

Enabling Quantum Sensing with Advanced VUV laser systems

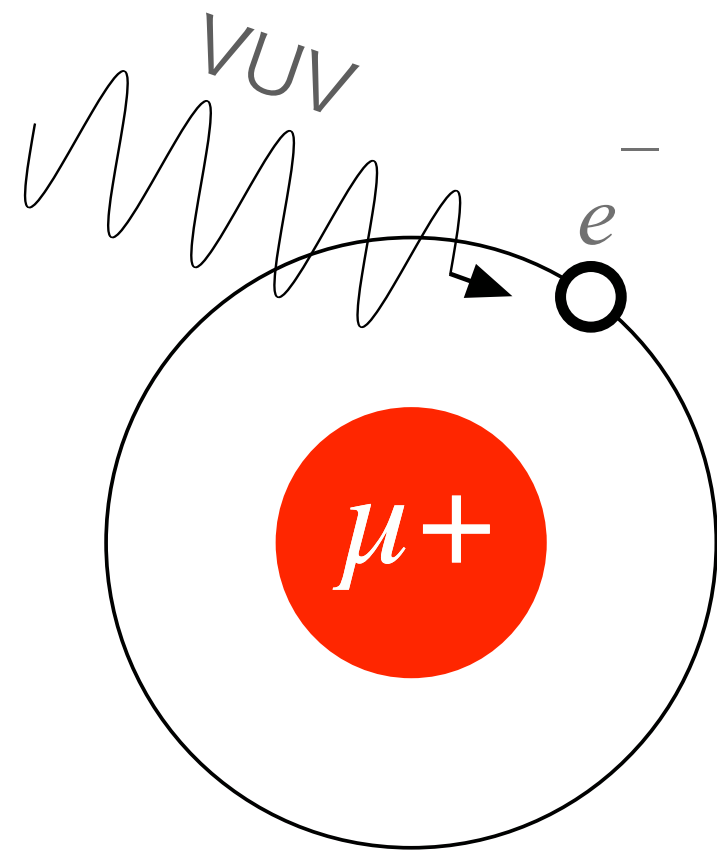
Yu OISHI
KEK (IMSS/QUP)



2026 TRIUMF-KEK Symposium

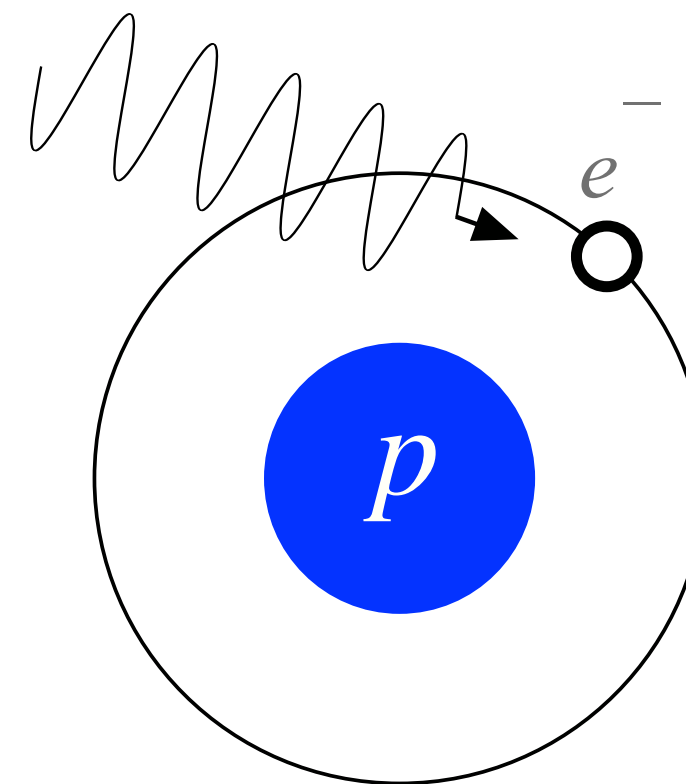
Why coherent VUV light?

Coherent VUV light is a key enabling technology for precision quantum sensing.



