# Investigation on ablation phenomena in capillary discharge produced plasmas for XUV radiation by time-resolved imaging

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# Contents

- Introduction
- Advantages to use of the ceramic capillaries.
- Experimental set-up.
- On axis plasma images.
  - In visible (440 – 460 nm).
  - UV range (299 – 309 nm).
  - XUV range (without and with Zr filter).
- Conclusion: The two different mechanism of the plasma formation.
- Ongoing work.

# Introduction

- Earlier studies indicated[1,2] that taking into account ablation of the plastic capillary is necessary for explanation of the stabilizing effect and the correct description of the pinch dynamics.

[1] Shlyaptsev *et al*.: In proc. SPIE **2520** (1995) 365-373.

[2] Nemirovsky A. *Et al*.: Phys. Rev. Let. **82** (1999) 3436-3439.

[3] Bobrova N.A. *Et al*.: Plasma phys. Reps. **26** (2000) 12-23.

- Recently it was shown[4] that the pinch is stable and homogenous also in ceramic channels whose ablation is negligible in comparison of plastic capillaries.

[4] Rocca *et al*.:Opt. Lett. **24** (1999) 1115-1119.

- For better understanding of the mechanism of the plasma formation and to provide some input data for the simulation of the discharge dynamics and pinching effect in ceramic capillaries the ablation phenomena in capillary discharge produced plasmas for XUV radiation was investigated experimentally, utilizing time-resolved on-axis imaging of the plasma column.

# Ceramic Capillaries

Main advantages:

- gas filled Z-pinches
  - stable
  - instability and pollution free
  - longer lifetime

Field of use:

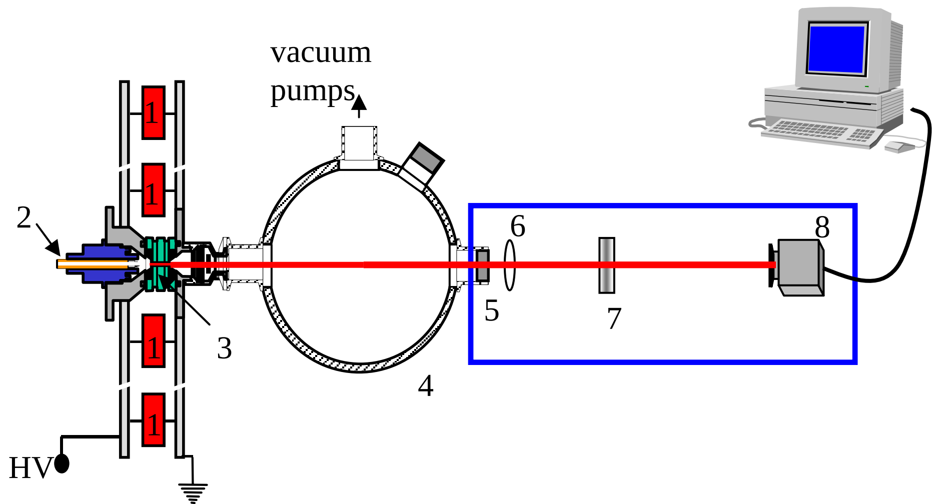
- capillary discharge pumped soft x-ray lasers
- incoherent sources (EUV lithography)
- plasma waveguides

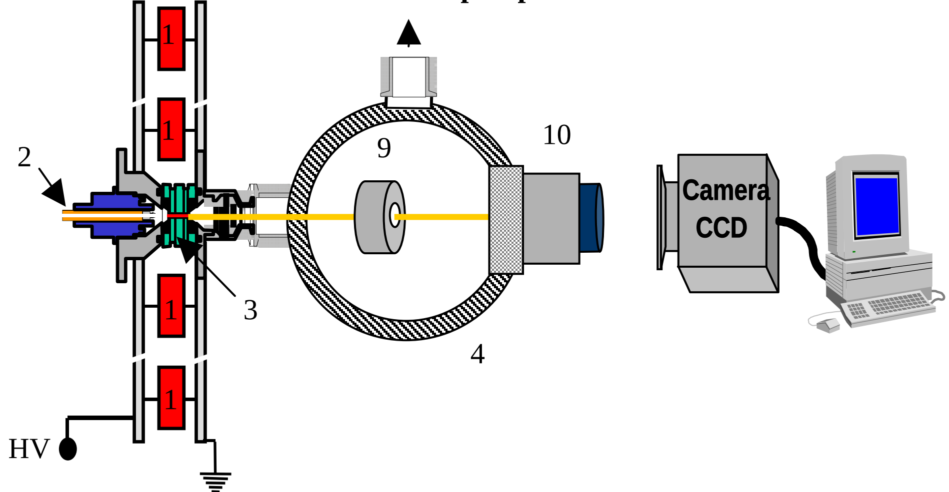
Remark:

In the case of gas-filled sources using recombination schemes the advantages are not evident[5].

[5] T. Boboc et al.: Appl. Phys. B **70** (2000) 399-405.

# Experimental Setup[6]




- 1:Knob capacitors
- 2:Axial view
- 3:Alumina $Al_2O_3$ capillary
- 4:Detection chamber
- 5:$MgF_2$ window
- 6:Focusing lens
- 7:Filter
- 8:ICCD camera
- 9:Pinhole
- 10:Gated MCP

-temporal resolution
~ 10 ns

[6] Mohanty S.R. *et al*.: Microelectronic Engineering 65 (2003) 47-59.

# Parameters of the discharge

Current pulses: up to 10 kA

Current slope: ~ $10^{11}$ A $s^{-1}$

Capillary:

$\phi$: 1 mm

length: 10 mm

Gas pressure range 0.5 – 2.5 mbar

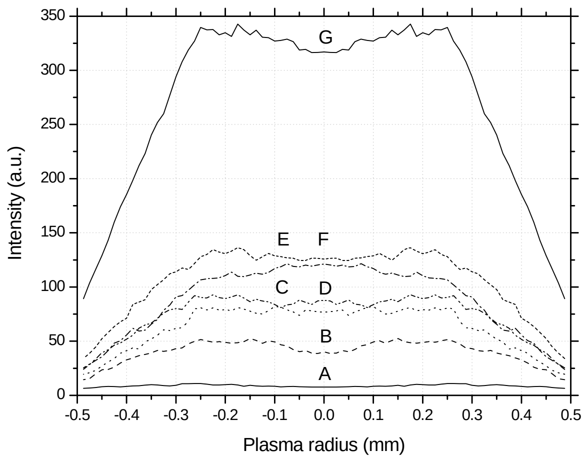
Energy densities W reached inside the capillary channel: up to ~ 650 J $cm^{-3}$ (for 22 kV charging voltage).

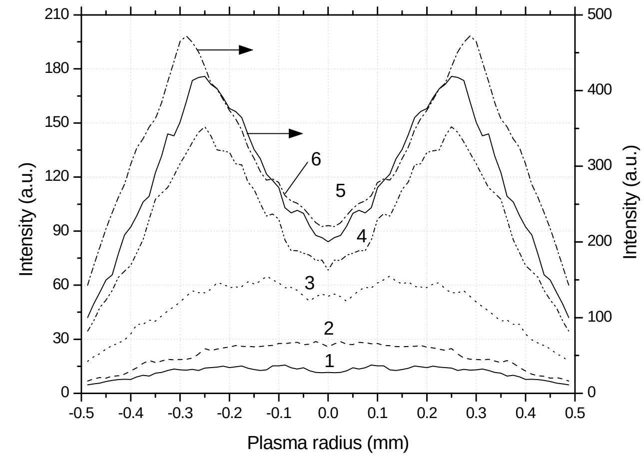
$W=E/V$, $E=1/2\ C\ U^2$

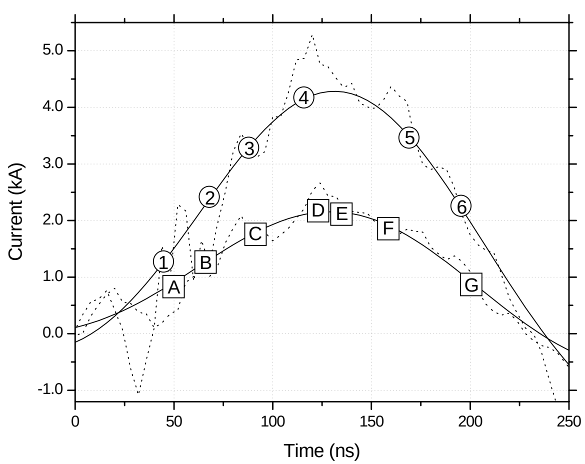
# Measurements in visible

-filter with a peak transmissivity of 50% at 450 ±10 nm.

