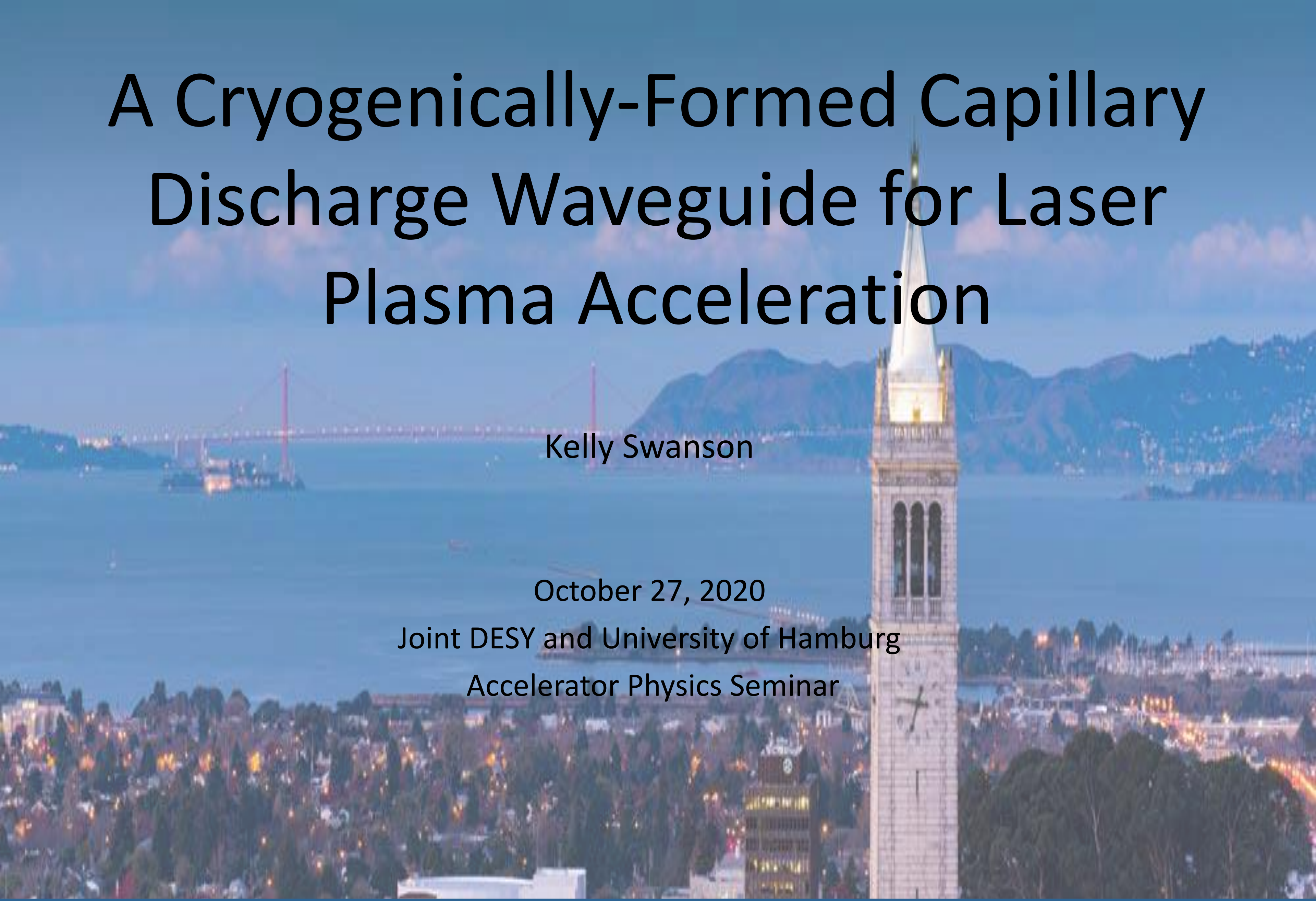


A Cryogenically-Formed Capillary Discharge Waveguide for Laser Plasma Acceleration

Kelly Swanson

October 27, 2020

Joint DESY and University of Hamburg

Accelerator Physics Seminar

Intense laser pulses can drive plasma wakes with large acceleration gradients

- Large accelerating fields

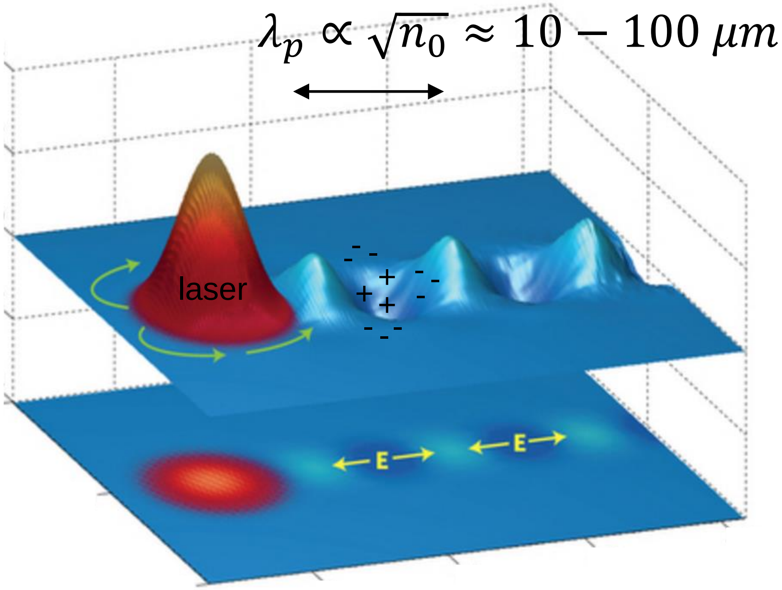
$$E_z[V/m] \approx 96\sqrt{n_0[cm^{-3}]}$$

100 GV/m ($n_0 = 10^{18}$ cm^{-3})

- Bunch duration < $\lambda_p/4$

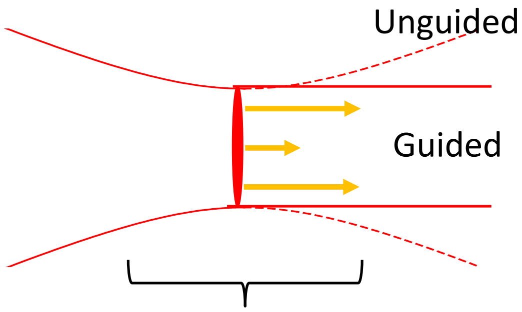
Ultrashort, fs bunches

$\lambda_p \propto \sqrt{n_0} \approx 10 - 100\ \mu m$



Hooker, S.M., *Nat. Photon* (2013)

Preformed waveguides enable large energy gains by mitigating laser diffraction

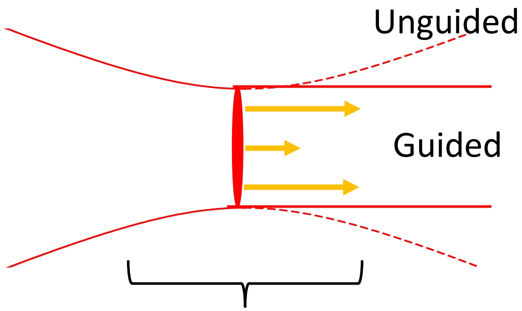


$$Z_R = \frac{\pi w_0^2}{\lambda}$$

- Pulse remains intense over Rayleigh range Z_R
- To extend acceleration length

  → Preformed plasma channel

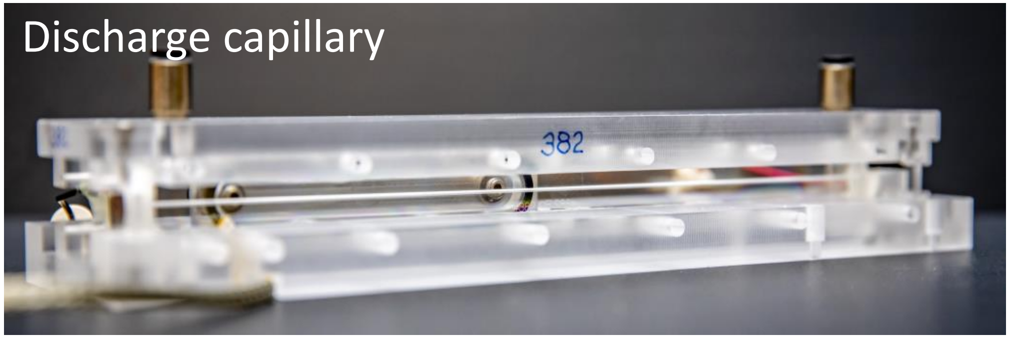
Preformed waveguides enable large energy gains by mitigating laser diffraction

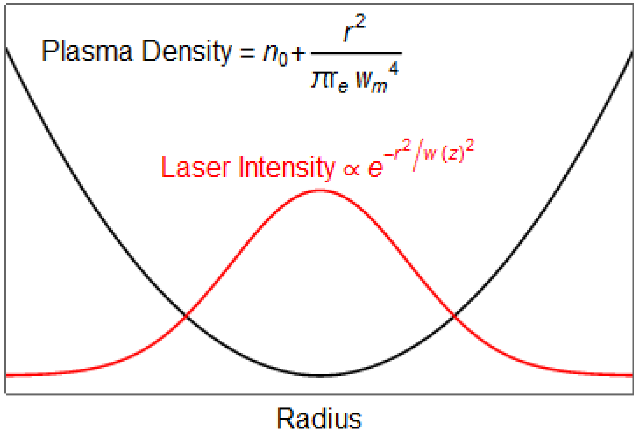


$$Z_R = \frac{\pi w_0^2}{\lambda}$$

- Pulse remains intense over Rayleigh range Z_R
- To extend acceleration length

→ Preformed plasma channel

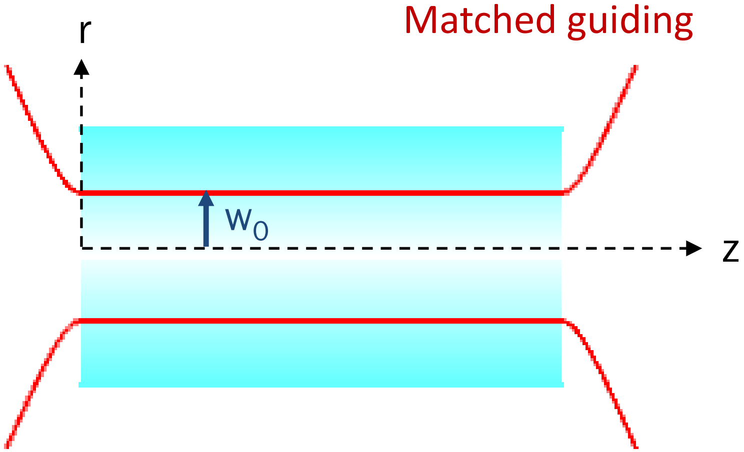

Discharge capillary

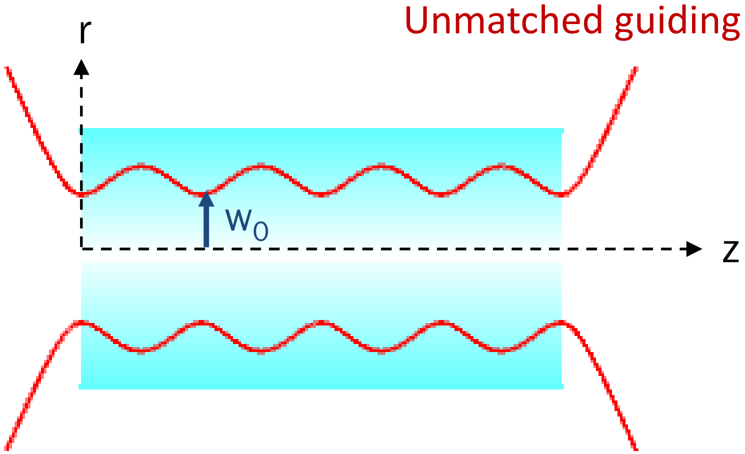


Laser pulse should be matched to the plasma channel to prevent spot size oscillations