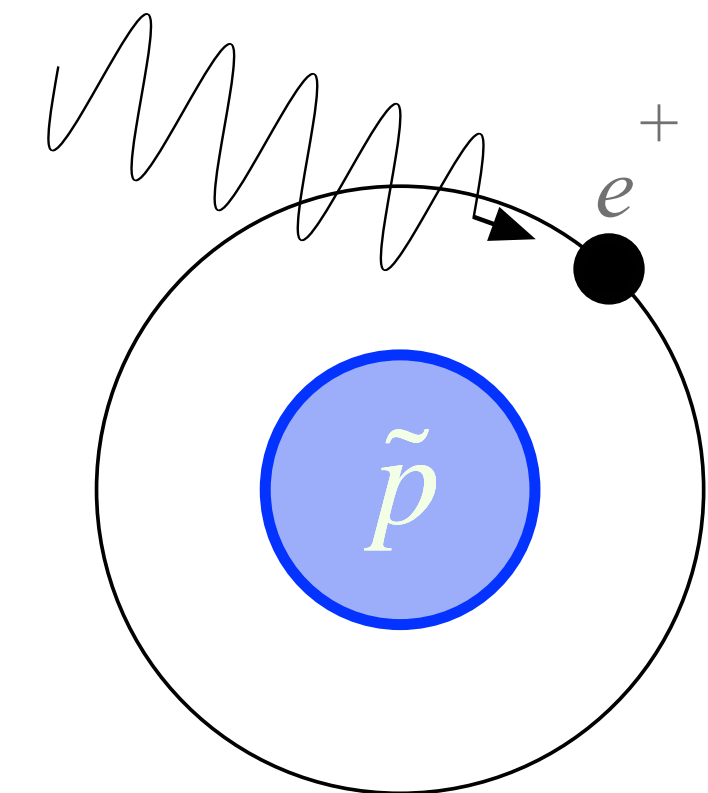
Muonium

Muon manipulation



Hydrogen

Atomic interferometry



Antihydrogen

Precision tests

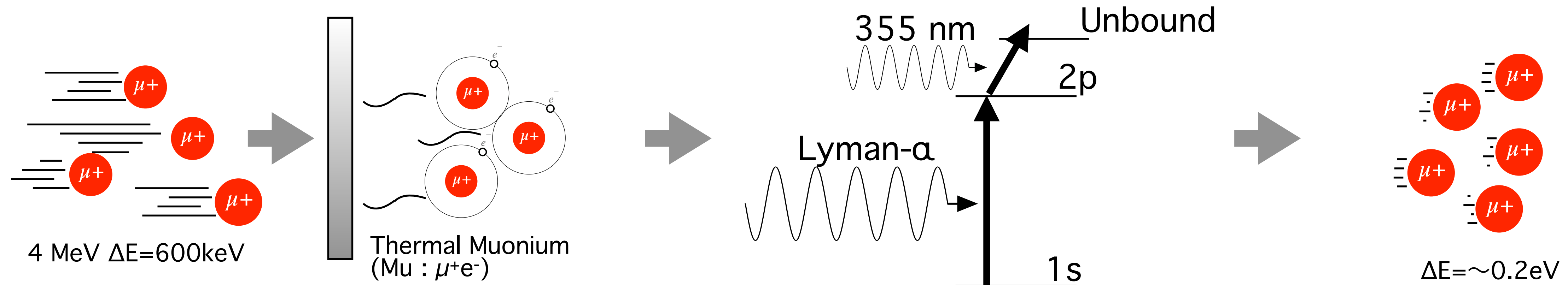
Ultra-Slow Muons: Muonium manipulation

1. Surface muon

2. Muonium production

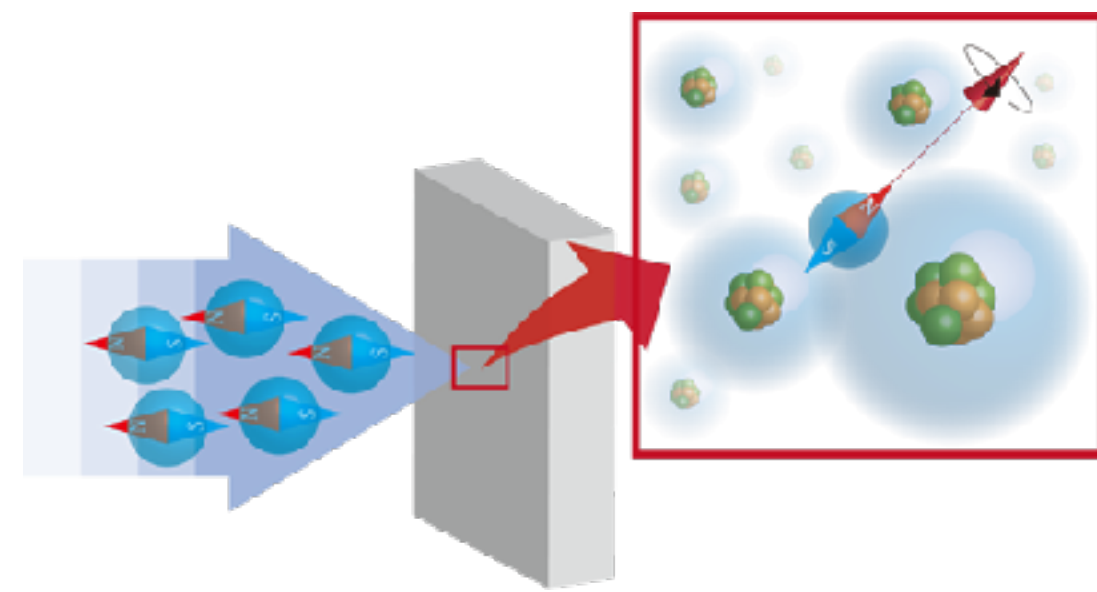
3. 2 photon ionization

4. Ultra-slow muon

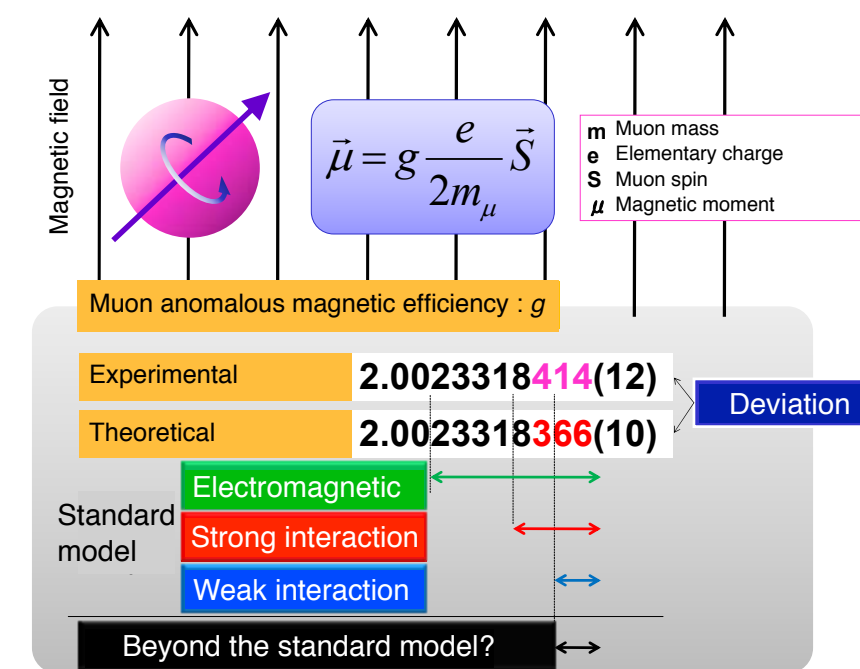


Applications of USM

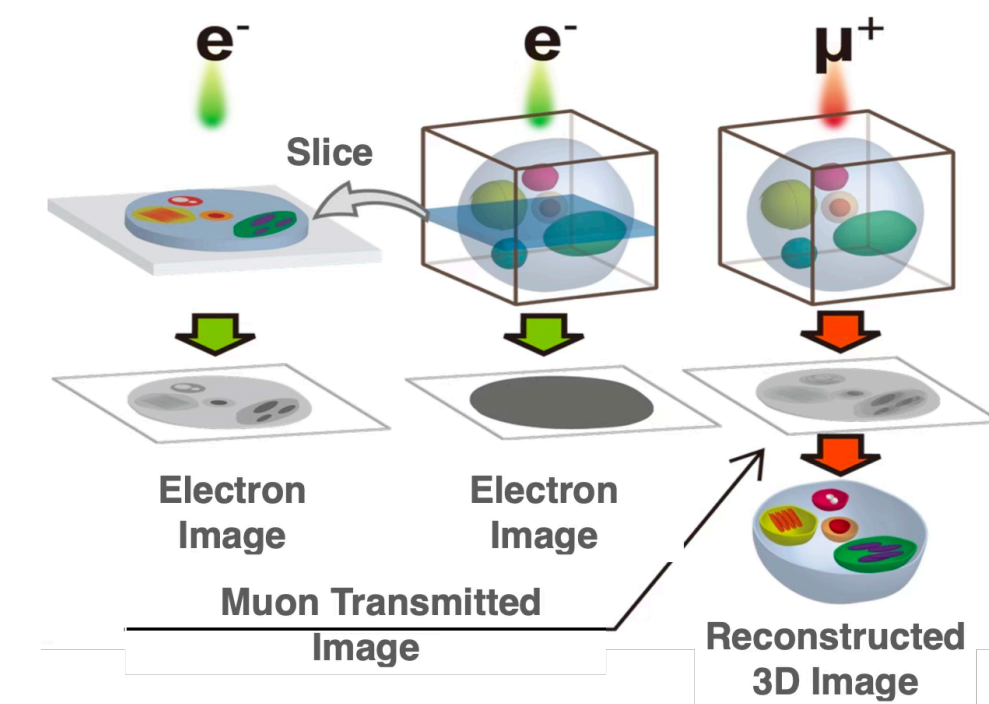
μSR for surface material science



Muon g-2/EDM experiment



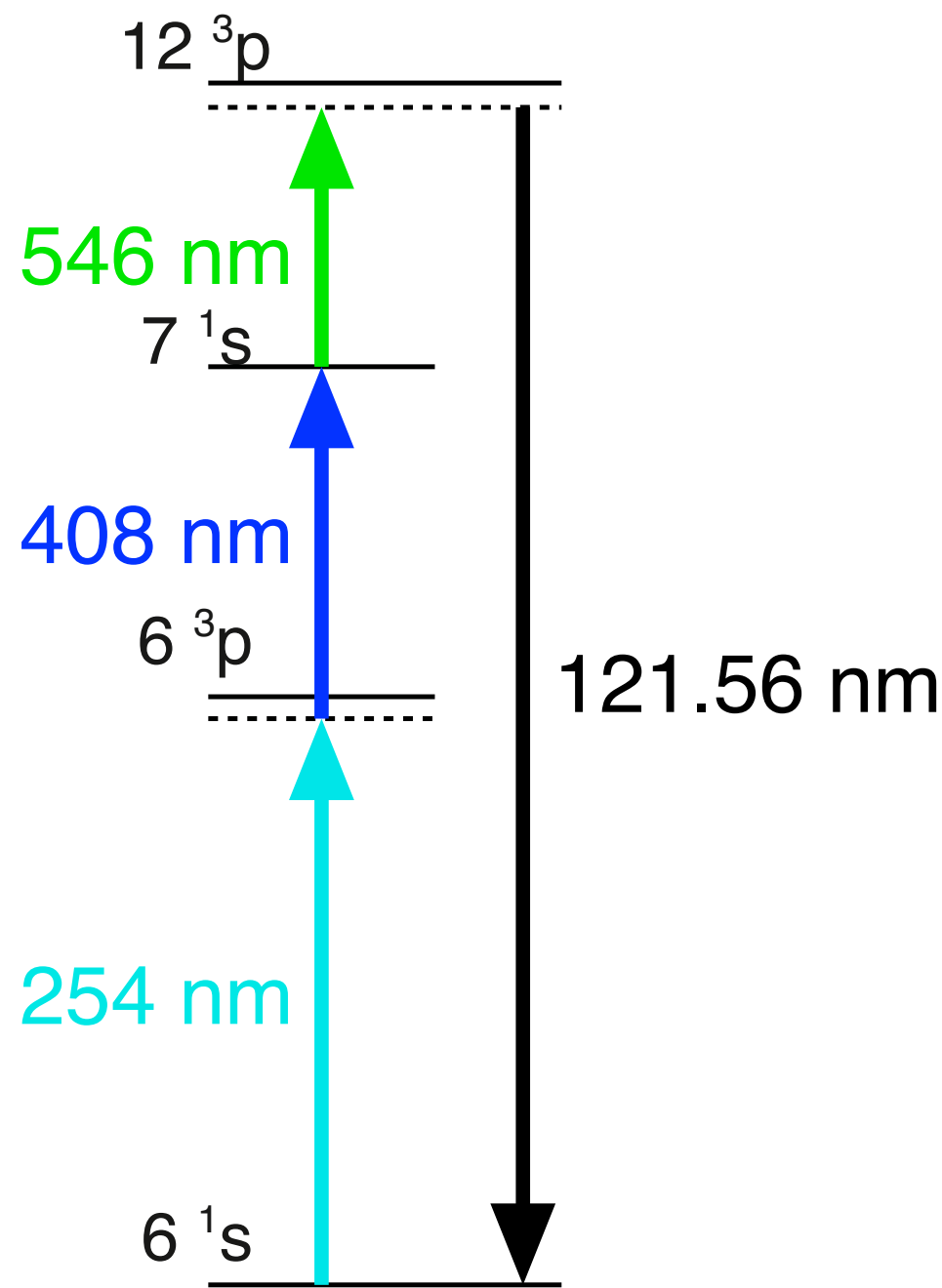
Transmission muon microscope



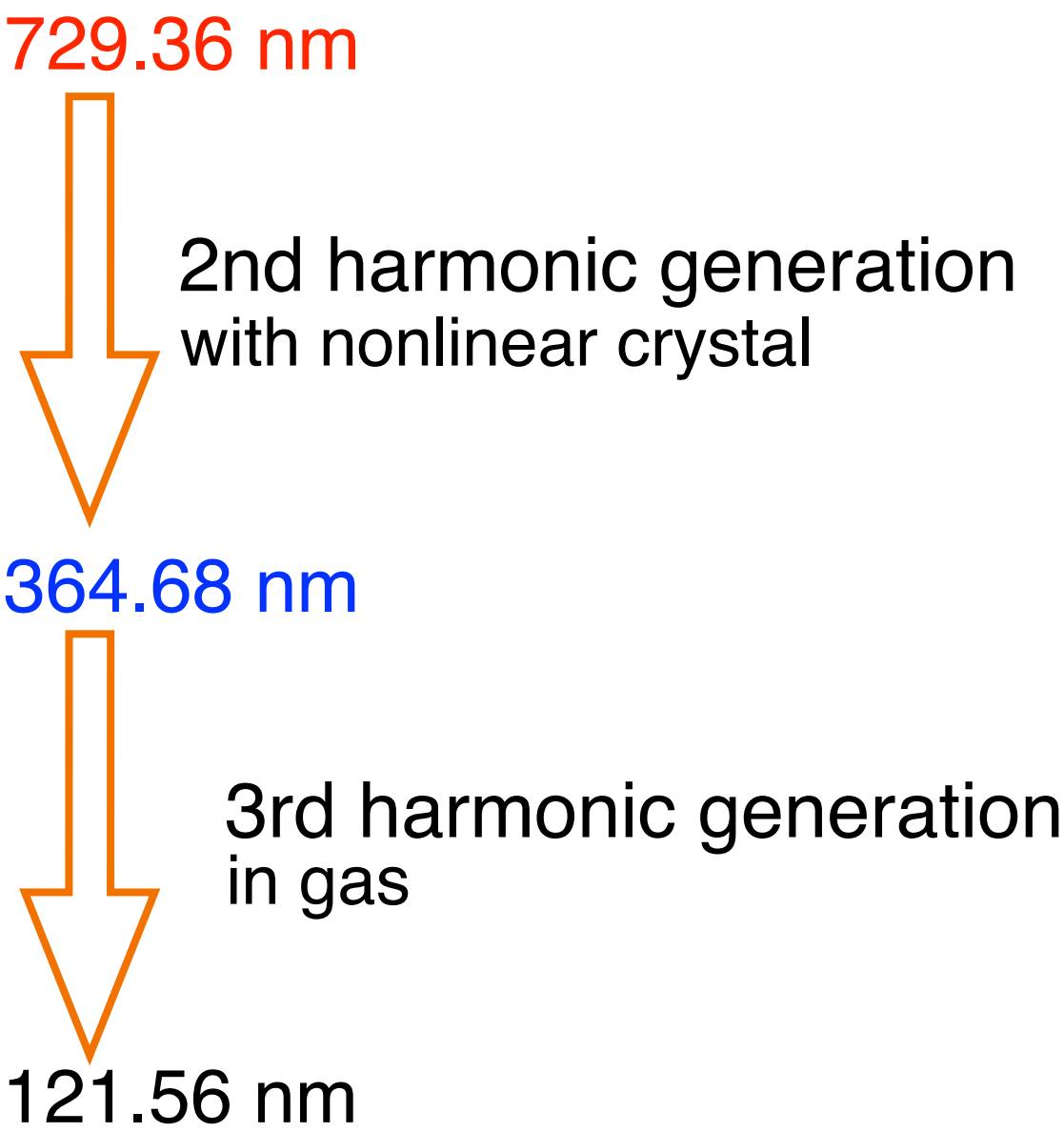
This requires intense coherent Lyman- α light.

Lyman-α Generation by TPR-FWM

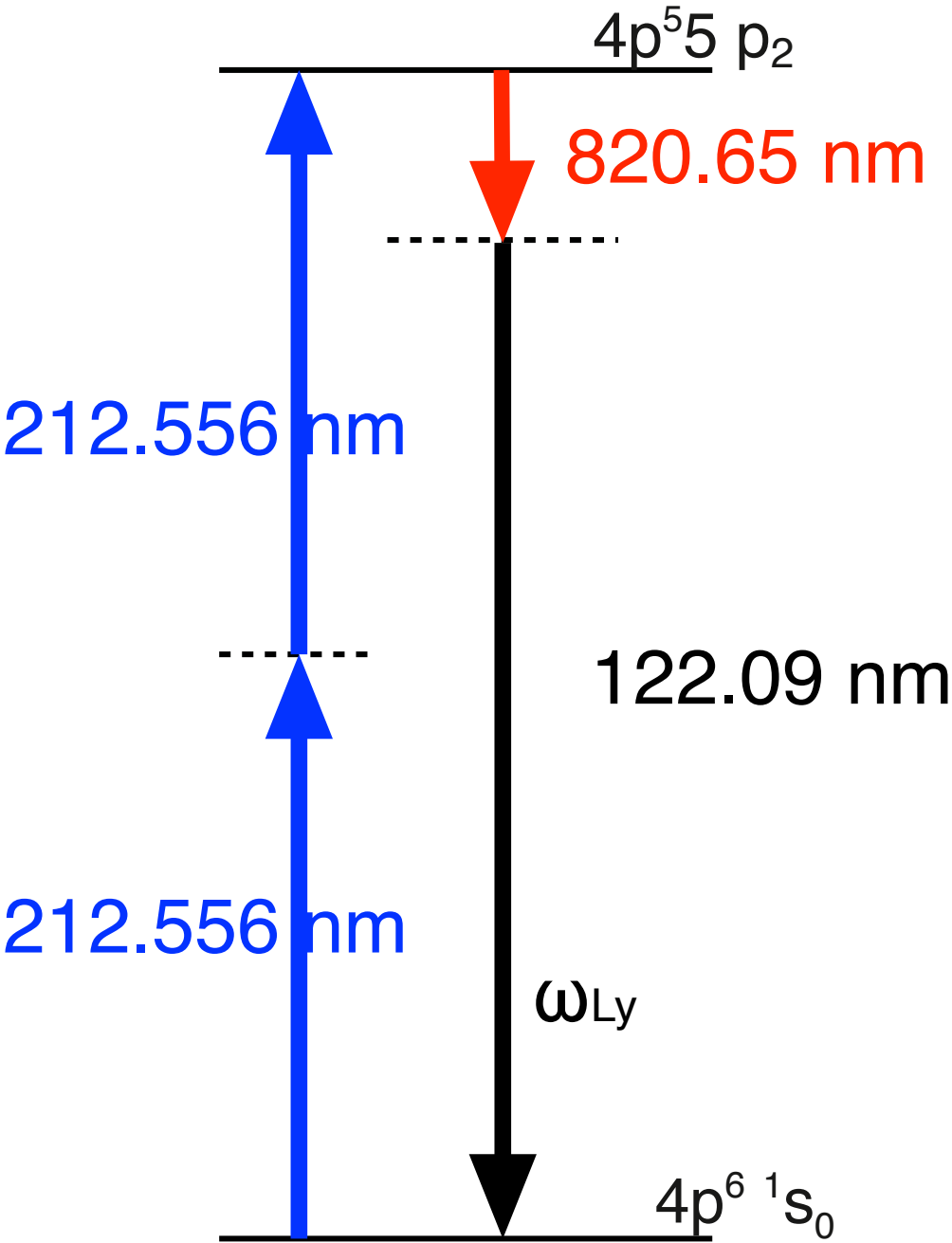
4 wave mixing in Hg vapor



Harmonic generation (2×3=6th)

