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X-ray and EUV emission induced by variable pulsewidth irradiation of Ar and Kr clusters and droplets

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Introduction

Motivation: The interaction of high intensity laser pulses with atomic clusters is known to produce efficient x-ray emission and energetic electrons & ions.

We are interested in producing an efficient light source for an EUV microscope. (Collaboration with NIST)

Problem: Electron densities in plasmas (from clusters with initial radii $\sim 5 - 100$ nm) exceed the plasma critical density for timescales of a few picoseconds. We expect reduced heating of clusters when using irradiation with pulse widths greater than these timescales.

BUT... Efficient x-ray emission has been demonstrated using 10 ns irradiation with resulting x-ray yields comparable to that of a solid Au target.¹

Question: What is the best laser pulse width to optimize the x-ray yield?

Experiment: We want to investigate the relative EUV spectra ($\lambda = 2-44$ nm) and x-ray emission ($\lambda > 1.5$ keV) under intense laser irradiation as a function of pulse width ($\tau = 120$ fs - 10 ns).

1) Kubiak et. al., OSA TOPS on Extreme Ultraviolet Lithography, G.D. Kubiak and D. Kania, eds., vol 4, 66 (1996).

Experimental Set-up

LASER

Ti:Sapphire ($\lambda = 800 \text{ nm}$)

$E = 50 \text{ mJ @ } 10 \text{ Hz}$

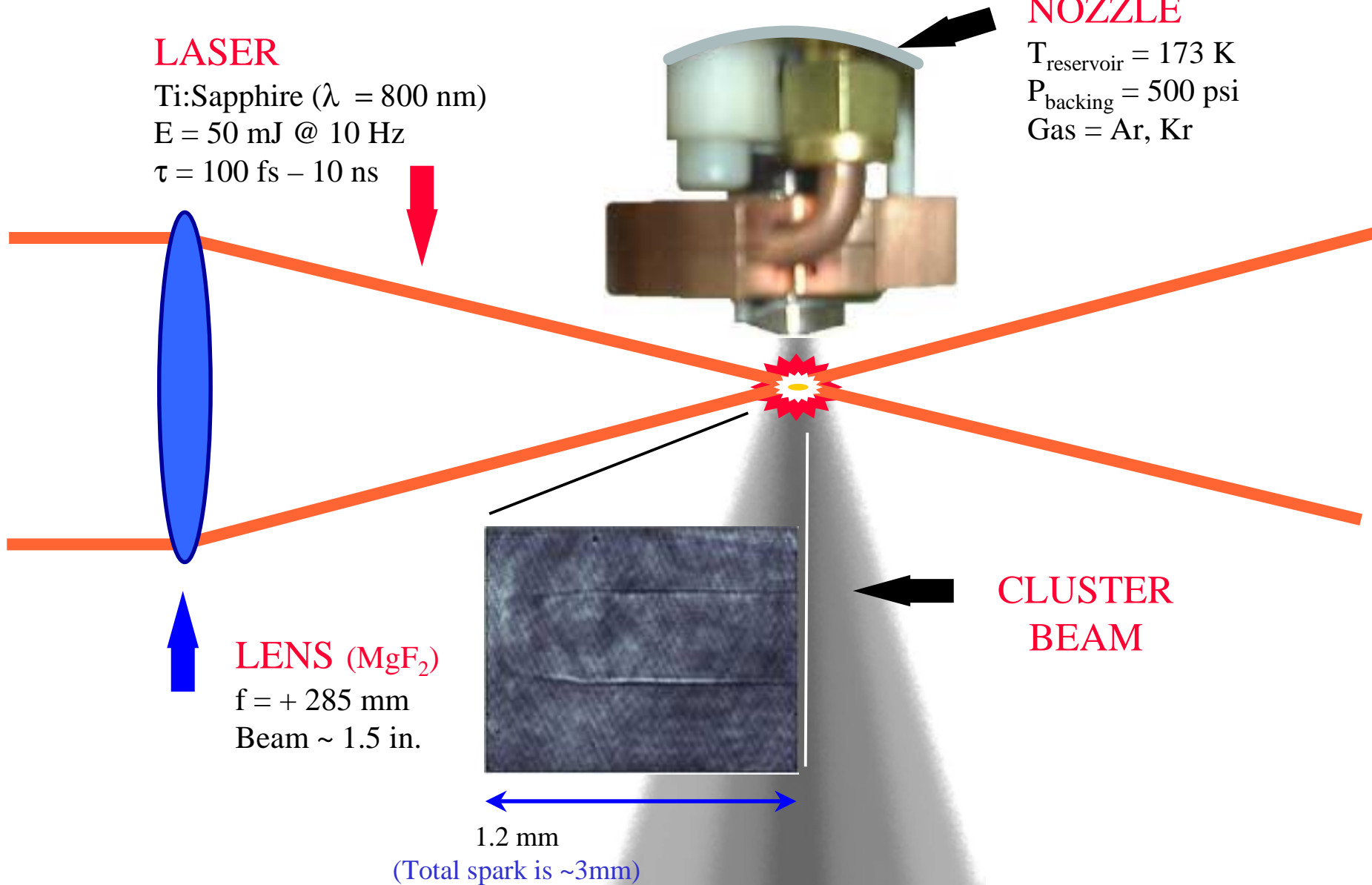
$\tau = 100 \text{ fs} - 10 \text{ ns}$

NOZZLE

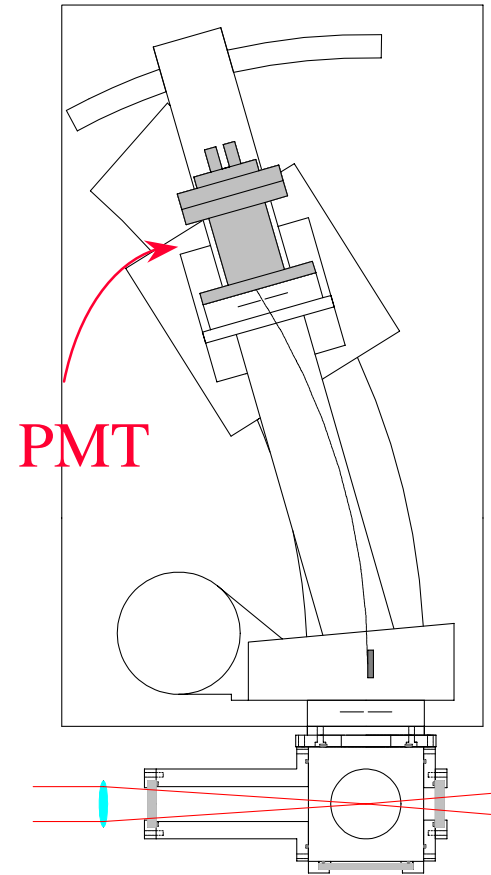
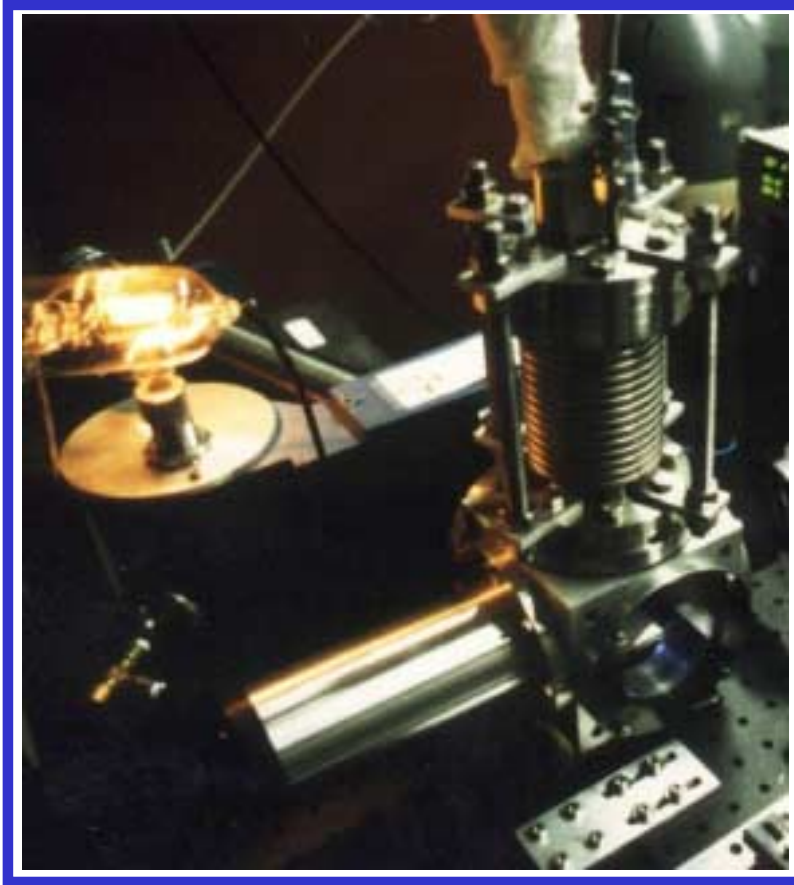
$T_{\text{reservoir}} = 173 \text{ K}$

