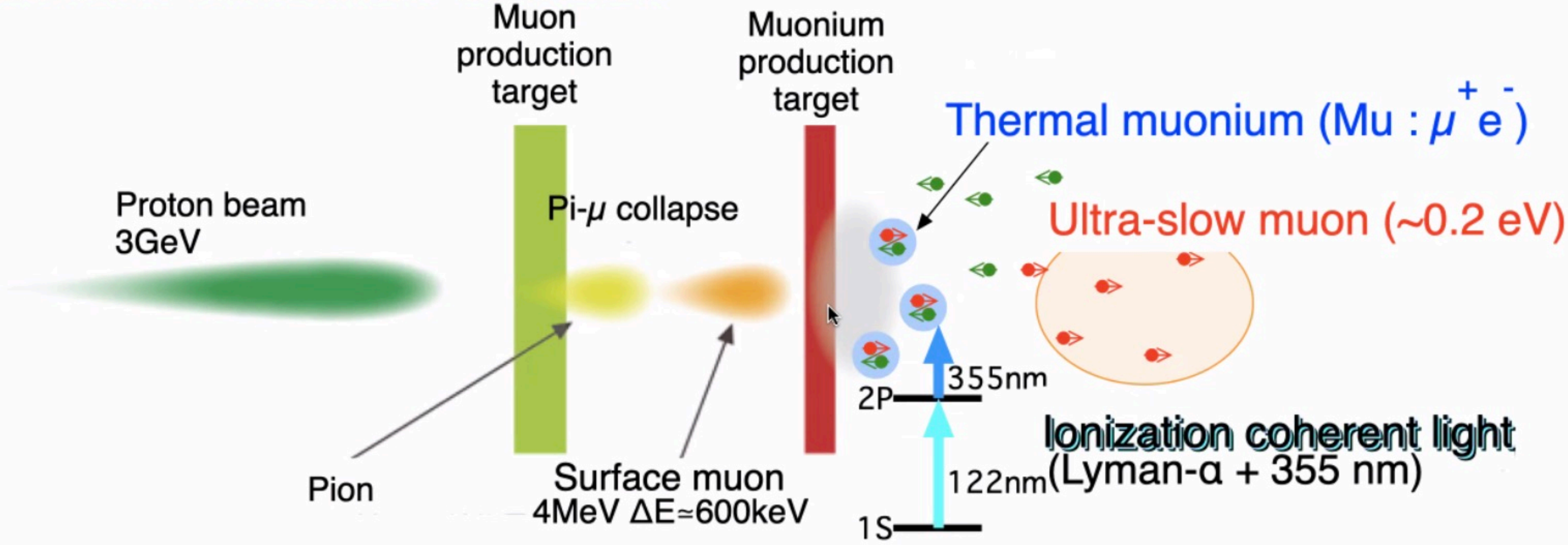
Ultra slow muon generation by laser ionization

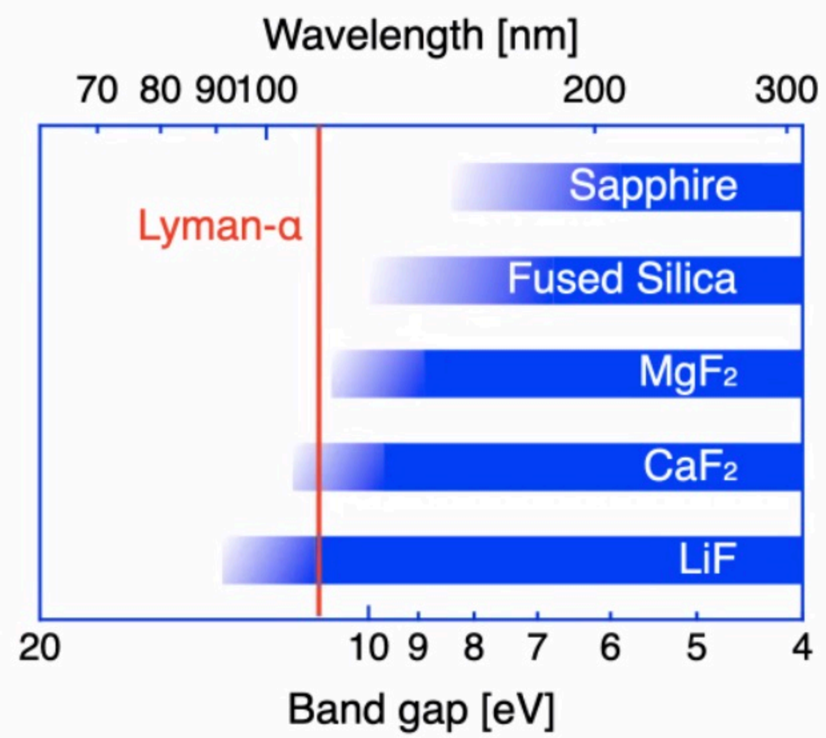
Resonant ionization of muon



Difficulty of generation

Lyman-α wavelength region is no

- laser material
- nonlinear wavelength conversion crystal.



We should generate the intense Lyman-alpha pulse in Gas medium

Lyman-α generation

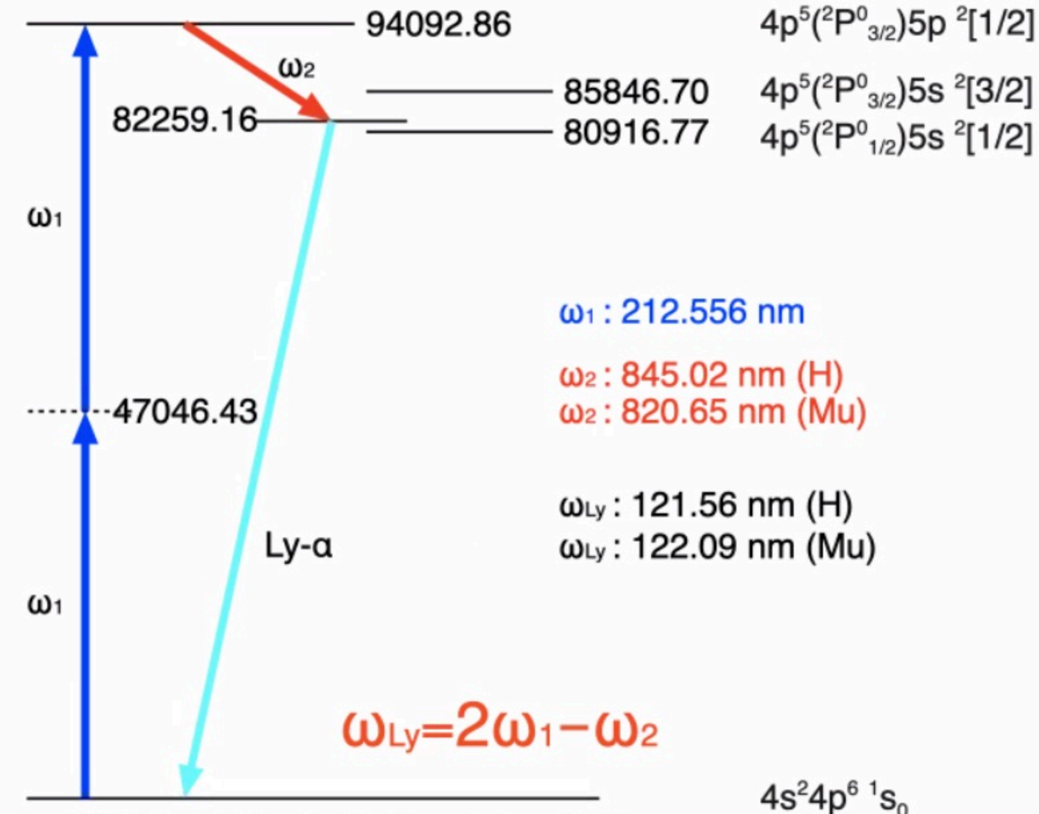
Various vuv generation by four-wave mixing