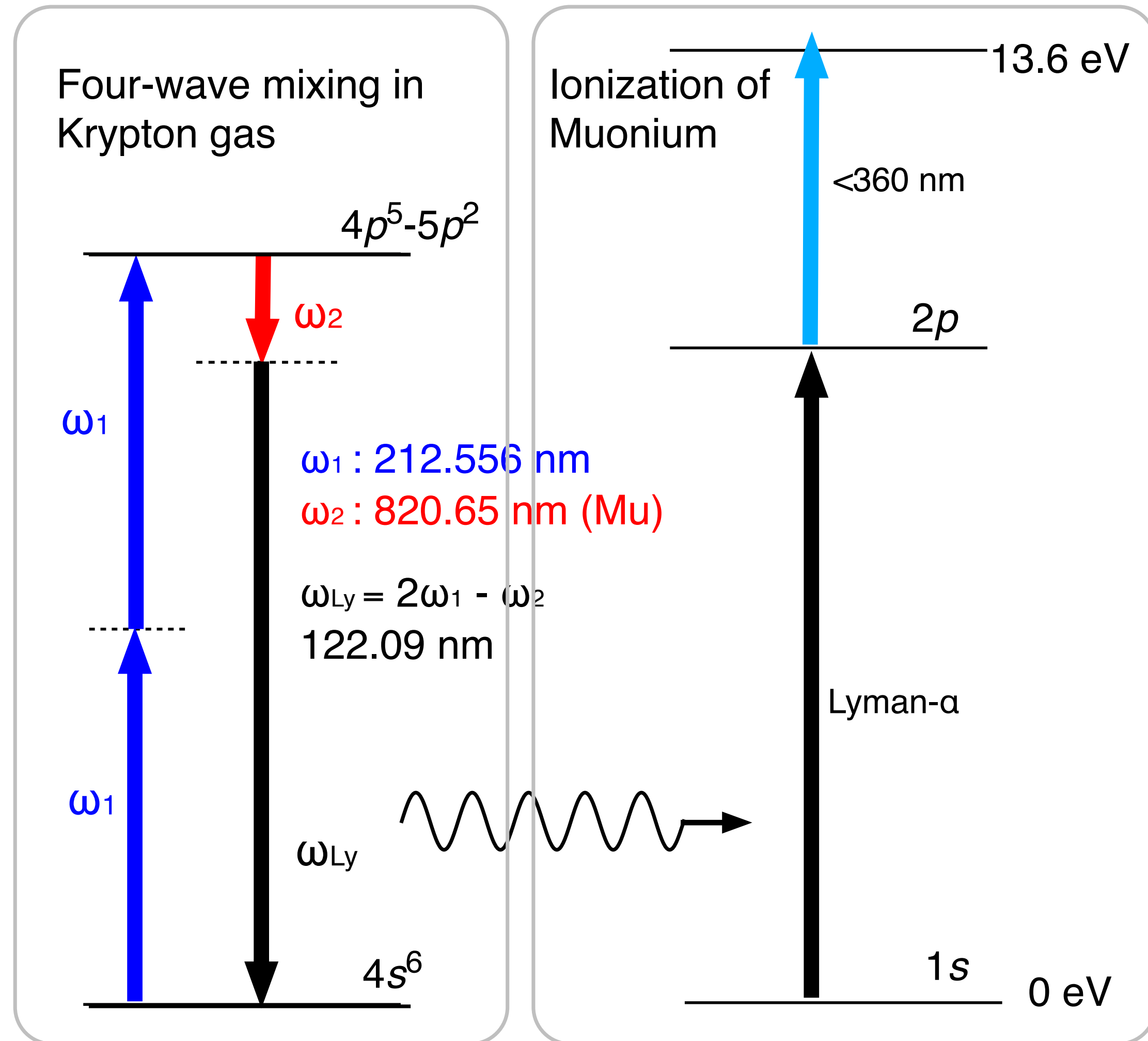


2 photon resonance 4 wave mixing



Method	Hg Four Wave Mixing	Harmonic generation	Two Photon Resonance Four Wave Mixing
Efficiency	High	10 ⁻⁵ –10 ⁻⁶	10 ⁻³ –10 ⁻⁴
Tunability	○	○	○
Phase Control	△	○	○
Experimental implementation	△	○	○

Requirements for High-Power Lyman- α



for Ultra-slow muon generation

Pulse energy : $\sim 100 \mu\text{J}$

Pulse width : 2 ns (1.6 ns lifetime@2p state)

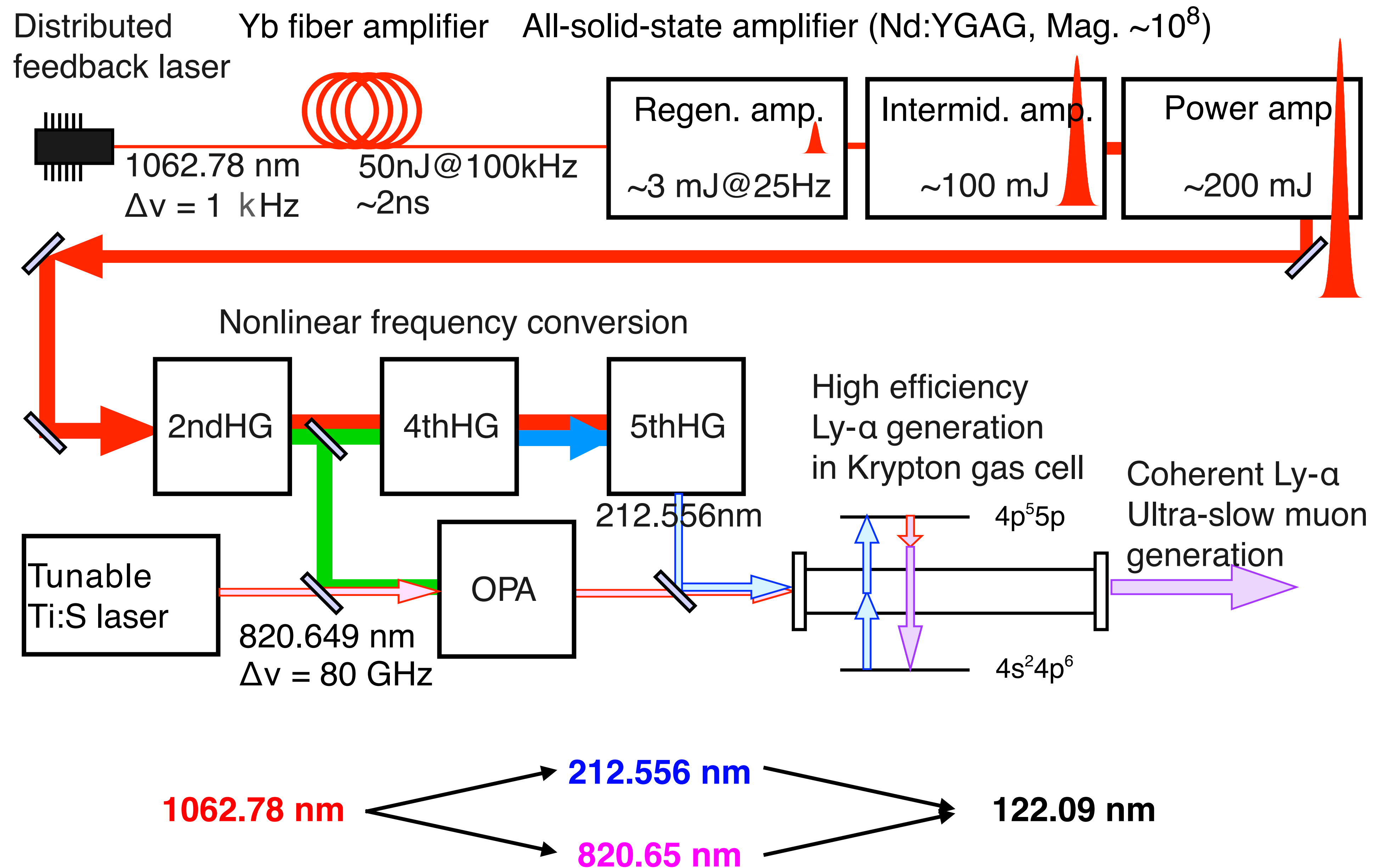
Line width : 230GHz or 80GHz (depend on Muonium target)

Timing synchronization : required for accelerator operation

for Lyman- α generation

- Wavelength locking for Kr gas resonance (212.556 nm)
- Generate synchronized 212 nm and 820 nm pulses from a single pulse
- Good beam quality for efficient conversion

All-Solid-State Lyman- α Laser System



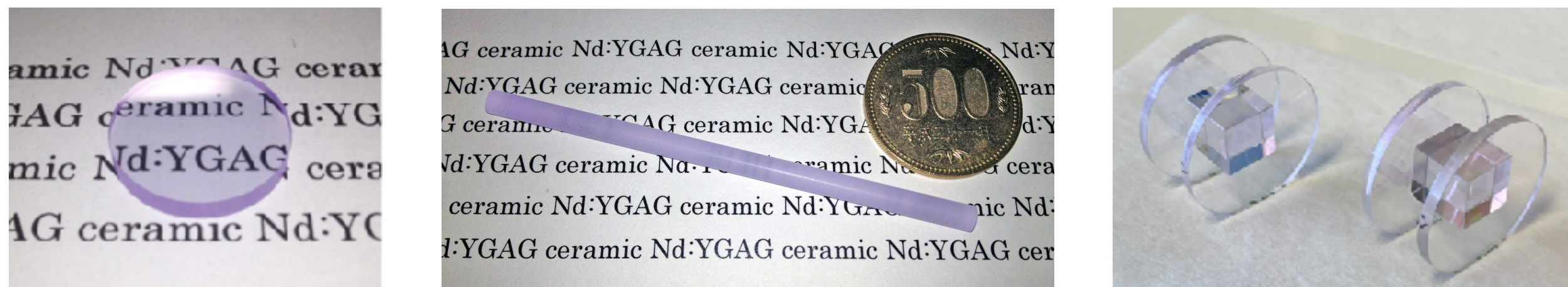
1062.78-nm High-Energy Laser Development

Gain peak wavelength of generally used Nd:YAG is 1064 nm.

Several gain media emitting around 1062.78 nm have been reported by partially substituting Ga or Sc for Al in YAG crystals.

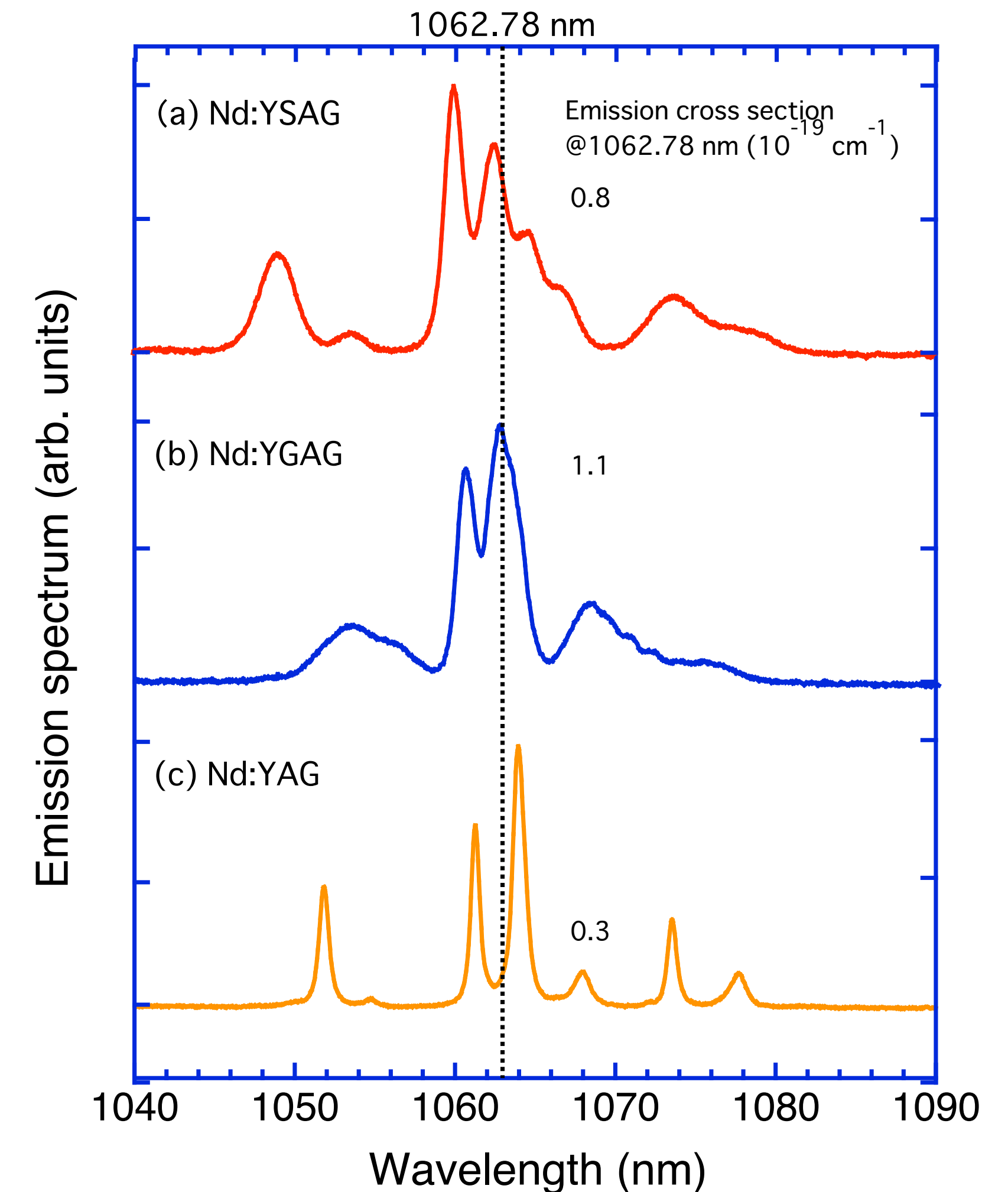
- Nd:YGAG ($\text{Nd:Y}_3\text{Ga}_2\text{Al}_3\text{O}_{12}$) B. Walsh et al. JOSA B. 15, 2794 (1998).
- Nd:YSAG ($\text{Nd:Y}_3\text{Sc}_2\text{Al}_3\text{O}_{12}$) Y. Sato et al. Opt. Mat. 29, 1277 (2007).

