GIGAPHOTON

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

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

Hiroaki Nakarai, Tamotsu Abe, Hiroshi Tanaka, Yukio Watanabe, Tsukasa Hori, Takeshi Kodama, Yutaka Shiraishi, Tatsuya Yanagida, Georg Soumagne, Tsuyoshi Yamada, Takashi Saitou

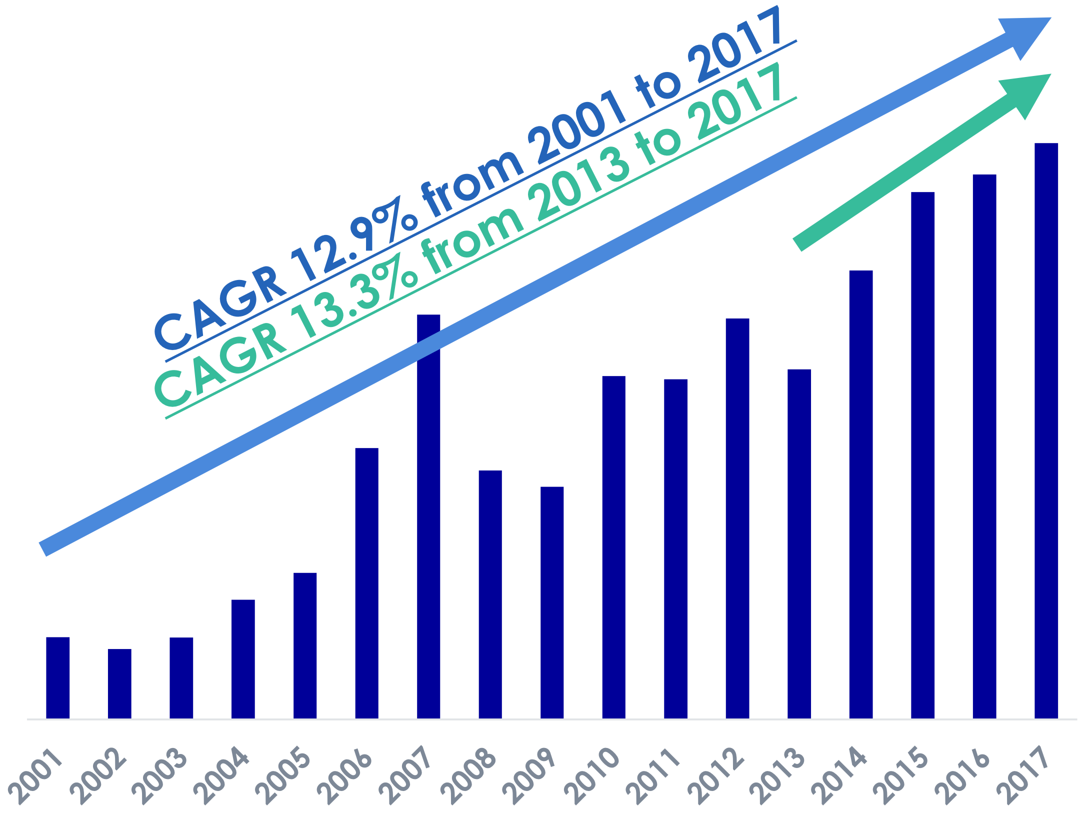
Gigaphoton Inc. Hiratsuka facility: 3-25-1 Shinomiya Hiratsuka Kanagawa 254-8567

Agenda

- Introduction
  - Gigaphoton Business update
  - EUV Research & Development History
- Current status update
- Gigaphoton's New Target ≧330W EUV Source
  - ① Beam uniformity at plasma
  - ② Optimization of plasma parameters
  - ③ Upgrade of CO2 Laser Power
  - ④ Lifetime Extension of Collector Mirror
- Summary
- Acknowledgement

INTRODUCTION

GIGAPHOTON Business update



Revenue Trends ($)

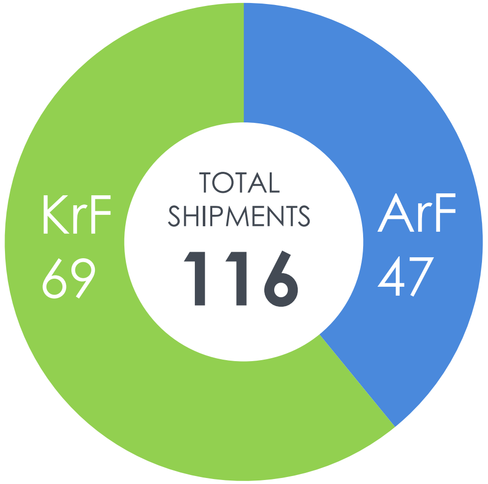
COMPANY NAME	Gigaphoton Inc.
BUSINESS	Development, manufacturing, and sales of core competencies in Advanced-Excimer-Laser Light Source applications
ESTABLISHMENT	August 1, 2000
CAPITAL	5 billion yen
SHAREHOULDERS	Wholly owned subsidiary of Komatsu Ltd.
HEADQUATERS	Oyama City in Tochigi Prefecture
PRESIDENT&CEO	Katsumi Uranaka, appointed on Aril 1, 2017
EMPLOYEES	912 (as of April 1, 2018) Consolidated, Gigaphoton World Wide

GIGAPHOTON

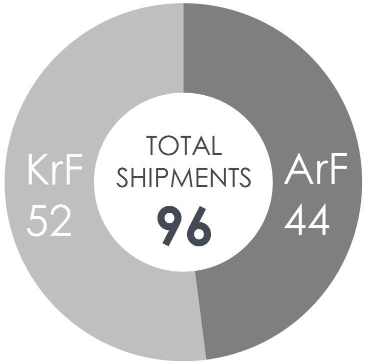
2Q2019 Business Highlights - DUV

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



FY2018

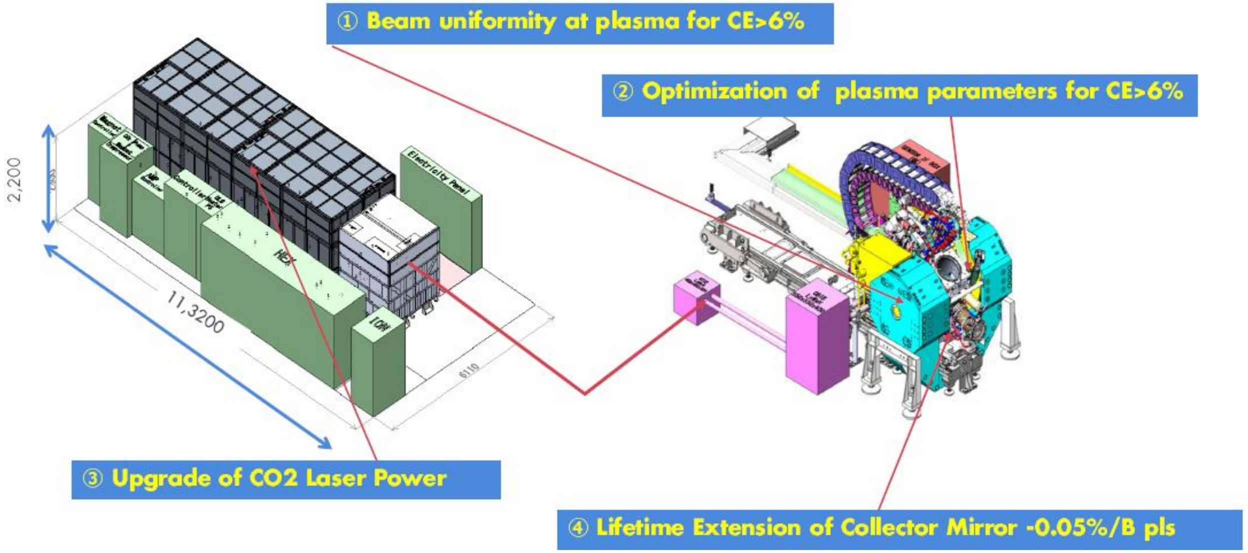


FY2017

2Q2019 Business Highlights - EUV

EUV Business

- Redefined target of reflectance degradation at collector mirror as ≥**330W** and **-0.05%** per Giga-pulse by the end of 2019
- Demonstrated on **125W** with 100% duty cycle operation



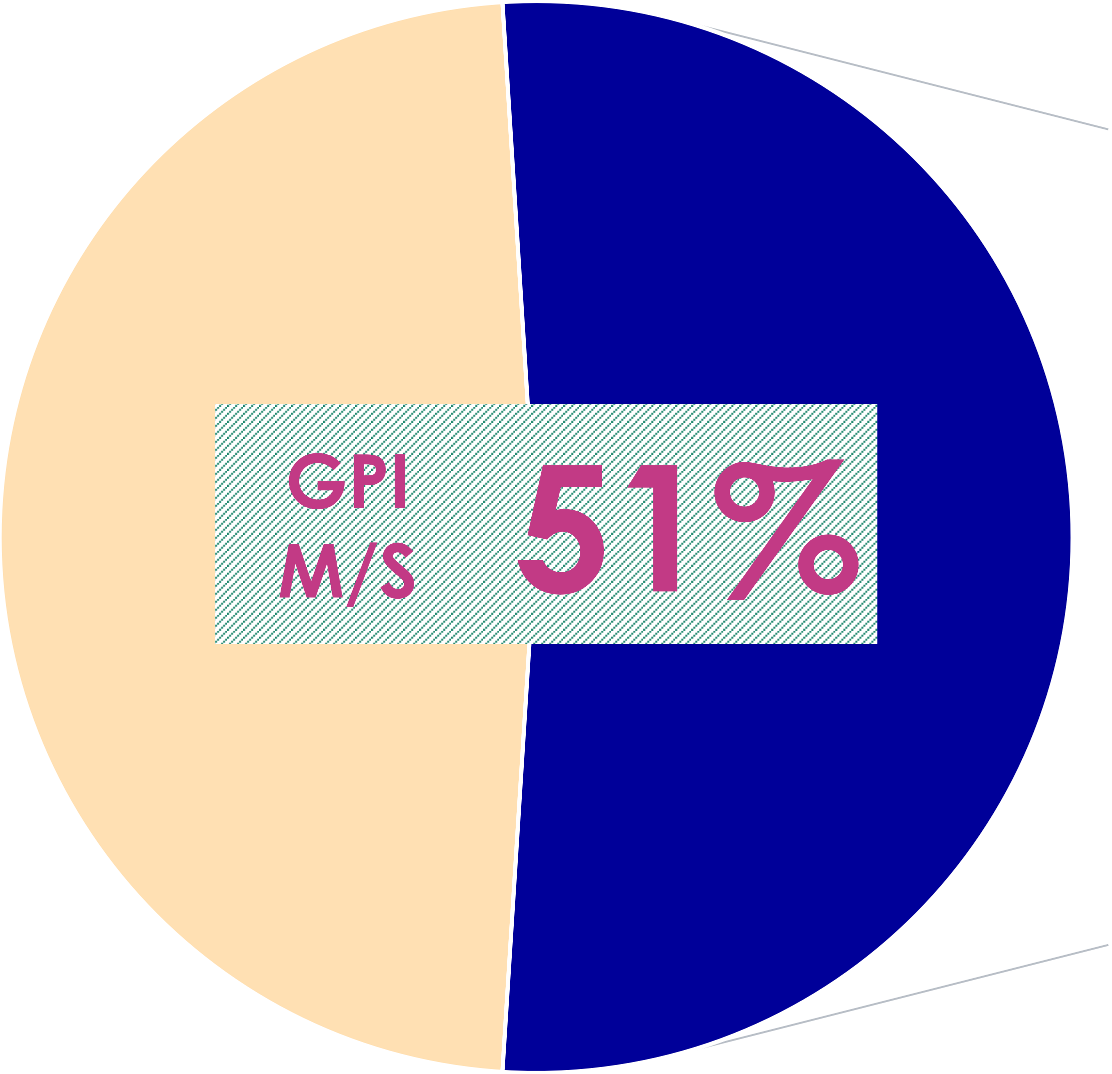
① Beam uniformity at plasma for CE>6%

② Optimization of plasma parameters for CE>6%

③ Upgrade of CO2 Laser Power

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

CY2018 Light Source Projected Install Share Analysis



TOTAL UNITS **209**

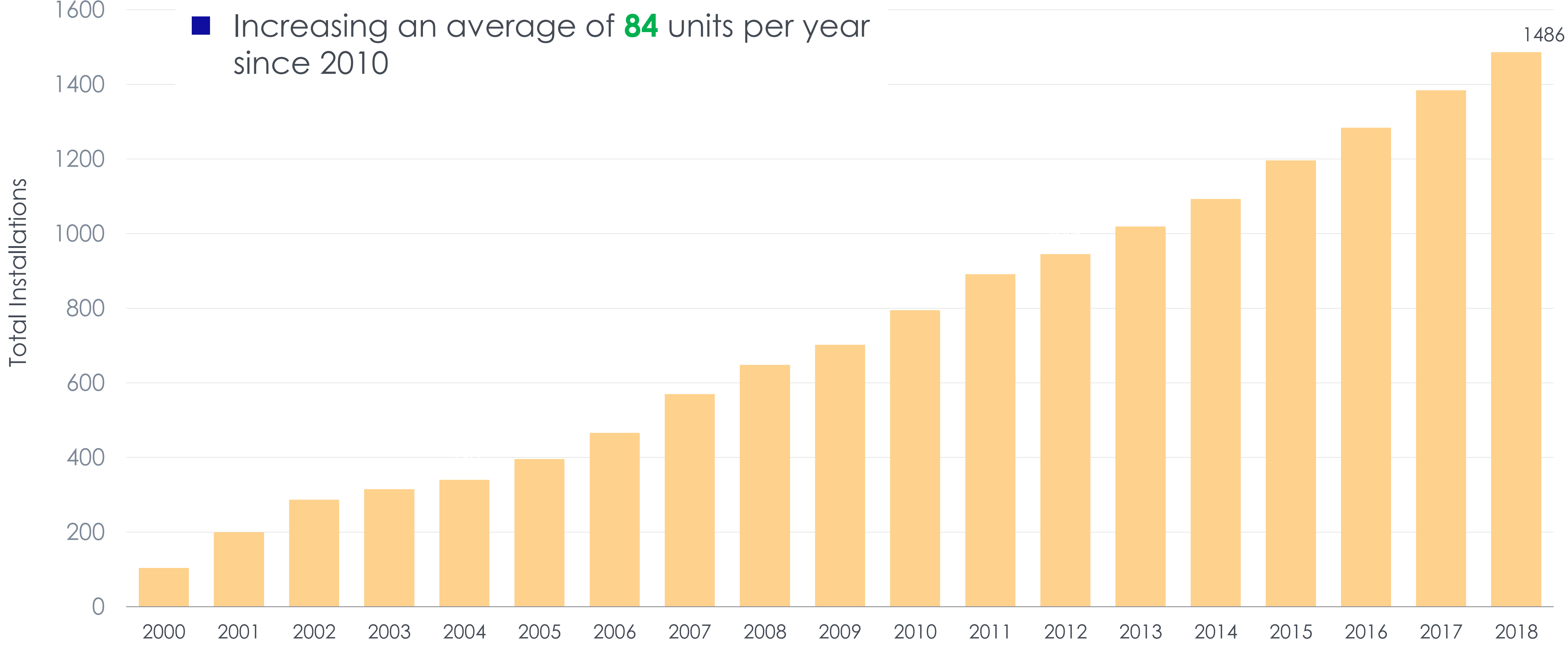
	GPI INSTALL UNITS	GPI INSTALL SHARE
Japan (21)	12	57%
Korea (85)	50	59%
Taiwan (17)	8	47%
Mainland China (47)	31	66%
US (18)	4	22%
S'pore+EU (21)	3	14%