$P_{\text{backing}} = 500 \text{ psi}$

Gas = Ar, Kr

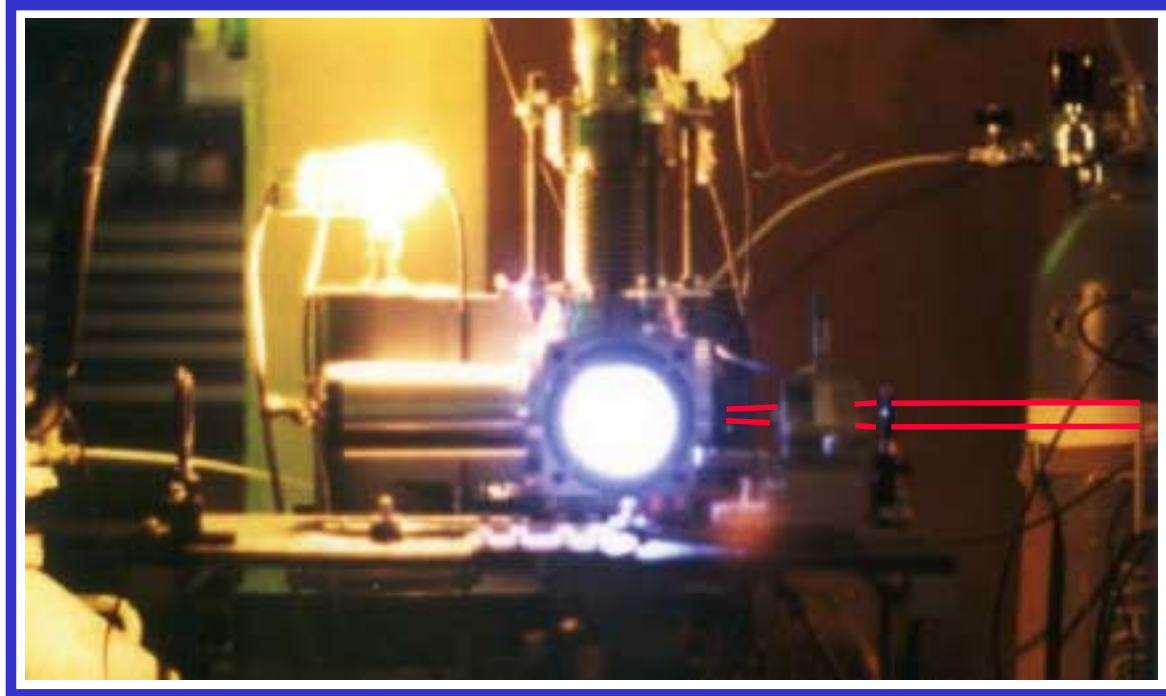


EUV Experimental Set-up

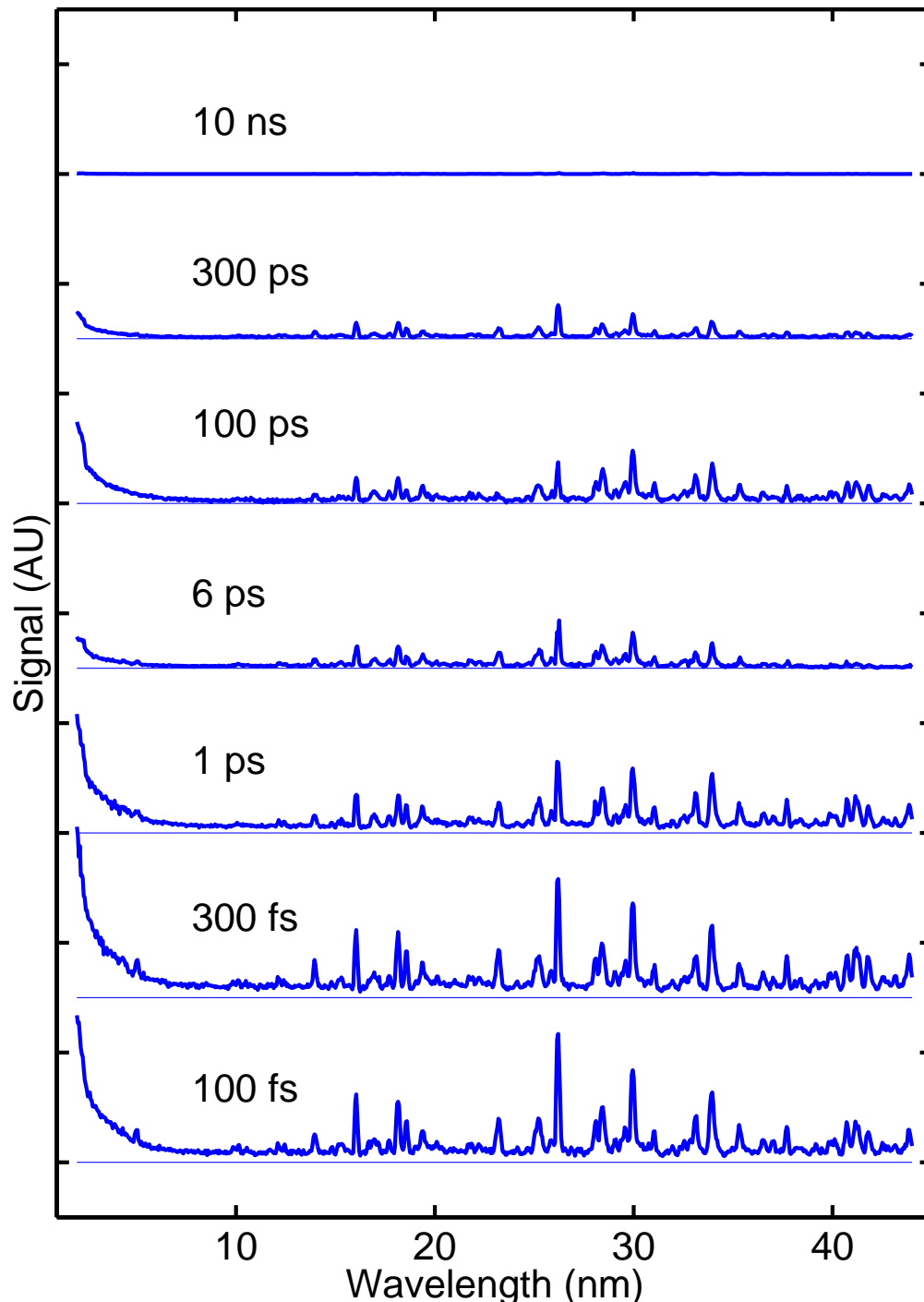


Nozzle chamber and grazing incidence EUV monochromator ($\lambda = 2-44$ nm).