However, it has been difficult to fabricate single crystals of practical size because of defects associated with Ga/Sc substitution and insufficient compositional homogeneity.



We introduced a transparent ceramic fabrication technique.

Emission spectrum of Nd:YGAG and Nd:YSAG ceramic

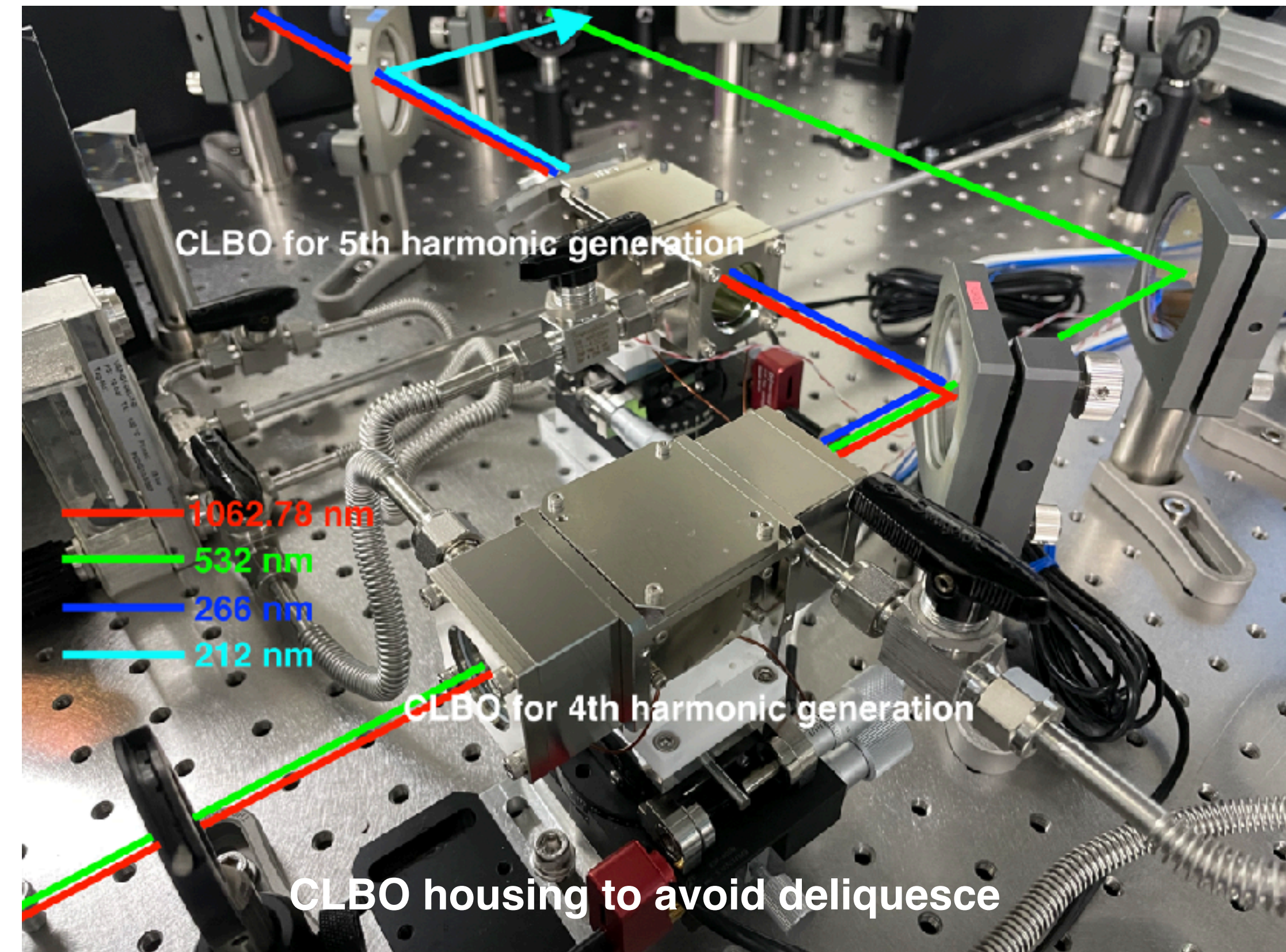
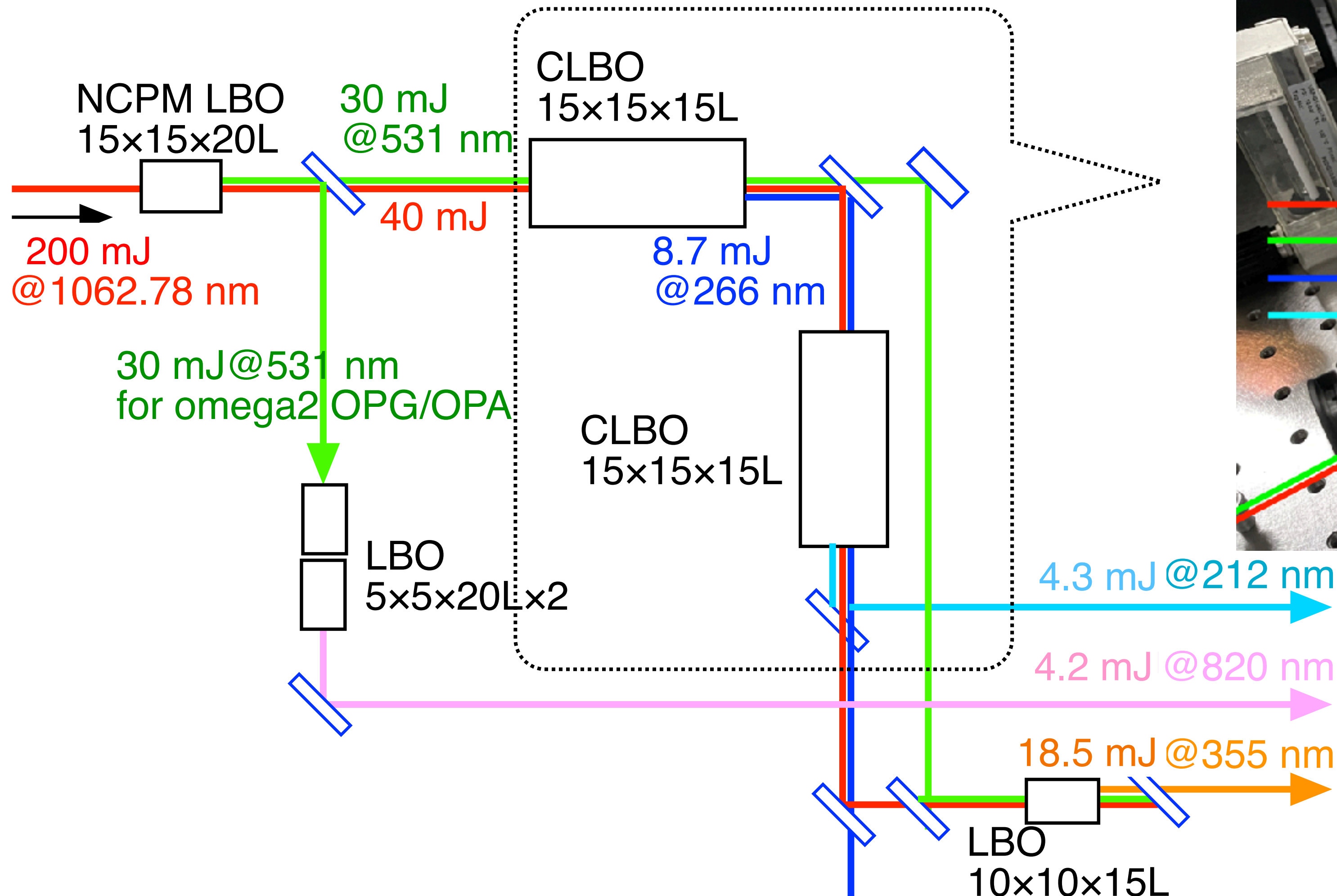


Transparent Nd:YGAG and Nd:YSAG ceramics enabled high-energy amplification at 1062.78 nm.

High-Energy UV Generation

CeLiB₆O₁₀ (CLBO) crystals are applied for 212 nm pulse generation.

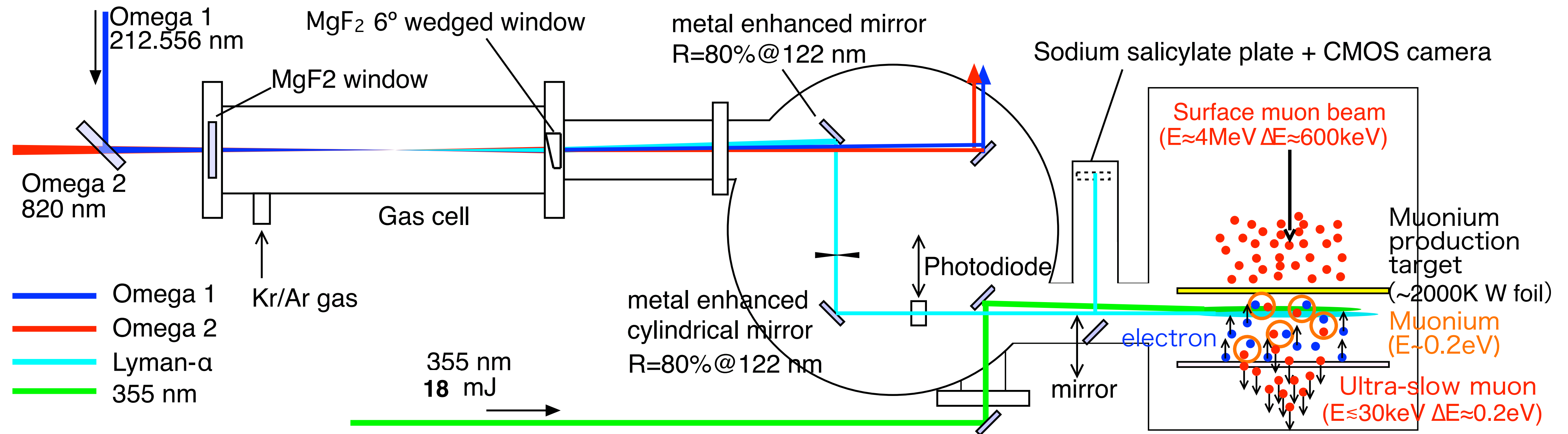
Y. Mori et. al., Jpn. J. Appl. Phys. 34 L296 (1995).



