Review of the present technology of the radiation source for Extreme Ultraviolet Lithography

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Outline

- Take off of EUV lithography:
  - HVM clean source architecture
- CO_2 laser produced Sn plasma for 13.5nm source
  - High EUV conversion efficiency of CO2 laser produced Sn plasma
  - Power scaling of short pulse CO2 laser
  - Physics of laser generated Sn droplet plasma
  - Sn plasma and vapor management
- System operation by major suppliers
- Next subjects : Actinic metrology source, 6.7nm
- Alternative source technologies in 2020

Take off of EUV lithography

2009 International EUVL (Extreme Ultraviolet Lithography) and 193 nm Immersion Extensions Symposia, held Oct. 18-23, in Prague, Czech Republic.

Experts from Cymer reported laser produced plasma (LPP) sources generate 50 watts at intermediate focus (IF). This compares with a system requirement of 180 watts needed to expose 100 wafers per-hour in high-volume manufacturing.

Two fundamental problems were basically solved:
power scaling to 400W, C1 mirror life time

INDUSTRY PERSPECTIVE TECHNOLOGY FOCUS

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).

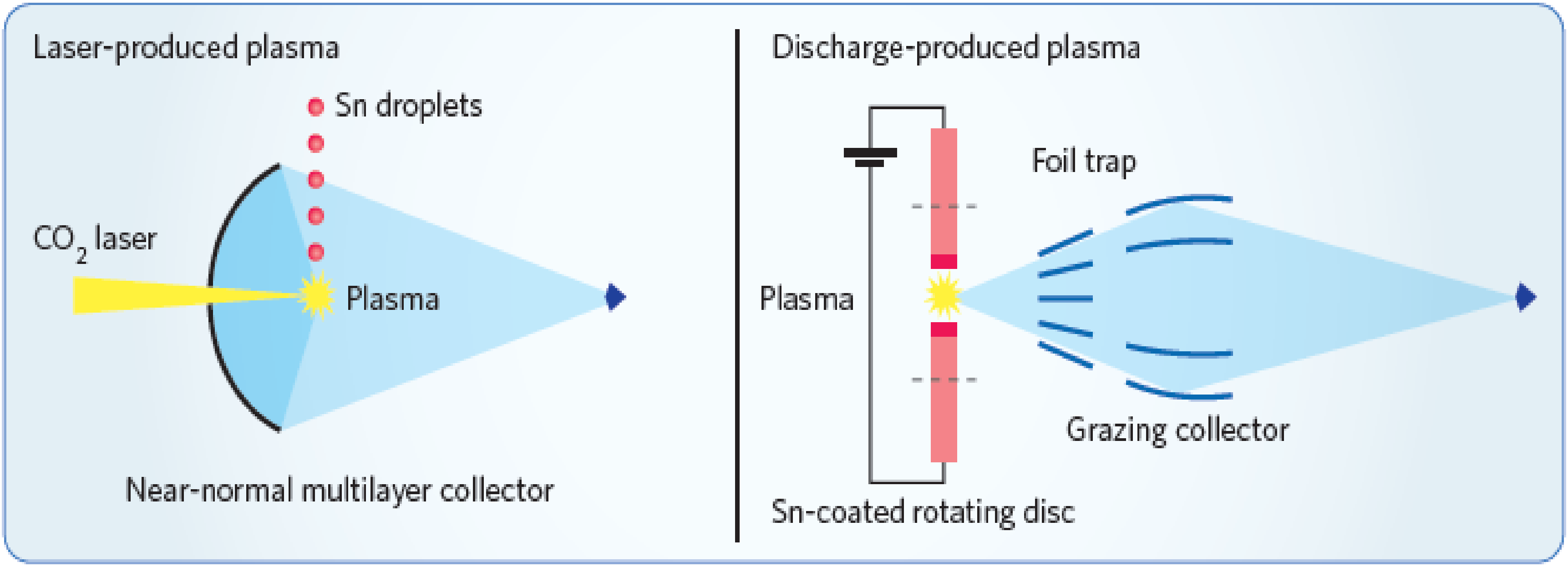
Extreme ultraviolet (EUV) lithography is the next step in this trend. It uses radiation of wavelength 13.5 nm, thereby

CARL ZEISS

Manufacturing mirrors for EUV lithography is a huge technical challenge.

Nature Photonics, January 2010

Sn debris processing in Cymer and Philips EUV source : gas flow



ASML

Figure 3 | EUV sources for lithography applications based on laser- (left) or discharge-produced (right) plasmas of tin. These schemes require very different strategies for collecting the maximum amount of light and for keeping plasma debris off the collector mirrors; the laser-produced plasma scheme uses a background gas, and the discharge-produced plasma exploits a foil trap.

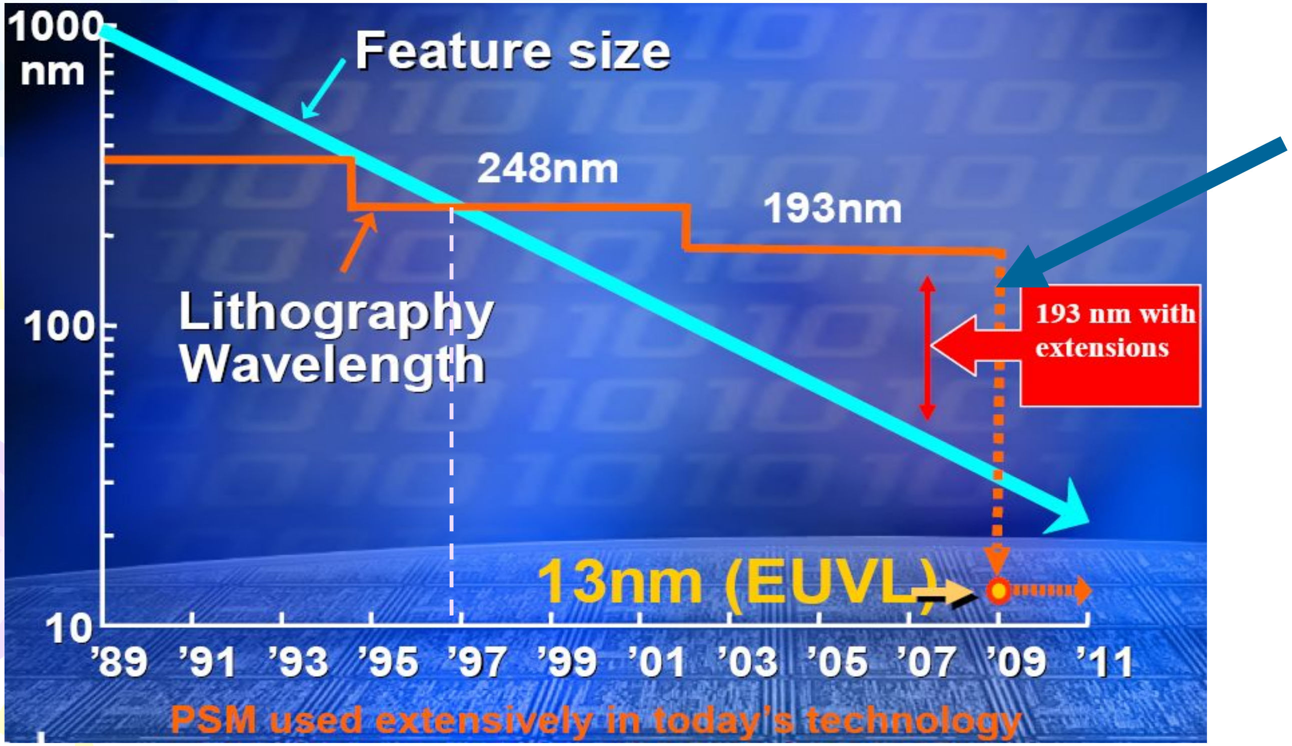
Road to EUV lithography

Minimum lithographic feature size = $\dfrac{K_1 \lambda}{NA}$

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)

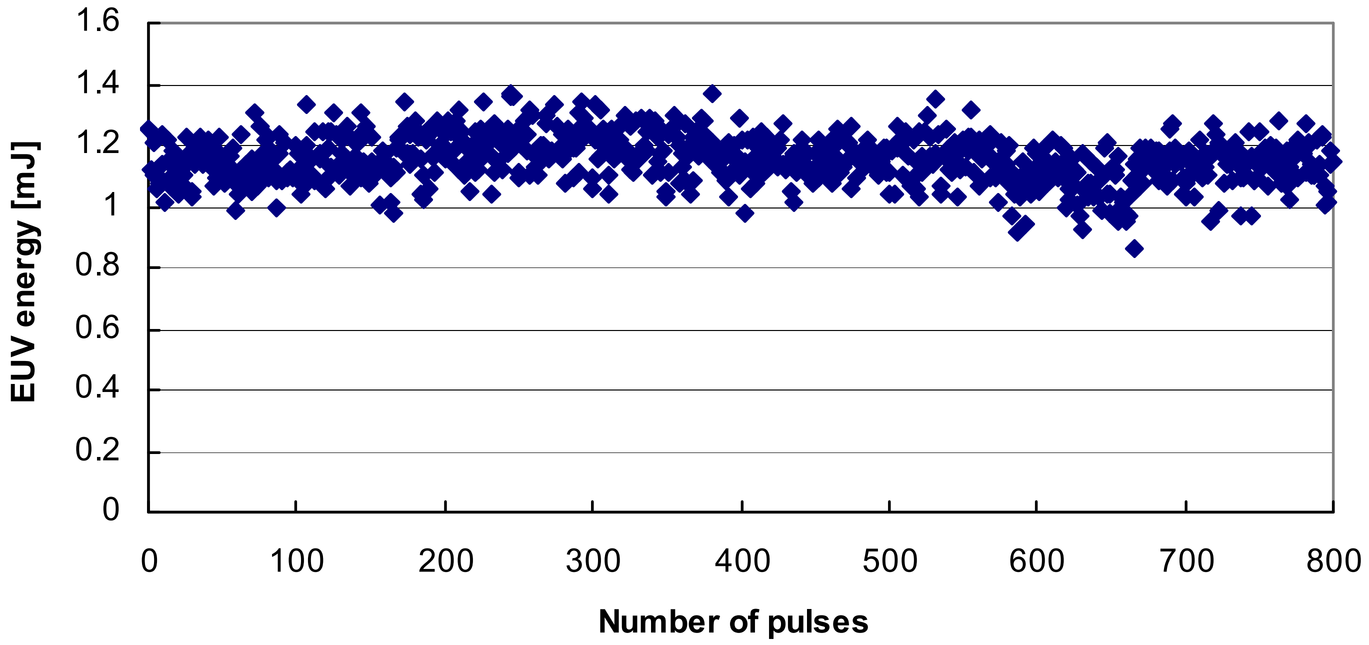


There are only so many "tricks" to increase this gap, and they are very expensive … to a shorter wavelength!

EUV generation from high power CO_2 laser produced Sn plasma (2007)

EUV source power : **110 W** (2 πsr、2%bw)

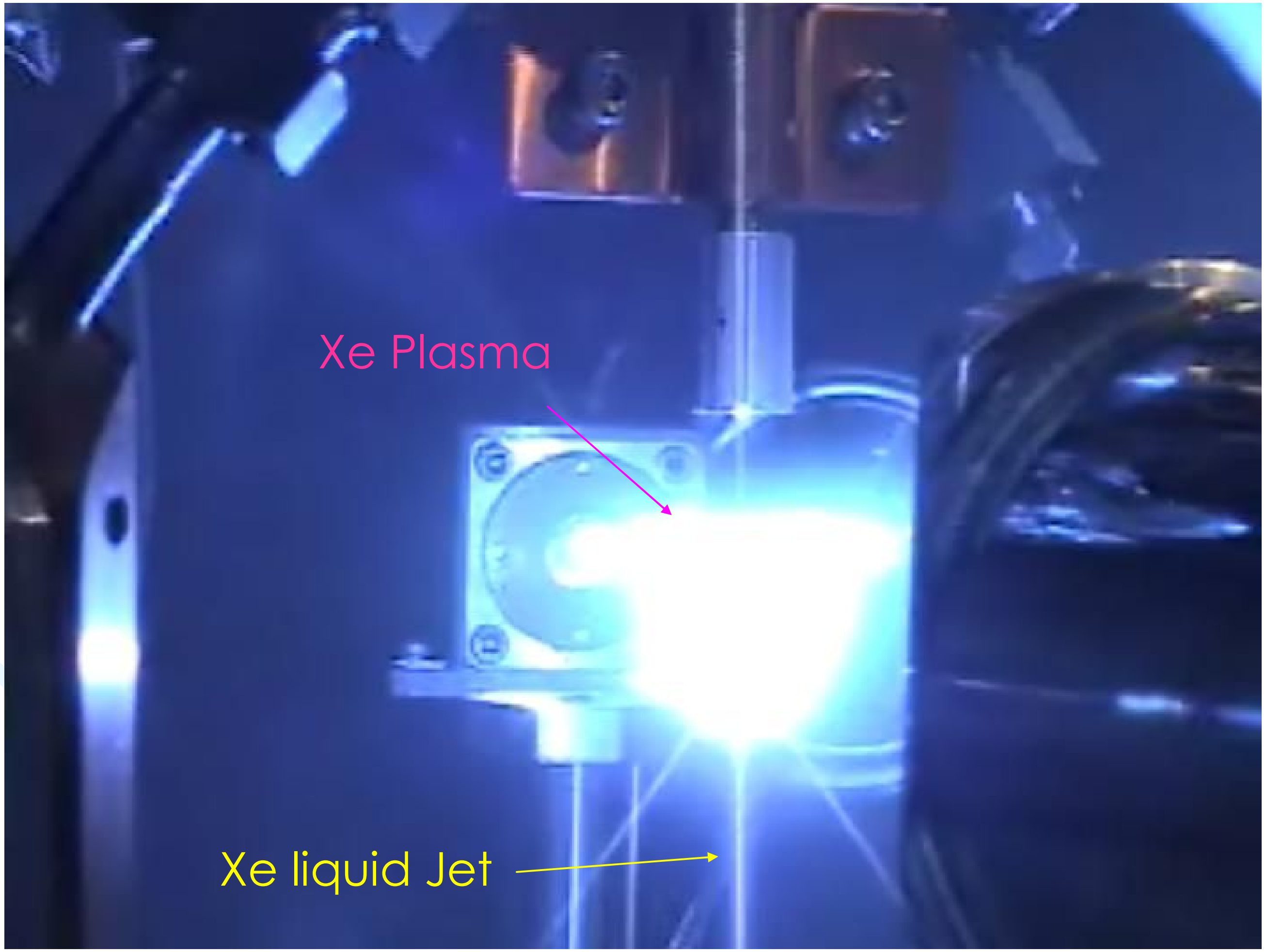
Target :	Rotating Sn plate
Laser irradiation power :	5 kW
Conversion efficiency (CE) :	2.2 %
EUV energy stability :	8% (3σ, 50 pulse)



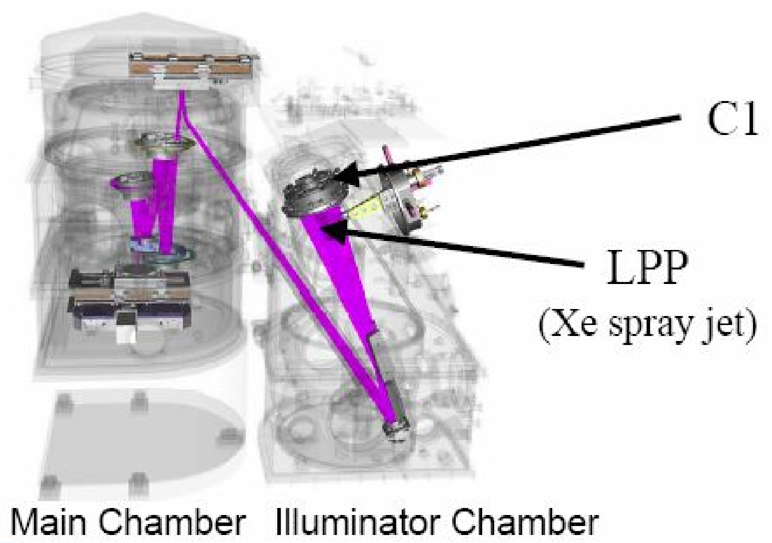
Two major technical issues with high average power EUV source architecture in 2003

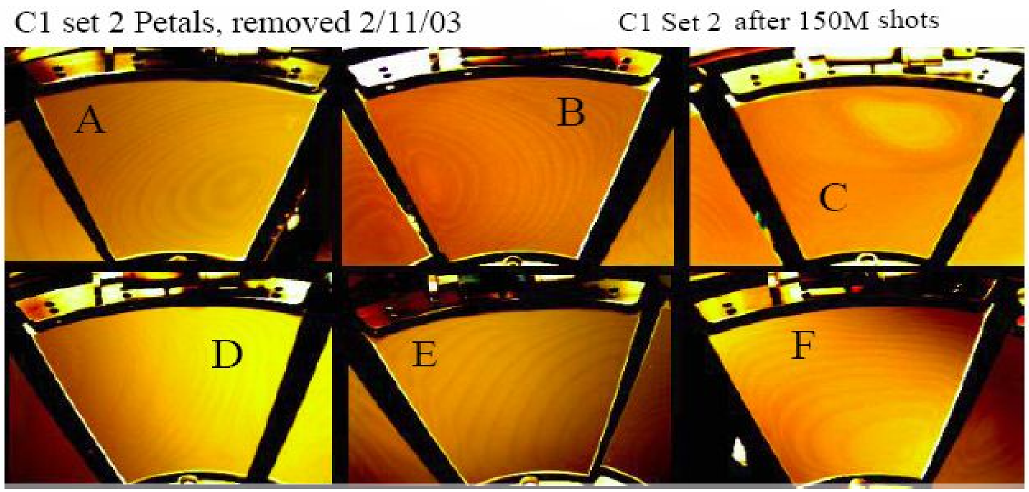
- Damage of C1 mirror by fast ions from high density target (high density target is required for high conversion efficiency)

- Scaling of laser average power in pulse mode more than 10kW within acceptable CoO


Xe Plasma
Xe liquid Jet

LPP source and mirror damage : ETS with Xe spray jet





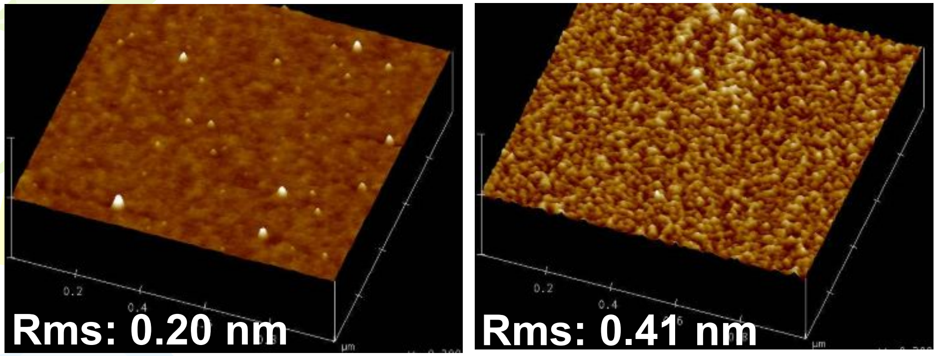
150M shot

Lennie Klebanoff

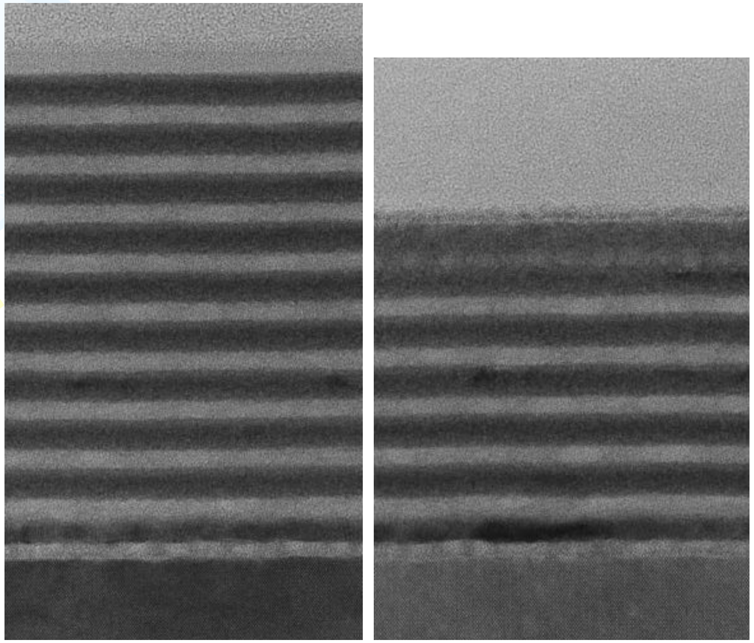
: 2nd EUV Symposium, October 1. 2003, "Condenser Erosion Observations in the ETS" Lennie Klebanoff, SNL

Analysis of ion exposed samples

AFM

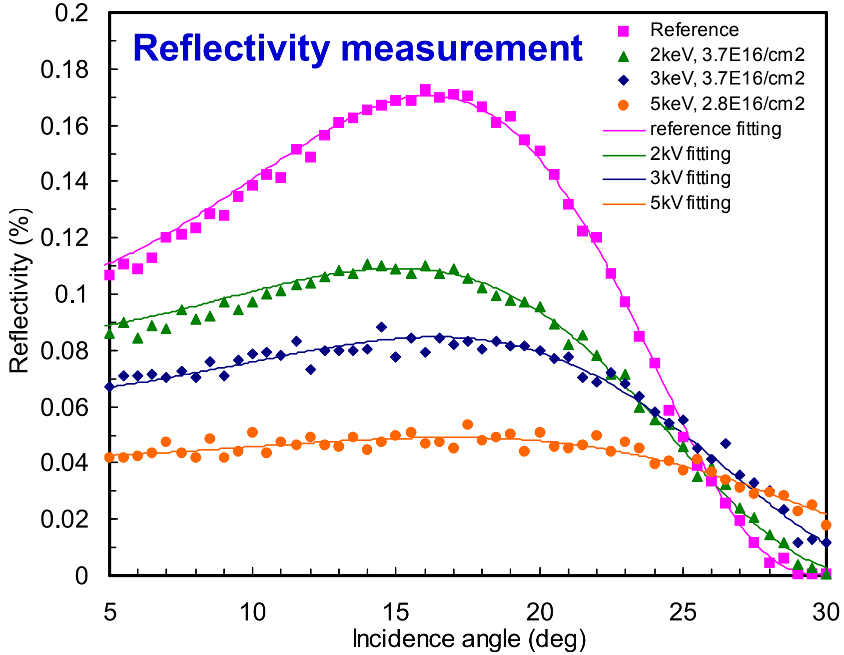


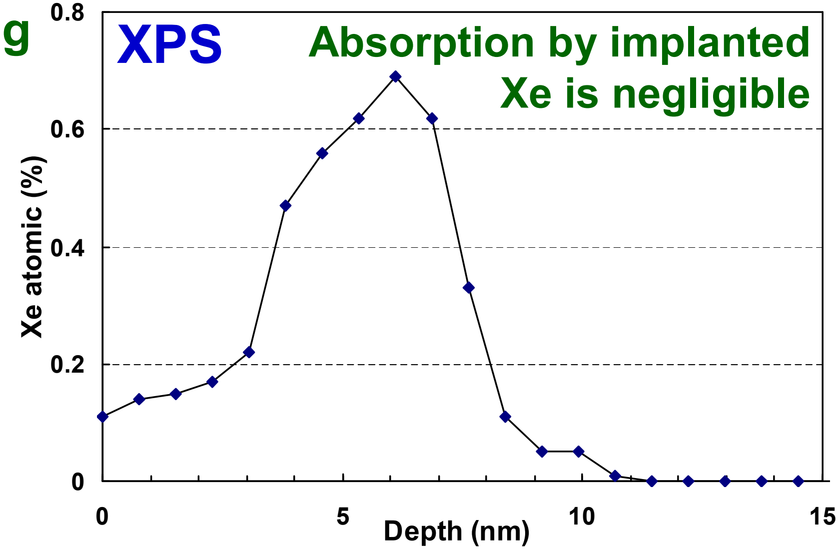
TEM



Reference
(10 Mo/Si bilayer)

