中央大學物理學系
Department of Physics National Central University

Development of laser-plasma proton acceleration at NCU

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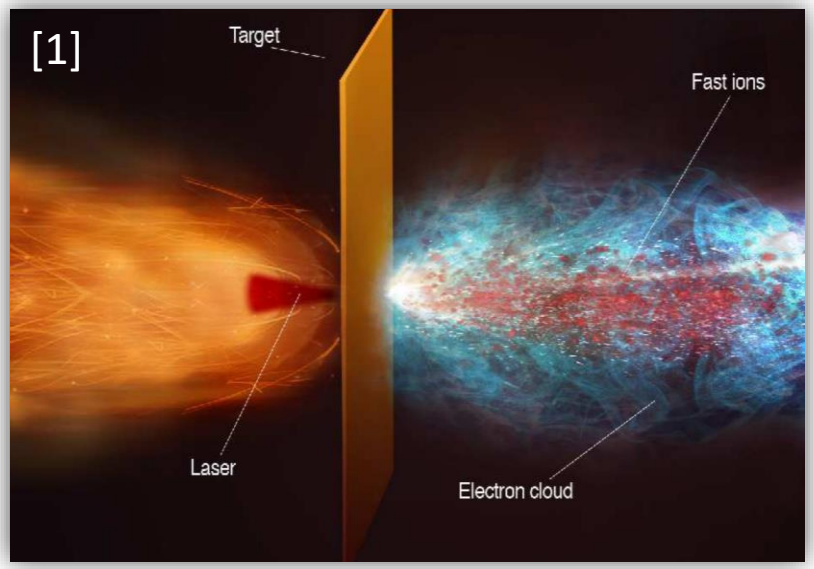
Nov. 24, 2023

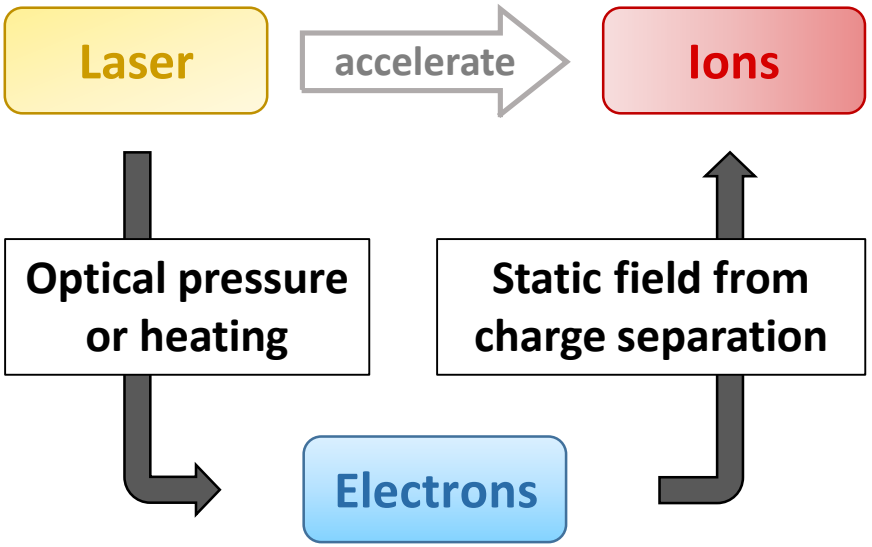
CHiP annual meeting

Outline

- Laser-plasma proton acceleration
- Experimental setup and diagnostics
- EPOCH 2D Particle-In-Cell Simulation
- Laser heating using nanowire targets

Laser plasma proton acceleration

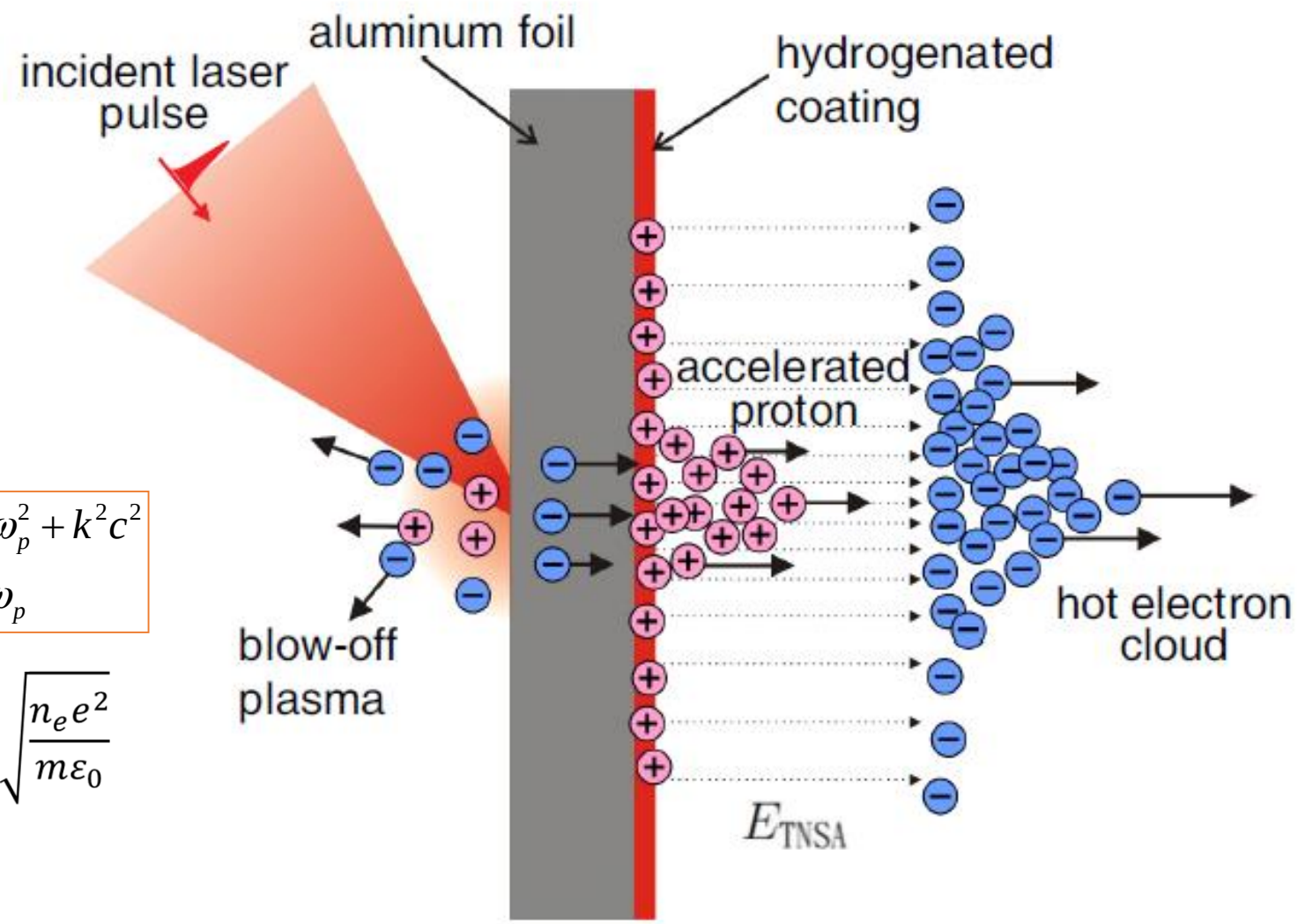




How do we maximize the transfer of laser pulse energy to electrons?

[1] A. Macchi, M. Borghesi, and M. Passoni, Rev. Mod. Phys. 85, 751 (2013)

Target normal sheath acceleration



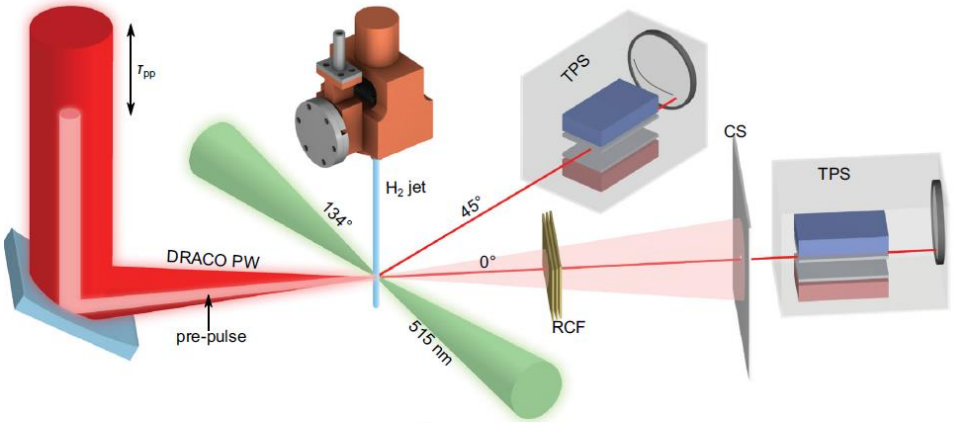
$$\omega_0^2 = \omega_p^2 + k^2 c^2$$

$$\omega_0 < \omega_p$$

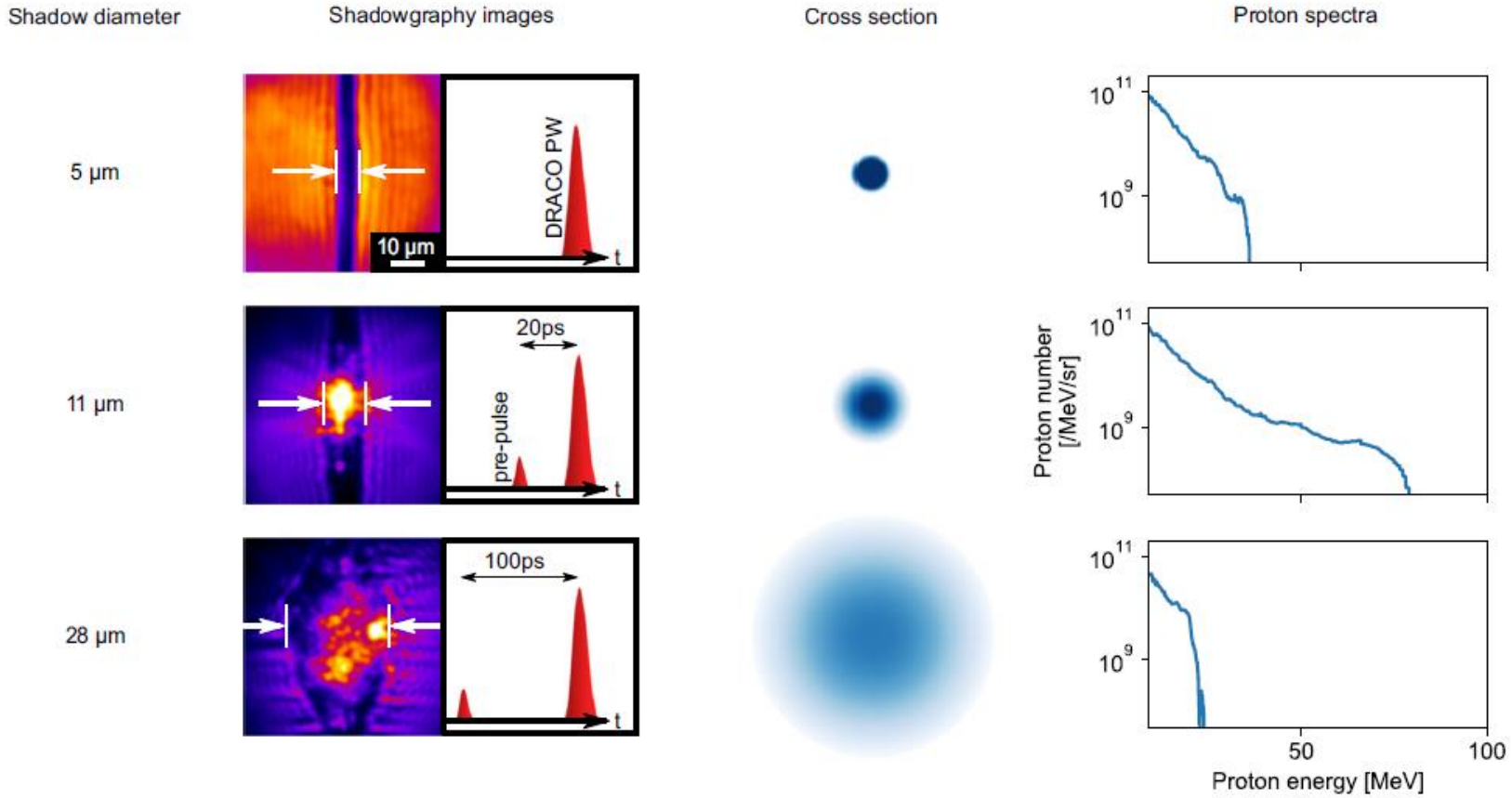
$$\omega_p = \sqrt{\frac{n_e e^2}{m\varepsilon_0}}$$

