Fraunhofer

GIGAPHOTON

4th Fraunhofer Symposium on
»Digital Photonics made in Germany«

Date: October 9th 2019

Location: Imperial Hotel Tokyo
1-1-1 Uchisaiwai-cho, Chiyoda-ku, Tokyo 100-8558, Japan

EUV/DUV SOURCE DEVELOPMENT AND ITS COLLABORATION WITH GERMANY

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Gigaphoton Inc. Hiratsuka facility: 3-25-1 Shinomiya Hiratsuka Kanagawa,254-8567, JAPAN

Agenda

- **Introduction**

  Gigaphoton Business update

- **EUV Research & Development History**

- **Experiment A: >330W Power Challenge of EUV Source**

  ① CO_2 Laser Power Upgrade
  ② Beam Uniformity Upgrade at Plasma Point
  ③ Optimization of Plasma Parameters

- **Experiment B:**
  Long-term Test and Challenge for Long-life Mirror and Availability

  ④ Lifetime Extension of Collector Mirror

- **Summary & Acknowledgement**

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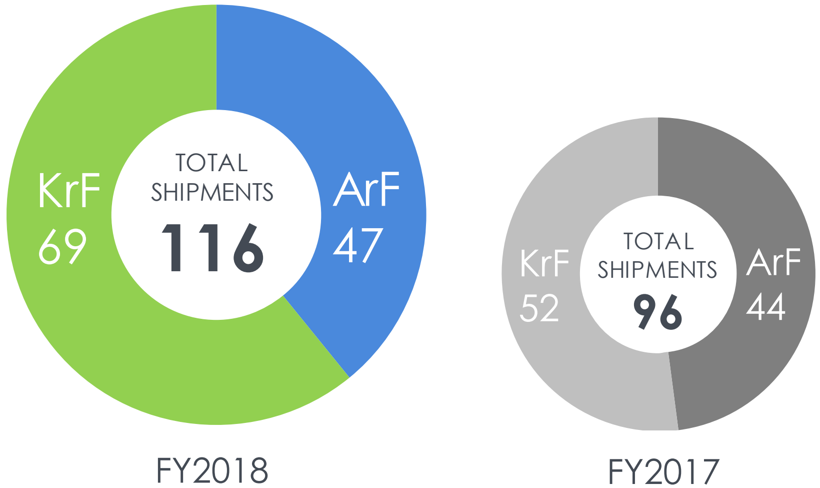
2Q2019 Business Highlights - DUV

DUV Business

- GPI recorded to ship **116 unit shipment** as **51% M/S** in FY2018 (Apr., 2018 – Mar., 2019)
- Stronger KrF demand driven by 3D NAND device transitioning
- Released G45K as higher power model to the market in 1Q2019



Products Lineup for Tomorrow

DUV Lithography

NEW 2019

KrF

G45K

248nm wavelength

4 kHz max repetition

40-50W output

20% module life* improvement

NEW 2020

ArF

GT45A

193nm wavelength

4~6kHz repetition

45W-90W output

Utilizing same platform with ArFi

ArFi

GT65A

193nm wavelength

6kHz max repetition

60-120W output

30% module life* improvement

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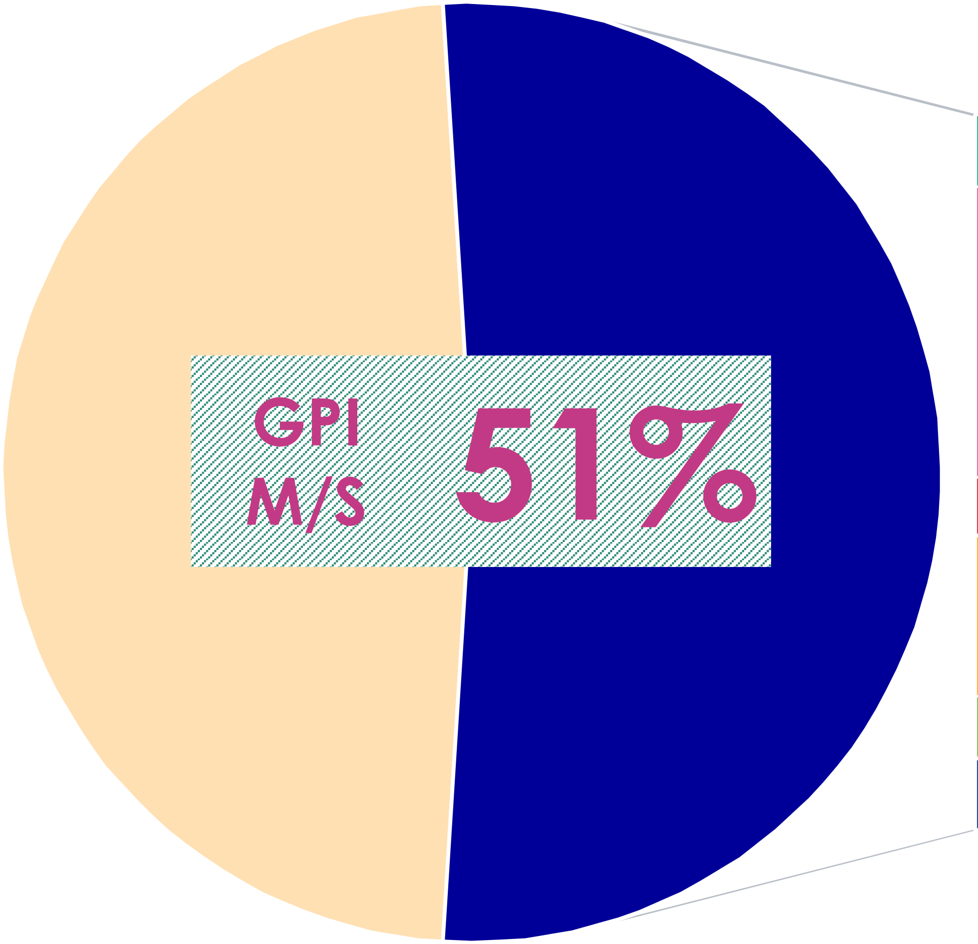
CY2018 Light Source Projected Install Share Analysis

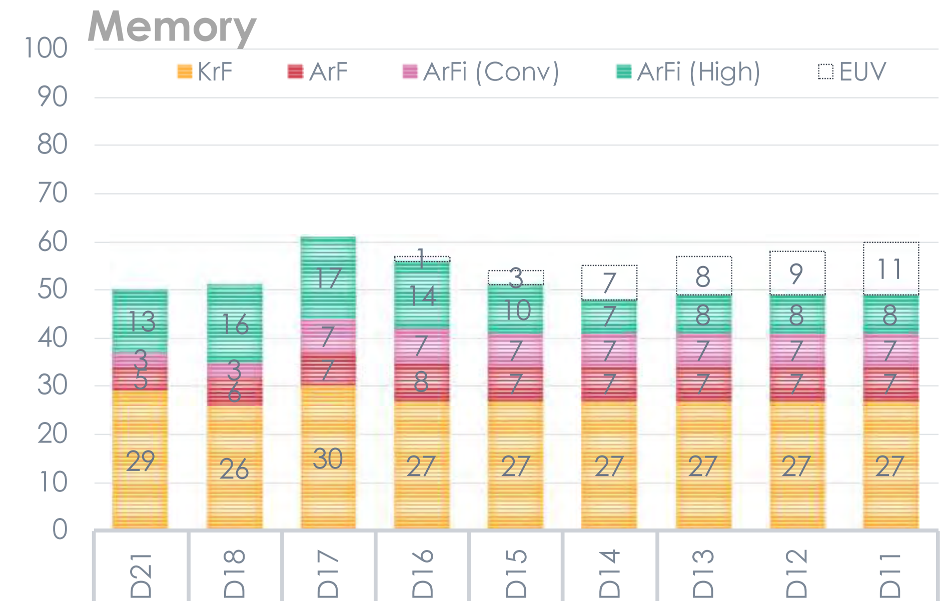


TOTAL UNITS 209	GPI INSTALL UNITS	GPI INSTALL SHARE
Japan (21)	12	57%
Korea (85)	50	59%
Taiwan (17)	8	47%
Mainland China (47)	31	66%
US (18)	4	22%
S'pore+EU (21)	3	14%

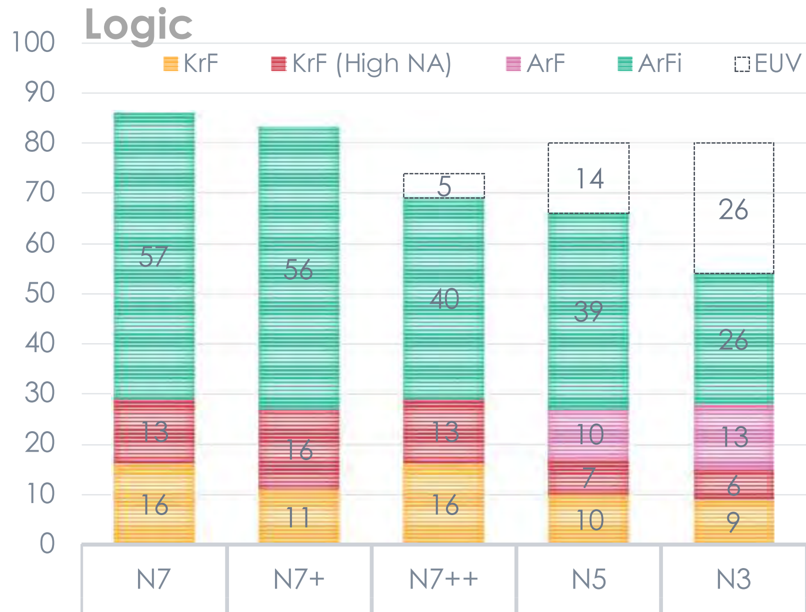
source: GPI analysis with internal source Oct. 2018
New machine only

DUV Layers would be decreased after EUV HVM

- CY2018 is the peak of DUV adoption in HVM.
- **CY2020-21 will be the Drastic Rump up of EUV at real HVM line.**



	2015	2016	2018	2020	2021	2022	Future		
EUV				1	3	7	8	9	11
KrF	29	26	30	27	27	27	27	27	27
KrF H/N	5	6	7	8	7	7	7	7	7
ArFD	3	3	7	7	7	7	7	7	7
ArFi	13	16	17	14	10	7	8	8	8
DUV TTL	**50**	**51**	**61**	**56**	**51**	**48**	**49**	**49**	**49**



2017	2018	2019	2021	2023
		5	14	26
16	11	16	10	9
13	16	13	7	6
			10	13
57	56	40	39	26
86	**83**	**69**	**66**	**54**

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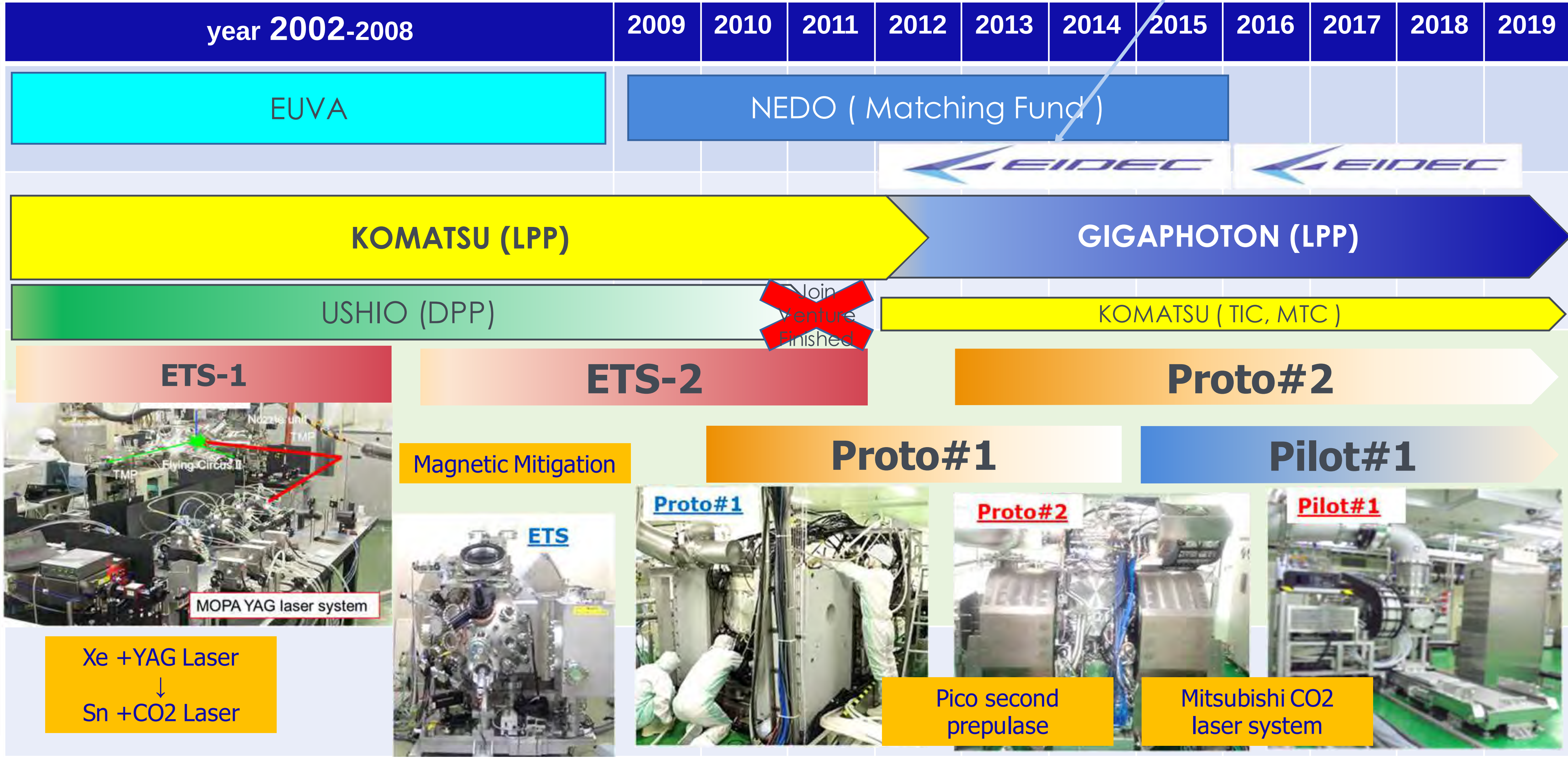
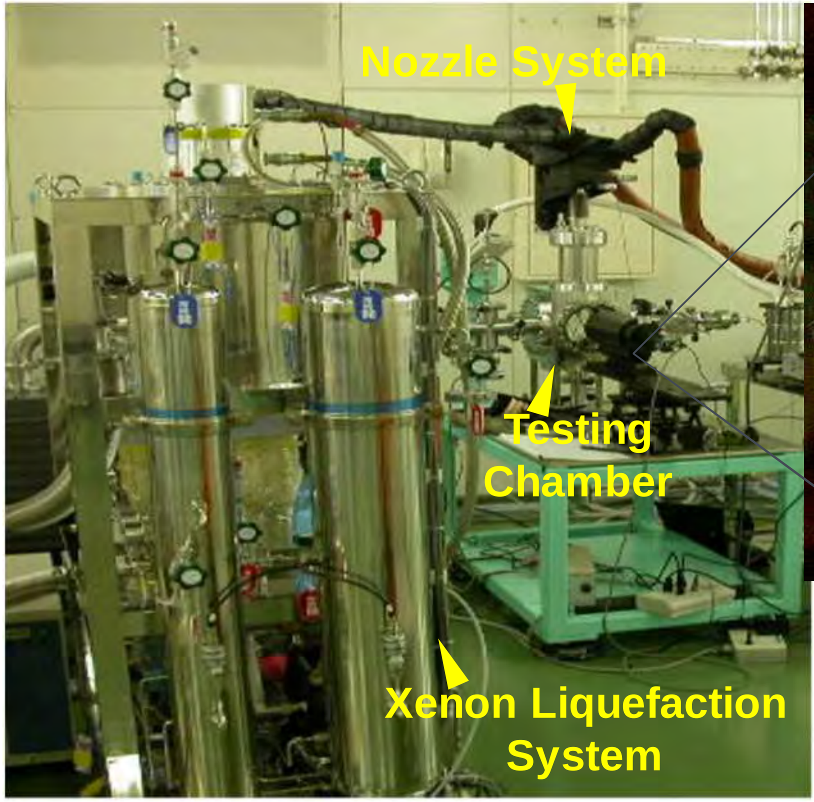
EUV Research & Development History

Study Apparatus EUV & Photo Material by EIDEC

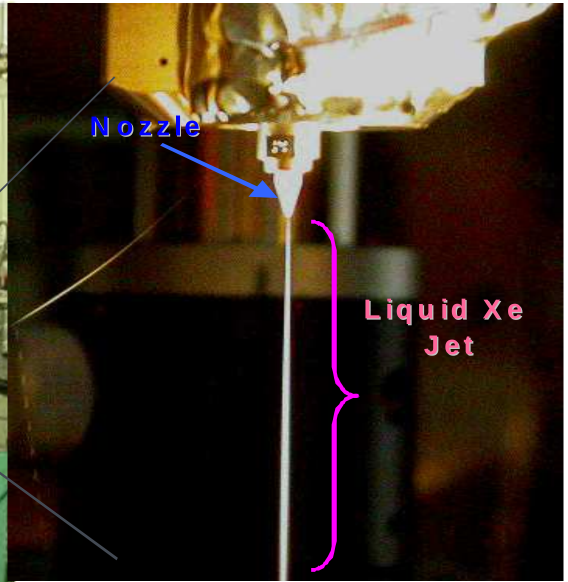


History of LPP source development 2004

■ **Start with Liquid Xe Jet target** experiment with **YAG laser driver**

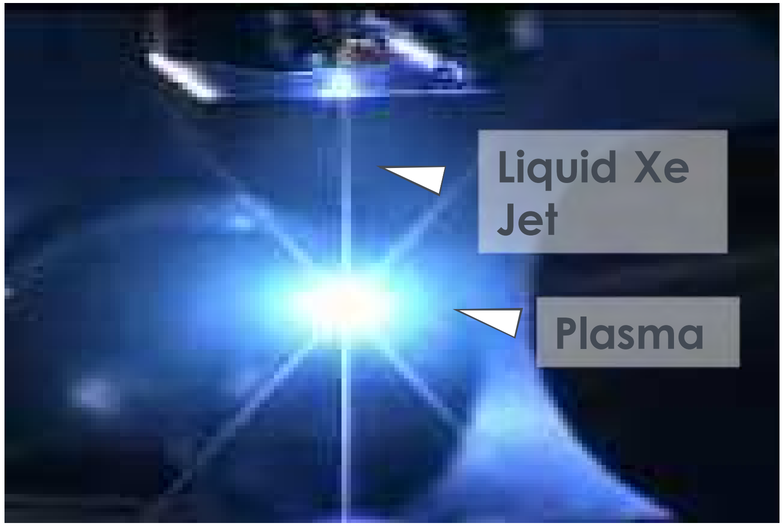


Liquid Xenon Jet System



Xe Jet

Velocity :30m/s
Stability σ : 10μm @10mm



Xe Jet and Plasma

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

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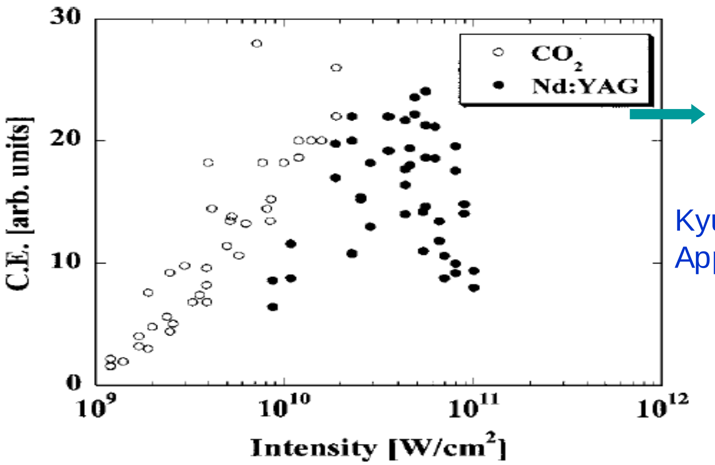
History of LPP source development 2006

- **We found out Tin + CO_2 laser could be around 8% efficiency** through Leading project & EUVA.

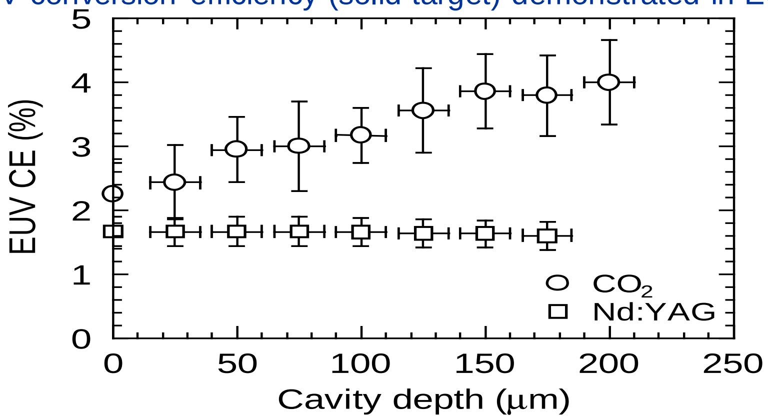


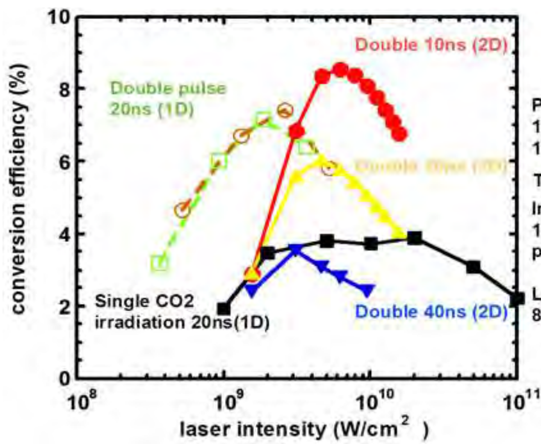
estimated to be 2%

Kyusyu Univ., H. Tanaka et al.
Appl. Phys. Lett. 87,041503(2005)

九州大学 Kyushu University

EUV conversion efficiency (solid target) demonstrated in EUVA (2005)

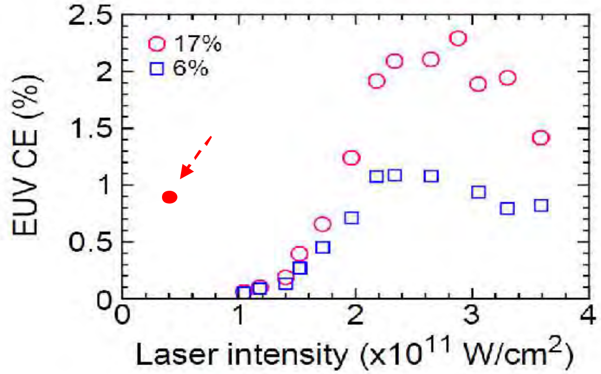




Pre-pulse
$1X10^8 W/cm^2$
10ns(0.53 μm)
Time delay :180ns
In 2D simulation,
150 μm pre-formed plasma is initially set.
Laser spot diameter:
800 μm.

