Controlled Electron Injection using a Segmented Capillary Gas-Cell in LWFA

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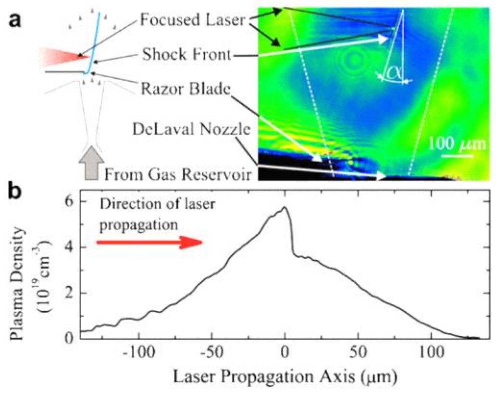
Down-ramp injection to control e-beam for LWFA

UNIST

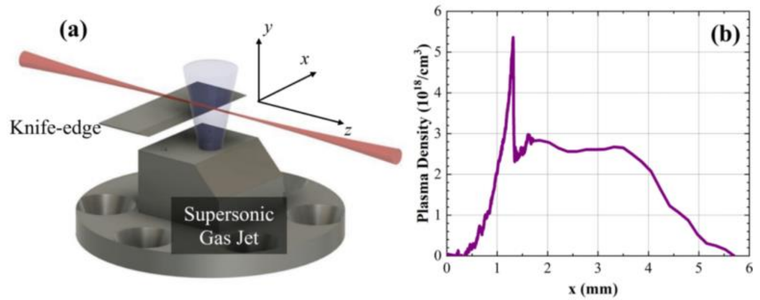
Experiments

Advantages: reduce energy spread, control charge, reproducibility

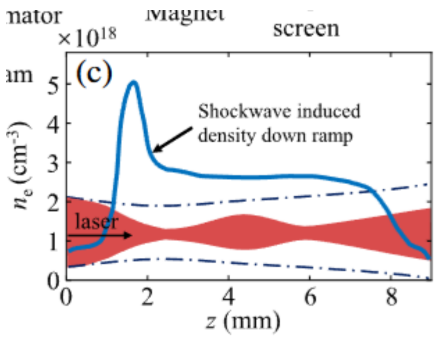
Limitations: rising density up to down-ramp, longer acceleration length



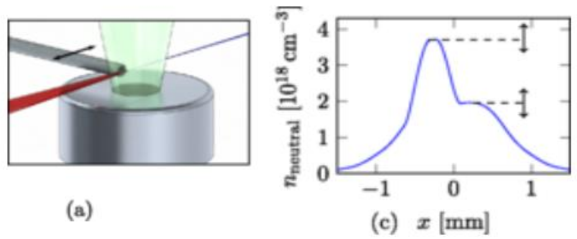
Phys. Rev. ST Accel. Beams **13**, 091301 (2010)



Phys. Rev. Research **8**, 013207 (2026)

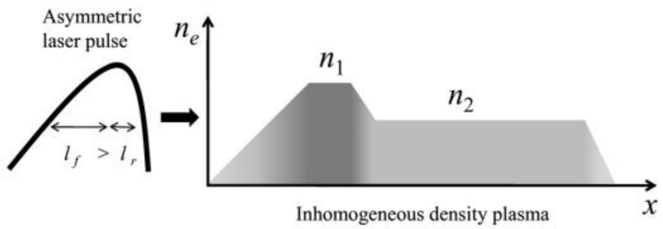


Phys. Rev. Lett. **126,** 214801 (2021)

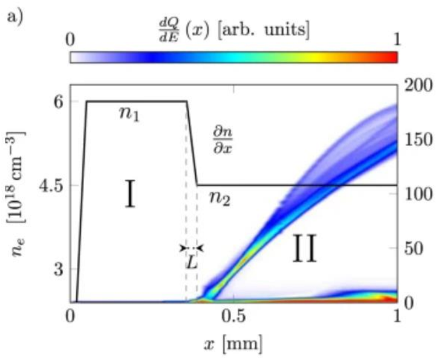


Phys. Rev. ST Accel. Beams **18**, 071303 (2015)

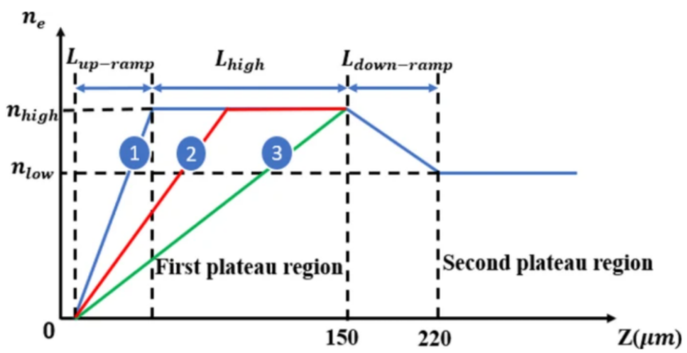
Simulations



Phys. Plasmas **18**, 043107 (2011)



Sci. Rep. **7**, 12229 (2017)



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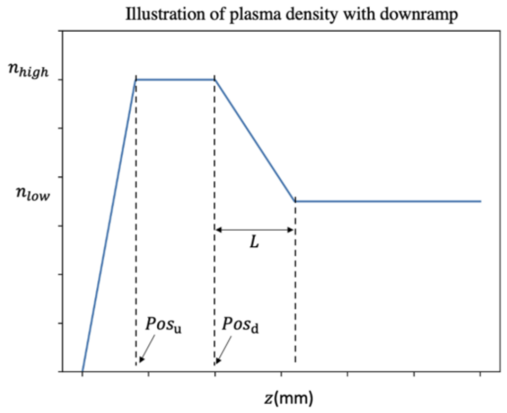


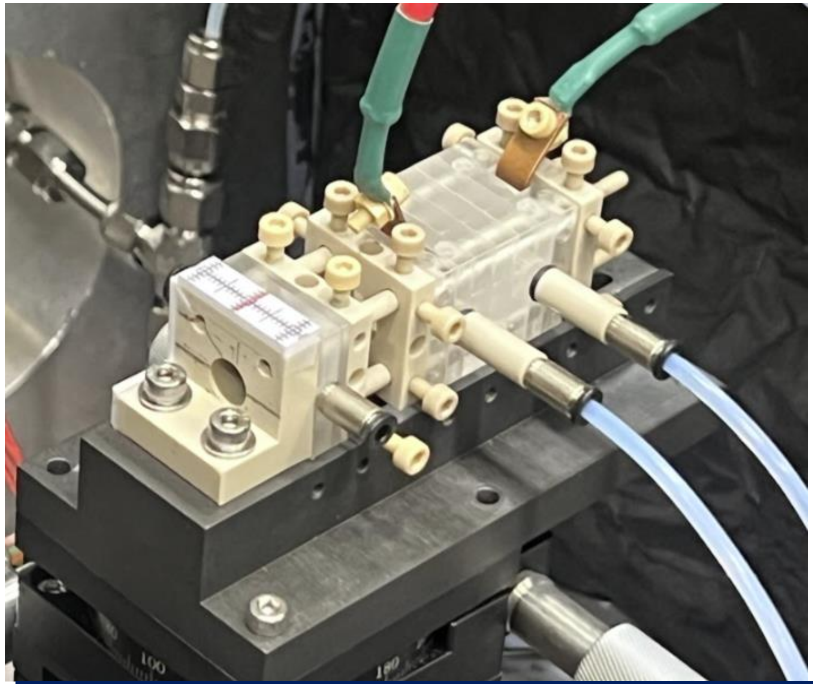
Matter Radiat. Extremes **8**, 024401 (2023)

Control knobs: length and density for first, second plateau, location of down-ramp

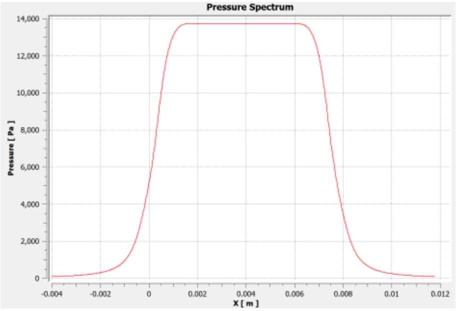
Fine tuning: beam charge, emittance, energy, energy spread

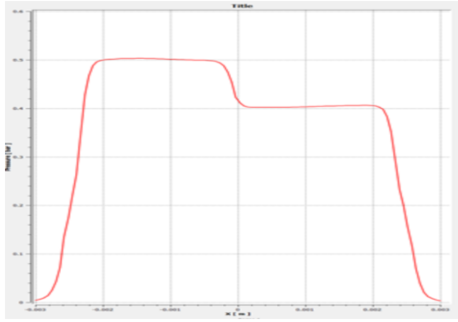
New plasma target source

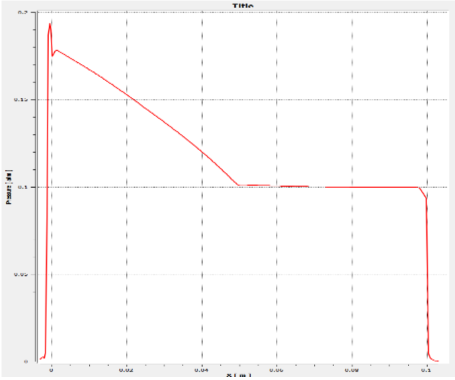
New plasma target: Variable longitudinal plasma density profile