S.C. Wilks, et al., *Phys. Plasmas* **8**, 542 (2001)

Optimal TNSA occurs at near-critical density



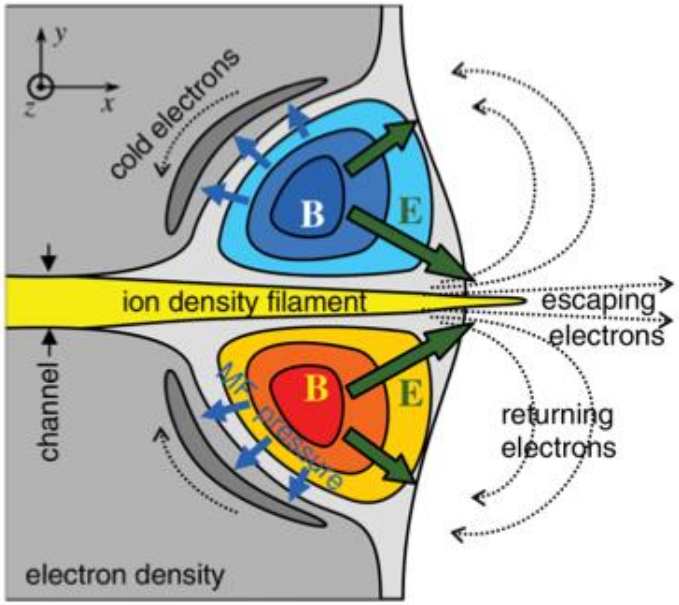
- Recent work shows a way to generate enhanced Proton acceleration at the relativistic transparency front for the optimal case, near critical density.



Laser-plasma proton acceleration using gas target

Acceleration with gaseous target

[4]

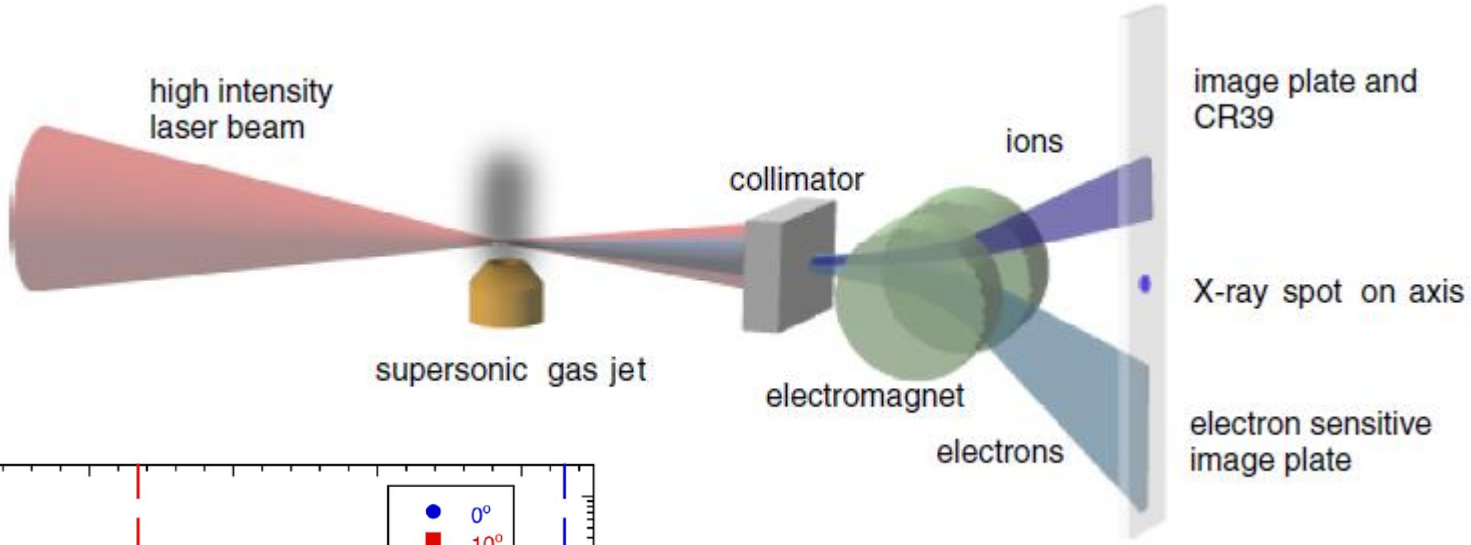


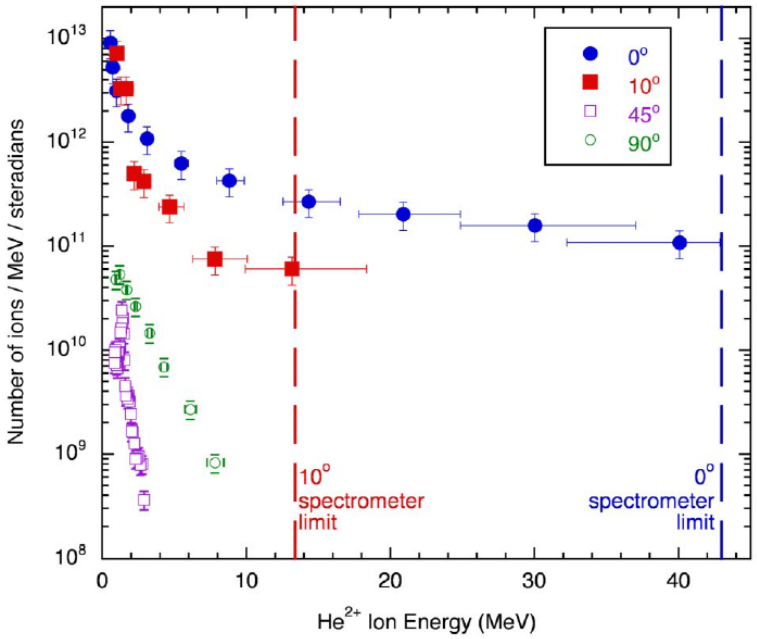
- Low demand on laser contrast
- Online adjustment of target density & thickness
- Higher laser-plasma coupling
- Measurement of the changes inside target

[4] S. V. Bulanov and T. Zh. Esirkepov, Phys. Rev. Lett. 98, 049503 (2007)

λ_L: 1054 nm /300 TW (a_0: 21) / τ_{FWHM}: 1.0 ps / w_{FWHM}: 7 μm
n_e: 0.02 n_c / 2 mm Nozzle / Helium target

Current Result of Experiment





- Maximum ion energy up to 40 MeV
- Number of ions (> 10 MeV) ~ 10^{11}

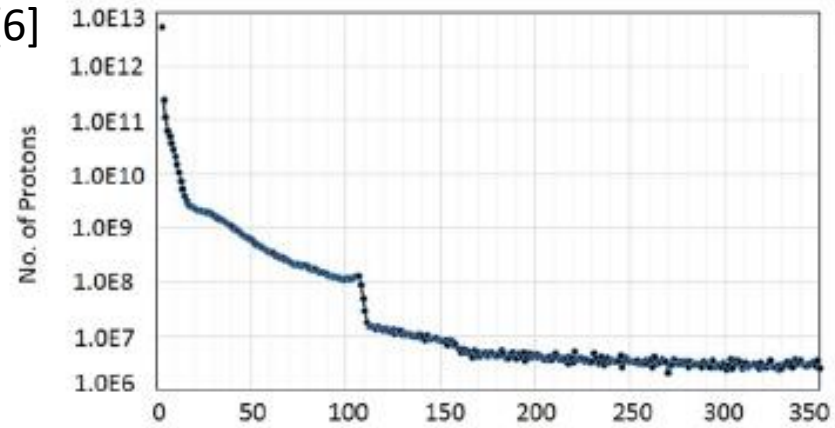
L. Willingale et al., Phys. Rev. Lett. 96, 245002 (2006)

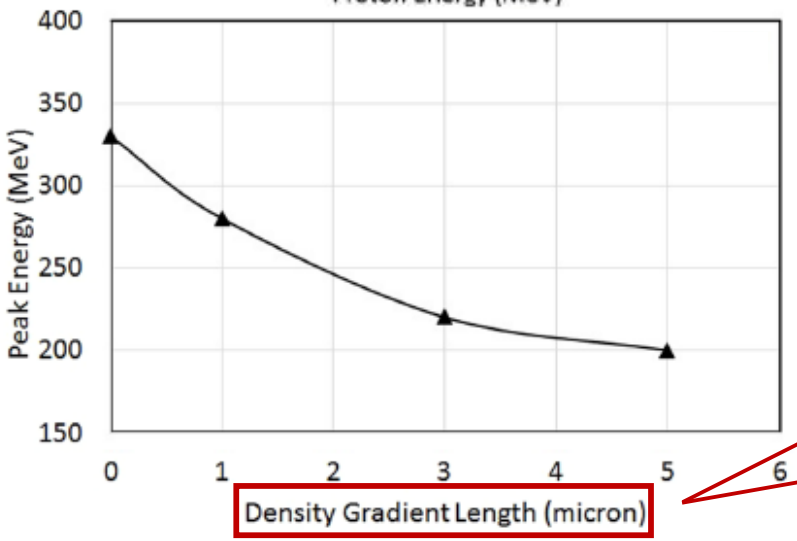
λ_L: 800 nm /2 PW (a_0: 81) / τ_{FWHM}: 20 fs / w_{FWHM}: 3 μm
n_e: 1 n_c / Hydrogen target

Current Result of Simulation

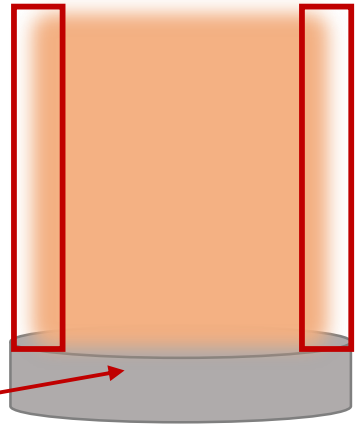
3D simulation using circular polarized laser

[6]





