TARA
TSUKUBA ADVANCED RESEARCH ALLIANCE
筑波大学先端学際領域研究センター

# EUV generation from rare gas clusters excited by ultrashort KrF laser


K. Kondo

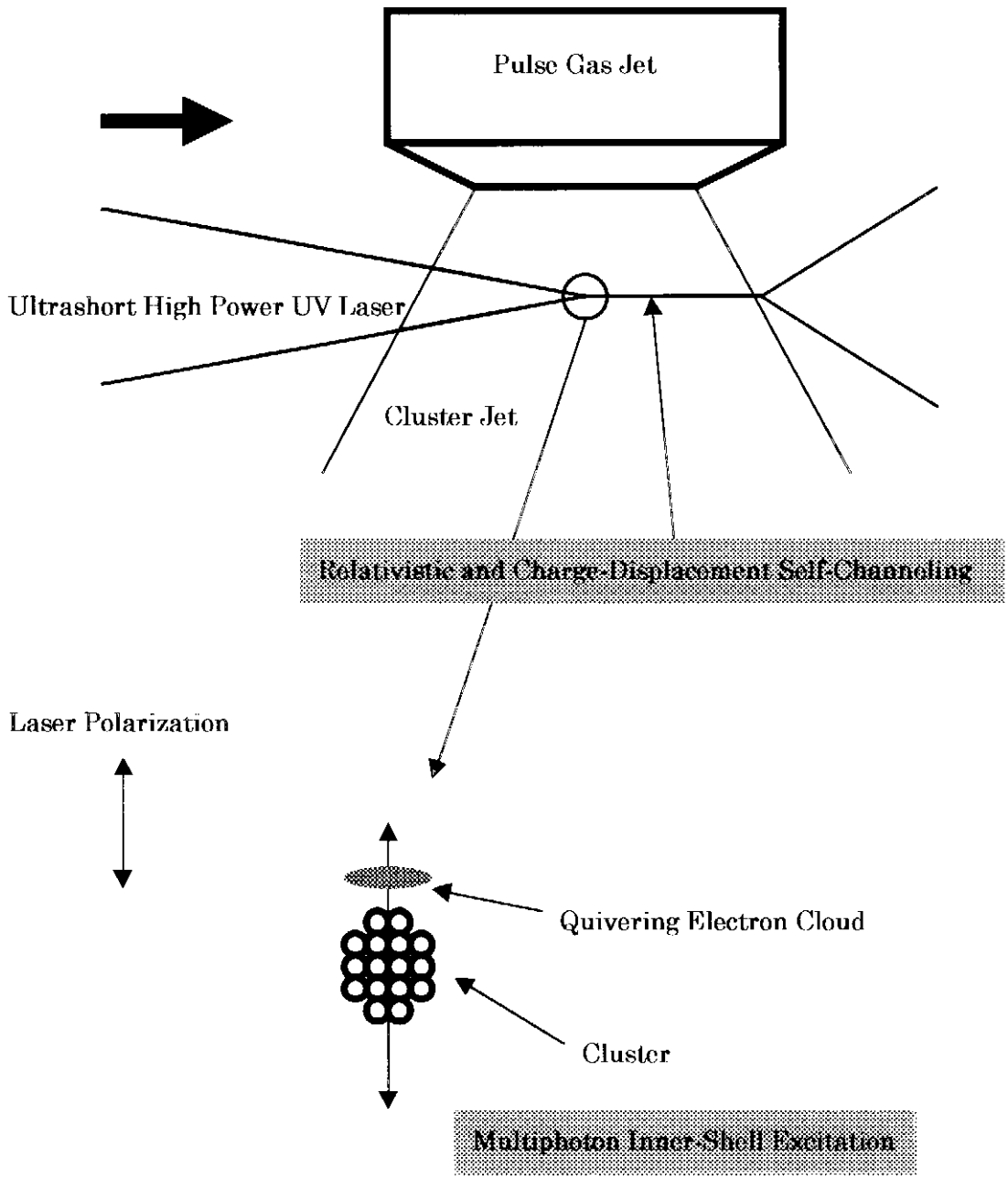
Center for Tsukuba Advanced Research Alliance (TARA),
University of Tsukuba



EUV Workshop on October 10-12, 1999
in Monterey CA, USA

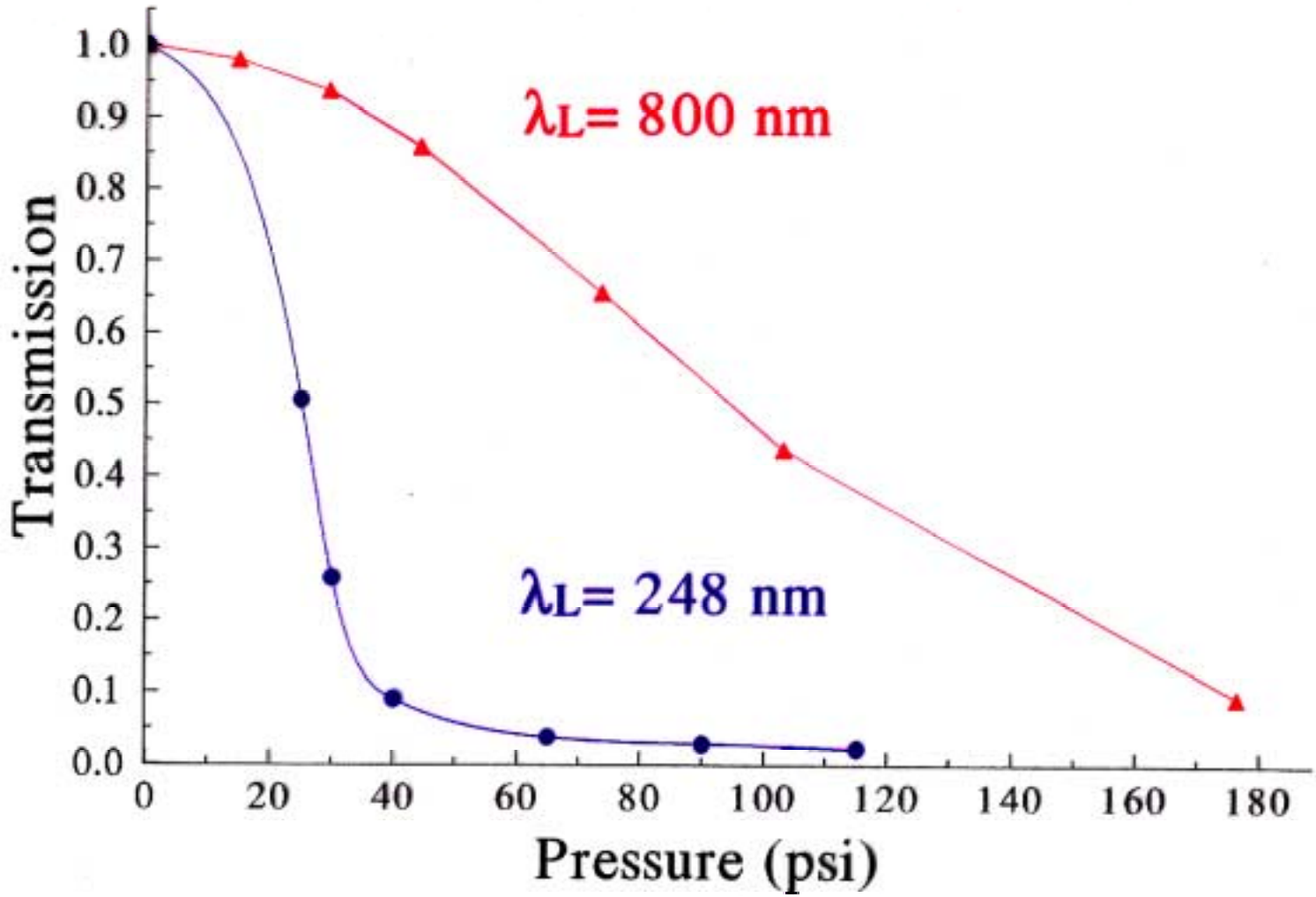
# C. K. Rhodes, University of Illinois at Chicago