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

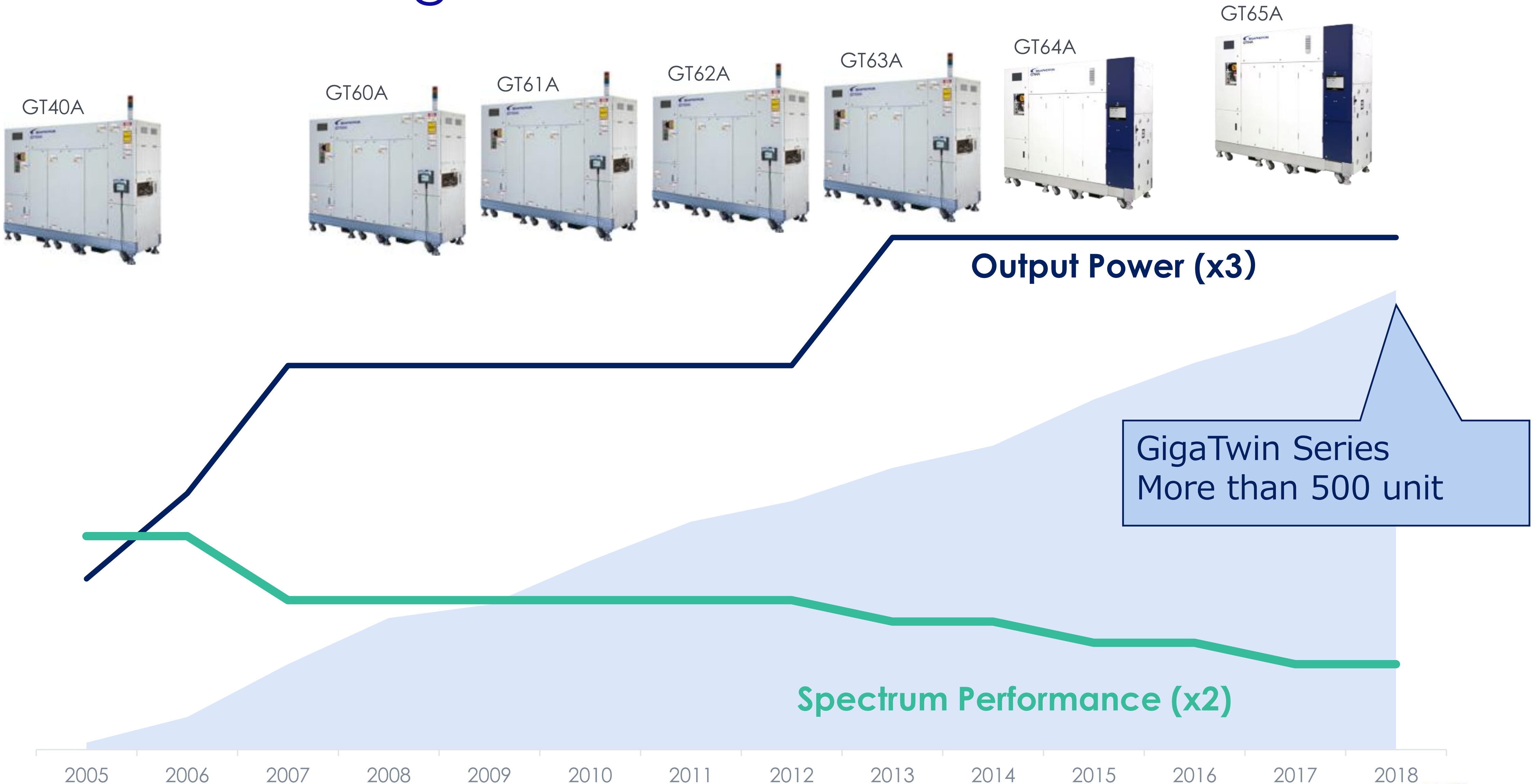
Continuous Installation Growth

Total light source installations

- More than **1400** light source is working
- Increasing an average of **84** units per year since 2010

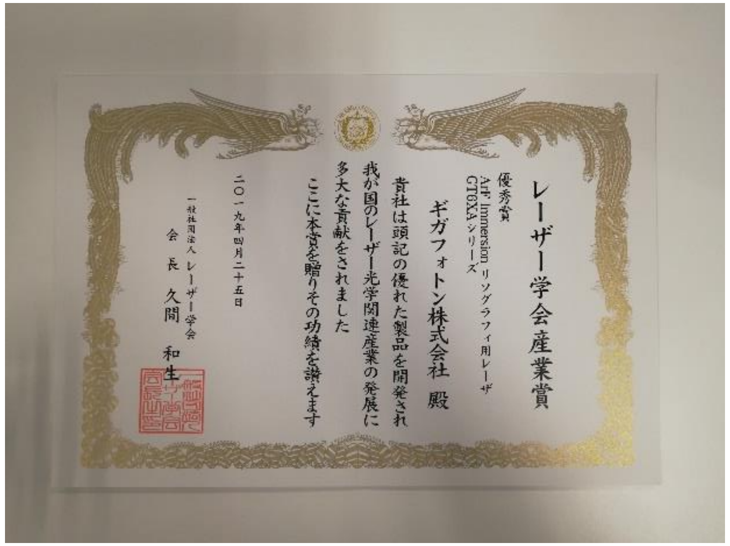


Evolution of GigaTwin Series



GigaTwin Series
More than 500 unit

GT-Series got Laser Industry Award from the Laser Society of Japan (2019.4.29)



レーザー学会産業賞

優秀賞
ArF Immersion リソグラフィ用レーザ
GT6XAシリーズ

ギガフォトン株式会社　殿

貴社は頭記の優れた製品を開発され
我が国のレーザー光学関連産業の発展に
多大な貢献をされました
ここに本賞を贈りその功績を讃えます

二〇一九年四月二十五日

一般社団法人　レーザー学会
会　長　久間　和生

EUV RESEARCH & DEVELOPMENT HISTORY

EUV Research & Development History

Study Apparatus EUV & Photo Material by EIDEC

year 2002-2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019

EUVA
Extreme Ultra-Violet Lithography System Development Association

NEDO (Matching Fund)
New Energy and Industrial Technology Development Organization

KOMATSU (LPP)

GIGAPHOTON (LPP)

USHIO (DPP)

~~Join Venture Finished~~

KOMATSU (TIC, MTC)

ETS-1

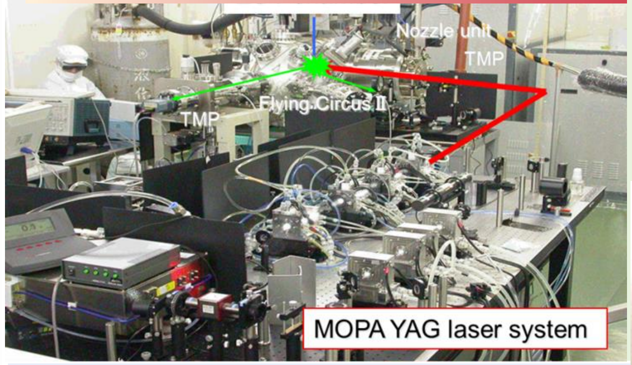
ETS-2

Proto#2

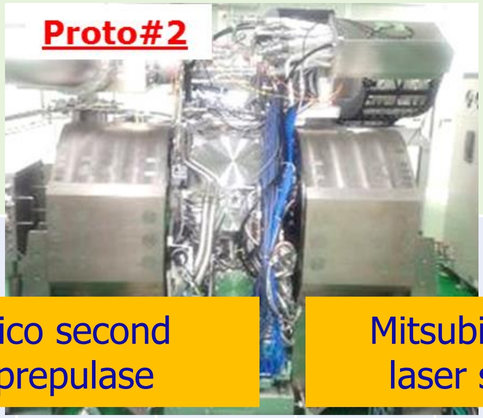
Magnetic Mitigation

Proto#1

Pilot#1



Xe +YAG Laser
↓
Sn +CO2 Laser

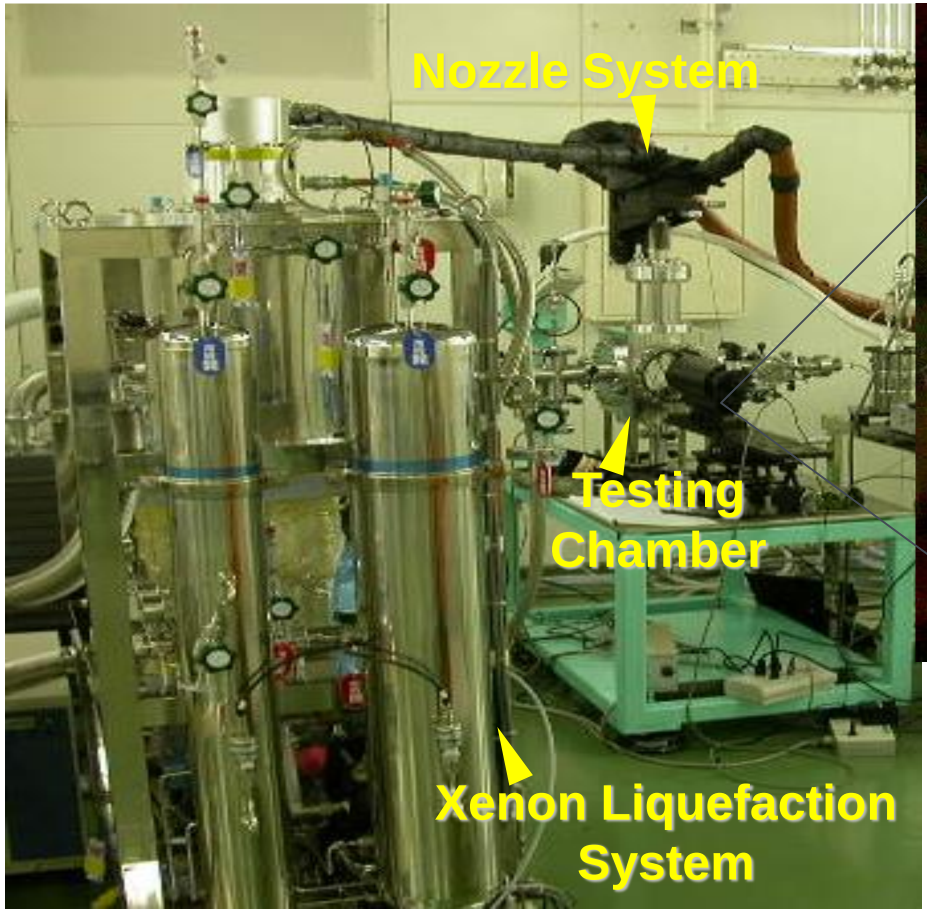


Pico second prepulase

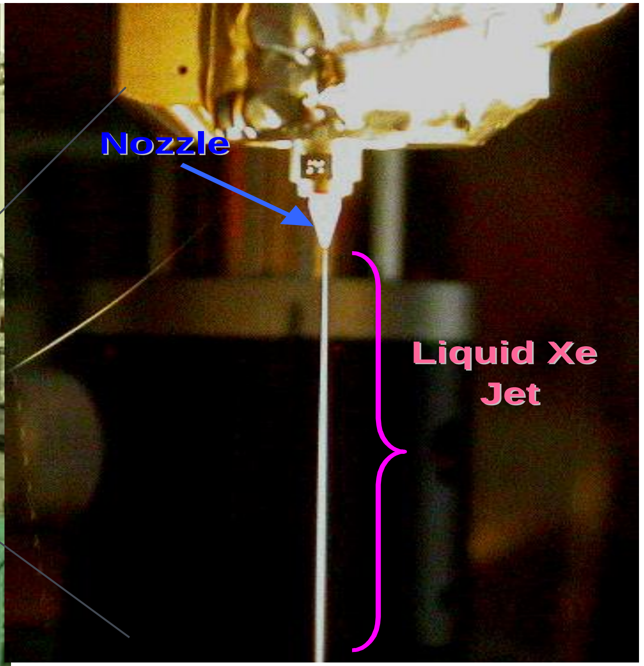
Mitsubishi CO2 laser system

History of LPP source development 2004

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

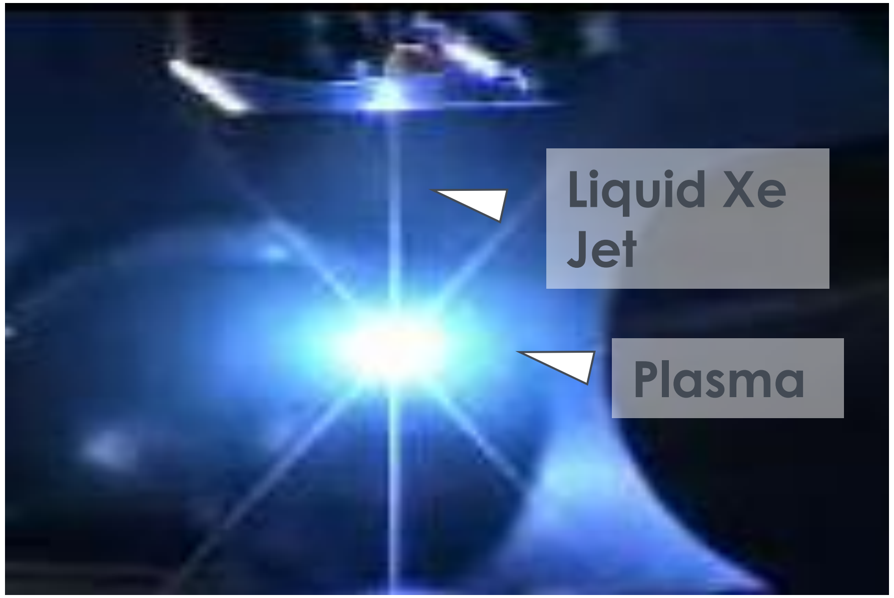


Liquid Xenon Jet System



Xe Jet

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



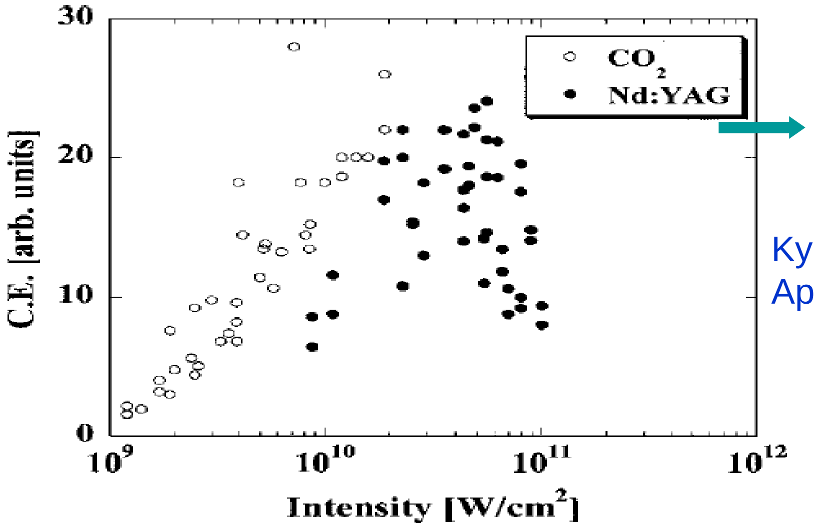
Xe Jet and Plasma

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

KOMATSU GIGAPHOTON

History of LPP source development 2006

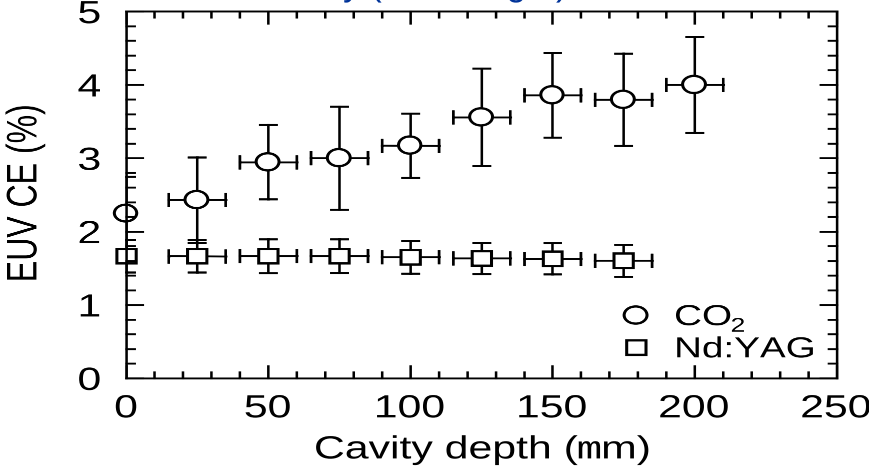
- **We found out Tin + CO2 laser could be around 8% efficiency** through Leading project & EUVA.