-He filled capillary at a pressure of 2 mbar.



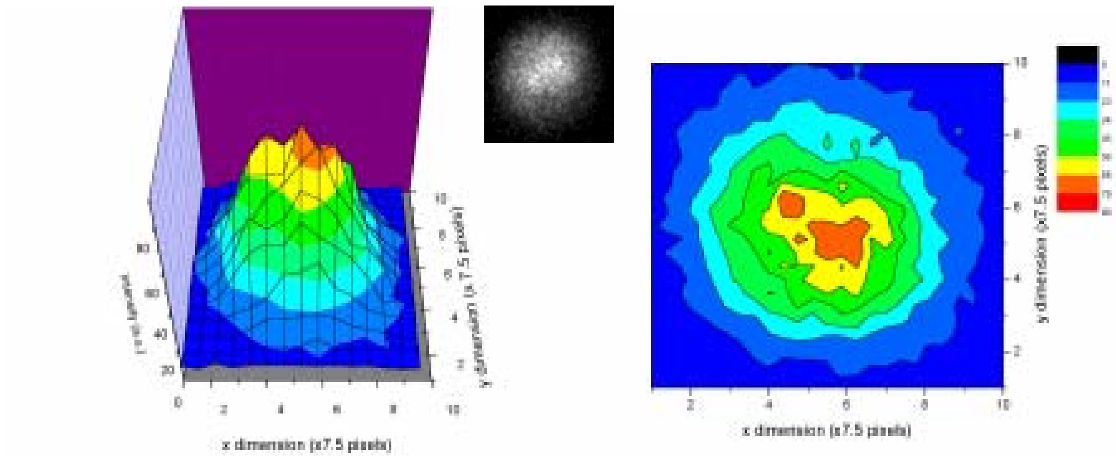

-different intensity distribution for the two regimes (W=220 J/cm$^3$ and W=405 J/cm$^3$).

-strong Al II lines and O lines in this spectral range.

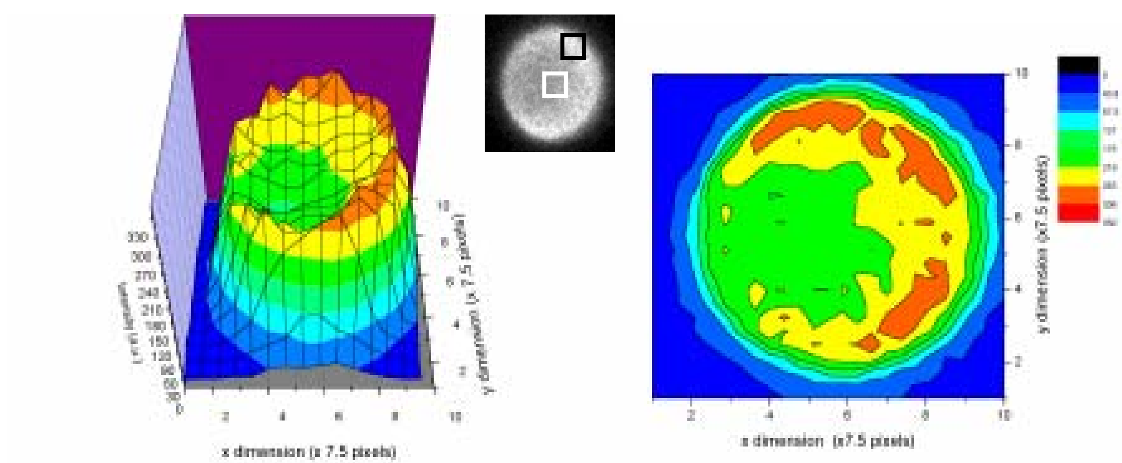
-more intense emission on the later stage of the discharge.