Matched spot size in parabolic plasma channel:

$$r_m \propto \frac{\sqrt{r_c}}{n_0^{1/4}}$$





Bobrova, N.A., et al., *Phys. Rev. E* (2001)

In the limit of laser depletion, lower plasma density increases energy gain

- Interaction length:

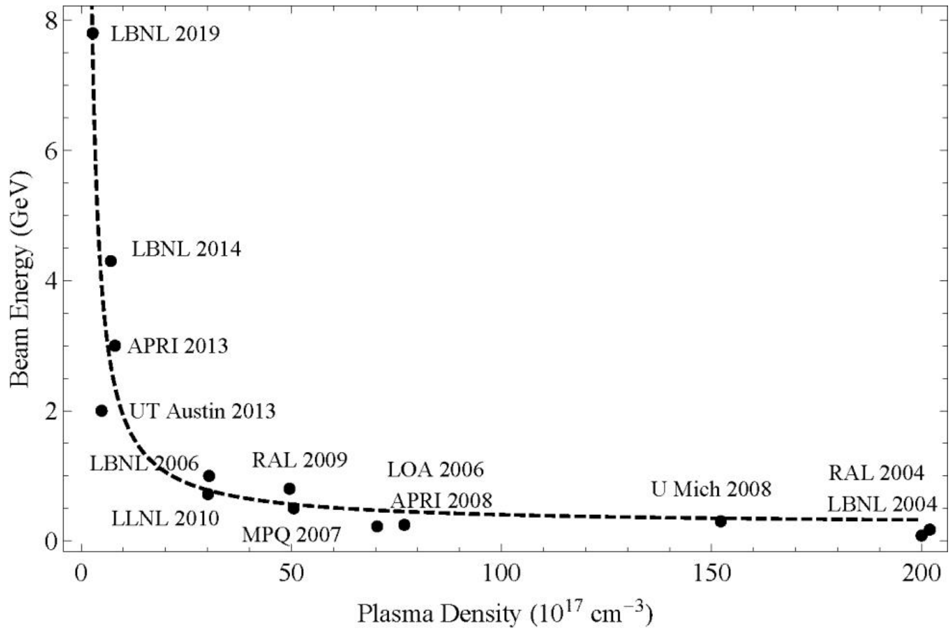
$$L_{depletion} \propto n_0^{-3/2}$$

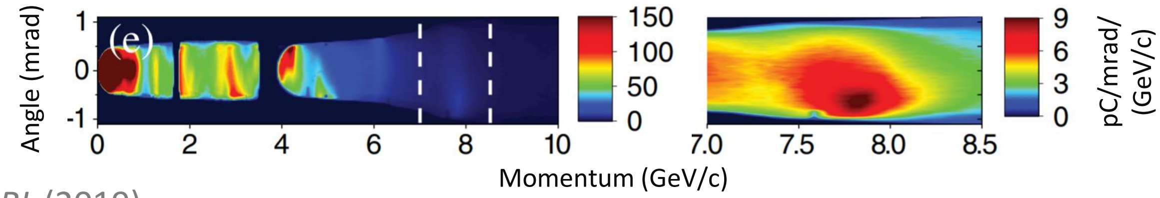
- Acceleration gradient:

$$E_z \propto n_0^{1/2}$$

- Energy gain/stage:

$$W = eE_zL_d \propto n_0^{-1}$$





Gonsalves, A.J., et al., *PRL* (2019)

Matched guiding at lower densities leaves waveguide susceptible to laser damage

Matched spot size in parabolic plasma channel:

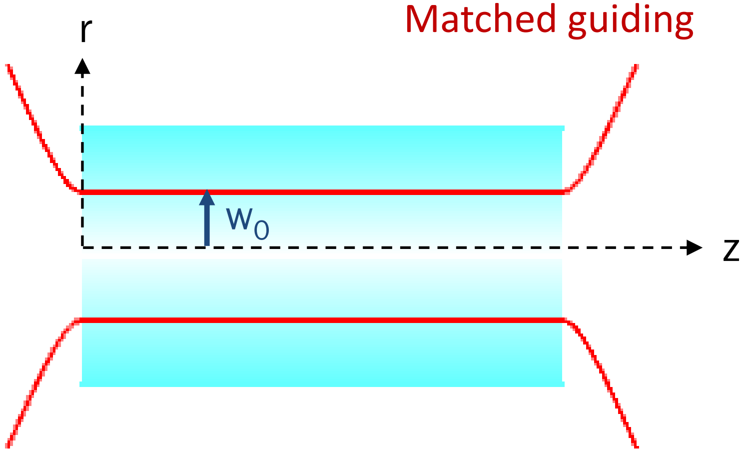
$$r_m \propto \frac{\sqrt{r_c}}{n_0^{1/4}}$$

Fixed: $w_0 = r_m$

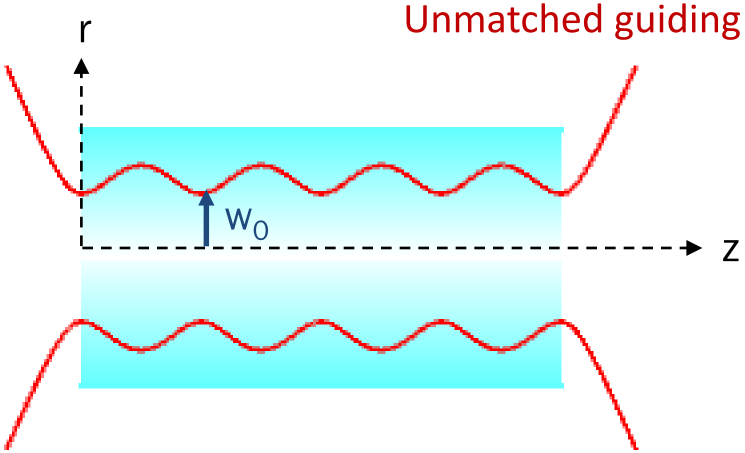
Decrease n_0

→ Laser damage

Matched guiding

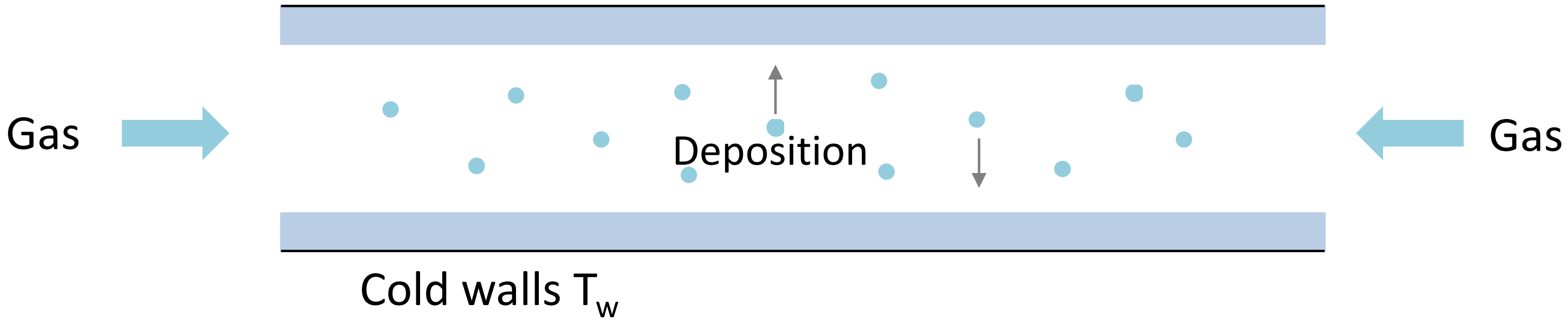


Unmatched guiding



Bobrova, N.A., et al., *Phys. Rev. E* (2001)

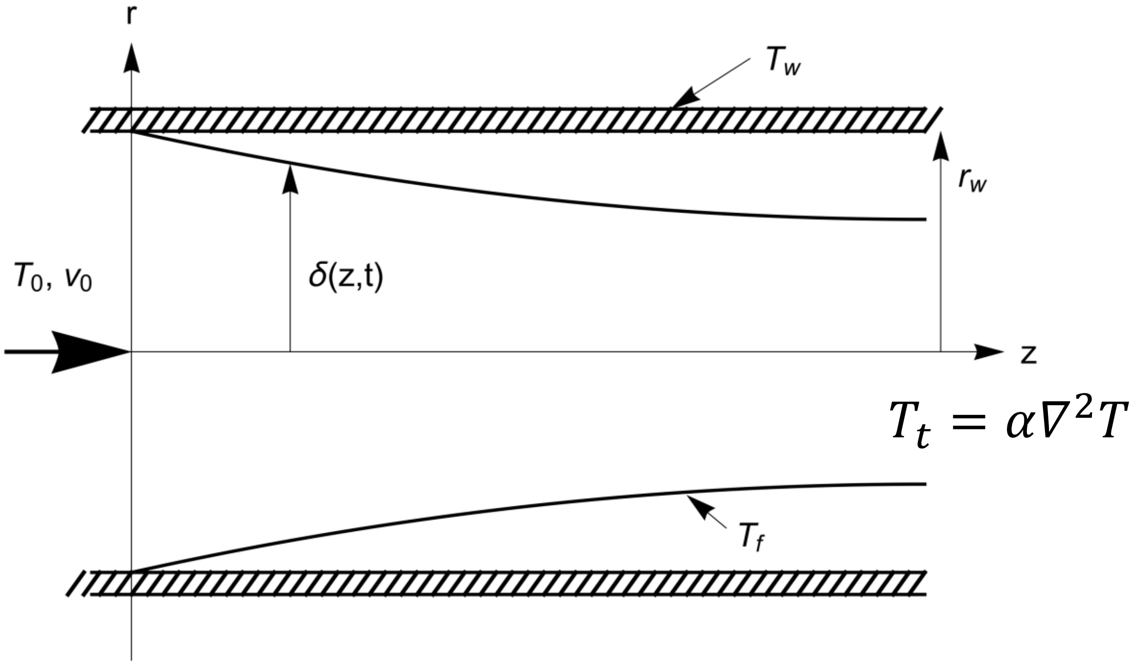
Regenerative waveguide formed by depositing gas onto cold channel walls can mitigate laser damage



- Gas 1 forms solid shell ($T_f > T_w$)
- Gas 2 adds on-axis density ($T_f < T_w$)

Swanson, K.K., et al., submitted

Gas-solid interface location determined by solving heat equations in both gas and solid phases