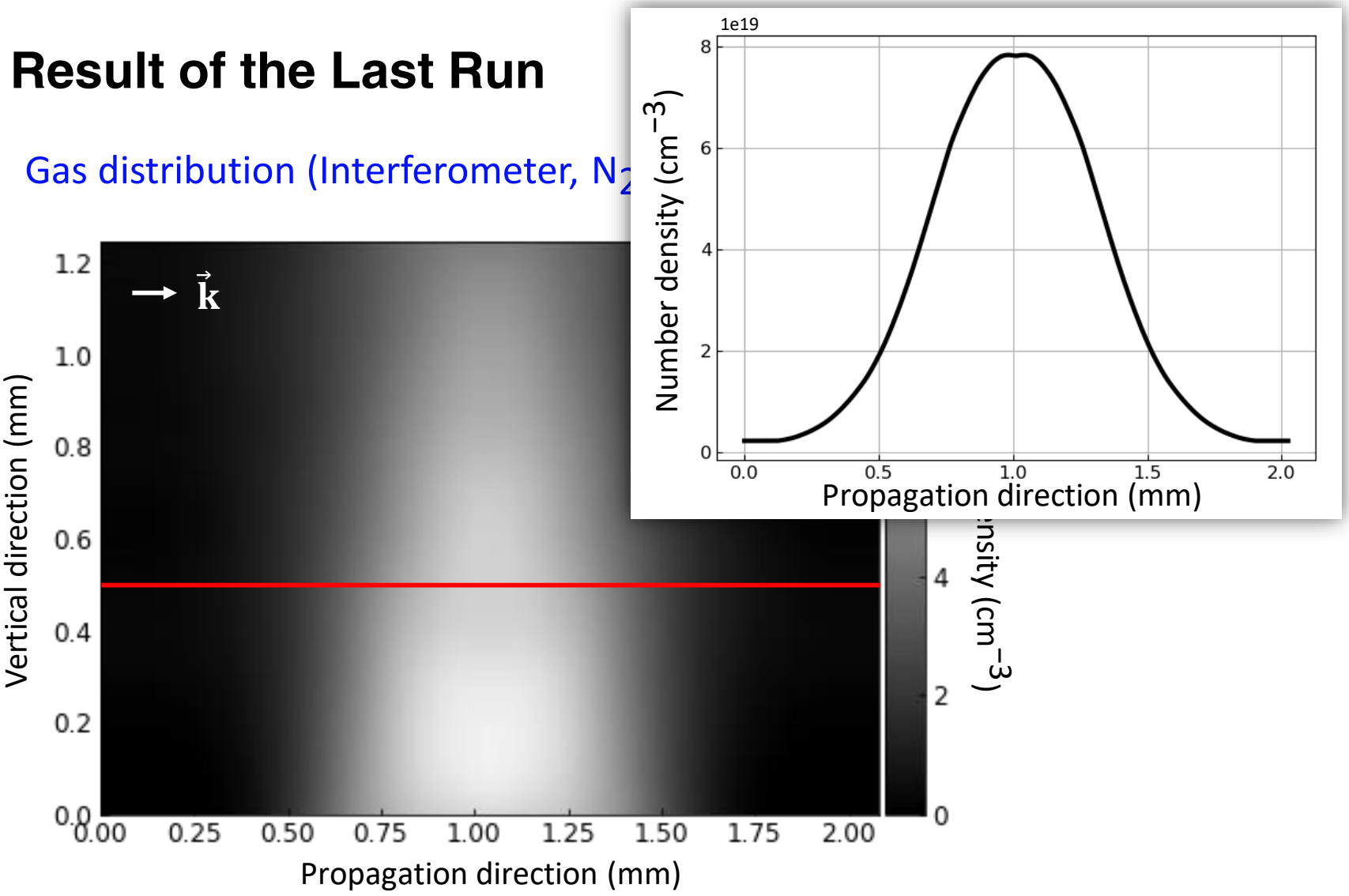
- Maximum proton energy up to 350 MeV
- Number of protons (> 100 MeV) ~ 10^9
- Density ramp affect the acceleration



[6] Sharma, A. *Sci Rep* **8**, 2191 (2018)

Result of the Last Run

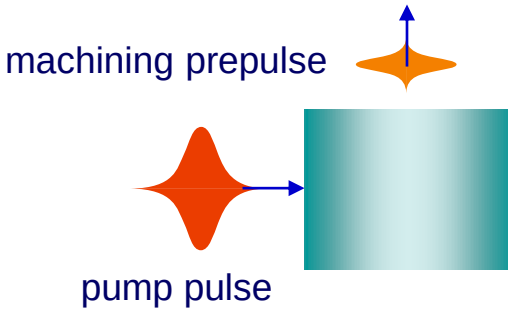
Gas distribution (Interferometer, N_2



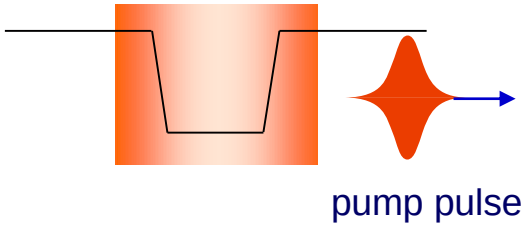
Fully ionization: 0.24 n_c

Reduction of local plasma density by laser machining

Step 1: A prepulse ionizes and heats up the gas target.



Step 2: The hot plasma expands. The density of the irradiated region is reduced.



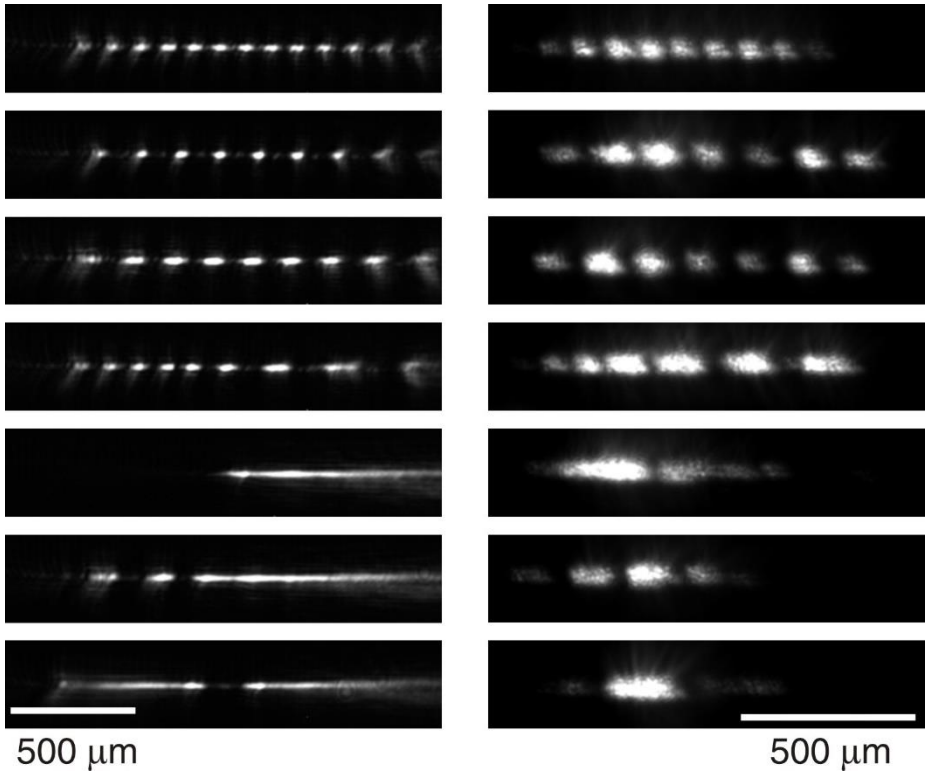
Step 3: The pump pulse ionizes the rest of the gas and interacts with a plasma well.

Fabrication of spatial transient-density structures by laser machining

intensity patterns set with a spatial light modulator

side scattering images

atom density: 3.2×10^{18} cm^{-3}



pattern parameters

duty-on region: 50 mm
period: 100 mm

duty-on region: 50 mm
period: 150 mm

duty-on region: 100 mm
period: 150 mm

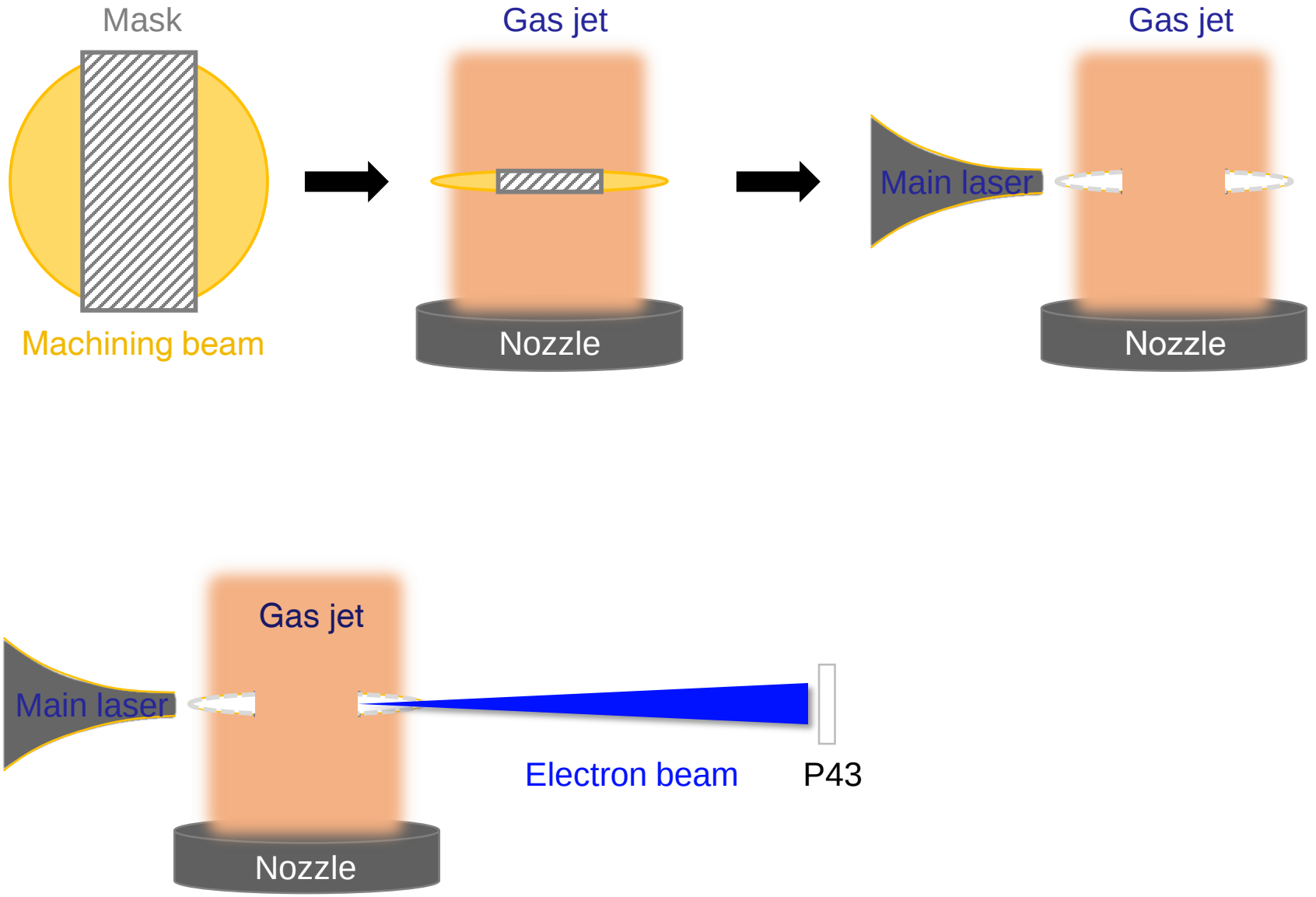
aperiodic pattern
period: 50 → 300 mm

blocking half

on after the third period

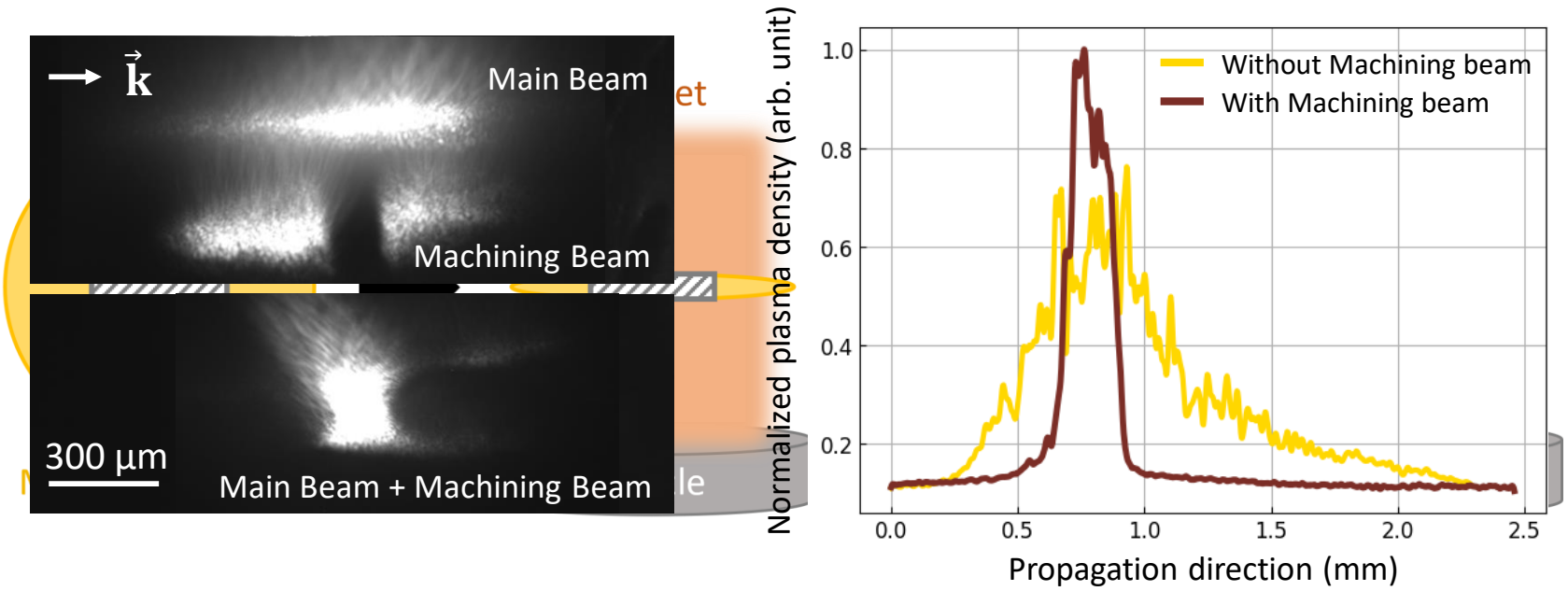
a well of 200-mm width

Phys. Plasmas 12, 070707 (2005)


