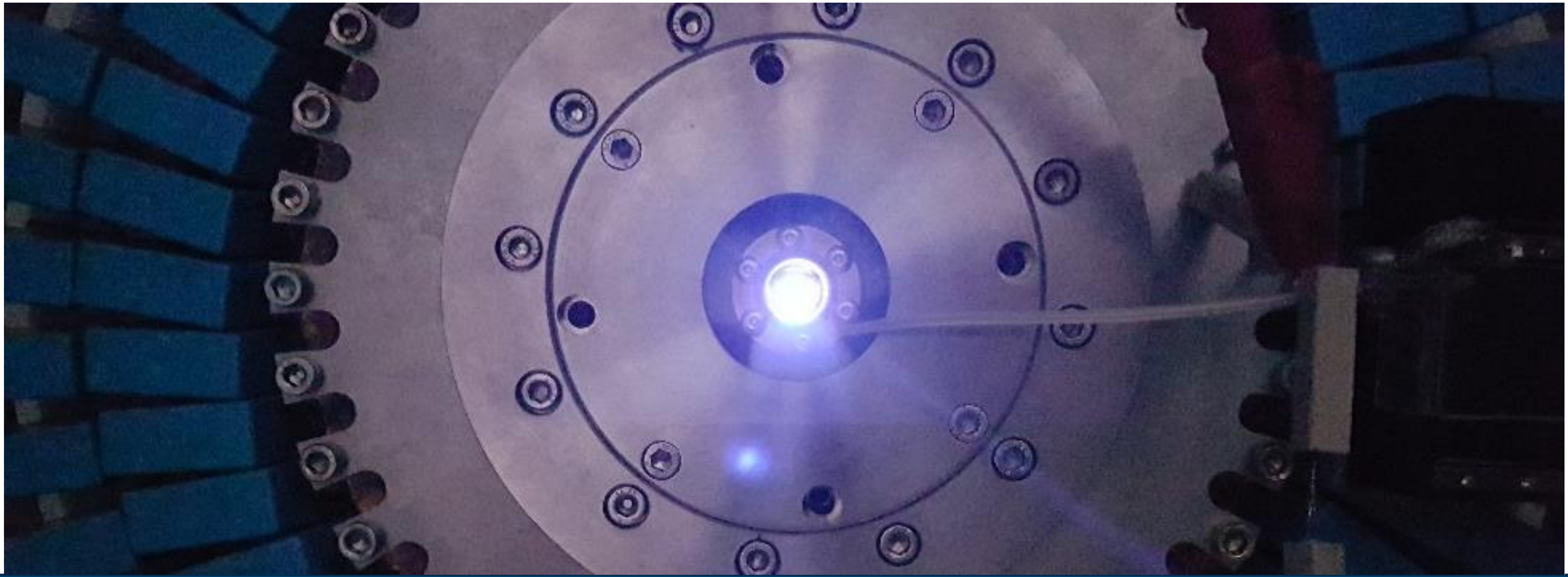


LASER HEATED DISCHARGE PLASMA

Increased EUV emission and change in plasma parameters

10 DECEMBER 2019 | FLORIAN MELSHEIMER

Detlev Grützmacher, Larissa Juschkin

RWTH Aachen University and Forschungszentrum Jülich

MOTIVATION

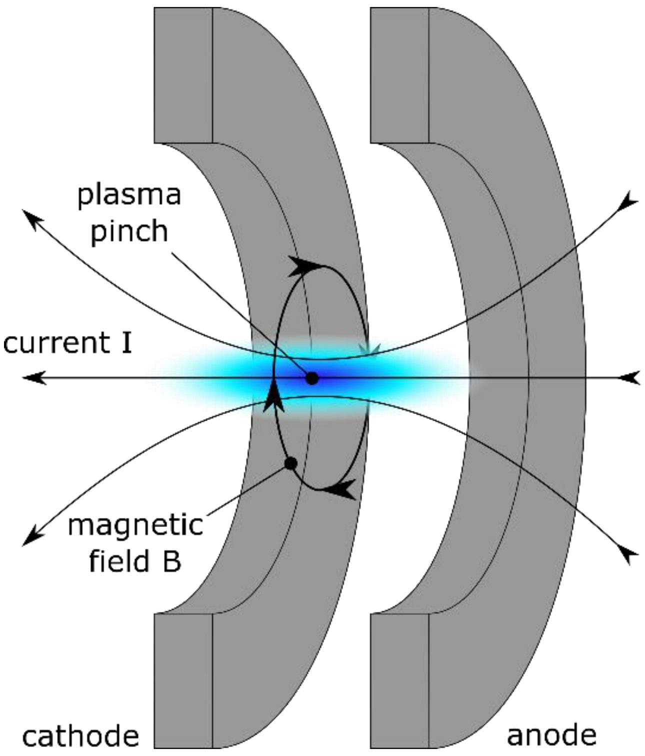
Discharge based EUV generation

Conventional gas discharge source

- Electric field ionized gas at low pressure
- Stored electric or magnetic energy is discharged through plasma
- Plasma compressed to a pinch confined by own magnetic field
- Hot pinch emits EUV (cooling)

Adjustable parameters:

- Gas type/pressure (flow)
- Discharge energy
- Geometry
- Electrical system



Conventional DPP EUV source

MOTIVATION

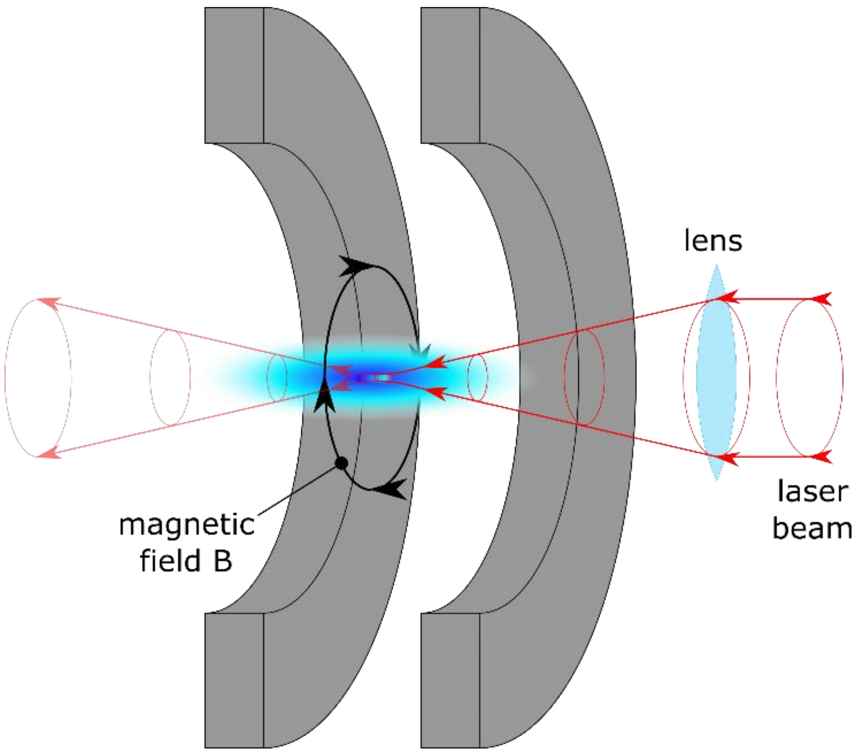
Discharge based EUV generation and laser heating

Laser heated discharge source

- Discharge source as target delivery system
- Compressed pinch as target
- Heating by laser pulse

Possible advantages:

- Restore energy loss from radiative cooling
- Prolong pulse duration
- Increase EUV output
- Stabilize discharge
- Higher radiance



Laser heated DPP EUV source

THEORY

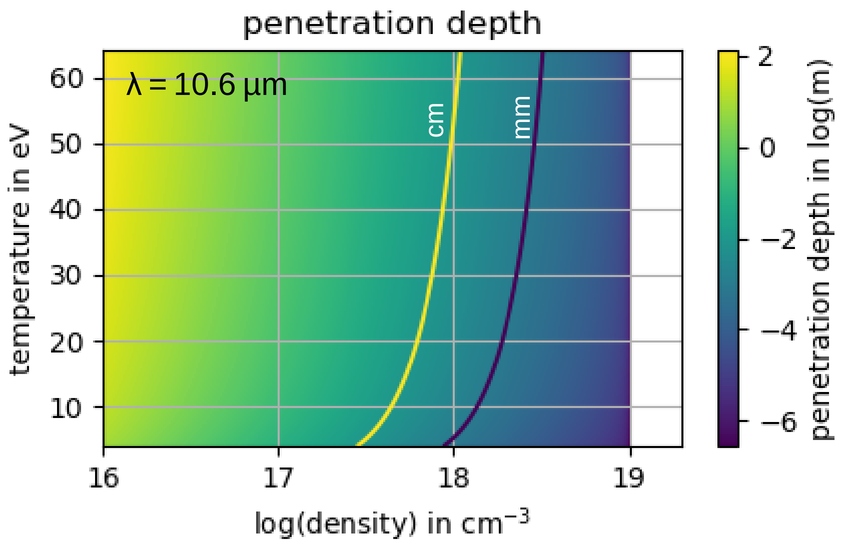
Laser plasma interaction

Inverse electron-ion bremsstrahlung

Absorption coefficient[1]:

$$\alpha \propto c_0 \frac{n_e^2}{n\omega_L^3} \cdot \sqrt{\frac{c_1}{T_e}} \cdot \left(1 - exp\left(-c_2 \frac{\omega_L}{T_e}\right)\right) \cdot \bar{g}$$

