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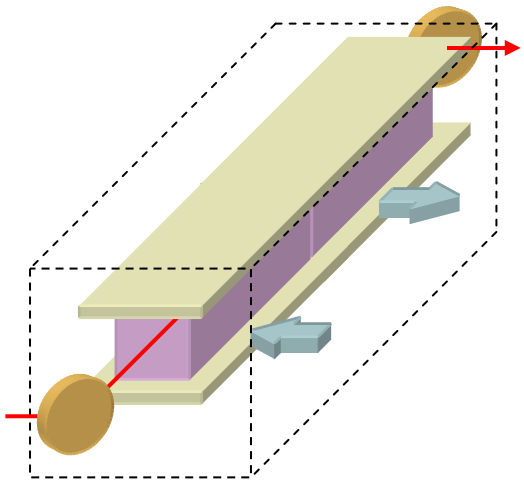
A Driver CO_2 Laser Using Transverse-flow CO_2 Laser Amplifiers



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  - Proposal of transverse-flow CO_2 laser
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- Summary & Acknowledgements

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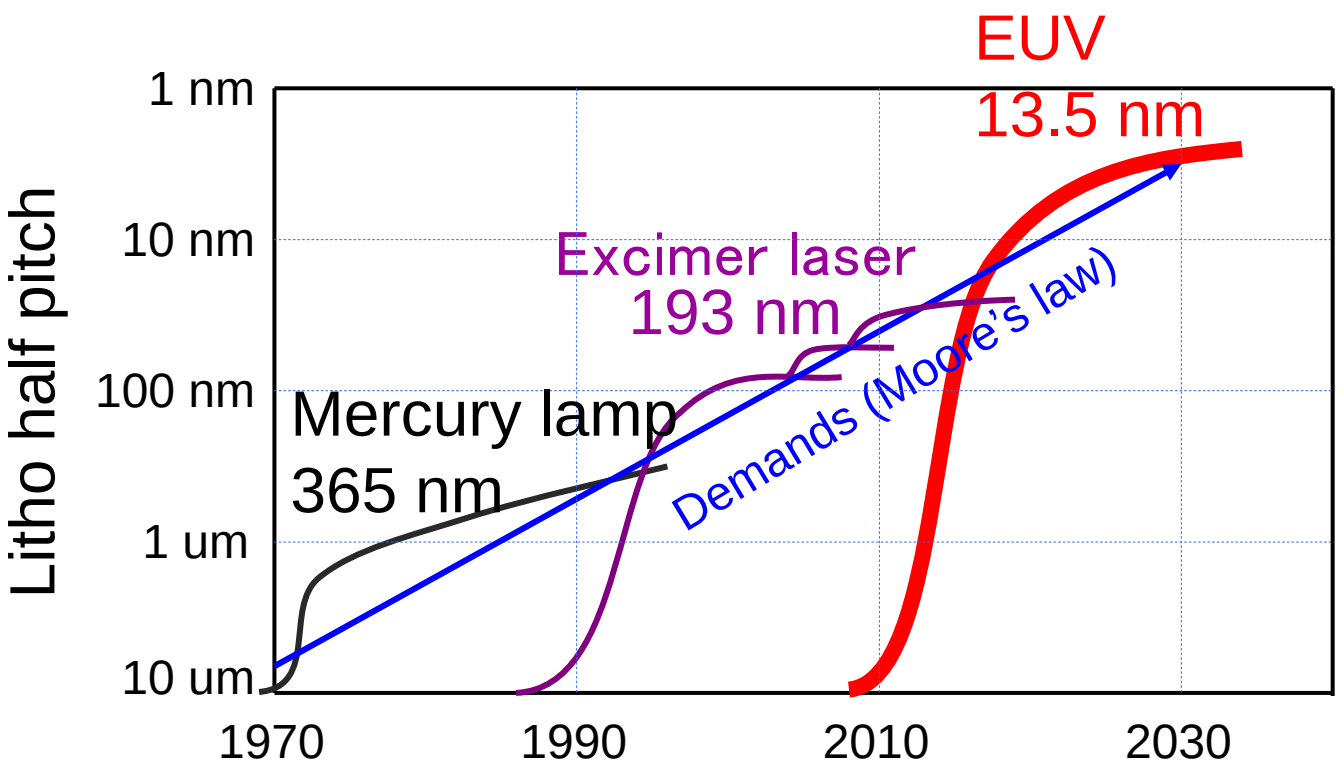
EUV* Lithography

- EUV Litho is developed for commercialization.
- EUV source power is the key for high volume manufacture.



*EUV: Extreme Ultraviolet

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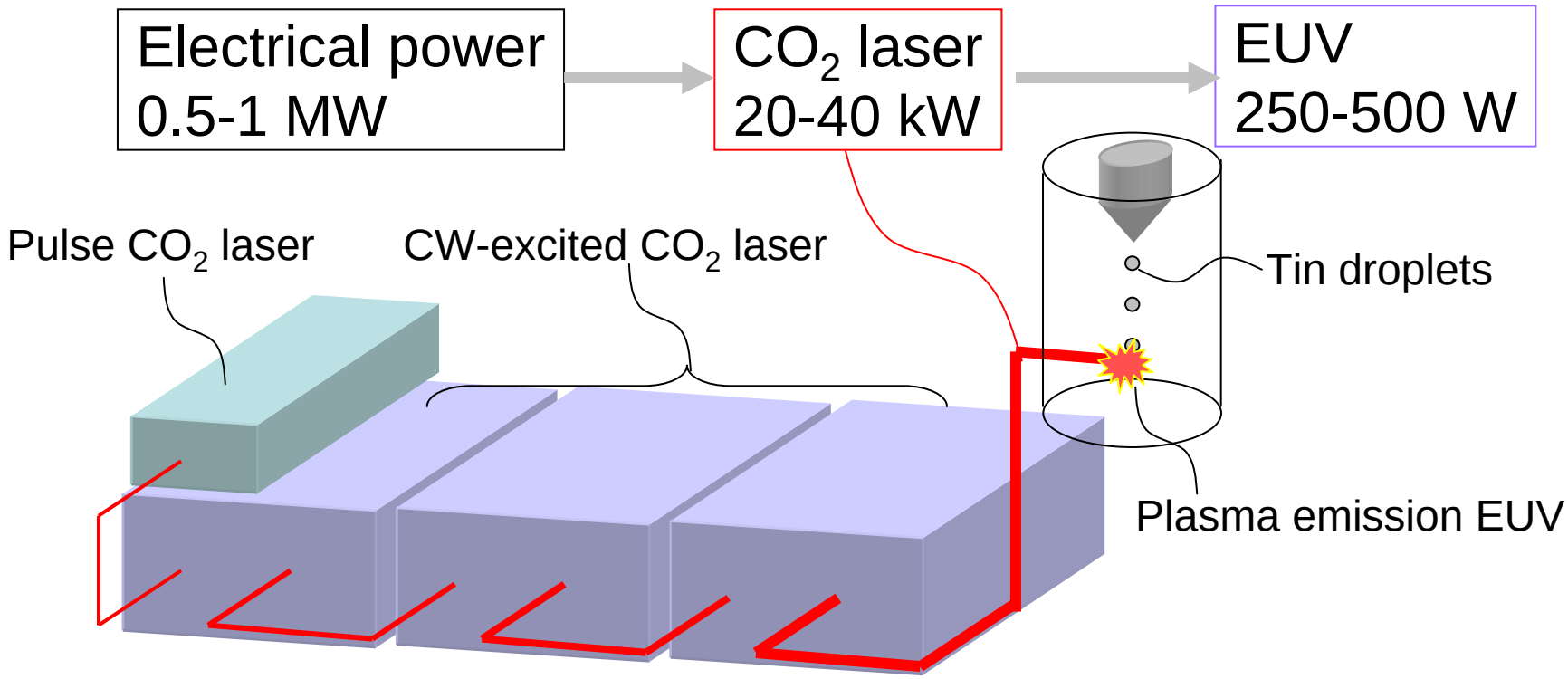
CO_2 Laser Amplifiers

- EUV: tin plasma irradiated by pulse CO_2 laser
- 20-40 kW CO_2 lasers for practical use
- Efficient laser amplification is desired



