Interaction of Dual Laser Pulses with Krypton Droplets

S. J. McNaught,[1,2] J. Fan,[1] E. Parra[1] and H. M. Milchberg[1]

[1]Institute for Physical Science and Technology, University of Maryland

and

[2]National Institute of Standards and Technology

Abstract

We have investigated the disassembly time of cryogenically cooled krypton droplets irradiated by two 100-ps, 1.064-μm laser pulses separated by a variable time delay. Using a new pulsed source, we produce krypton droplets whose size can be varied by precisely controlling the temperature of a valve backed with krypton at high pressure. The first laser pulse heats the droplets, forming a plasma, and the second pulse serves as a heater probe for measuring the characteristic disassembly time of the Kr droplets. Using EUV and X-ray (>1.5keV) signals generated by the second pulse as diagnostics, it has been found that the disassembly time of the droplets varies monotonically with their size and can be as long as several nanoseconds.

This work is supported by the National Science Foundation (ECS-96-12204).

Introduction

Motivation:

(1) A laser plasma-based source for extreme ultraviolet (EUV) lithography is being developed.[1] The interaction of intense laser pulses with noble gas droplets produces EUV radiation with efficiencies (~0.5% in-band conversion efficiency) comparable to those of solid targets, but with minimal debris generation.

(2) An understanding of the disassembly time scale of these droplets would help efforts to optimize the EUV output of the laser plasma source.

Goals:

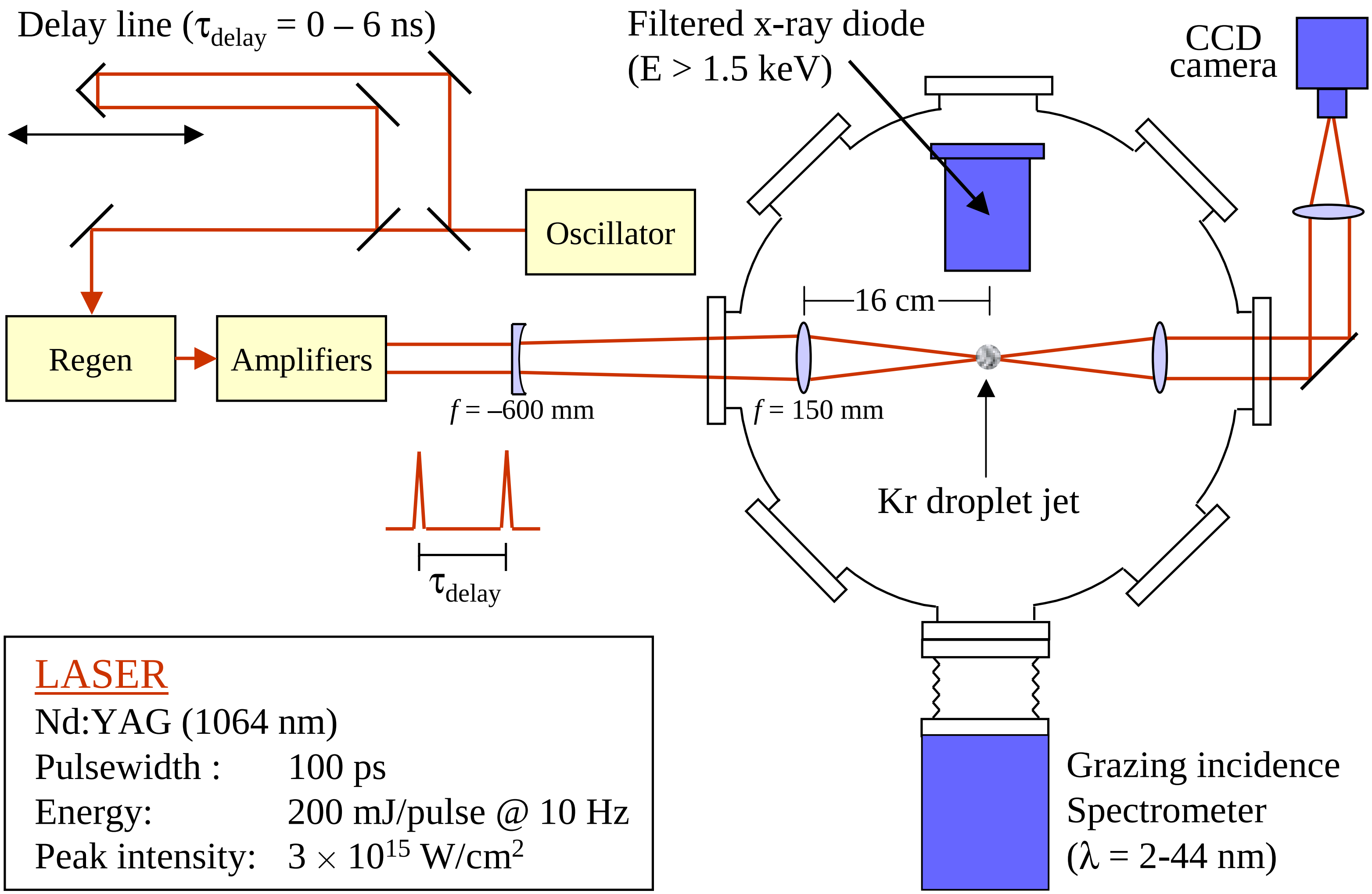
(1) Measure the disassembly time scale of large (~1-10 μm size) krypton droplets using a pump-probe experiment.

