EUV Source Development in Japan

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Acknowledgements
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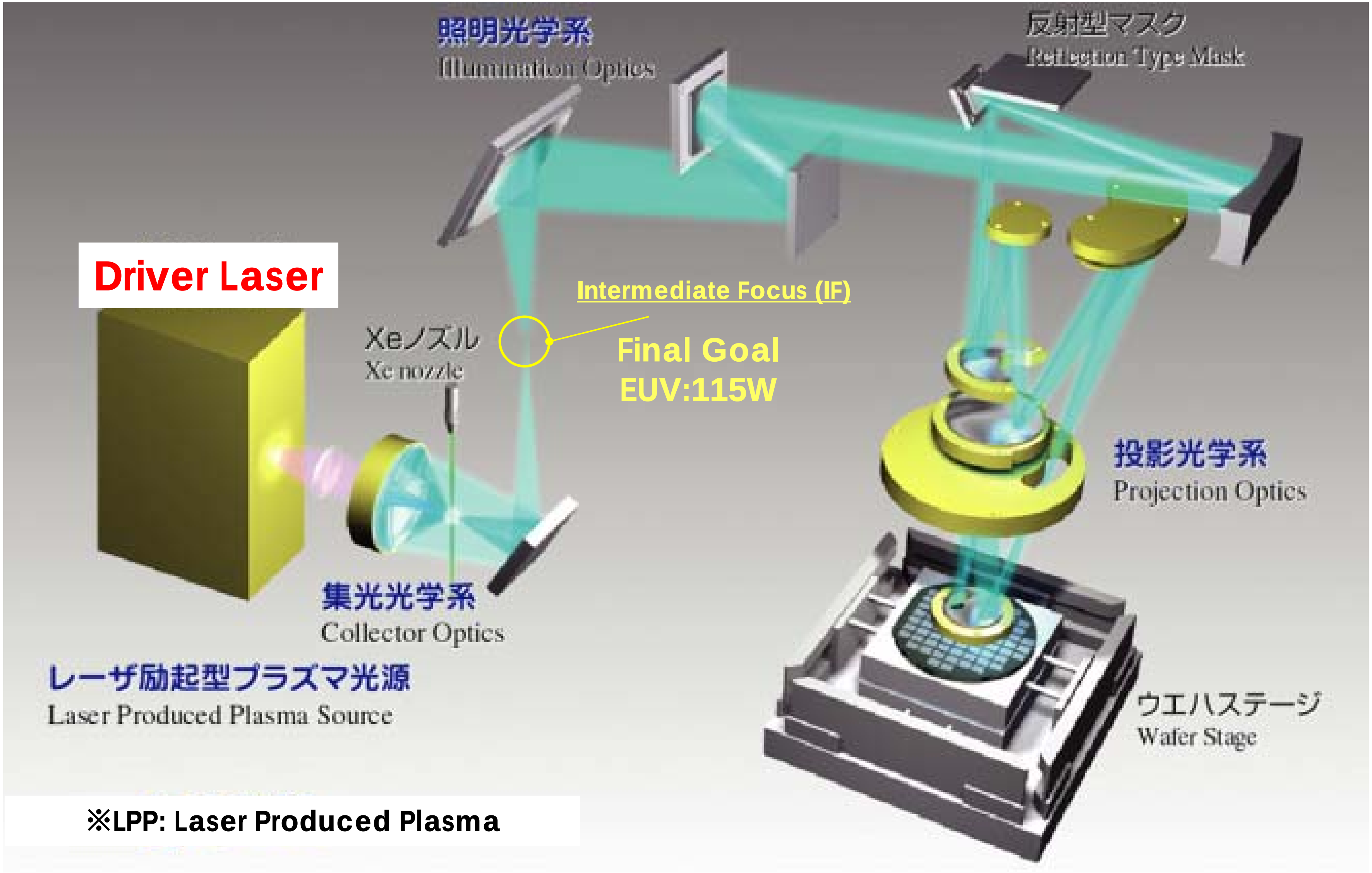
Outline

- Back Ground and Development Roadmap
- Choice of Driver Laser, Nd:YAG / CO_2 Laser
    - Status of High-Power Nd:YAG Laser and Xenon Jet
    - Cost merit of CO_2 Laser
- EUV light source by CO_2 laser driven Xe droplets for HVM
    - Characterization of CO_2 laser driven EUV Source
    - Xe Droplet Target
    - Magnetic Field Ion Mitigation
    - High-Power CO_2 Laser
- Summary

Laser Produced Plasma EUV Microlithography System



※LPP: Laser Produced Plasma

Issues for EUV Source Development

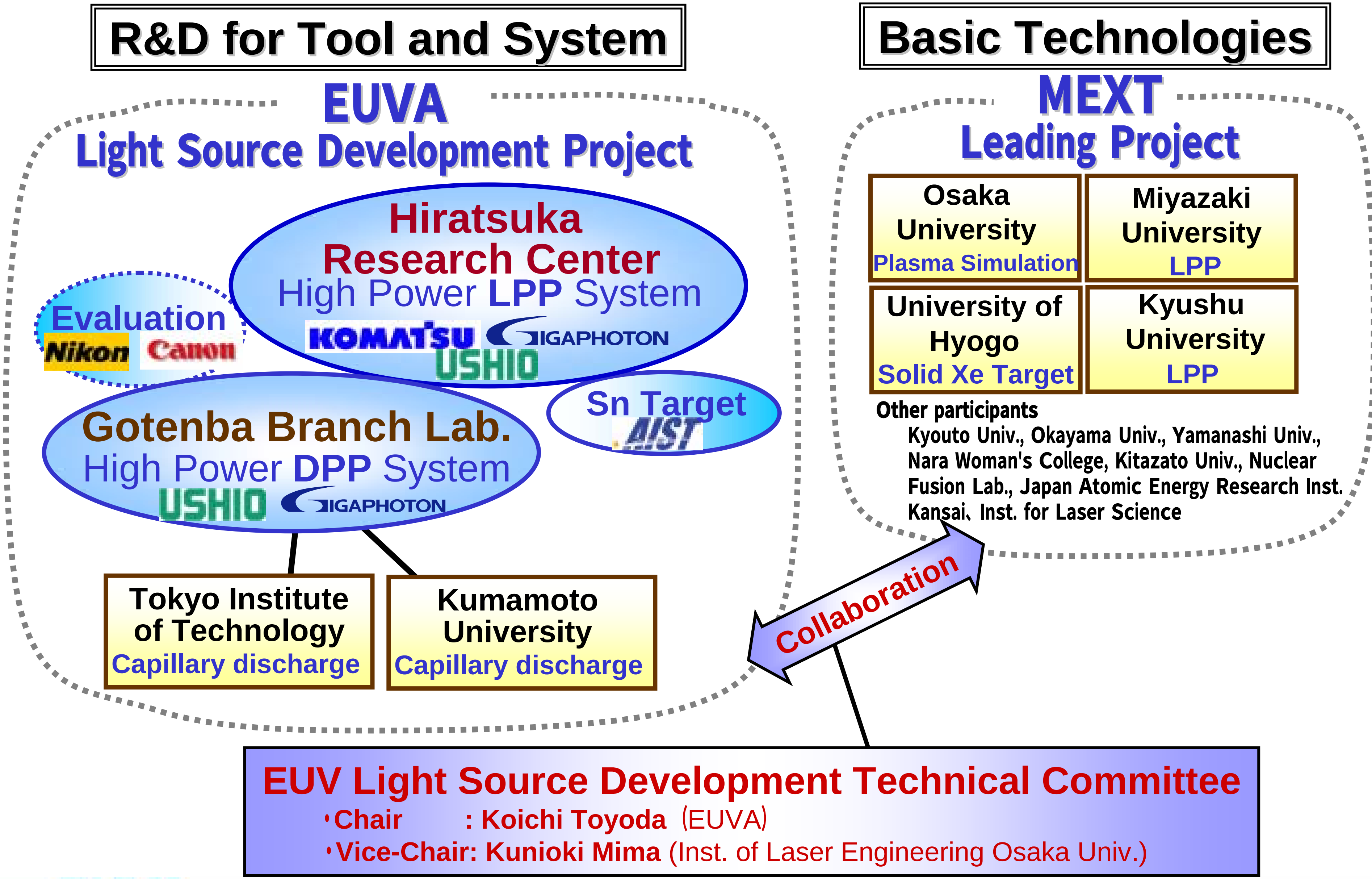
EUVL Light Source Requirements (100 wafer/hr throughput, 300mm wafer)

- 115W EUV in-band power (intermediate focus)
- ±0.3% energy stability (3σ, 50 pulses moving average)
- Acceptable Initial cost and CoO

Issues of Source Development

- High Conversion Efficiency (CE)
  - laser optimization, e.g. laser pulse energy & laser pulse width
- High Repetition Rate Laser (>10kHz)
  - achieve EUV energy stability increasing the integral pulse number
- Driver Laser Choice for Initial cost
  - introduction of industrial CO2 laser
- Mirror Lifetime Extension for CoO
  - magnetic field ion mitigation

R&D Organization of EUV Light Source



R&D for Tool and System

EUVA

Light Source Development Project

Hiratsuka Research Center
High Power **LPP** System
KOMATSU GIGAPHOTON USHIO

Evaluation
Nikon Canon

Sn Target
AIST

Gotenba Branch Lab.
High Power **DPP** System
USHIO GIGAPHOTON

Tokyo Institute of Technology Capillary discharge	**Kumamoto University** Capillary discharge

Basic Technologies

MEXT

Leading Project

Osaka University Plasma Simulation	**Miyazaki University** LPP
University of Hyogo Solid Xe Target	**Kyushu University** LPP

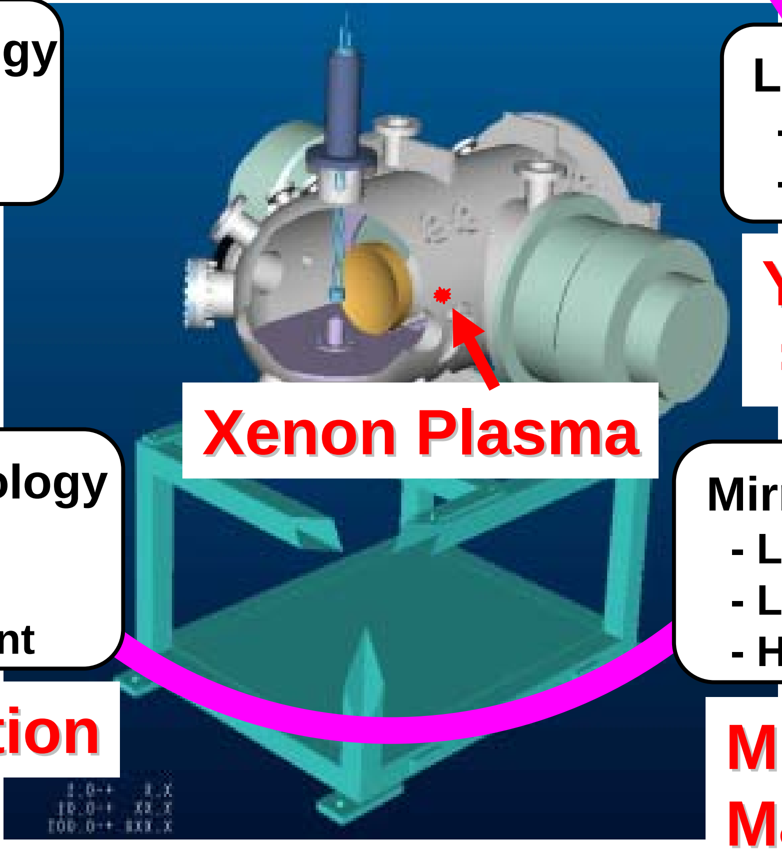
Other participants
Kyouto Univ., Okayama Univ., Yamanashi Univ., Nara Woman's College, Kitazato Univ., Nuclear Fusion Lab., Japan Atomic Energy Research Inst. Kansai、Inst. for Laser Science

Collaboration

EUV Light Source Development Technical Committee

- **Chair : Koichi Toyoda** (EUVA)
- **Vice-Chair: Kunioki Mima** (Inst. of Laser Engineering Osaka Univ.)

Key Technologies of EUVA LPP Light Source



LPP-EUV light source
- High power/stability
- Long lifetime
- Low CoO

Target Technology
- High velocity
- High stability

Xe Jet
⇒ Xe Droplets

Chamber Technology
- High vacuum
- Small foot print
- Heat management

Xe Re-circulation

Laser Technology
- High power
- Short Pulse duration

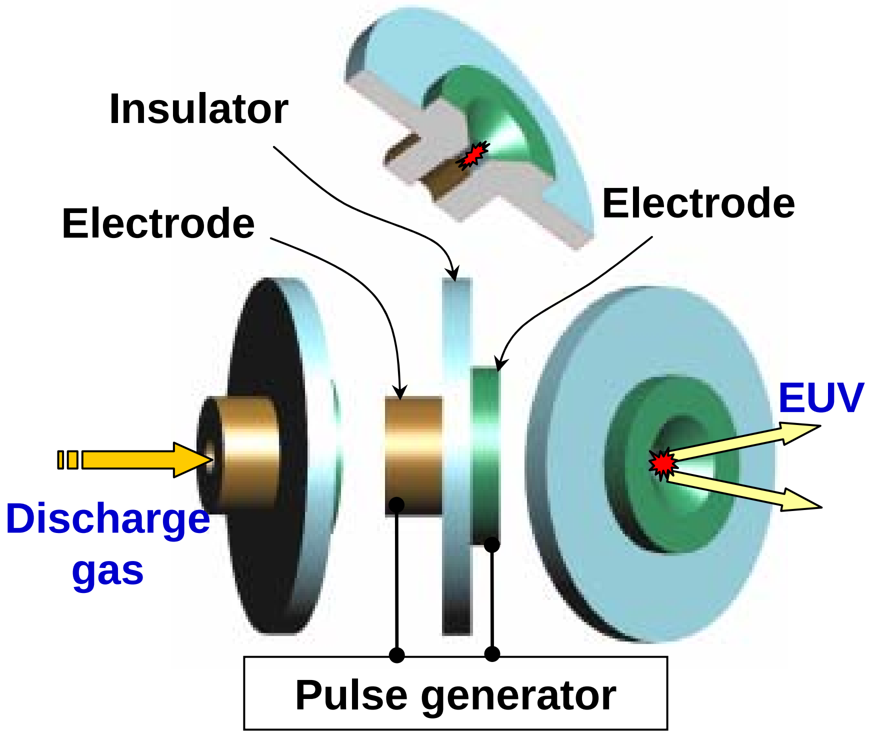
YAG Laser
⇒ CO_2 Laser

Mirror Technology
- Long lifetime
- Large solid angle
- High reflectivity

Mitigation by Magnetic Field

Xenon Plasma

DPP source development



***D**ischarge **P**roduced **P**lasma*

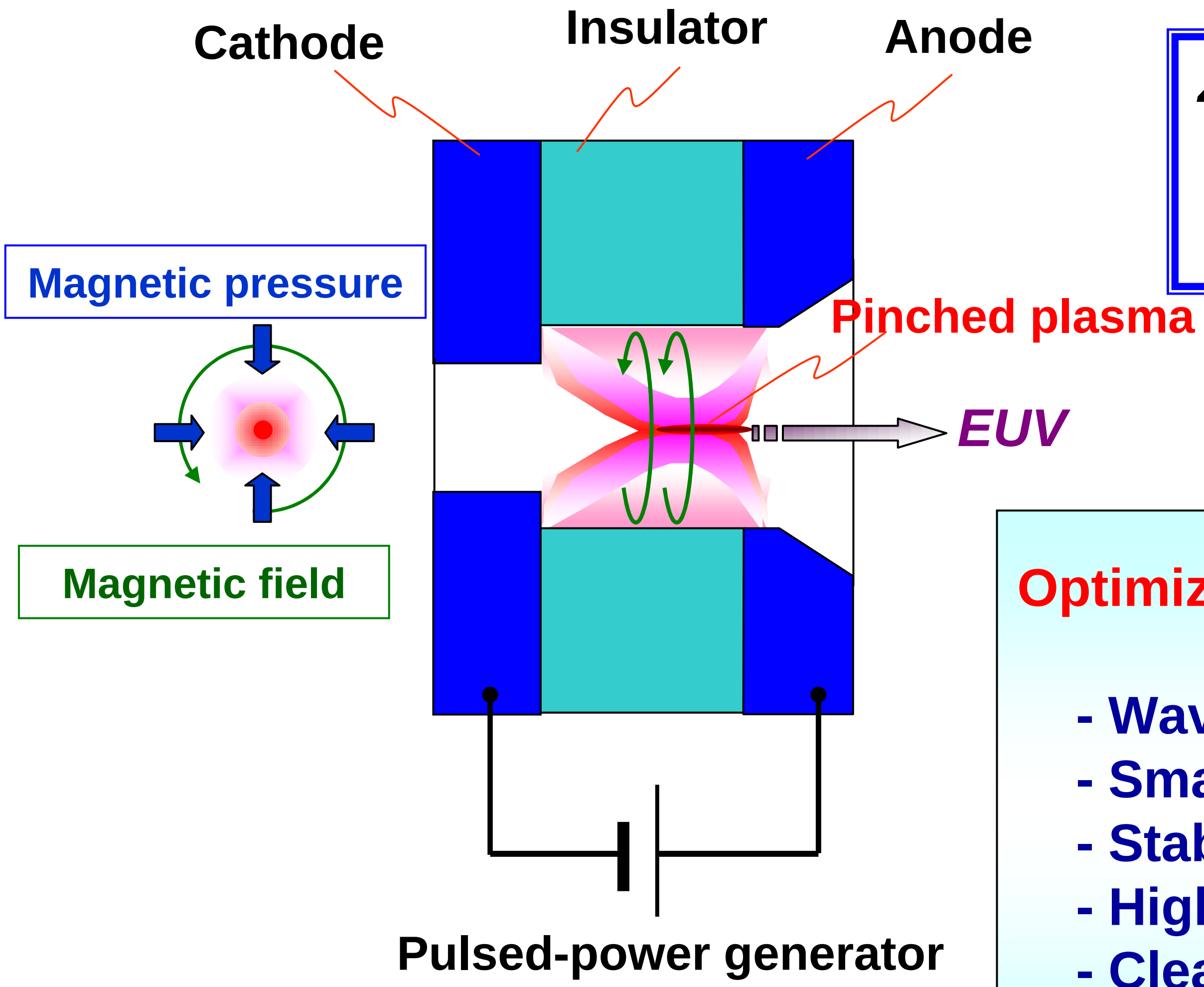
Directly produced by discharge current.
Controllable by discharge condition.