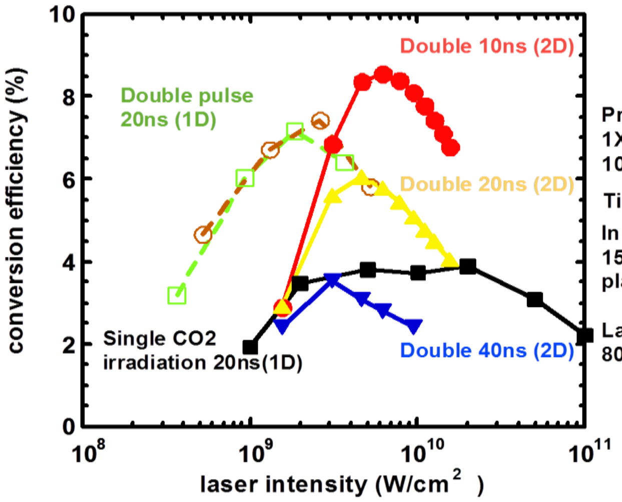


estimated
to be 2%

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

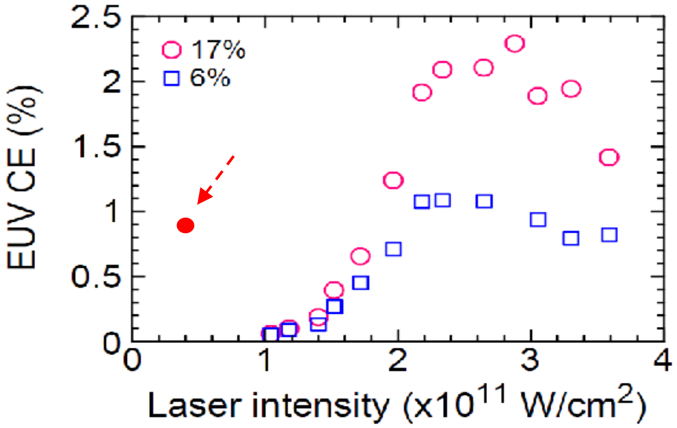
EUV conversion efficiency (solid target) demonstrated in EUVA (2005)





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



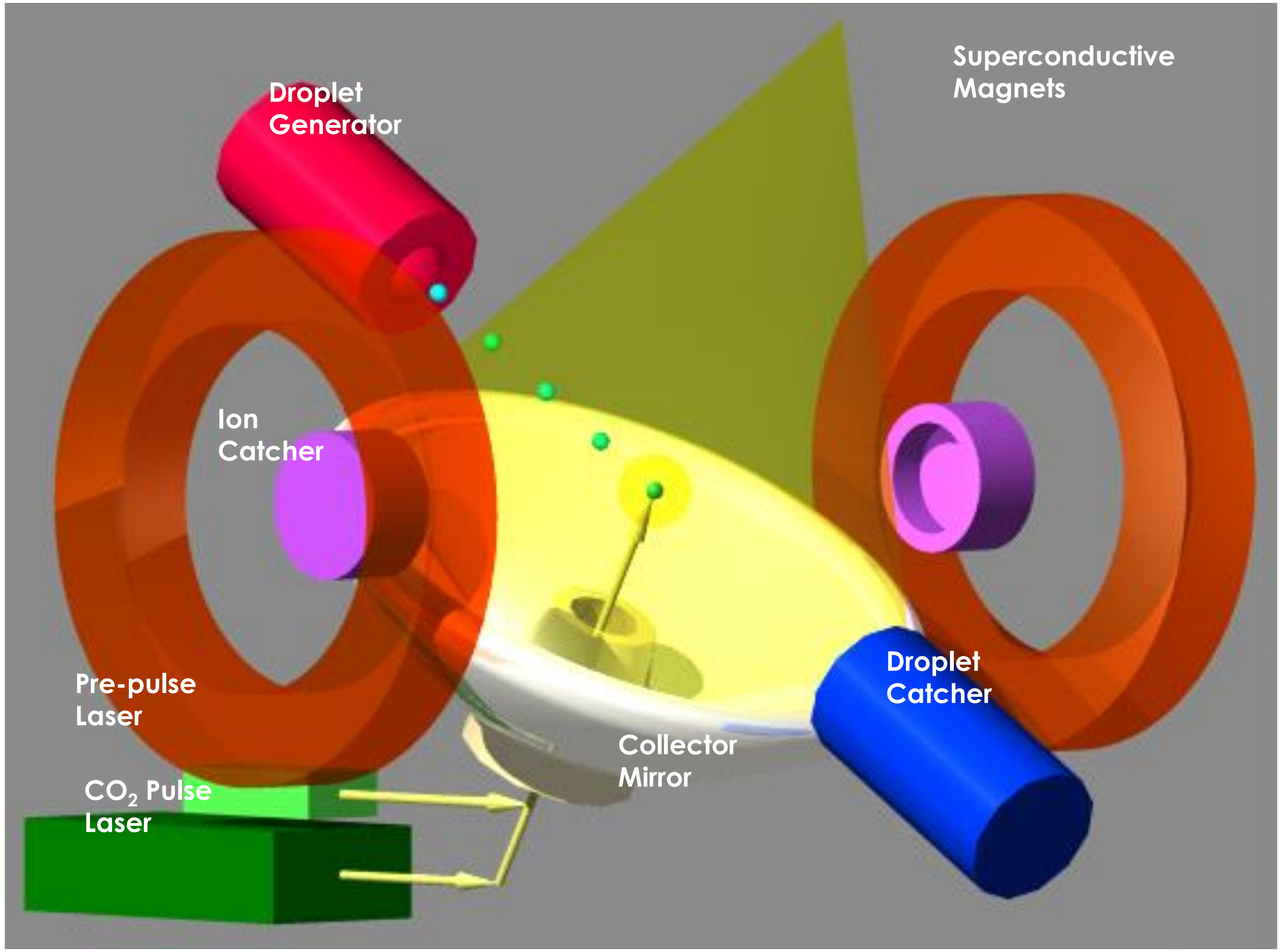
liyazaki Univ., T.
ligashiguchi et al.
SPIE Microlithography
006, 6151-146(2006)

EUV conversion efficiency simulation by Osaka Univ. team (20

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



KOMATSU GIGAPHOTON

History of LPP source development 2010

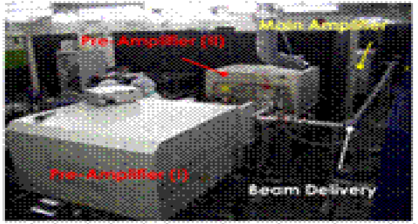
- **ETS-2 demonstrated at 10W avg. power and 50W power** with Magnetic Mitigation.

- Laser System

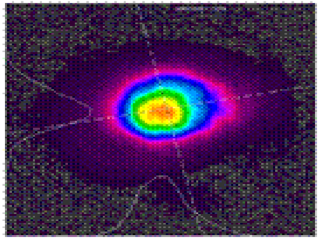
Oscillator
Wave length: 10.6um
Rep. rate :100kHz
Pulse width :20 ns (FWHM)

Pre-Amplifier
RF-excited CO2 laser

Main-Amplifier
RF-excited CO2 laser

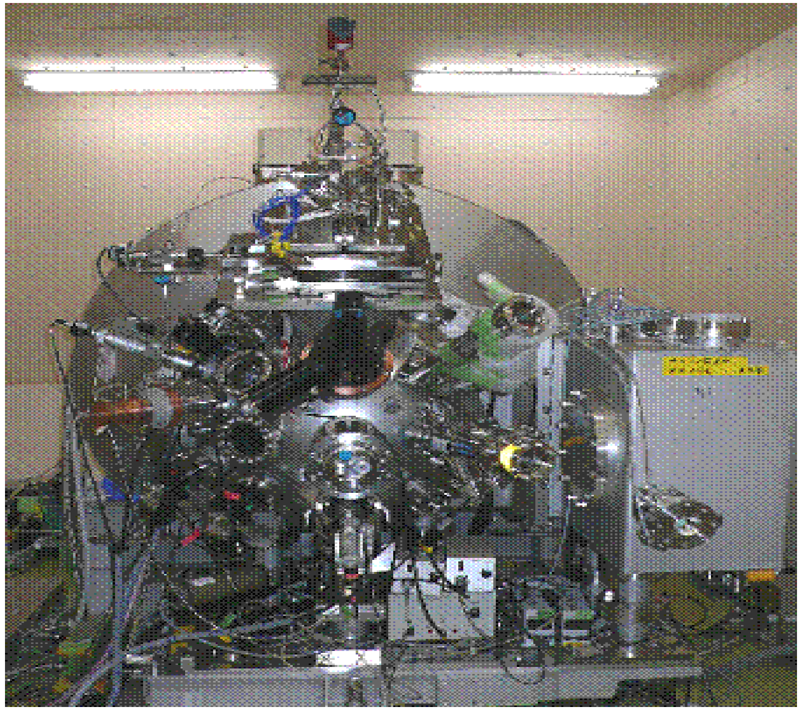


Laser beam profile



	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

- EUV chamber



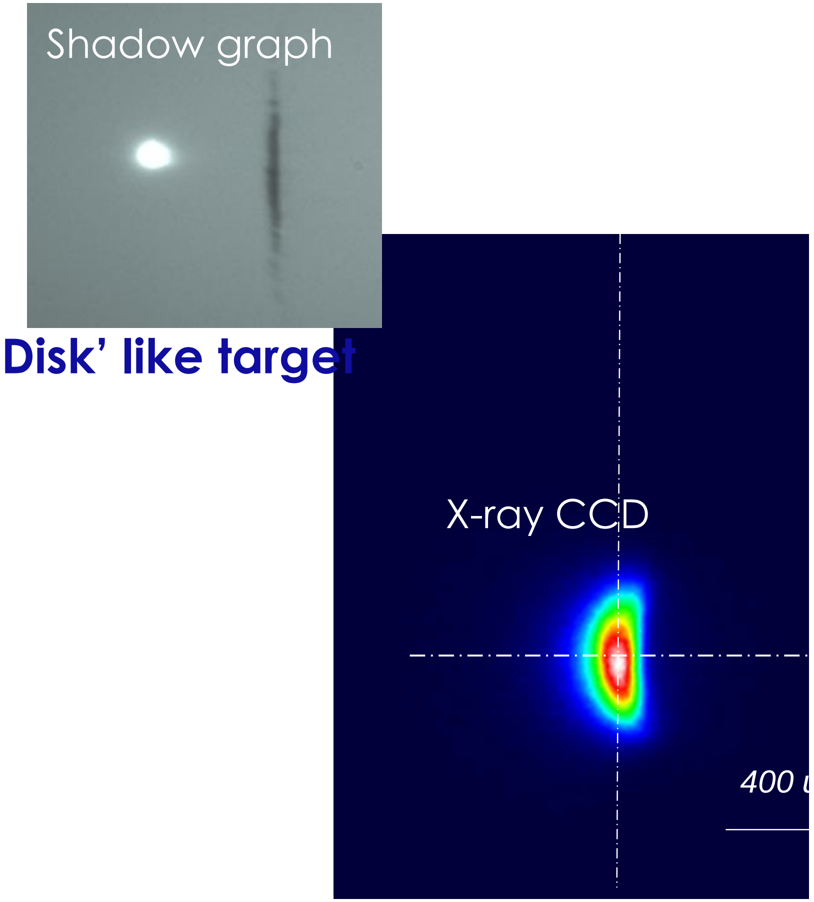
KOMATSU

GIGAPHOTON

History of LPP source development 2012

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

Pre-pulse (nano-second)

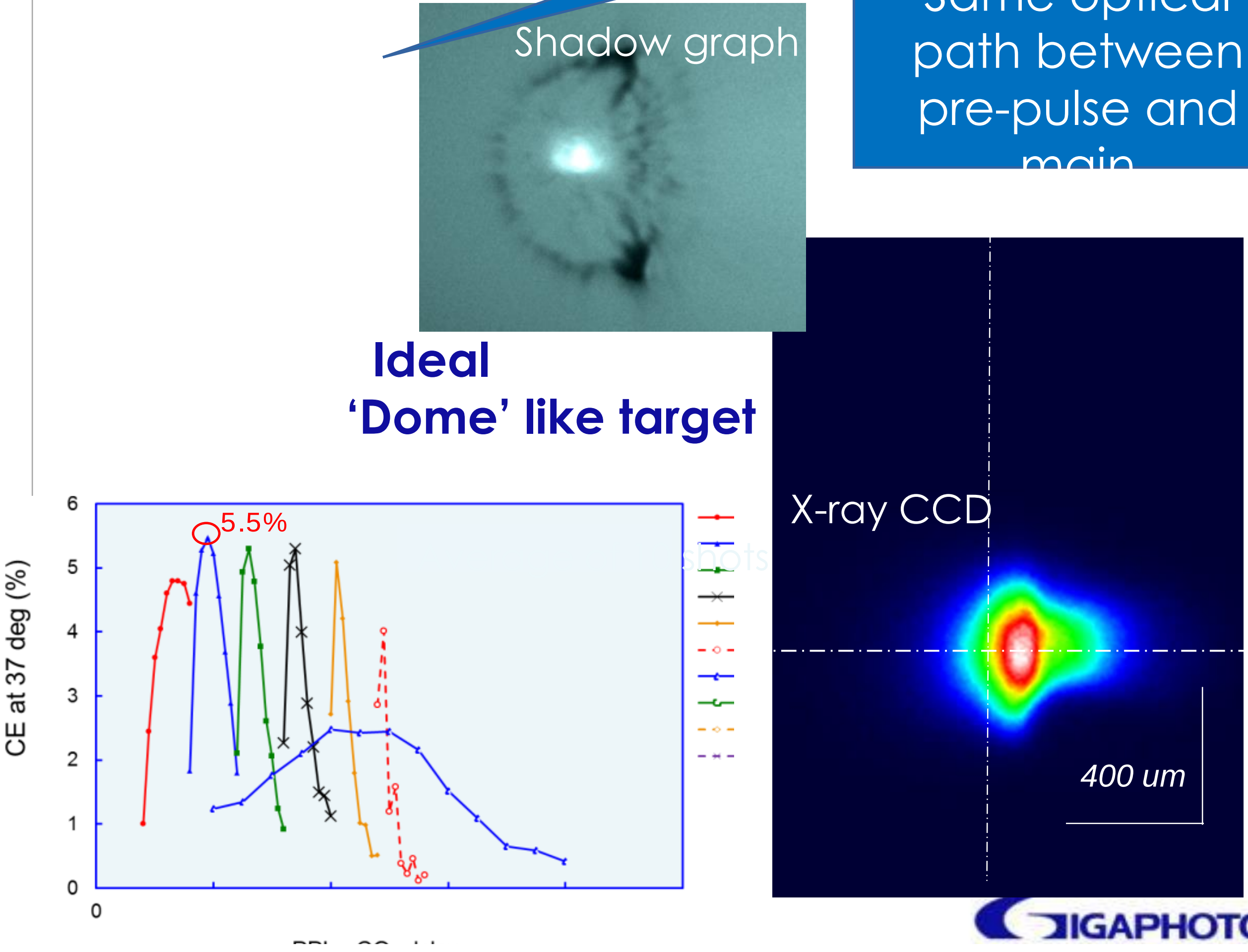


'Disk' like target

Pre-pulse(pico-second)

Very short pulse duration with 1um wavelength laser

Same optical path between pre-pulse and main

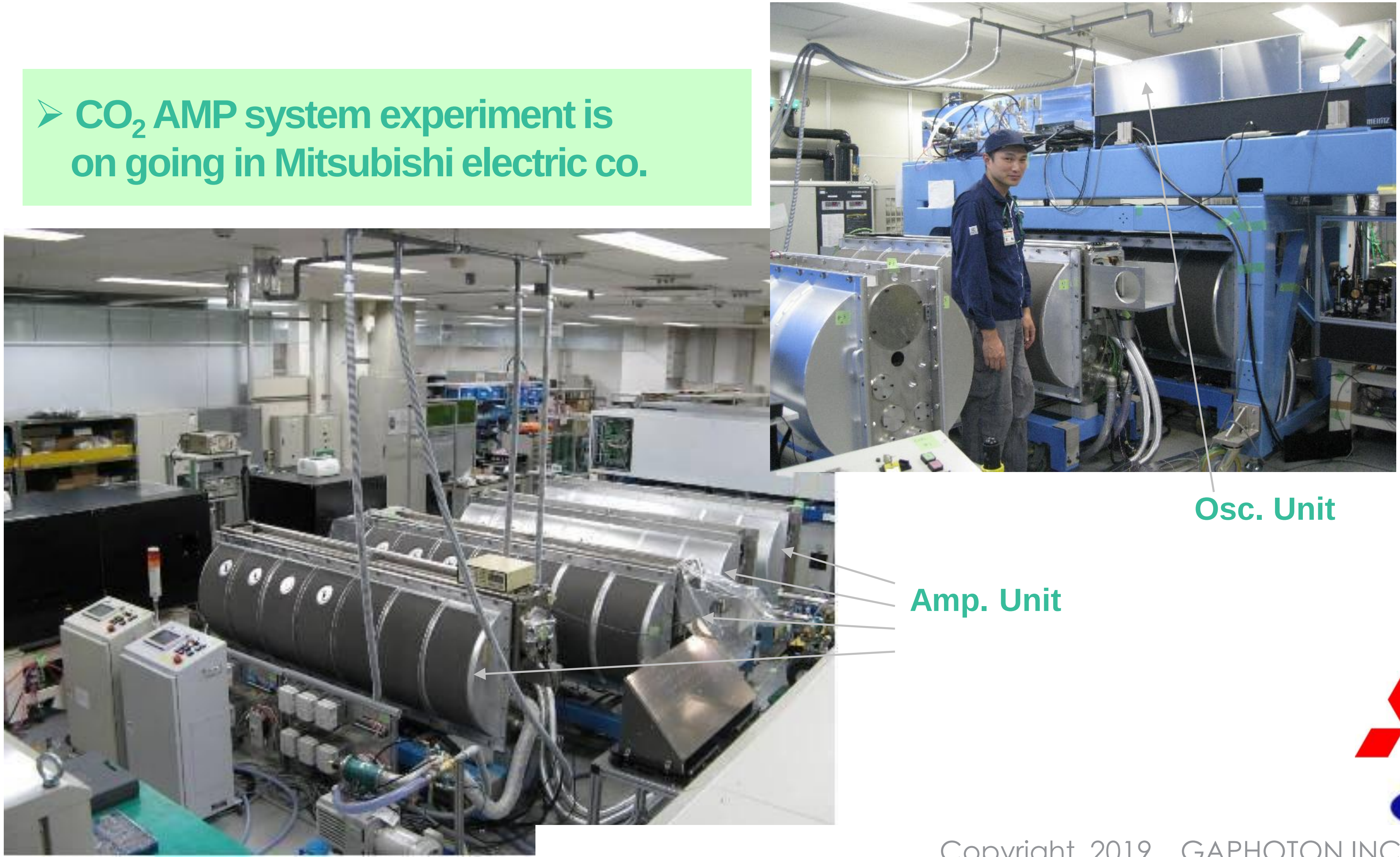


Ideal
'Dome' like target

History of LPP source development 2013

- *High power amplifier ETS achieved 20kW peak power.*

➢ CO_2 AMP system experiment is on going in Mitsubishi electric co.