(2) Determine the size of the droplets emitted from the pulsed krypton source as a function of valve backing pressure and temperature.

(3) Compare these experimental data to calculations of the droplet disassembly dynamics.

[1]G.D. Kubiak et. al., *EUV, X-Ray and Neutron Optics and Sources*, Proc. SPIE., v. **3767**, 136 (1999).

Experimental setup

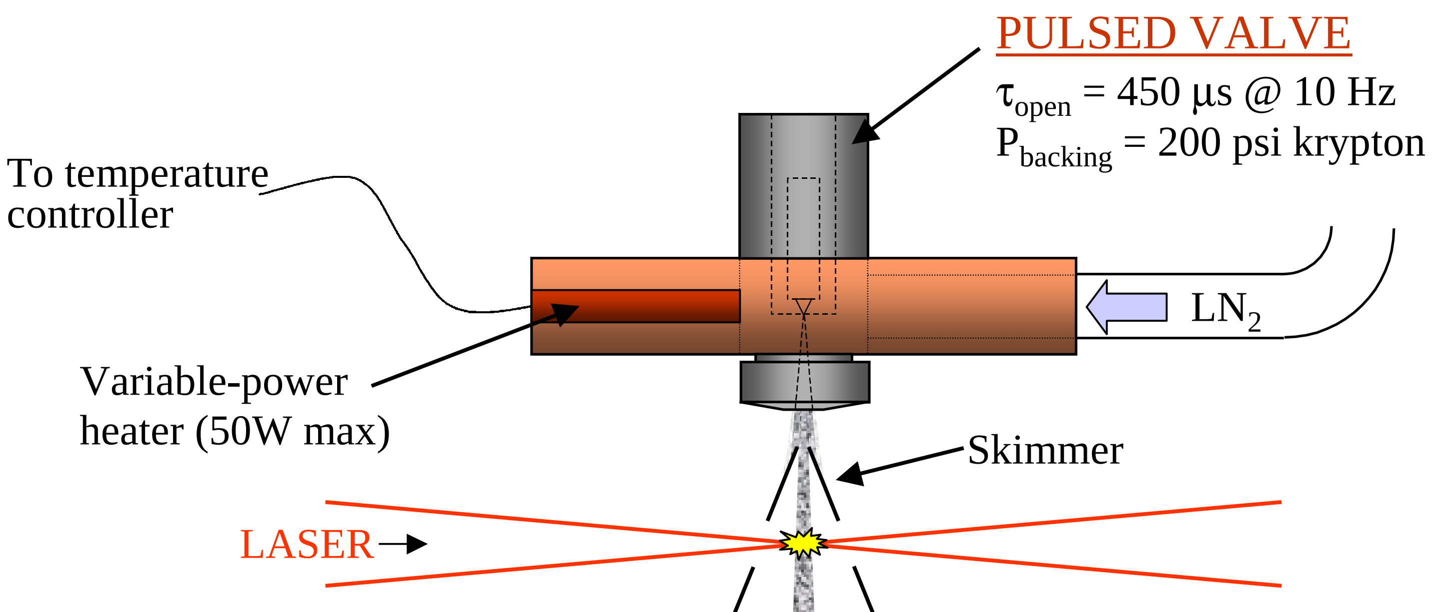


LASER

Nd:YAG (1064 nm)

