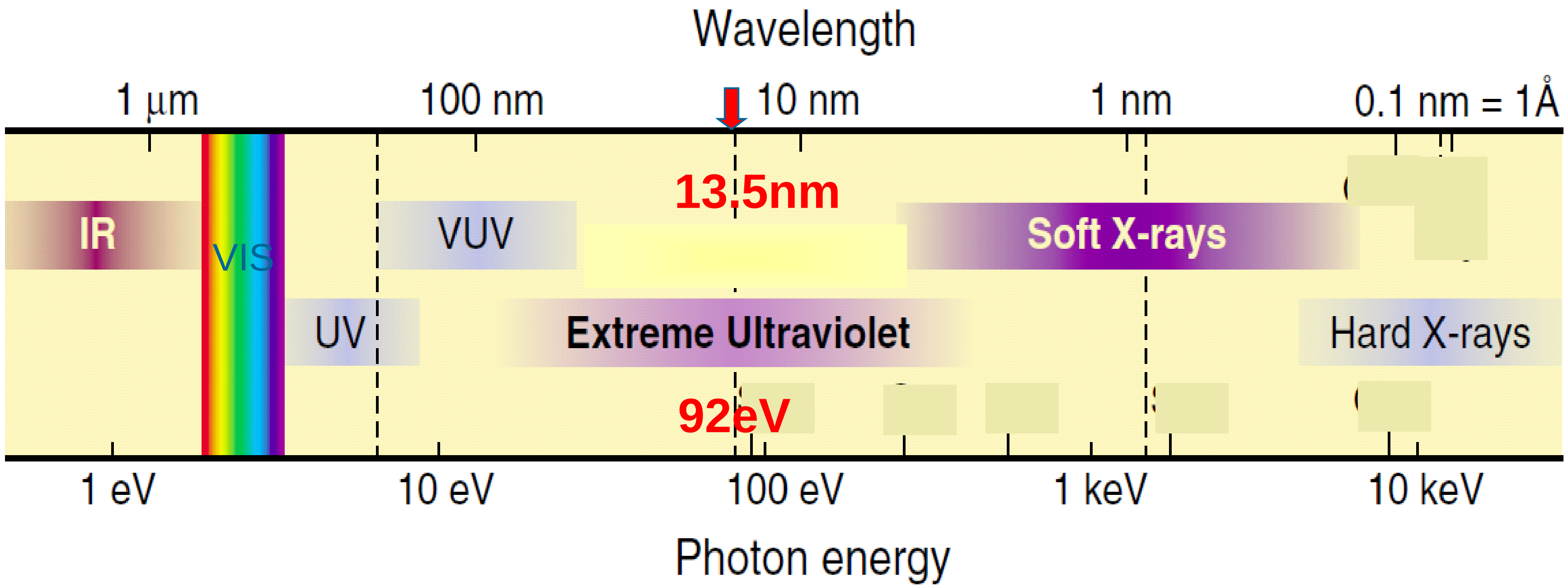
EUV lithography and Source Technology

History and Present

Akira Endo
Hilase Project

22. September 2017
EXTATIC, Prague

Optical wavelength and EUV (Extreme Ultraviolet)



From Prof. Atwood

Characteristics of EUV light

wavelength a few nm - a few 10 nm

- propagation only in vacuum
- reflective optics only

EUV LITHOGRAPHY

Lithography gets extreme

Christian Wagner and Noreen Harned

Extreme ultraviolet lithography extends photolithography to much shorter wavelengths and is a cost-effective method of producing more-advanced integrated circuits. Although some infrastructure challenges still remain, this technology is expected to begin high-volume microchip production within the next three years.

Progress in semiconductor manufacturing is all about reducing the size of the features that make up integrated circuit (IC) designs. Smaller features allow for faster and more advanced ICs that consume less power and can be produced at lower cost.

For semiconductor manufacturing, photolithography is the key driver for this shrink in features. Photolithography uses light to transfer a pattern of features from a mask to a light-sensitive chemical photoresist on a semiconductor wafer. As the pattern is transferred, it is reduced in scale by a projection lens.

The history of photolithography is a continuous effort to improve the resolution of lithography systems (commonly known as scanners). This can be achieved using optical and processing tricks to increase the numerical aperture of the projection lens in the system, or by reducing the wavelength of the light used. Since the 1980s, cutting-edge lithography has shifted from the 365 nm 'i-line' of mercury vapour lamps to deep-ultraviolet light from excimer lasers at 248 nm (krypton fluoride lasers) and 193 nm (argon fluoride lasers; Fig. 1).

Extreme ultraviolet (EUV) lithography is the next step in this trend. It uses radiation of wavelength 13.5 nm, thereby

CARL ZEISS

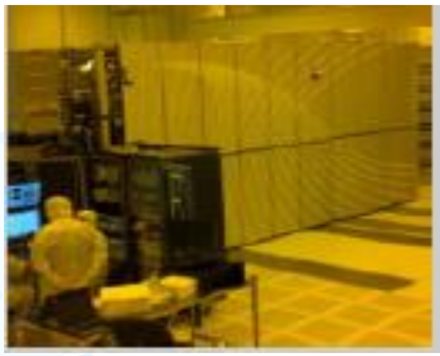
Manufacturing mirrors for EUV lithography is a huge technical challenge.

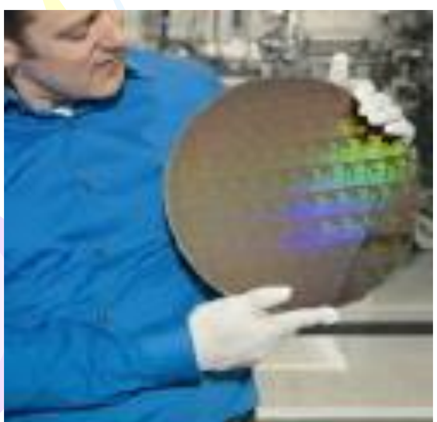
Nature Photonics, January 2010

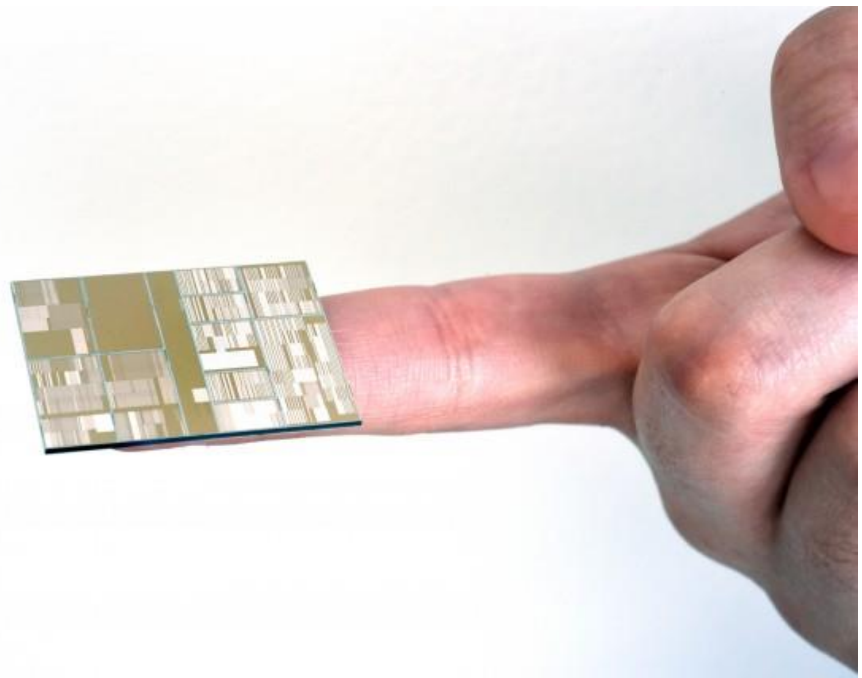
IBM unveils world's first 5nm chip

Built with a new type of gate-all-around transistor, plus extreme ultraviolet lithography.

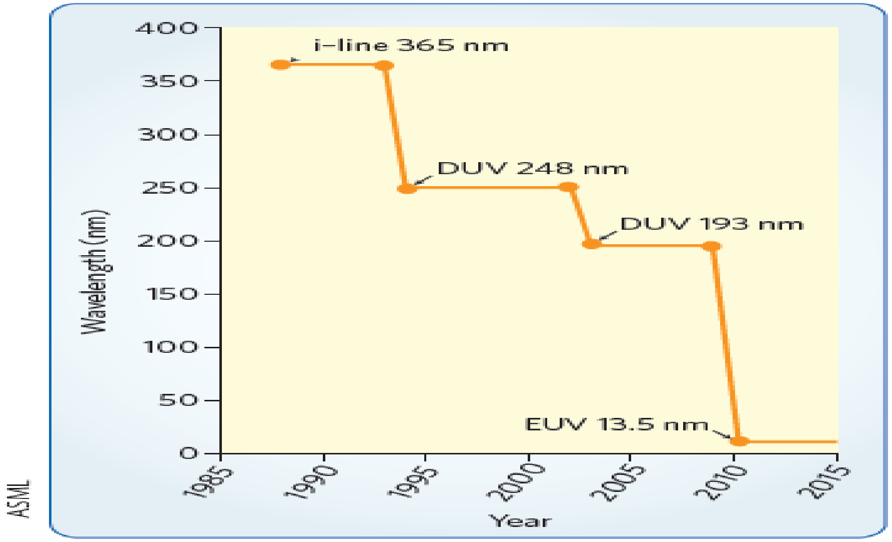
SEBASTIAN ANTHONY - 5/6/2017, 06:01







Lithography wavelength evolution

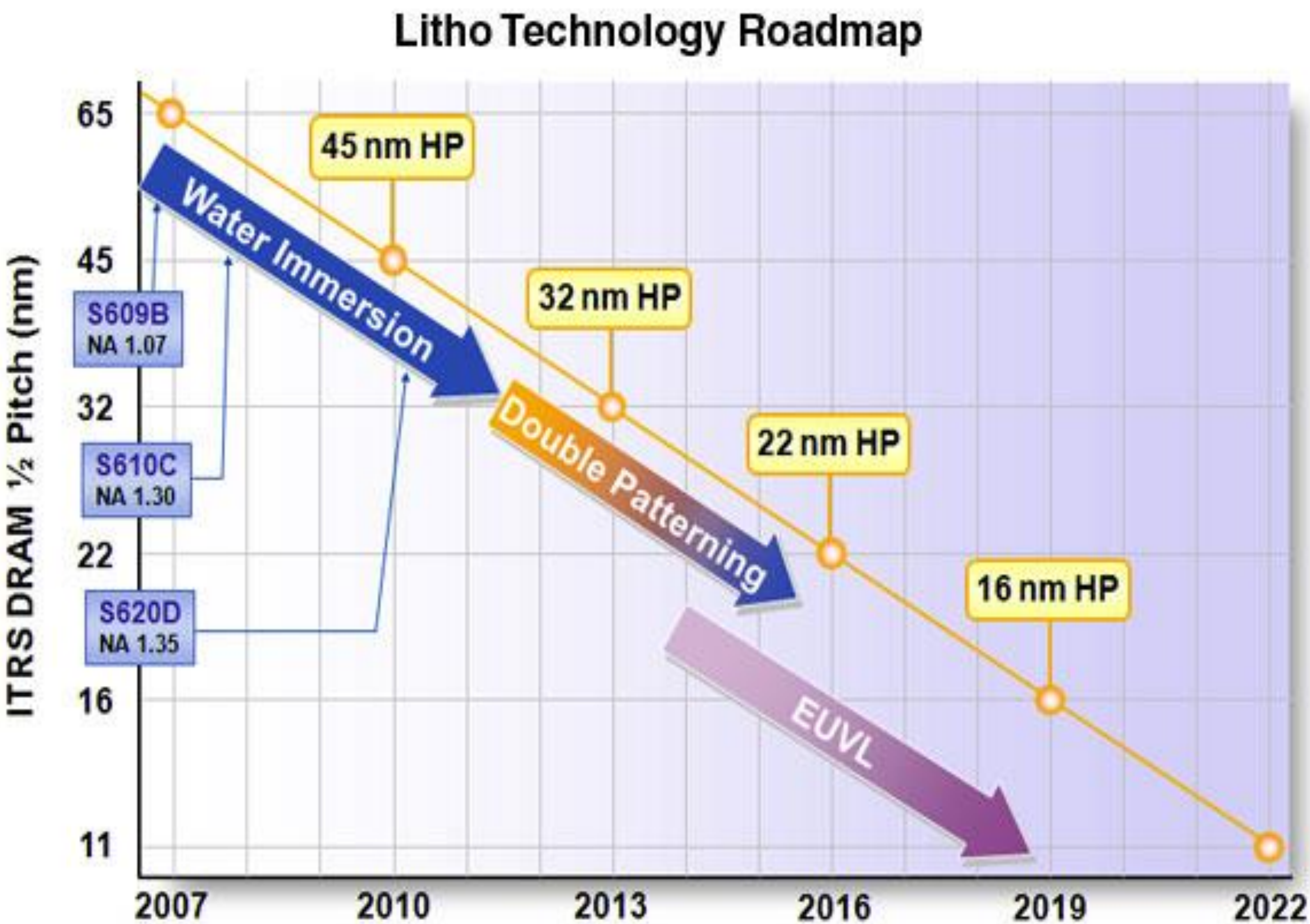


Minimum lithographic feature size = $\frac{K1\ \lambda}{NA}$

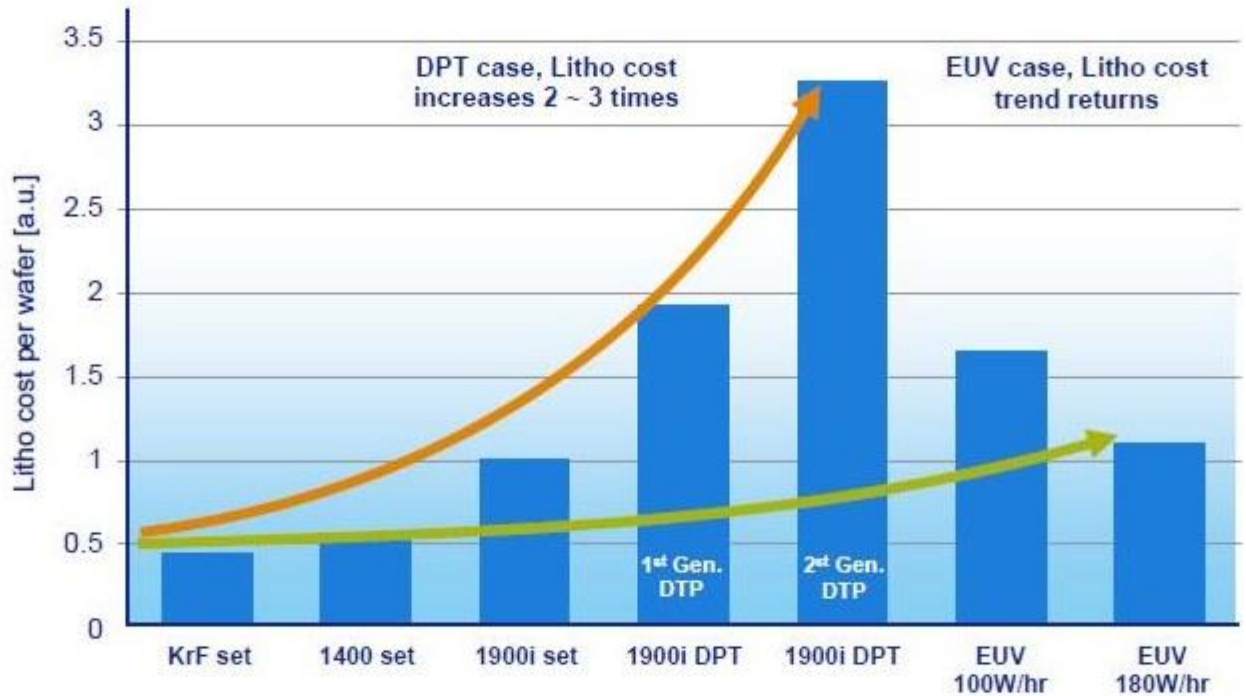
k1: "Process complexity factor" – includes "tricks" like phase-shift masks