Segmented capillary plasma target

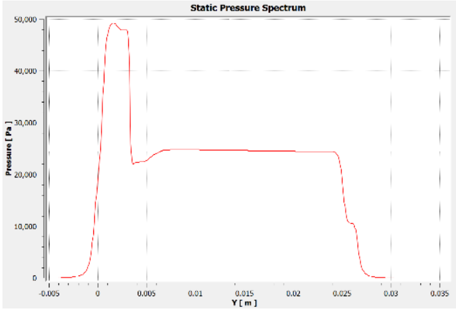


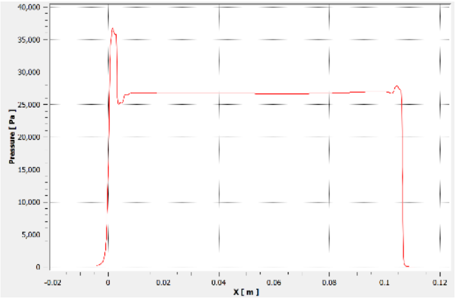


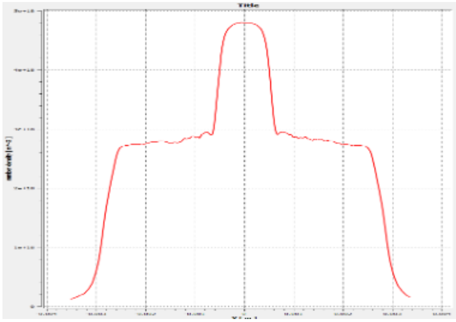


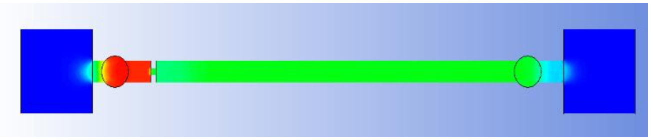
25 mm

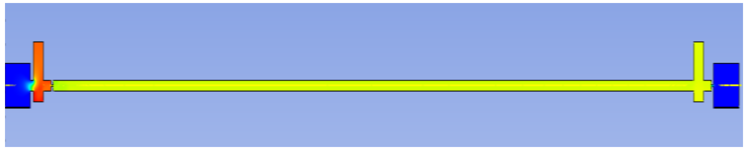
100 mm

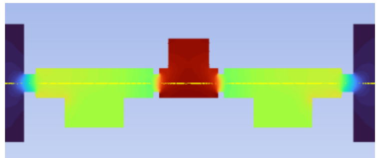




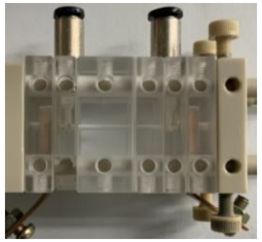


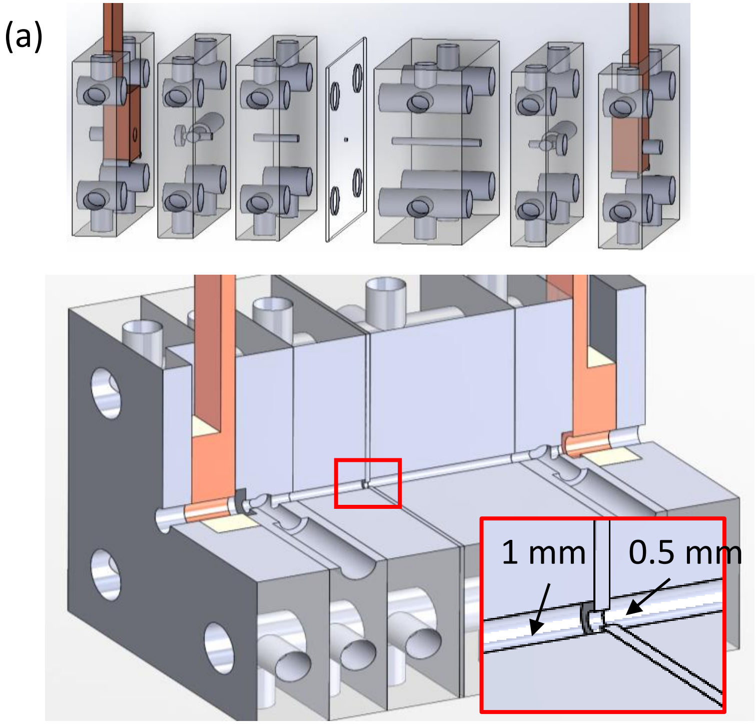




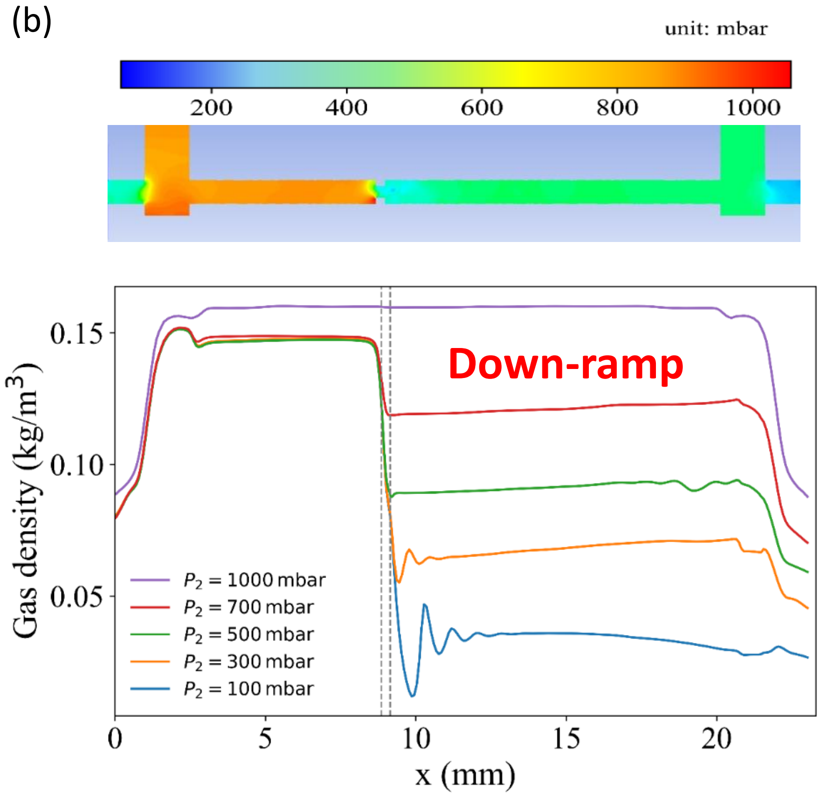


Segmented capillary with an orifice for down-ramp





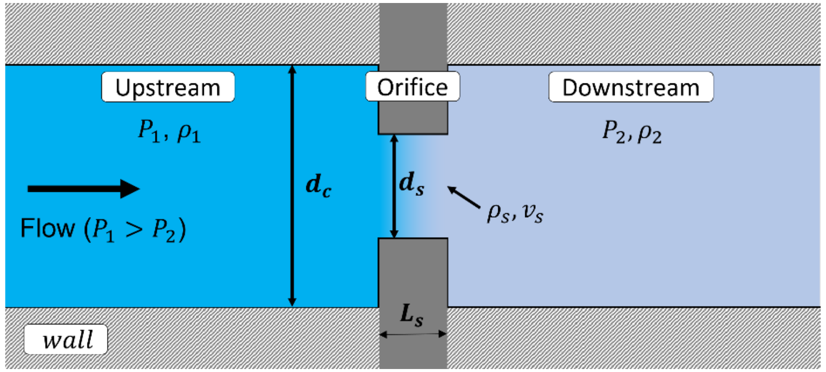
Venturi effect



- **Segmented discharge capillary plasma source**

- **Easy to assemble:** different length and functions by adding special blocks
- **Controlled injection & reliable operation**: Controllable longitudinal density profile for downgradient injection
- **Enhance beam energy using waveguide**: Discharge plasma with a transverse quadratic density structure for the laser guiding
- **Plasma lens:** Focus electron beam using radial magnetic fields by discharged plasma current

Gas flow dynamics



- Plasma density can be tailored by introducing flow restriction through an orifice

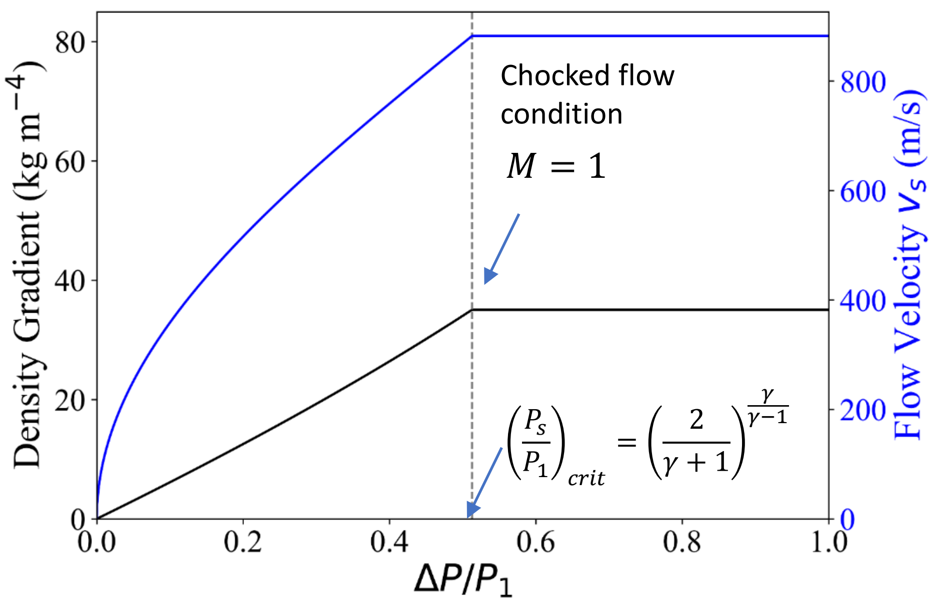
$$\dot{m} = \rho_1 v_1 A_1 = \rho_s v_s A_s = \rho_2 v_2 A_2, \quad \text{Mass conservation (compressible flow)}$$