Pulsewidth :	100 ps
Energy:	200 mJ/pulse @ 10 Hz
Peak intensity:	3×10^{15} W/cm^2

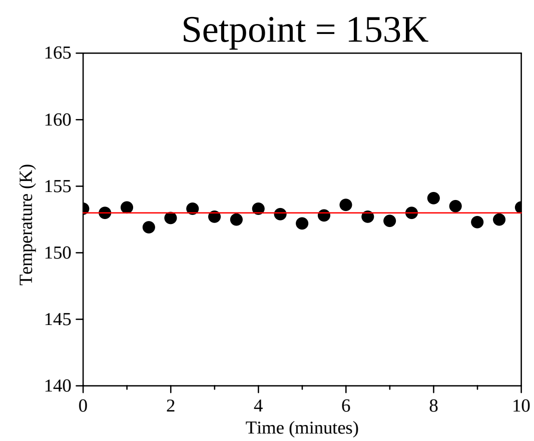
Cryogenic krypton droplet source



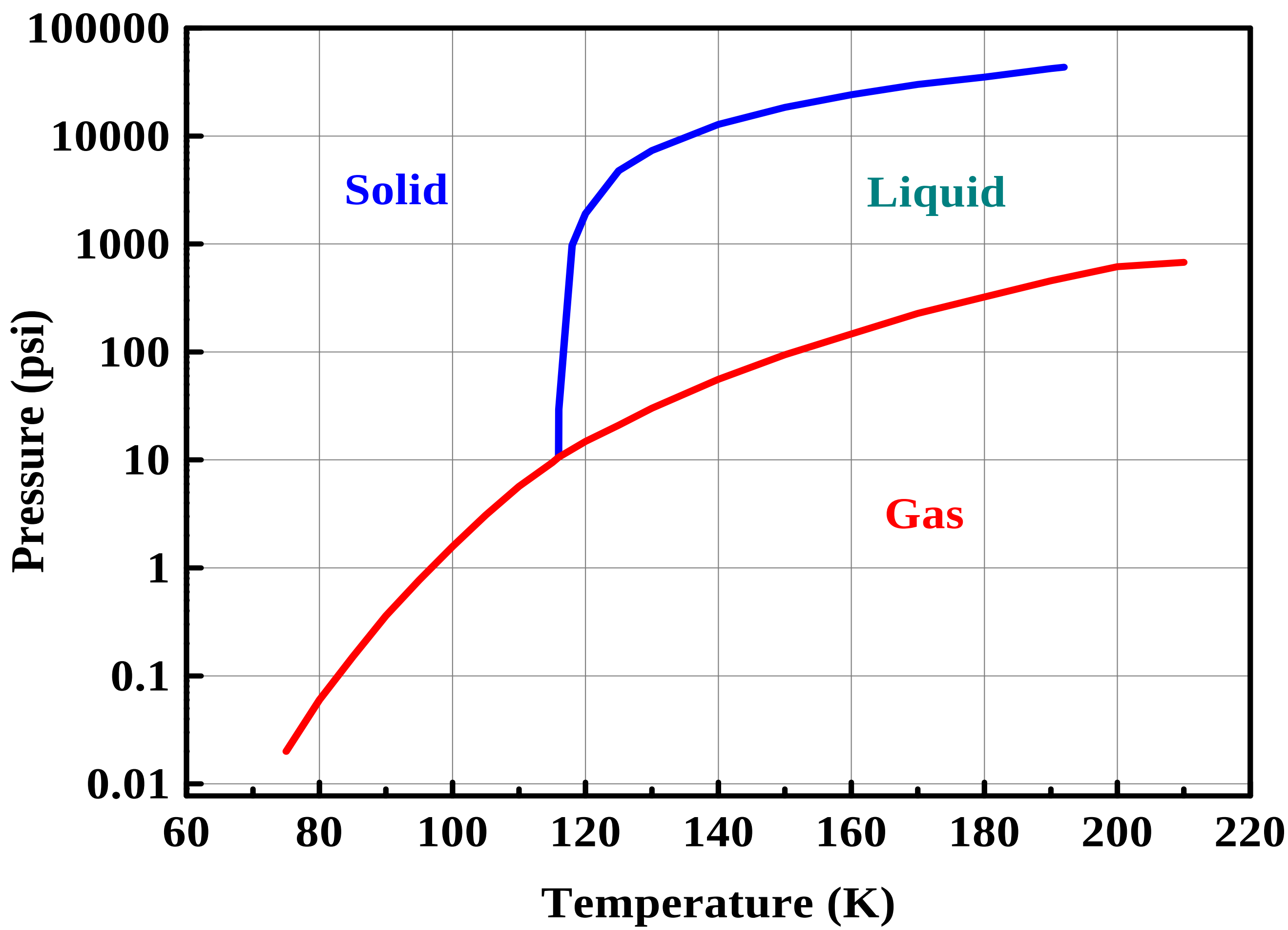
TEMPERATURE CONTROL