# ~1994



**Kondo, C. K. Rhodes, et. al., J. Phys. B 30, 2707 (1997).**

# Absorption in Xe Clusters

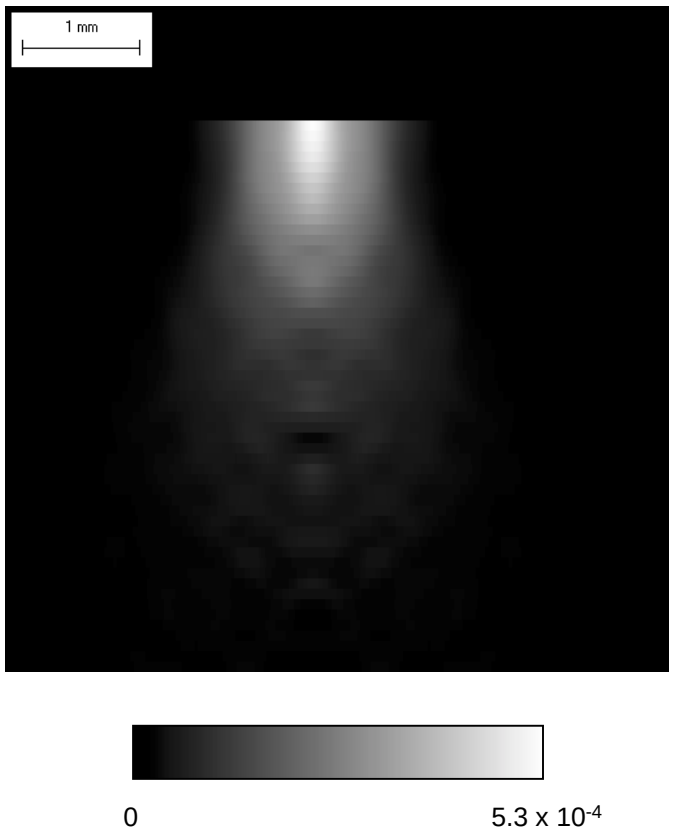


# Number Density of Xe Jet

TARA
TSUKUBA ADVANCED RESEARCH ALLIANCE
筑波大学先端学際領域研究センター

## Refractive index distribution

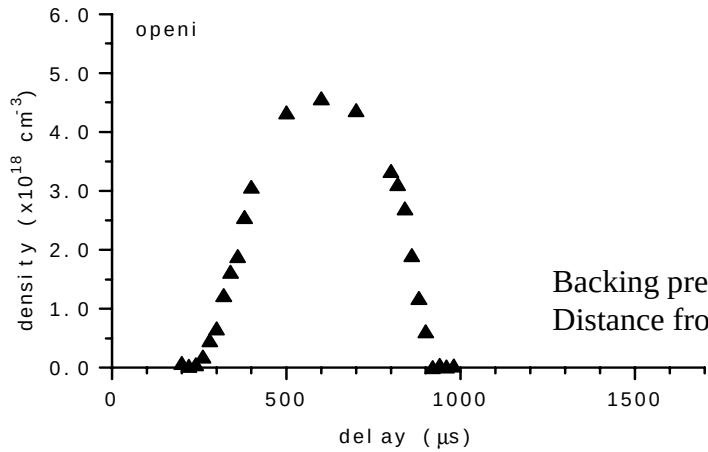
Backing pressure: 0.7 MPa
Delay: 600 μm



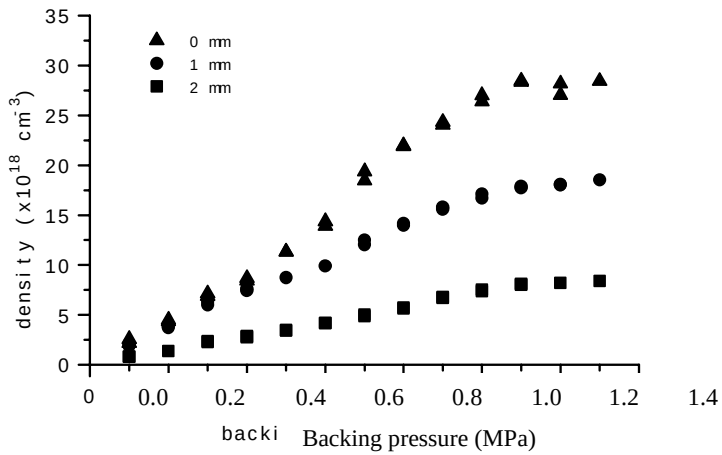

*n* - 1
(*n*: Refractive index)