# UV measurements

-filter with a peak transmissivity of ~15% at 309 ±10 nm.
-He filled capillary at a pressure of 2 mbar.

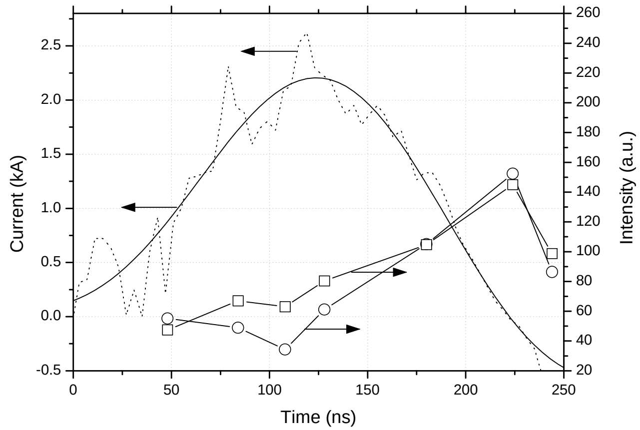



W ~ 220 J cm$^{-3}$
Image taken ~100 ns after starting the current pulse.

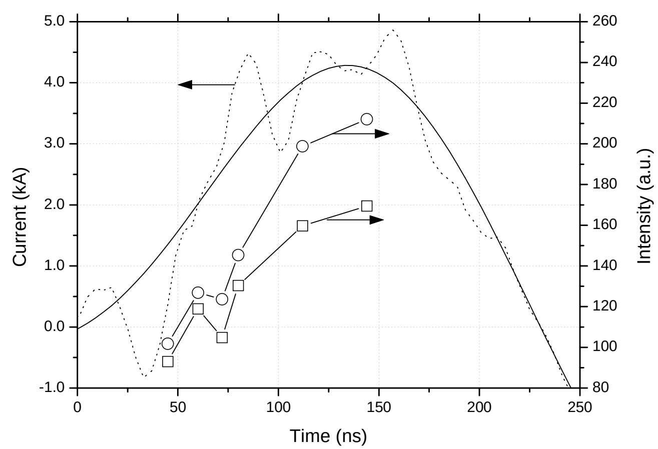



W ~ 405 J cm$^{-3}$
Image taken ~110 ns after starting the current pulse.

# UV measurements




-"non-ablative" regime,
W ~ 220 J cm$^{-3}$.
-the intensity of the emitted radiation is higher in the middle of the capillary (on the earlier stage of the discharge)