Range: 100 to 300 Kelvin

Stability: ± 0.5 K

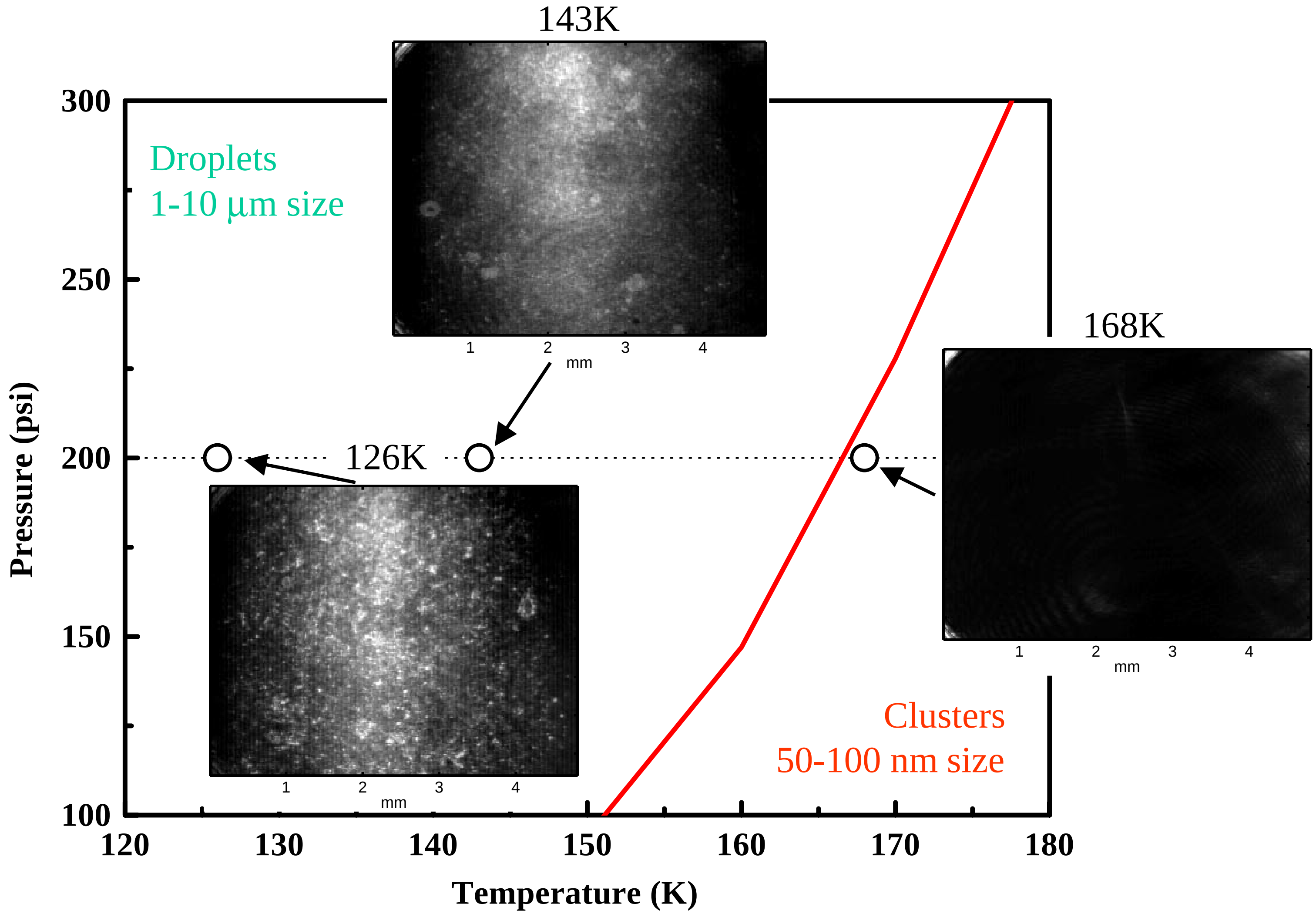


Krypton phase diagram



A. C. Hollis Hallett, in *Argon, Helium and the Rare Gases*, Ed. G.A. Cook (Interscience Publishers, New York, 1961), pp. 322-335.