A_s (orifice) < A_1 (capillary)

$$\dot{m}_1(P_s; P_1) = \frac{C_d A_s P_1}{\sqrt{1-\beta^4}} \sqrt{\frac{2\gamma}{RT_1(\gamma-1)}\left[\left(\frac{P_s}{P_1}\right)^{\frac{2}{\gamma}} - \left(\frac{P_s}{P_1}\right)^{\frac{\gamma+1}{\gamma}}\right]} \qquad \beta = \frac{d_s}{d_c}$$

$$\frac{P_s}{P_1} = \left[1 + \frac{\gamma-1}{2} M^2\right]^{-\frac{\gamma}{\gamma-1}}, \quad \frac{\rho_s}{\rho_1} = \left(\frac{P_s}{P_1}\right)^{\frac{1}{\gamma}} \qquad \text{Isentropic relation}$$

$$v = Ma = M\sqrt{\gamma RT}$$

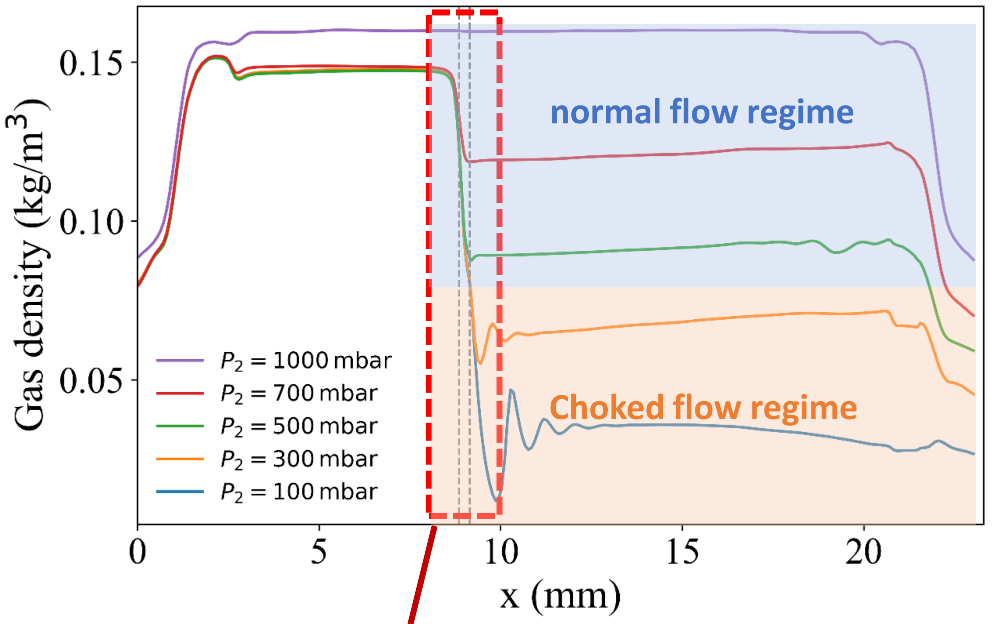


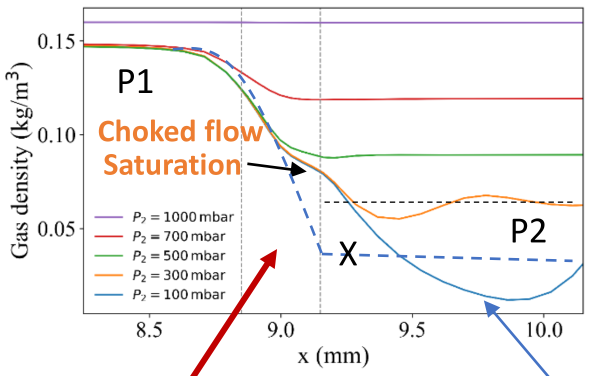
- Maximum flow speed is limited by choked condition

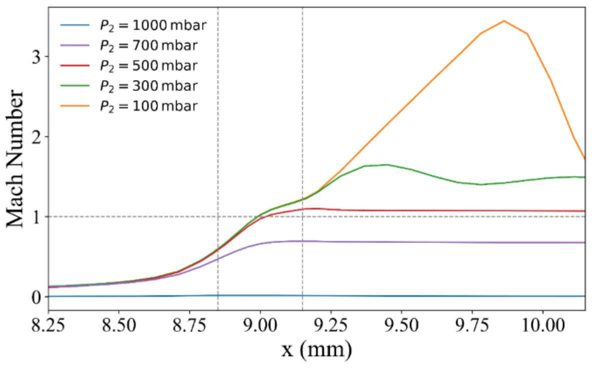
$$\frac{d\dot{m}}{dM} = 0 \rightarrow M = 1 \qquad \dot{m}_{crit} = K_s P_1$$

- **Limited pressure ratio P_2/P_1 = 0.487**

CFD simulation results







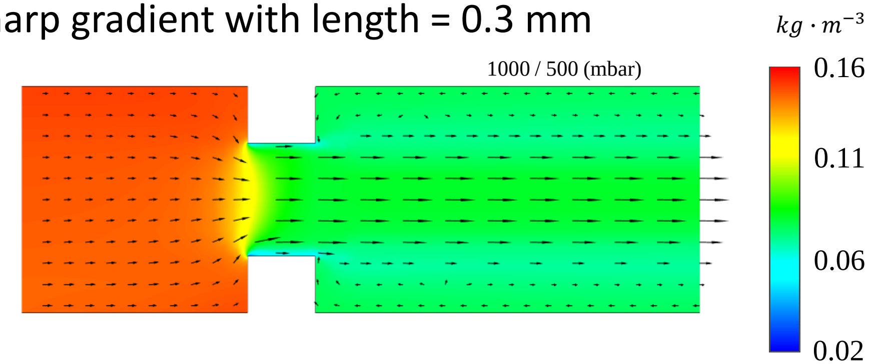
Down ramp length: 300 μm

Pressure fluctuates: Over shooting

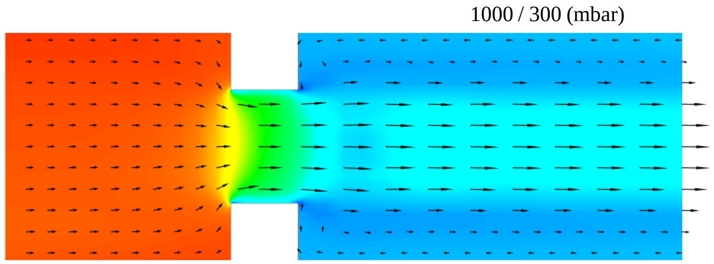
- Results are divided by critical pressure ratio

$$\left(R_c = \left(\frac{P_2}{P_1}\right)_{crit} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} = 0.487\right) \text{ with } P_1 = 1000\ mbar$$

- Normal flow regime ($P_2/P_1 = 0.5$)
  - Sharp gradient with length = 0.3 mm



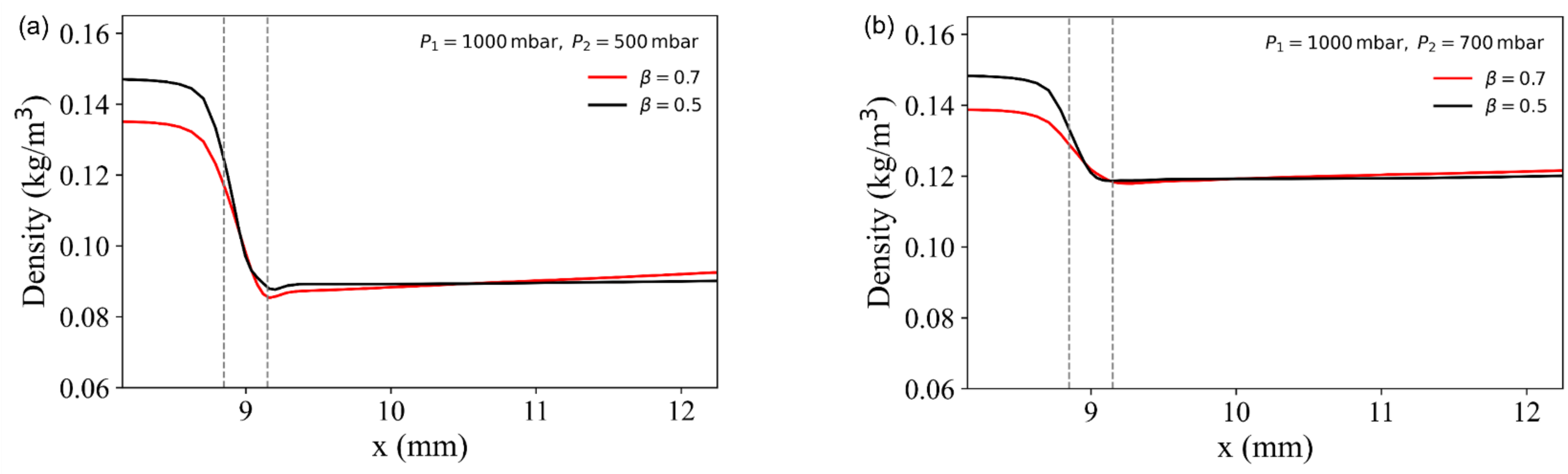
- Choked flow regime ($P_2/P_1 = 0.3$)
  - Choked flow
  - shock-expansion structure (oscillation)