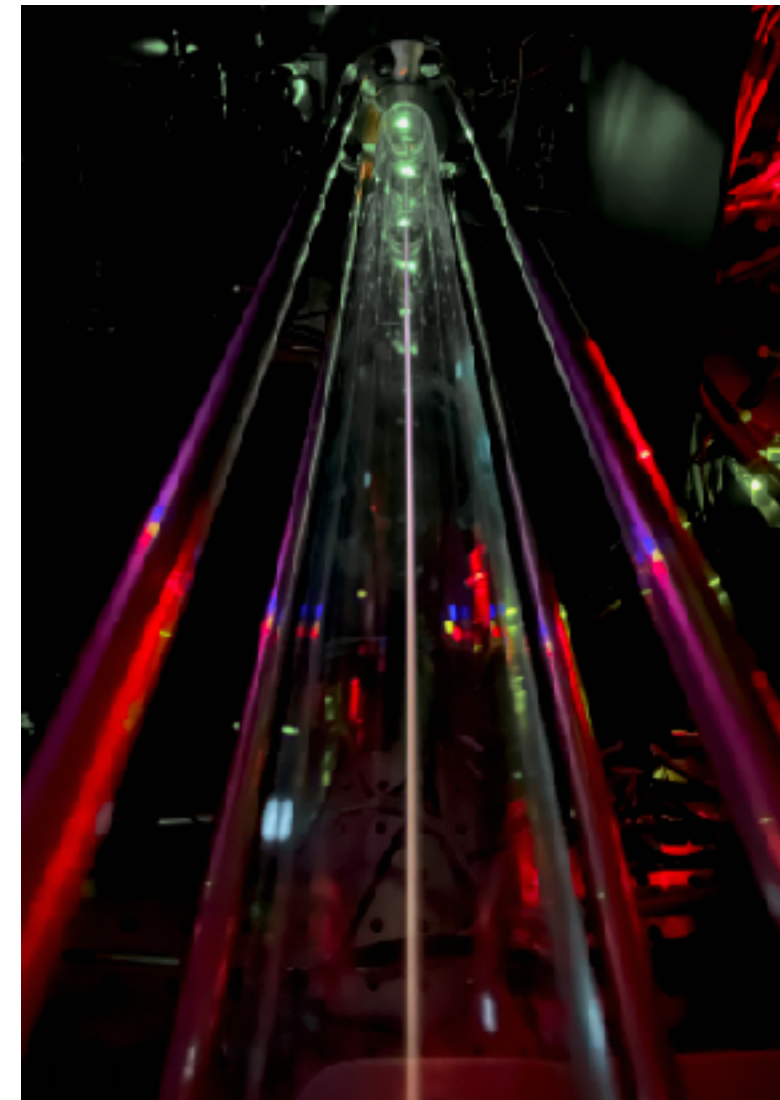
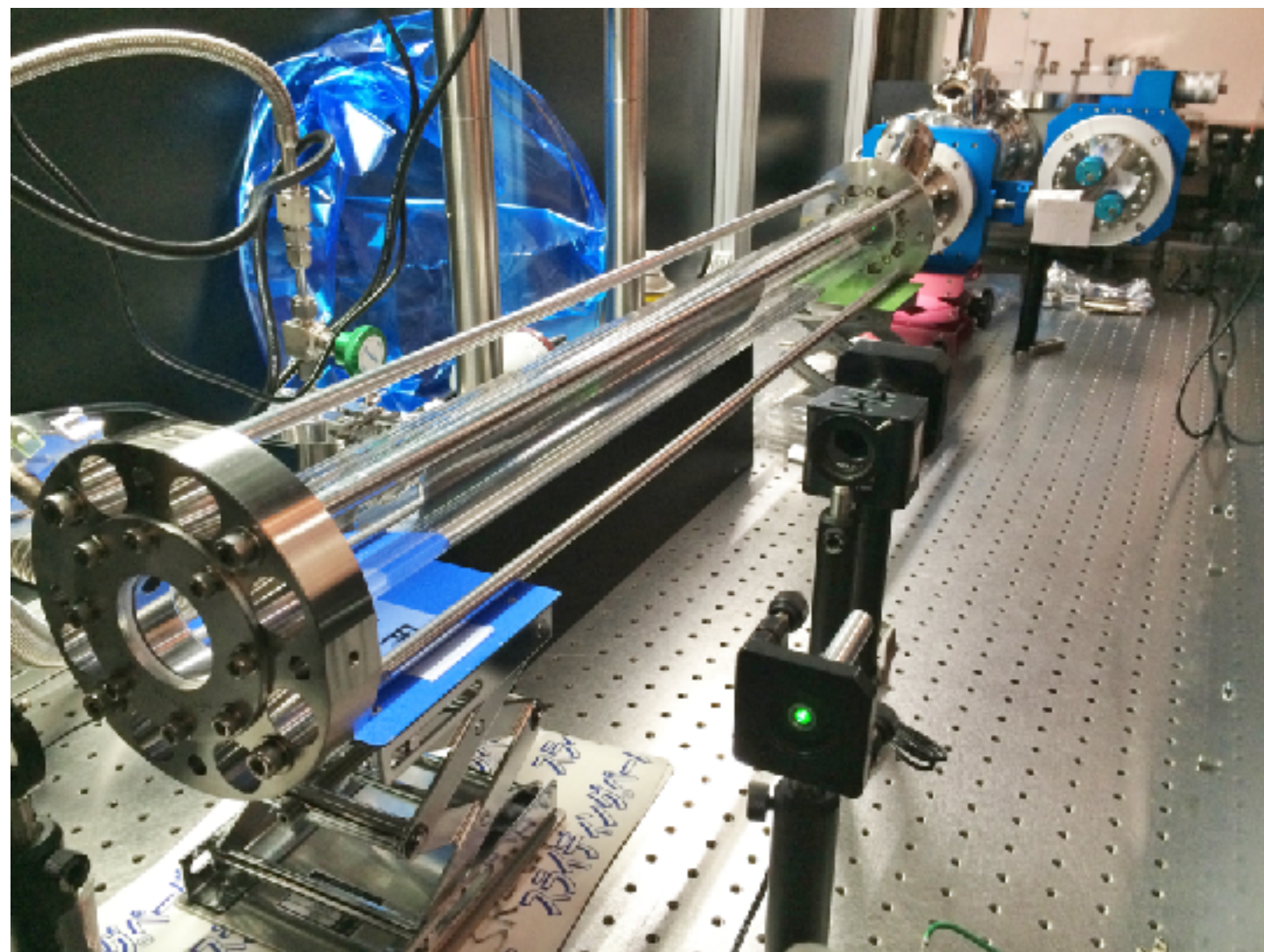
Four-wave-mixing in Kr

The driving pulses for Lyman- α generation are now available.

Coherent Lyman- α generation at J-PARC



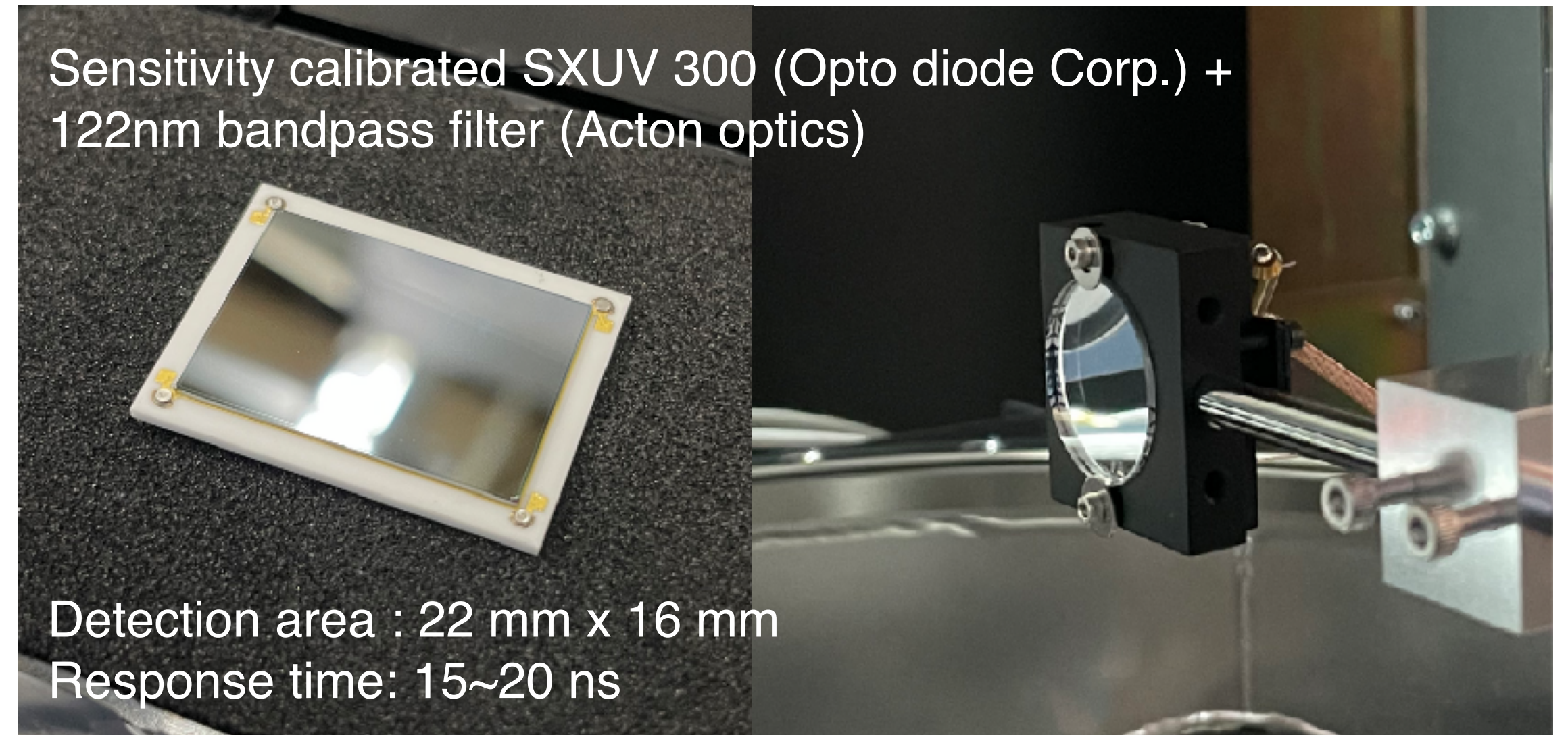
Gas cell



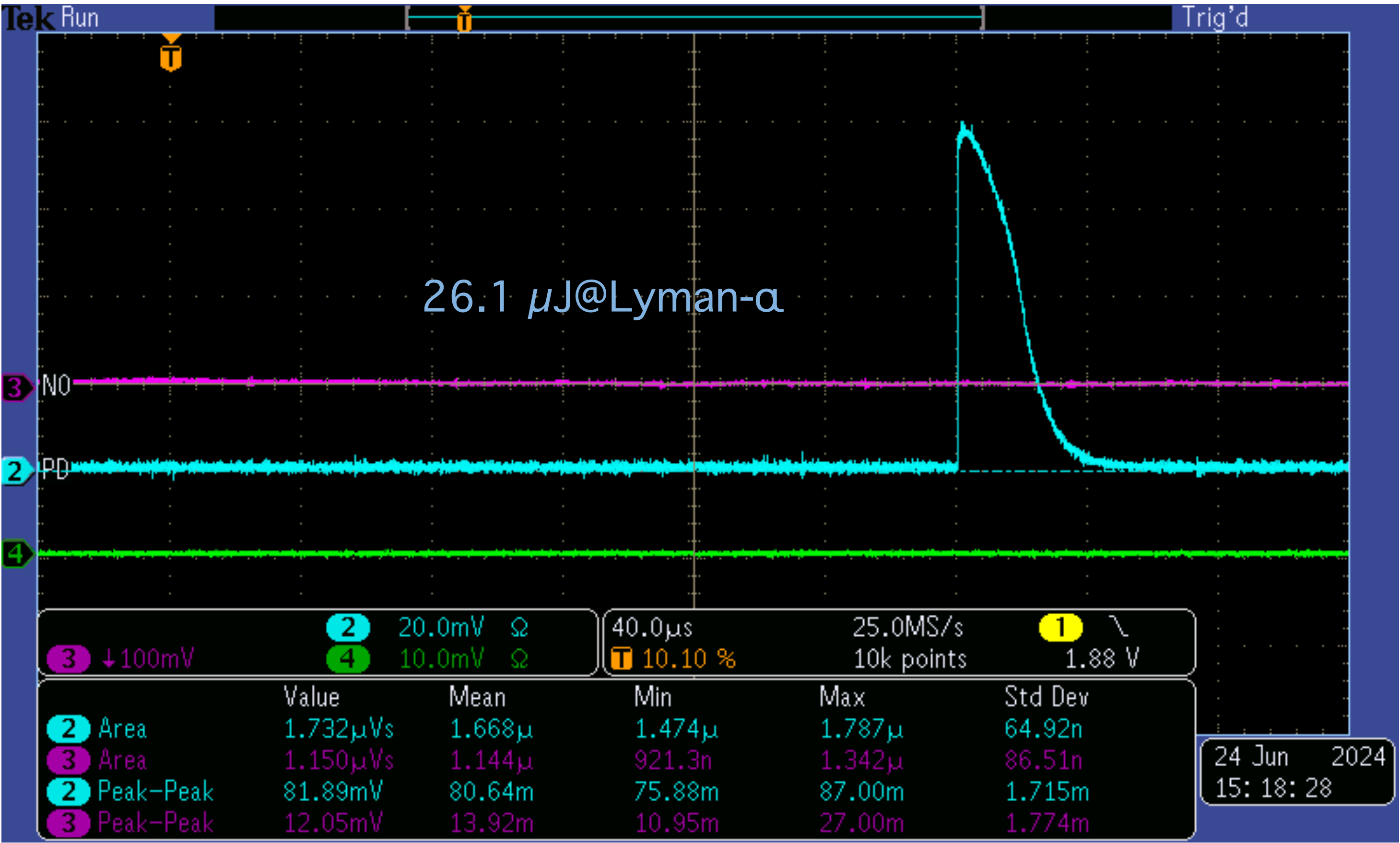
Lyman- α pulse energy meter

Sensitivity calibrated SXUV 300 (Opto diode Corp.) + 122nm bandpass filter (Acton optics)