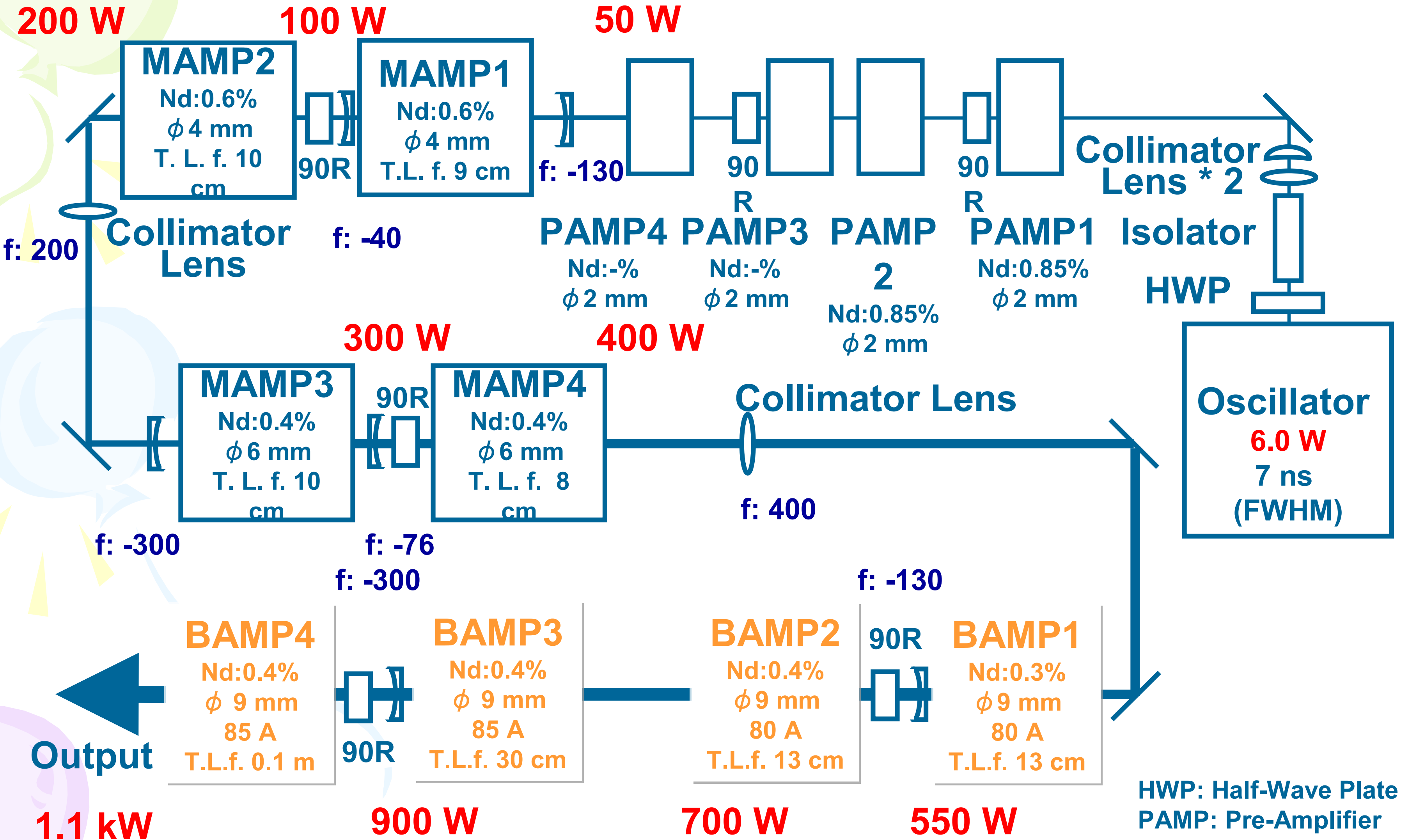
Ion energy 5 keV
Ion dose 2.8 X 10^{16} atoms/cm^2





Absorption by implanted Xe is negligible

Nd:YAG laser : Optical Setup Jan 2004



Oscillator
6.0 W
7 ns
(FWHM)

HWP

Isolator

Collimator Lens * 2

PAMP1
Nd:0.85%
ϕ2 mm

90R

PAMP 2
Nd:0.85%
ϕ2 mm

PAMP3
Nd:-%
ϕ2 mm

90R

PAMP4
Nd:-%
ϕ2 mm

50 W

f: -130

MAMP1
Nd:0.6%
ϕ4 mm
T.L. f. 9 cm

100 W

f: -40

90R

MAMP2
Nd:0.6%
ϕ4 mm
T. L. f. 10 cm

200 W

Collimator Lens

f: 200

f: -300

MAMP3
Nd:0.4%
ϕ6 mm
T. L. f. 10 cm

300 W

90R

f: -76

MAMP4
Nd:0.4%
ϕ6 mm
T. L. f. 8 cm

400 W

Collimator Lens

f: 400

f: -130

BAMP1
Nd:0.3%
ϕ9 mm
80 A
T.L.f. 13 cm

550 W

90R

BAMP2
Nd:0.4%
ϕ9 mm
80 A
T.L.f. 13 cm

700 W

BAMP3
Nd:0.4%
ϕ 9 mm
85 A
T.L.f. 30 cm

900 W

f: -300

90R

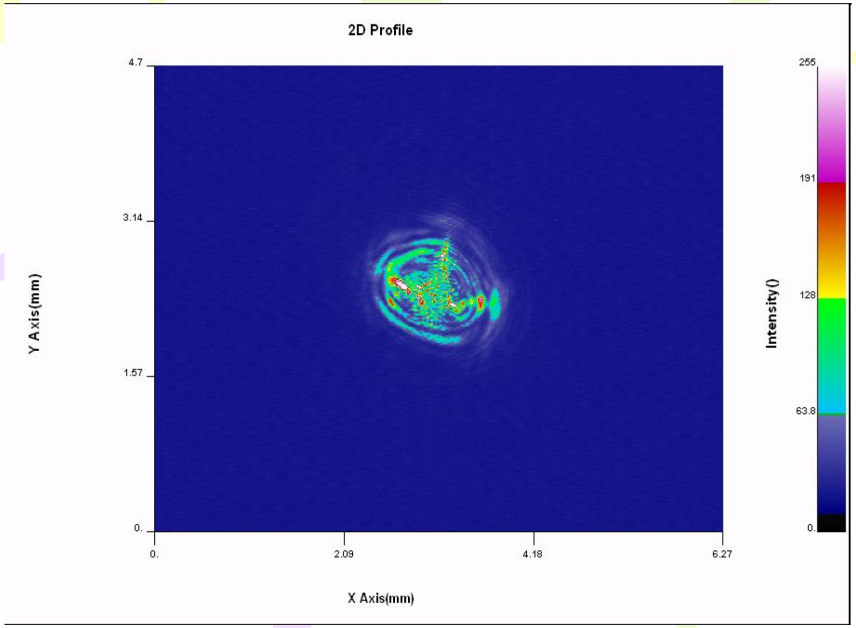
BAMP4
Nd:0.4%
ϕ 9 mm
85 A
T.L.f. 0.1 m

Output

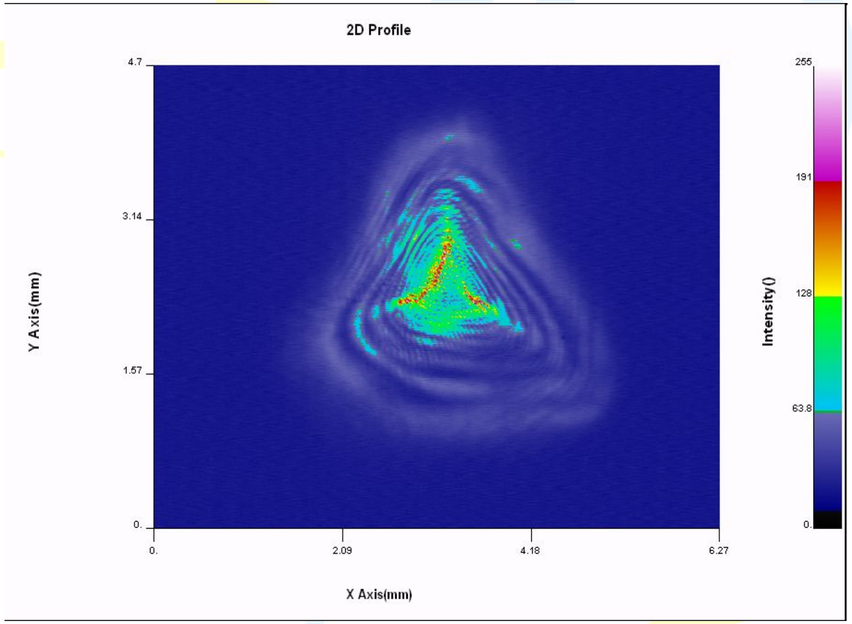
1.1 kW

HWP: Half-Wave Plate
PAMP: Pre-Amplifier
MAMP: Main Amplifier
BAMP: Booster Amplifier
f : focal length (mm)
90R: 90-degree Rotator

Beam Profile after 4-Booster Amplifiers (after beam waist)

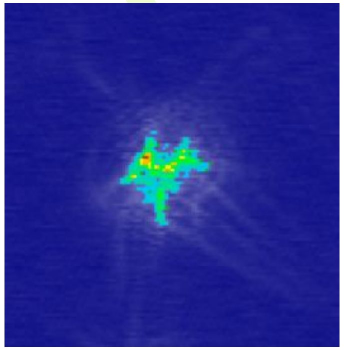


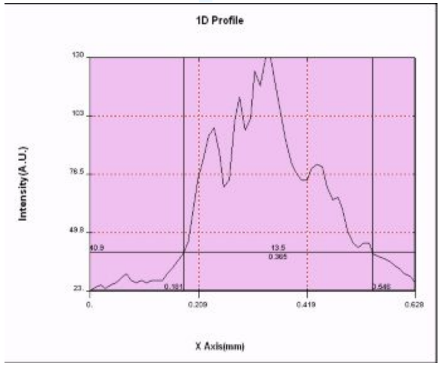
920 W @Nov 2003



1100 W @Jan 2004

near beam waist
with a 100-mm lens





Horizontal profile
Spot size ~350 μm

Critical limitations with HVM source technology in 2004

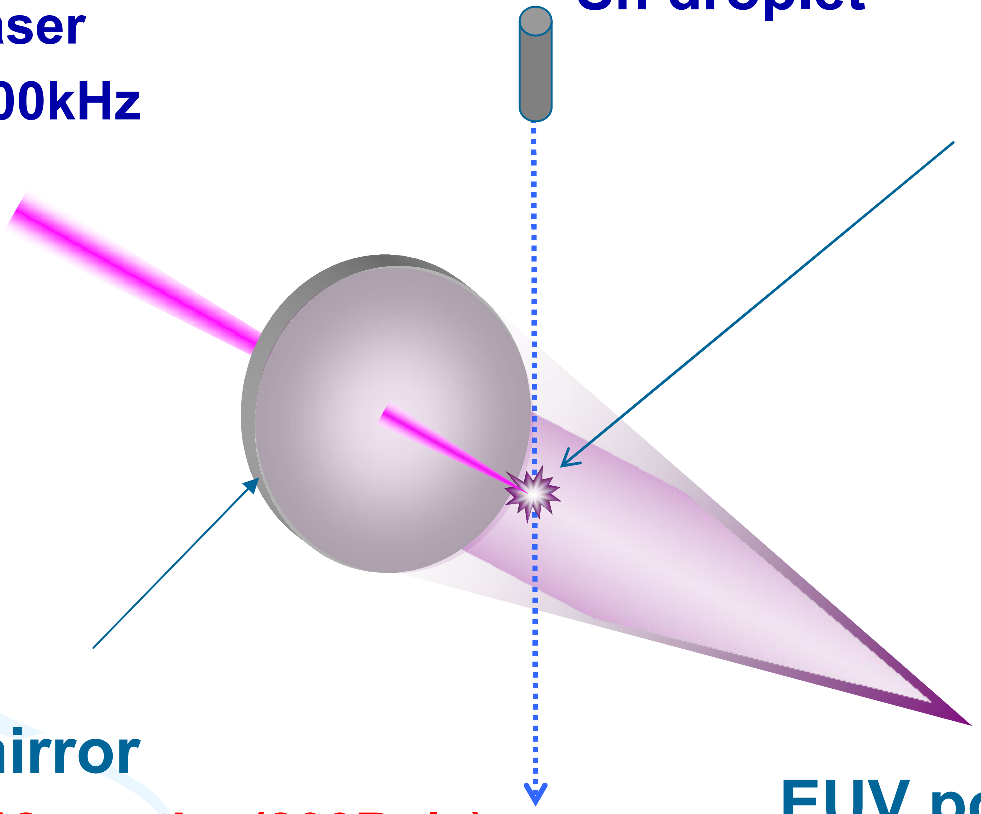
LPP

- Plasma target	Stable operation of Xenon jet
- Average power of driver laser	Scale up limited by thermal effect
- EUV conversion efficiency	Too low for higher power scaling
- Cleanness	Ion sputtering

DPP

- EUV conversion efficiency	Too low for higher power scaling
- Repetition rate	
Burst mode operation	Limited by thermal effect
-Cleanness	Sputtering, electrode erosion

Configuration of EUV source



CO2 laser
>10kw 100kHz

Sn droplet

EUV power at plasma
> 720W

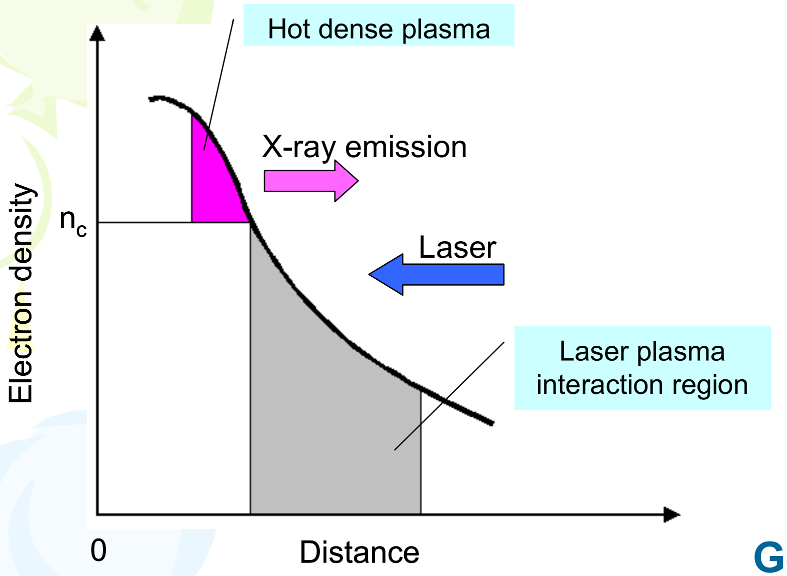
EUV C1 mirror

lifetime : > 12months (800Bpls)

（R10%loss＝Sn deposition ＜thickness 1nm ）

EUV power at IF
> 180W
13.5nm 2%BW
(fwhm:0.27nm)

CO_2 laser is efficient, clean driver for Sn EUV plasma



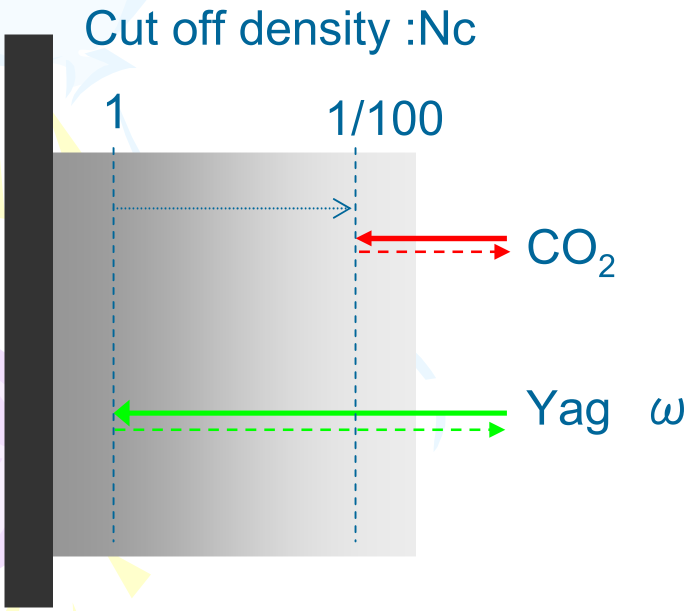
EUV radiation is emitted from hot dense plasma near the electron critical density nc.

$$n_c = \frac{\varepsilon_0 m \omega^2}{e^2}$$

$$= \frac{1.11\times 10^{21}}{\lambda^2}(\mathrm{cm}^{-3})$$

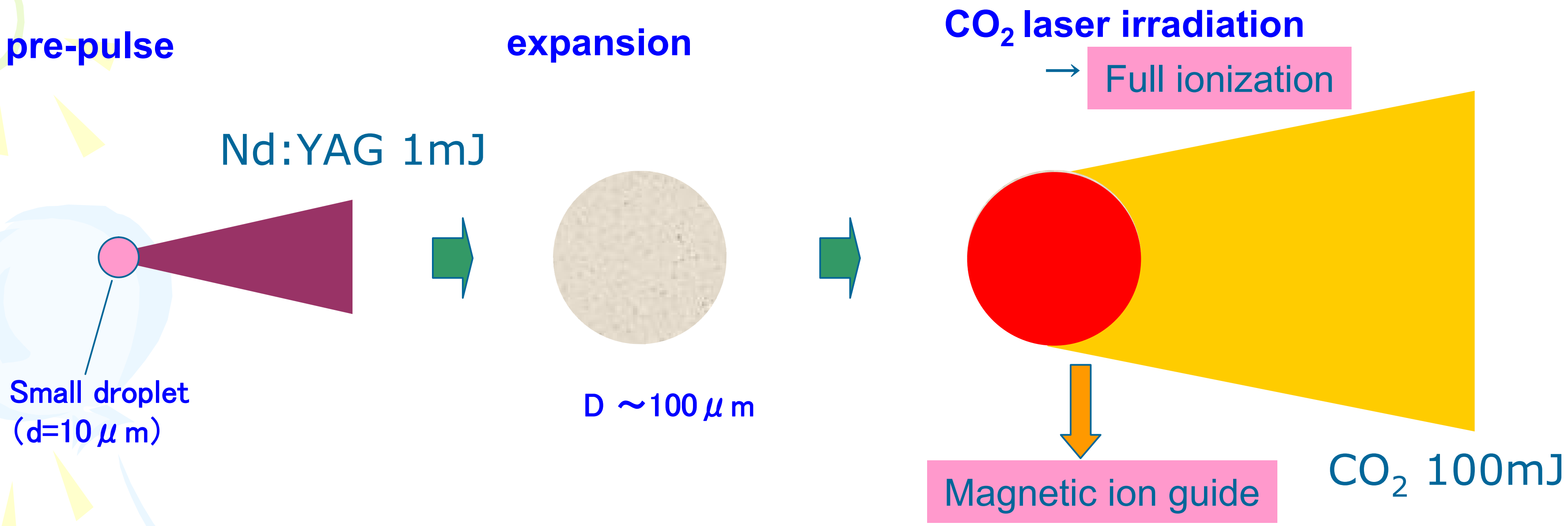
λ: wavelength in μm

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



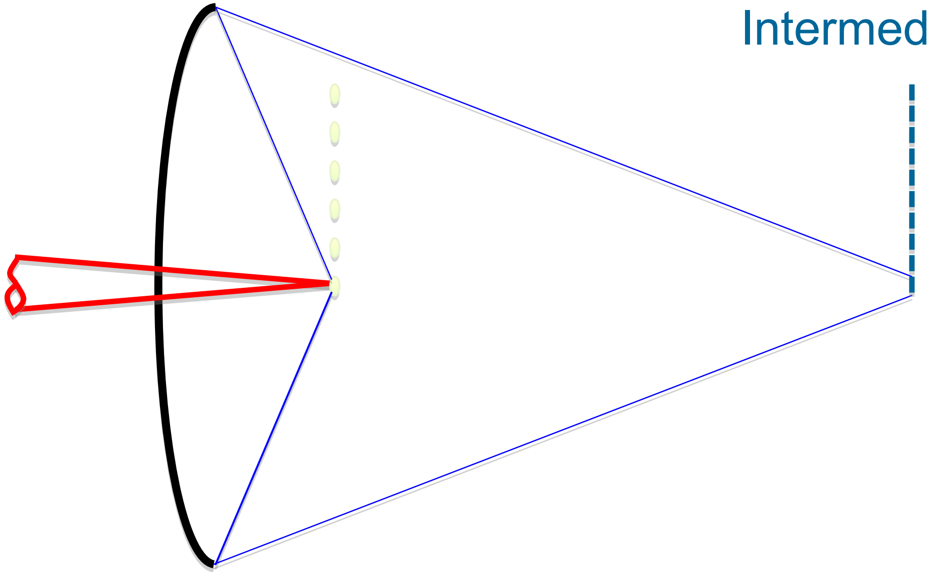
CO_2 laser light is absorbed by low density plasma. Thermal boiling of liquid Sn is avoided.