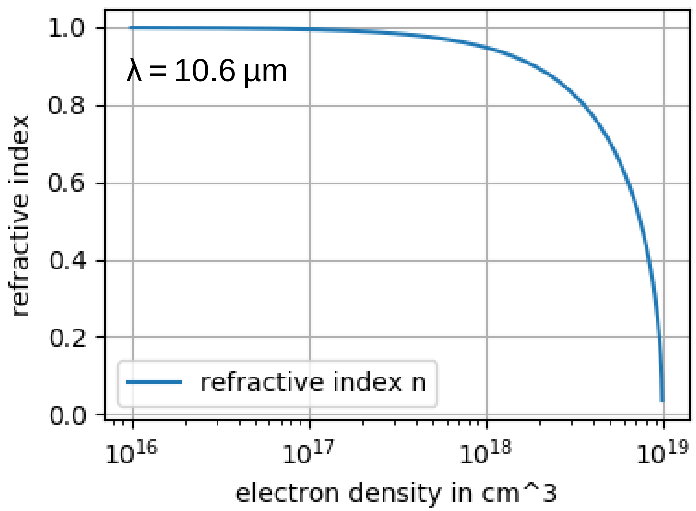
Gaunt factor: $\bar{g} \propto \sqrt{c_3 \frac{T_e}{\omega_L}}$



Refraction

Dielectric permittivity: $\varepsilon = 1 - \frac{\omega_P^2}{\omega_L^2} = n^2$

with $\omega_P = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$



[1] S. Brückner, S. Wieneke and W. Viöl, „Generation of Double Pulses in the Extreme Ultraviolet Spectral Range Using a Laser Combined Pinch Plasma Source", The Open Plasma Physics Journal, 2009, 2, 17-23

EXPERIMENTAL SETUP

Laser heated discharge source

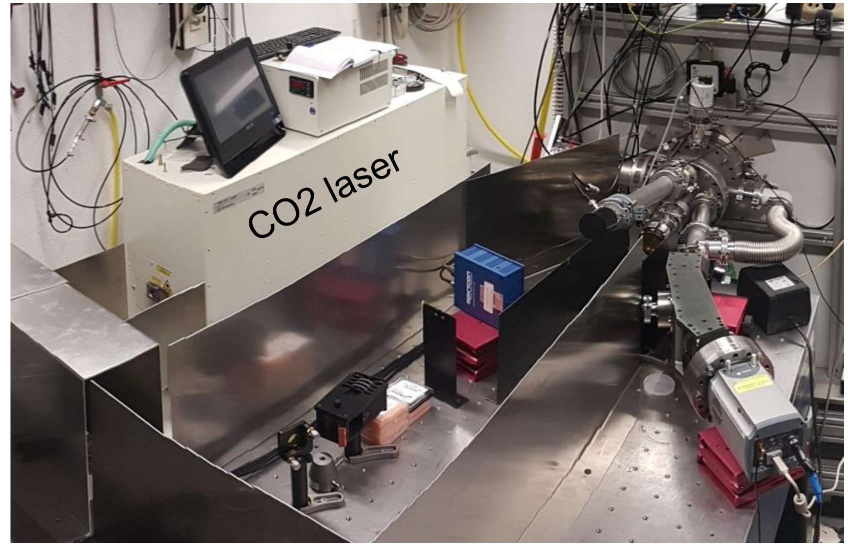
Gas discharge source

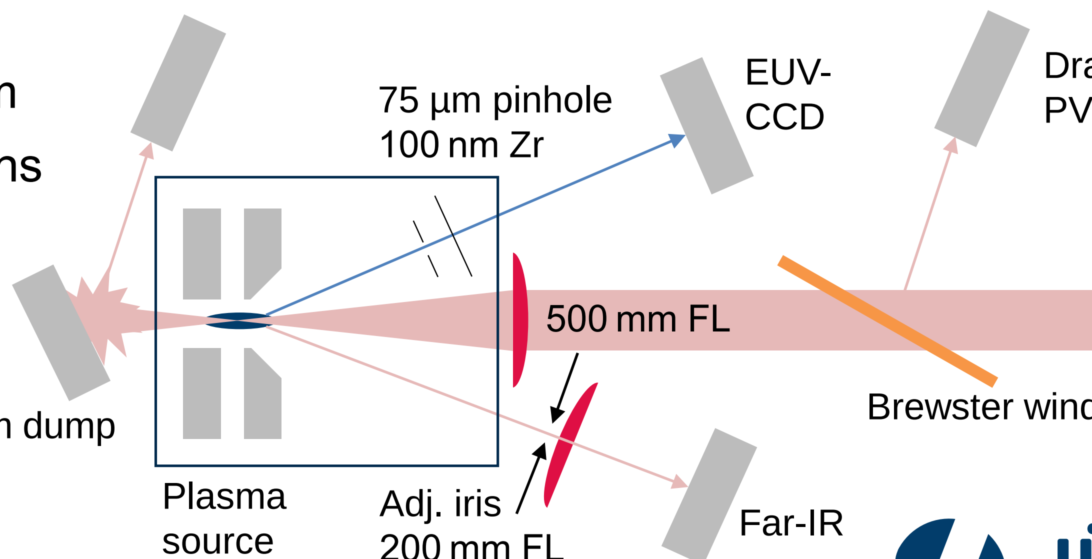
- Voltage: 2 kV
- Energy: 2.2 J
- Pulse duration 100 ns
- Gases: Xe, Ar, O_2, N_2

CO_2 -TEA Laser

- Wavelength: 10.6 µm
- Pulse duration: 100 ns
- Energy <1 J/pulse

→Courtesy of ASML





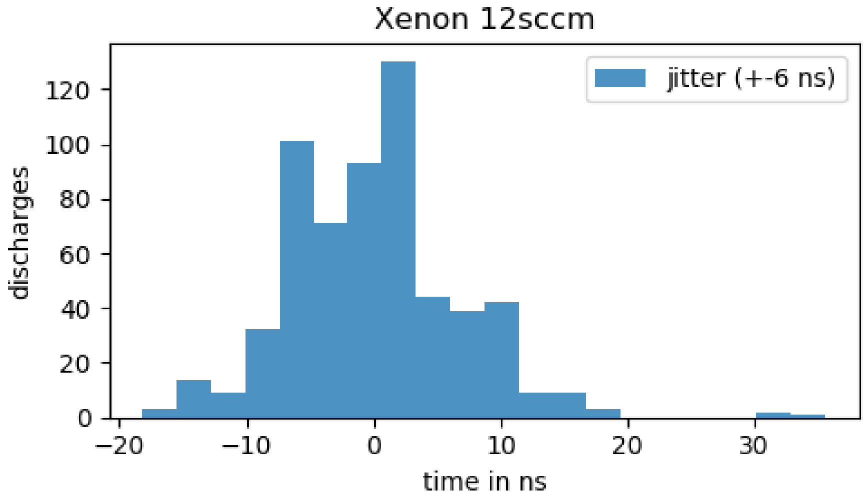
EXPERIMENTAL SETUP

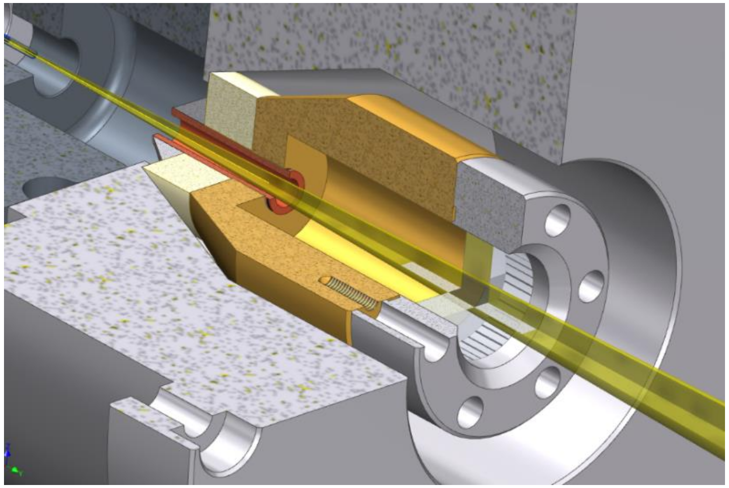
Custom trigger design

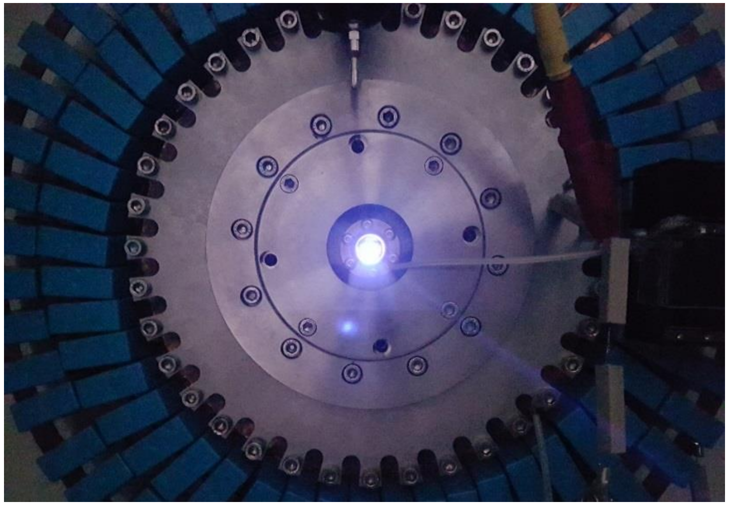
- Special hollow cathode trigger to enable outcoupling of laser beam
- Blocking potential