Dr.Sunahara

大阪大学 OSAKA UNIVERSITY



Miyazaki Univ., T. Higashiguchi et al.
SPIE Microlithography 2006, 6151-146(2006)

EUV conversion efficiency simulation by Osaka Univ. team (20

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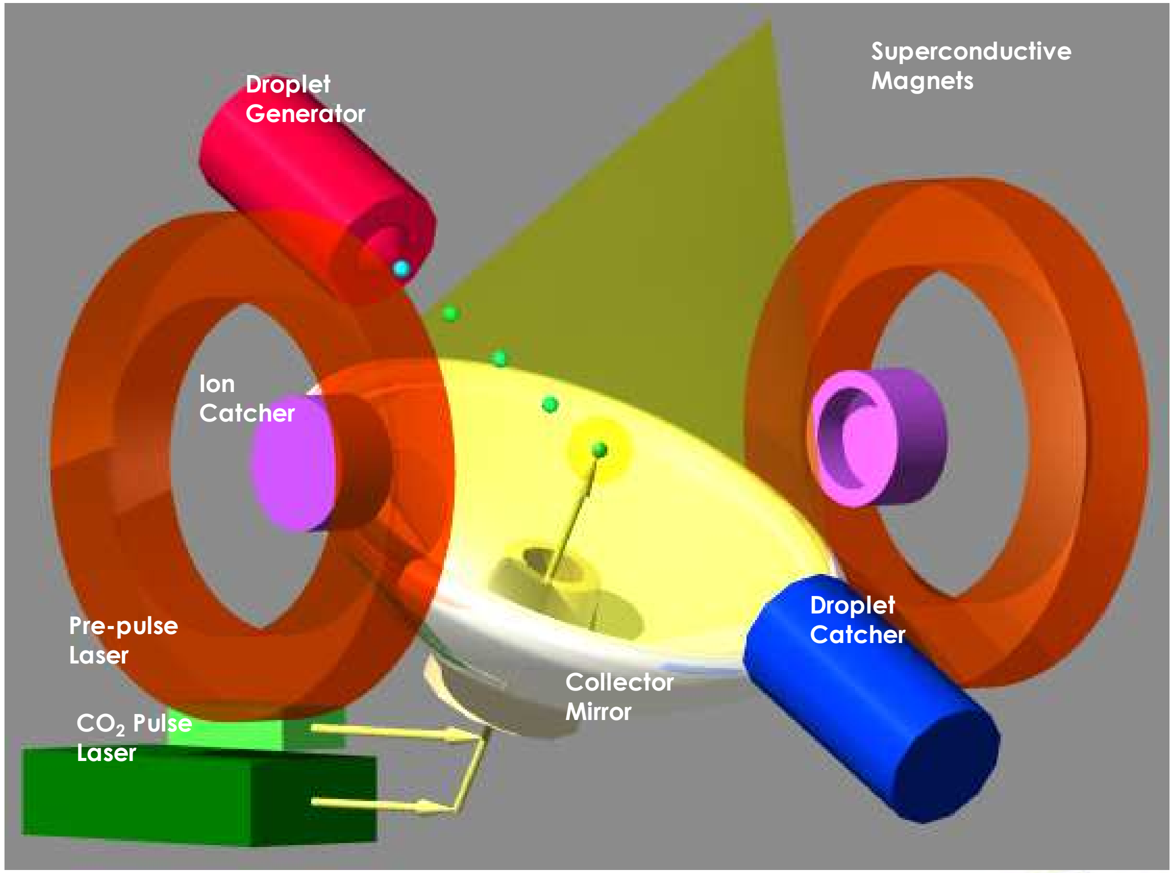
History of LPP source development 2007

State of Art Gigaphoton LPP Source Configuration* was Established in 2007 *several patented

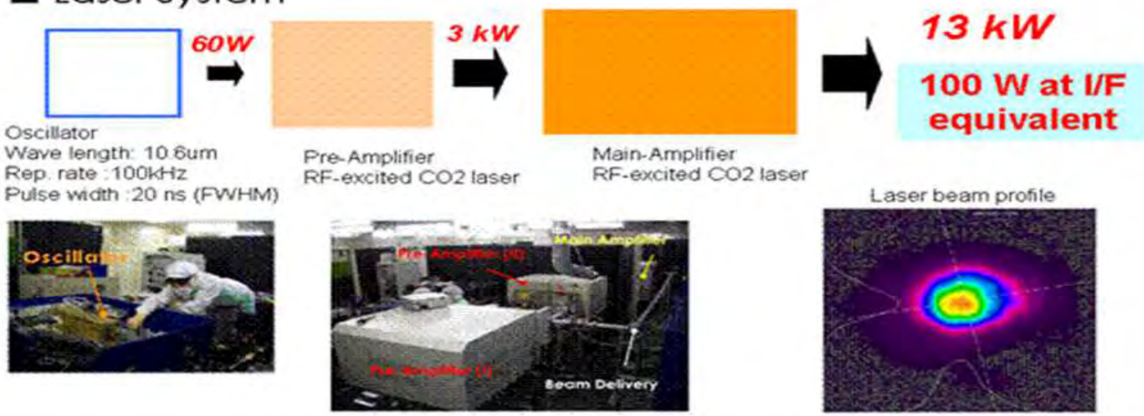
1. High ionization rate and CE EUV tin (Sn) plasma generated by dual-wavelength shooting via CO_2 and pre-pulse solid-state lasers
2. Hybrid CO_2 laser system with short pulse high repetition rate oscillator and commercial cw-amplifiers
3. Tin debris mitigation with a super conductive magnetic field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



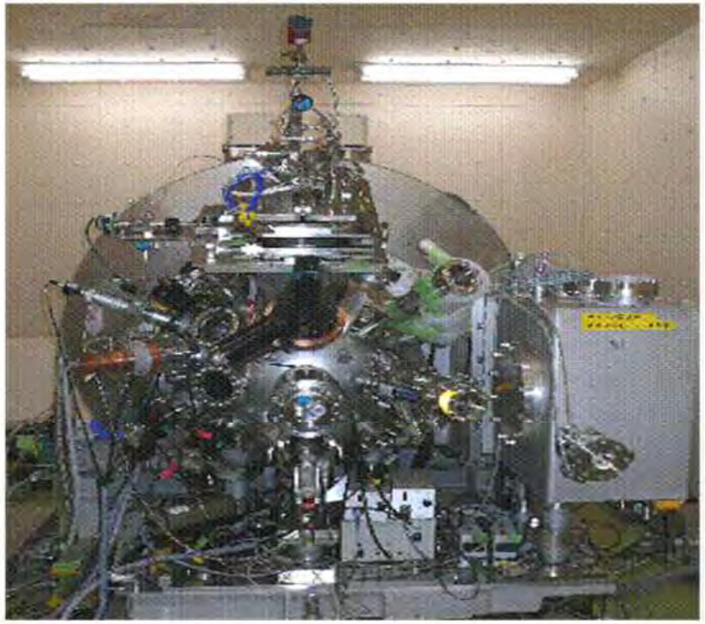
History of LPP source development 2010

- **ETS-2 demonstrated at 10W avg. power and 50W power** with Magnetic Mitigation.

■ Laser System



■ EUV chamber



	SPIE 2010 (Feb.2010)	EUV Symposium (Oct.2010)	SPIE2011 (Feb,2011)
EUV power (@ I/F)	69 W	104 W	42 W
EUV power (clean @ I/F)	33 W	50 W	20 W
Duty cycle	20 %	20 %	5%
Max. non stop op. time	>1 hr	<1 hr	>7 hr
Average CE	2.3 %	2.5 %	2.1%
Dose stability :simulation	(+/- 0.15%)		-
Droplet diameter	60µm	60µm	30µm
CO_2 laser power	5.6 kW	7.9 kW	3.6kW

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History of LPP source development 2012

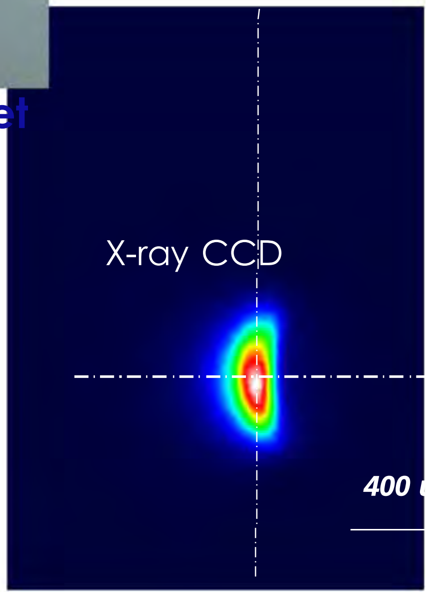
- Gigaphoton found **>50% advantage of conversion efficiency** by pico-second pre-pulse.

Very short pulse duration with 1um wavelength laser

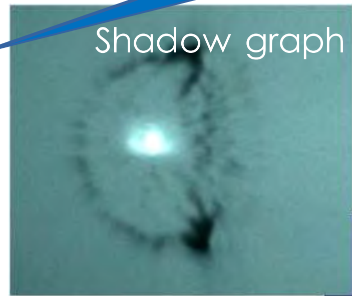
Same optical path between pre-pulse and main

Pre-pulse (nano-second)

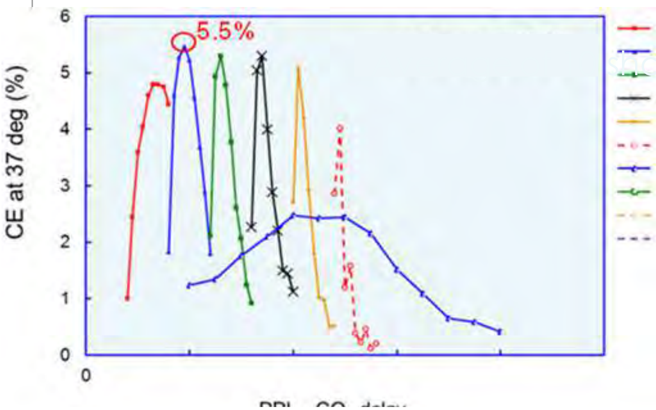
'Disk' like target

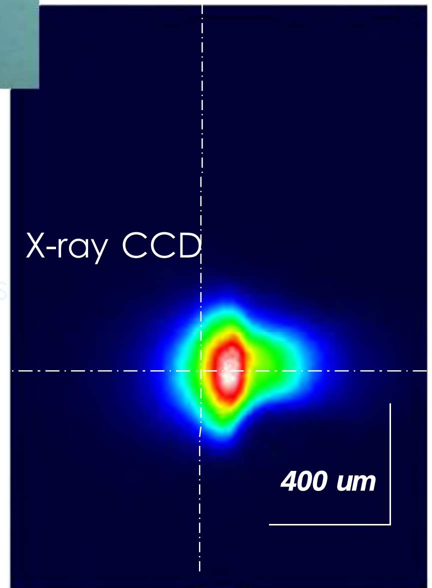


Pre-pulse(pico-second)

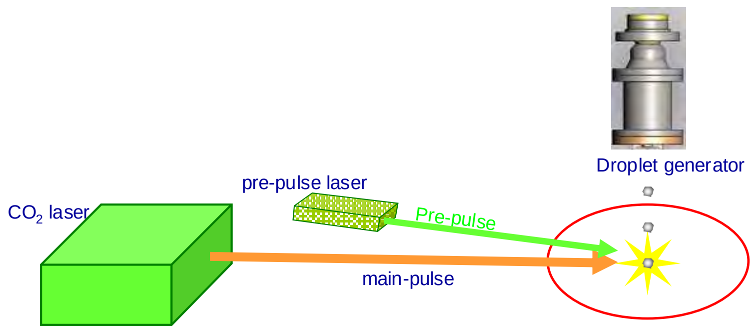


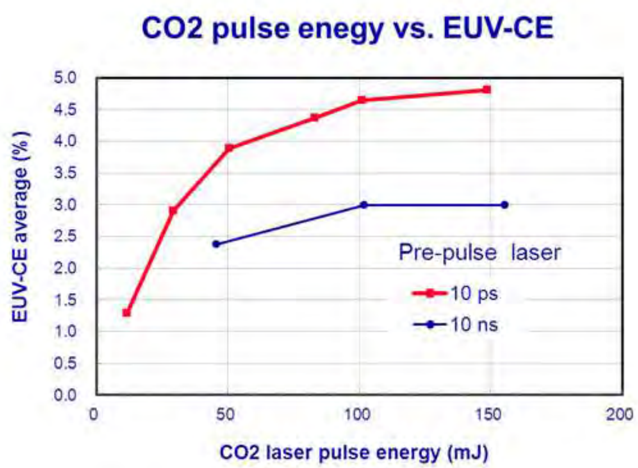
Ideal
'Dome' like target





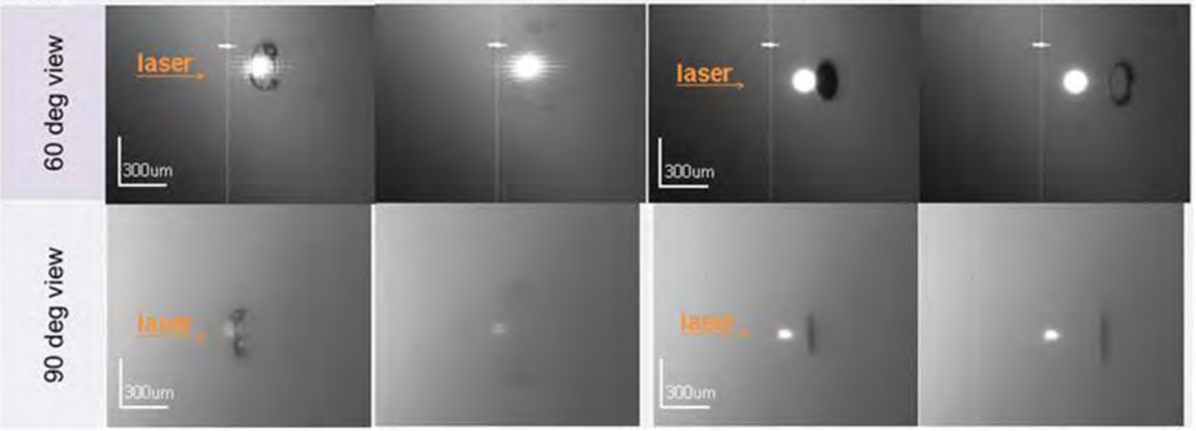
Pre-Pulse Technology: Begin of Progress in 2012





- 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

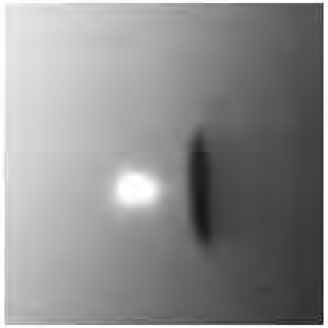
	10 ps		10 ns	
Pulse energy	2.0 mJ		2.7 mJ	
delay	1 μs	2 μs	1 μs	2 μs



Pre-Pulse Technology

Modeling nanosecond pre-pulses

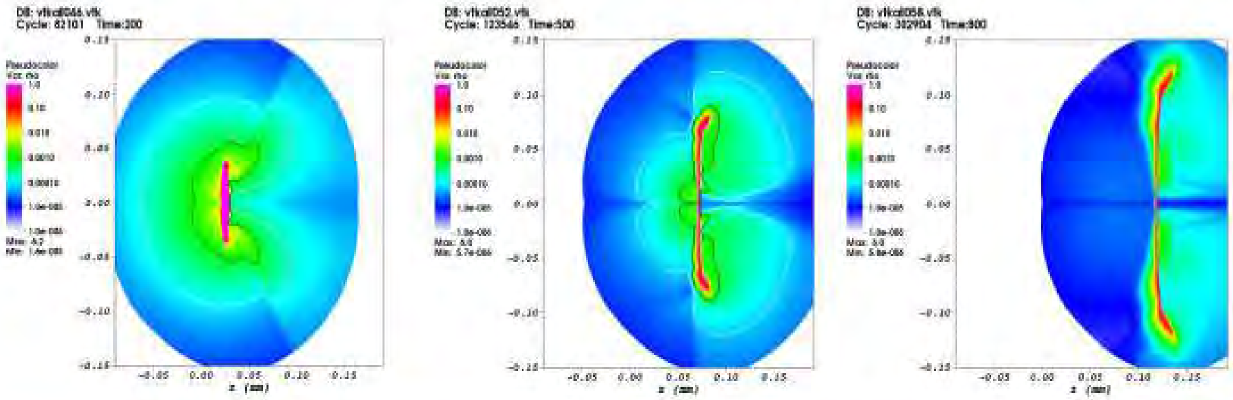
~ 10 ps pre-pulse
"Disk like target"



H. Mizoguchi, Dublin (2013)

RALEF simulations

Evolution of Sn density profile for 10 ns pre-pulse



time

"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*

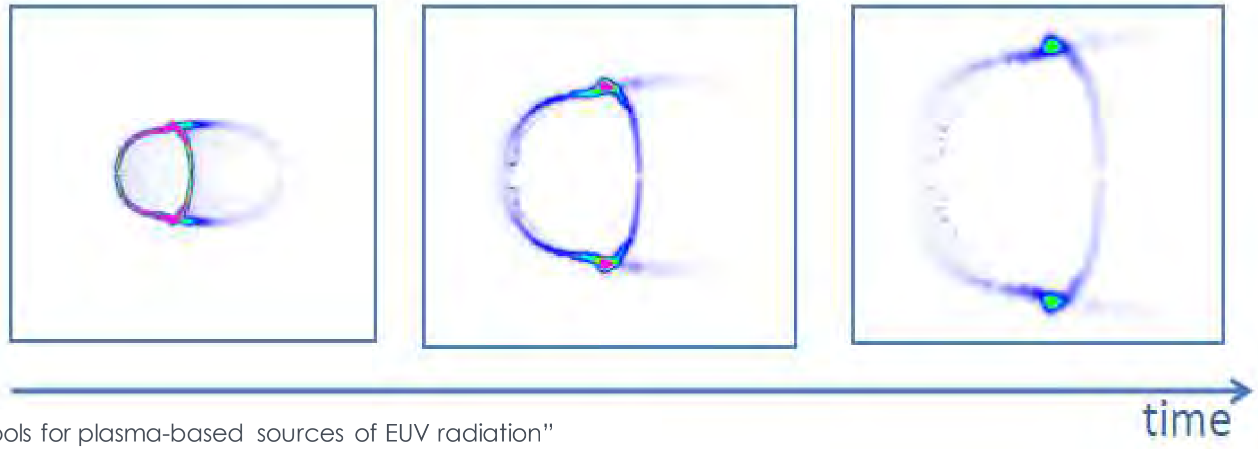
Pre-Pulse Technology

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



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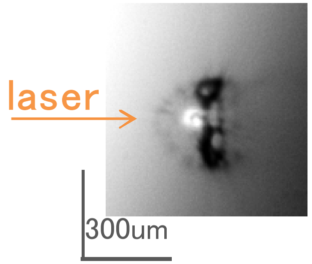
[1] RnD-ISAN/EUV Labs, Moscow, Troitsk, Russia
[2] Institute for Spectroscopy RAS, Moscow, Troitsk, Russia
[3] Keldysh Institute of Applied Mathematics RAS, Moscow, Russia

Pre-Pulse Technology (4)

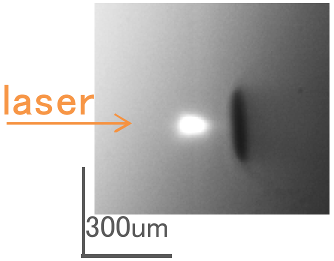
Experiment shows pico-second pre-pulse dramatically enhances ionization rate and CE

Sn Droplet Smash

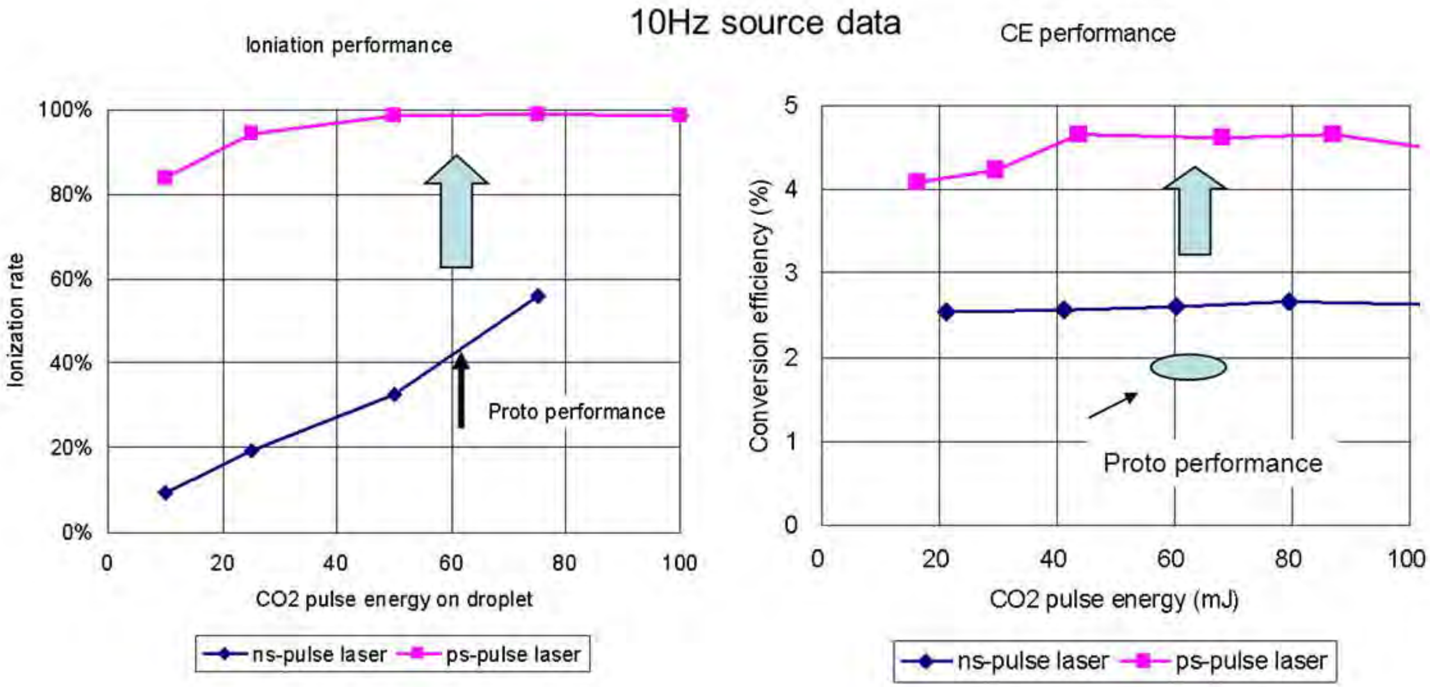
psec Dome like target



nsec Flat disk like target



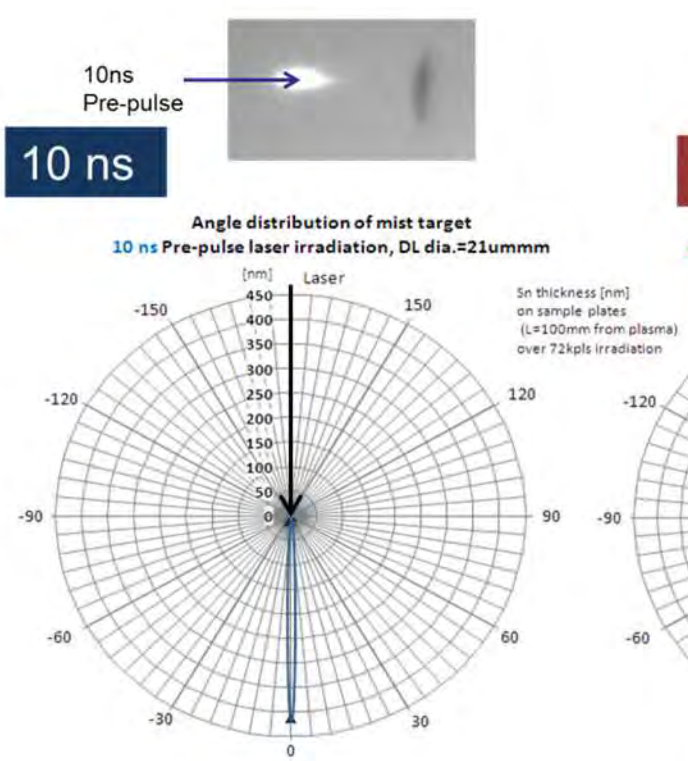
Data in 10Hz Experimental Device

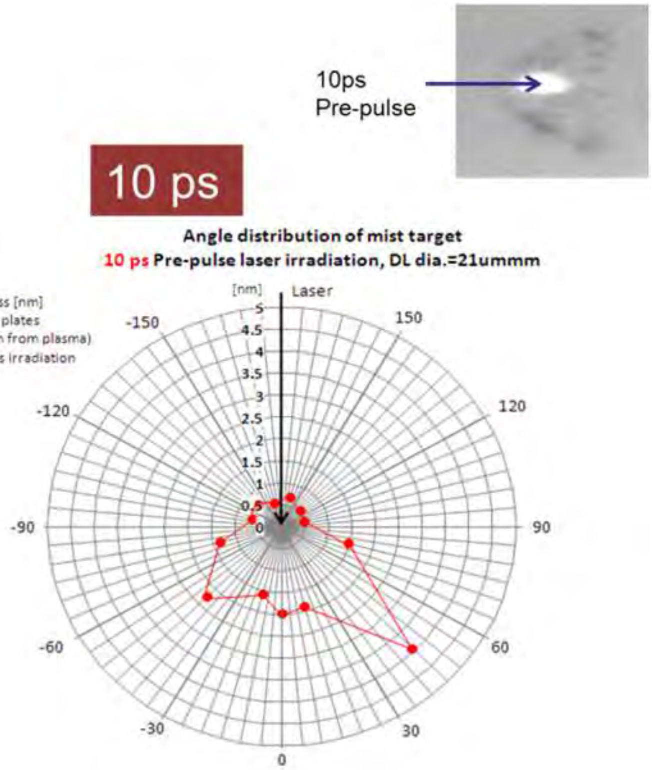


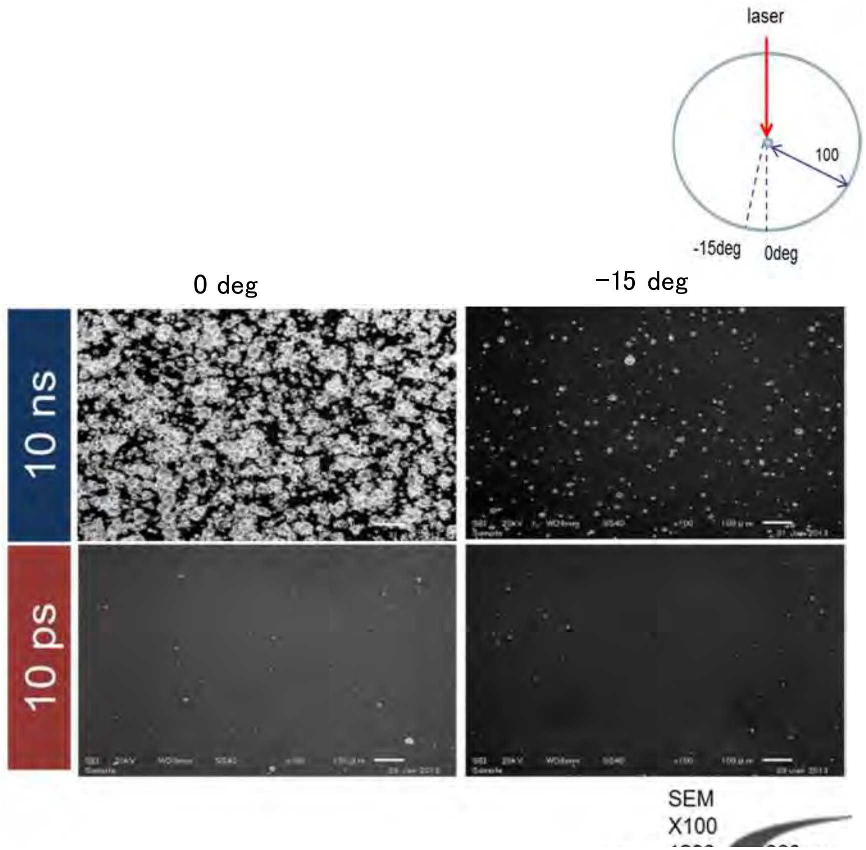
Pre−Pulse Technology (5)

Expanding distribution of Tin mist（10ns vs.10ps）

Remarkable reduction of mist is demonstrated by the pico-second pre-pulse.