Concept of pre-plasma conditioning



Optimized density, temperature for main pulse heating
to achieve high EUV conversion efficiency

Etendue=plasma size x collection angle (mm ^{2} Sr)



EUV source size (mm2)

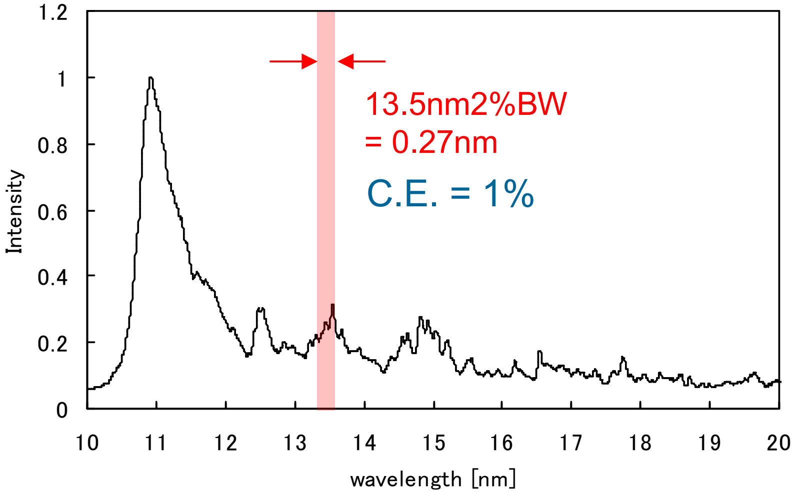
Intermediate Focus

CO2 laser

Collection angle (Sr)

Target material

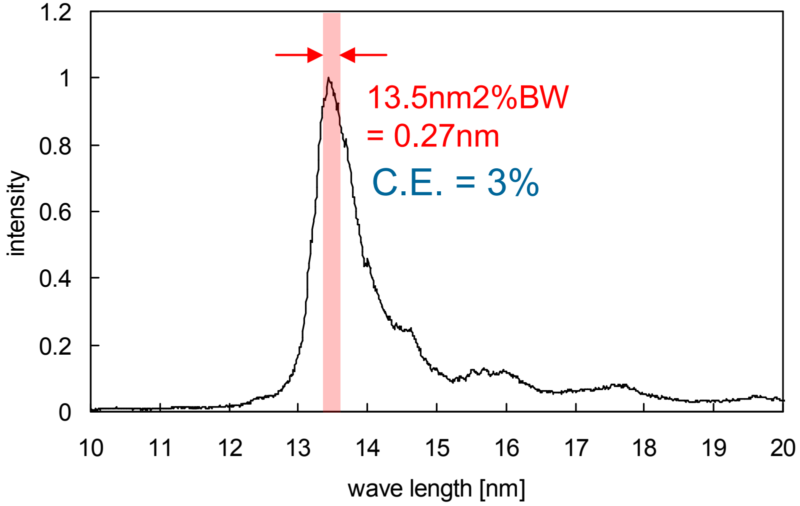
Xe target



13.5nm2%BW
= 0.27nm

C.E. = 1%

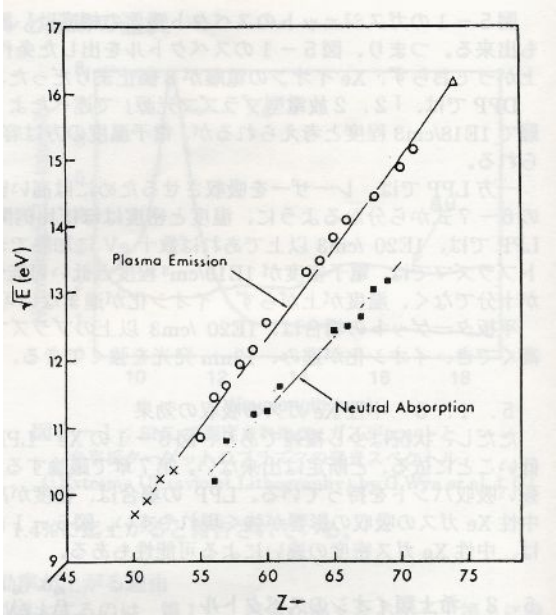
Sn target



13.5nm2%BW
= 0.27nm

C.E. = 3%

G.O'sullivan et al. J.Opt.Soc.Am.71 (1981)227



4d−4f transition :

Xe : low CE　clean

Sn : high CE　contaminant

fast ions in both cases

Wavelength dependence of laser produced Sn plasma

Conversion efficiency dependence on the laser intensity

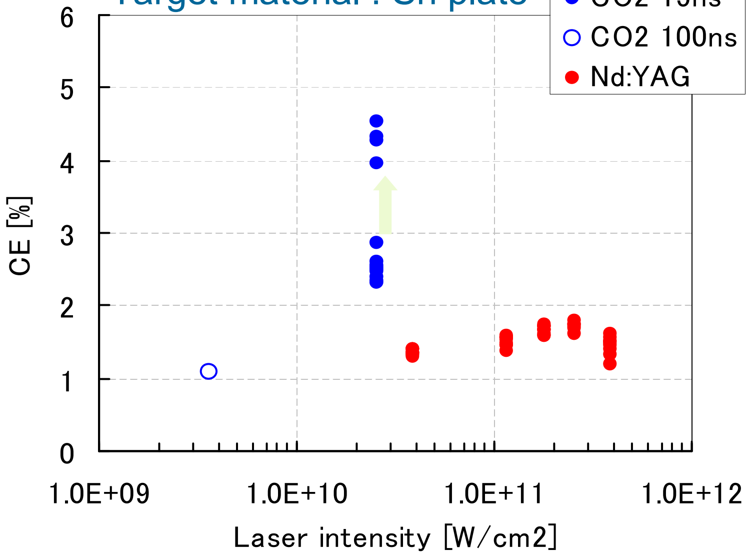
CE: 2.5% - 4.5% with CO2 laser

Laser intensity: 3×10^{10} W/cm^2

*energy:30mJ

*Pulse width:11ns

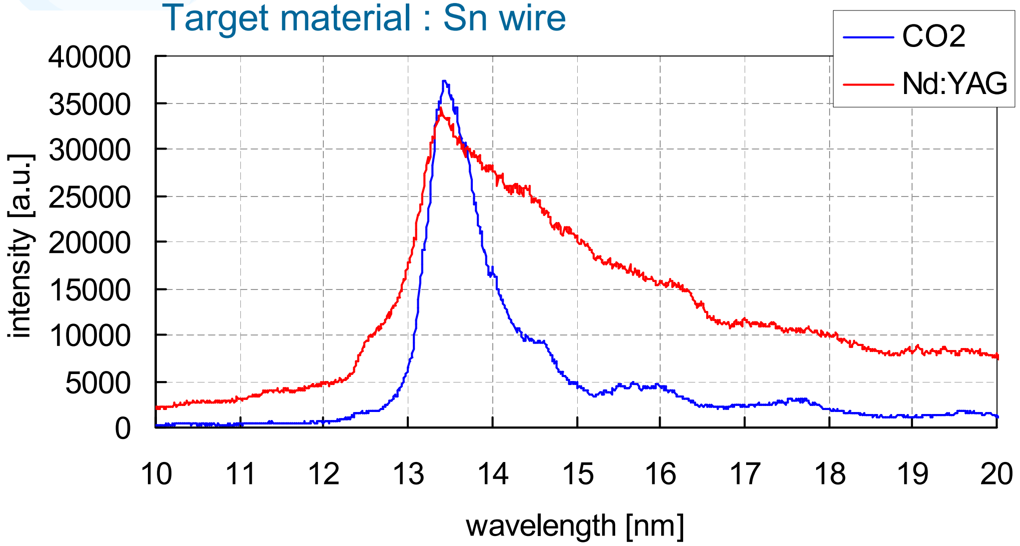
*Spot size: d=100um


Target material : Sn plate

10.6um

1.064um

Target material : Sn wire



EUV spectra from Sn plasma

Narrow in-band spectrum with CO2 laser

Characteristics of a CO_2 produced Sn plasma source

Target material: Sn plate

Items	CO2		Nd:YAG
CE	2.5 - 4.5%		1.5 - 2.5%
In band spectral bandwidth (nm, FWHM)	0.8		2.5
Debris		<	
Fast ion	1	:	2
Out-of-band		<	
Cost			
Initial	1	:	2 - 3
CoO (exclude electricity)	1	:	5
Mo/Si reflectivity at laser wavelength	> 90%		30%

High power CO2 laser MOPA system

Laser Power: 13 kW
Pulse Width: 20 ns
Repetition Rate: 100 kHz
Pulse energy stability : 2% (3s, 500 pulses)

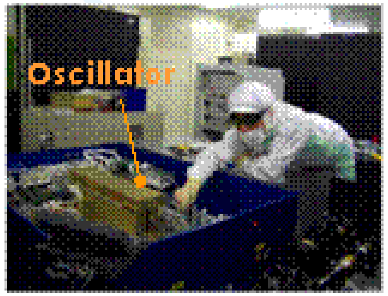
Laser System

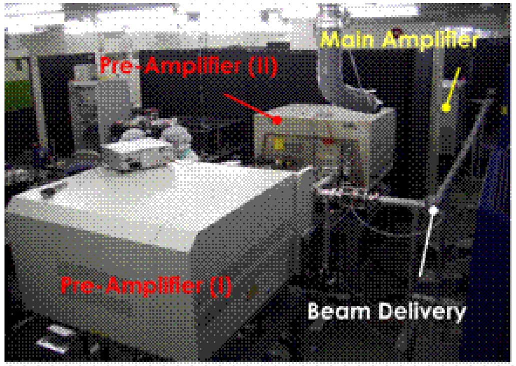
100 W at I/F equivalent

Oscillator
Wavelength: 10.6um
Rep. rate :100kHz
Pulse width :20 ns (FWHM)

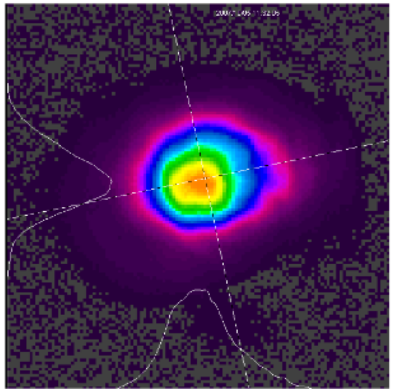
Pre-Amplifier
RF-excited CO2 laser

Main-Amplifier
RF-excited CO2 laser



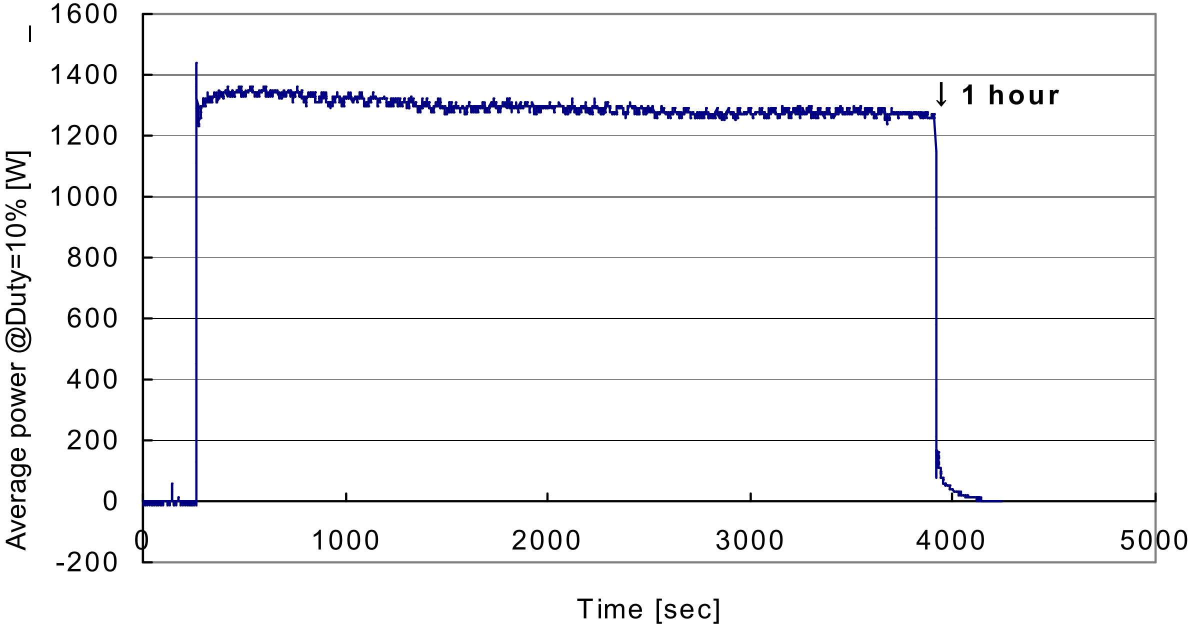


Laser beam profile



Continuous operation

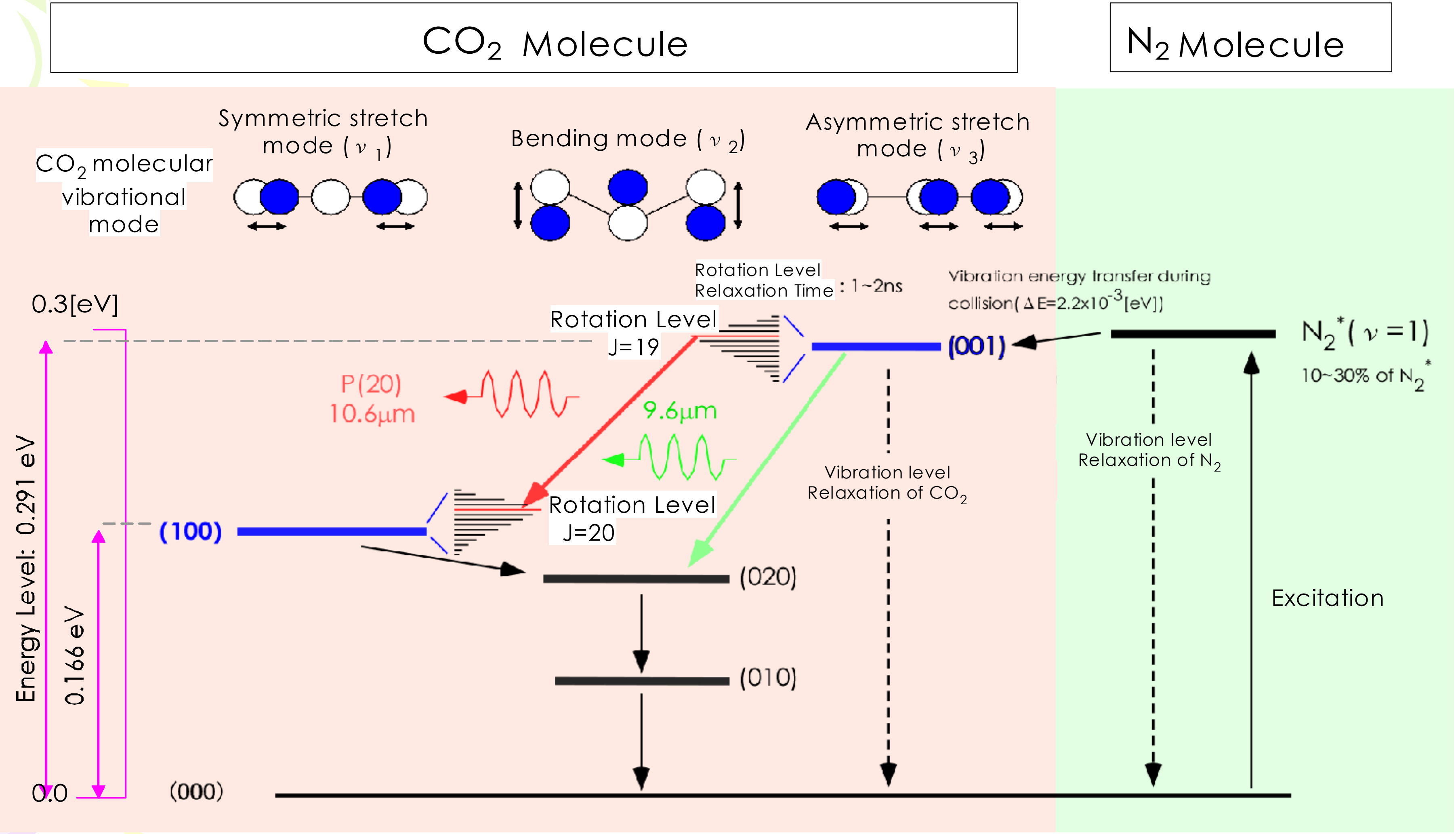
1hr non-stop operation of 100kHz CO2 laser, 13kW, 10% duty cycle



On: 1.6 ms
Off: 14.4 ms

■100% duty cycle / Full MOPA system by improved optics (thermal distortion)

§ Vibrational - Rotational CO_2-N_2 Laser Energy Level Diagram



20 kW short pulse CO_2 laser MOPA system

Pre-AMP
RF-excited CO2 laser
Pumping : 50 kW

20 kW
(200mJ at 100kHz)

Multi-line Oscillator
Rep. rate :100kHz
pulse width :20 ns (FWHM)

AMP1
RF-excited CO2 laser
Pumping power : 120 kW

AMP2
RF-excited CO2 laser
Pumping power : 120 kW

Single beam, 20 kW CO_2 laser is now in sight

- **Power Limitation**
  - ***Damage of Optics***
    ⇒ Diamond window
  - ***Filling Factor***
    ⇒ Compensation of beam diffraction and thermal lens
  - ***Saturation***
    ⇒ Multi line amplification

Scaling of LPP EUV source

EUV power estimation with laser power & CE

Laser kW \ CE %	2.0	2.5	3.0	3.5	4.0	5.0
2.5	14 18	18 23	21 27	25 32	28 36	35 45
5.0	28 36	35 45	42 54	49 63	56 72	70 90
7.5	42 54	53 68	63 81	74 95	84 108	105 135
10	56 72	70 90	84 108	98 126	112 144	140 180
20	112 144	140 180	168 216	196 252	224 288	280 360

HVM source

Transfer efficiency from primary source to IF

	Total	Debris shield	Collectable angle	Reflectivity	T%	SPF
Case1	0.28	0.8	5sr	0.6	0.9	0.8
Case2	0.36	1	4sr	0.6	0.94	1

Dynamics of Sn droplet after pre-pulse irradiation

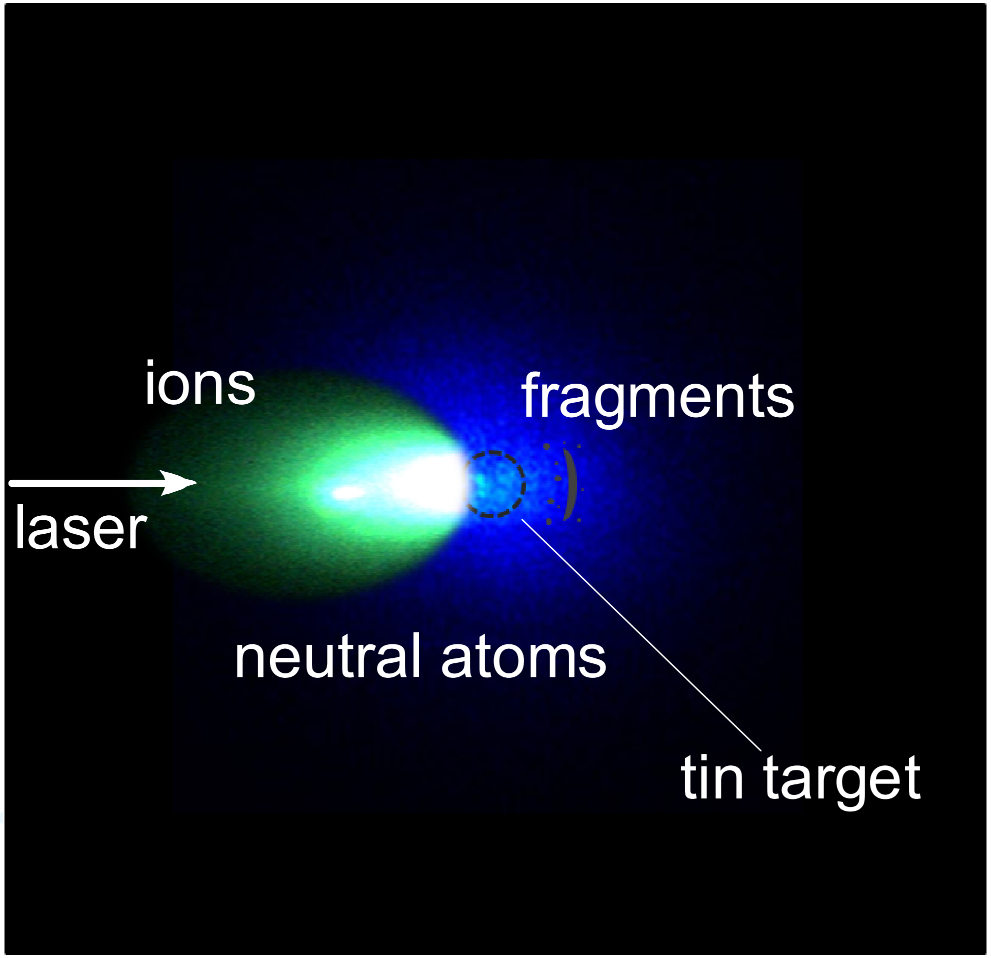
Droplet: spatially and electrically isolated object

Ablation

Spallation

Breakup

vaporization

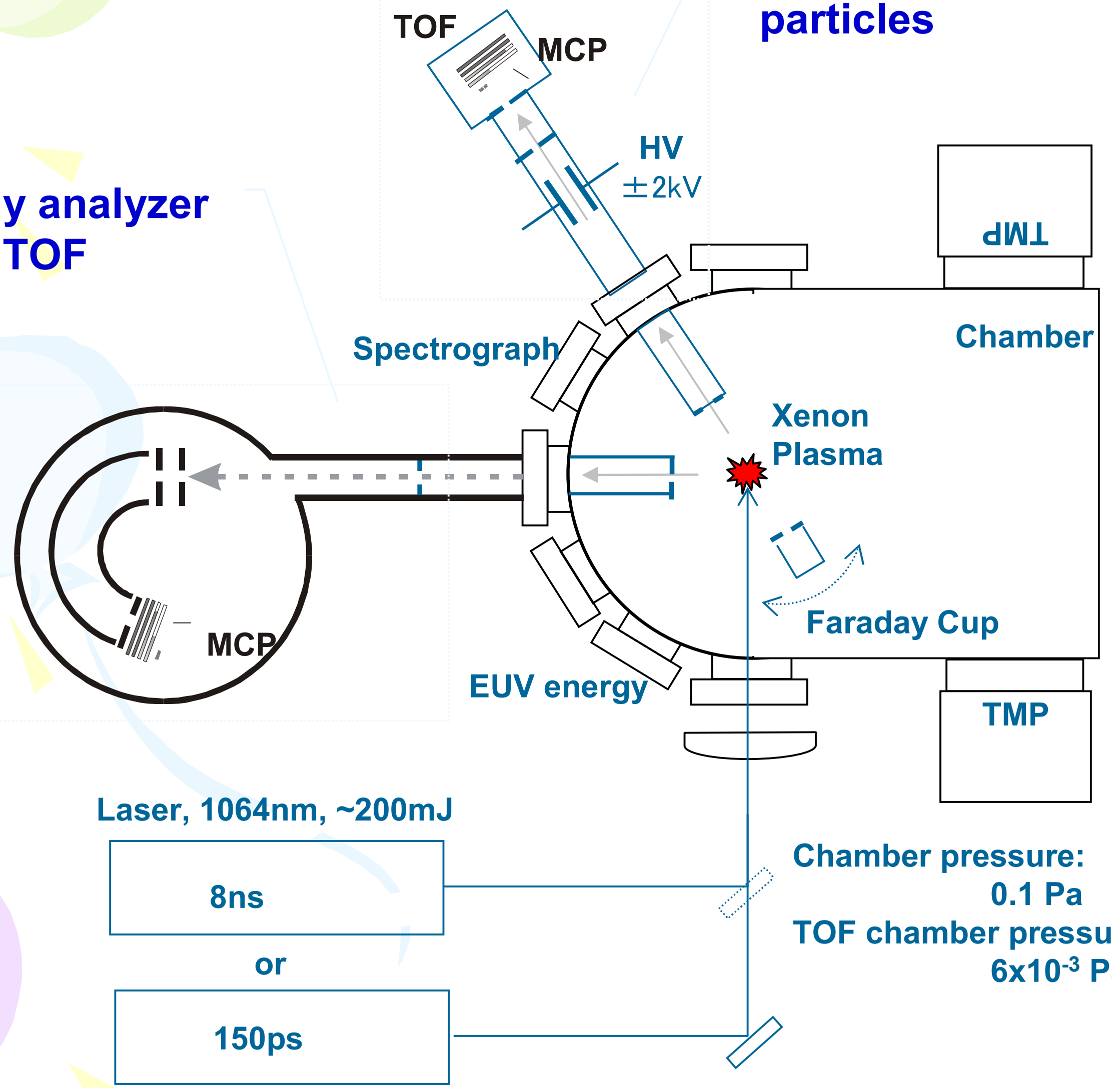


Liquid droplet discomposes into energetic plasma ion and neutrals, and slow gas and fragments (the majority of the target material)