Experimental Set-up



$\tau_{\text{exposure}} \sim 1\text{-}2 \text{ sec, (400 ASA)}$



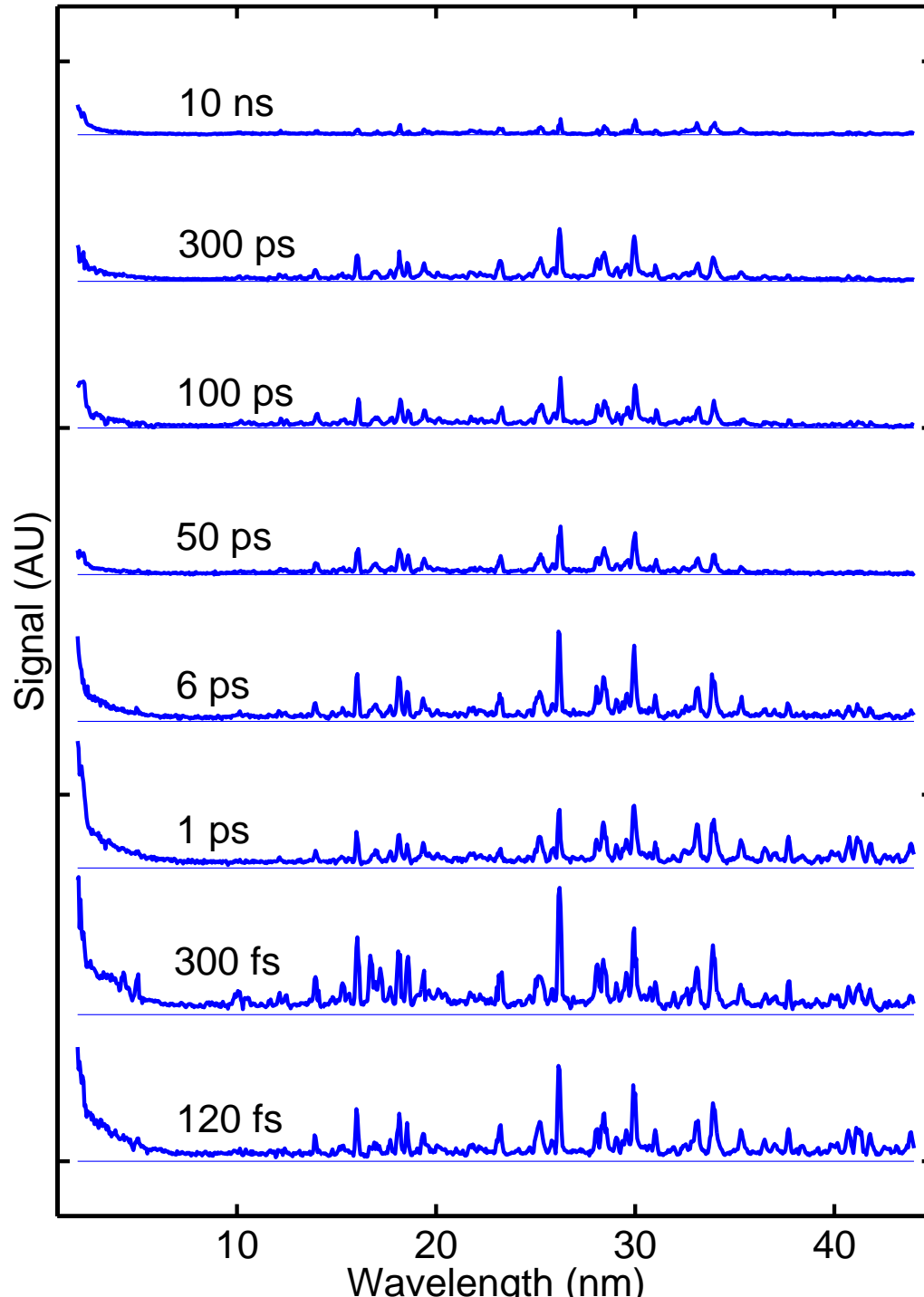
Argon

$E = 50 \text{ mJ}$

$P_{\text{backing}} = 500 \text{ psi}$

$T = 300 \text{ K}$

$R_{\text{Hagena}} \sim 39 \text{ nm}$



Argon

$E = 50 \text{ mJ}$

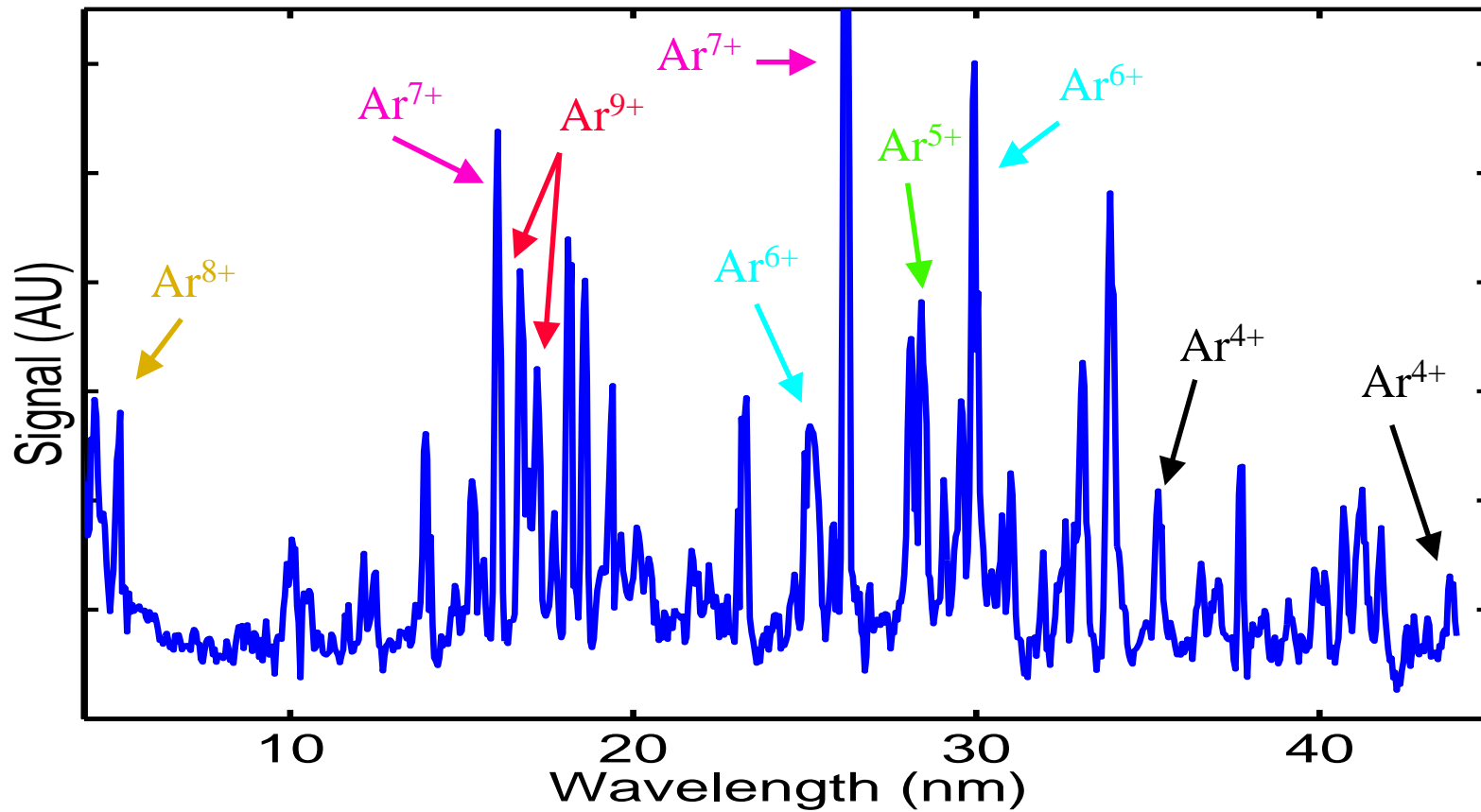
$P_{\text{backing}} = 500 \text{ psi}$

$T = 173 \text{ K}$

$R_{\text{Hagena}} \sim 100 \text{ nm}$

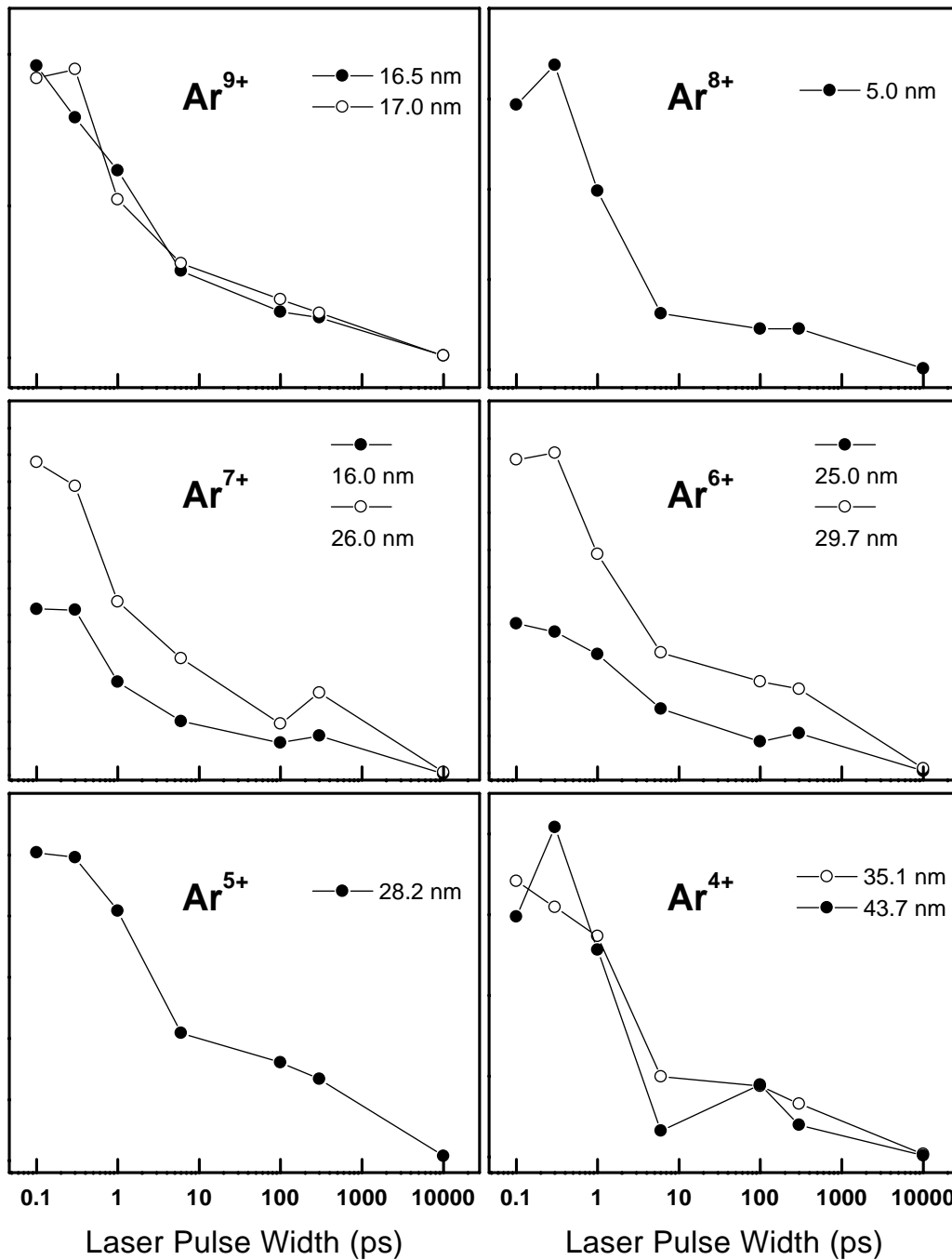
ARGON

($E = 50$ mJ, $P_{\text{backing}} = 500$ psi, $T = 173$ K)