  → Inhibits discharge at high gas flow
- Active flashover ignition

  → Very low jitter of discharge timing (<10 ns)

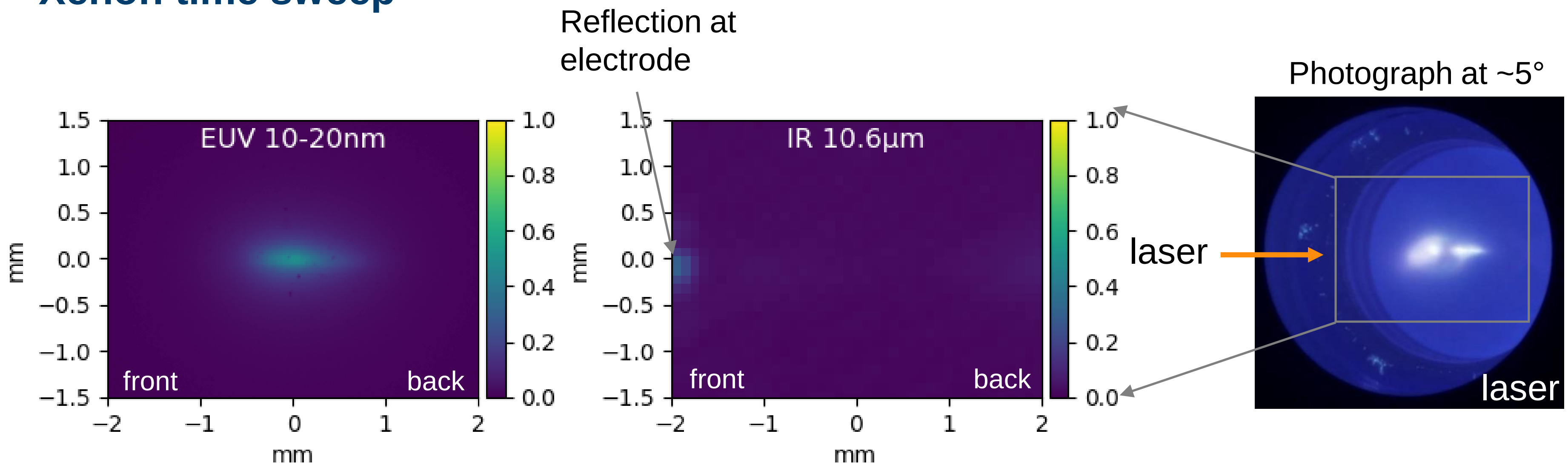


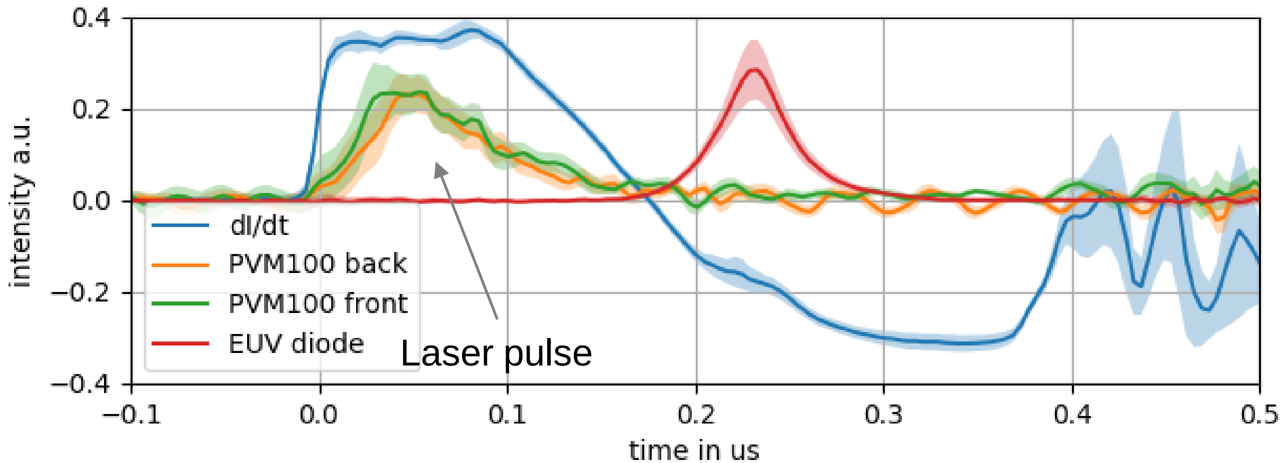




PINHOLE IMAGES

Xenon time sweep

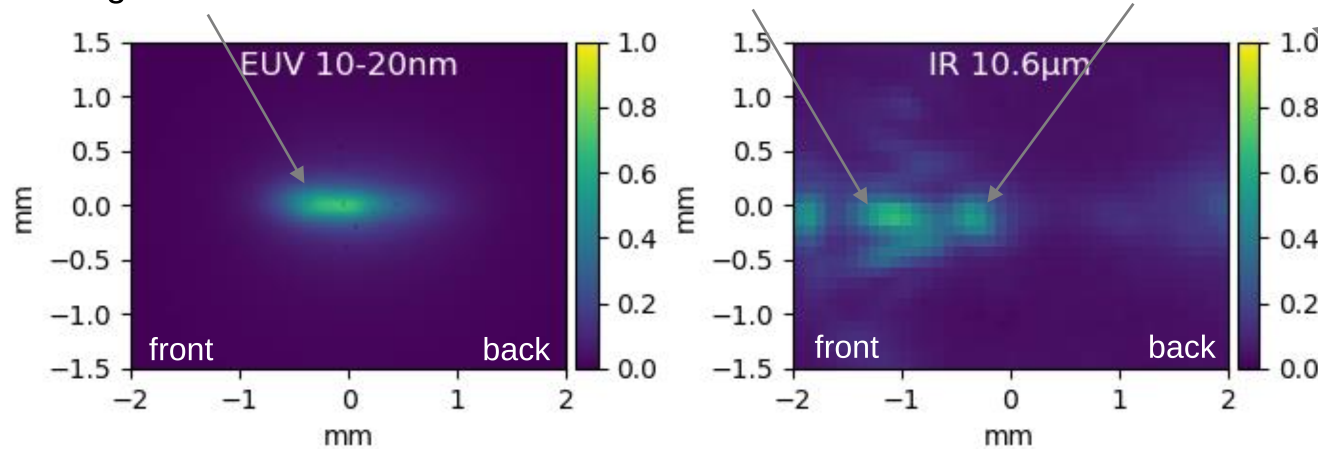




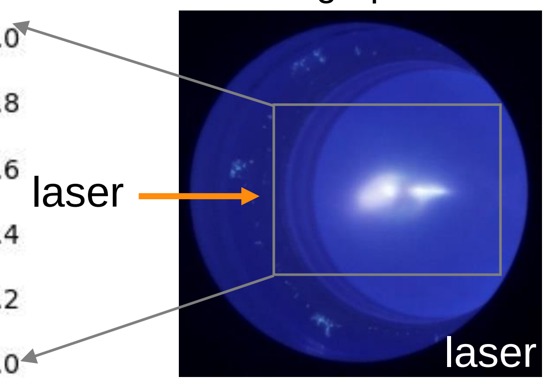
- Xenon 10 sccm at 2 kV
- 600 mJ laser pulse
- 100 shot average
- Viewing angle 13°

