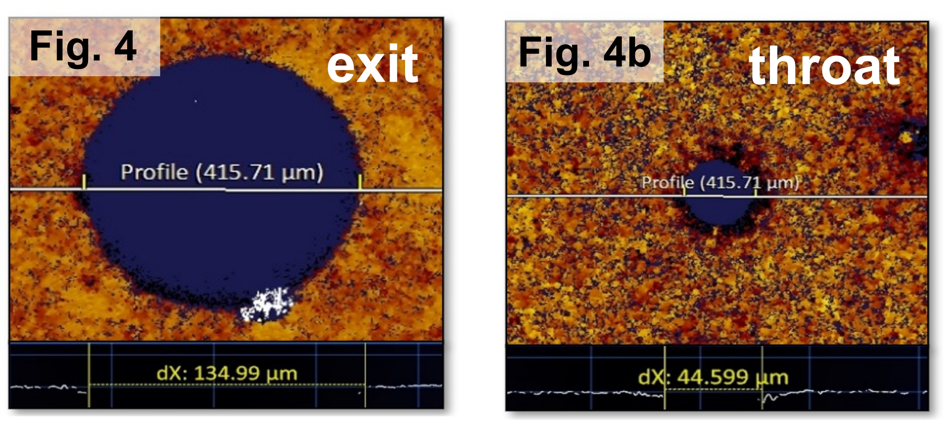
Smallest nozzle diameters were reached with the following parameters [5]:

f=75mm, $\mathcal{E}$≈400μJ, pos=center, t>10s

Analysis of dielectric de Laval nozzles features

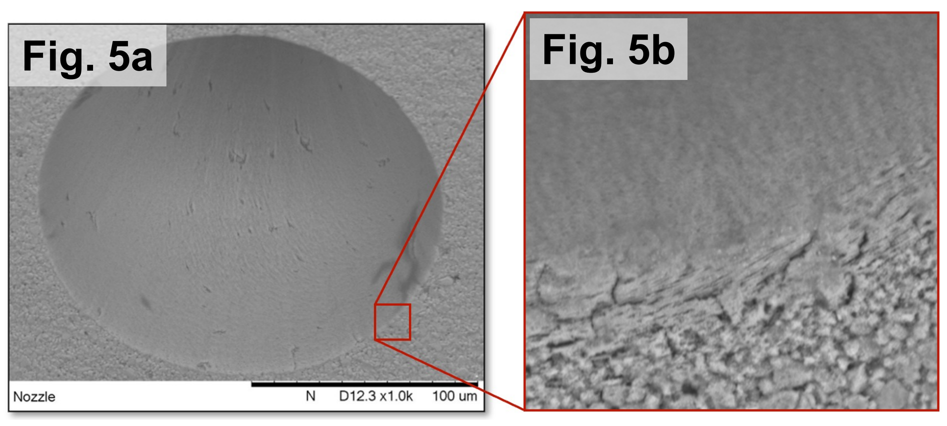
- Nozzles exhibit desirable micrometric diameters for exits ($\emptyset_e$) and throats ($\emptyset_t$) with highly circular shapes, as shown in Figs. 4a and 4b
- Smooth internal walls due to the melting and ressolidification of ablated ceramic (Figs. 5a and 5b), enhancing suitability for high-density jets
- The process produces directly “convex trumpet” nozzles (Fig. 6), although varying focus position during ablation leads towards a “concave bell” shape that is more desirable for achieving focused regions of gas with higher densities [6]

profilometries of a nozzle with $\emptyset_e$=135μm and $\emptyset_t$=45μm



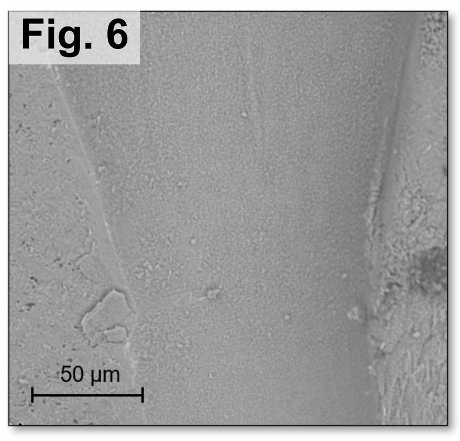
*manufacture parameters: $\mathcal{E}$=480μJ, f=75mm, pos=center/back, t=15s