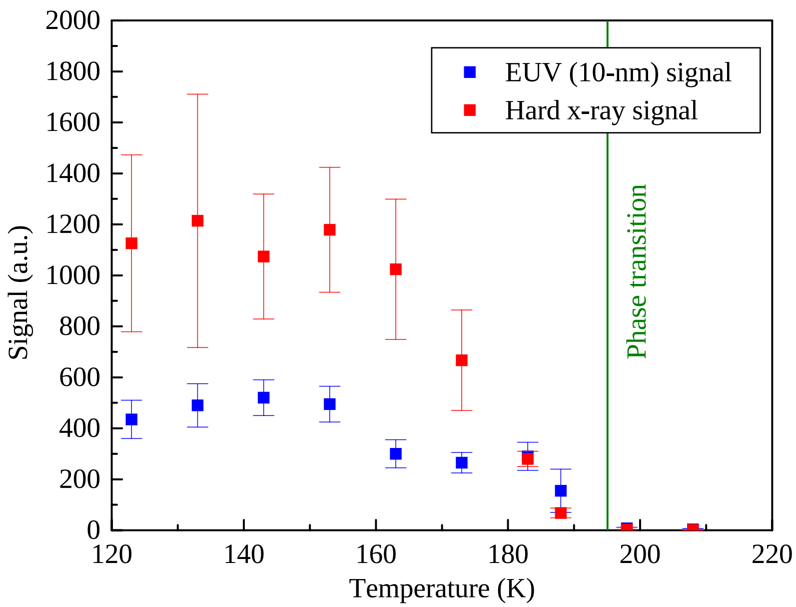
Images of krypton droplet jet



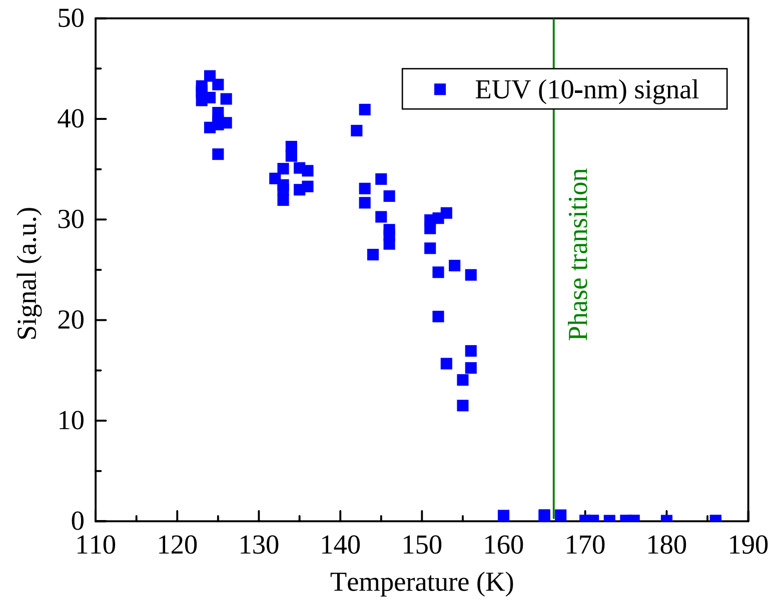
EUV and x-ray emission vs. temperature

Single pulse emission