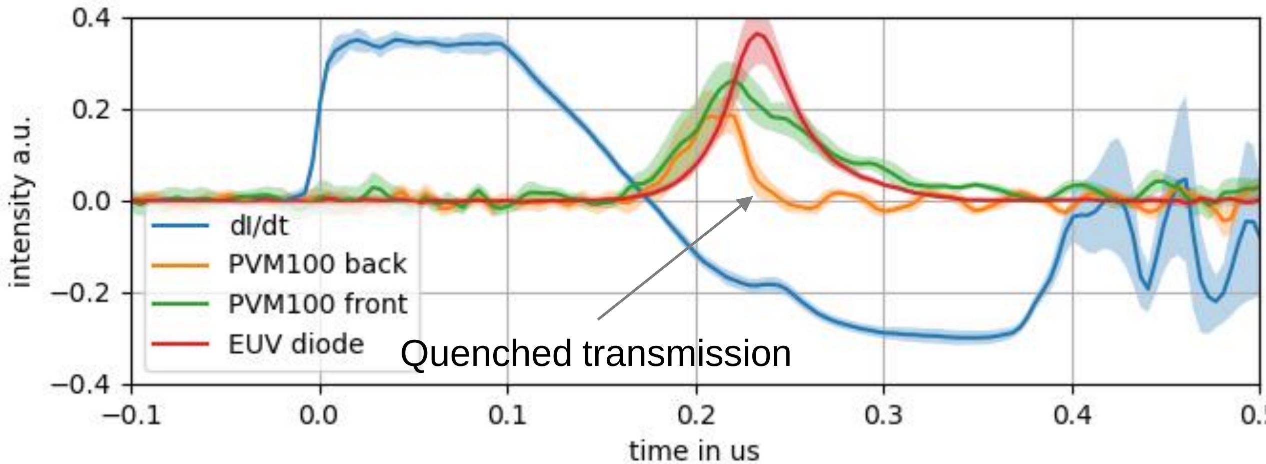
PINHOLE IMAGES

Xenon time sweep



Photograph at ~5°





- Xenon 10 sccm at 2 kV
- 600 mJ laser pulse
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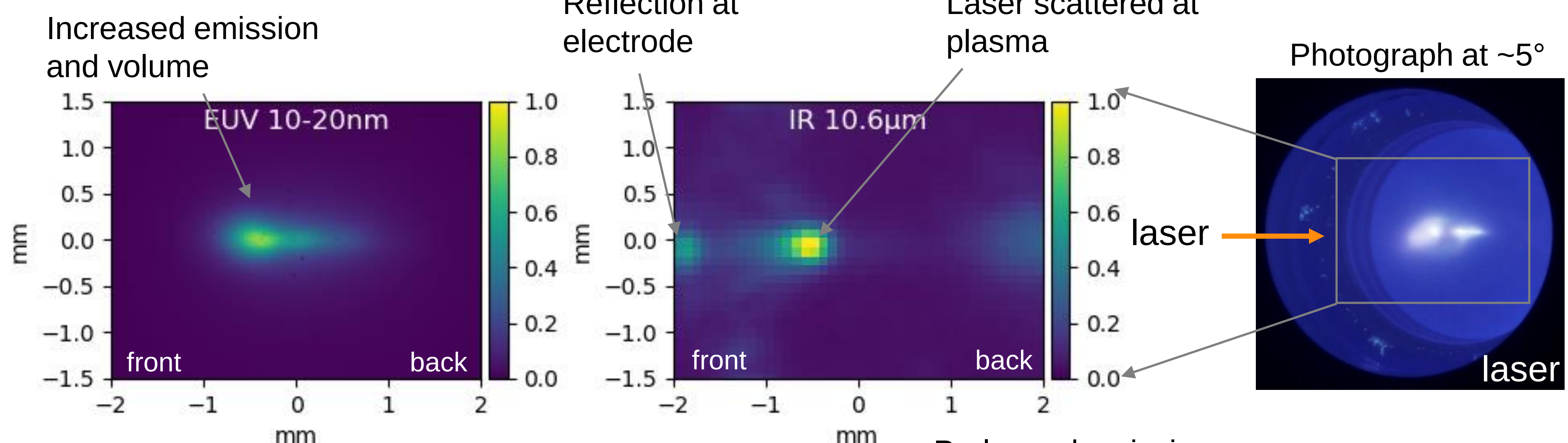
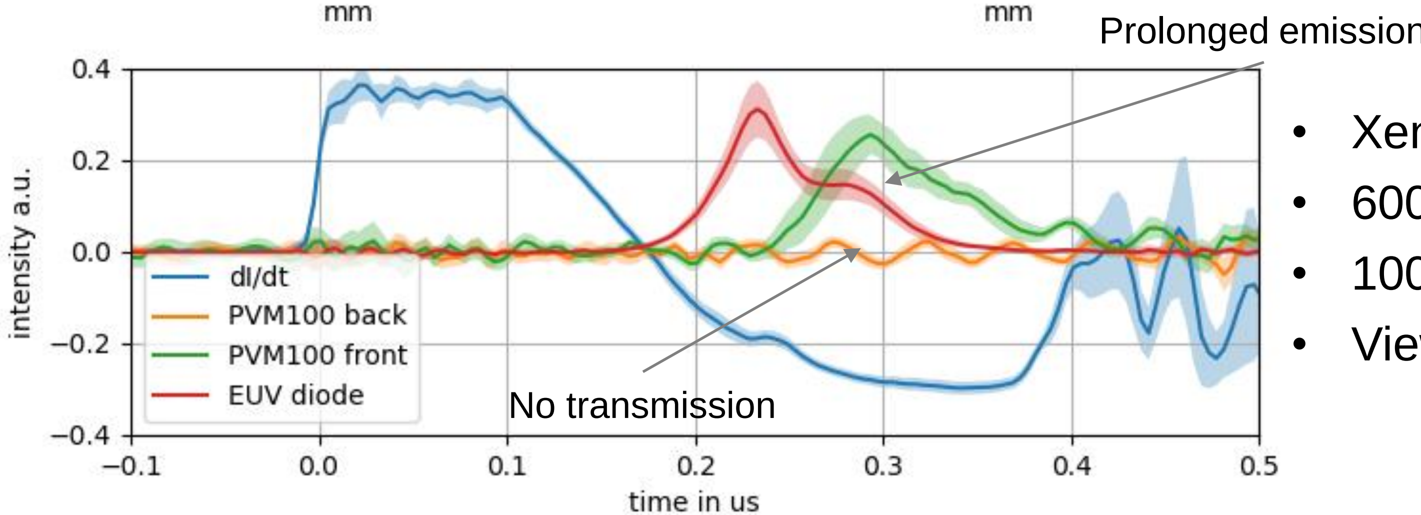
- Viewing angle 13°

PINHOLE IMAGES

Xenon time sweep





- Xenon 10 sccm at 2 kV
- 600 mJ laser pulse
- 100 shot average
- Viewing angle 13°

PINHOLE IMAGES

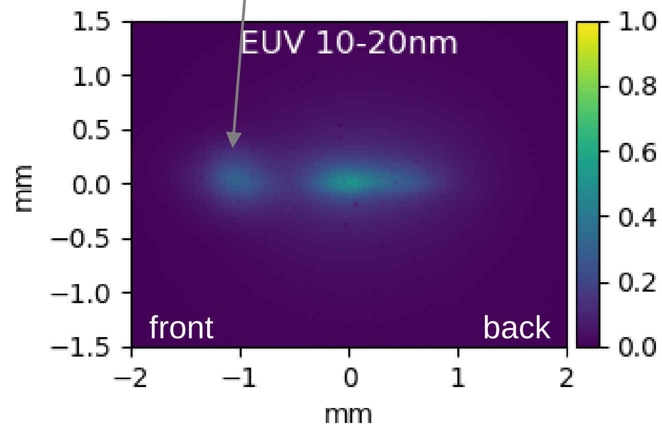
Xenon time sweep

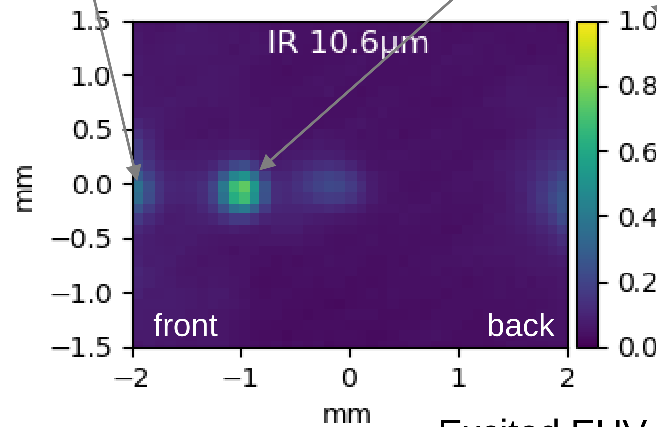
Excited EUV emission

Reflection at electrode

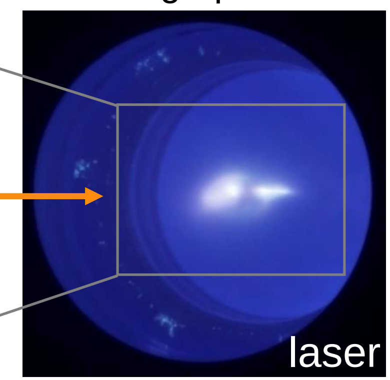
Laser scattered at excited emission

Photograph at ~5°

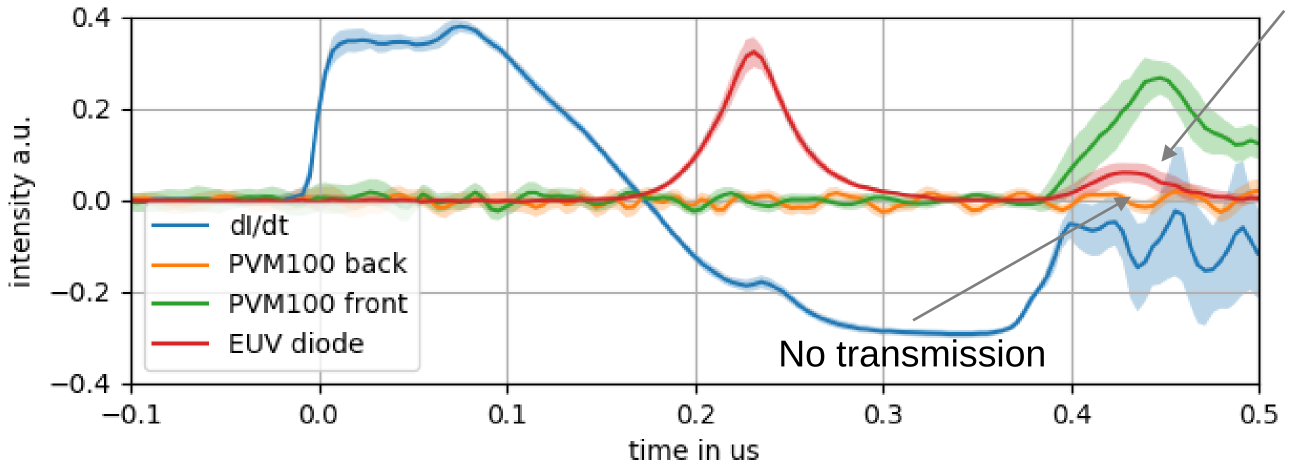




laser



Excited EUV emission



- Xenon 10 sccm at 2 kV
- 600 mJ laser pulse
- 100 shot average
- Viewing angle 13°