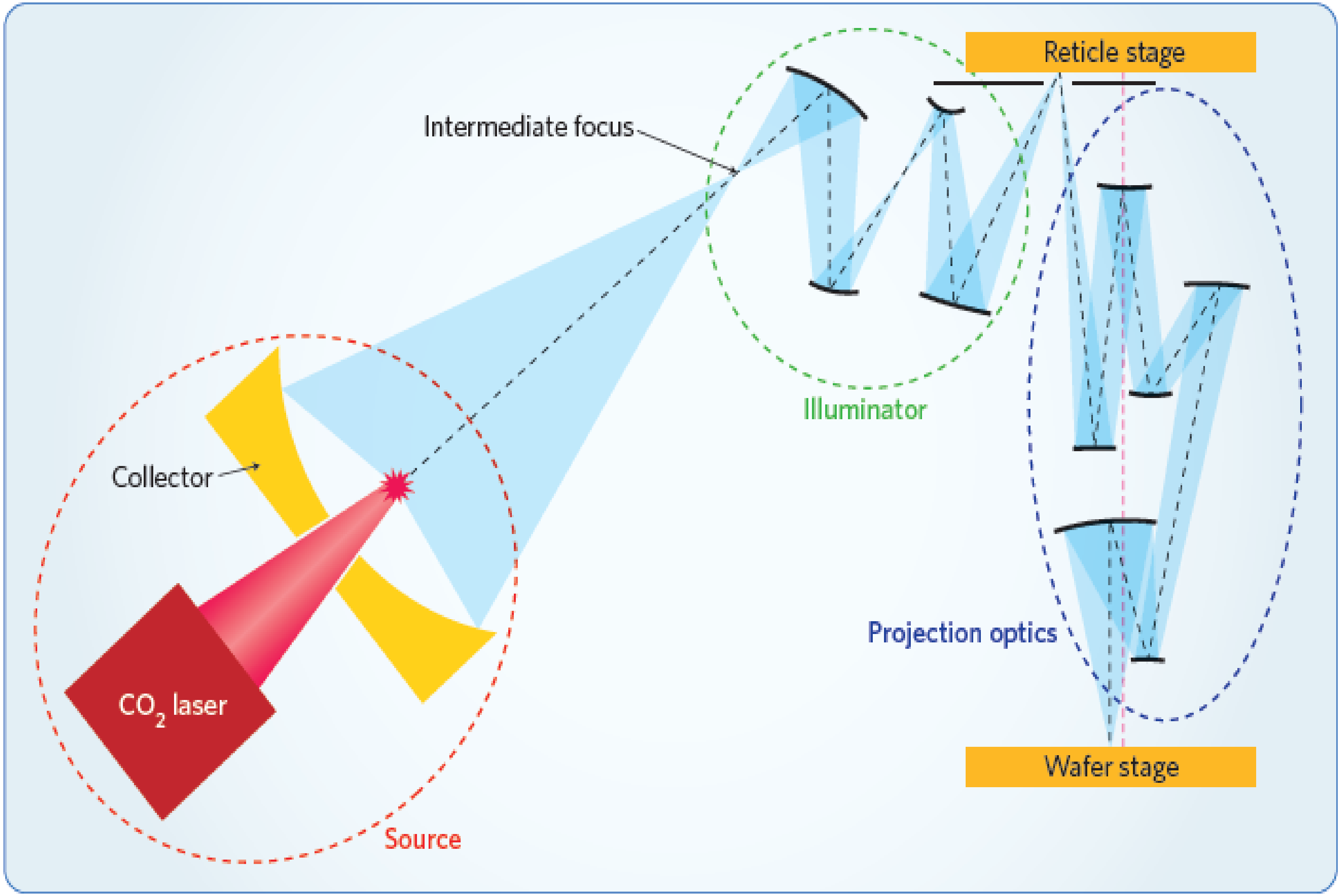
λ: Exposure wavelength

NA: Numerical aperture of the lens – maximum of 1 in air, a little higher in immersion lithography (Higher NA means smaller depth of focus, though)


Litho Technology Roadmap
ITRS DRAM ½ Pitch (nm)
65
45
32
22
16
11
2007
2010
2013
2016
2019
2022
45 nm HP
32 nm HP
22 nm HP
16 nm HP
Water Immersion
Double Patterning
EUVL
S609B
NA 1.07
S610C
NA 1.30
S620D
NA 1.35

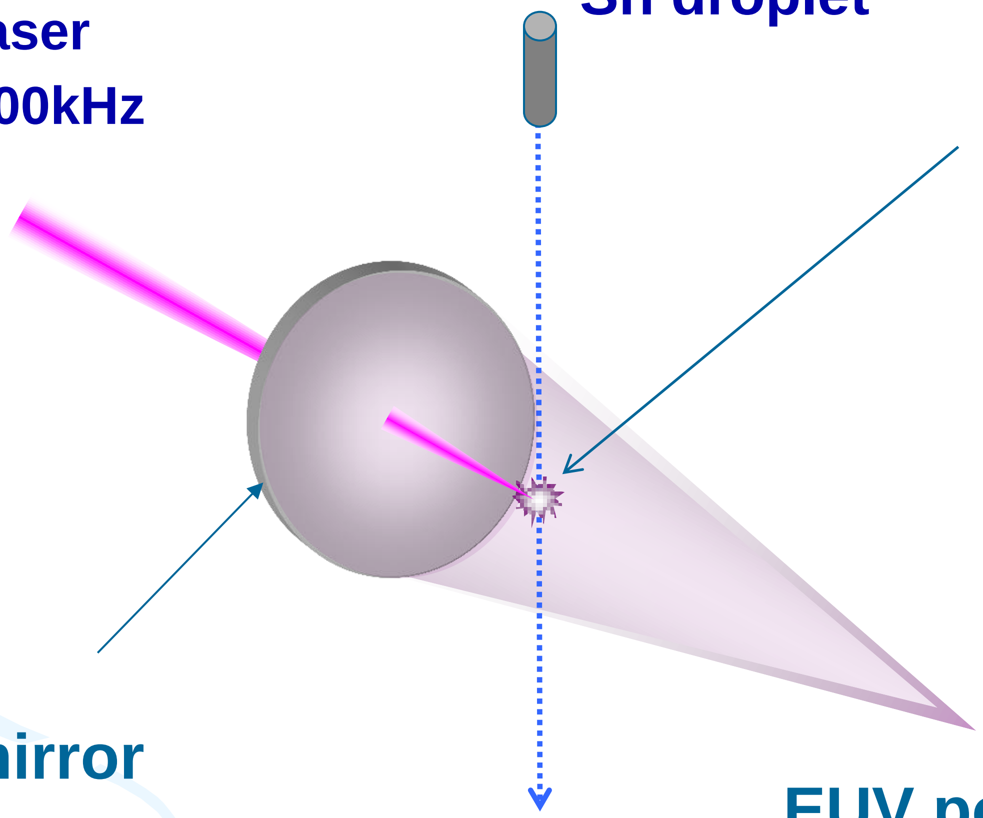
Litho costs back to normal with EUV >100 W/hr



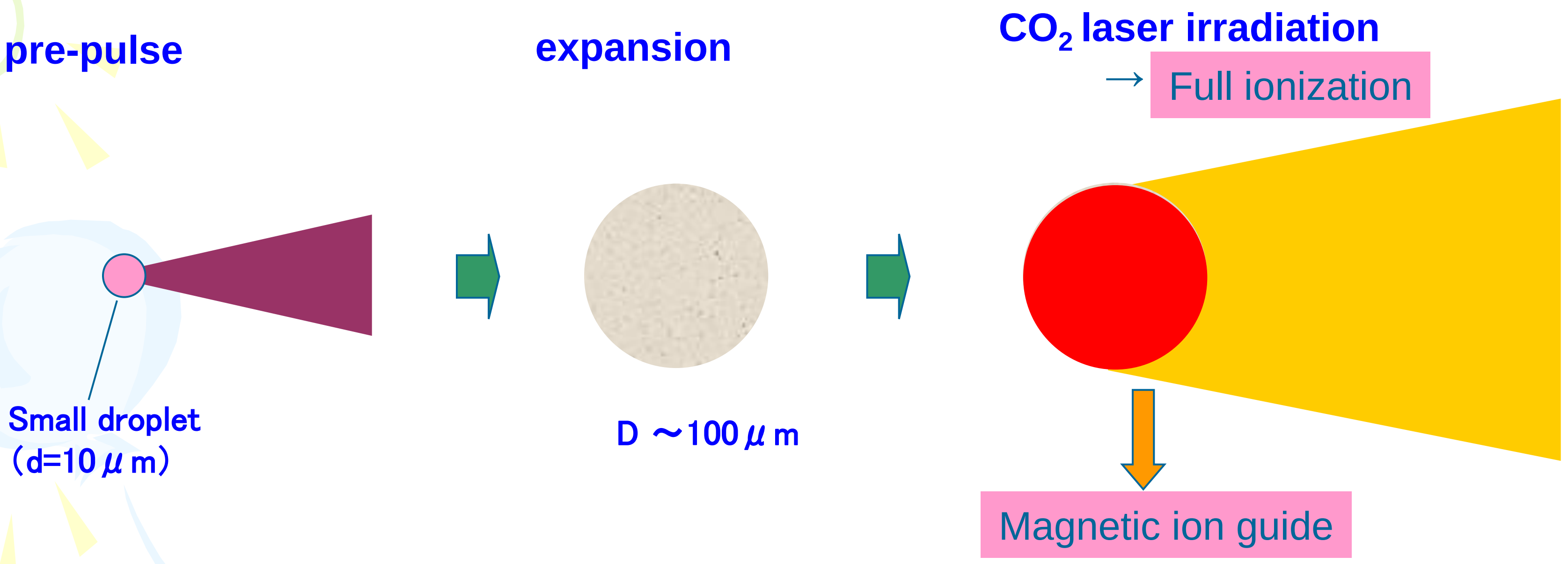


Reticle stage
Intermediate focus
Illuminator
Collector
CO_2 laser
Source
Projection optics
Wafer stage

Configuration of EUV source



Optimization of pre-plasma conditioning



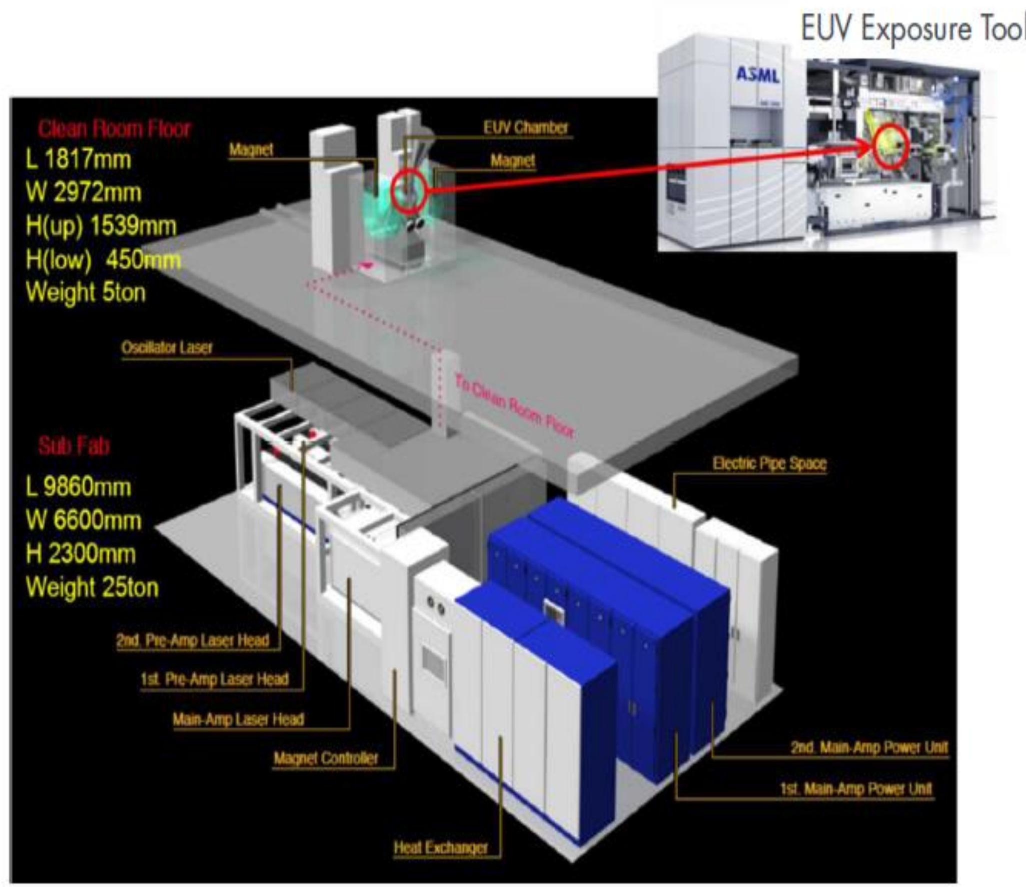
Optimize density, temperature and spatial distribution
for main pulse heating to achieve high EUV conversion efficiency
and **full exhaust of Sn atoms**

Layout of 250W EUV Light Source Pilot #1

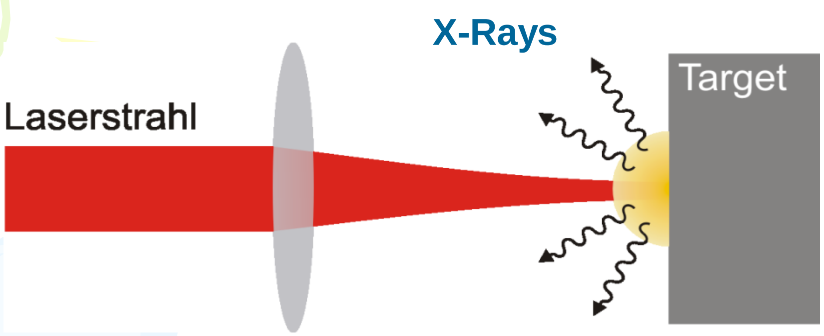
First HVM EUV Source

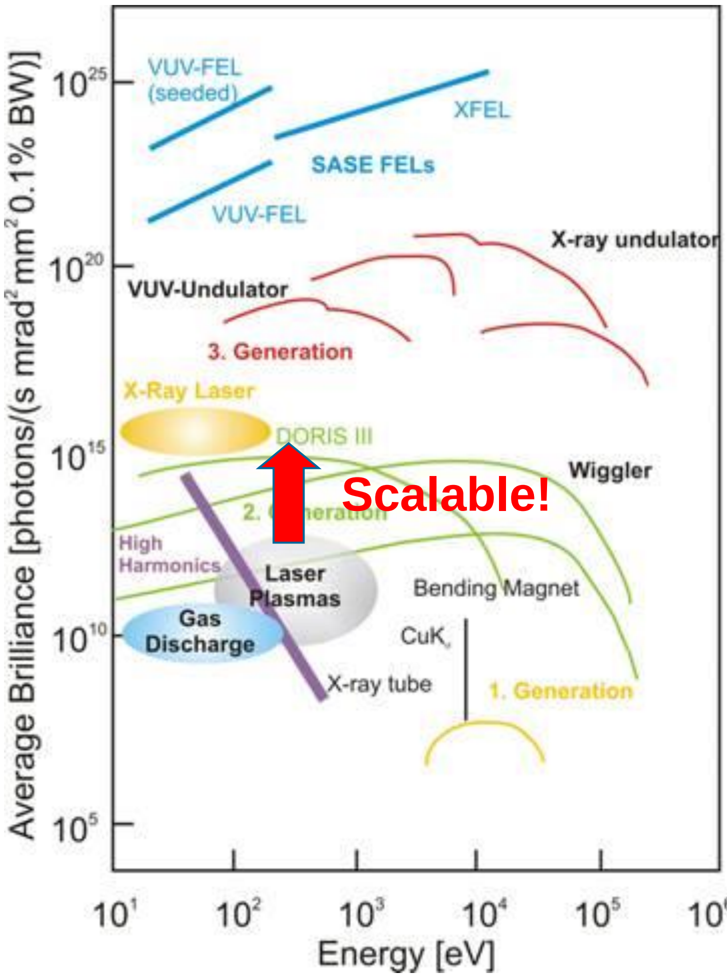
- 250W EUV source

Operational specification (Target)			HVM Source
Perform ance	EUV Power		> 250W
	CE		> 4.0 %
	Pulse rate		100kHz
	Availability		> 75%
Techno logy	Droplet generator	Droplet size	< 20mm
	CO2 laser	Power	> 20kW
	Pre-pulse laser	Pulse duration	psec
	Debris mitigation	Magnet, Etching	> 15 days (>1500Mpls)