## Number density of Xe

Opening time: 300 μs




Backing pressure: 0.7 MPa
Distance from nozzle tip: 2 mm



# Experimental Conditions

TARA
TSUKUBA ADVANCED RESEARCH ALLIANCE
筑波大学先端学際領域研究センター

## *Laser:* KrF laser

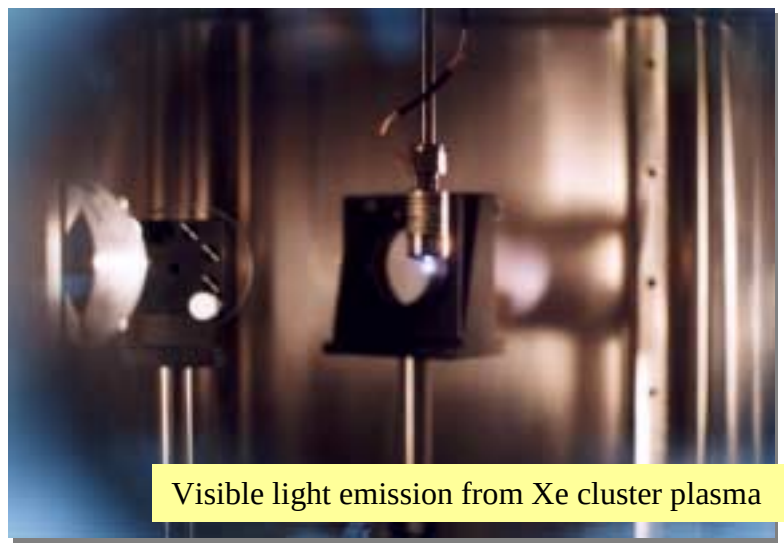
| | |
|---|---|
| Wavelength: | 248 nm |
| Pulse energy: | 20 mJ |
| Pulse width (FWHM): | 350 fs |
| Peak power: | 57 GW |
| Repetition: | 10 Hz |
| Beam size: | 50 mmϕ |
| F-number: | 3.3 |
| Focal spot size (FWHM): | 3 μm |
| Rayleigh length: | 80 μm |

Intensity at the focus in vacuum:
$8 \times 10^{17}$ W/cm$^2$

## *Target:* Xe cluster jet

| | |
|---|---|
| Nozzle orifice: | 2 mm |
| Maximum backing pressure: | 1.1 MPa at 293 K |
| Opening time: | 300 μs |
| Repetition: | 10 Hz |

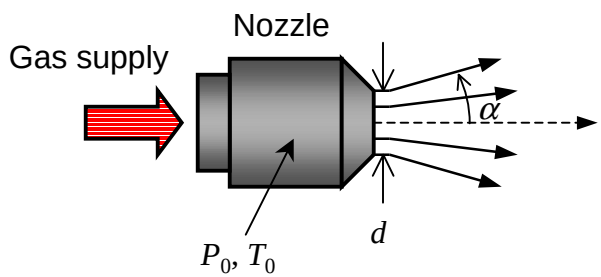
Xe clusters are produced by injection of Xe gas into vacuum from a pulsed valve.


Visible light emission from Xe cluster plasma

# Cluster Size

An empirical formula for mean cluster size injected from nozzles was given by Hagena.

Ref.: O. F. Hagena., Rev. Sci. Instrum **63**, 2374 (1992)

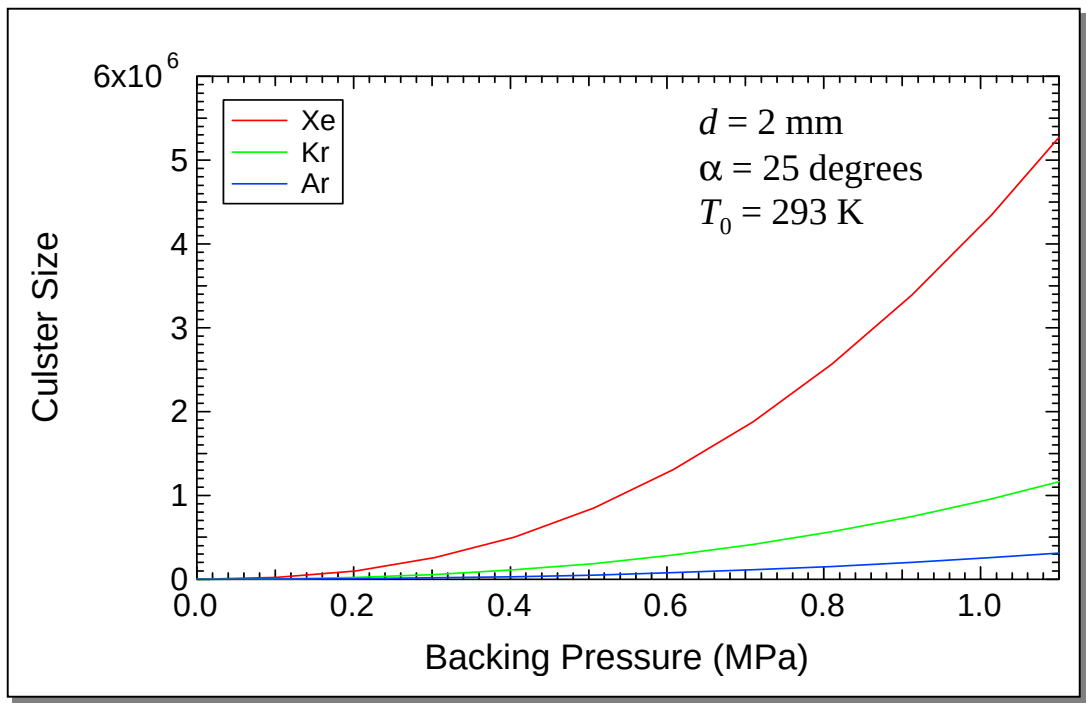



$$\langle N \rangle = 33\left(\frac{\Gamma^*}{1000}\right)^{2.35} \qquad \left(\Gamma^* > 1000\right)$$

$$\Gamma^* = k\frac{\left(d[\mu\text{m}]/\tan\alpha\right)^{0.85} P_0[\text{mbar}]}{T_0^{\,2.29}[\text{K}]}$$

<$N$>: mean cluster size
$k$: condensation parameter
$d$: nozzle diameter
α: cone angle
$P_0$: backing pressure
$T_0$: source temperature

| | Ar | Kr | Xe |
|---|---|---|---|
| $k$ | 1650 | 2890 | 5500 |



# KrF Laser System

TARA
TSUKUBA ADVANCED RESEARCH ALLIANCE
筑波大学先端学際領域研究センター

Where has the absorbed energy gone?

