Nov. 7-9, 2016, Amsterdam, The Netherlands

DEVELOPMENT OF 250W EUV LIGHT SOURCE FOR HVM LITHOGRAPHY

Nov. 8, 2016 *International Workshop on EUV & Soft X-Ray Sources 2016*

T. Yanagida, S. Nagai, G. Soumagne, K. M Nowak, Y. Kawasuji, H. Tanaka, H. Hayashi, Y. Watanabe, T. Hori, Y. Shiraishi, T. Yamada, T. Abe, T. Okamoto, T. Kodama, H. Nakarai, T. Yamazaki, T. Saitou and H. Mizoguchi

Gigaphoton Inc., 3-25-1 Shinomiya, Hiratsuka-shi, Kanagawa 254-8555, Japan

AGENDA

- Introduction
- 250W Pilot#1 System
  - Configuration & Key Components
    - CO2 Driver Laser, Droplet Generator, Mitigation
    - Pre-Pulse Technology
      - High CE
      - Plasma Parameter: Measurement & Simulation
  - Average Power & CE
- Prototype LPP Source Systems
  - Brief Update
- EUV Source Development - Higher Power
- Summary

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Technology Concept

Pre-pulse laser technology

Short pulse laser

- High conversion efficiency
- High ionization rate

CO_2 laser technology

Short pulse multi-line oscillator

- High efficiency

Debris mitigation technology

Super conductive magnets

- Protecting collector mirror from debris.

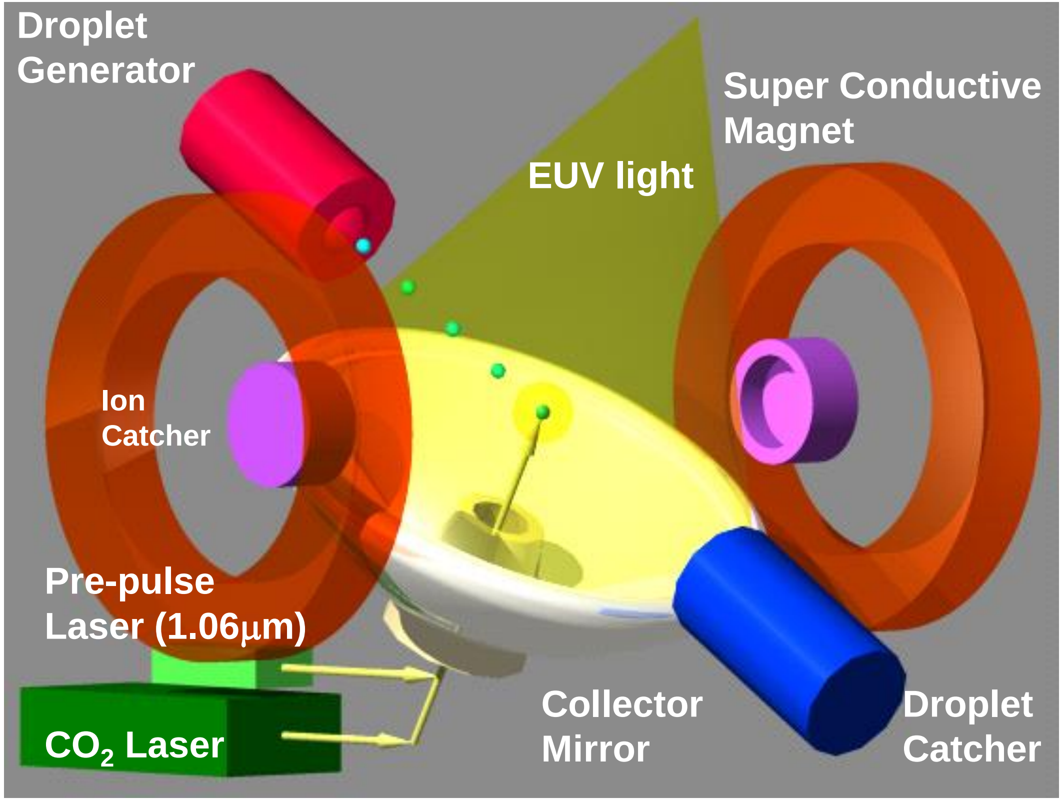
Shooting control technology

Accurate position and timing control between lasers and droplets

- High system performance

Collector Mirror

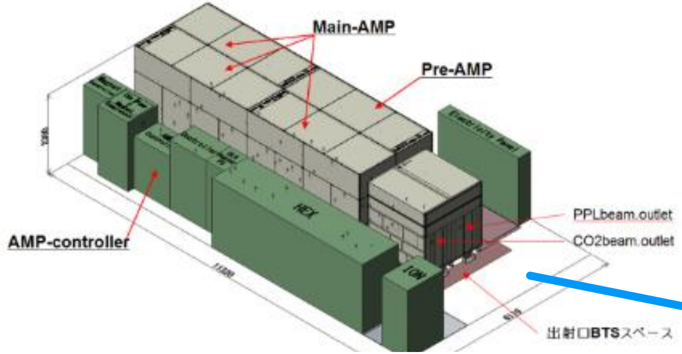
Highly efficient out-of-band reduction with grating structure



Gigaphoton EUV Sources

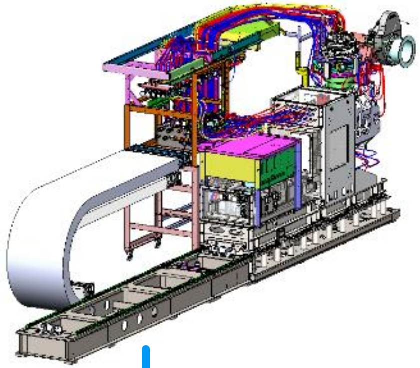
NEW - Pilot #1

in operation since Aug. 2016



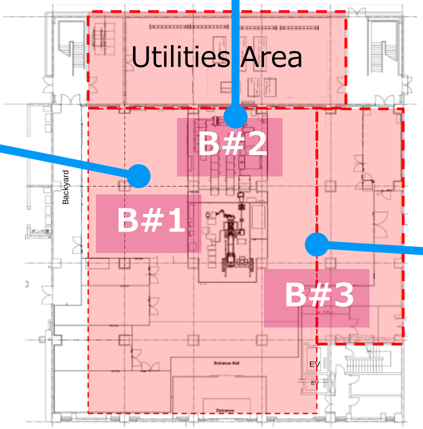
Pilot #1

Production tool compatible
Target: 250W



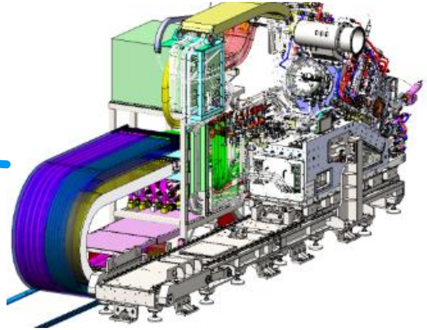
Proto #1

1st EUV light source
from Oct. 2012
10W level



Proto #2

upgrade of Proto #1
from Nov 2013
>100W level



Pilot and Proto Target Specifications

Operational Specification Concept		**Pilot #1** HVM readiness	**Proto #2** Power scaling	**Proto #1** Proof of concept
Target Performance	EUV Power	250 W	> 100 W	25 W
	CE	4%	3.5%	3%
	Pulse rate	100 kHz	100 kHz	100 kHz
	Output angle	62° (wrt. horizontal, matched to NXE)	62° (wrt. horizontal, matched to NXE)	0°, horizontal
	Availability	> 75%	1 week operation	1 week operation
Technology	Droplet	< 20 μm	20 μm	20 – 25 μm
	CO_2 laser	**27 kW**	**20 kW**	5 kW
	Pre-pulse laser	picosecond	picosecond	picosecond
	Debris mitigation	> 3 months	10 days	validation of magnetic mitigation

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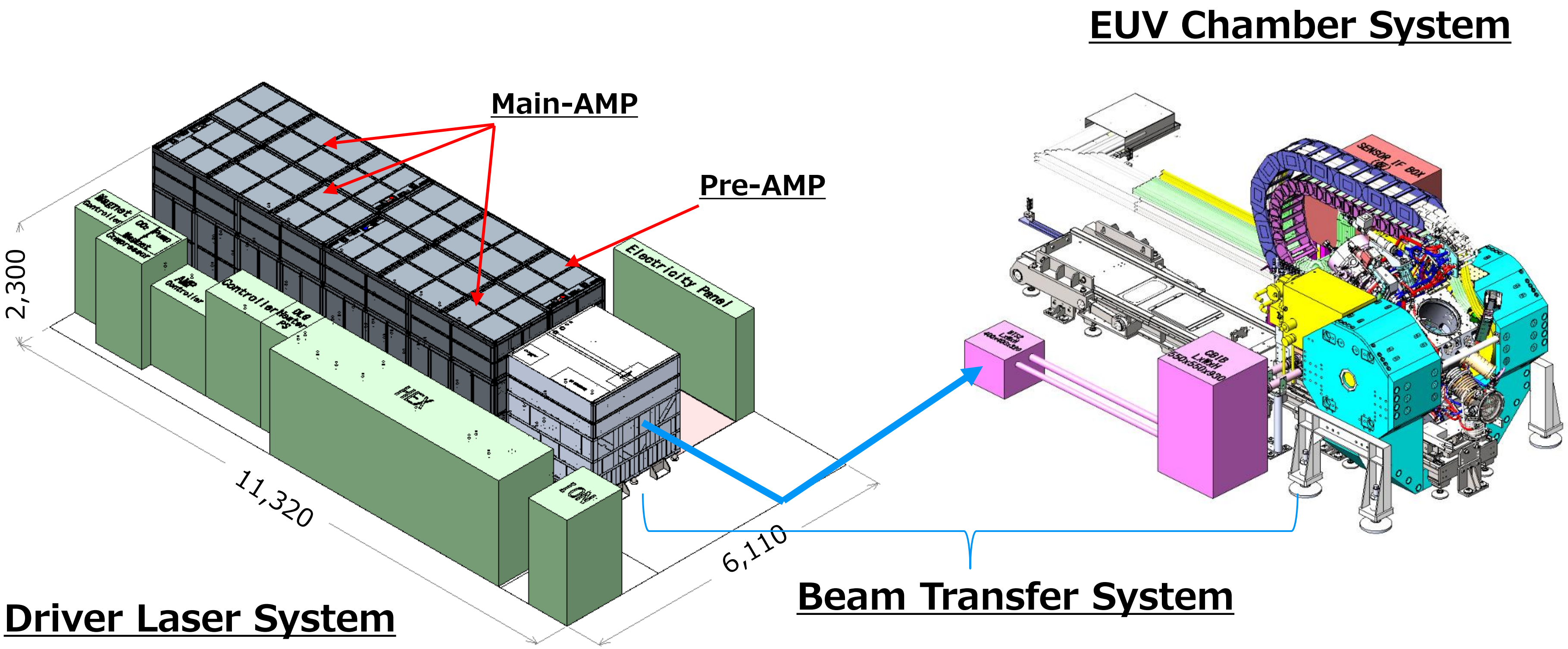
Pilot#1: Configuration - System