Mask
Machining beam
Gas jet
Nozzle
Main laser
Gas jet
Nozzle
Gas jet
Main laser
Nozzle
Electron beam
P43

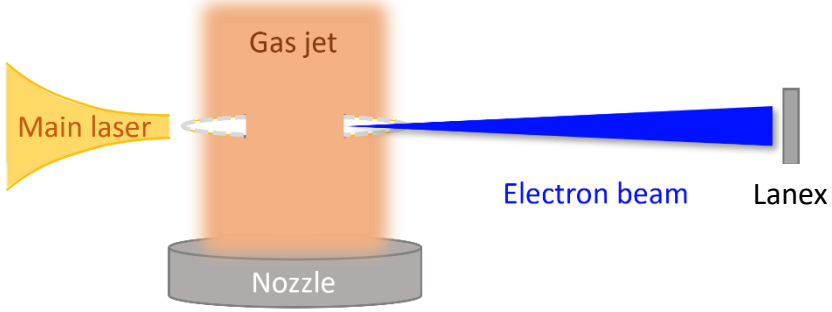
Result of the Last Run

Tailored plasma density distribution

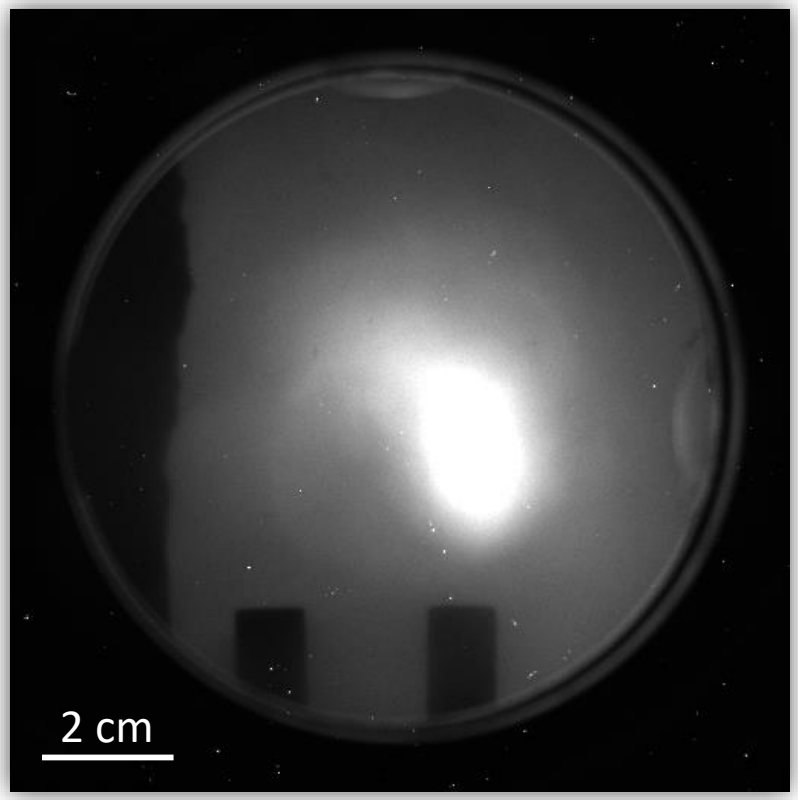


- Thickness of plasma plateau: 150 µm
- Ramp length: 60 µm (from 90 % to 10 %)

Result of the Last Run



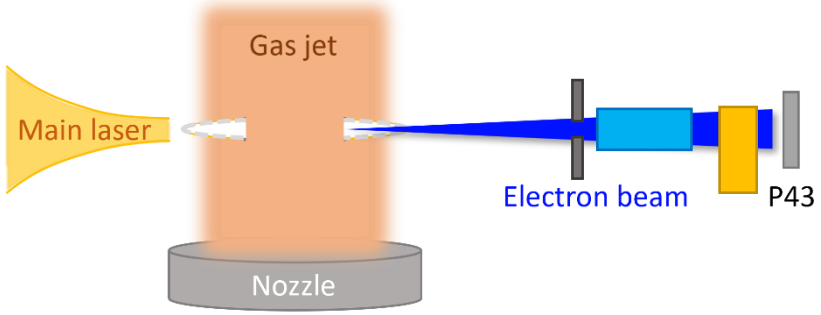
Electron acceleration



Lanex

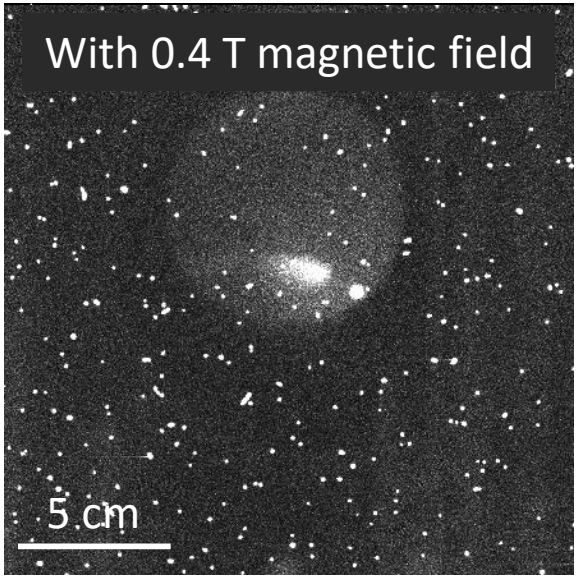
20-mrad diverge angle

Result of the Last Run



Electron deflection by Thomson Parabola

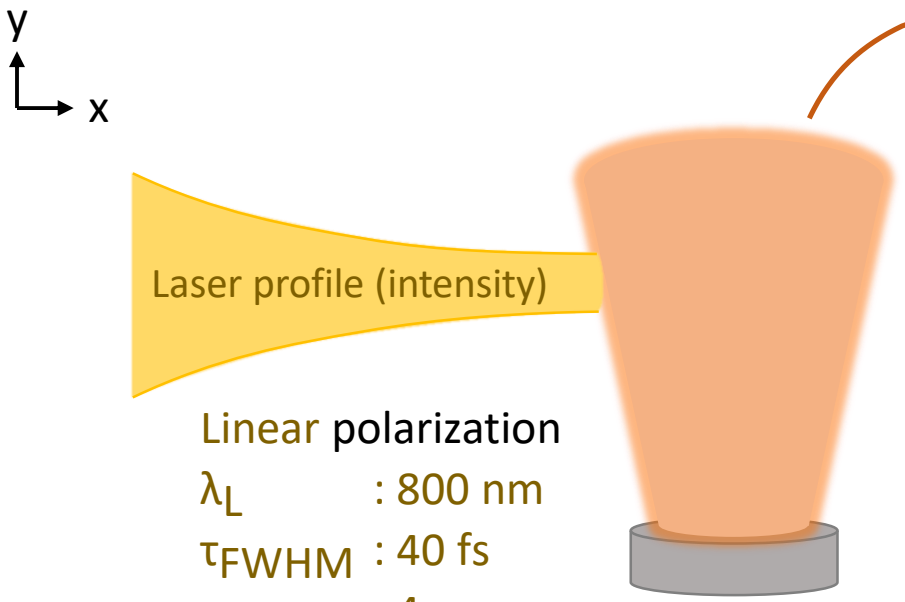
P43



Parameters for Simulation

- 2D relativistic Particle-in-cell (PIC) EPOCH code

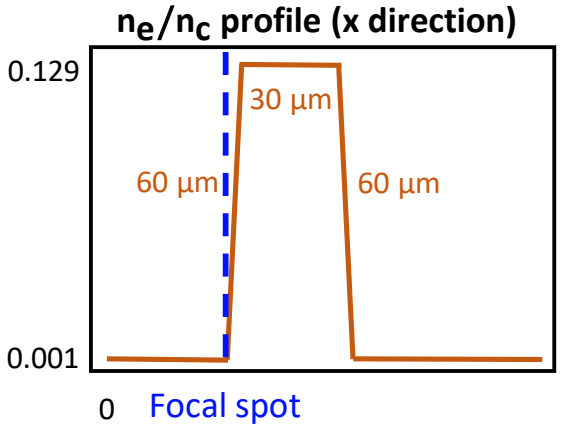
$|E| = a_0 m_e \omega_L c / e \quad n_c = \omega_L m_e \varepsilon_0 / e^2$



Linear polarization
λ_L : 800 nm
τ_{FWHM} : 40 fs
w_{FWHM} : 4 μm
a_0 : 7.3

(Laser Energy 1.358 J)
(Enlosed energy factor: 0.65)

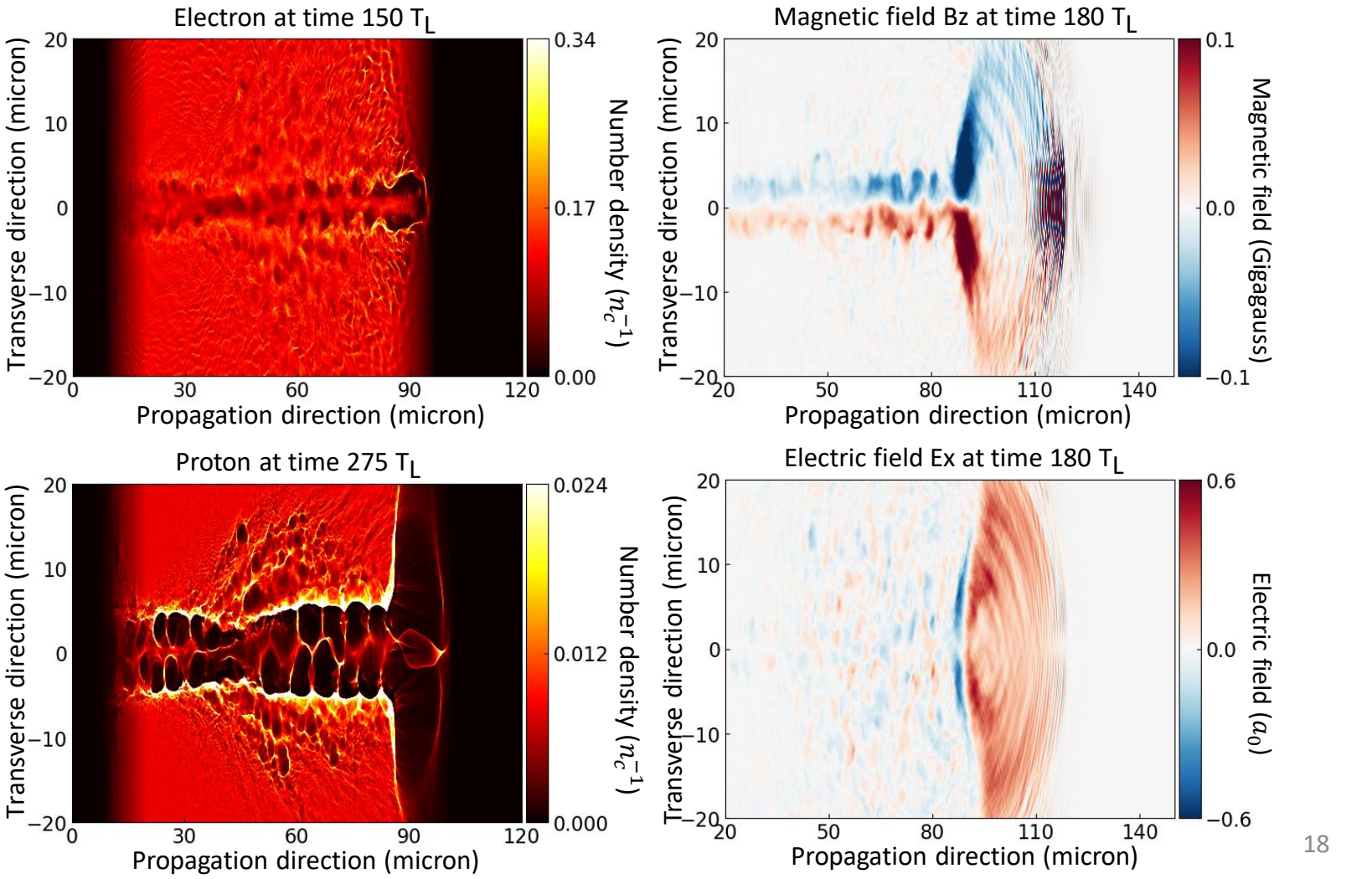
NCD, N : H = 2 : 1 target
Pre-ionized, cold plasma