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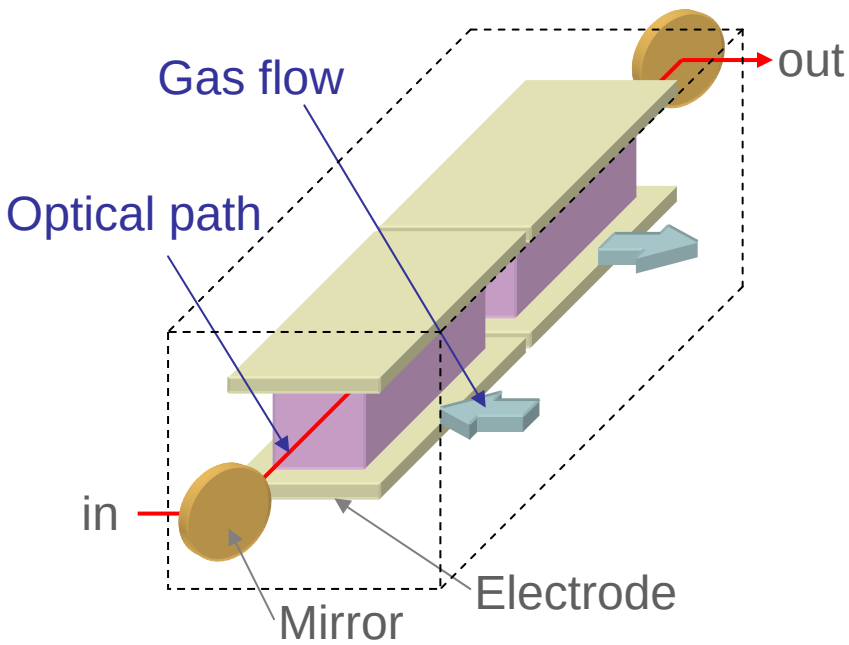
Transverse-flow & Axial-flow

- CW (RF*) excited CO_2 lasers for power amplifiers
- A limited selection of high power (>10 kW) CO_2 lasers

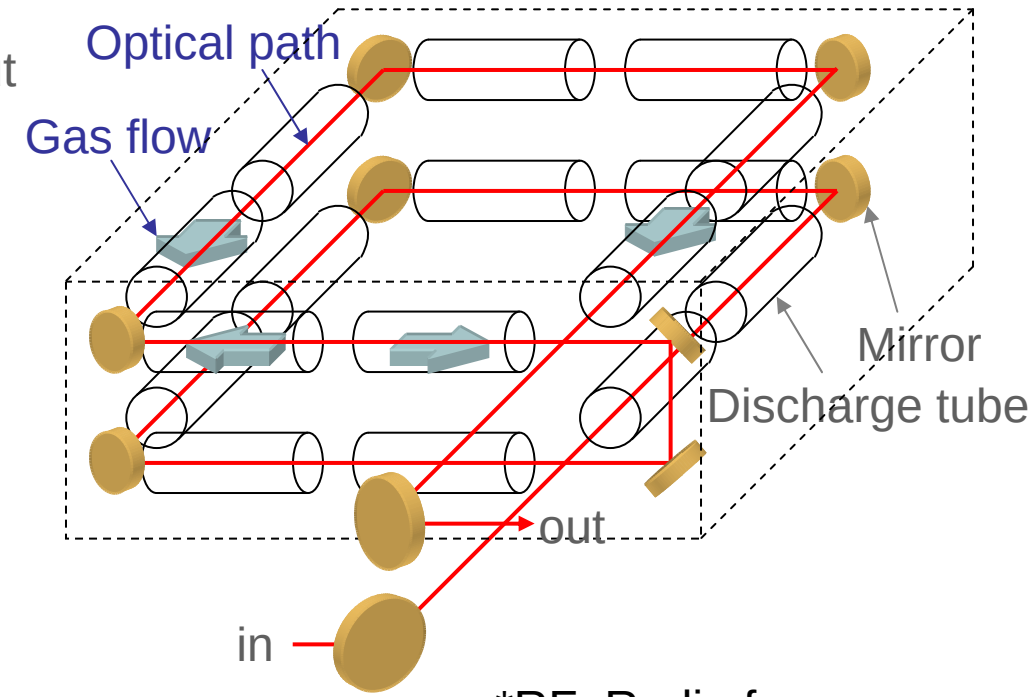
Transverse-flow:

Gas flow ⊥ Optical path



Axial-flow:

Gas flow // Optical path



*RF: Radio frequency

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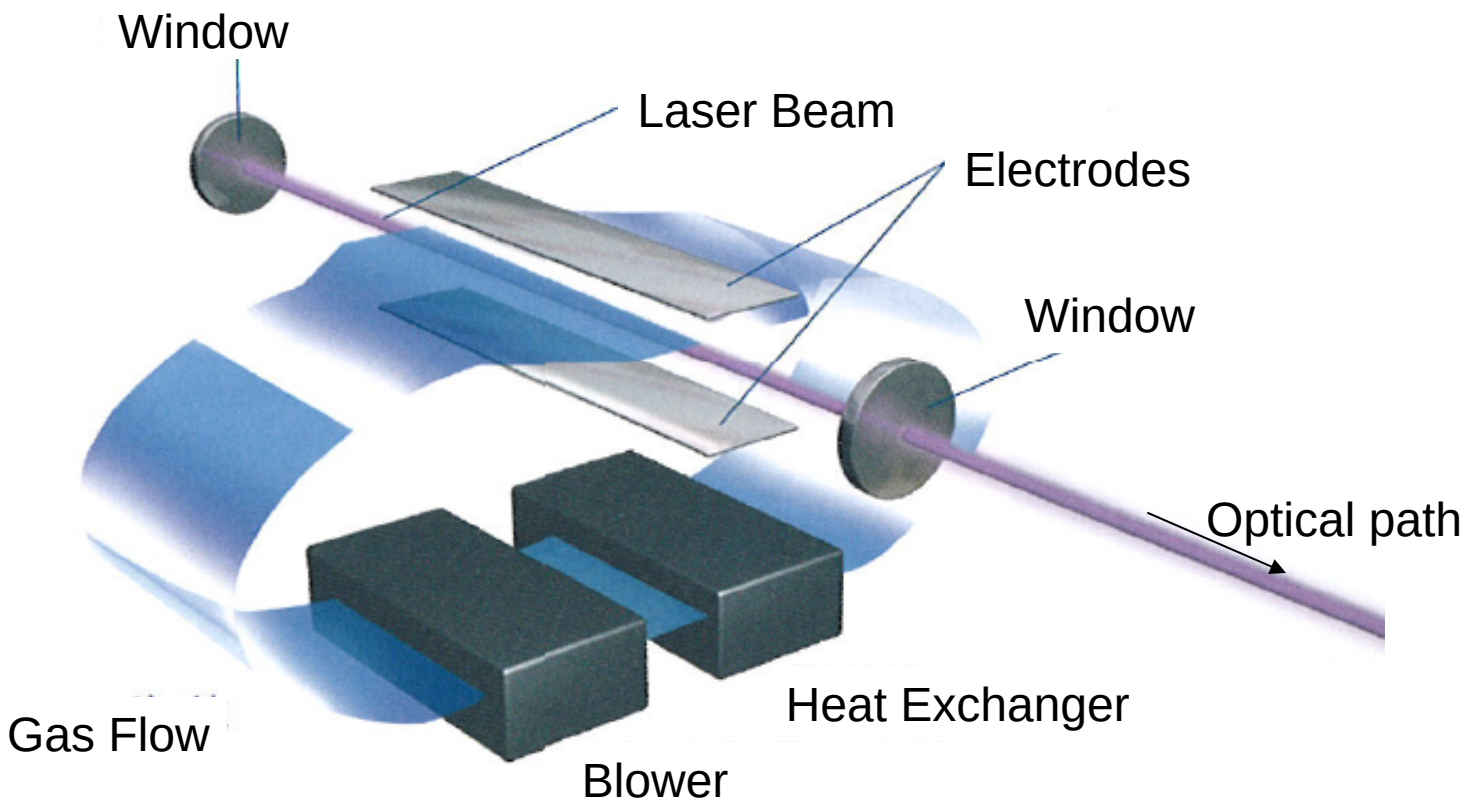
Transverse-flow CO_2 laser

- Gas flow is perpendicular to the optical path.
- Easy to flow, easy to cool the gas