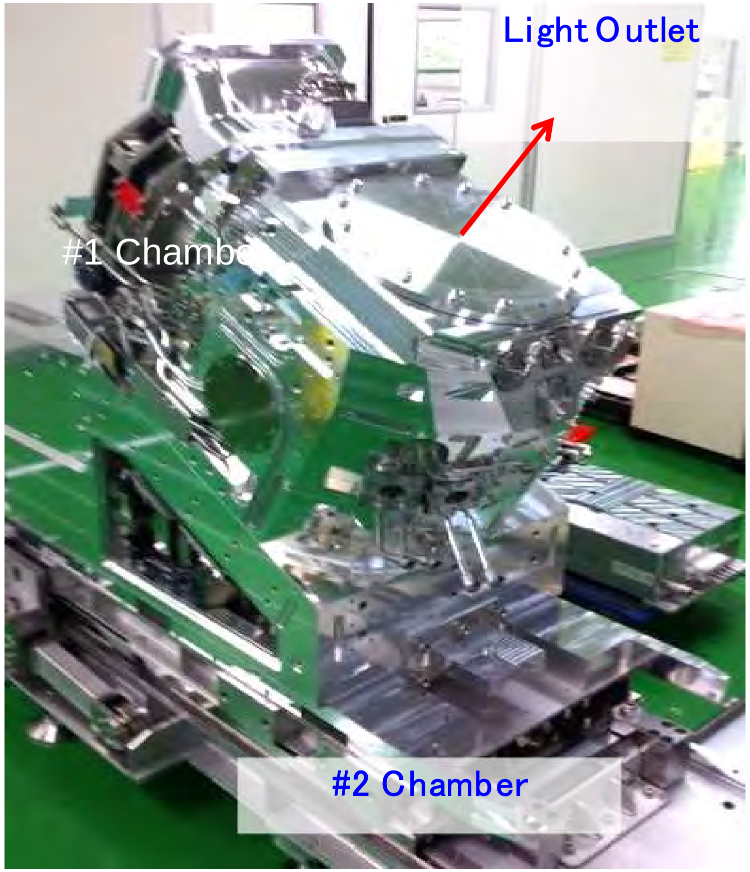


High Power EUV Source System: EUV Chamber (2013)

Status of proto light sources, #1 and #2

- System #1 : For EUV irradiation experiment (Operational)
  - The whole system (lasers and chambers) is working now
  - There are some issues and improvement activity is in progress

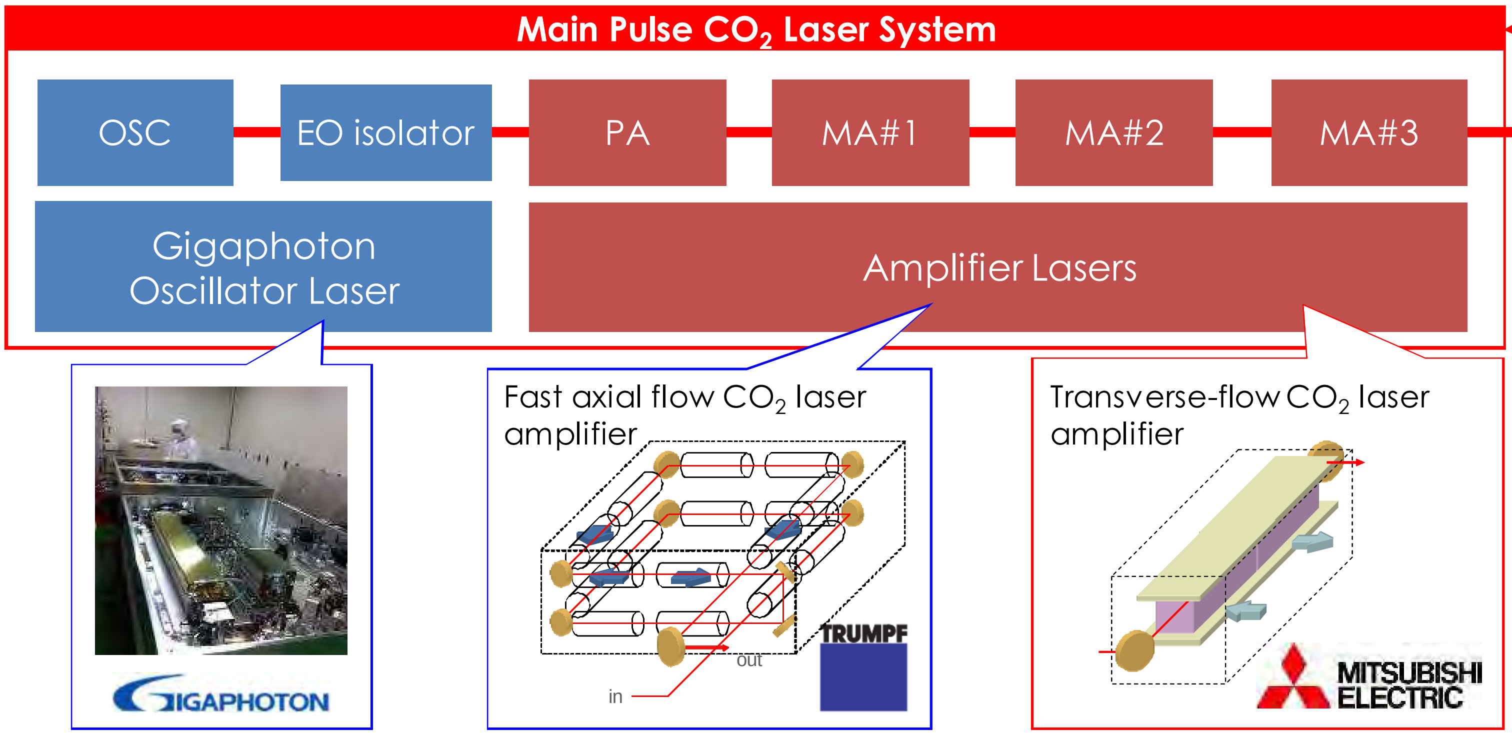
- System #2 :For high power development (Under construction)
  - The design and procurement was finished
  - The assembly will be finish soon
  - After the initial adjustment, the first EUV emission will be in this Q4

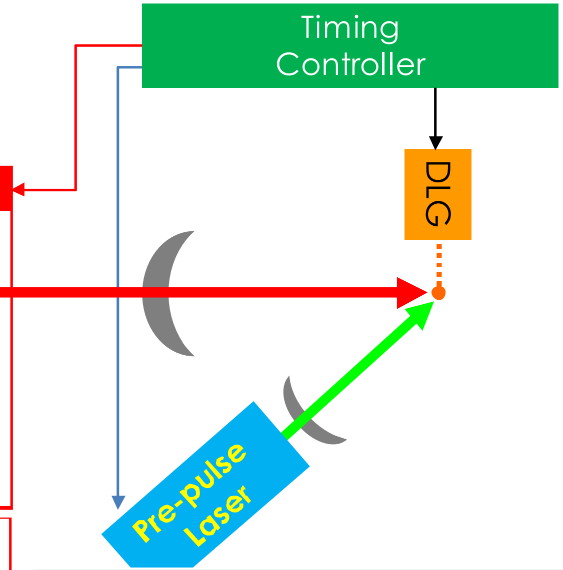


High Power CO_2 Laser & Pre-Pulse Laser

Driver Laser System

Gigaphoton, in cooperation with CW-CO_2 laser companies, has been jointly developing a unique high power pulsed CO_2 laser system since 2004

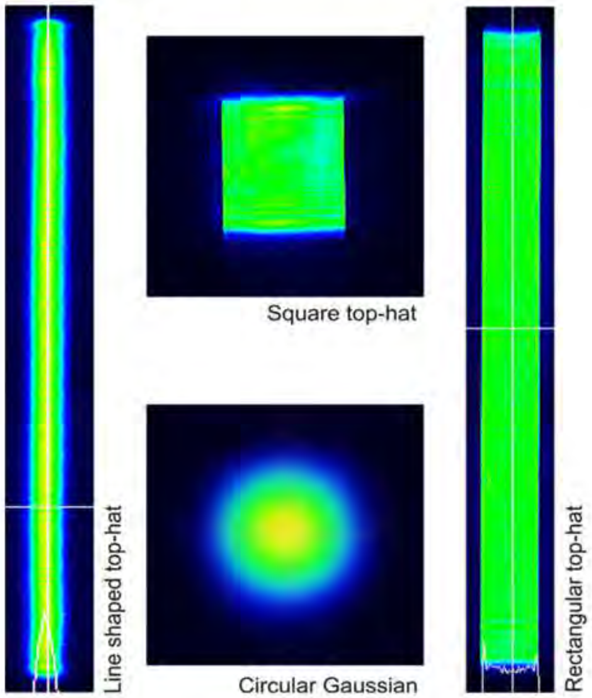




Laser Performance		
	Pre pulse	Main Pulse
Wavelength	10.6µm	1.06µm
Max Pulse Energy	200mJ	1mJ
Pulse Duration	14ns	12ps
Rep Rate	～100kH	～100kHz
Average Power	20kW	100W

Pre-pulse Laser

Summary of ultra-short Pulse Laser Specifications



- highest beam quality: $M^2 = 1.1$
- average power: up to 600W
- high pulse energy: up to 2000µJ
- short pulse length: down to 500fs
- high peak power: up to 200MW
- high pulse rep. rate: up to 100 MHz
- scalability of energy and power
- wavelength: 1064, 532, 355, 266
- efficient nonlinear frequency conversion
- unique flexibility in beam profile:
  - circular Gaussian
  - line shaped 1D Top-hat
  - square or rectangular 2D Top-hat

IAPLE 2018, Cape Town

High Power CO_2 Laser Development

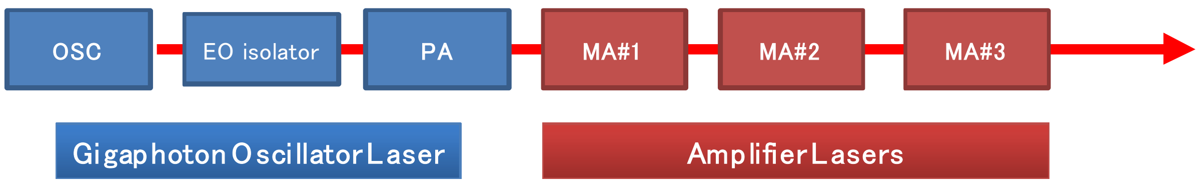
	Laser Power @Plasma	System	Oscillator	Pre-Amplifier	Main Amplifier		
1G Proto #1	5kW	Endurance Testing Platform	GPI	R	T	T	
2G Proto #2	10kW	Power Up Testing	GPI	R	T	T	T
3G Proto #2	**20kW (4λ)**	Power Up Testing	GPI	M	T	T	T
4G Pilot #1	**>27kW (4λ)**	Customer Beta Unit	GPI	M	M	M	M

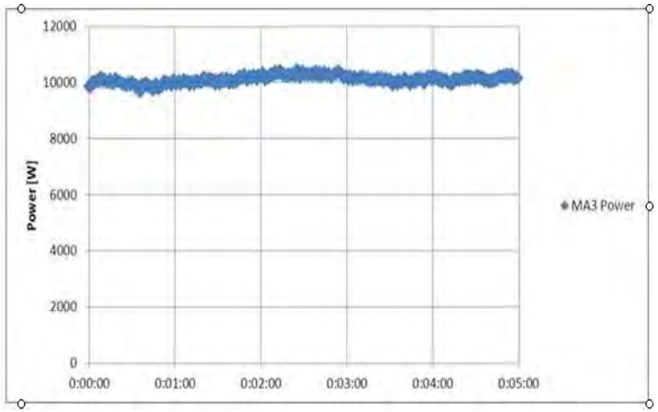
High Power CO_2 Laser Technology 1G,2G (2012)

Amplifier System A: experiment on present system using Trumpf amplifier laser

Performance data with 3x MA

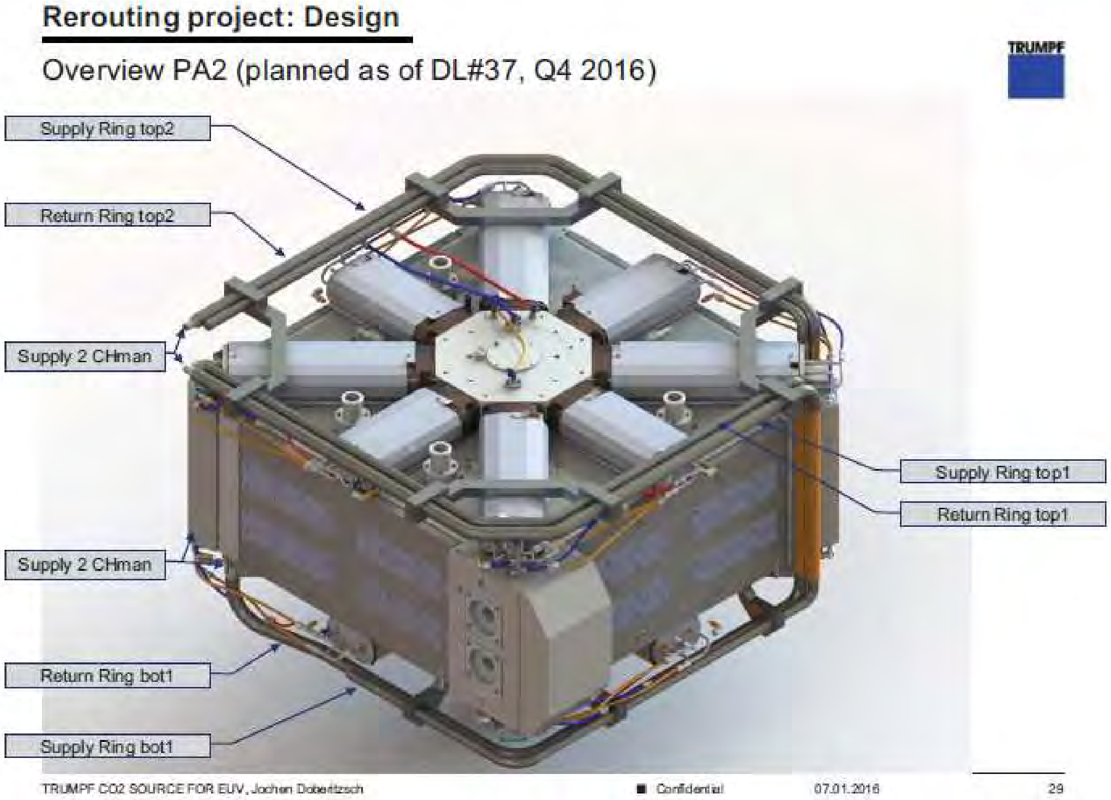
- 10kW performance was confirmed during hour level operation
  - Pulsed CO2 laser system experiment with Gigaphoton oscillator laser and Trumpf amplifiers x3units laser system.
- Next challenge
  - Confirm operation at target shooting
  - Further power improvement

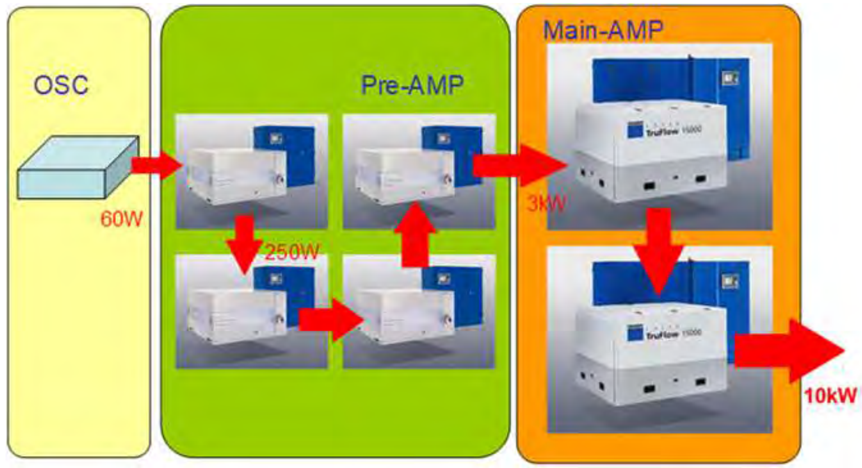


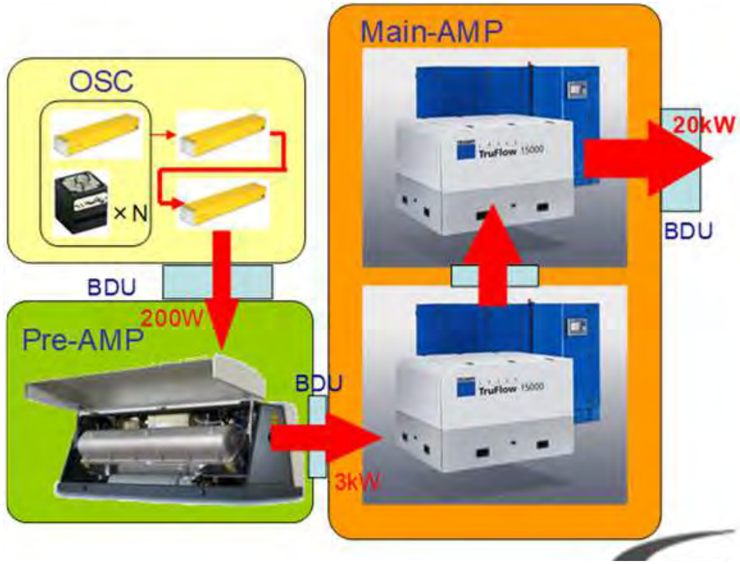


Compact high power pulsed CO2 laser (2010)

Trump laser base module

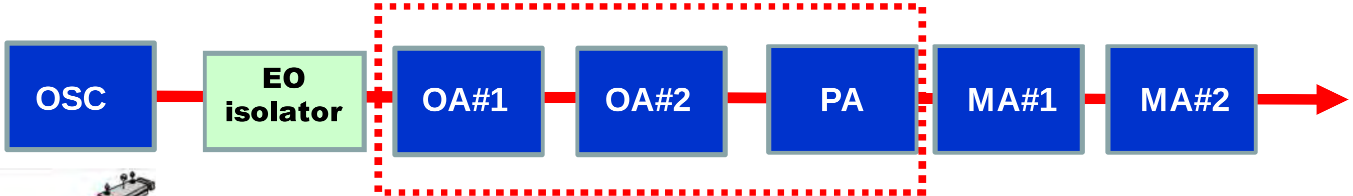


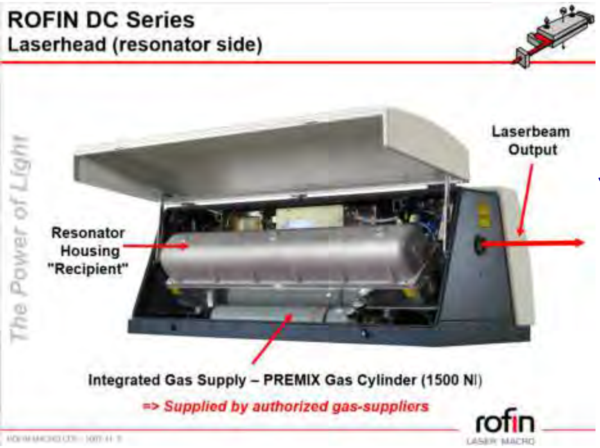




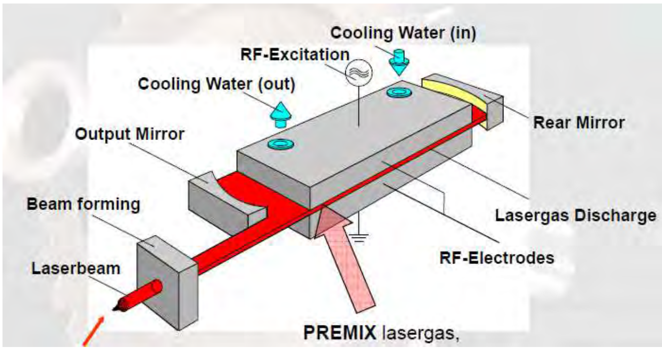
Compact Slab type CO2 laser

- Using slab laser as amplifier is GPI’s new concept. Merit is foot print. Demerit is the difficulty to prevent self-oscillation. Currently, we can not decide yet if slab laser is useful or not.



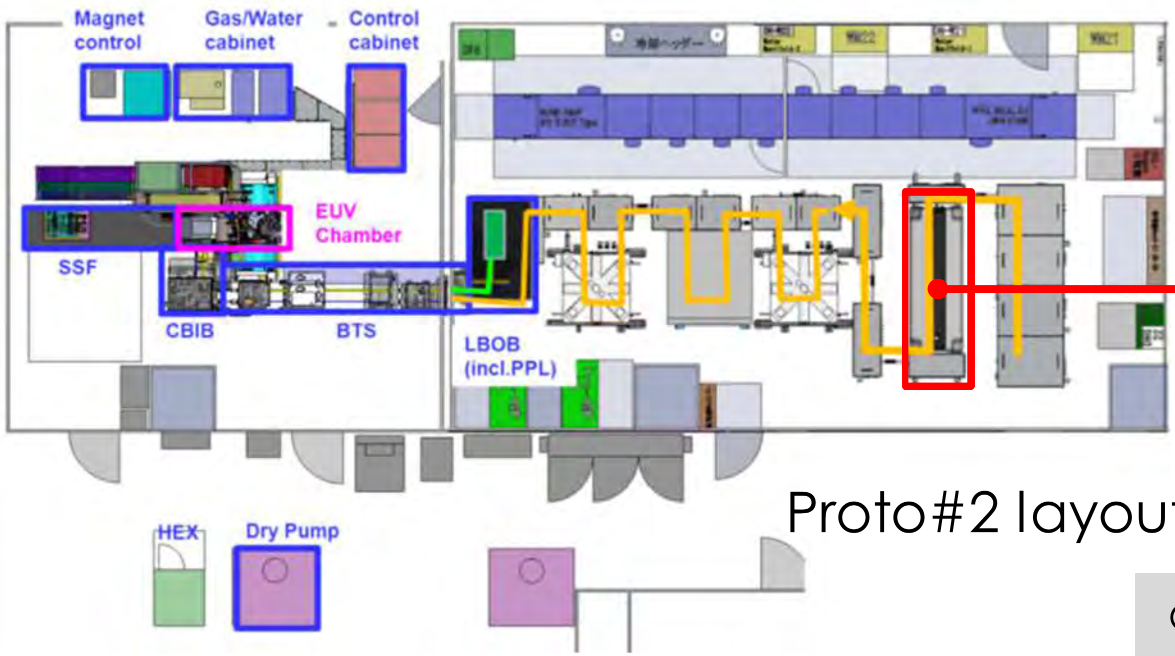


Slab laser



High Power CO_2 Laser Technology 3G (2015)

Mitsubishi pre-amplifier was installed in Proto #2 and performance was confirmed



Proto#2 layout

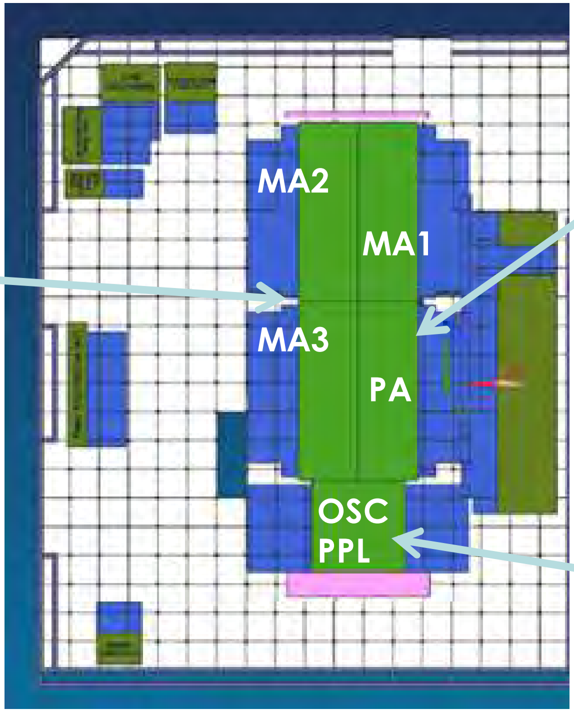
GPI — Mitsubishi — Trumpf — Trumpf — Trumpf

MA#1 MA#2 MA#3

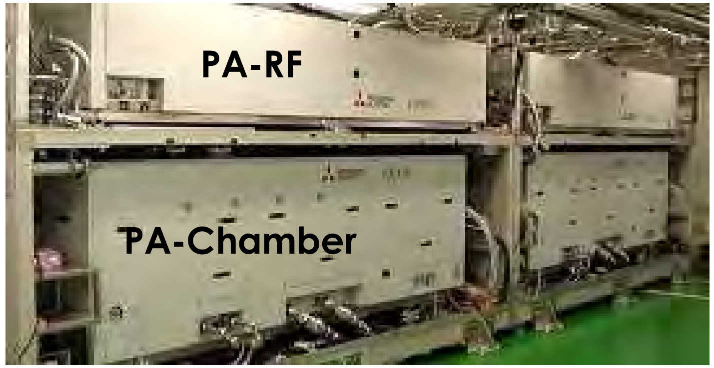
High Power CO_2 Laser Technology 4G (2017)

- **Mitsubishi CO2 amplifiers were set in driver laser frame.**
- **Oscillator construction is going on.**

Left side of driver laser



Sub Fab Area



Right side of driver laser

Agenda

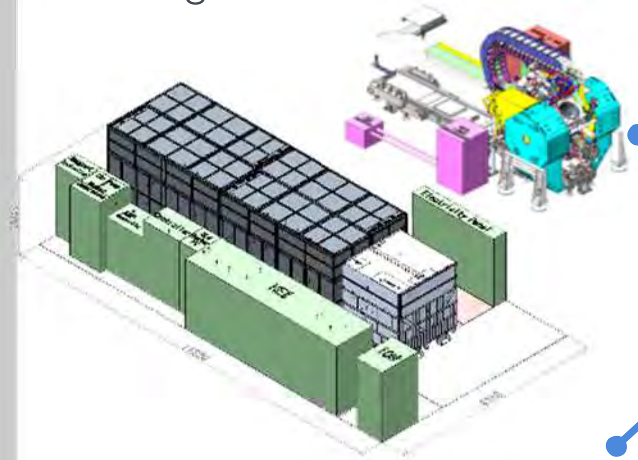
- **Introduction**
  - Gigaphoton Business update
- **EUV Research & Development History**
- **Experiment A: >330W Power Challenge of EUV Source**
  - ① CO2 Laser Power Upgrade
  - ② Beam Uniformity Upgrade at Plasma Point
  - ③ Optimization of Plasma Parameters
- **Experiment B:**
  Long-term Test and Challenge for Long-life Mirror and Availability
  - ④ Lifetime Extension of Collector Mirror
- **Summary & Acknowledgement**

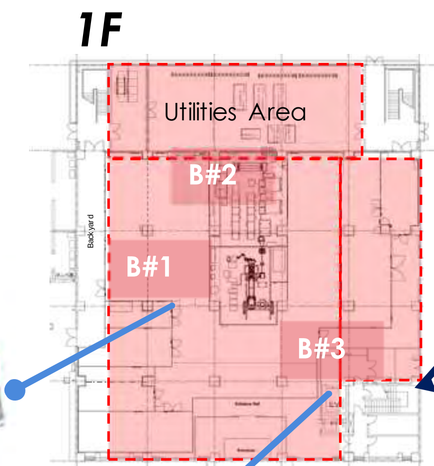
Hiratsuka Center at present

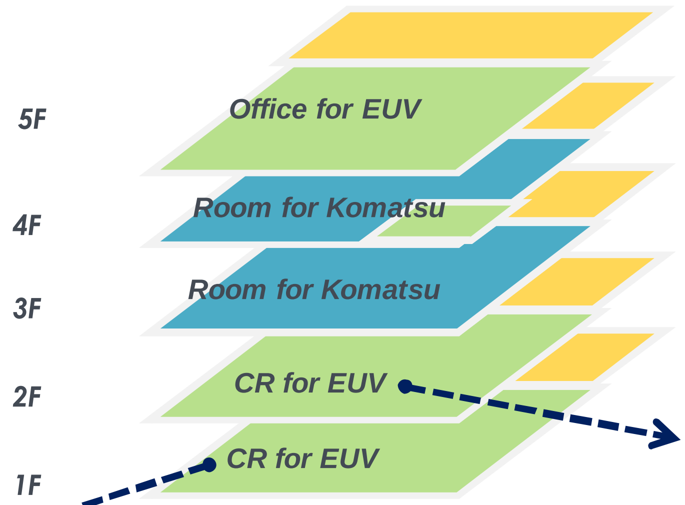
Pilot#1

Operational since July 2016

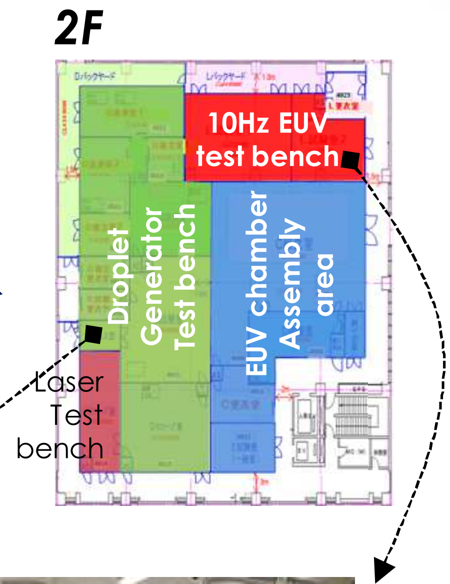
First pilot system designed for NXE integration







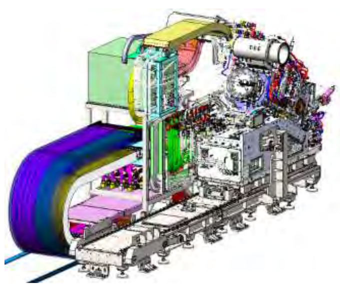
Hiratsuka center



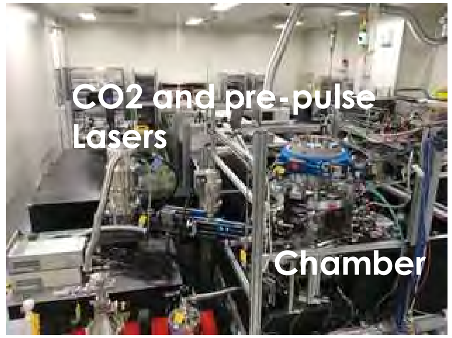
Proto#2

Operational since November 2013

System for key technology development in >100W power level



■ Droplet test bench
Reliability, Stability etc.