Δx : 25 nm
Δy : 25 nm
10 particles per cell

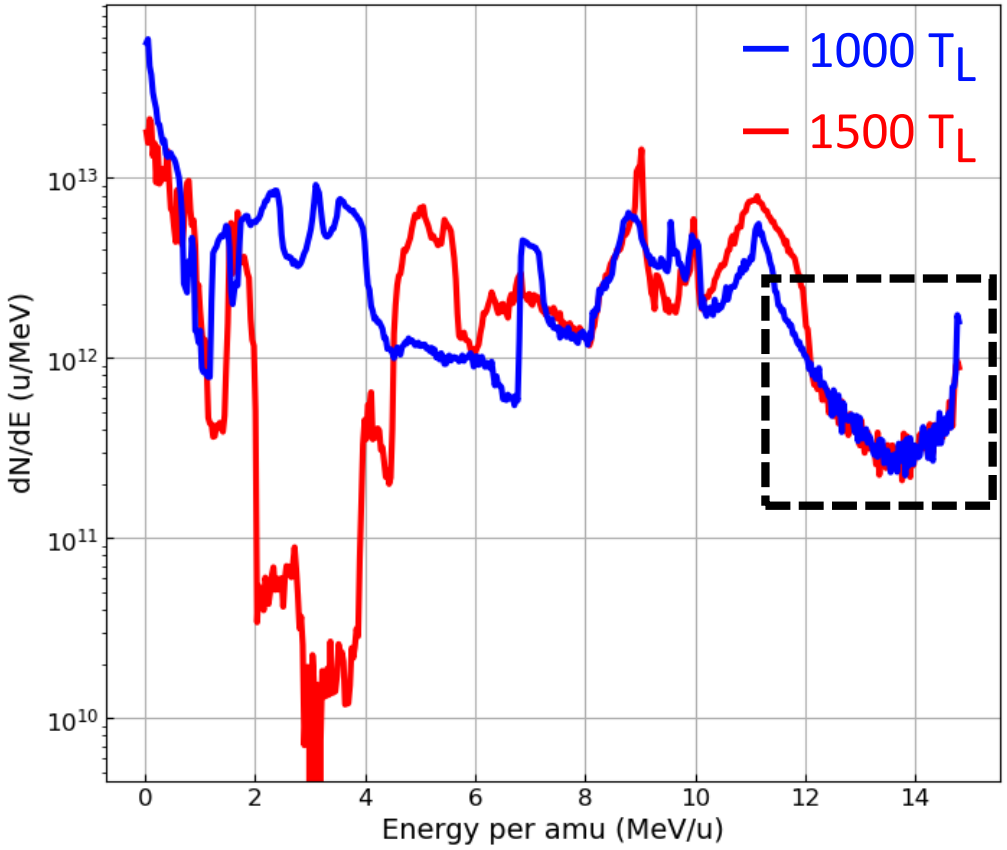
Result of Simulation

Acceleration with gaseous target

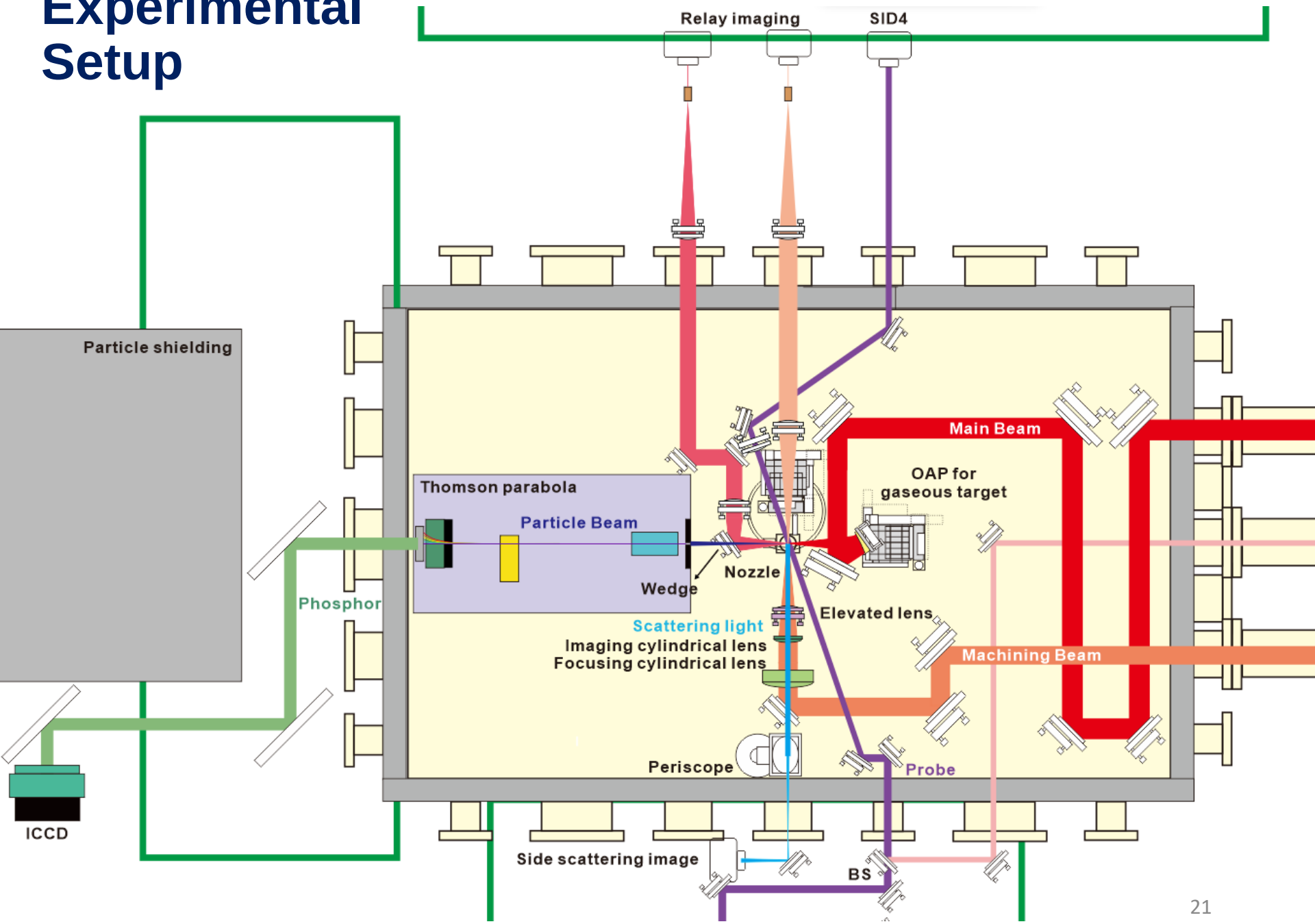


2D Particle-In-Cell Simulation

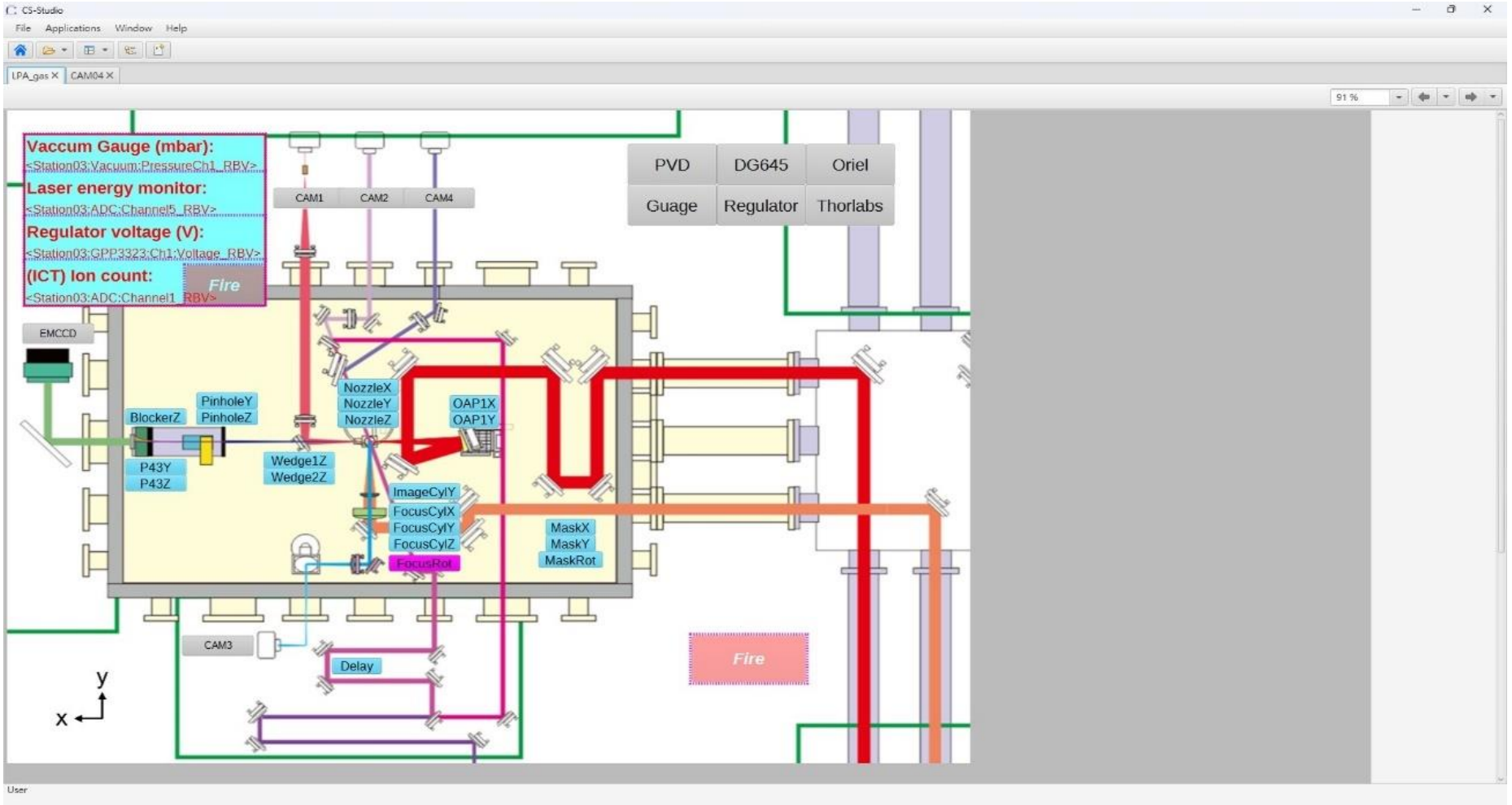
Proton energy spectrum



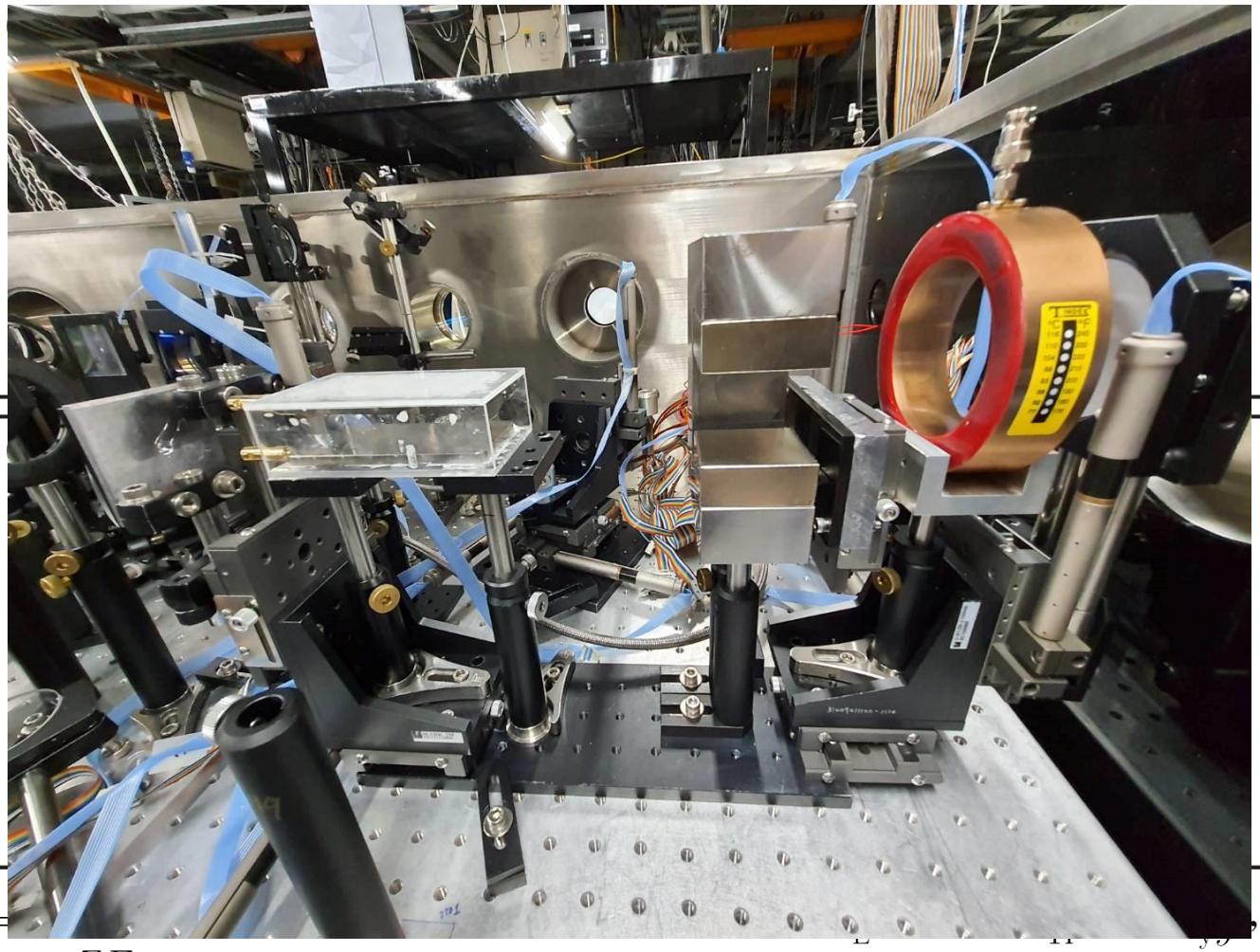
Experimental Setup



Supervision interface based on EPICS



Proton beam diagnosis-Thomson parabola



$$\vec{F}_{\mathrm{B}} =$$