Effect of diameter ratio of β

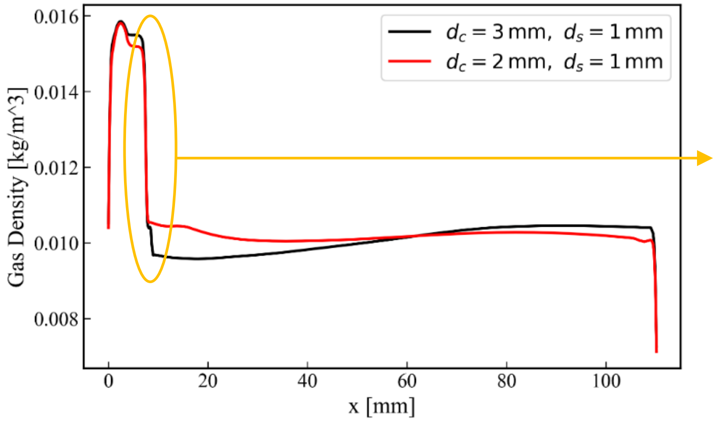
β = orifice diameter / capillary diameter ($\boldsymbol{\beta} = \frac{\boldsymbol{d_s}}{\boldsymbol{d_c}}$)

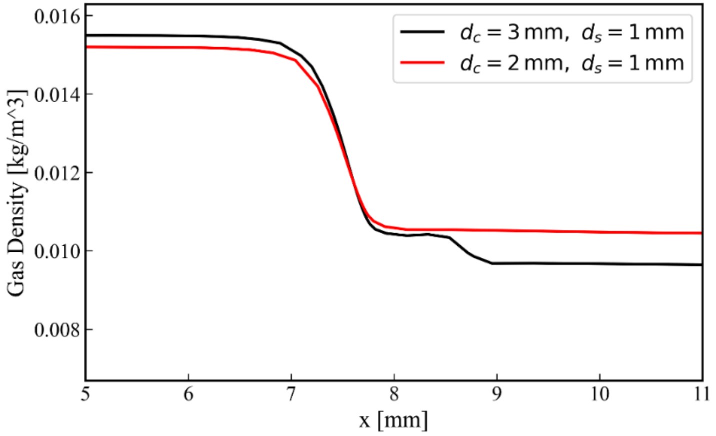
- Hole size ratio β controls effective flow rate
- Decreasing β (Orifice hole diameter decreases)
  - Restricted flow
  - Higher upstream density



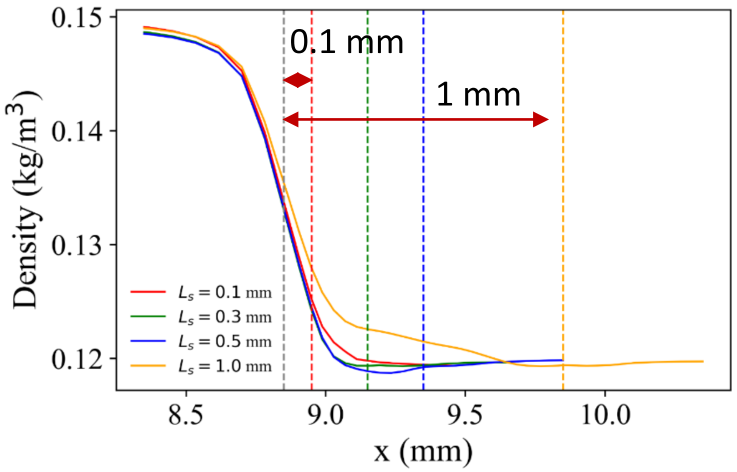
Effect of various orifice diameter, orifice thickness

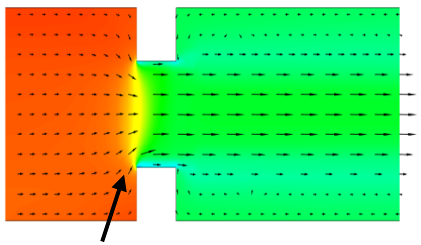
- Scaled up capillary also show same performance with normal size one
- Orifice diameter is 1 mm, capillary diameter is 3 mm for PW laser system





- Reducing the orifice slit thickness has no effect on improving the density gradient

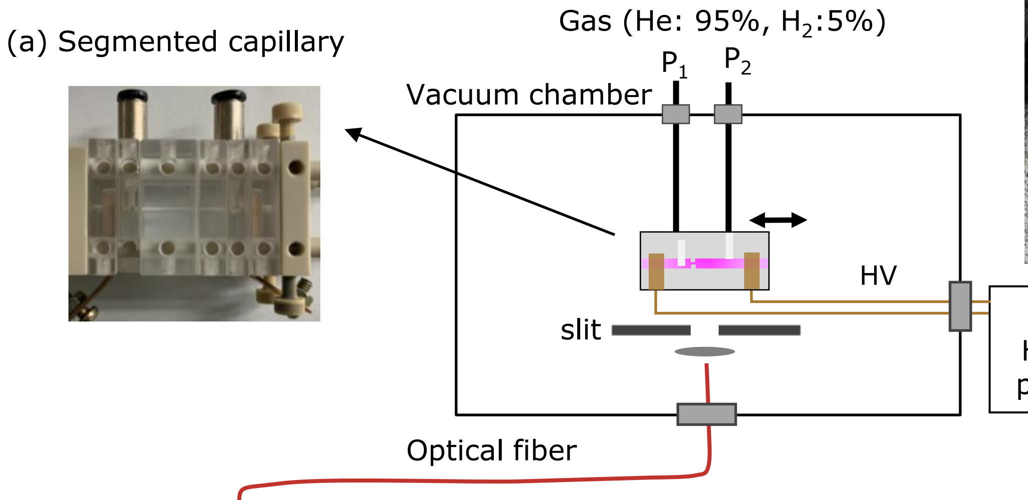


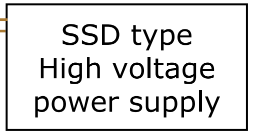


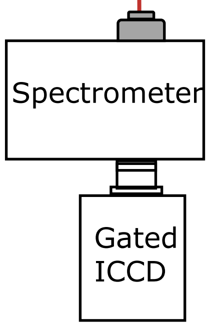
Down-ramp is produced at front of the orifice

Diagnostic of electron density

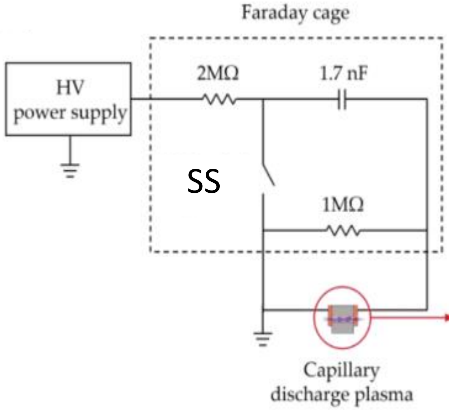
- The Stark broadening of the Hydrogen alpha line is used to measure electron density.
- ICCD spectrometer gating time = 25 ns
- Spectrum was measured at 650 ns after HV applied







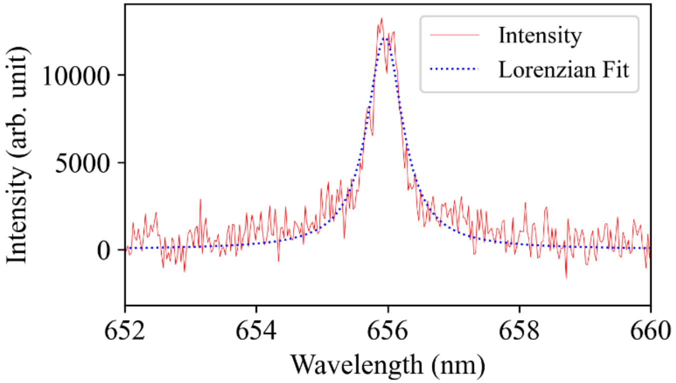
Size = 40 x 50 x 30 cm³



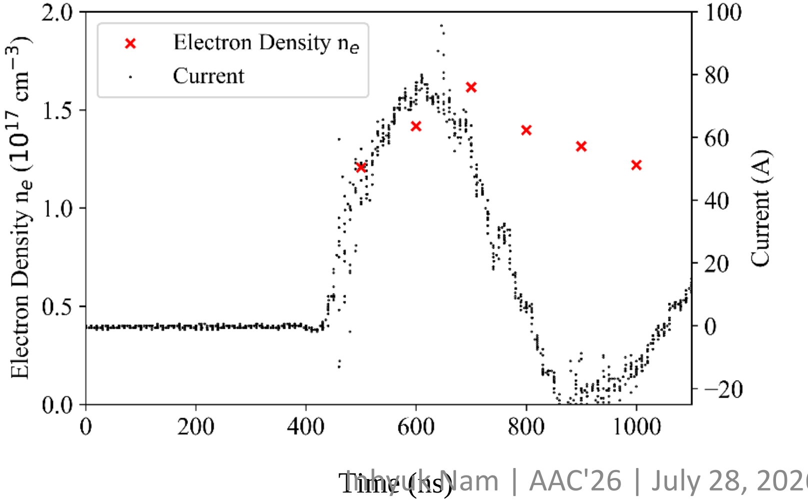
- Pulsed high voltage system using solid state switch
- Voltage = 15 kV
- Pulse duration = 10 µs

$$\Delta\lambda(\mathrm{nm}) = \alpha\,(n_e, T)\; n_e\,(10^{18}\mathrm{cm}^{-3})^{2/3}$$