Medium	Two Photon Resonant State	Tuning Range	Conversion Efficiency	Ref.
Kr	4*p*-5*p* [1/2, 0]	Lyman-*α*	5 x 10^{-4}	[1]
Kr	5*p* [5/2, 2]	129-181 nm	10^{-3} ~ 10^{-4}	[2]
		72.5-83.5 nm	1.2 x 10^{-5}	
Kr	5*p* [5/2, 2]	92.1-94.3 nm	~ 10^{-5}	[3]
Xe	5*p*-6*p* [1/2, 0]	155 nm	2 x 10^{-3}	[4]
Xe	6*p* [3/2, 2]	162.6 nm	4 x 10^{-3}	[5]
Xe	6*p* [5/2, 2]	154-223 nm	~ 2 x 10^{-3}	[6]
Xe	7*p* [1/2, 0]	125.9 nm	≥ 10^{-4}	[7]
	7*p* [3/2, 0]	126.1 nm		
	6*p*' [3/2, 2]	125.4 nm		
Xe	8*p* [1/2, 0]	81.7-86.6 nm	~ 10^{-6}	[8]

Wavelength (nm): 80, 100, 120, 140, 160, 180

[1] J. P. Marangos *et al.*, J. Opt. Soc. Am. B **7**, 1254 (1990).
[2] G. Hilber *et al.*, J. Opt. Soc. Am. B **4**, 1753 (1987).
[3] K. D. Bonin *et al.*, J. Opt. Soc. Am. B **2**, 527 (1985).
[4] H.R. Hutchinson *et al.*, IEEE J. Quantum Electron. **19**, 1823 (1983).
[5] J. Hager *et al.*, Chem. Phys. Lett. **90**, 472 (1982).
[6] R. Hilbig *et al.*, IEEE J. Quantum Electron. **19**, 194 (1983).
[7] Y. -M. Yiu *et al.*, Opt. Lett. **7**, 268 (1982).
[8] K. Miyazaki *et al.*, Appl. Opt. **28**, 699 (1989).

FWM in Kr gas



"NIST Atomic Spectra Database," Dec. 2013.

Previous work (@RIKEN-RAL)

Based on flash lamp pumped lasers
(poor long term stability)

ω_1: 24 mJ@6 ns
ω_2: 24 mJ@6 ns

→ ω_{Ly}: ~1 μJ
(Maximum instantaneous)

Conversion efficiency ~10^{-5}

P. Bakule et al. Nucl. Instr. and Meth. in Phys. Res. B 266 335 (2008).

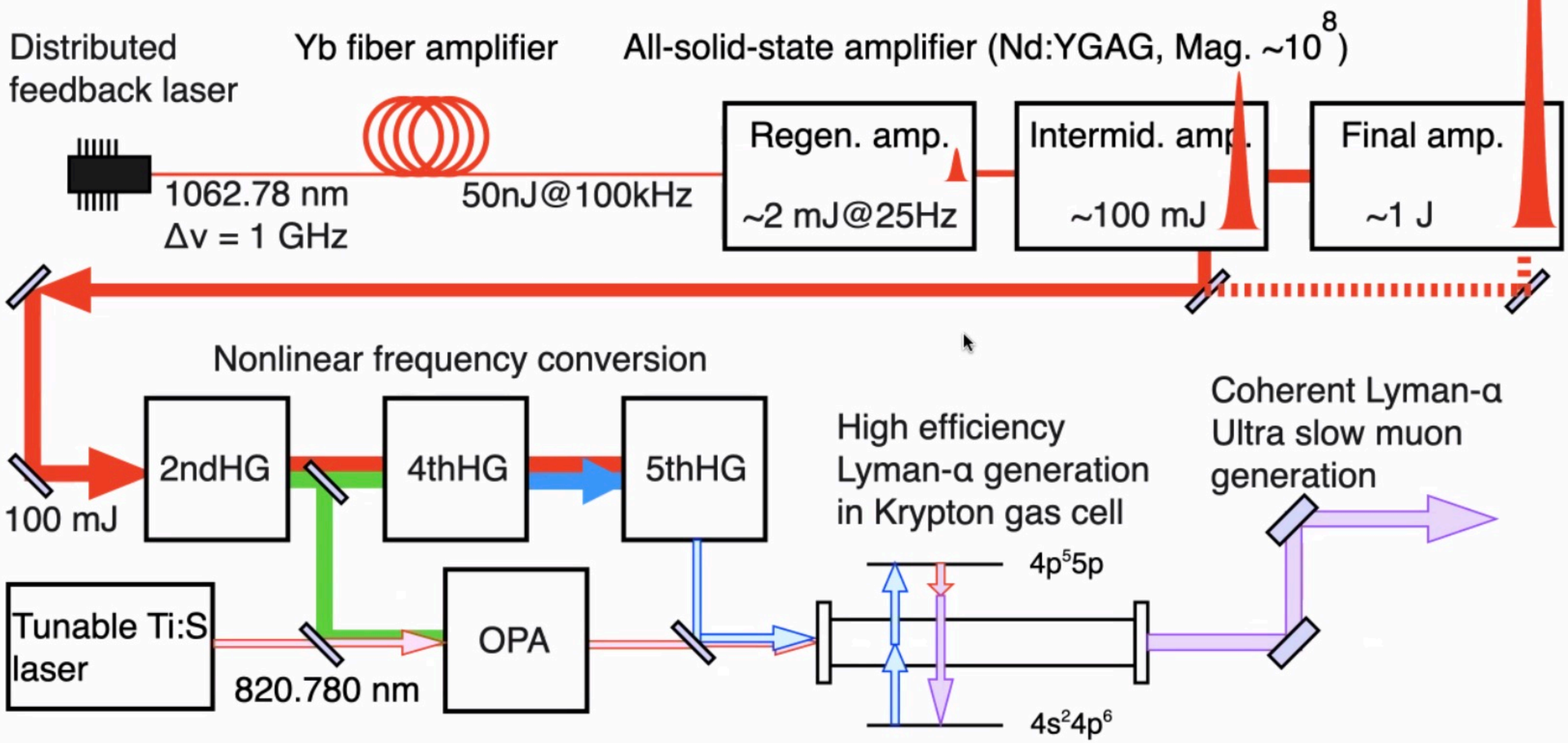
Conversion efficiency

$$P_{Ly} \propto \left[\chi^{(3)}\right]^2 P_1^2 P_2 \frac{\mathrm{sinc}^2(\Delta kL/2)}{(\Delta kL/2)^2}$$

- low beam quality
- depletion of neutral Kr atom by ionization
- short interaction length
- phase mismatch by plasma