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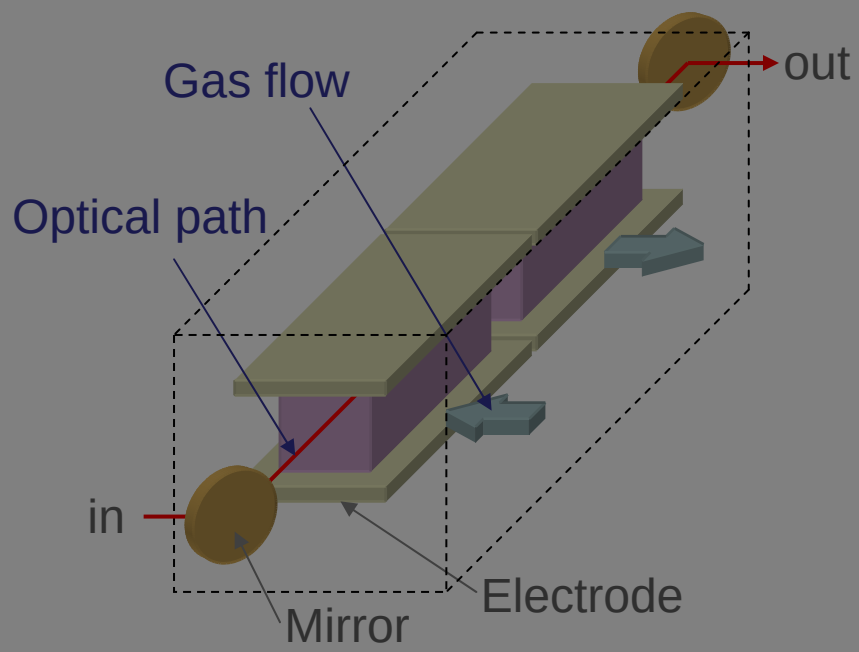
Conventional Pulse Amplifier

- Only axial-flow amplifiers have been developed for EUV.

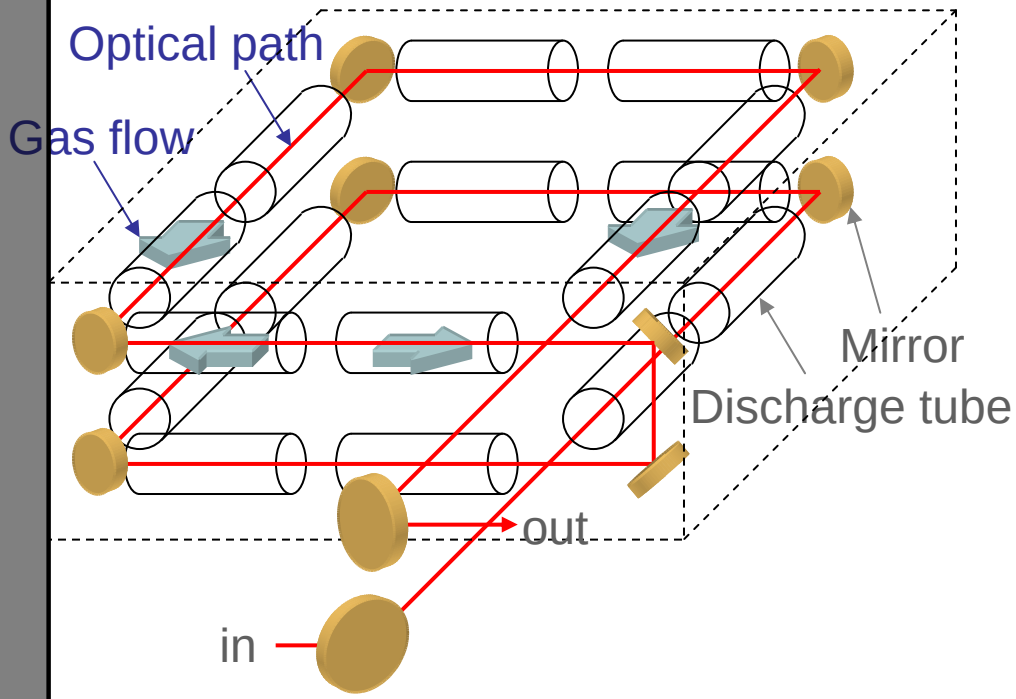
Transverse-flow:

Gas flow ⊥ Optical path



Axial-flow:

Gas flow // Optical path



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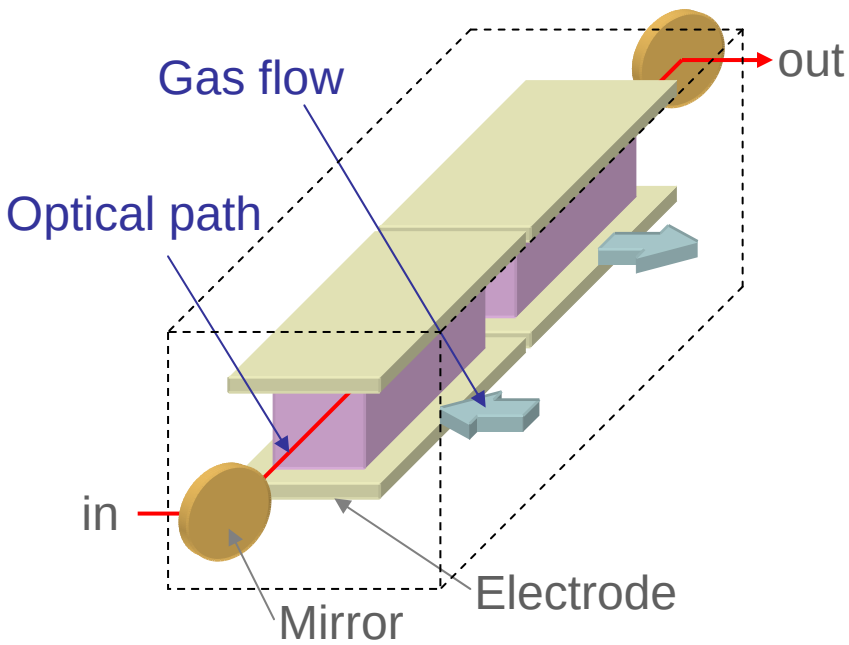
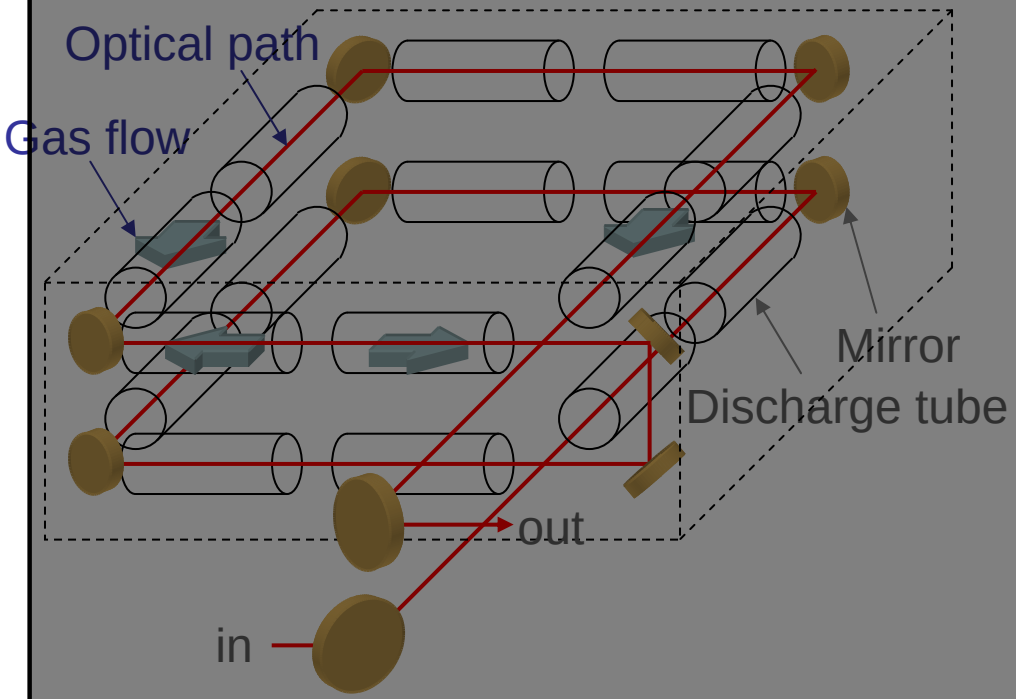
Proposal: transverse-flow amp.