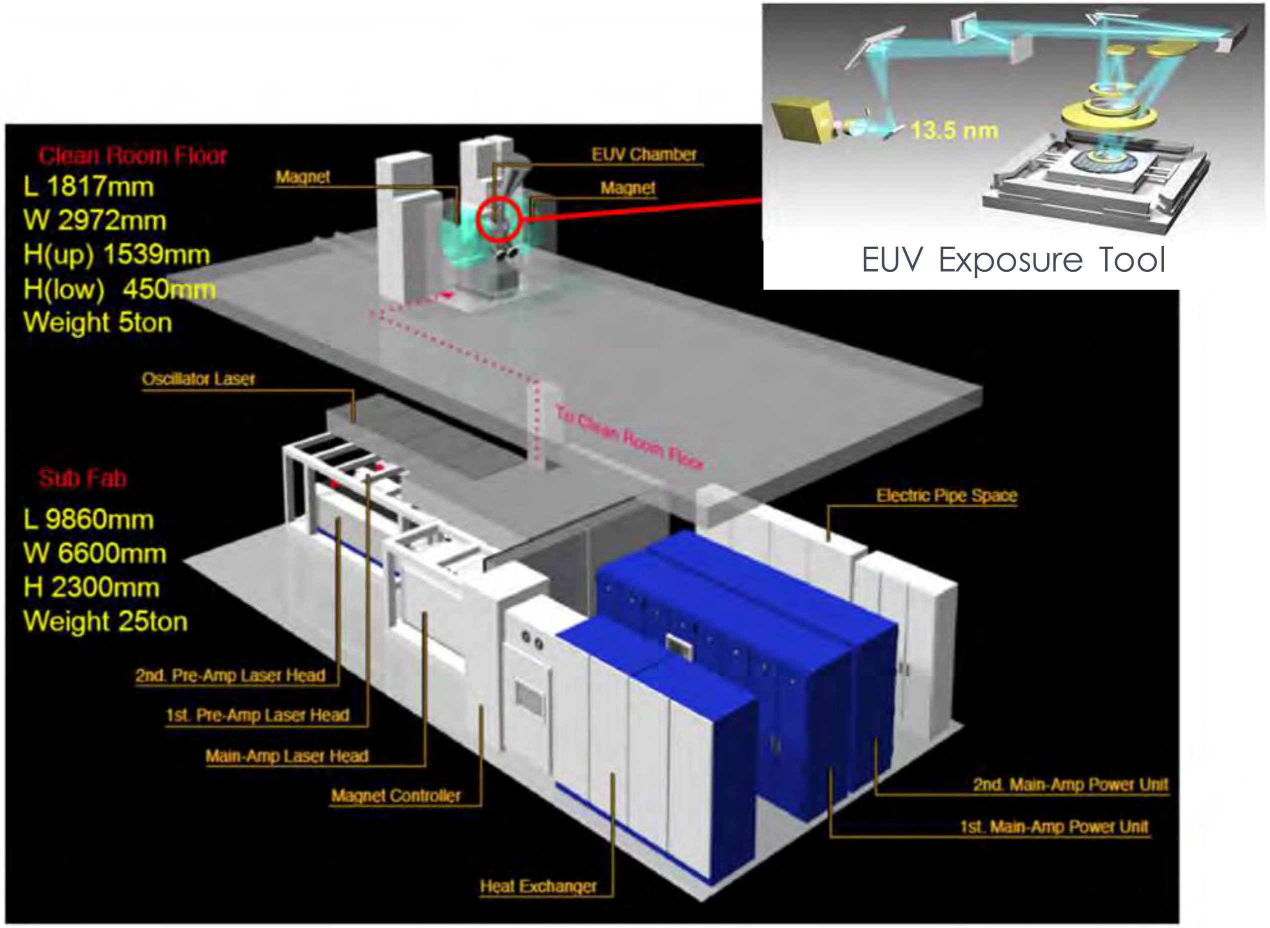
■ EUV plasma study (<10Hz)
CE, ions energy etc.

Layout of >330W EUV Light Source Pilot #1

First HVM EUV Source

- Original design was 250W EUV source
- **>330W Power Challenge with Upgraded Hardware**

Operational specification (Target)			HVM Source
Performance	EUV Power		> 330W
	CE		> 5.5-6.0%
	Pulse rate		100kHz
	Availability		> 90 %
Technology	Droplet generator	Droplet size	< 20 micron
	CO2 laser	Power	> 27 kW
	Pre-pulse laser	Pulse duration	~10 ps pulse duration
	Debris mitigation	Magnet, Etching	>3 months



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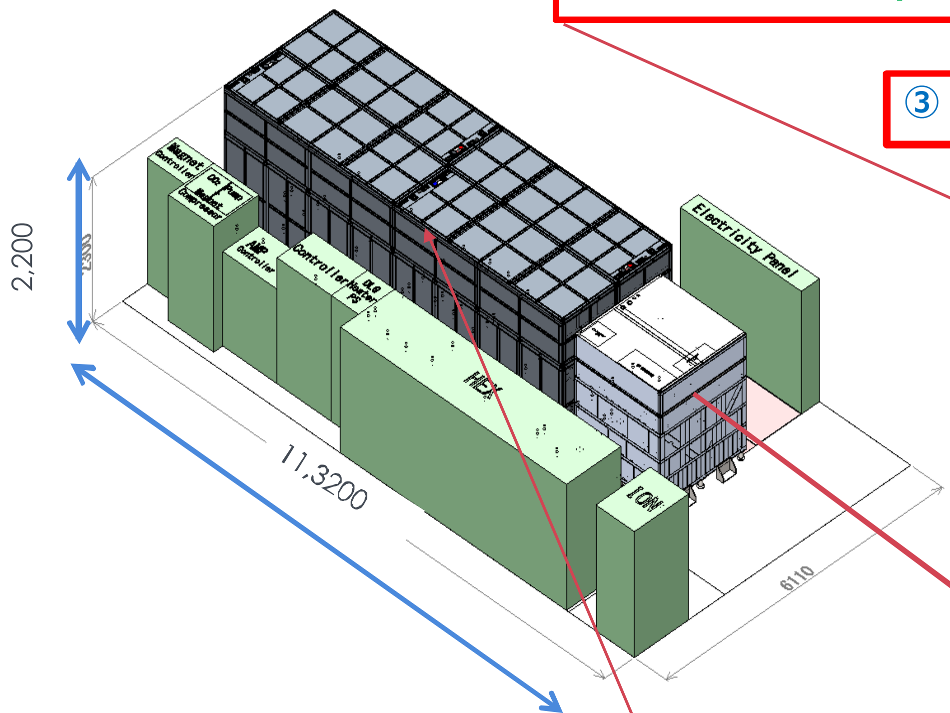
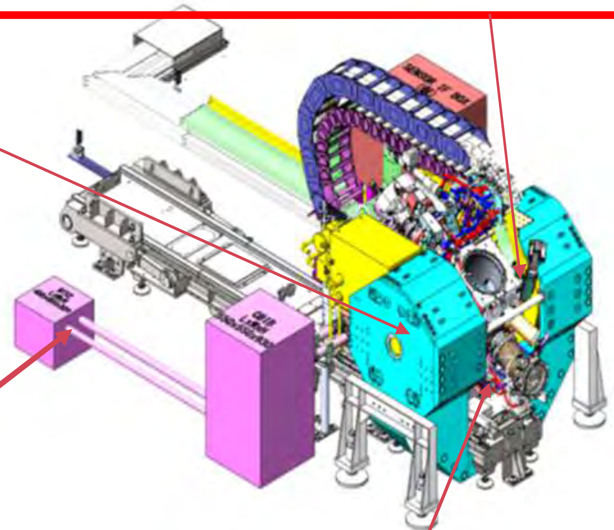
>330W Power Challenge with Upgraded Hardware

② Beam Uniformity Upgrade at Plasma Point ✓ Done

③ Optimization of plasma parameters for higher CE ✓ On going

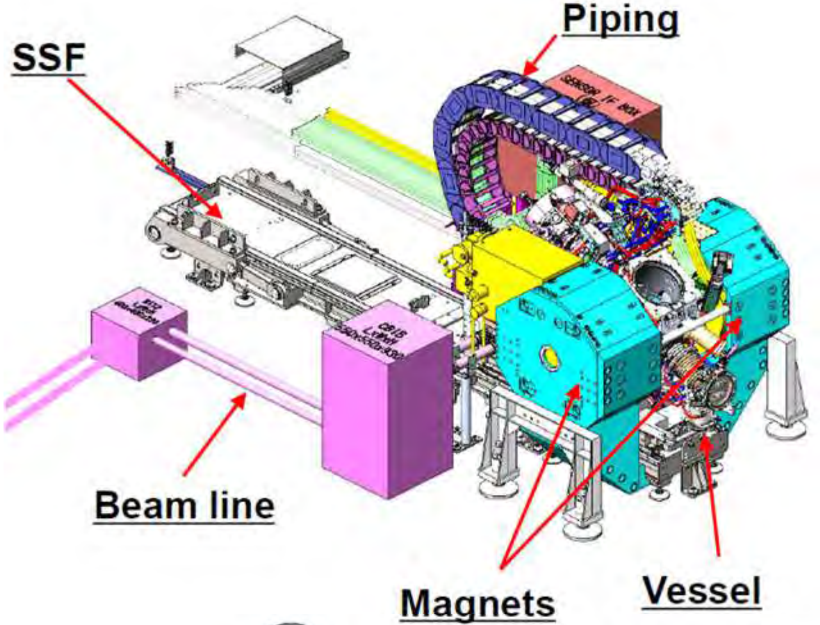


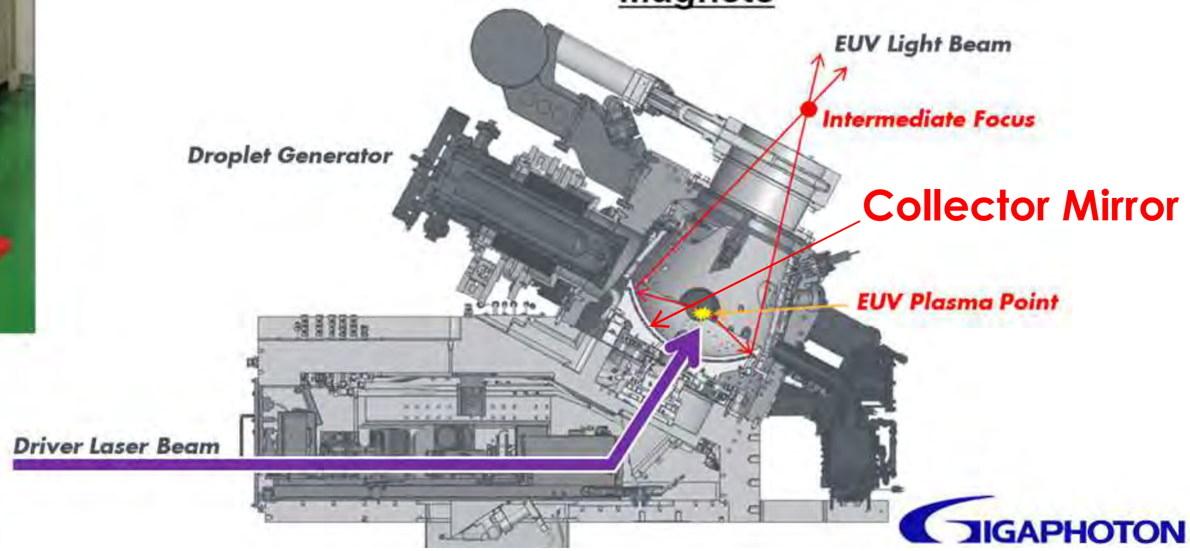


① CO2 Laser Power Upgrade ✓ Done

④ Lifetime Extension of Collector Mirror -0.05%/B pls ✓ On going

Pilot System EUV Chamber

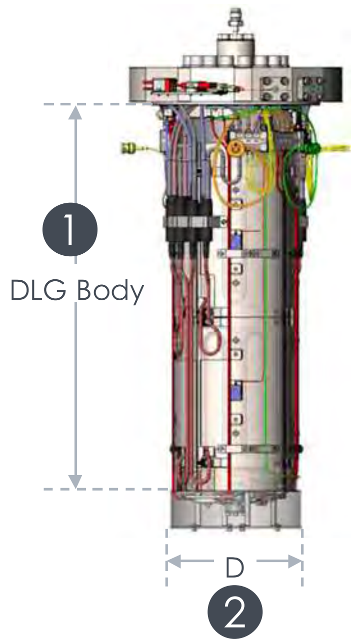




Droplet Generator : **Lifetime**

- Lifetime is about 15 days limited by Tin volume. Target is 60 days.

		Current	Target
Droplet speed	m/s	90	90
Back pressure	MPa	40	40
Repetition rate limit of system	kHz	100	100
Lifetime	day	15	**60**
Length	mm	450	**650**
Diameter	mm	140	**200**

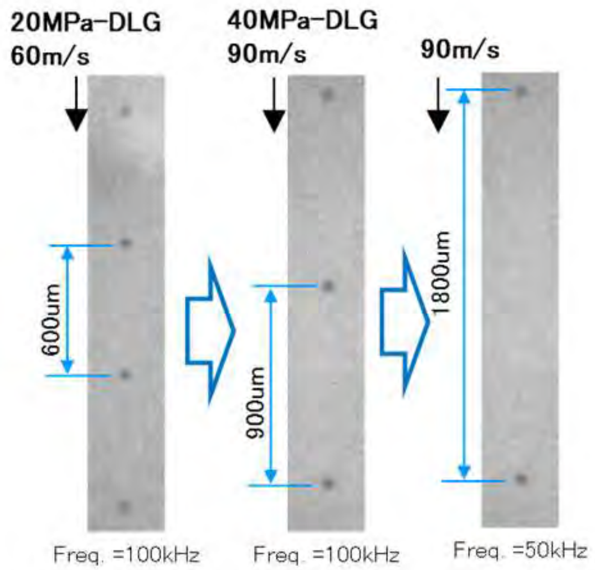


- Investigation for large size material was completed. Development is on going. Projected completion by 2020. .

Pilot System Droplet Generator Technology Transfer

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

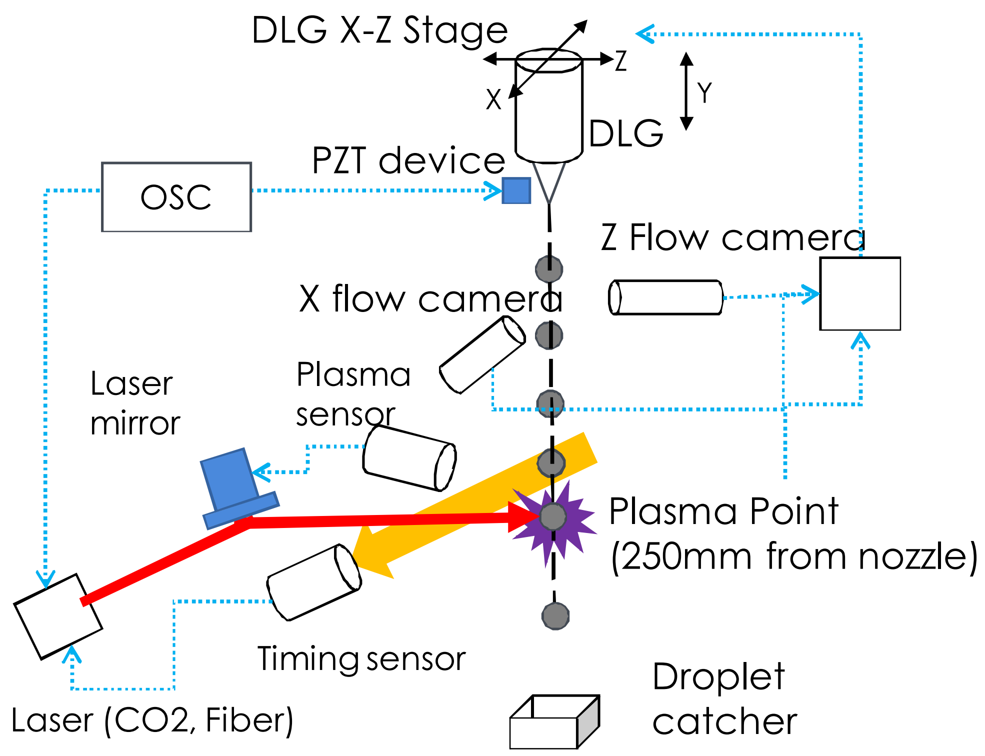
	Proto#1	Proto#2	Proto#2	⇨ Pilot#1
Droplet Speed (m/s)	45	60	90	90 (100)
Back Pressure (MPa)	12	20	40	40 (50)
Max Repetition Rate (kHz)	50	80	100	100



Droplet Status

Pilot System Droplet Generator

LPP EUV Source Shooting Control System



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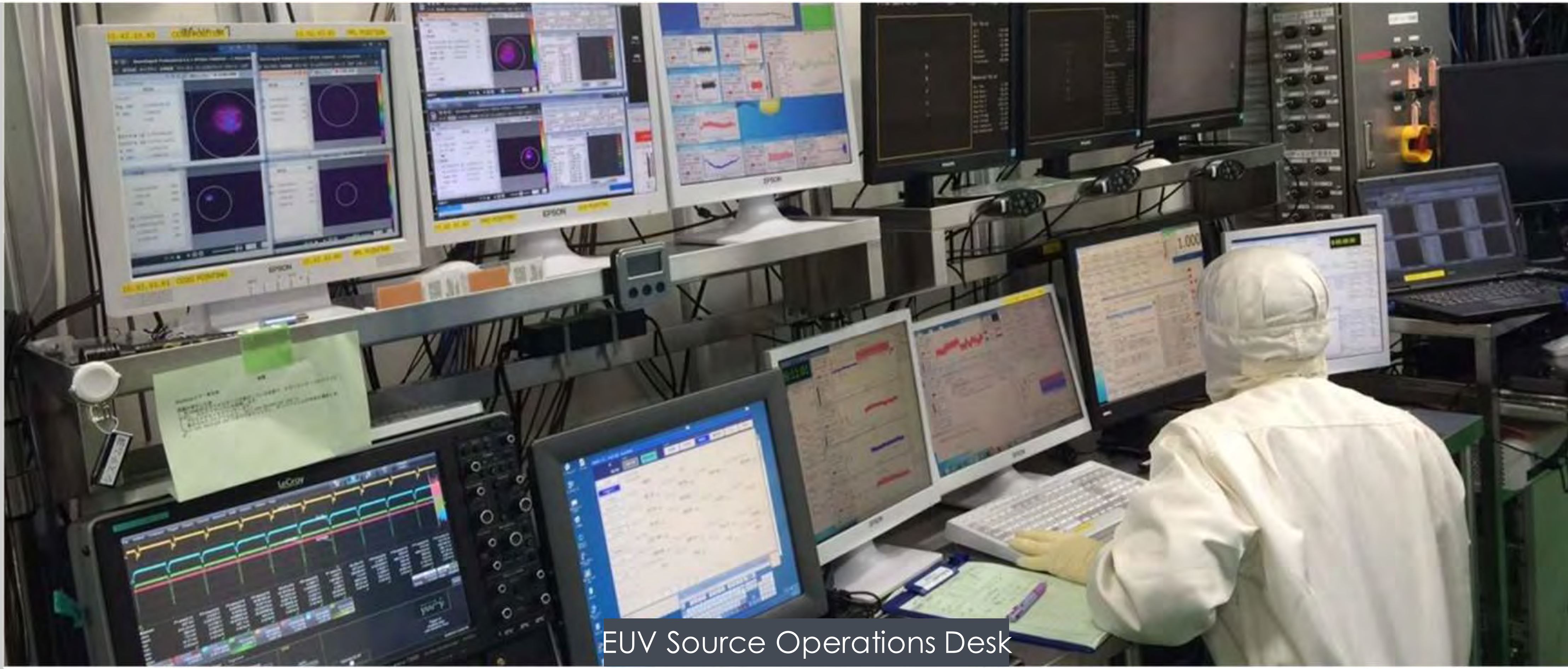
Pilot#1 System in Operation



EUV Source Operations Desk

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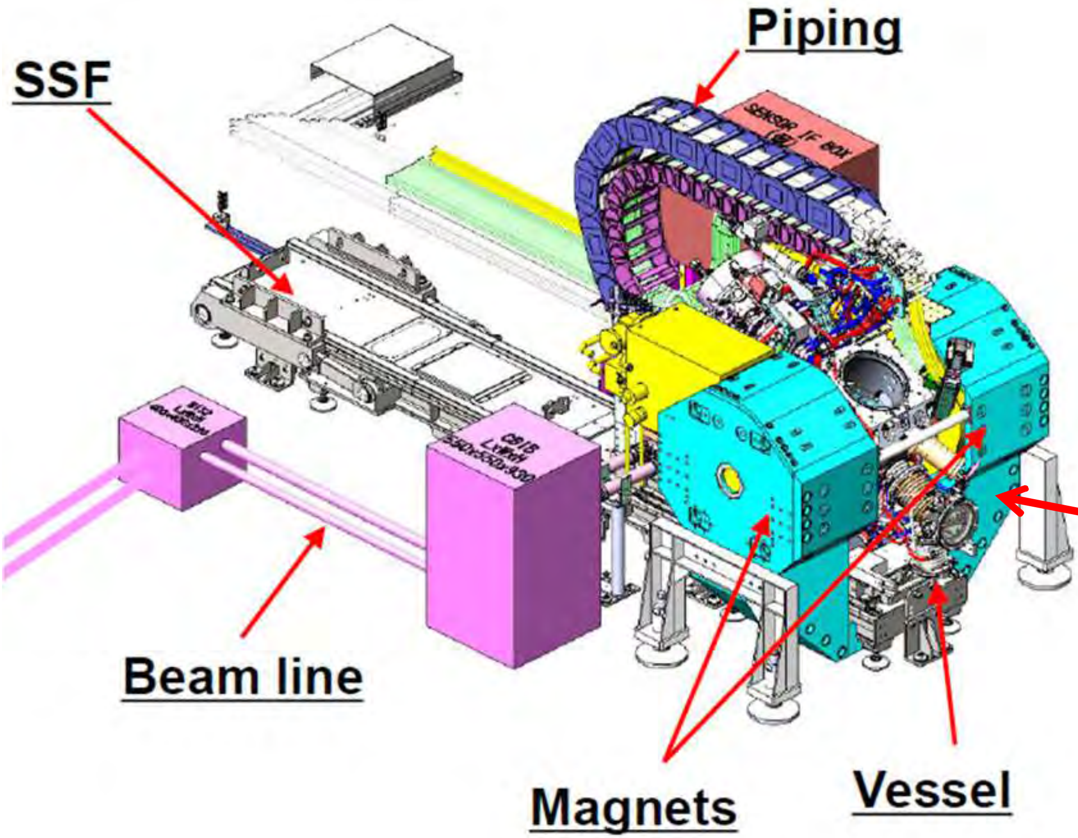
Pilot #1 construction status (3) : EUV Chamber System