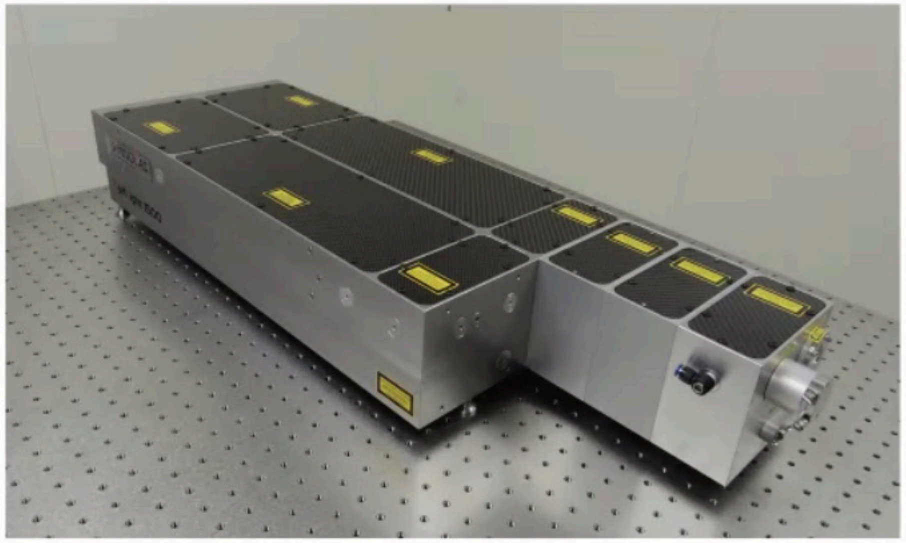
Design of laser system

- wavelength locking for Kr resonance → Distributed feedback laser at front end
- efficient amplify of 1062.78 nm light → gain center controlled laser medium
- timing jitter free (between ω_1 and ω_2) → both pulses generated from single pulse
- high conversion efficiency → optimization of phase match with long interaction length



Changing of 355 nm pulse source

Previous setup



All-solid-state laser + Lyman α generation

~4 μJ, 2ns

Flashlamp pumped 355 nm laser

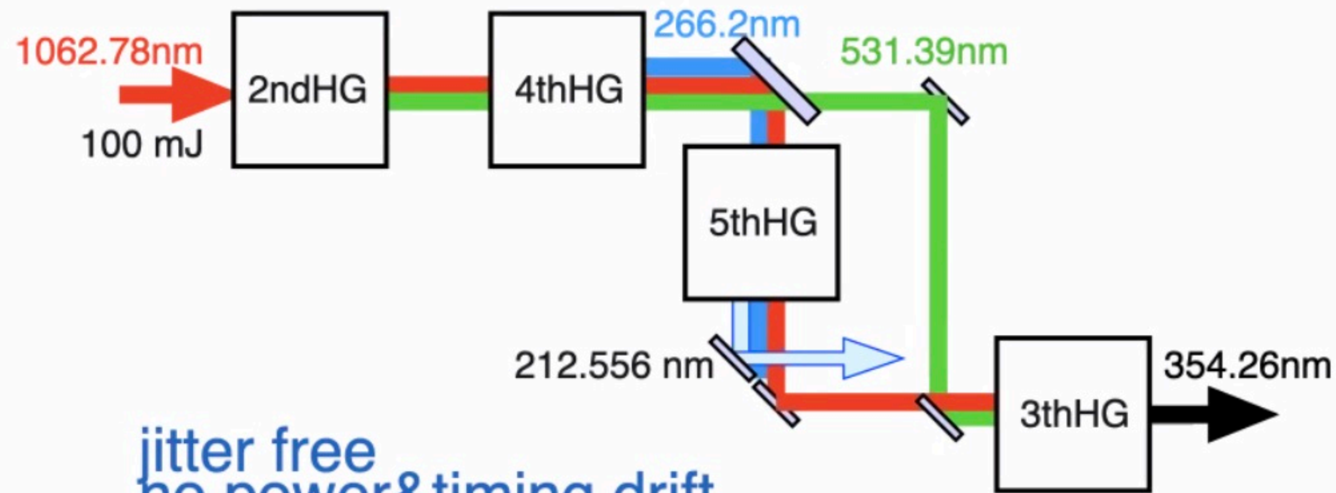
220 mJ, 8ns

Ultraslow muon generation
laser volume : 2x10x70mm^3

130 count/sec.@F3 MCP
(MCP η=55%)

236 USM/sec. @ 500kW

Current setup



jitter free
no power&timing drift

All-solid-state laser + Lyman α generation

~5 μJ, 2ns

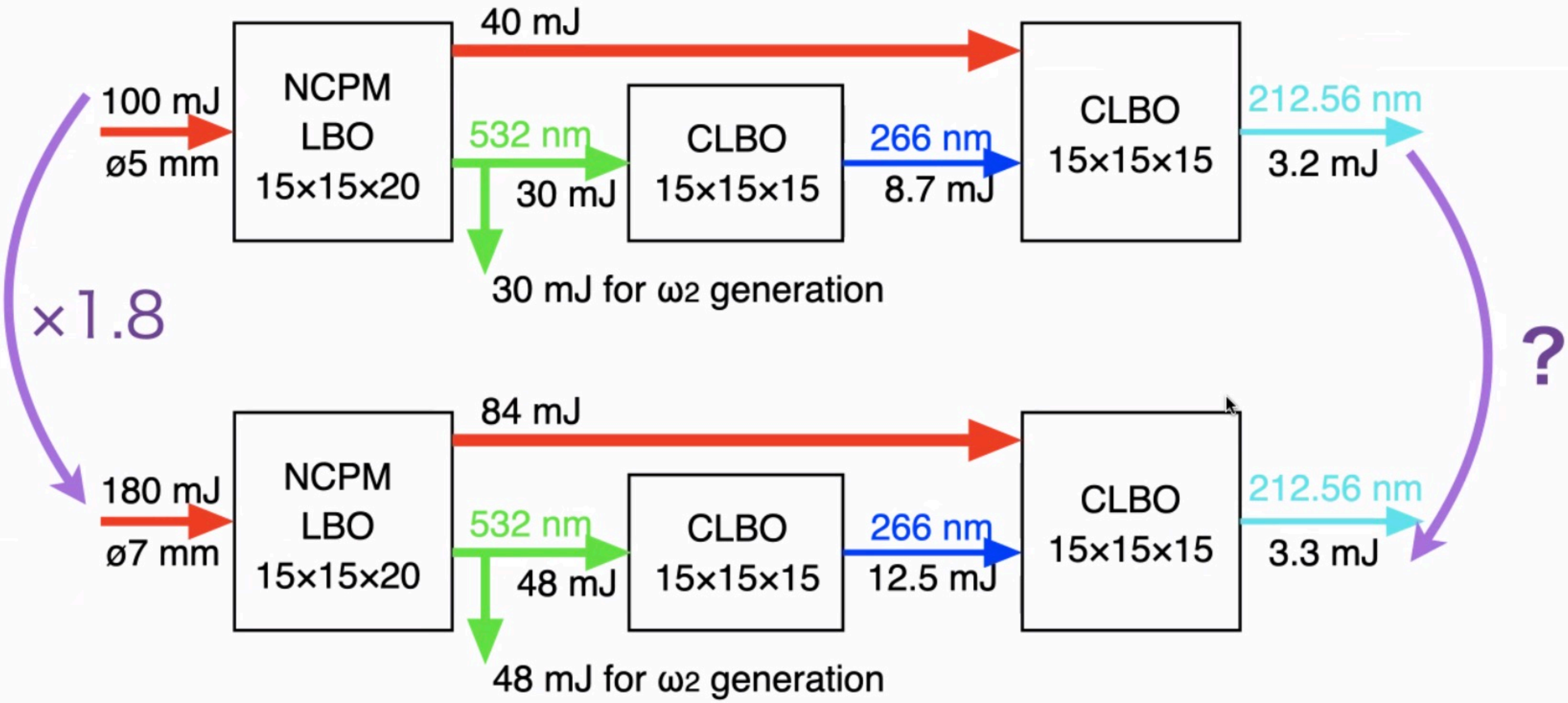
9.2 mJ, 2ns

Ultraslow muon generation
laser volume : 2x10x70mm^3

122 count/sec.@F3 MCP
(MCP η=55%)