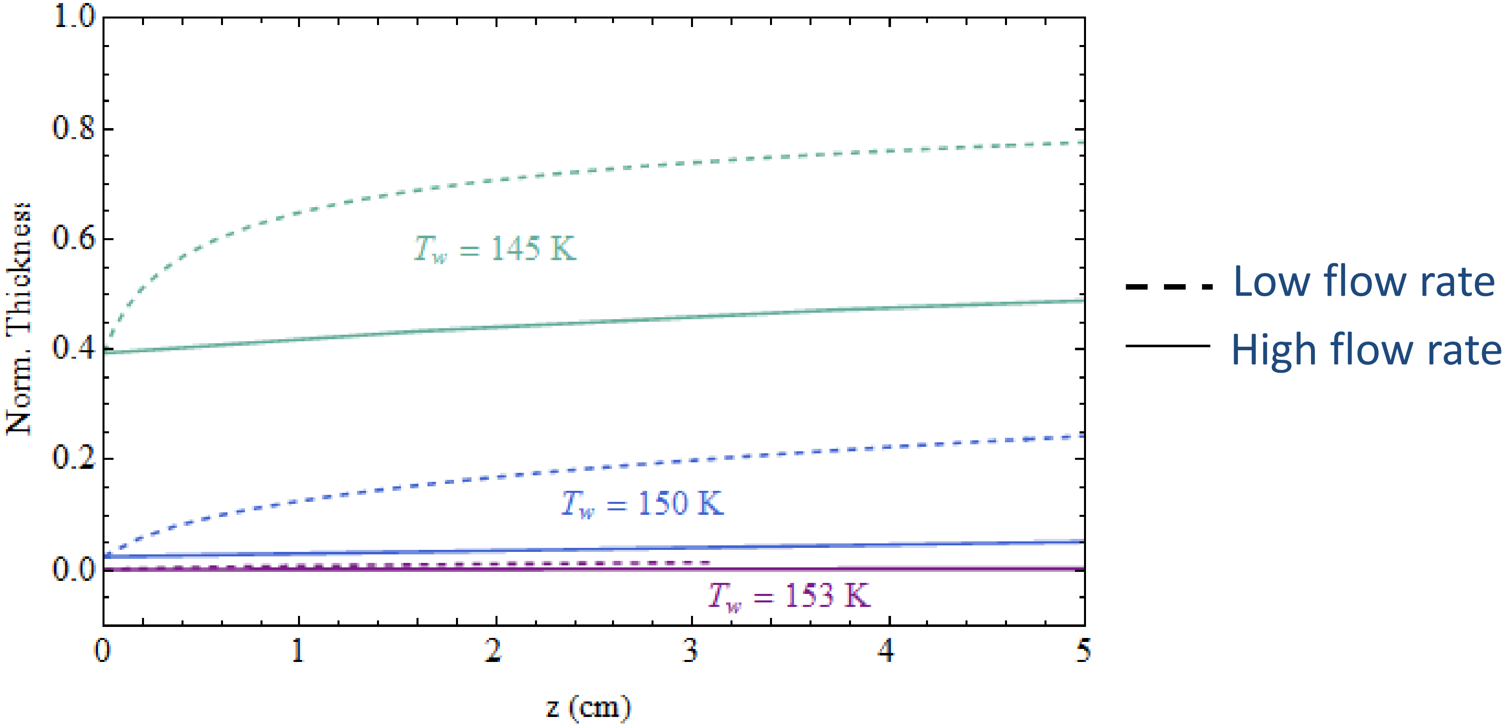
$$T_t = \alpha \nabla^2 T$$

Semi-analytically solved heat equations assuming constant wall temperature, initial gas temperature and gas velocity

Ozisik, M. N., et al., *J. Heat Transfer* (1969)

Steady-state deposition longitudinally non-uniform

*Gas freezing temperature = 153 K

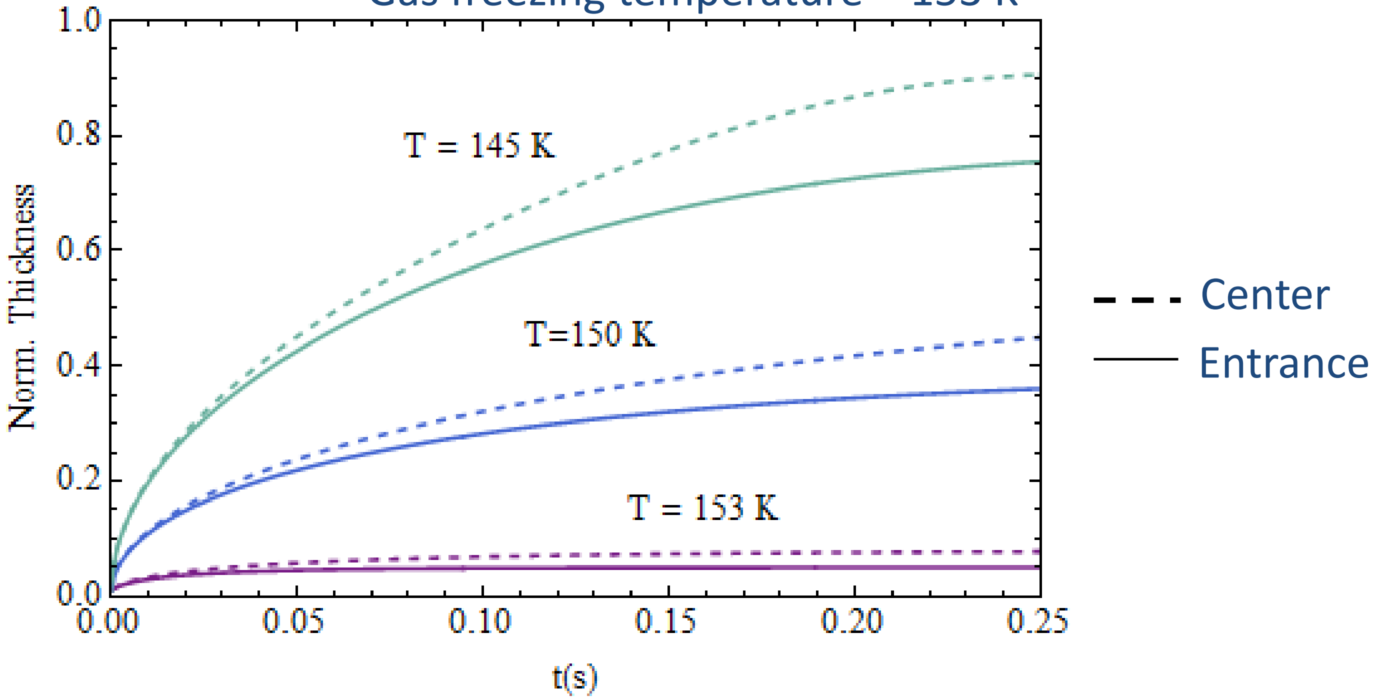


Thicker shells when transfer of heat is larger

(e.g. lower wall temperature, lower velocity)

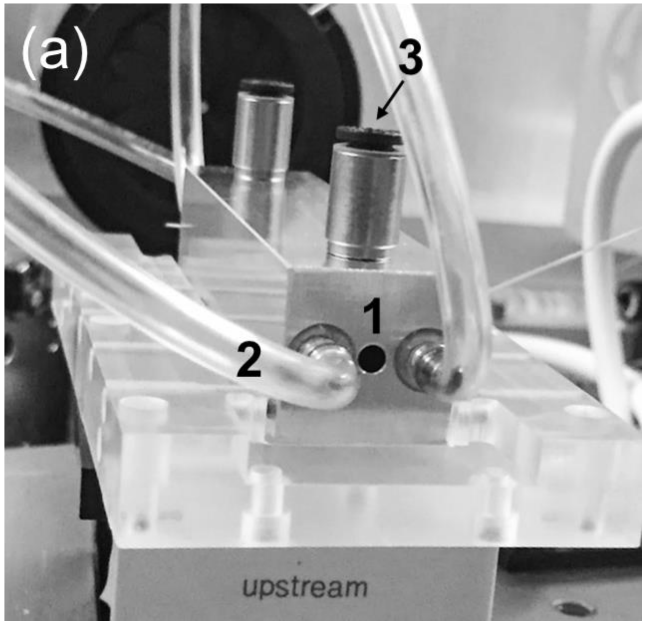
Deposition process can be controlled using wall temperature and deposition time

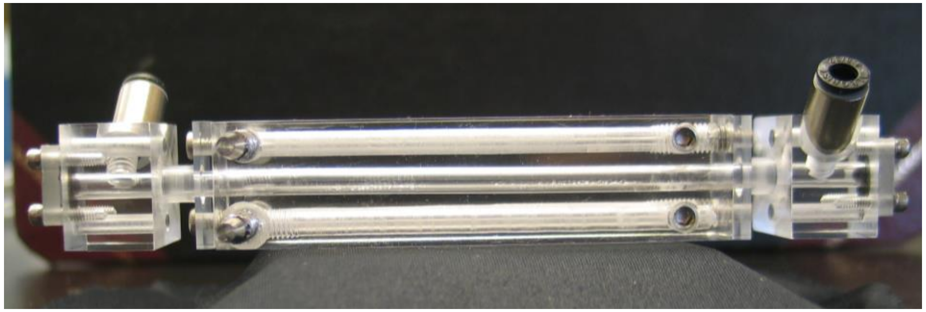
*Gas freezing temperature = 153 K

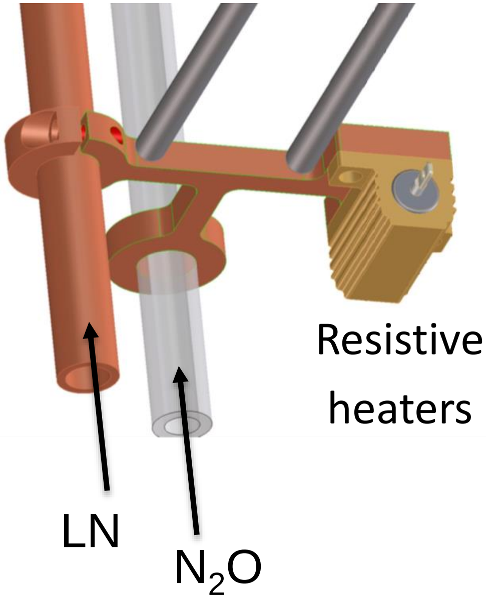


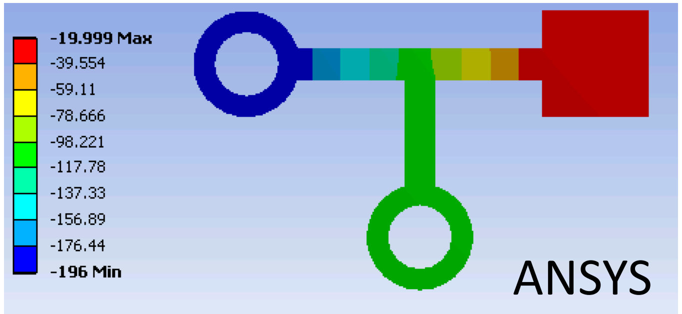
Shell thickness more uniform when wall temperature is near freezing temperature