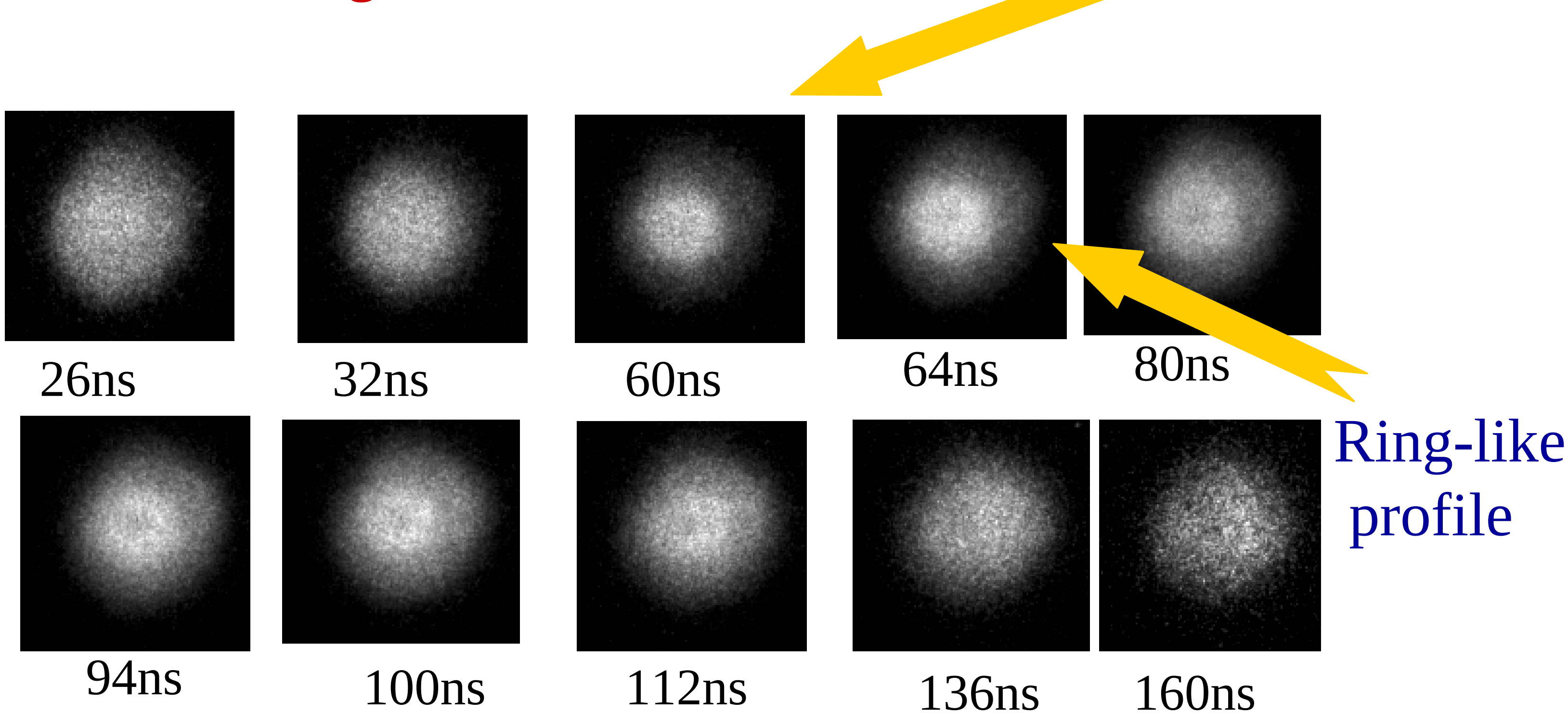

-"ablative" regime
W ~ 405 J cm$^{-3}$.
-strong Al II lines and O lines in this spectral range.
-more intense emission on the later stage of the discharge.

# XUV measurements

-Emission of the plasma column in the range 10-200 nm (MCP without filter)

-Xe filled capillary, pressure 2 mbar.

- “Ablative regime” W ~ 611 J cm$^{-3}$.

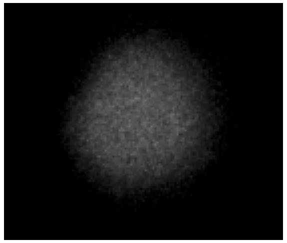


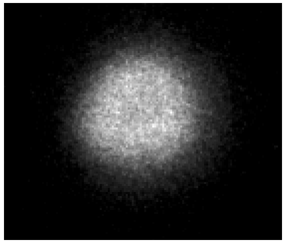
# XUV measurements

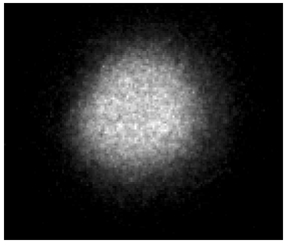
-Emission of the plasma column in the range 10-18 nm (MCP + Zr filter)

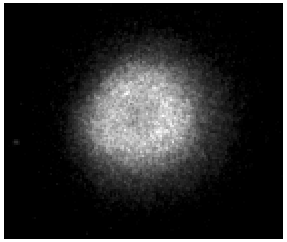
-Xe filled capillary, pressure 2 mbar.

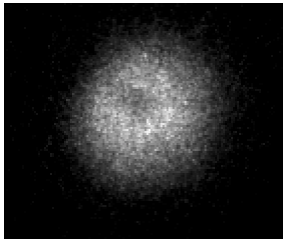
- “Ablative regime” W ~ 611 J $cm^{-3}$.