221 USM/sec. @ 600kW

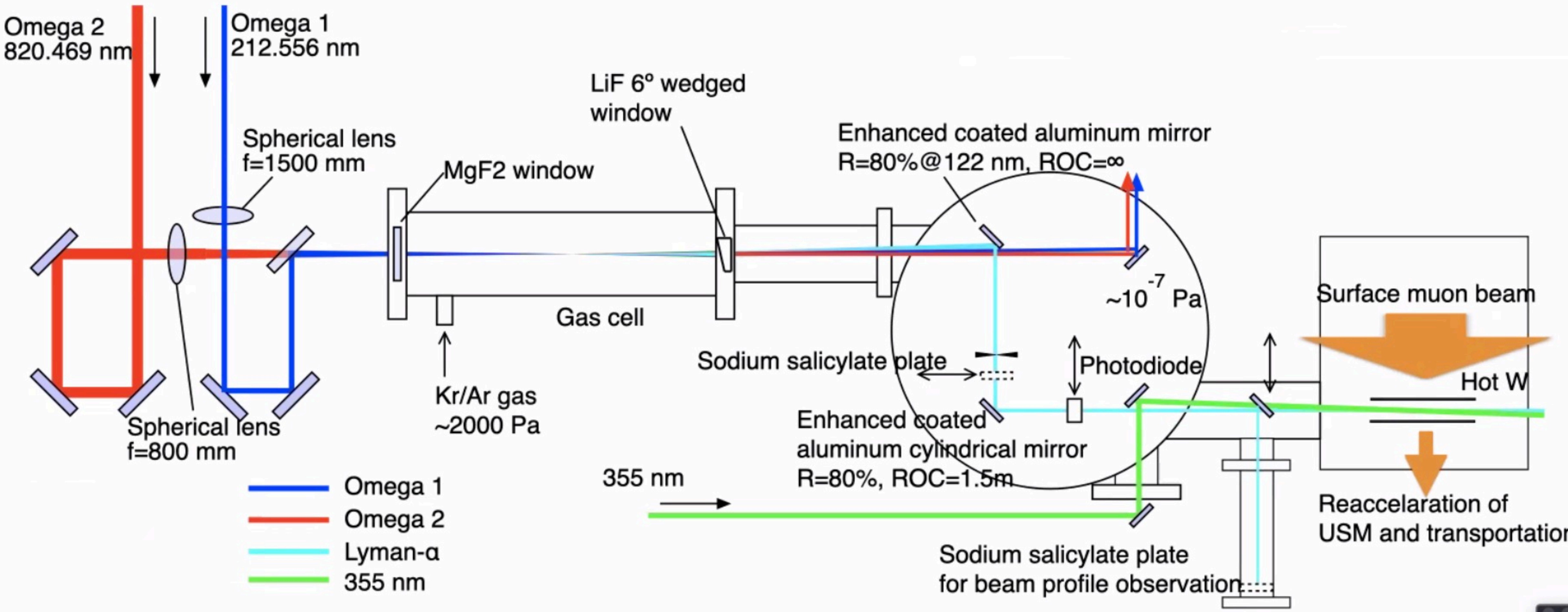
All solid-state wavelength conversion



	Without power Amp.	With power Amp.
LBO for SHG	60%	53%
CLBO for 4th HG	29%	26%
CLBO For 5th HG	36%	26%

Beam fluence was kept constant. However conversion efficiency decreased.

Lyman-α generation

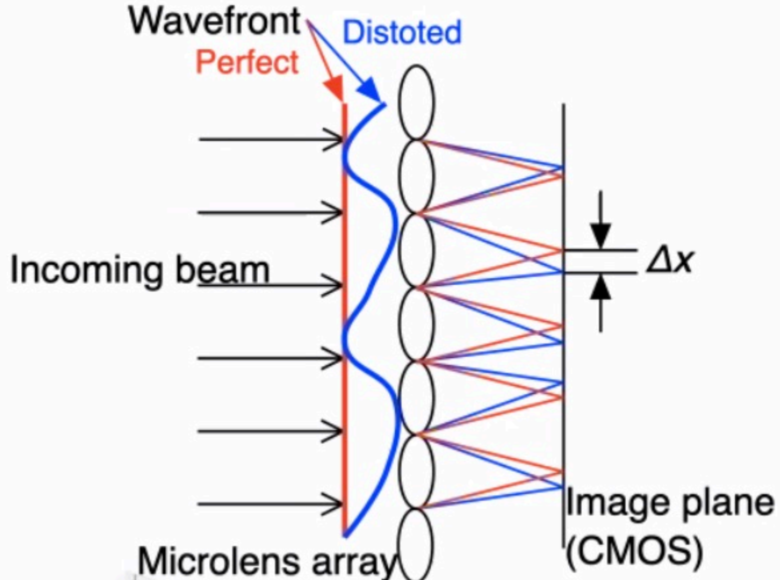


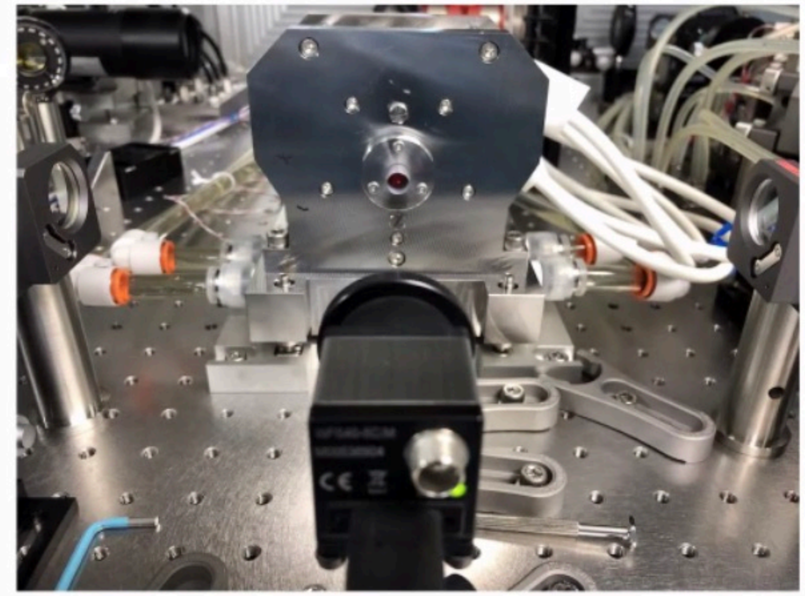
	Without power Amp.	With power Amp.
Omega1	2.8 mJ	2.8 mJ
Omega2	3.2 mJ	3.4 mJ
Lyman-α	5 μJ@PD	3.4 μJ@PD

Final output of Lyman-α also decreased.