Developed several waveguide iterations



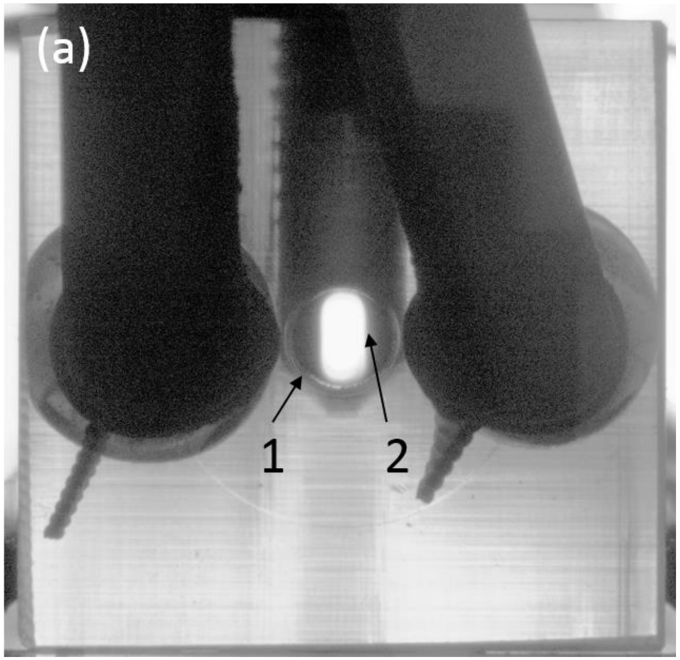




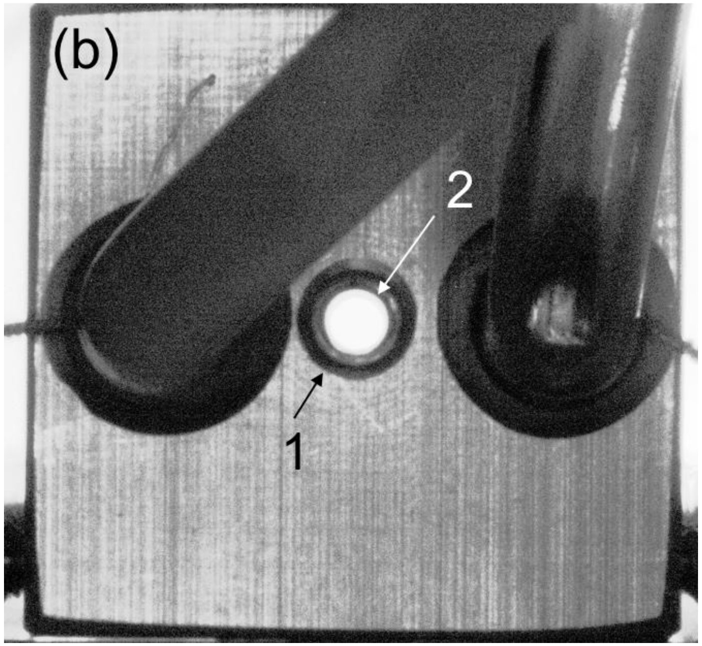


Temperature distribution around channel determines radial uniformity

Acrylic



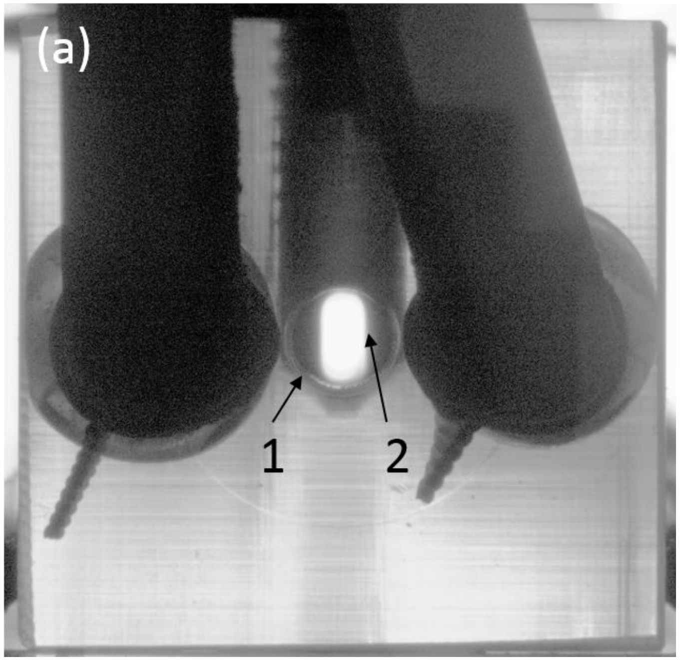
Aluminum

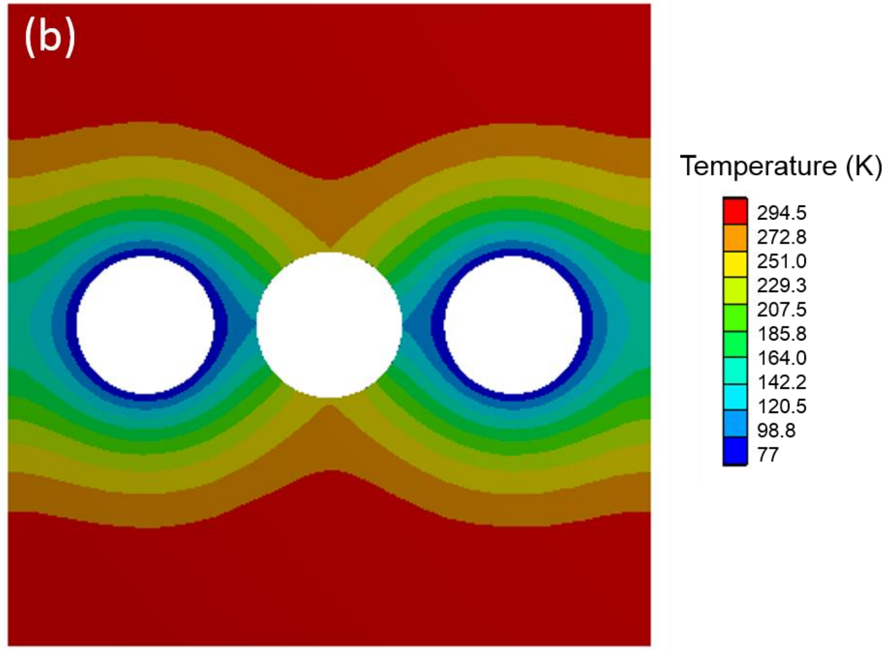


Thermal conductivity:
acrylic = 0.2 W/(m K)
aluminum = 205 W/(m K)

Temperature distribution around channel determines radial uniformity

Acrylic

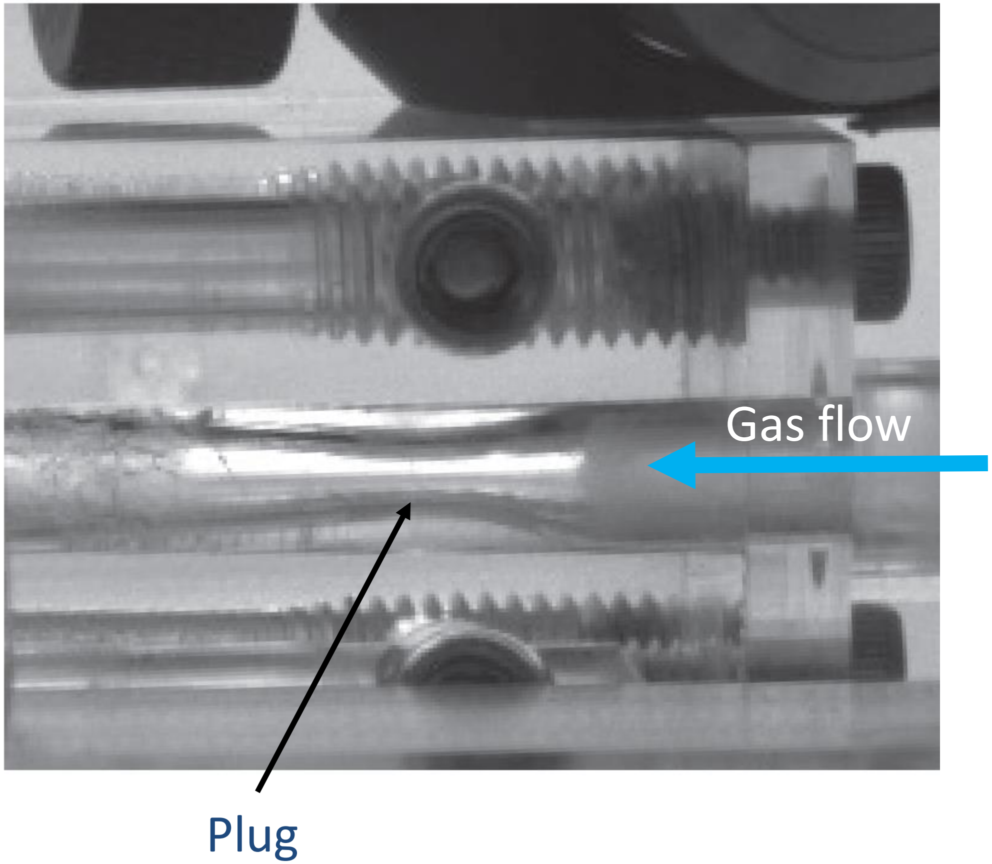




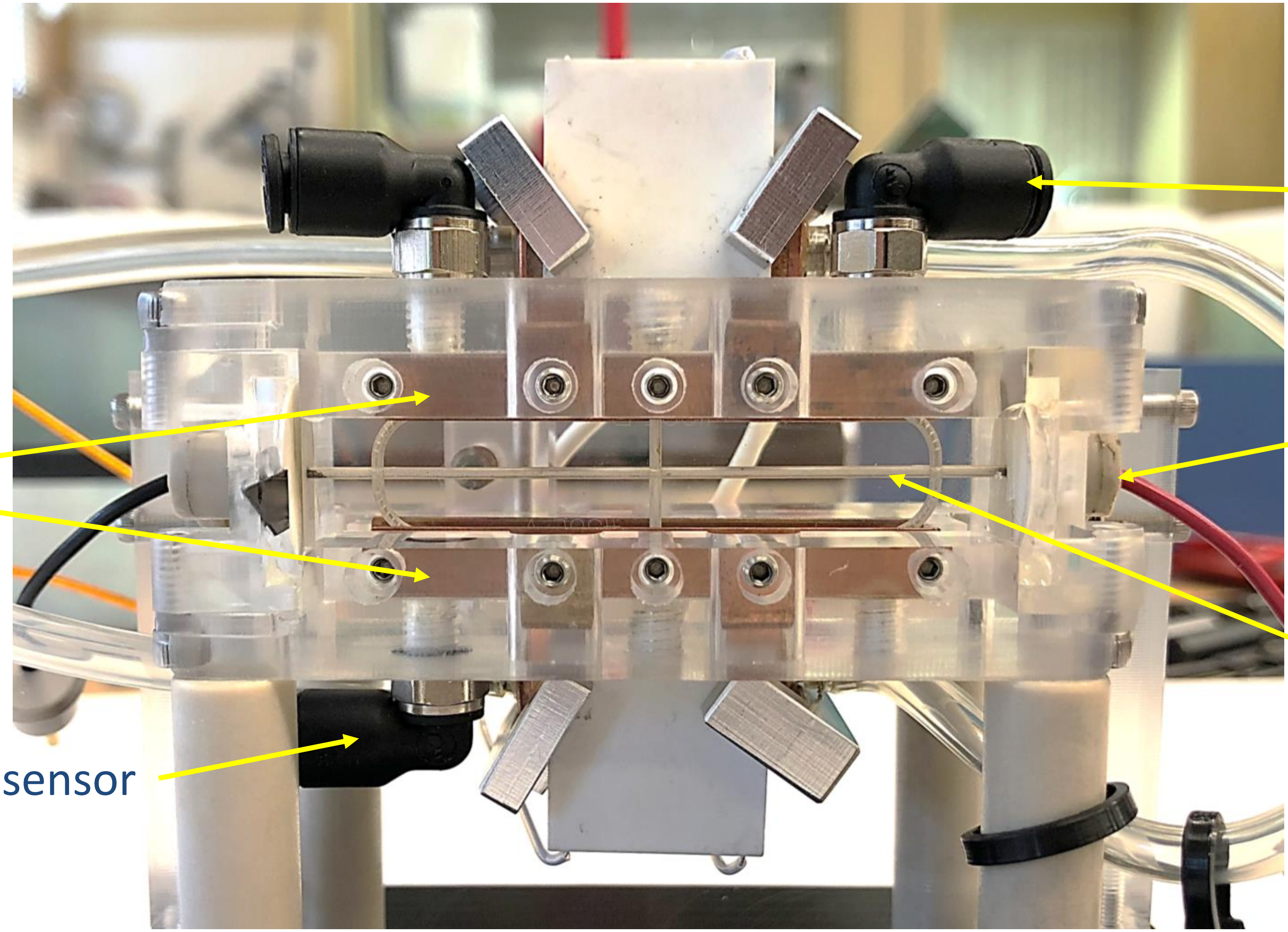
Thermal conductivity:
acrylic = 0.2 W/(m K)
aluminum = 205 W/(m K)