*** Simple & compact source system**
*** Flexibility as a light source**

Key issues for DPP as a EUV source

- **Increase of EUV power at intermediate focus.**
- **Debris mitigation & collector lifetime.**
- **Electrode lifetime.**

Z-pinch plasma for EUV radiation



Z-pinch plasma **:**

- **Magnetic confinement**
- **Dynamic plasma**

Optimization for Lithography :

- **Wavelength = 13.5nm**
- **Small plasma size**
- **Stable**
- **High repetition rate**
- **Clean**
- **Long lifetime and CoO**

LPP EUV Source Roadmap

Item	1st Mid term 2004/9	2nd Mid term 2006/3	EUVA Final 2008/3	HVM Source (2009)
EUV Power (IF)	5.7W	10W	50W	115W
Stability	---	s<±10%	s <±5%	3s<±0.3%
Laser	YAG:1.5kW	CO_2*:6.8kW	CO_2*: 30kW	CO_2*: 60kW
Laser freq.	10kHz	100kHz	100kHz	100kHz
CE (source)	0.9%	0.5%	0.6%	0.7%
Target	Xe-Jet	Xe-Droplet	Xe-Droplet	Xe-Droplet

***with Pre-Pulse YAG Laser**

Technology for 10W

Nd:YAG Laser, Liquid Xe jet

Technology for 115W

CO_2 Laser, droplet target

Magnetic field mitigation

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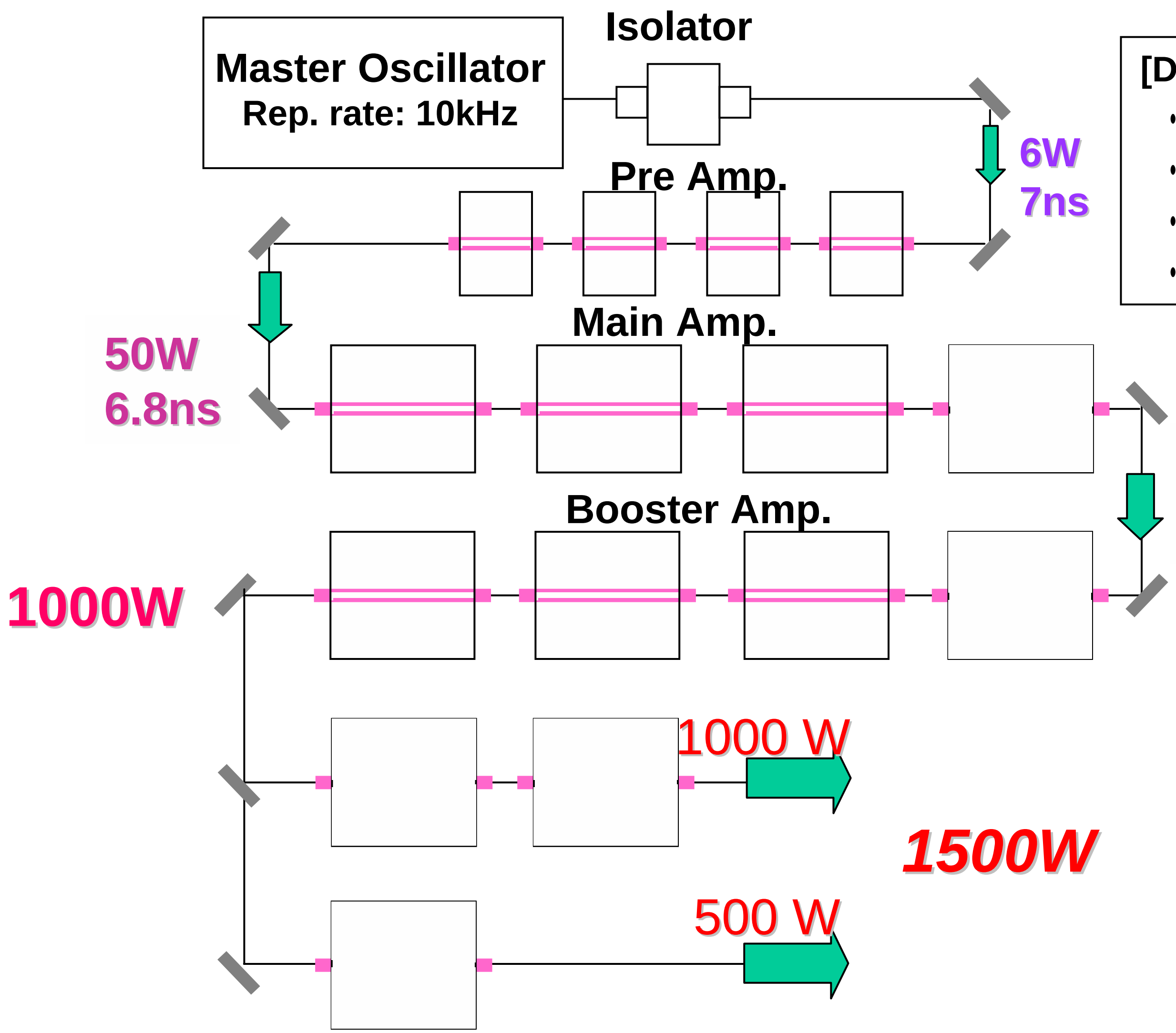
1.5-kW Nd:YAG Laser System

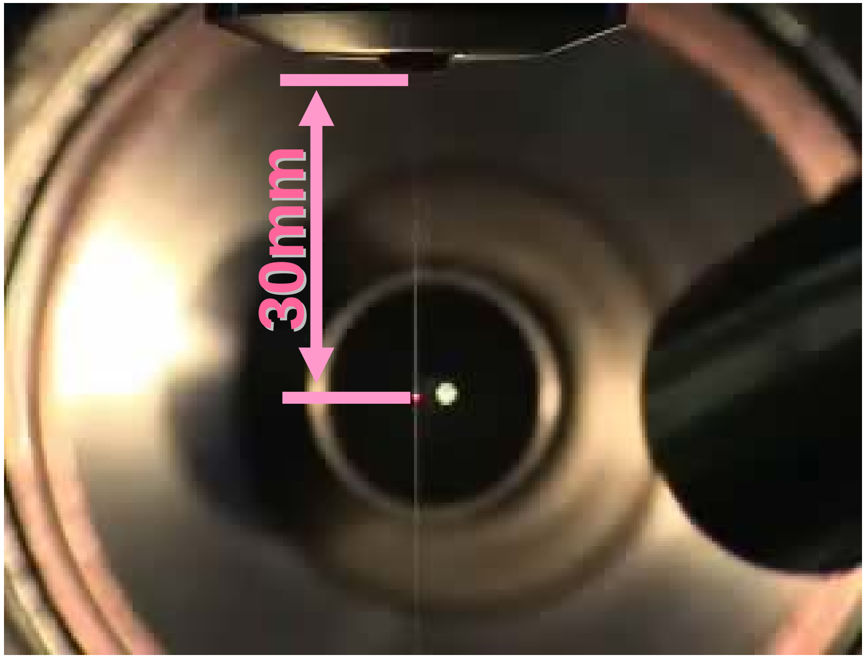


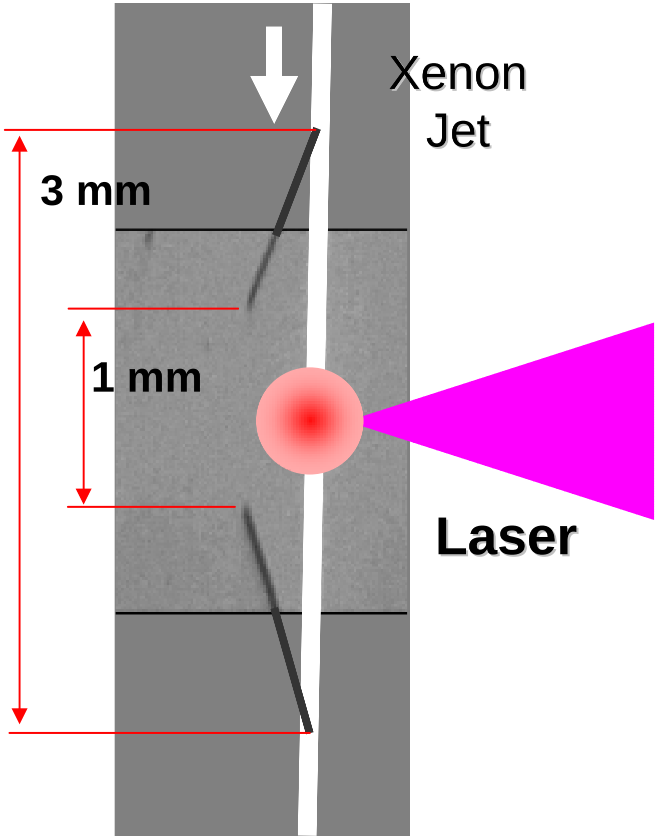
[Description]

- Nd:YAG MOPA※ System
- Output power：1500W
- Repetition rate：10ｋHz
- Pulse duration：6ns(FWHM)

※ MOPA : Master Oscillator and Power Amplifier

Xenon Jet Target





■ Xenon jet

- Jet diameter: Approx. 50 μm
- Jet speed: >35m/s
- Jet stability: 9% (1σ)

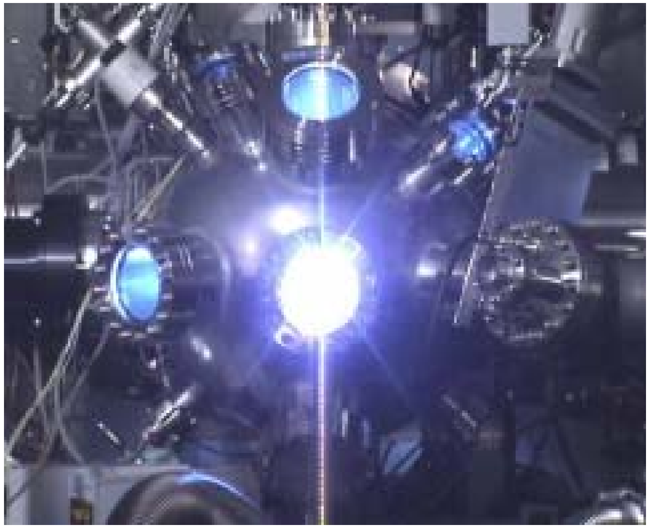
@ 30mm from nozzle

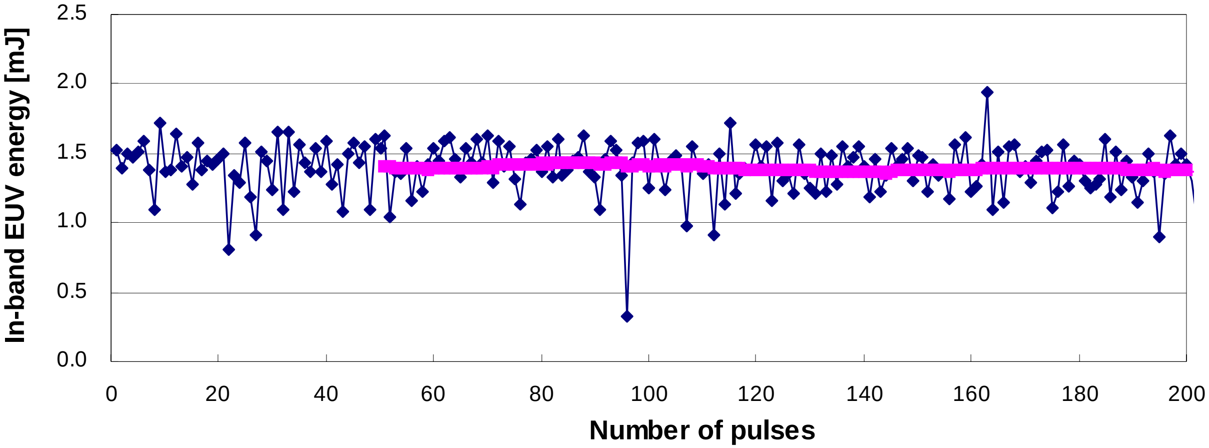
■ Behavior after laser irradiation (115mJ, 2Hz)

- Break up length 1mm/pulse
- Deformation length 3mm/pulse

EUV Output with 1.5-kW YAG Laser System

- EUV Power at Source: **13.3W** (2%BW/2πsr)
  at I.F.: **5.7W** (Calculated)
- Conversion Efficiency: **0.9%**
- EUV Energy Stability: 1.3% (1σ, 50-pulse ave.)
- Laser Power: 1500W@10kHz, 6ns
- Target: Liquid Xenon jet





Cost estimation of LPP light source

- **Initial Cost** ： **5.6~9.0** Mill.$ @ CO_2, **21.7~31.7** Mill. $ @ YAG
- **Running Cost**： **0.55~0.82** Mill.$/year @ CO_2, **2.54~3.63** Mill.$/year @ YAG

110 JYen = 1 USD Component	CO_2 (C.E.=1.0~0.5%)		YAG (C.E.=1.2~0.8%)	
	Initial Cost (M$)	Running Cost (M$/year)	Initial Cost (M$)	Running Cost (M$/year)
Total	**5.6~9.0**	**0.55~0.82**	**21.7~31.7**	**2.54~3.63**
Laser System	**3.7~7.1**	**0.32~0.43**	**20.0~30.0**	**2.29~3.33**
	⟨42~84kW, 100kHz⟩		**⟨35~53kW, 10kHz⟩**	
EUV Chamber	**1.2**	**0.03**	**1.0**	**0.02**
Xe Re-Circulation System	**0.5**	**0.14**	**0.5**	**0.14**
Collector Mirror	**0.2**	**0.06~0.22**	**0.2**	**0.09~0.14**

※ Estimation based on:
- 115W Source Power at I.F.
- 100 units produced in 2016.
- 120 wafer/hr throughput ⇒ 21.3 Billion pulse /year @ 10kHz
  ⇒ 213 Billion pulse /year @ 100kHz