EUV Chamber System

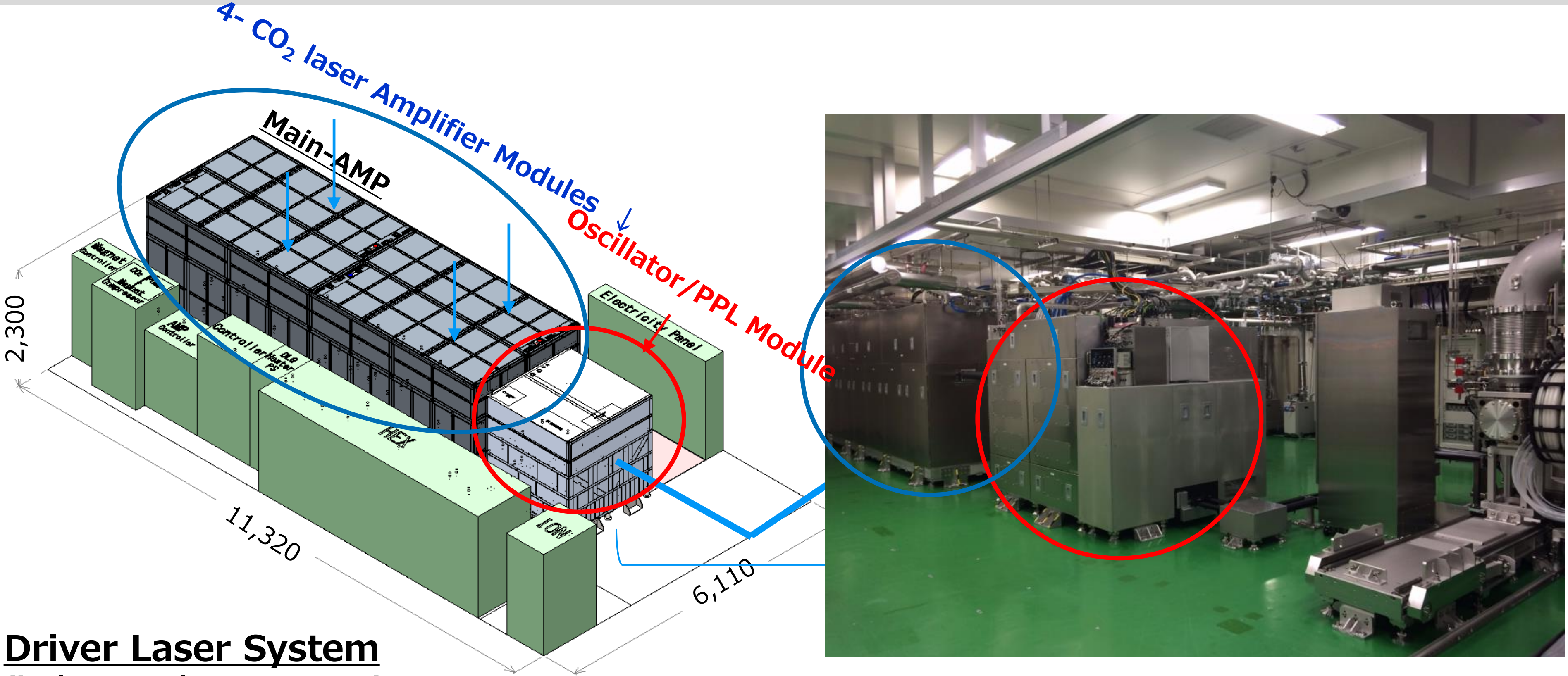
Main-AMP

Pre-AMP

Beam Transfer System

Driver Laser System

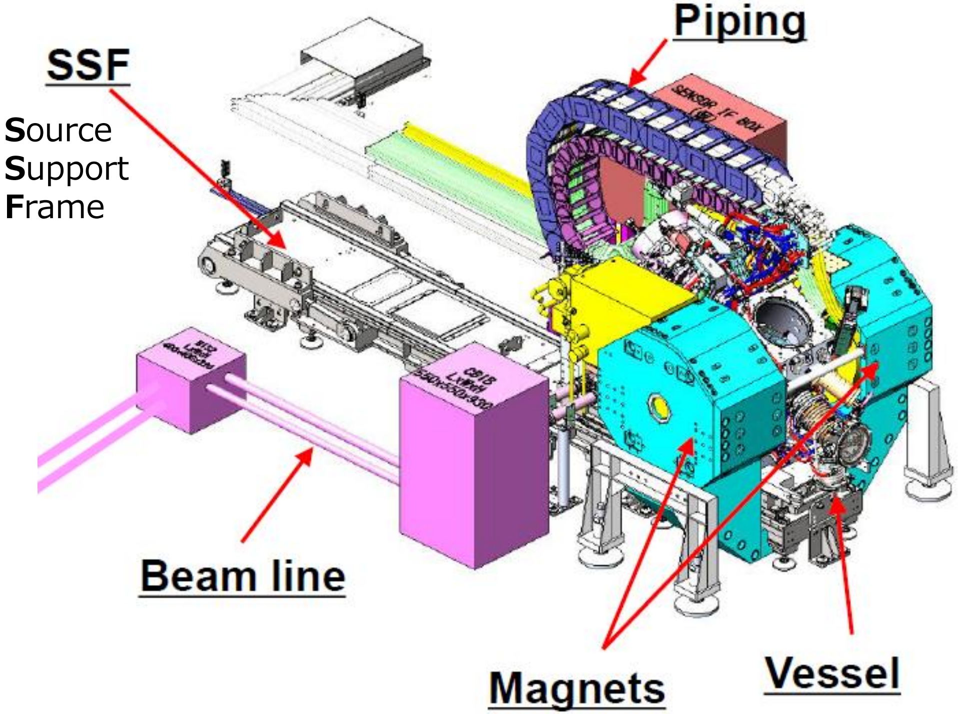
Pilot#1: Configuration – Driver Laser & PPL

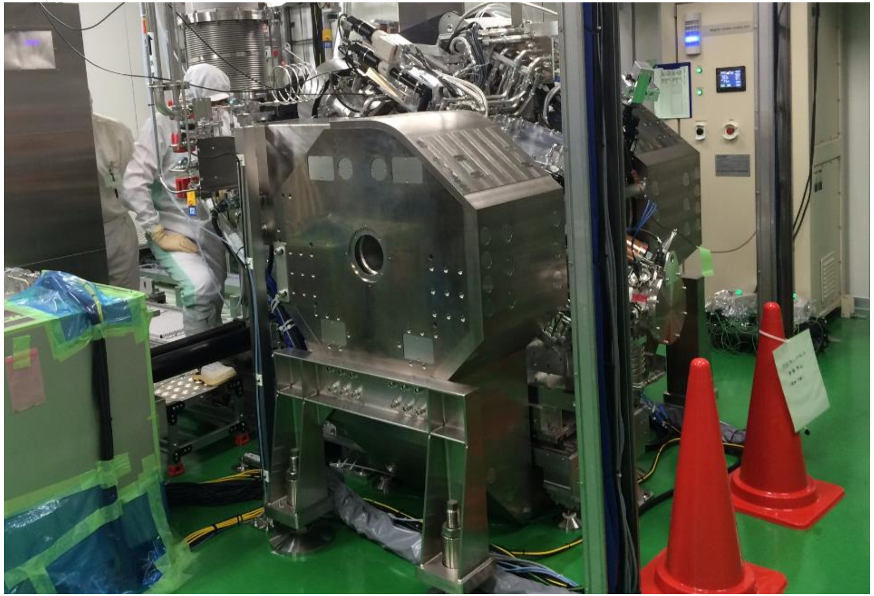


Driver Laser System
(incl. Pre-Pulse-Laser, PPL)

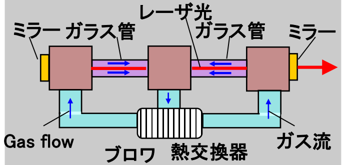
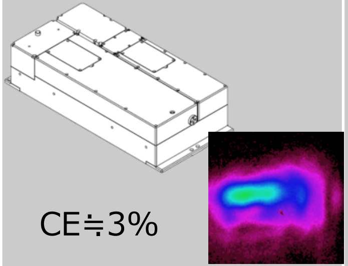
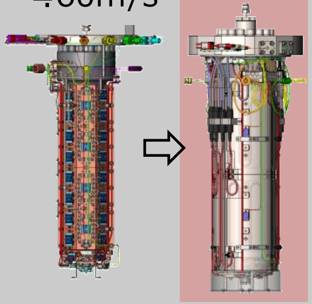
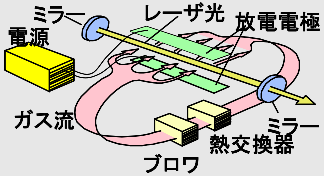
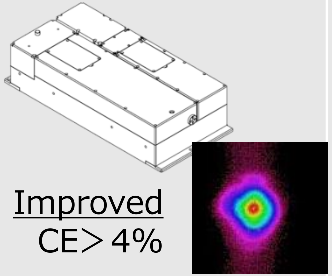
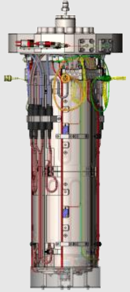
Pilot#1 : Configuration - EUV Chamber System

EUV Chamber System

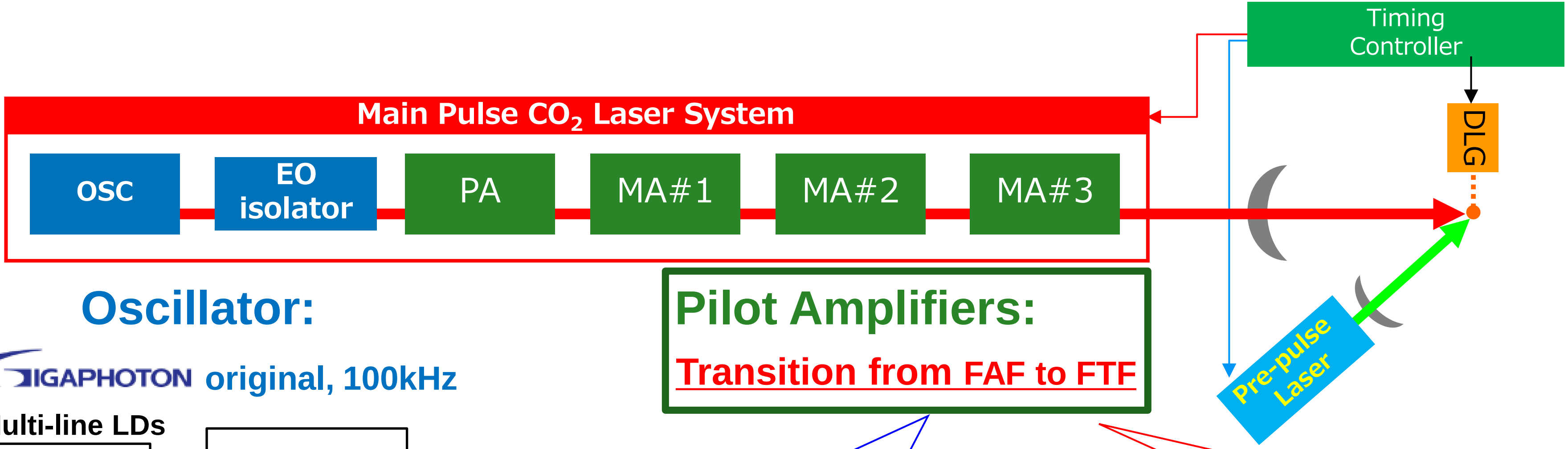




Evolution to Pilot#1 (compared to Proto#2)

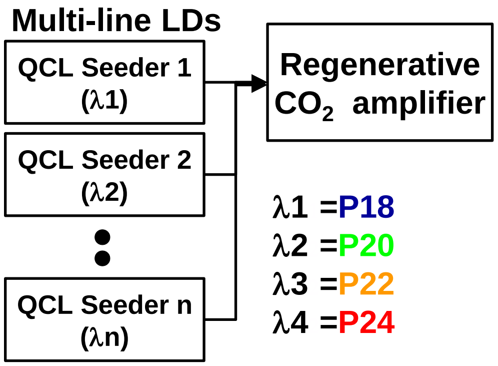
	①CO2 Laser	②Pre-Pulse laser	③DLG	④Debris Mitigation	Target
Proto#2 	Trans. Gas Flow×1 Fast Axial Flow×3 20kW FAF CO2 laser 	Pico Second Pre-pulse laser  CE≒3%	High Speed ≒60m/s 	Type-F Design > 100H	125W 100H ⇩ 250W 100H
Pilot#1 	Trans. Gas Flow×4 27kW FTF CO2 laser 	Pico Second Pre-pulse laser  Improved CE＞4%	High Speed  ≒90m/s	**Type-G Design** ＞1000H	250W 1000H

1) CO2 laser for Pilot#1 (1)

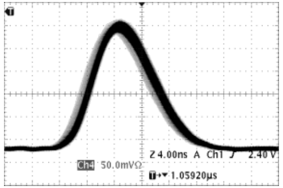


Oscillator:

GIGAPHOTON original, 100kHz



λ1 =P18
λ2 =P20
λ3 =P22
λ4 =P24

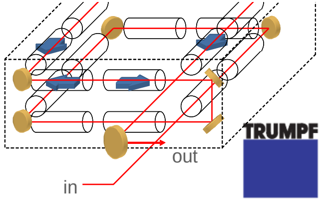


14 ns FWHM

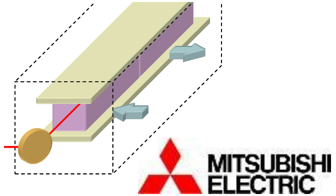
Pilot Amplifiers:

Transition from FAF to FTF

Fast axial flow (FAF) CO_2 laser amplifier



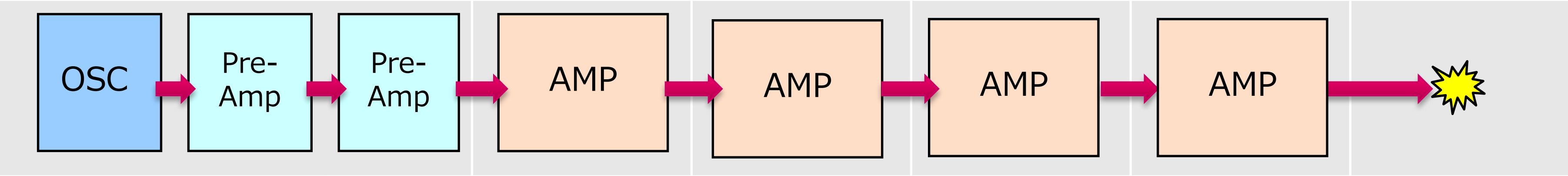
Fast transverse-flow (FTF) CO_2 laser amplifier



1) CO2 laser for Pilot#1 (2)

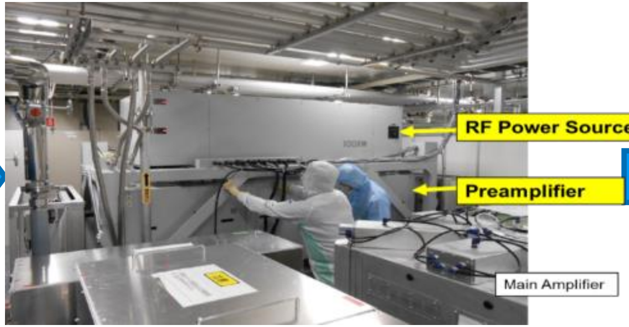
<Configuration & History of Amplifier development>

In cooperation with MITSUBISHI ELECTRIC



	OSC	PA1	MA1	MA2	MA3	Plasma Point
For 250W EUV	100W	5kW	10kW	20kW	30kW	25kW

Basic Experiment in 2013



1st Amplifier installation in 2015

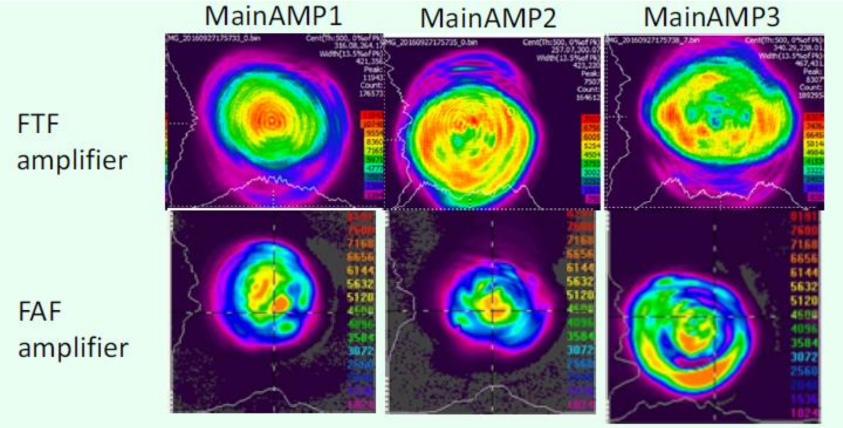
Amplifier system installation in 2016

1) CO2 laser for Pilot#1 (3)

Why shift from Fast-Axial-Flow (FAF) to Fast-Transverse-Flow (FTF) ?

- Larger beam profile, i.e. reduced laser pulse fluence on optics
- Shorter propagation path
- No internal folding mirrors

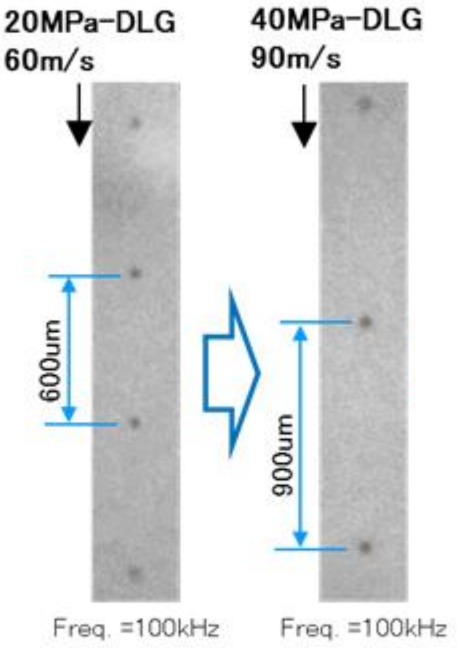
Overall, improved beam quality & beam profile with higher stability which result in higher CE



3) Droplet Generator for Pilot#1 (1)

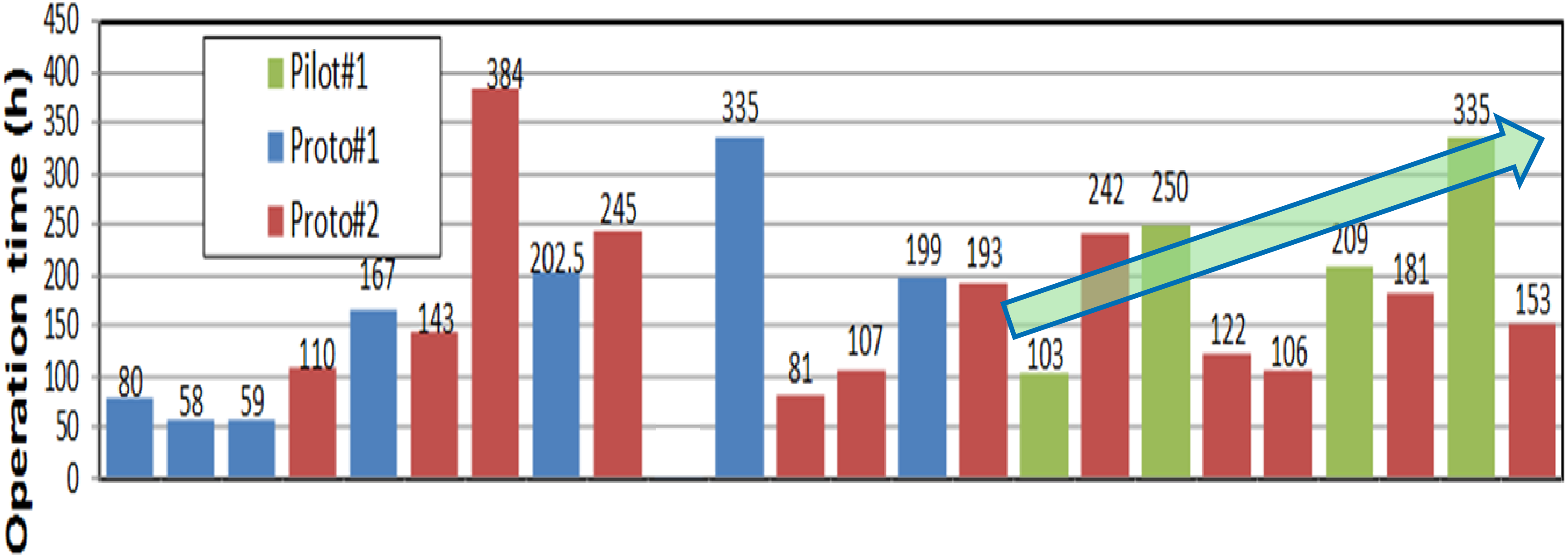
- High speed droplet generator was successfully transferred to Pilot system

		2013 Jan Proto#1	2014 Sep Proto#2	2015 Dec Proto#2	2016 Pilot#1
Droplet speed	m/s	45	60	**90**	**90**
Back pressure	MPa	12	20	**40**	**40**
Max Repetition rate	kHz	50	80	100	100



3) Droplet Generator for Pilot#1 (2)

- Lifetime of New Droplet Generator for Pilot#1 extended to more than 200 hours.

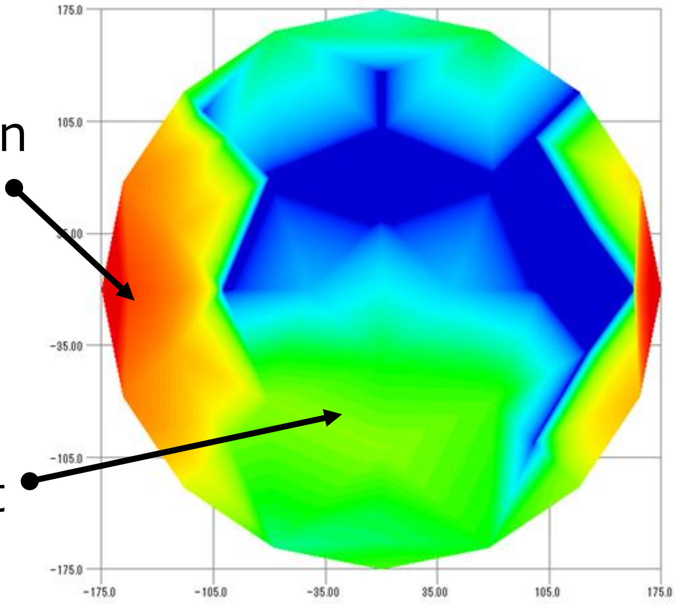


4) Debris - Mitigation Challenges from Proto#2

Root Cause

①Back Diffusion

②Miss Hit (Laser-Droplet)



Data from Proto#2,
mapping from witness samples placed on a dummy collector

Mitigation Improvement for Pilot#1, Type-G design:

H2-flow pattern inside vacuum chamber

Cooling system performance

Shooting accuracy Laser-Droplet

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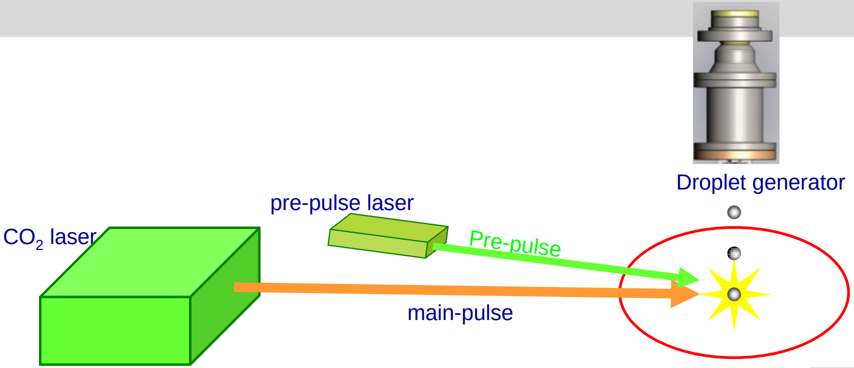
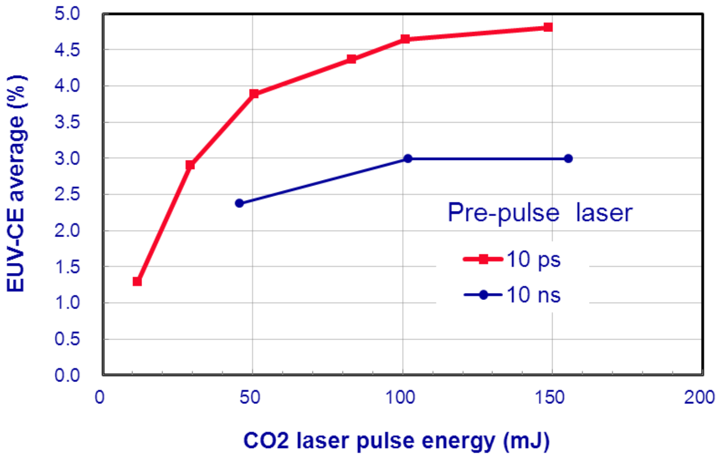
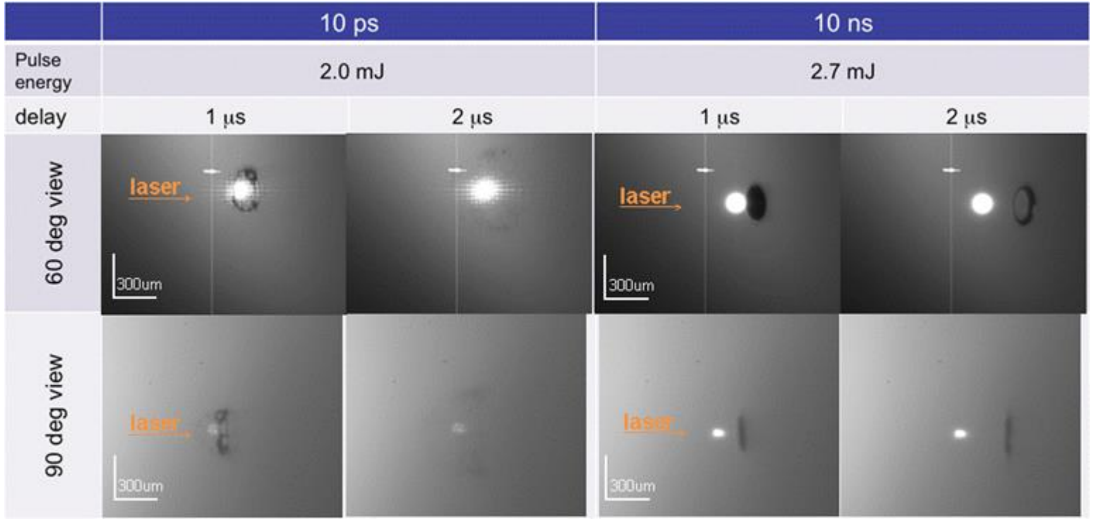
Pre-Pulse Technology (1)



- Sn mist shape depends on pre-pulse laser pulse length
- Nano-cluster distribution could be a key factor for high CE

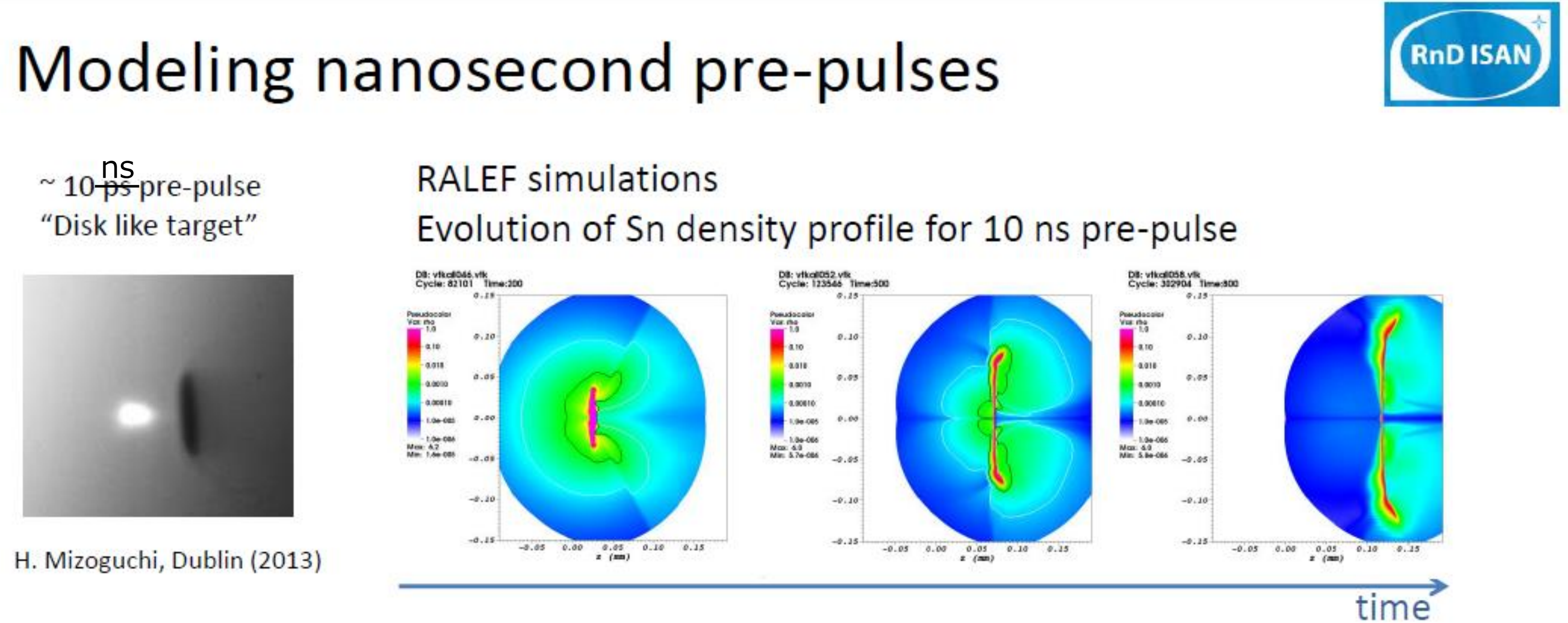
CO2 pulse enegy vs. EUV-CE





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

Pre-Pulse Technology (2)



Modeling nanosecond pre-pulses

RnD ISAN

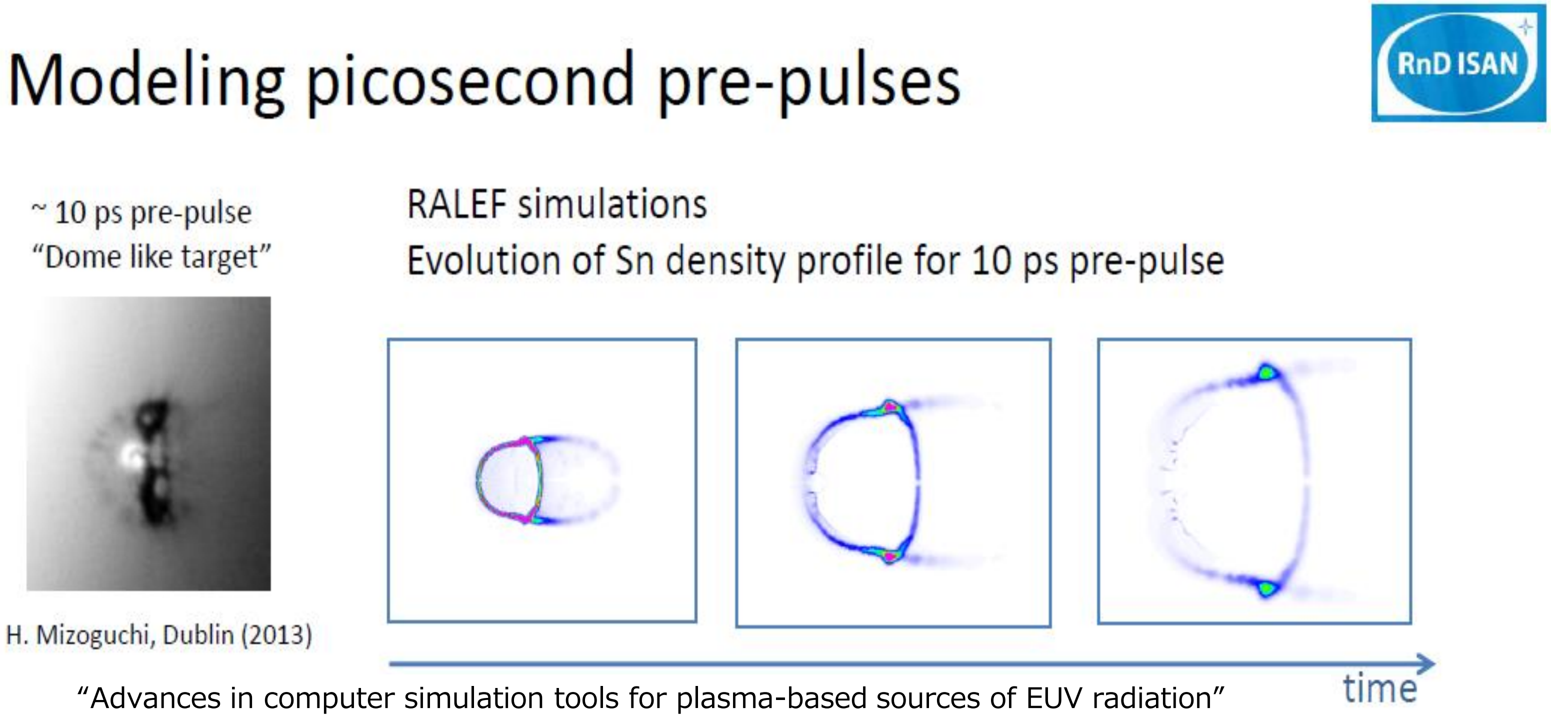
~ 10 ~~ps~~ ns pre-pulse
"Disk like target"

H. Mizoguchi, Dublin (2013)

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

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

Pre-Pulse Technology (3)



Modeling picosecond pre-pulses

~ 10 ps pre-pulse
“Dome like target”

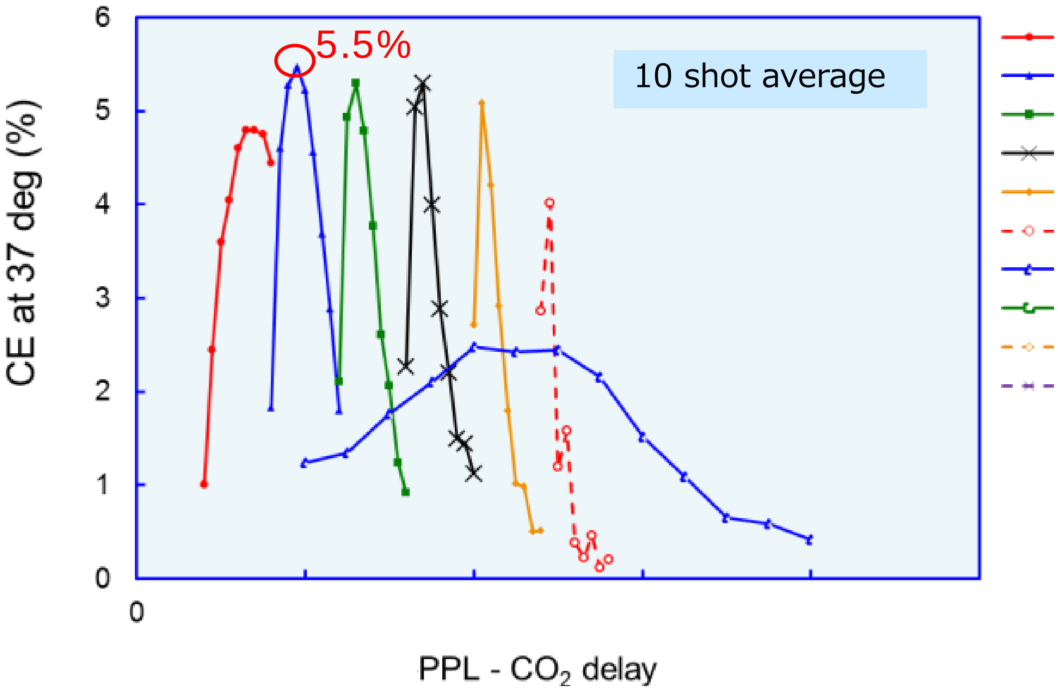
H. Mizoguchi, Dublin (2013)

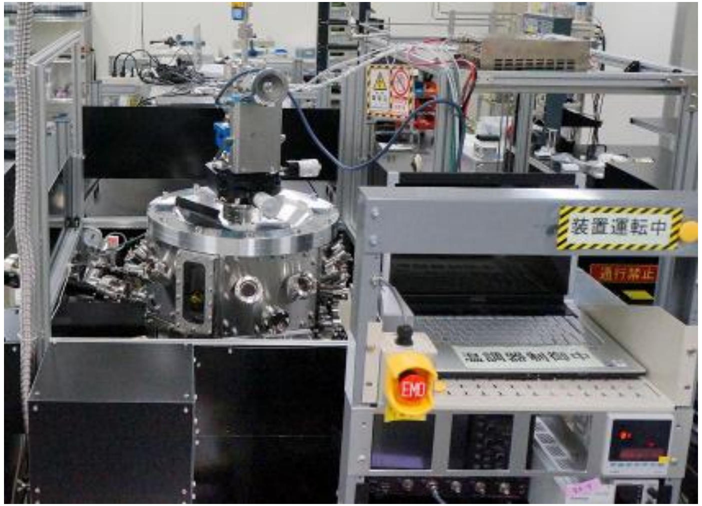
RALEF simulations
Evolution of Sn density profile for 10 ps pre-pulse

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

Pre-Pulse Technology (4)

In small experimental device, we observed **5.5% CE** under optimized condition.**17 % increase** from old champion data (CE=4.7%).