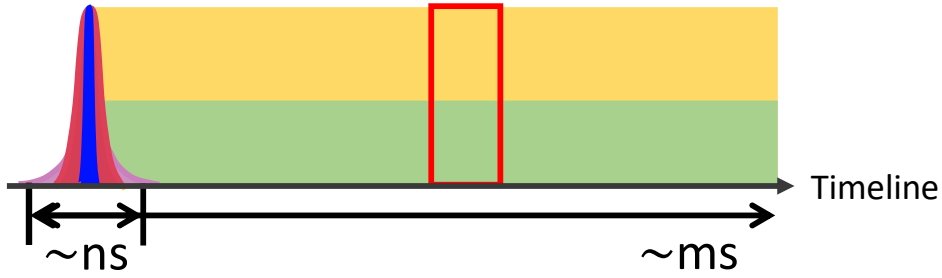
$$\Rightarrow \quad a_{\mathrm{x}} = \frac{eZE_{\mathrm{TP}}}{M}\,,$$

$$\Rightarrow \quad \Delta \mathrm{x} = \frac{eZB_{\mathrm{TP}}}{Mv} \cdot L_{\mathrm{B}} \left(\frac{L_{\mathrm{B}}}{2} + L_1 \right) .$$

$$\Rightarrow \quad a_{\mathrm{y}} = \frac{eZE_{\mathrm{TP}}}{M}\,,$$

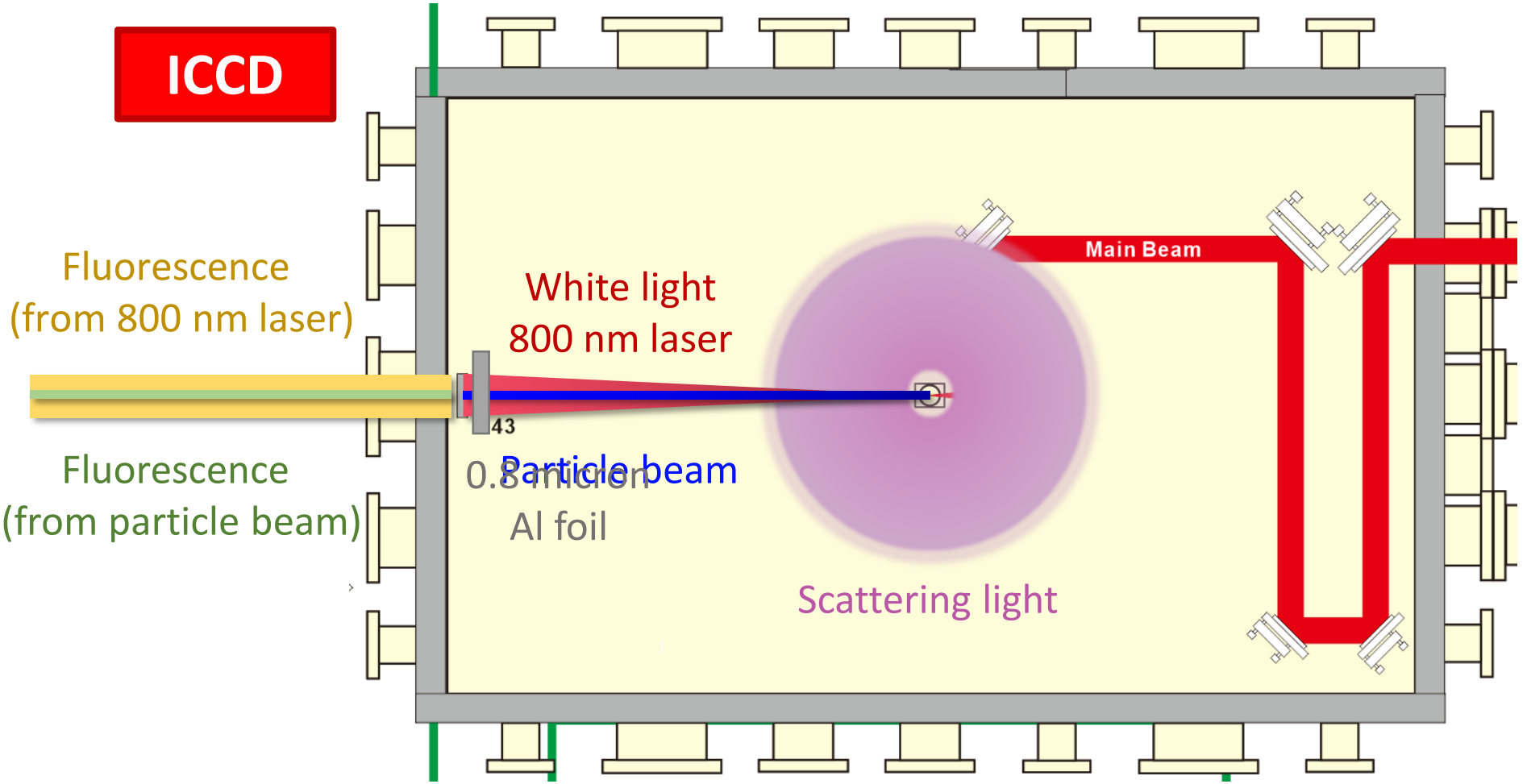
$$\Rightarrow \quad \Delta y = \frac{eZE_{\mathrm{TP}}}{Mv^2} \cdot L_{\mathrm{E}} \left(\frac{L_{\mathrm{E}}}{2} + L_2 \right) .$$