MITSUBISHI ELECTRIC

GIGAPHOTON

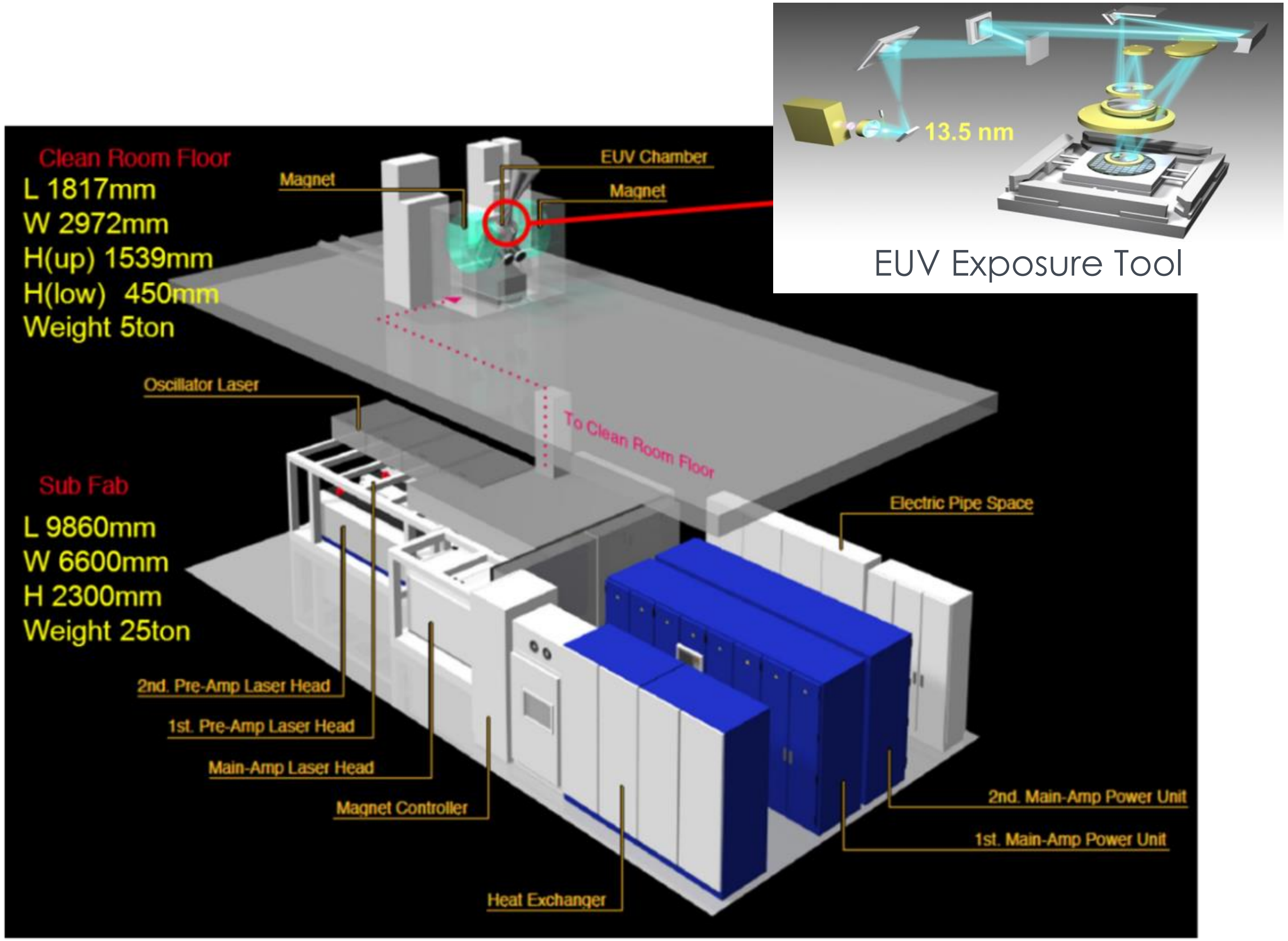
CURRENT STATUS UPDATE

Layout of 250W EUV Light Source Pilot #1

First HVM EUV Source

- 250W EUV source specification

Operational specification (Target)			HVM Source
Performance	EUV Power		> 250W
	CE		> 4.0 %
	Pulse rate		100kHz
	Availability		> 80 %
Technology	Droplet generator	Droplet size	< 20mm
	CO2 laser	Power	> 20kW
	Pre-pulse laser	Pulse duration	psec
	Debris mitigation	Magnet, Etching	> 15 days (>1500Mpls)

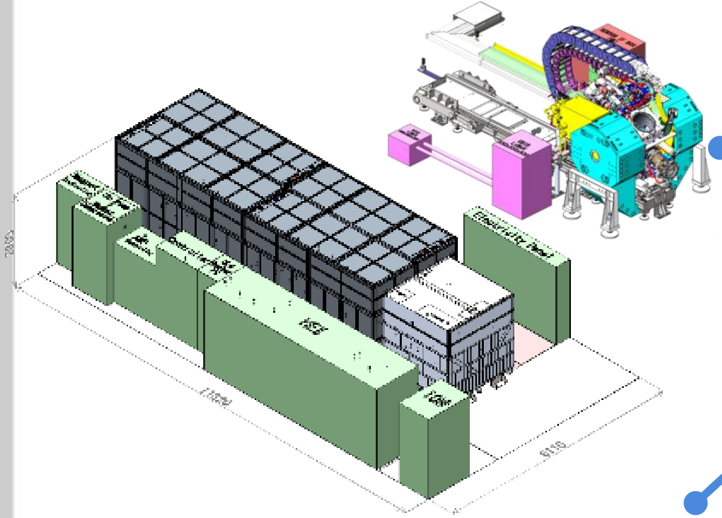


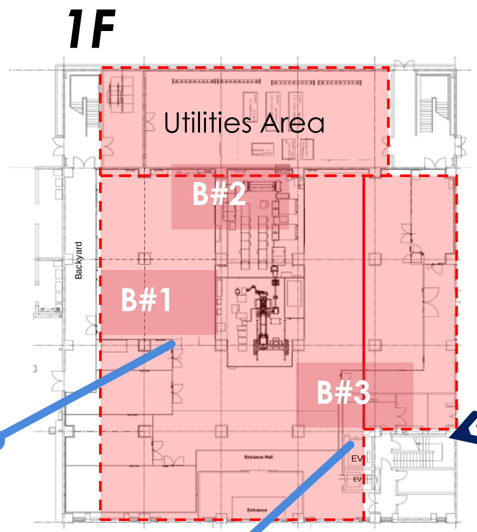
Hiratsuka Center

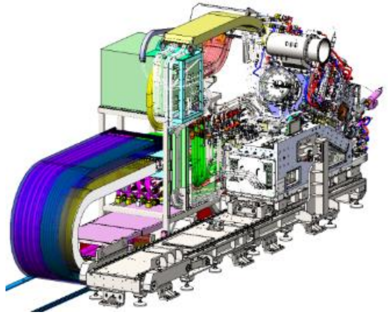
Pilot#1

Operational since July 2016

First pilot system designed for NXE integration



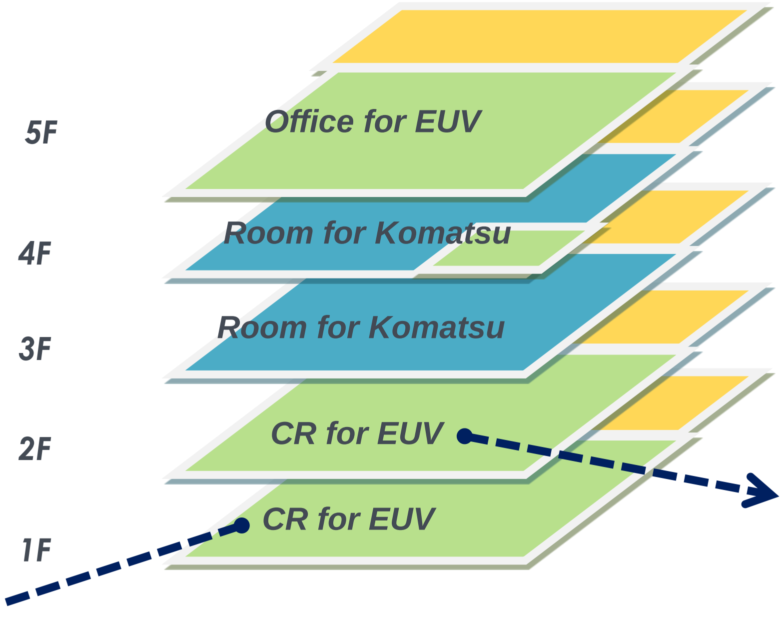




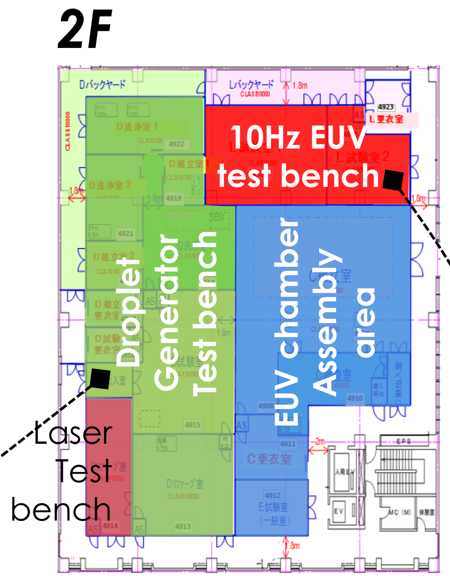
Proto#2

Operational since November 2013

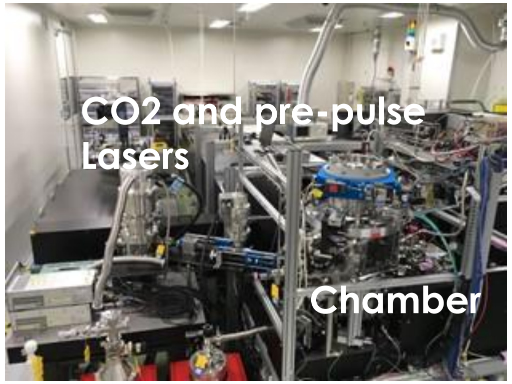
System for key technology development in >100W power level



Hiratsuka center

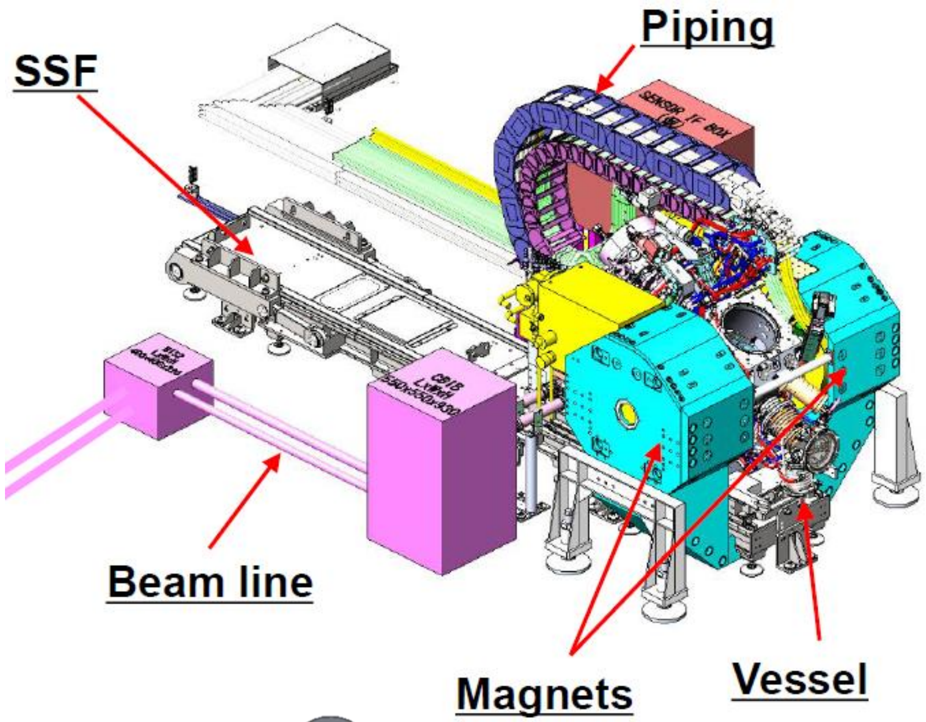


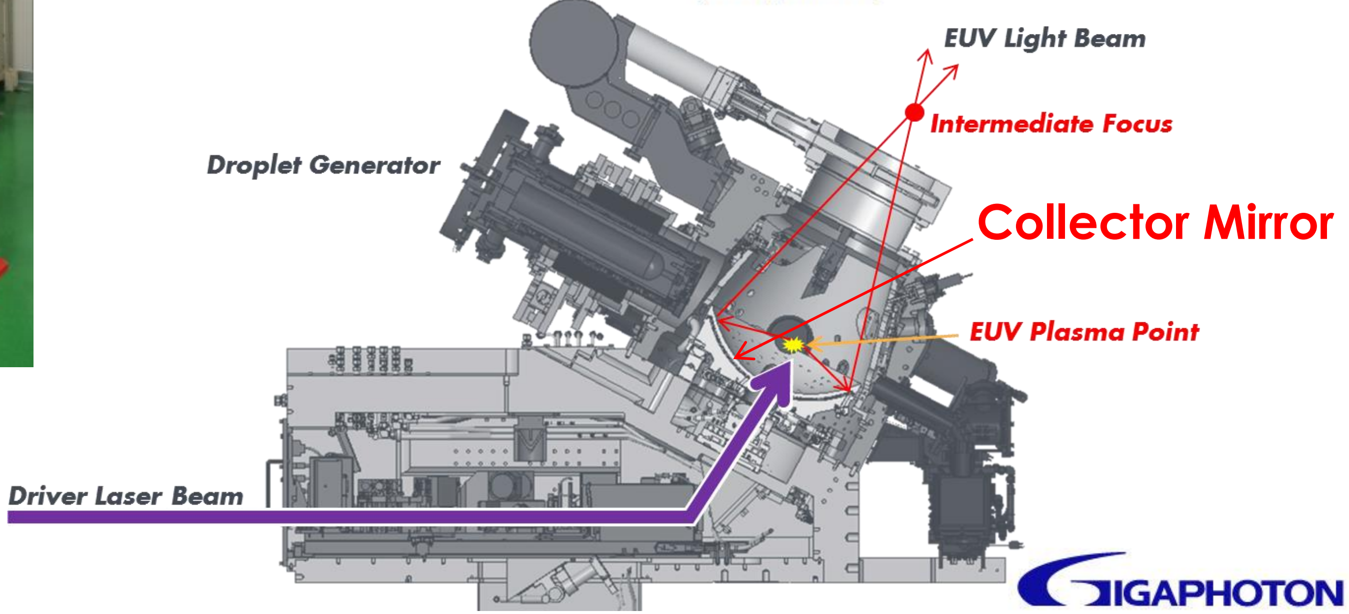
- Droplet test bench
  Reliability, Stability etc.