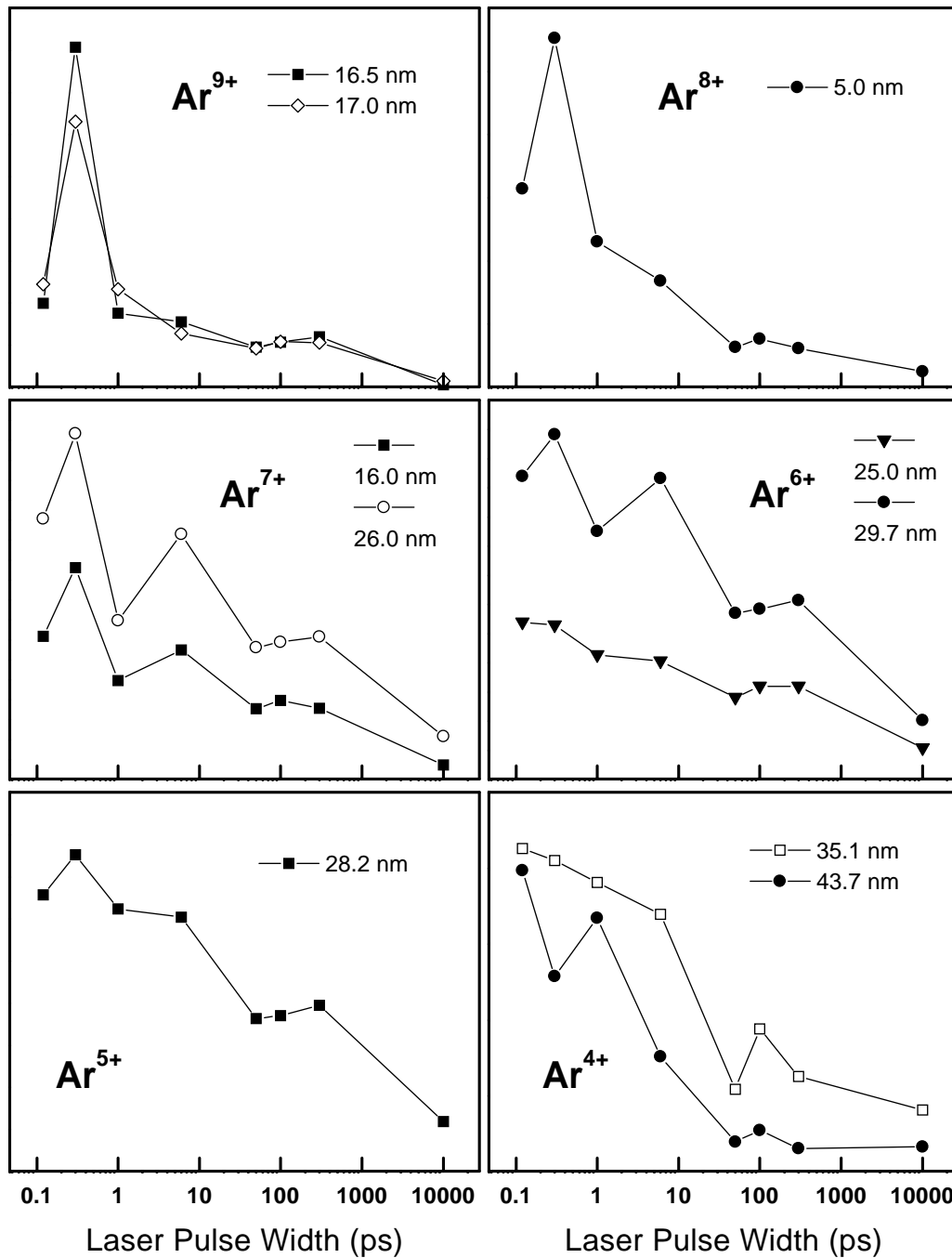
Argon

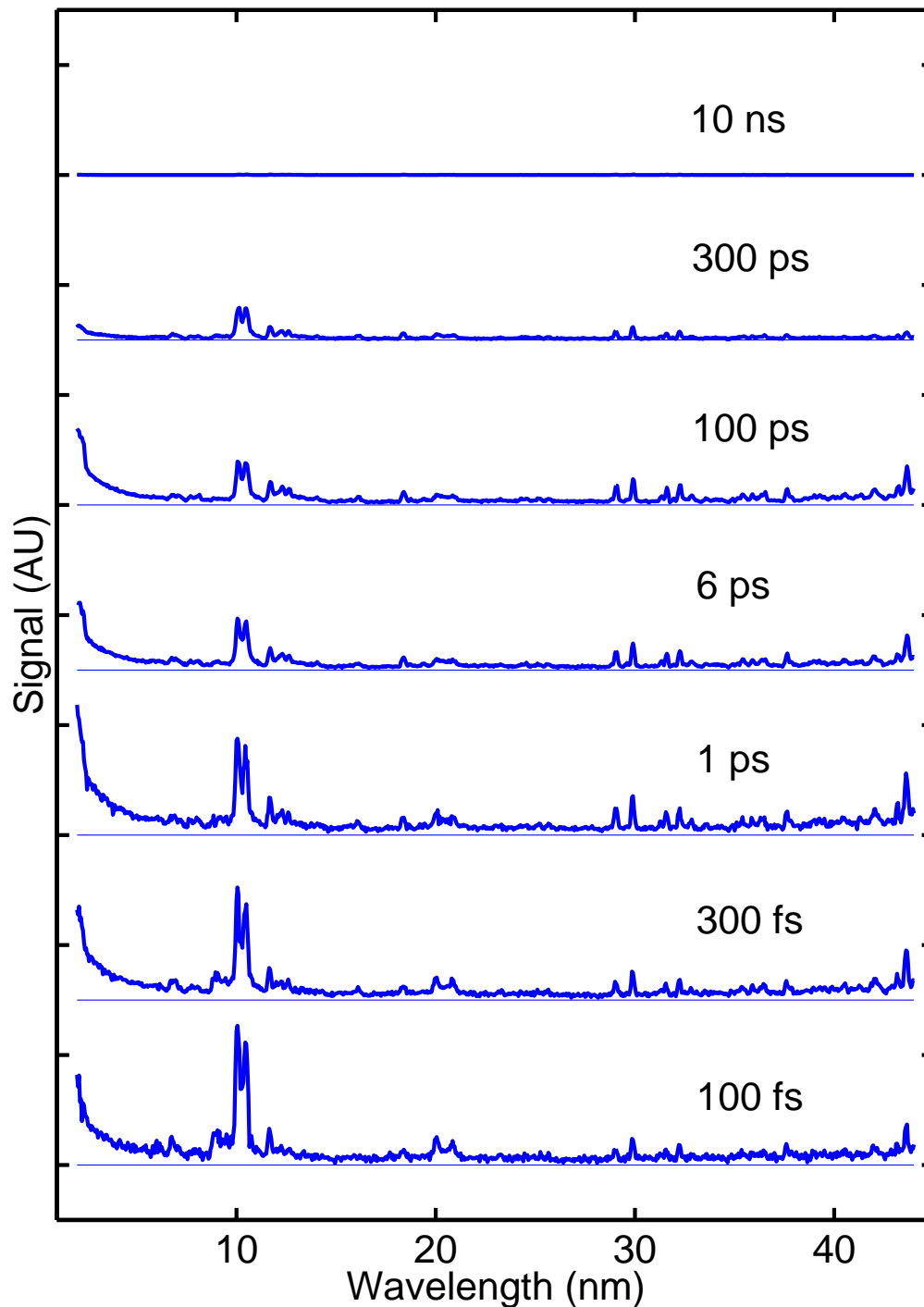
Selected EUV lines vs. laser pulse width.
(T = 300 K)



Argon

Selected EUV lines vs. laser pulse width.
($T = 173 \text{ K}$)