CO_2 Driver laser system for LPP

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- **EUV light source by CO_2 laser driven Xe droplets for HVM**
  - **Characterization of CO_2 laser driven EUV Source**
  - **Xe Droplet Target**
  - **Magnetic Field Ion Mitigation**
  - **High-Power CO_2 Laser**
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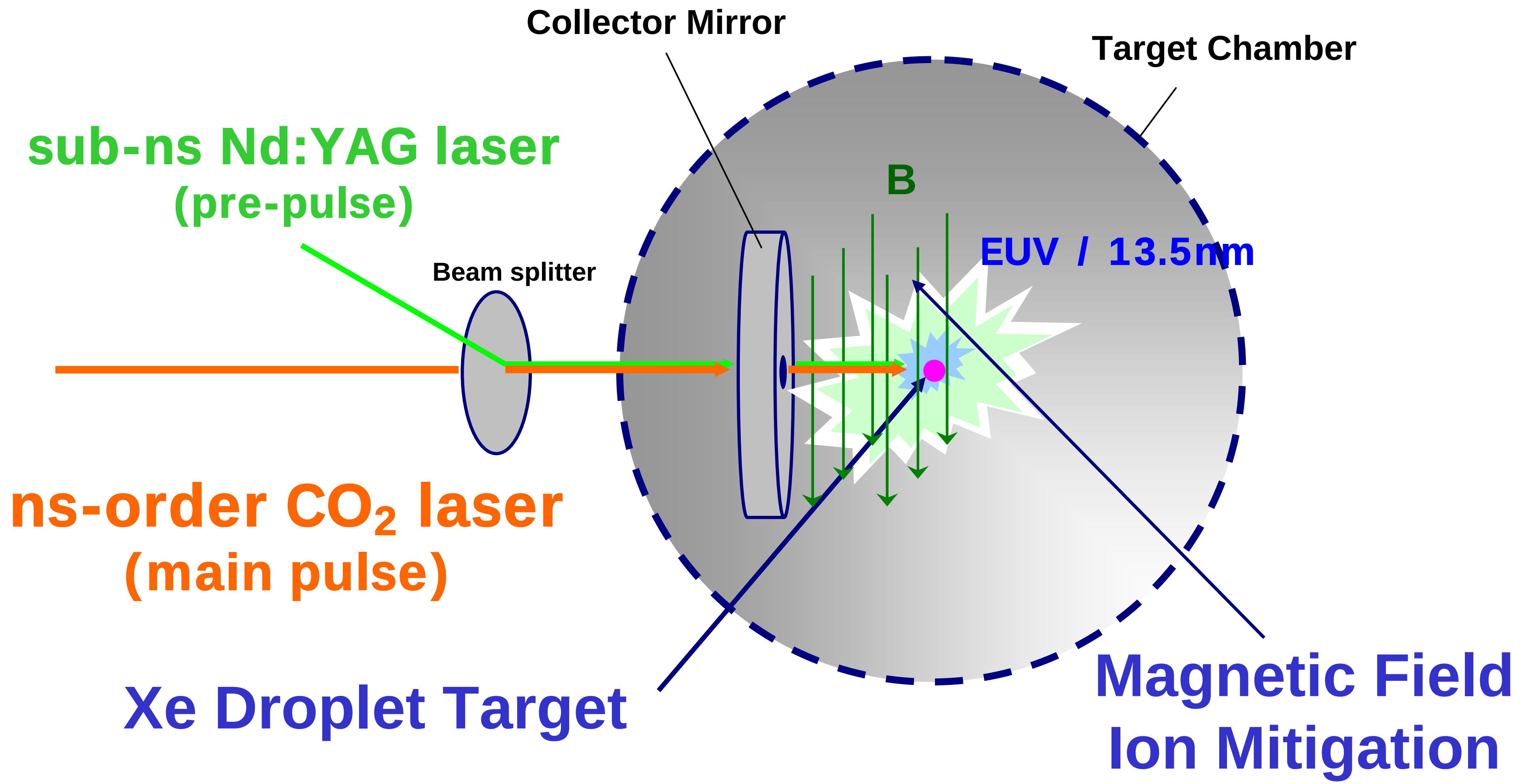
Light Source Concept for 115W



Conversion Efficiency (CE) of
0.6 % has been achieved (Xe Jet)

Characterization of pre-pulsed CO2 Laser Plasma

1) EUV image

Etendue < 1mm^{2}sr

2) plasma emission

in-band, out-of-band characteristics

3) Time of Flight (TOF)

ion energy distribution with pre-pulse

4) Quartz Crystal Microbalance (QCM)

mirror erosion rate (lifetime estimation)

Experimental Setup

Main Pulse Laser

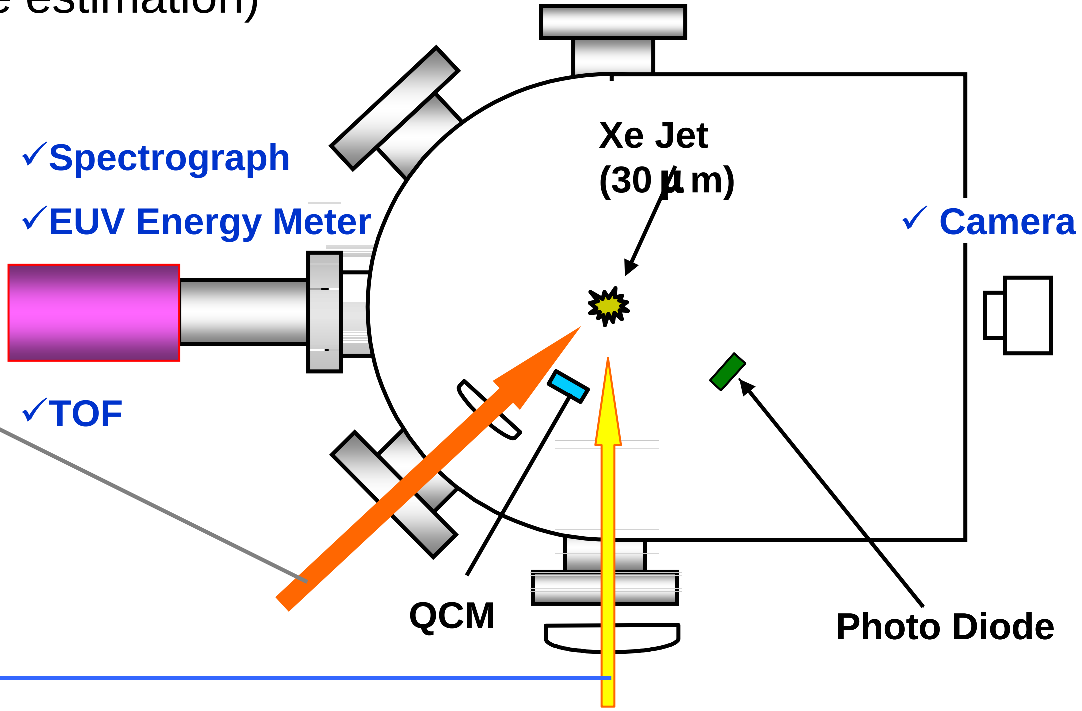
⟨CO$_2$ Laser⟩

✓ Energy:	50 mJ
✓ Pulse Width:	25 ns
✓ Intensity:	6x10^9 W/cm^2
✓ Repetition rate:	10 Hz

Pre-Pulse Laser

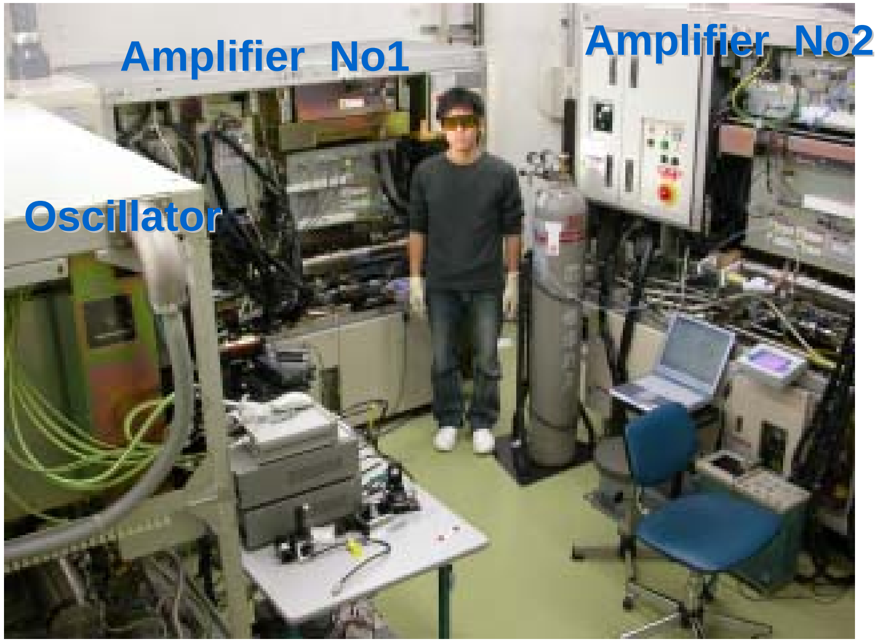
⟨Nd:YAG Laser⟩

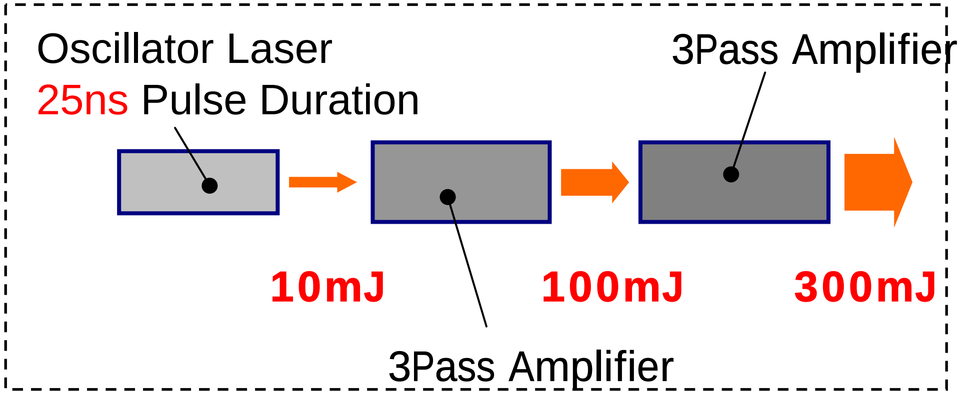
✓ Energy:	5 mJ,
✓ Pulse Width:	10 ns,
✓ Intensity:	8x10^9 W/cm^2,
✓ Repetition rate:	10 Hz



TEA CO_2 Laser Driver System

3-Stage CO_2 Laser System Configuration



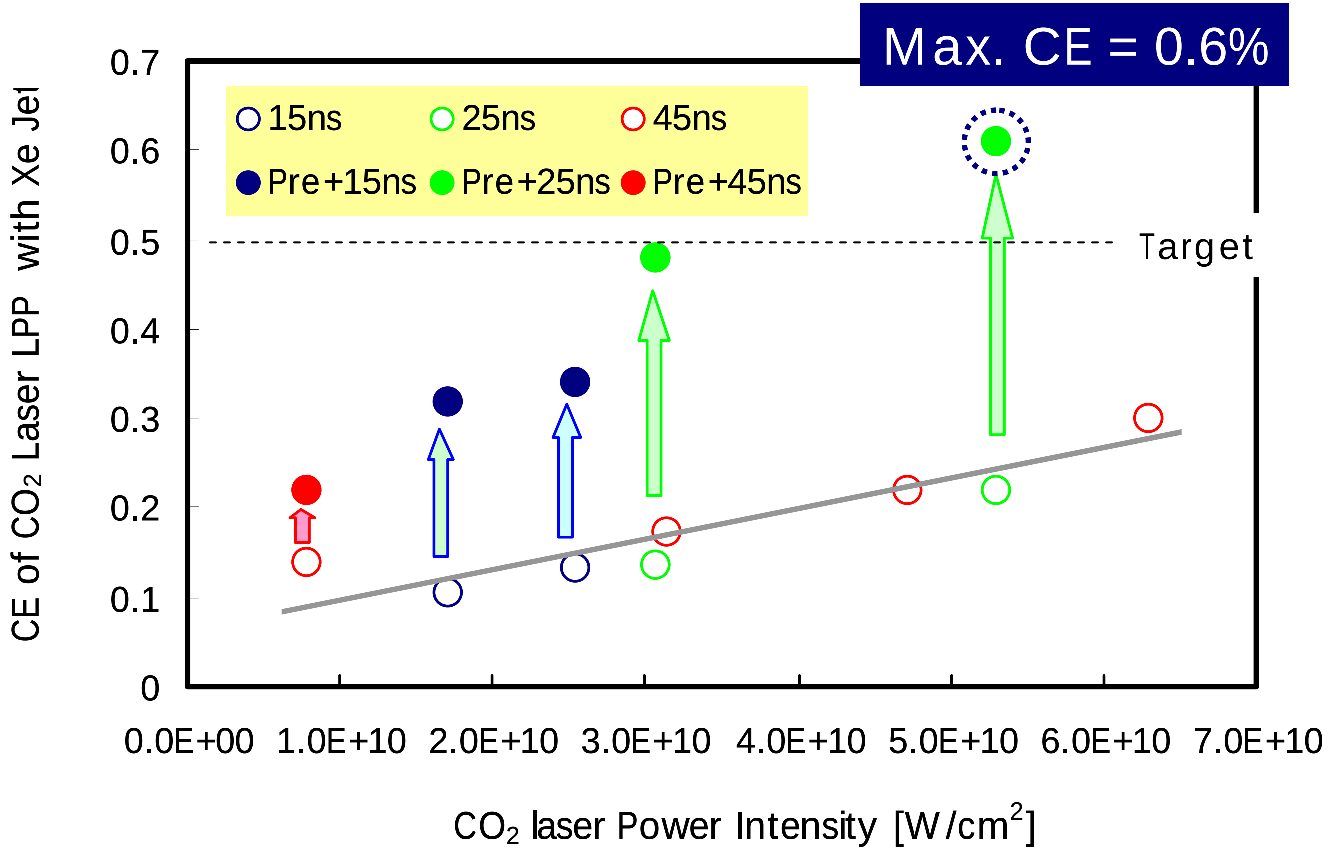


■ Specifications

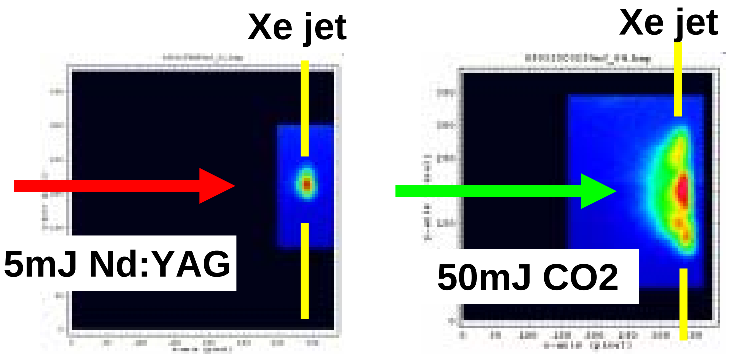
Pulse Energy: 300 mJ, Pulse Duration: 25 ns
Rep. rate: 10 Hz

Conversion Efficiency of pre-pulsed CO2 laser Plasma

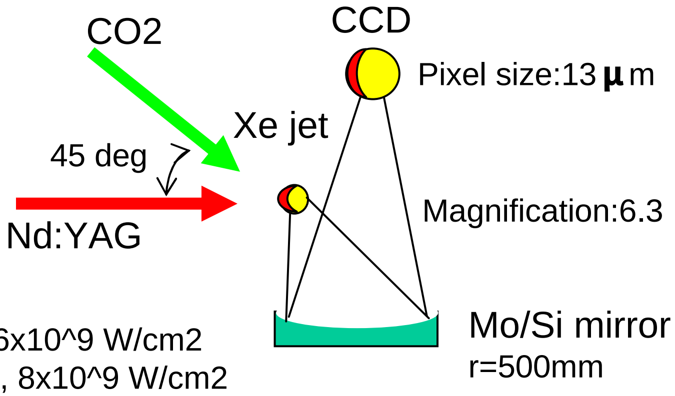
Pre-pulse laser increases CE significantly:



EUV in-band Plasma Image - delay time dependence -

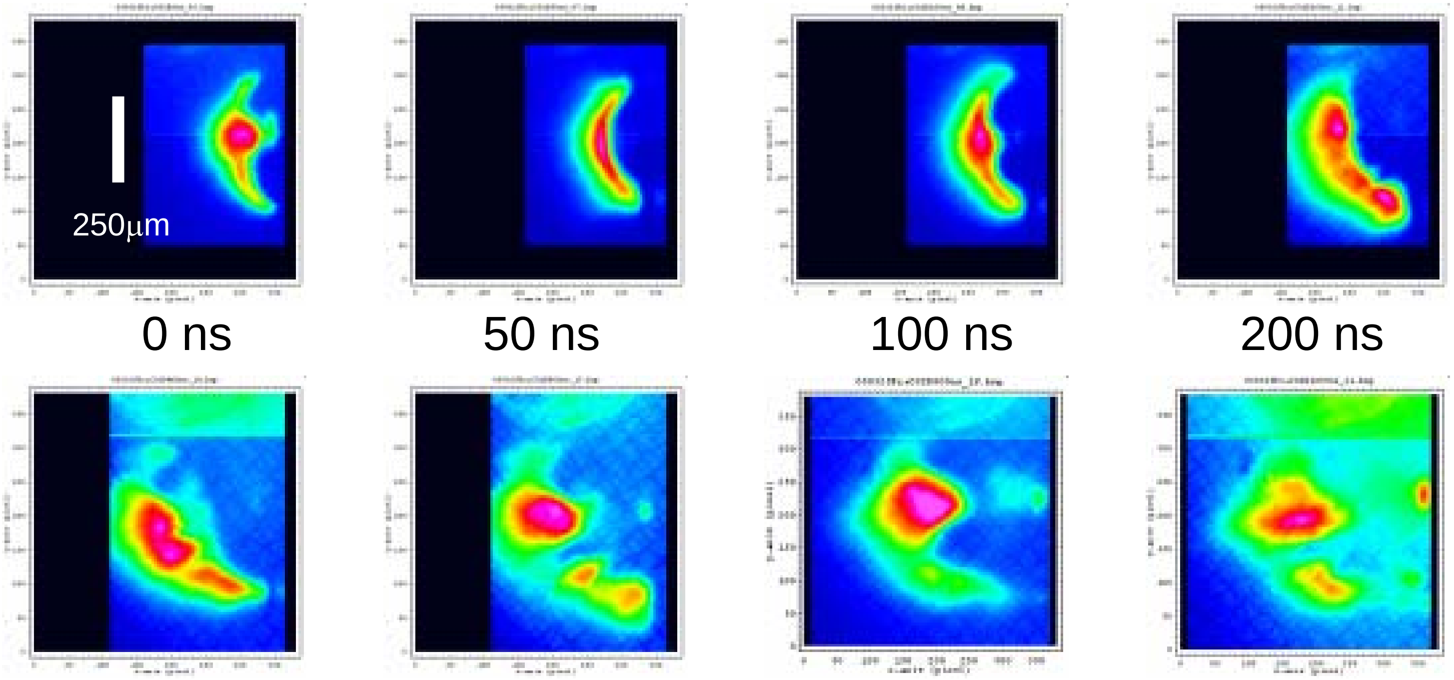


CO2 50mJ, 25ns, 6x10^9 W/cm2
Nd:YAG, 5mJ, 8ns, 8x10^9 W/cm2



Nd:YAG
+
CO_2

delay:



0 ns | 50 ns | 100 ns | 200 ns

400 ns | 600 ns | 800 ns | 1000 ns

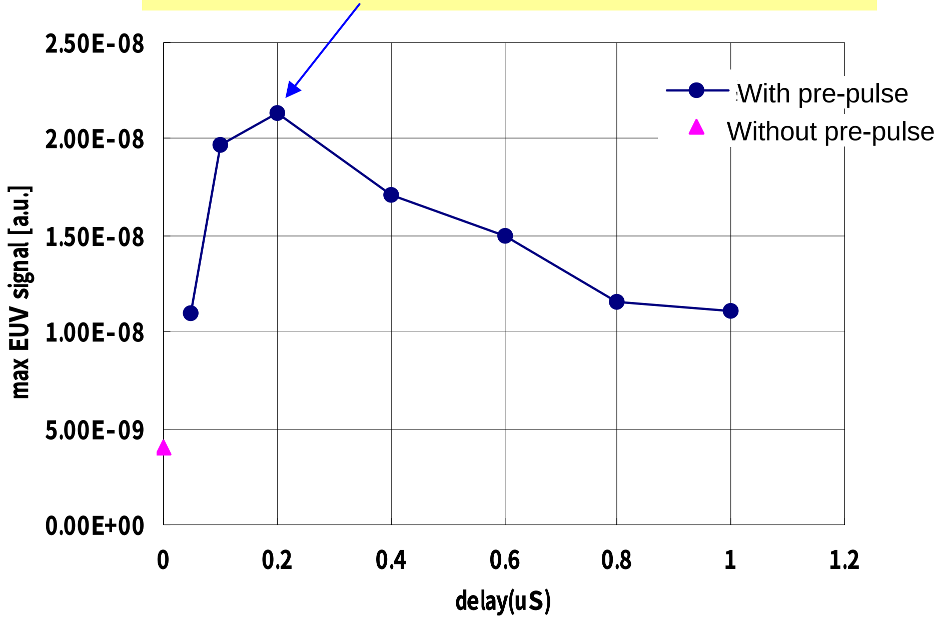
CO2 Laser Plasma emission - delay time dependence -

Photo diode measurement: EUV (AXUV-100G+Zr filter)
Out-of-Band (AXUV-100G + low-pass filter)

CO2 50mJ, 25ns, 6x10^9 W/cm2
Nd:YAG, 5mJ, 8ns, 8x10^9 W/cm2
Xe-jet, 30um diameter

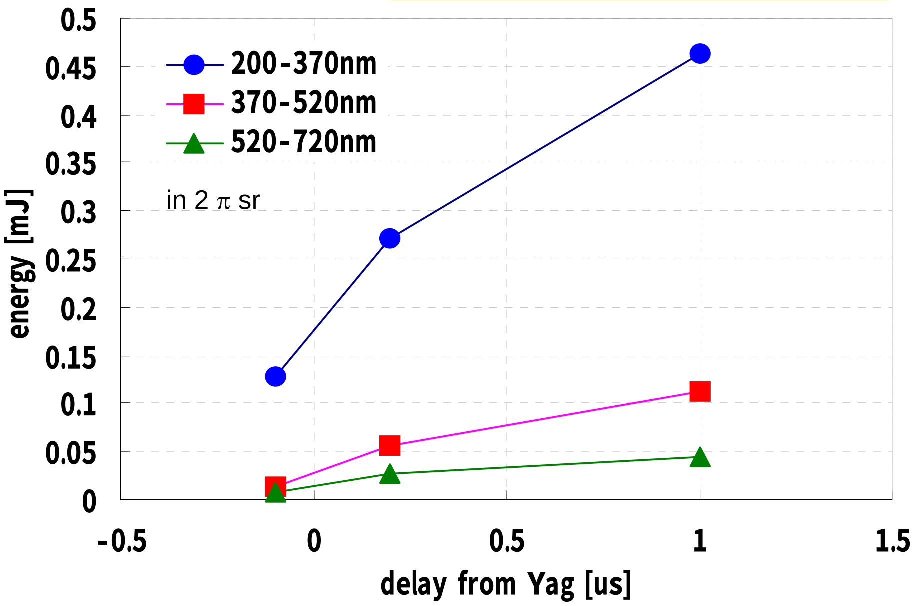
EUV

max. EUV emission (about 250 μJ, 2Pi) at about 200ns



Out-of-Band

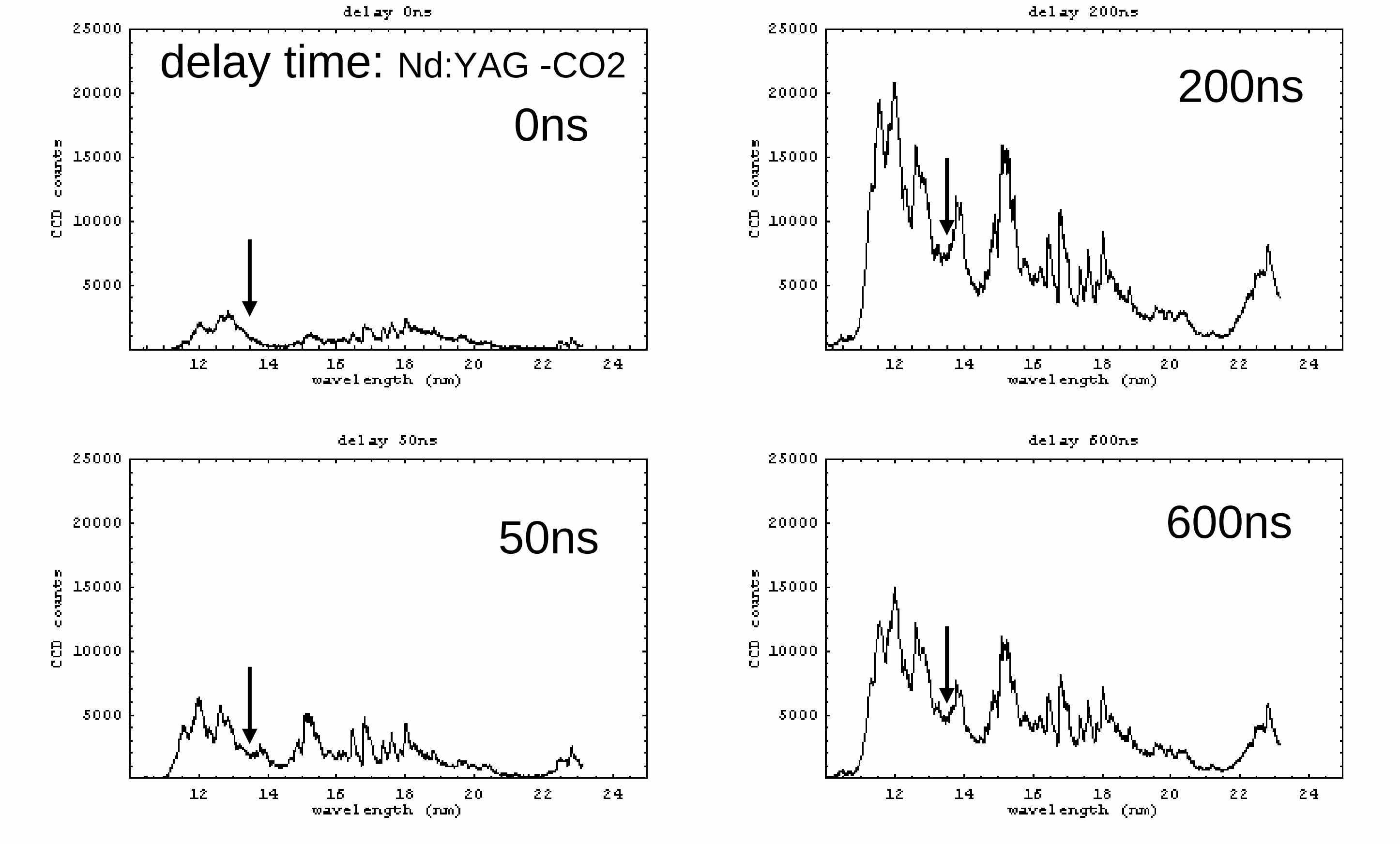
energy emitted into 2π sr:
EUV: 250uJ
1.06um: 500uJ



Plasma emission（In-band, 10 – 20nm)

Observed in-band emission at plasma source

CO2 50mJ, 25ns, 6x10^9 W/cm2
Nd:YAG, 5mJ, 8ns, 8x10^9 W/cm2
Xe-jet, 30um diameter



wavelength (nm)

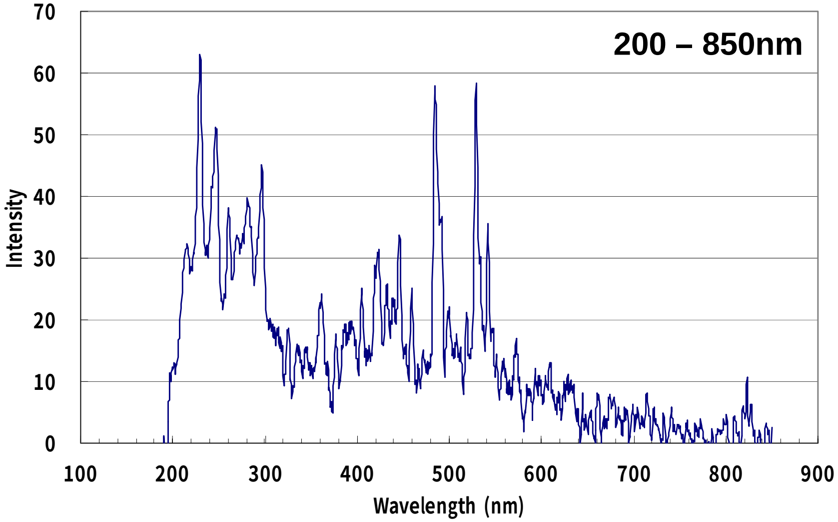
wavelength (nm)

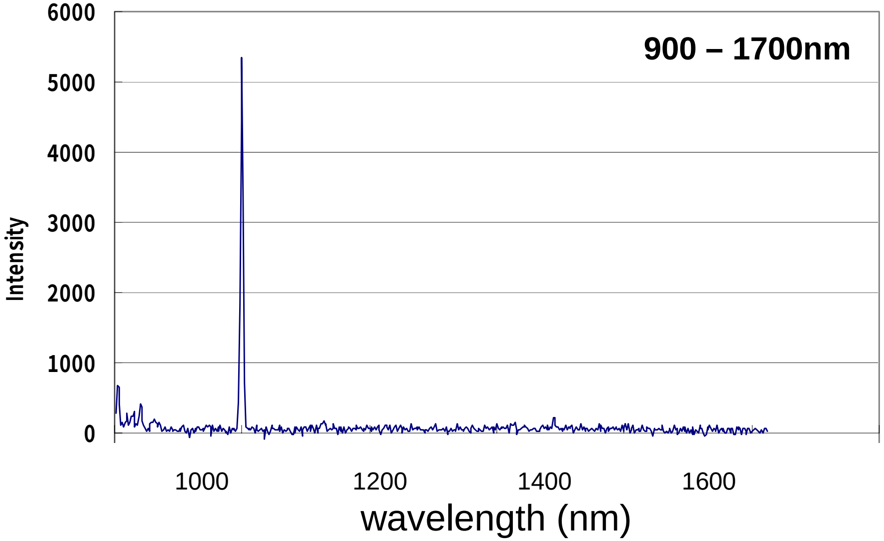
max. EUV emission at about 200ns delay time

Plasma emission（out-of-band, 200-1700nm)

Observed out-of-band emission at plasma source

CO2 50mJ, 25ns, 6x10^9 W/cm2
Nd:YAG, 5mJ, 8ns, 8x10^9 W/cm2
Delay time: 200ns
Xe-jet, 30um diameter



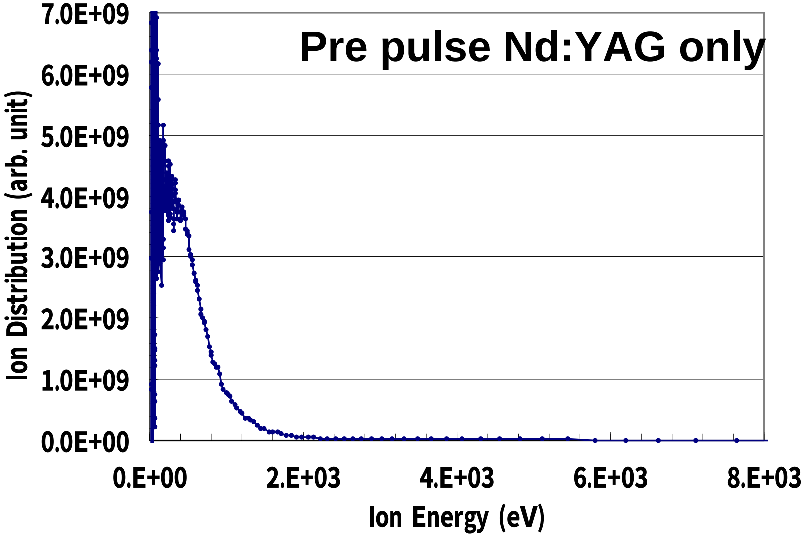


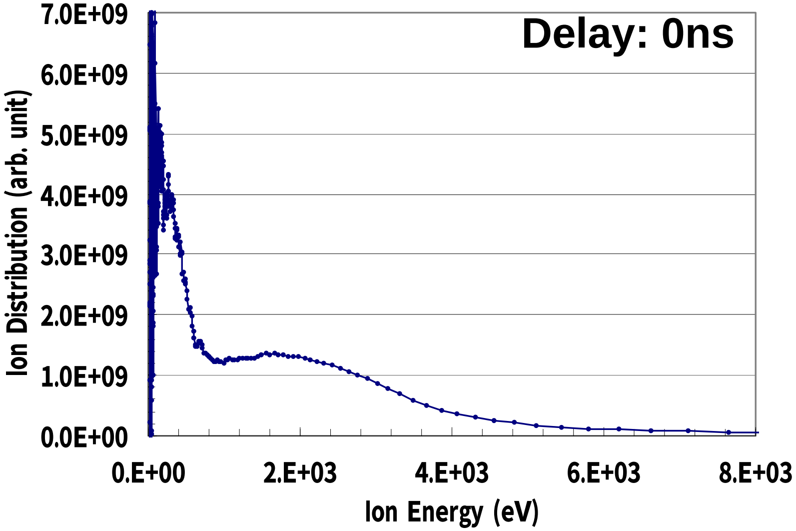
Obtained out-of-band ratio from the spectrum was correspond with the result from photo diode measurement