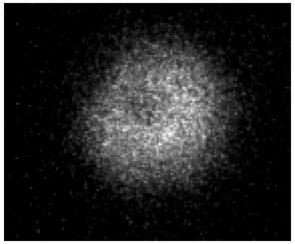

30ns


46ns


50ns


58ns


98ns

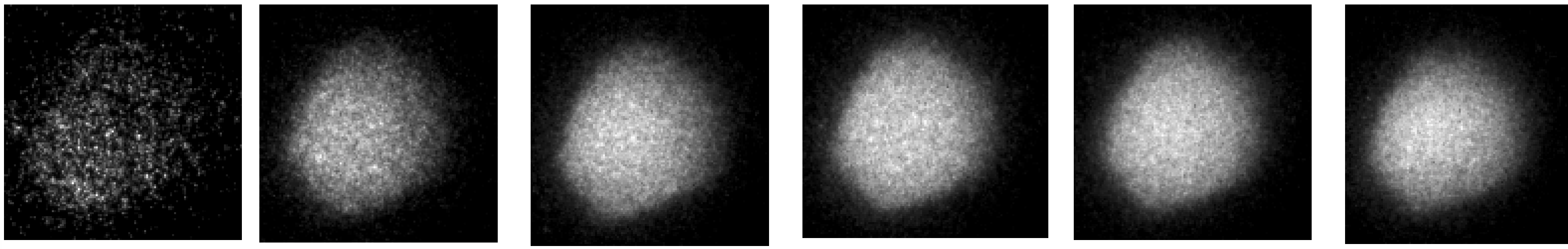

116ns

-Formation of the ring-like profile.

# XUV measurements

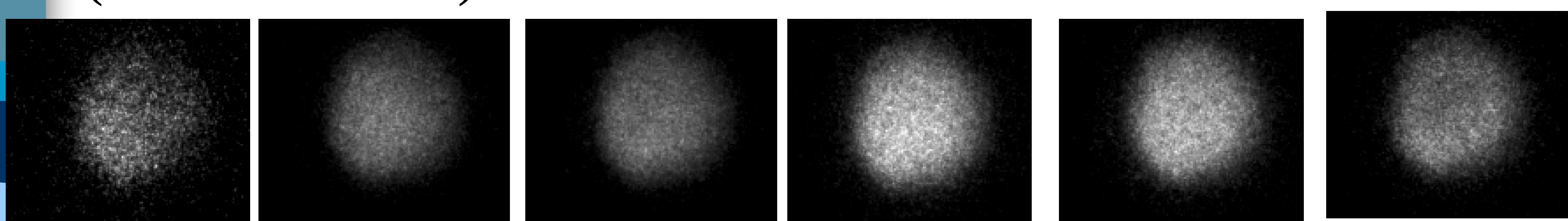
-Emission of the plasma column in the range 10-200 nm (MCP without filter) ;Xe filled capillary, pressure 2 mbar.

- "Non-ablative regime" W ~ 288 J $cm^{-3}$.



10ns 38ns 58ns 72ns 92ns 100ns

-Emission of the plasma column in the range 10-18 nm (MCP + Zr filter)