Plugs will form near channel entrance with low gas flow

For longitudinally uniform layers, high flow rate is required

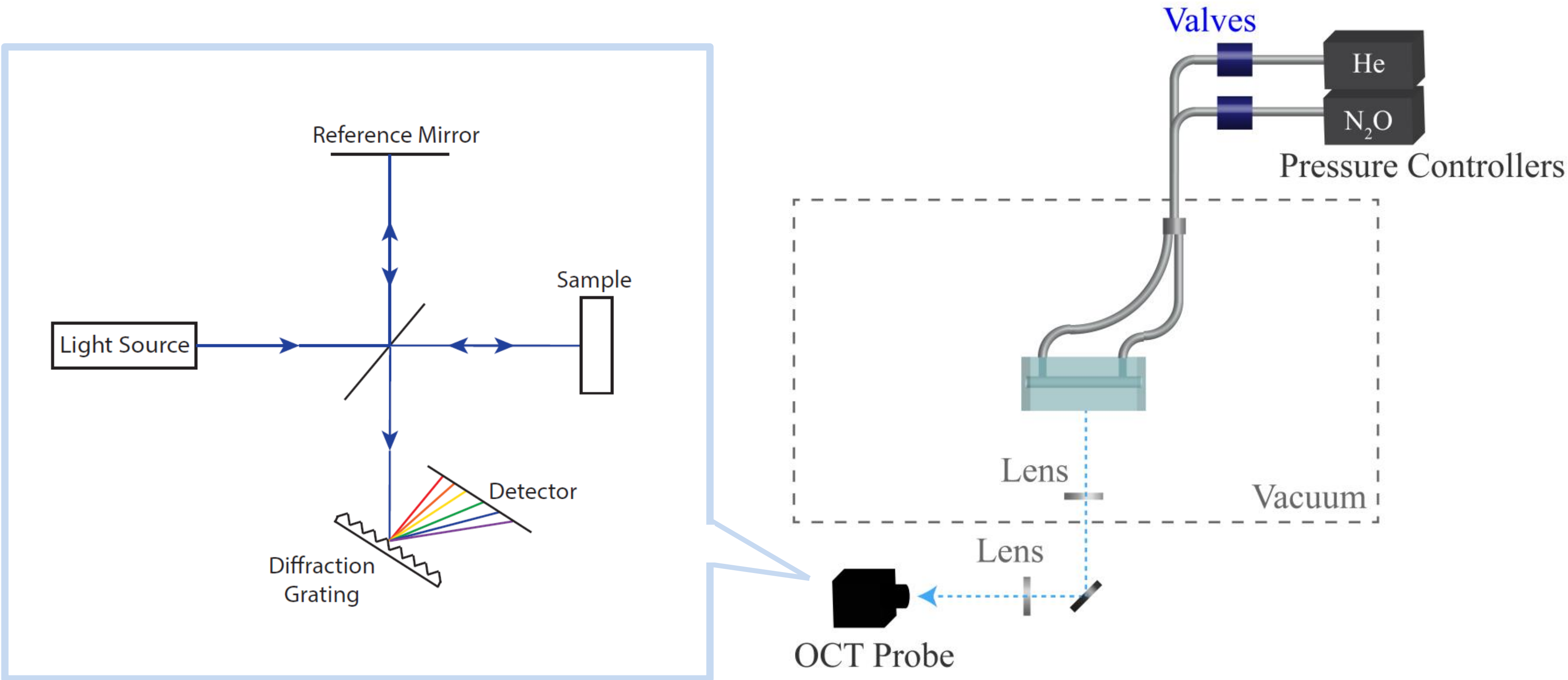


Final iteration: cooled sapphire channel

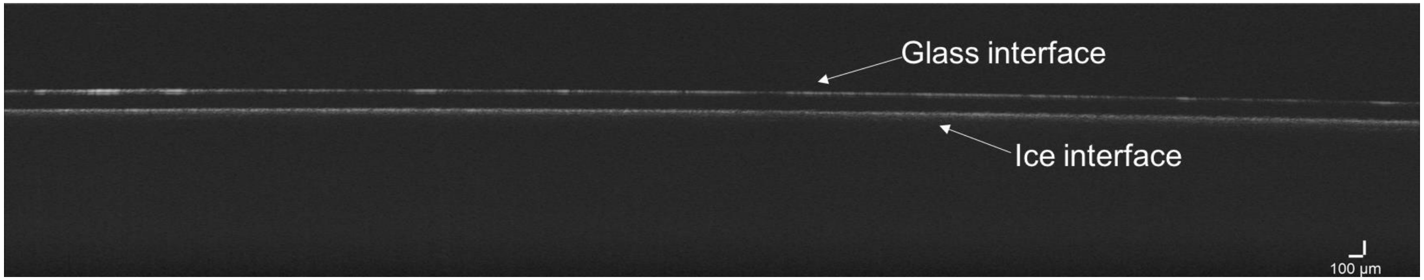


Patent in progress

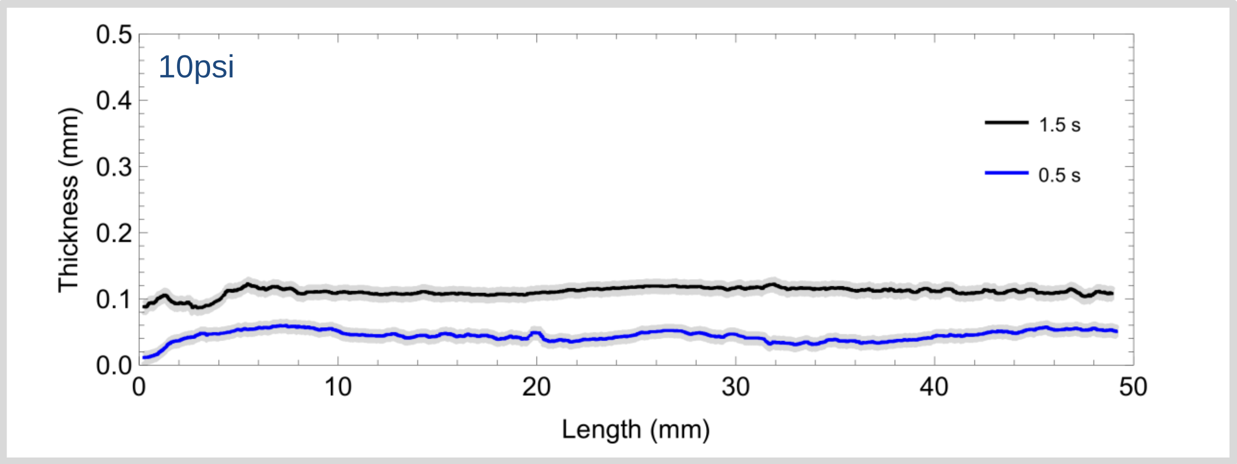
Longitudinal shell thickness measured by optical coherence tomography