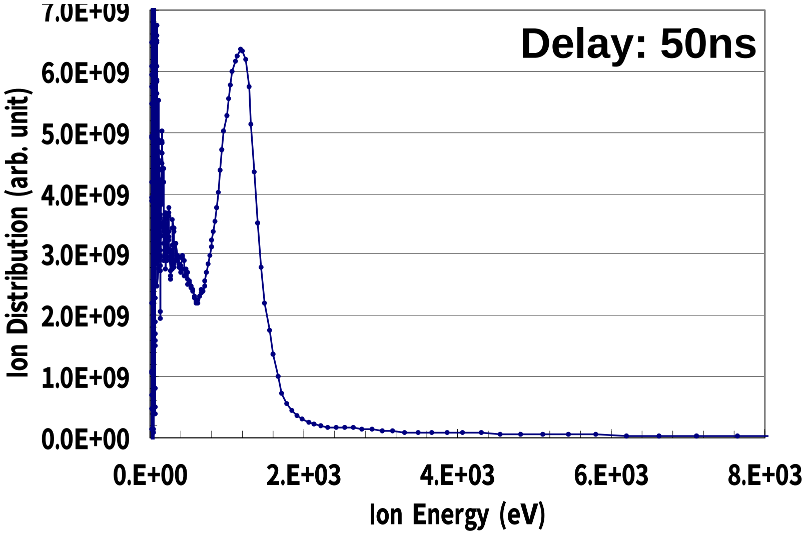
900 – 1700nm: only Nd:YAG observed (10% scattered into 2π sr, 500μJ); CO2 wavelength range not yet measured

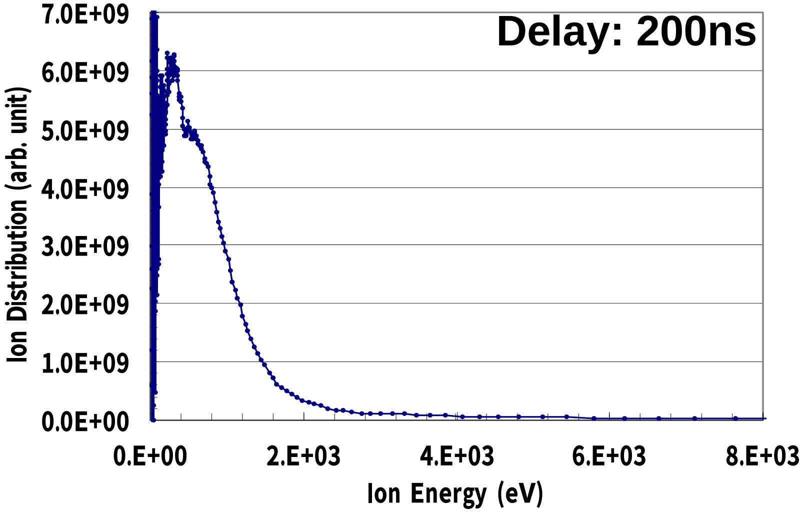
Ion Energy Distribution of pre-pulsed CO2 Laser Plasma

Fast ion TOF measurement Pre-pulse (Nd:YAG 5mJ) + CO_2 (65mJ),







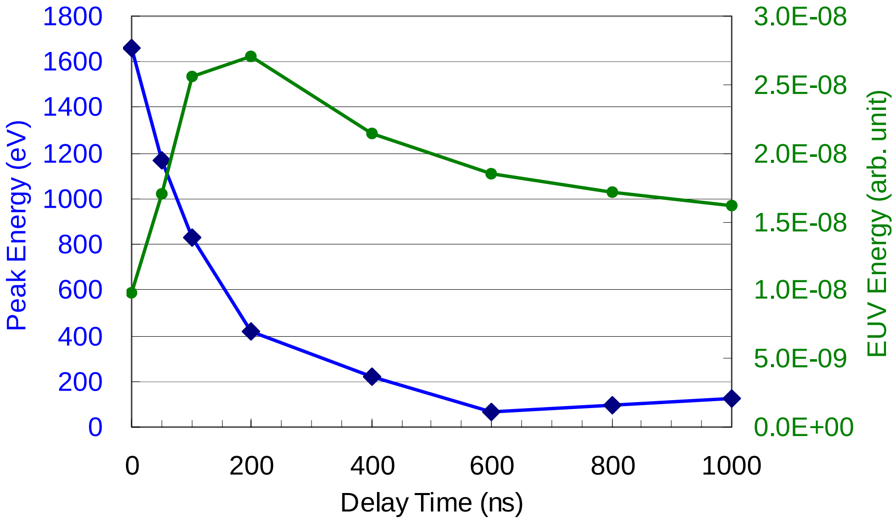


TOF and Erosion Rate Measurement of CO2 Plasma

TOF results

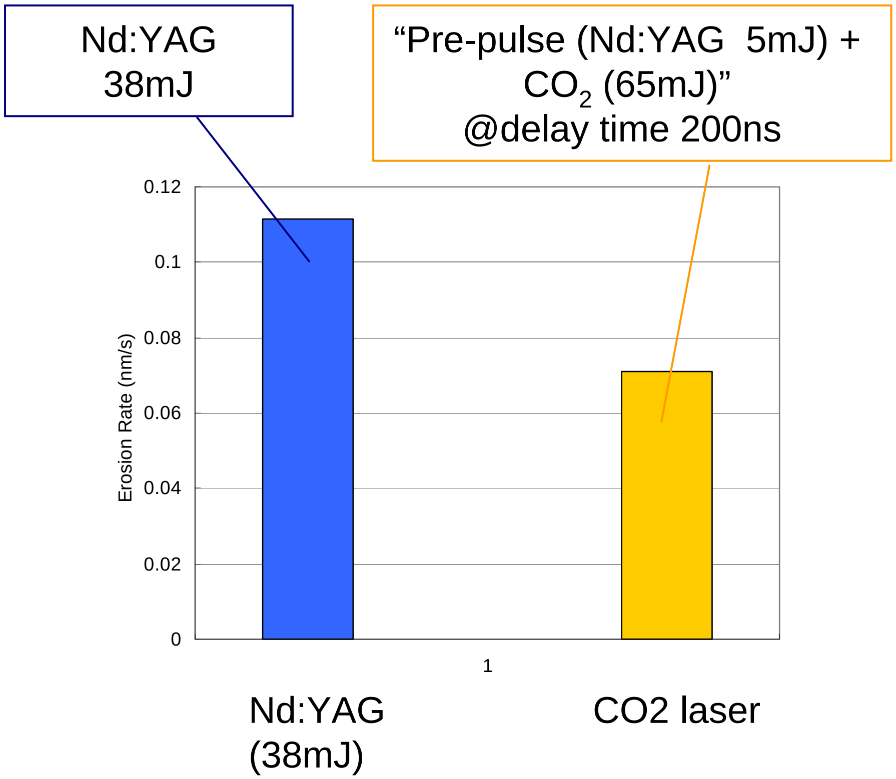
Pre-pulse (Nd:YAG 5mJ) + CO_2 (65mJ),

Peak kinetic ion energy



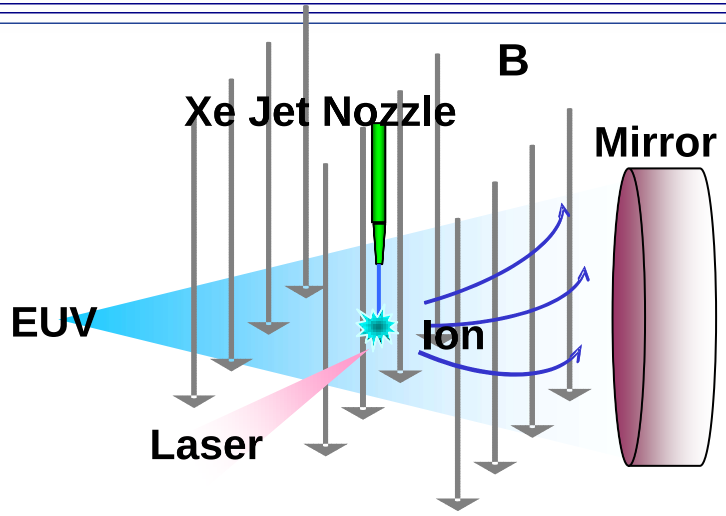
ion kinetic energy drops with increasing delay time

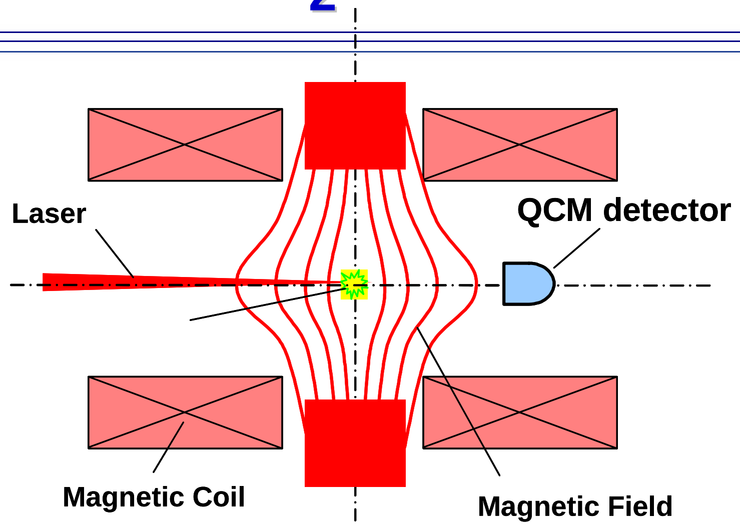
QCM (Au) erosion rate at same EUV output



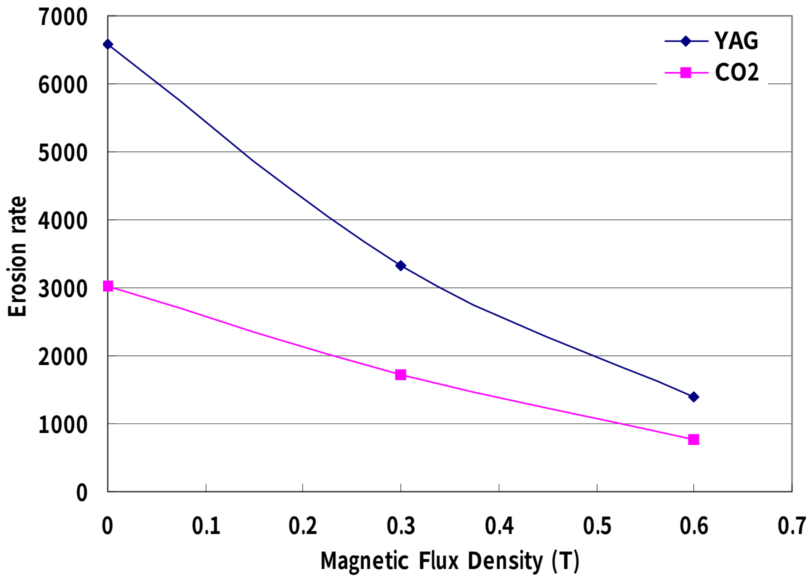
CO_2 laser erosion rate is 64% of Nd:YAG erosion rate

Magnetic Field Ion mitigation for CO$_2$ laser Plasma

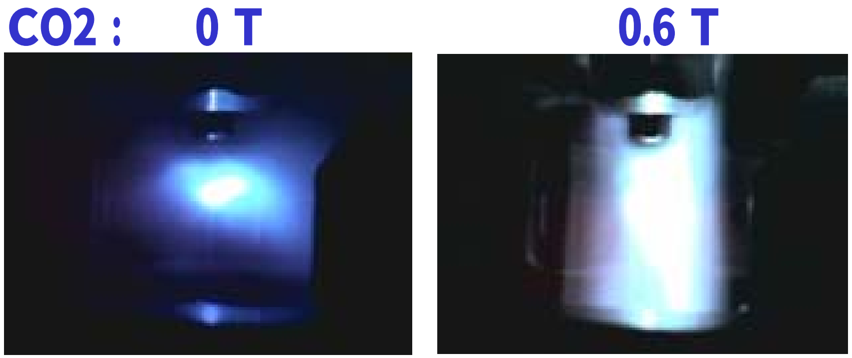




Erosion rate was measured by QCM with same EUV output Nd:YAG and CO2 laser

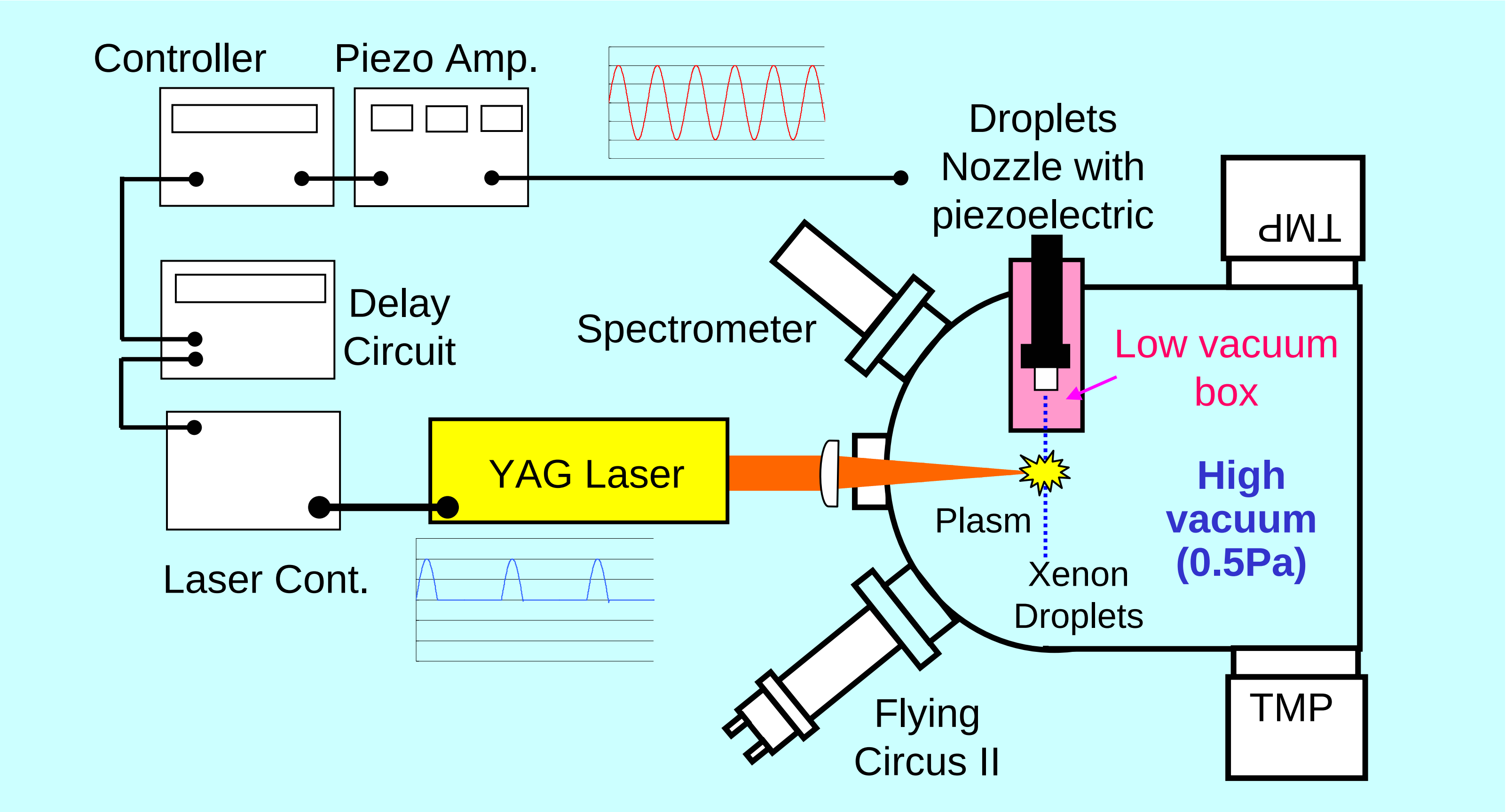


✧ Nd:YAG 32mJ
✧ Pre-pulse (Nd:YAG 5mJ) + CO$_2$ (50mJ)
@delay time 200ns



Xe Droplet Target Generator

droplets generated in high vacuum (0.5Pa)