- No one has developed transverse-flow amplifiers for EUV except for us.

Transverse-flow:
Gas flow ⊥ Optical path



Axial-flow:
Gas flow // Optical path



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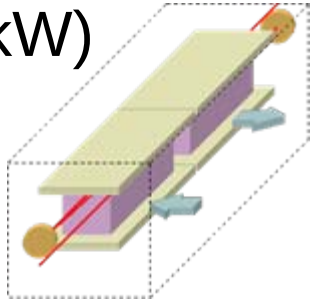
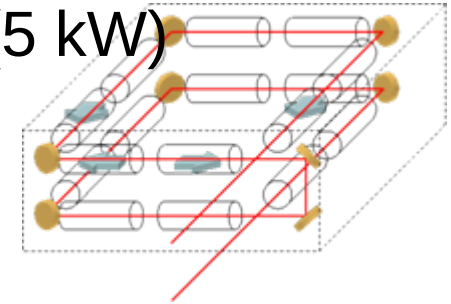
Parameter Study

- With a classical model: $P = P_s\left(g_0 L + \ln\sqrt{1-r}\right)$*
- Transverse-flow : Higher gain → Higher amplification efficiency
- Wider gas flow channel → Lower gas pressure → Higher gain

	Transverse-flow (4 kW)	Axial-flow (5 kW)
		
Gas flow cross-section	700 cm^2	40 cm^2
Gas pressure	7 kPa	20 kPa
Small signal gain	3.7	2.2
Multi-fold path	Possible	Impractical

(*) P : Power, P_s : Saturation power, $g_0 L$: Small signal gain, r : Loss

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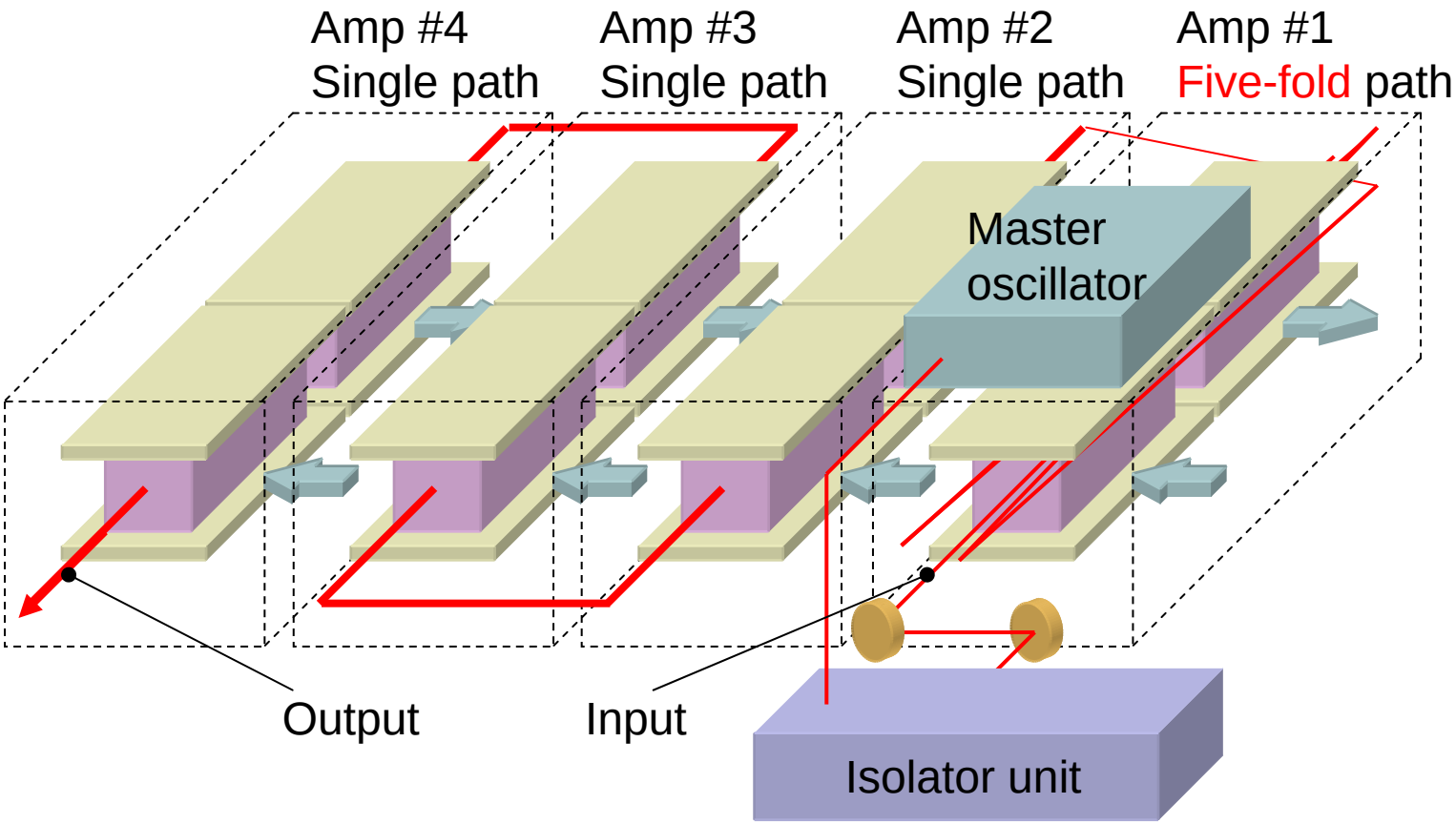
Test Method

- Four transverse-flow amplifiers in series
- Five-fold optical path in amp #1
- Single paths in amp #2-4



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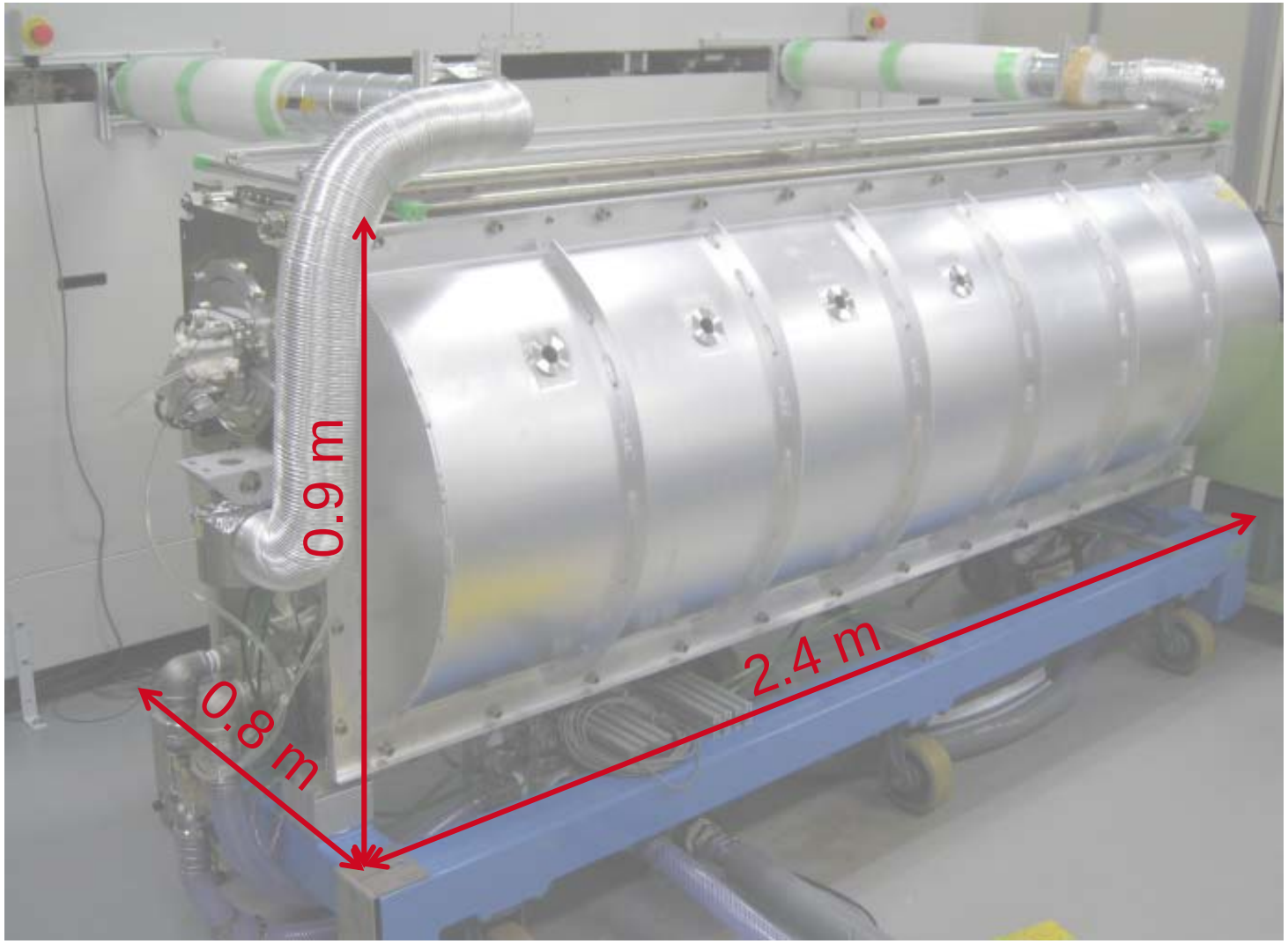
Amp #1