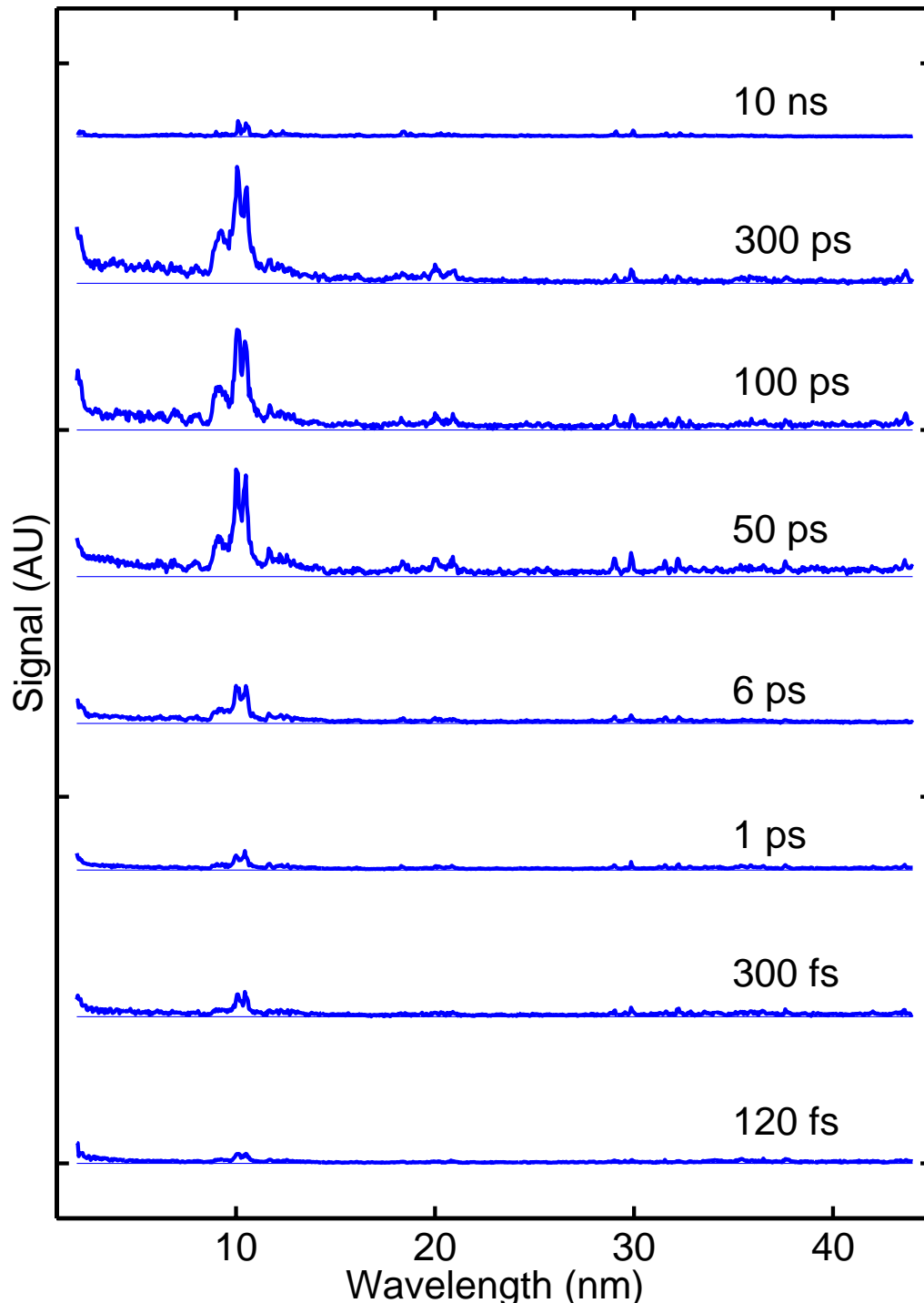
Krypton

$E = 50 \text{ mJ}$

$P_{\text{backing}} = 500 \text{ psi}$

$T = 300 \text{ K}$

$R_{\text{Hagena}} \sim 66 \text{ nm}$



Krypton

$E = 50 \text{ mJ}$

$P_{\text{backing}} = 500 \text{ psi}$

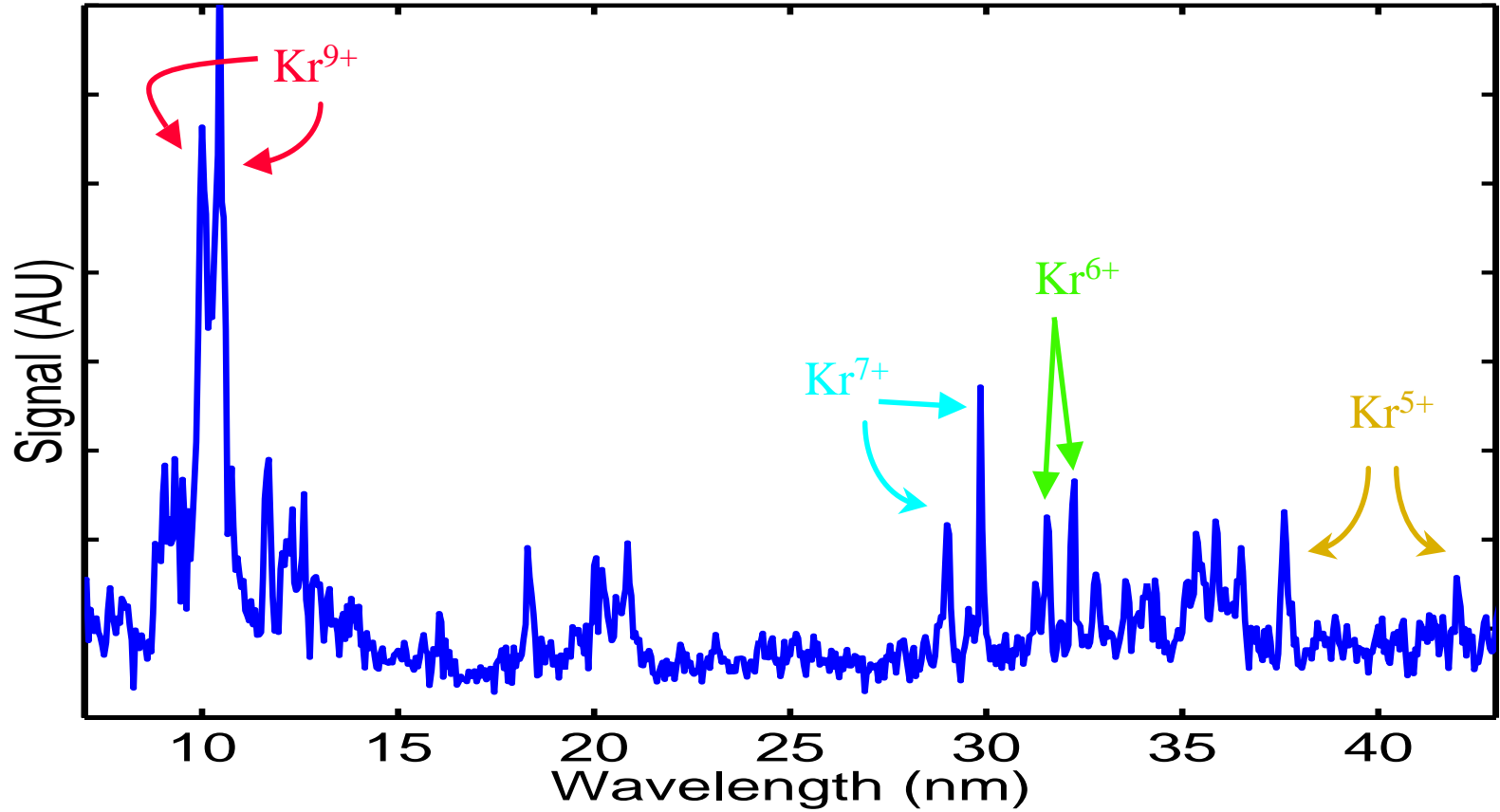
$T = 173 \text{ K}$

$R_{\text{Hagena}} \sim 178 \text{ nm}$