KeV X-ray → 0.2% of $E_{abs}$

↓

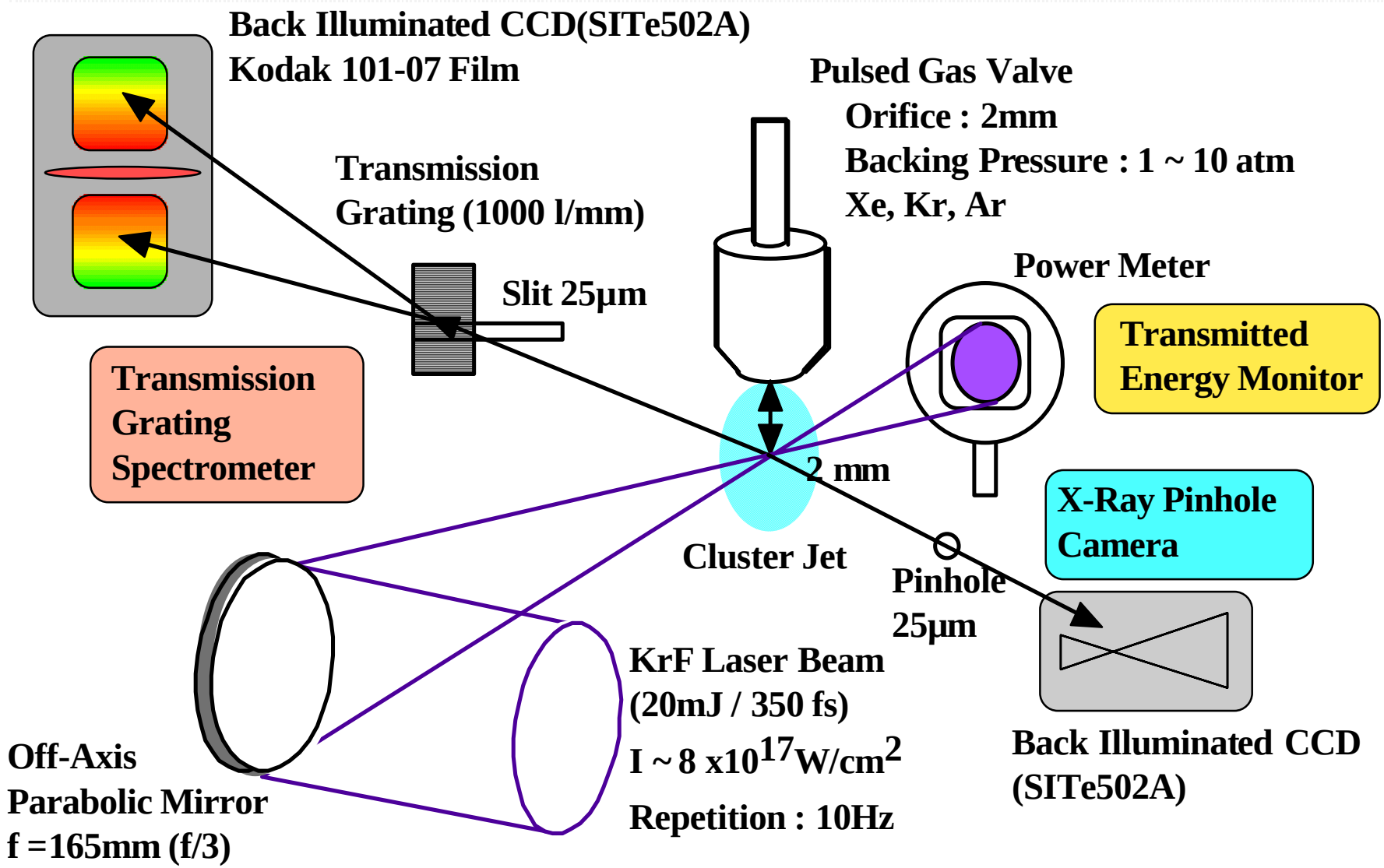
~10 % of $E_{abs}$ must change to

**<u>EUV Light!</u>**

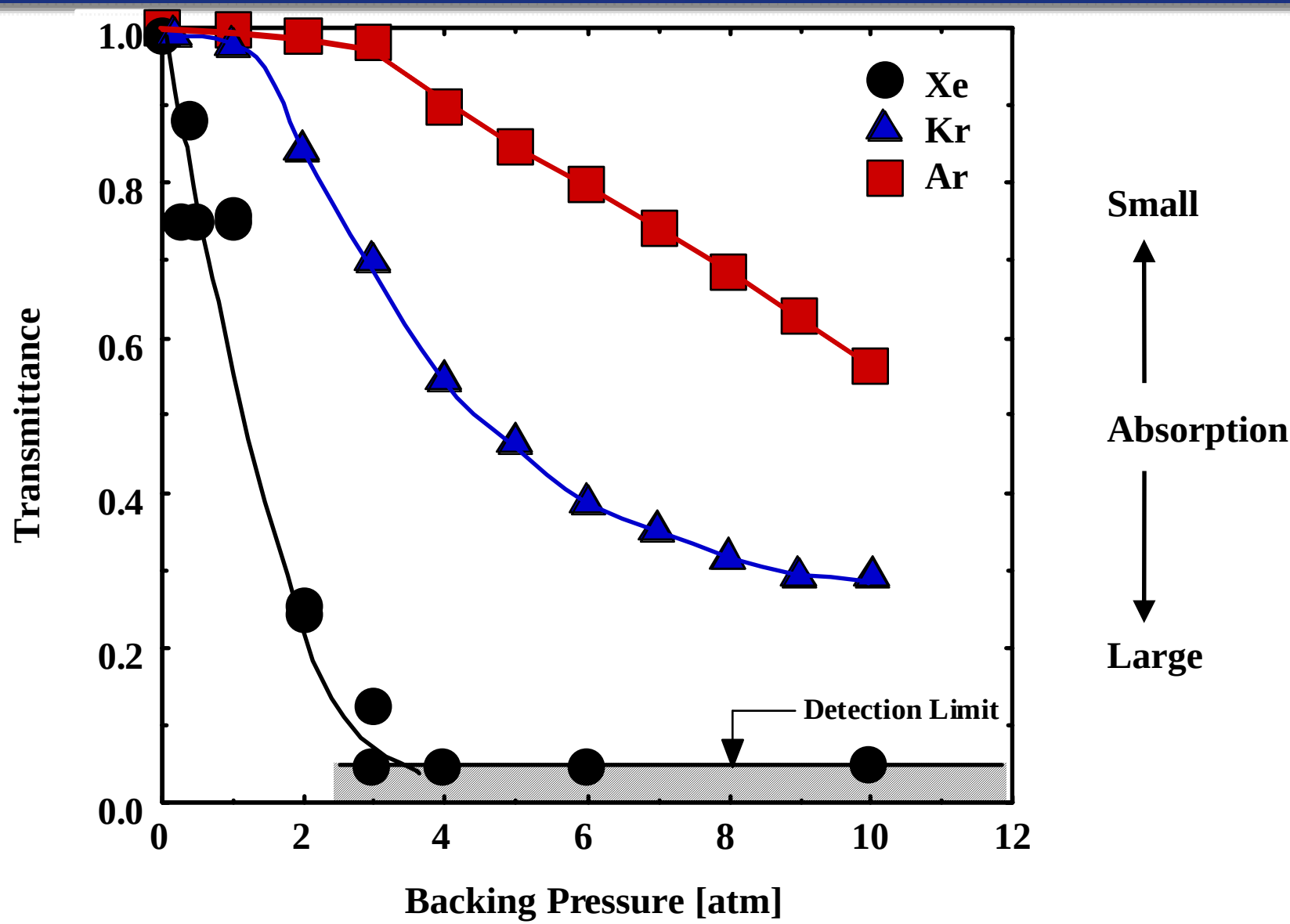
Cluster Jet → Debris Free

EUV Lithography Source!