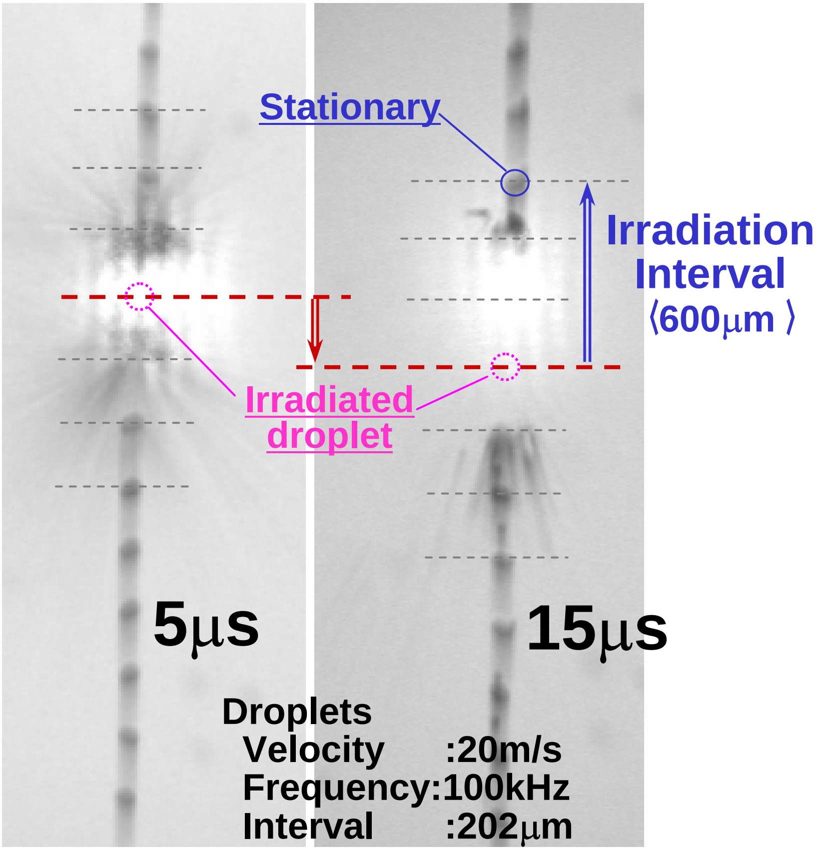
Xe droplet target

Xe droplet target for 100kHz operation

- ■ **required speed**

- Droplet distance : > 600μm
- Driver laser frequency : 100kHz

- Required droplet speed : > 60m/s

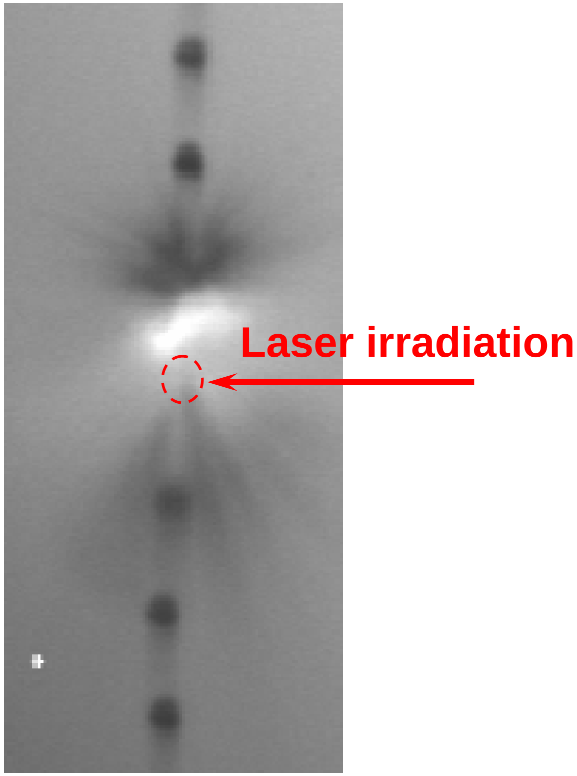


Droplets
Velocity :20m/s
Frequency:100kHz
Interval :202μm

EUV emission with Xe droplet and pre-pulsed CO_2 Laser Irradiation

==Droplet==

Velocity:20m/s
Diameter:98µm
Spacing:250µm
Freqency:80kHz



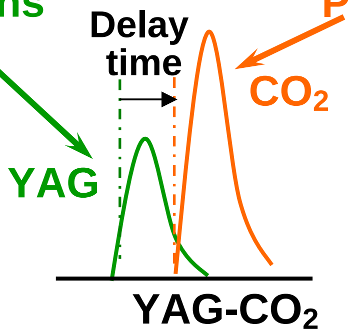
10µs after
YAG & CO_2

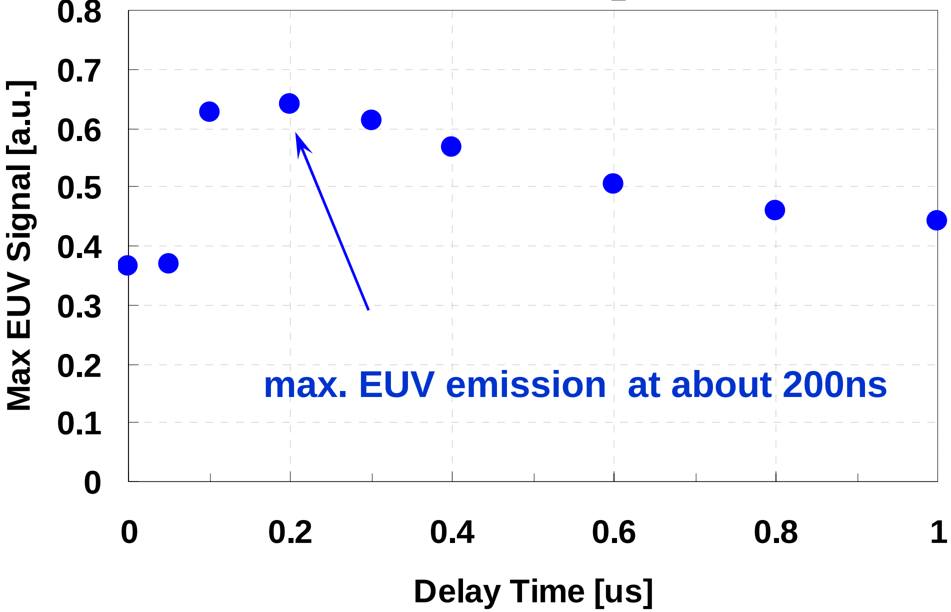
==YAG==

Energy : 5mJ
Pulse Duration : 8ns

==CO_2==

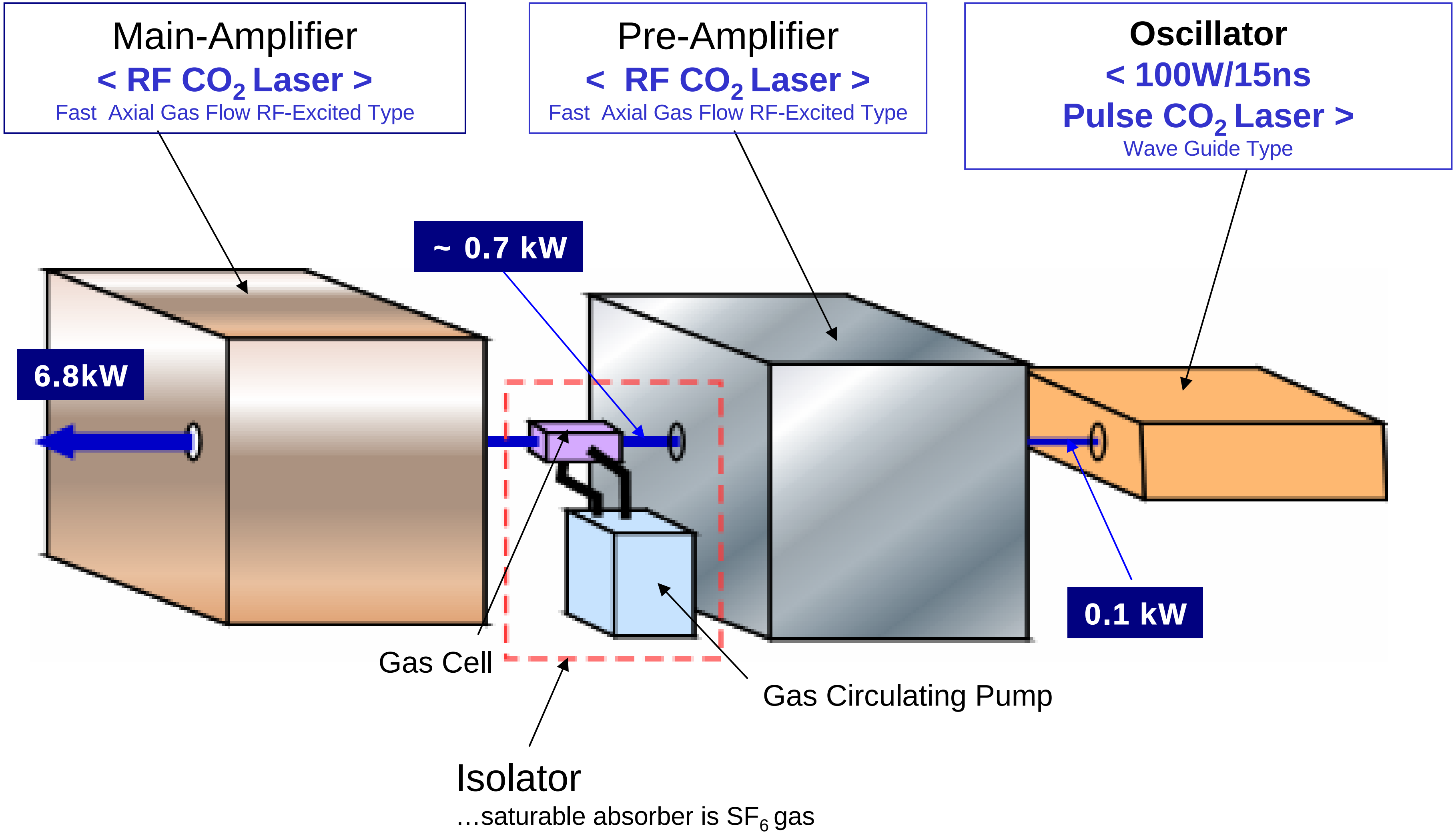
Energy : 50mJ
Pulse Duration : 25ns





EUV emission change with delay time between pre-pulse and main pulse

High-power CO2 laser system for 10W at IF



Main-Amplifier
< RF CO_2 Laser >
Fast Axial Gas Flow RF-Excited Type

Pre-Amplifier
< RF CO_2 Laser >