Experimental Device,
10Hz Source

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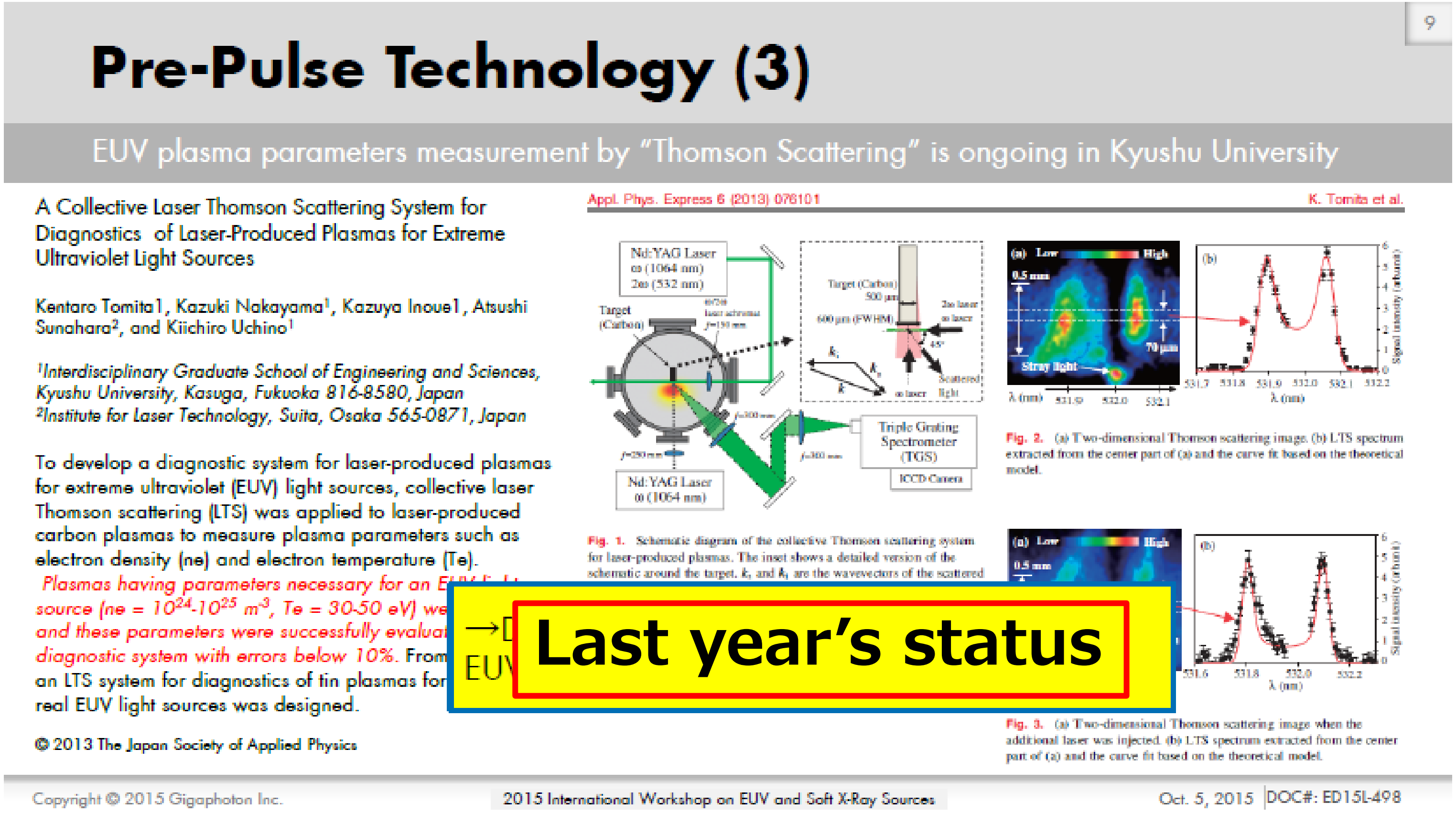
Pre-Pulse Technology (5)



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Pre-Pulse Technology (3)

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

Appl. Phys. Express 6 (2013) 076101

K. Tomita et al.

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 E*
source (ne = 10^{24}-10^{25} m^{-3}, Te = 30-50 eV) we
and these parameters were successfully evaluat
diagnostic system with errors below 10%. From
an LTS system for diagnostics of tin plasmas for
real EUV light sources was designed.

→D
EUV

© 2013 The Japan Society of Applied Physics

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

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.

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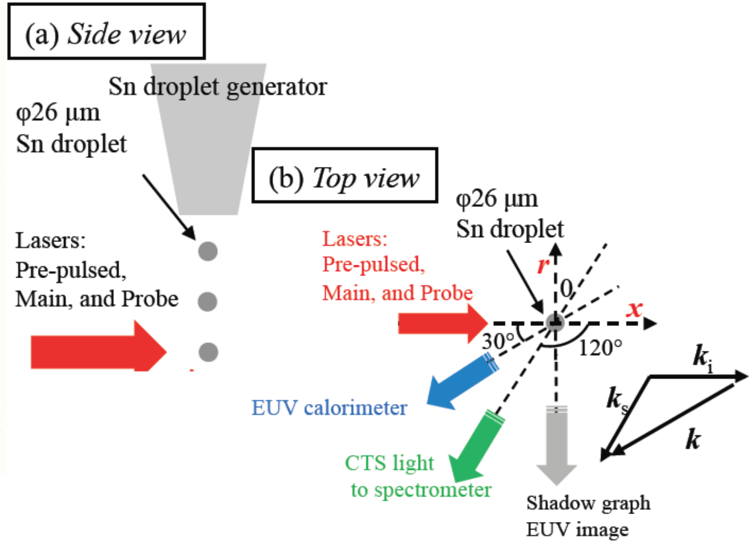
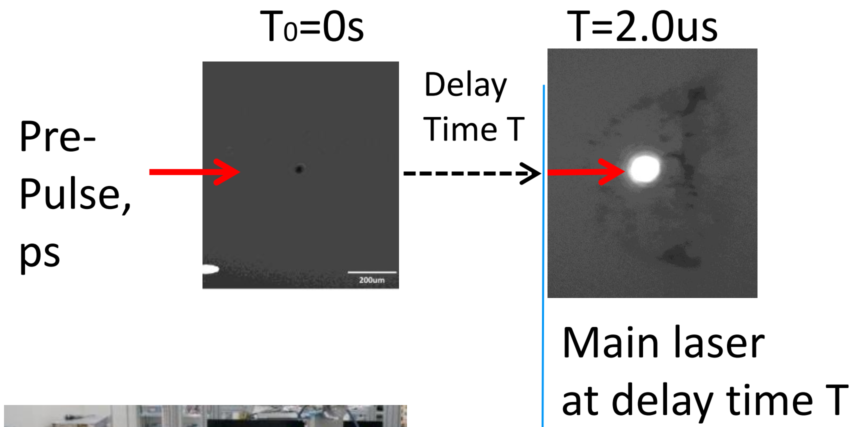
2015 International Workshop on EUV and Soft X-Ray Sources
Oct. 5, 2015 DOC#: ED15L-498

Last year's status

Update: Thomson Scattering Measurement on EUV lithography plasma





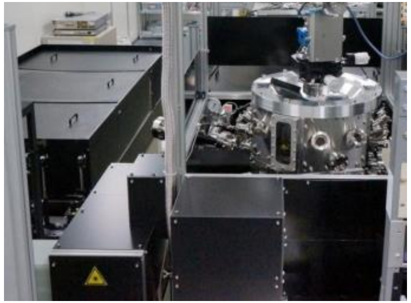
T₀=0s

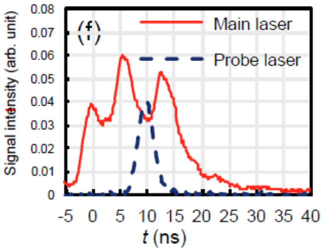
T=2.0us

Pre-Pulse, ps

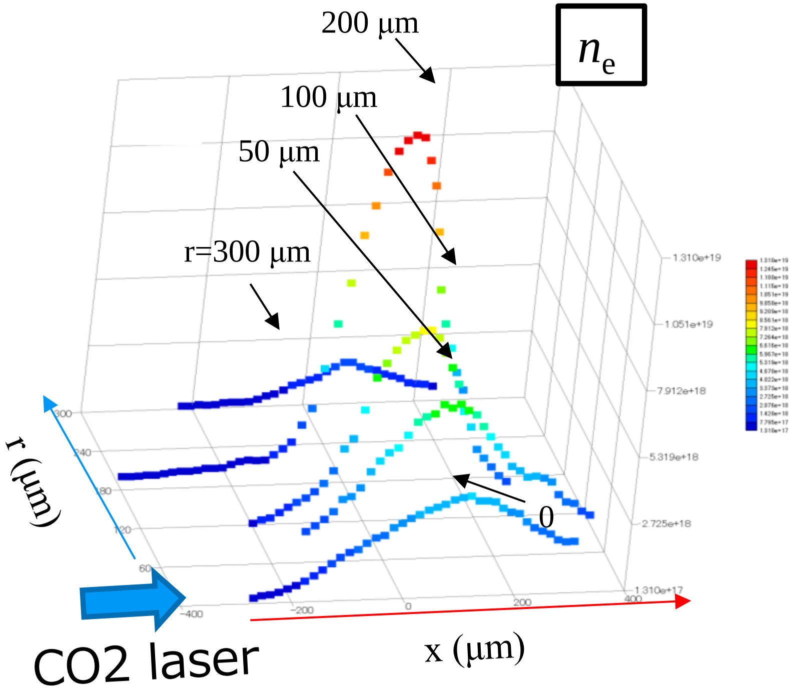
Delay Time T

Main laser at delay time T





Next Presentation (S12) by Kentaro Tomita (Kyushu Univ.)