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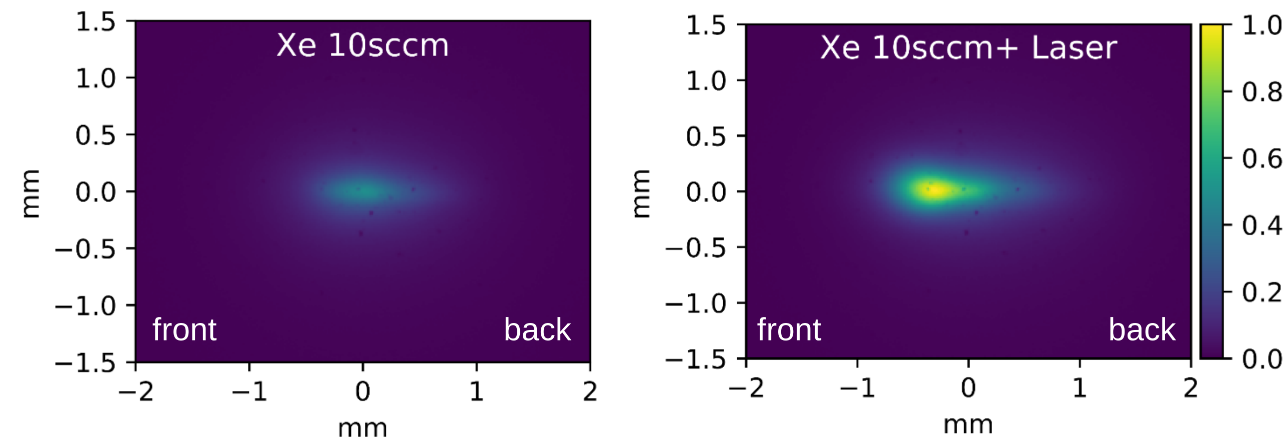
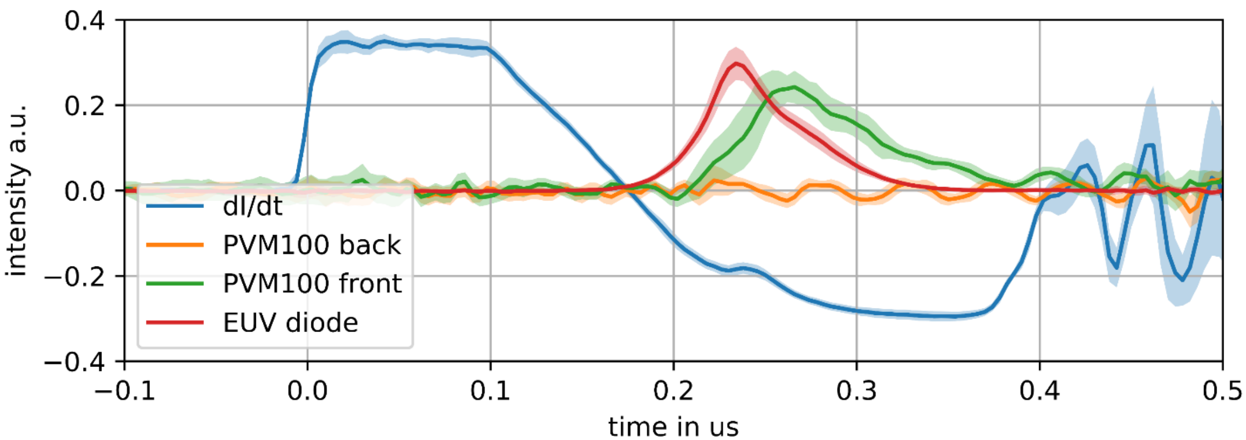
PINHOLE IMAGES

