UGAP2022, 13 Jun. 2022 @Noda campus, Tokyo University of Science.

Laser isotope separation of Ca

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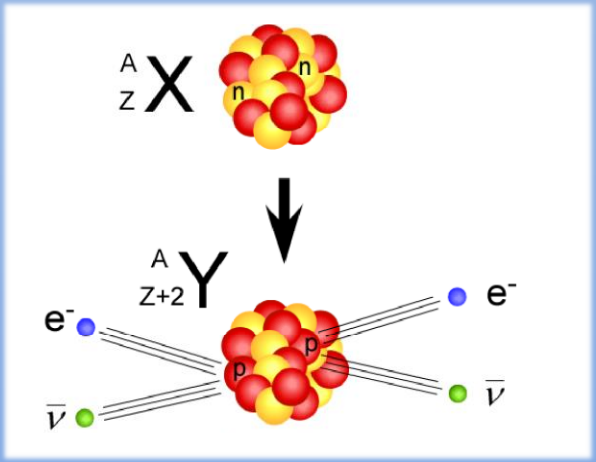
Neutrino-less double beta decay

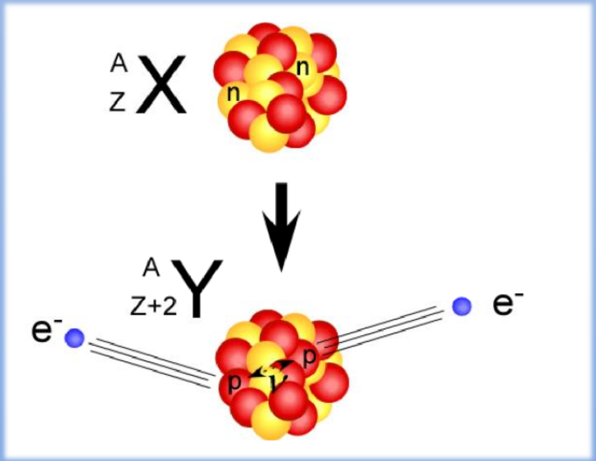
A lepton-number-violating nuclear process

test the *Majorana* nature of neutrinos

2ν double beta decay
within Standard Model (SM)
observed : $T^{2\nu}_{1/2} \sim 10^{19-21}$ yr

0ν double beta ($0\nu\beta\beta$) decay
beyond SM
Not yet: $T^{0\nu}_{1/2} > 10^{26-27}$ yr





Neutrino-less double beta decay

Ultra rare process

Maximize signal-to-noise ratio (S/N)

Reduce the noise (background; BG)

Select the nucleus with high Q-value

4.27 MeV for ^{48}Ca,

3.37 MeV for ^{150}Nd,

3.35 MeV for ^{96}Zr, …

Increase the number of target nucleus

$S \sim \mathcal{O}(1)$ events/yr

$n > 1$ kmol for $T_{1/2} \sim 10^{26}$ yr

$n > 10$ kmol for $T_{1/2} \sim 10^{27}$ yr

….

Natural radioactive BG

Maximum energy of γ-rays

2.62 MeV

(^{208}Tl in Th-chain)

Maximum energy of β-rays

3.27 MeV

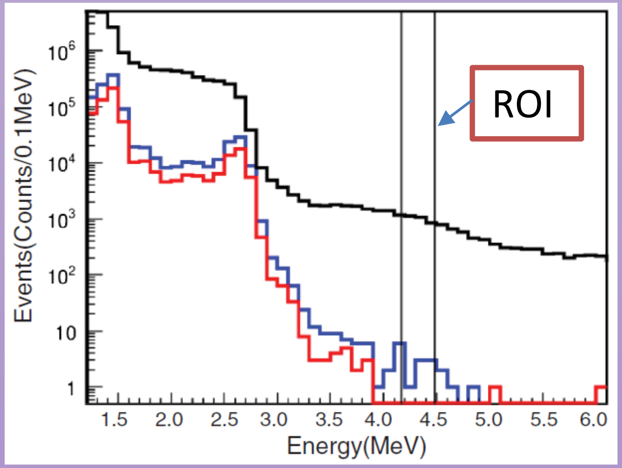
(^{214}Bi in U-chain)

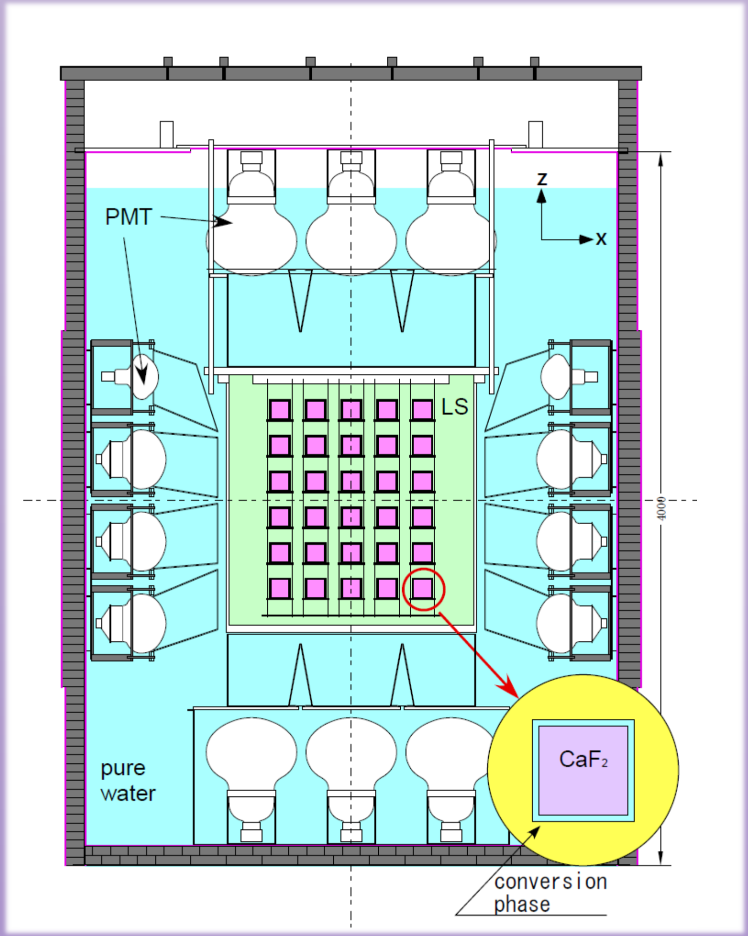
Neutrino-less double beta decay

CANDLES project for $0\nu\beta\beta$ study of ^{48}Ca

We select ^{48}Ca as a target nucleus

Number of BG events:
0 events (ROI) for 131 days of meas.
number of target nuclei
$n \sim 1.6\ \mathrm{mol}$: $^{nat.}CaF_2$ scintillator



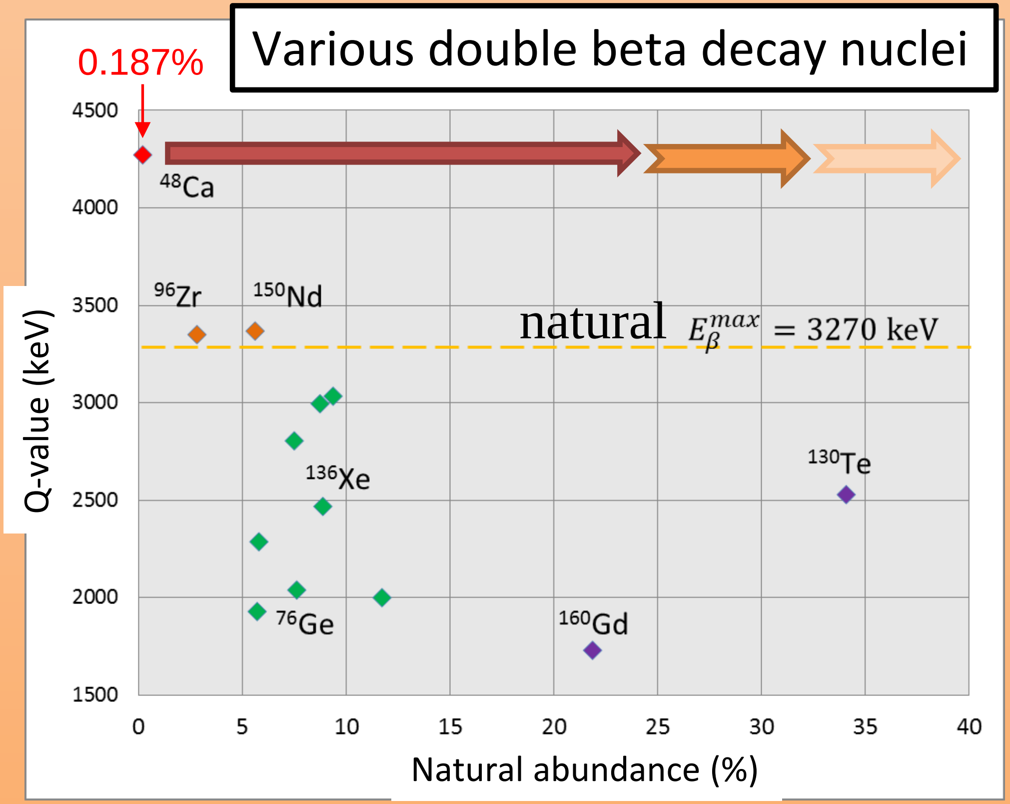


Ref. PHYS. REV. D 103, 092008 (2021)

Neutrino-less double beta decay

Improve the sensitivity

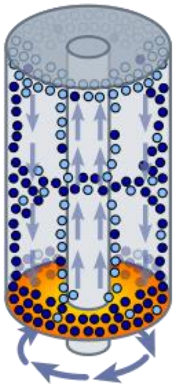
Isotope enrichment is the key!



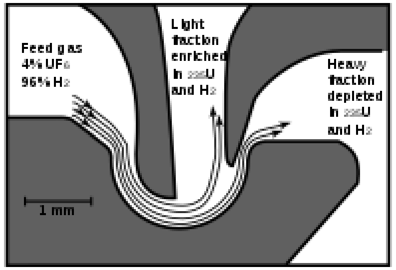
Isotope separation methods (for uranium)

Methods	U	Ca	Issues
Gas diffusion	○	×	Huge power consumption
Zippe-type centrifuge	○	×	Very high-speed rotation
Aerodynamic	○	×	Huge power consumption
Molecular laser	○	×	Development of high-power lasers
Atomic vapor laser (AVLIS)	○	○	
Chemical	○	○	Limitation of concentration
Plasma	○	○	Huge power consumption
Electromagnetic	○	○	

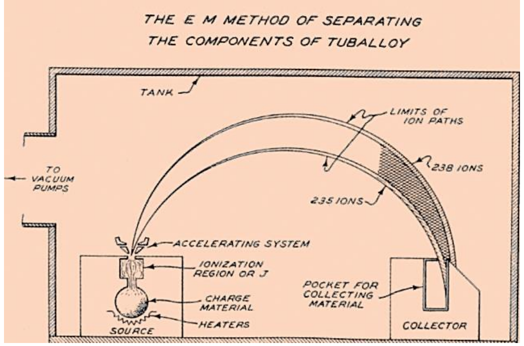
https://en.wikipedia.org/wiki/Enriched_uranium