Entitled:

"Correlation of Fundamental Plasma Parameters with EUV Emission Profiles of Laser-produced Sn Plasmas for EUV Lithography Light Sources"

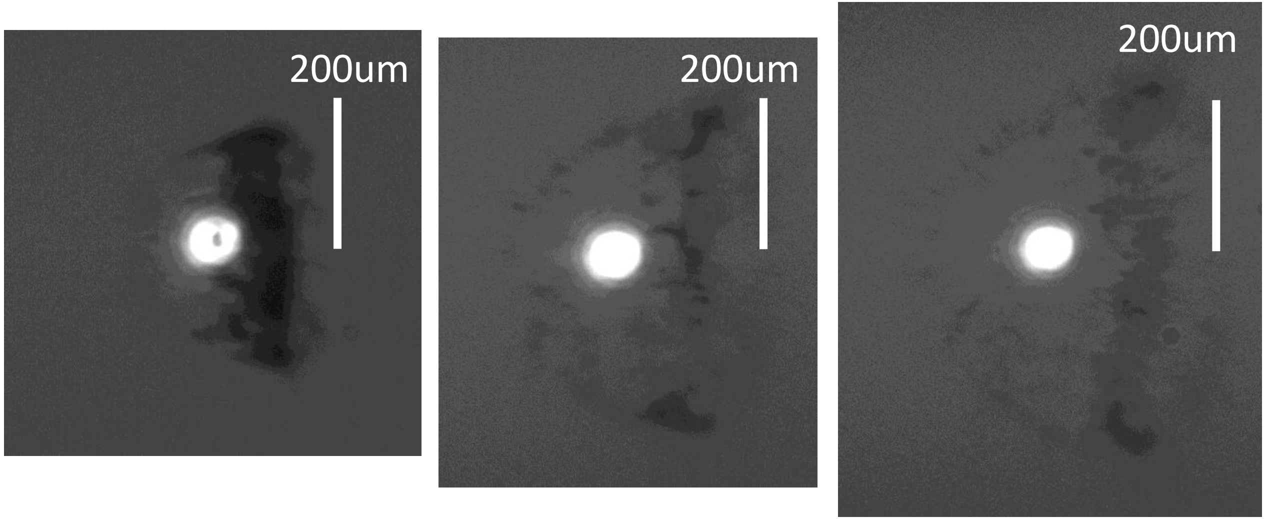
Plasma Simulation

Simulations performed with code RZLINE
from RnD-ISAN, Troitsk, Russia

Initial Target Distribution - Shadowgraph

- Sn target at 1.3us, 2.0us and 2.5us after the application of the pre-pulse as observed by Shadowgraph:

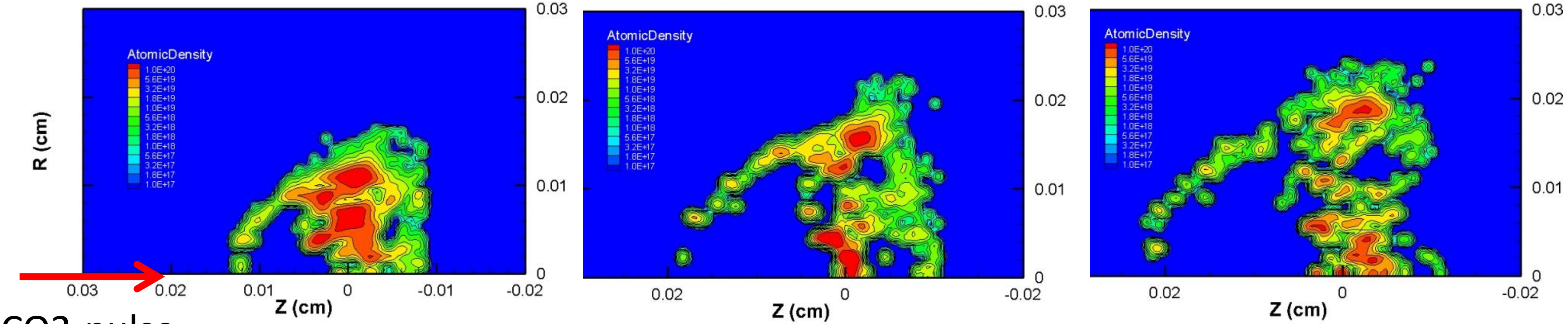
Pre-pulse
at 0us



after: 1.3us 2.0us 2.5us

Initial Target Distribution - Simulation

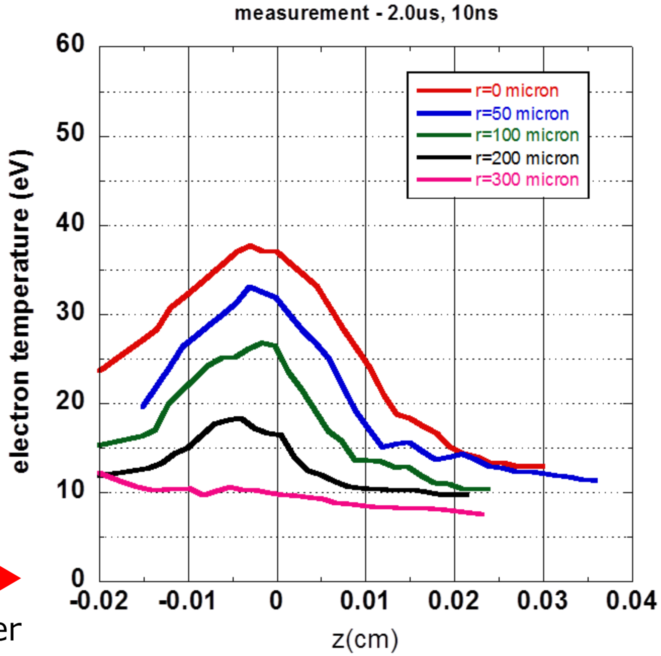
- Target distribution generated from Shadowgraph data
  - » axial symmetry with respect to z-axis



CO2-pulse applied at: 1.3us 2.0us 2.5us after pre-pulse

Electron temperature at 2.0us, 10ns

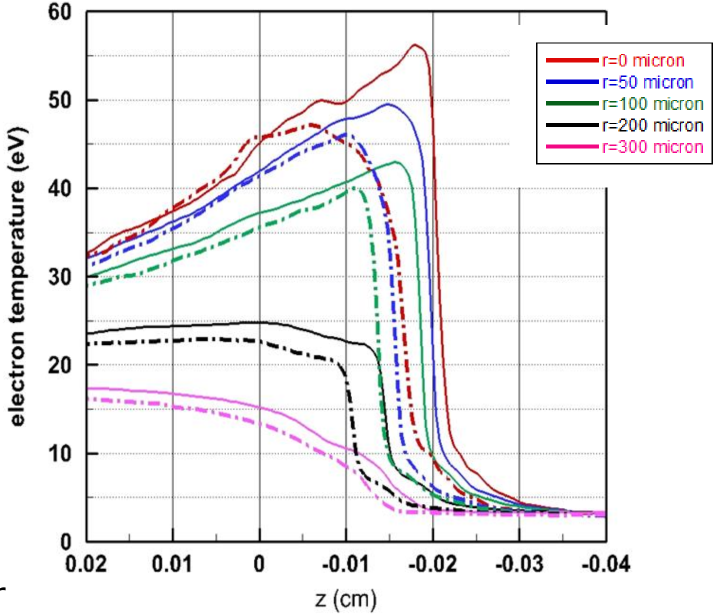
- Te, measured



CO2 laser

- Te, simulated

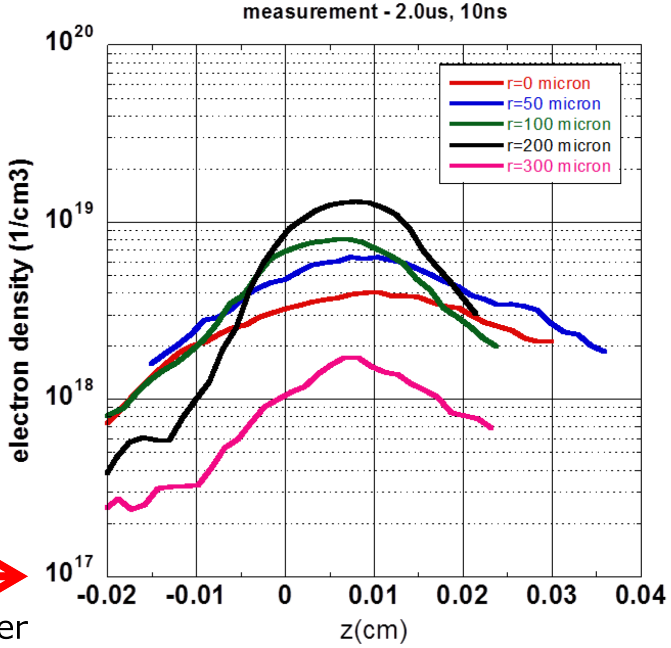
CO2 pulse energy
line: 100mJ,
dash-dot: 85mJ