- Amplifier chamber: 2.4 x 0.8 x 0.9 m^3



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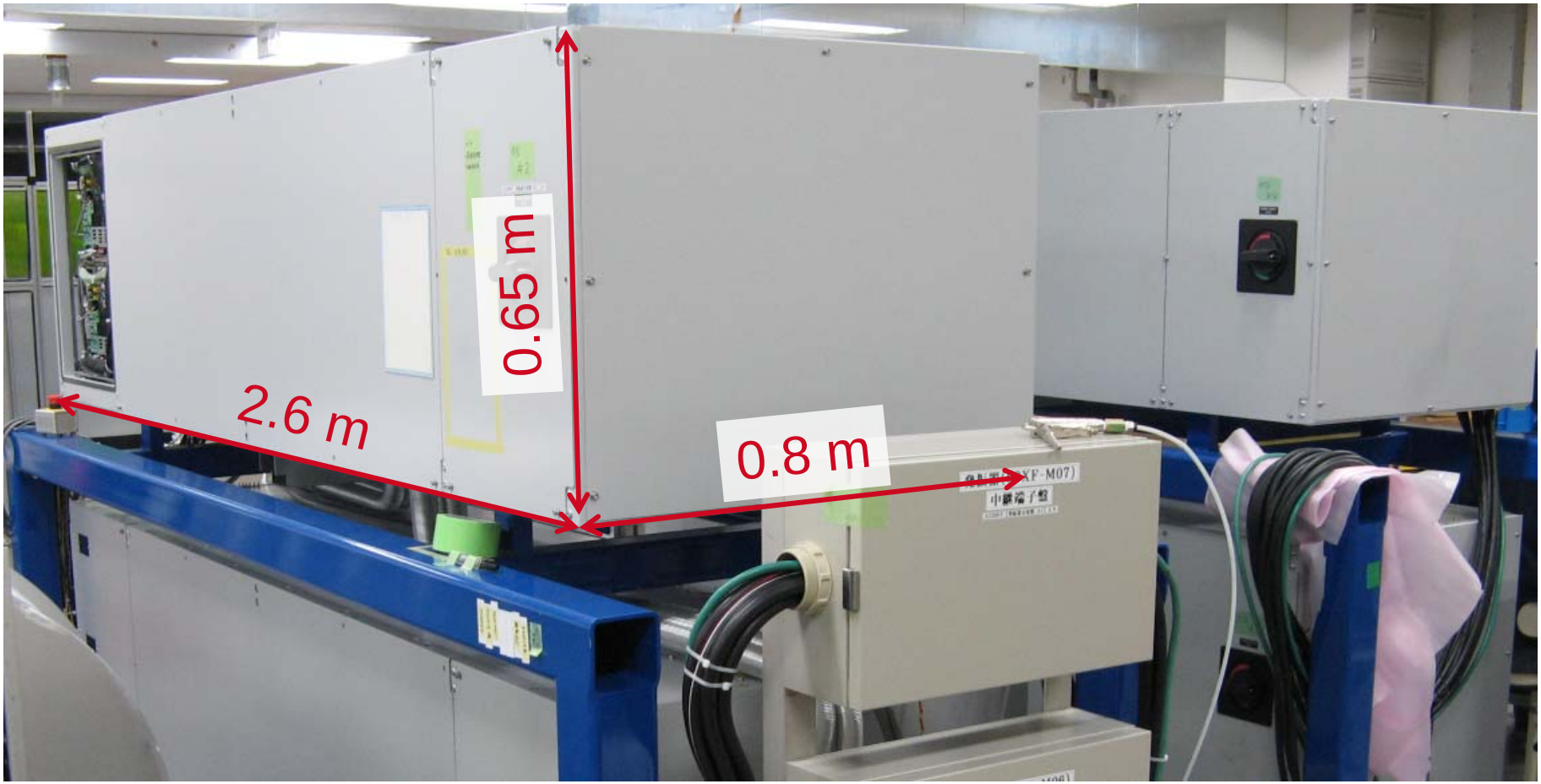
Power source #1

- Power source for an amplifier: 2.6 x 0.8 x 0.65 m^3



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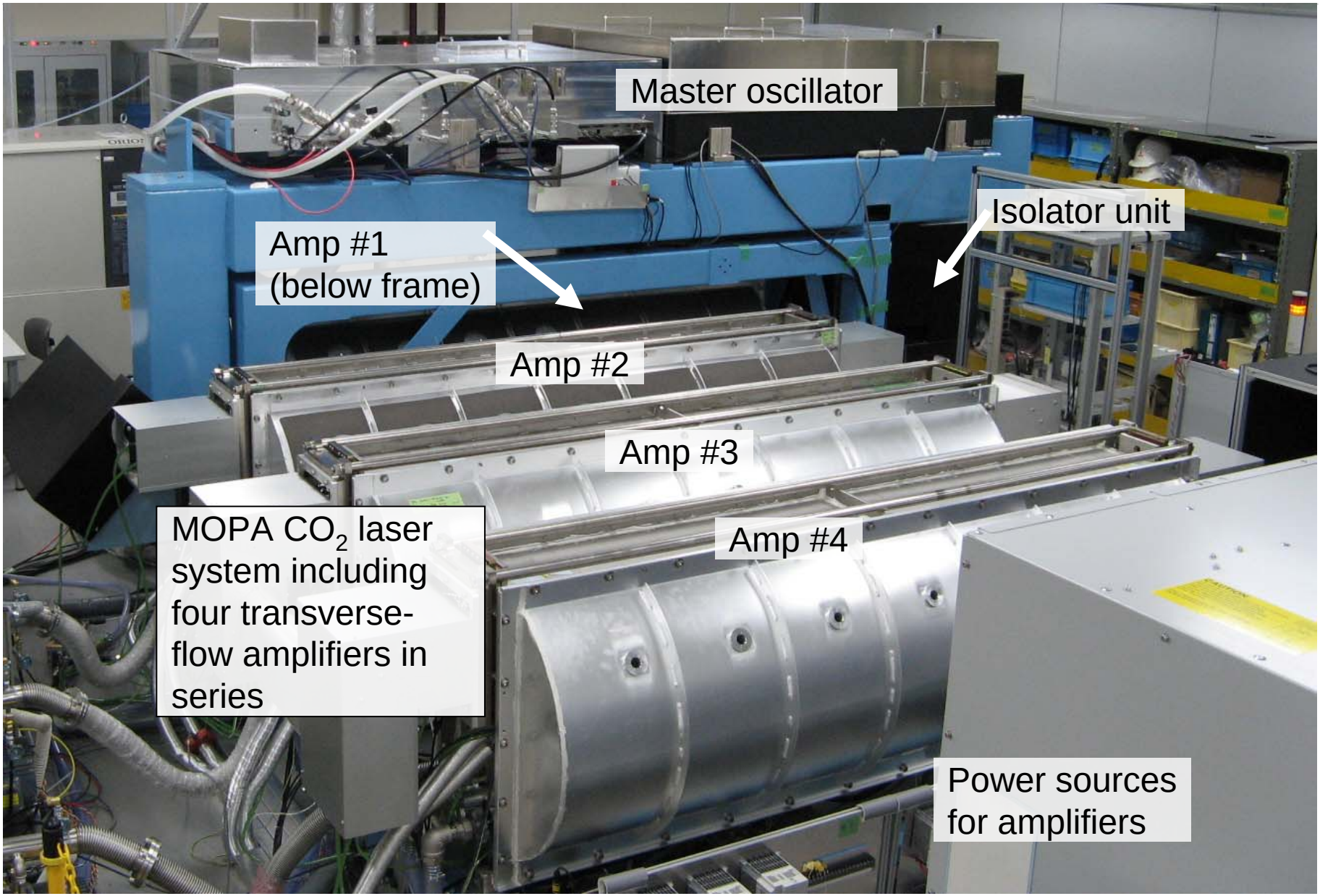
A prototype laser system