Laser-produced plasma

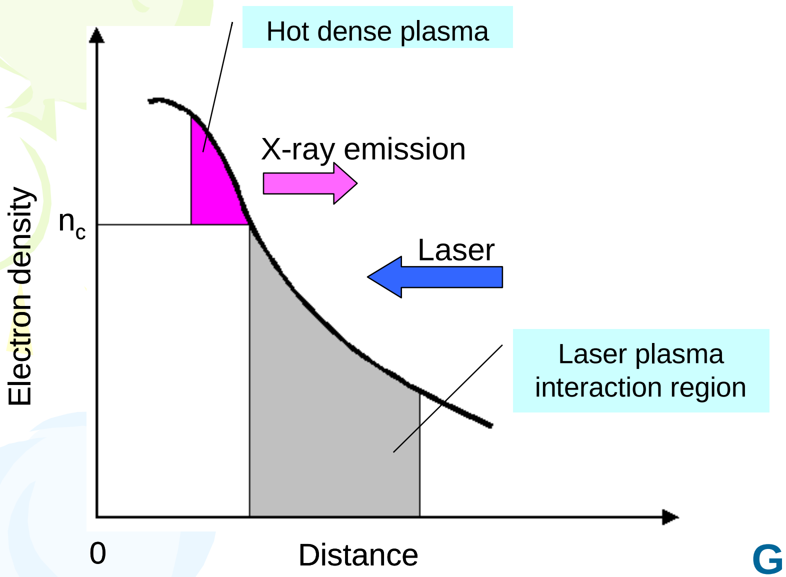




- ionization of target material
- heating by inverse Bremsstrahlung
- hot, dense plasma
  ($T_e > 50$eV; $10^{20} < n_e < 10^{24}$ e/cm^3)
- emission of Bremsstrahlung and charact. x-rays

$$Brilliance = \frac{N_{Photonen}}{s \cdot mm^2 \cdot mrad^2 \cdot 0{,}1\% BW}$$

CO_2 laser is efficient, clean driver for Sn EUV plasma



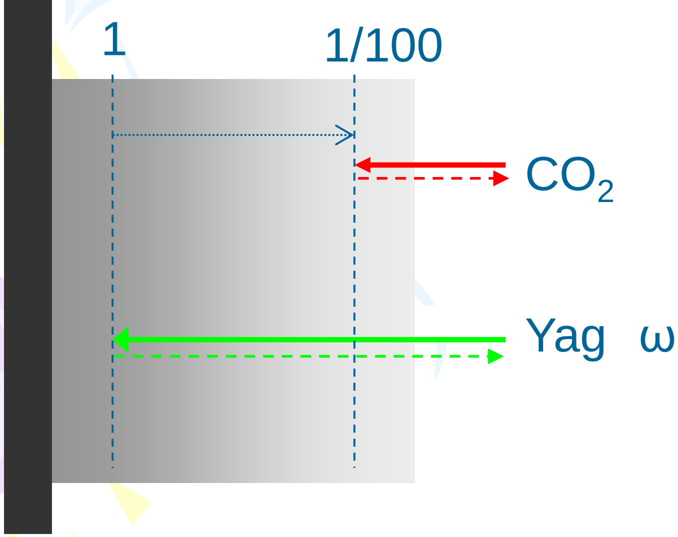
EUV radiation is emitted from hot dense plasma near the electron critical density nc.

$$n_c = \frac{\varepsilon_0 m \omega^2}{e^2} = \frac{1.11\times 10^{21}}{\lambda^2}(\mathrm{cm}^{-3})$$

λ: wavelength in μm

Generated EUV is reabsorbed by plasma. CO_2 laser produced plasma reduces EUV propagation loss.

Cut off density :Nc



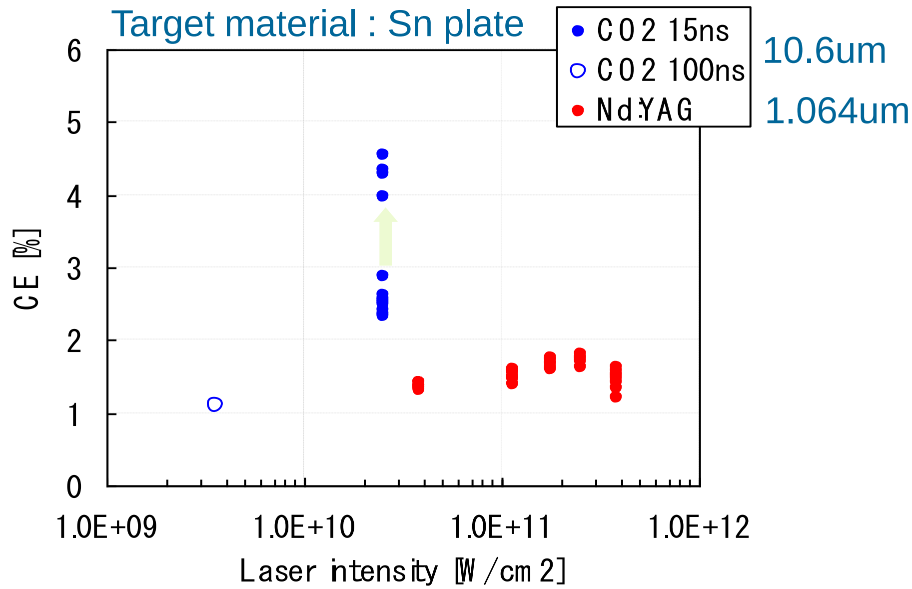
CO_2 laser light is absorbed by low density plasma. Thermal boiling of liquid Sn is avoided.

Sn plasma generated by Nd:YAG and CO_2 laser

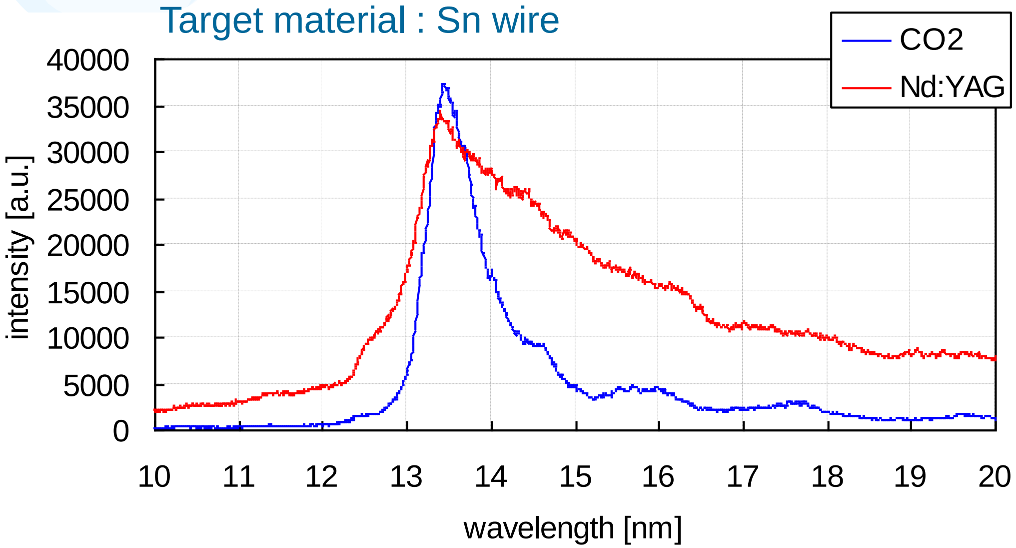
Conversion efficiency
dependence on the laser intensity

CE: 2.5% - 4.5% with CO2 laser
Laser intensity: 3×10^{10} W/cm^2
*energy:30mJ
*Pulse width:11ns
*Spot size: d=100um

Target material : Sn plate



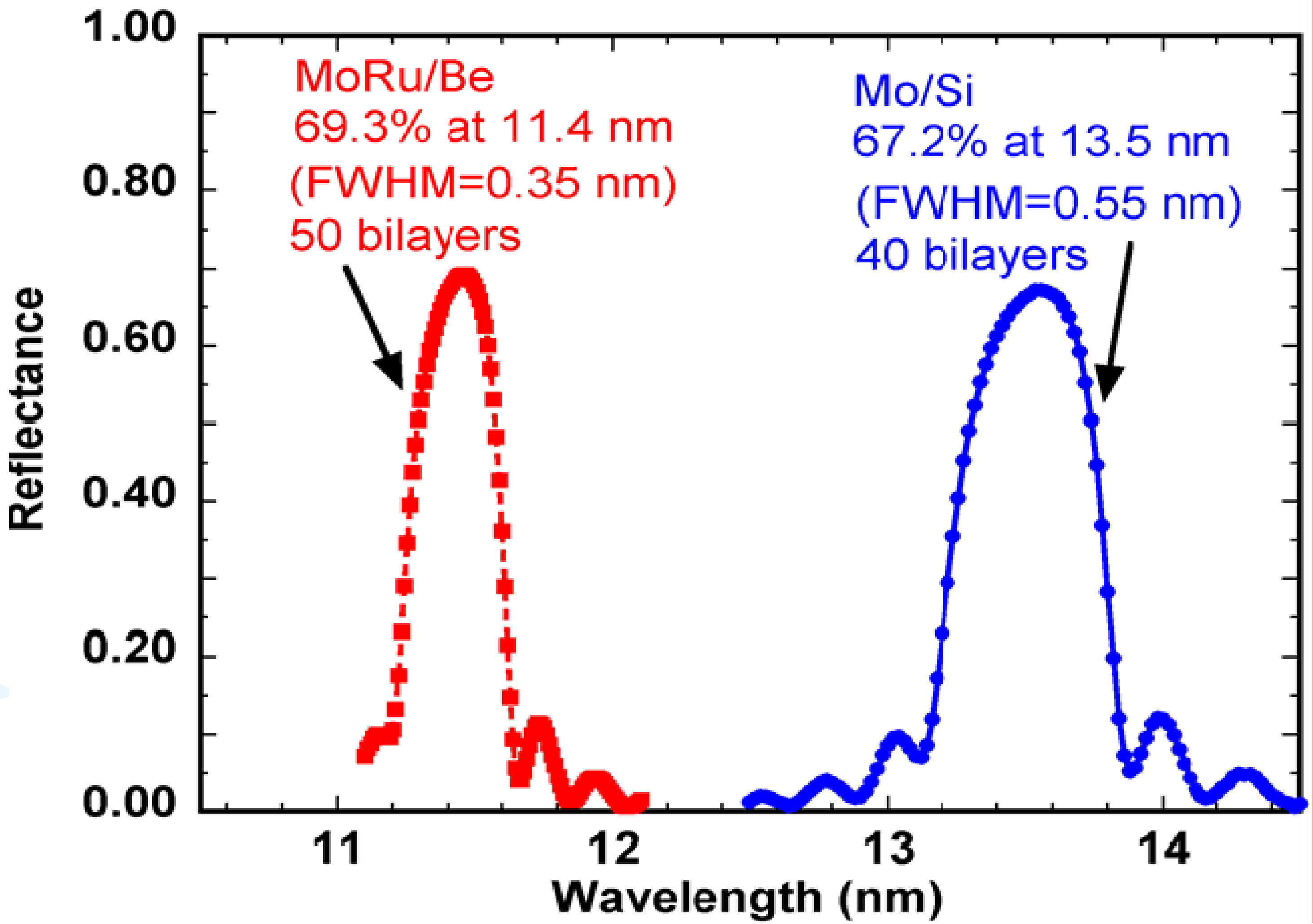
Target material : Sn wire



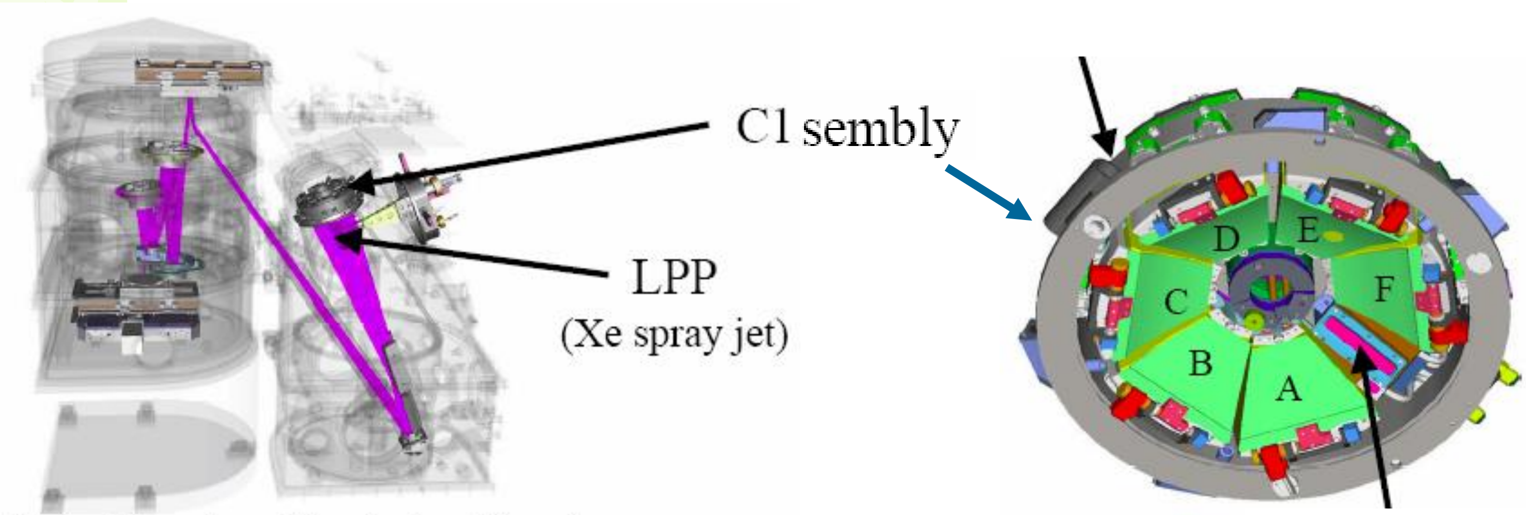
EUV spectra from Sn plasma

Narrow in-band spectrum with CO2 laser

Selection of Reflective optics

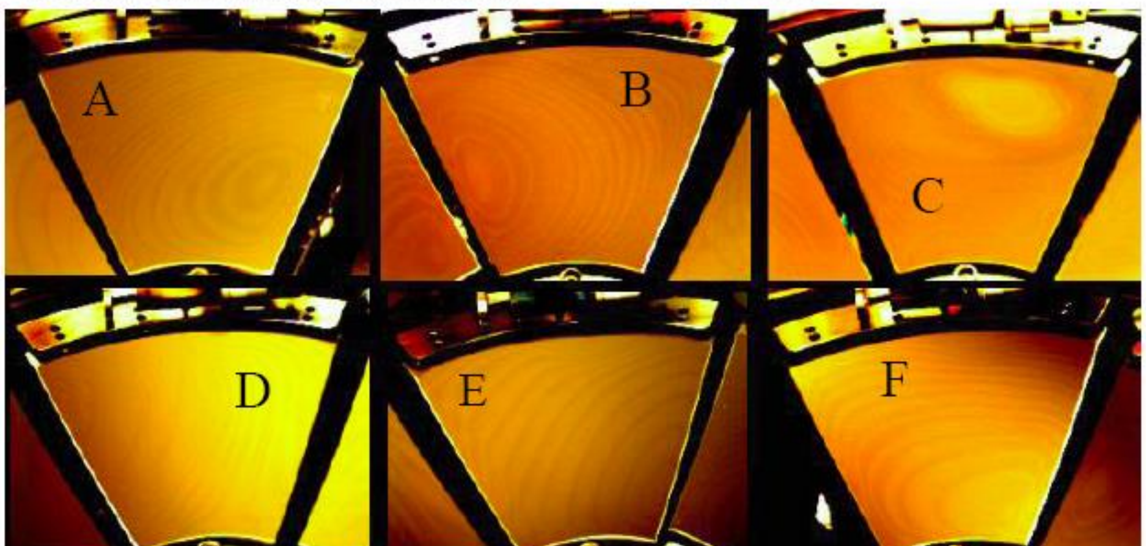


LPP source and mirror damage：ETS with Xe spray jet



C1 set 2 Petals, removed 2/11/03

C1 Set 2 after 150M shots



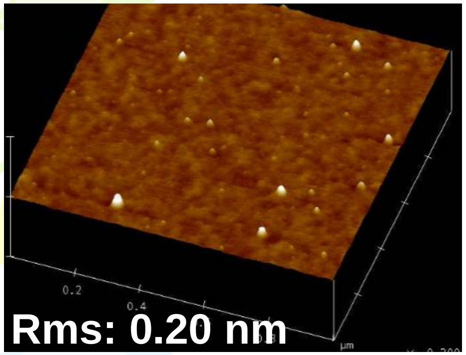
150M shot

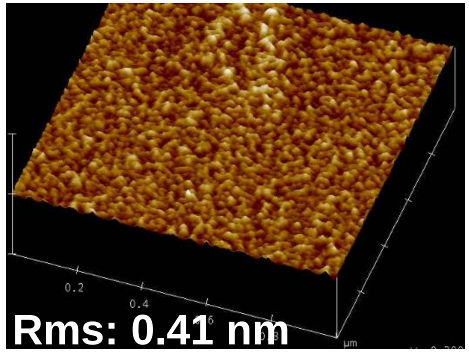
VNL Virtual National Laboratory
Lennie Klebanoff