Strongest effect in Xenon





- Xe 10 sccm at 2 kV
- 600 mJ laser pulse
- 100 shot average
- Viewing angle 13°

✓ >2x peak intensity

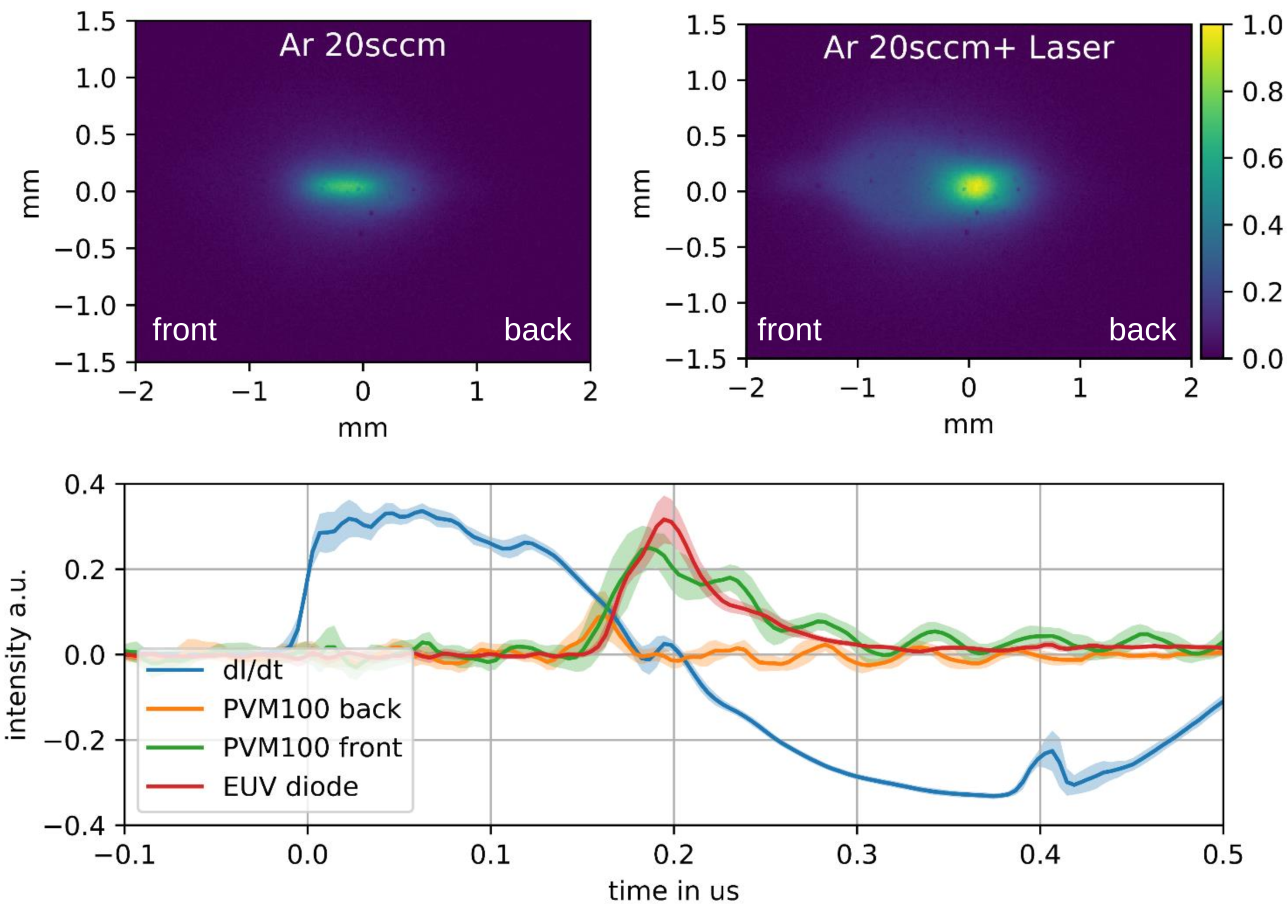
✓ Increased emission volume

✓ Prolonged pulse

✓ No transmission of laser pulse

PINHOLE IMAGES

Strongest effect in Argon



- Ar 20 sccm at 2 kV
- 600 mJ laser pulse
- 100 shot average
- Viewing angle 13°

✓ ~2x peak intensity

✓ Increased emission volume

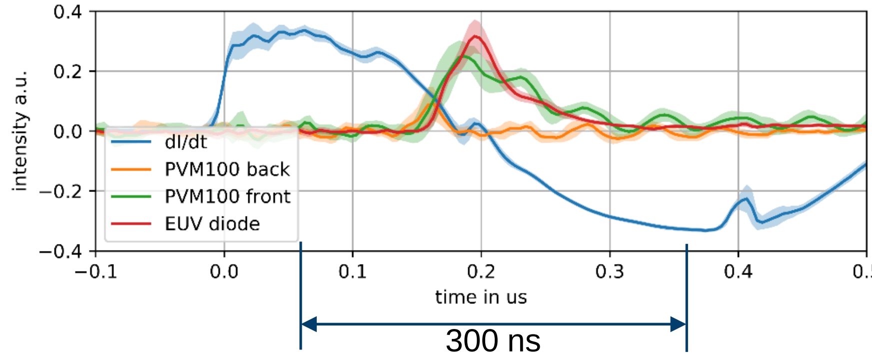
✓ Prolonged pulse

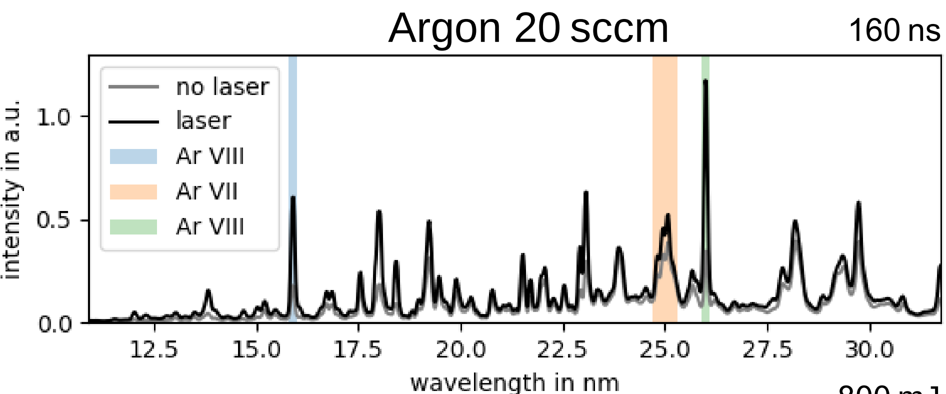
✓ No transmission of laser pulse

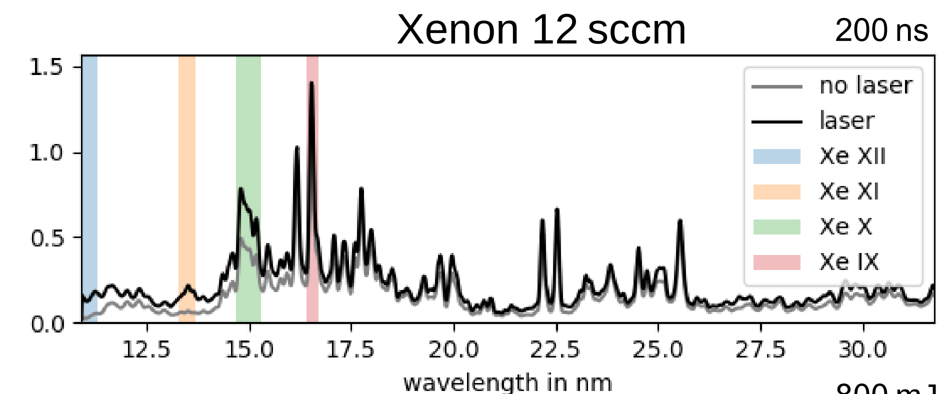
SPECTRA

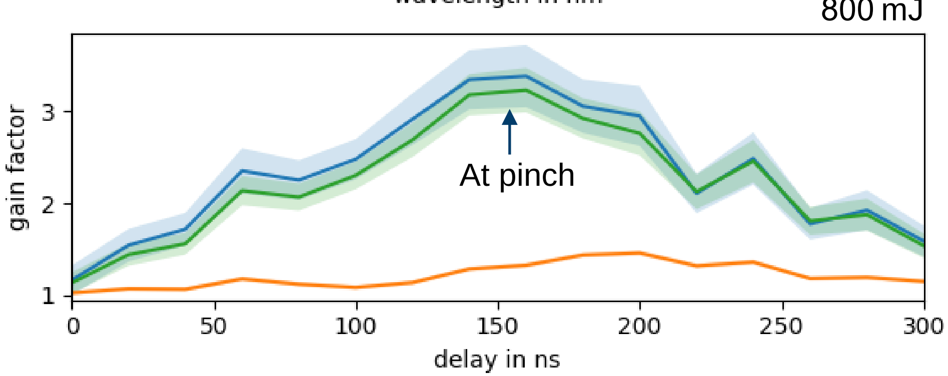
Influence of synchronization

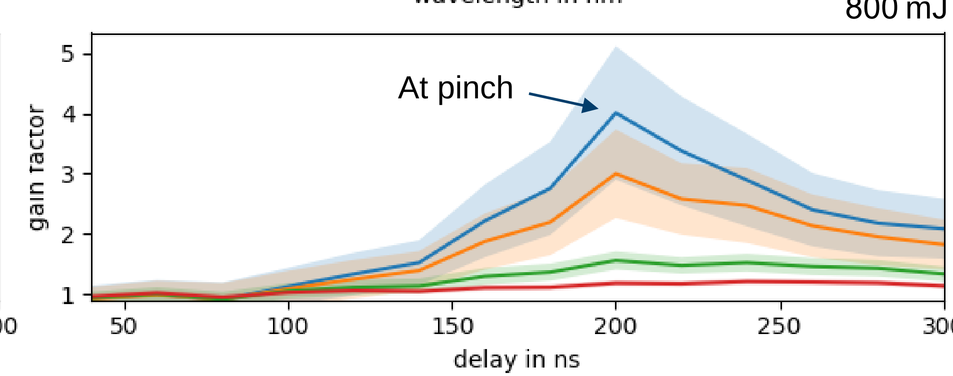
- Higher ionization levels show more gain
- Later timing affects lower levels more
- Maximum when synched to pinch







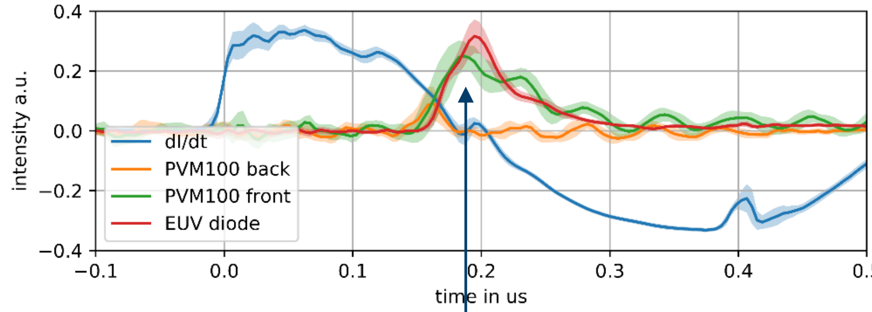




SPECTRA

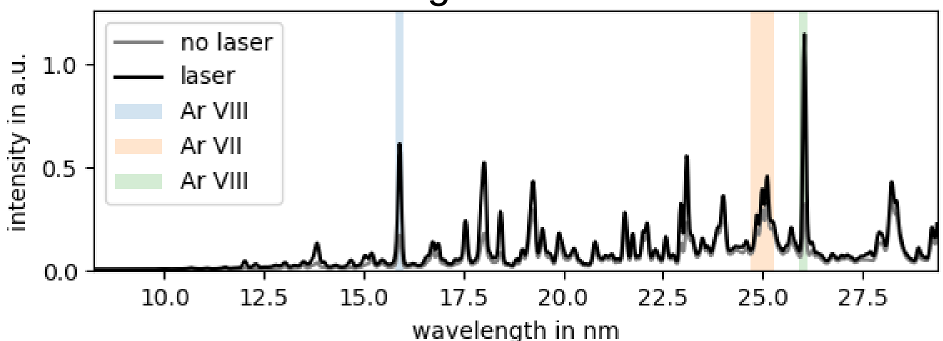
Influence of laser pulse energy

- Laser pulse energy at 100% = 800 mJ
- Synched to pinch
- Gain saturates differently for different ion. levels