CO2 laser

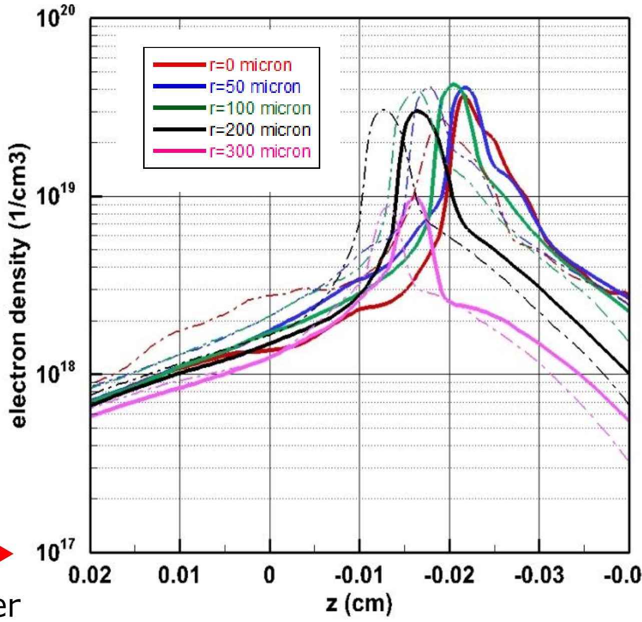
Electron density at 2.0us, 10ns

- ne, measured



- ne, simulated

CO2 pulse energy
line: 100mJ,
dash-dot: 85mJ

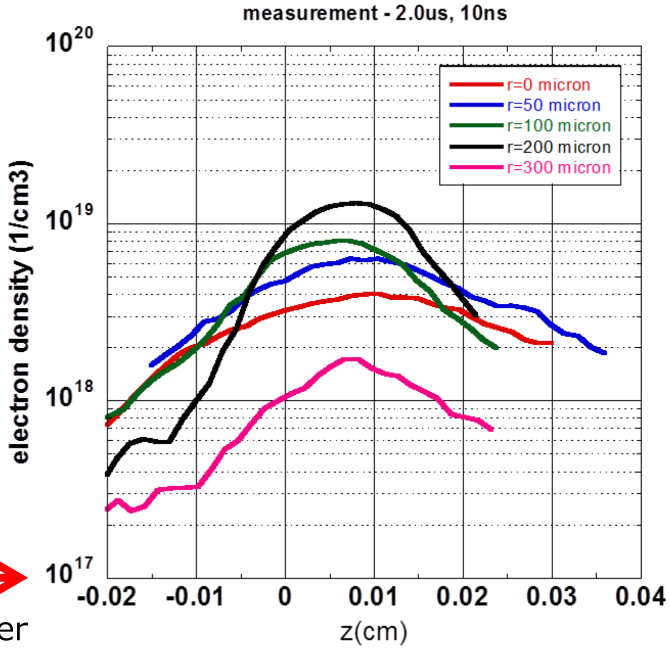


CO2 laser

CO2 laser

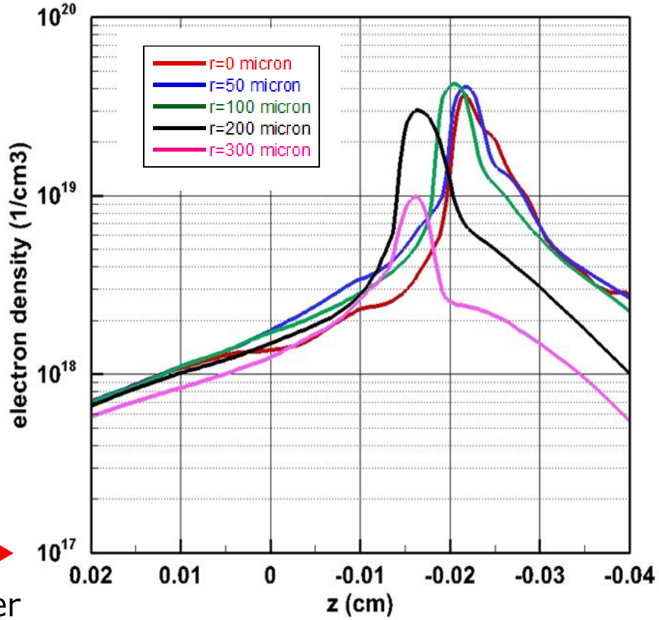
Electron density at 2.0us, 10ns

- ne, measured



CO2 laser

- ne, simulated, 100mJ

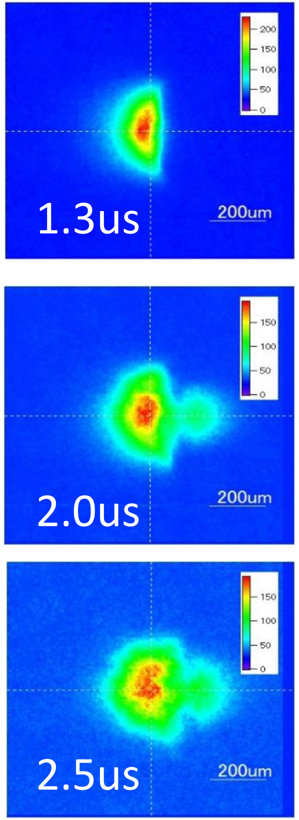


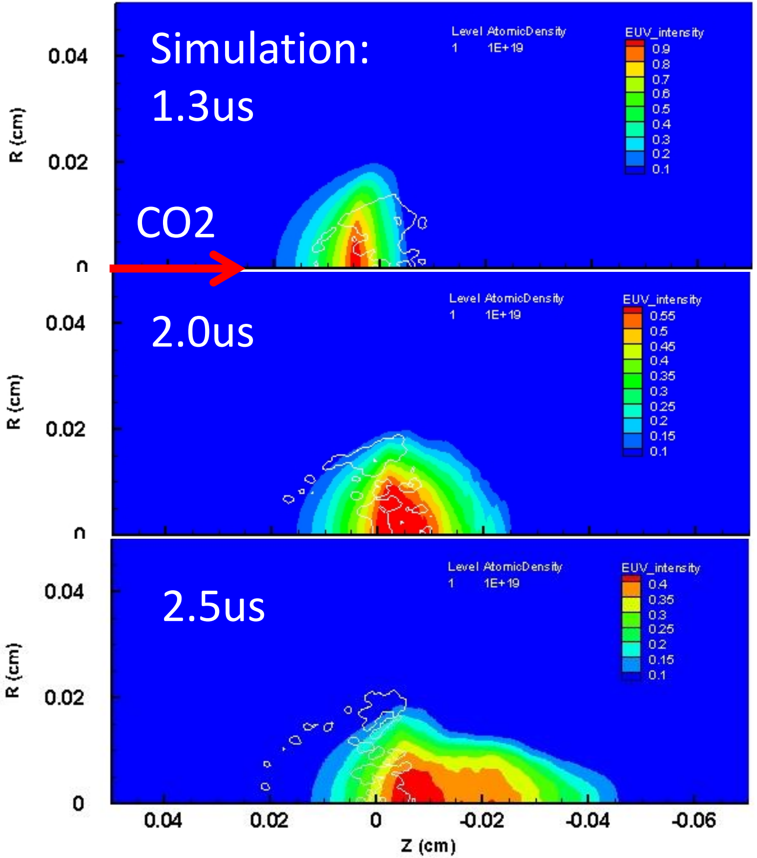
CO2 laser

EUV in-band at 90deg, time averaged

Experiment:

CO2 →





Simulation:

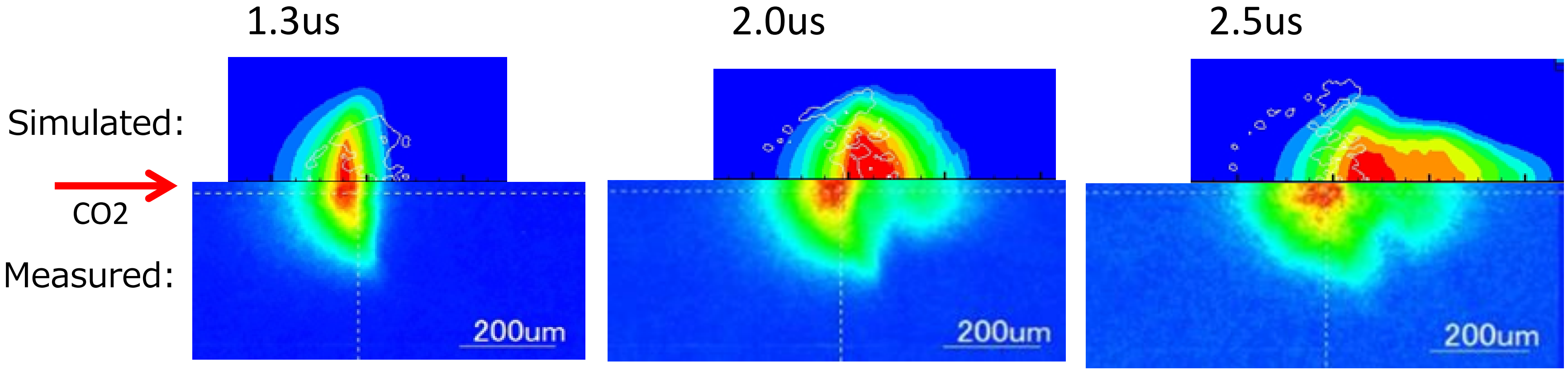
CE (2pi sr)

3.7% (3.1% exp.)

4.0% (4.0% exp.)

3.3% (2.8% exp.)

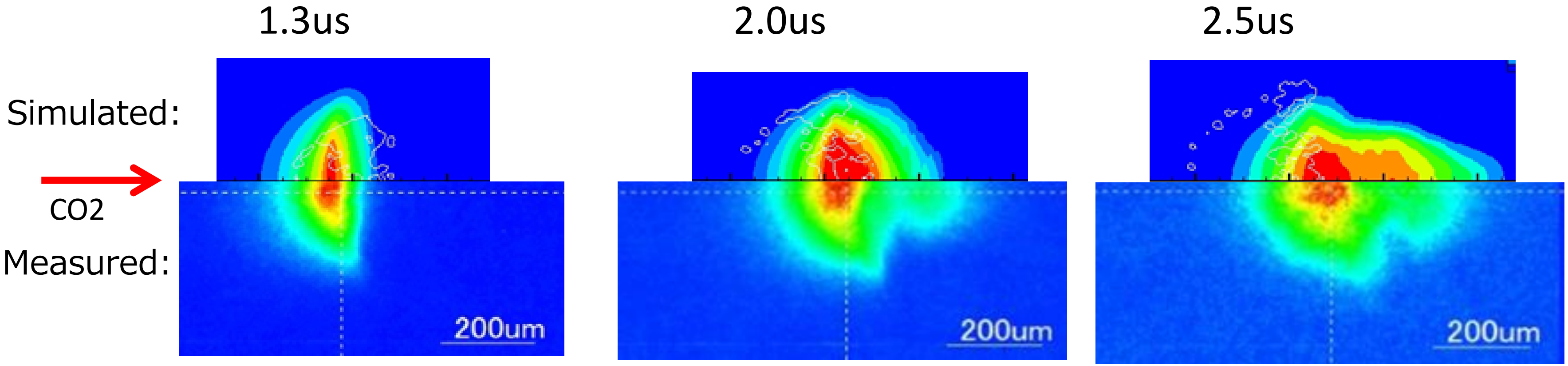
EUV in-band at 90deg, time averaged



Very good agreement at 1.3us but simulated EUV distributions shift at larger delay times whereas measured EUV does not. However...

EUV in-band at 90deg, time averaged

plasma shapes & sizes correspond well:



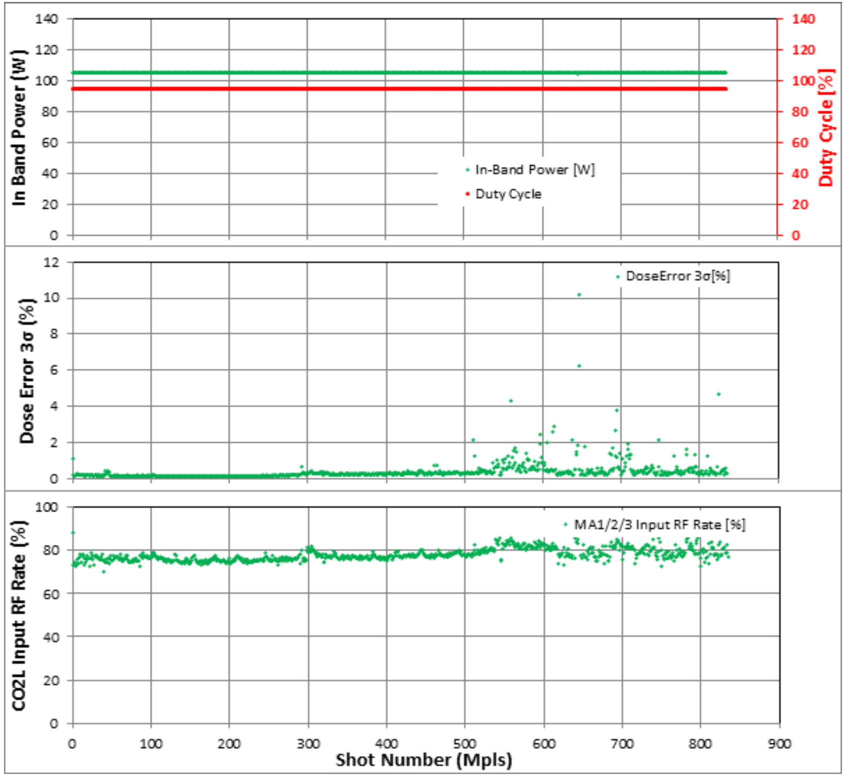
Note: EUV images axially adjusted to better compare distributions

AGENDA

- Introduction
- 250W Pilot#1 System
  - Configuration & Key Components
    - CO2 Driver Laser, Droplet Generator, Mitigation
    - Pre-Pulse Technology
      - High CE
      - Plasma Parameter: Measurement & Simulation
  - Average Power & CE
- Prototype LPP Source Systems
  - Brief Update
- EUV Source Development - Higher Power
- Summary

Pilot#1 - Average Power

Pilot#1 has generated 100W average power with 5% CE !



» Pilot#1 Performance Summary:

» Conversion Eff.	5.0%
» Power (in burst)	105W
» Duty cycle	95%
» Power (average)	100W
» Operation Pls Num.	0.83Bpls
» Operation Time	5hr
» Dose Stab. (avg.)	0.39%(3σ)

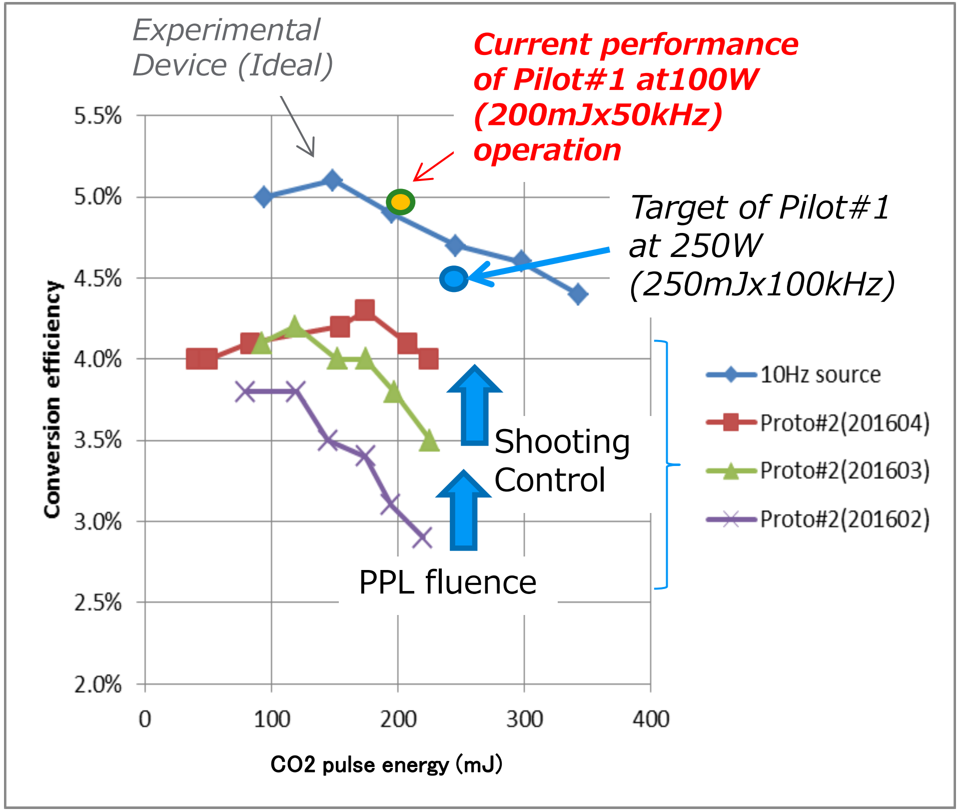
» OSC+4xAmplifier（Mitsubishi Electric)