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

Pilot System EUV Chamber

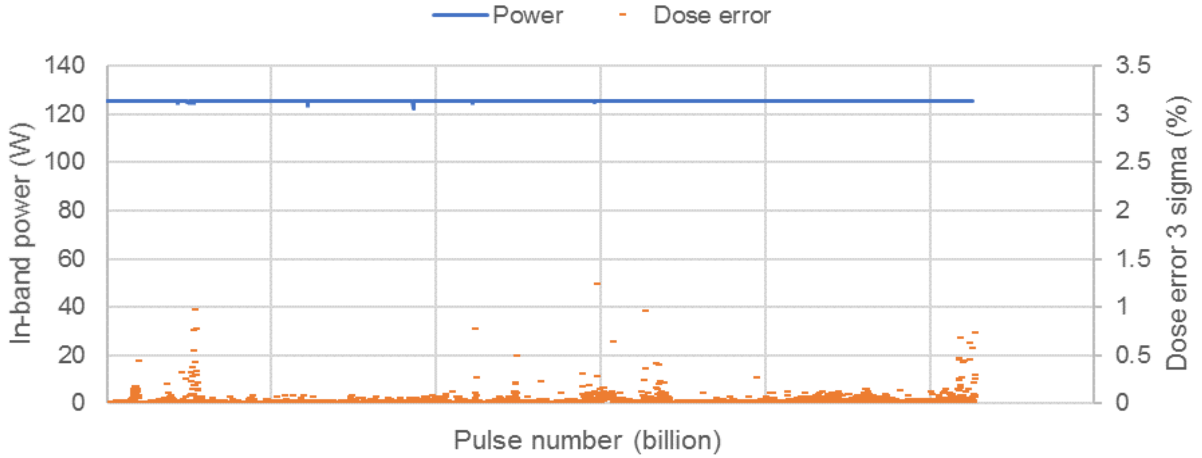


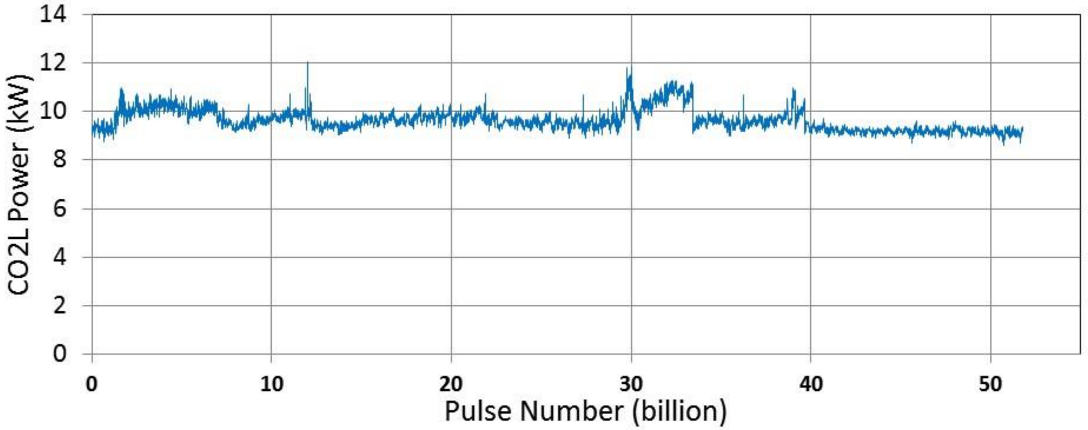


System Performance: 125W Operation Data 1/2

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

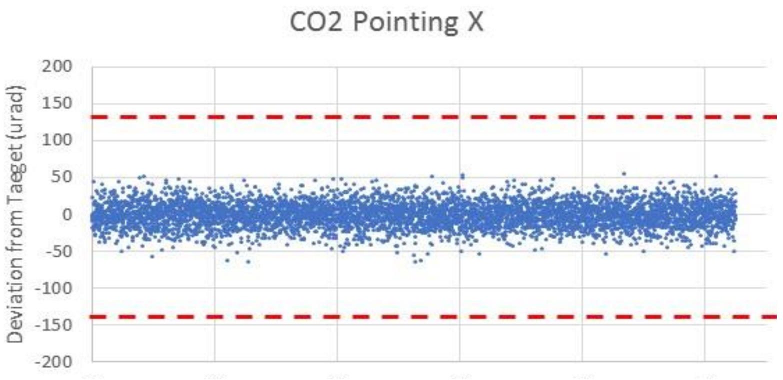
	Performance
Average power at IF	125W
Dose error average (3 sigma)	0.04%
Die yield (<0.16%)	98.5%
Pulse Number	53Bpls
Duty cycle	100%
In-band power	125W
Dose margin	40%
Collector lifetime	0.9%/Bpls
Repetition rate	100kHz

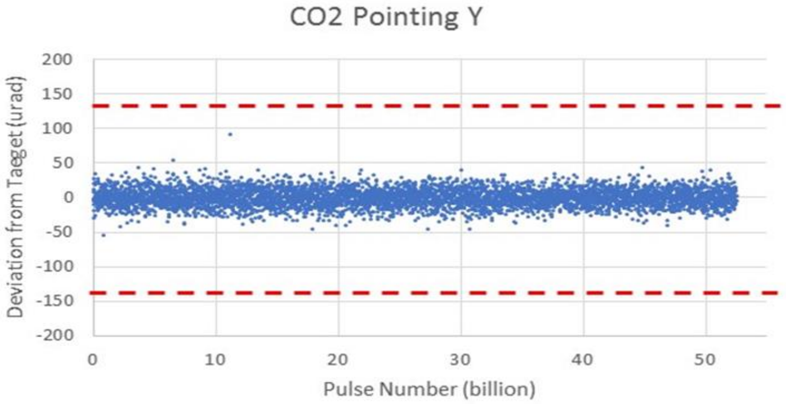




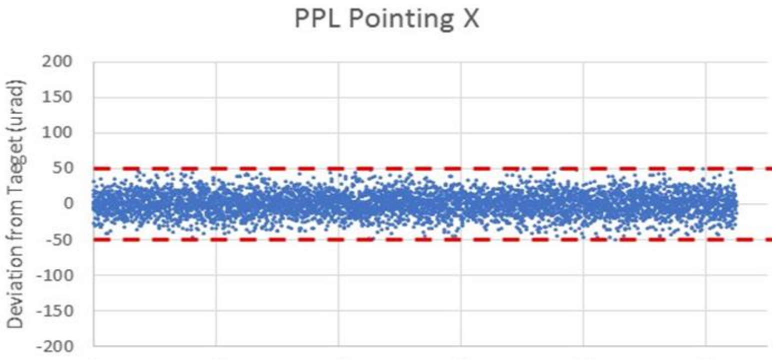
System Performance: 125W Operation Data 2/2

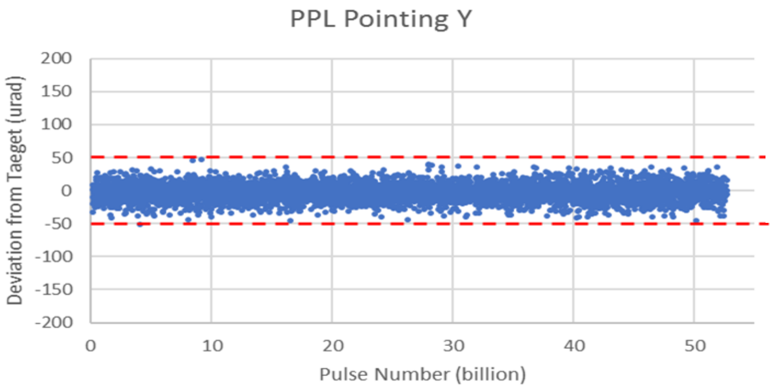
CO2 Laser Pointing at Combiner



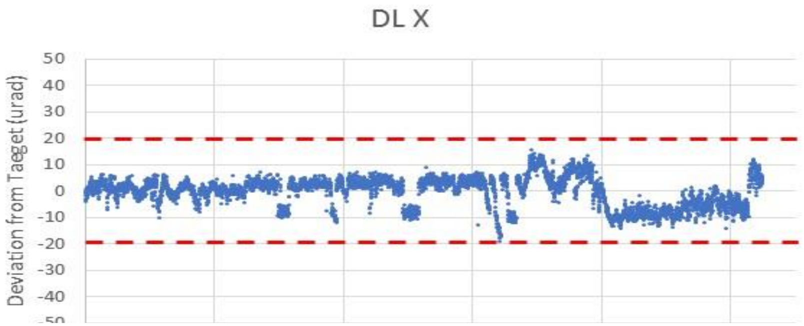


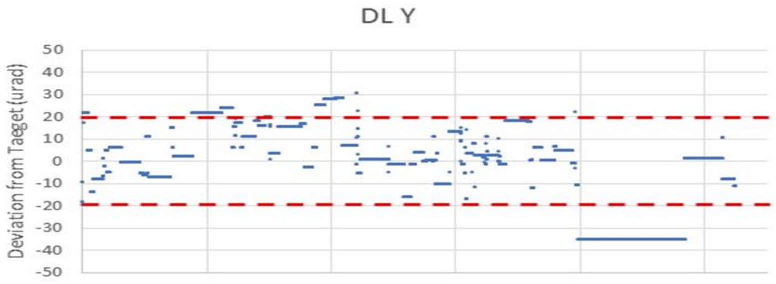
PPL Laser Pointing at Combiner

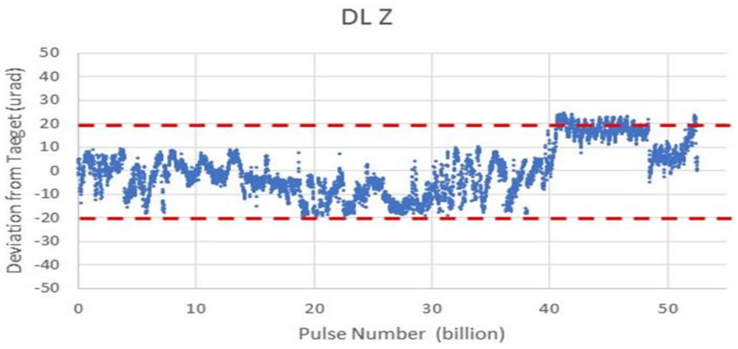




Droplet Position at Plasma

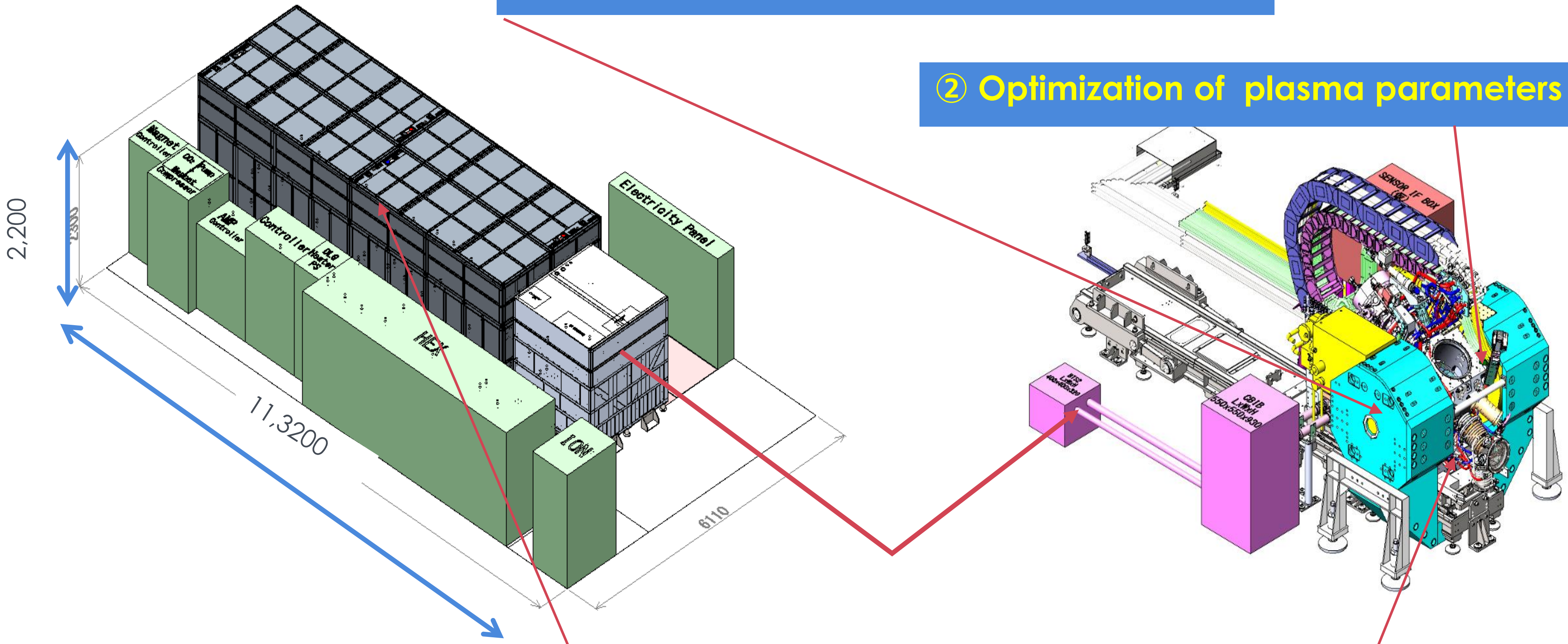






GIGAPHOTON'S REDEFINED TARGET OF ≧330W EUV SOURCE

Development Items for Power Target of ≧330W



① Beam uniformity at plasma for CE>6%

② Optimization of plasma parameters for CE>6%

③ Upgrade of CO2 Laser Power

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

GIGAPHOTON

Redefined Power Target ≧330W

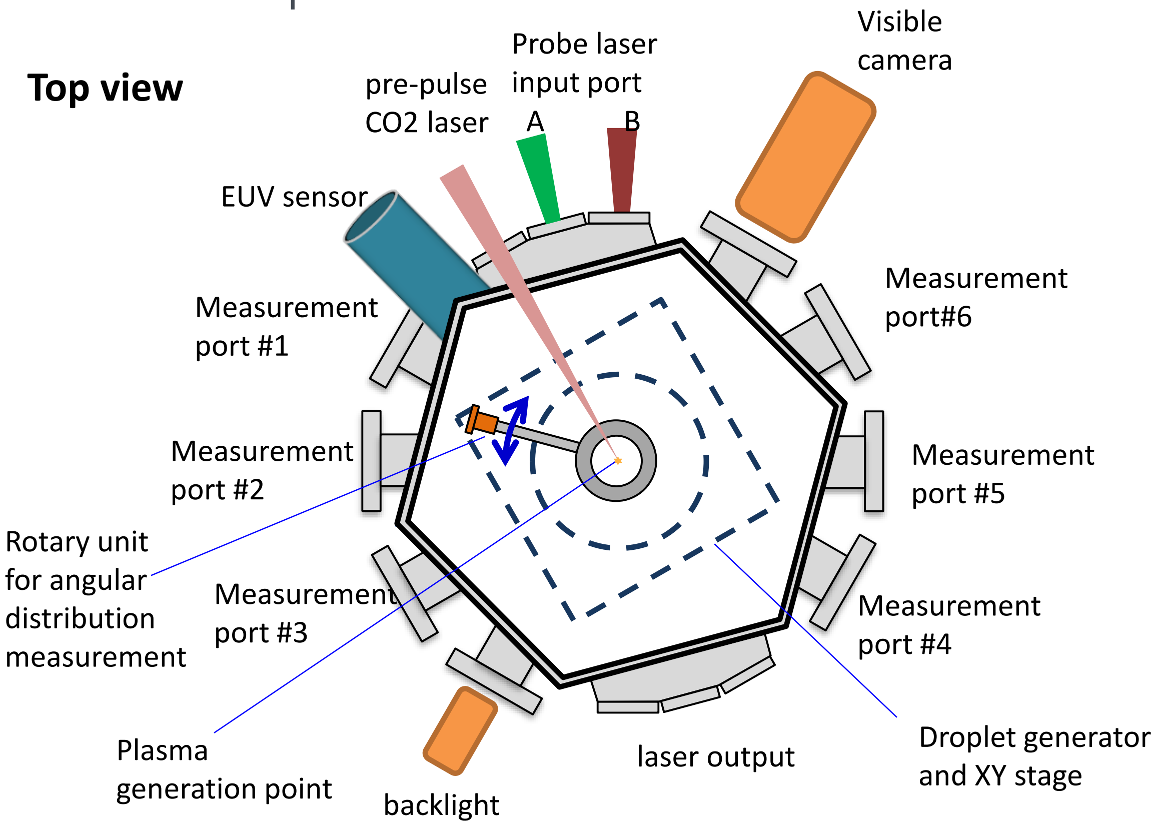
Target	Q4 2018	Under testing	Q4 2019
Average Power	125W	**250W**	**≧330W**
Repetition rate	100kHz	100kHz	100kHz
CO2 power (energy) at plasma operation with dose ctrl./maximum	10kW/16kW (100mJ/160mJ)	**18kW/23kW** **(180mJ/230mJ)**	18kW/23kW (180mJ/230mJ)
CE	4.0%	**4.5%**	**5.5～6%**
Technology for high power			
① Beam uniformity at plasma for CE>6%			✓
② Optimization of plasma parameters for CE>6%		✓	✓
③ Upgrade of CO2 Laser Power		✓	✓
④ Lifetime Extension of Collector Mirror -0.05%/B pls			✓