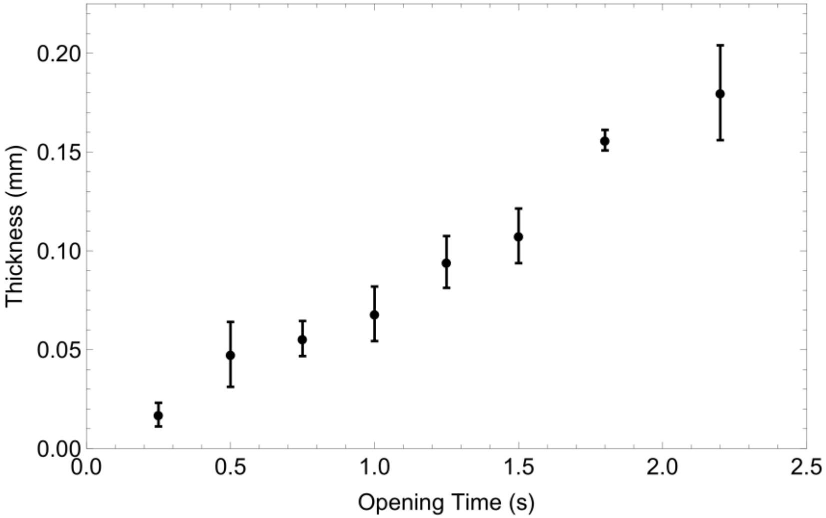
Raw OCT image



Shell thickness controlled using flow duration

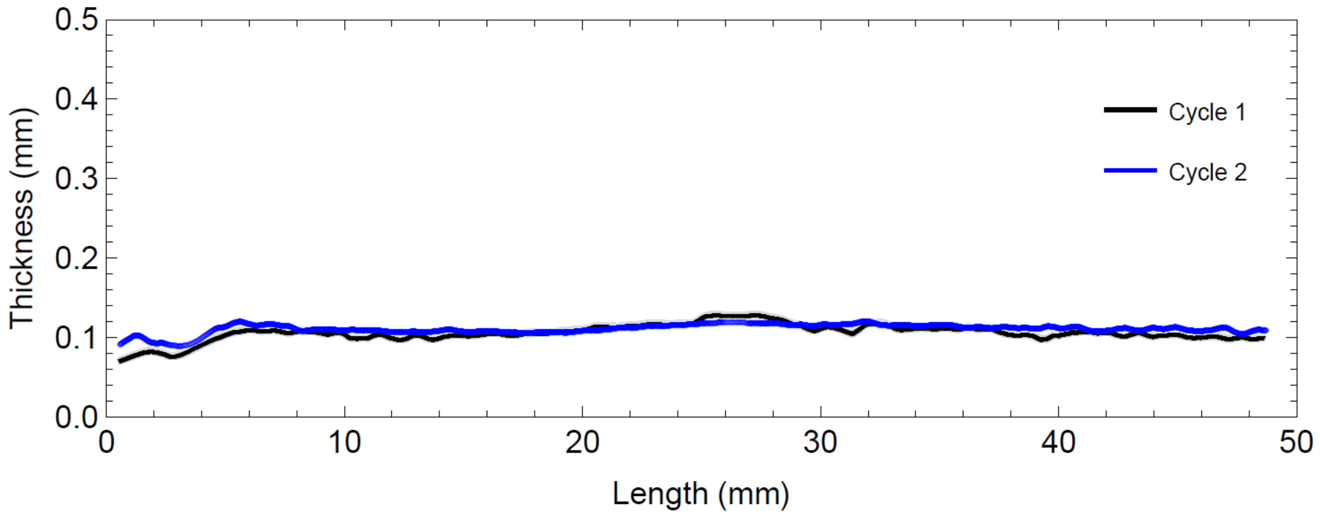


Growth rate = 67 um/s

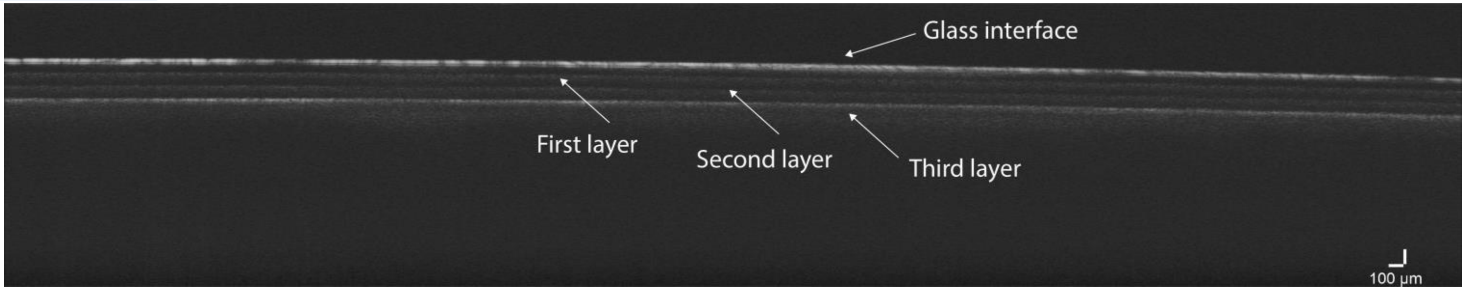


Deposition reproducible, and multiple bursts increase thickness

Reproducible

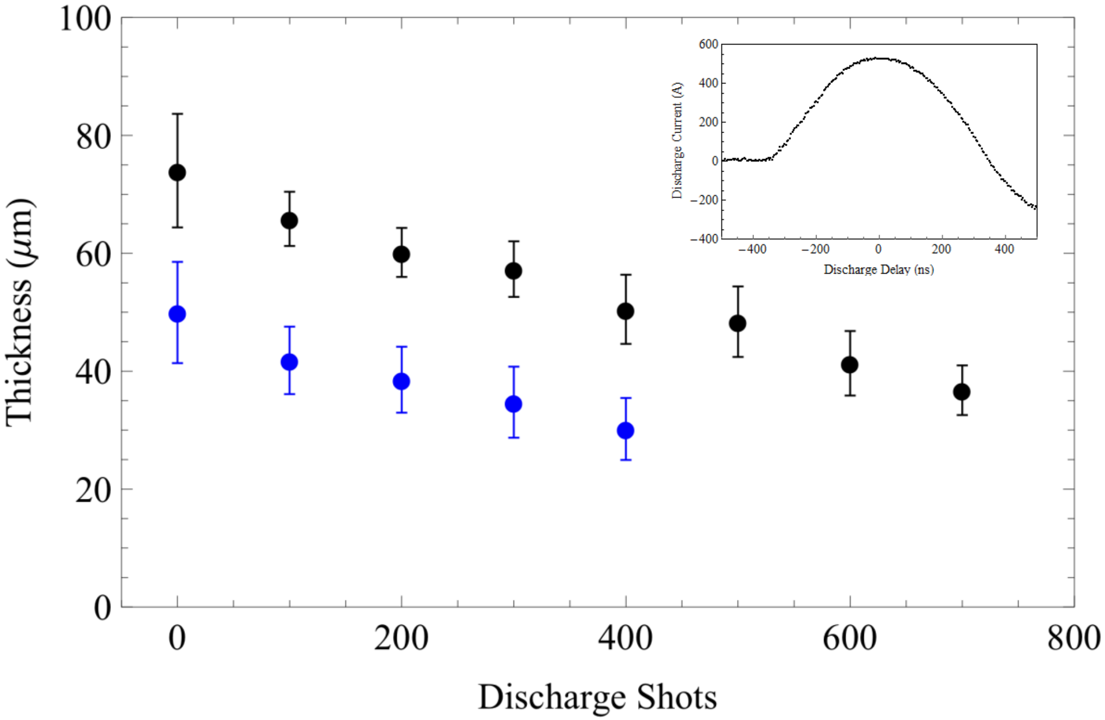


Stackable

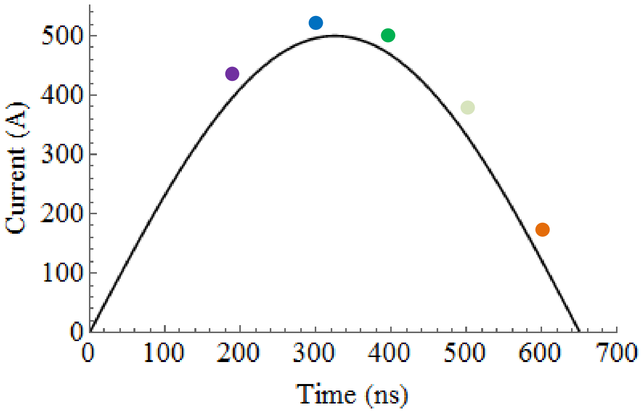


Discharge pulse ablates outer layer of the nitrous oxide shell

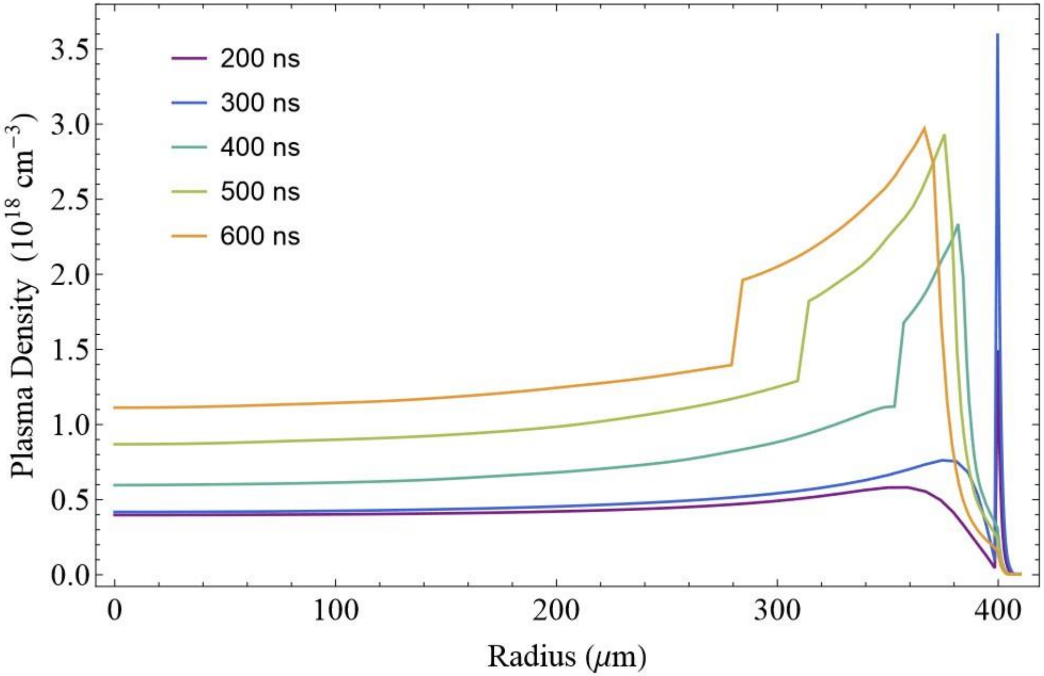
- He facilitates discharge
- 50 nm/shot ablation rate