Zippe centrifuge

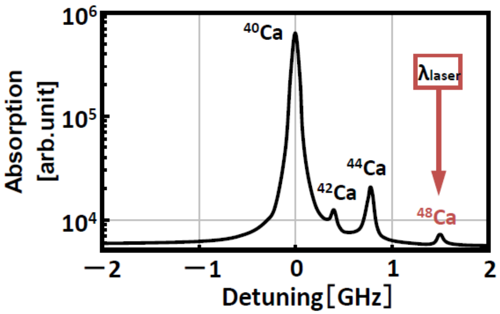


Aerodynamic processes

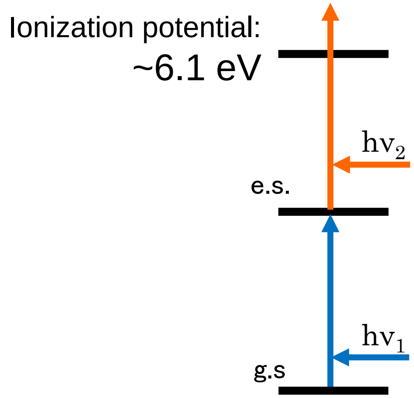


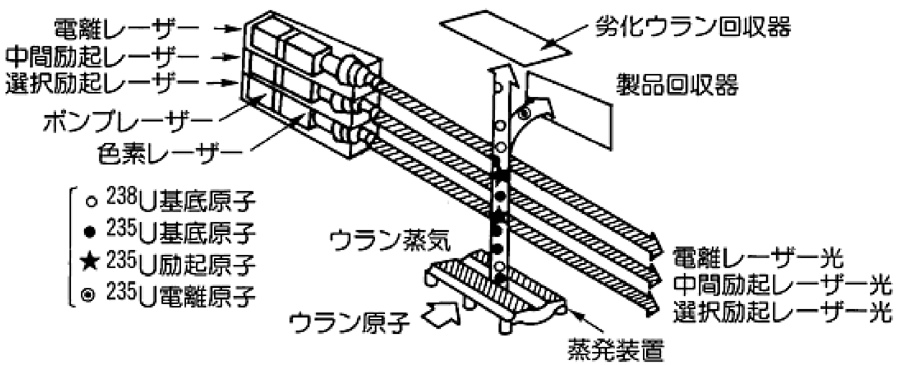
Electromagnetic method

Ionization vs. Deflection

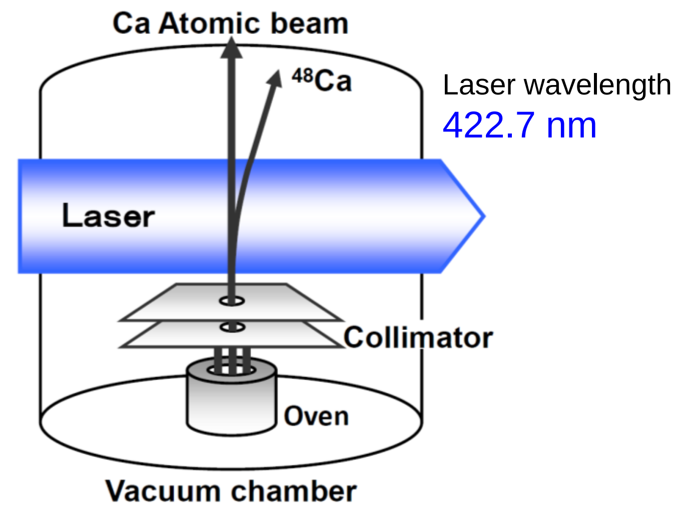


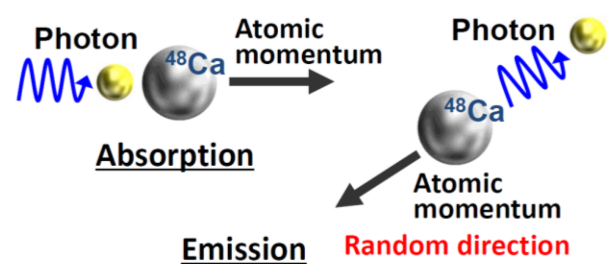
Absorption spectrum of Ca at 423nm





[出典]日本原子力産業会議(編):原子力年鑑1994年版(平成6年11月)、p135

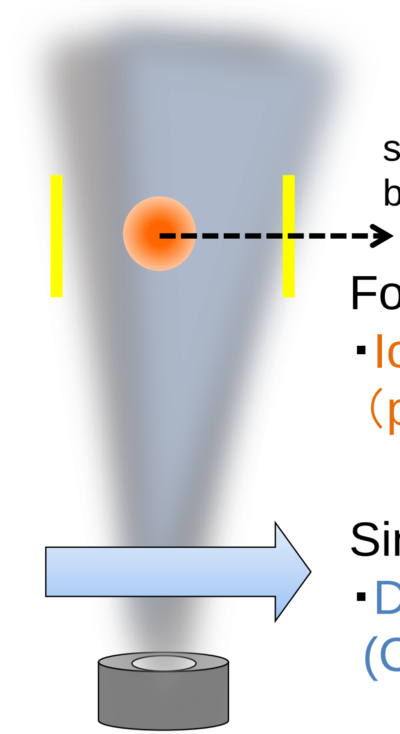




- **2 to 3 photons for 1 atom**
- Multiple laser wavelength
- Pulsed laser

- ~1000 photons for 1 atom
- **Single laser wavelength**
- **CW laser**

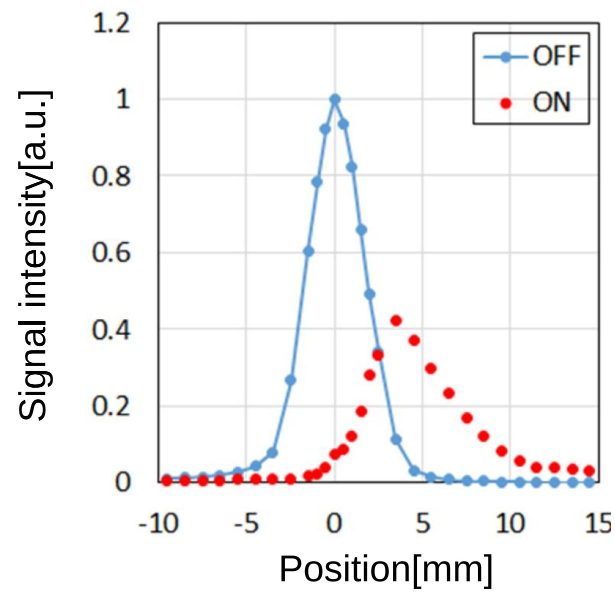
Experiment of atomic beam deflection

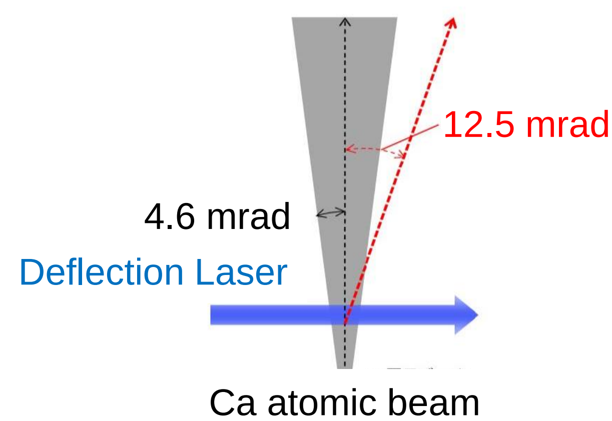


For TOF measurement
- Ionization
（pulse, YAG laser）

Single laser (~10 mW)
- Deflection
(CW, diode laser)

Ca in crucible
(~900 K)





Strategies for mass production

- 1st milestone
  - One atom absorbs/emits 1000 photons to be deflected (~ 30 mrad)
  - Production rate : $n \sim 1$ mol/yr

Evaporation rate of $^{nat.}Ca$

Collection efficiency

Duty factor

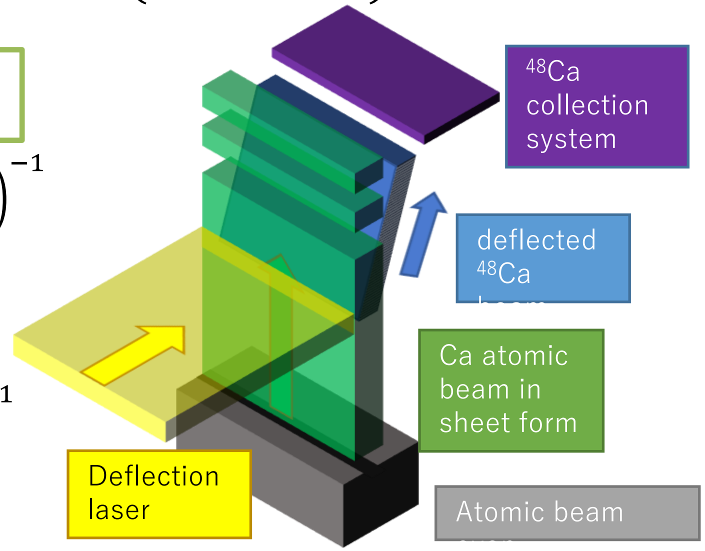
$$v_{ev}(\mathrm{g/sec}) = 2.71 \times 10^{-3} \left(\frac{n}{1\ \mathrm{mol/yr}}\right) \left(\frac{\varepsilon_{coll}}{0.5}\right)^{-1} \left(\frac{\tau}{0.5}\right)^{-1}$$

oven temperature : $T_{oven} \approx 870$ K

Laser power

$$P(W) = 35.2 \left(\frac{n}{1\ \mathrm{mol/yr}}\right) \left(\frac{\varepsilon_{las}}{1.0}\right)^{-1} \left(\frac{\varepsilon_{coll}}{0.5}\right)^{-1} \left(\frac{\tau}{0.5}\right)^{-1}$$

Laser utilization efficiency



U. Of Fukui

- Proof of Principle
  - Small vacuum chamber
  - Small commercial crucible
  - Collimation by slit(s)
  - Single ECDL
  - TOF measurement

U. of Fukui

- Atomic beam
  - Small vacuum chamber
  - Large size crucible
  - Collimation test

ILE & ILT

- Laser system
  - Stabilized master laser
  - Multiple slave laser

RCNP

- Collection system
  - Automatic collection

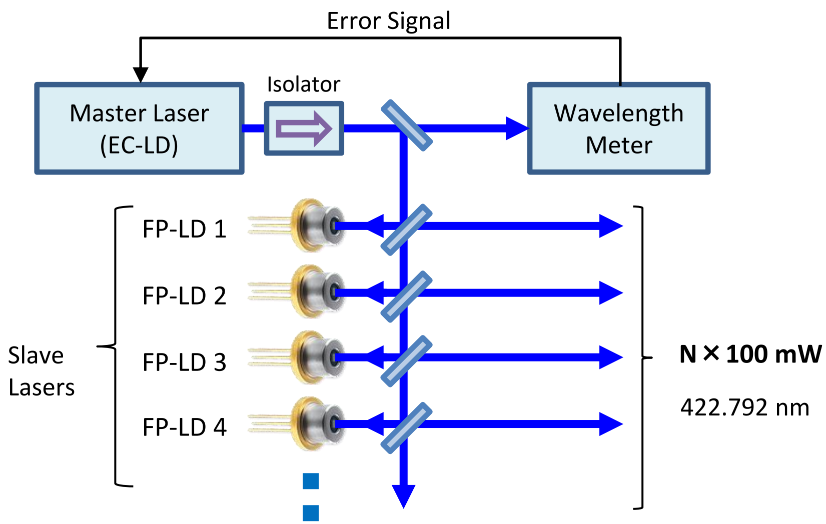
- Mass production
  - Large size chamber
  - Production rate

    ~1 mol/yr

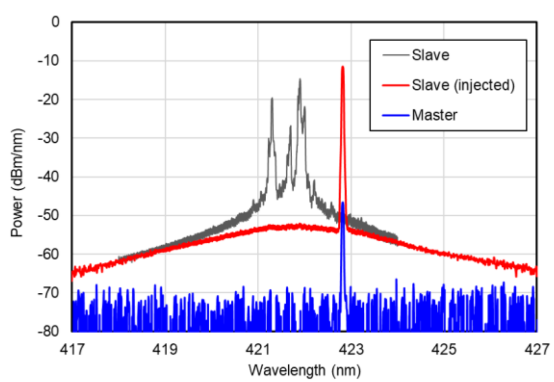
R&D for mass production

Laser system

- High power laser by injection locking
  - InGaN diode laser



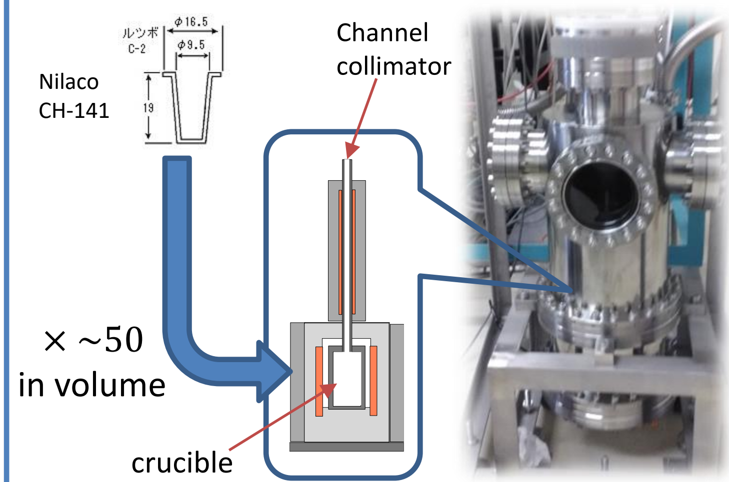
Injection locking
Master laser
+
1 slave laser



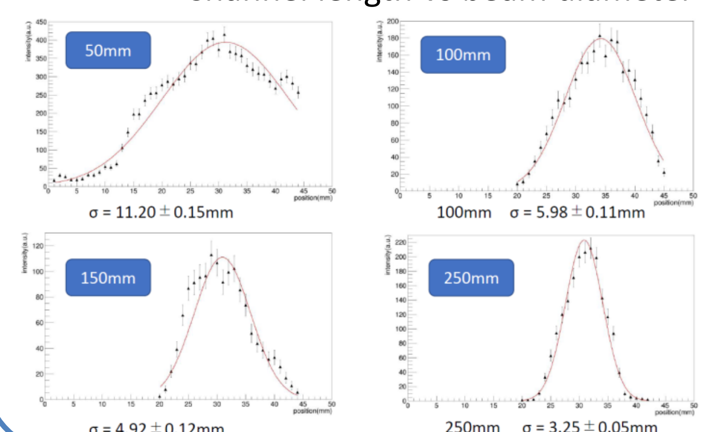
We are developing a method of laser-power scaling using wavelength-stabilized multiple slave lasers.