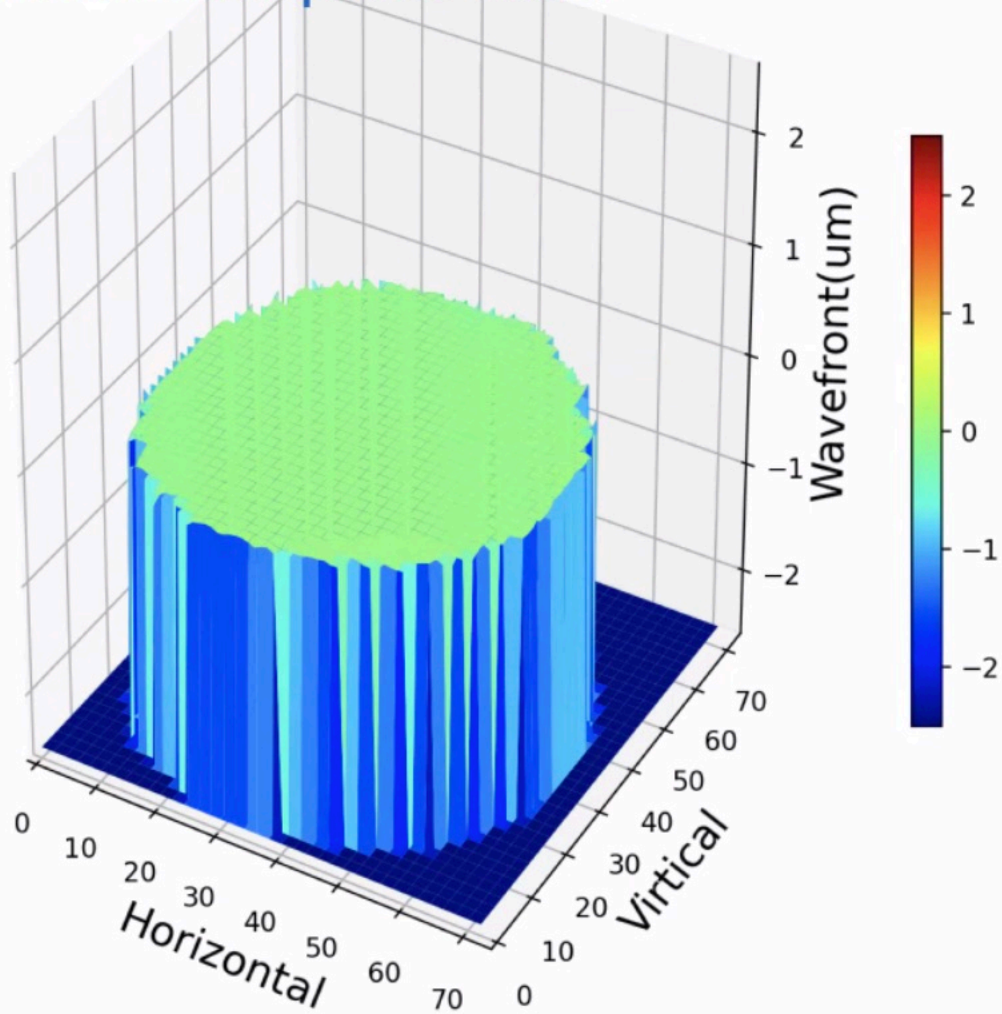
Wavefront distortion in Nd:YSAG ceramic

Principle of wavefront sensor

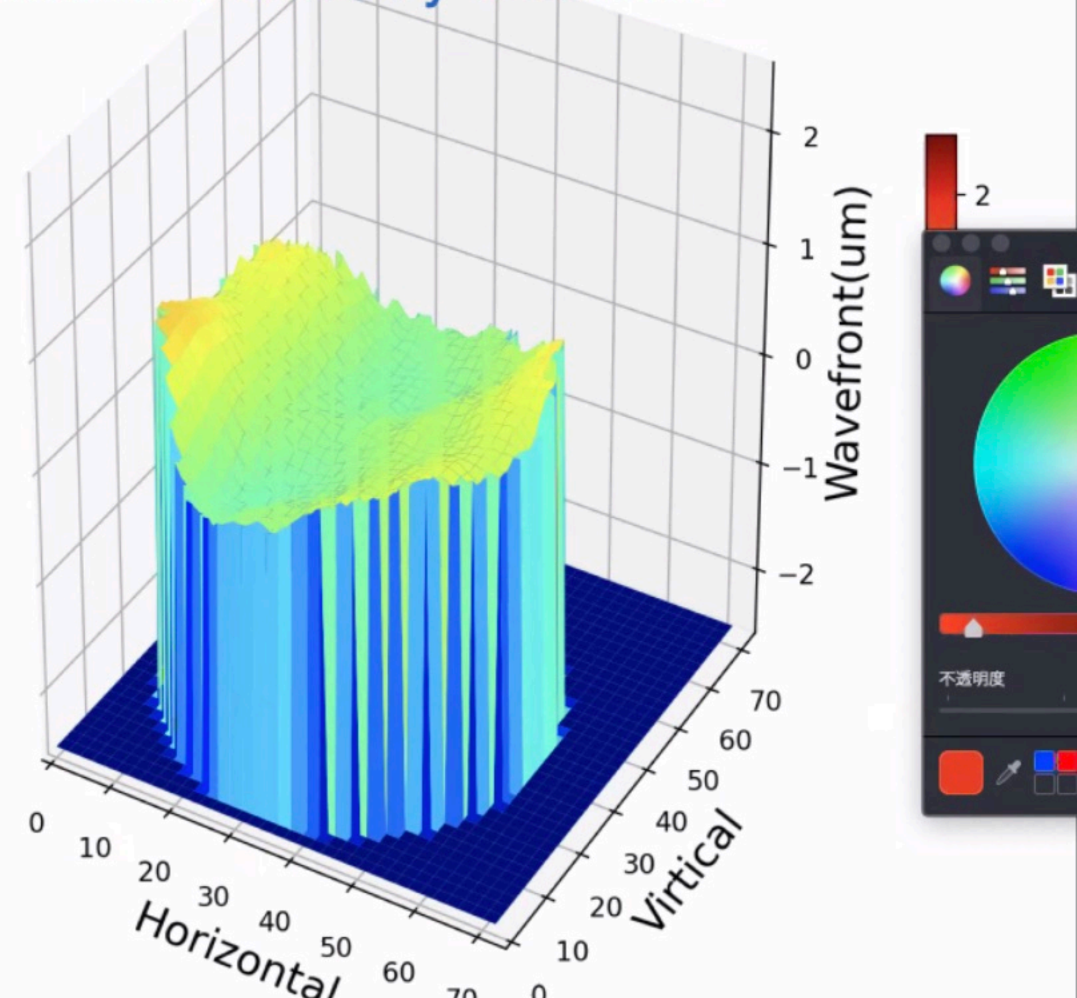




Reference plane wave

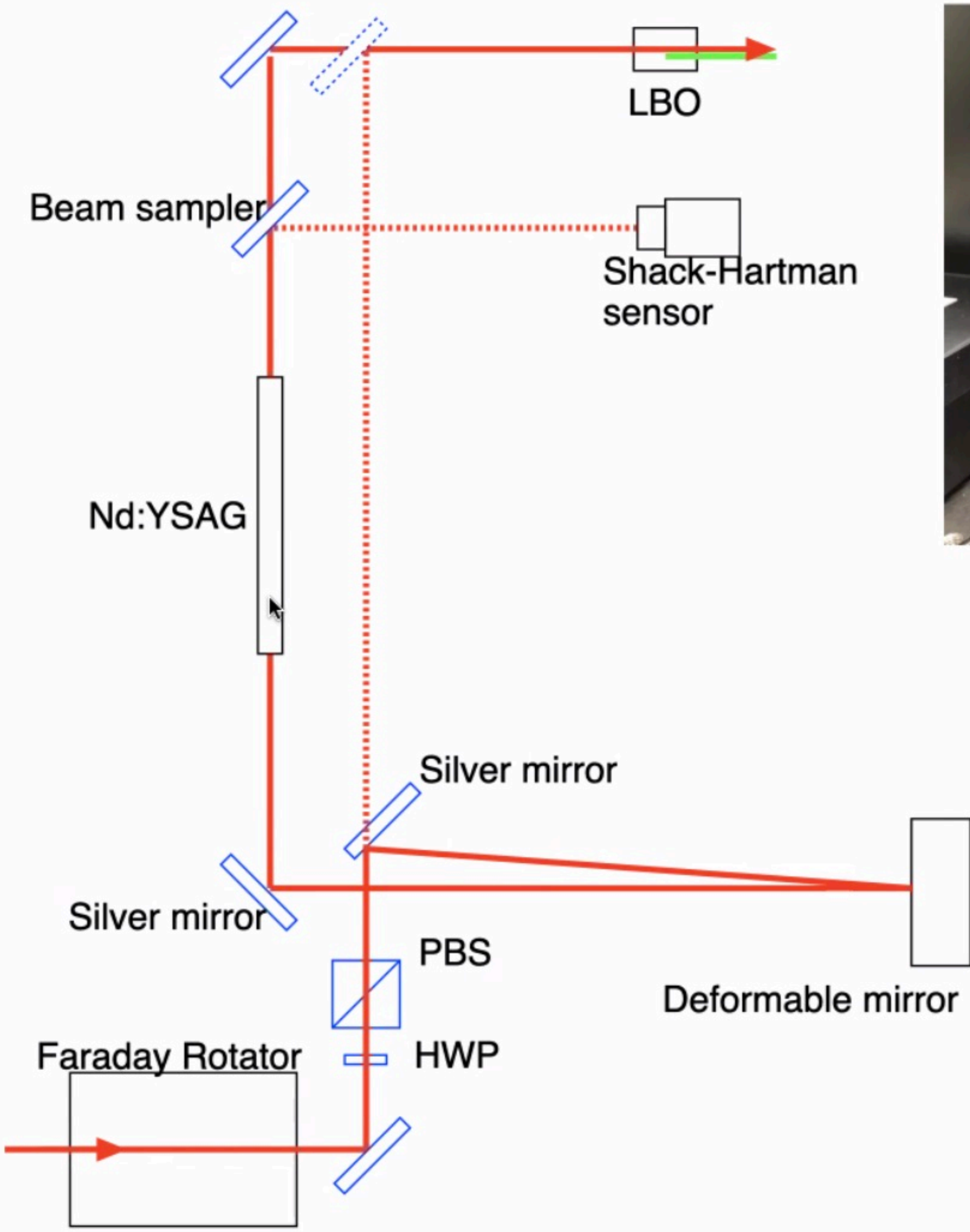