$P_{backing}$ = 500 psi ➡ T_{trans} = 195 K

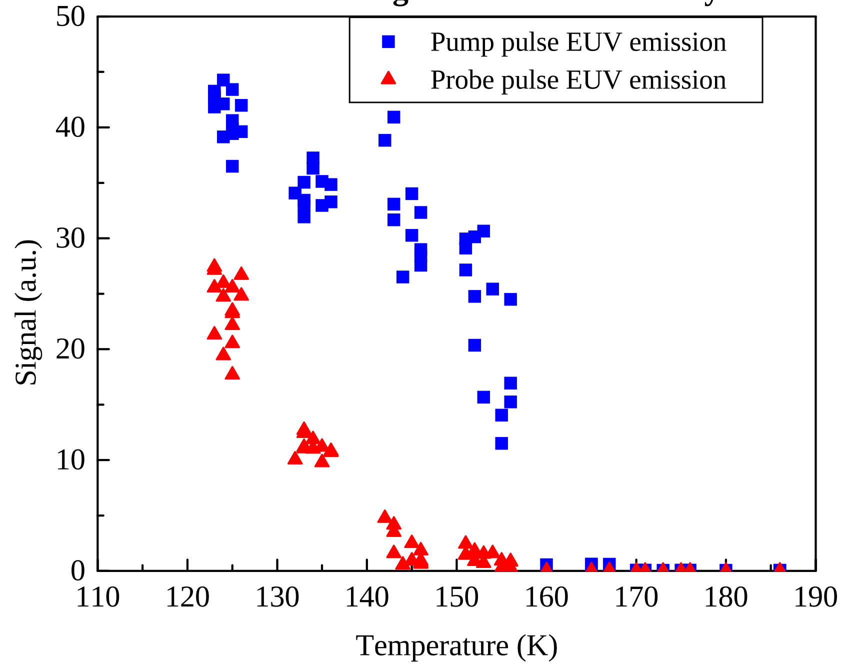


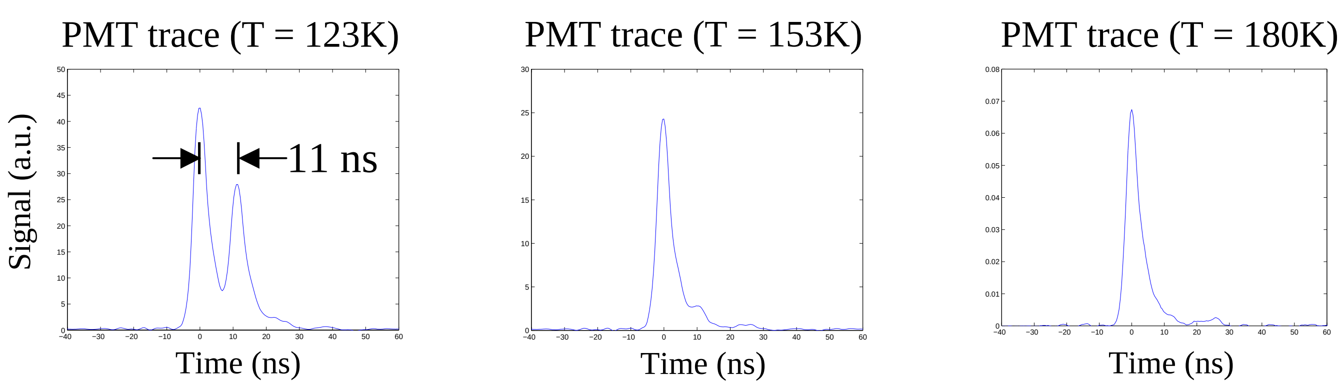
$P_{backing}$ = 200 psi ➡ T_{trans} = 167 K