$R_{\text{droplet}} \sim 3.4 \text{ }\mu\text{m}$

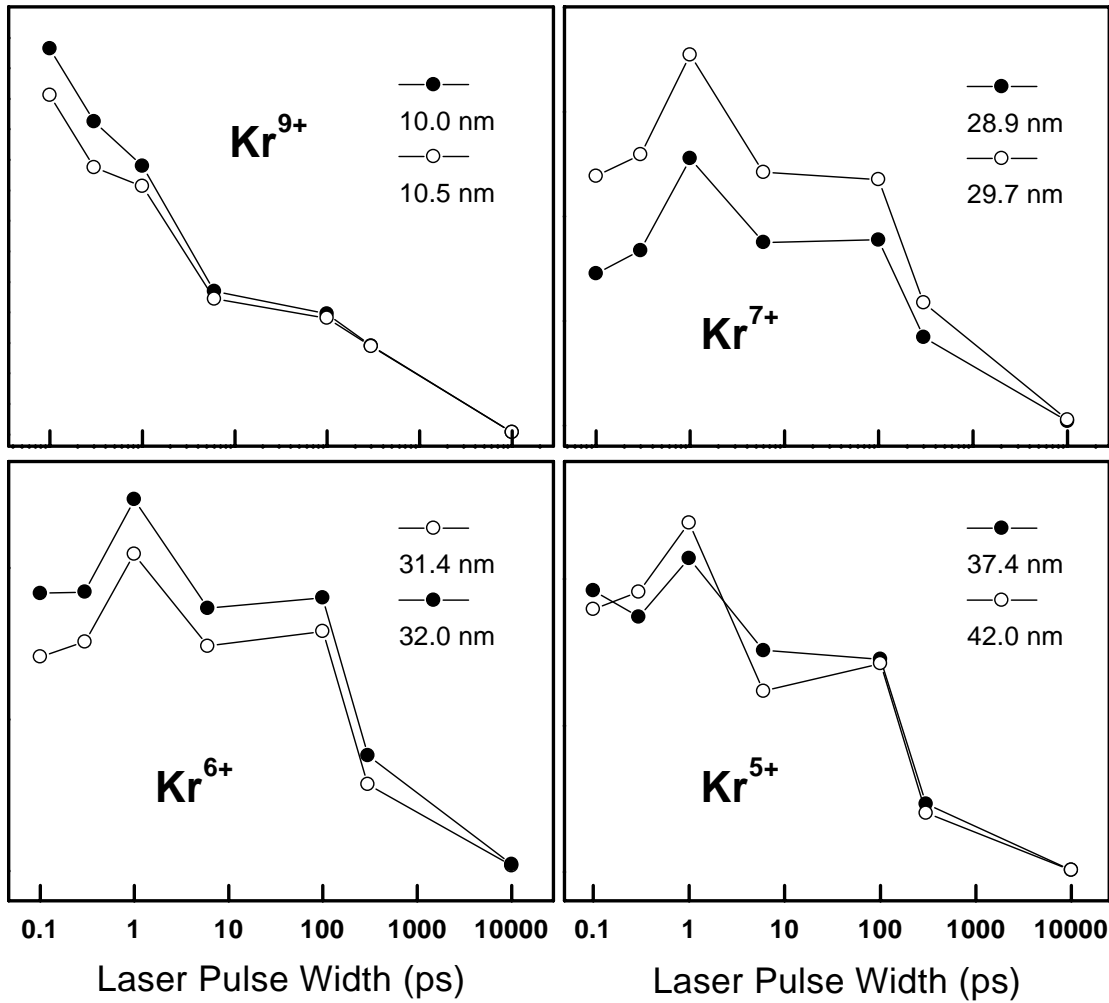
KRYPTON

($E = 50$ mJ, $P_{\text{backing}} = 500$ psi, $T = 173$ K)



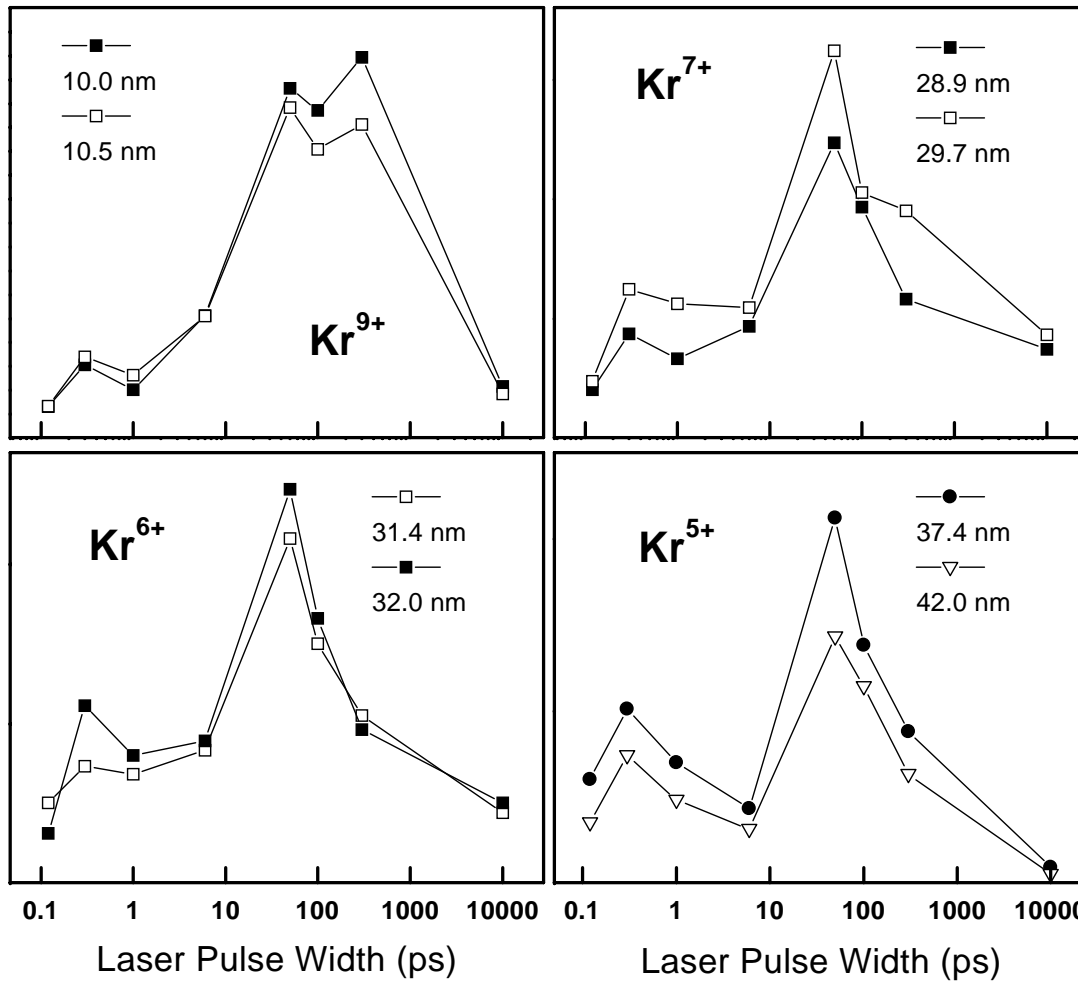
Krypton

Selected EUV lines vs. laser pulse width.
(T = 300 K)

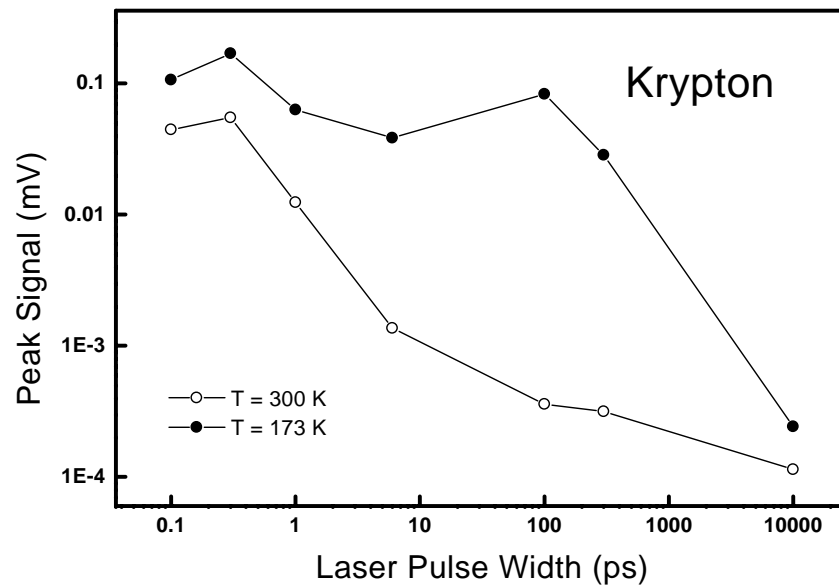
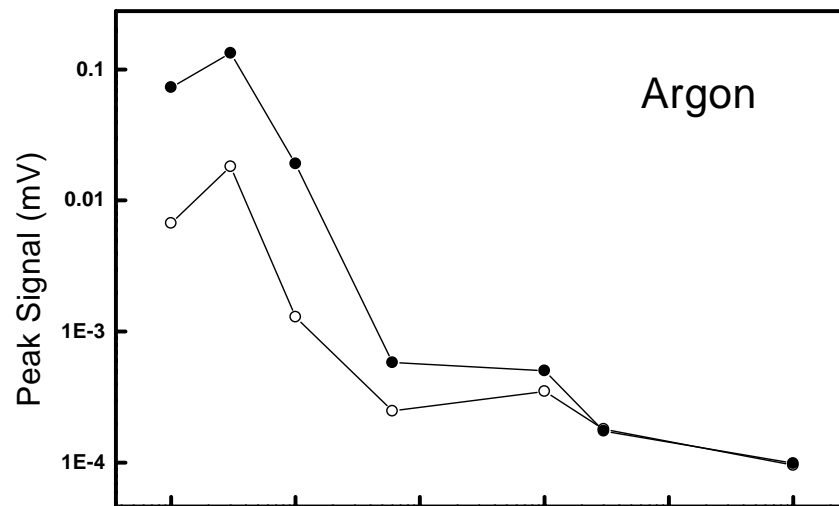
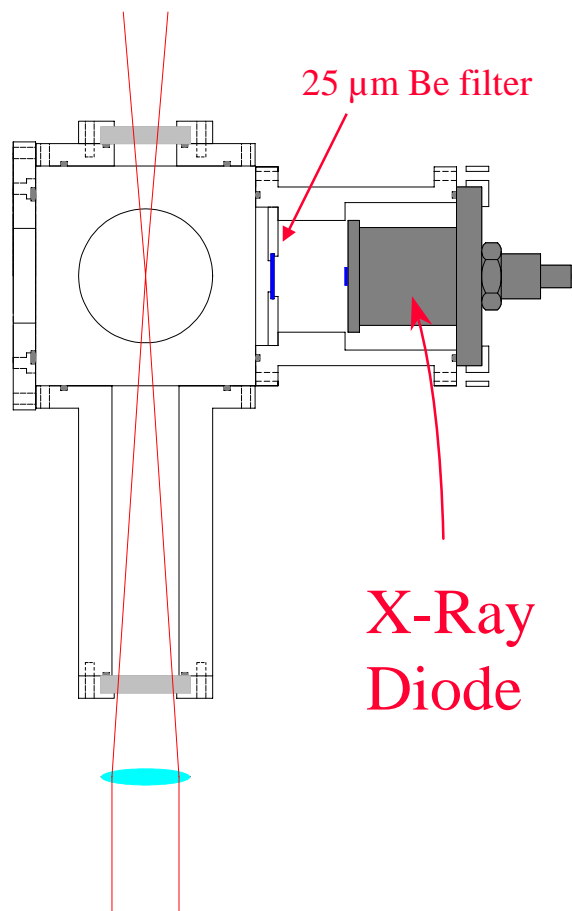