$\alpha\,(n_e, T) = 5.4$



Current evolution profile



Measured longitudinal density profiles

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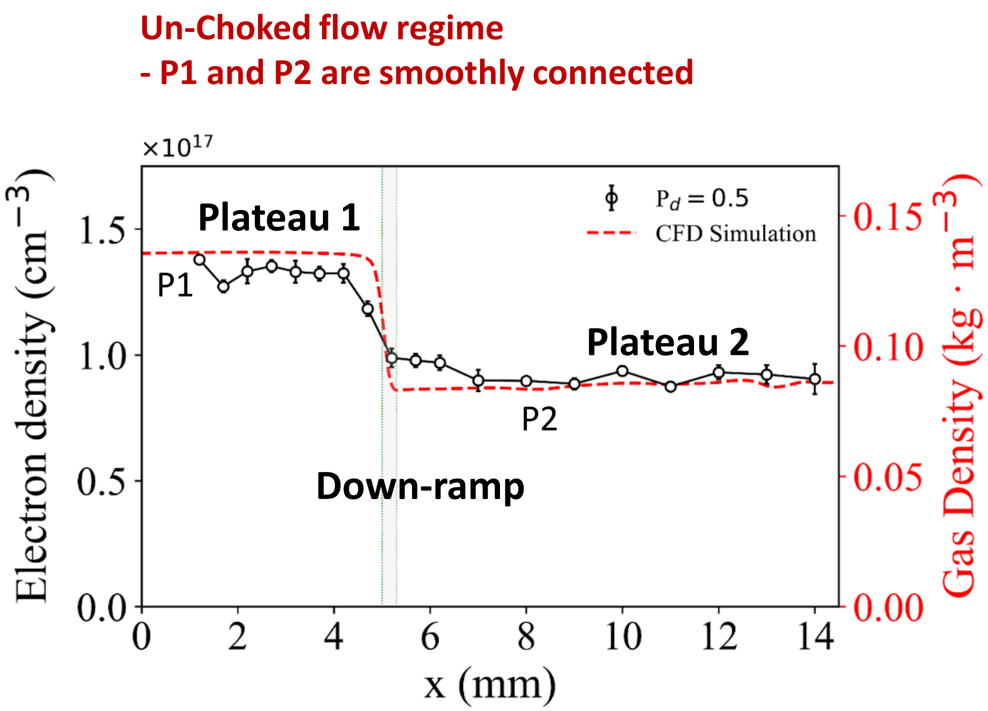
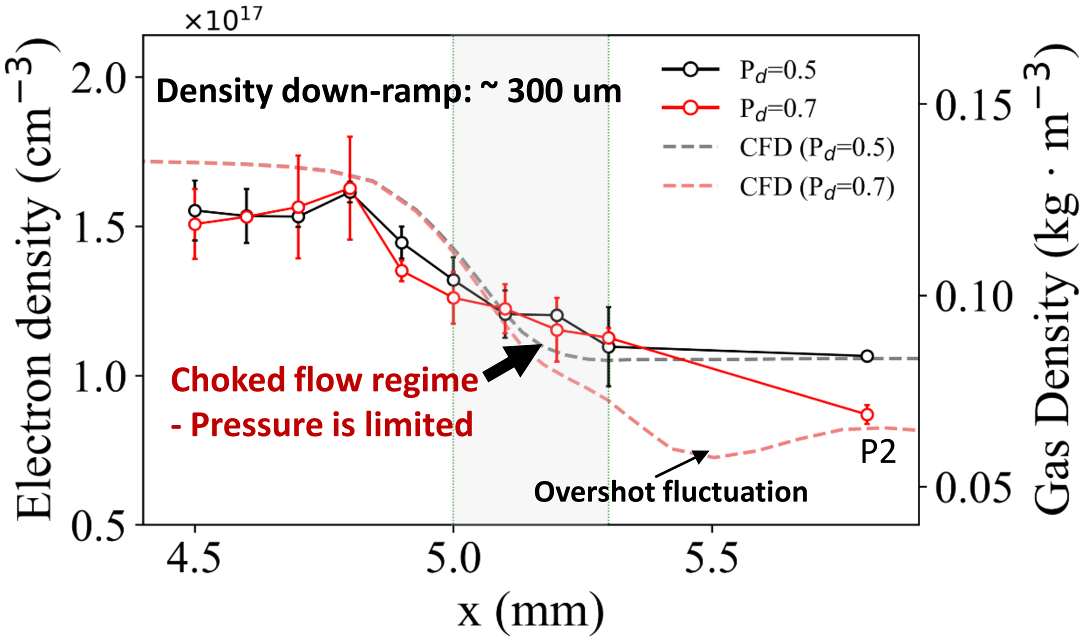




- Un-choked region $P_d = 0.5$
- Deconvoluted down-ramp length: ~ 0.3 mm

- Down-ramp profiles for $P_d = 0.5$, $P_d = 0.7$ (Choked)
- In the choked case, the density is saturated in the orifice region, then fluctuated after exiting of the orifice

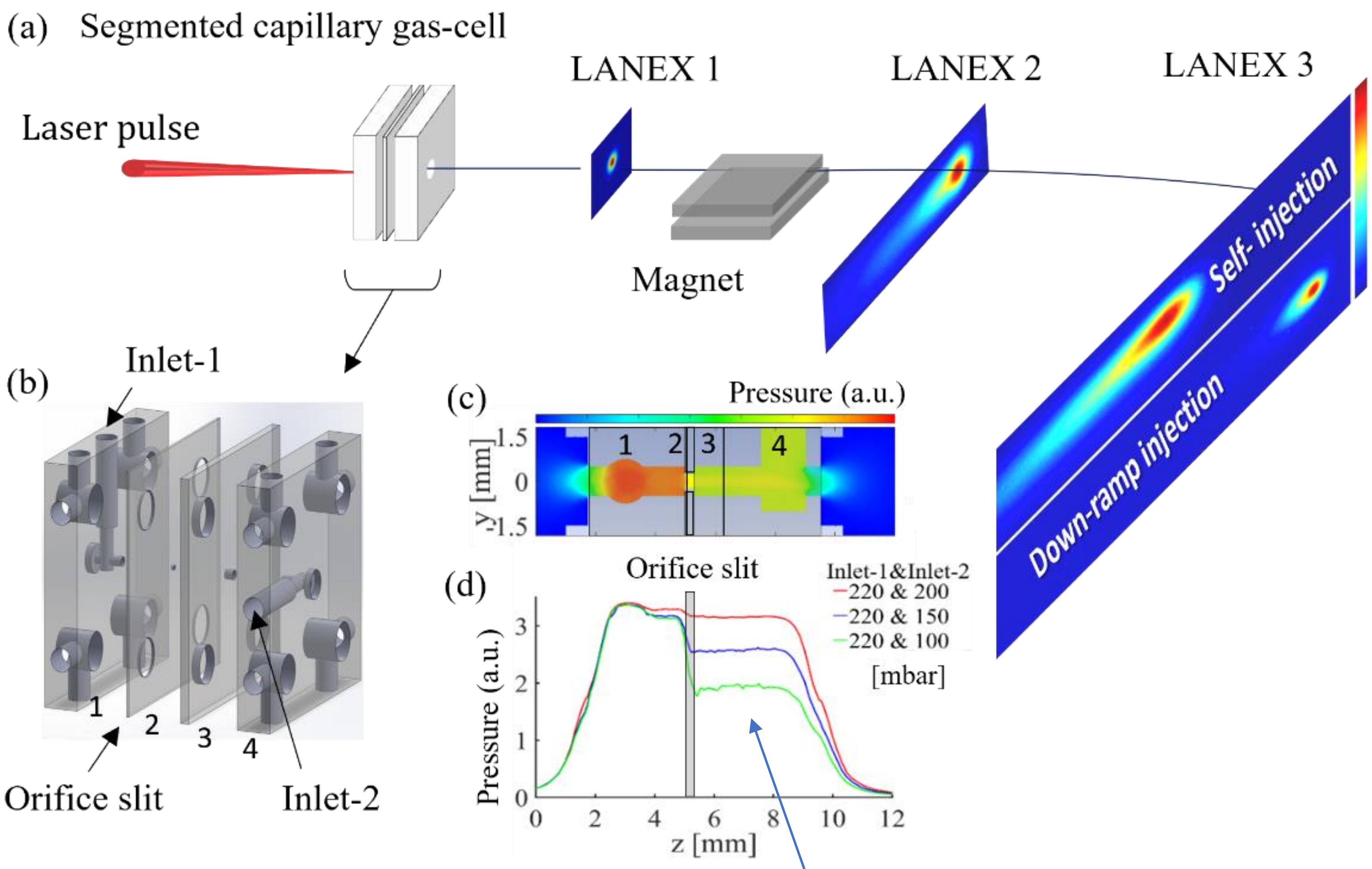
Preliminary results

J. Jeong et el., in preparation

Experimental setup for LWFA using SC gas-cell

CoReLs IBS at GIST, Korea

- 150 TW laser system
- Pulse energy: ~ 4 J
- Pulse length: 25 fs (FWHM)