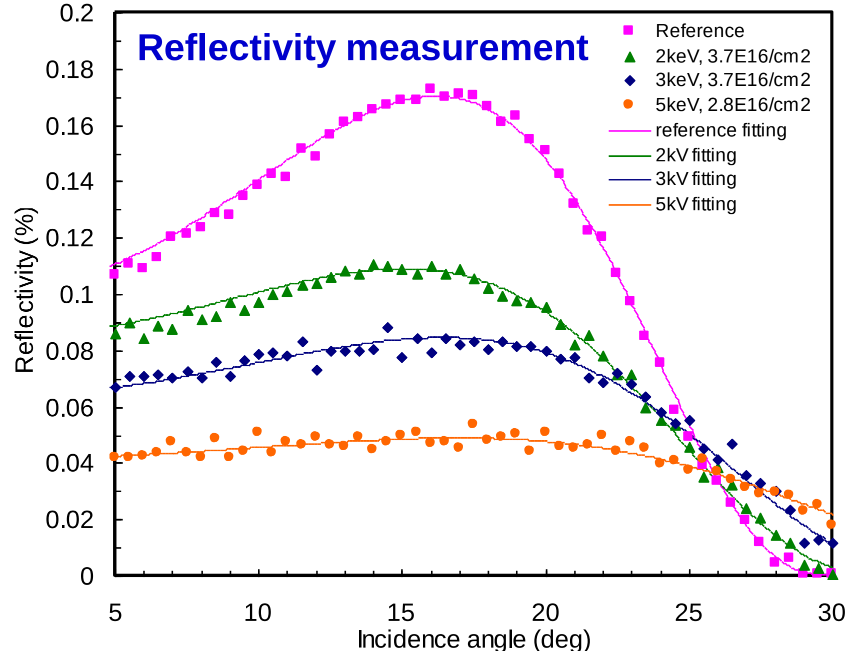
：2nd EUV Symposium, October 1. 2003, “Condenser Erosion Observations in the ETS” Lennie Klebanoff, SNL

Analysis of ion exposed samples

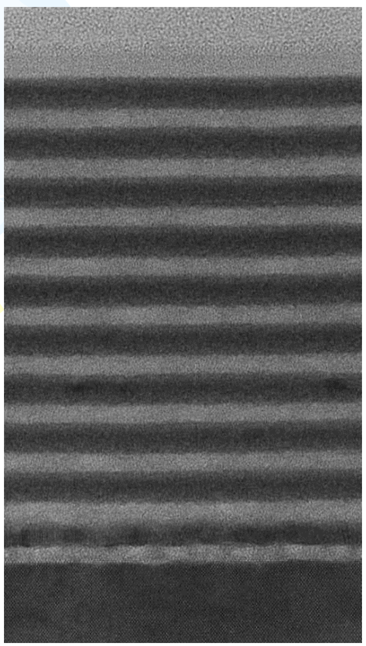
AFM

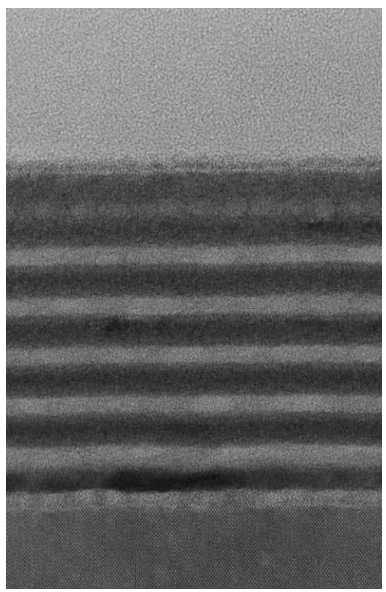




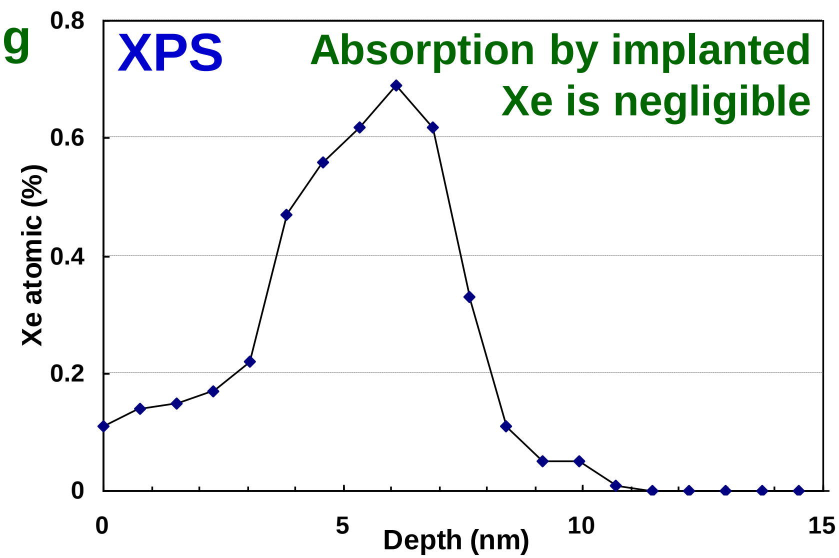


TEM





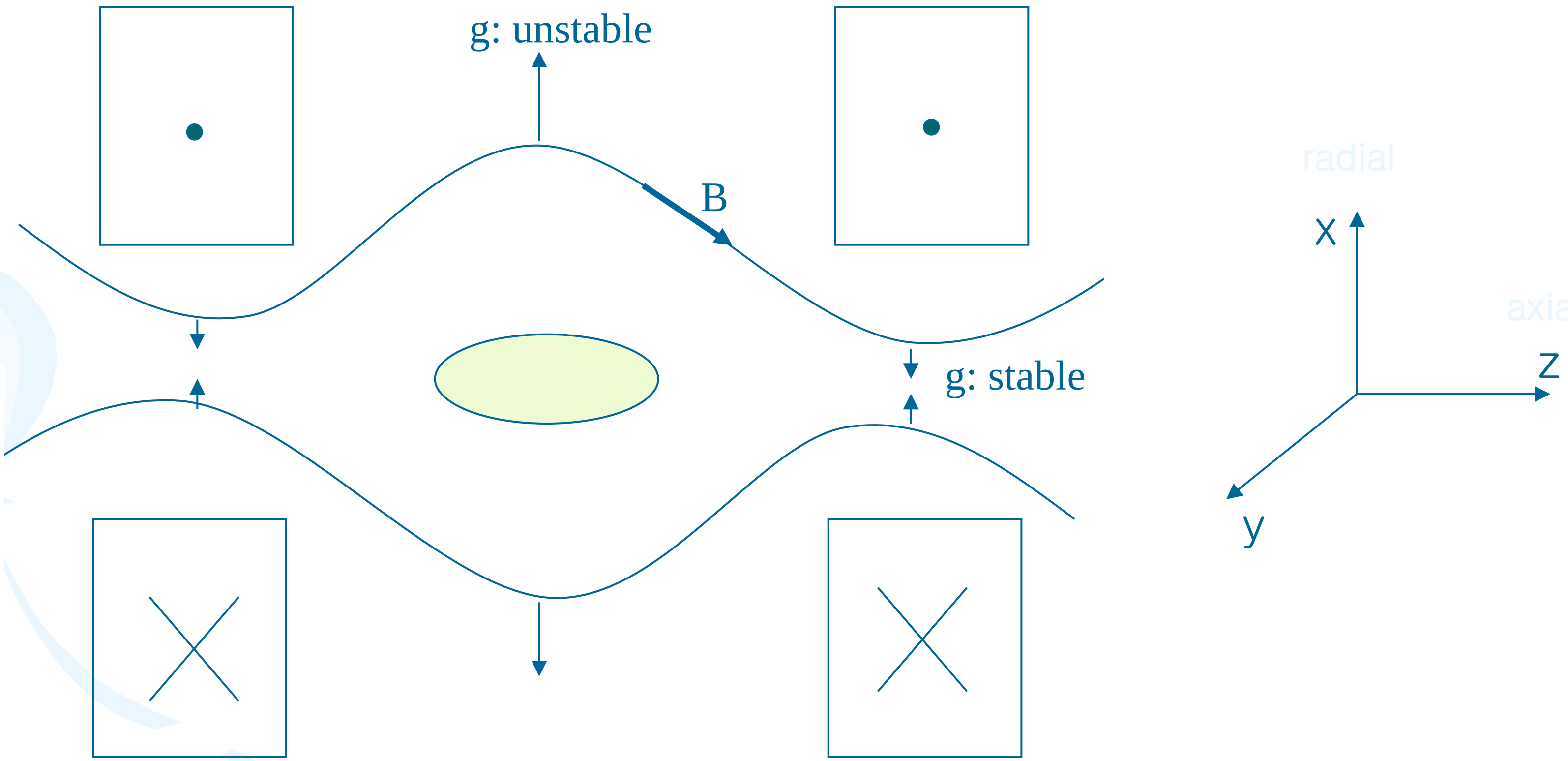
Mixing



Reference
(10 Mo/Si bilayer)

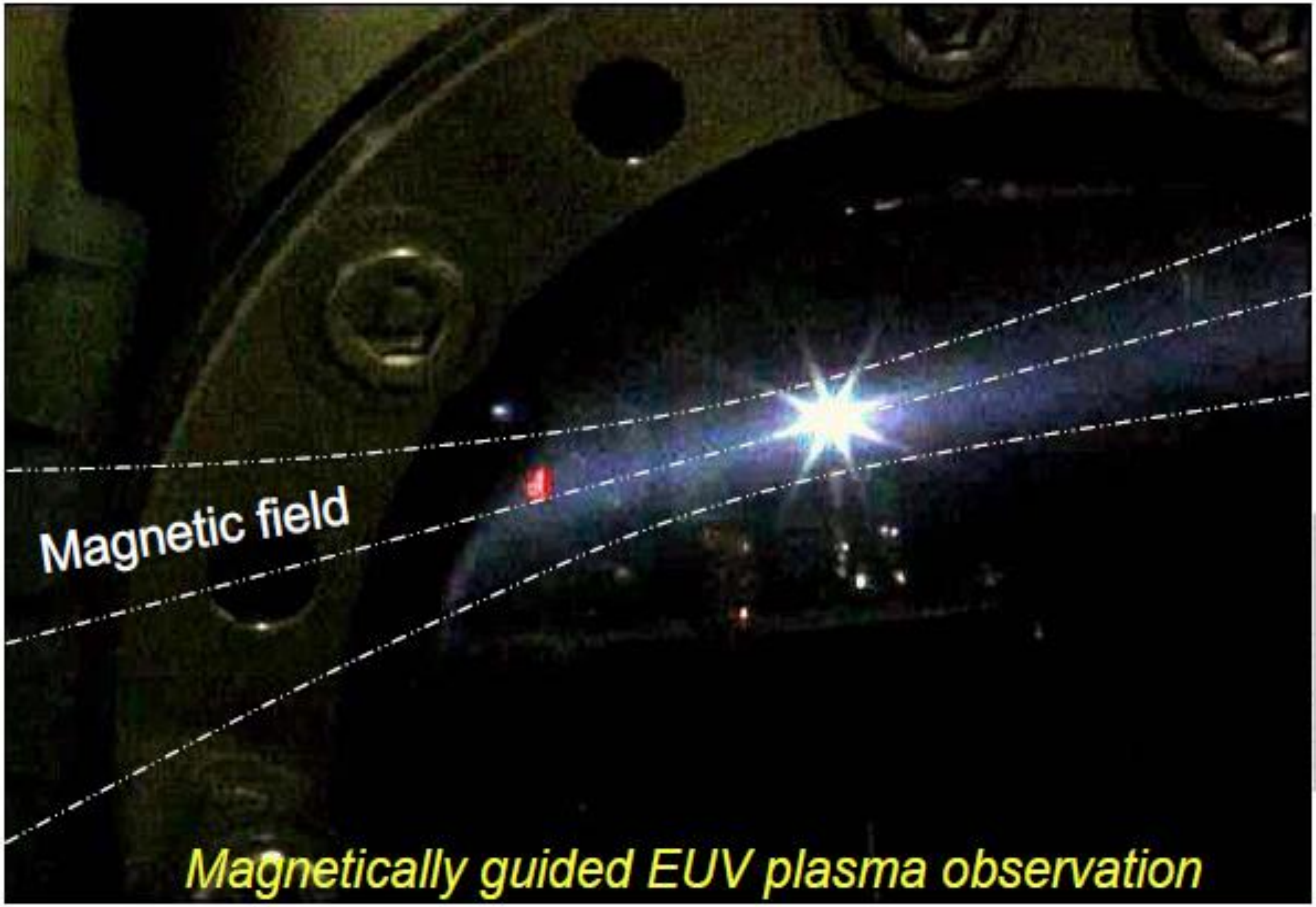
Ion energy 5 keV
Ion dose 2.8 X 10^{16} atoms/cm^2