- Super conductive magnet
  - Installation is finished
- EUV Vessel
  - Under fabrication

>330W Power Challenge with Upgraded Hardware

Target	Q4 2018	On Going	Q4 2019
Average Power	125W	**250W-330W**	**≧330W**
Repetition rate	100kHz	**100kHz**	100kHz
CO2 power (energy) at plasma operation with dose ctrl./maximum	10kW/16kW (100mJ/160mJ)	**18kW/25kW (180mJ/250mJ)**	18kW/25kW (180mJ/250mJ)
CE	4.0%	**4.5~5.0%**	**5.5～6%**
Technology for high power			
① CO2 Laser power Upgrade		✓	✓
② Beam Uniformity Upgrade at Plasma Point		✓	✓
③ Optimization of Plasma Parameters			✓
④ Lifetime Extension of Collector Mirror <0.05%/Bpls			✓

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① CO_2 LASER POWER UPGRADE

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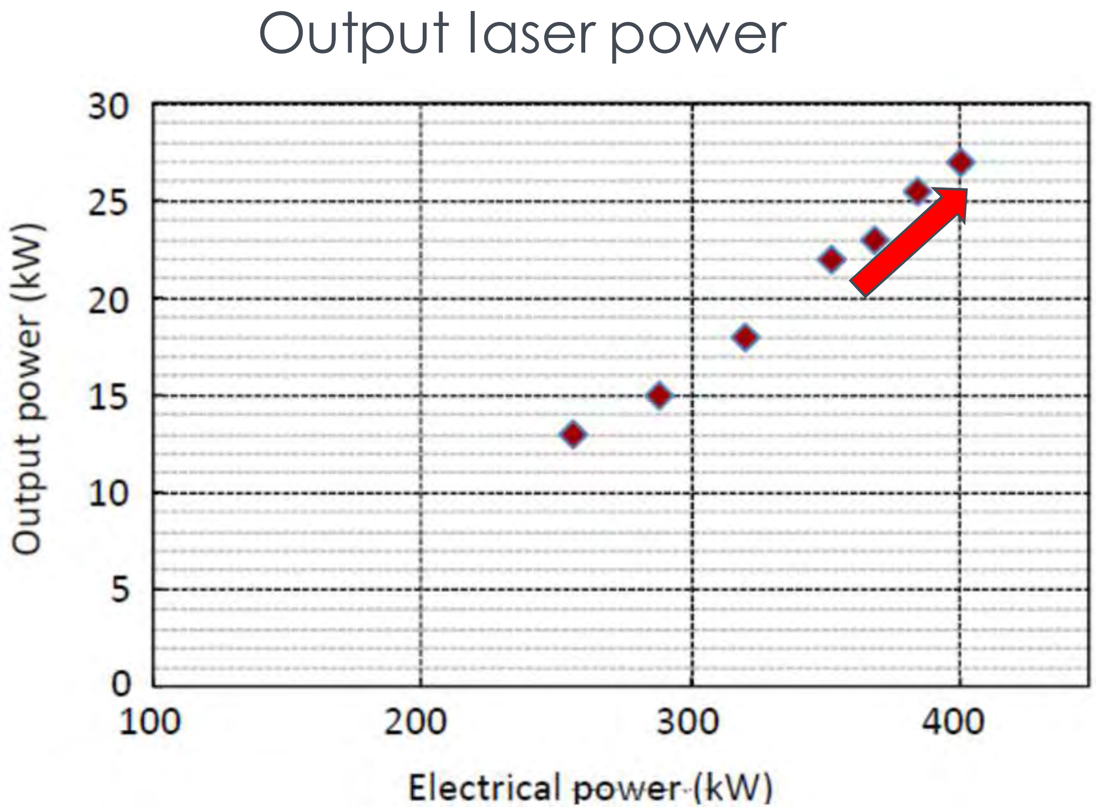
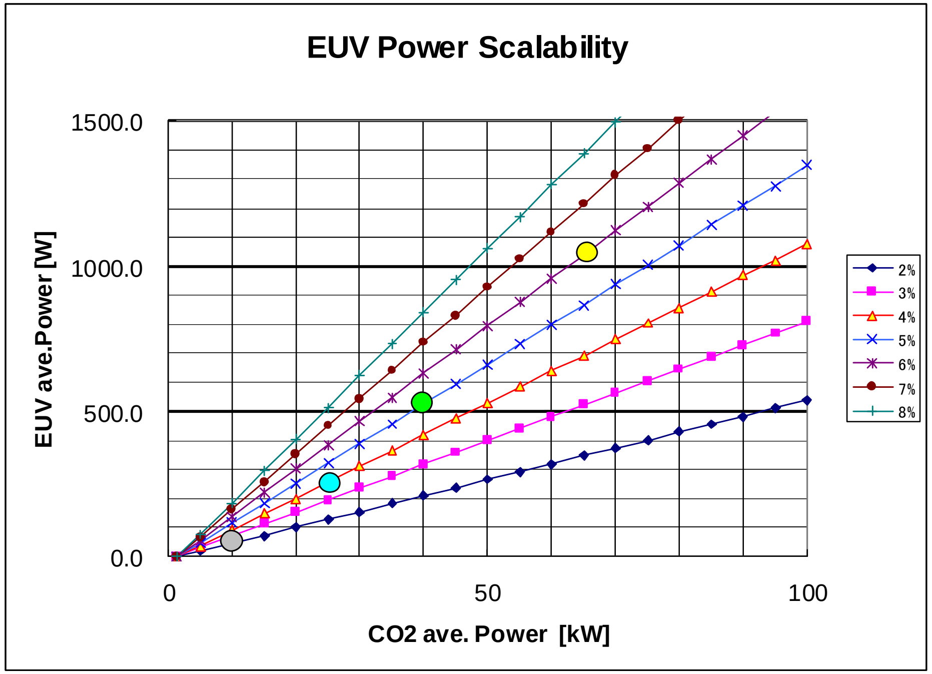
Improvement of Higher-power CO_2 laser

- High-efficient laser amplifier with transvers flow concept (Mitsubishi electric).
- Recent improvement achieved **27 kW** laser power operation.



Extendibility to 1kW EUV Power (1)

Feasibility study of EUV Output Power vs. CO2 Input Power



Feasibility study of extendibility to 1kW

- Conversion efficiency is Key. At least achievement of CE＞4% is essentially important. If not, CO2 laser will become ＞100kW.
- At least ＞50kW CO2 laser power must be realized. Even in best case of CE=8%.
- I believe; 1000W EUV source is feasible in future, from the technical data (experiment of CE and CO2 laser) and technical expectation at present.

Extendibility to 1kW EUV Power (2)

Possible scale up scenario of EUV Output Power vs. CO_2 Input Power

CO2 laser Energy [mJ]	CO2 laser ave. Power [kW]	EUV ave.Power[W] @100kHz — Conversion Efficiency [%]: 2%	3%	4%	5%	6%	7%	8%
15	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50	5	19.1	28.7	38.2	47.8	57.3	66.9	76.4
100	10	46.4	69.6	92.8	116.0	139.2	162.4	185.6
150	15	73.7	110.6	147.4	184.3	221.1	258.0	294.8
200	20	101.0	151.5	202.0	252.5	303.0	353.5	404.0
250	25	128.3	192.5	256.6	320.8	384.9	449.1	513.2
300	30	155.6	233.4	311.2	389.0	466.8	544.6	622.4
350	35	182.9	274.4	365.8	457.3	548.7	640.2	731.6
400	40	210.2	315.3	420.4	525.5	630.6	735.7	840.8
450	45	237.5	356.3	475.0	593.8	712.5	831.3	950.0
500	50	264.8	397.2	529.6	662.0	794.4	926.8	1059.2
550	55	292.1	438.2	584.2	730.3	876.3	1022.4	1168.4
600	60	319.4	479.1	638.8	798.5	958.2	1117.9	1277.6
650	65	346.7	520.1	693.4	866.8	1040.1	1213.5	1386.8
700	70	374.0	561.0	748.0	935.0	1122.0	1309.0	1496.0
750	75	401.3	602.0	802.6	1003.3	1203.9	1404.6	1605.2
800	80	428.6	642.9	857.2	1071.5	1285.8	1500.1	1714.4
850	85	455.9	683.9	911.8	1139.8	1367.7	1595.7	1823.6
900	90	483.2	724.8	966.4	1208.0	1449.6	1691.2	1932.8
950	95	510.5	765.8	1021.0	1276.3	1531.5	1786.8	2042.0
1000	100	537.8	806.7	1075.6	1344.5	1613.4	1882.3	2151.2

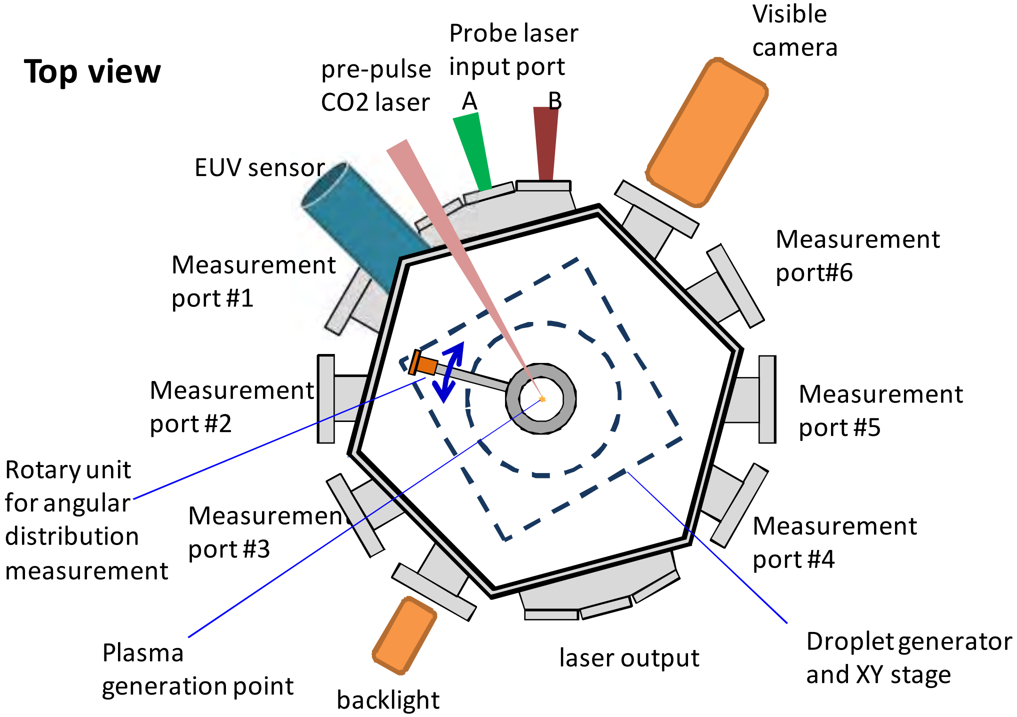
Our possible scale-up scenario

	HVM (1st)	HVM (2nd)	HVM(3rd)
EUV power	250W	500W	1000W
CE	4%	5%	6%
Pulse rate	100 kHz	100kHz	100kHz
Pre-pulse laser	Pico-s	Pico-s	Pico-s
CO2 laser power	25kW	40kW	65kW
# of main amps	3	5	8

② BEAM UNIFORMITY UPGRADE AT PLASMA POINT

Test apparatus for pre-pulse study

- EUV generation at 10Hz
- Studies on CE improvement and debris mitigation
- Measurement tools for EUV radiation and tin particles and plasma characterization



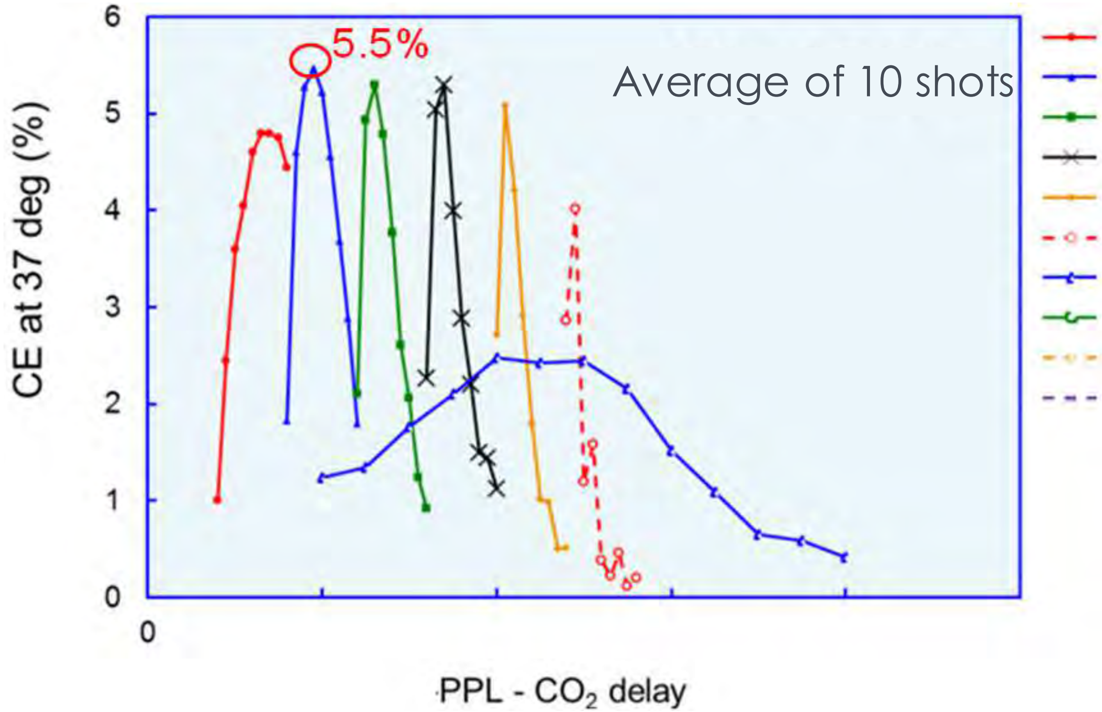
Overview of test apparatus

Measurement tools

- EUV radiation
  - spectrometer
  - imaging camera
- Sn ions
  - Faraday cup
  - Electro static analyzer
- Sn atoms
  - Laser induced fluorescence
- Sn fragments
  - Mie scattering
- Plasma
  - Thomson scattering

Pre-Pulse Technology: Improvement in 2015

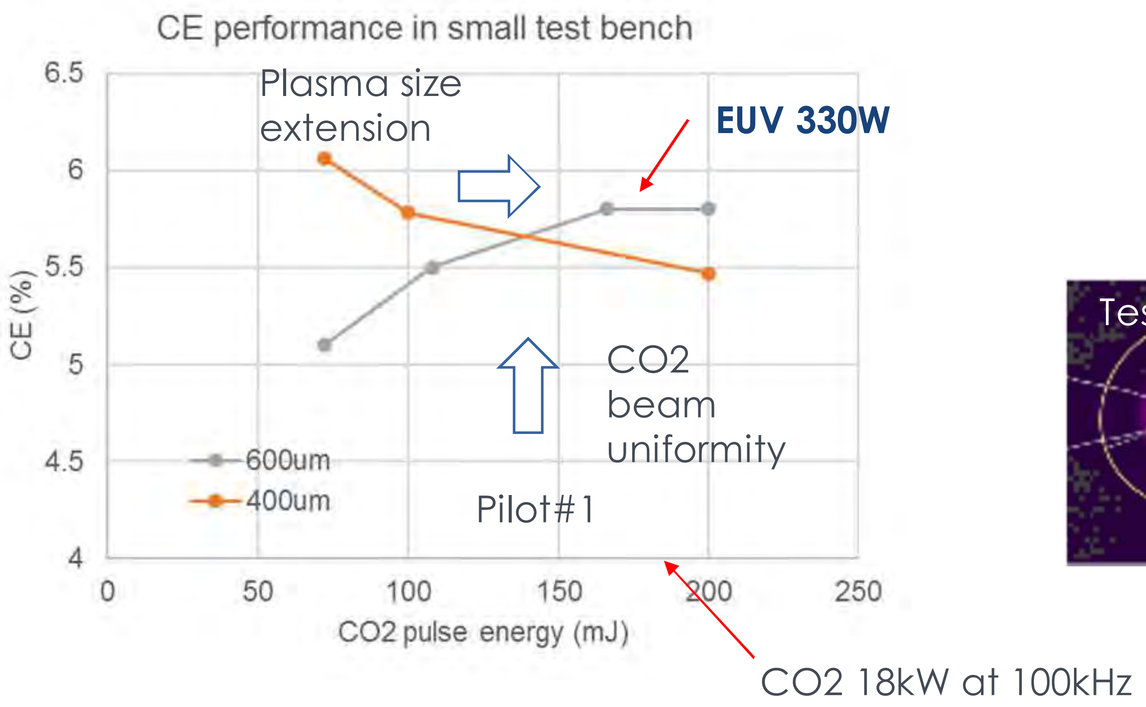
In an experiment device, we observed **5.5% CE** under optimized conditions. This was a **17% increase** from our old champion data (CE = 4.7%).

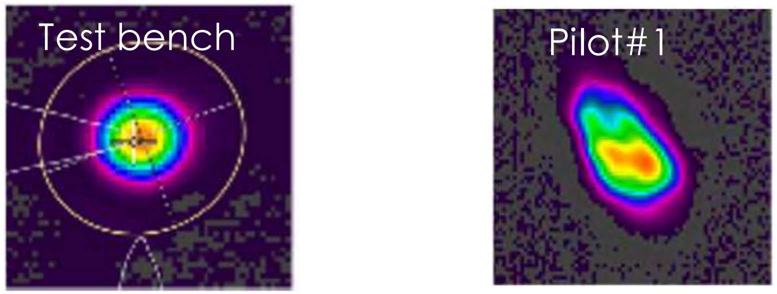


Experiment Device

Key Technology for higher CE

- 5.8% CE at 180mJ was already confirmed in **small test bench** by increased plasma size.
- CO2 beam non-uniformity of Pilot#1 due to beam expander design is improved.



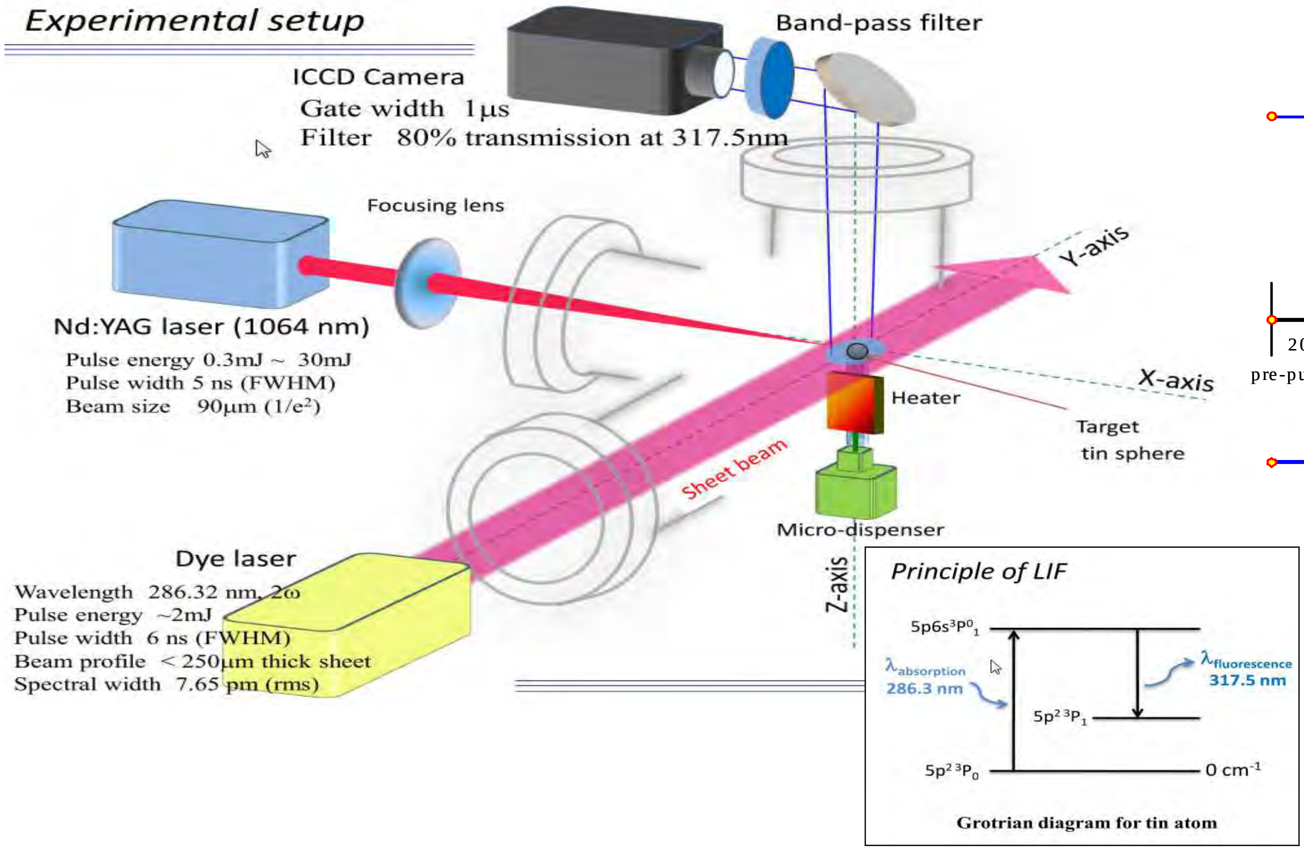


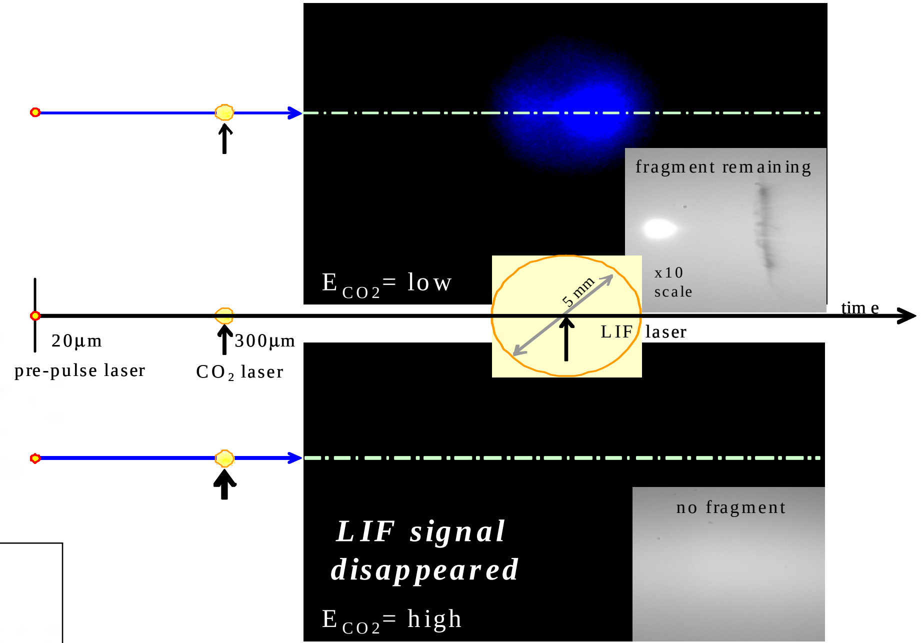
CO2 spot profile

③ OPTIMIZATION OF PLASMA PARAMETERS

Pre-Pulse Technology (3)

Neutral atoms measurement: ionization ratio is investigated



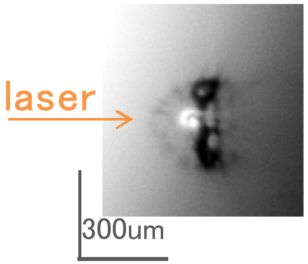


Pre-Pulse Technology(4)

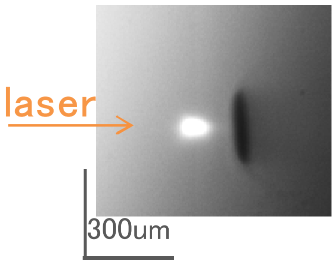
Experiment shows pico-second pre-pulse dramatically enhances ionization rate and CE