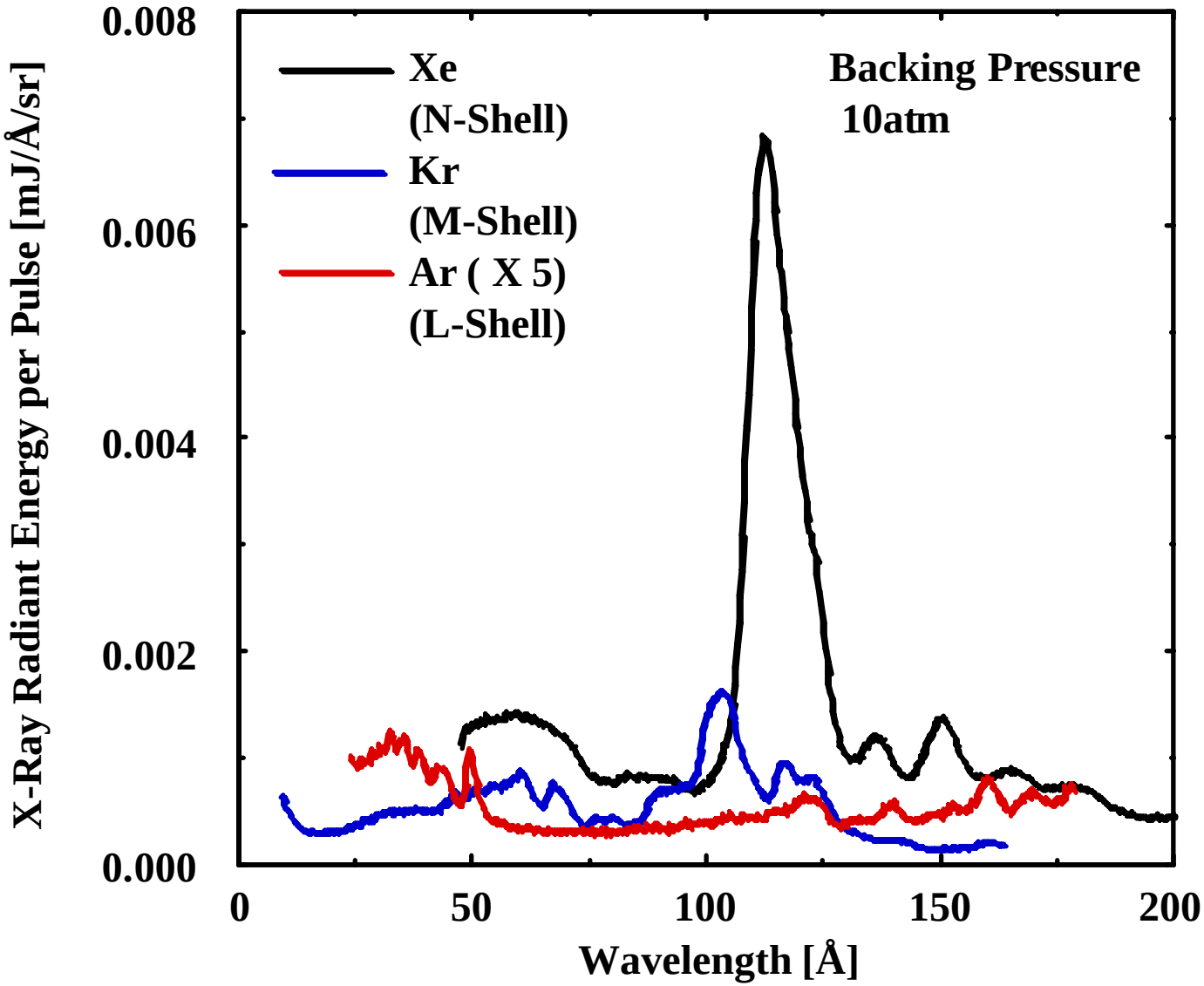
# Experimental Setup



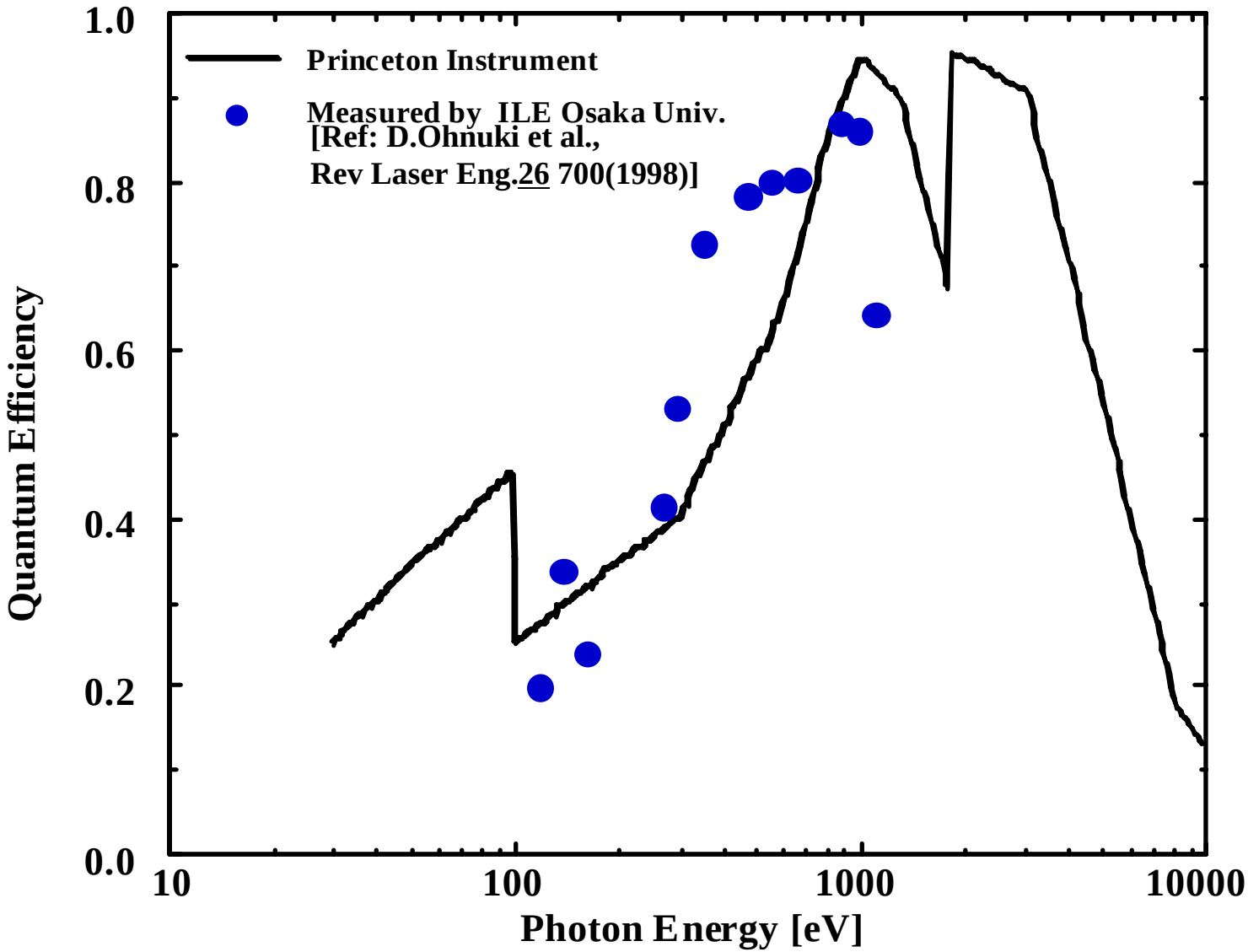