Plasma in magnetic mirrors

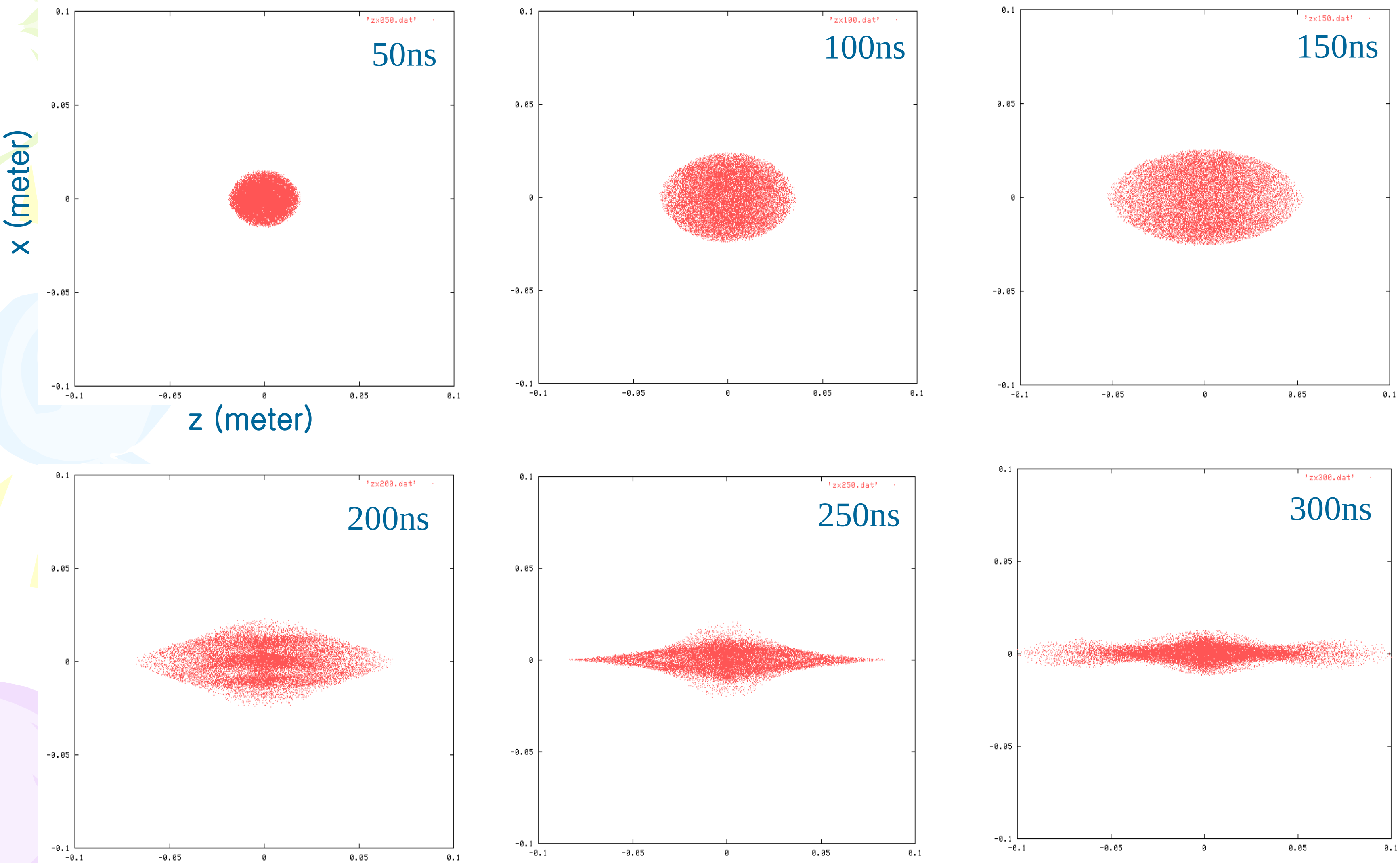


Curvature drift $v = \frac{mv_{\parallel}^2}{qB^2} \frac{R \times B}{R^2}$

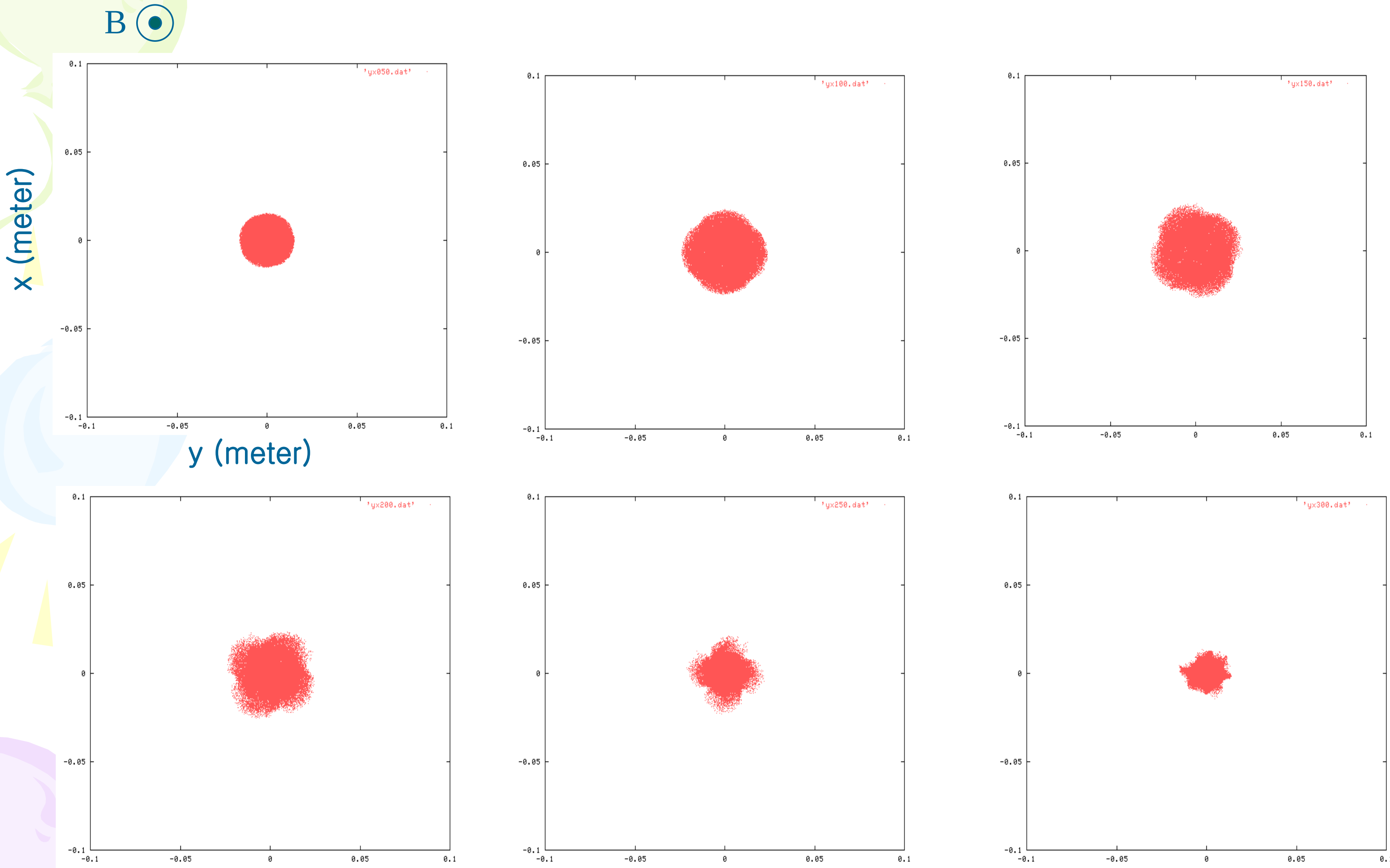
Silver line in tin vapor



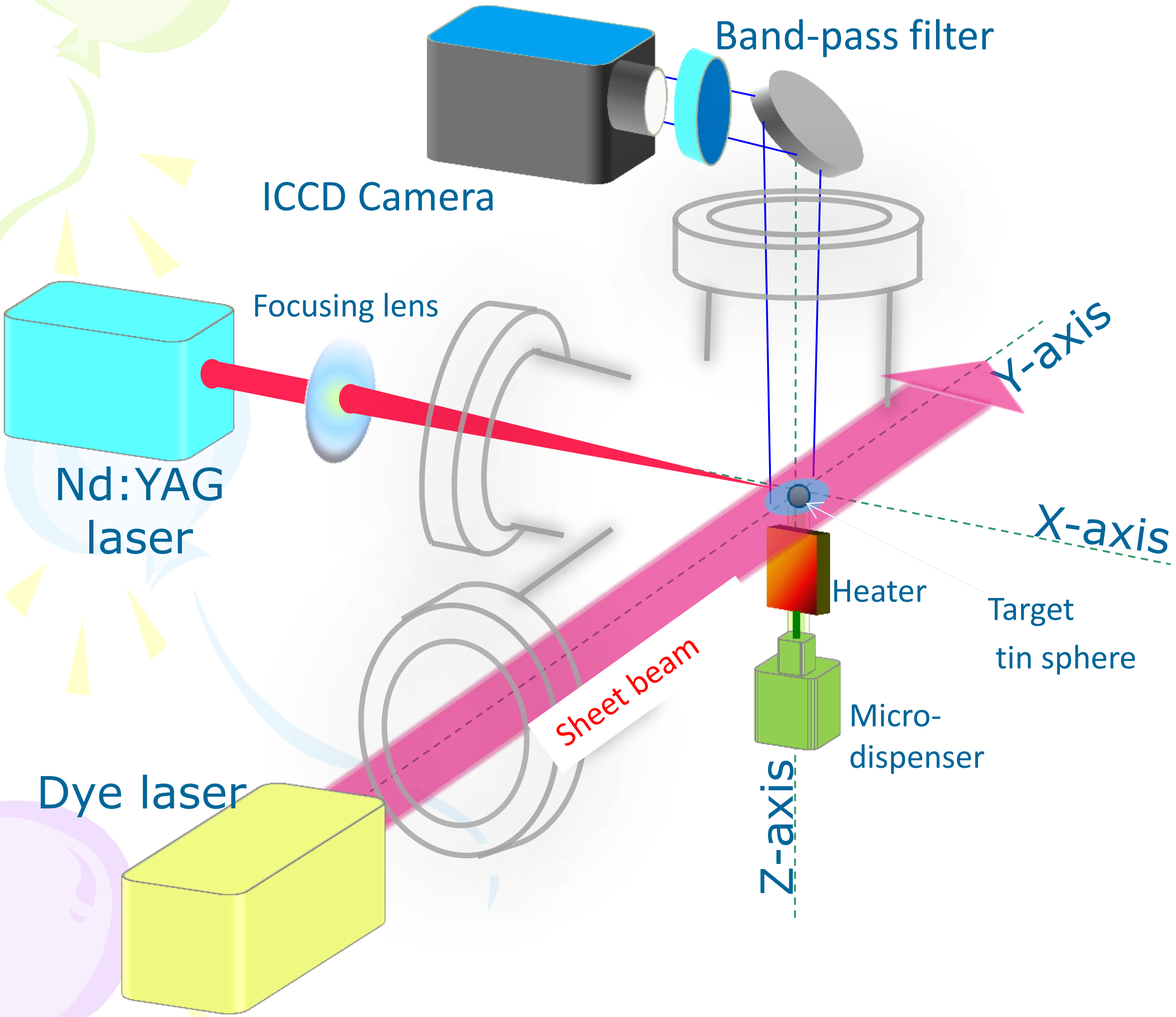
Simulation results of particle positions (zx-plane)



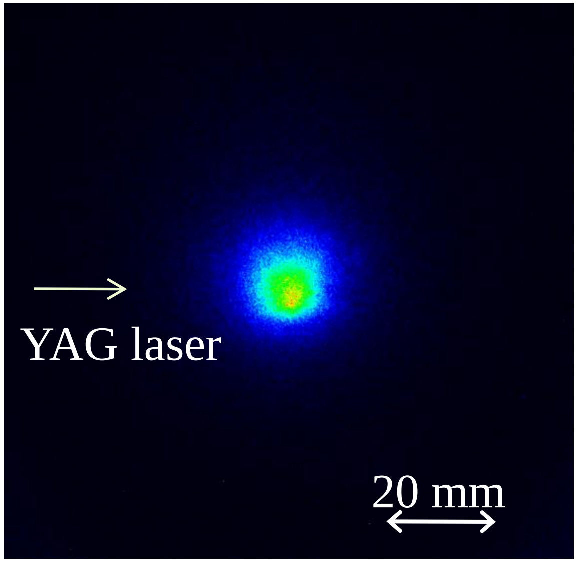
Simulation results of particle positions (yx-plane)



Sn vapor measurement by laser induced fluorescence (LIF)



Neutral characteristics

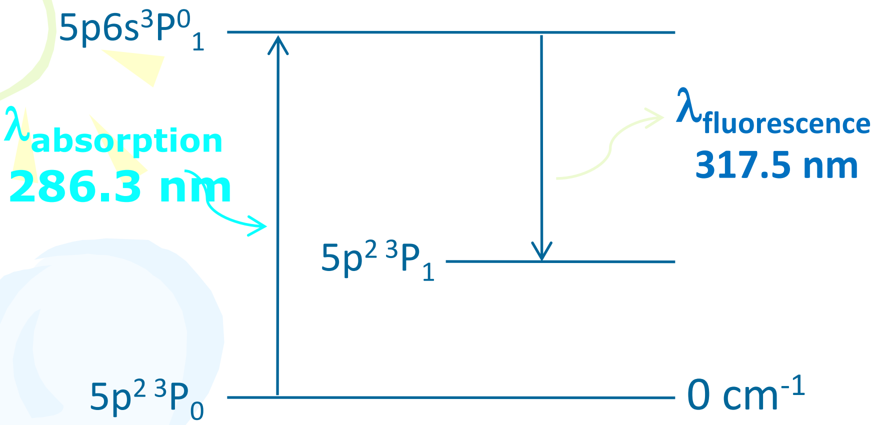


LIF image of tin vapor
(10^9 W/cm^2, after 3μs)

Laser induced fluorescence (LIF) imaging for tin atom

Principle of LIF

Neutral characteristics



Grotrian diagram for tin atom

Advantages

- Spectrally selective pumping and observation
- High sensitivity
- Cross sectional imaging with a sheet laser beam

Definition of Source Power

- 13.5nm, 2% band width, 2ϖ Sr

- Power is described at plasma, and IF (Intermediate focus)

- Average power, burst avrage power

Intemediate Summary

- EUV source effort started in 1997 in US for the next generation optical lithograpy.
- Commercial prototypes in 2003 were not matured for factory use.
- New architecture established based on Tin droplet and CO_2 laser with magnetic plasma guide.
- Laser produced plasma (LPP) selected, >10 years engineering study to fulfill the requirements on average power and C1 mirror life time.

SPIE. PHOTOMASK TECHNOLOGY + EUV LITHOGRAPHY

11 – 14 September 2017
Monterey, California, USA

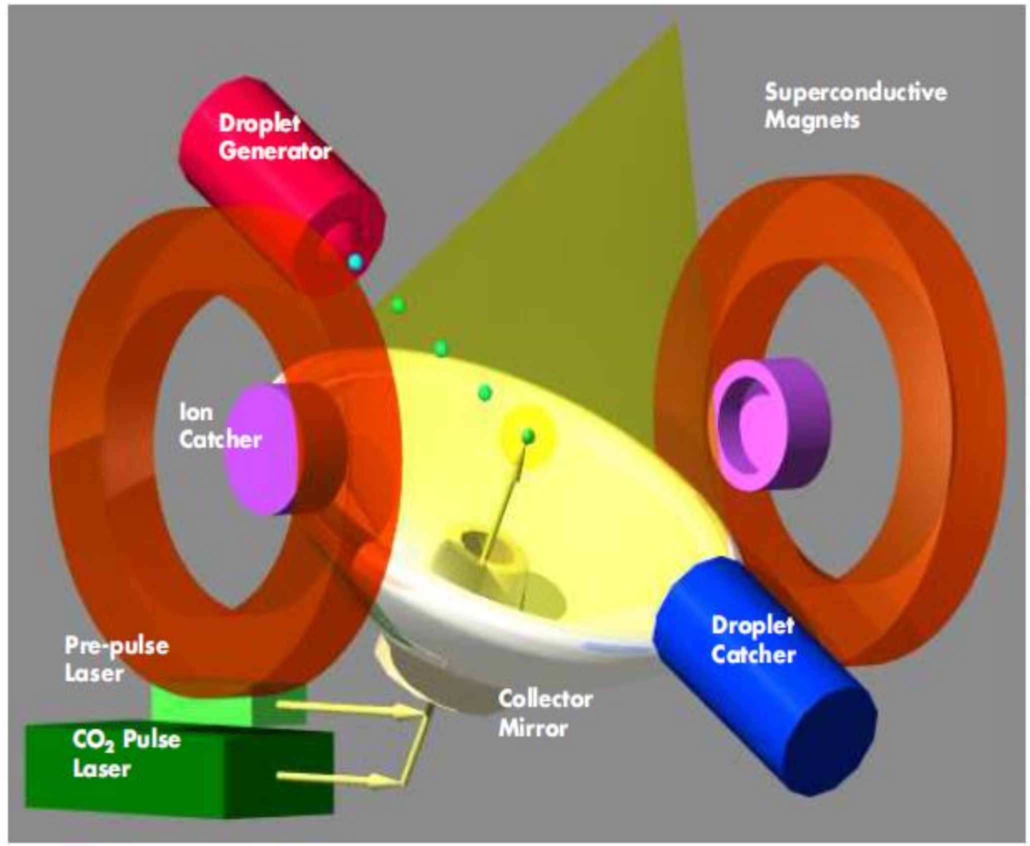
GIGAPHOTON

HIGH POWER LPP-EUV SOURCE WITH LONG COLLECTOR MIRROR LIFETIME FOR HIGH VOLUME SEMICONDUCTOR MANUFACTURING

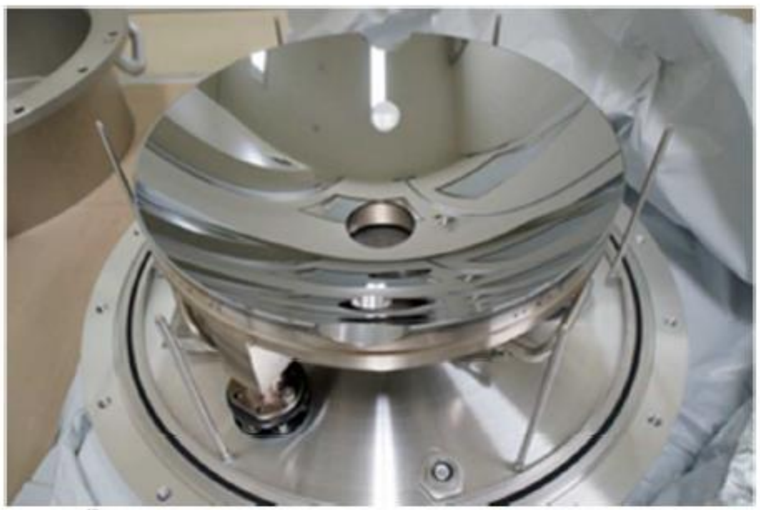
Dr. Hakaru Mizoguchi
Vice President, CTO, Gigaphoton Inc.