Sn Droplet Smash

psec Dome like target

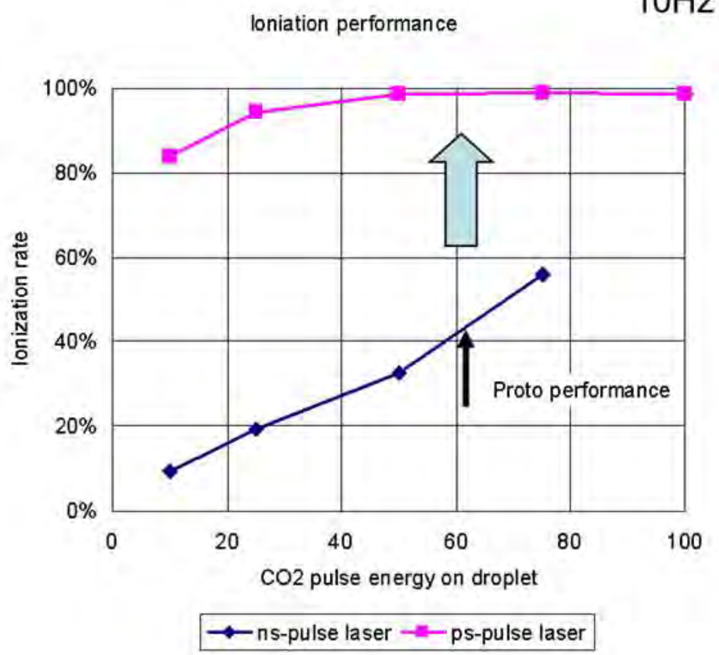


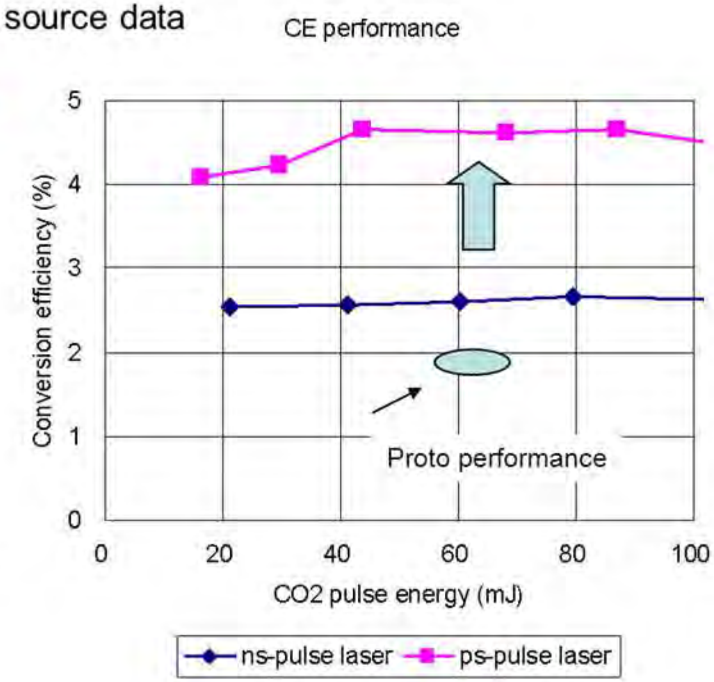
nsec Flat disk like target



Data in 10Hz Experimental Device

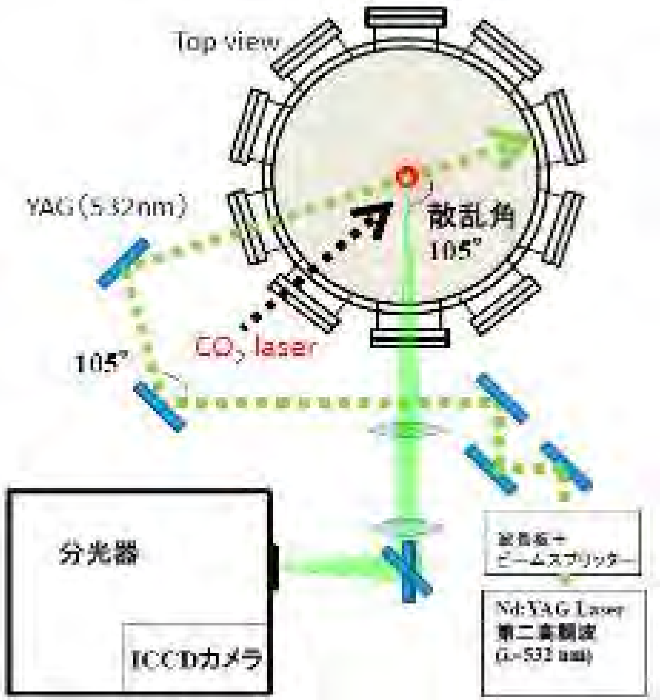
10Hz source data

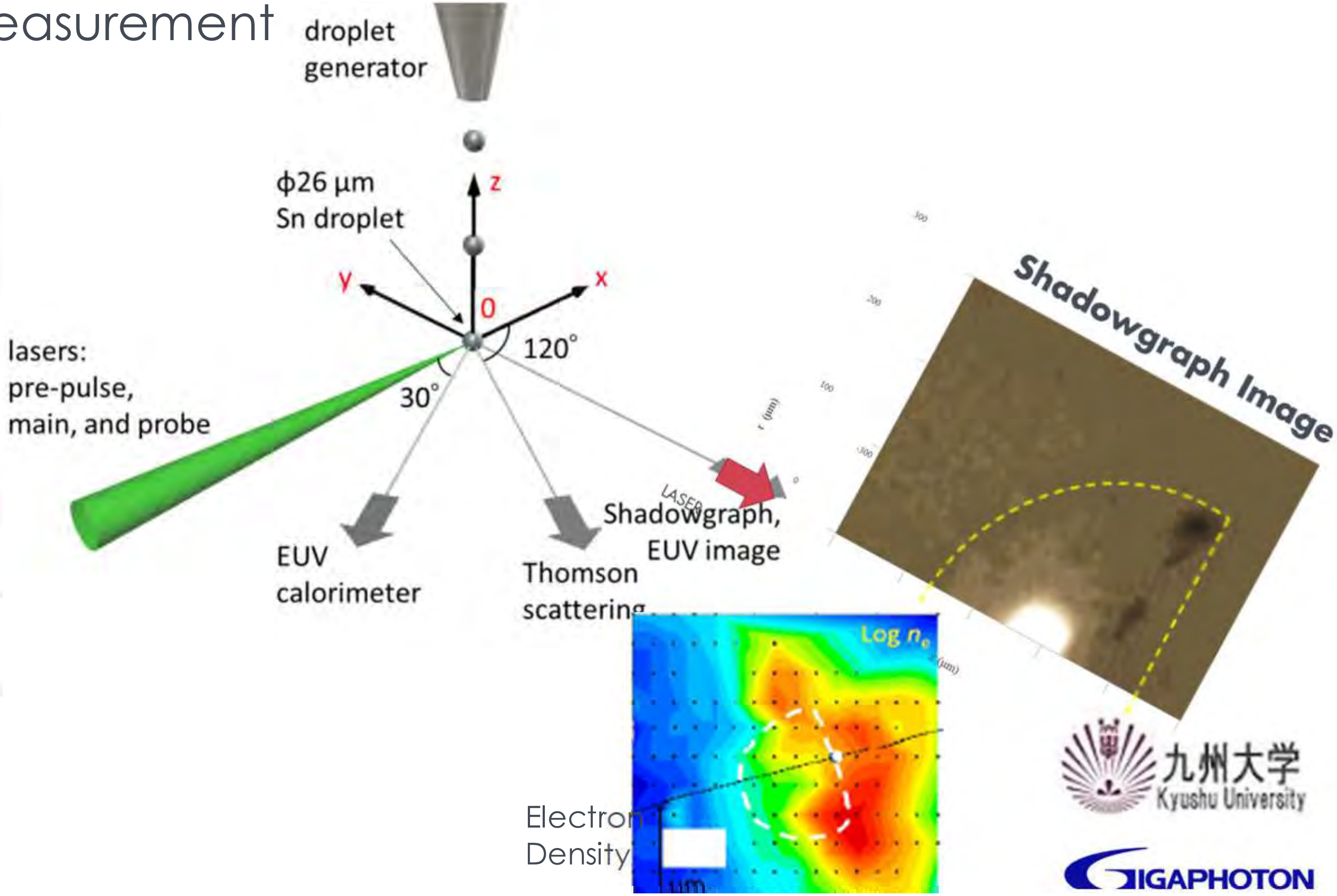




Plasma Parameter Measurement (1/2)

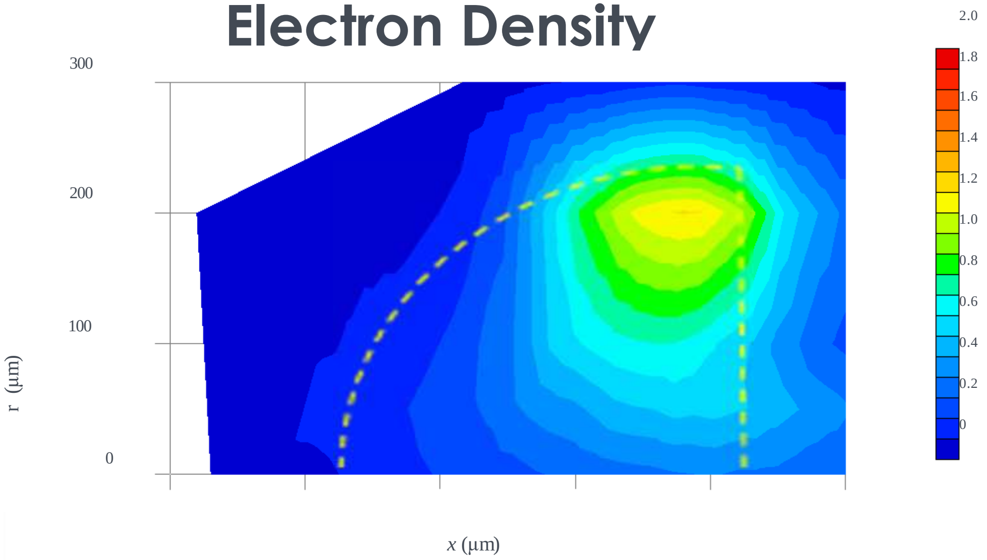
Thomson Scattering Measurement



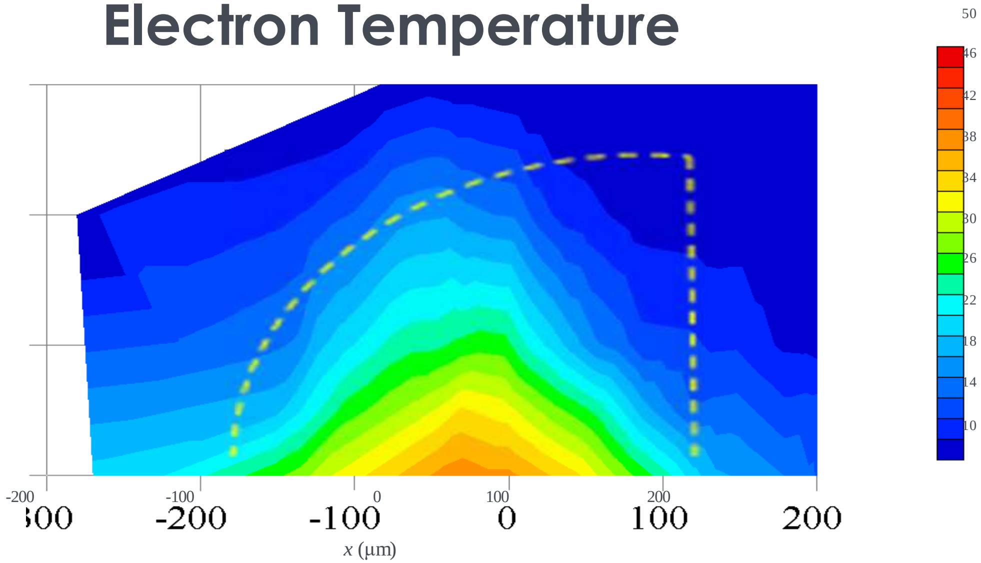


Plasma Parameter Measurement (2/2)

Electron Density



Electron Temperature



Tomson Scattering measurement characterize pre-pulse plasma in detail !

Next step: *CE enhancement by plasma optimization.*

九州大学 Kyushu University

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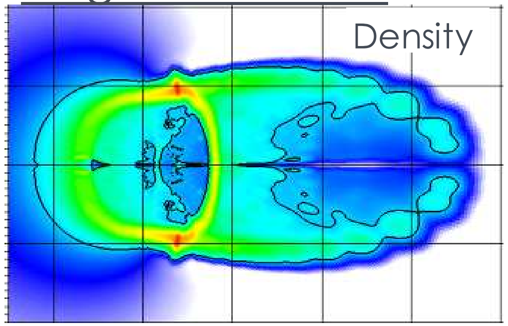
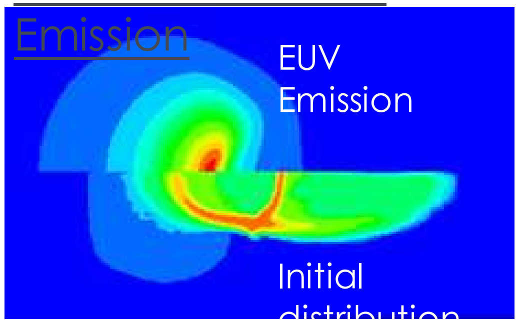
For Next Progress: Ce Simulation and Diagnostics of EUV Plasma

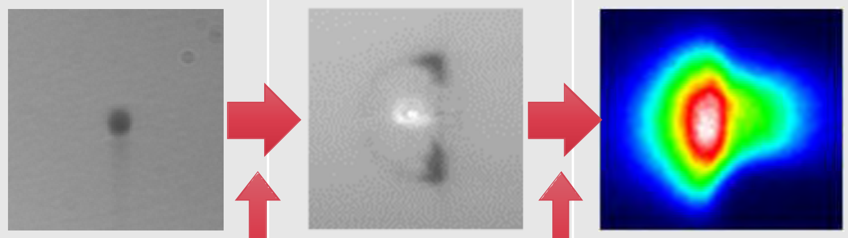
Target Simulation



Simulation of EUV Emission



Thin Target	Mist	EUV Emission



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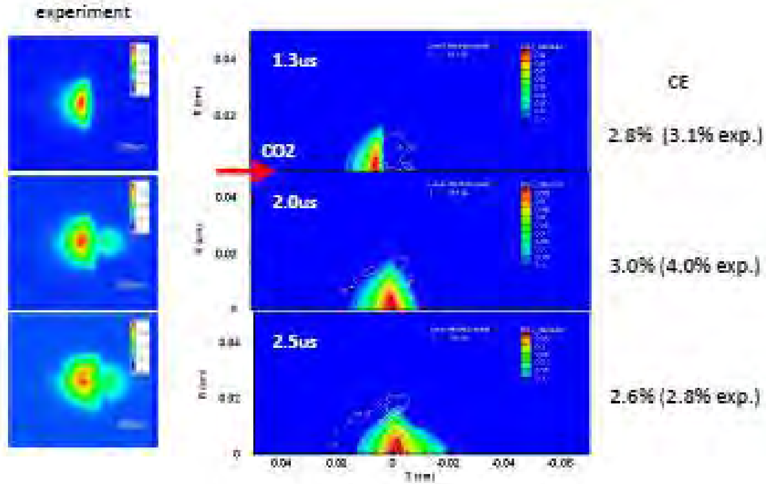
9. EUV image (in-band, time-average) at 90deg, 50mJ



Thomson Scattering

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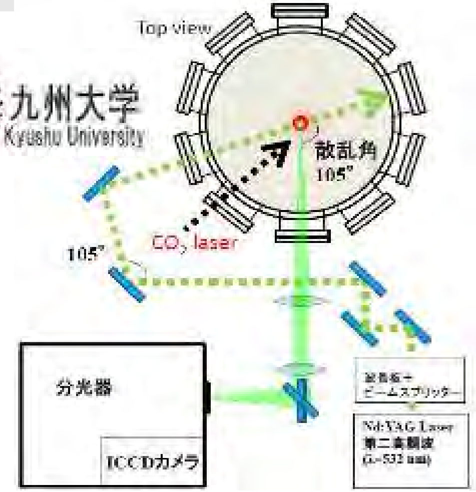

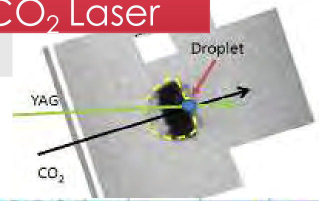

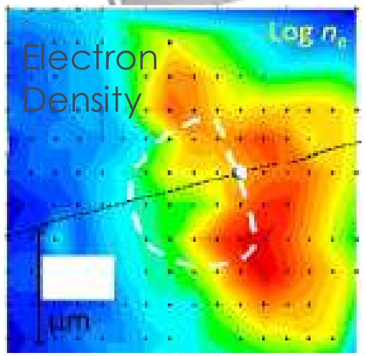

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Pre-Pulse Technology (5)

EUV plasma parameters measurement by "Thomson Scattering" is ongoing in Kyushu University

A Collective Laser Thomson Scattering System for Diagnostics of Laser-Produced Plasmas for Extreme Ultraviolet Light Sources

Kentaro Tomita1, Kazuki Nakayama[1], Kazuya Inoue1, Atsushi Sunahara[2], and Kiichiro Uchino[1]

[1]*Interdisciplinary Graduate School of Engineering and Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*
[2]*Institute for Laser Technology, Suita, Osaka 565-0871, Japan*
To develop a diagnostic system for laser-produced plasmas for extreme ultraviolet (EUV) light sources, collective laser Thomson scattering (LTS) was applied to laser-produced carbon plasmas to measure plasma parameters such as electron density (ne) and electron temperature (Te).
Plasmas having parameters necessary for an EUV light source (ne = 10^{24}-10^{25} m^{-3}, Te = 30-50 eV) were achieved, and these parameters were successfully evaluated by a pilot diagnostic system with errors below 10%. From these results, an LTS system for diagnostics of tin plasmas for real EUV light sources was designed.

Appl. Phys. Express 6 (2013) 076101 K. Tomita et al.

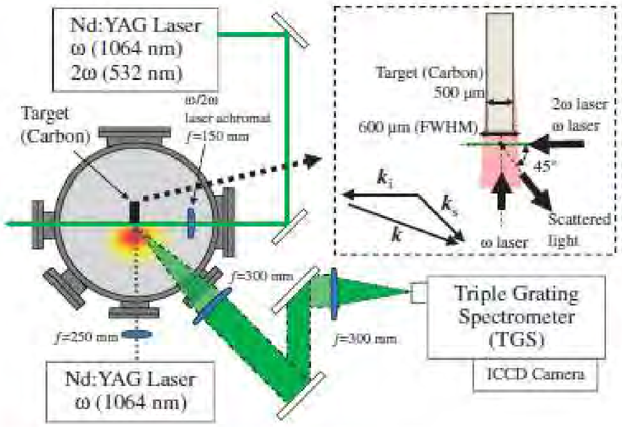


Fig. 1. Schematic diagram of the collective Thomson scattering system for laser-produced plasmas. The inset shows a detailed version of the schematic around the target. k_s and k_i are the wavevectors of the scattered light and the incident probing laser, respectively. k is the difference between these wavevectors.

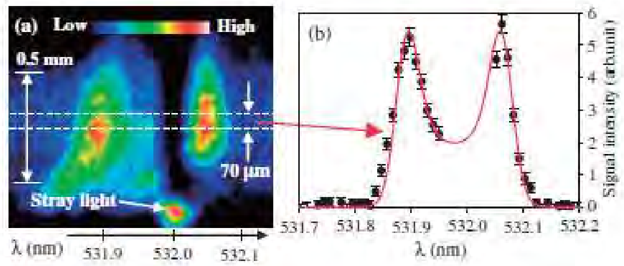


Fig. 2. (a) Two-dimensional Thomson scattering image. (b) LTS spectrum extracted from the center part of (a) and the curve fit based on the theoretical model.

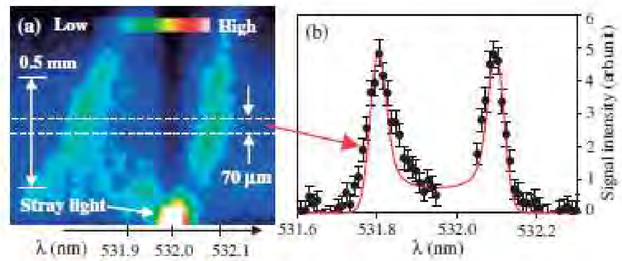


Fig. 3. (a) Two-dimensional Thomson scattering image when the additional laser was injected. (b) LTS spectrum extracted from the center part of (a) and the curve fit based on the theoretical model.

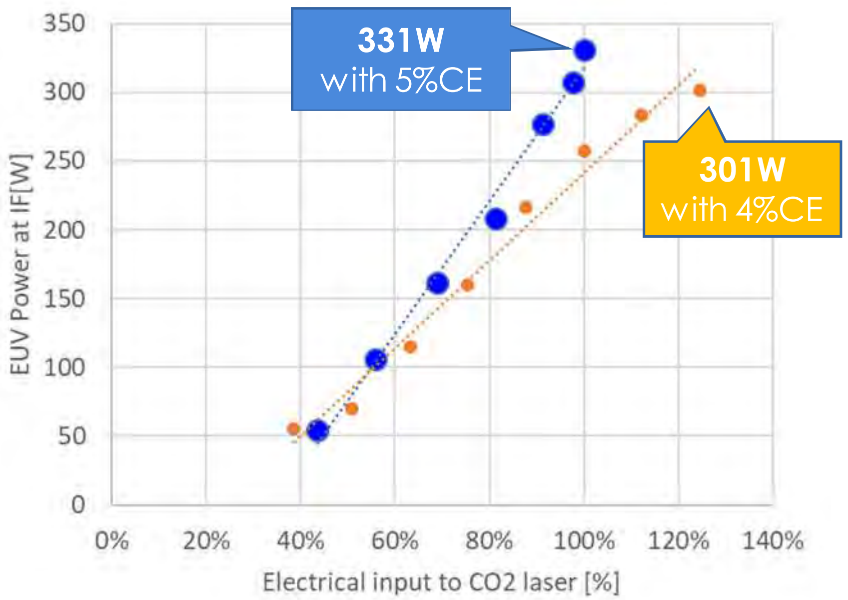
LATEST SYSTEM OPERATION DATA OF PILOT#1

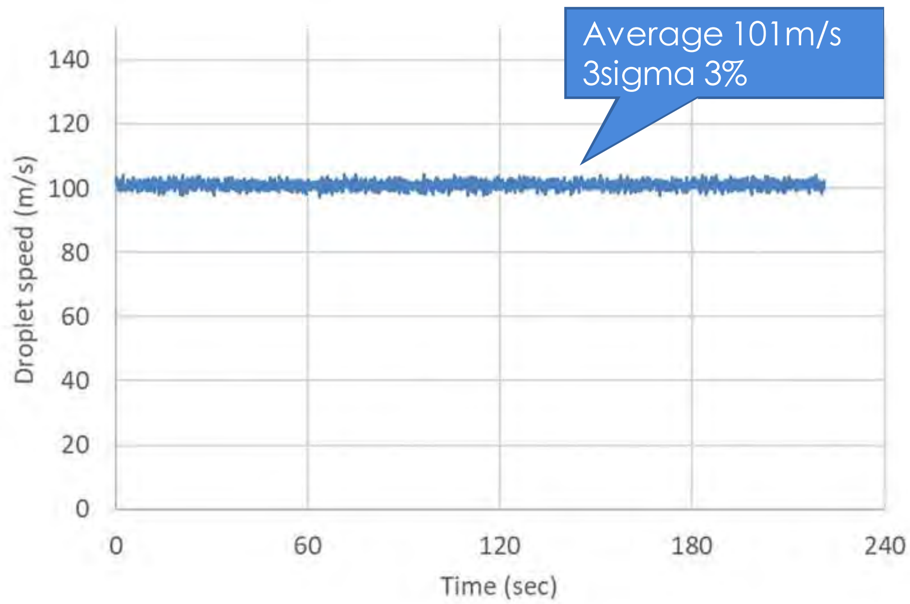
Preliminary data (1/2):

>330W Power Challenge with Upgraded Hardware

>330W with 5% CE at 100kHz operation is demonstrated at Pilot#1 (short term)

Higher Droplet speed(>100m/s) realize 1mm spacing and demonstrate stable EUV generation

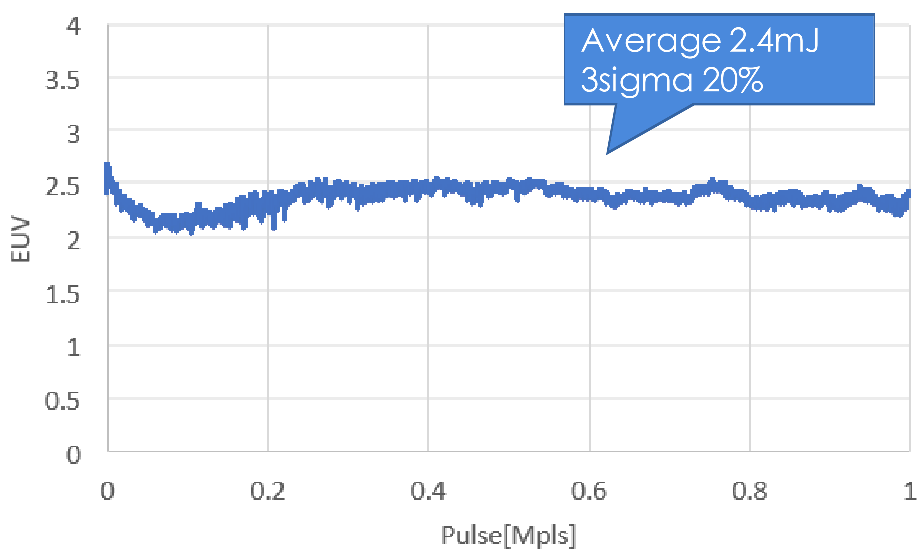




Preliminary data (2/2):

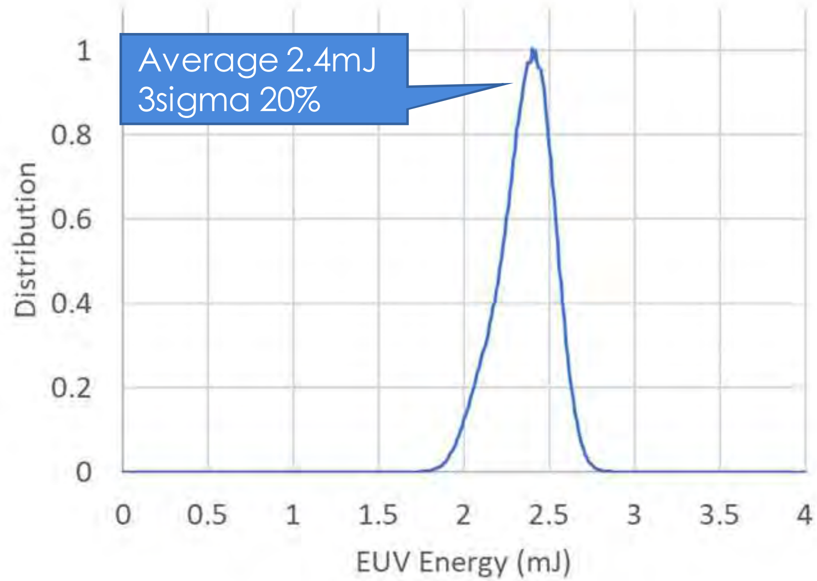
>330W Power Challenge with Upgraded Hardware

Open loop EUV energy (moving ave.)
100kHz 100% duty cycle



(240W at 330W config.)

Open loop EUV energy distribution
100kHz 100% duty cycle



(240W at 330W config.)