Detection area : 22 mm x 16 mm
Response time: 15~20 ns



Up to 32 μJ Coherent Lyman- α Generation

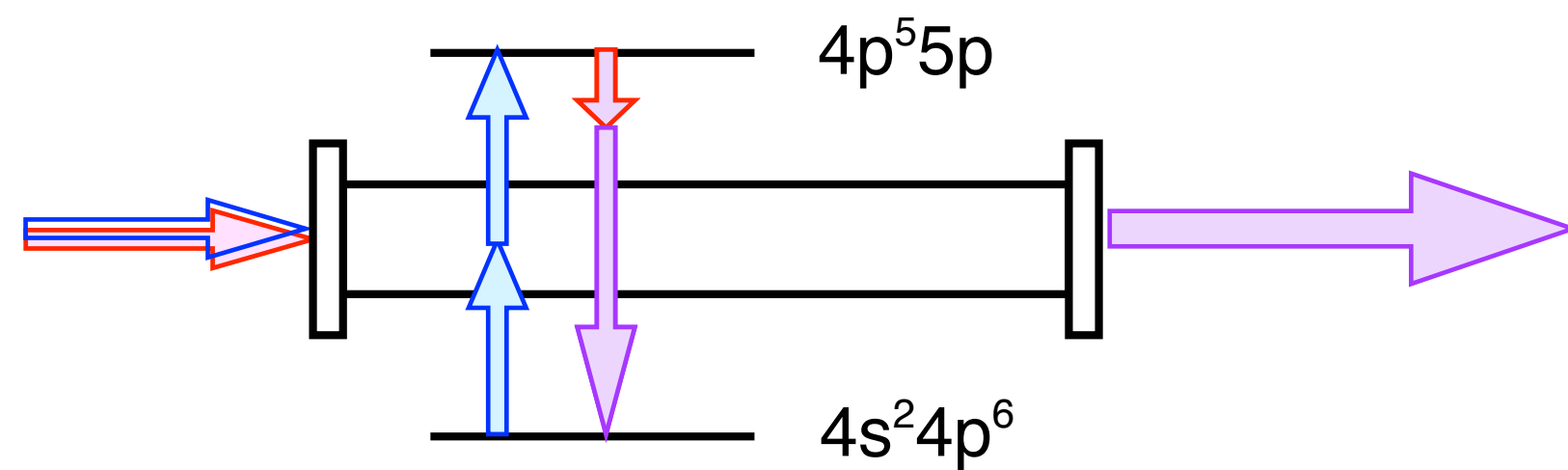


26.1 μJ Lyman- α pulse is available for Ultra-slow muon generation
32 μJ is estimated inside the gas cell

High-power coherent VUV generation demonstrated.

High power VUV (Achieved)

32 μ J coherent Lyman- α



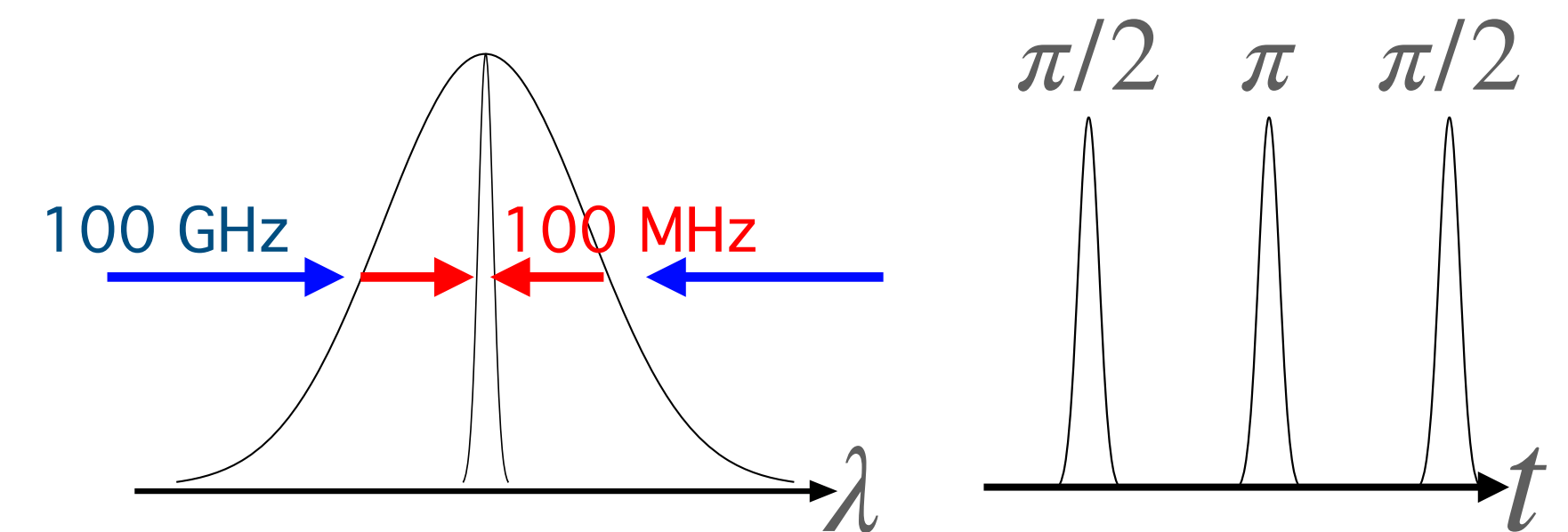
- All-solid-state laser system
- Nd:YGAG / Nd:YSAG
- Efficient Lyman- α generation
- USM generation



Add precision
control to the
VUV source

Advanced VUV (Next step)

100 MHz / 5 ns / phase control



- Narrow linewidth
- Pulse burst
- Multiple beam
- Phase measurement & control

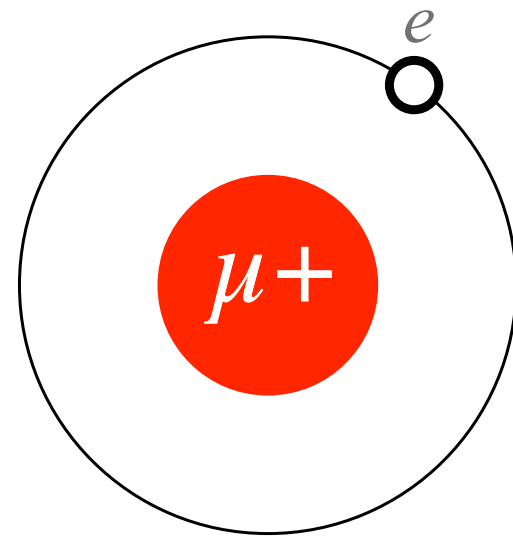
High power is the foundation

Precision control is the next step
Toward quantum sensing

Lyman- α wavelength and linewidth control

The wavelength of Lyman- α

for muonium (J-PARC)



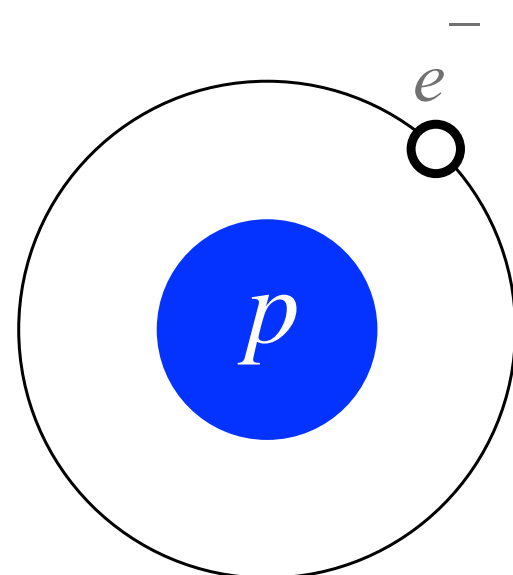
$$rm_{Mu} = \frac{m_{mu}m_e}{m_{mu} + m_e}$$

$$E_{Mu} = \frac{rm_{Mu}e^4}{2(4\pi\epsilon_0\hbar)^2} \left(1 - \frac{1}{n^2}\right)$$

$$= 10.155157 [eV]$$

$$= \underline{122.0913 [nm]}$$

for hydrogen atom (TRIUMF)



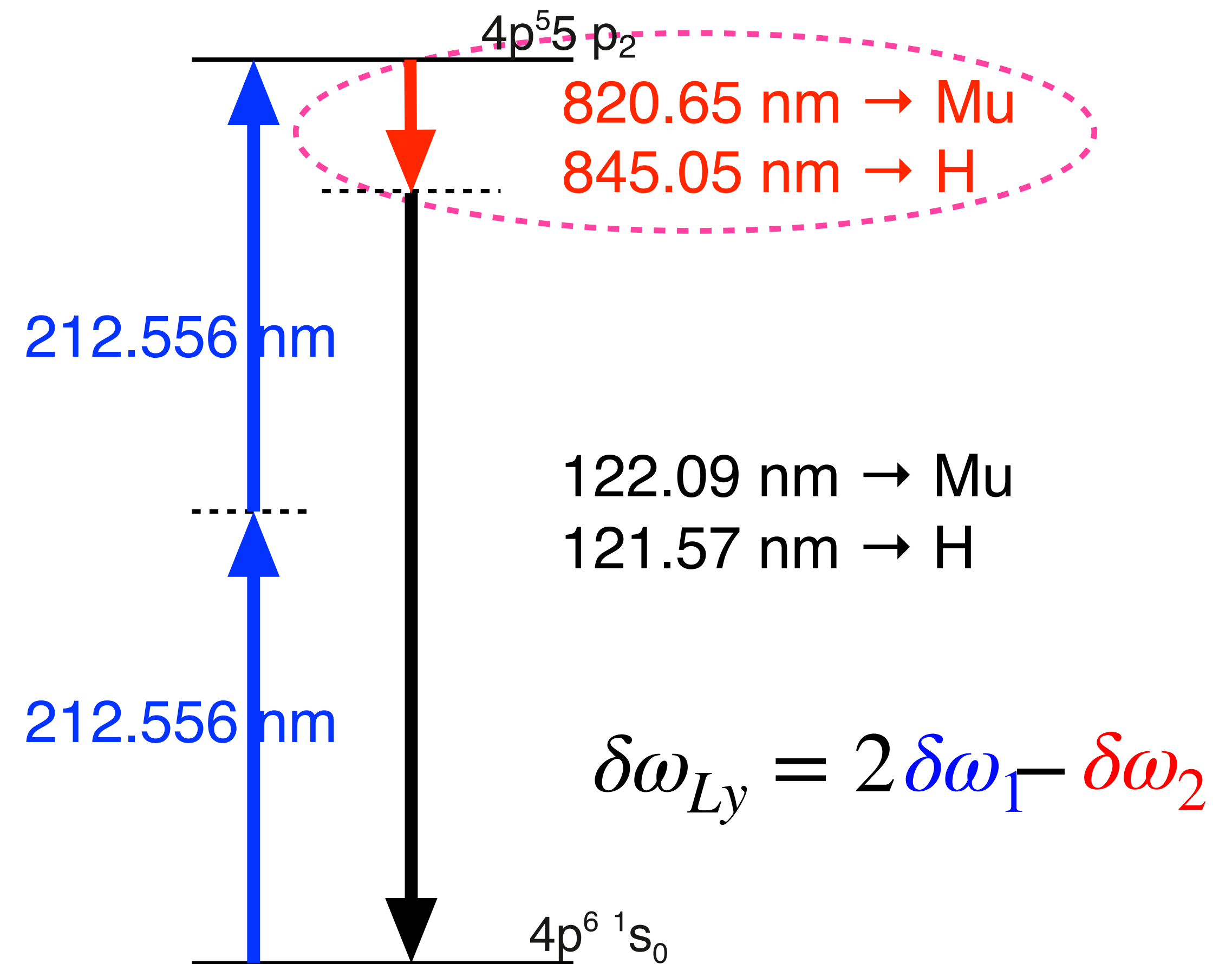
$$rm_H = \frac{m_p m_e}{m_p + m_e}$$

$$E_H = \frac{rm_H e^4}{2(4\pi\epsilon_0\hbar)^2} \left(1 - \frac{1}{n^2}\right)$$