Acceleration length: ~ 4 mm

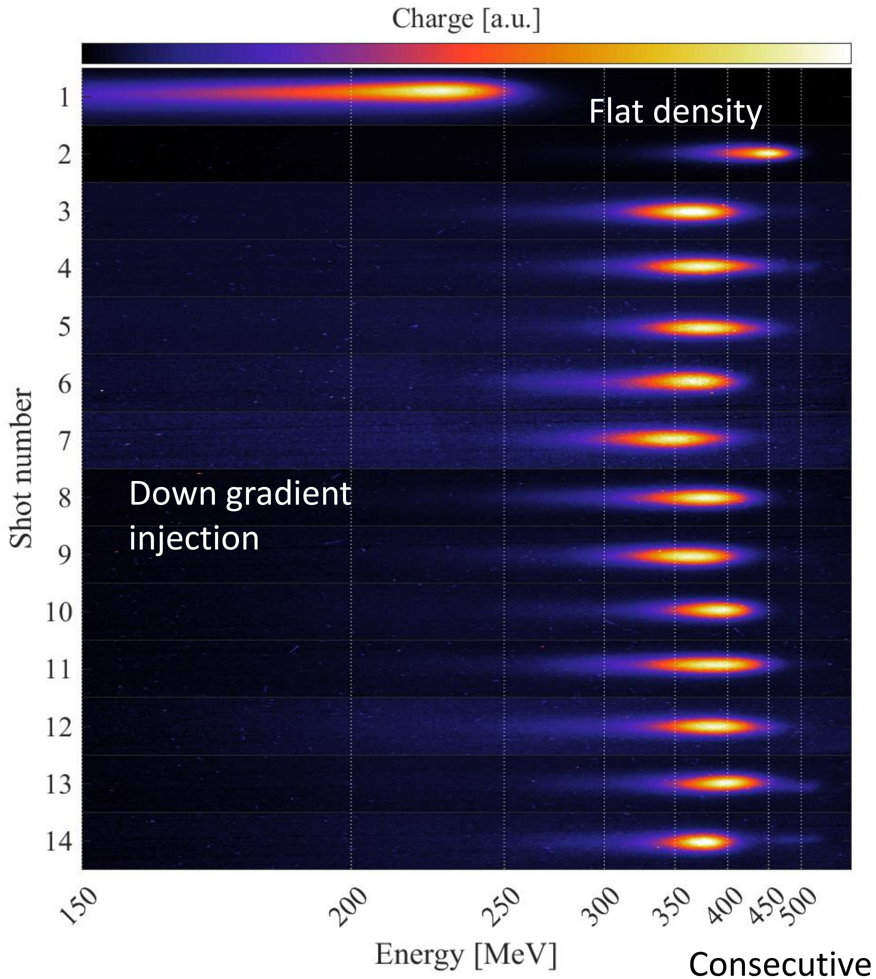
Preprimary experimental results

- Laser: 150 TW, 25 fs, f/20
- Gas: He
- Flat density P1 = P2 $n_e = \sim 5 \times 10^{18}\ cm^{-3}$
- Down gradient injection P1 > P2: $n_{e\_1} = \sim 5 \times 10^{18}\ cm^{-3}$

  $n_{e\_2} = \sim 3.5 \times 10^{18}\ cm^{-3}$

- Electron beam characteristics

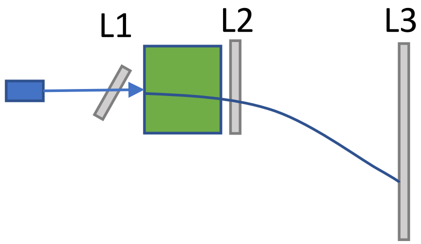
- Beam divergence (FWHM) : ~1 mrad (Down gradient)
- Energy spread (FWHM) : ~5 % (Down gradient), ~35 % (Flat density)
- Peak energy: 348 (3.2% rms jitter) (Down gradient), 300 MeV (Flat density)