# Transmittance of Laser Energy through Gas Jets



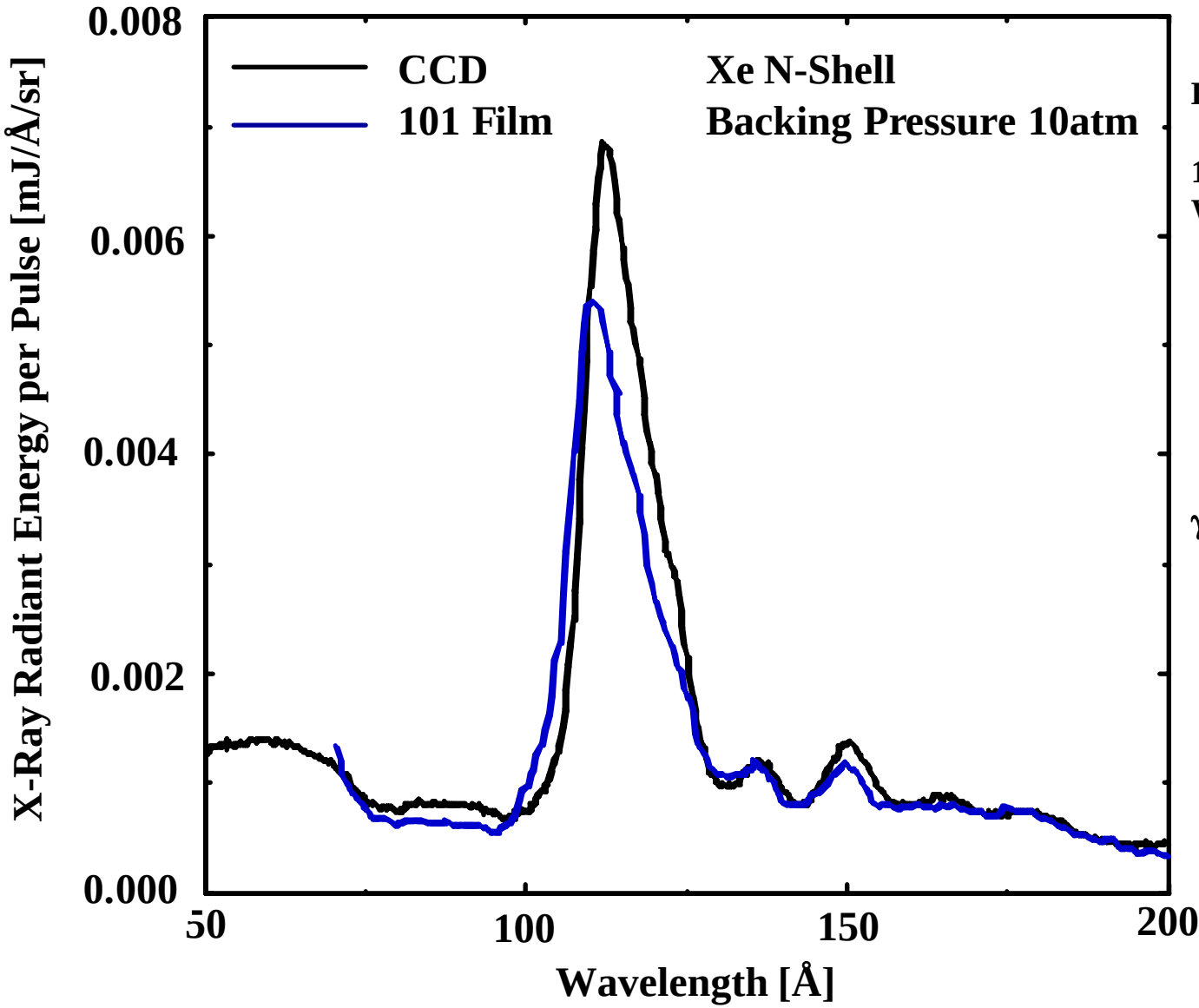
# Soft X-ray Spectra from Various Clusters