GIGAPHOTON

① BEAM UNIFORMITY AT PLASMA

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



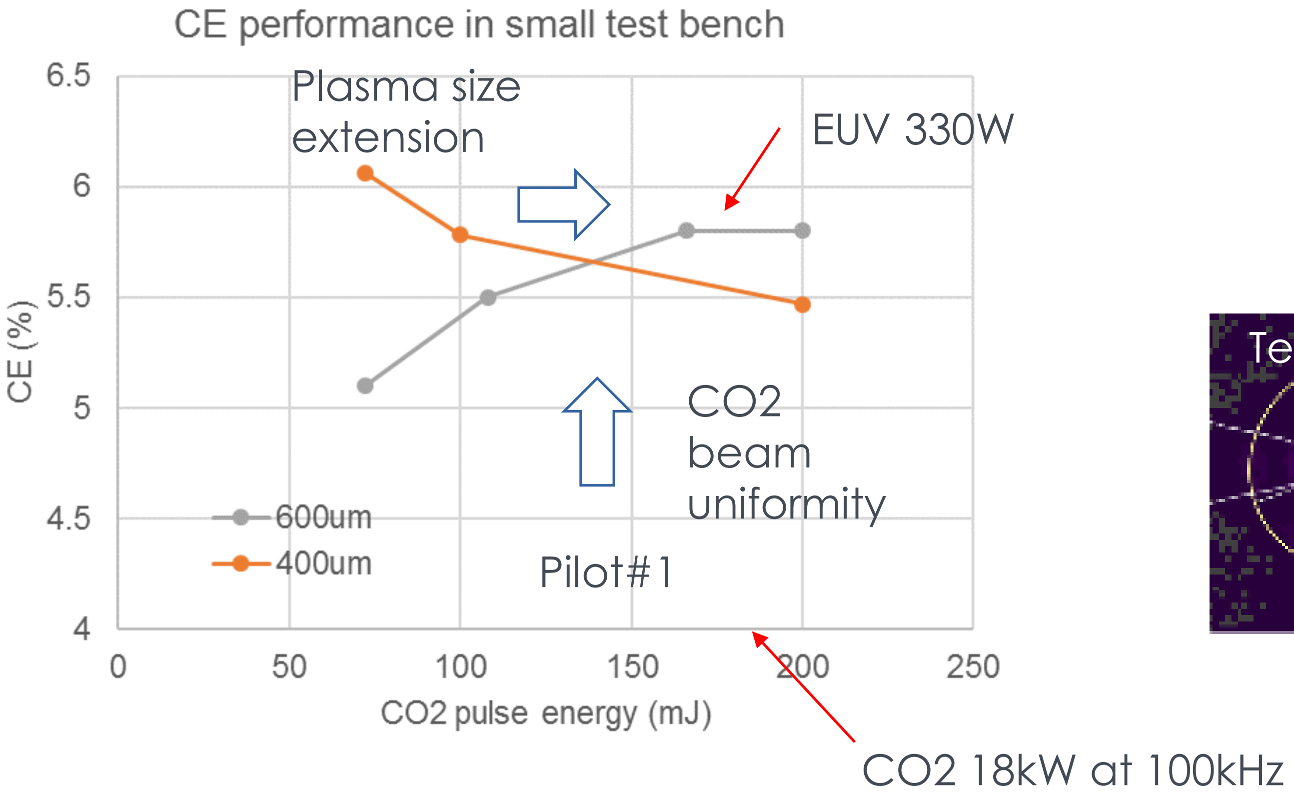
Overview of test apparatus

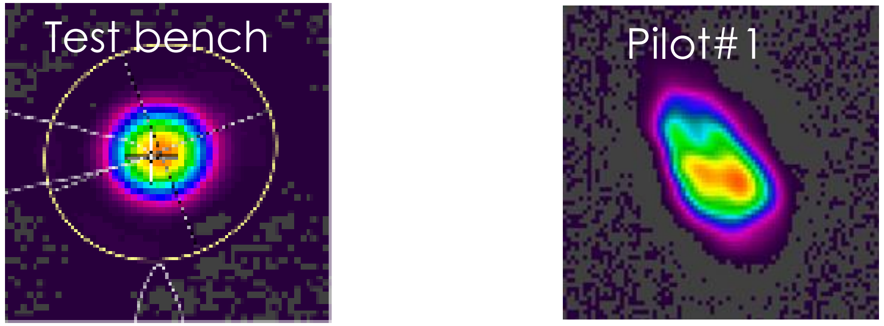
Measurement tools

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

Key Technology for 6% 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 planned to be improved.



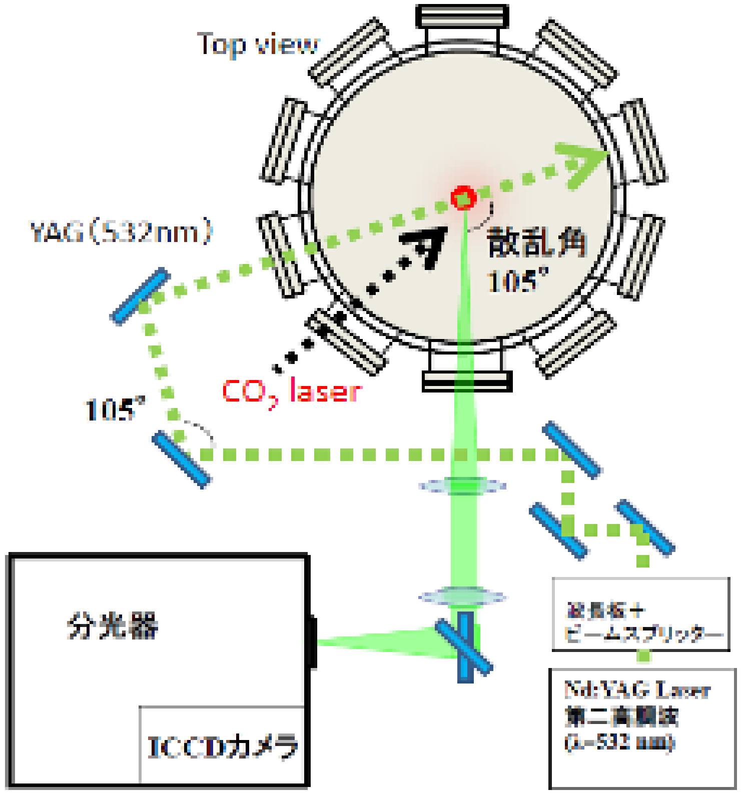


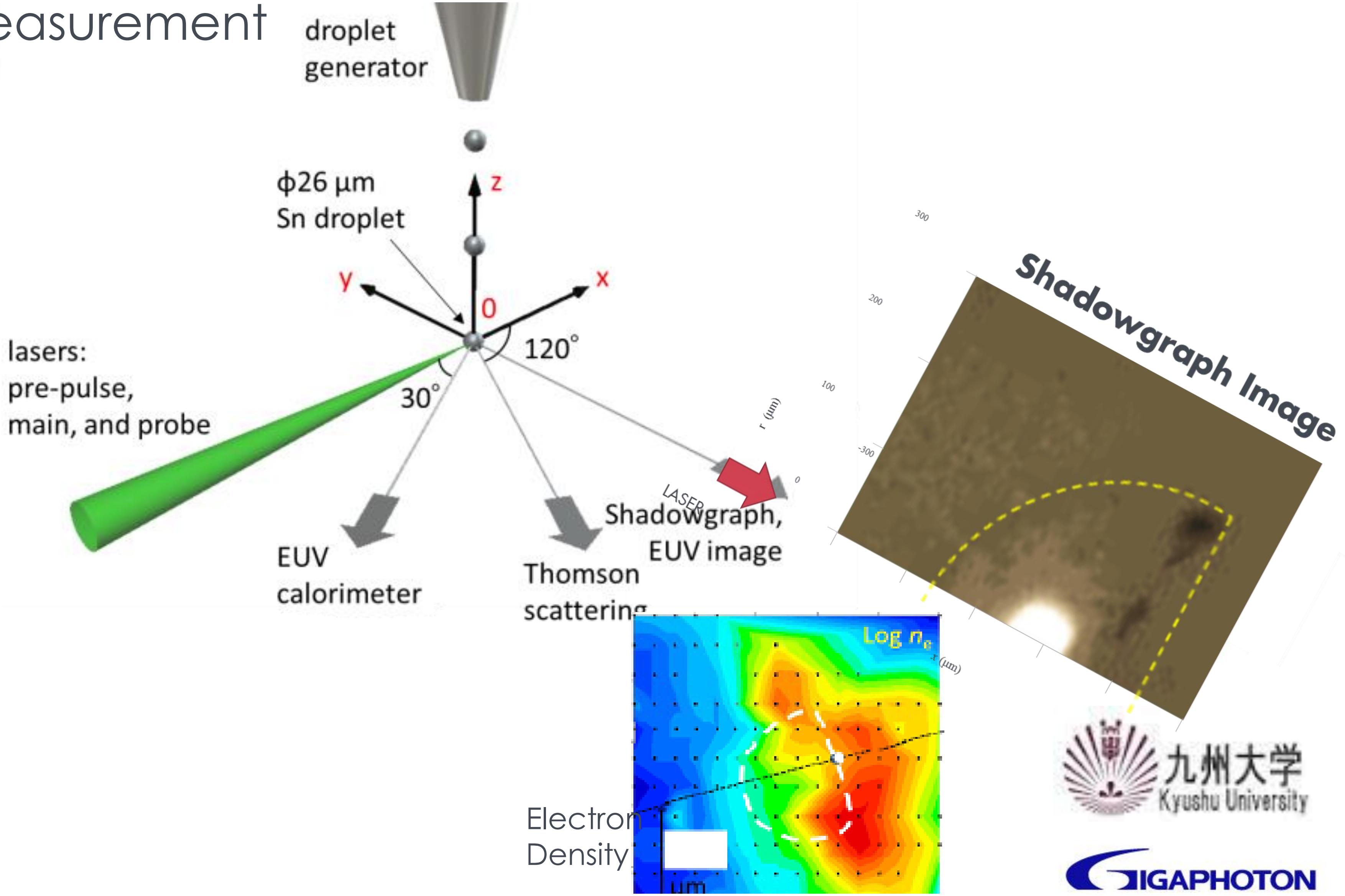
CO2 spot profile

② OPTIMIZATION OF PLASMA PARAMETERS

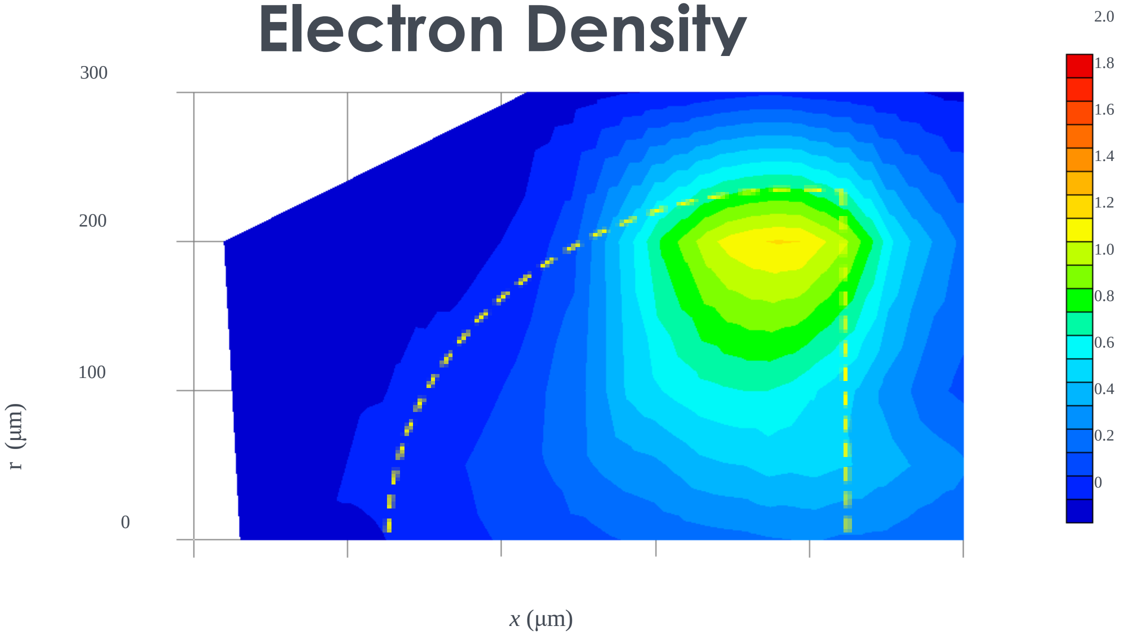
Plasma Parameter Measurement (1/2)

Thomson Scattering Measurement

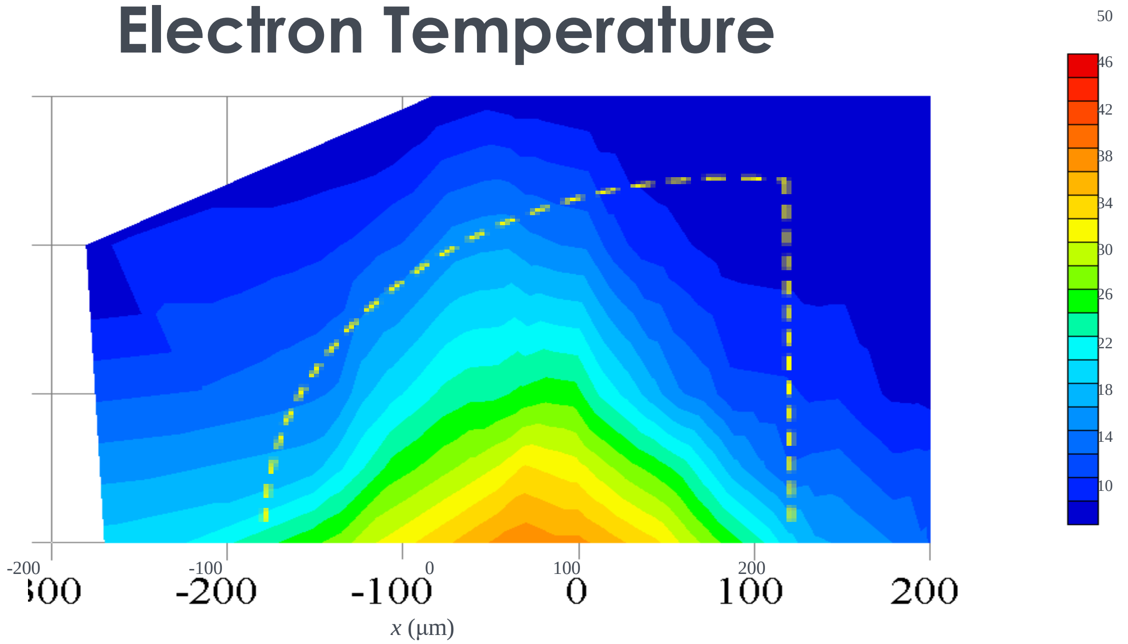




Plasma Parameter Measurement (2/2)



Electron Density



Electron Temperature

Tomson Scattering measurement characterize pre-pulse plasma in detail !

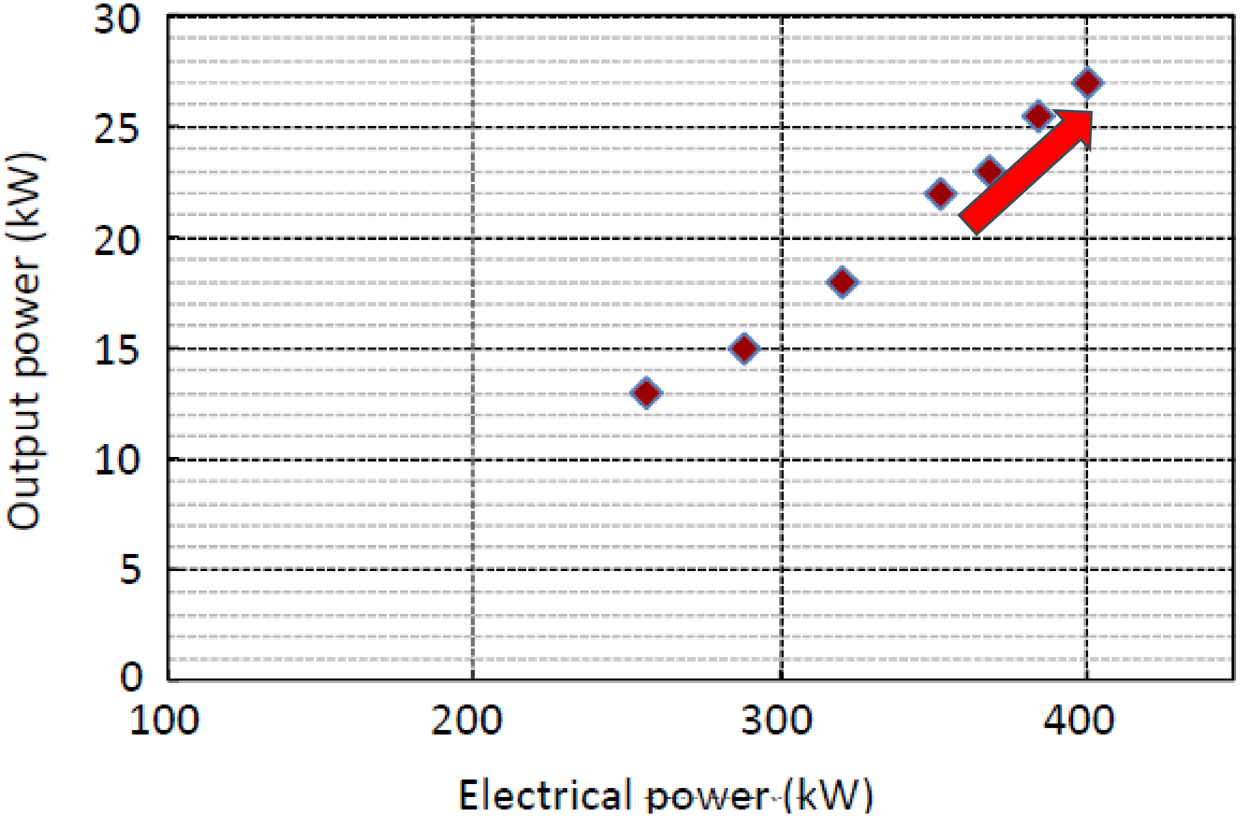
Next step: *CE enhancemer*

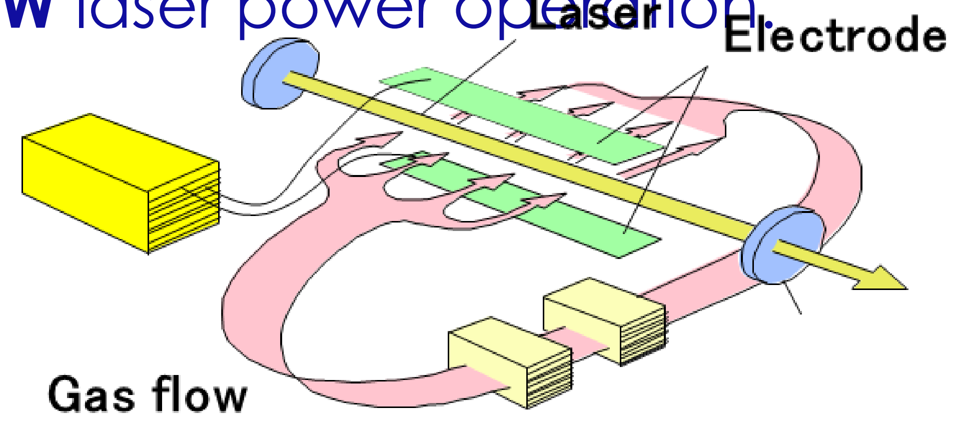
③ UPGRADE OF CO2 LASER POWER

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.