Agenda

- **Introduction**
  - Gigaphoton Business update
- **EUV Research & Development History**
- **Experiment A: >330W Power Challenge of EUV Source**
  - ① CO2 Laser Power Upgrade
  - ② Beam Uniformity Upgrade at Plasma Point
  - ③ Optimization of Plasma Parameters
- **Experiment B: Long-term Test and Challenge for Long-life Mirror and Availability**
  - ④ Lifetime Extension of Collector Mirror
- **Summary & Acknowledgement**

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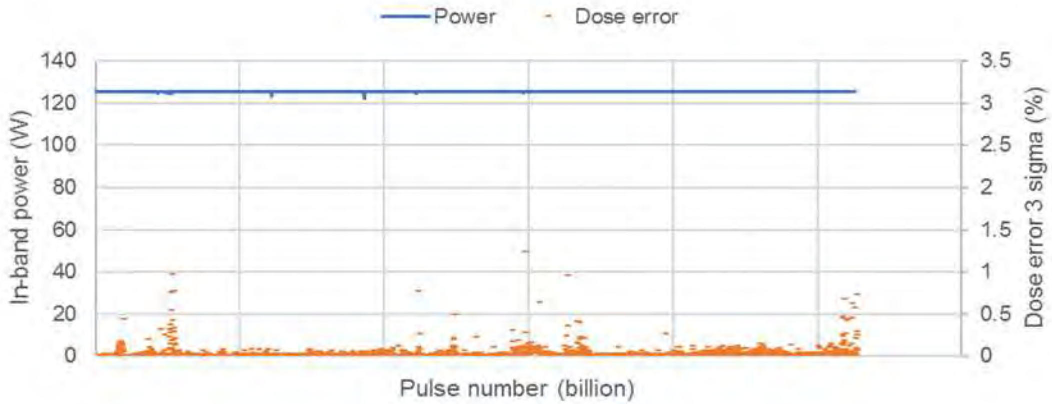
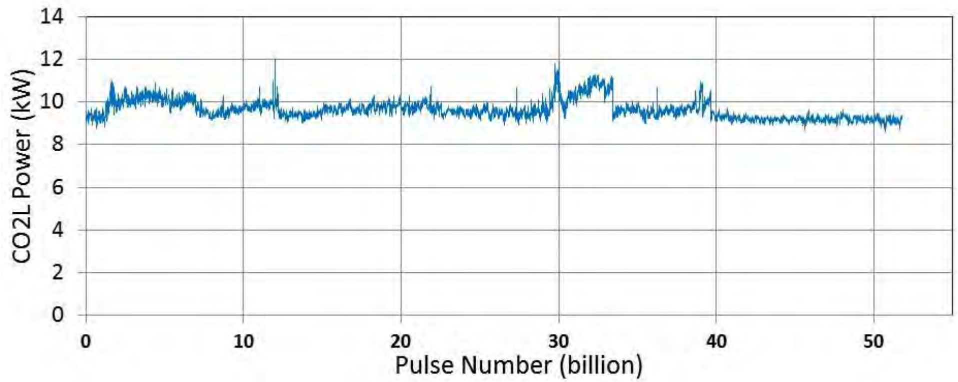
System Performance: 125W Operation Data (1/2)

- 125W had been achieved with only 10 kW of CO_2 power for 53Bpls operation.

	Performance
Average power at IF	125W
Dose error average (3 sigma)	0.04%
Die yield (<0.16%)	98.5%
Pulse Number	53Bpls
Duty cycle	100%
In-band power	125W
Dose margin	40%
Collector lifetime	0.9%/Bpls
Repetition rate	100kHz





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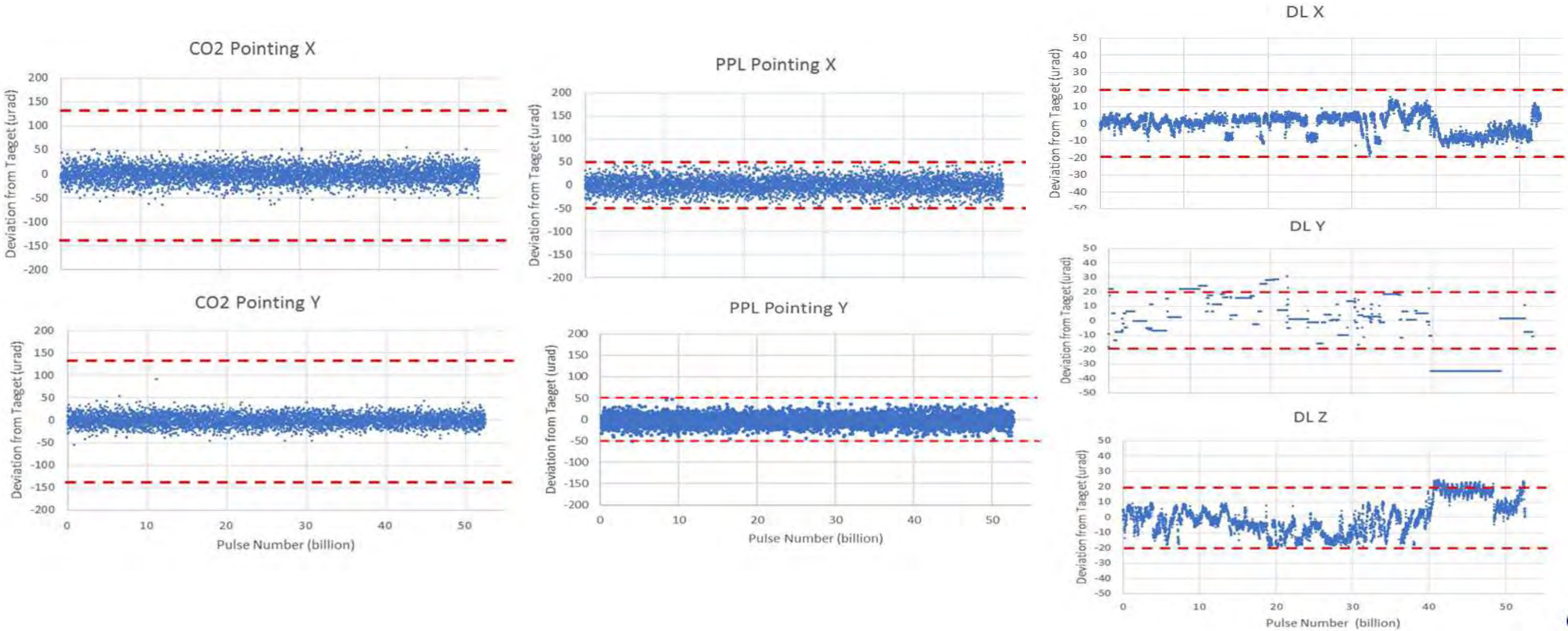
System Performance: 125W Operation Data (2/2)

CO2 Laser Pointing at Combiner

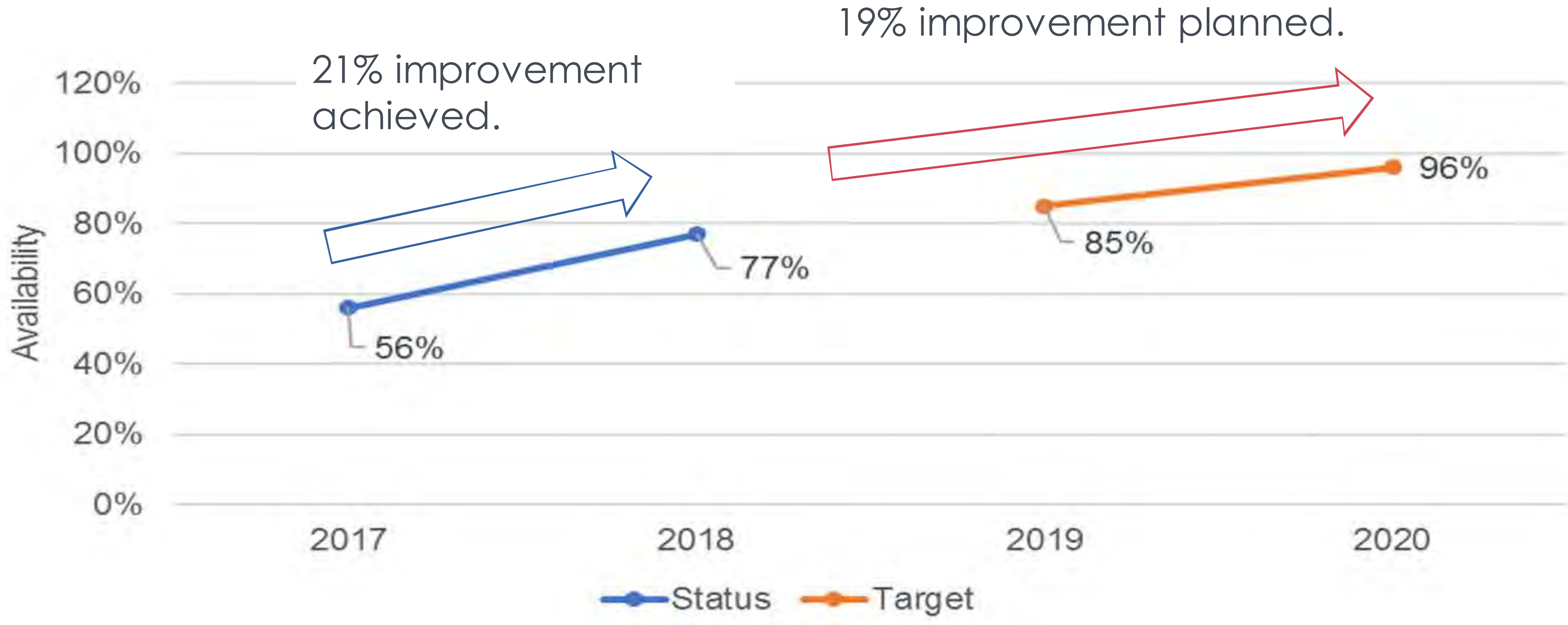
PPL Laser Pointing at Combiner

Droplet Position at Plasma



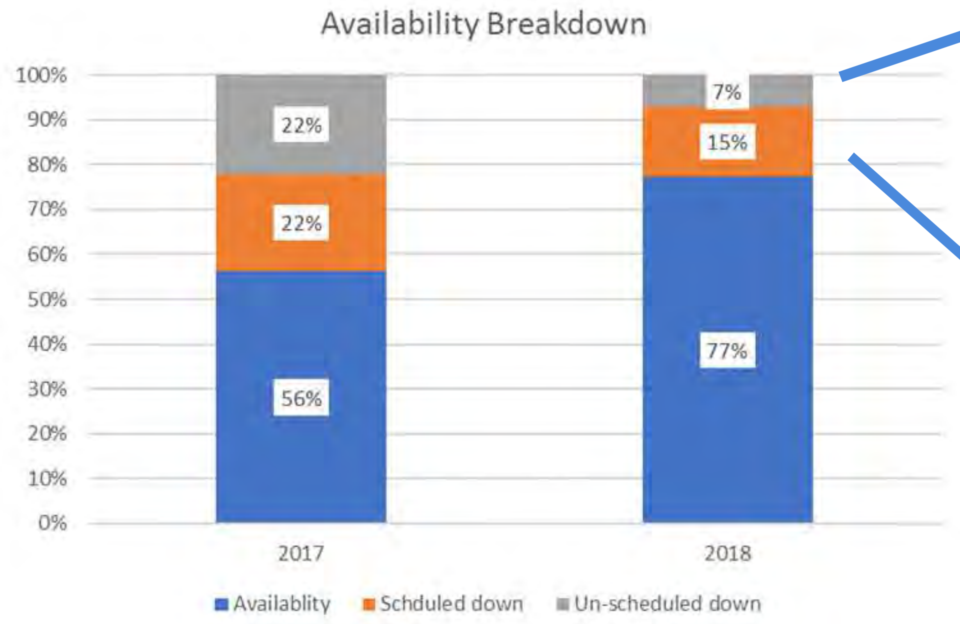
Availability: Status and Targets

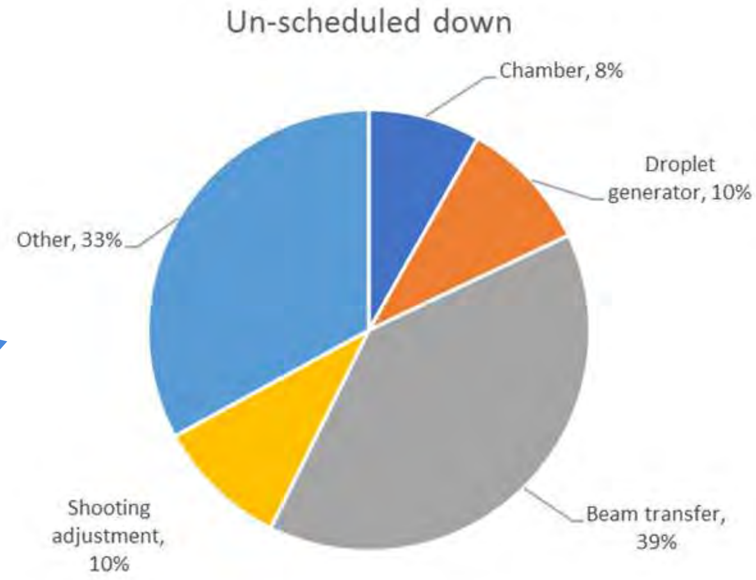
* Potential availability is calculated, based on module lifetime and maintenance time.

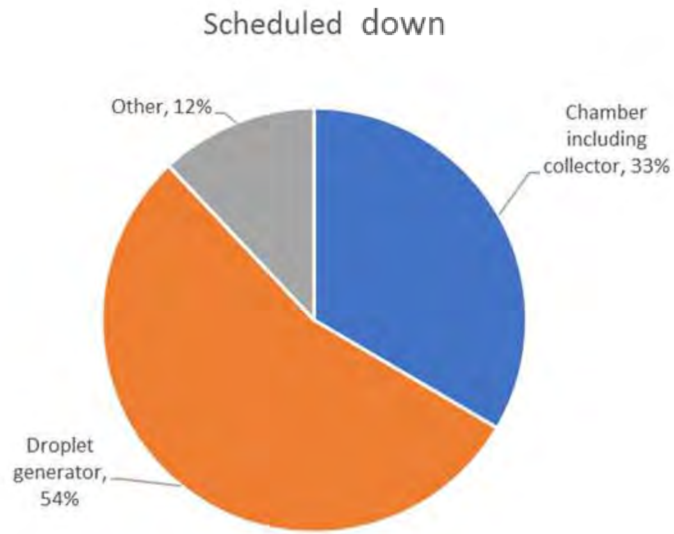


	2017	2018	2019	2020
DLG lifetime	15 days	15 days	15 days	60 days
DLG swap time	26 hrs	18 hrs	16 hrs	11 hrs
Collector lifetime	< 1 mo.	3 mo.	6 mo.	12 mo.
Chamber maintenance	58 hrs.	45 hrs.	38 hrs.	28 hrs.

Availability: Breakdown







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④ LIFETIME EXTENSION OF COLLECTOR MIRROR

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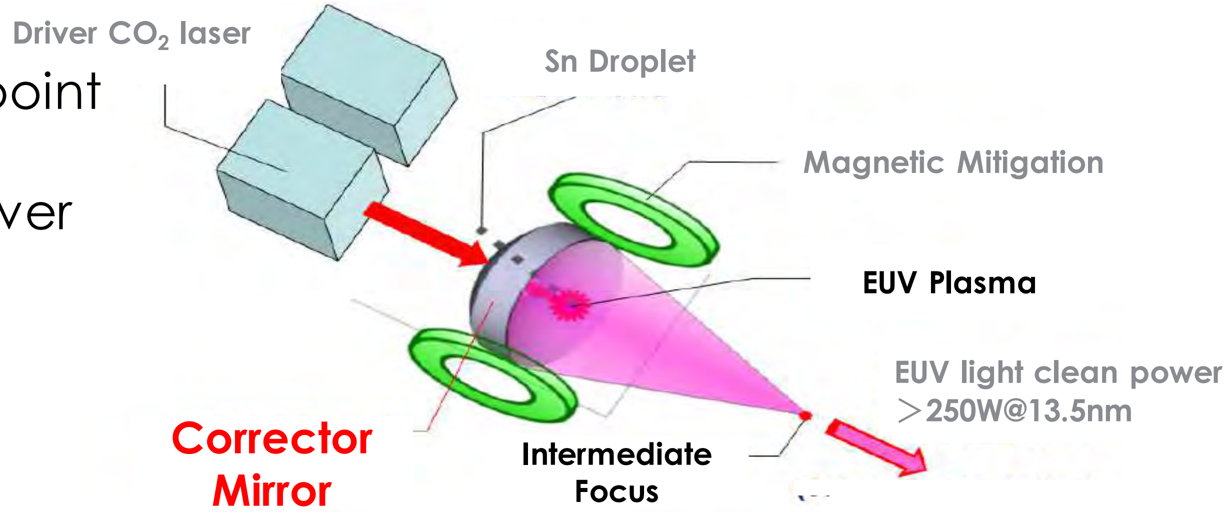
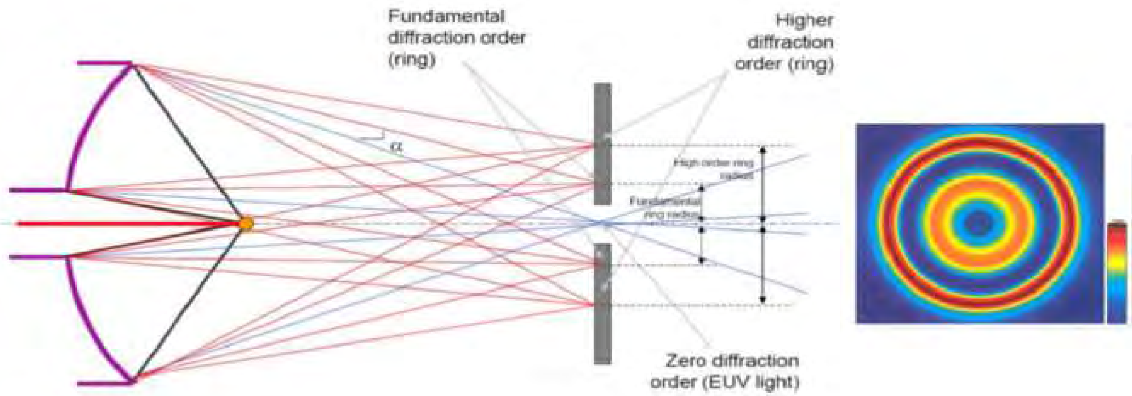
Corrector Mirror Technology (1)

Role of Corrector Mirror

- Transmit the EUV light from plasma point to intermediate focus
- Filtering the IR light originate from driver CO_2 laser (Patented)
- Periodical maintenance is required (Refurbishments)

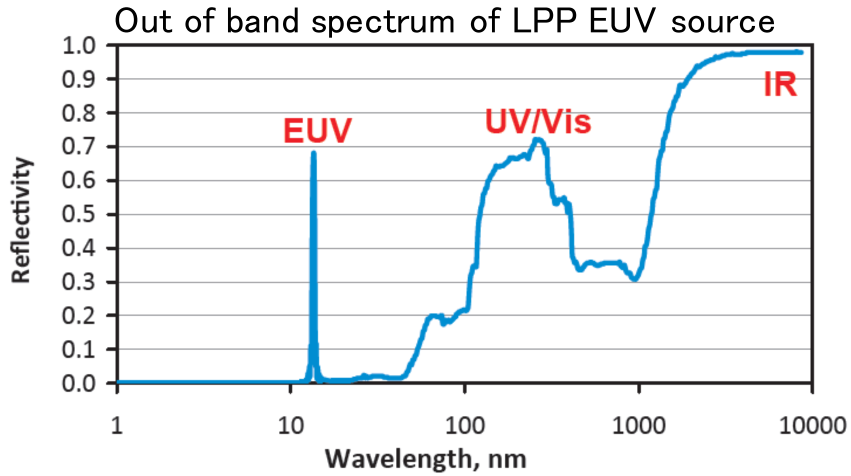




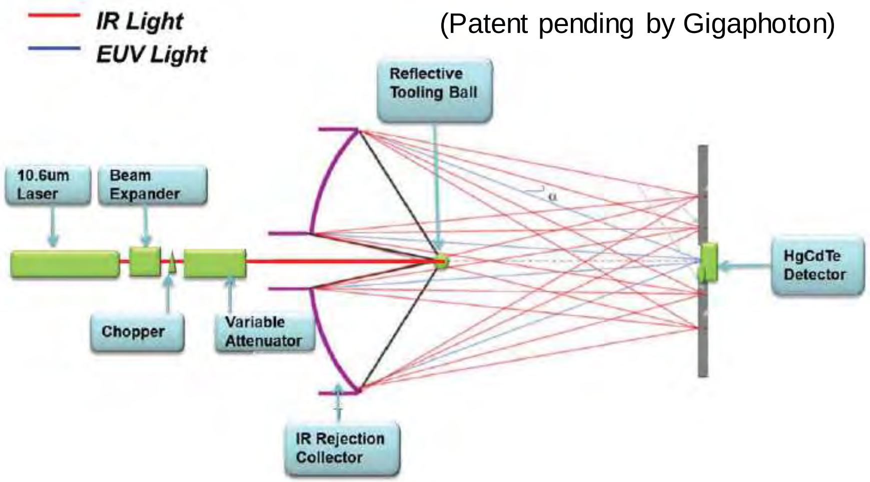
Collector Mirror and IR Reduction Technology

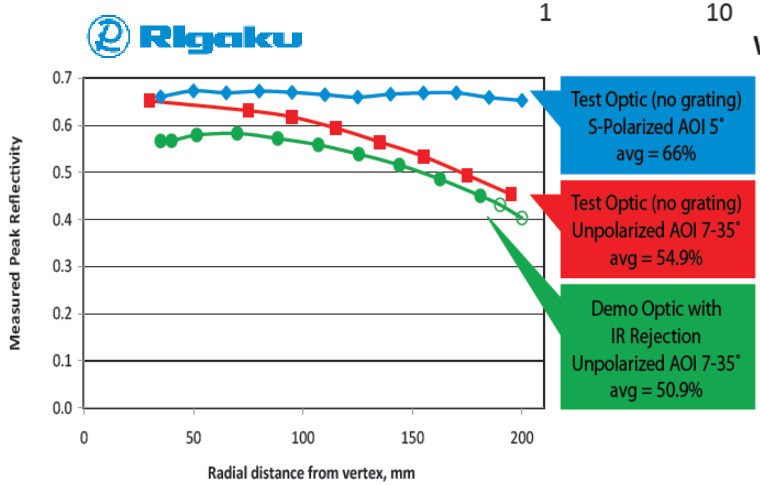
Cllrector Mirror Progress

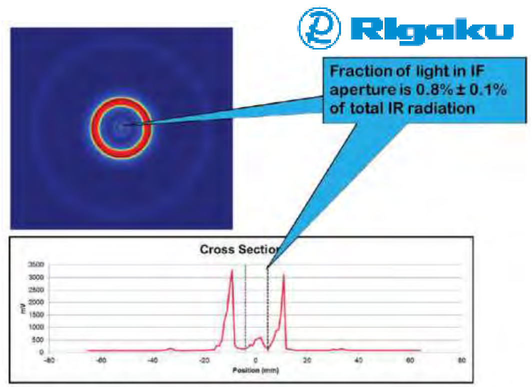
IR Reduction Technology is advancing:
– Gigaphoton is developing IR reduction mirror co-operate with multiple mirror suppliers.
– Rigaku demonstrated efficient and dramatic IR reduction by grating on the mirror surface– Prefabrication test is completed.
(Data is reported EUV symposium 2013 in Toyama)
– Next step is proto type fabrication and evaluation.



IR Reduction Technology

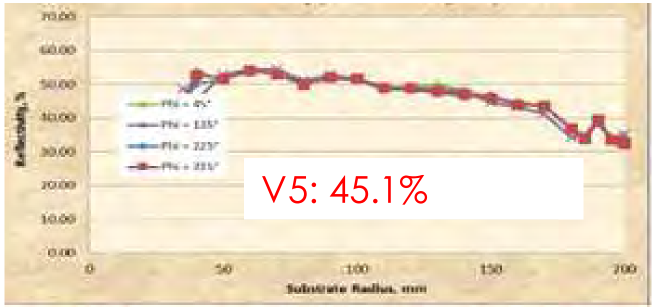


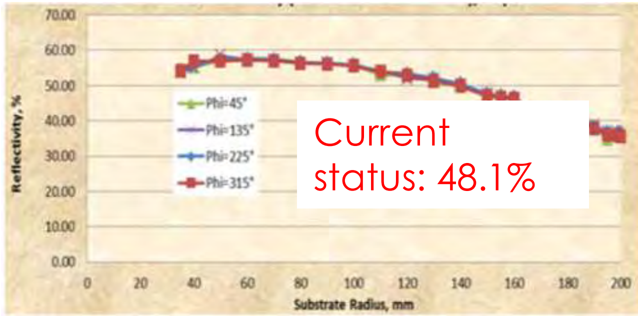




Corrector Mirror Technology (2)

– Collector reflectivity is one of the key item for power improvement



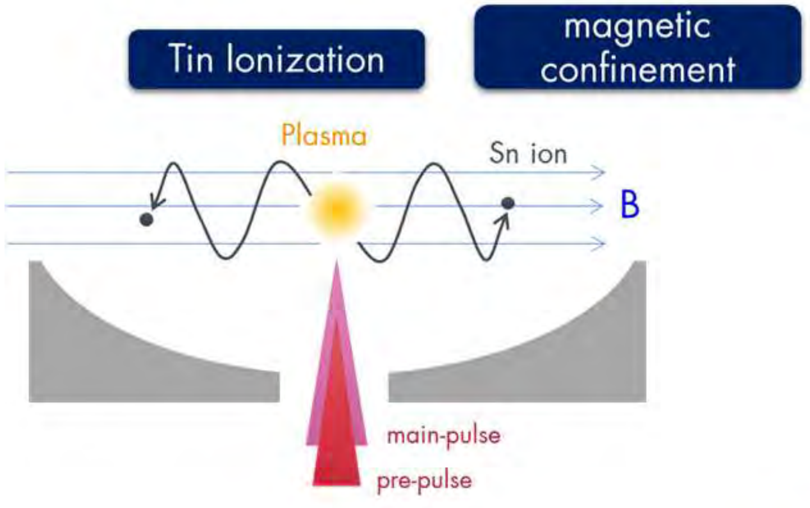


	Current	250W target
Collector type	V5	V5+
H2 Pressure	<20Pa	<20Pa
Collector Efficiency	>74%	>74%
Collector Reflectivity	>45%	>50%
Gas Transmittance	>95%	>95%
Plasma to clean	31.6%	35.1%

Fraunhofer IOF optiX fab.