# Quantum Efficiency of Back-Illuminated CCD (SITe 502A)



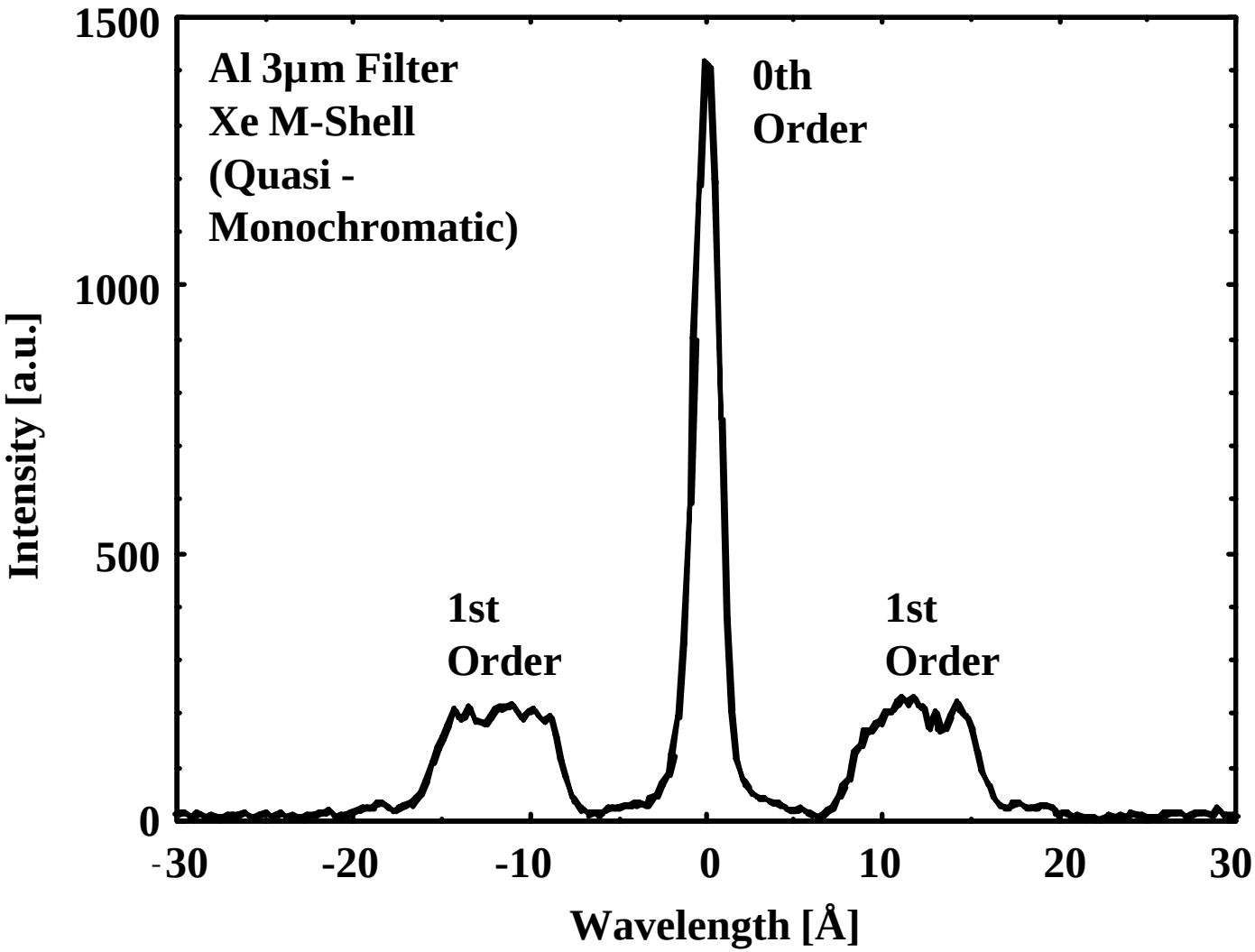
# Comparison of X-Ray Spectra Recorded on Back Illuminated CCD and Kodak 101-07 Film




H.Nishimura et al.,
J. X-Ray Sci. Technol.3 14(1991)
W.Shwanda et al.,
Appl.Opt. 31 554(1992)