Output laser power





Transverse flow type amplifier

MITSUBISHI ELECTRIC

GIGAPHOTON

Transverse flow type CO_2 Laser

Benefits

- Excellent beam uniformity enables efficient EUV creation
- Short maintenance down time
  - Separated optical binding module design
  - Auto beam adjustment
- Efficient CO2 Laser and eco-friendly

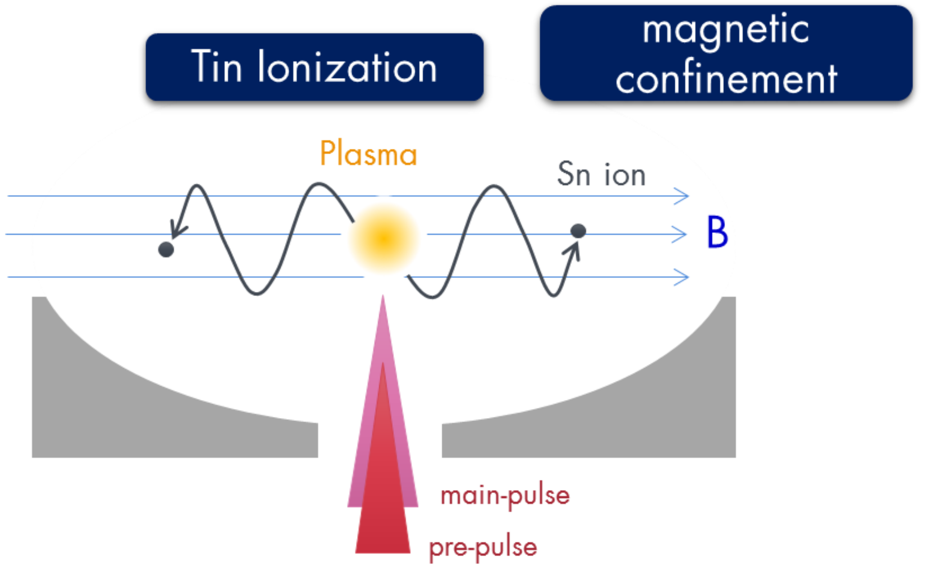
Utility	Spec.		Pilot#1
Input Electricity (full load)	1690 kVA	>	880 kVA
Cooling Water Flow Rate	2221 L/min.	>	1608 L/min.
Hydrogen Flow Rate	600 L/min.	>	360 L/min.
Laser Gas	*TBD*		351 kL/year

	Conventional	GPI	Remark
Beam profile uniformity	Not uniform	**Uniform**	Uniform beam profile leads higher CE.
Separate Optical Binding module	N/A	**Yes**	Minimize chamber replace time
Auto Beam adjustment	N/A	**Yes**	Keep uniform beam profile without interruption for adjustment
Utility requirement	▲	◎	30% less electricity and other utilities

④ LIFETIME EXTENSION OF COLLECTOR MIRROR

Etching and Dissociation Sn balance on the Mirror Surface

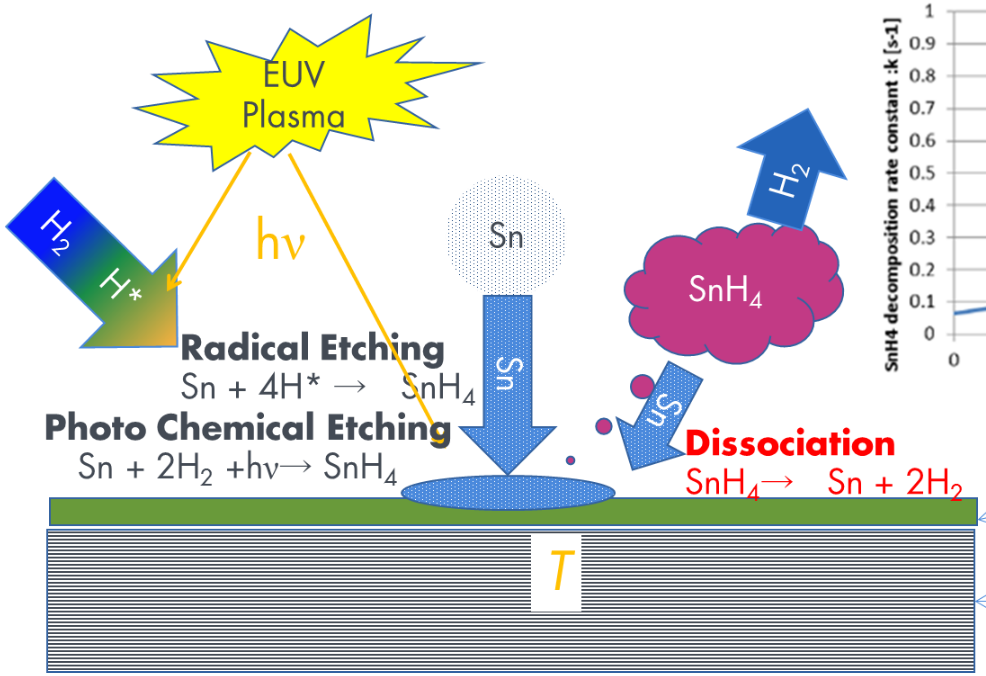
Chemical Aquarium on the Mirror Surface



- 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.

- 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

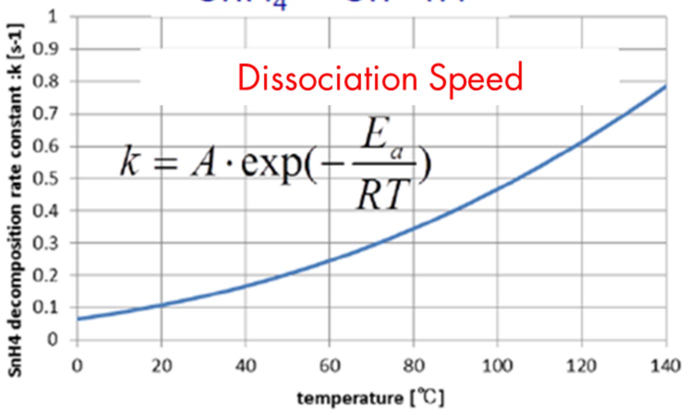


Radical Etching
$Sn + 4H^* \rightarrow SnH_4$

Photo Chemical Etching
$Sn + 2H_2 + h\nu \rightarrow SnH_4$

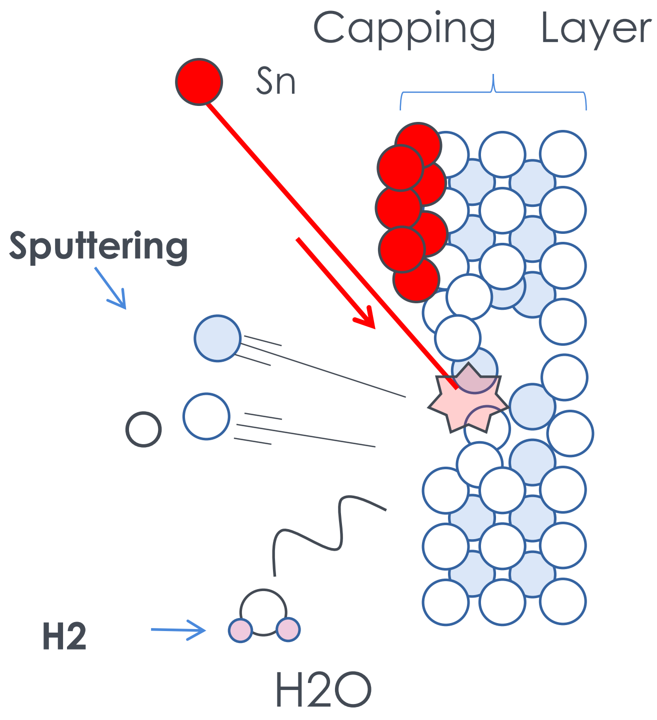
Dissociation
$SnH_4 \rightarrow Sn + 2H_2$

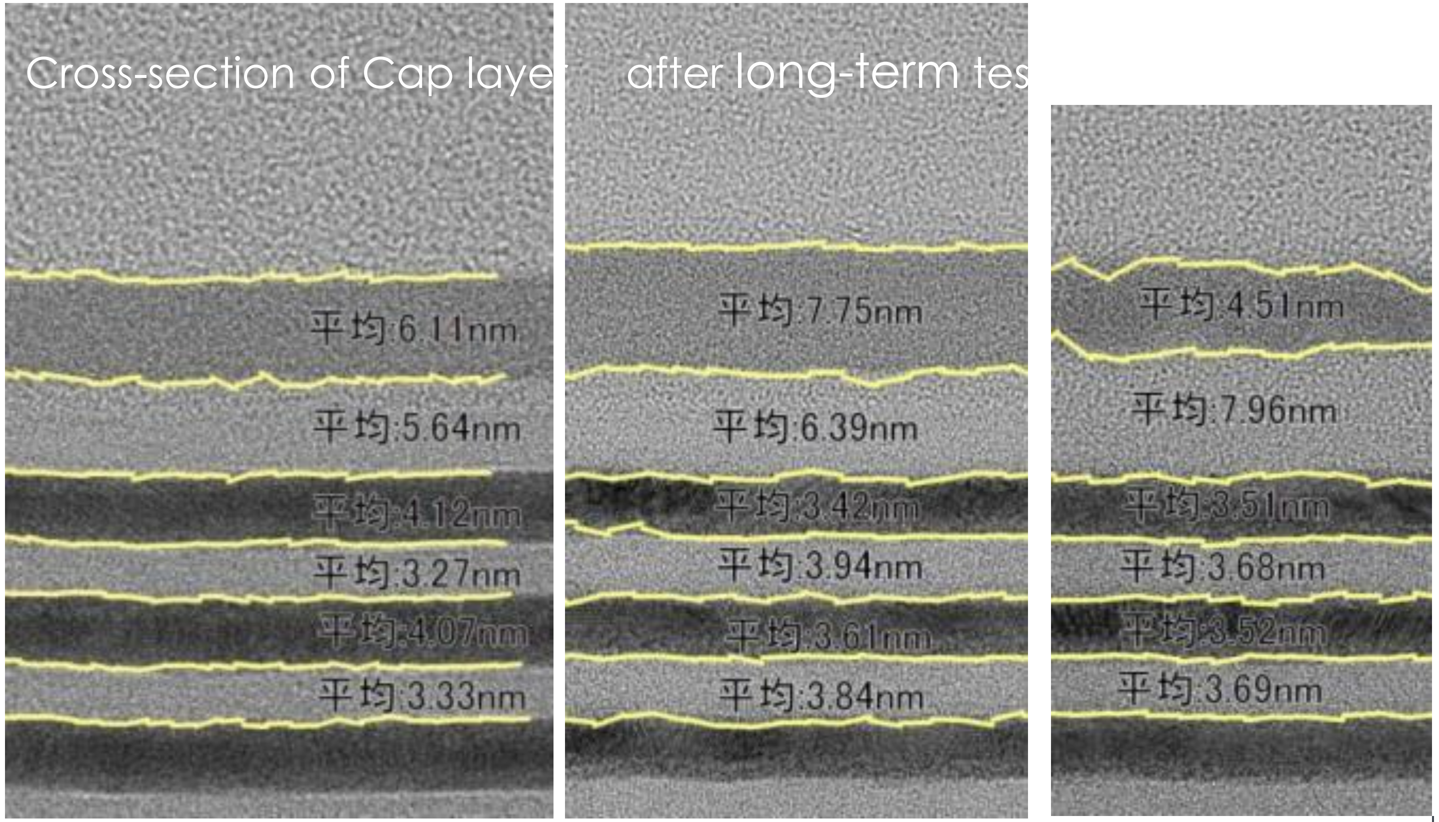
$SnH_4 \rightarrow Sn+4H$



Capping Layer and Multi-Layer Durability under Sputtering

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





Capping Layer

1st Si Layer

2nd Mo Layer

3rd Si Layer

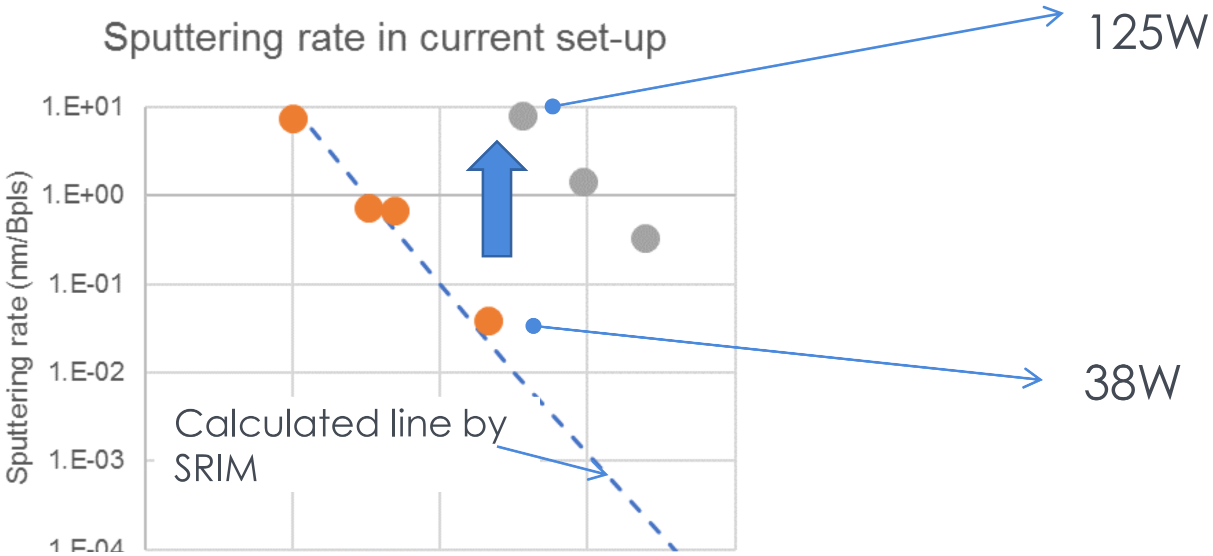
・
・
・

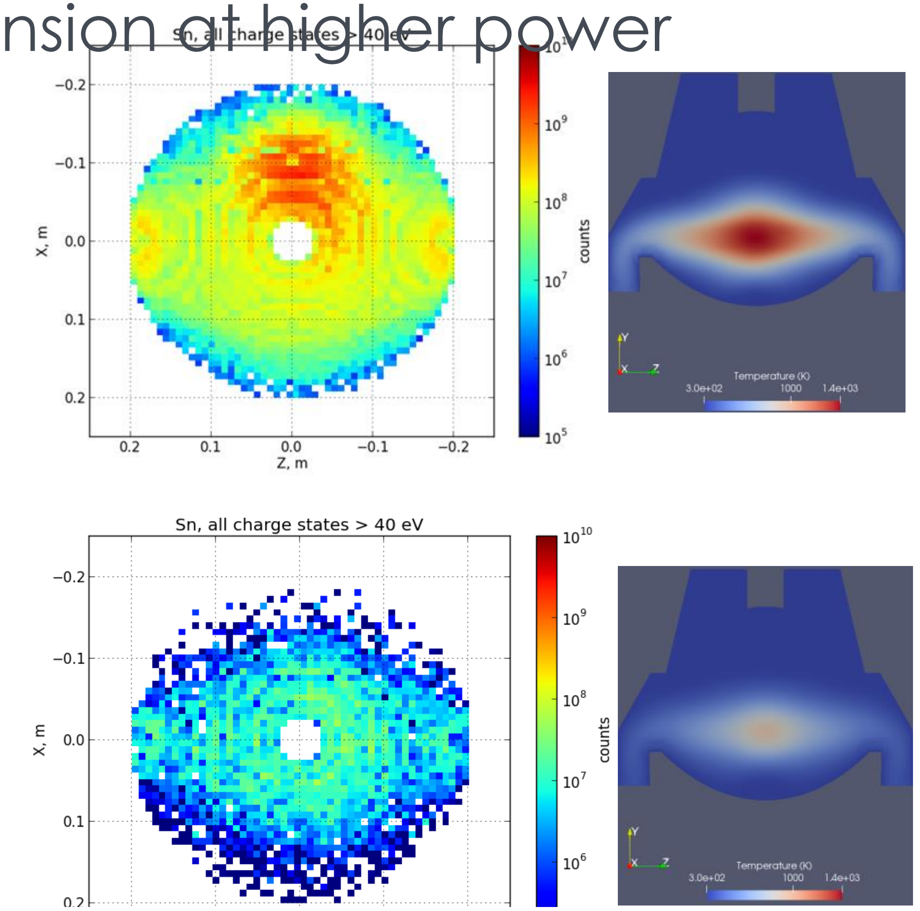
Sputtering Effect Increase with Higher Operation Power