Atomic beam system

- Employ a large size crucible



- Collimation by a channel $(\phi 5)$
  - Channel length vs beam diameter



Development of Laser System

What is the required laser power?

Photon energy: 4.7×10^{-19} J @ 423 nm

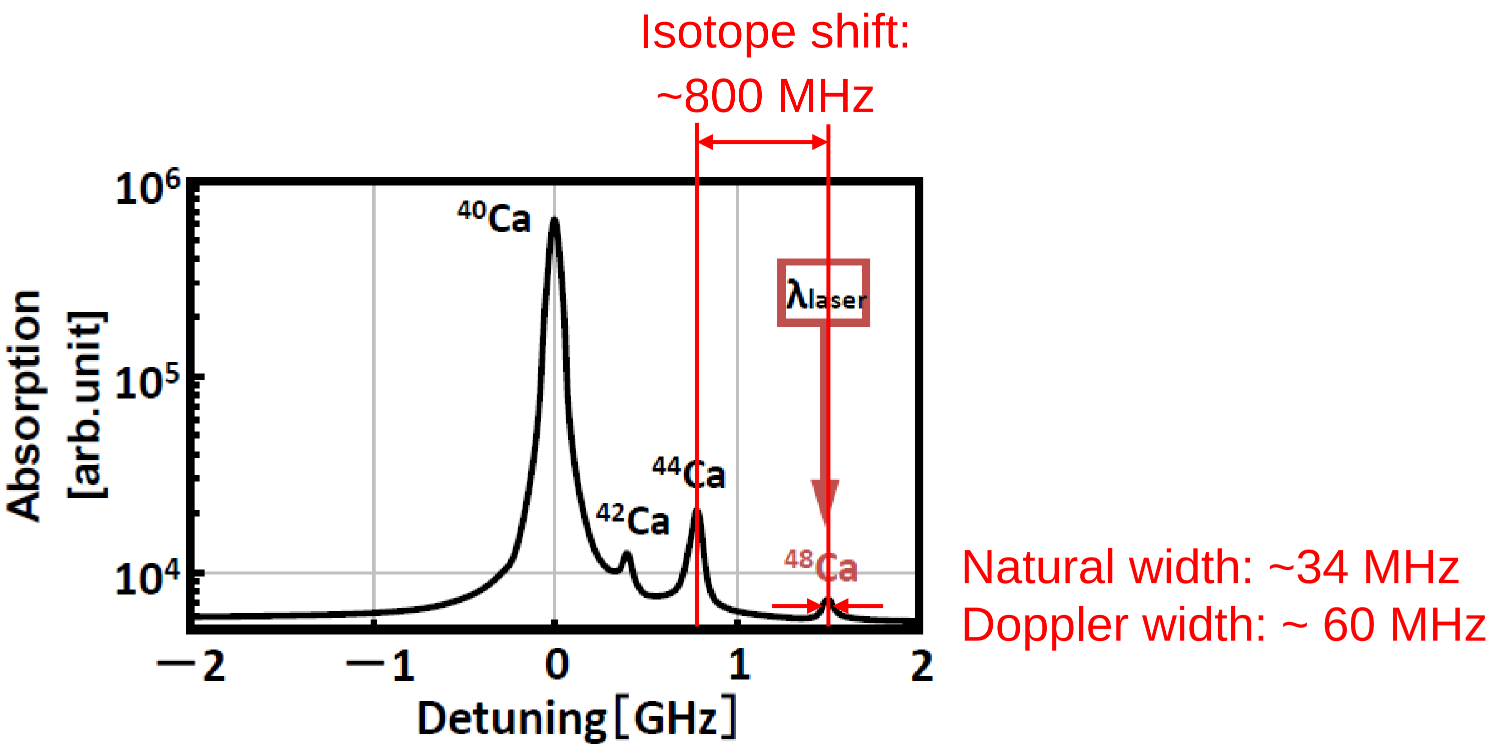
Number of photons absorbed by 1 atom: 1,000

→ Number of ^{48}Ca produced by 1 W laser: 2×10^{15} sec^{-1} → ~5 g/W/year

>200 W of laser power produces ^{48}Ca of 1 kg/year.

Current	FY2022	Near future	Future
100 mW →	2 W →	2 kW →	60 kW
	(~10 g / year)	(~10 kg / year)	(~300 kg / year)

What is the required wavelength stability?



Absorption spectrum of Ca at 423nm

Target of laser frequency stability:

2 MHz rms → 422.792xxxxx ±0.0000006 nm

Laser performances required for isotope separation

- ✓ Wavelength: ~422.792 nm
- ✓ Frequency stability: <2 MHz rms
- ✓ Power scalability: >100 W (1 unit)
- ✓ Long life time: >30,000 hours
- ✓ Continuous wave (CW)
- ✓ High efficiency
- ✓ Low cost

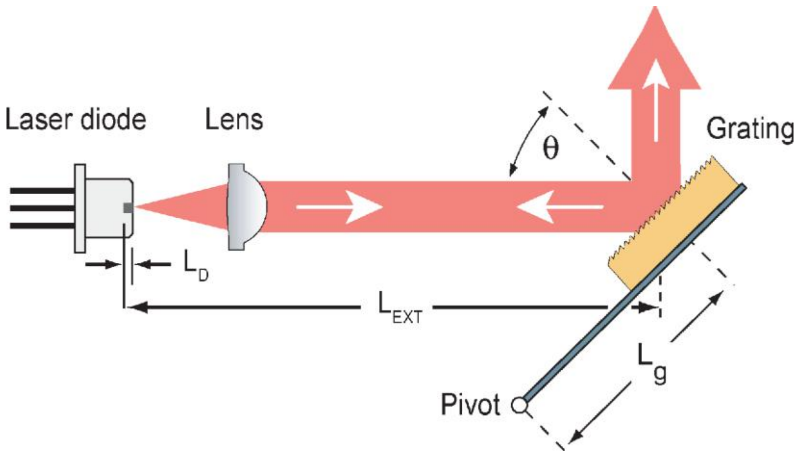
- ✓ No need for high intensity: <1 W/cm^2

Comparison of blue-violet (423 nm) lasers

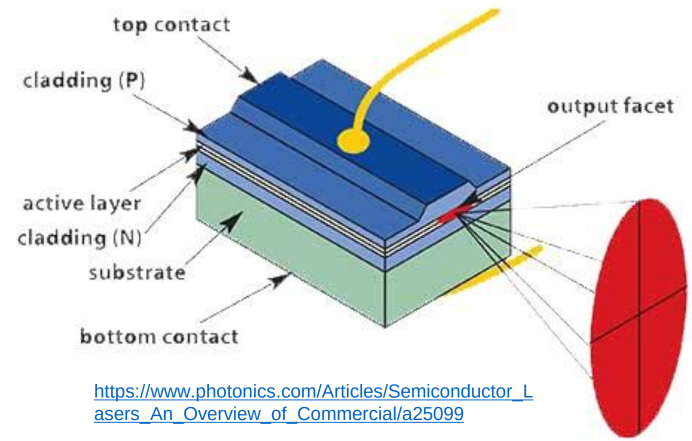
	InGaN laser diode	Second-harmonic of IR laser diode	Second-harmonic of Ti:sapphire laser
Power of a beam	>100 mW	500 mW～1 W	2 W
Cost	500～600 万円/W	500～1000万円/W	1000万円/W
Cost reduction possibility	High	Low	Very low
Long-term stability	High	Average	Low
E-O efficiency	20%	5～15%	1%
Footprint	30×30 ㎠	50×40 ㎠	80×80 ㎠

The cost is not so different currently, but considering the efficiency, stability, and the possibility of cost reduction by mass production, the InGaN laser diode is the most promising.

External cavity LD vs. Fabry-Perot cavity LD



https://doi.org/10.1364/AO.48.006692



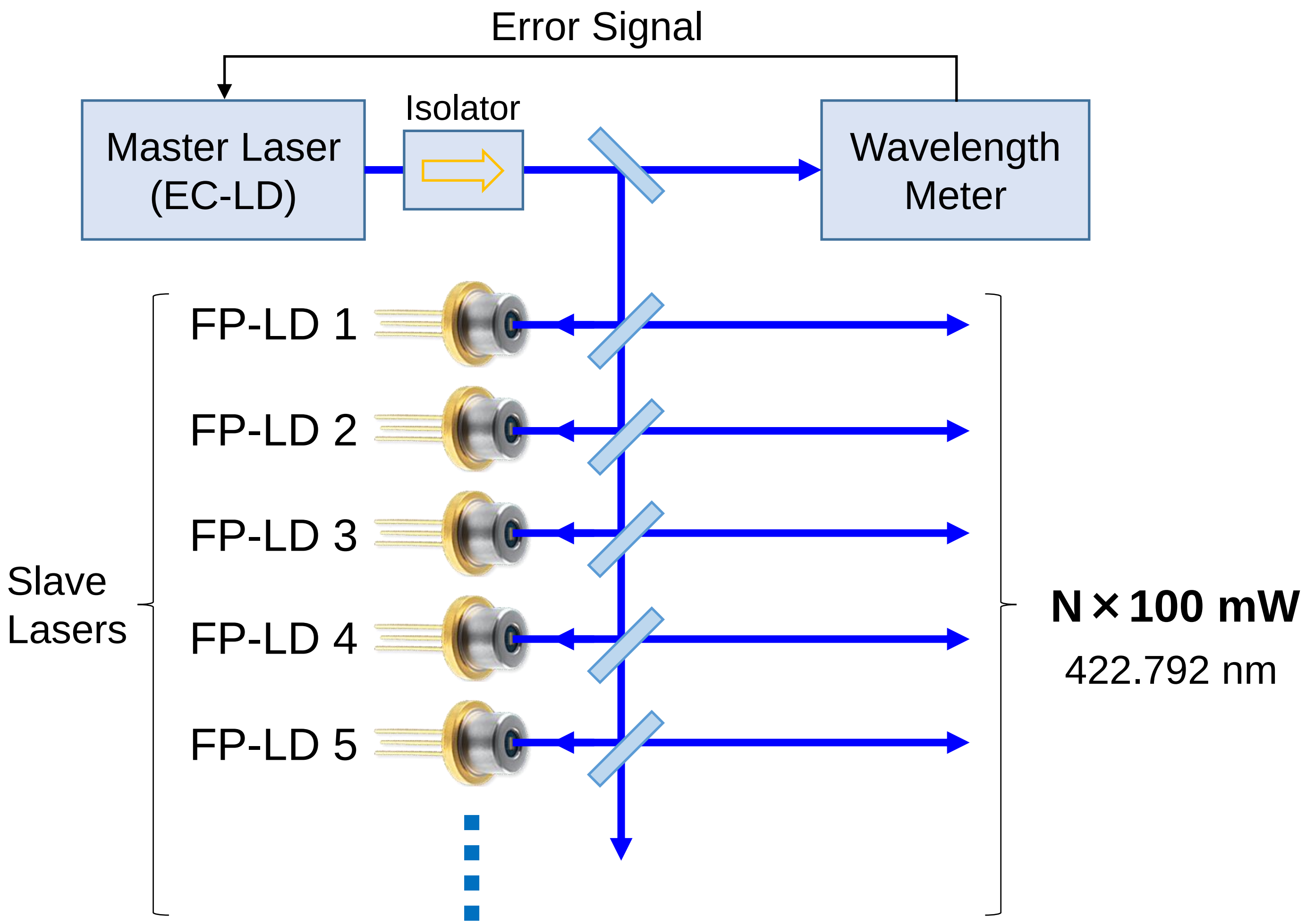
https://www.photonics.com/Articles/Semiconductor_Lasers_An_Overview_of_Commercial/a25099