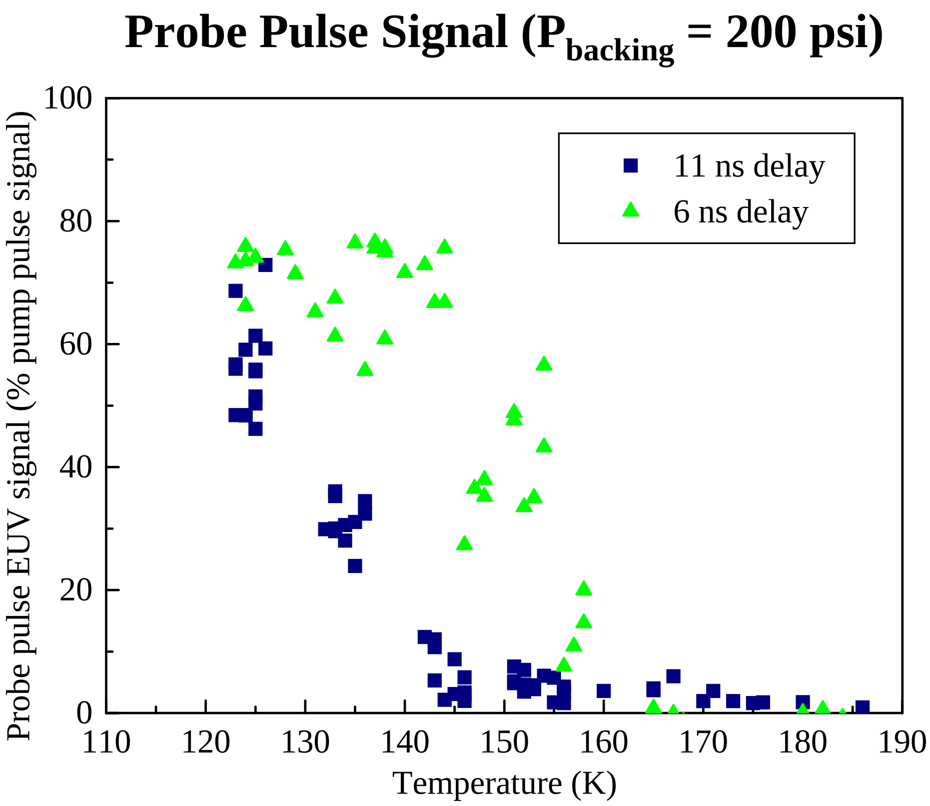
Dual pulse interaction with droplets

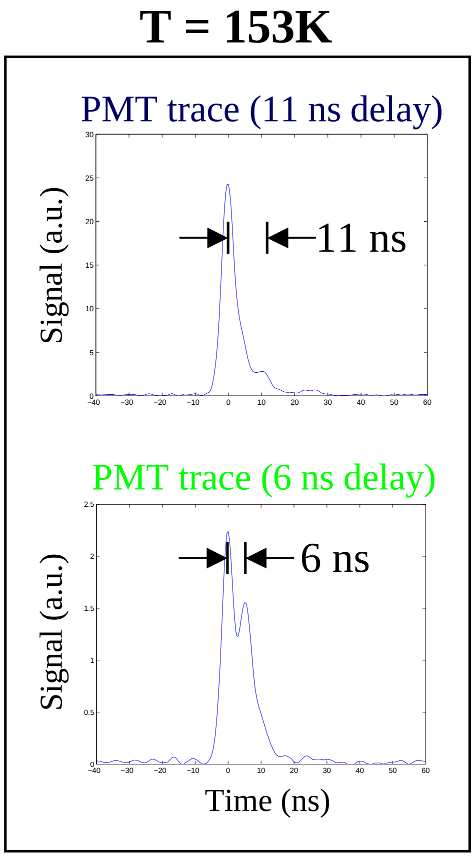
EUV signal ($P_{backing}$ = 200 psi, τ_{delay} = 11 ns)