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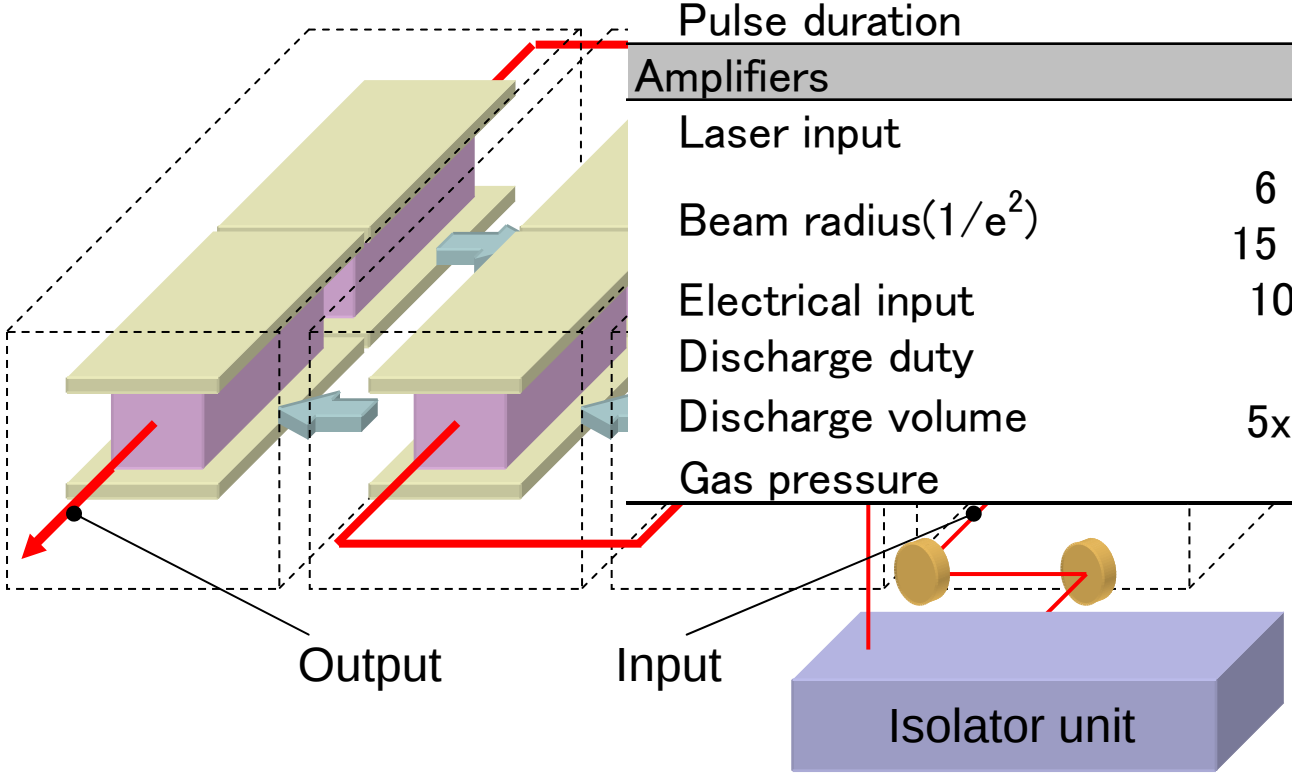
Test Condition

- Laser input: 15 ns, 100 kHz
- Electrical input for discharge: 100 kW x4, duty 33%

Master Oscillator	
Wavelength	10.6 μm P(20)
Repetition frequency	100 kHz
Pulse duration	15 ns
Amplifiers	
Laser input	22 W max
Beam radius($1/e^2$)	6 mm@amp#1 , 15 mm@amp#2-4
Electrical input	100 kW max x4
Discharge duty	33%
Discharge volume	5x4x188 cm^3 x4
Gas pressure	7.0 kPa



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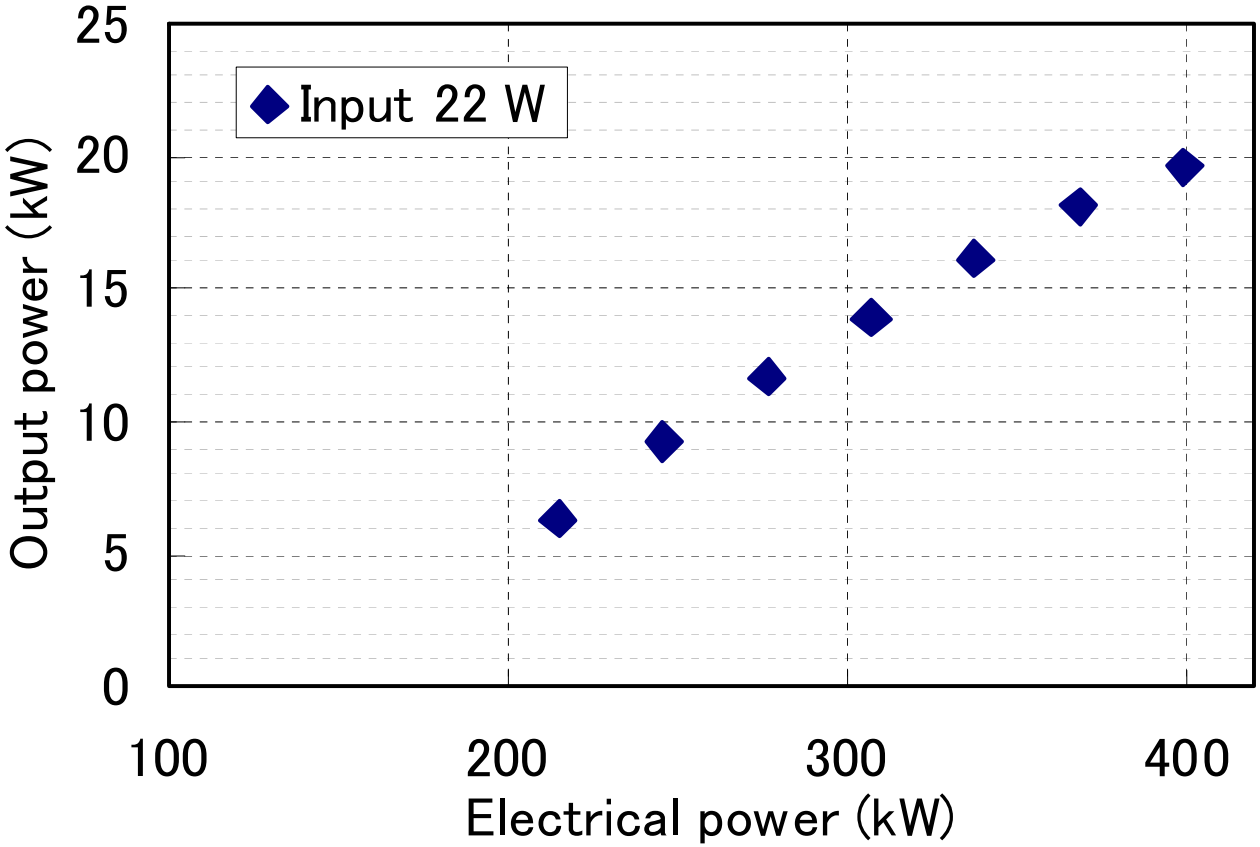
Results: Power

- Output power 19.6 kW was demonstrated at 33% duty.
- Input power was 22 W. Electrical power for discharge was 400 kW (all powers in burst).