- Single longitudinal-mode (Line width: <1 MHz)
- Wavelength tunable

↔

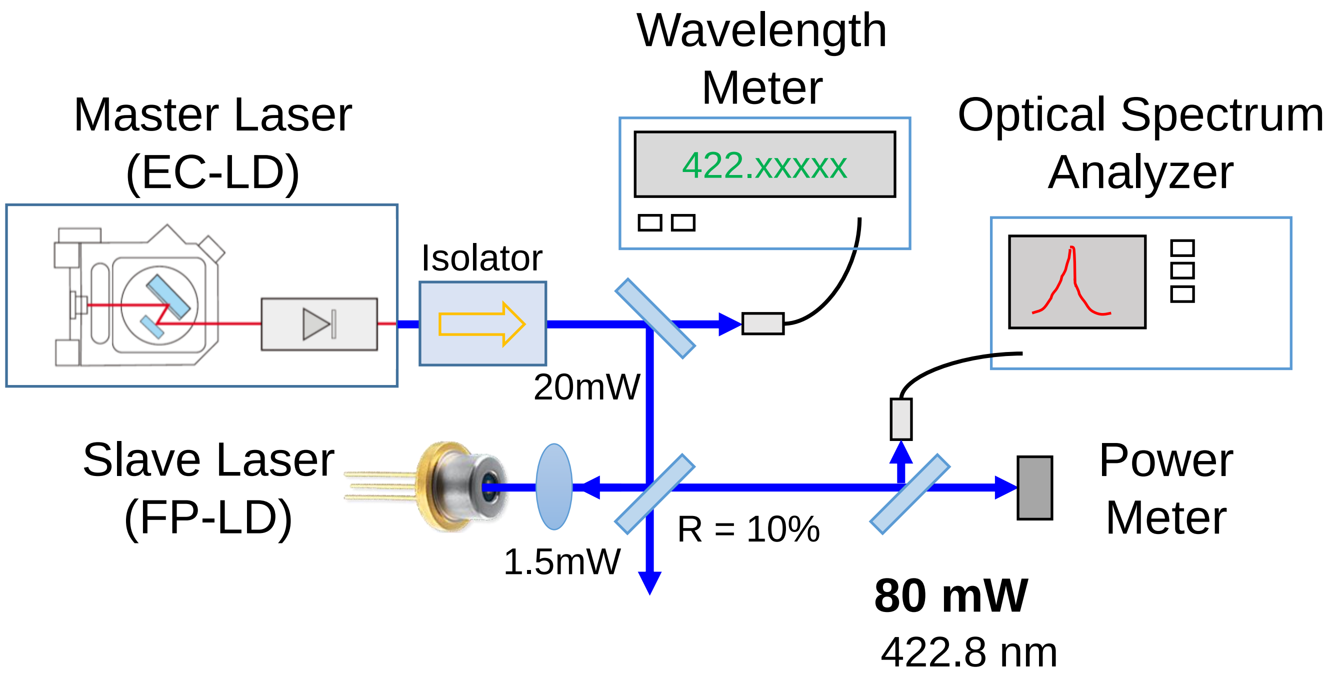
- Multi longitudinal-mode (Wide spectral width)
- Low cost
- Compact
- High efficiency

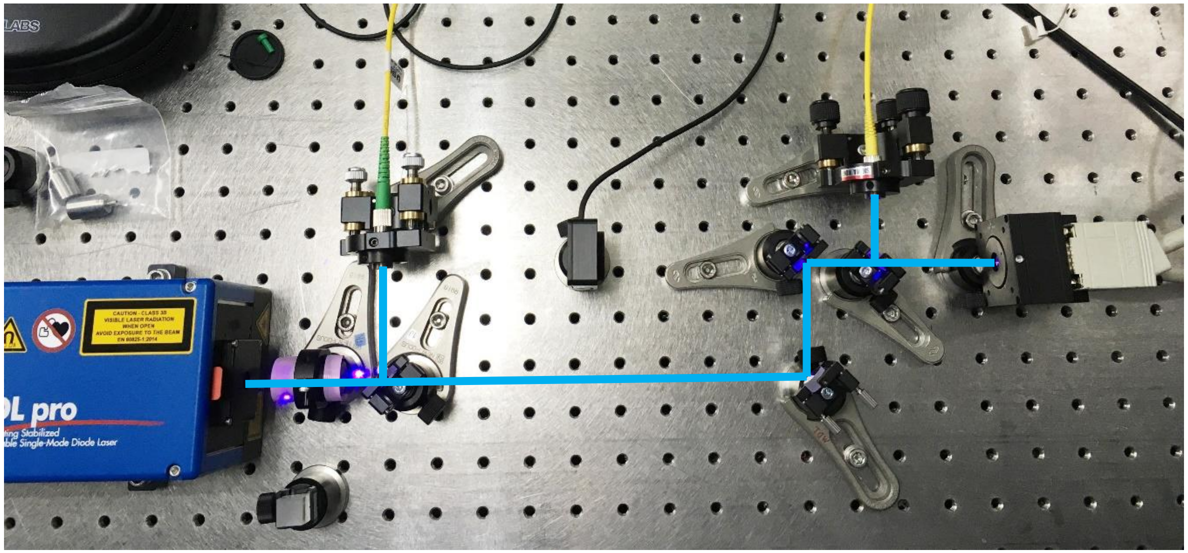
Injection-locked multi-beam laser array



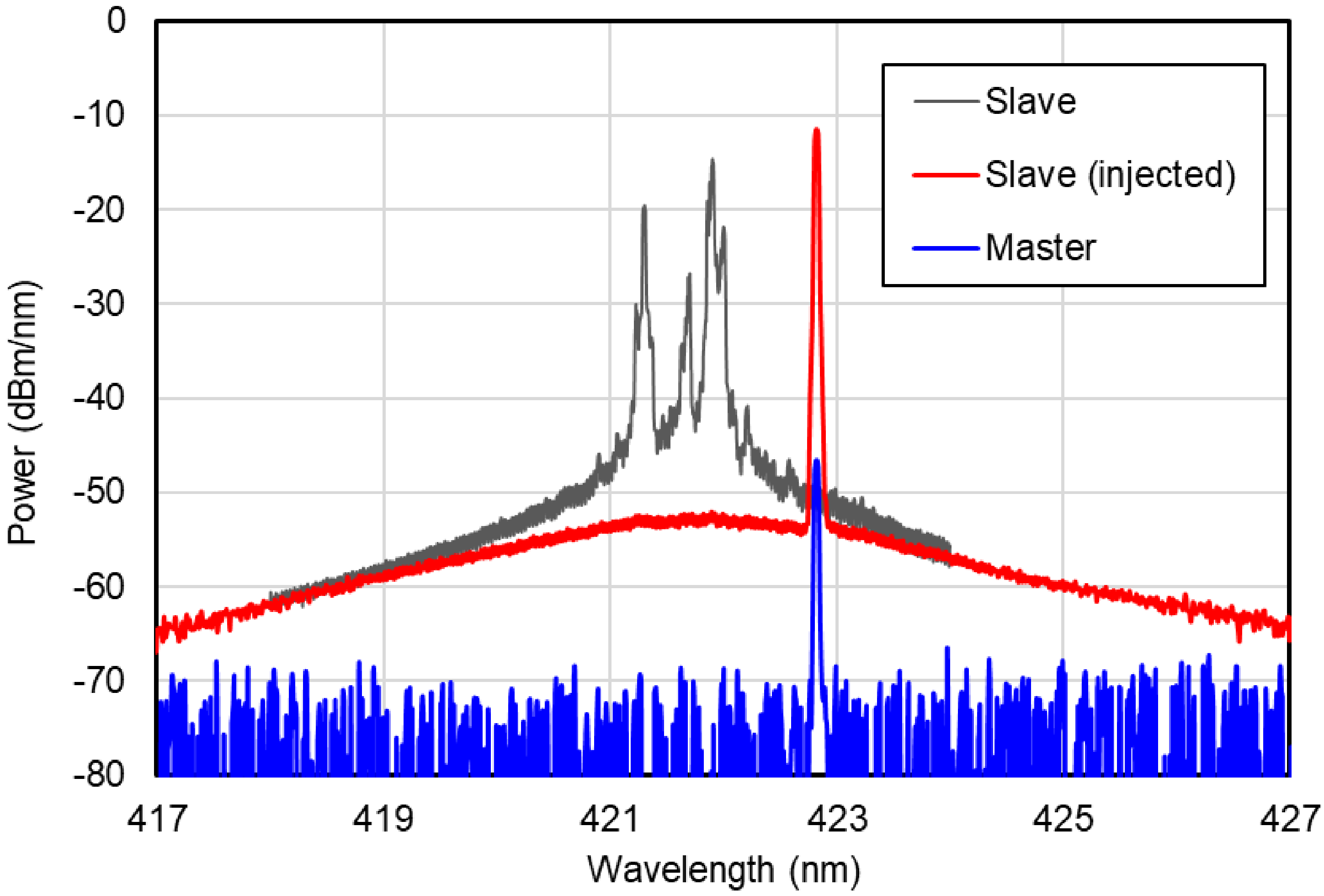
By injecting the narrow line width laser light generated by the external cavity laser diode (EC-LD) into multiple Fabry-Perot laser diodes (FP-LD), all LDs oscillate at almost the same wavelength.