γ - Curve of Kodak 101 Film

# Measurement of Diffraction Efficiency of Transmission Grating



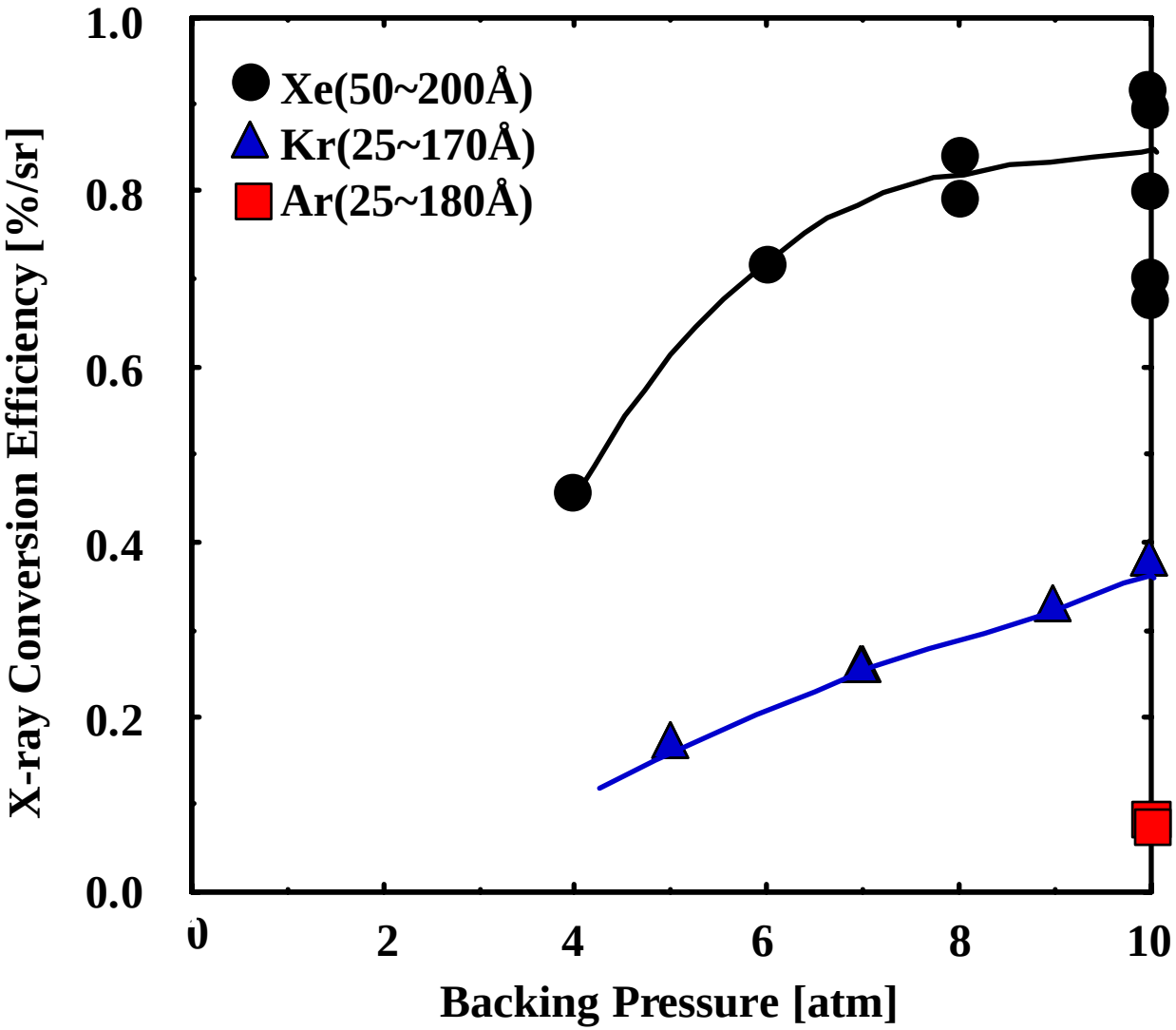

$$\eta_{1st} = \frac{I(1st\ \ order)}{I(on\ \ CCD)} \times \left(\frac{a}{d}\right)$$

d:Period of Grating
a:Gap Width

↓

Diffraction Efficiency = 7.5%
(Theoretical Value ~ 10%)

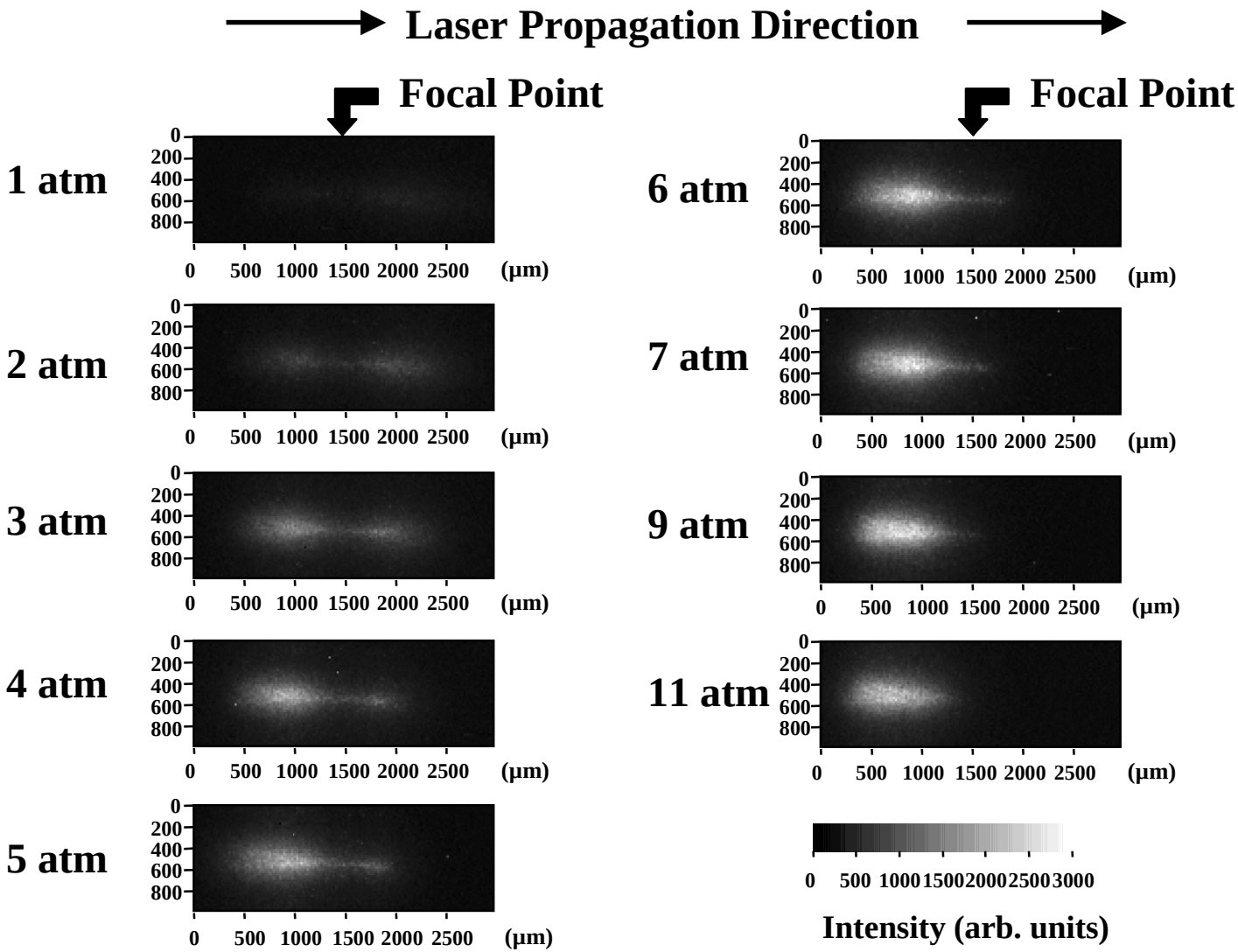
# Dependence of X-Ray Conversion Efficiency on Backing Pressure of Pulsed Valve




**Total Conversion Efficiency**
**>10%**
**(Assuming the Uniform Angular Distribution)**

**2mJ/ 10Hz**
**Average Power ~ 20mW**

# Soft X-ray Images from Xe Clusters



# Conclusion

**Conversion Efficiency from Laser Light toEUV Light (5-20 nm) was 13%. It Corresponds to 0.5% at 13.5 nm in 0.5 nm bandwidth.**