Distorted wave by ceramics

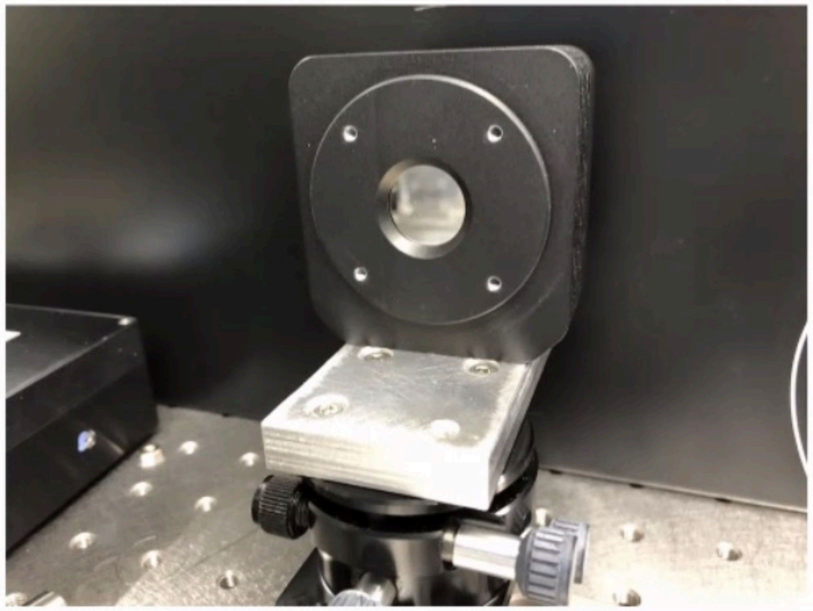


Wavefront distortion compensation by DM

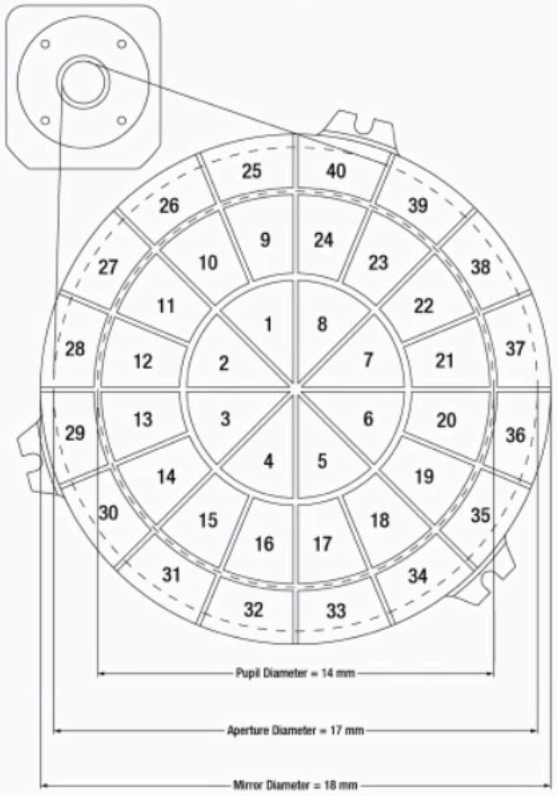
Experimental setup

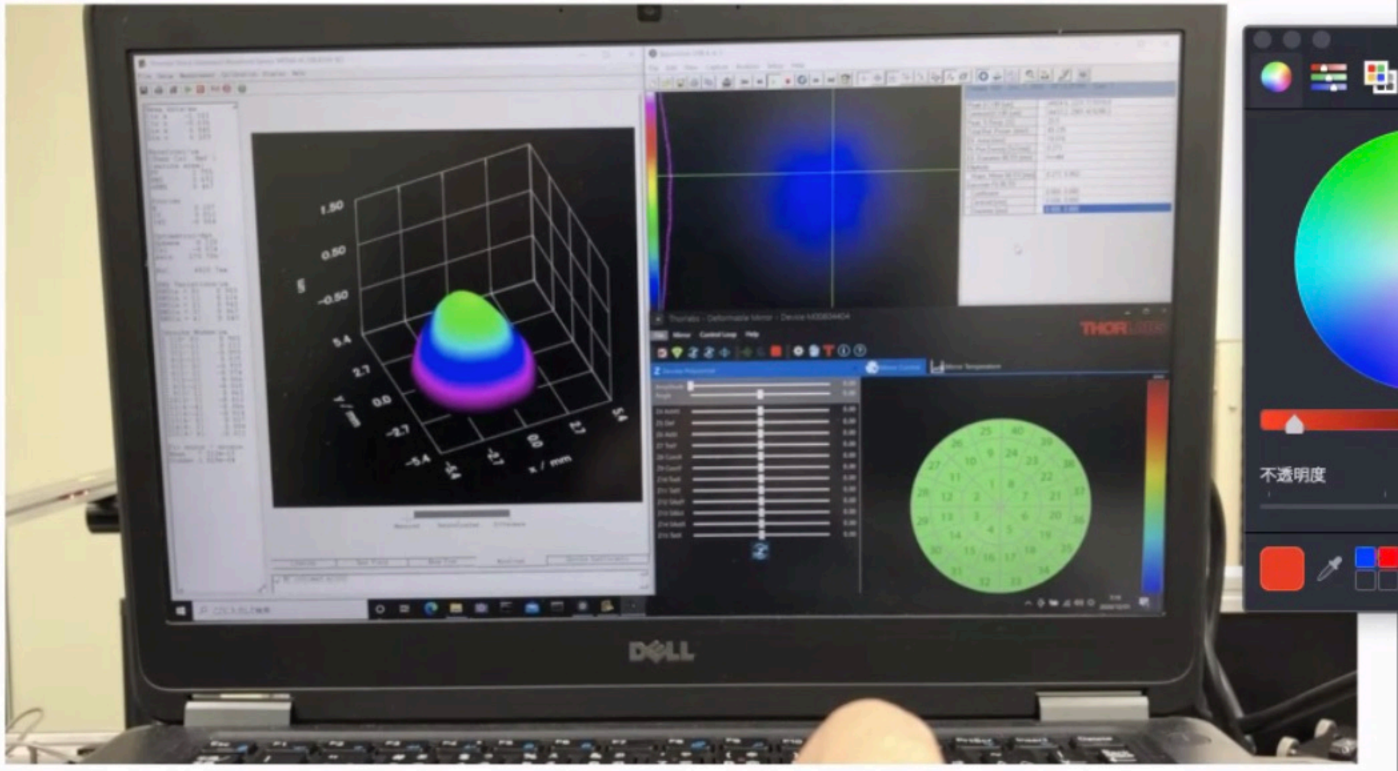


Deformable mirror