Experimental set up for ion energy measurement

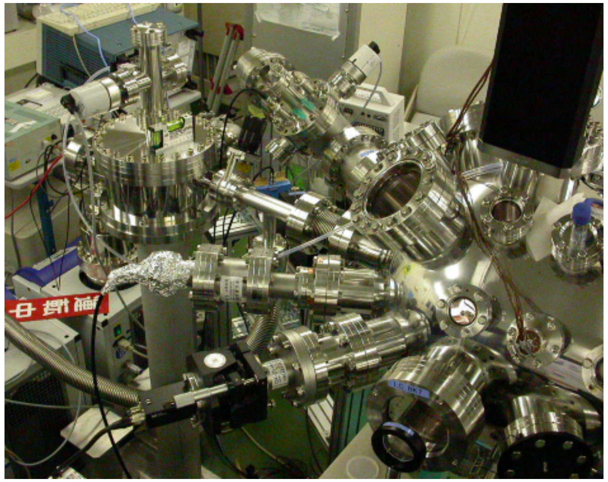
TOF for neutral particles

Energy analyzer TOF



Chamber pressure: 0.1 Pa

TOF chamber pressure: 6×10^{-3} Pa

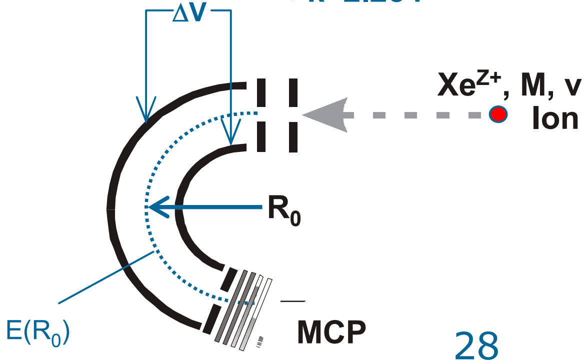


$Mv^2/R_0 = eZE(R_0)$

(Centrifugal force
=Charge
x Electric field strength)

$E_{kin}/Z = Mv^2/2Z$
$= e R_0 E(R_0) / 2$
$= ke \Delta V$ [eV]
k=2.254

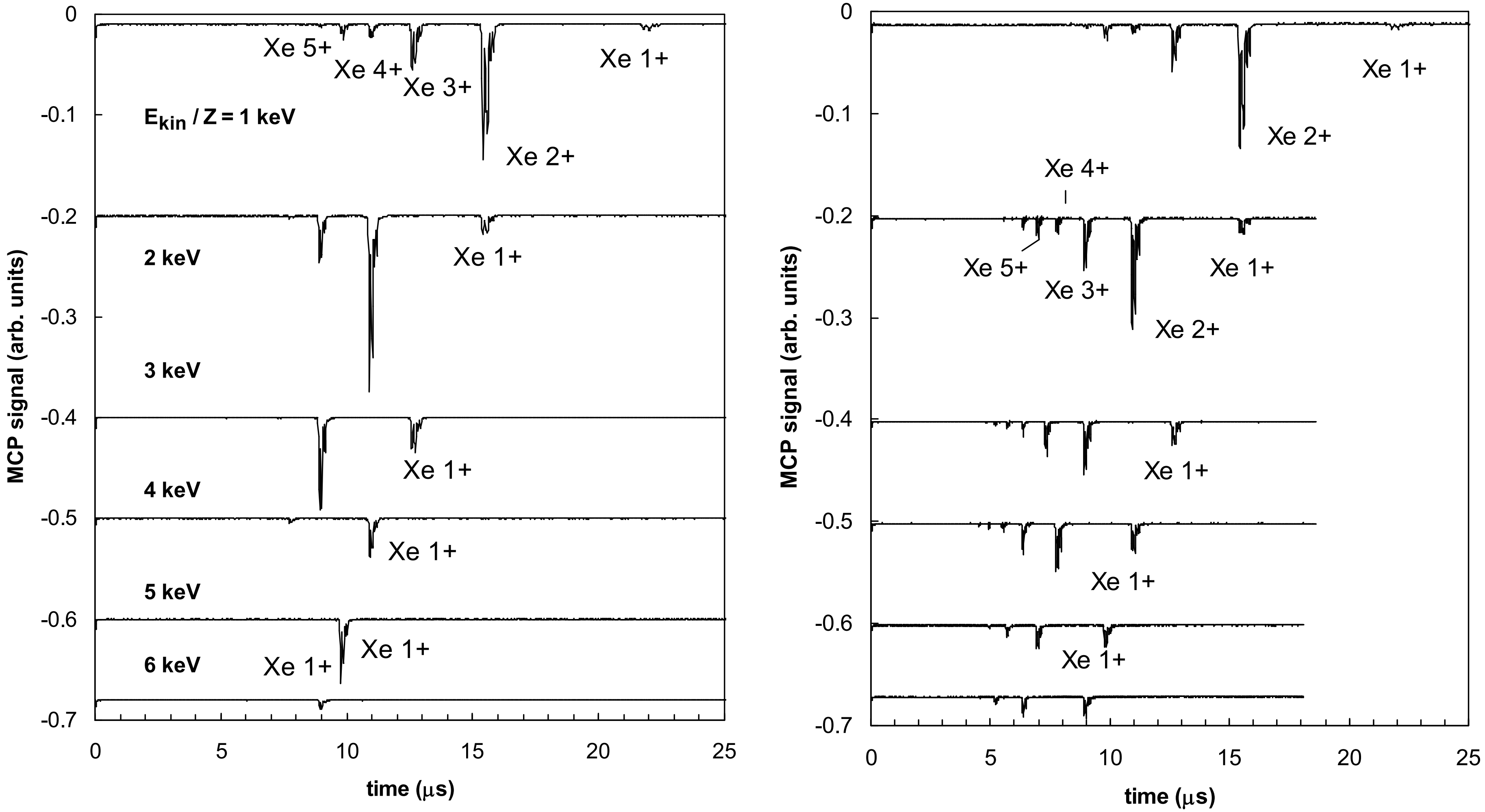
ESA



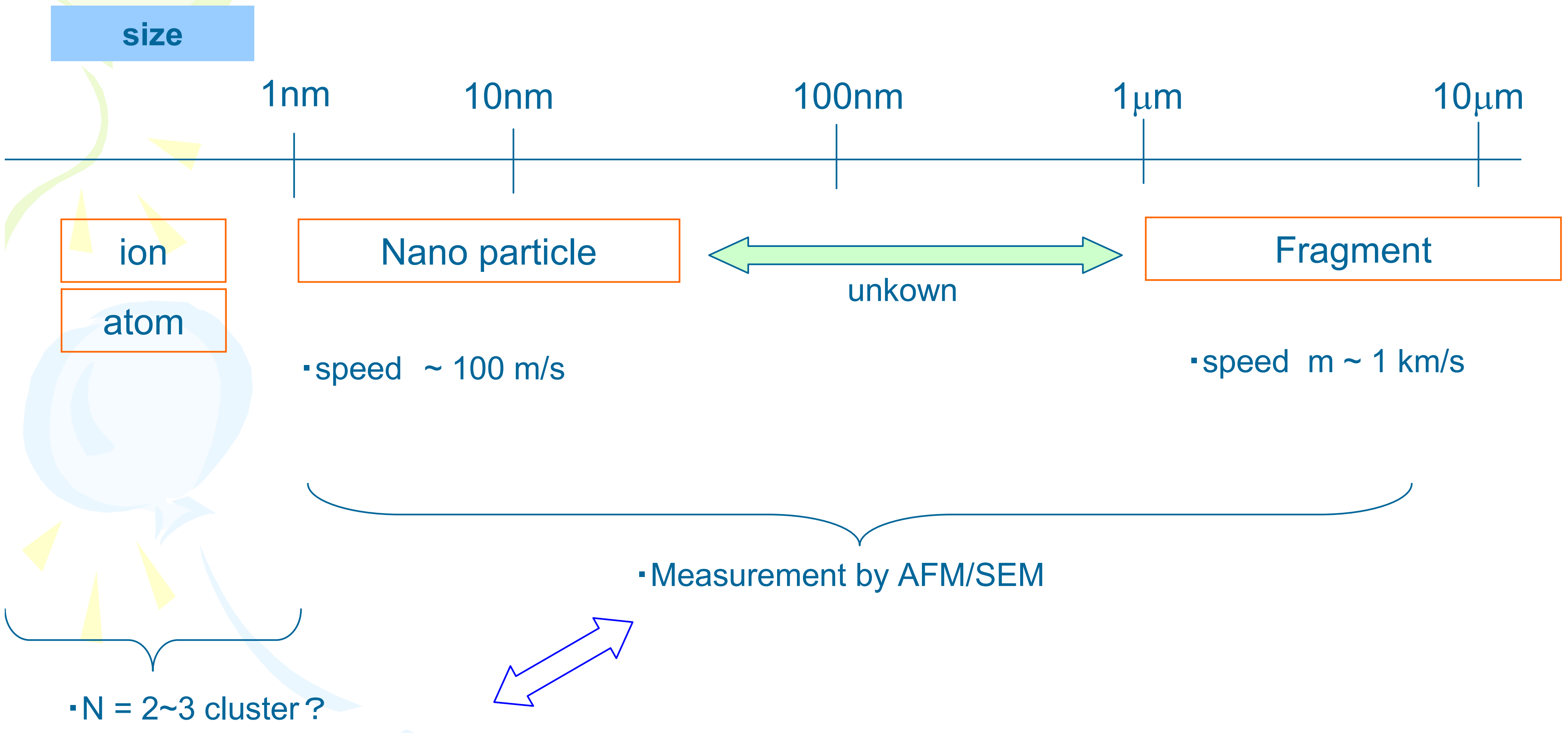
ESA TOF signal dependence on laser pulse duration

Laser energy: 100mJ

Pulse duration: 8 ns, Intensity: 3.8×10^{11} W/cm^2 150 ps, 2×10^{13} W/cm^2



Particles from Sn laser ablation



size

1nm 10nm 100nm 1μm 10μm

ion

atom

Nano particle

unkown

Fragment

・speed ~ 100 m/s

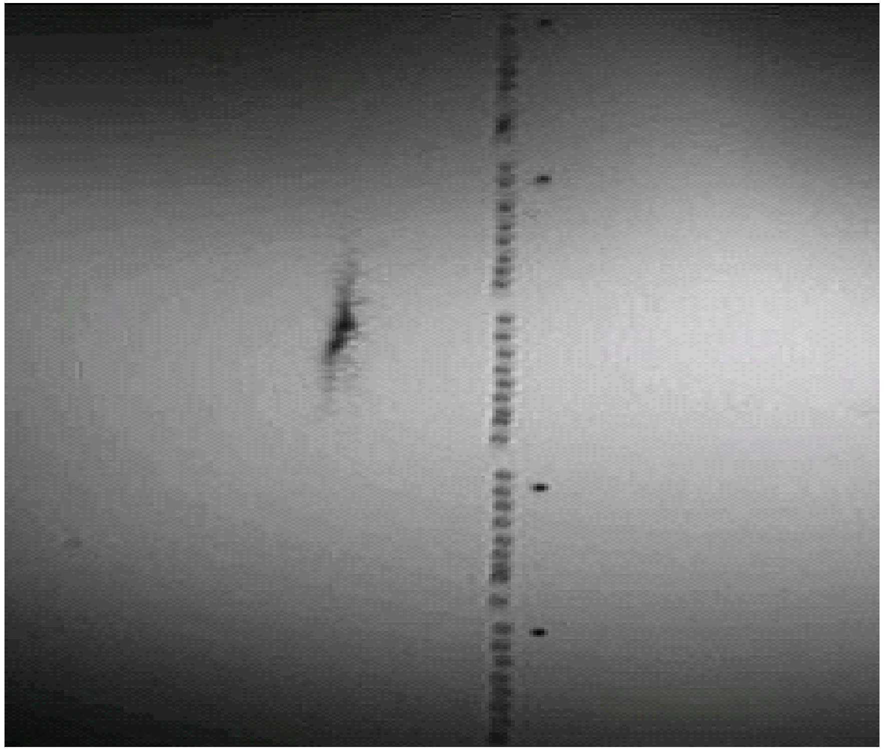
・speed m ~ 1 km/s

・Measurement by AFM/SEM

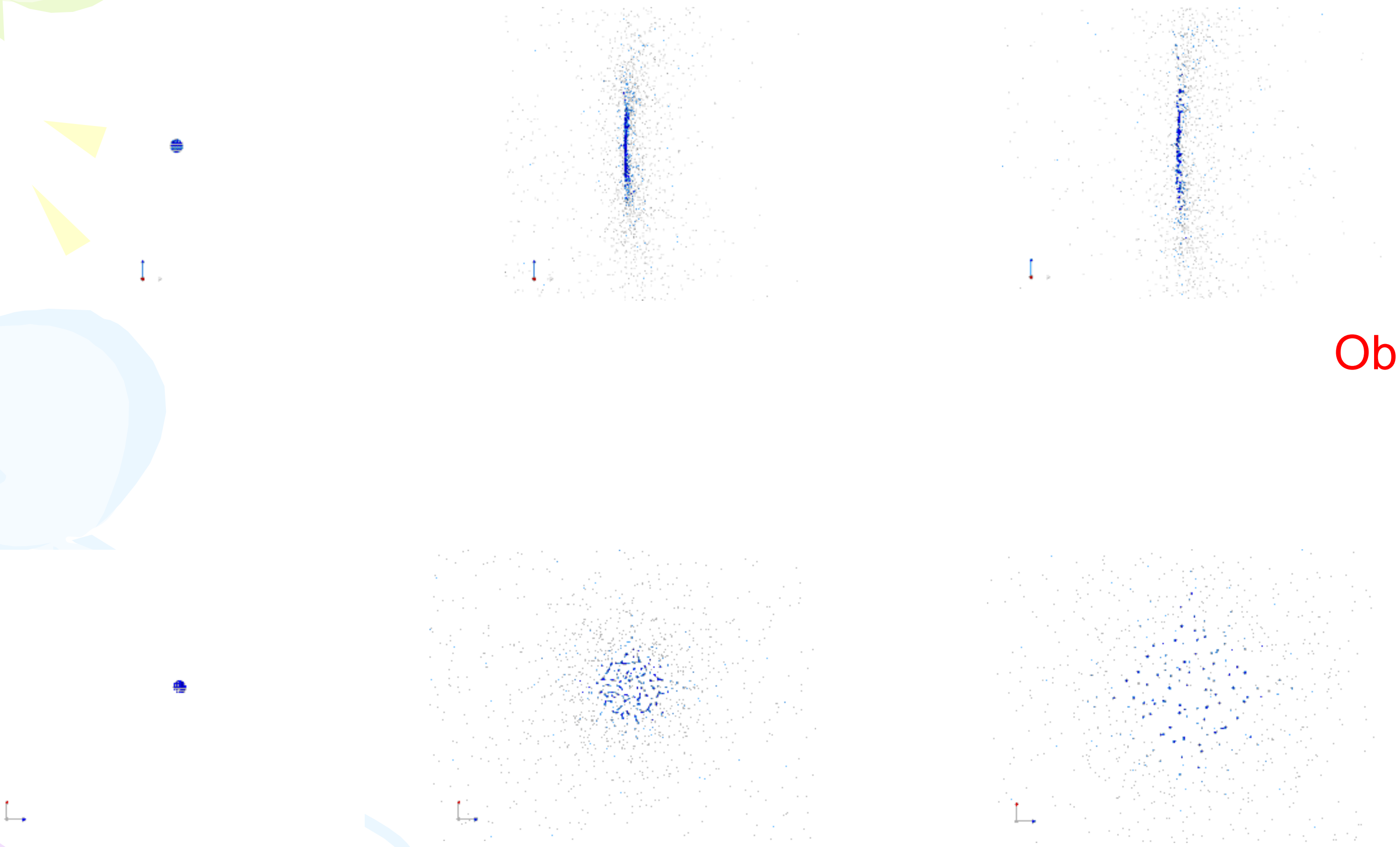
・N = 2~3 cluster？

Cluster science by laser ablation

Dispersion of Sn droplet by a pre-pulse



Particle simulation of 10μm droplet dispersion (Pizza shape)

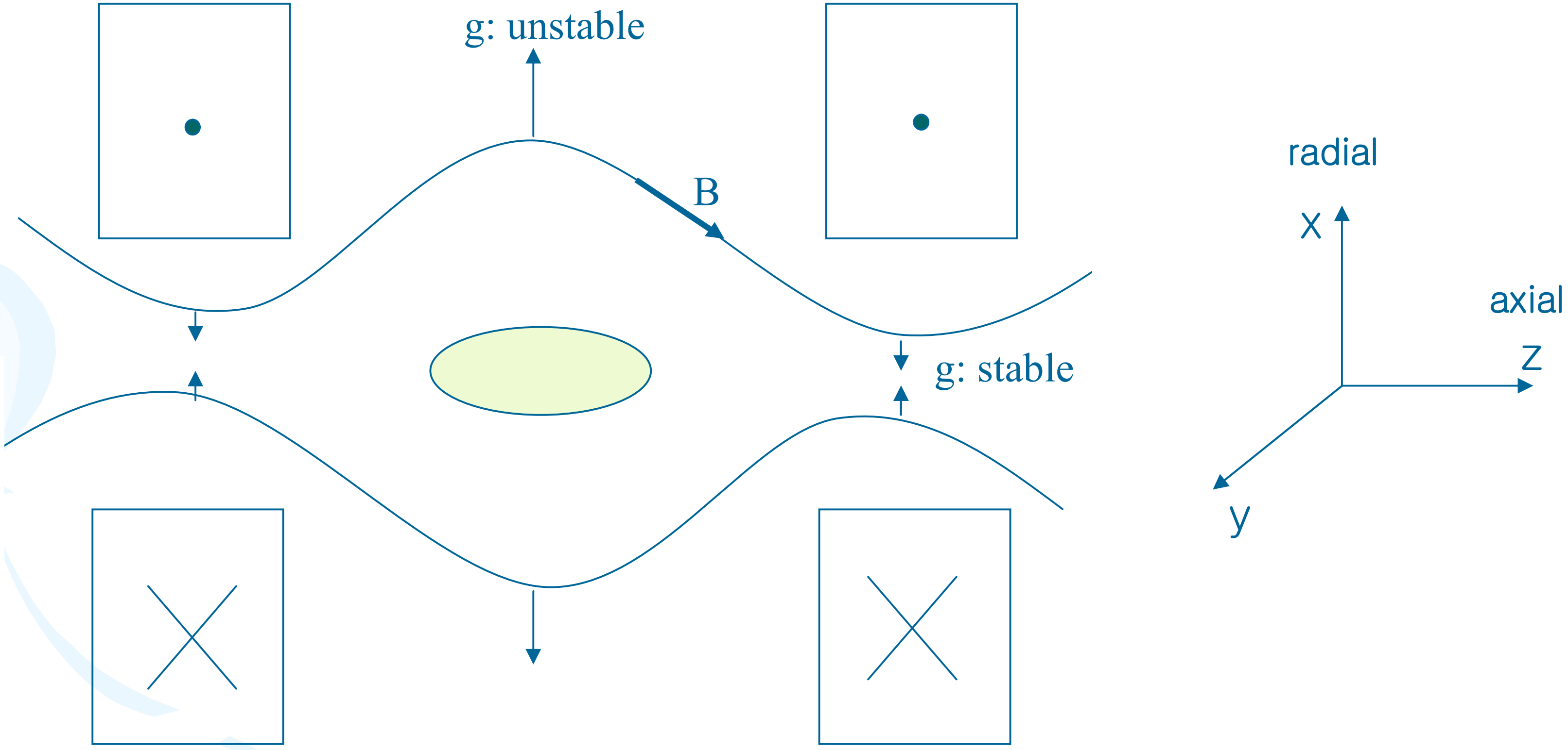


Oblique image

On axis image

Fragment generation is avoided with 10μm Sn droplet

Plasma in magnetic mirrors

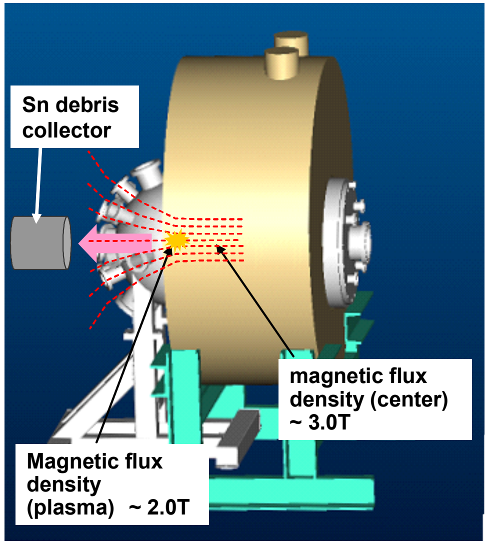


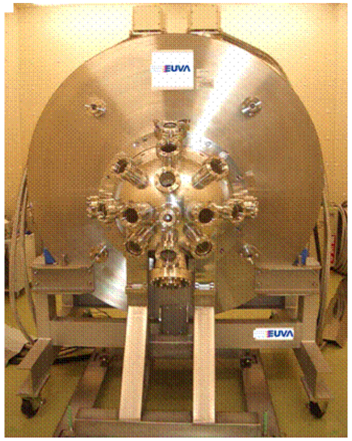
Curvature drift $v = \frac{m v_{II}^2}{qB^2} \frac{R \times B}{R^2}$

Magnetic plasma ion guiding

Ion characteristics

Superconducting magnet was employed
1) Characterization of Sn ion flux
2) Optimization of Sn evacuation.