micrographies of a nozzle with $\emptyset_e$=160μm and $\emptyset_t$=45μm



*manufacture parameters: $\mathcal{E}$=400μJ, f=30mm, pos=center t=30s

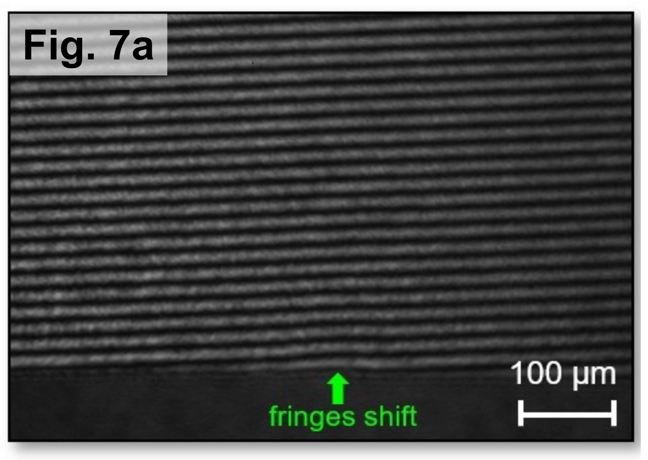
transversal profile “convex trumpet” shape



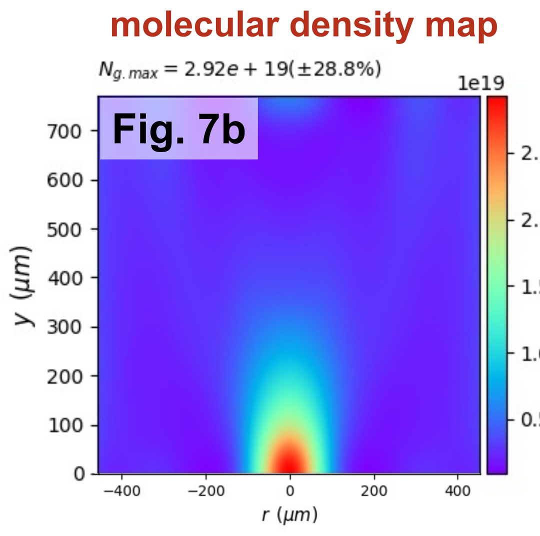
Submillimetric gas jet diagnostic by interferometry

- A Mach-Zehnder-like interferometer setup was built to measure interferograms of jet expansion in vacuum environment
- Interferograms were analyzed using homemade GUI software developed by the IPEN team with Python algorithms. The GUIs for retrieving density profile of gas targets and laser-induced plasmas are publicly available on GitHub, accessible via the QR code on this poster
- A typical interferogram analysis of an N_2 jet expanding from the nozzle with $\emptyset_e$=135 μm and $\emptyset_t$=145 μm under a backing pressure of 50 bar is shown in Fig. 7. Similar results were observed for other micro-jets produced by the manufactured nozzles.

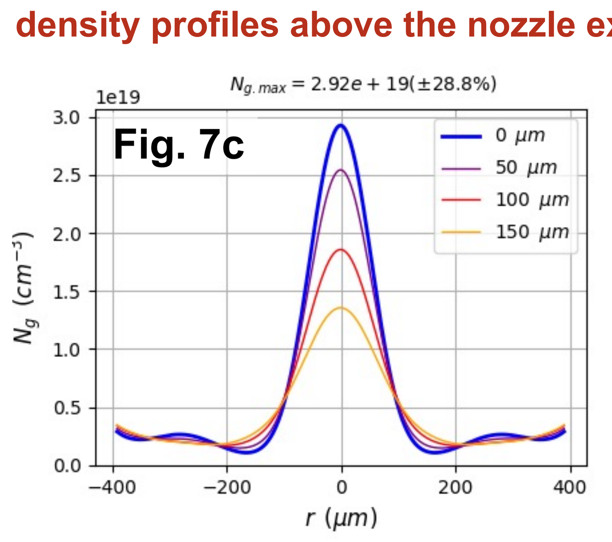
Interferogram of N_2 jet in vacuum



molecular density map



density profiles above the nozzle exit



quasi-1D model predictions :

Mach number: 4.1

Peak density: 1.6×10^{19} cm^{-3}

measured peak density:

(2.9±0.8)×10^{19} cm^{-3}

The maximum density near the nozzle exit exceeds quasi-1D model predictions, indicating a lower Mach Number. This findings aligns with previous studies on submillimetric nozzles [4] and shown the density profile and dimensions comparable to [3], supporting their use for kHz LPA

Conclusions and Outlook

- **Novel Method:** We have successfully developed a technique for manufacturing micrometric-scale de Laval nozzles
- **High Quality Etch:** Ensures production of high-precision circular nozzles with well-defined geometries
- **kHz LPA Application:** These nozzles can produce high-density supersonic micro-jets suitable for kHz LPA experiments
- **Future Enhancements:** Potential improvements can include exploring more complex focusing systems, designing nozzle structures entirely with dielectric materials (see [7]), and achieving sharper plateaus

Acknowledgment:

FAPESP

inct institutos nacionais de ciência e tecnologia

CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico

CAPES

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