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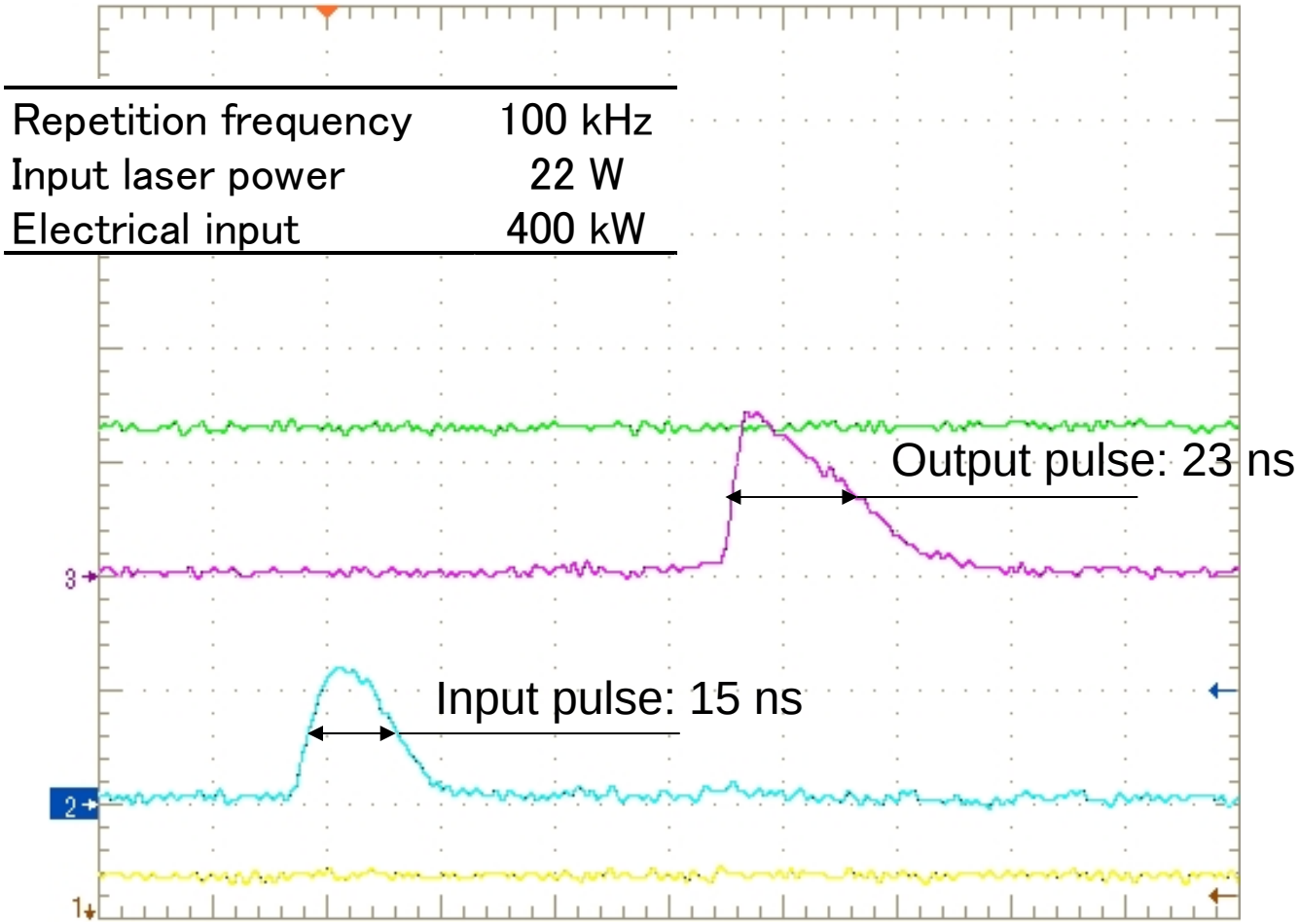
Results: Waveform

- Output pulse duration: 23 ns @19.6 kW
- Expected pulse stretch



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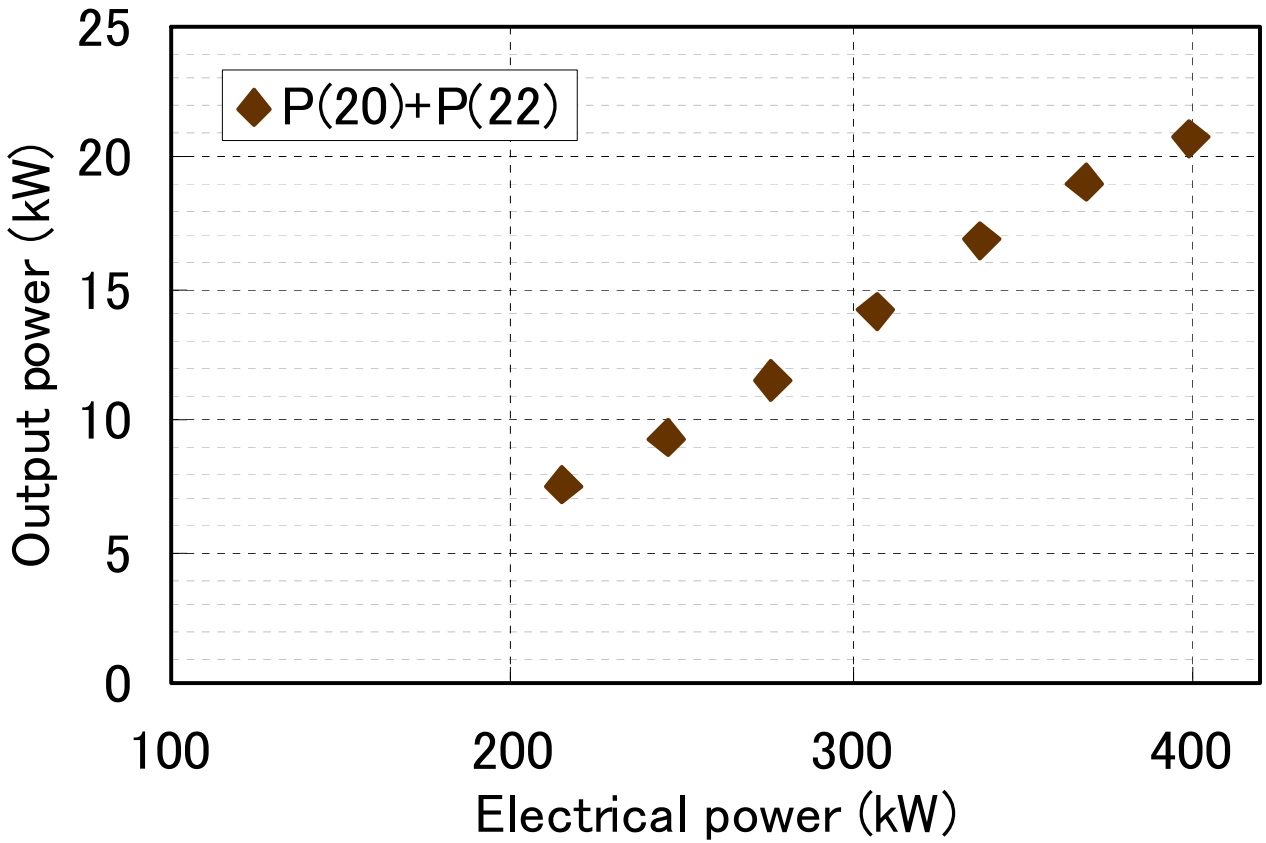
Results: Two-line oscillator

- Output power 21 kW was demonstrated with two-line oscillator (See poster P-SO-60).