Visible image of Sn ion flow in magnetic field

Laser : CO2 laser, Target : Sn plate

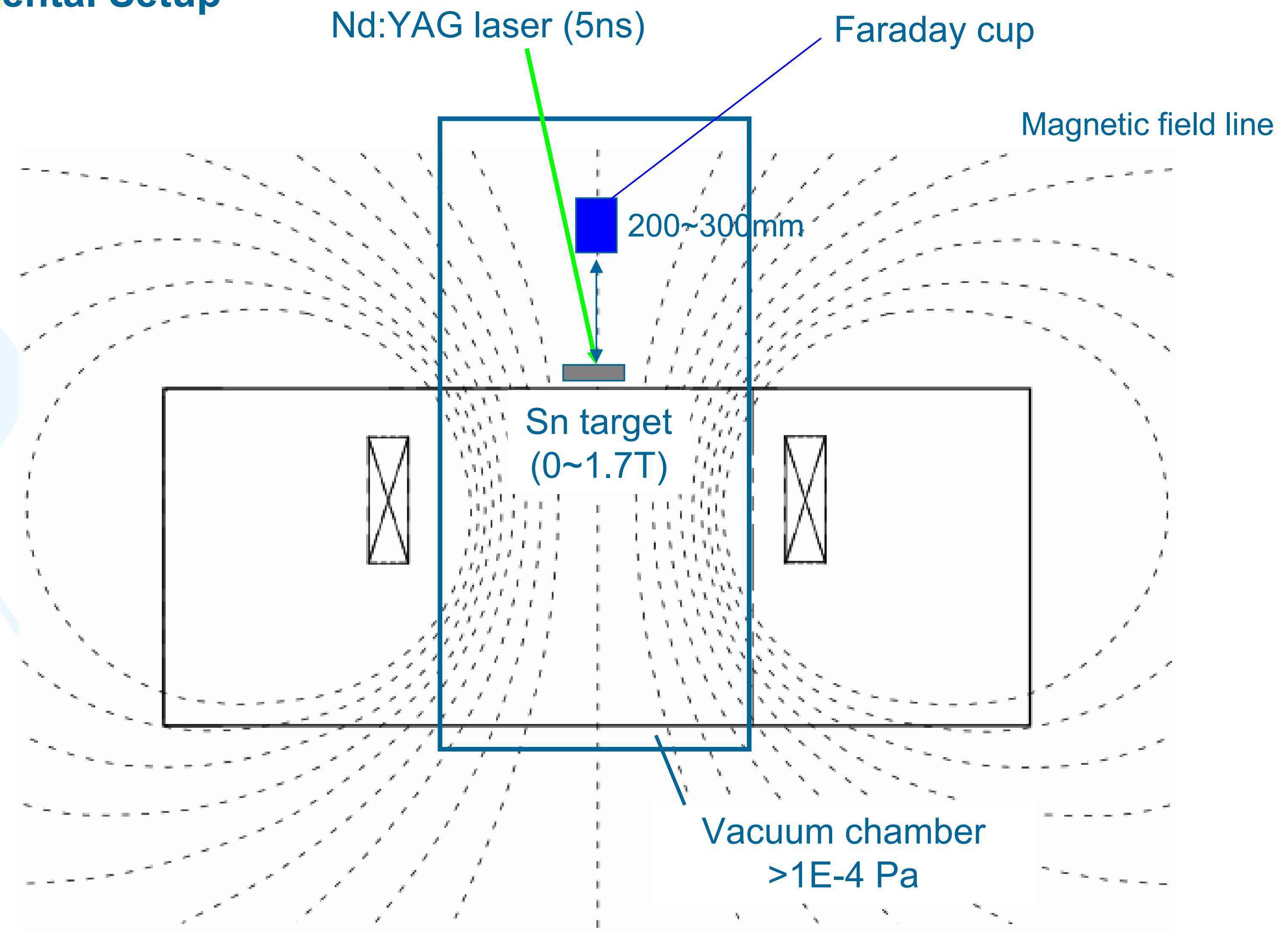
Without magnetic field

Magnetic field : 2T

Ion current measurement

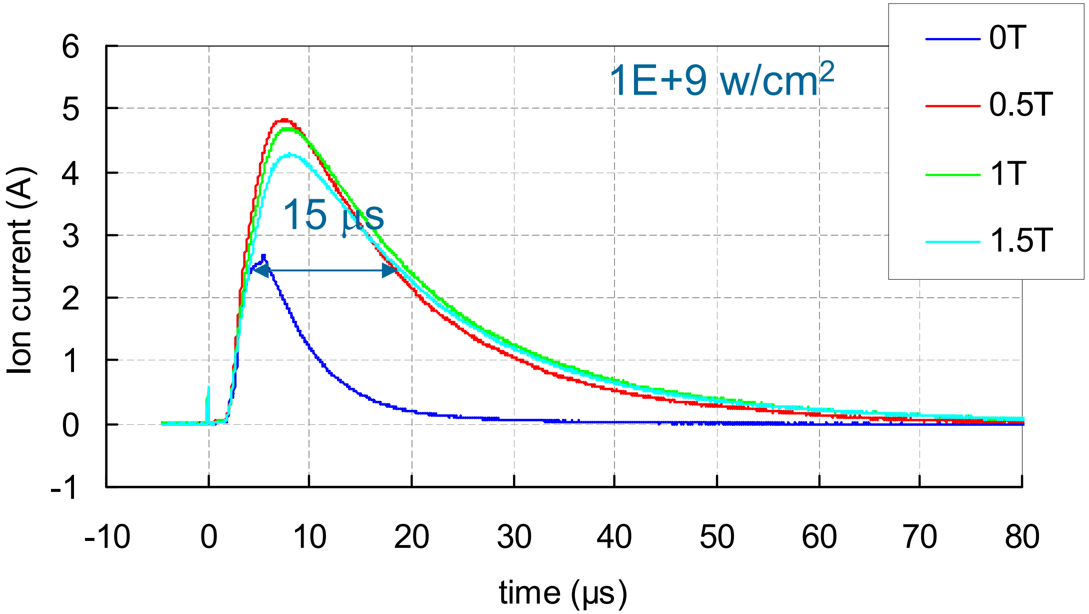
Ion characteristics

Experimental Setup



Ion current waveform

Typical ion waveforms



Peak ion current : ~ 5 A

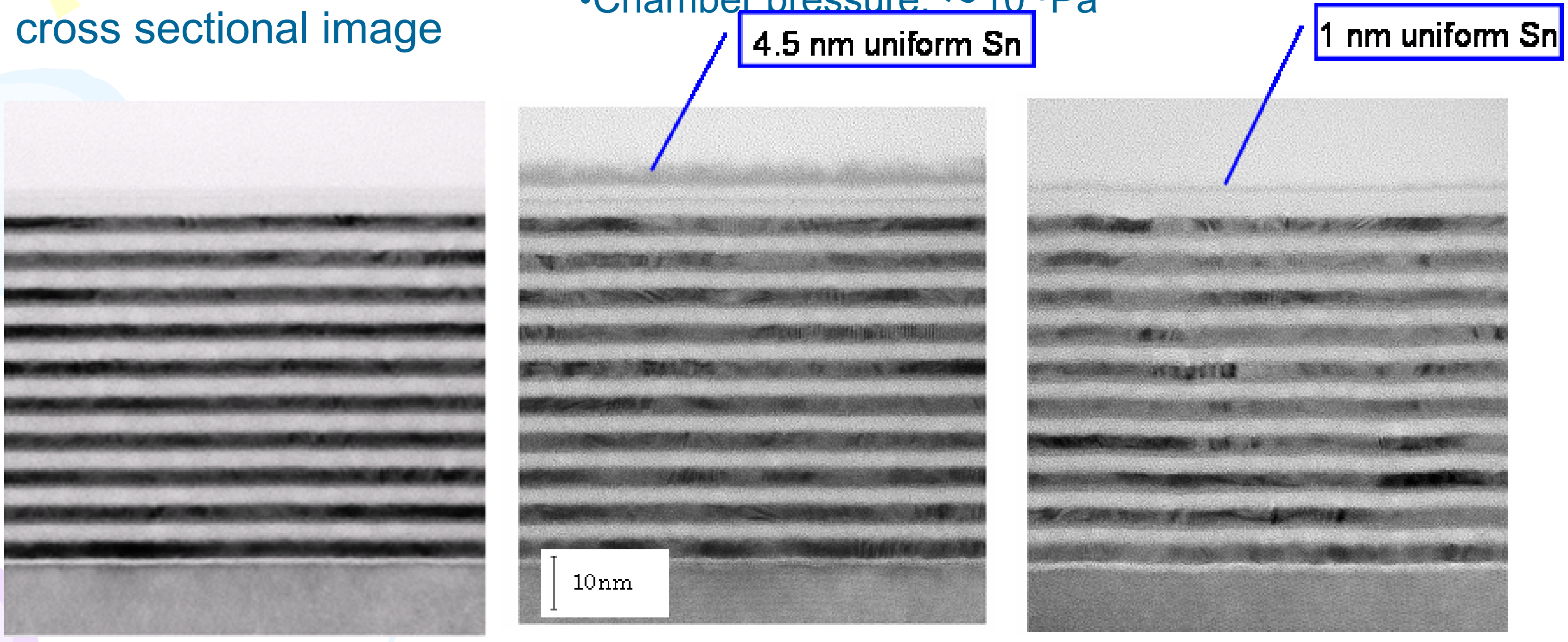
Total charge amount : 1E-4 C

Magnetic field Sn ion exhaust

Experimental conditions

- Mo/Si mirror sample :10 bilayer
- Distance from plasma: 60 mm
- Angle to laser incidence: 45 degree
- Laser pulse energy: 20 mJ
- Laser pulse number: 4×10^4 pulse
- Chamber pressure: $\sim 10^{-3}$Pa

TEM cross sectional image


4.5 nm uniform Sn

1 nm uniform Sn

Before exposure

B= 0 T

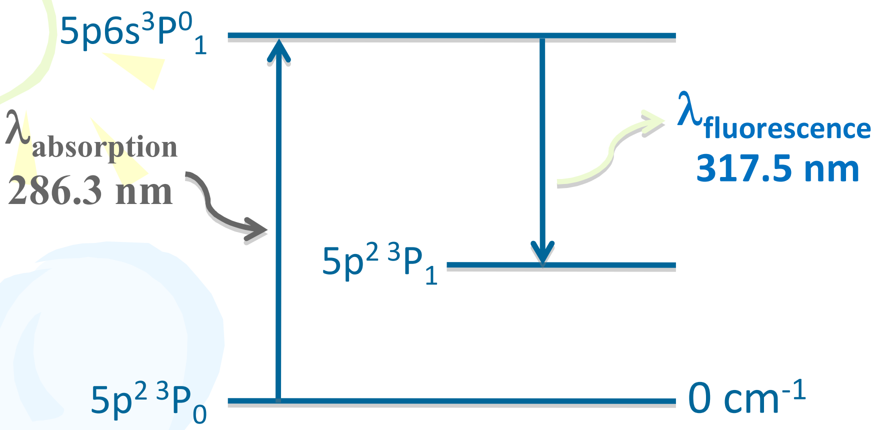
B= 1 T

Sn deposition decreased to 1/4～1/5 with 1T B field

Laser induced fluorescence (LIF) imaging for tin atom

Principle of LIF

Neutral characteristics

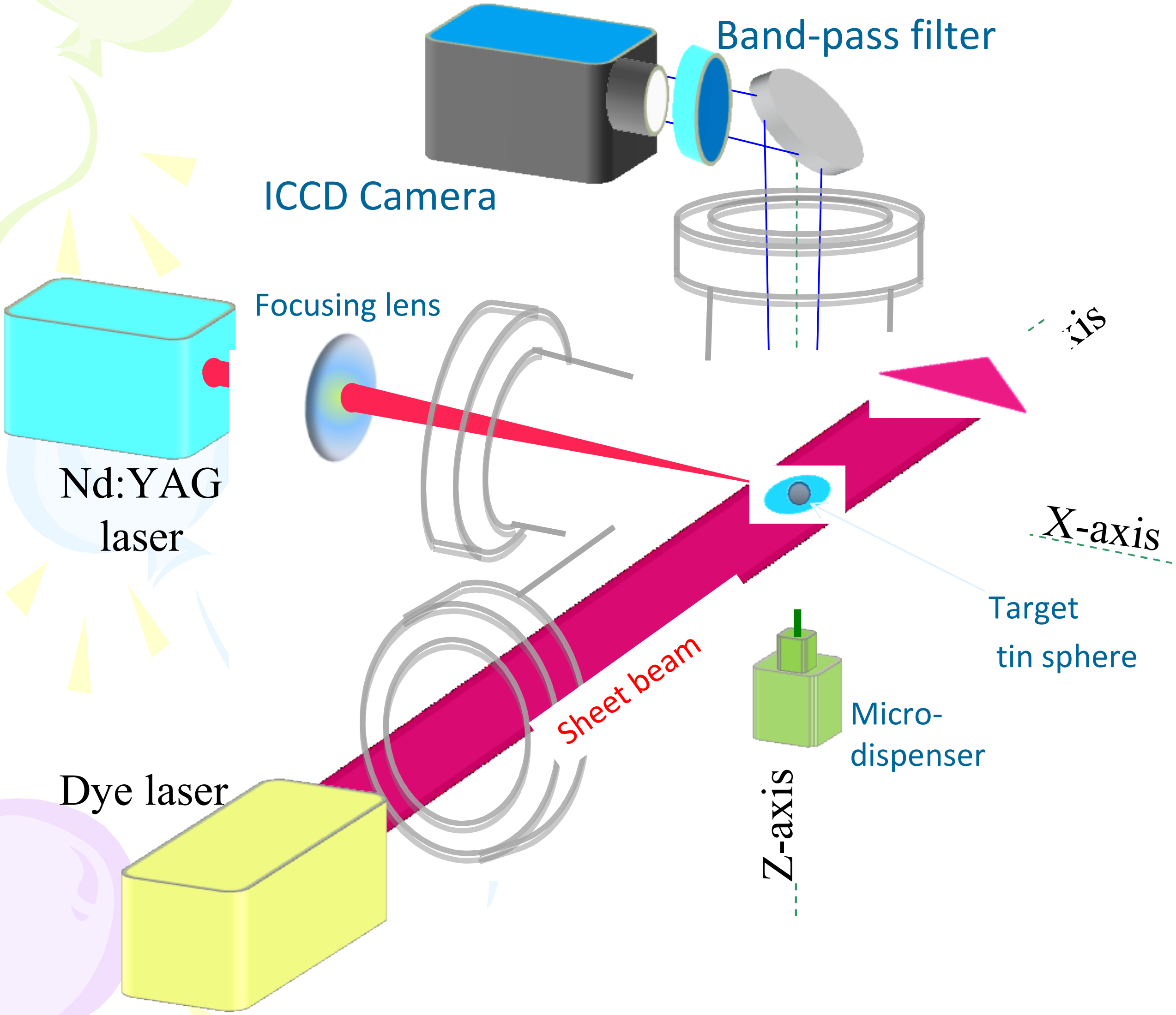


Grotrian diagram for tin atom

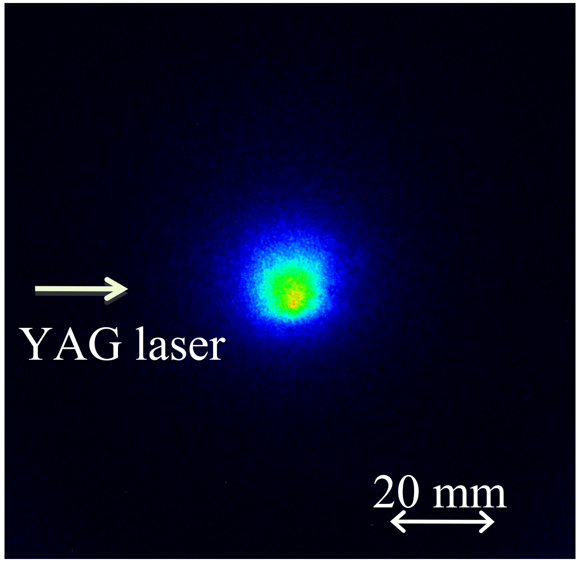
Advantages

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

Sn vapor measurement by laser induced fluorescence (LIF)

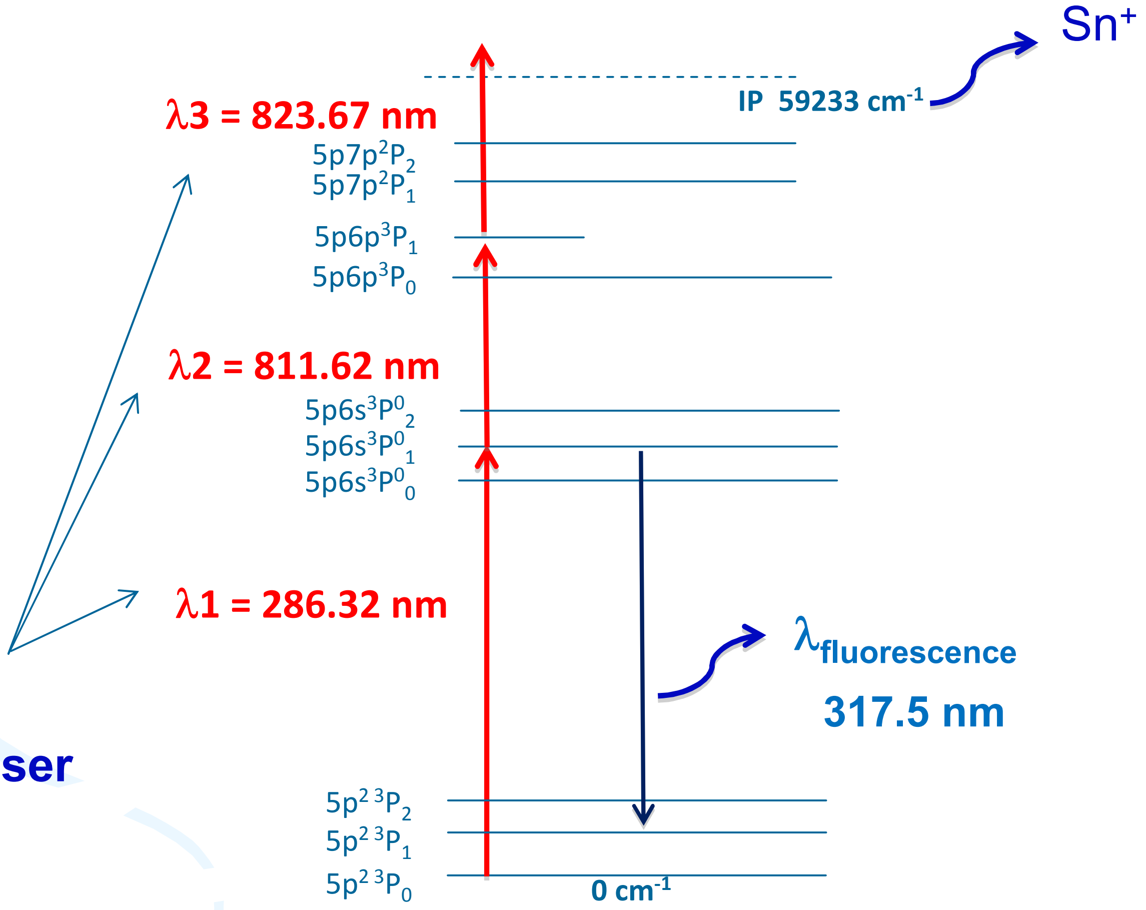


Neutral characteristics



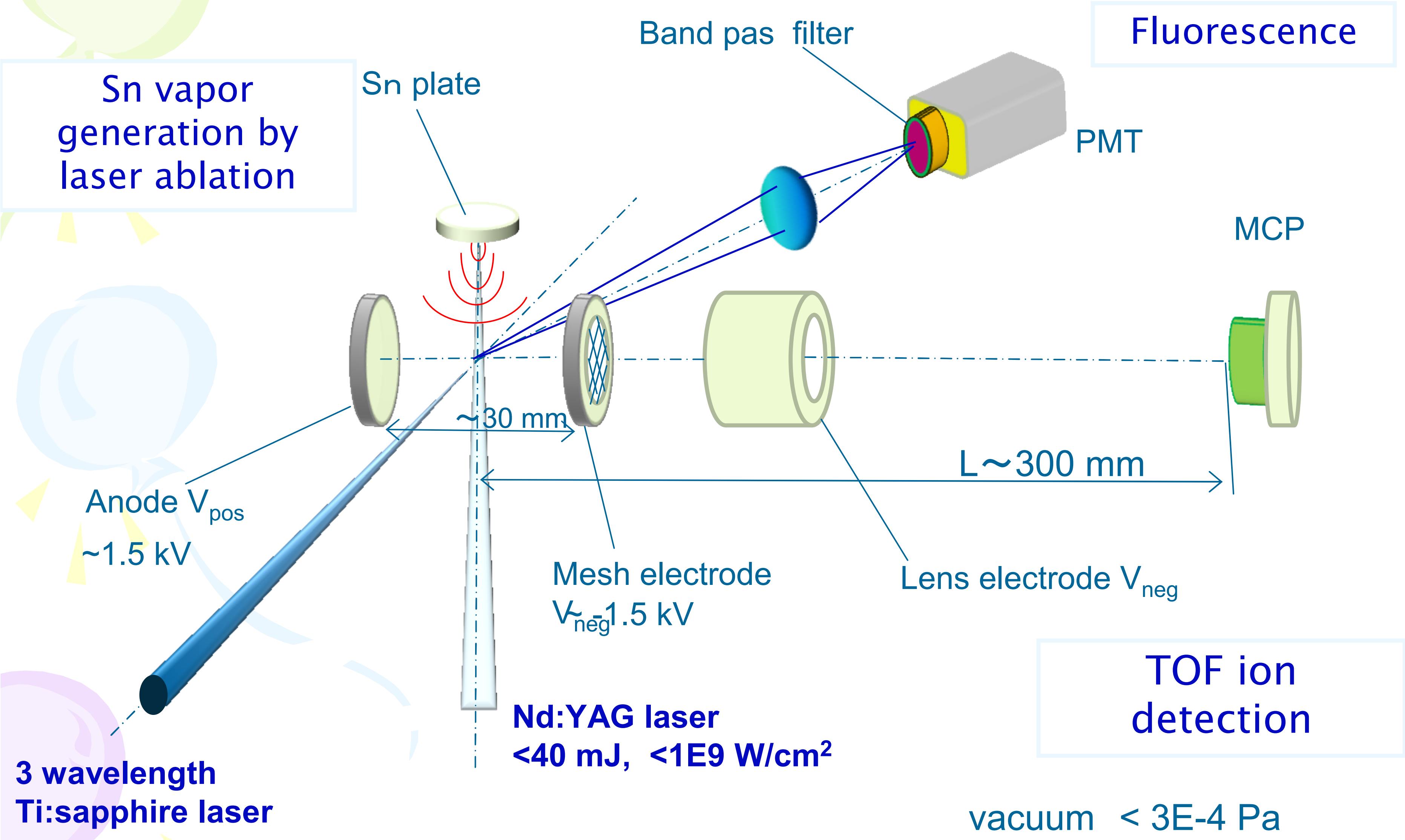
LIF image of tin vapor (10^9 W/cm^2, after 3μs)

Resonant laser ionization of Sn vapor



3 wavelength
Ti:sapphire laser

Experiment of laser ionization of Sn vapor



Sn vapor generation by laser ablation

Sn plate

Band pas filter

Fluorescence

PMT

MCP

~30 mm

L～300 mm

Anode V_{pos}

~1.5 kV

Mesh electrode

V_{neg}~-1.5 kV

Lens electrode V_{neg}

TOF ion detection

3 wavelength
Ti:sapphire laser

Nd:YAG laser
<40 mJ, <1E9 W/cm^2

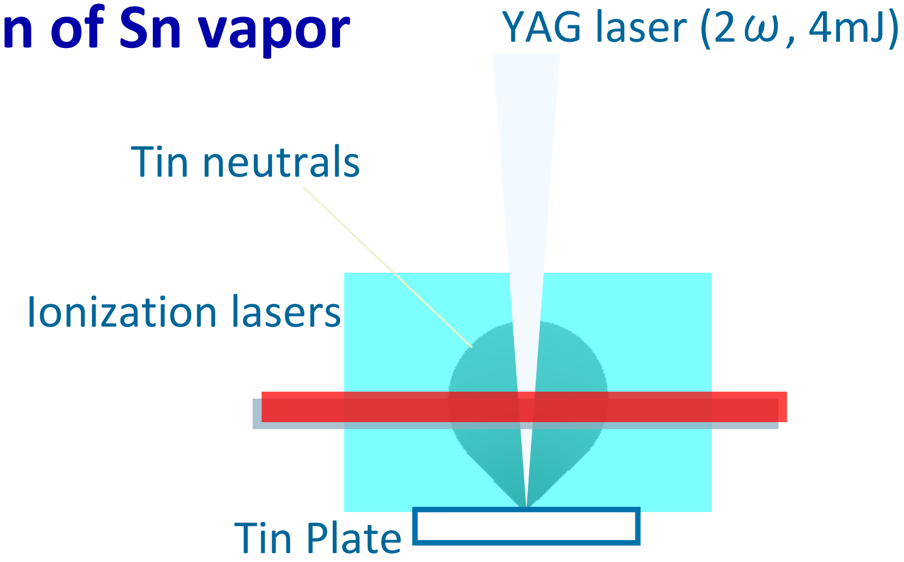
vacuum < 3E-4 Pa

LIF measurement of ionization of Sn vapor

- YAG 2ω、4mJ

- Laser 1 (286.3nm)
- Laser2(811.5nm), Laser3(823.3nm)