Problems & Improvements



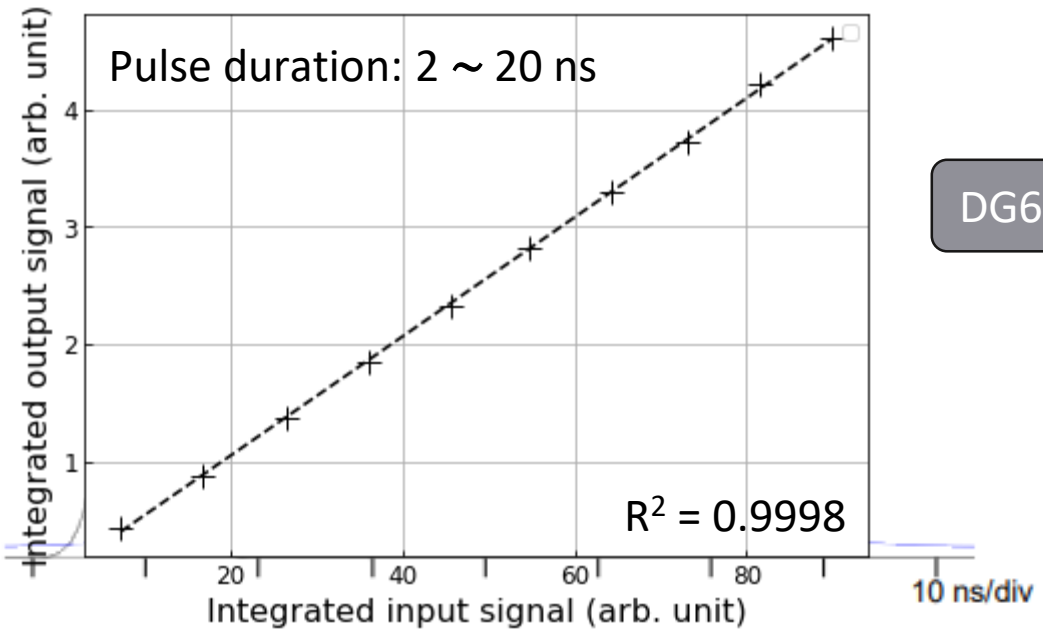
Light Source

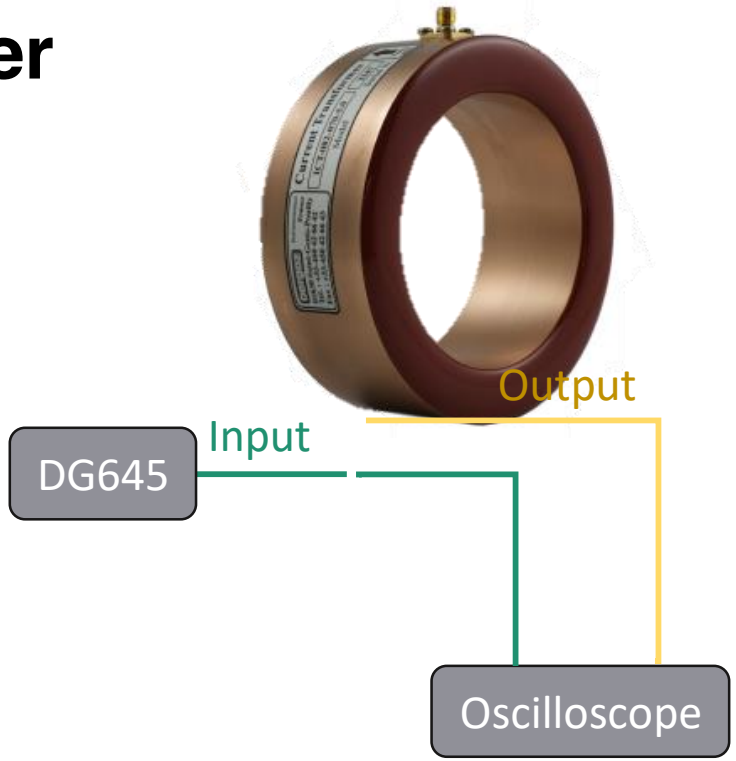
ICCD



Calibration of Proton Number

Integrating Current Transformer



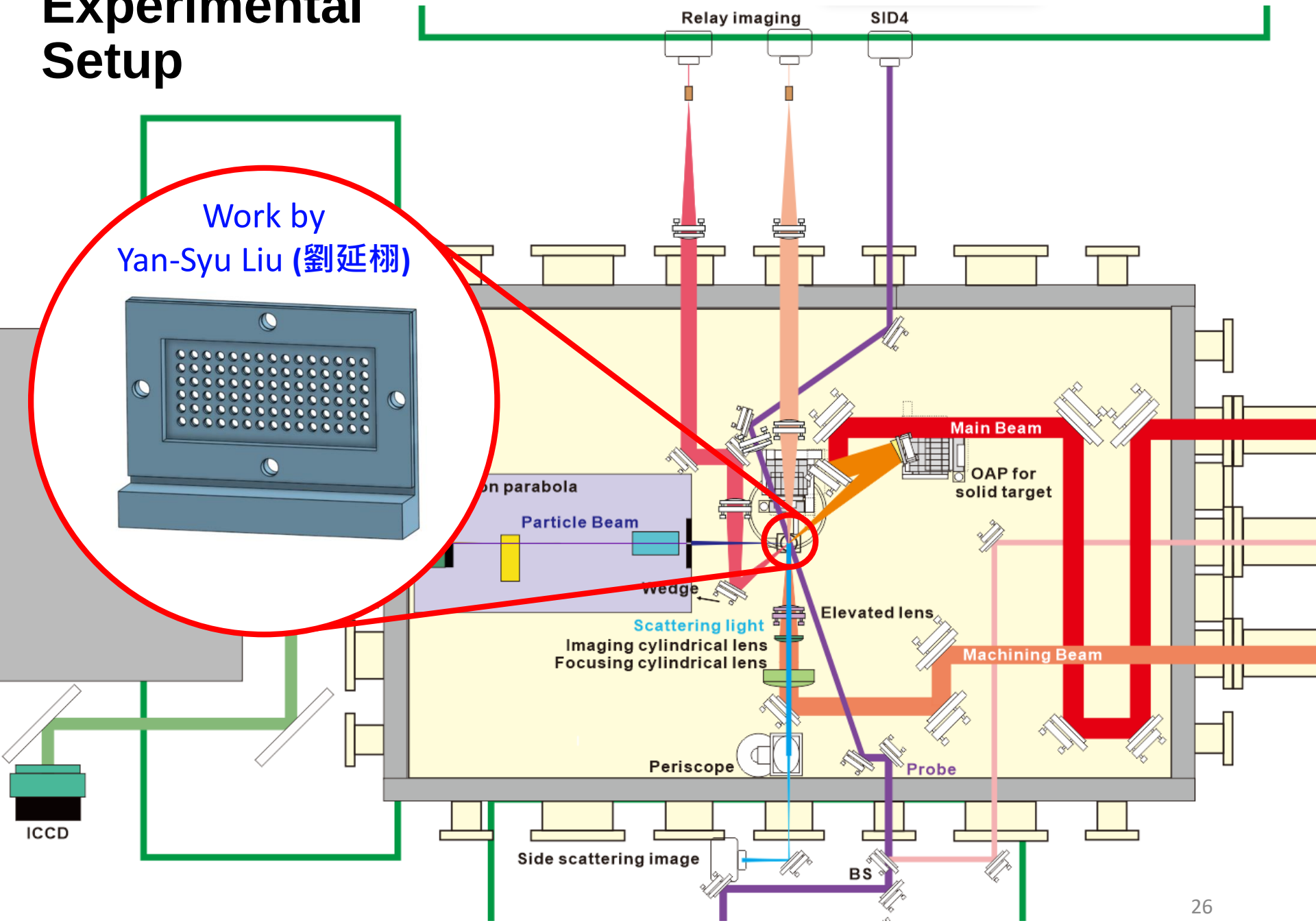


The output pulse charge is in exact proportion to the beam pulse charge [9]

It is capable of integrating a pulse of length < 1 fs with no significant loss [9]

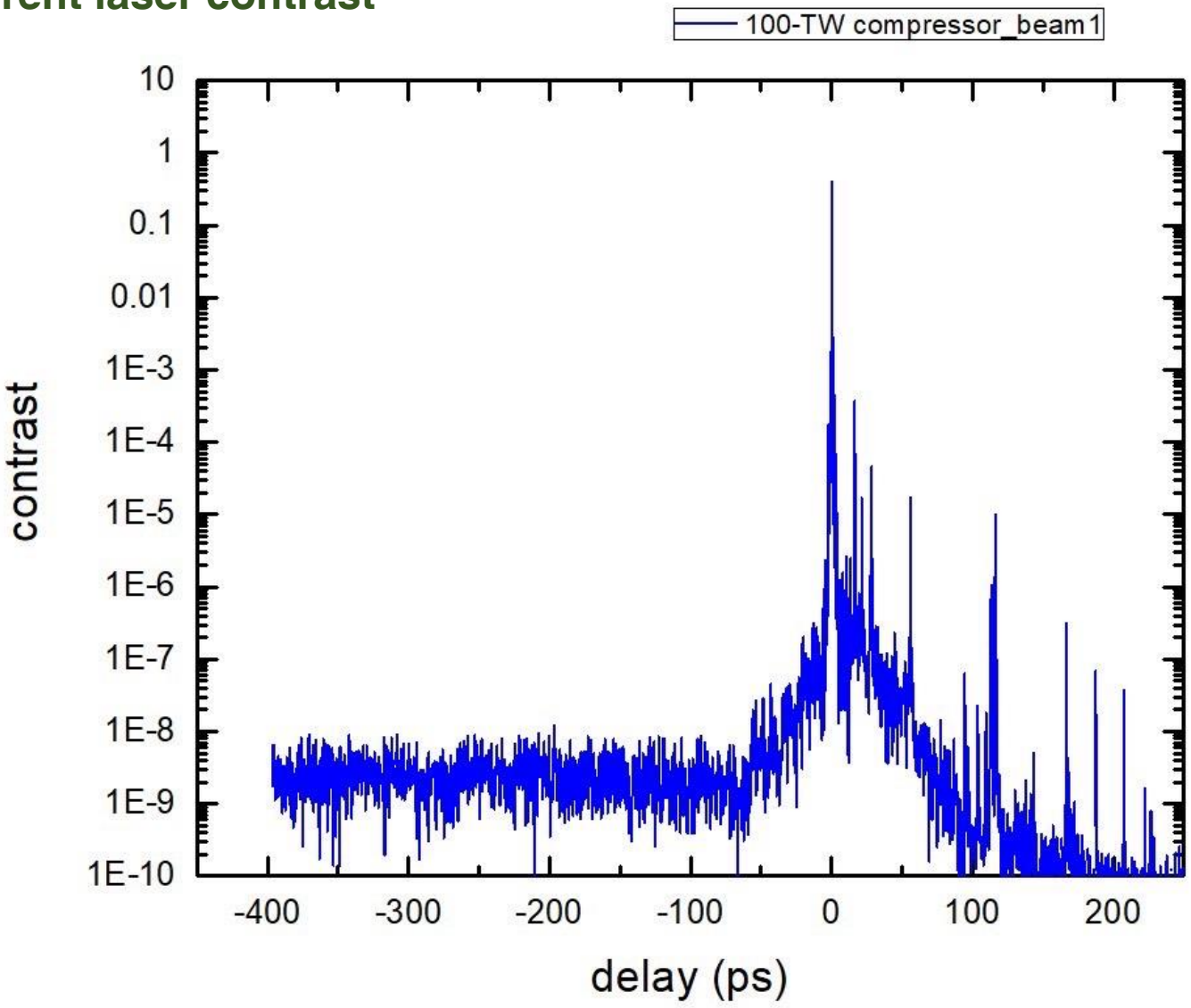
[9] Bergoz (2019). Integrating Current Transformer User's Manual

Experimental Setup



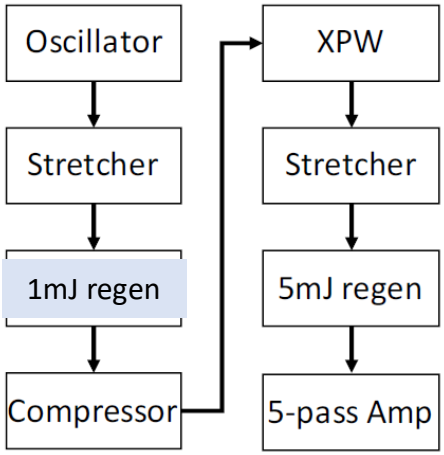
Enhancing laser contrast for proton acceleration