$$= 10.198716 [eV]$$

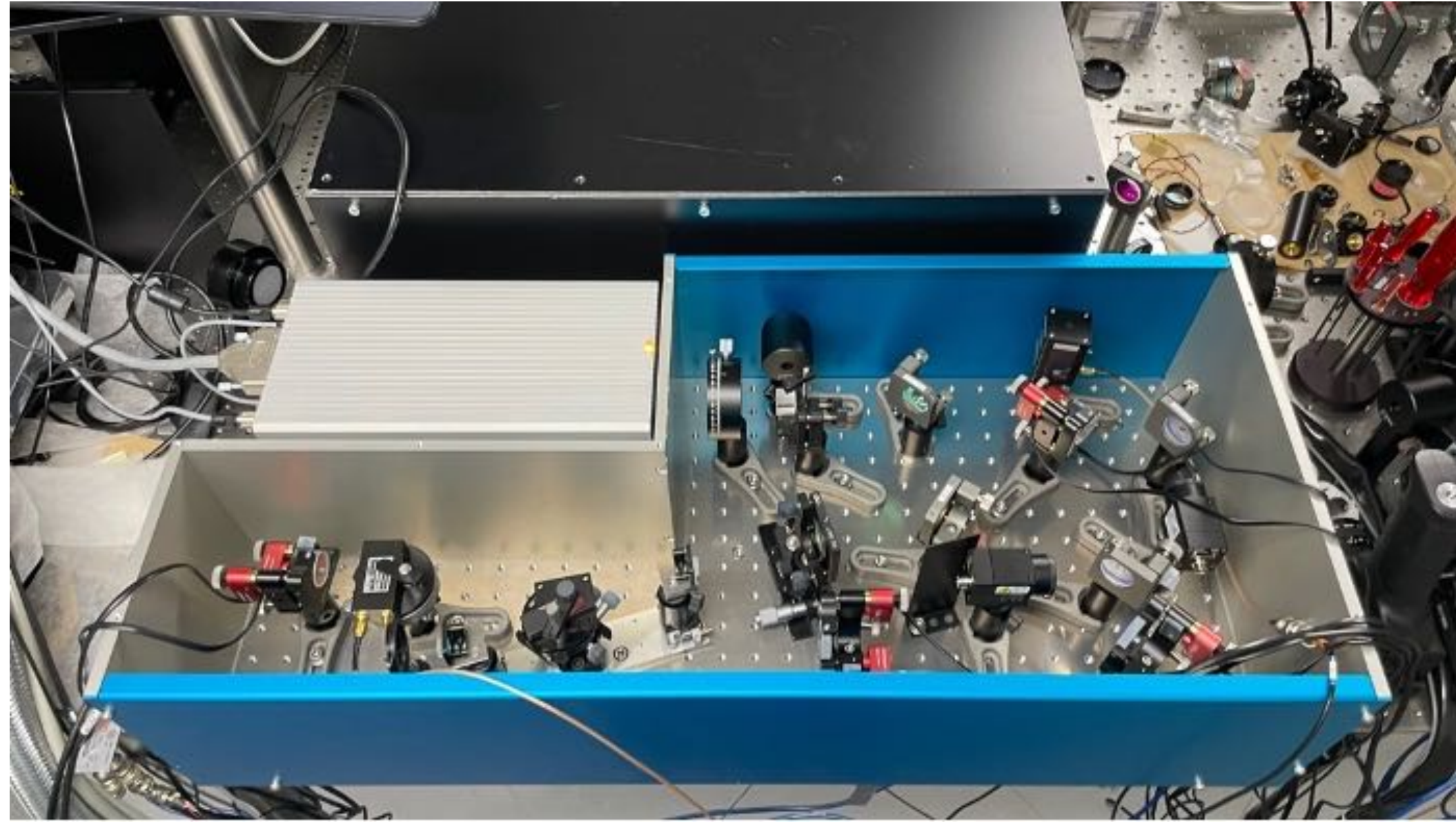
$$= \underline{121.5698 [nm]}$$

The wavelength and linewidth of Lyman- α can be controlled by adjusting IR wavelength and linewidth.

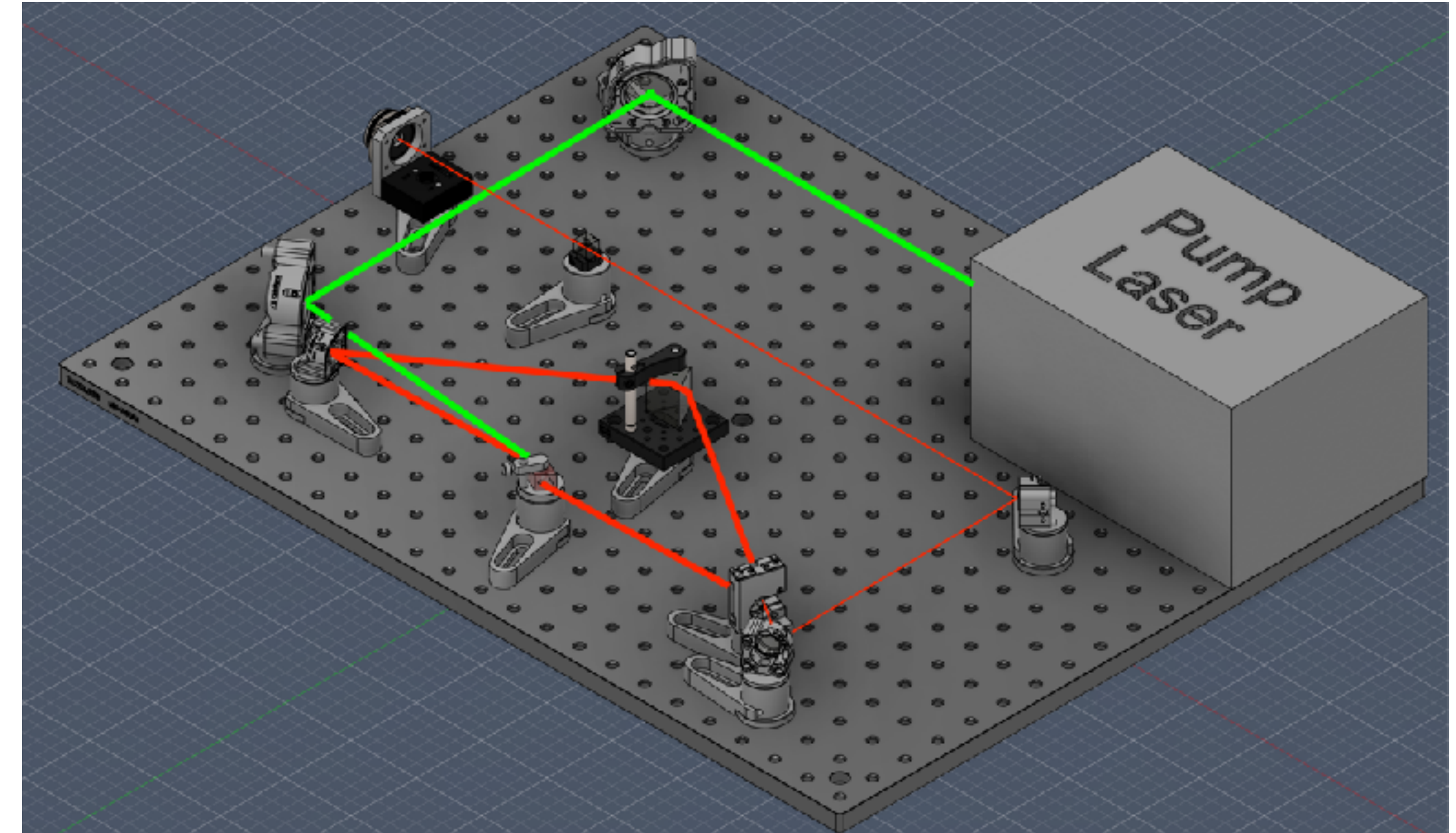
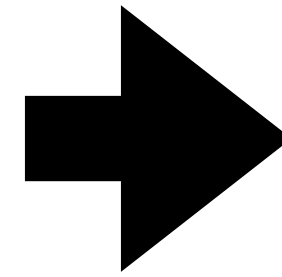


Narrowed and Phase-Controlled VUV Pulses

Narrow-linewidth and phase-control capabilities are not yet available at J-PARC.



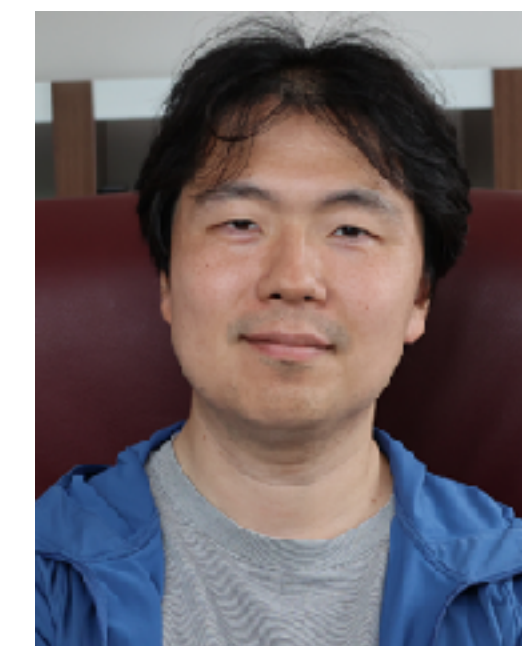
Current Ti:S straight cavity + AO tunable filter
(broad & random phase)



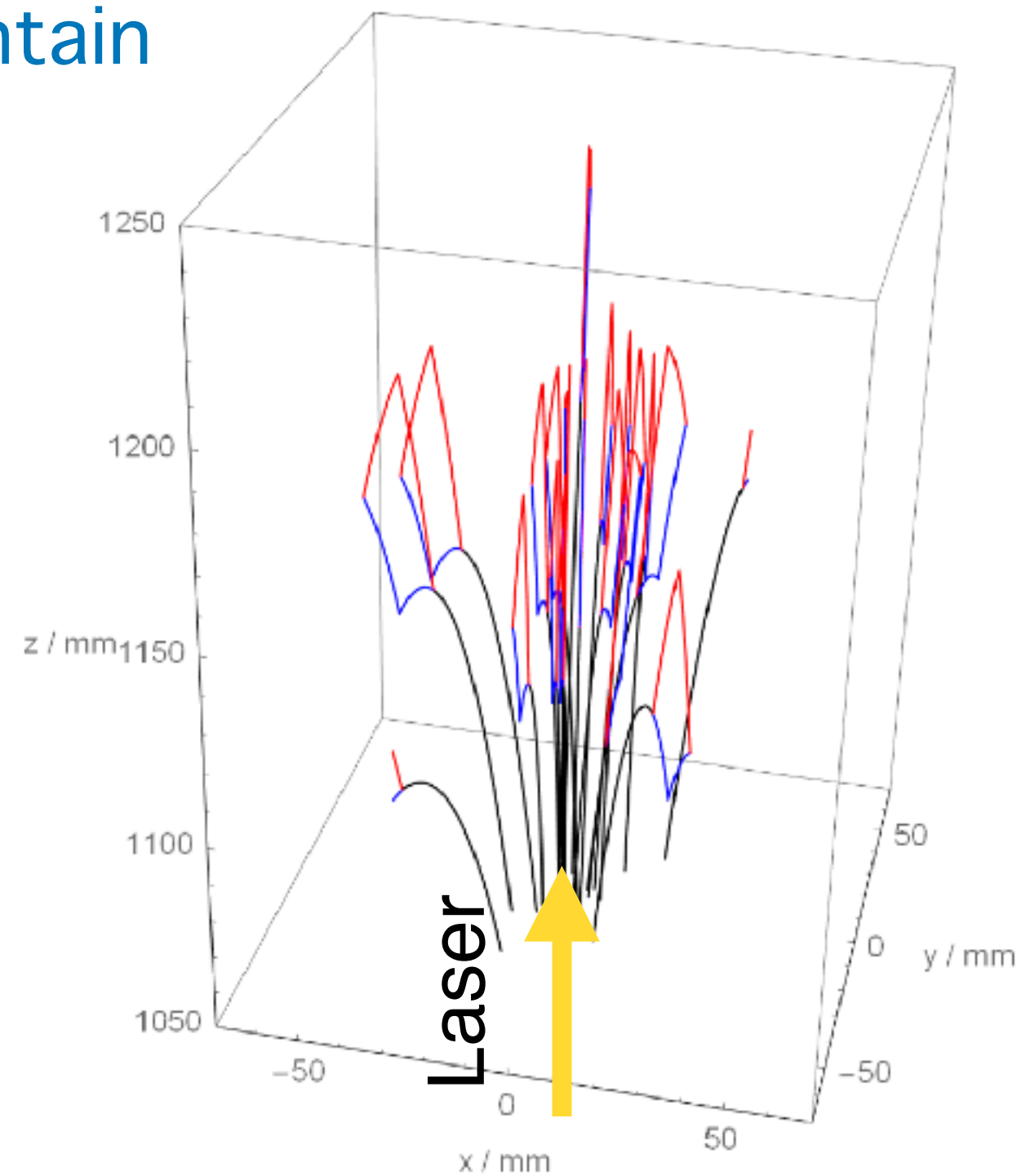
Ti:S ring cavity + single-mode ECLD seed laser
(narrow linewidth & phase coherent)