Fast Axial Gas Flow RF-Excited Type

Oscillator
< 100W/15ns
Pulse CO_2 Laser >
Wave Guide Type

6.8kW

~ 0.7 kW

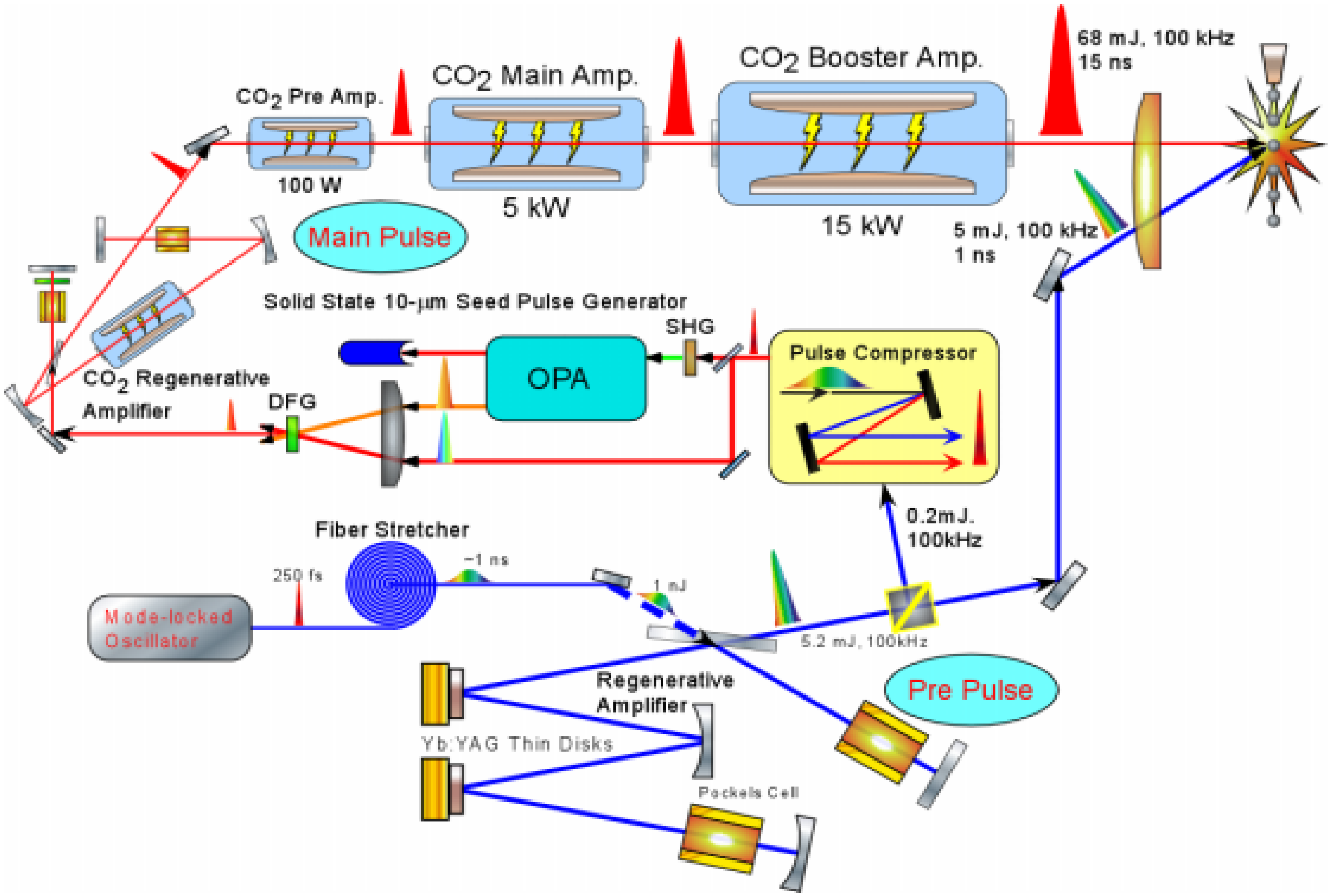
0.1 kW

Gas Cell

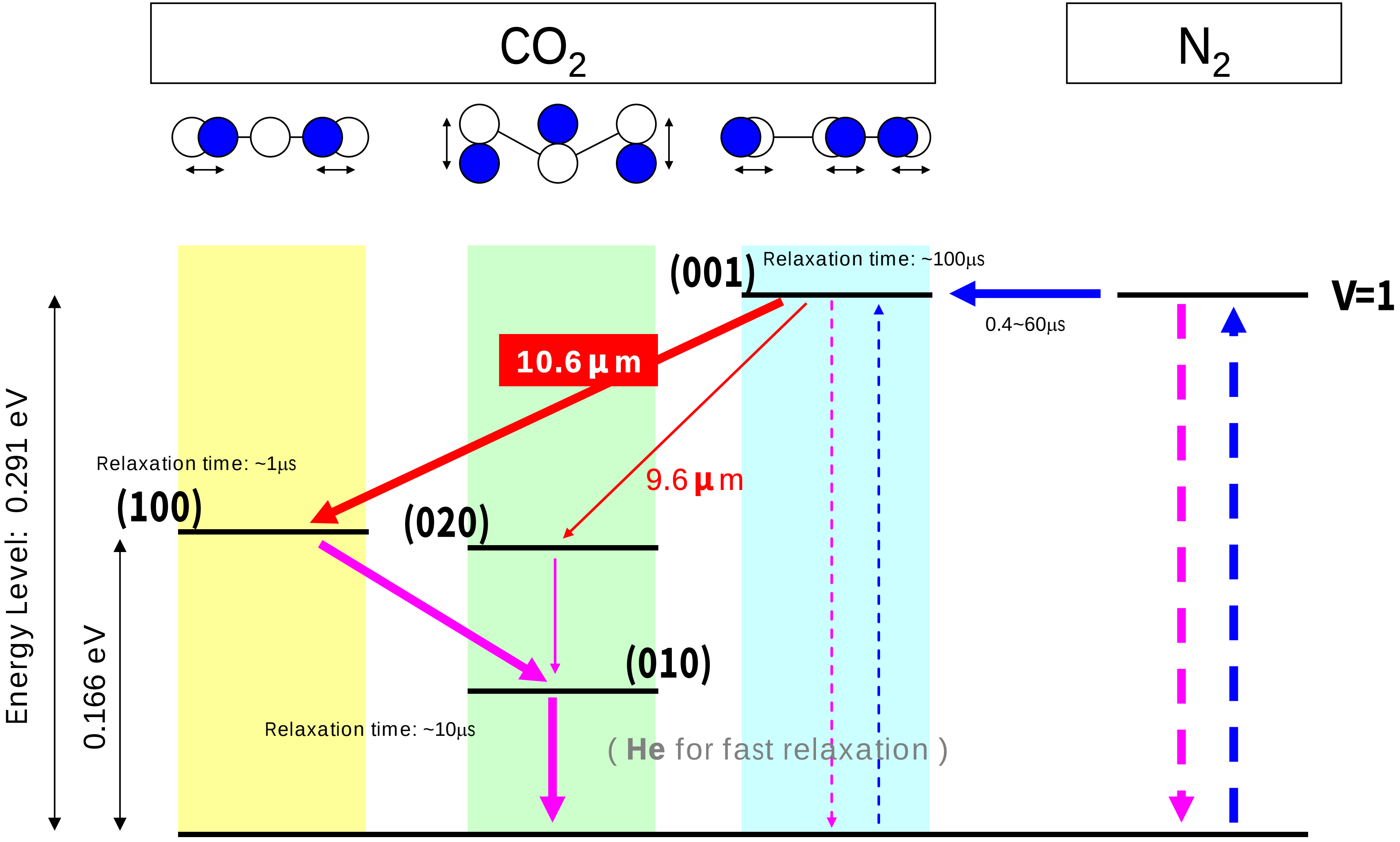
Gas Circulating Pump

Isolator
…saturable absorber is SF_6 gas

Laser System Overview

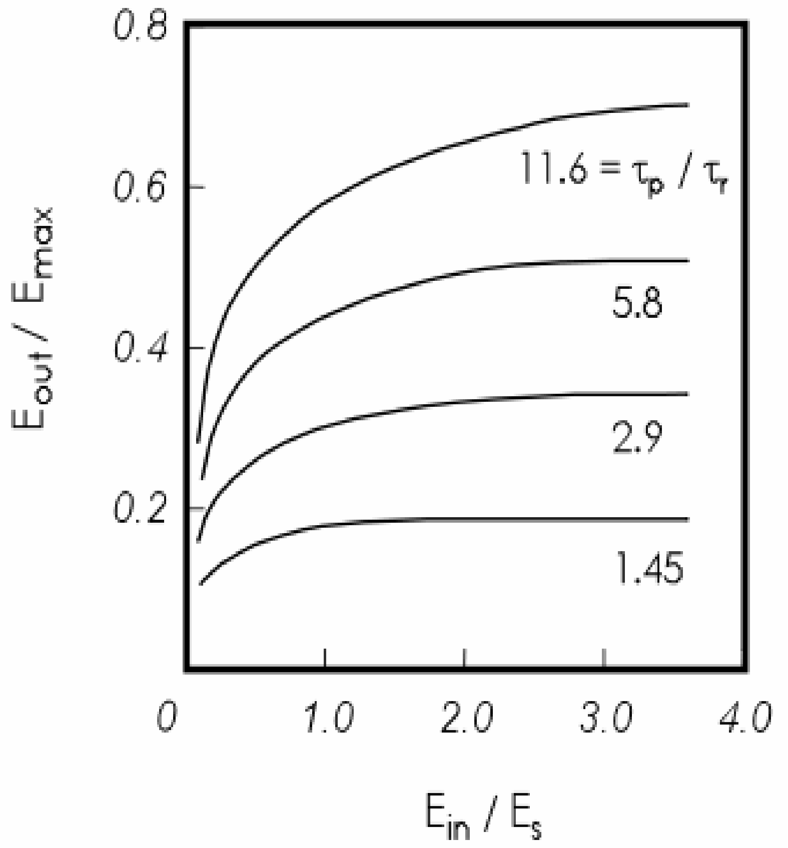


Energy Levels of CO_2 Laser (vibration)



Quantum efficiency: (0.291eV-0.166eV)/0.291eVx100=43%

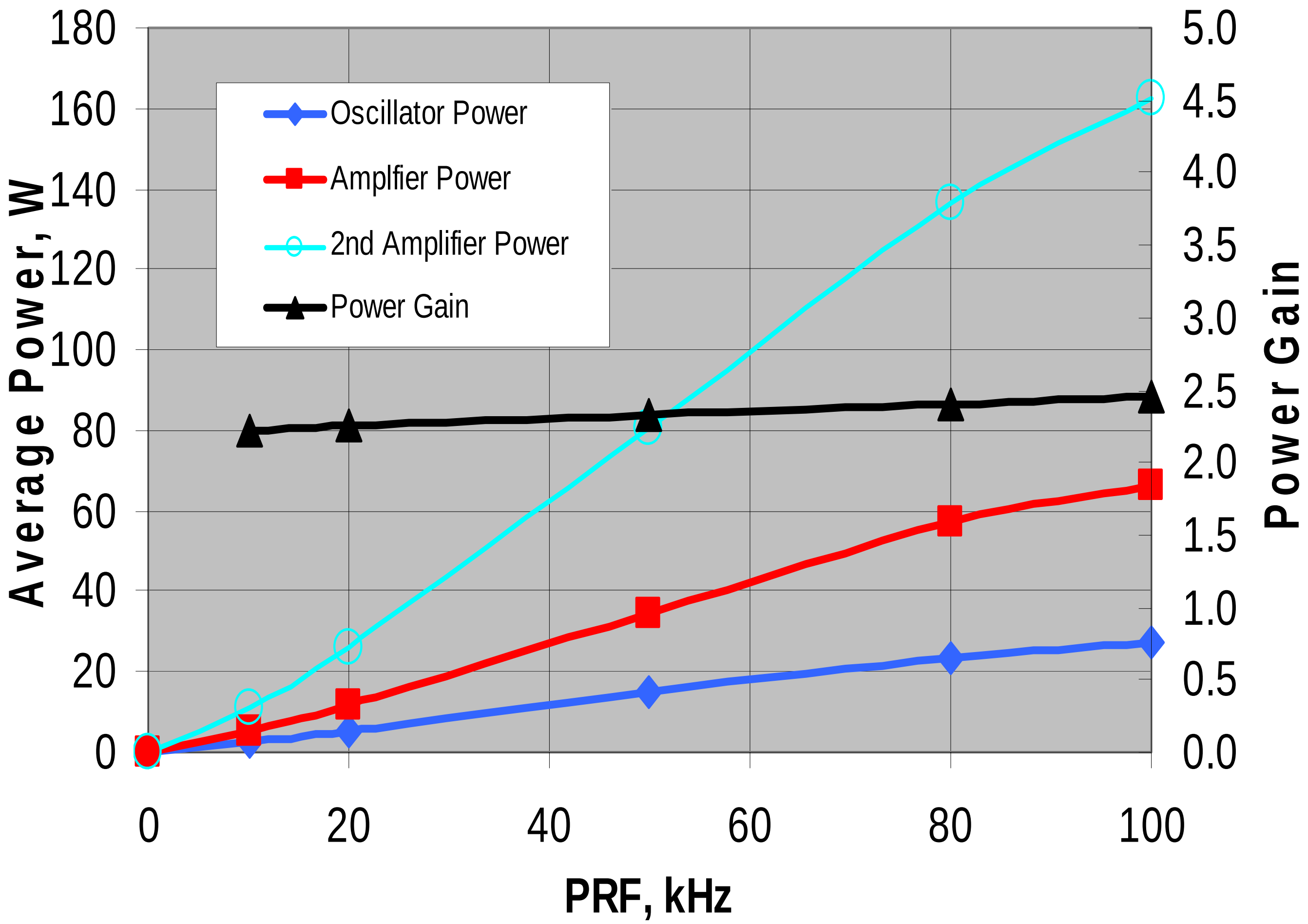
Extraction Efficiency



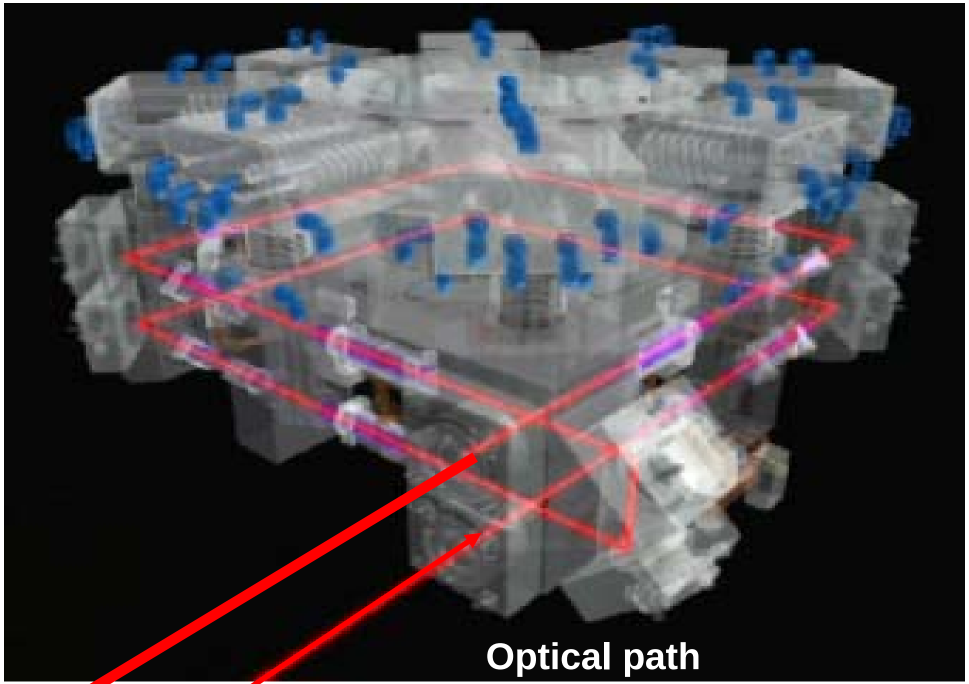
E_s : saturation fluence
E_{max} :maximum output
E_{in} : input fluence
E_{out} : output fluence

τ_p : pulse width
τ_r : rotational relaxational time

P(20) oscillator output power vs. rep. rate



Amplifier / RF pumped axial flow CO_2 Laser

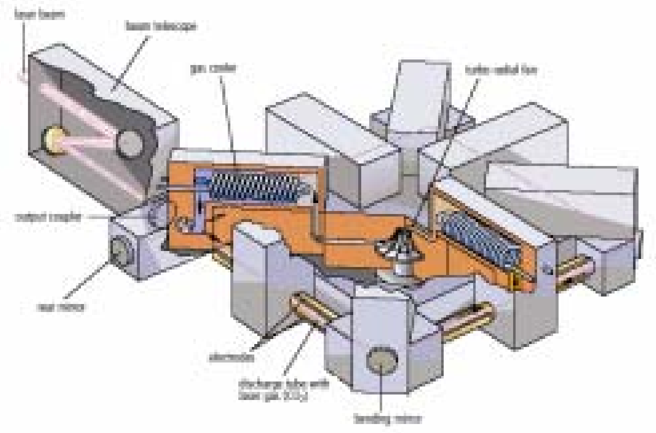


Laser Output

Laser Input

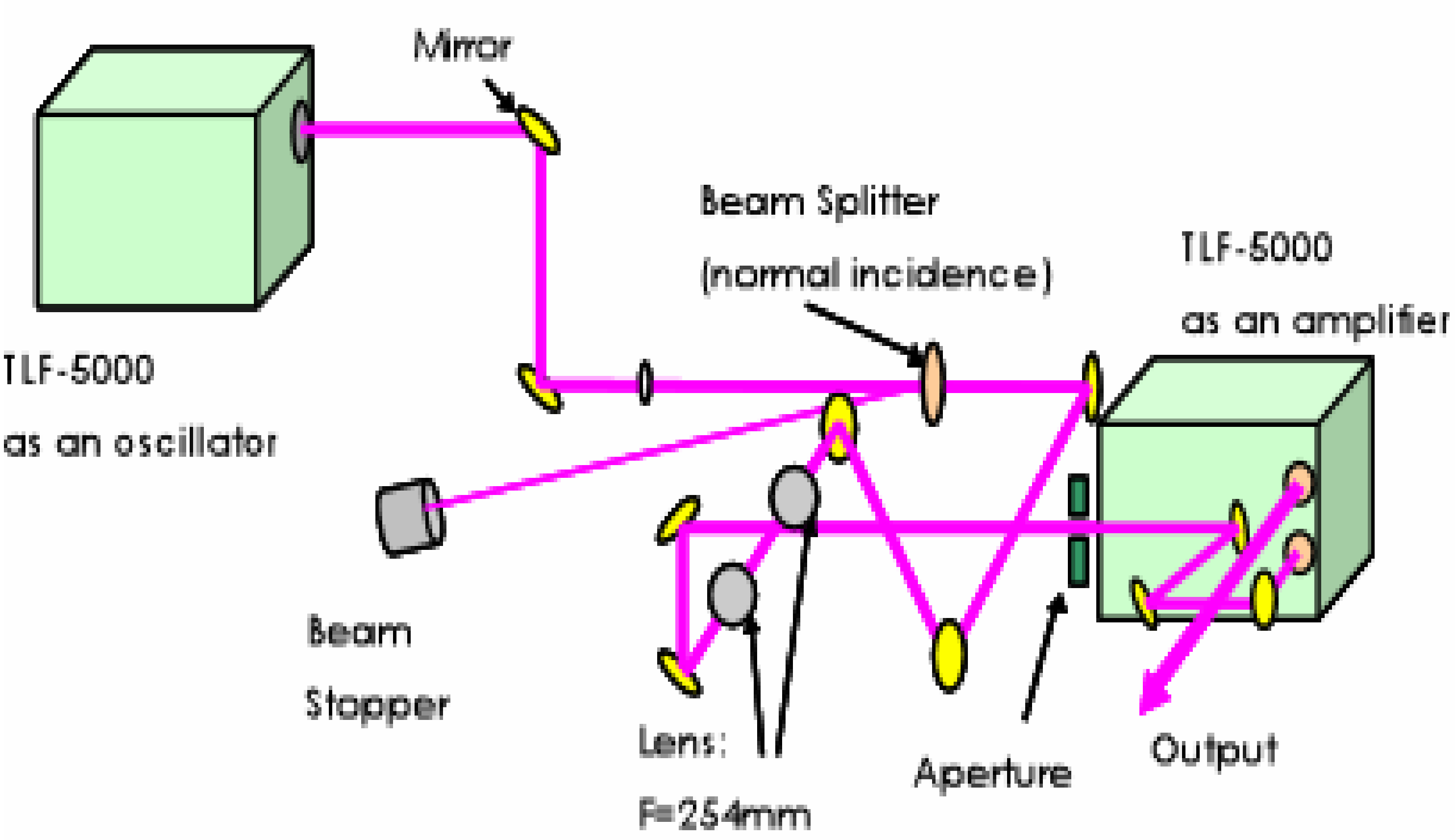
TLF5000 (5W) &TLF15000 (15kW)