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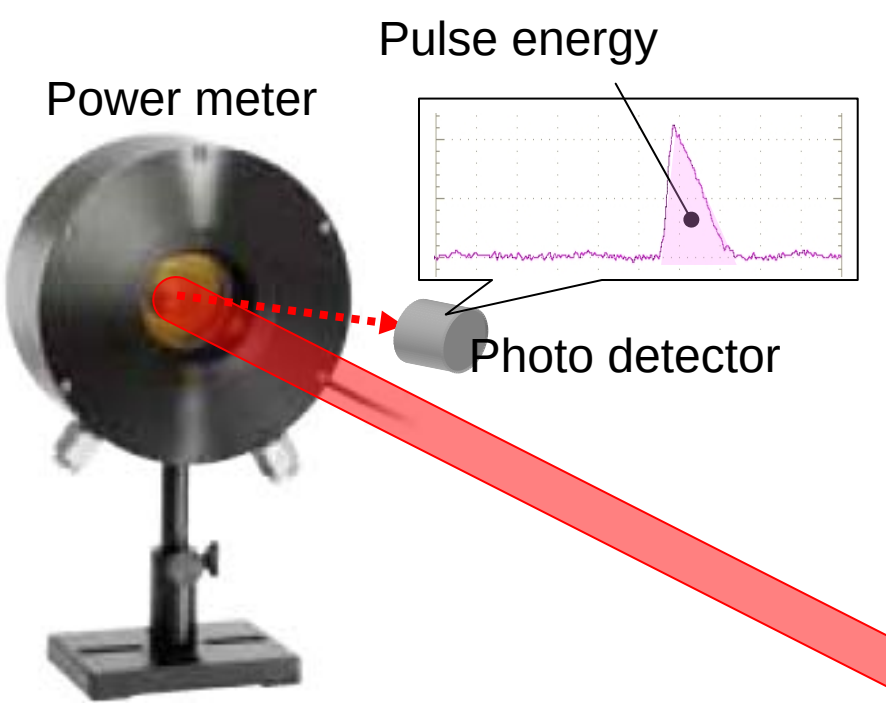
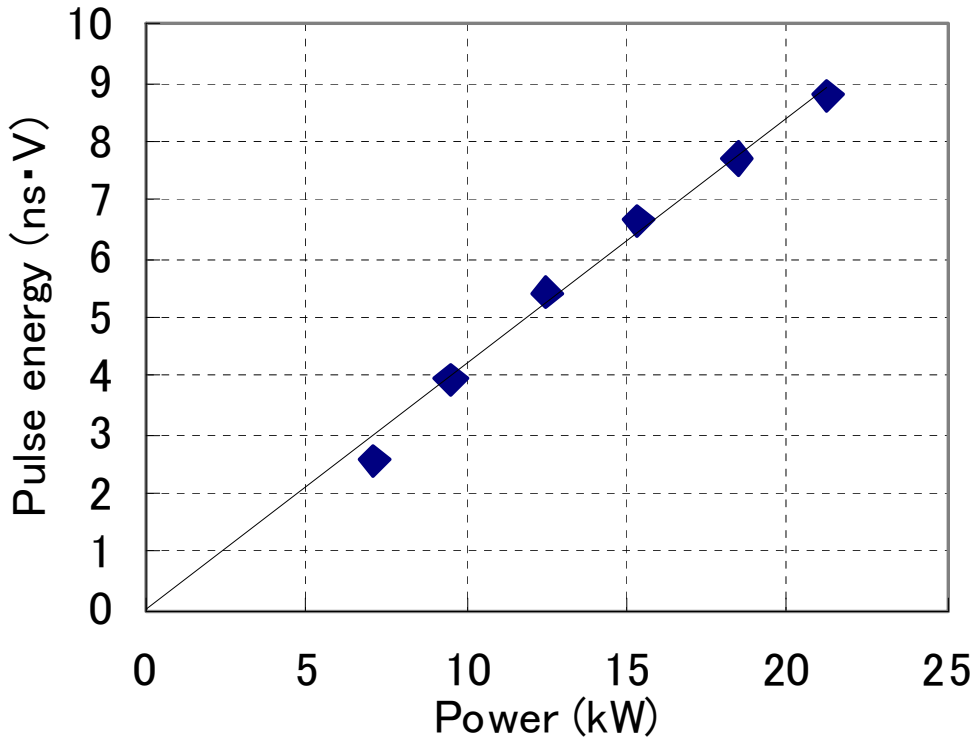
Results: Few CW part

- Measured pulse energy was proportional to measured power.
- There was few/no CW part in the pulse amplification.





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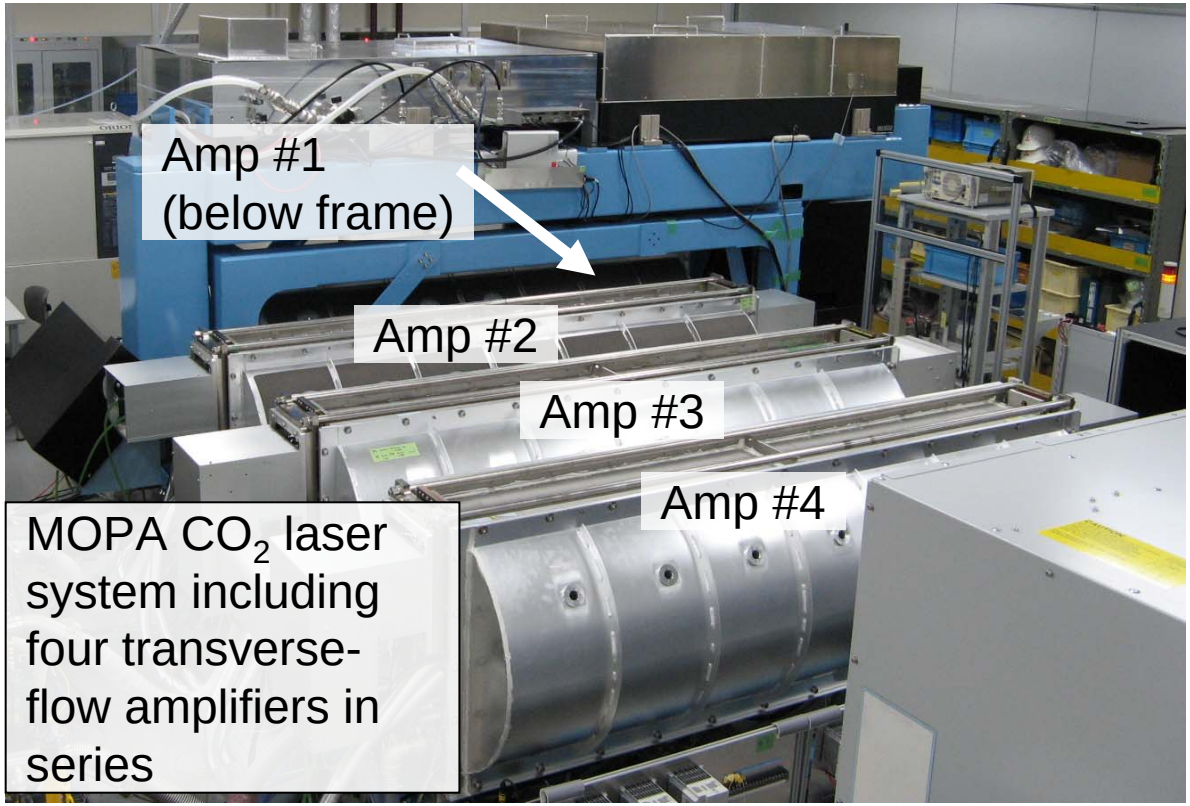
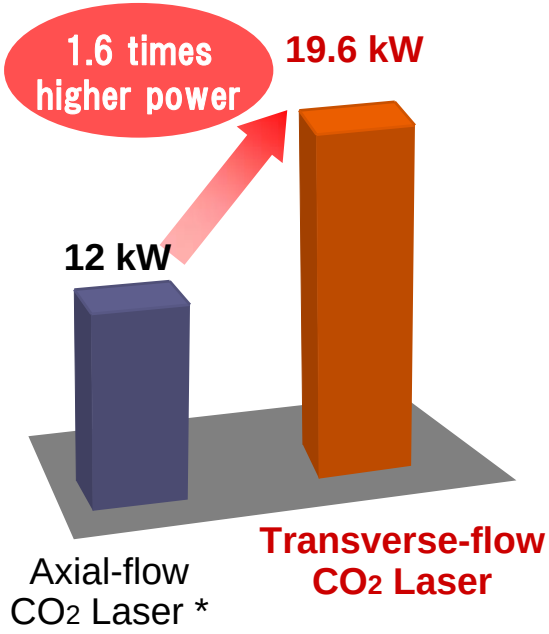
Discussion

- CO_2 laser power was 19.6 kW (single-line), 21 kW (two-line).
- The power was higher compared to the axial-flow CO_2 laser at the same electrical input of 400 kW.
- Electrical-to-optical efficiency was 5.2%



MOPA CO_2 laser system including four transverse-flow amplifiers in series



(*)2013 SPIE AL, 8679-51

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Summary

- Transverse-flow CO_2 lasers are promising candidate for EUV Driver.
- Pulse amplification test:
  - Four amplifiers
  - Output power: 21 kW demonstrated
  - Electrical-to-optical efficiency: 5.2%
- Commercialization is underway by Mitsubishi Electric and Gigaphoton

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