- vacuum level ~1E-3Pa
- Measurement after 1μs of ablation



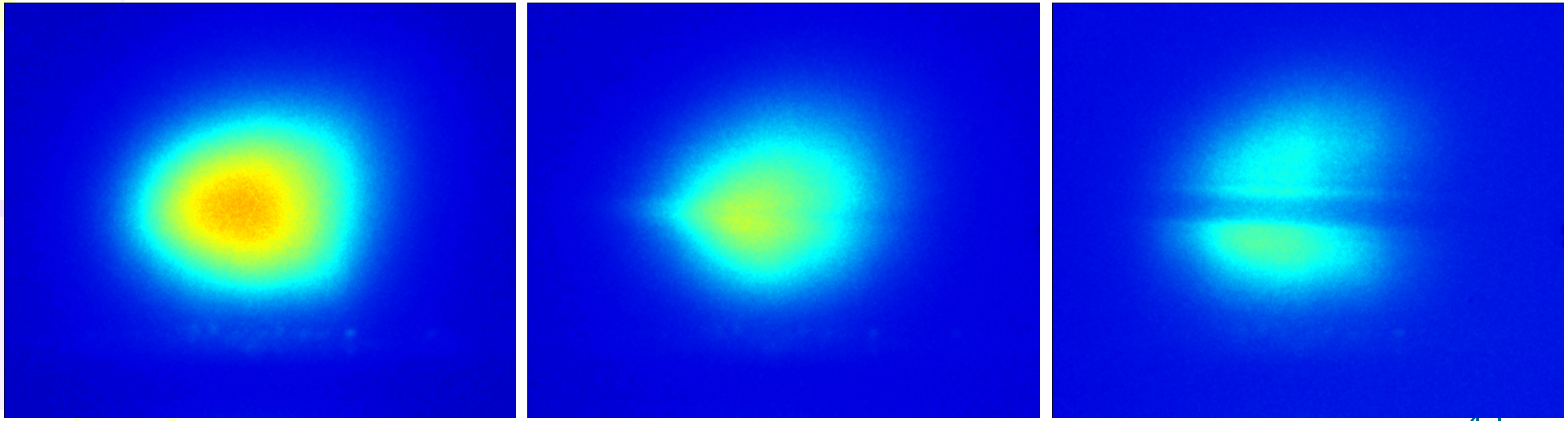
YAG laser (2ω, 4mJ)

Tin neutrals

Ionization lasers

Tin Plate

LIF—ICCD image of neutral Sn



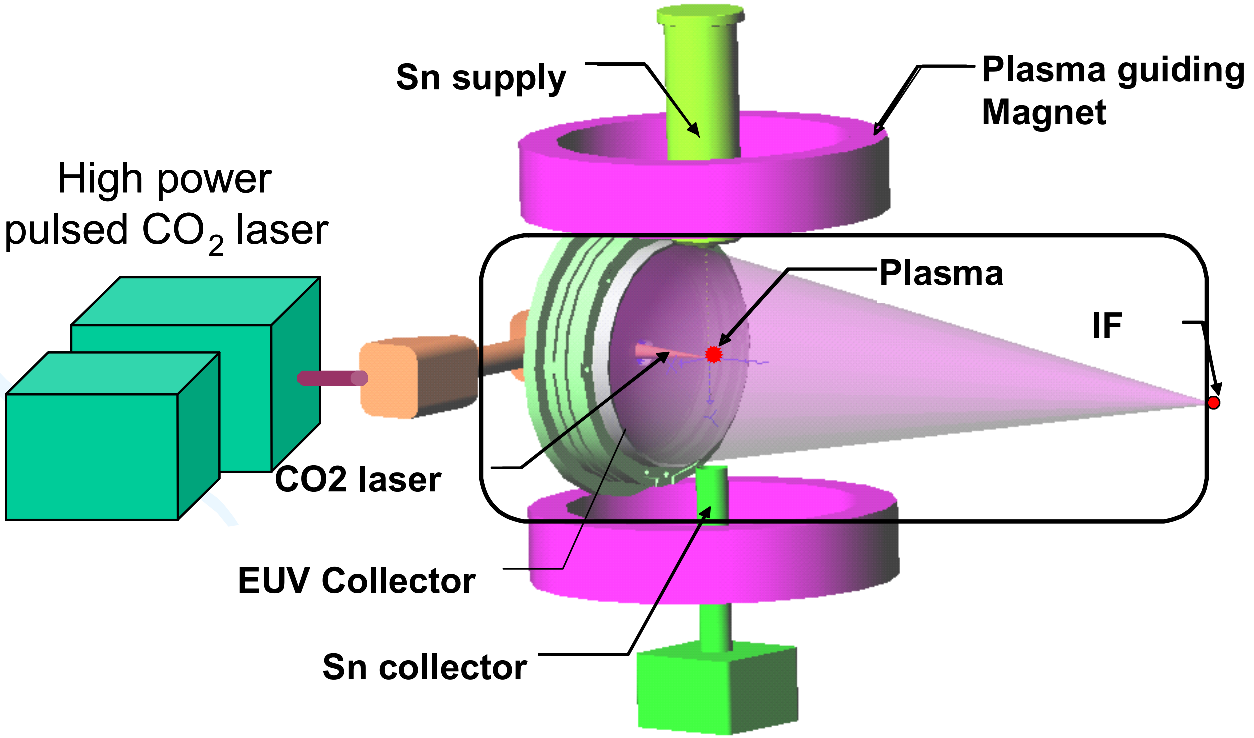
Laser1 **Laser 1 +2** **Laser1+2+3**

Clean Light Source Concept

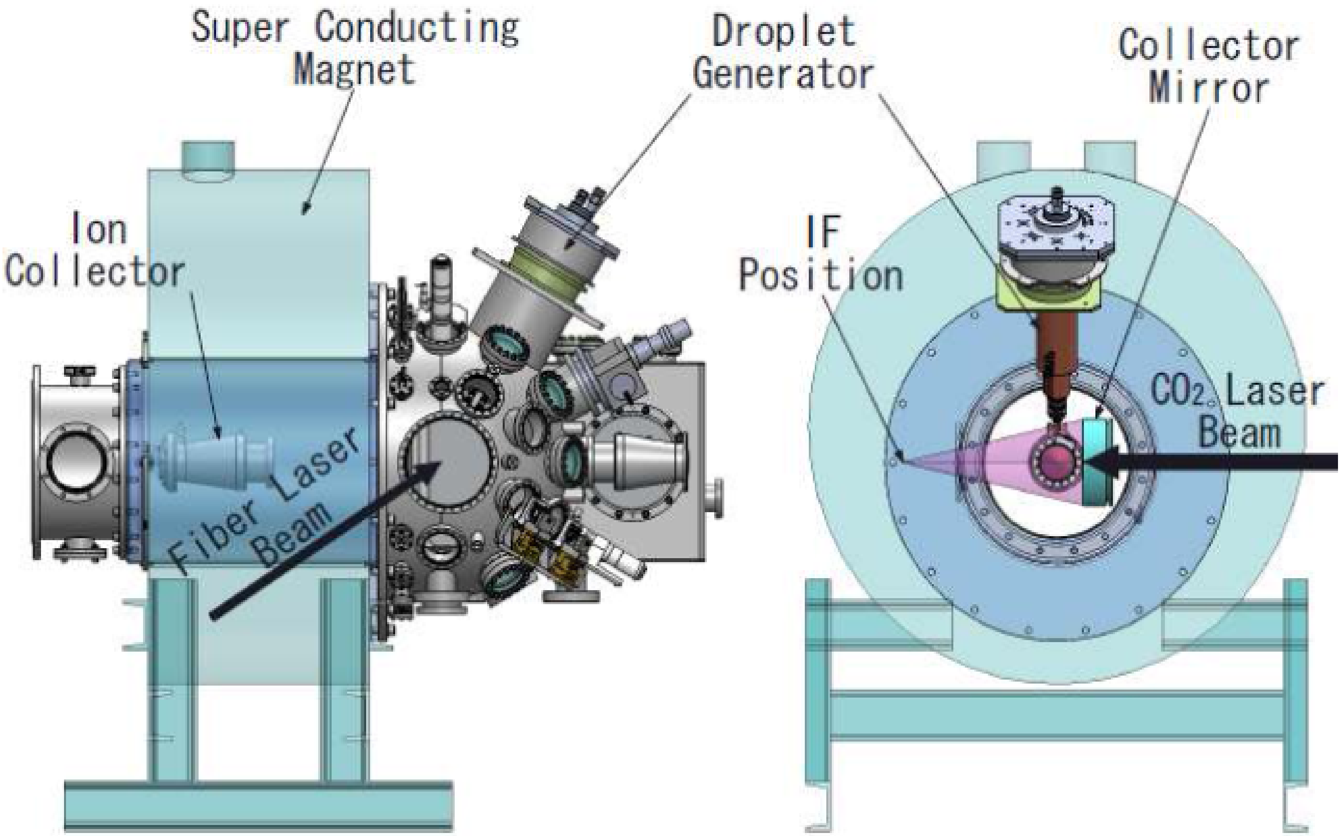
Requirement for EUV source for HVM

- High EUV power : 400 W
- EUV Stability
- Collector mirror lifetime
- Low CoG / CoO

CO_2 laser + Sn LPP light source
+ Magnetic field Sn recovery



ETS EUV chamber configuration



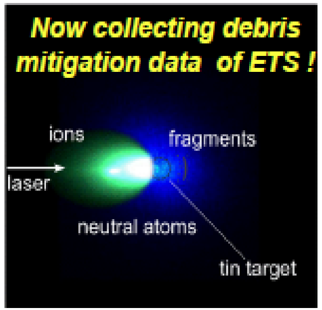
SPIE Advanced Lithography 2010 P12

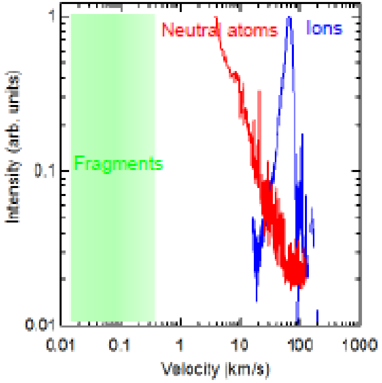
Silver line in tin vapor

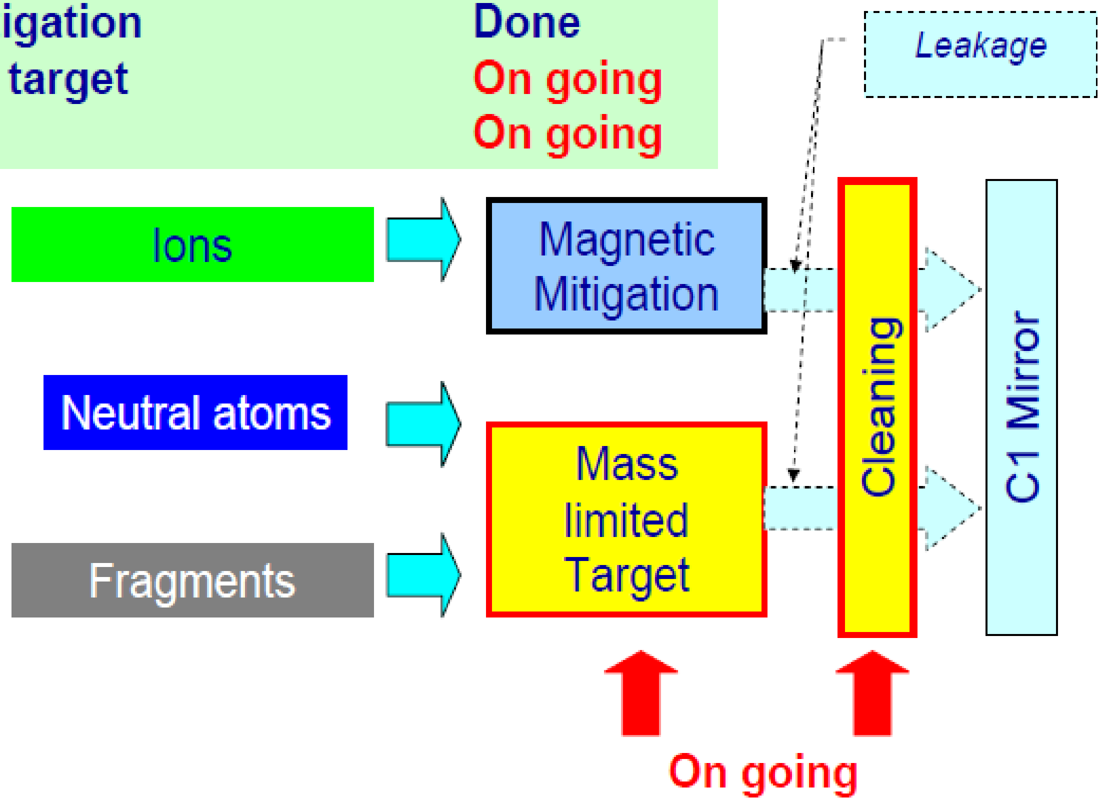
Sn mitigation strategy

New technologies:

✓ Magnetic mitigation	Done
✓ Mass limited target	On going
✓ Tin Cleaning	On going


Now collecting debris mitigation data of ETS !




Ions

Neutral atoms

Fragments

Magnetic Mitigation

Mass limited Target

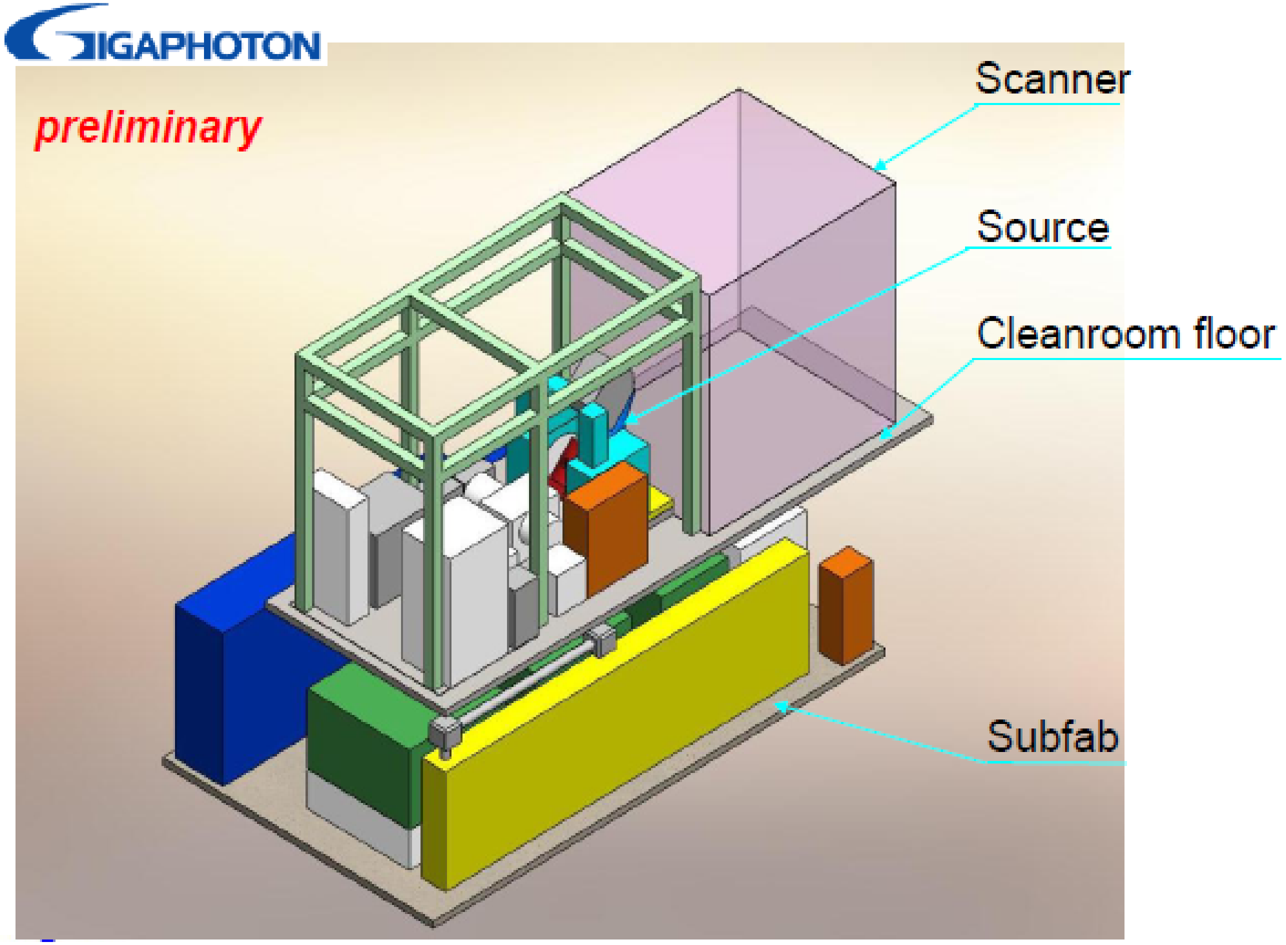
Leakage

Cleaning

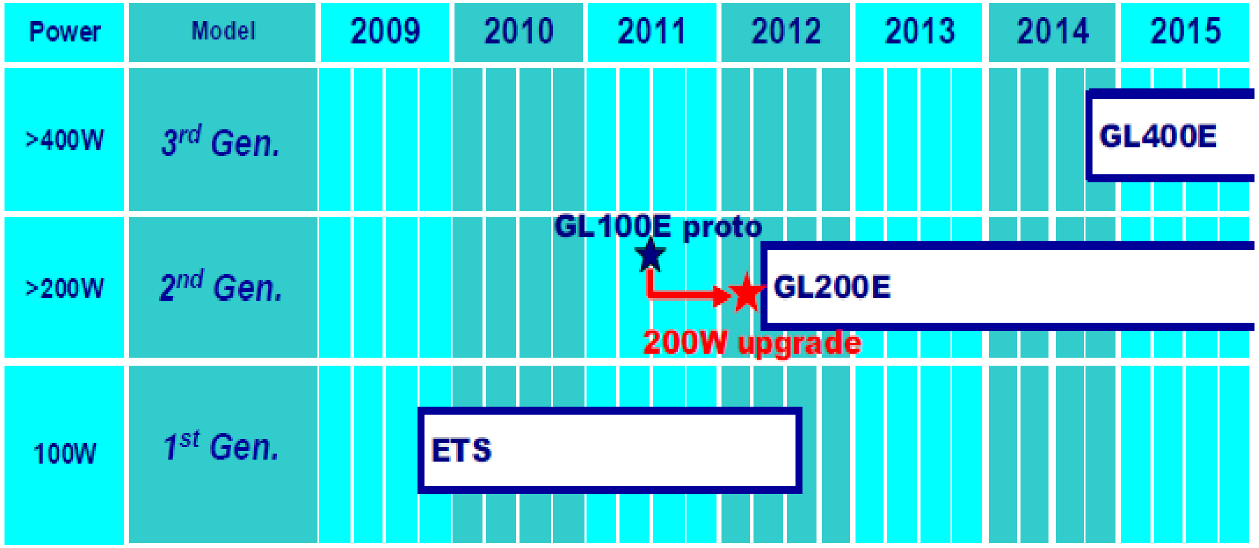
C1 Mirror

On going

Layout of GL-100E

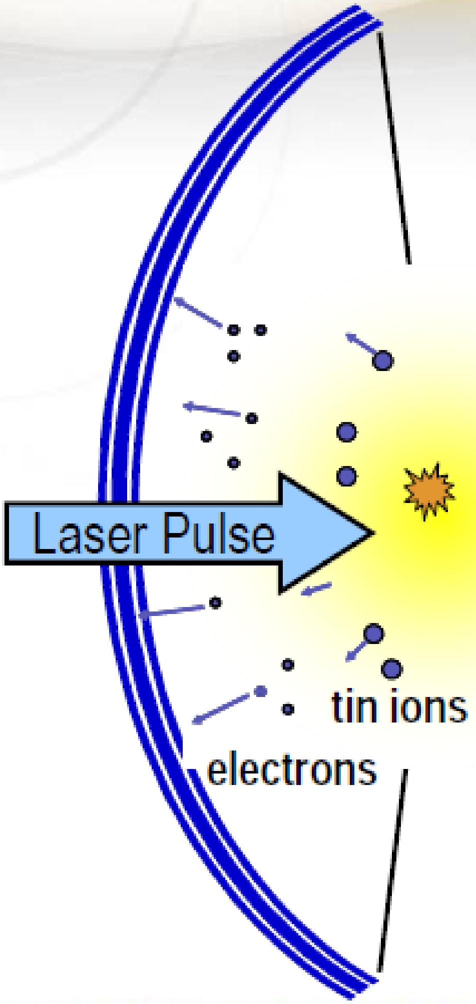


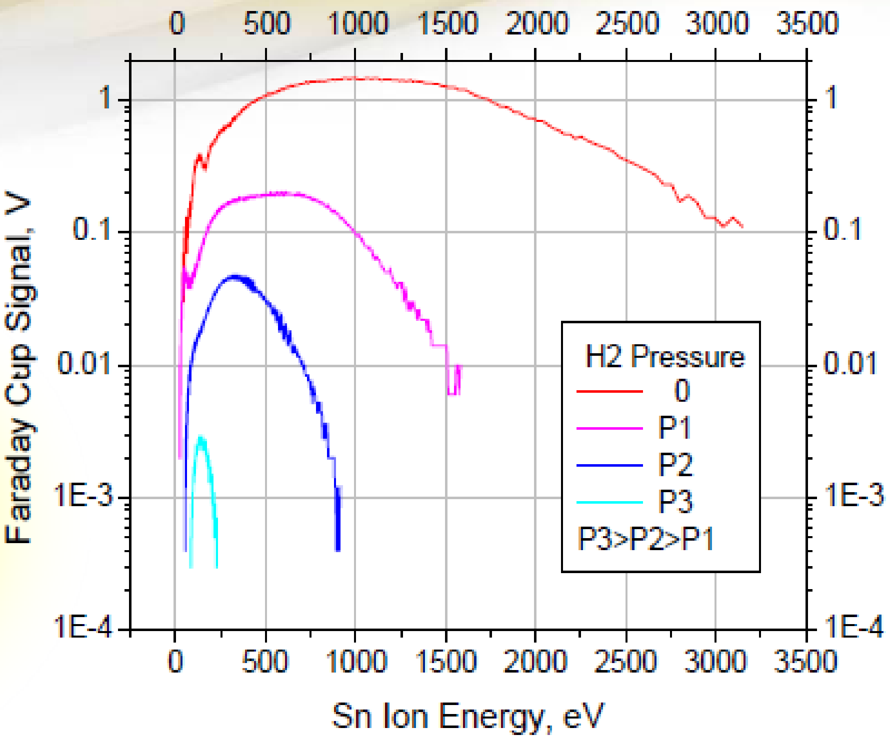
EUV light source roadmap

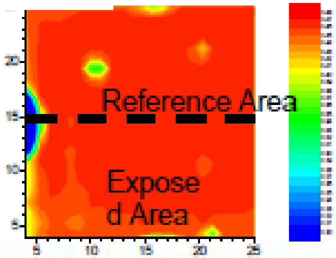


Hydrogen Buffer Gas Stops Ion Erosion and Implantation

Simple, Effective, and Low Cost

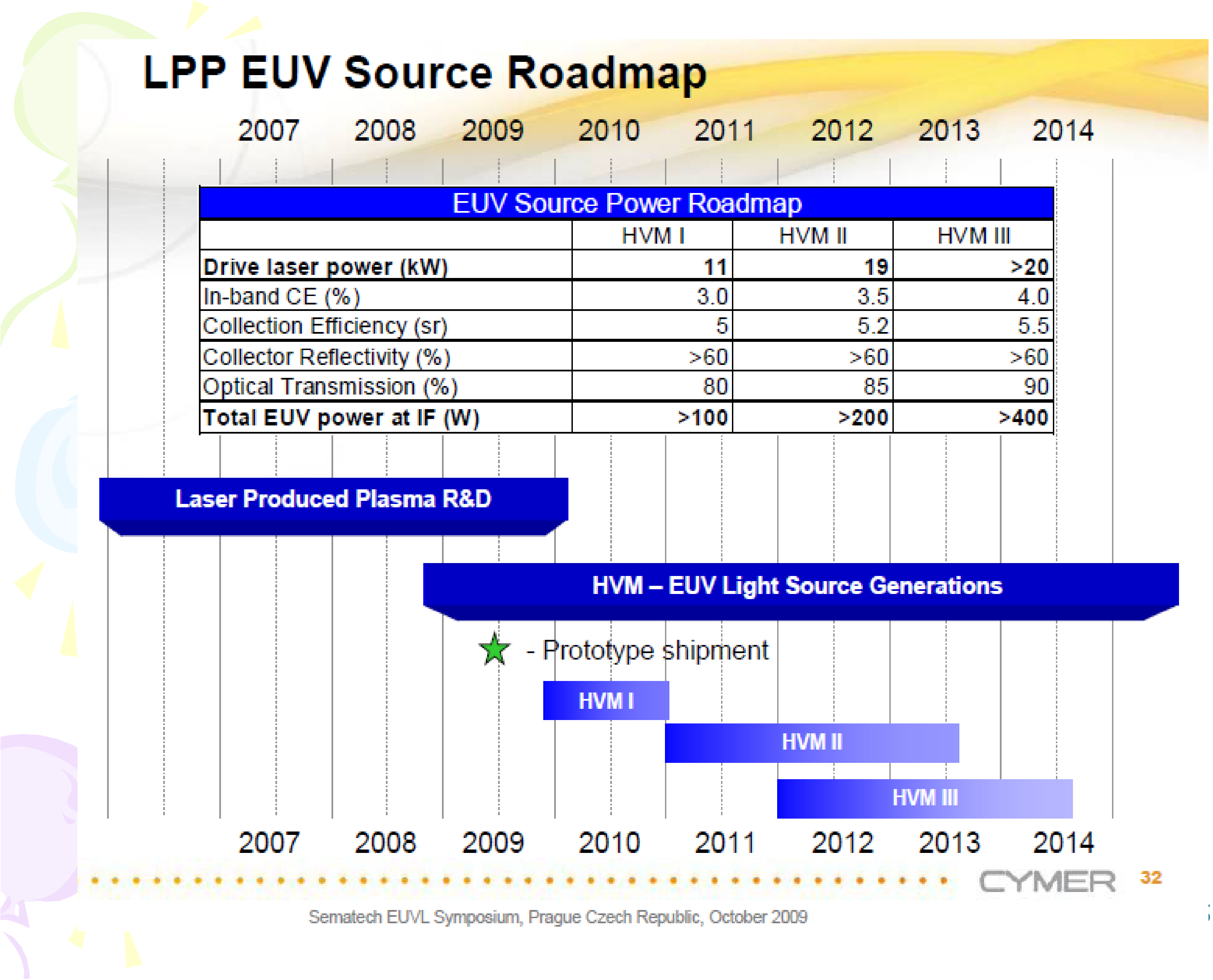






- 2D reflectivity maps show <1% change between exposed and reference areas
- 2 hours exposure at 60W / 10% duty cycle