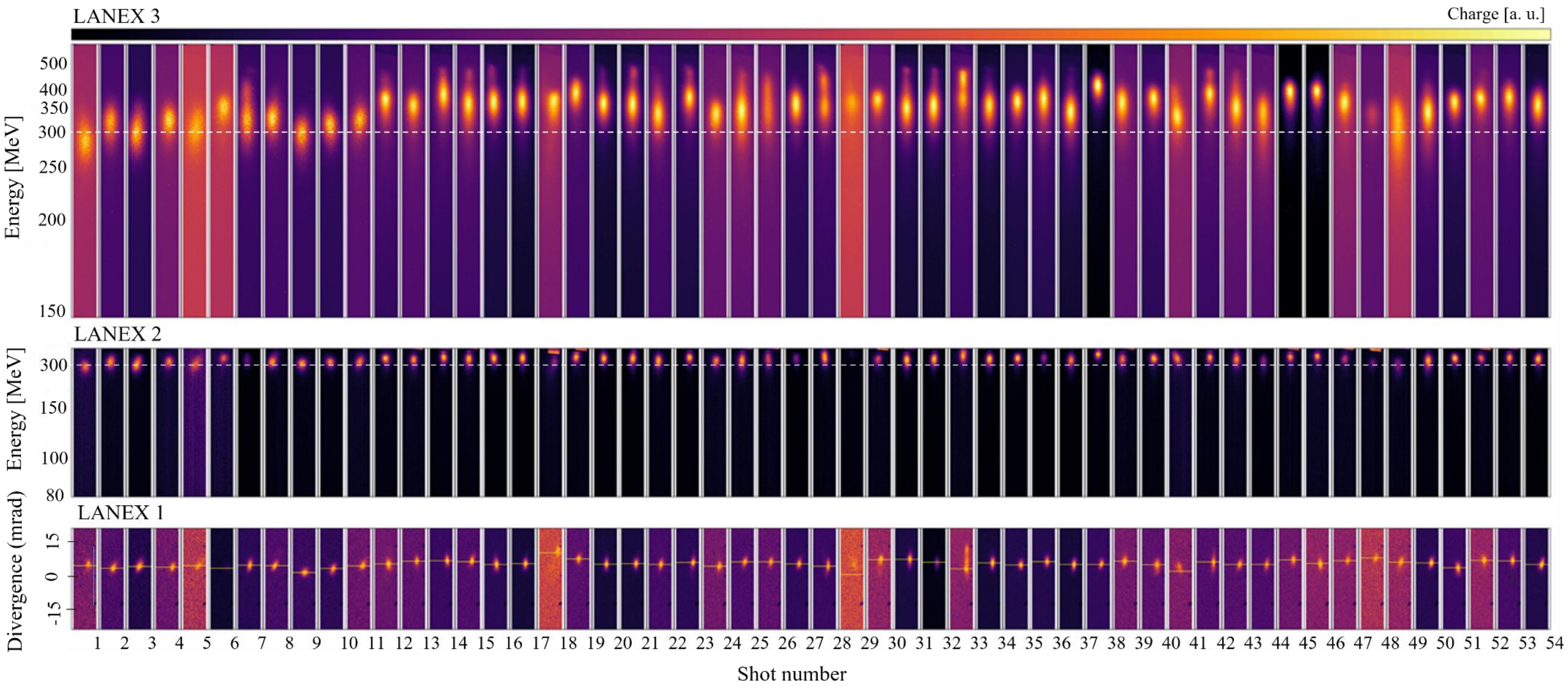


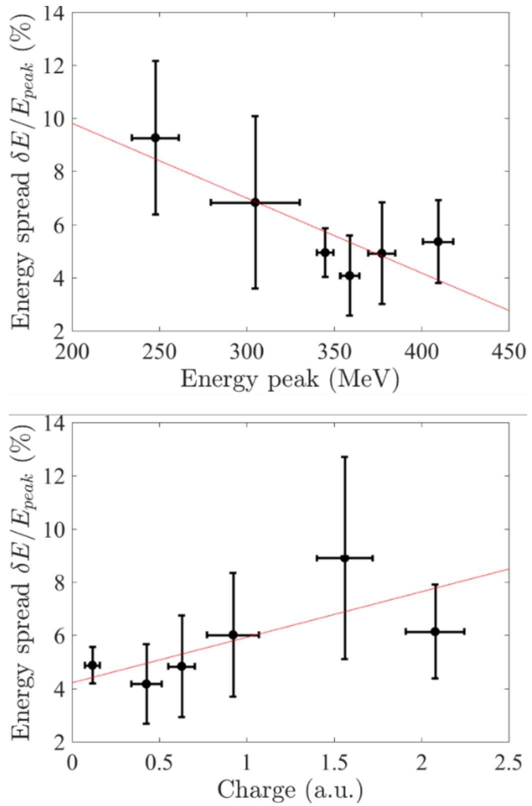
Consecutive shots

Electron beams with a dark-current free with a energy spread of ~ 5%

Preprimary experimental results



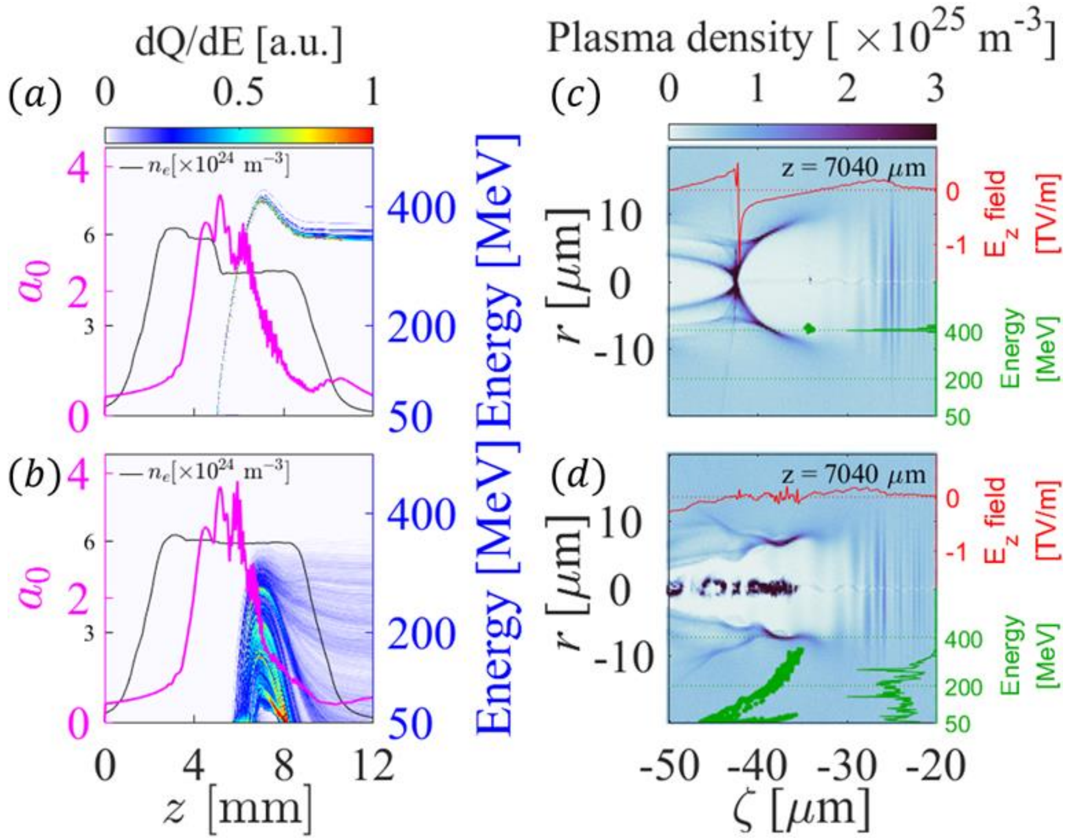




S. Lee et al., in preparation

PIC simulation results

Energy spread: ~1%



Preliminary results

Condition for injection

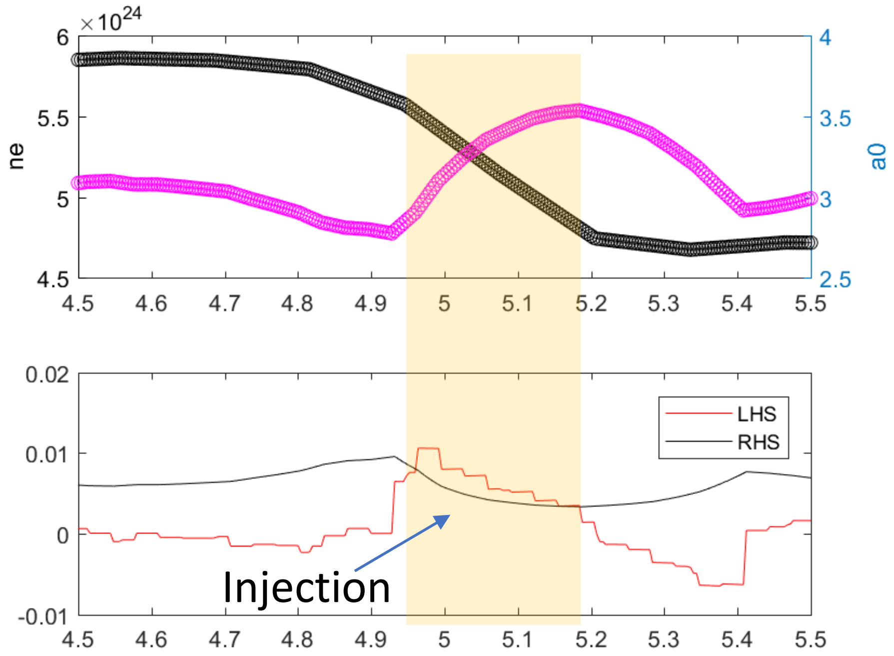
$$\boxed{3.8\gamma_0 < R^2F^2}$$

$$r_m \sim \frac{2\sqrt{a0}}{k_p} = R_u$$

$$R_u k_p = 2\sqrt{a_0}$$

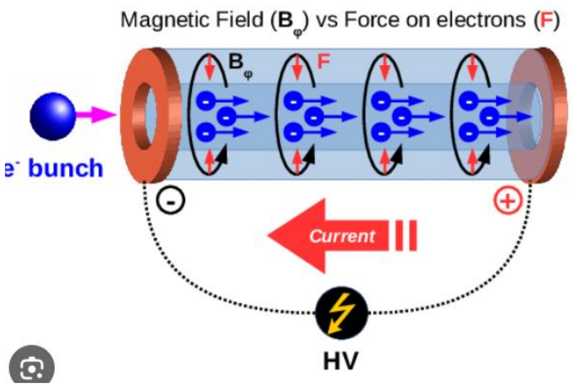
$$F = \frac{E_u\,|e|}{m_e c\omega_p} \qquad \gamma_0 = \left(\frac{2d(2R)}{dt}\right)^{-1/2}$$

$$\frac{dR_u}{dt_u}\frac{1}{c} > 0.9\frac{\left(1+\frac{a_0^2}{2}\right)}{a_0^6}$$



Application 1 using SC target

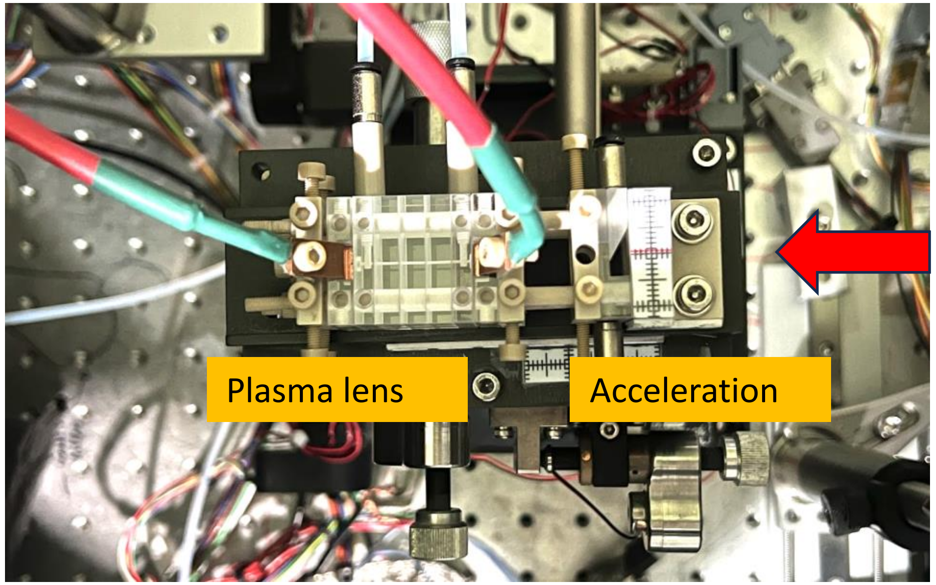
Plasma lens



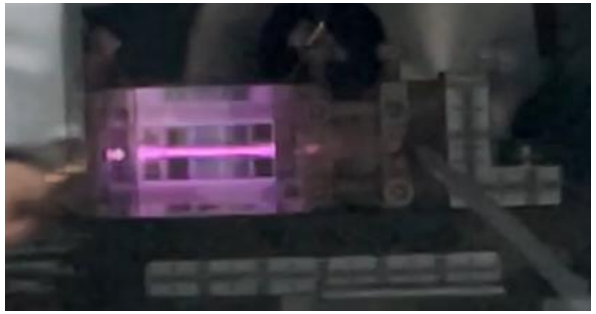
- Electron beam can be focused by a radial magnetic field induced from discharged current

Planed experimental campaign at 2027 (IBS 150 TW)

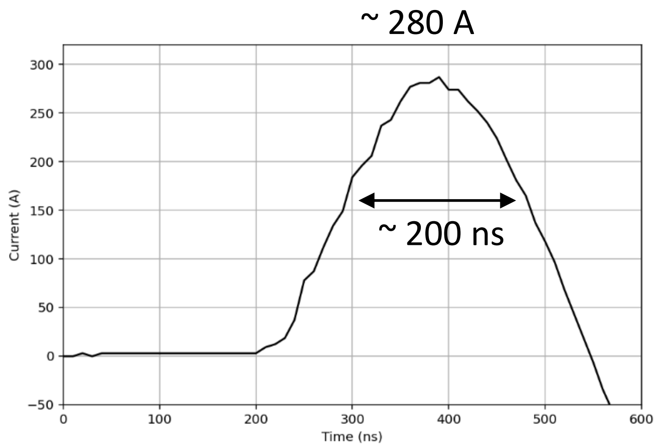
Combined capillary gas-cel: Acceleration + Plasma lens