- 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>

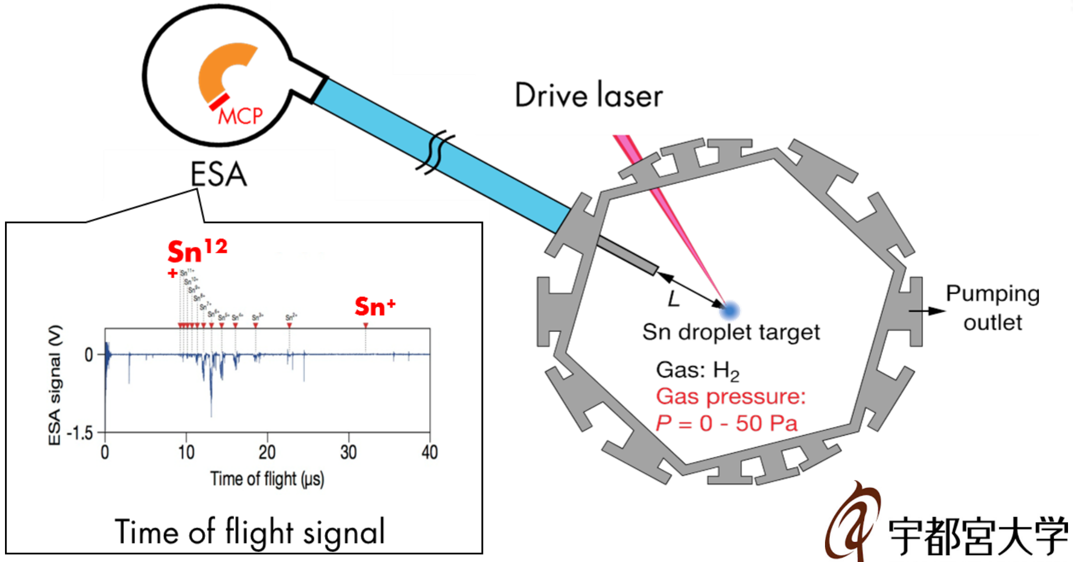
Higher power → **Gas heating** → **Gas density decrease** → **Gas stopping decrease**

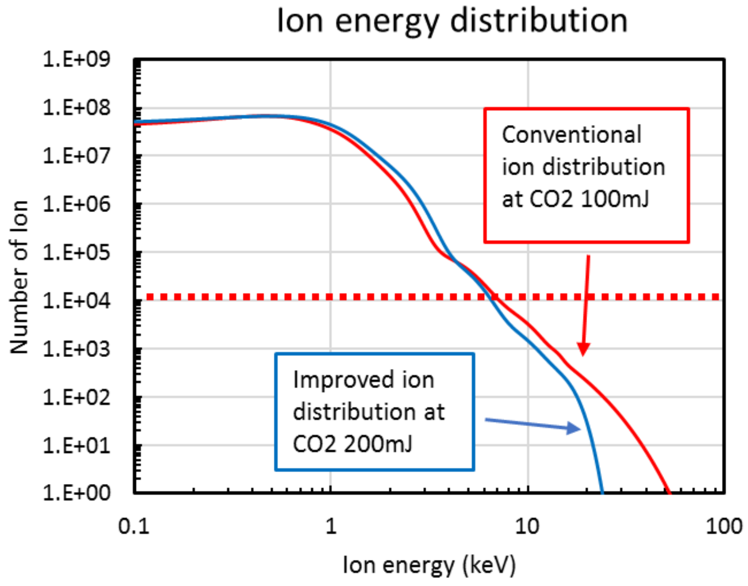


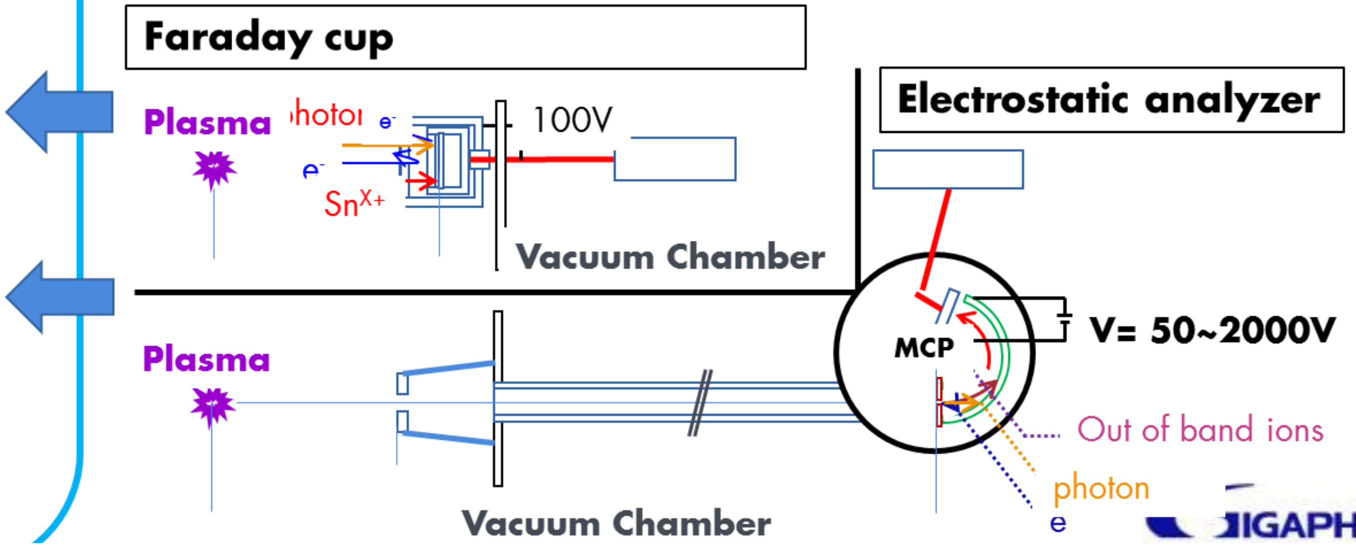


Deceleration of fast tin ion

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

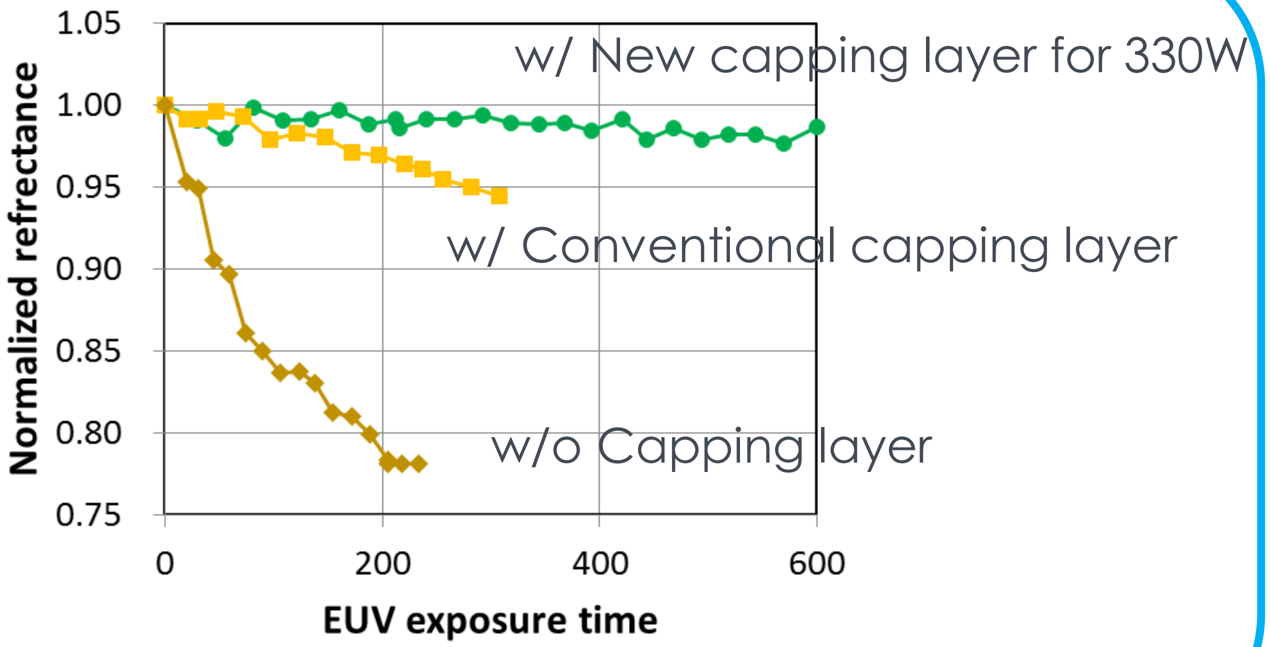






Durability test of collector capping layer at New SUBARU

- 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

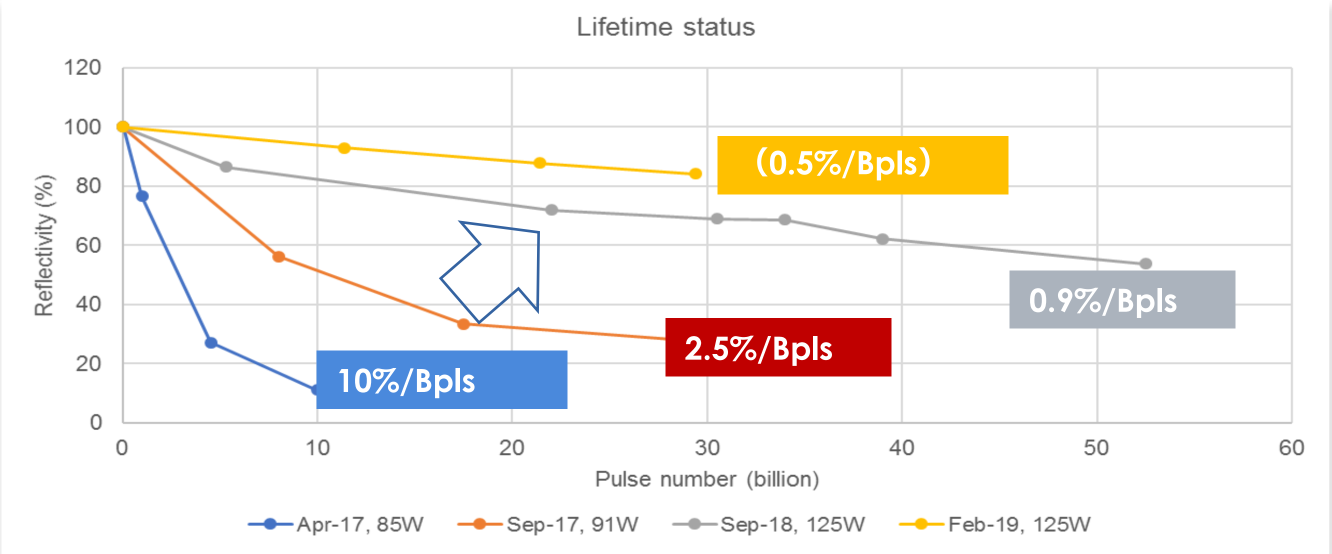
Two beam lines for EUV test in "New SUBARU"

GIGAPHOTON

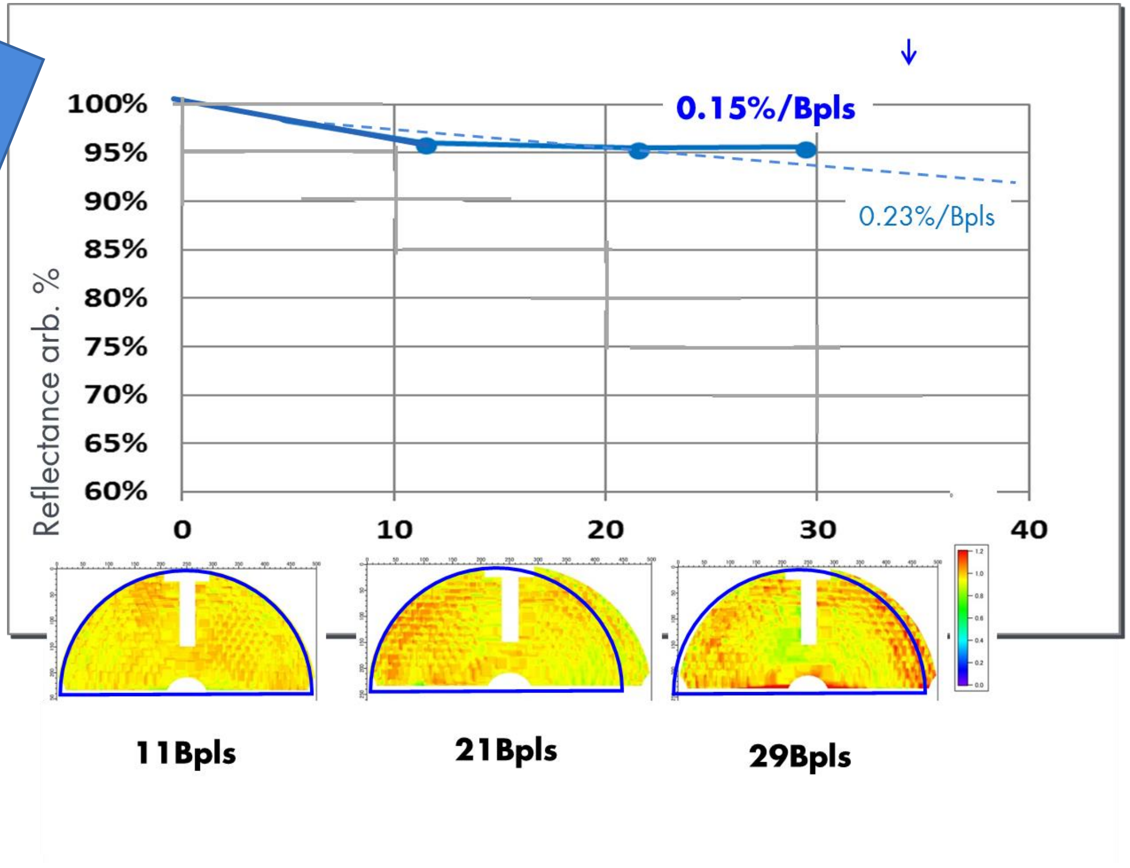
Collector Mirror: Lifetime Status

- 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)



SUMMARY

Summary

Pilot#1 is up running and its demonstrates HVM capability;

- *High conversion efficiency 4.5% is realized with Pre-pulse technology.*
- *High speed (>90m/s) & small (20micron) droplet is realized.*
- *High power CO2 laser power level is 20kW.*
- *Output power 250W in-burst power @50% duty (125W ave.) several min.*
- *Pilot#1 system achieved potential of 89% Availability (2weeks average).*
- ***-0.15%/Gpls with 125W ave.** was demonstrated during 30Mpls with mirror test.*

Redefined Target Power to ≧330W

- *Gigaphoton redefined power target to ≧330W ave. with -0.05%/Gpls, >90% availability*
- ***CO2 laser power upgrade >27kW** is successfully demonstrated.*
- ***CE enhancement condition >6%** is clarified through small experimental device by Tomson scattering measurement.*

Component level demonstration of ≧330W operation will be by Q4 2019

Acknowledgemen…

Thank you for co-operation:

- 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*
- *Prof. Takeshi Higashiguchi in Utsunomiya Univ.*
- *Prof. Takeo Watanabe in New Subaru Institute*
- *Dr. Jun Sunahara, Predu Univ. and Dr. Katsunori Nishihara, Prof. Hiroaki Nishimura in Osaka University*

Thank you for funding:

EUV source development funding is partially support by *NEDO ((New Energy and Industrial Technology Development Organization) in JAPAN*

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 Saito and other engineers*

2018 EUVL Workshop

June 11-14, 2018, CXRO, LBL, Berkeley, CA

THANK YOU

GIGAPHOTON