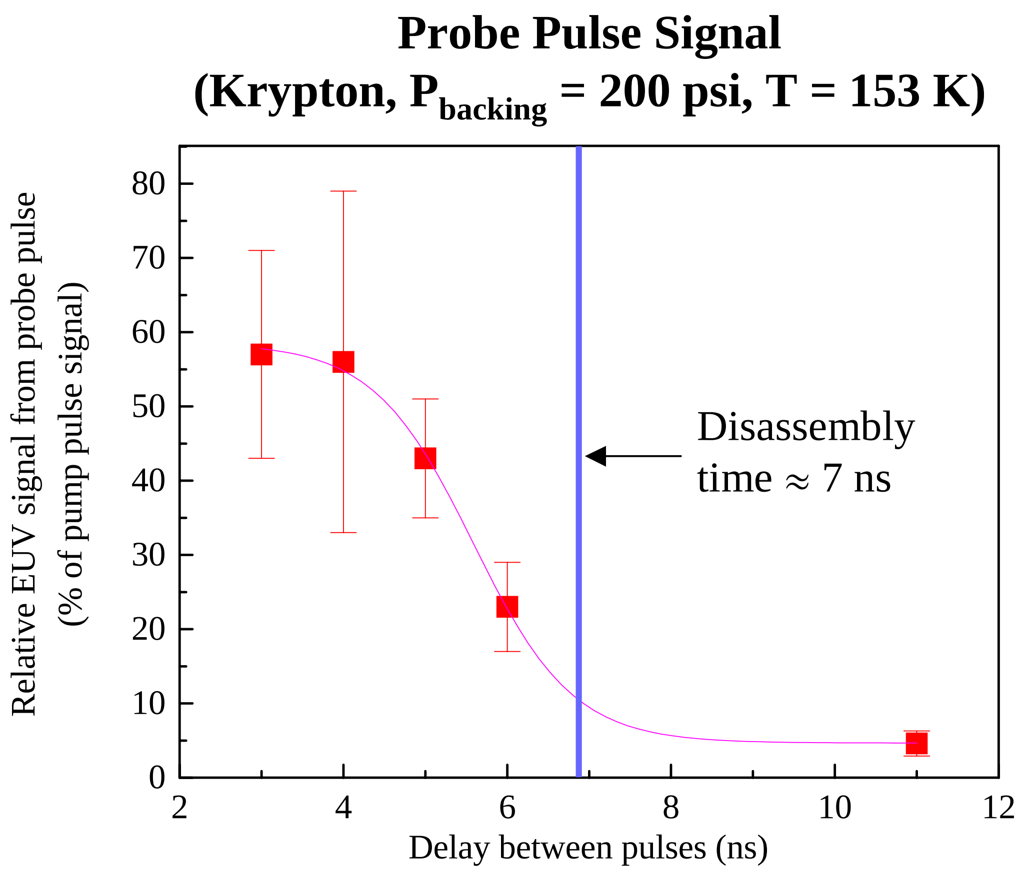


Relative probe pulse EUV signal





Krypton droplet disassembly



Calculation of disassembly time scale

- The time for a plasma generated from a krypton droplet to remain above the critical density is approximated by

$$\tau_{crit} = \frac{R}{c_s}\left(\frac{n_{e0}}{n_{cr}}\right)^{1/3}$$

where R is the droplet radius, c_s is the plasma sound speed, n_{e0} is the initial electron density, and n_{cr} is the plasma critical density. For $n_{e0} \approx 2\times10^{23}$ cm^{-3}, and $c_s \approx 2\times10^{7}$ cm/s for plasma temperatures of several hundred eV, τ_{crit} values are as follows for various droplet sizes:

R	τ_{crit}
50 nm	1.5 ps
0.5 μm	15 ps
5 μm	150 ps

- This calculation is in disagreement with our data. The plasma sound speed would have to be overestimated by a factor of ~30, or the average plasma temperature by a factor of ~1000, in order to reach agreement.

Conclusions

- We have begun to investigate the characteristic disassembly time of large micron-sized krypton droplets in an intense laser field. EUV radiation measurements have shown this time scale to vary directly with droplet size.

- Significant EUV radiation is produced by the droplet remnants and the background plasma several nanoseconds after the pump pulse.

- This time scale is in significant disagreement with both a simple calculation of the disassembly time scale and the results of a hydrodynamic computer simulation. Such calculations, which are better suited to smaller droplets and clusters, may underestimate the droplet disassembly time due to the dominant role played by ablative forces in large droplets.

- Future experiments include probing the droplet disassembly with a picosecond laser pulse during plasma formation by a high-energy nanosecond pump pulse.