» CO2 Laser Power	9.1kW
» Pulse Rate	50kHz
» Pulse Duration	～10ns

Pilot#1 – CE (2π sr)

CE improvement

- Proto#2:
  - CE improved to 4.0% at 250W
- Pilot#1: (CE target)
  - CE of 5.0-4.5% at 100-250W



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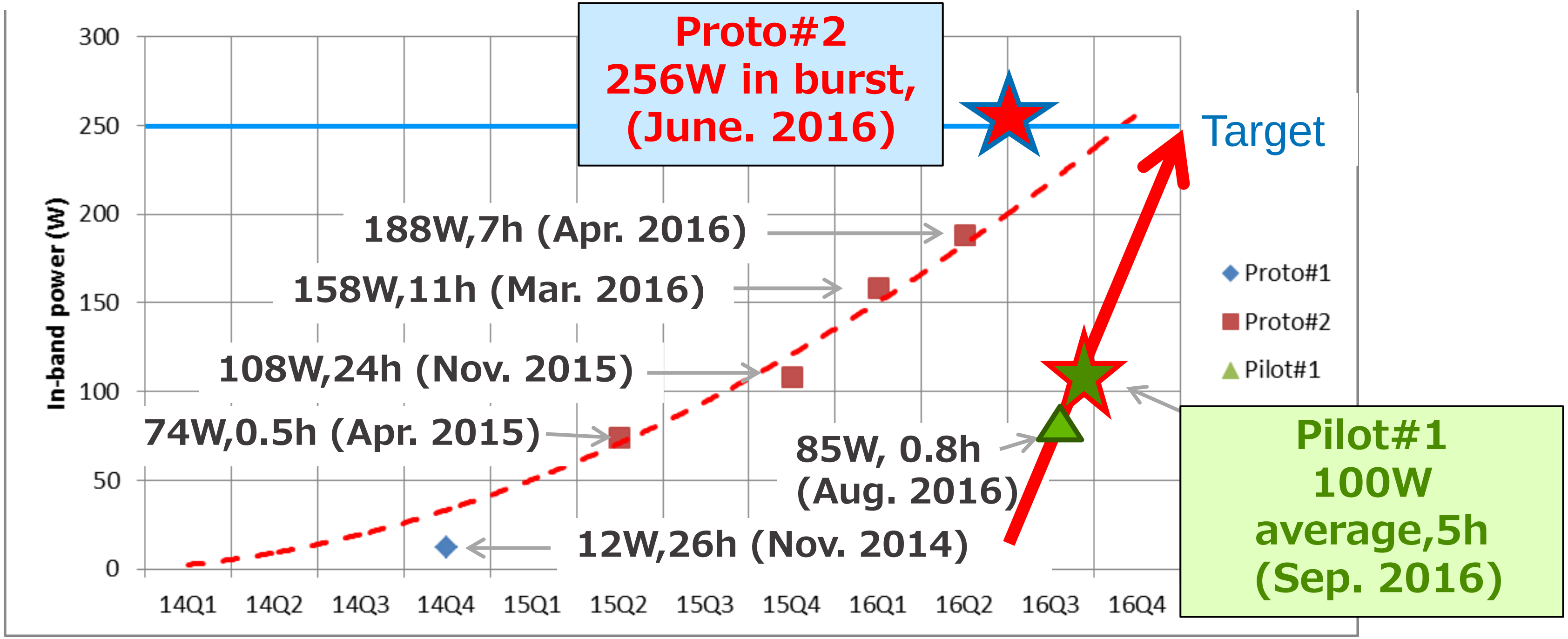
LPP Systems – Power Update (EUV in-band)

Power Status of Proto#2 & Pilot#1 (with dose control)



Proto#2
256W in burst,
(June. 2016)

188W,7h (Apr. 2016)

158W,11h (Mar. 2016)

108W,24h (Nov. 2015)

74W,0.5h (Apr. 2015)

85W, 0.8h
(Aug. 2016)

12W,26h (Nov. 2014)

Pilot#1
100W
average,5h
(Sep. 2016)

Summary of Operation Data and Target (Proto#2, Pilot#1)

	2016 Mar.	2016 Jun.	2016 Aug.	2016 Sep.	2016 Sep.	2016 Dec.
	Proto#2	**Proto#2**	Proto#2	Proto#2	**Pilot#1**	**Pilot#1 target**
Power (avg.)	79-52W	128W	62-99W	**101W**	**100W**	**250W**
Duty Cycle	40-50%	50%	50-80%	**95%**	**95%**	**100%**
Power (in Burst)	158-132W	256W	115-124W	**106W**	**105W**	**250W**
Dose Margin	**40%**	**15%**	**30-35%**	**30%**	**30%**	**30%**
Power (open loop)	221-184W	301W	177W	**151W**	**150W**	**325W**
Conv. Eff. (CE)	**3.5%**	**4.0%**	**4.0%**	**3.8%**	**5.0%**	**4.5%**
Operation time	**119h**	**-**	56h	**49h**	**5h**	**>1000h**
Rep. Rate	100kHz	100kHz	50kHz	**50kHz**	**50kHz**	**100kHz**
CO2 Laser Power	15kW	20kW	13kW	**11.9kW**	**9.1kW**	**25 kW**

AGENDA

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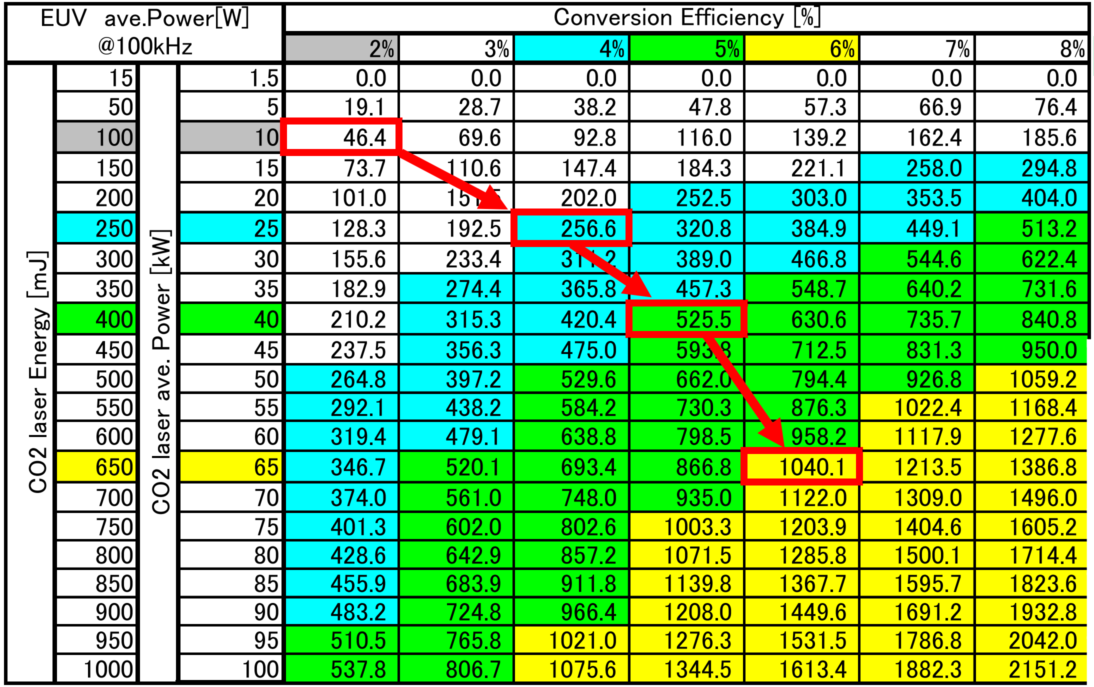
EUV Source Development - Higher Power (1)

- Scaling of EUV Output Power vs. CO_2 Input Power



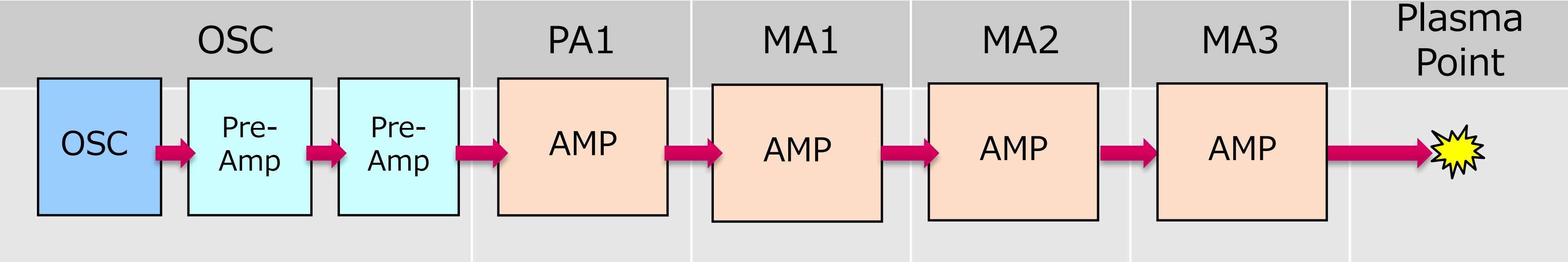
EUV ave.Power[W] @100kHz		Conversion Efficiency [%]						
CO2 laser Energy [mJ]	CO2 laser ave. Power [kW]	2%	3%	4%	5%	6%	7%	8%
15	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
50	5	19.1	28.7	38.2	47.8	57.3	66.9	76.4
100	10	46.4	69.6	92.8	116.0	139.2	162.4	185.6
150	15	73.7	110.6	147.4	184.3	221.1	258.0	294.8
200	20	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 likely scenario:

	HVM (1^{st})	**HVM (2^{nd})**	**HVM (3^{rd})**
EUV power	250W	**500W**	1000W
Pulse Rate	100 kHz	**100kHz**	100kHz
CE	4.5%	**5%**	6%
CO_2 Laser Power	25kW	**40kW**	65kW

EUV Source Development - Higher Power (2)

In cooperation with MITSUBISHI ELECTRIC



OSC		PA1	MA1	MA2	MA3	Plasma Point
250W	100W	5kW	10kW	20kW	30kW	25kW
500W	**100W**	**10kW**	**20kW**	**30kW**	**50kW**	**40kW**

Basic Experiment in 2013

Ist Amplifier installation in 2015

25kW Amplifier system installation in 2016

Summary (Light Source Systems)

- **Pilot#1: operating, with the target to demonstrate HVM capability**
  - **100W EUV average power** (105W stabilized, 95% duty) **with 5% conversion efficiency** (CE) for 5hours operation in September 2016 demonstrated.
  - High conversion efficiency realized with several key engineering efforts.
  - CO_2 driver laser tests for 27kW started.
  - Next target is >100W average power at high duty cycle with collector mirror.
- **Proto#2: power scaling and availability proceeding**
  - 256W in burst power, closed loop operation with CE=4.0% demonstrated.
  - 119 hours, 158-132 W power (in burst, 50% duty, closed loop) demonstrated.
  - 43% availability during 13 weeks average (10h x 5 day).
- **>250W EUV power:**
  - Scaling scenario towards 500W EUV source power is under investigation.

Summary (Pre-Pulse Technology)

- In cooperation with Kyushu University plasma parameters have been measured for an EUV lithography plasma at Gigaphoton’s experimental device.
- Simulation done with RZLINE show good qualitative agreement with experiments. In a next step, spatial resolution of experiment has to be taken into account for a better quantitative comparison.
- Comparison with measured in-band EUV images shows (very) good agreement in plasma size and distribution. However, a plasma shift is observed in simulation contrary to the experiment.

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