Density profile evolution affected by ablated nitrous oxide

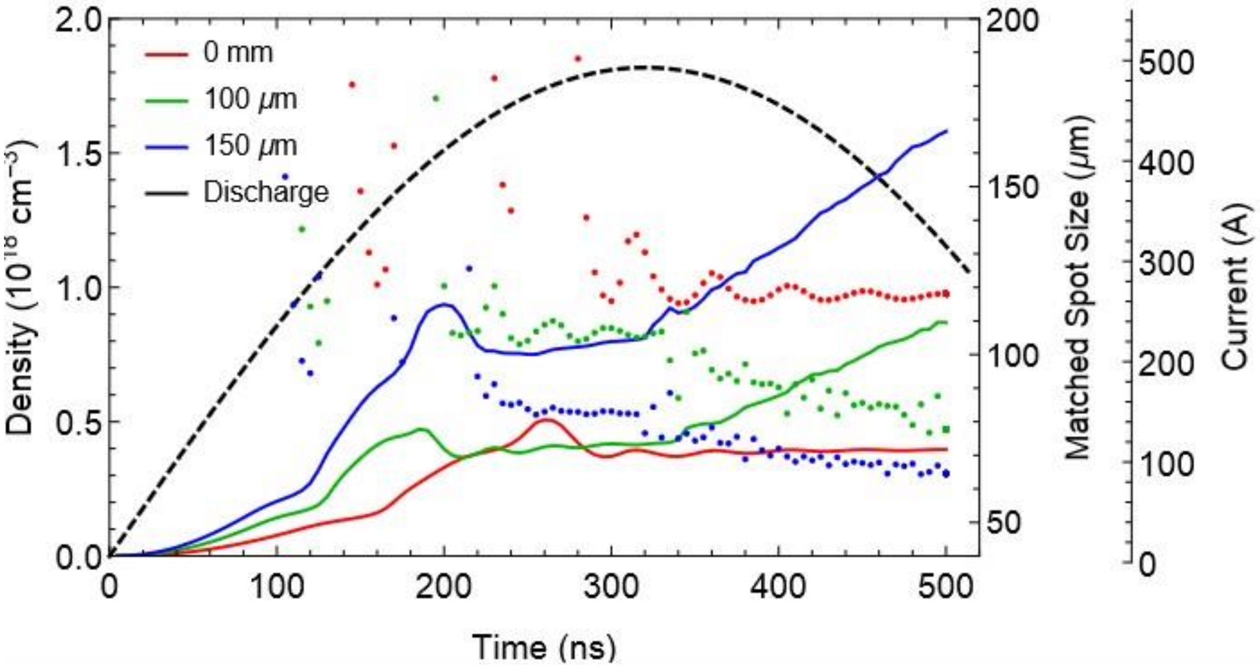


MHD code NPINCH



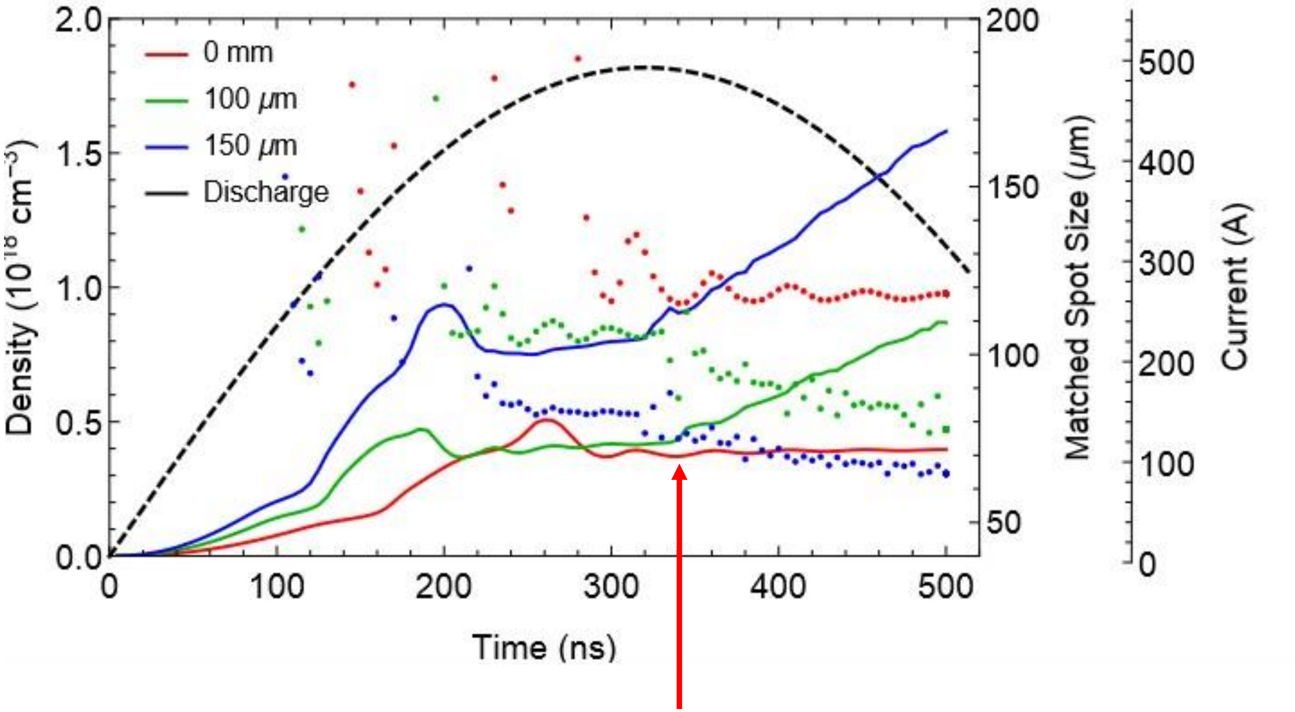
- Ablated N2O propagates inward, increasing on-axis density
- Guide maintains parabolic density profile near axis

Matched spot size and density evolve during discharge pulse



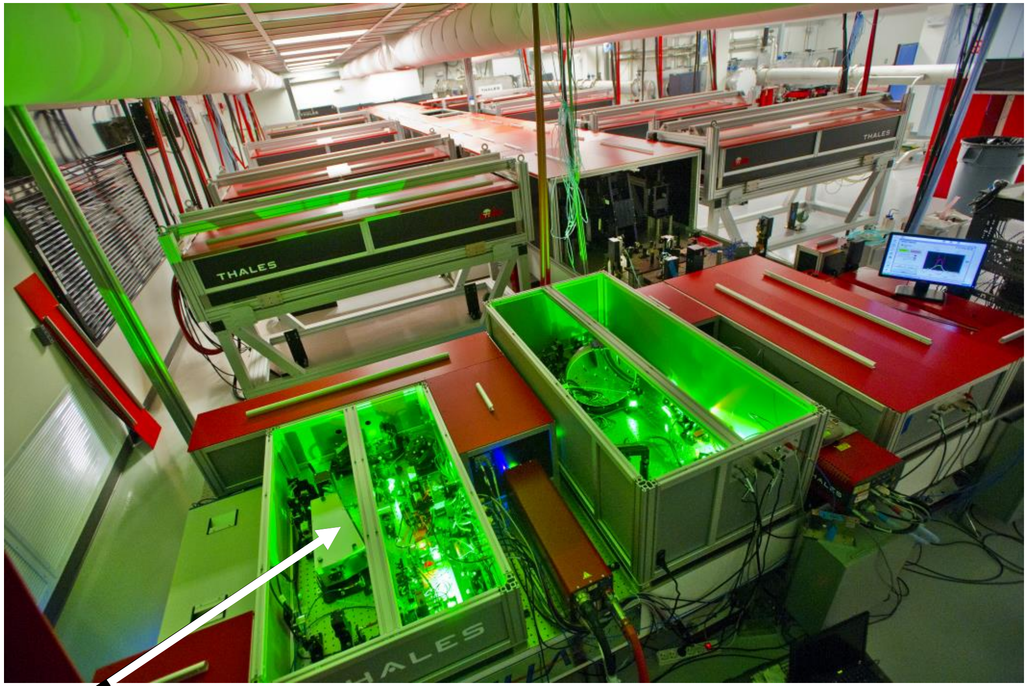
With nitrous oxide shells, density and matched spot size continue to evolve during discharge pulse

Matched spot size and density evolve during discharge pulse



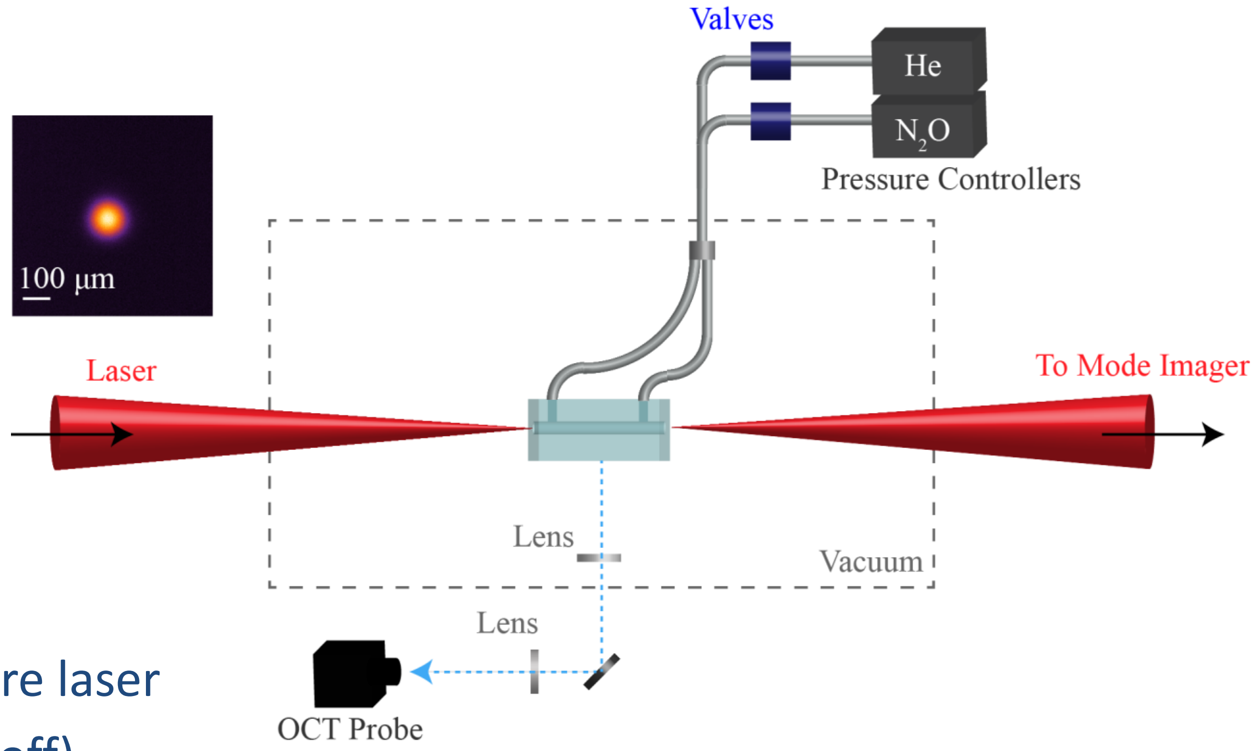
Tunability in matched spot size with constant density

Tested guiding properties using the BELLA laser



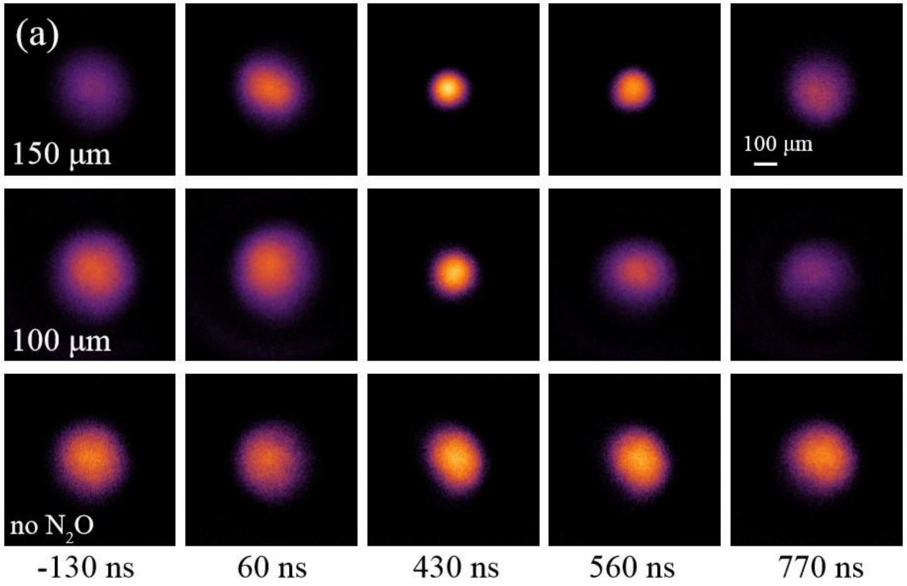
- BELLA Ti:Sapphire laser (front end pickoff)
- 100 ps, 37 nJ, 87 µm

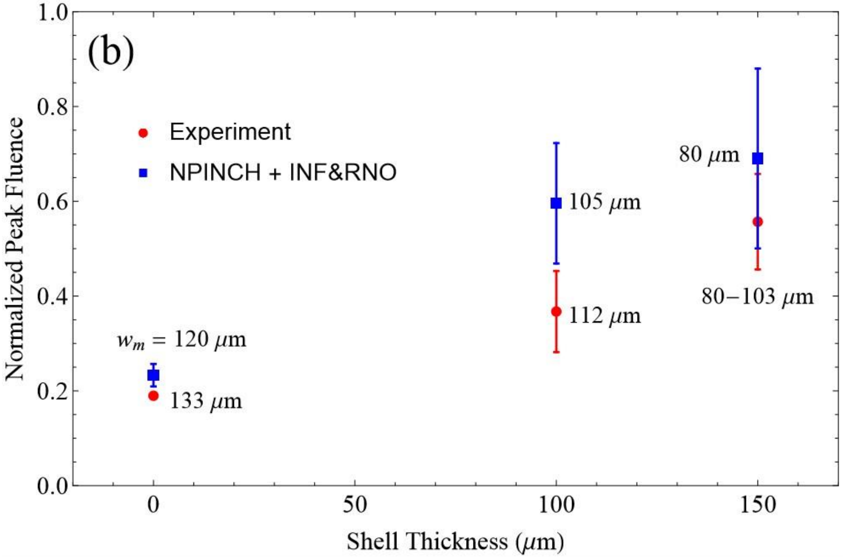
Tested guiding properties using the BELLA laser