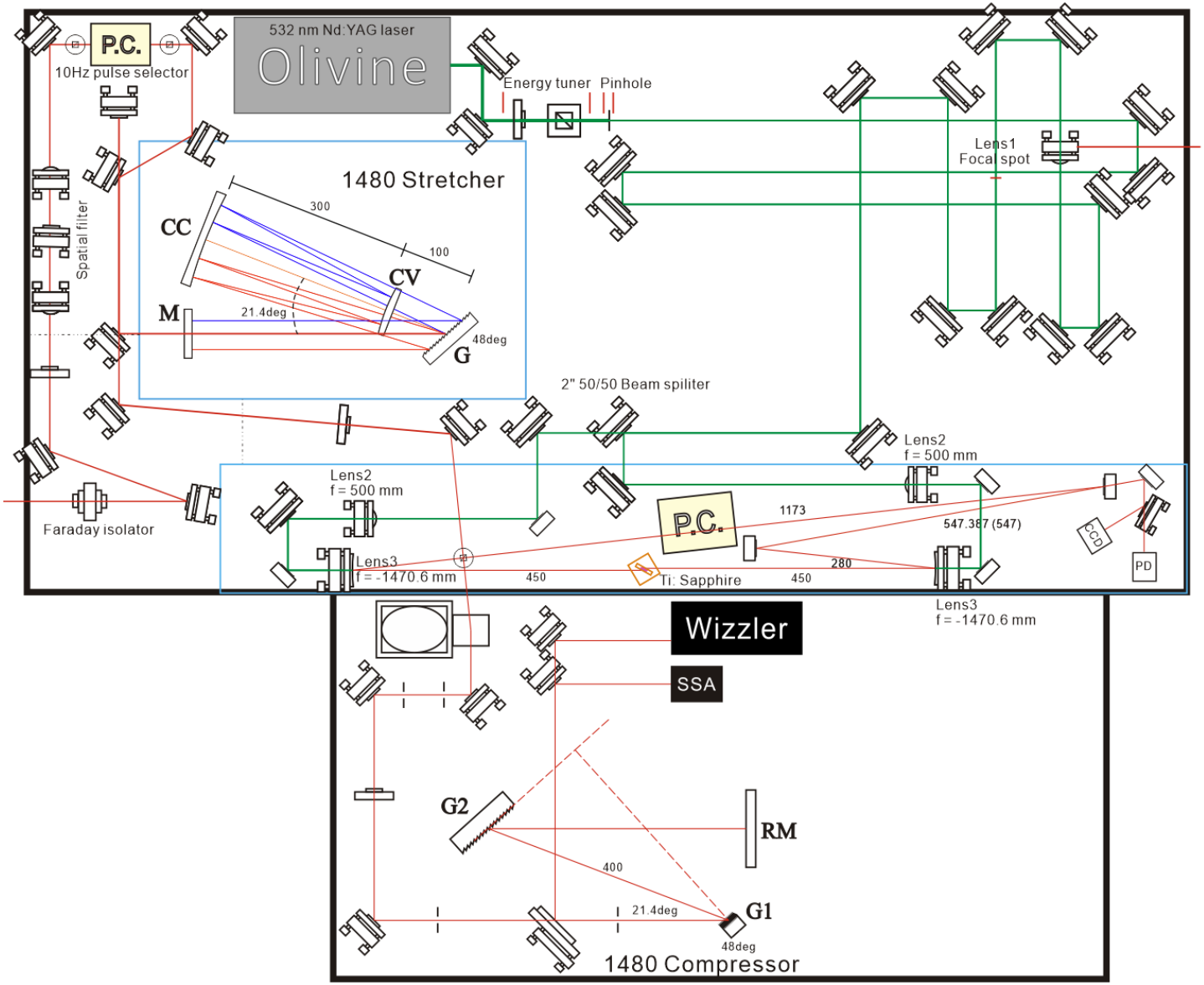
Current laser contrast



Enhancing laser contrast for proton acceleration

Double CPA

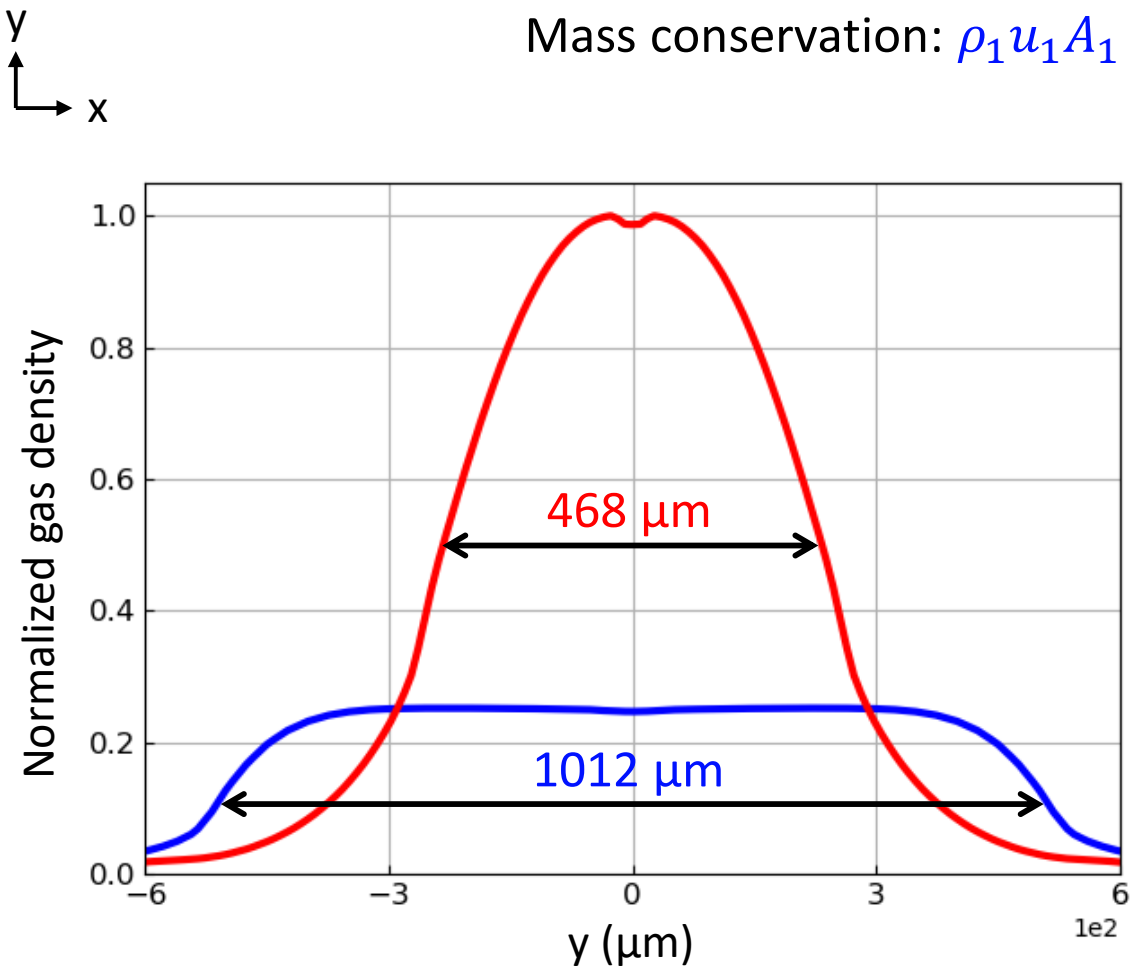


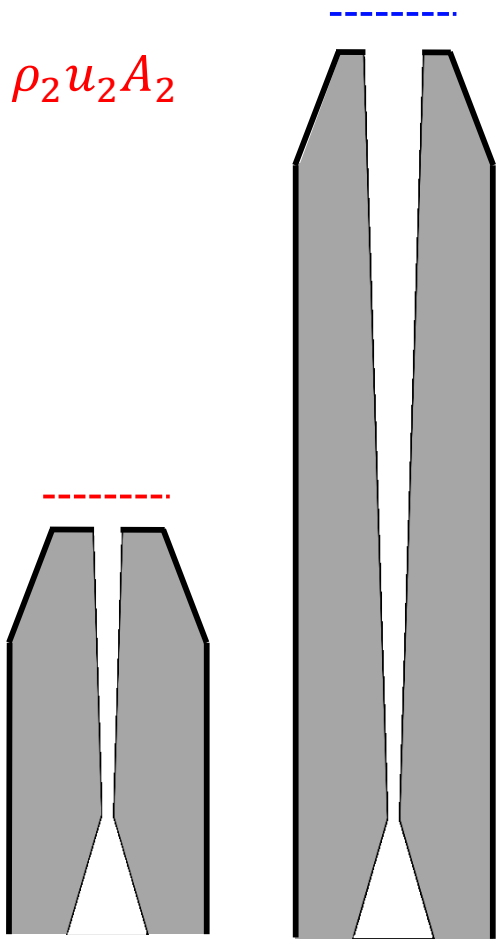


Near-critical-density gas targets

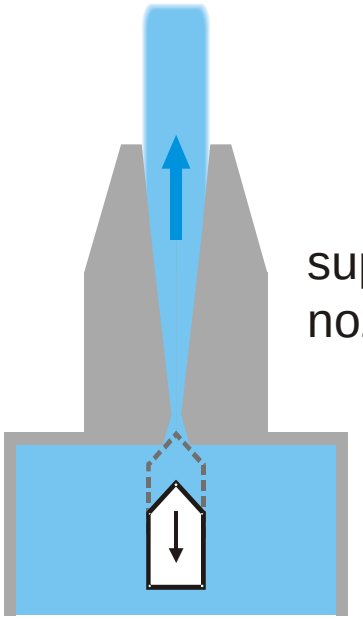
Nozzle improvement

Mass conservation: $\rho_1 u_1 A_1 = \rho_2 u_2 A_2$





Near-critical-density gas targets



supersonic nozzle

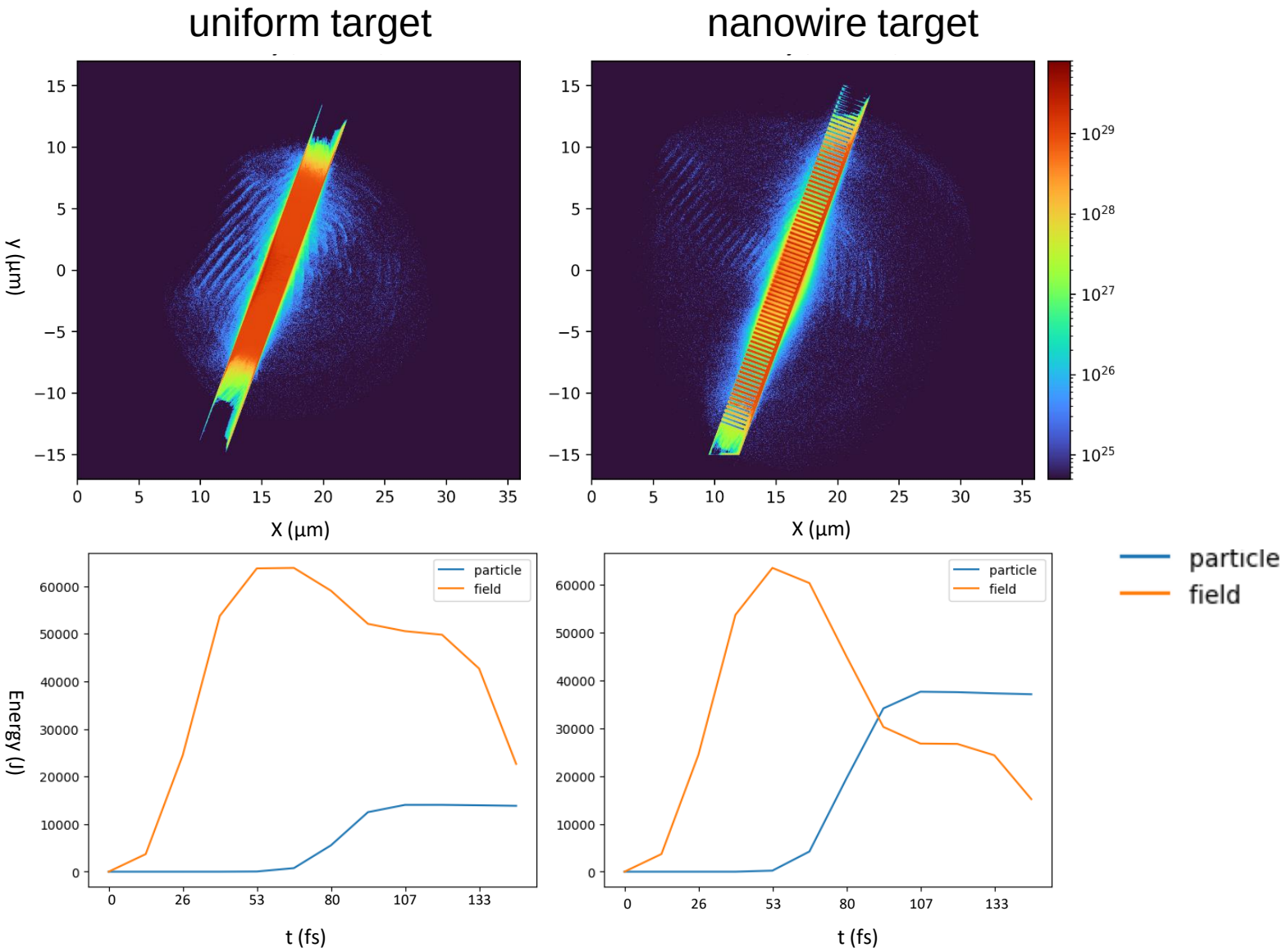
pulsed valve

High-pressure booster
(Haskel 86981)
Inlet: 17 bar
Outlet: 1034 bar/15000 psi

- By modifying the supersonics nozzle and using high-pressure booster (Haskel 86981), 1-2 Nc hydrogen gas jet can be used for laser-plasma proton acceleration.

Heating with nanowire target

Tk = 2 μm
Tilt = 20°
100 nc



Summary

- The experimental station for developing laser-plasma proton acceleration has been installed and calibrated.
- Programmable near-critical-density gas targets will be used.
- Experimental and simulation will be compared to understand the underlying mechanism.
- Searching for a reliable route to guide this field is still ongoing.

Thank you for your attention.