40 piezo layout

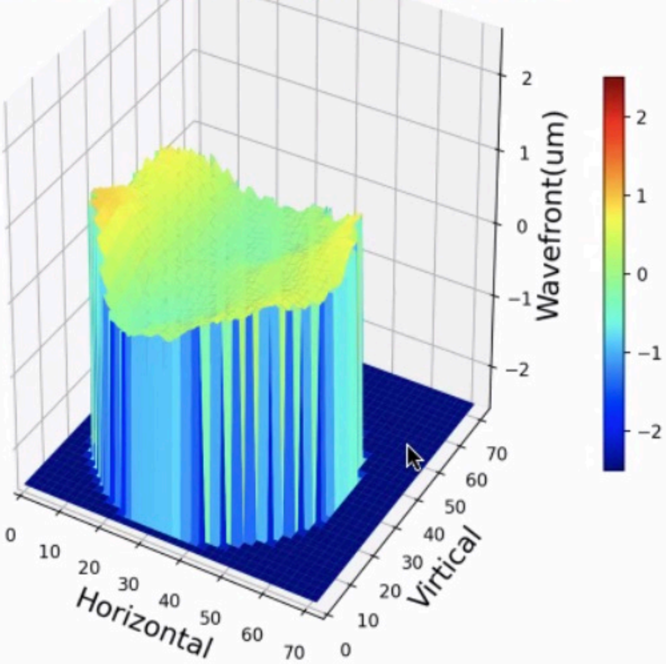




Wavefront distortion compensation by DM

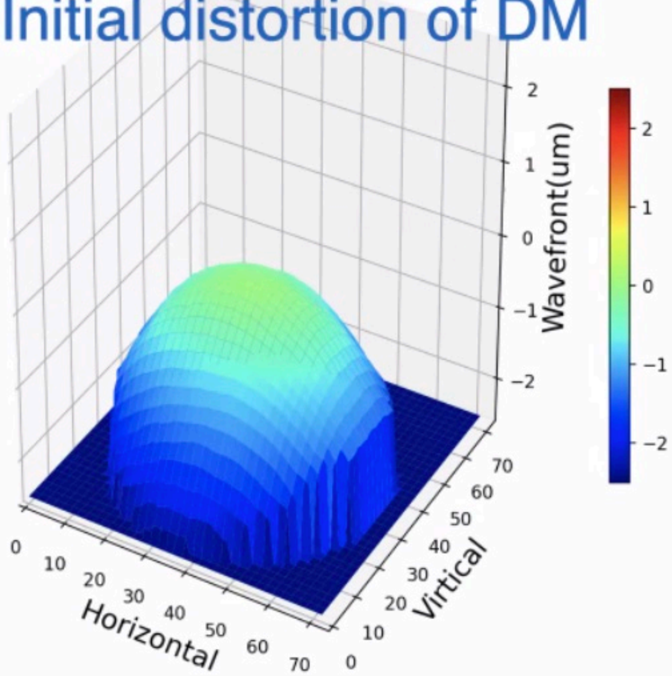
Wavefront distortion of Nd:YSAG ceramic was successfully compensated without pumping.