Experiment of injection locking





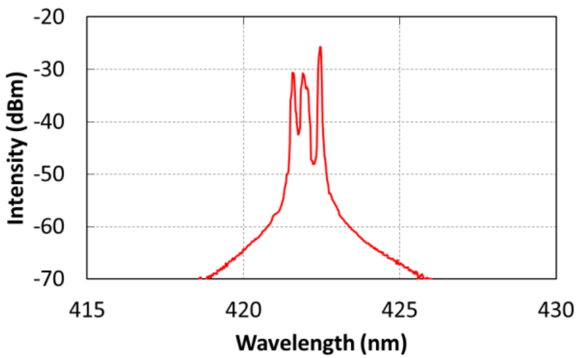
Demonstration of injection locking



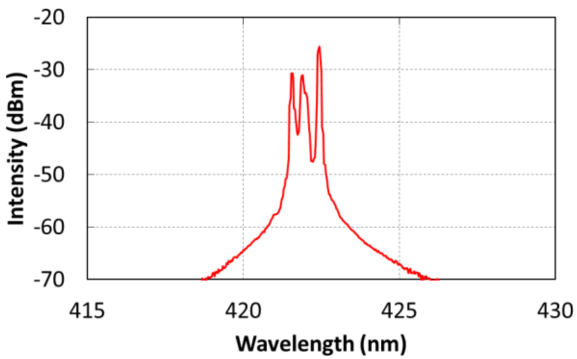
Laser spectrum depending on seed wavelength

~0.3 pm step (Longitudinal mode interval of the slave laser： ~30 pm)

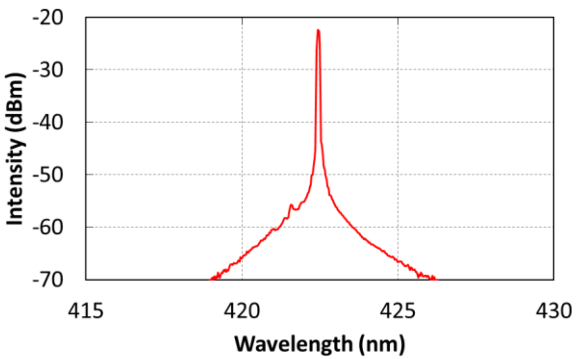
422.86149 nm



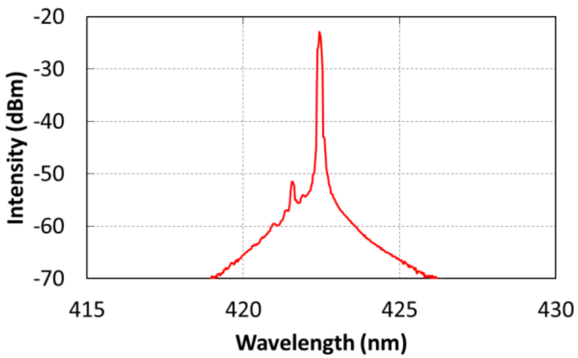
422.86121 nm



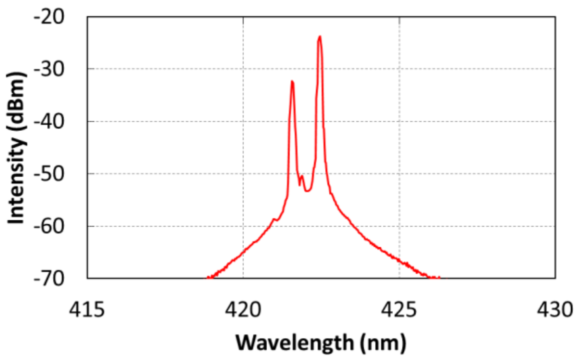
422.86094 nm



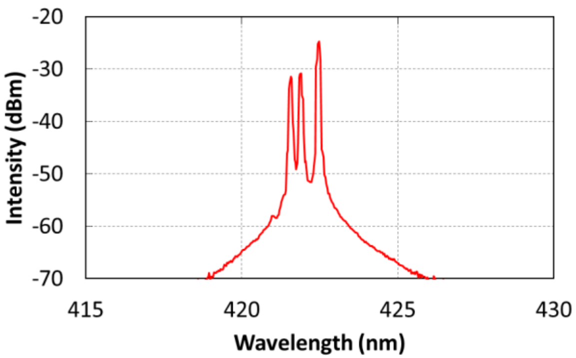
422.86066 nm



422.86037 nm

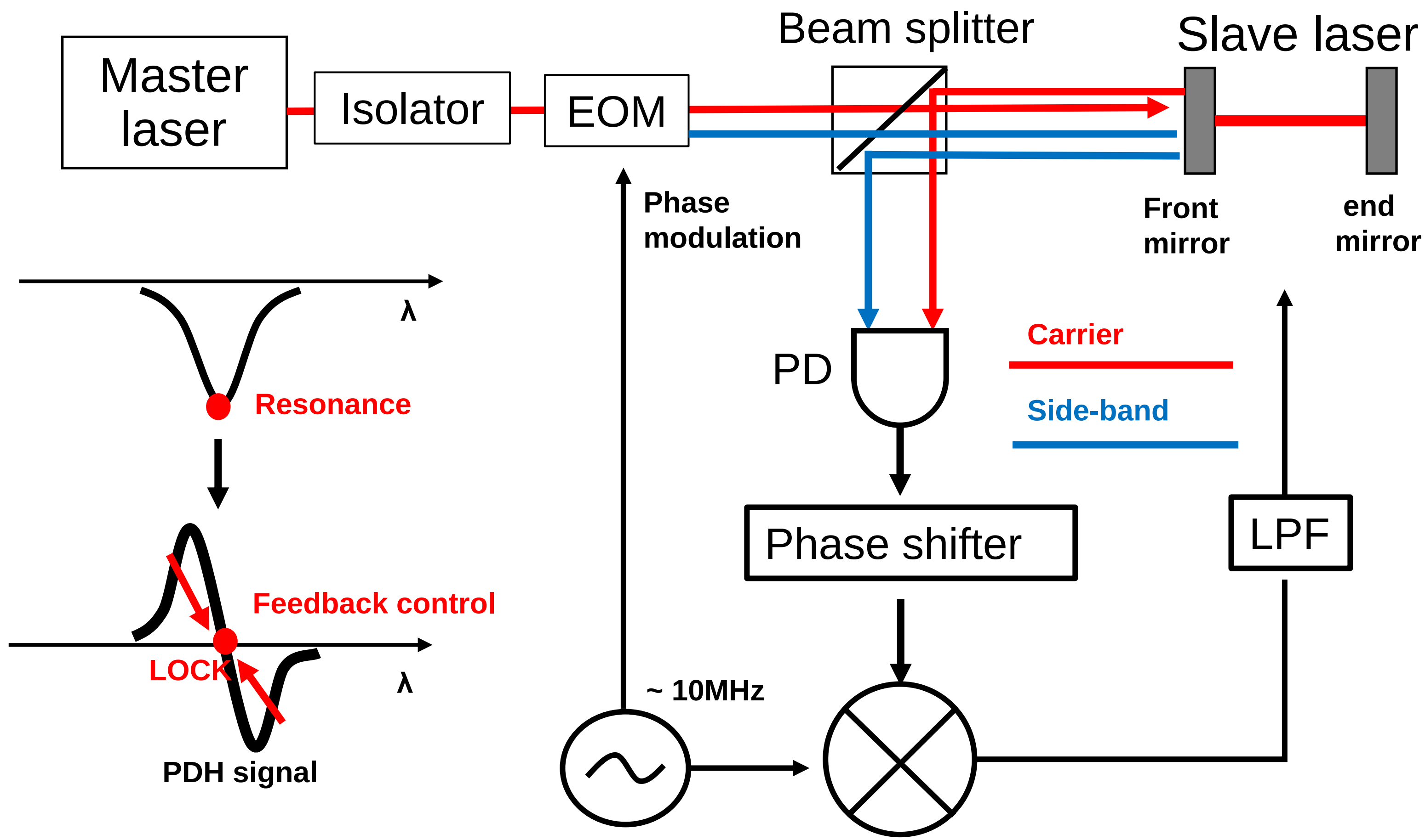


422.86008 nm



Injection locking was succeeded in the range of ~0.3 pm (~500 MHz).

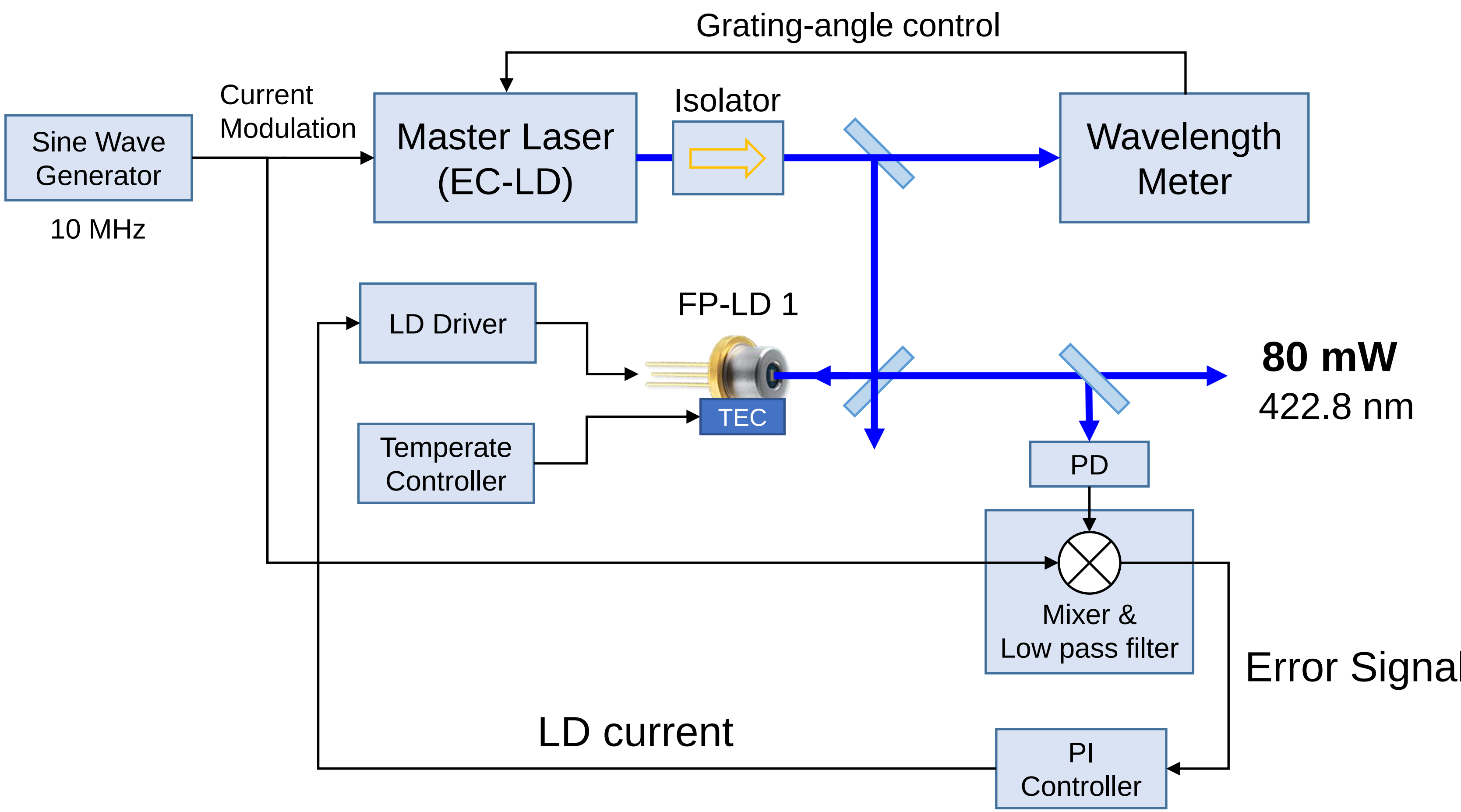
Cavity length stabilization by using Pound–Drever–Hall method