- BELLA Ti:Sapphire laser (front end pickoff)
- 100 ps, 37 nJ, 87 µm

Matched spot size decreases with thicker nitrous oxide shells

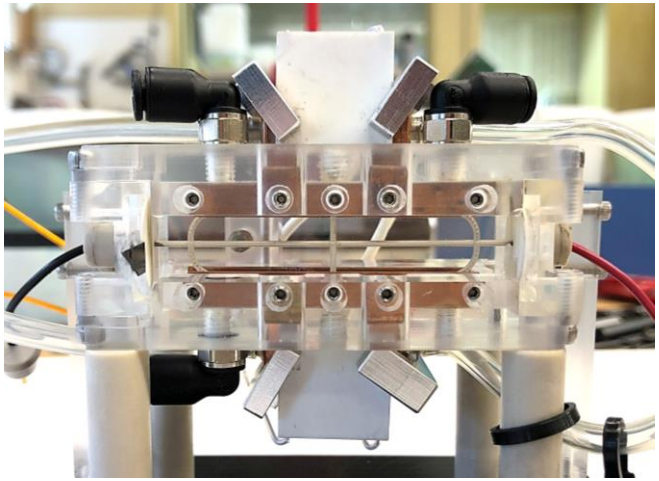




← Discharge delay →

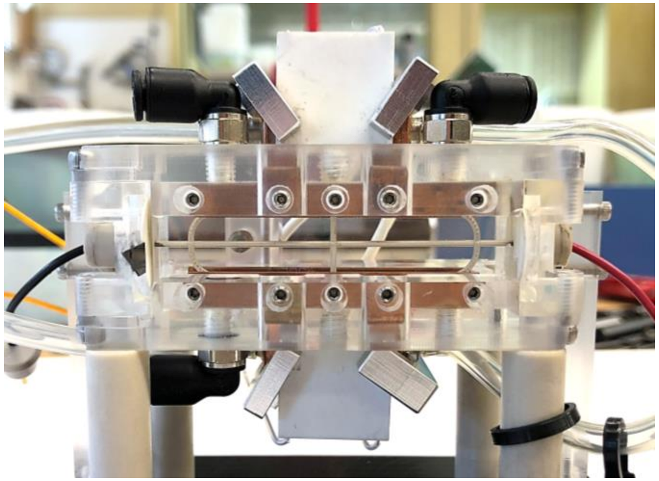
Matched spot sizes derived from propagating measured laser mode in parabolic plasma channels and compared with NPINCH channels

Cryogenic waveguide offers flexibility for a variety of applications



1. Regenerative capabilities
2. Independent control of density and channel radius

Cryogenic waveguide offers flexibility for a variety of applications



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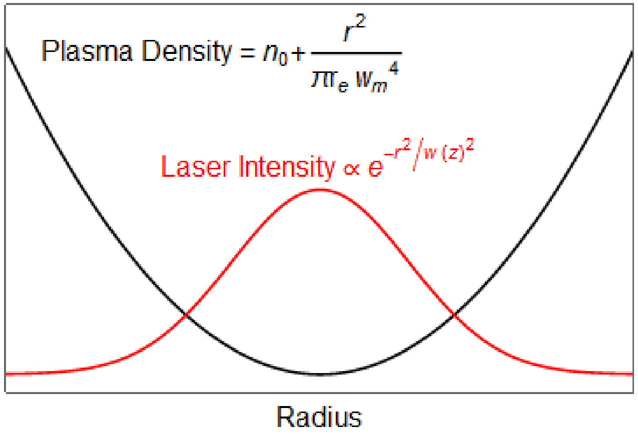
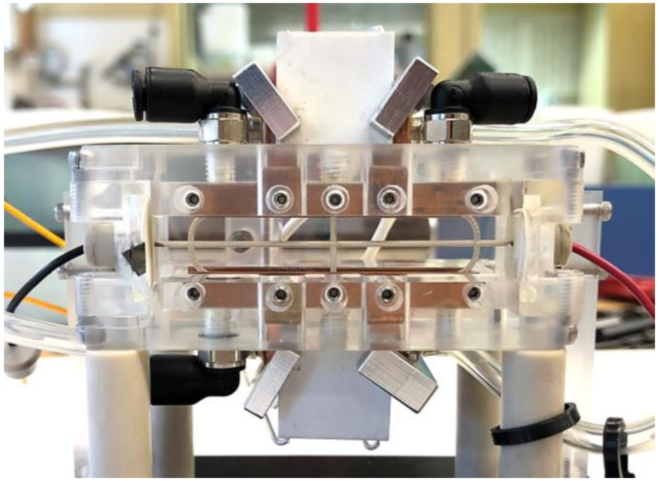


Improved guiding in parabolic plasma channels:

$$r_m \propto \frac{\sqrt{r_c}}{n_0^{1/4}}$$

Cryogenic waveguide offers flexibility for a variety of applications



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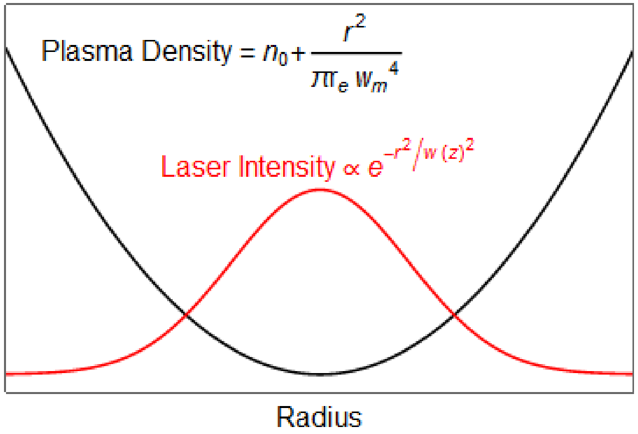
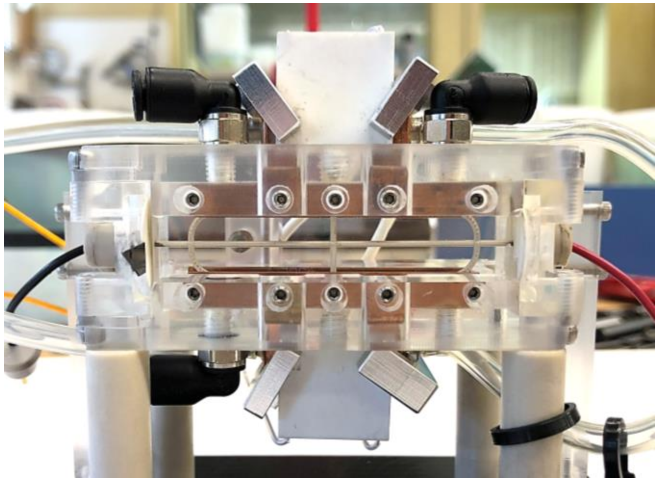


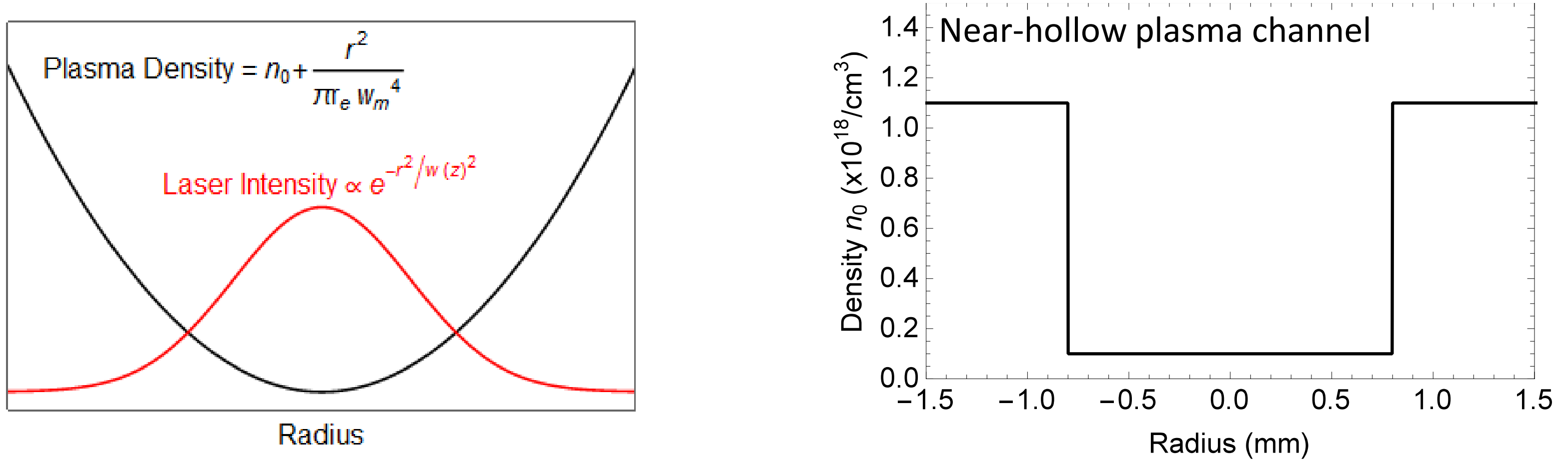
How to accelerate positrons?

Cryogenic waveguide offers flexibility for a variety of applications

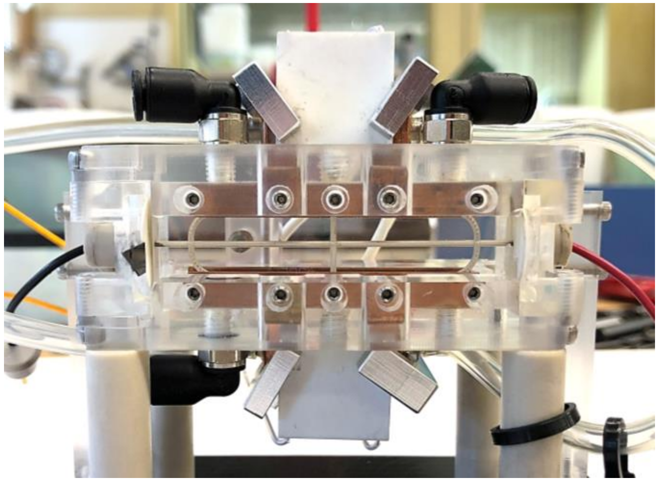


1. Regenerative capabilities
2. Independent control of density and channel radius

Chiou, T.C., *et al.*, Phys. Plasmas (1995)



Cryogenic waveguide offers flexibility for a variety of applications



1. Regenerative capabilities
2. Independent control of density and channel radius

Next steps:

1. High-power laser guiding
2. Operation in other guiding regimes

Acknowledgements

BELLA Center

A. J. Gonsalves, H. -S. Mao, T. Sipla, S. S. Bulanov, C. Benedetti, C. V. Pieronek, C. B. Schroeder, C. G. R. Geddes, E. Esarey, W. P. Leemans*

Simulations

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