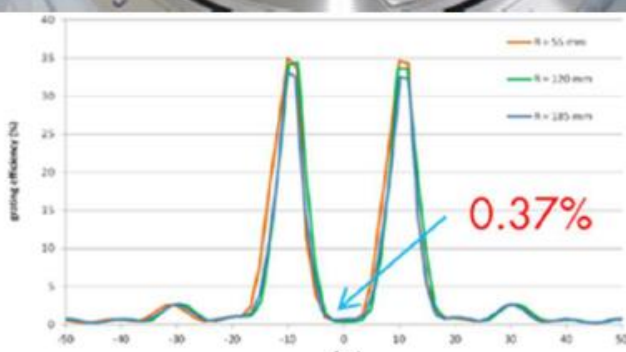
Gigaphoton LPP Source Concept

1. High ionization rate and CE EUV tin (Sn) plasma generated by dual-wavelength shooting via CO_2 and pre-pulse solid-state lasers
2. Hybrid CO_2 laser system with short pulse high repetition rate oscillator and commercial cw-amplifiers
3. Tin debris mitigation with a super conductive magnetic field
4. Accurate shooting control with droplet and laser beam control
5. Highly efficient out-of-band light reduction with grating structured C1 mirror

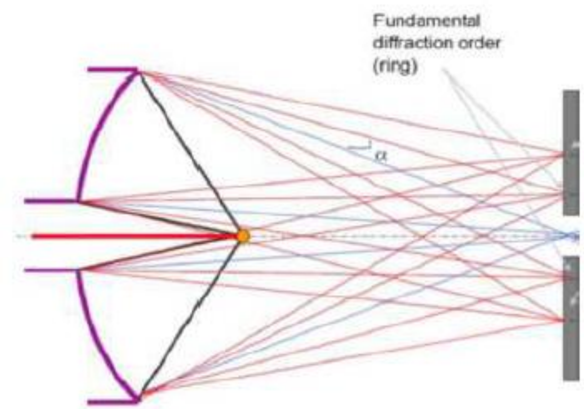


HVM Collector Mirror Specifications





- Size Φ412mm
- Weight 22kg
- Collector efficiency >74%
- Collector reflectivity >48%
- Grating structure

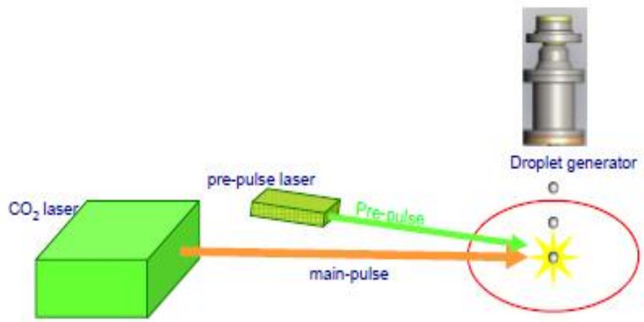


- Measured IR reflectivity: 0.37%

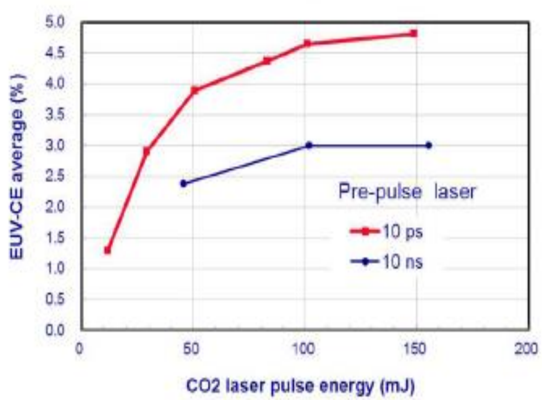
Target System Specification

		Proto#1 Proof of Concept	⇨	Proto#2 Key Technology	⇨	Pilot#1 HVM Ready
Target Performance	EUV Power	25W		>100W		**250W**
	CE	3%		> 4%		**> 5%**
	Pulse Rate	100kHz		100kHz		**100kHz**
	Output Angle	Horizontal		62°upper		**62°upper**
	Availability	~1 week		~1 week		**>80%**
Technology	Droplet Generator	20 - 25㎛		< 20㎛		**< 20㎛**
	CO_2 Laser	5kW		20kW		**27kW**
	Pre-pulse Laser	picosecond		picosecond		**picosecond**
	Collector Mirror Lifetime	Used as development platform		10 days		**> 3 months**

Pre-Pulse Technology

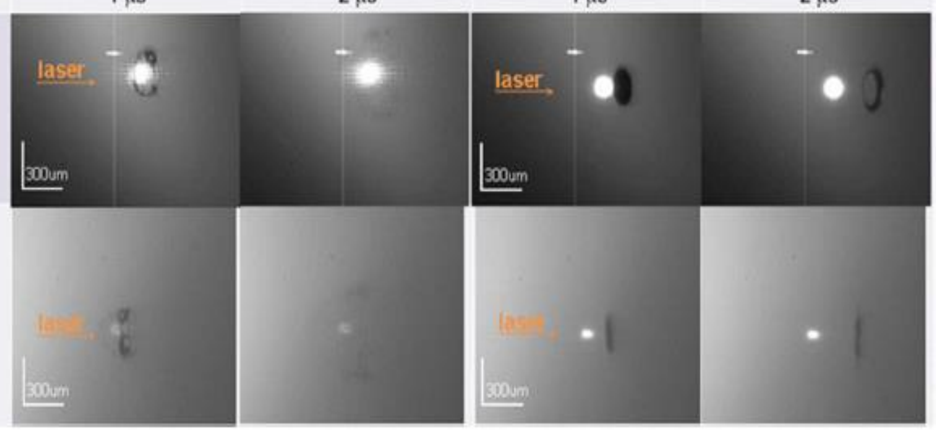


CO2 pulse enegy vs. EUV-CE



- The mist shape of a picosecond pre-pulse is different from that of a nanosecond
- Nano-cluster distribution could be a key factor for high CE

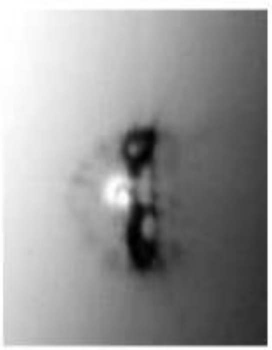
	10 ps		10 ns	
Pulse energy	2.0 mJ		2.7 mJ	
delay	1 µs	2 µs	1 µs	2 µs
60 deg view				
90 deg view				



Pre-Pulse Technology

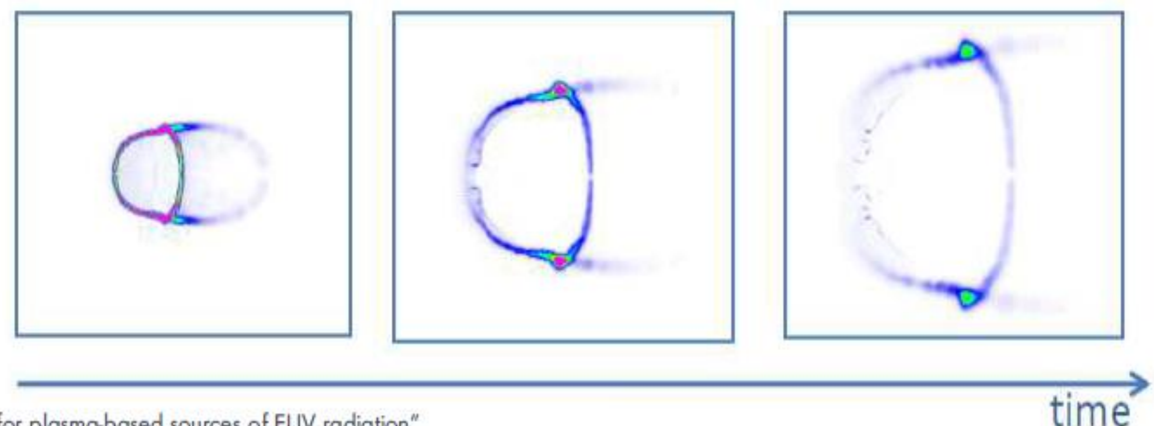
Modeling picosecond pre-pulses

~ 10 ps pre-pulse
"Dome like target"



H. Mizoguchi, Dublin (2013)

RALEF simulations
Evolution of Sn density profile for 10 ps pre-pulse



"Advances in computer simulation tools for plasma-based sources of EUV radiation"
V.V. Medvedev[1,2], V.G. Novikov[1,3], V.V. Ivanov[1,2], et.al.
[1] *RnD-ISAN/EUV Labs, Moscow, Troitsk, Russia*
[2] *Institute for Spectroscopy RAS, Moscow, Troitsk, Russia*
[3] *KeldyshInstitute of Applied Mathematics RAS, Moscow, Russia*

Pilot#1 – Driver Laser and PPL System

OSC		PA1	MA1	MA2	MA3	Plasma Point
OSC → Pre-Amp → Pre-Amp		AMP MITSUBISHI ELECTRIC	AMP MITSUBISHI ELECTRIC	AMP MITSUBISHI ELECTRIC	AMP MITSUBISHI ELECTRIC	
For 250W EUV	100W	5kW	10kW	20kW	30kW	27kW