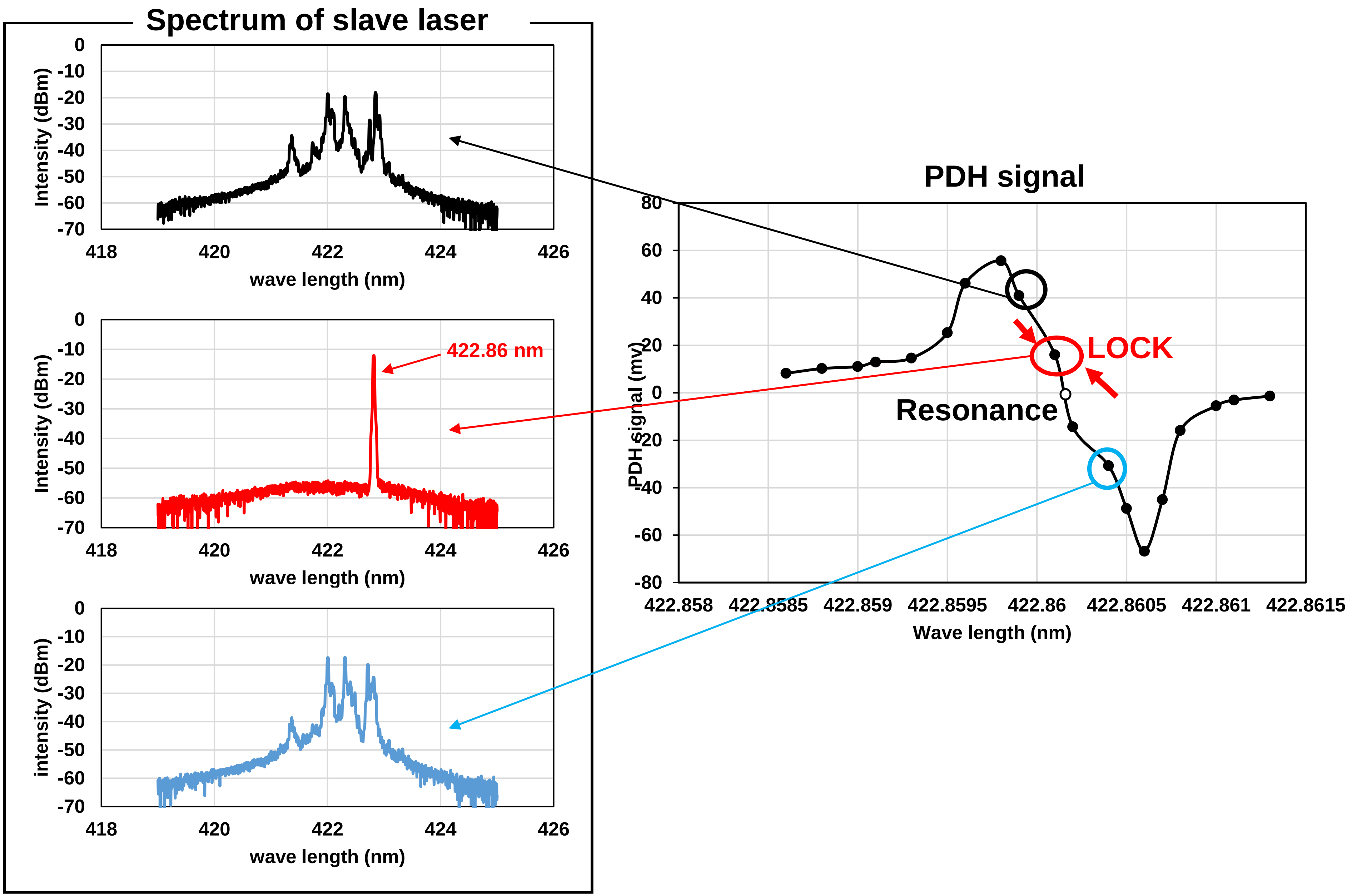
$$
\begin{aligned}
E_1 &= E_0 e^{i(\omega t+\beta \sin(\omega_m t))} \\
&\approx E_0 e^{i\omega t}[1+i\beta \sin(\omega_m t)] \\
&= E_0 e^{i\omega t}\left[1+\frac{\beta}{2}e^{i\omega_m t}-\frac{\beta}{2}e^{-i\omega_m t}\right].
\end{aligned}
$$

R. Pound, Rev. Sci. Instrum. **17**, 490 (1946)
R. Drever, J. Hall, *et al., Appl. Phys. B* **31,** 97 (1983).

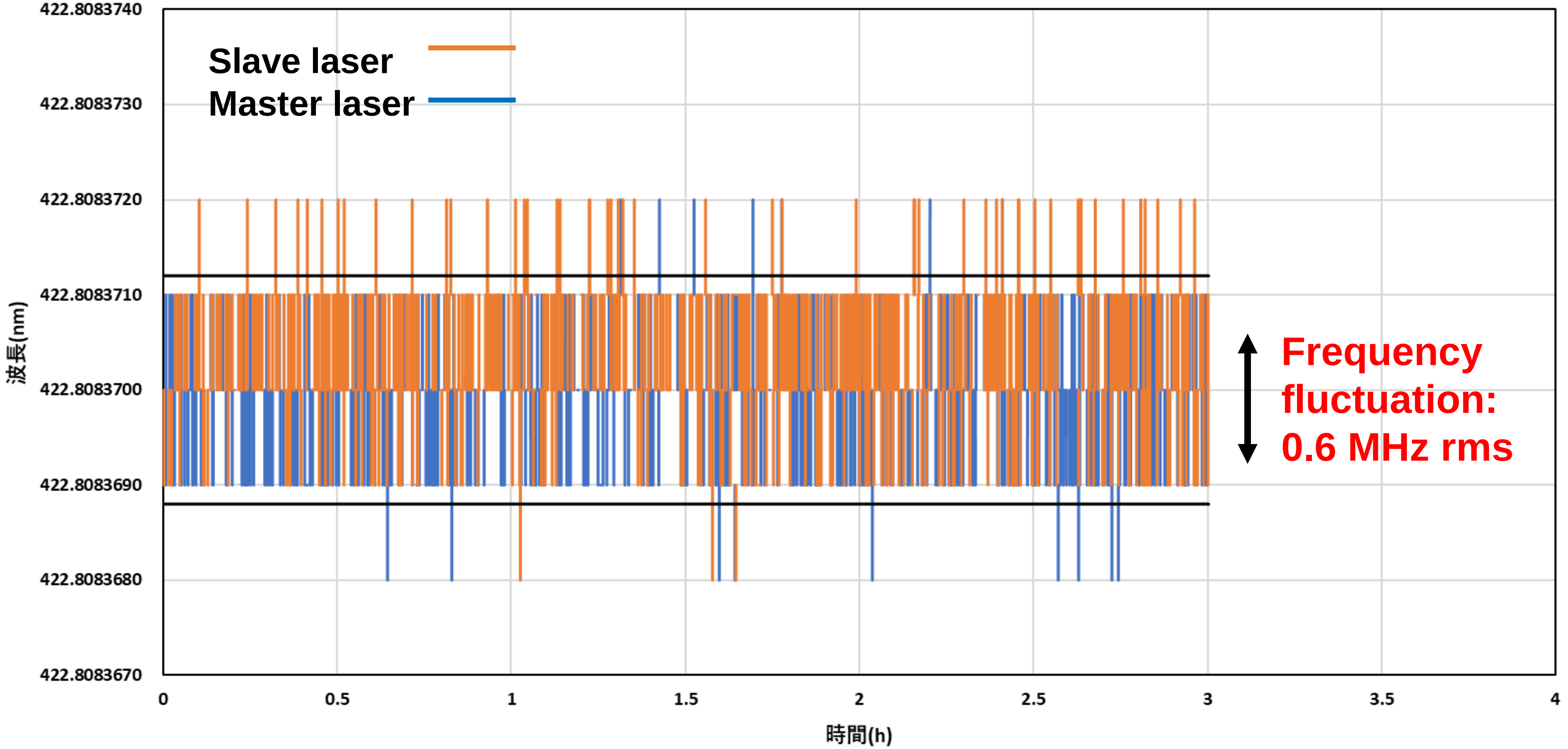
Experiment of wavelength stabilization by using PDH method



Spectrum and PHD error signal



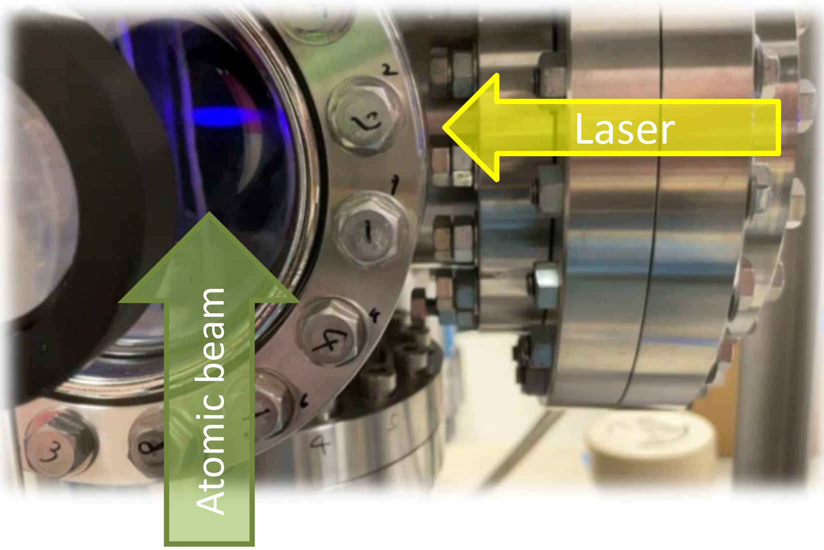
Long-term stability measurement

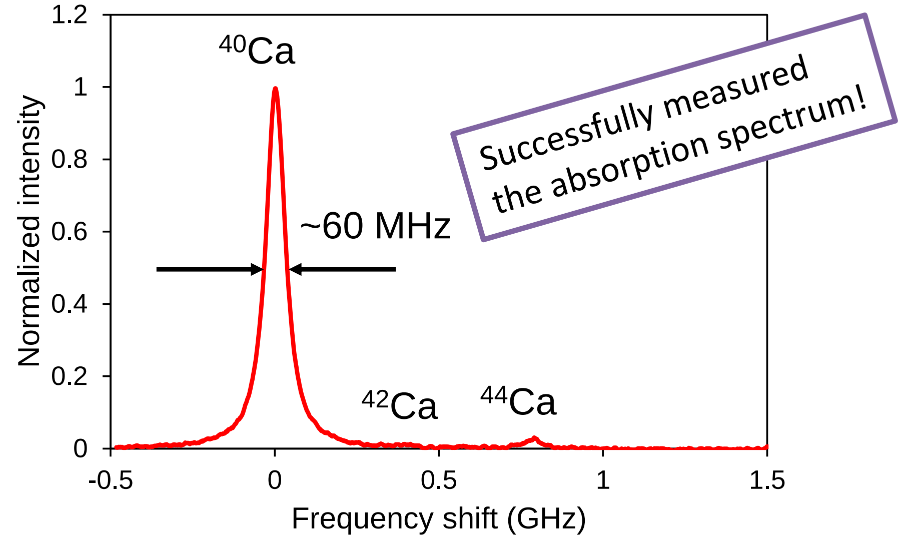


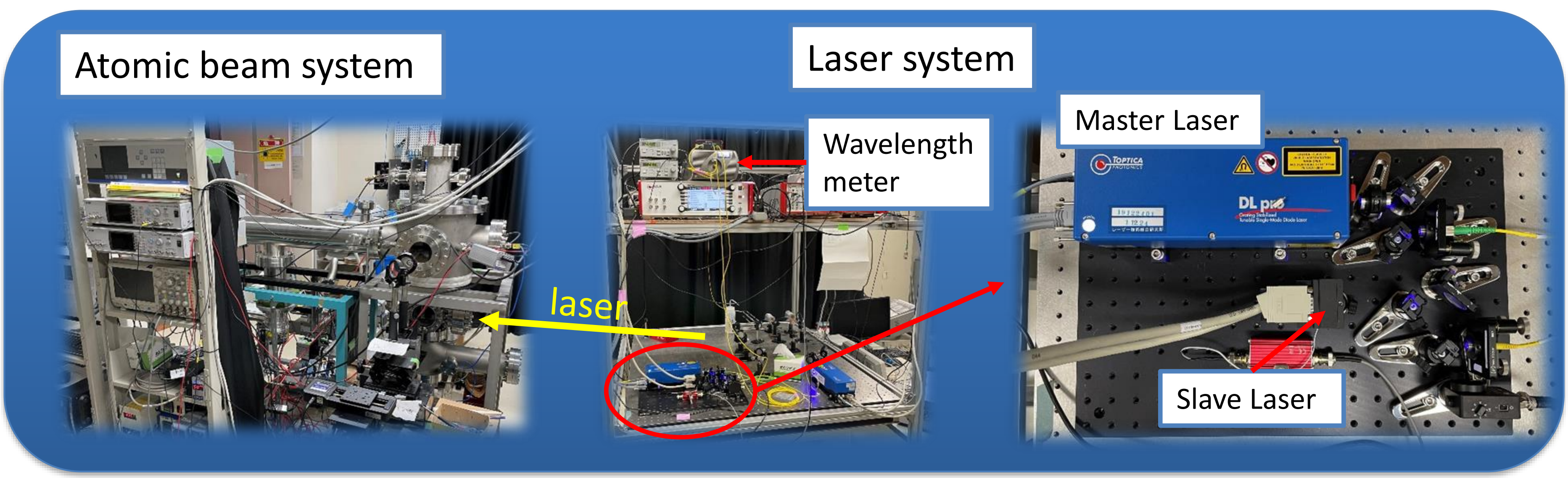
Measured by a wavelength meter (WS7-60, absolute accuracy: 60MHz).