Phase measurement & active control

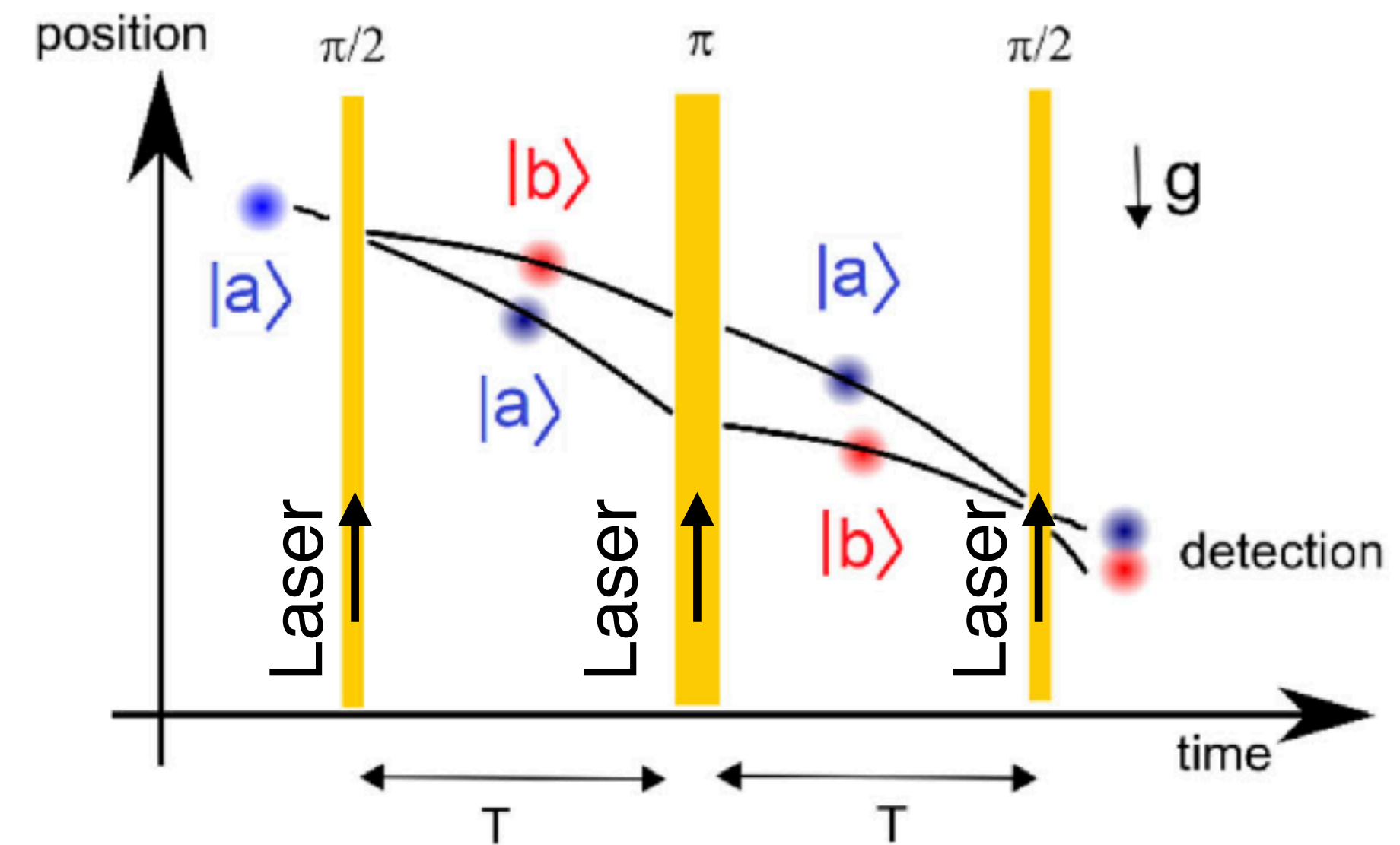
The technology will be developed and installed
with Prof. Momose (UBC) and Dr. Imai (QUP).



Hydrogen fountain



Temporal and phase diagram



Required Changes to the Light Source

- Narrowing of spectral line width : 80GHz $\rightarrow$ 100MHz
- Pulse duration expansion : 2 ns $\rightarrow$ 5 ns
- Multiple beam : counter propagation
- Pulse train arrangement : single pulse 25Hz $\rightarrow$ 25Hz with burst of 3 pulses at 1ms intervals
- Phase measurement & control : optical phase measurement method

Maintaining Lyman-α Conversion Efficiency

New configuration of pulse structures

- longer pulse duration (decided by linewidth)

→ lower pulse peak power of driving laser

Intensity of Lyman-α

$$P_{Ly} = N^2 \left[\chi^{(3)} \right]^2 P_1^2 P_2 F(\Delta k L, b / L)$$

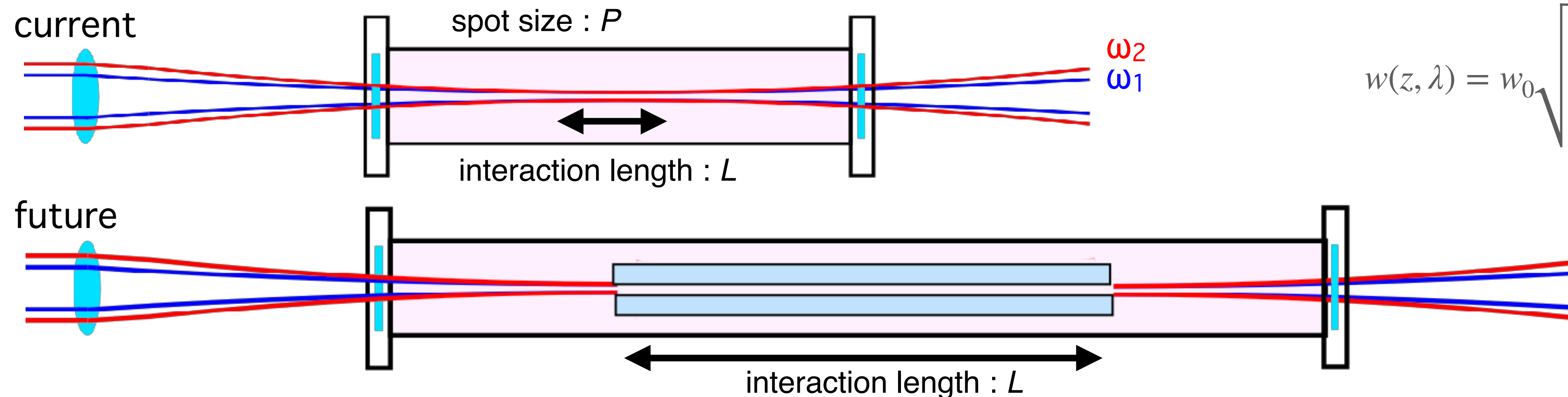
P_1 : ω_1 intensity

P_2 : ω_2 intensity

Δk : phase matching

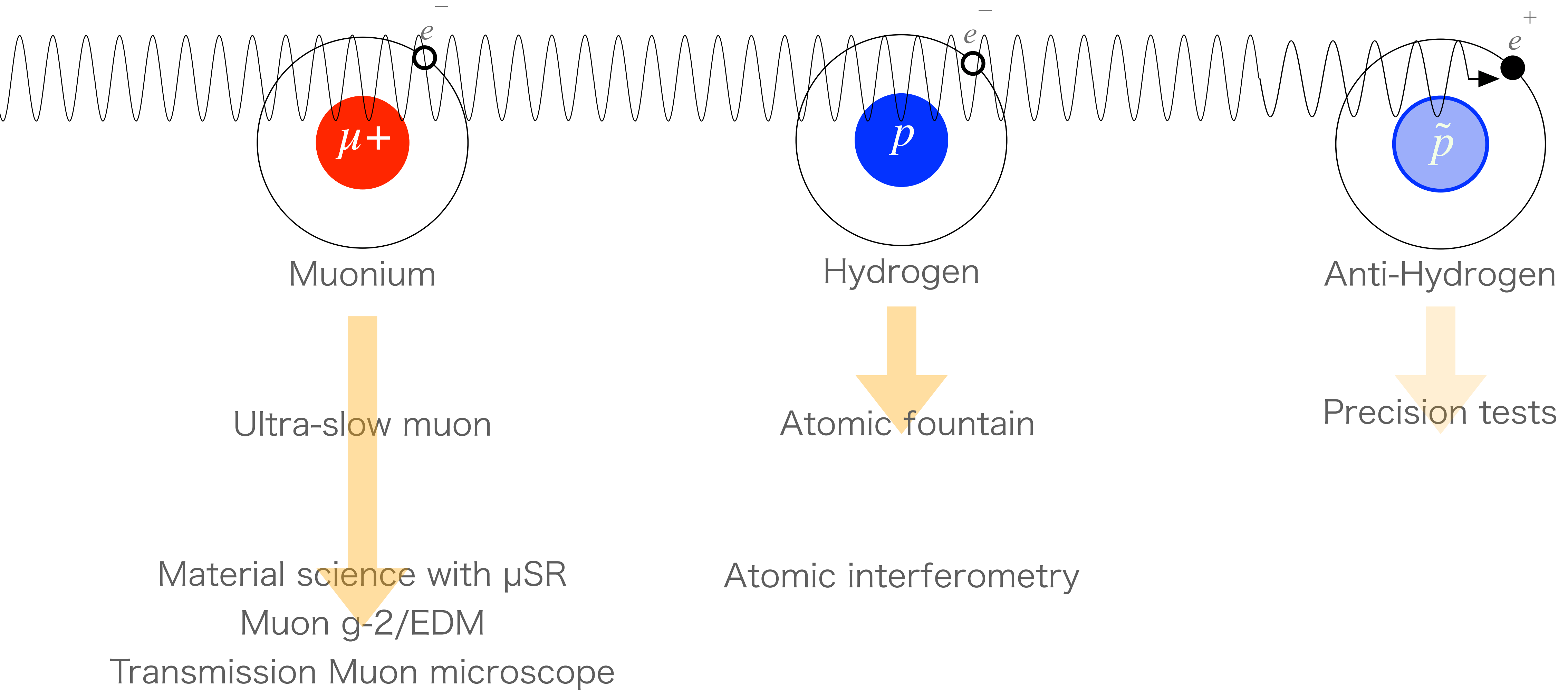
$\chi^{(3)}$: nonlinear susceptibility

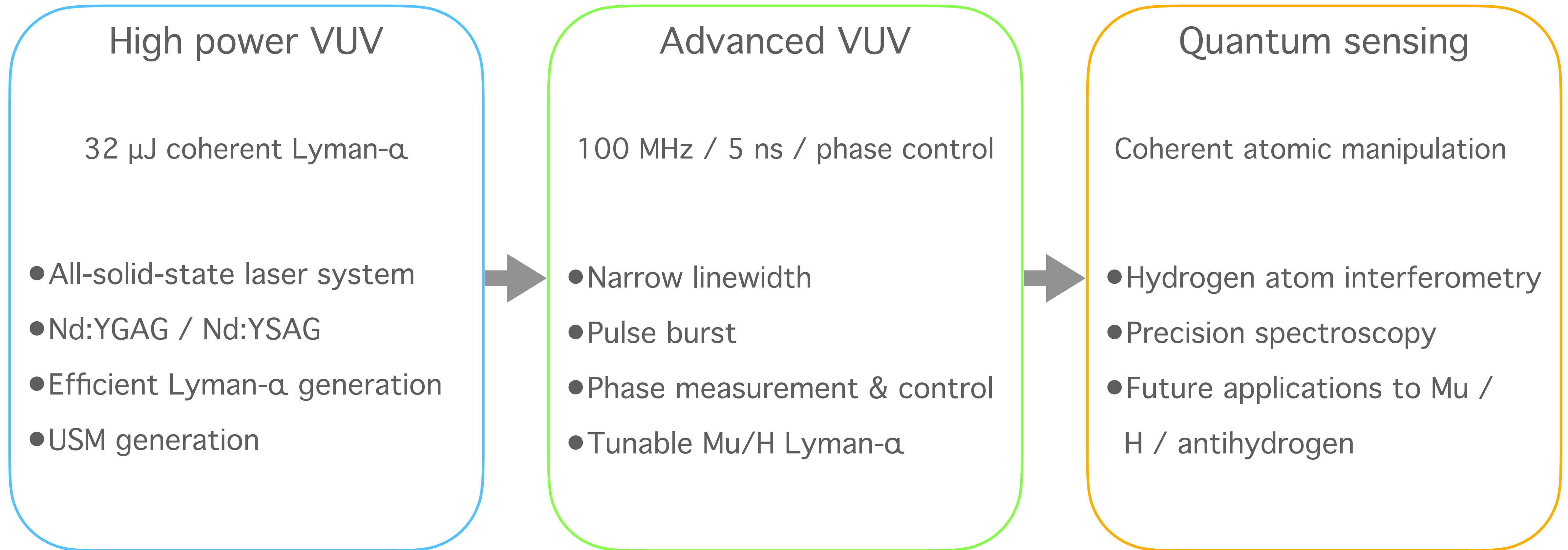
Hollow-core fiber technique to recover conversion efficiency by extending the interaction length



$$w(z, \lambda) = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2} \right)^2}$$

Toward Muonium, Hydrogen and Antihydrogen





From high-power VUV to precision quantum sensing