2026 March IBS Experiment



Discharge current



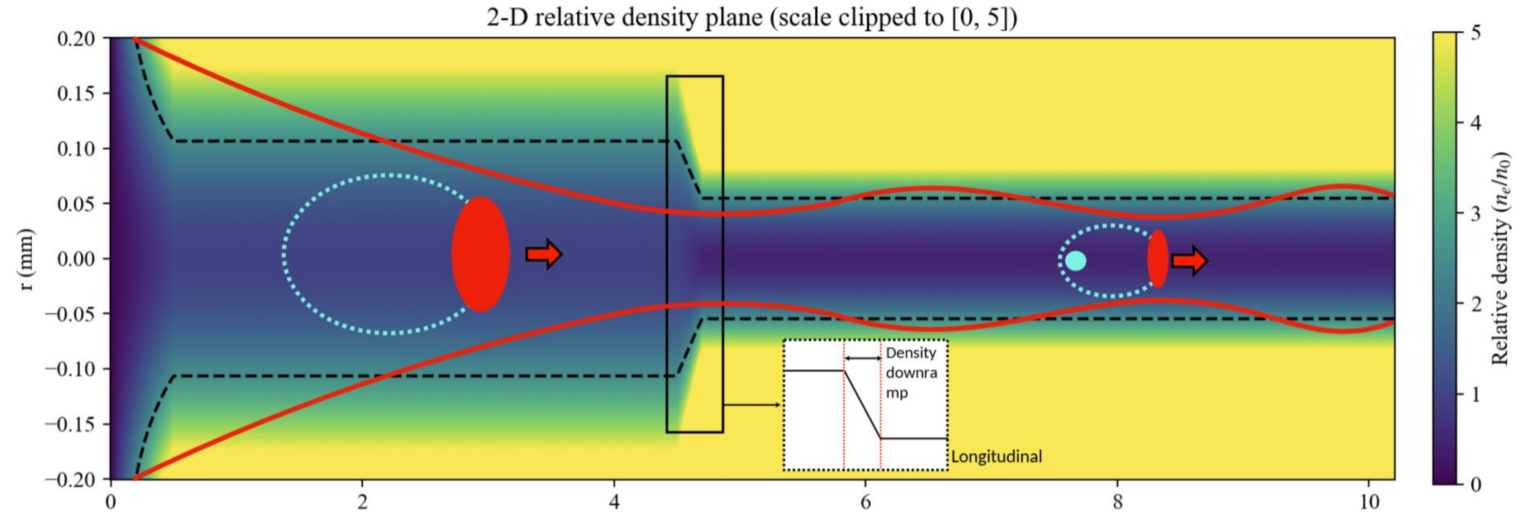
- Argon gas, 100 mbar
- HV: 15 kV

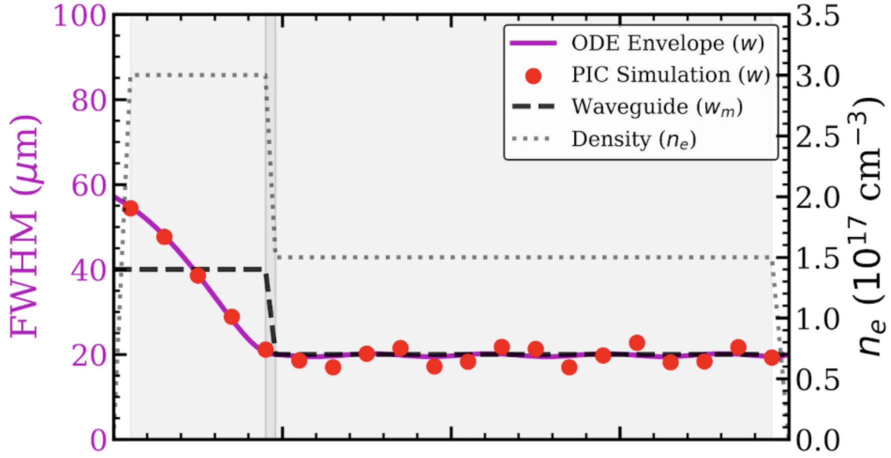
- Rising: 200 ns
- Max current: 300 A

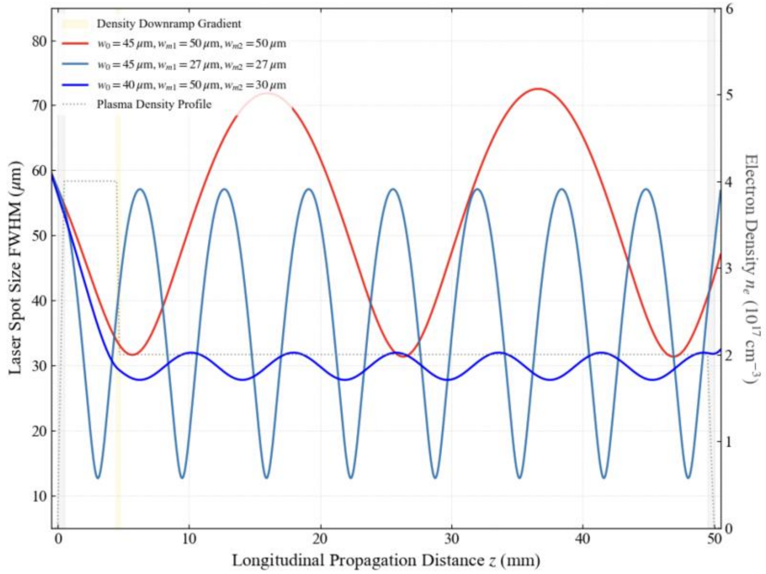
Application 2 using SC target

- **Proposed two-stage waveguide with a down ramp**

  - Beam injection in low density using a down ramp
  - Acceleration in long distance using a waveguide

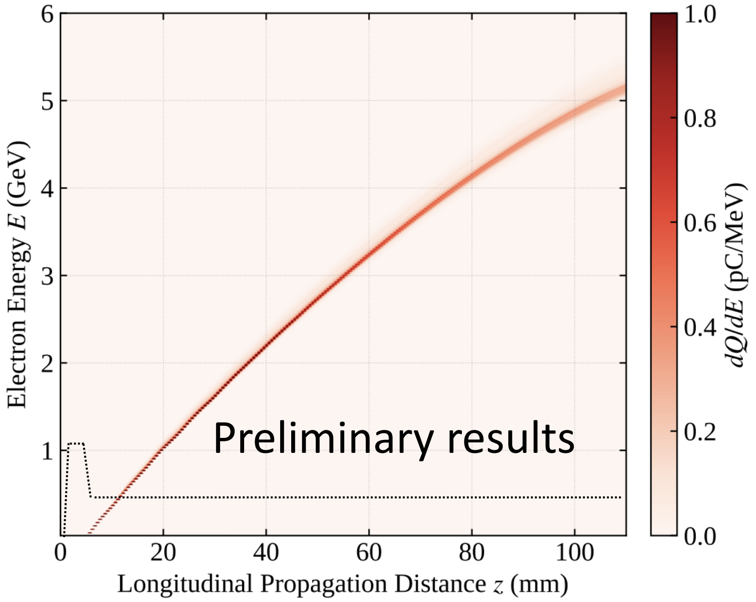


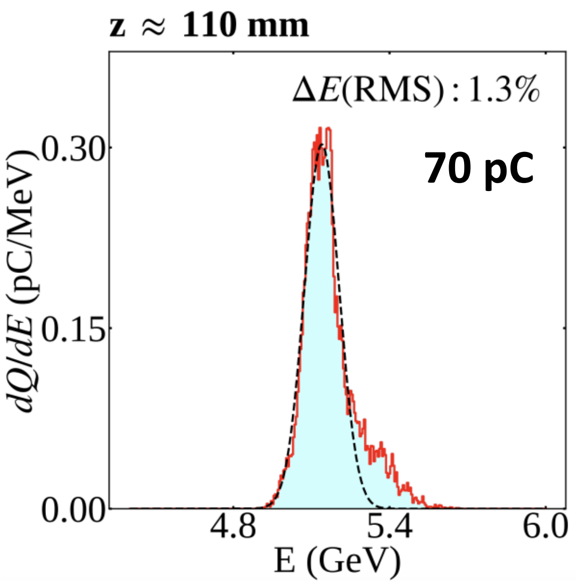




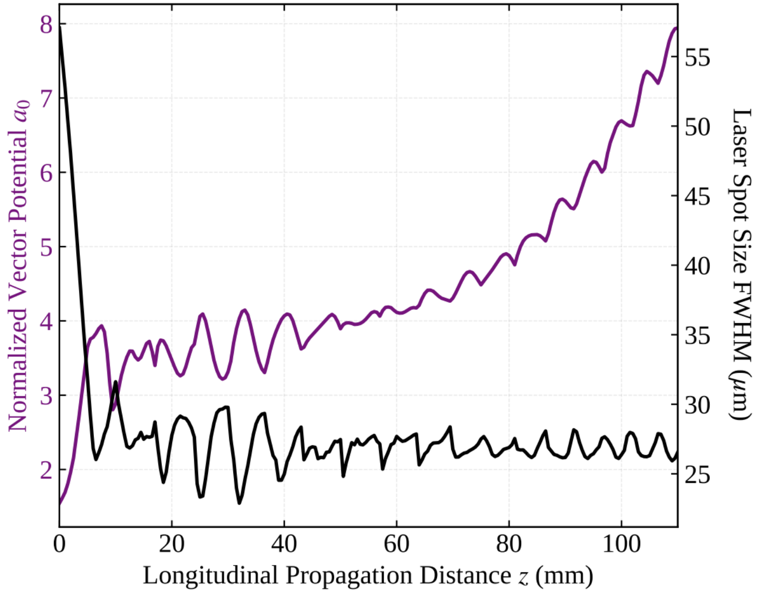
PIC simulation results

Electron beam energy evolution





Laser pulse and spot size evolution



Plasma density: $n_{e1} = 4 \times 10^{17}/\text{cm}^3, n_{e2} = 4 \times 10^{17}/\text{cm}^3$

Laser parameters: $\boldsymbol{a_0 = 2.0}, w_0 = 45\ \mu\text{m}\ \tau = 40\ \text{fs}$

Electron beam energy of 5 GeV with energy spread 1.3 % and 70 pC

H. Jeoung et al., in preparation

Summary

- Developed segmented capillary gas-cell for down-ramp injection with a flat density profile
- Measured down-ramp profile in the SC discharge plasma using optical emission spectroscopy
- Dark current free electron beams with low energy spread are generated by SC using 150 TW laser at IBS, GIST
- Proposed applications
  - Combined Segmented capillary target: Acceleration + Plasma lens
  - Two-staged discharged segmented capillary waveguide with a density down-ramp

Thank you for your attention

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