LPP EUV Source Roadmap

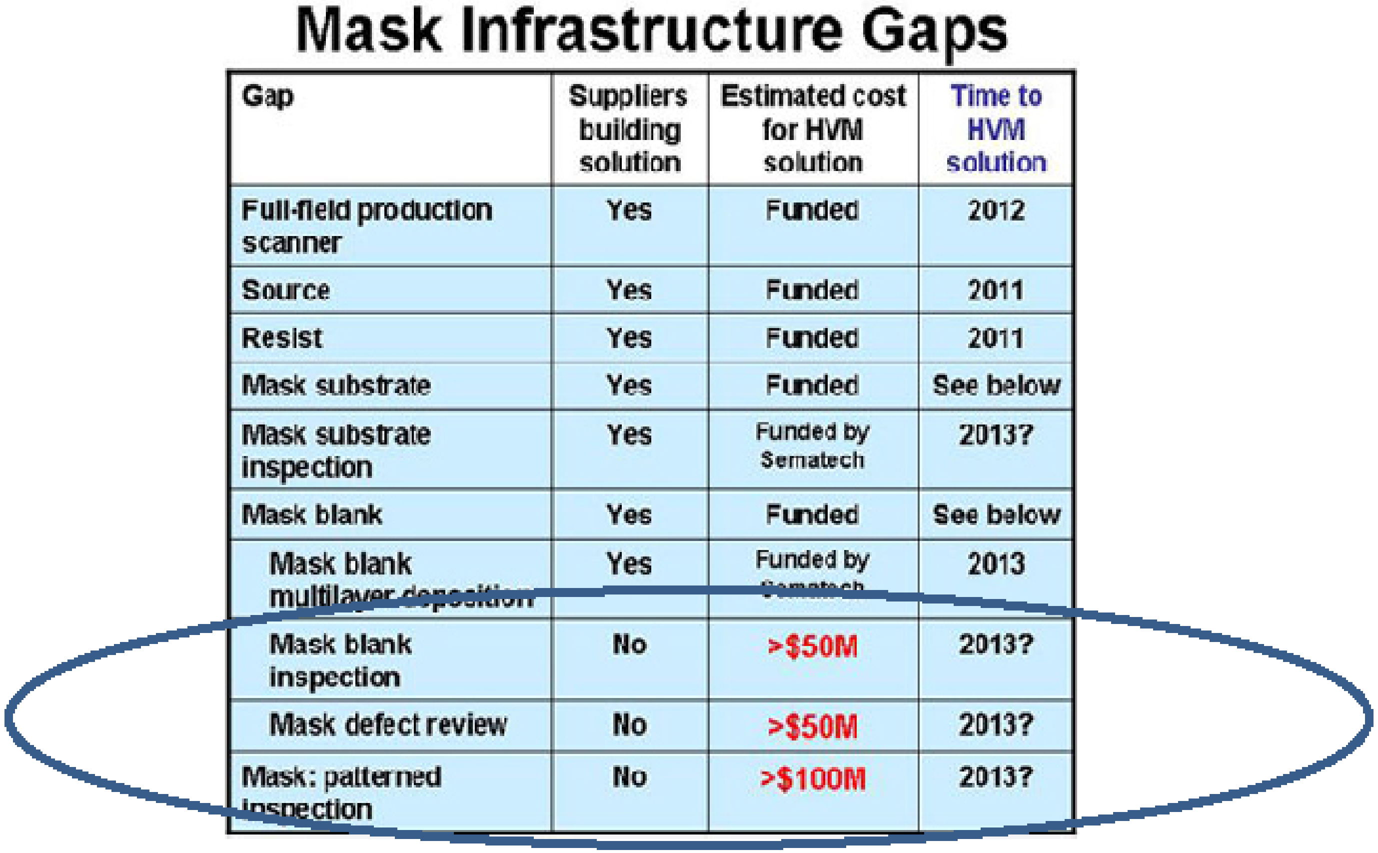


EUV Source Power Roadmap			
	HVM I	HVM II	HVM III
Drive laser power (kW)	**11**	**19**	**>20**
In-band CE (%)	3.0	3.5	4.0
Collection Efficiency (sr)	5	5.2	5.5
Collector Reflectivity (%)	>60	>60	>60
Optical Transmission (%)	80	85	90
Total EUV power at IF (W)	**>100**	**>200**	**>400**

★ - Prototype shipment

Sematech EUVL Symposium, Prague Czech Republic, October 2009

Mask Inspection Tools Represent Serious EUVL Infrastructure Gap



Mask Infrastructure Gaps

Gap	Suppliers building solution	Estimated cost for HVM solution	Time to HVM solution
Full-field production scanner	Yes	Funded	2012
Source	Yes	Funded	2011
Resist	Yes	Funded	2011
Mask substrate	Yes	Funded	See below
Mask substrate inspection	Yes	Funded by Sematech	2013?
Mask blank	Yes	Funded	See below
Mask blank multilayer deposition	Yes	Funded by Sematech	2013
Mask blank inspection	No	>$50M	2013?
Mask defect review	No	>$50M	2013?
Mask: patterned inspection	No	>$100M	2013?

Source: Bryan Rice, SEMICON West, July 15, 2009

EUV Litho, Inc.

Extreme Ultraviolet Microscope (EUVM)

Current power at BL3 beamline in NewSUBARU
3.74 mW @ 200 mA storage electron beam current
Observation time: 10 seconds

To achieve a throughput of 3 hrs / (ULE6025 mask)

Observation area (mm^2)	0.03 × 0.03	0.10 × 0.10	0.30 × 0.30
Observation time for one shot	0.4 ms	3.6 ms	40 ms
Glancing mirror reflectivity	85%	85%	85%
Mo/Si ML mirror reflectivity	65%	65%	65%
Current EUV power	>86.5 W	>7.8 W	>0.87 W
Etendue (mm2 sr)	3e-2	3e-3	3e-4
Brightness	2883 W/ mm^2 sr	2600 W/ mm^2 sr	2900 W/ mm^2 sr

Current Technology Status

EUV Source Brightness: Current Status

Technology	Power (W)	Viewing Angle (sr)	Source Radius (mm)	Area (mm2)	Etendue (mm2-sr)	Brightness (W/mm2-sr)
DPP	5	2 Pi	0.15	0.07	0.44	11.27
	15	2 Pi	0.15	0.07	0.44	33.81
	40	2 Pi	2.00	12.56	78.88	0.51
	100	2 Pi	2.00	12.56	78.88	1.27
	200	2 Pi	3.00	28.26	177.47	1.13
	0.1				1.00E-04	1.00E+03
	1				1.00E-04	1.00E+04
LPP	25	2 Pi	0.10	0.03	0.20	126.78
	50	2 Pi	0.10	0.03	0.20	253.56
	100	2 Pi	0.10	0.03	0.20	507.12
	200	2 Pi	0.10	0.03	0.20	1.01E+03
Alternate 1	1.00E-03	1.00E-04	0.01	6.15E-04	6.15E-08	1.62E+04
Alternate 2	1.00E-03	1.00E-04		3.00E-03	3.00E-07	3.33E+03

Typical parameters

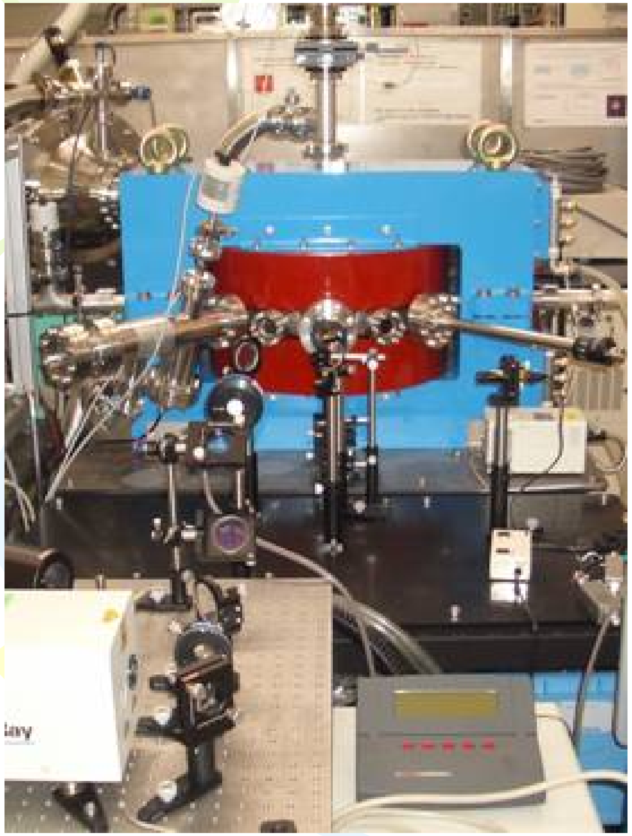
Type	Source Power (W)	Collection Angle (Sr)	Source Radius (mm)	IF power (W)	Etendue (mm^2-Sr)	Brightness (W/mm^{2}Sr)
HVM	720	5	0.10	180	1.5×10^{-1}	1.2k
Metrology	10	1	0.01	1.5	3×10^{-4}	5k

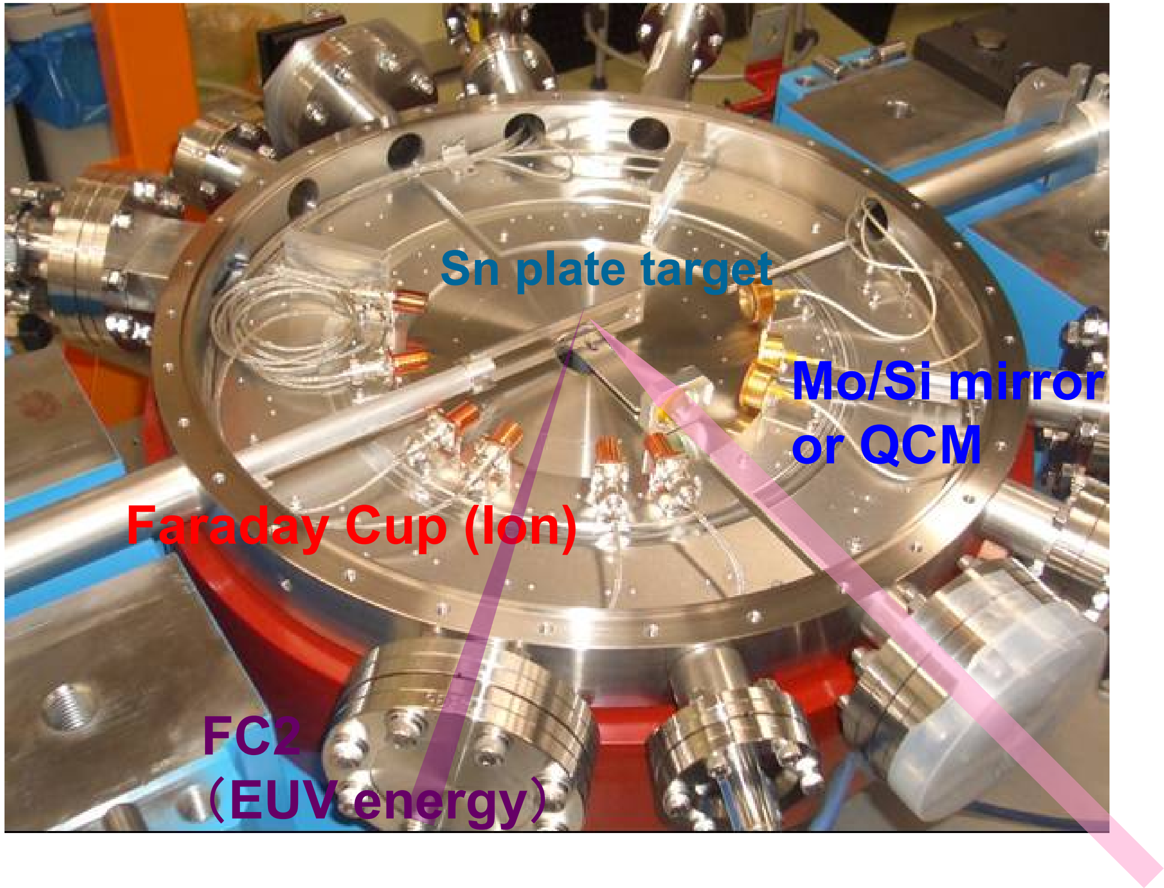
HVM: 100mJ, 100µm, 10ns laser at 100kHz

Metrology: 1mJ, 10µm, 10ns-100ps laser at 1MHz

Plasma size effect to be checked

50mm gap 1T magnet





Item	Description
Magnetic flux density	1.1 T (center)
Coil diameter	530 mm
Coil distance	50 mm

- Mo/Si mirror sample :10 bilayer
- Distance from plasma: 60 mm (Mo/Si mirror)
  100 mm (Faraday-cup)
- Static experiment (zero Sn vapor recovery)
- Chamber pressure: ～ 10^{-3}Pa

Fiber Lasers
State-of-the-art short pulse fiber lasers

- Kilowatt average power / 3.7 mJ demonstrated from spectral beam combining

O. Schmidt, C. Wirth, I. Tsybin, T. Schreiber, R. Eberhardt, J. Limpert, and A. Tünnermann, "Average power of 1.1 kW from spectrally combined, fiber-amplified, nanosecond-pulsed sources," Opt. Lett. **34**, 1567-1569 (2009)

O. Schmidt, T. V. Andersen, J. Limpert, and A. Tünnermann, "187 W, 3.7 mJ from spectrally combined pulsed 2 ns fiber amplifiers," Opt. Lett. **34**, 226-228 (2009)

- Kilowatt directly from single fiber (1 ns, streched femtosecond pulse)

Tino Eidam, Stefan Hanf, Enrico Seise, Thomas V. Andersen, Thomas Gabler, Christian Wirth, Thomas Schreiber, Jens Limpert, and Andreas Tünnermann, "Femtosecond fiber CPA system emitting 830 W average output power," Opt. Lett. **35**, 94-96 (2010)

- 12 mJ, 25 ns using 915 nm pumping and long fiber

➡ Multi mJ Energy Extraction
Kilowatt average power
High repetition rates (1kHz to GHz)
Nearly diffraction limited beam $M^2<1.3$

➡ 1 kW, 1MHz, 1 mJ, sub ns

by fiber laser system
without cryo cooling

Next wavelength of EUV lithography

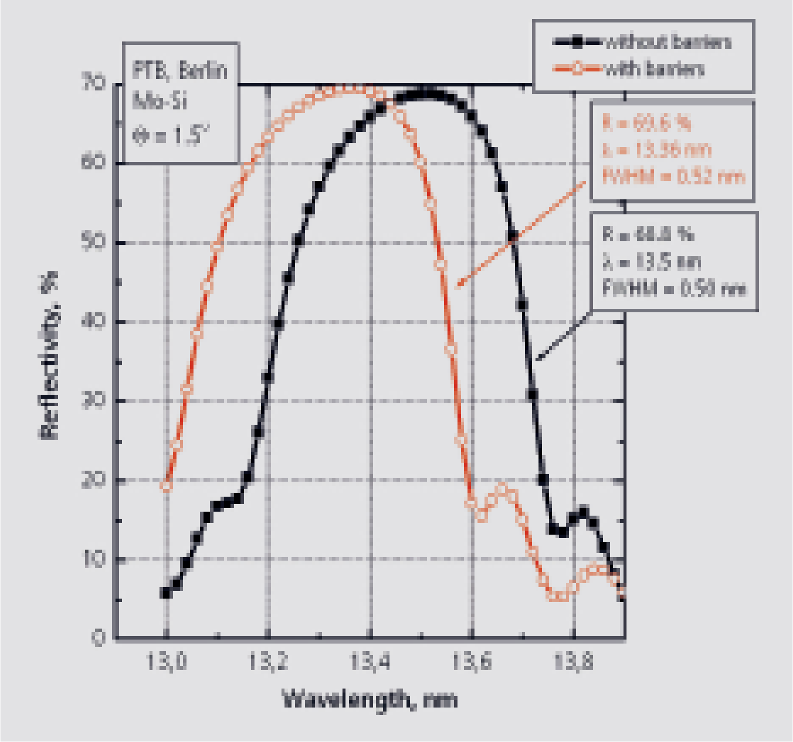


Abb. 5:
Reflexion von Mo/Si ohne und mit Barriereschichten für EUVL.