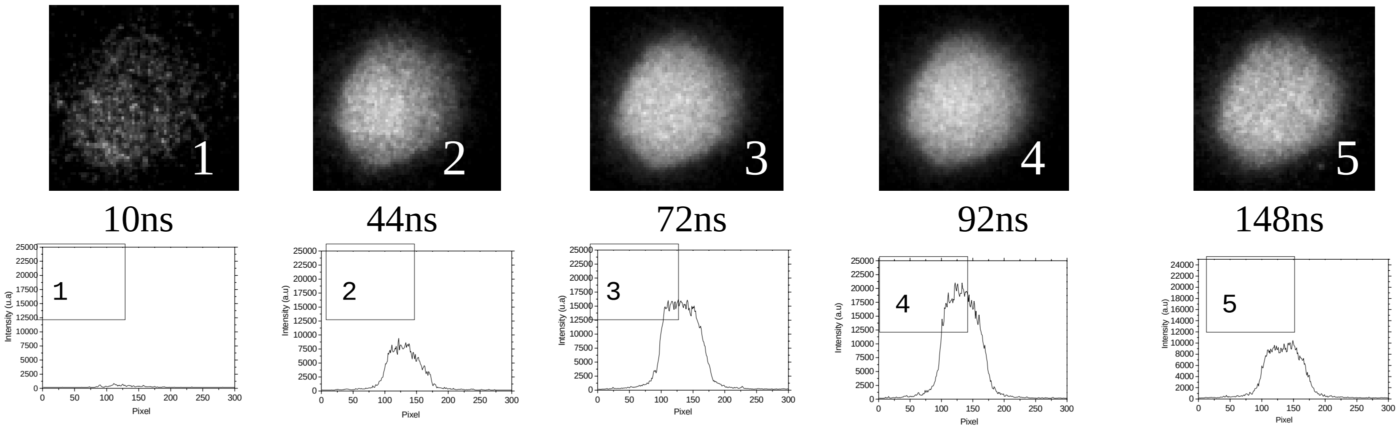


12ns 30ns 54ns 62ns 88ns 110ns

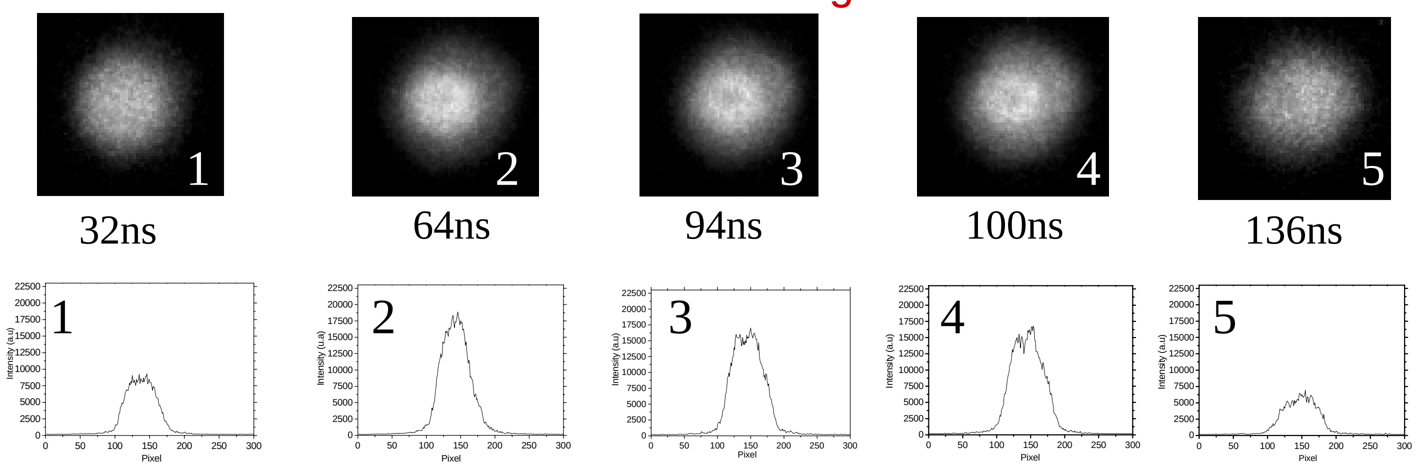
-No compression of the plasma column

-Formation of the ring-like profile was not observed.

# XUV measurements – comparison




Sequences of time resolved pinhole images corresponding to the non ablative regime




Sequences of time resolved pinhole images corresponding to the ablative regime

# Conclusion - The two different regimes of plasma formation

- Ablation mechanism in a capillary discharge based XUV source equipped by ceramic capillary and filled with different gases was investigated experimentally.
- Time integrated and time-resolved spectroscopic measurements as well as plasma imaging were utilized in visible, UV and XUV range.
- Threshold between “non-ablative” and “ablative” regime was found.
- Dependence of the discharge mechanism on applied energy density was demonstrated.

# Ongoing work

- Investigation of the ablation mechanism in capillaries with different size.
- Investigation of the role of pre-ionization on ablation mechanism and on the overall mechanism of plasma formation by time-resolved spectroscopic and imaging techniques.
- Accomplish the experimental investigation in order to have a set of data for utilizing theoretical approaches.
- In cooperation with other groups working out a theoretical model, which will take in consideration the ablation mechanism in ceramic capillaries.

# Acknowledgments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