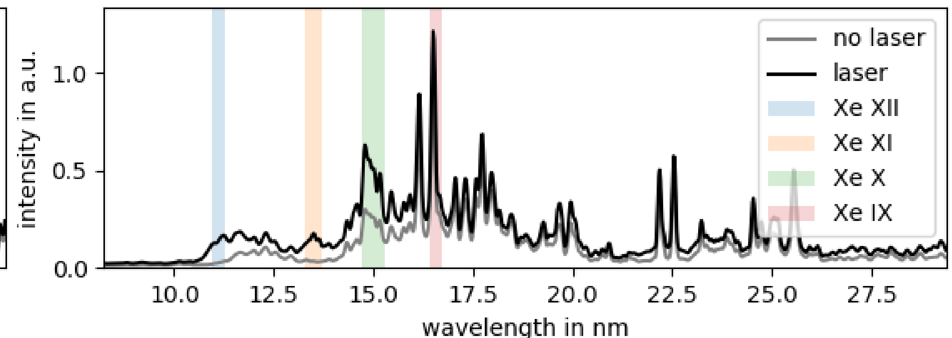


Synched to pinch

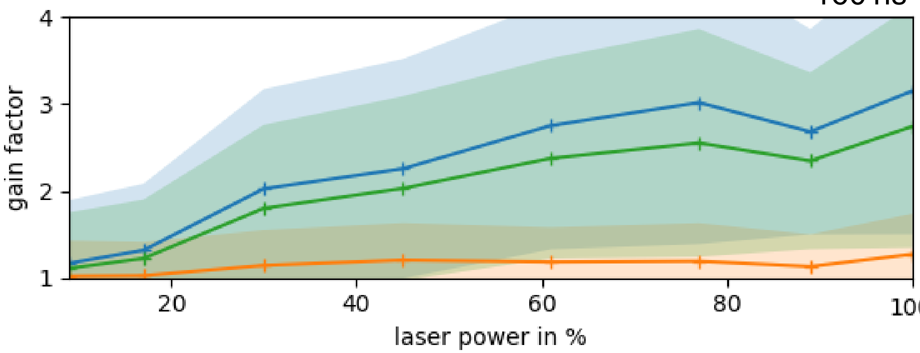
Argon 20 sccm 800 mJ



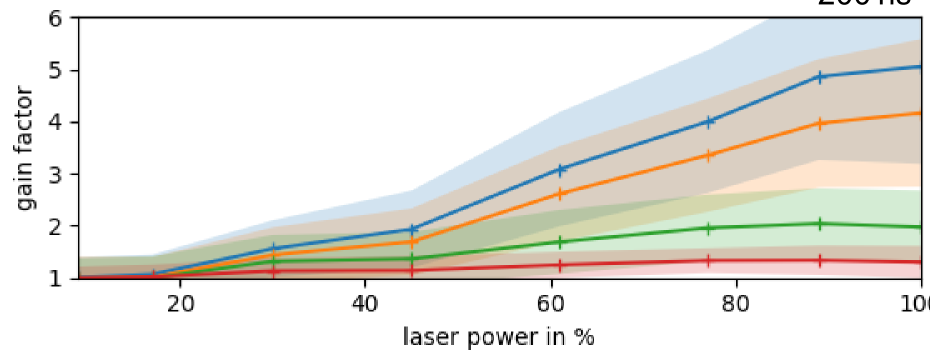
Xenon 12 sccm 800 mJ



160 ns



200 ns



PINCH PROFILE – XENON

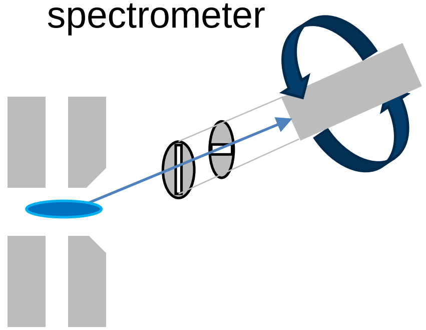
Tomographic reconstruction

- 3d-reconstruction exploits rotational symmetry
- Input: Spatially resolved spectra at different angles

Result:

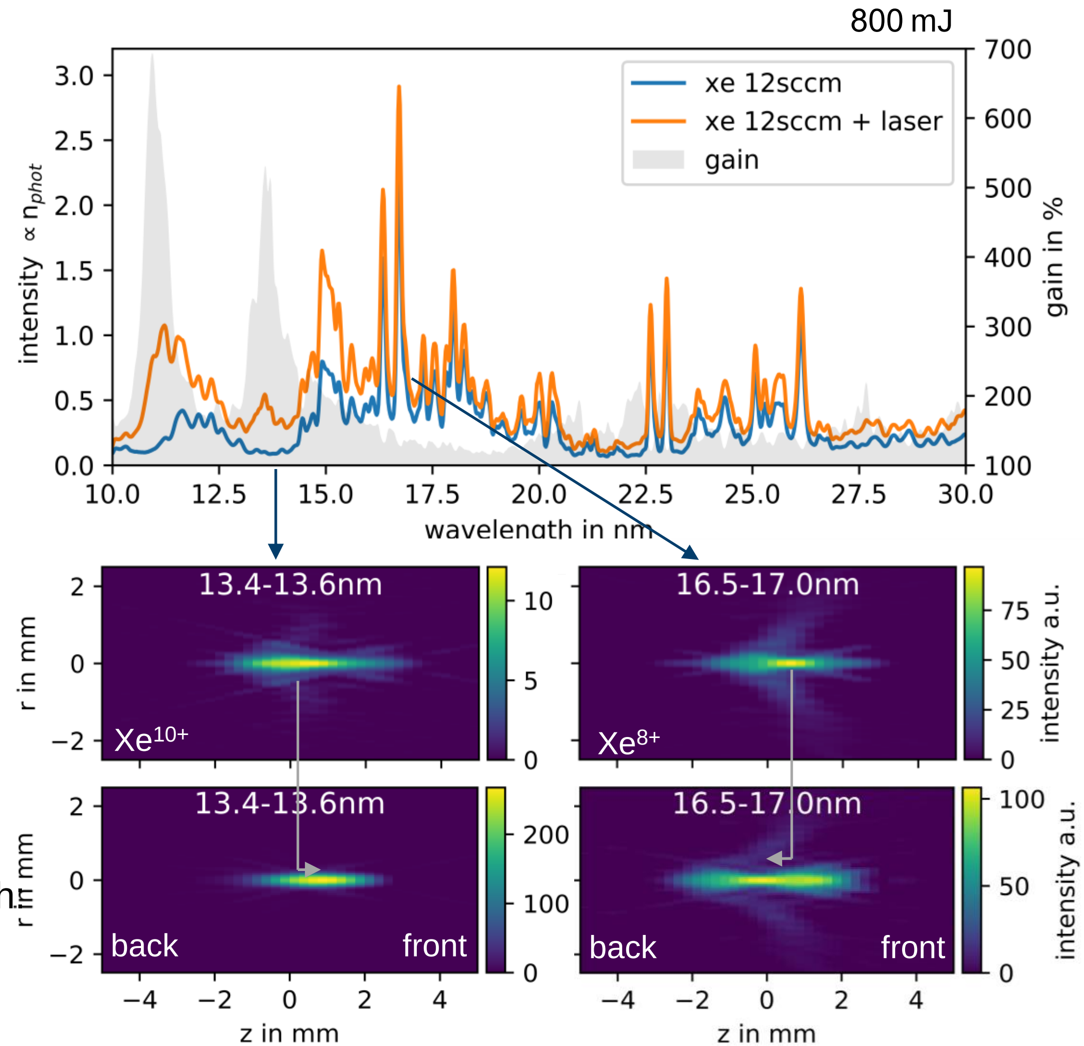
- RZ-profile of plasma at arbitrary wavelength
- Xe^{10+} moves to front
- Xe^{8+} shifts back

Rotatable spectrometer



No laser:

Laser 800 mJ synced to pinch



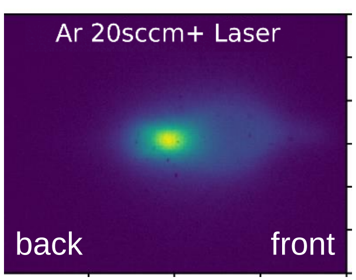
PINCH PROFILE – ARGON

Tomographic reconstruction

- 3d-reconstruction exploits rotational symmetry
- Input: Spatially resolved spectra at different angles

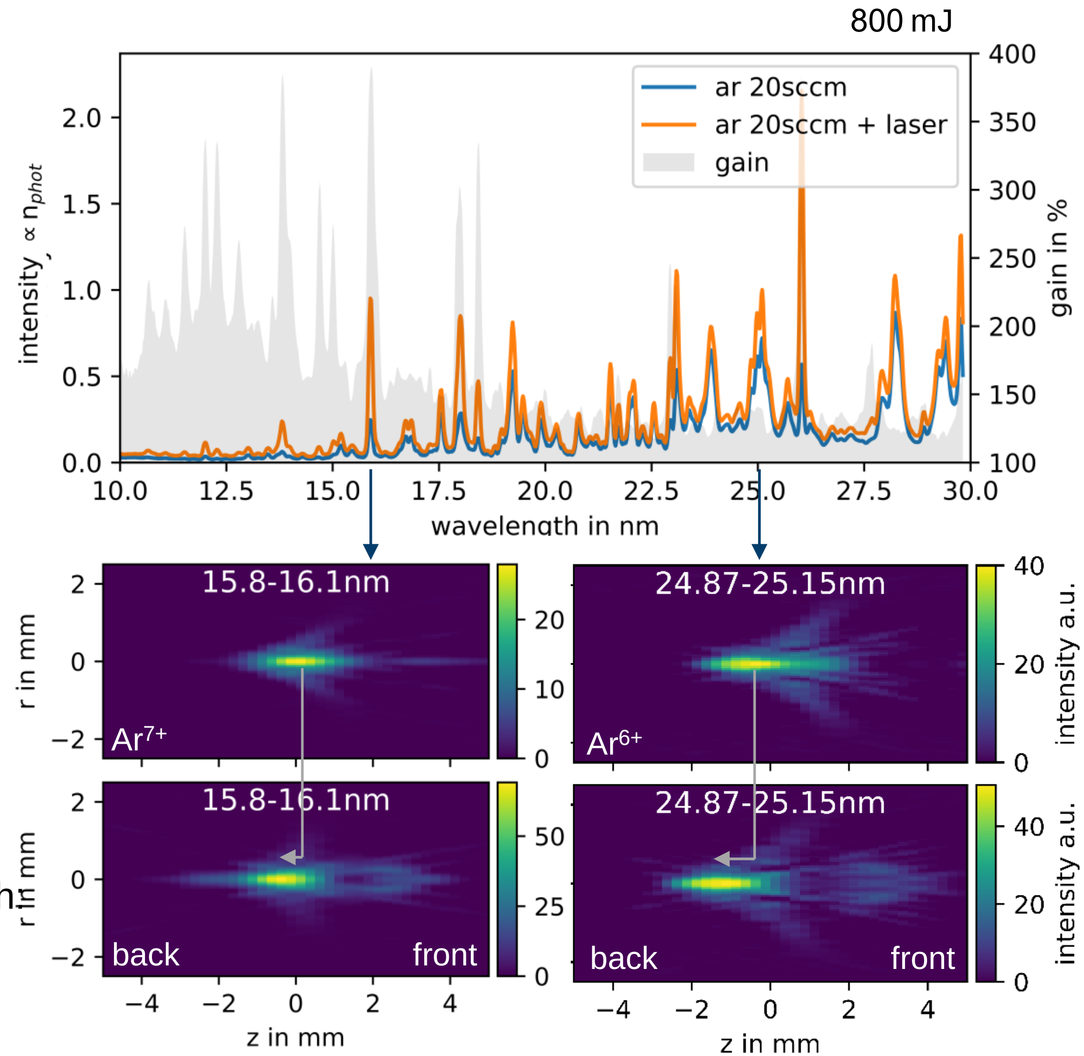
Result:

- RZ-profile of plasma at arbitrary wavelength
- Expanded emission region at front as seen in pinhole images



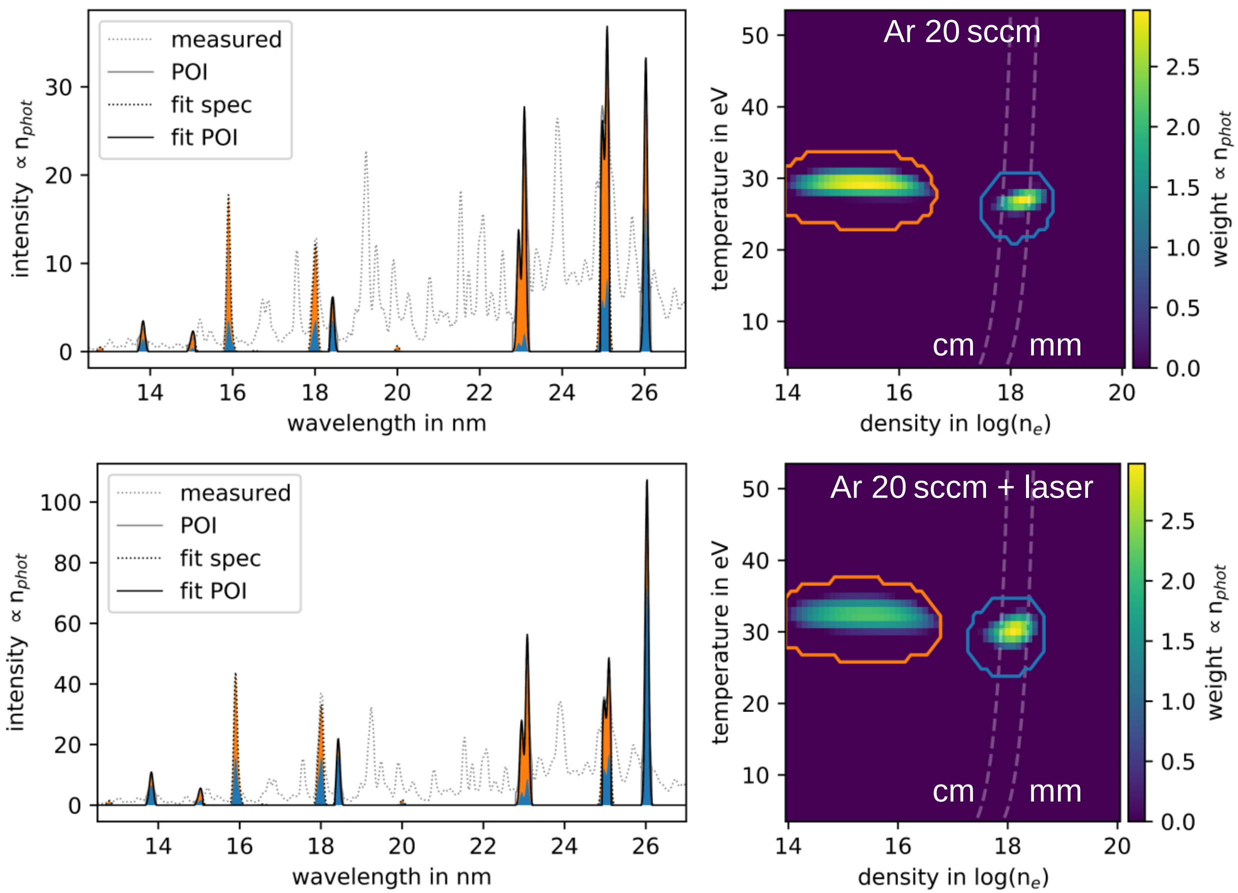
No laser:

Laser 800 mJ synced to pinch



PLASMA PROPERTIES

Temperature and density analysis for Argon



- Regularized linear least squares fit of selected peaks (POI)
- Resonance peaks ignored → self absorption/opacity
- Composition sensitive
- Plasma physics computations beforehand, not at runtime → fast
- Based on ChiantiPy

<u>Ar at 20 sccm</u>

✓ Reaches optimum density for laser absorption (|)

✓ Background pressure resolved (|)

✓ ~3 eV temp. increase

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FDTD-SIMULATION

Laser absorption and refraction

- 2d-finite difference time domain simulation with MEEP
- Absorption coefficient from inverse electron-ion bremsstrahlung
- Re[ε] from electron density (plasma frequency)
- $n_{e\,max} = 10^{18.3}\ cm^{-3}$, T_e = 30 eV

<u>Result:</u>

→ Energy absorbed at front

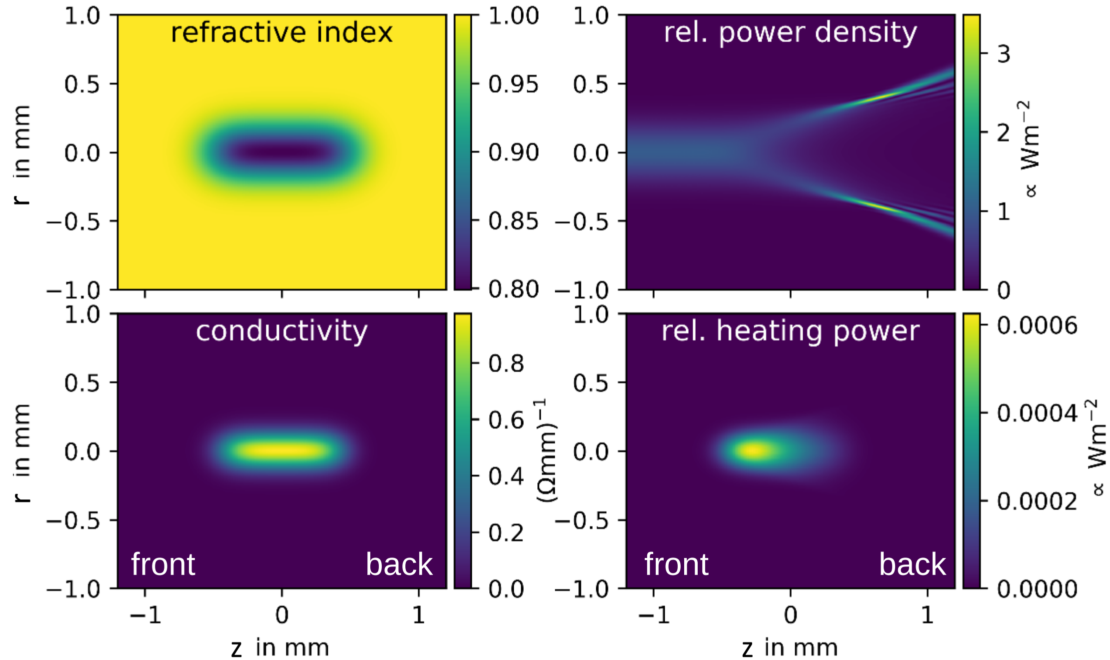
→ Laser is refracted by plasma

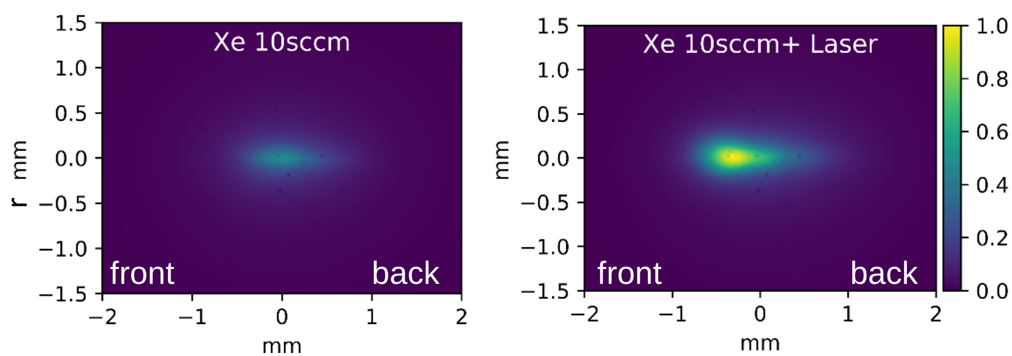
<u>Experiment</u>:

✓ Front part of pinch is heated

✓ Back part is unaffected

✓ No transmission observed, even with under-dense plasma





SUMMARY AND OUTLOOK

Laser heating

- ✓ Increases EUV output (up to 700%)
- ✓ Hotter plasma (~3 eV)
- ✓ Increased brightness and emission volume
- ✓ Reheating possible (2^{nd} emission peak)
- ✓ Bonus: Low jitter trigger

Metrology

- ✓ Fast composition sensitive T_e and n_e fit
- ✓ Spectrally resolved tomographic plasma imaging
- ✓ FDTD-simulation of laser absorption in plasma

Outlook

- Tomographic results for T_e and n_e analysis
  → spatial temperature and density map
- FDTD-simulation with determined density and temperature distribution
- Conversion efficiency from energy calibrated spectra

ACKNOWLEDGEMENT

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Thank you!

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