Distortion by ceramic

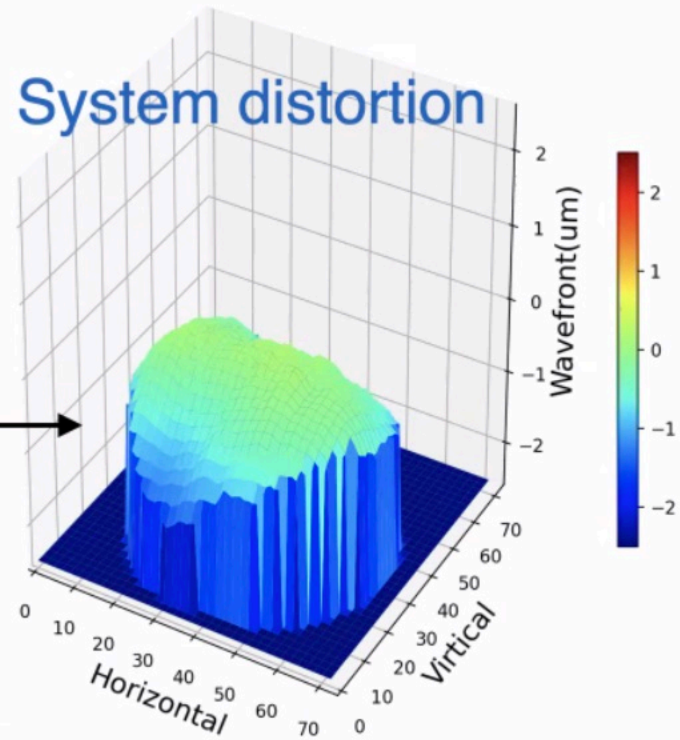


+

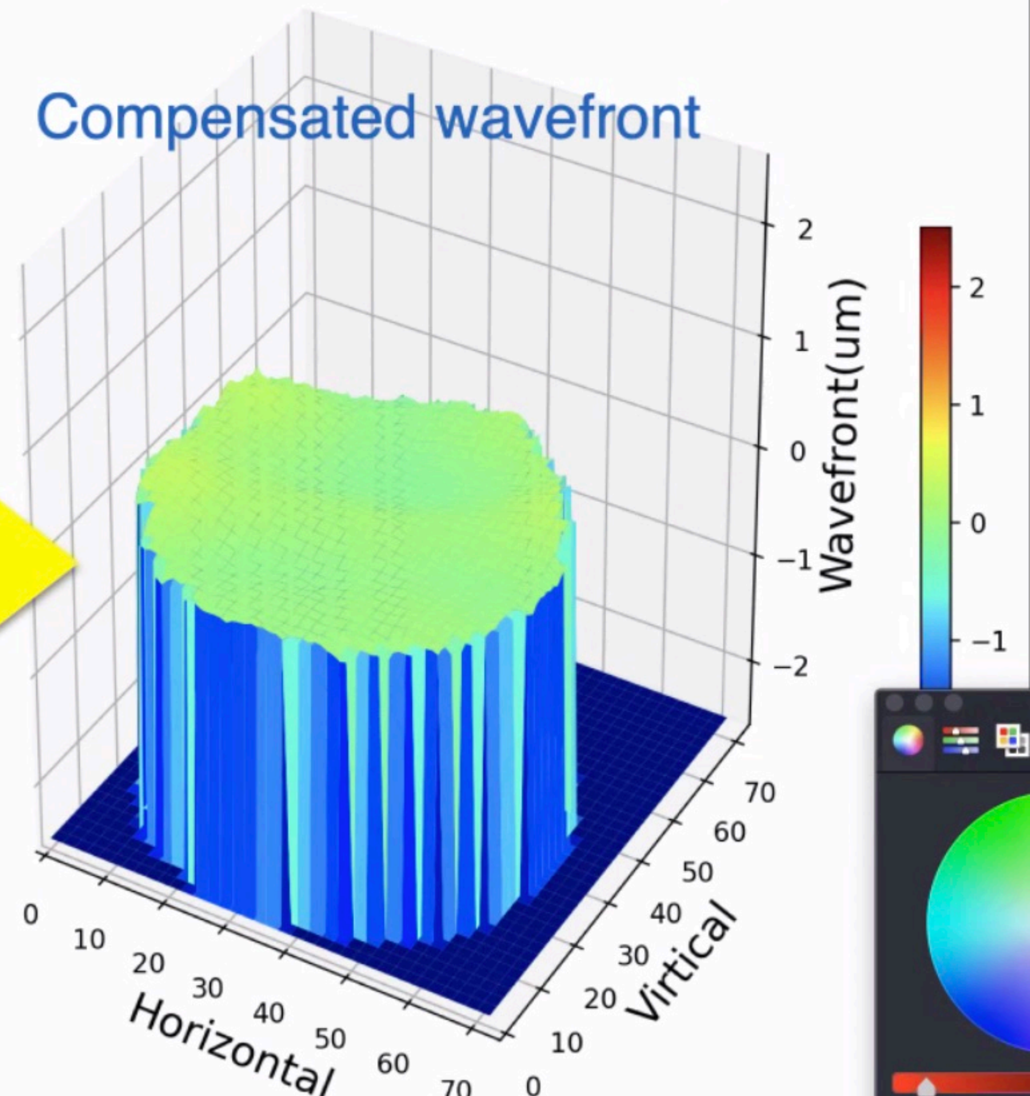
Initial distortion of DM



System distortion



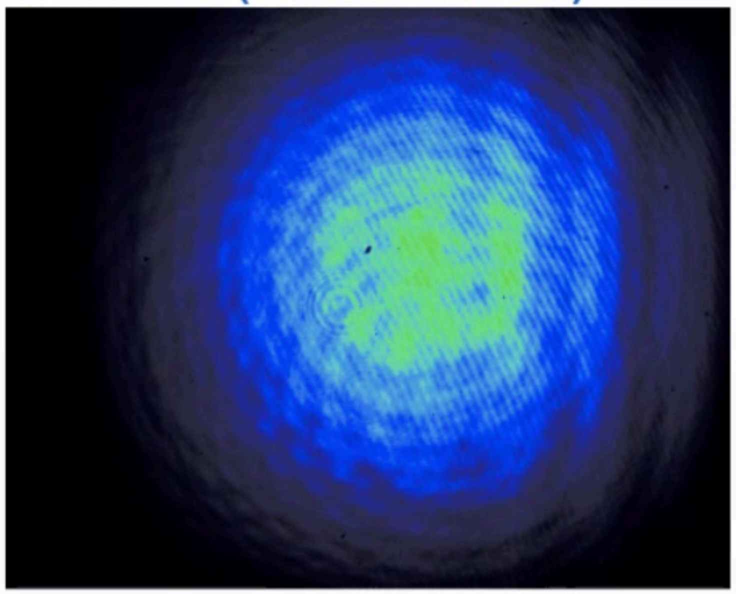
Compensated wavefront



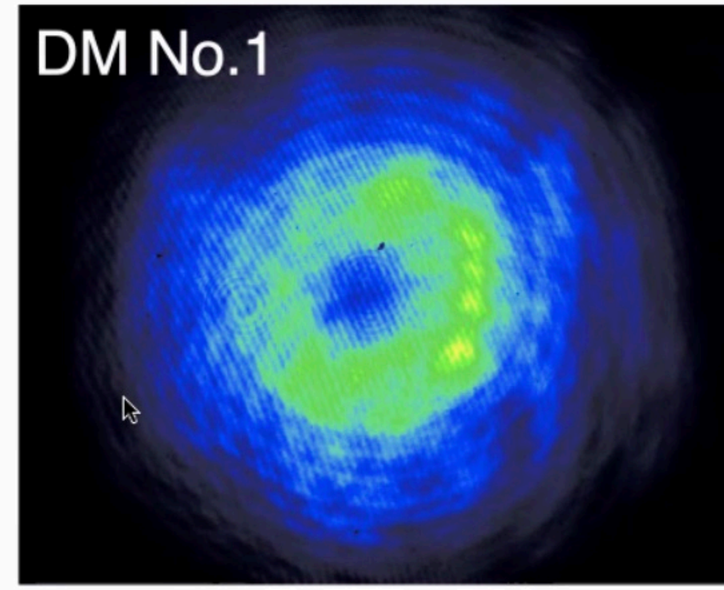
Adaptive program has an error with pumping operation.

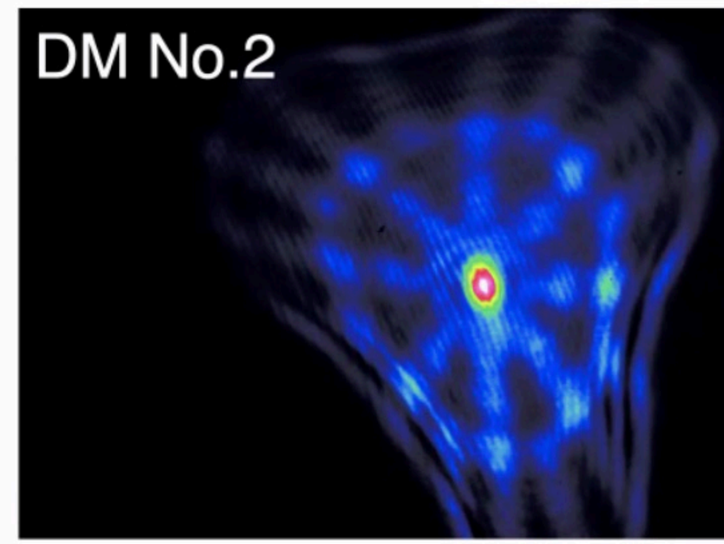
Trouble in DM

Reference (silver mirror)



after high power operation





Damage threshold of DM

1 J/cm² (1064 nm, 10 ns, 10 Hz, Ø10 mm)

Irradiation condition

0.09 J/cm² (1063 nm, 2 ns, 25 Hz, Ø12 mm)

↓

Safety factor : 2

Damage to the mirror coating occurred
when steep modulation was applied between neighboring pixels.

Summary

1. Development of power amplifier
   - Optimized Nd:YSAG shows a good amplification gain at 1062.78 nm light
   - Conversion reduction was obtained with amplified pulse
   - Compensation of wavefront distortion with low poser laser beam was demonstrated
   - Power up of Lyman-α intensity is not achieved due to deformable mirror damage

2. Upcoming upgrade
   - Replacement of deformable mirror to high-damage threshold product
   - Automatic mirror moving in vuv chamber for stable operation
   - Spectrum shaping of Lyman-a pulse for the matching of Doppler of Mu