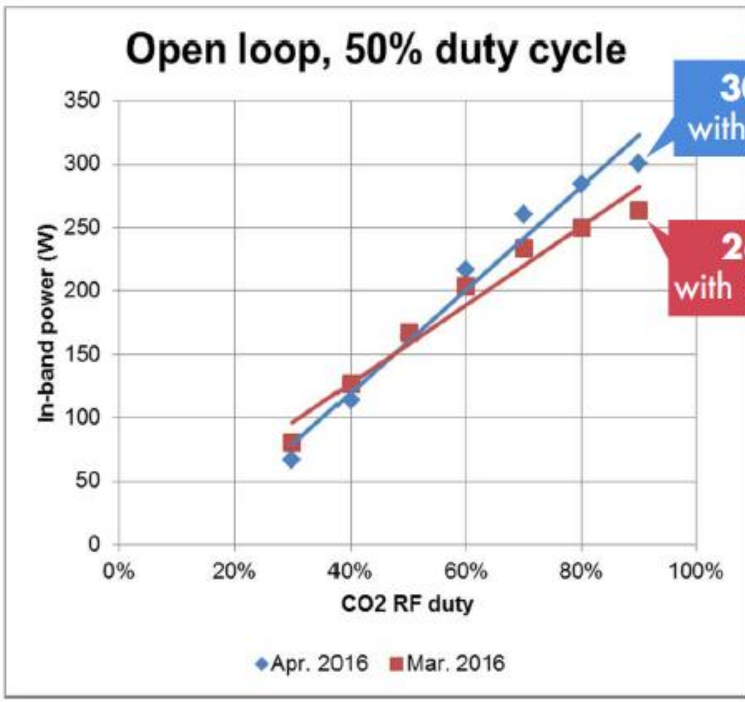
Basic Experiment in 2013

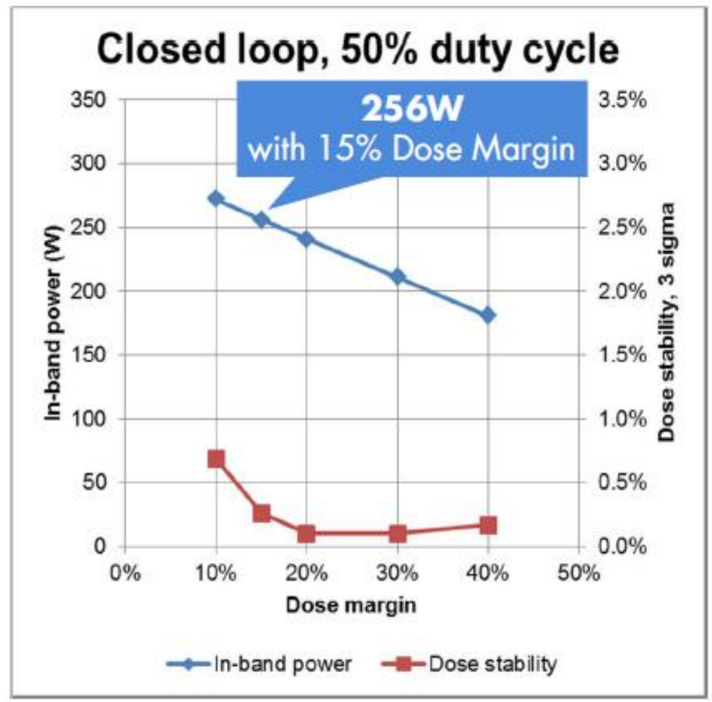
1st Amplifier installation in 2015

Amplifier system installation in 2016

Latest LPP Source Systems Experiment Update

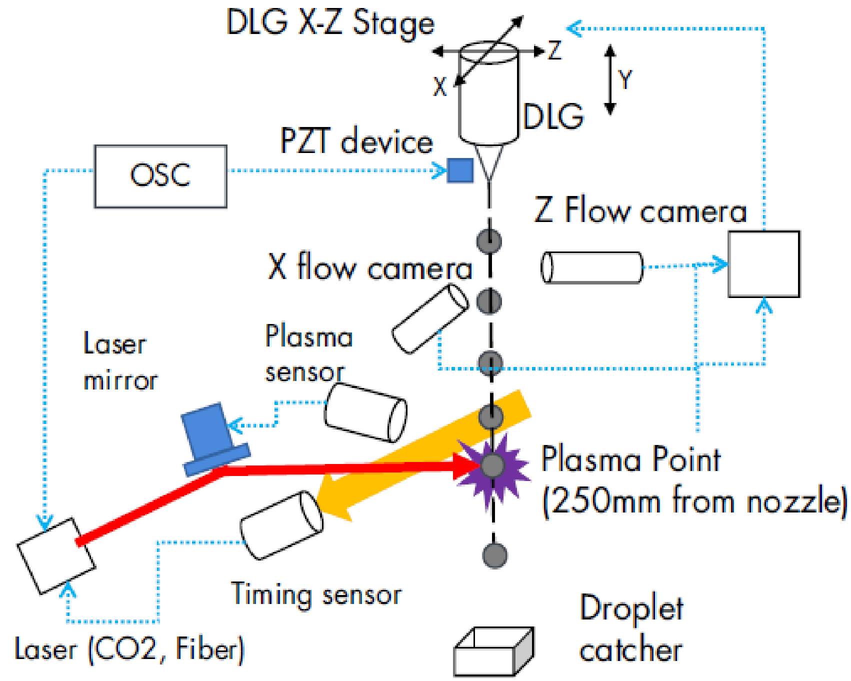
Proto#2: 250W with 4% CE at 100KHz





Pilot System Droplet Generator

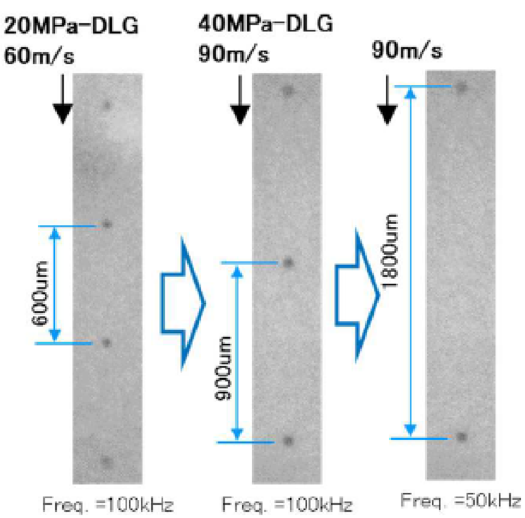
LPP EUV Source Shooting Control System



Pilot System Droplet Generator Technology Transfer

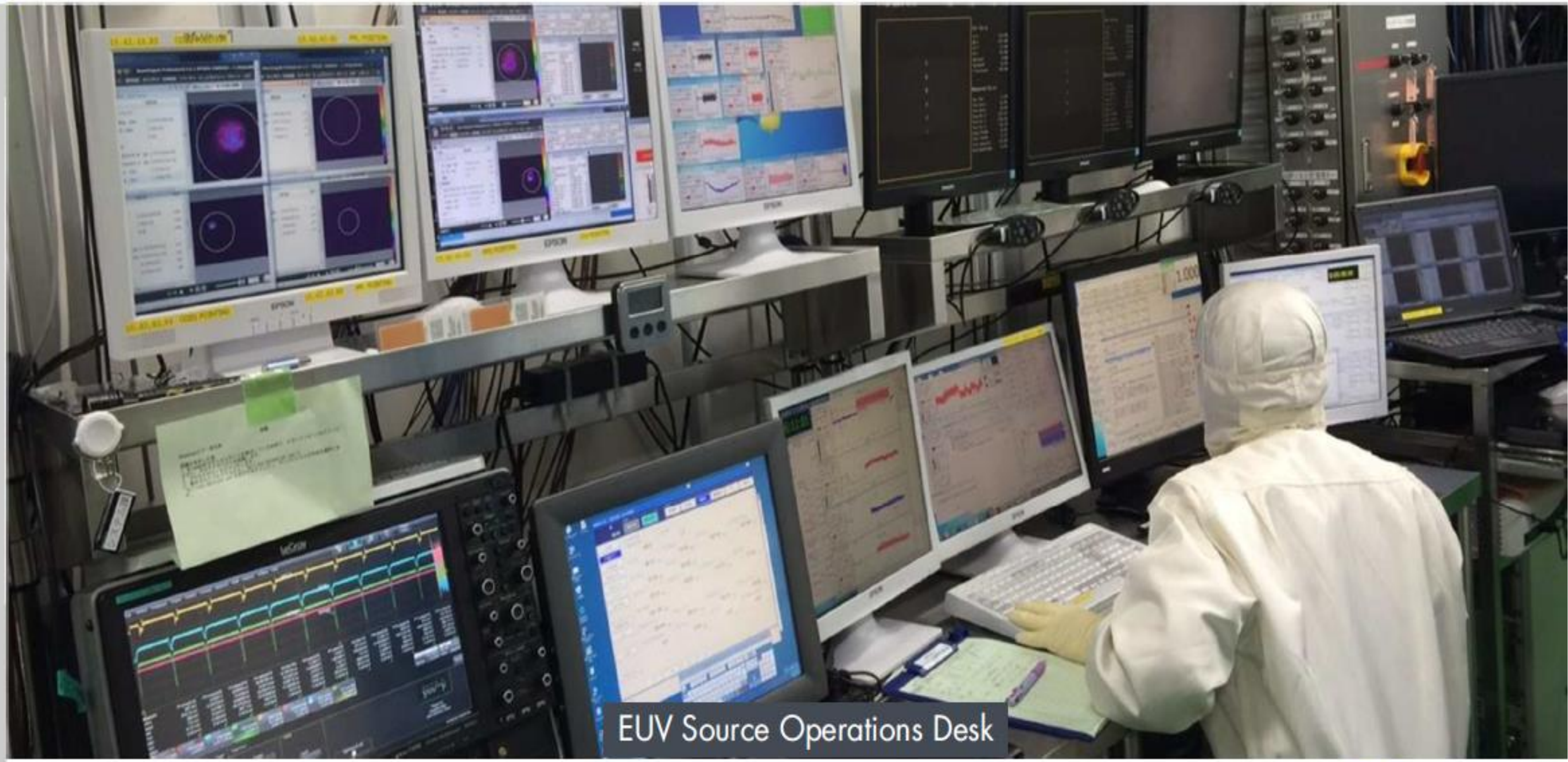
High speed droplet generator technology was successfully transferred from Prototype to the Pilot system

	Proto#1	Proto#2	Proto#2 ⇨	Pilot#1
Droplet Speed (m/s)	45	60	90	90
Back Pressure (MPa)	12	20	40	40
Max Repetition Rate (kHz)	50	80	100	100



Droplet Status

Pilot#1 System in Operation



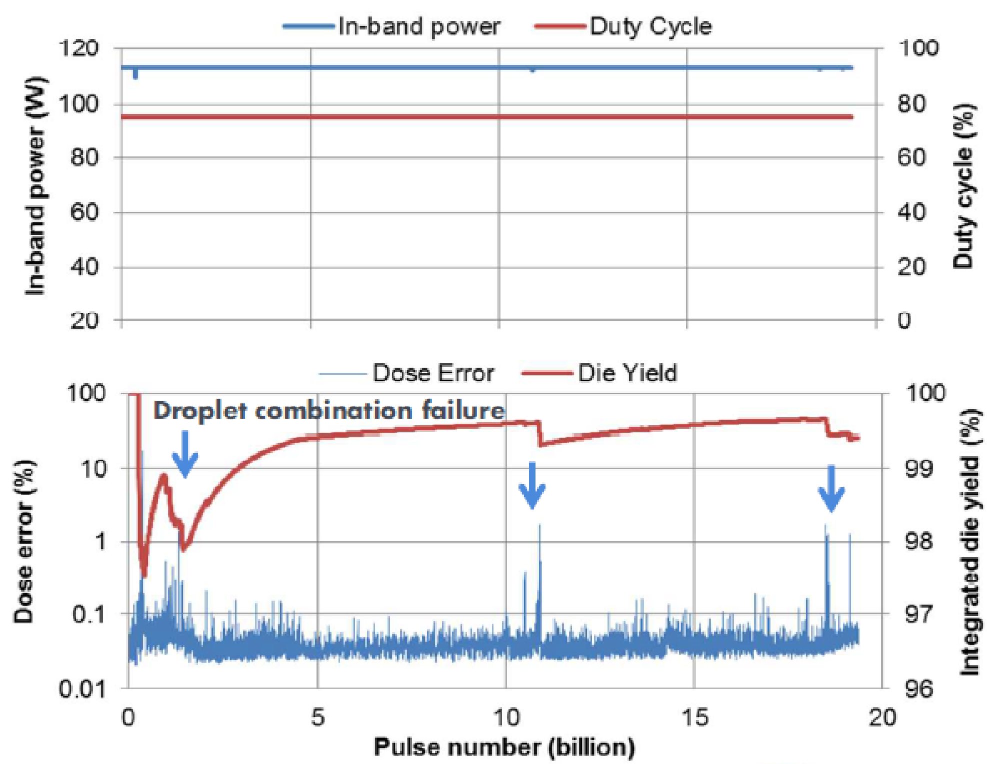
Dose stability performance (Apr.-17)

Burst pattern: 1000ms ON, 333ms OFF
Dose error: including pre-exposure phase(10ms)
Die yield: defined by 0.16% dose error

	Performance
Average power at IF	**85W**
Dose error (3 sigma)	**0.04%**
Die yield (< 0.16%)	**99.4%**
Operation time	**143h**
Pulse Number	**19Bpls**
Duty cycle	**75%**
In-band power	**113W**
Dose margin	35%
CE	4.4%
Availability 4wk	32%
Collector lifetime	-10%/Bpls
Repetition rate	50kHz
CO2 power	12kW

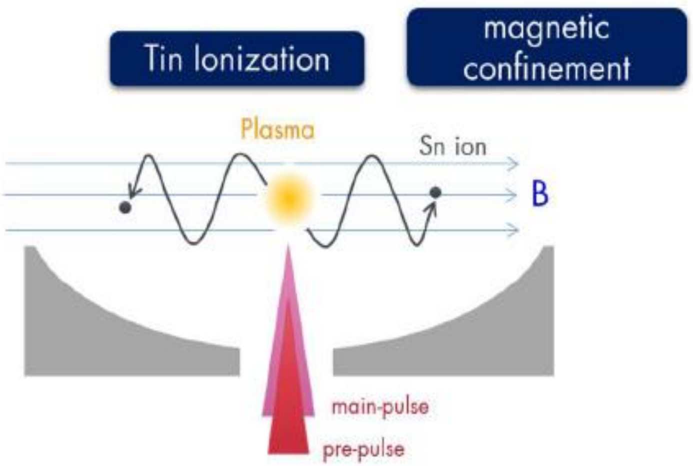
Note

Dose error was mainly due to droplet combination failure and it was improved by droplet generator improvement(but not perfect).



Etching and Dissociation of Sn on the Collector Mirror Surface

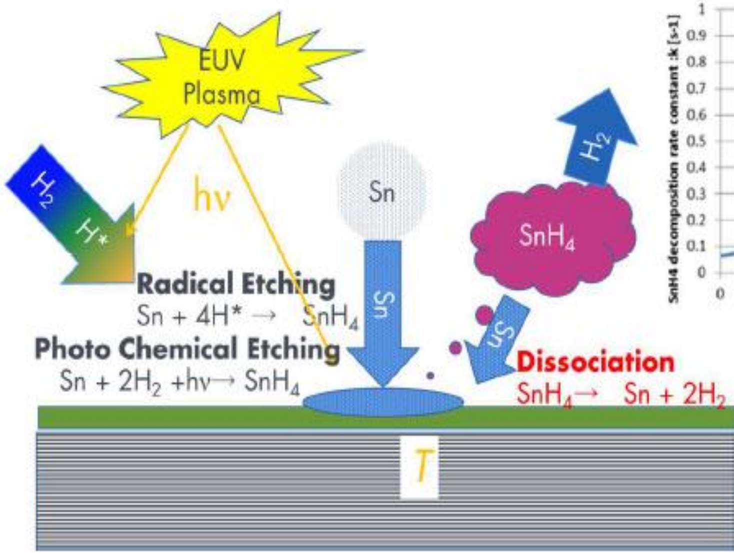
Chemical Equibrium on the Mirror Surface

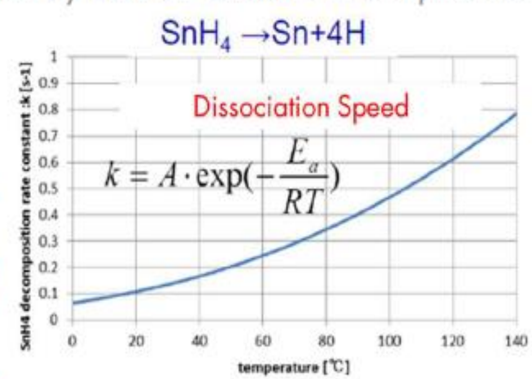


- Tin ionization & magnetic guiding
  - Tin is ionized effectively by double pulse irradiation
  - Tin ions are confined with magnetic field
  - Confined tin ions are guided and discharged from exhaust ports

- Protection & cleaning of collector with H_2 gas
  - High energy tin neutrals are decelerated by H_2 gas in order to prevent the sputtering of the coating of collector.
  - Deposited tin on the collector is etched by H radical gas*.
  - Gas flow and cooling systems for preventing decomposition of etched tin (SnH_4)

*H_2 molecules are dissociated to H radical by EUV-UV radiation from plasma.

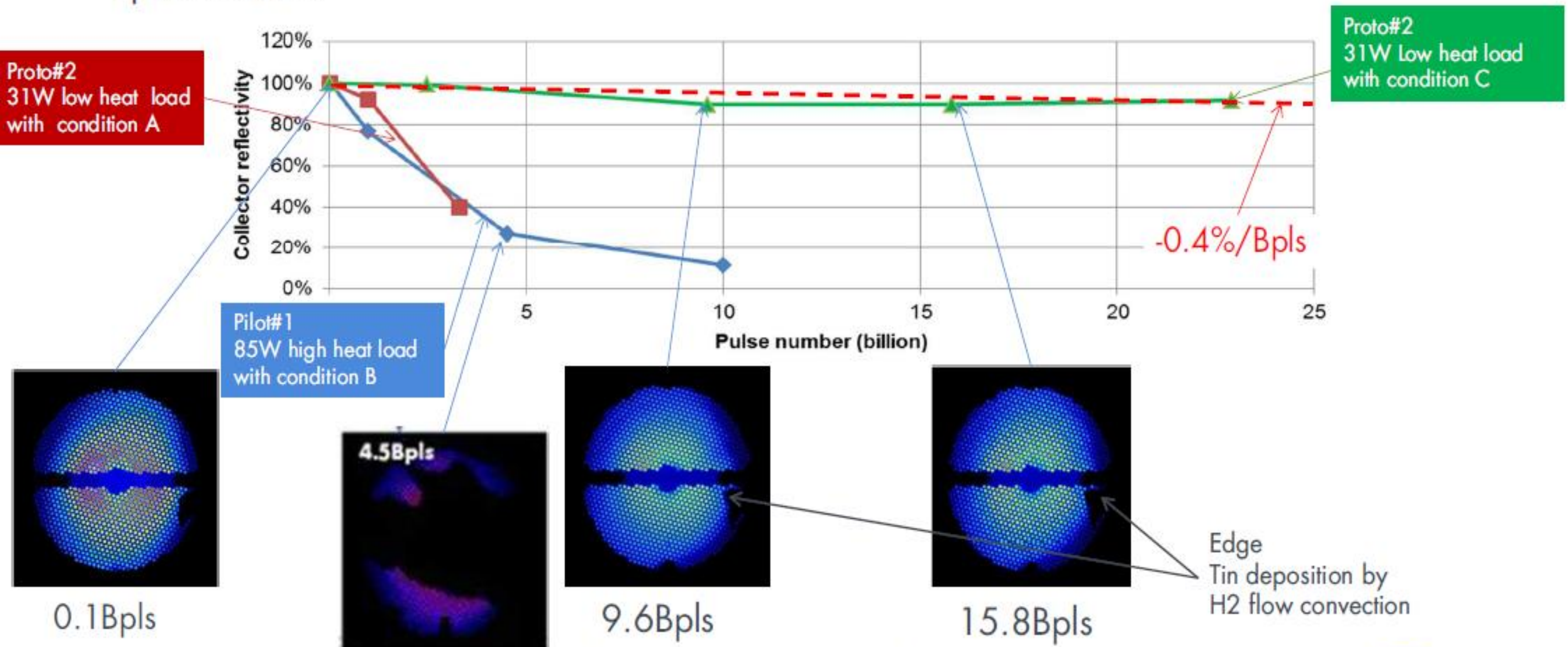




TON
/ 2017

Collector lifetime status after improvement

- Power level of EUV: 100W in Burst, (= 2mJ x 50kHz), 33% duty cycle, 30W in average.
- Collector lifetime was improved to -0.4%/Bpls by magnetic debris mitigation technology optimization.