Krypton

Selected EUV lines vs. laser pulse width.
(T = 173 K)

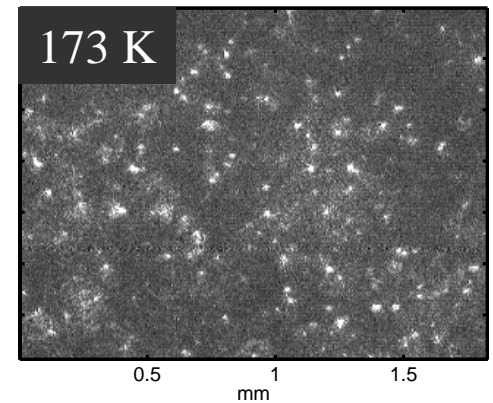
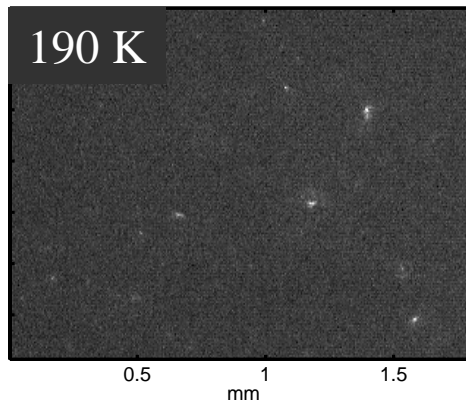
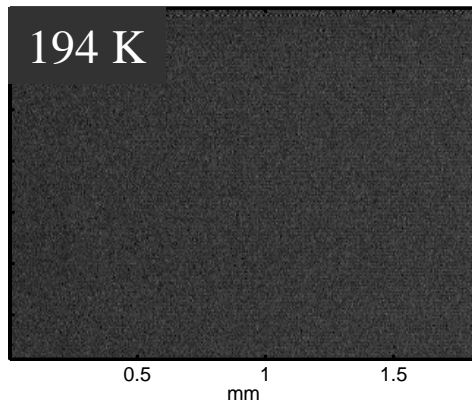


X-Ray ($E > 1.5$ keV) Experimental Set-up & Data

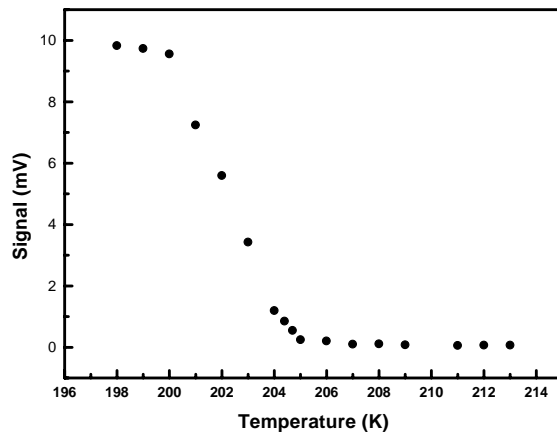


Images of the Droplet Transition in Krypton

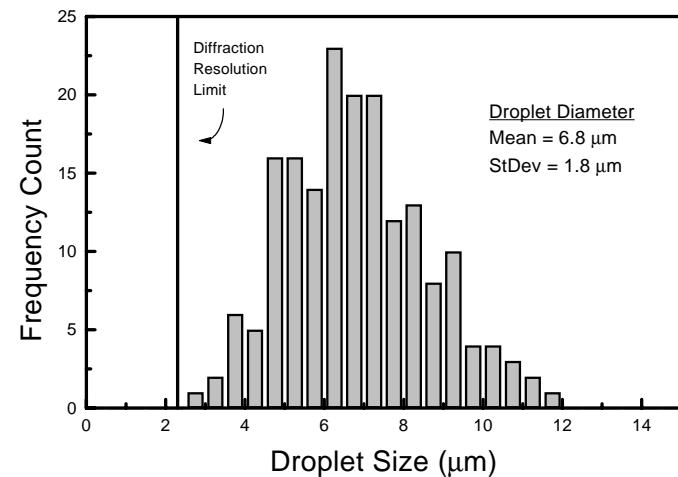
For 500 psi, Krypton undergoes a gas – liquid phase transition at $T = 192.6$ K.



X-Rays ($E > 1.5$ keV) vs. Temperature



Histogram ($T = 173$ K)



Conclusions

We summarize all the time scales for optimal EUV (from the highest observed ion stages) and X-ray ($E > 1.5$ KeV) emissions:

	Krypton		Argon	
	Droplets $T = 173$ K	Clusters $T = 300$ K	Clusters $T = 173$ K	Clusters $T = 300$ K
EUV	50-100 ps	100 fs - 1 ps	300 fs	100-300 fs
X-rays	300 fs	300 fs	300 fs	300 fs

We propose that two time scales govern these results...

Conclusions

τ_{crit} - Time for expanding plasma to drop below critical density.

Bulk thermal heating where $n_{e0} > n_e > n_{\text{crit}}$

$$\sim R (n_{e0} / n_{\text{crit}})^{1/3} / c_s$$

$$\tau_{\text{crit}} \sim 1 - 1.7 \text{ ps} \quad (R \sim 40 - 70 \text{ nm cluster})$$

$$\tau_{\text{crit}} \sim 80 \text{ ps} \quad (R \sim 3.4 \text{ } \mu\text{m droplet})$$

τ_{res} - Time for optimal resonant absorption at the critical density layer in the expanding plasma.