Etching and Dissociation Sn balance on the Mirror Surface

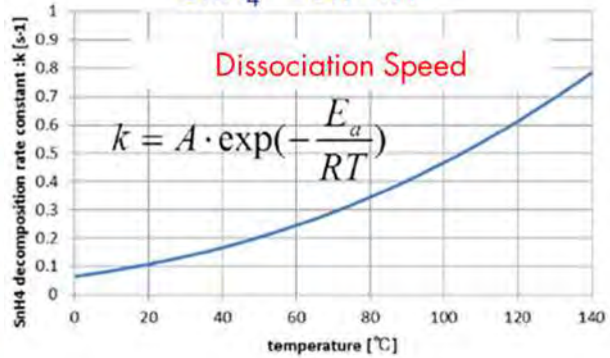
■ Chemical Aquarium on the Mirror Surface

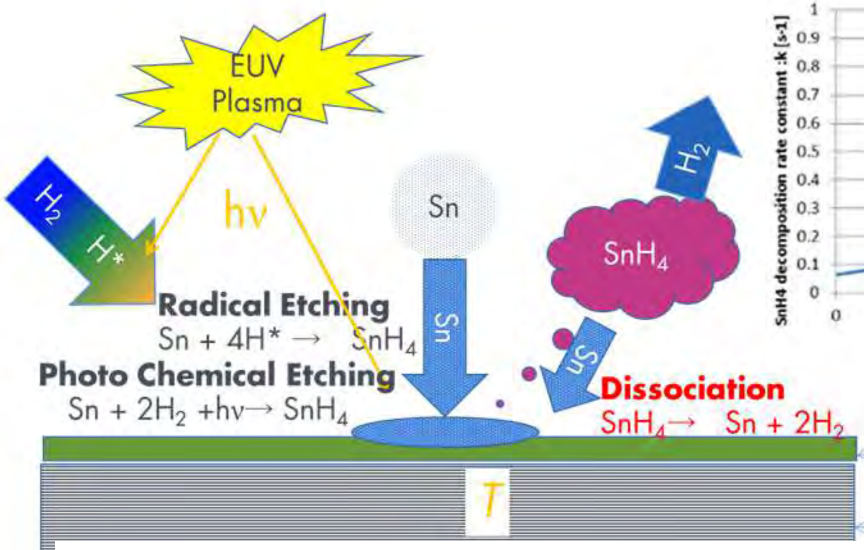


- Tin ionization & magnetic guiding
  - Tin is ionized effectively by double pulse irradiation
  - Tin ions are confined with magnetic field
  - Confined tin ions are guided and discharged from exhaust ports

- 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)

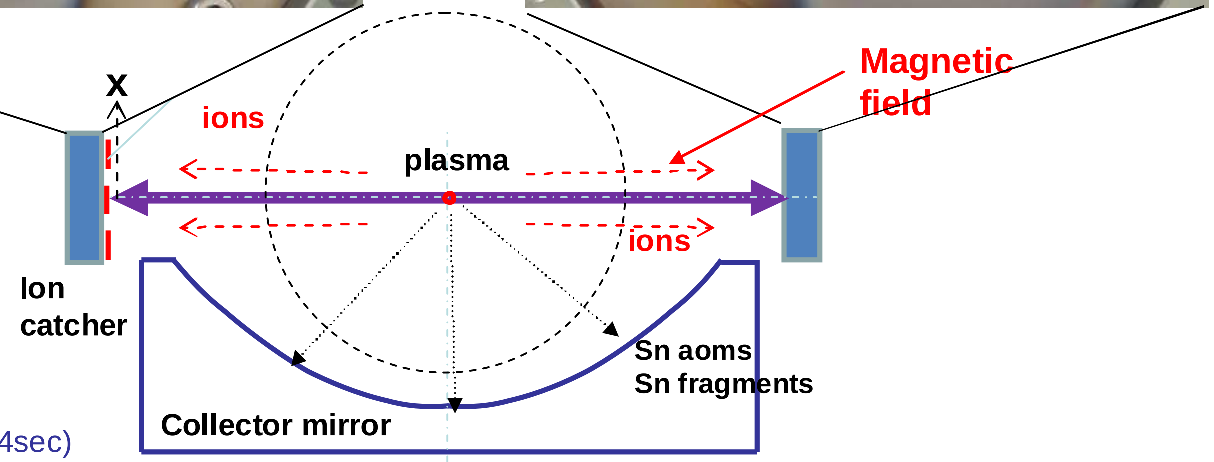
*H_2 molecules are dissociated to H radical by EUV-UV radiation from plasma.





Magnetic Mitigation Technology

Generated ion is corrected at Ion catcher



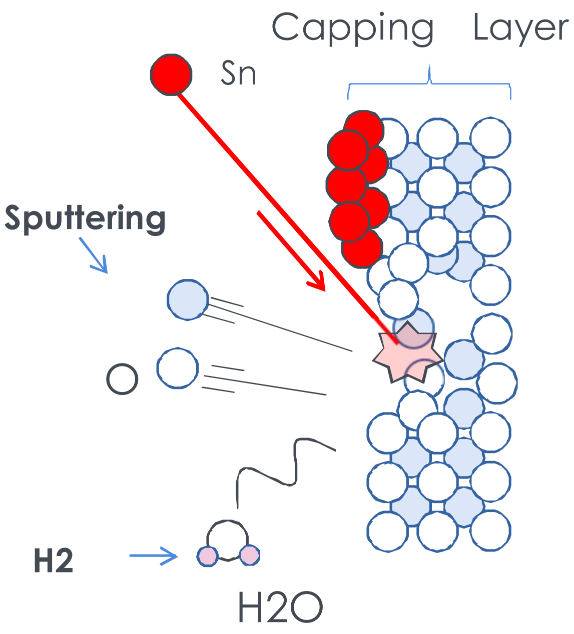
Magnetically guided ion are clearly corrected by ion catcher at both end of magnetic pole.

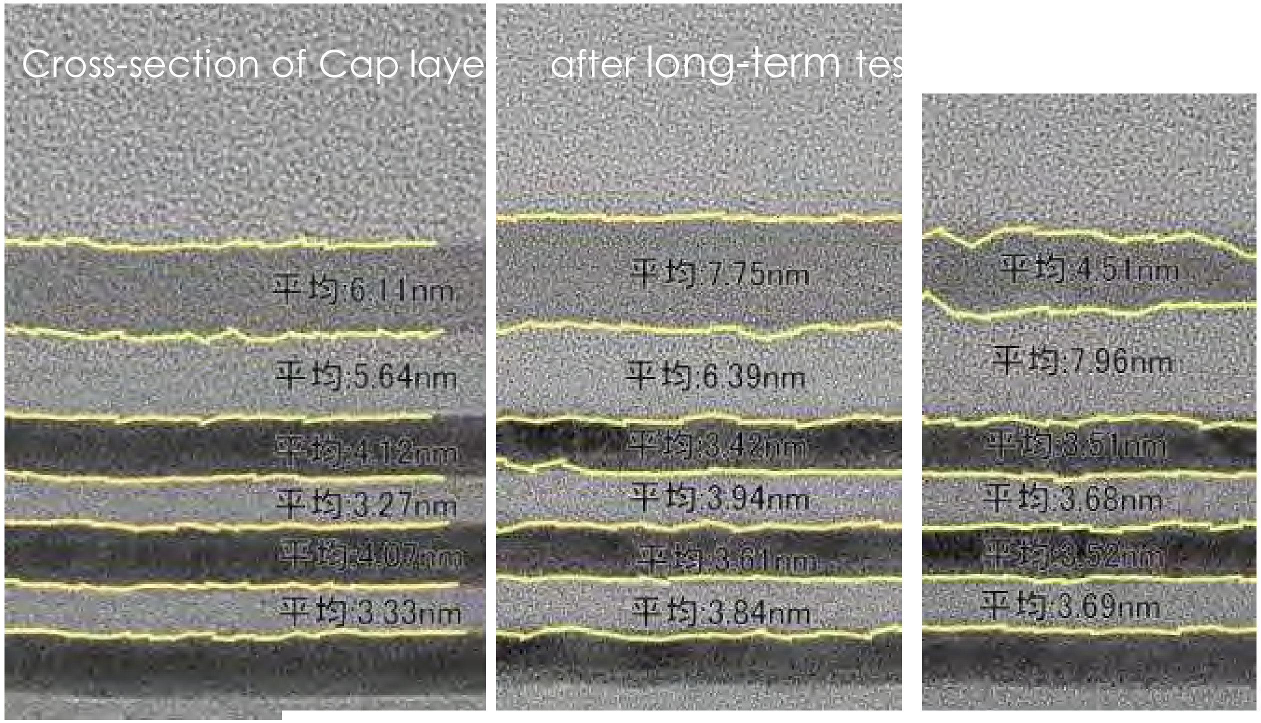
✓4.86Mpls (50kHz, 30% duty, 324sec)

✓Pre-pulse 3.1mJ, CO2 laser 54mJ, DL=ϕ30um,

Change of Capping Layer and Multi-Layer under Tin Plasma Sputtering

- Thickness changes at capping layer due to sputtering.
- First Si layer become thicker and reflectance down around 30% due to oxidization.





Capping Layer

1^{st} Si Layer

2nd Mo Layer

3rd Si Layer

⋮

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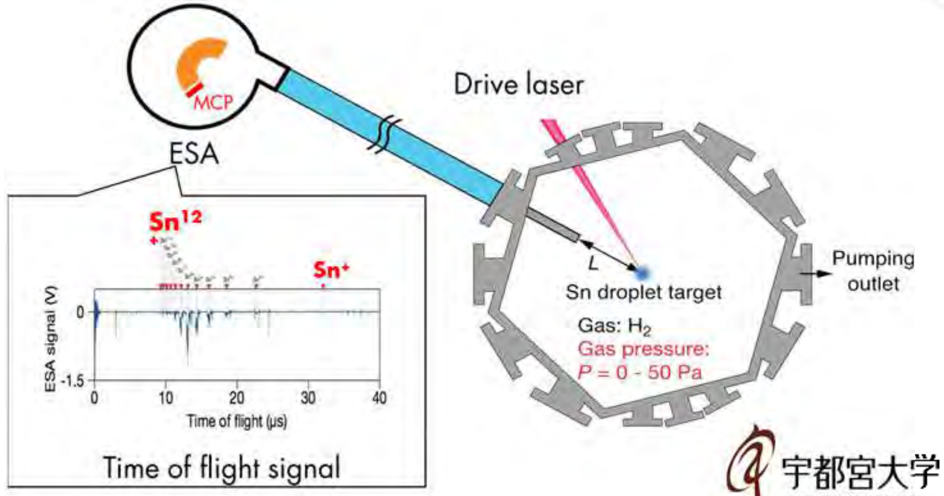
Suppression of Fast Tin Ion

- Ion energy and charge-state measurement with electro-static analyzer(ESA)
- Improvement of Ion energy distribution is essentially effective.



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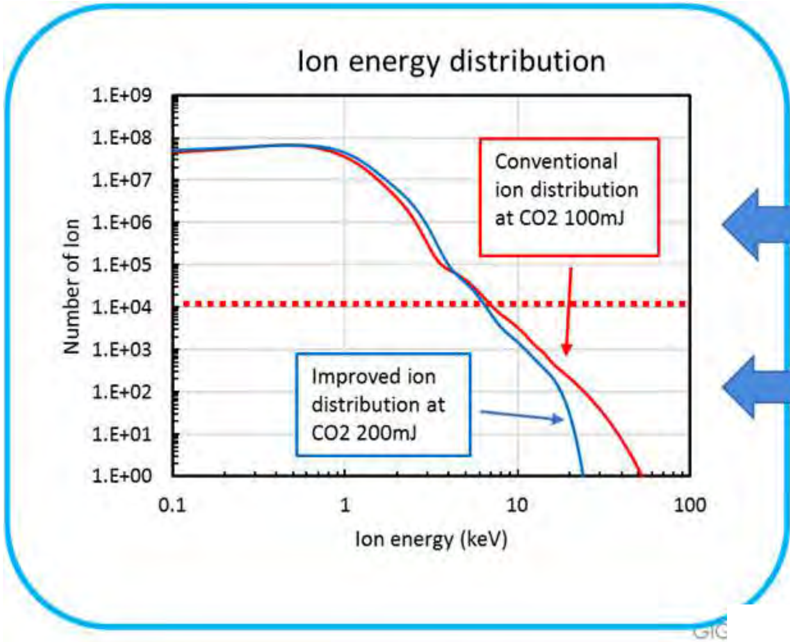

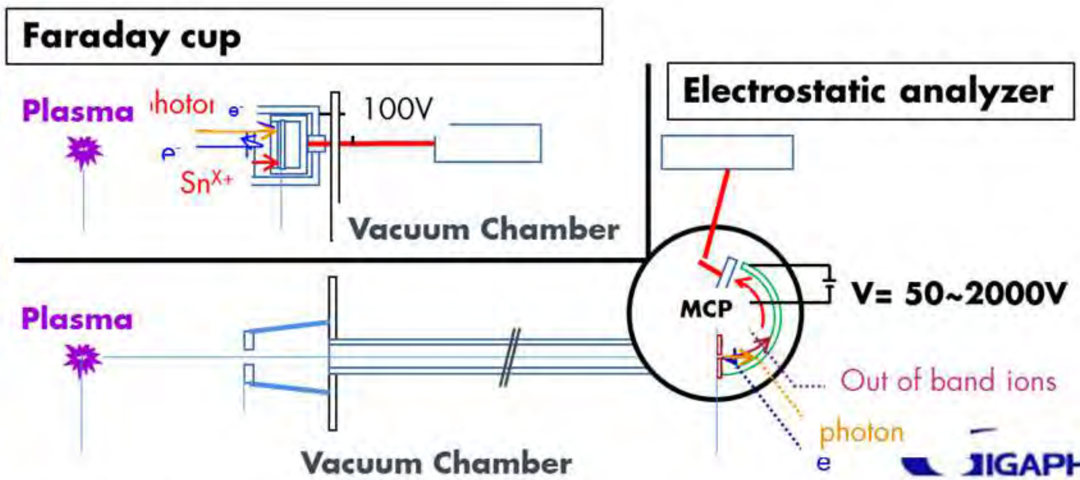

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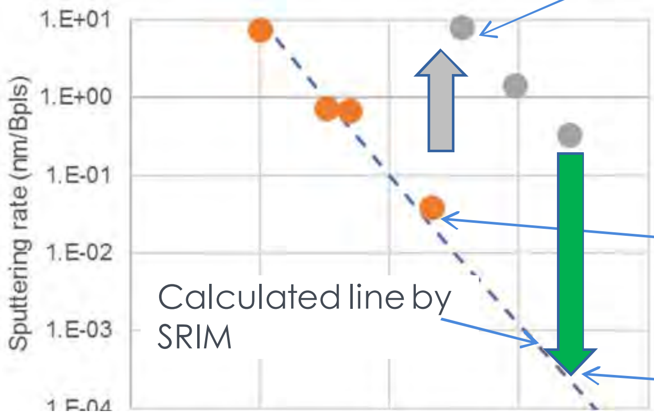
EUV Plasma Cooling

- Sputtering rate enhancement occurred by gas heating at higher output power.
- **EUV plasma cooling** is key of mirror lifetime extension at higher power operation.

<Mechanism>

Higher power → Gas heating → Gas density decrease → Gas stopping decrease

Sputtering rate in current set-up

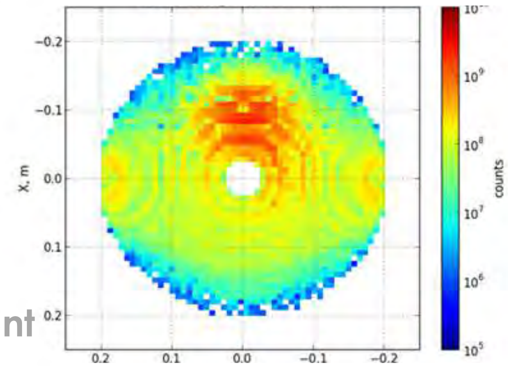


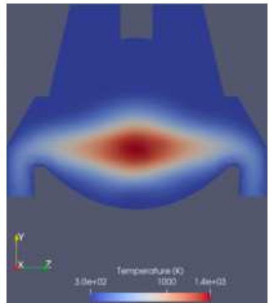
Higher plasma Temp.
at Old 125W experiment

38W

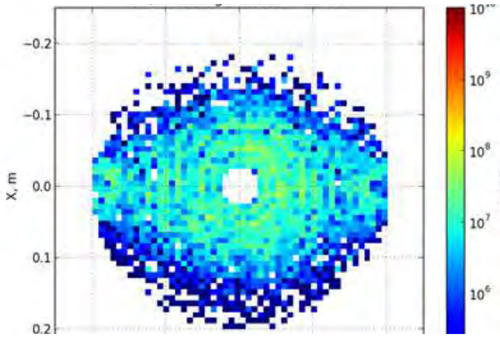
Cooled plasma temp.
New125W experiment

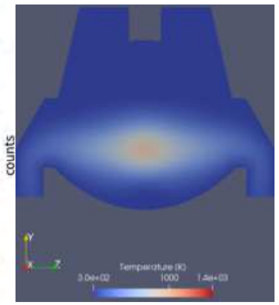
Higher plasma Temp.





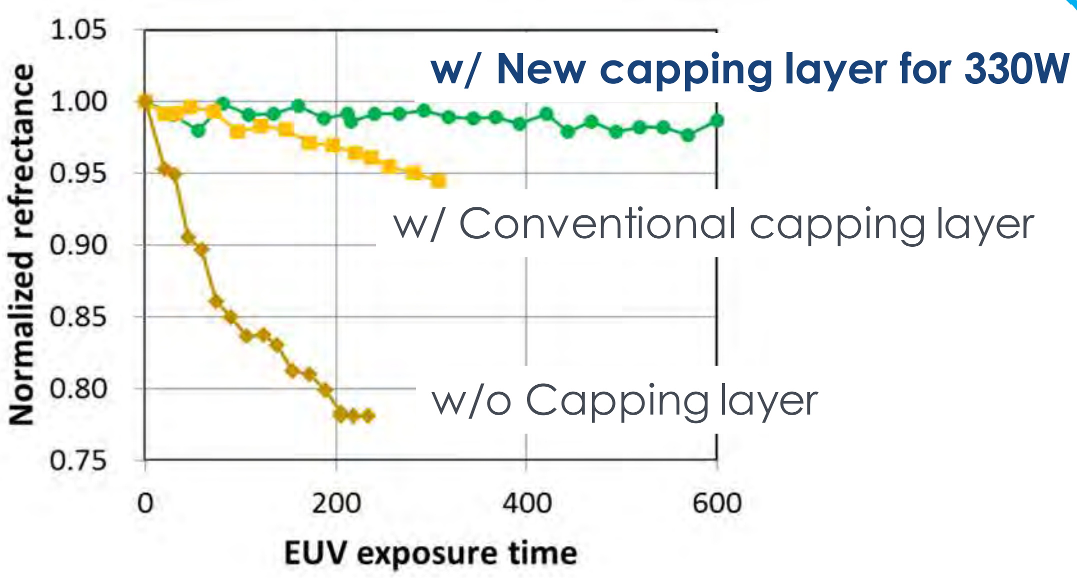
Cooled plasma temp.





New Capping Layer Search at New SUBARU Japan

- Screening of oxidation of reflection layer with synchrotron radiation (λ=13.5nm) source (Name of SOR in Hyogo Univ.= "New SUBARU")
- Improvement of collector lifetime is on going



Capping layer evaluation results by New SUBARU

Two beam lines for EUV test in "New SUBARU"

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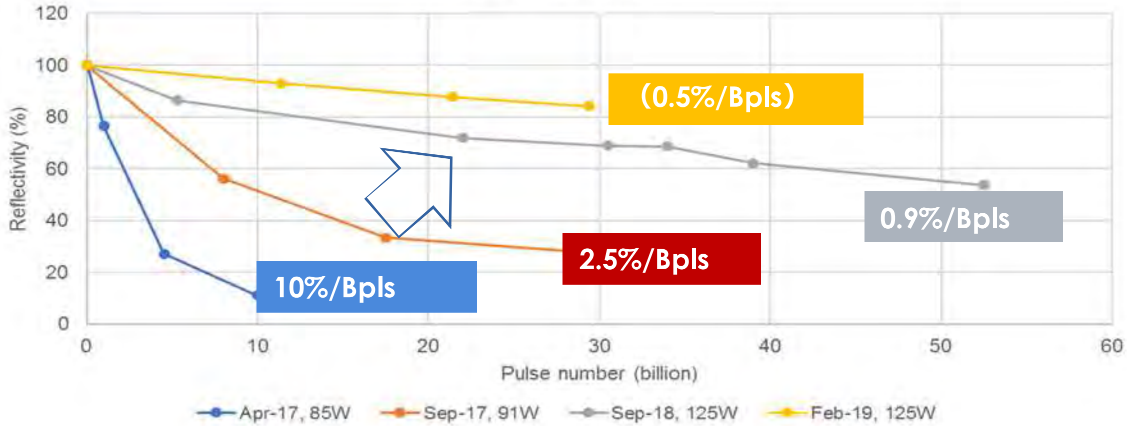
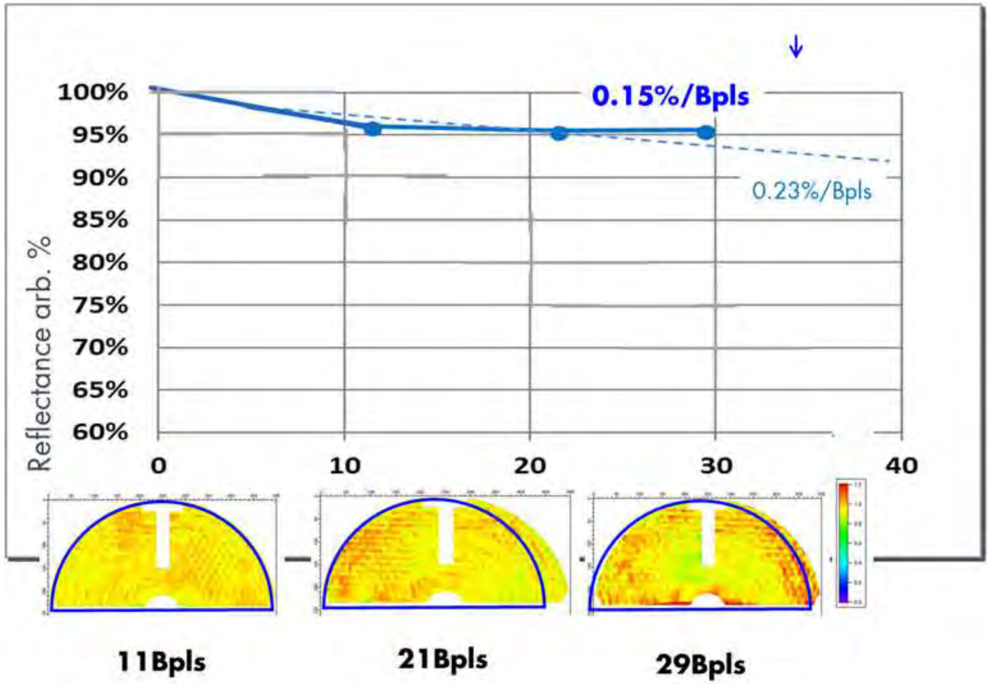
Collector Mirror: Lifetime Status

- Capping layer and Tin contained Gas flow Improvement are effective.
- Collector reflectivity degradation is certainly improving.

Data at SPIE AL-2019 (Feb.2019)



Latest Data (June 2019)



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- **Introduction**
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  - ③ Optimization of Plasma Parameters
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  - ④ Lifetime Extension of Collector Mirror
- **Summary & Acknowledgement**

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Summary

- ***EXPERIMENT-A: >330W Power Challenge of EUV Source***
  - *Gigaphoton redefined power target to ≧330W ave. with -0.05%/Gpls, >90% availability*
  - *High conversion efficiency 5.0% is realized with improved driver laser technology.*
  - *High speed (>100m/s) & small (20micron) droplet successfully stabilize EUV emission..*
  - ***CE enhancement >6% by plasma parameter optimization** is clarified through small experimental device by Tomson scattering measurement.*
  - ***CO2 laser power upgrade >27kW and Beam uniformity upgrade** is successfully done.*
  - *>**330W operation is successfully demonstrated at Pilot#1 system (short term) .***

- ***EXPERIMENT-B: Long-term Test and Challenge for Long-life Mirror and Availability***
  - *125W had been achieved with only 10 kW of CO2 power for around 50Bpls operation.*
  - *Pilot#1 system achieved potential of >85% Availability (2weeks average).*
  - ***-0.15%/Gpls with 125W ave.** was demonstrated during 30Mpls with mirror test.*

- ***Demonstration of Full Spec. >330W operation will be by Q4 2019***

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Acknowledgements

Thank you for co-operation:

- **Trumpf, Edgewave, OptiX fab., Rofin Laser, Franhofer IOF in Germany for excellent commercially available laser and optics technology.**
- Mitsubishi electric CO_2 laser amp. develop. team: *Dr. Junichi Nishimae, Dr. Shuichi Fujikawa, Dr. Yoichi Tanino* and others*
- *Dr. Kentaro Tomita, Prof. Kiichiro Uchino and others in Kyushu University*
- *Dr. Akira Endo :HiLase Project (Prague) and Prof. Masakazu Washio and others in Waseda University*
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Thank you for funding:

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Thank you to my colleagues:

EUV development team of Gigaphoton: *Hiroaki Nakarai, Tamotsu Abe, Takeshi Ohta, Krzysztof M Nowak, Yasufumi Kawasuji, Hiroshi Tanaka, Yukio Watanabe, Tsukasa Hori, Takeshi Kodama, Yutaka Shiraishi, Tatsuya Yanagida, Tsuyoshi Yamada, Taku Yamazaki, Takashi Saitou and other engineers*

THANK YOU

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The Future is Today