Far field pattern in test condition C

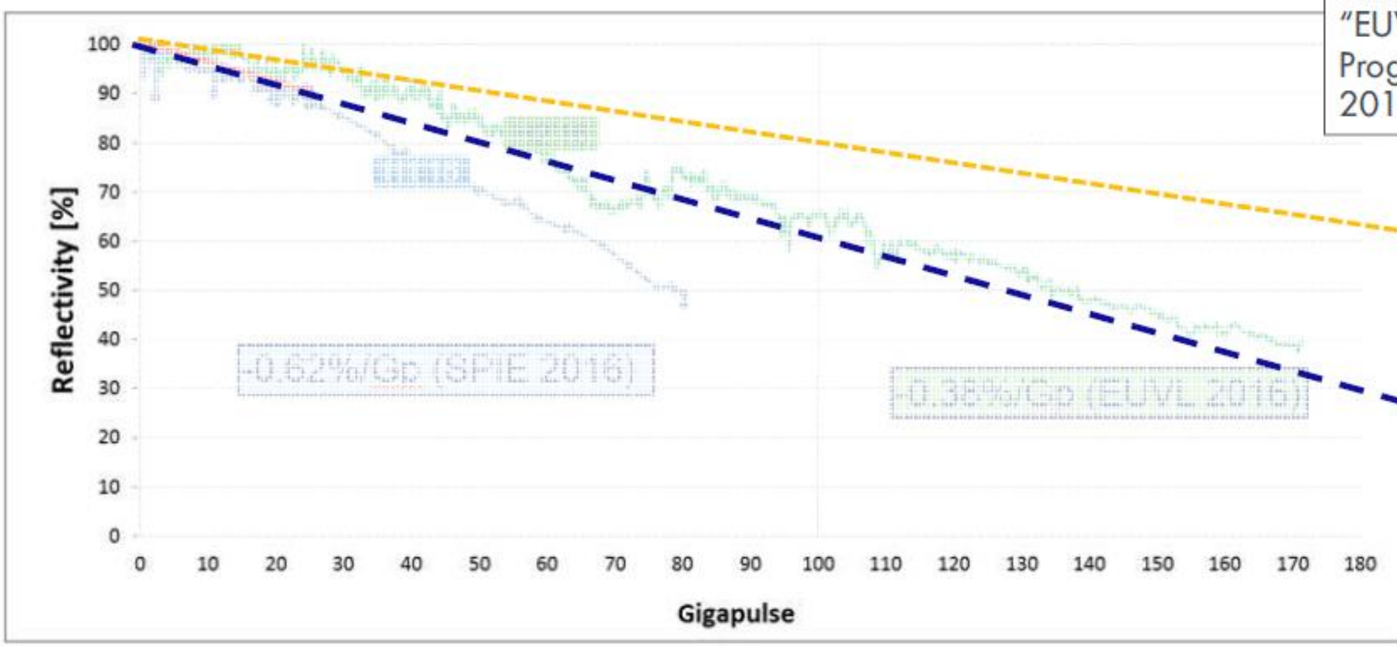
Mirror lifetime comparison between Another Source Data

Typical collector lifetime improved by factor 1.5 in 2016

Data from 80W configuration

ASML
Public
Slide 2

Christophe Smeets (ASML)
"EUV Lithography Industrialization Progress", EUVL Symposium- 2016
2016/10/24-26 Hiroshima, Japan



GPI Target
-0.2%/Bpls

At present
-0.4%/Bpls

For comparison two lines are added by Gigaphoton

GIGAPHOTON

Summary

- Pilot#1 is up running and its demonstrates **HVM Ready Power**;
  - *High* ***conversion efficiency 5%,250W power*** *are realized with two machines.*
  - *Demonstrated EUV power at 113W In-burst power at 75% duty (85W average) for 143hours operation.*
  - *Next target is 250W full specification long term operation with Pilot#1 by 1H 2018.*
- Pilot#1 Full scale Collector Mirror test shows **HVM Capable Lifetime**;
  - ***S****uperconducting* ***M****agnet* ***M****itigation* ***M****ethod* ***"SM3"*** *realized very low degradation at* ***0.4%/Gp*** *of reflectance, above 100W level operation (in burst mode, up to 30Gp at present).*
- Pilot#1 shows **HVM Ready Availability**;
  - *Pilot#1 system achieved potential of* ***89% Availability*** *(2weeks average).*

Will Gigaphoton's Source be on time for meeting145wph HVM by 2019 ?

Yes, *Gigaphoton's Source will be on time for meeting145wph HVM by 2019 .*

Historical interests

Prototype machine: Engineering Test Stand (**ETS**) by EUV LLC

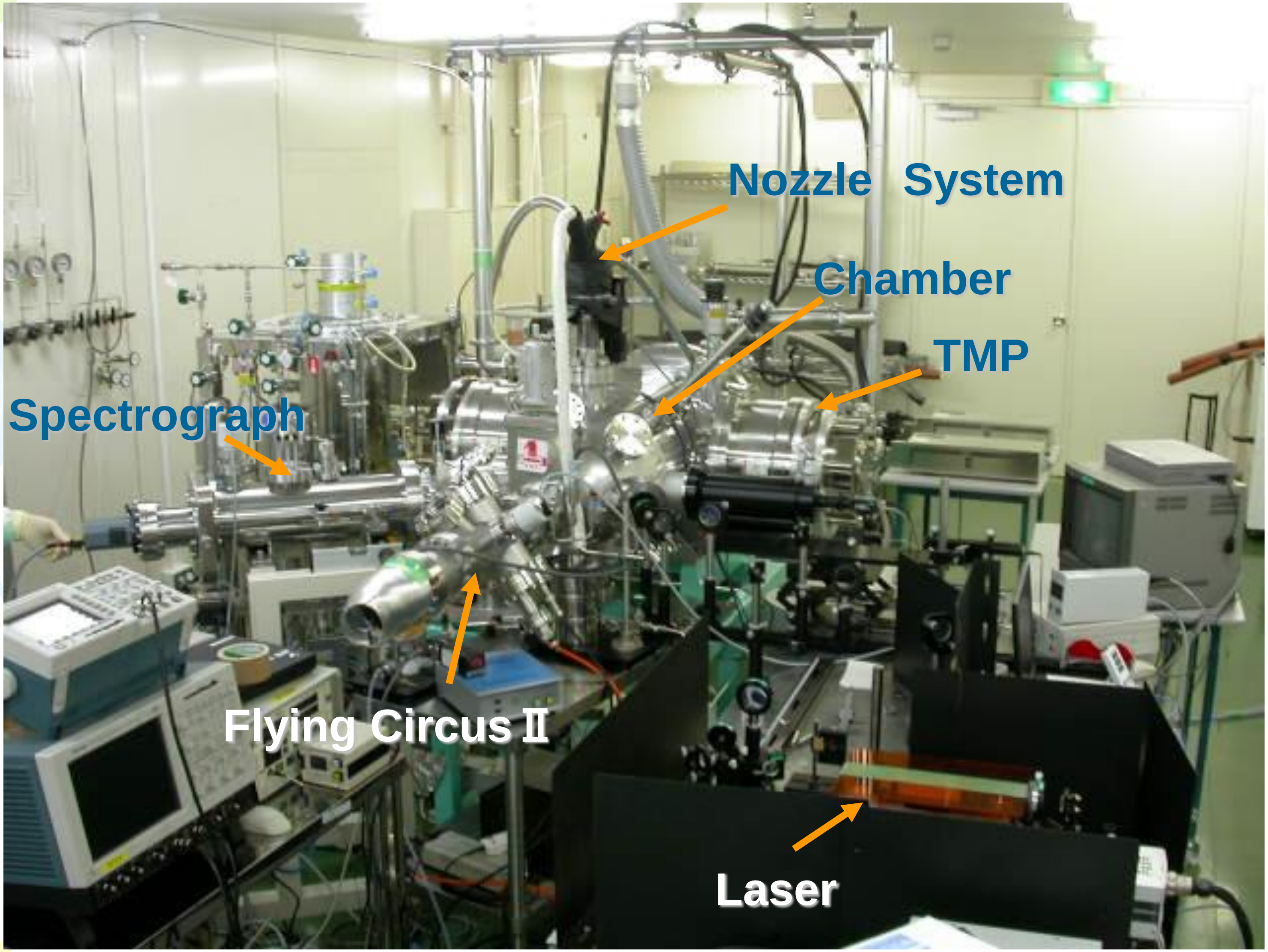
From Semiconductor International, June 2001

LPP(Lasre produced plasma) EUV source; 1.6kW, 2kHz, CE 0.13%

Target: Xe gas jet

Laser: Nd.YAG 280mJ x 3, 2kHz, 1.1 x DL

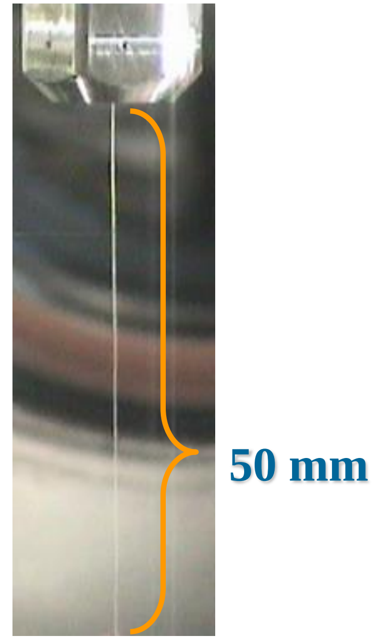
LPP (laser produced Xenon plasma) EUV System



LPP

Xenon Jet experimental test-stand

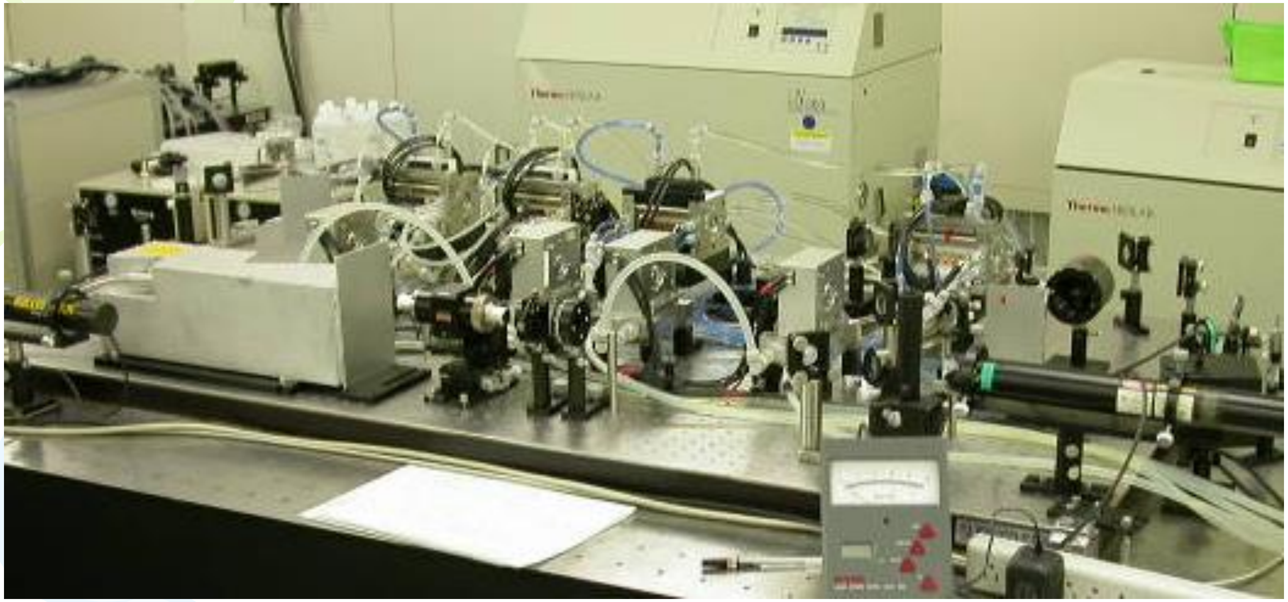
Liquid Xenon Jet System



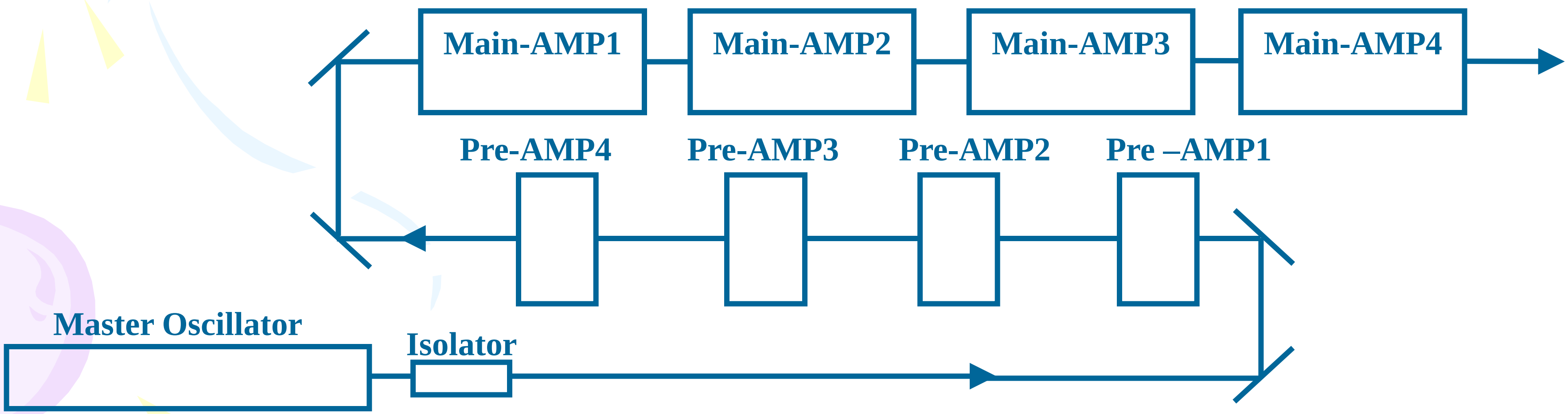
Xe Jet

Xe Temperature: 160K - 190K
Xe Pressure: <5MPa

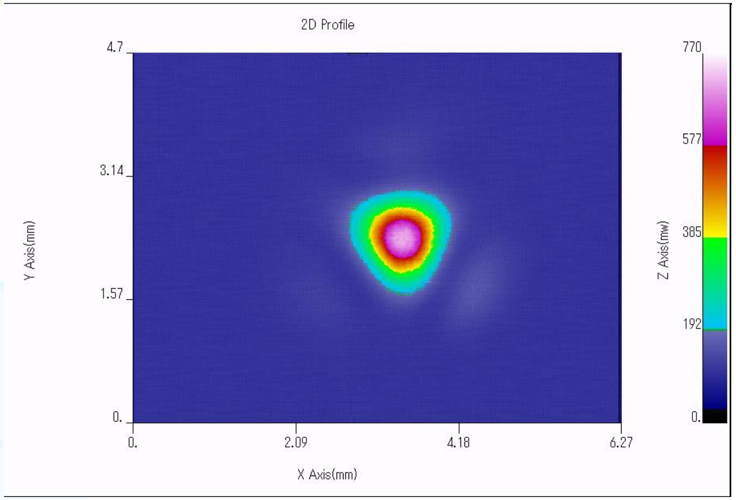
Nd:YAG driver laser based on LD pumped rod module



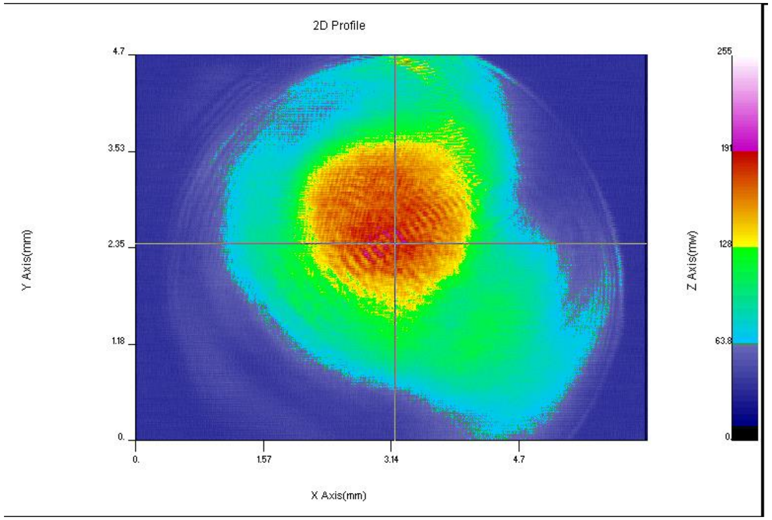
- -Average Power: 500 Watt
- -Rep. Rate: 10 kHz
- -Pulse duration: 30 ns



Driver Laser System - *Beam Profile* -



Before Main Amplifier
60W



After 3-Main Amplifier
350W

-We achieved 500 Watt @ 10kHz.
-Further driver laser system improvements:
Deformable mirror (beam quality)
Shorter pulse duration oscillator (several ns)

LPP