Non-thermal heating at the edge layer where $n_e \sim n_{\text{crit}}$

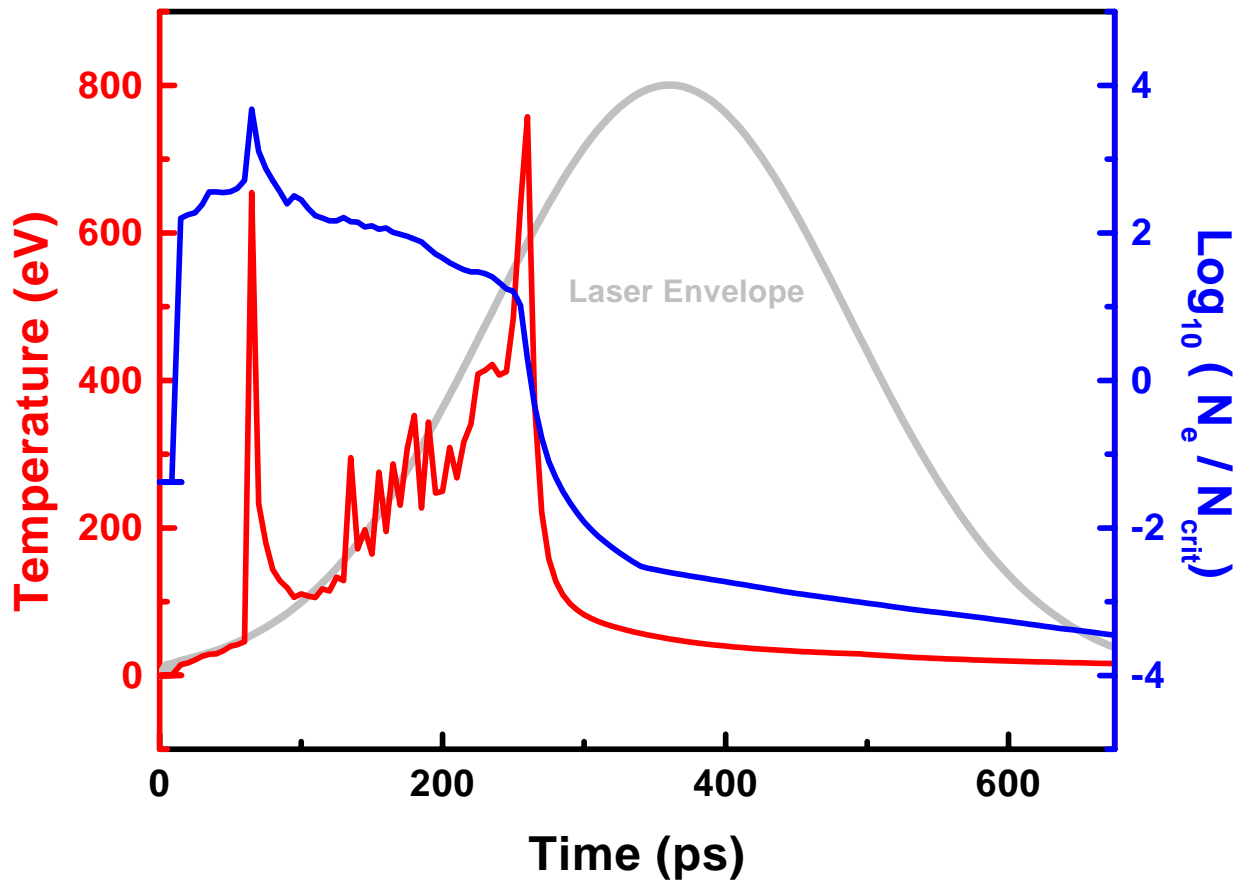
$$\sim L_{\text{opt}} / c_s$$

$$\tau_{\text{res}} \sim 400 \text{ fs}$$

Numerical calculations

Argon

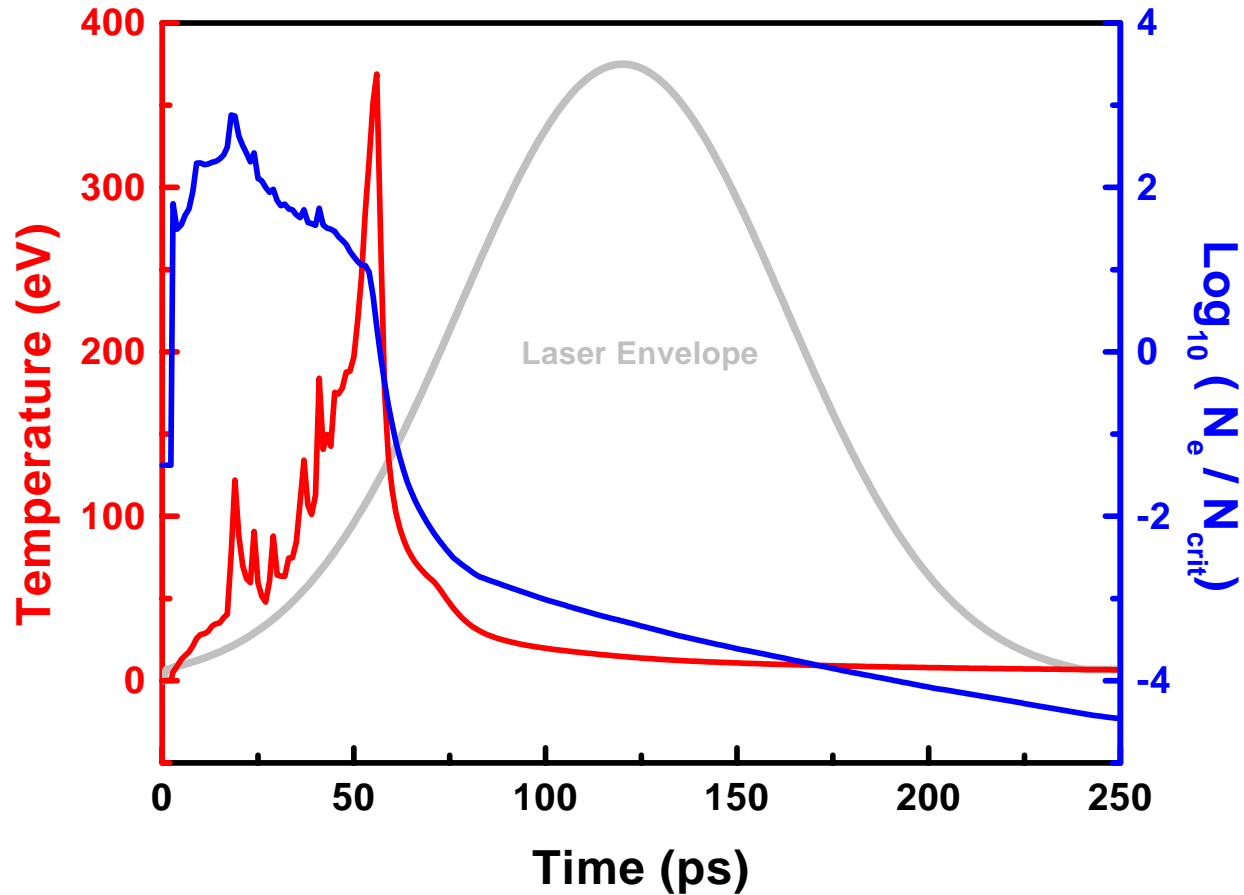
$$R_{\text{droplet}} = 3.4 \mu\text{m}, \quad I_{\text{max}} = 3.33 \times 10^{12} \text{ W/cm}^2, \quad \tau_{\text{pulse}} = 300 \text{ ps (FWHM)}$$



Numerical calculations

Argon

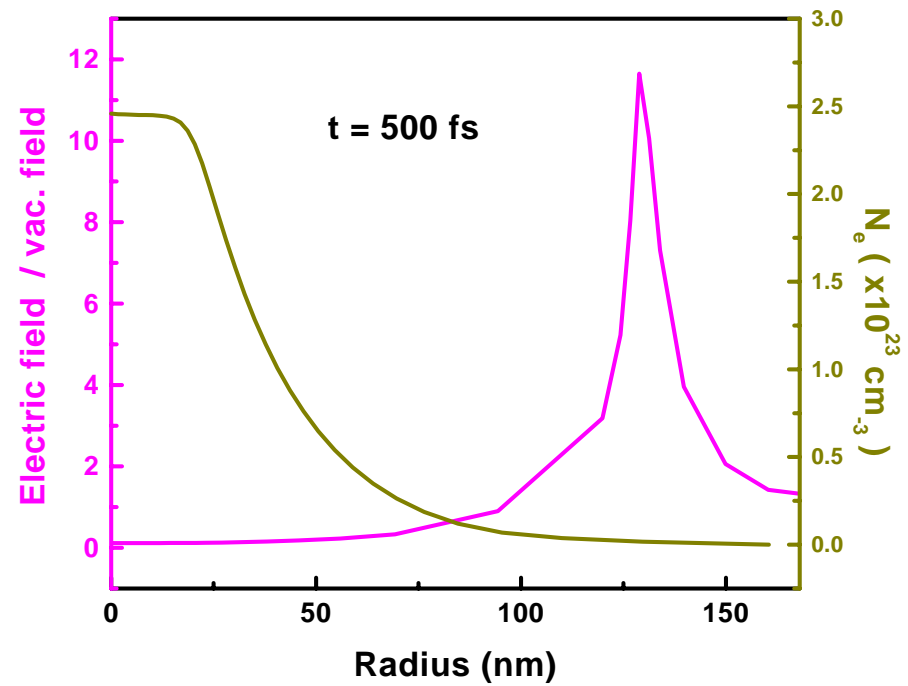
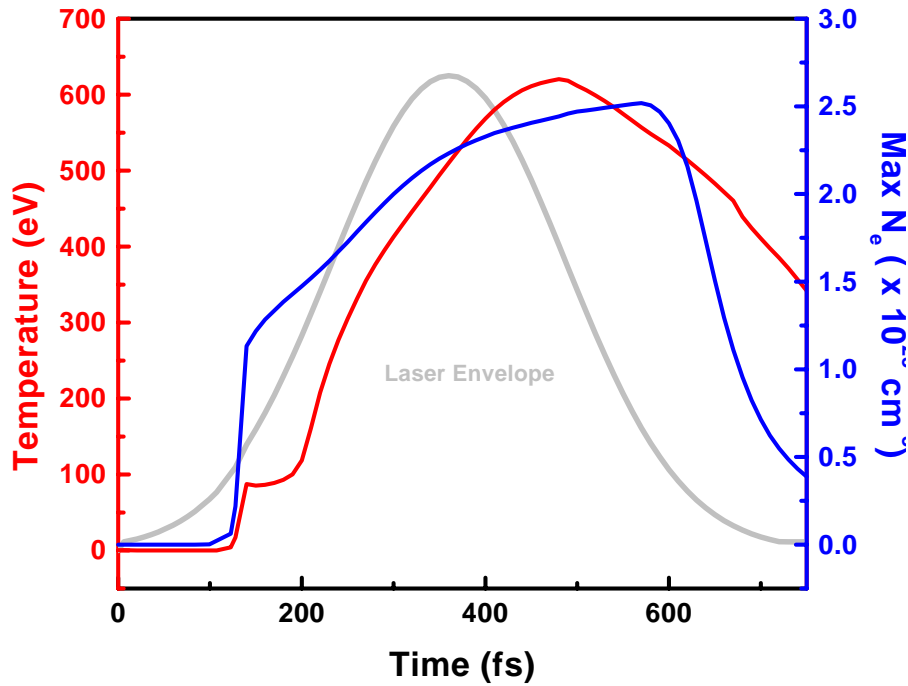
$$R_{\text{droplet}} = 0.5 \mu\text{m}, \quad I_{\text{max}} \sim 10^{13} \text{ W/cm}^2, \quad \tau_{\text{pulse}} = 100 \text{ ps (FWHM)}$$



Numerical calculations

Argon

$$R_{\text{cluster}} = 60 \text{ nm}, \quad I_{\text{max}} = 10^{15} \text{ W/cm}^2, \quad \tau_{\text{pulse}} = 300 \text{ fs (FWHM)}$$



Conclusions

- ▶ Time scales for optimal EUV / x-ray yield are consistent with the expansion (τ_{crit}) and resonant absorption (τ_{res}) time scales which are natural to laser generated cluster plasmas.

- ▶ Cost effective optimization of EUV / x-ray yields can be achieved by matching the incident laser pulse width and the target size (e.g. via a phase transition) for maximal energy coupling.