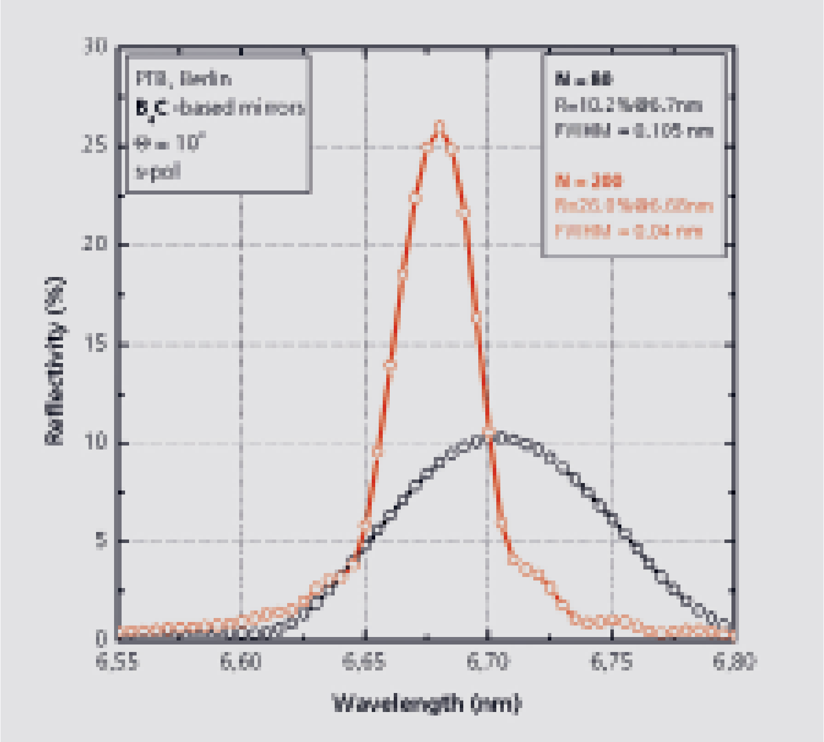
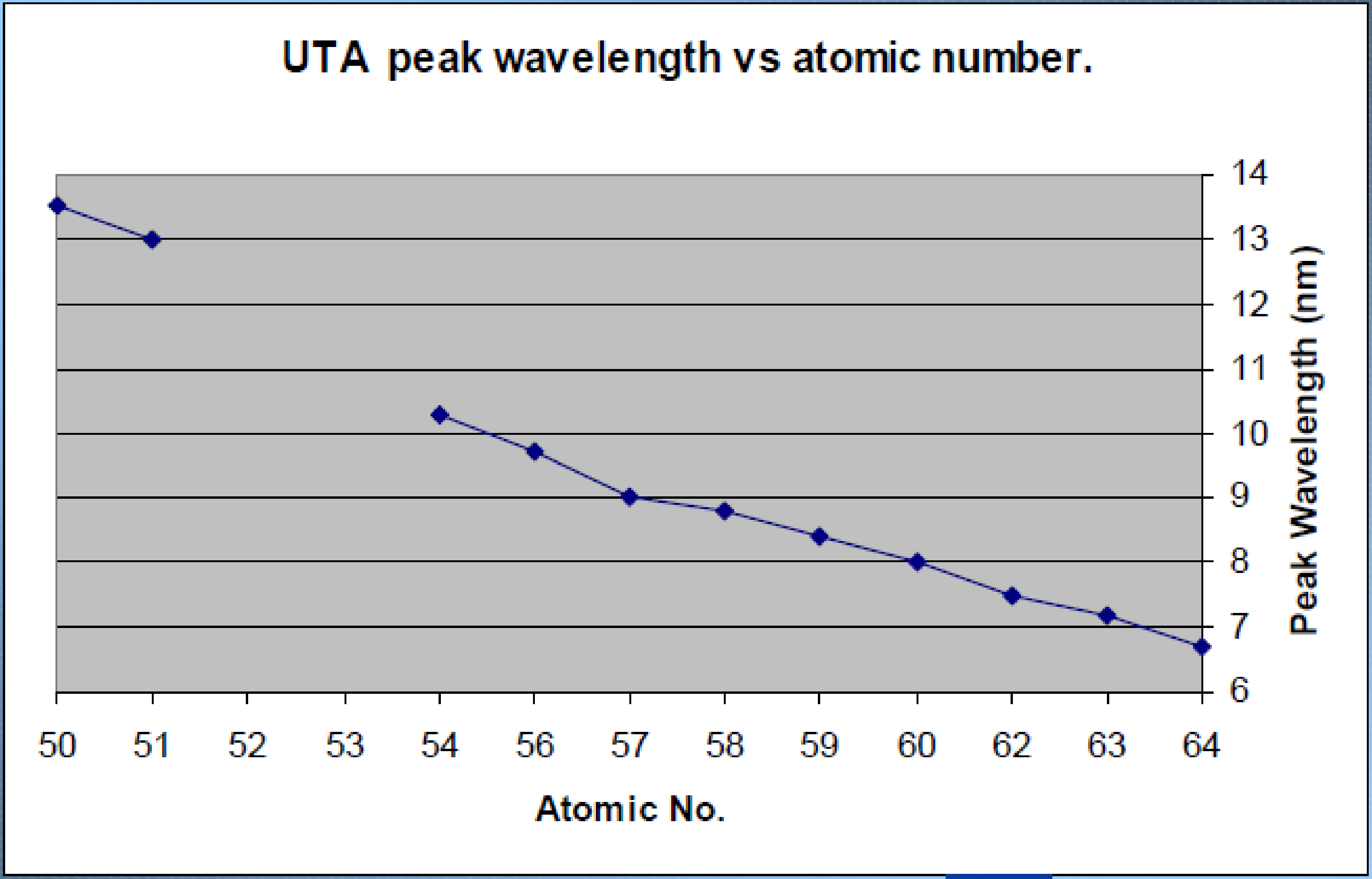
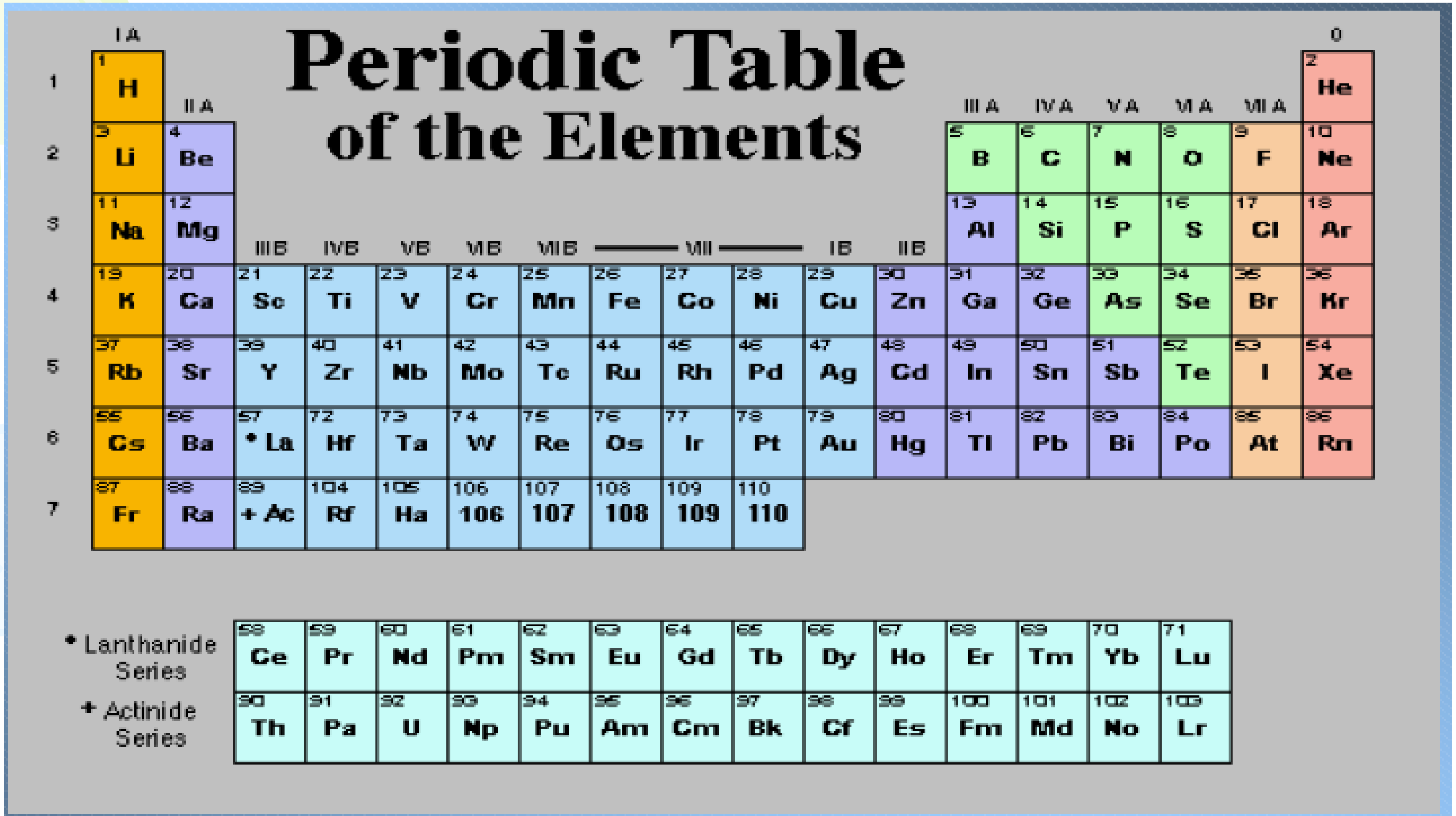


Abb. 8:
Reflexion von Multilayern auf B_4C-Basis an der B K-Absorptionskante.

Peak λ depends on Z – atomic no.



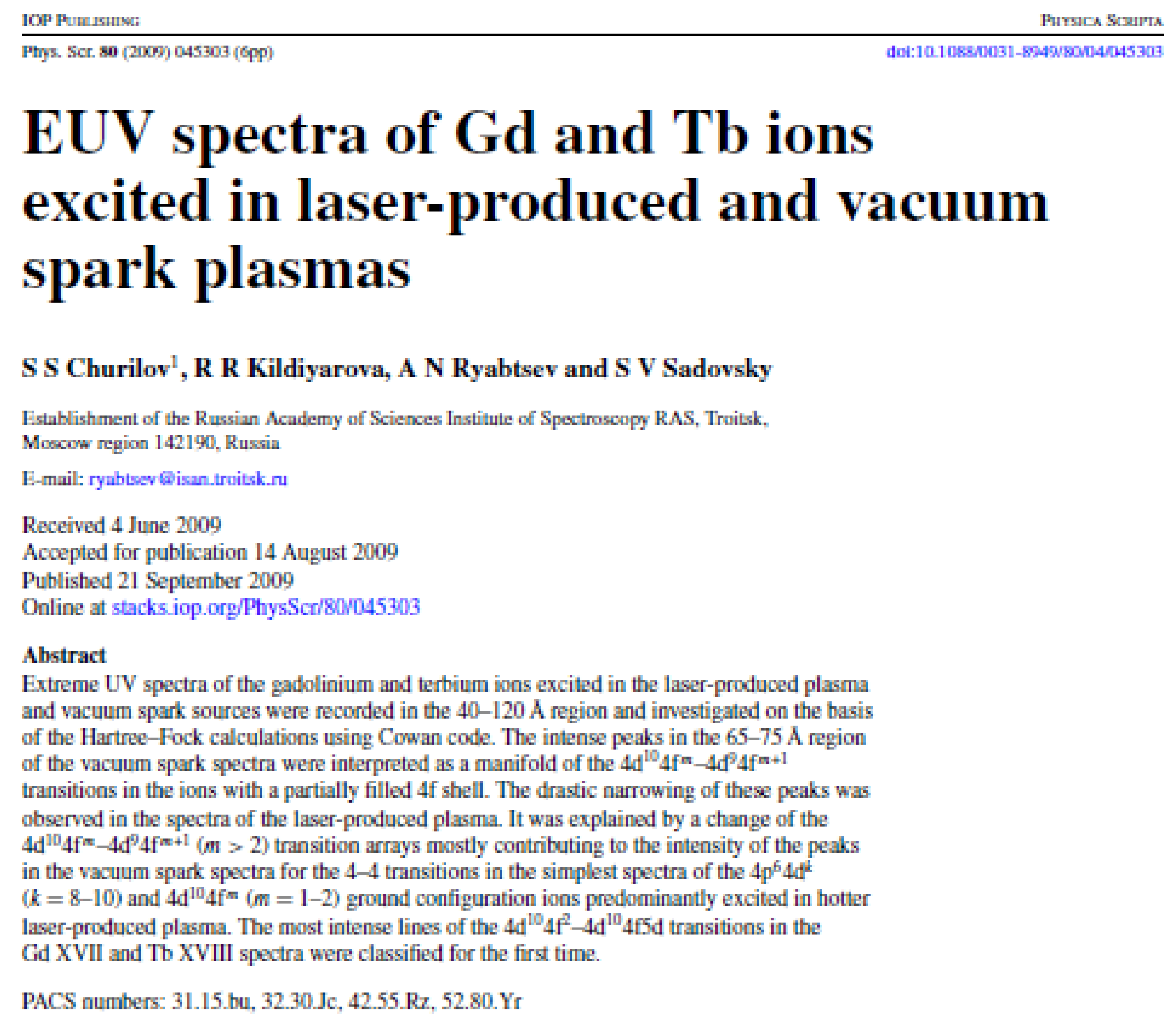


Periodic Table of the Elements

	I A	II A	IIIB	IVB	VB	VIB	VIIB	VII			IB	IIB	III A	IV A	V A	VI A	VII A	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 * La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 + Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110								

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Alternative Target materials : Sn, Li, F & Sc for 13.5 nm emission.



IOP Publishing Physica Scripta

Phys. Scr. **80** (2009) 045303 (6pp) doi:10.1088/0031-8949/80/04/045303

EUV spectra of Gd and Tb ions excited in laser-produced and vacuum spark plasmas

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Abstract

Extreme UV spectra of the gadolinium and terbium ions excited in the laser-produced plasma and vacuum spark sources were recorded in the 40–120 Å region and investigated on the basis of the Hartree–Fock calculations using Cowan code. The intense peaks in the 65–75 Å region of the vacuum spark spectra were interpreted as a manifold of the $4d^{10}4f^m$–$4d^9 4f^{m+1}$ transitions in the ions with a partially filled 4f shell. The drastic narrowing of these peaks was observed in the spectra of the laser-produced plasma. It was explained by a change of the $4d^{10}4f^m$–$4d^9 4f^{m+1}$ ($m > 2$) transition arrays mostly contributing to the intensity of the peaks in the vacuum spark spectra for the 4–4 transitions in the simplest spectra of the $4p^6 4d^k$ ($k = 8$–10) and $4d^{10}4f^m$ ($m = 1$–2) ground configuration ions predominantly excited in hotter laser-produced plasma. The most intense lines of the $4d^{10}4f^2$–$4d^{10}4f5d$ transitions in the Gd XVII and Tb XVIII spectra were classified for the first time.

PACS numbers: 31.15.bu, 32.30.Jc, 42.55.Rz, 52.80.Yr

Phys. Scr. **80** (2009) 045303 S S Churilov *et al*

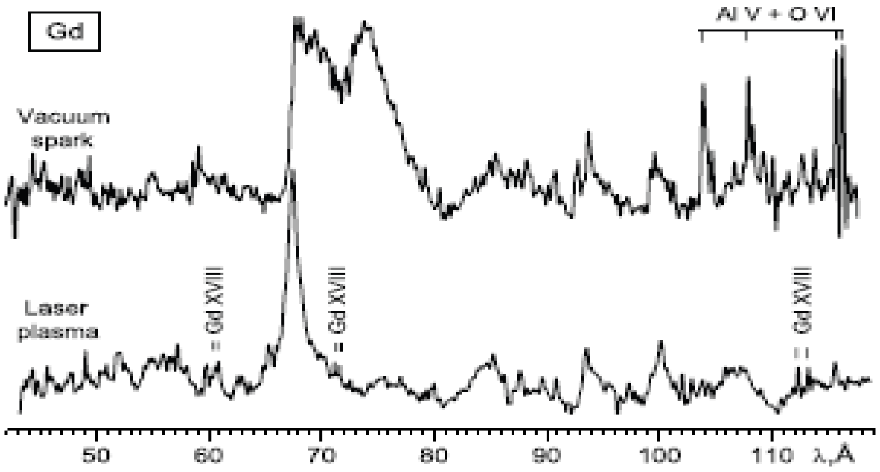


Figure 1. Spectra of gadolinium ions excited in the vacuum spark (upper trace) and in the laser-produced plasma (bottom trace).

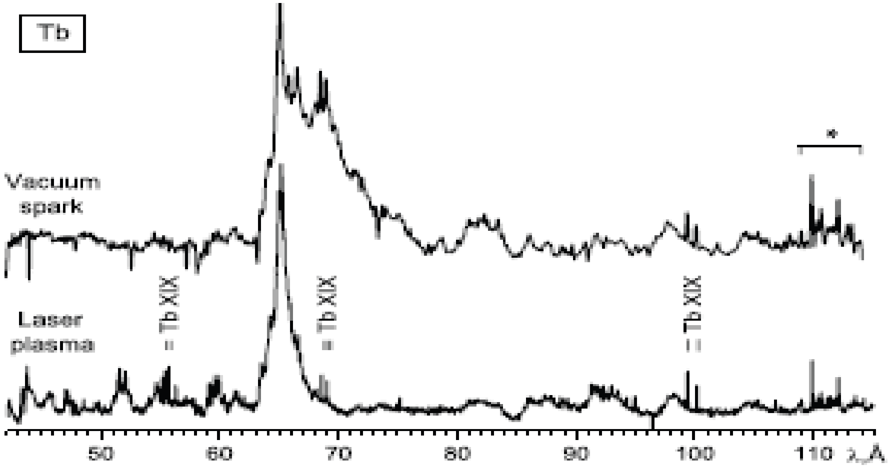
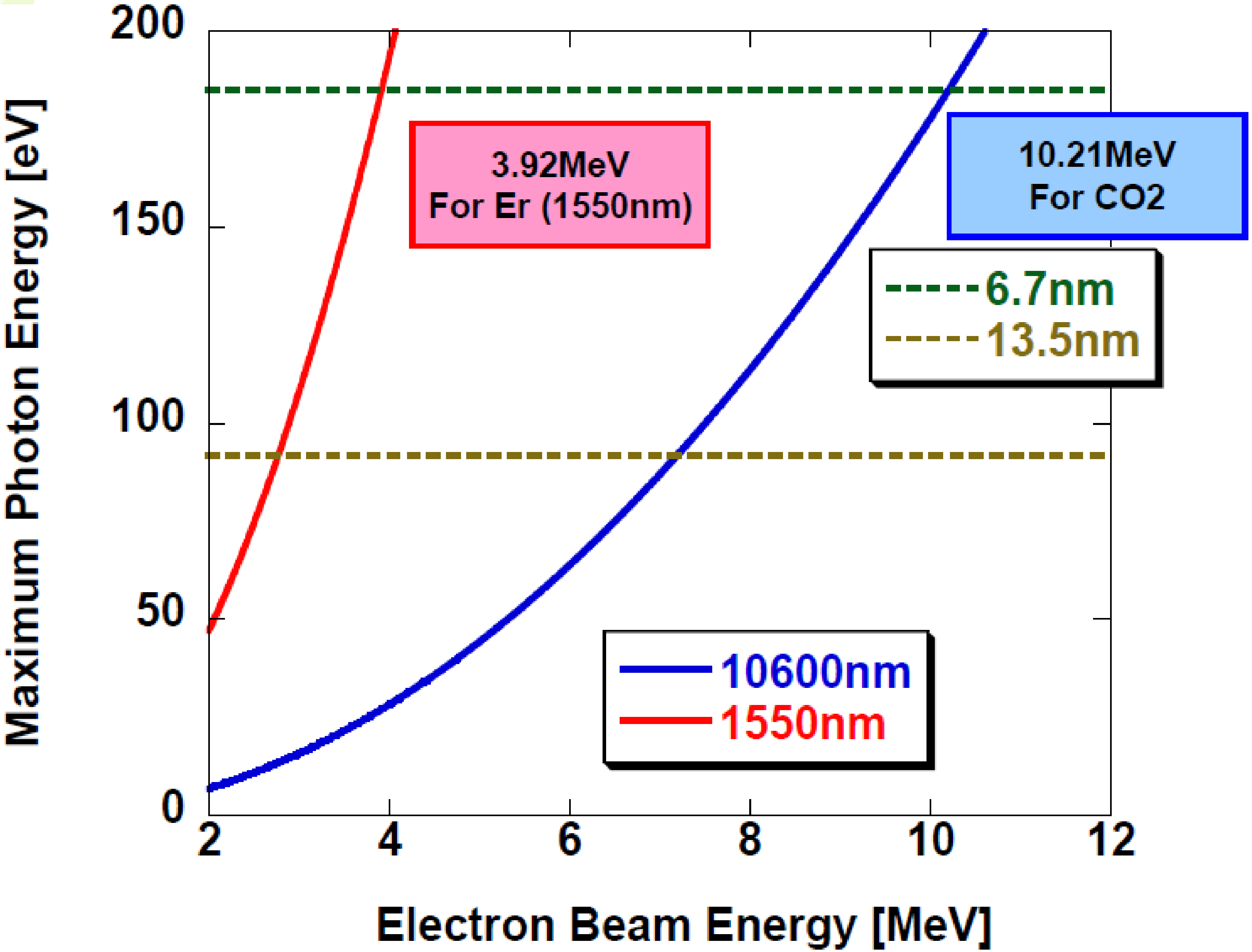


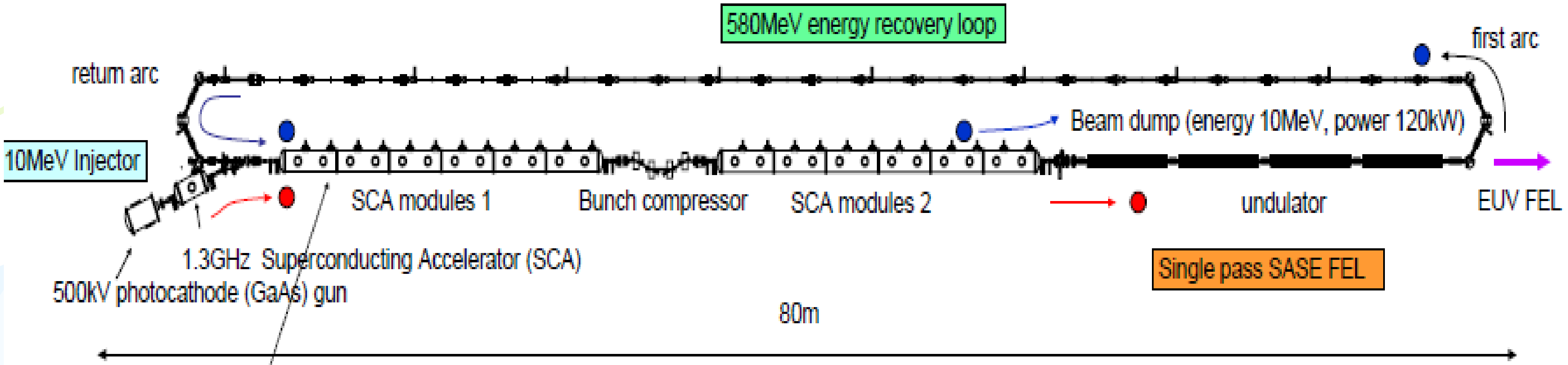
Figure 2. Spectra of terbium ions excited in the vacuum spark (upper trace) and in the laser-produced plasma (bottom trace). ∗, $4f^2$–4f5d transition array in Tb XVIII classified in the present work.

Electron beam energy vs peak X-ray energy with laser wavelength in laser Compton scheme

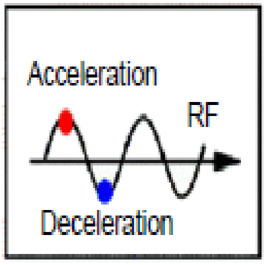


Non plasma alternative EUV source: ERL FEL

EUV ERL FEL



Energy Recovery Linac (ERL)



Energy of spent e-beam is recycled to accelerate succeeding e-beam.

High-average current is achieved with saving RF source.

beam parameters

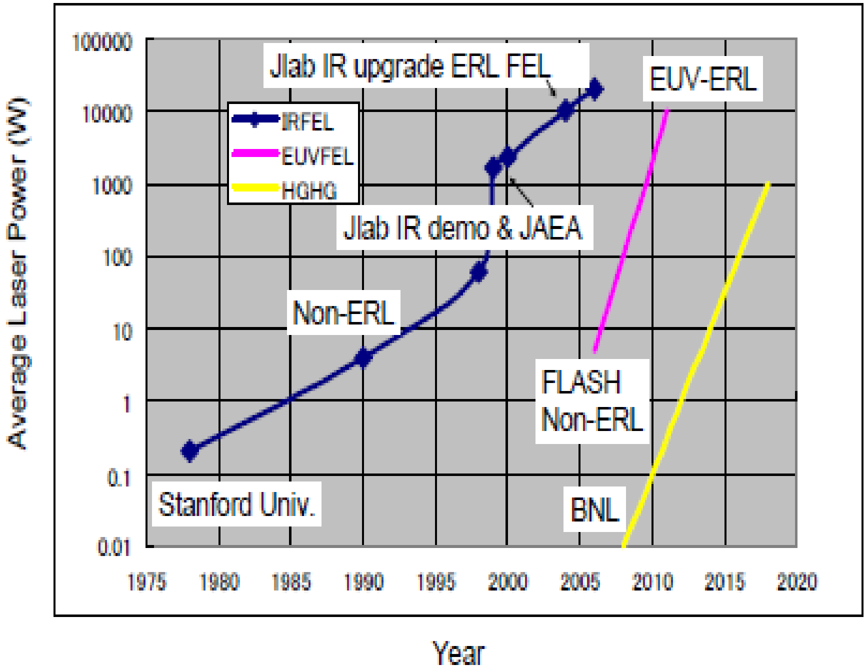
Beam energy at undulator	580 MeV
Average current at undulator	11.8 mA
Bunch charge at undulator	0.33nC
Bunch length at undulator (rms)	0.1 ps
Peak current	1300 A
Energy spread before undulator (rms)	0.16%
after undulator (full width)	1%
Normalized horizontal emittance (rms)	0.8 mm mrad
Normalized vertical emittance (rms)	0.4 mm mrad
Bunch repetition	36 MHz

FEL parameters

Undulator period	λ_w	2.0 cm
Number of undulator periods	N_w	222 x 4
Undulator Gap		6 mm
Undulator parameter (rms)	a_w	0.81
Rayleigh range		6.77 m
FEL wavelength	λ	13.5 nm
FEL parameter	ρ	0.00172
SASE gain length (3D)		1.44 m
SASE saturation power (3D)		2.54 kW

From Dr R.Hajima

EUV FEL Road Map



EUV-FEL Construction and Operation Costs

Construction Cost (total)		73.4M$
	Building 120mx20mx15m	16.7M$
	Shielding Iron/Concrete 10000t	1.2M$
	air conditioning facility	1.0M$
	water cooling facility	1.0M$
	primary & indoor substation facility	1.5M$
	He gas refrigerator facility 1.8K 1kW	13.9M$
	accelerator facility 10mA 570MeV	31.4M$
	EUV fel facility 10 beamlines	6.7M$
Operational Cost (total) for 1 year		7.86M$
	employment cost 1engineer + 5technicians	0.28M$
	factory supplies expenses	1.58M$
	electricity costs 25cents/kWh	6.00M$

Summary

- Take off of EUV lithography:
  - High average power clean source architecture established after one decade

- CO_2 laser produced Sn plasma for 13.5nm source
  - High EUV efficiency of CO2 laser produced Sn plasma
  - Power scaling of short pulse CO2 laser
  - Physics of laser generated Sn plasma : clean source architecture

- System shipping plan by two major suppliers

- Next subjects :13.5nm mask inspection actinic source, 6.7nm as the next generation
- ERL FEL, coherent laser Compton