Wavelength tuning to a calcium absorption line

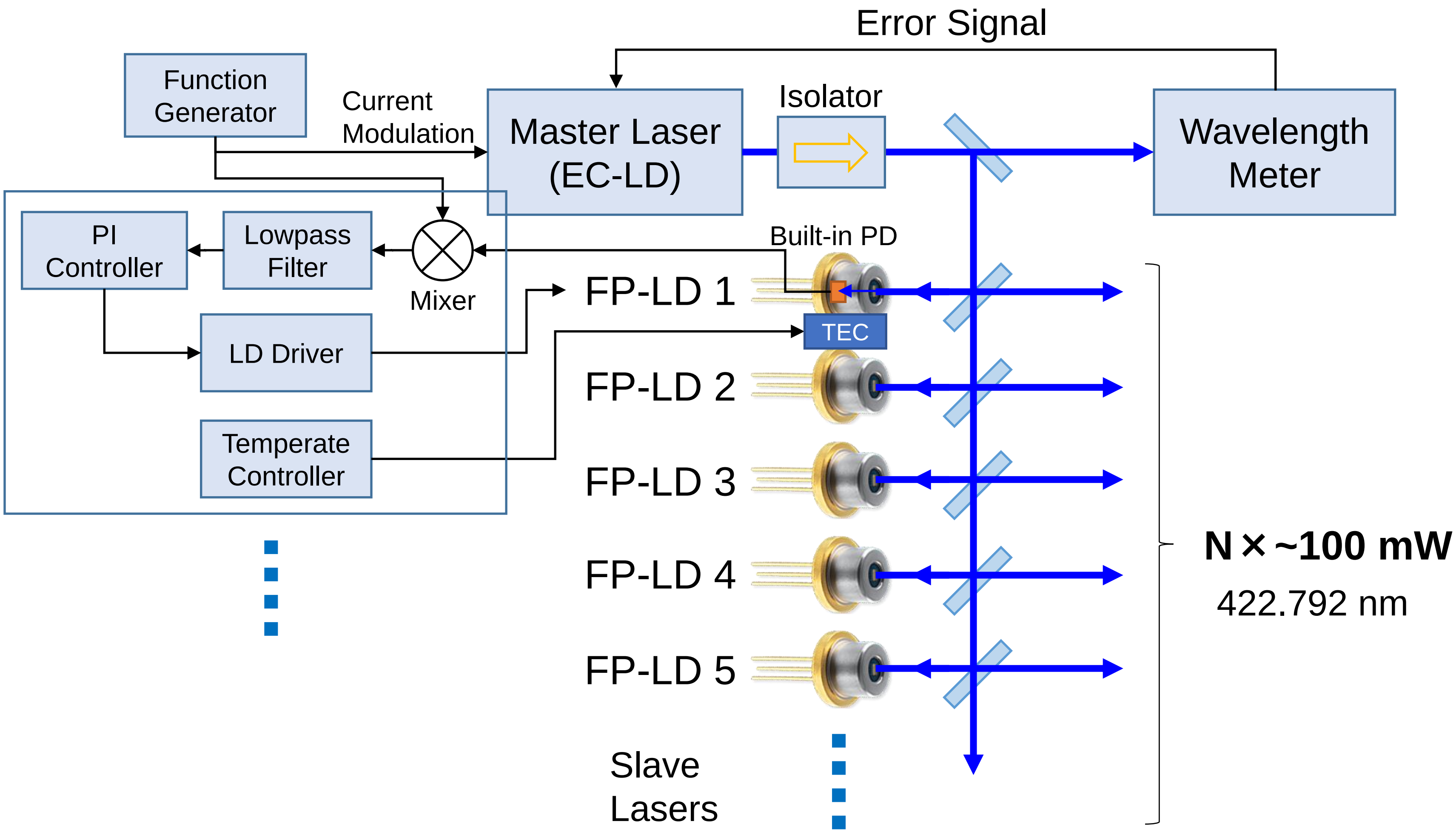
Fluorescence from calcium atoms was observed to confirm the wavelength tuning performance of the injection-locked laser.



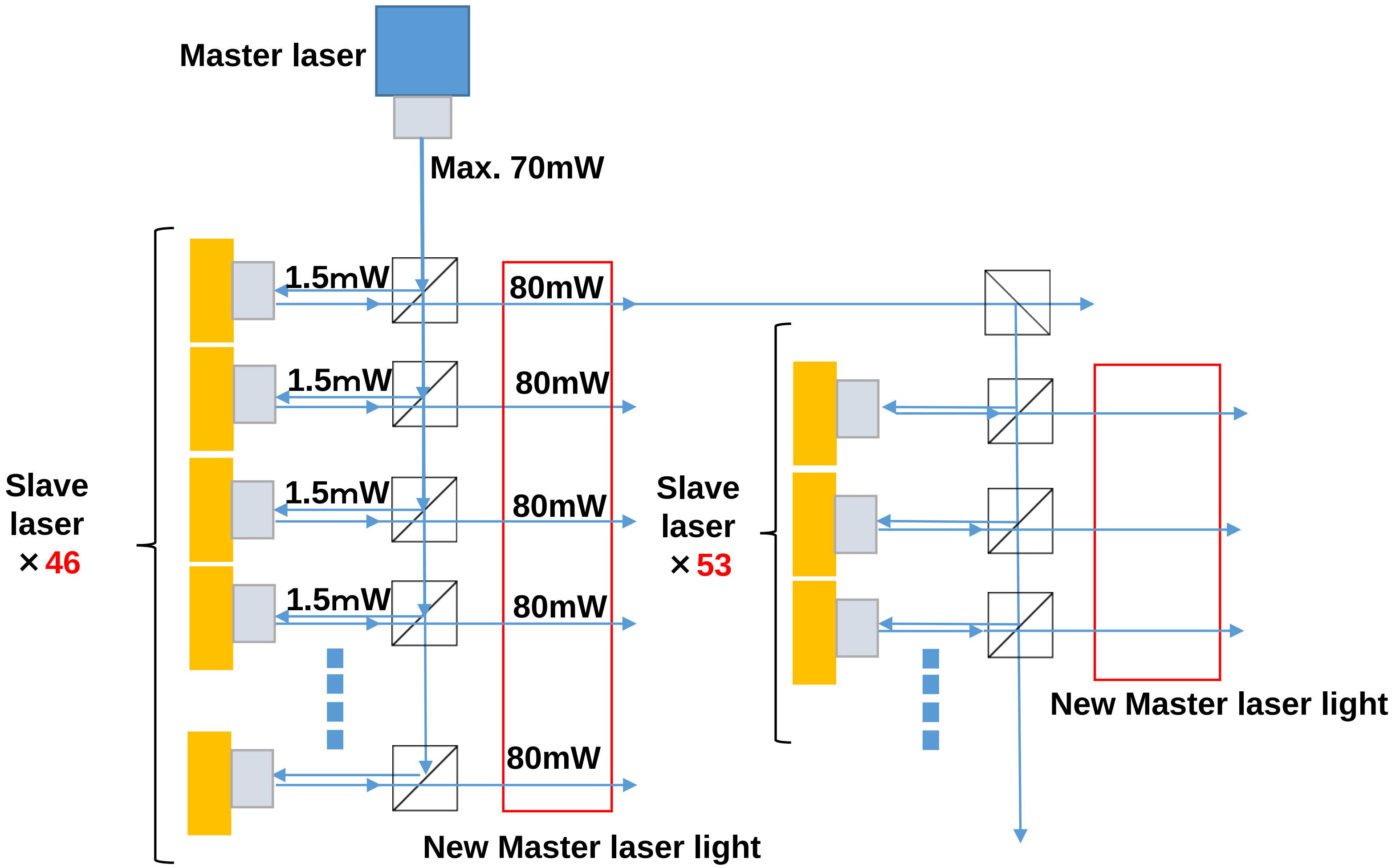




Concept of multi-slave laser system



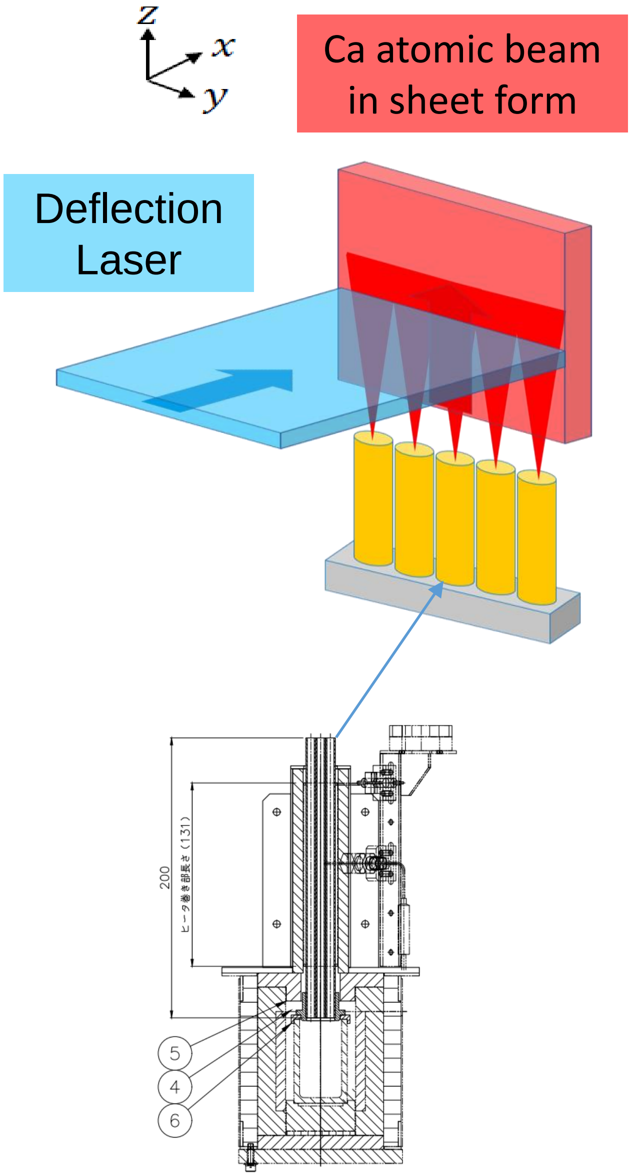
Power scaling



200 W laser system can be realized using ~2,500 slave lasers and 1 master lasers.

Development of Atomic Beam System

R&D of the atomic beam system



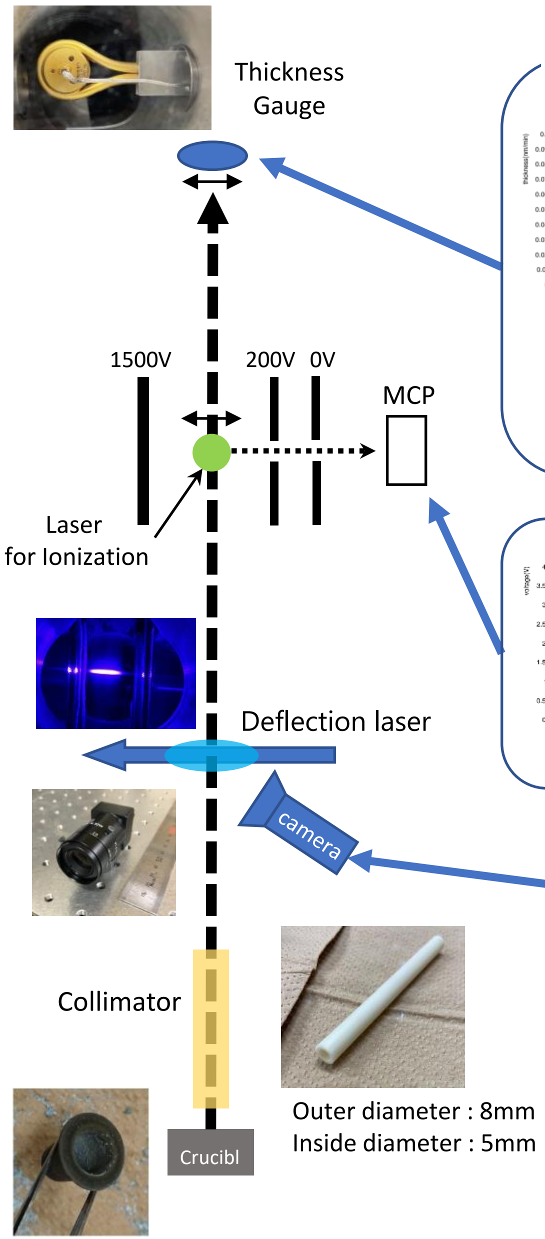
Development of an atomic beam system that maximizes production rate while maintaining high collection efficiency.