Laser equipment



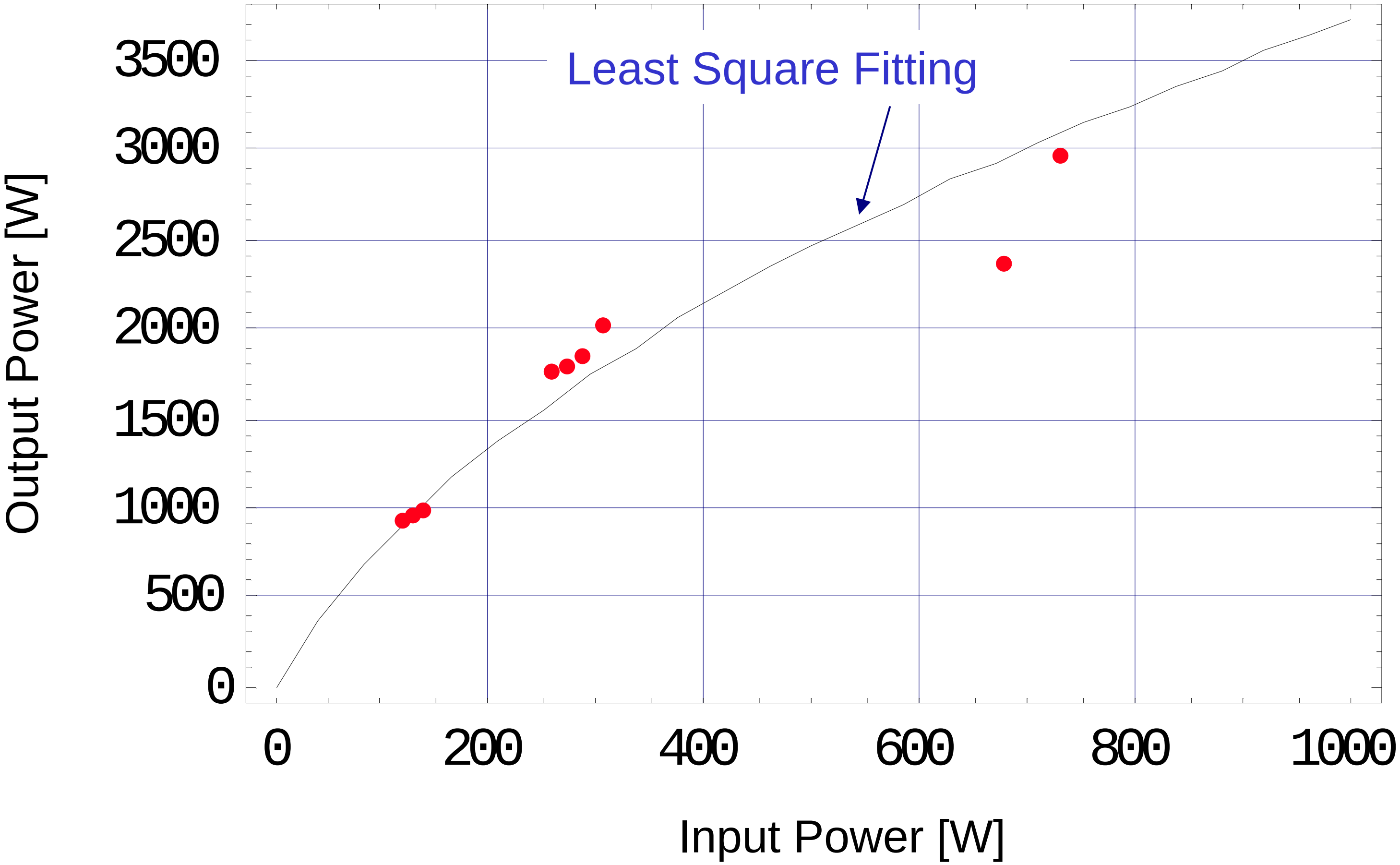
Laser Head

2 stage experiment : two cw 5kW lasers

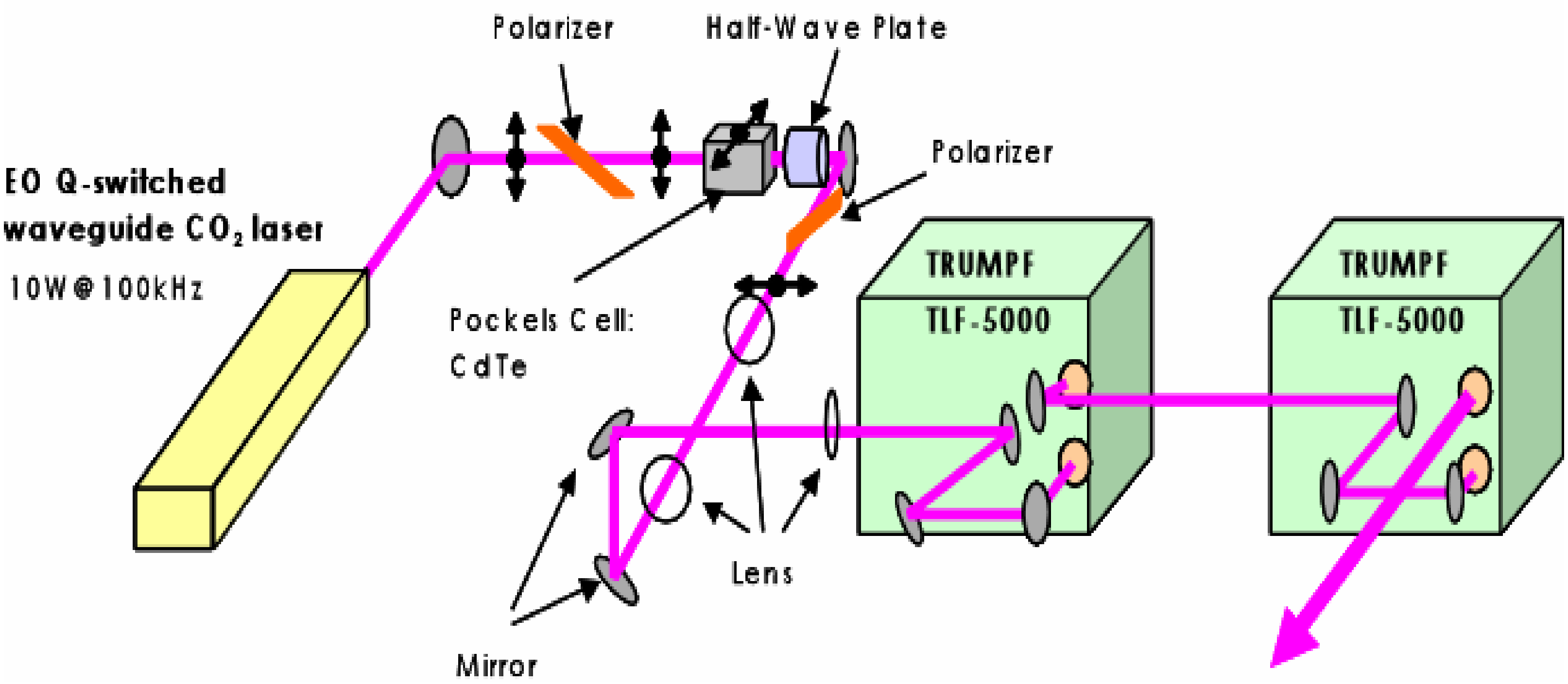


CW amplification of TLF5000

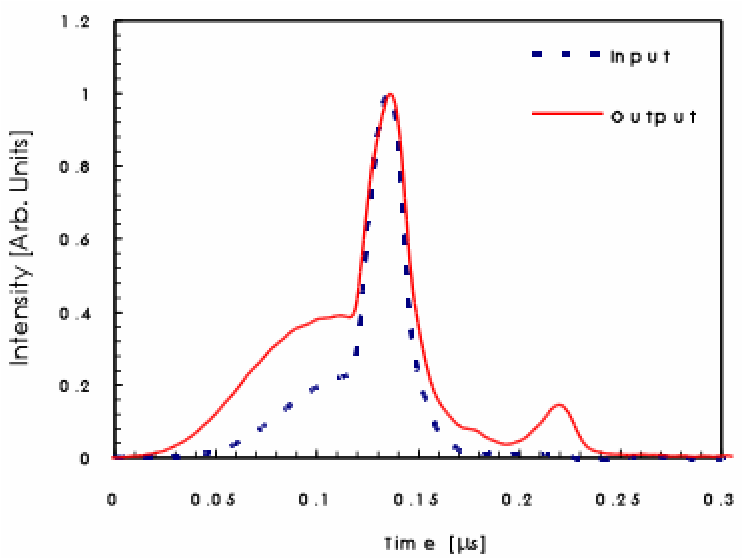
- ✓ Gain Length L= 240 cm
- ✓ Diameter D= 1.4 cm
- ✓ Small Signal Gain g_0=0.99 [%/cm]
- ✓ Saturation Intensity I_s=1624 [W/cm^2]

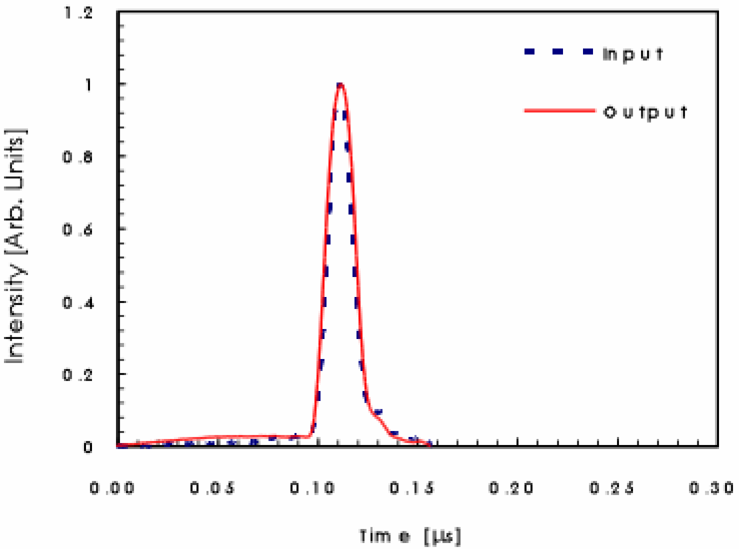


Experimental Arrangement (15ns Pulse Amplification)



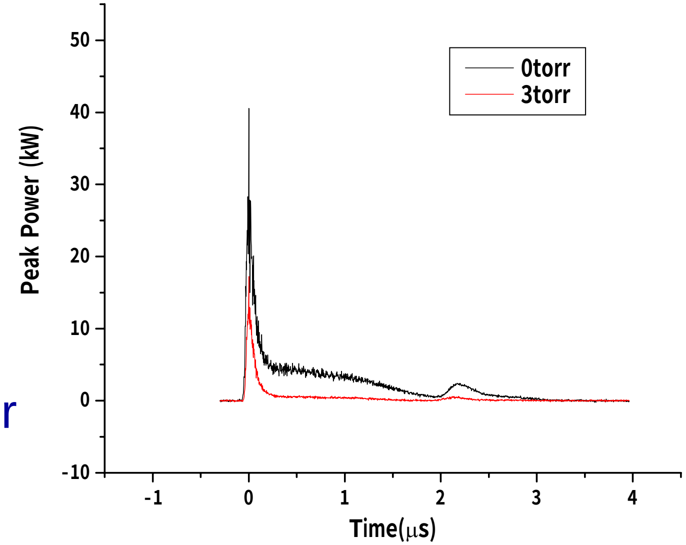
Pedestal Control



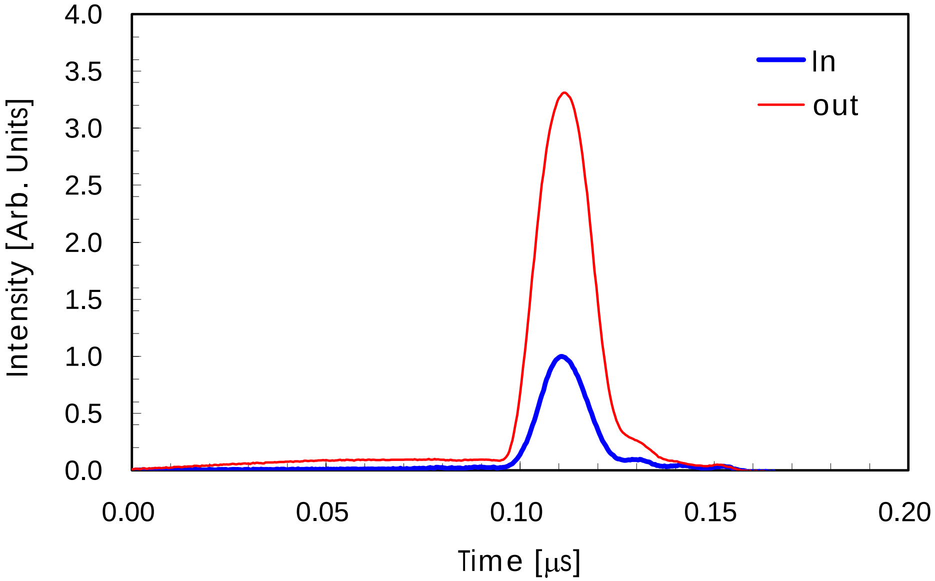


CdTe Pockels Cell

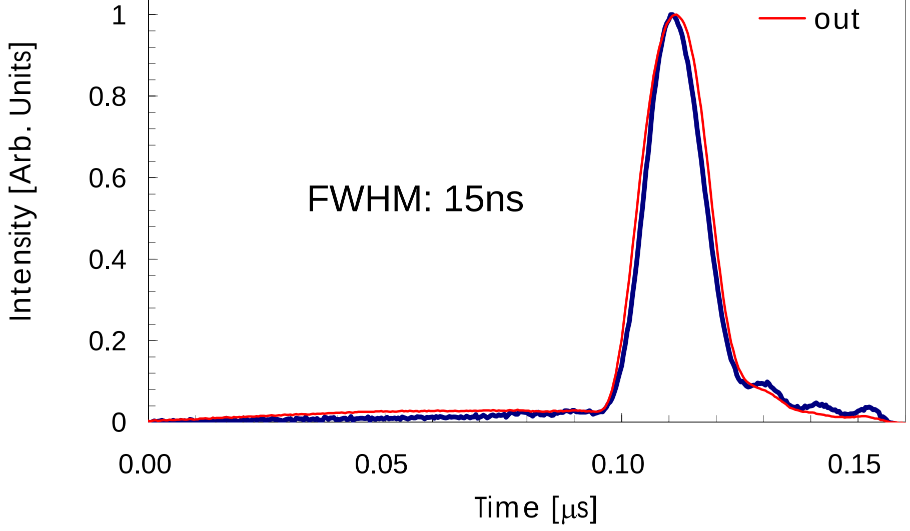
SF_6 Saturable Absorber



Amplification of 15ns pulse by TLF5000



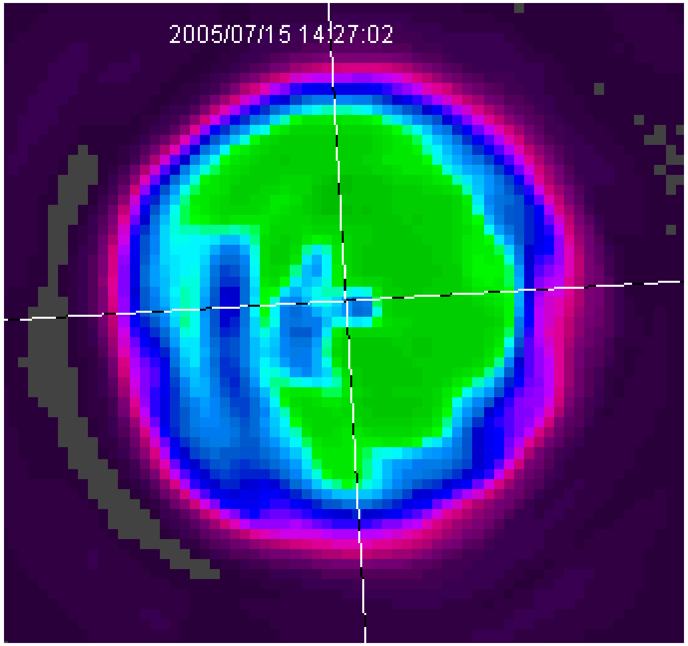
Input energy: 1.6μJ
Output energy: 6.1μJ



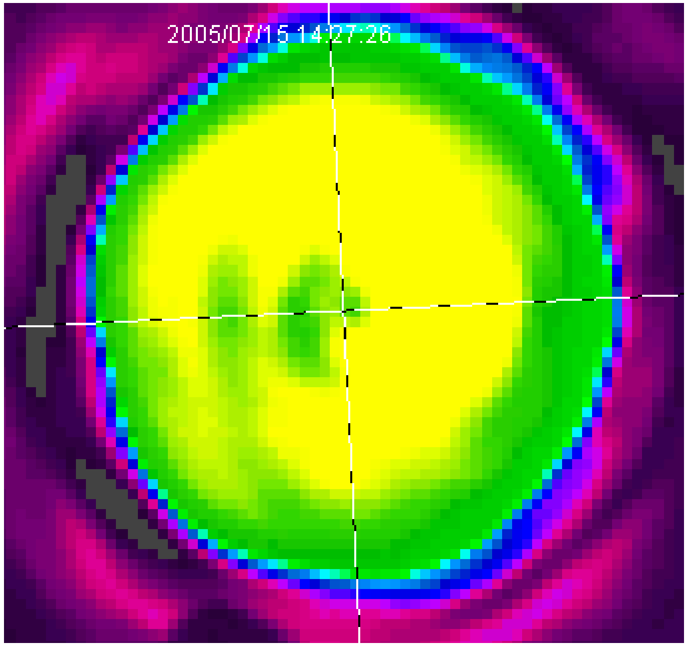
FWHM: 15ns

Small signal amplification

Beam Profile without and with RF pumping



Amplifier Exit (without pumping)



Amplifier Exit (with CW pumping)

No beam quality degradation observed

Summary

EUV light source by CO_2 laser driven Xe droplets for HVM was characterized.

- For 115W light source alternative technologies (RF-CO2, droplet, magnetic field mitigation) are considered.
- Testing feasibility with TEA CO2 laser system
- Pre-pulse laser increases conversion efficiency.
- Xenon droplet target has been generated in high vacuum.
- Effectiveness of magnetic field ion mitigation has been experimentally confirmed.

Achieved performance:

- LPP Source by YAG laser
  - In-band Power 5.7 W (2%BW) at IF <Estimate>
  - Conversion Efficiency 0.9 % @ 10kHz (2%BW, 2p sr)
- by CO2 laser
  - Conversion Efficiency 0.6 % @ 10Hz (2%BW, 2p sr)
    max. EUV emission at delay time of 200ns
  - Short Pulse 6kW CO2 laser is under development