<u>Using a collimated atomic beam in sheet form.</u>

Multiple tubes arranged in a row as collimators.

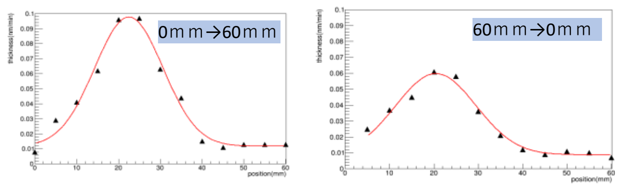
Verify the collimating effect of a single tube as a first step.

Atomic beam monitoring system



Thickness Gauge

Spatial Distribution



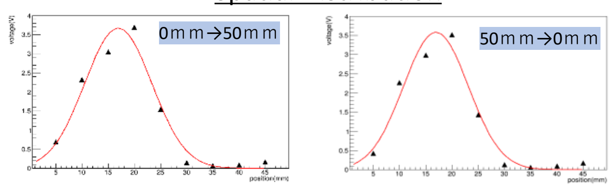
$\sigma = 8\text{mm}$　$\sigma = 9\text{mm}$

$\sigma^{※} = 5\text{mm}$　$\sigma^{※} = 5\text{mm}$

Accuracy is not good because of the BG.

TOF

Spatial Distribution

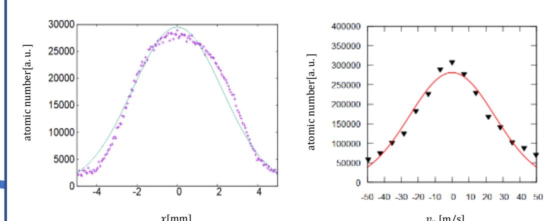


σ = 6.422mm　σ = 6.202mm

- σ is the standard deviation when fitted assuming the spatial distribution is Gaussian.
- The thickness gauge and ionizing laser irradiation position can be moved for spatial distribution measurement.
- Sigma for measurements using fluorescence and thickness gauges are converted to TOF position

Fluorescence measurement

Spatial Distribution　Velocity Distribution



x : Position coordinates perpendicular to the atomic beam

$\sigma = 2.24\text{mm}$

$\sigma^{※} = 19.1\text{mm}$

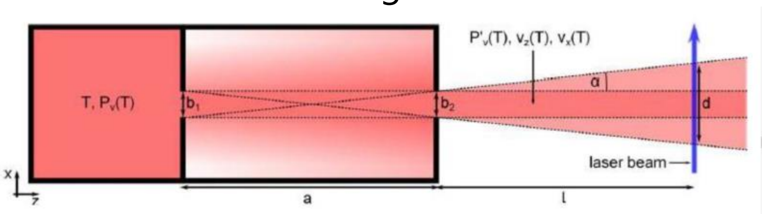
$\sigma_{v_x} = 25.1\text{m/s}$ (Measured value)

$\sigma_{v_x} = 9.2\text{m/s}$ (Calculated value)

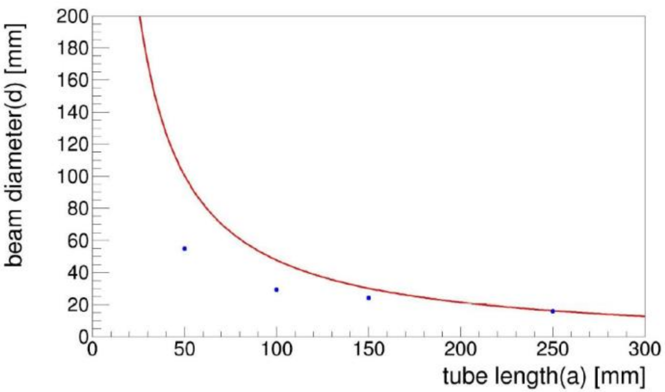
Further studies are needed.

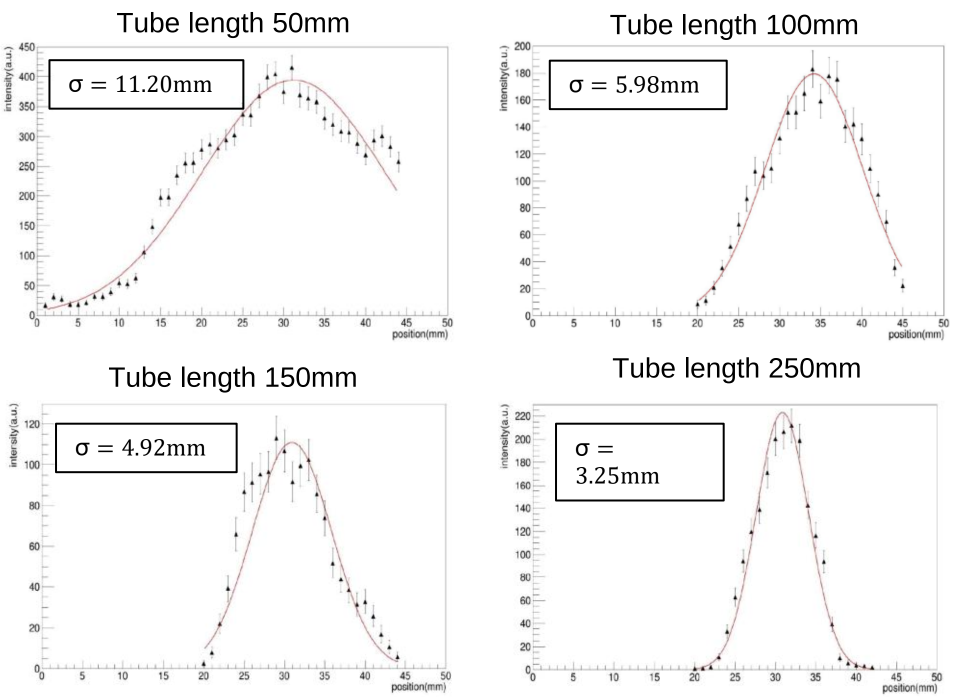
Verification of the collimate effect

The length of the tube was varied to check the collimating effect.



$$d = 2\left((a+l)\frac{{b_1}/_2 + {b_2}/_2}{a} - \frac{b_1}{2} \right)$$





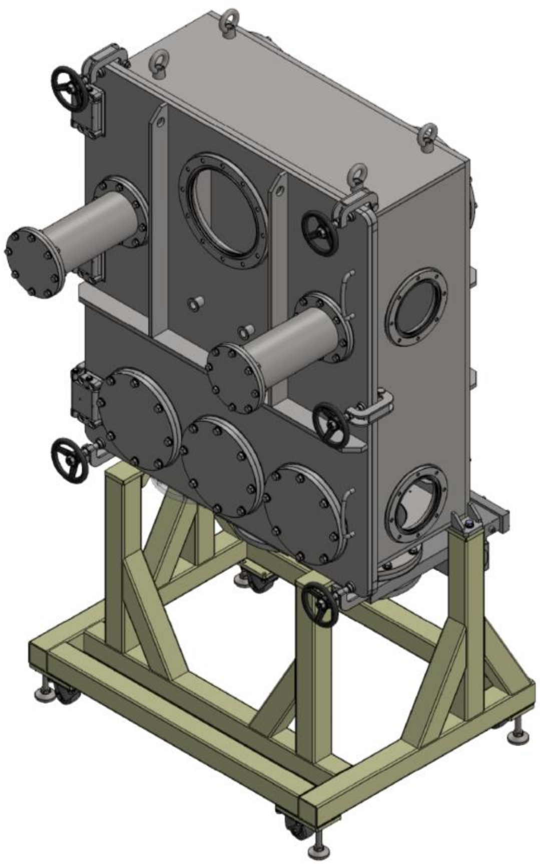
<u>Longer tubes increase the collimating effect.</u>

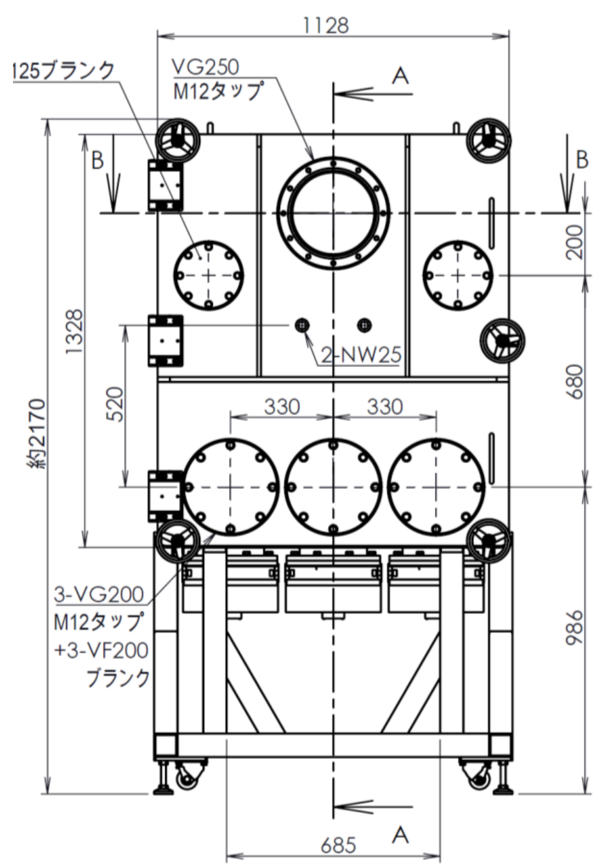
σ is the standard deviation when fitted assuming the spatial distribution is Gaussian.

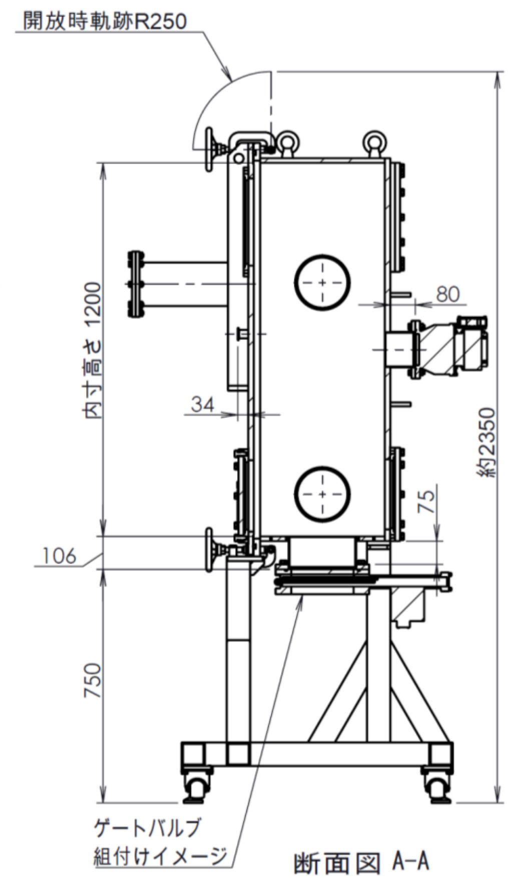
Higher collimating effect than the geometrically calculated value could be obtained.

Design of vacuum chamber for 1 mol/year

(40 g/year)







- ➢ 6 atomic beams
- ➢ >10 W laser power

Summary

【Laser】

- A power-scalable (>100 W), narrow-line-width (<1 MHz), diode laser system has been proposed.
- 80 mW injection-locked laser with 1.5 mW seed power was demonstrated.
- 0.6 MHz rms wavelength stabilization using PDH method was demonstrated.
- (Next step) Power up from 80 mW → 2 W (24 beams)

【Atomic beam】

- Atomic beam monitoring system was developed.
- Collimating effect of tubes was verified experimentally.
- Tube length was varied to check the collimating effect.
- (Next step) Generation of a sheet atomic beam using a collimator with three tubes in a row with a large-volume crucible.

⇒ 5 g/year demonstration will be performed until FY2023.

Thank you for your attention.

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