The 15th International Workshop on Fundamental Physics Using Atoms (FPUA2024)
March 14, 2024

Current status of laser and optical system for EDM search using cold francium atoms at RIKEN/CNS

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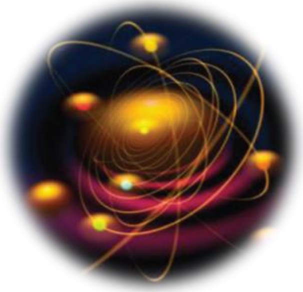
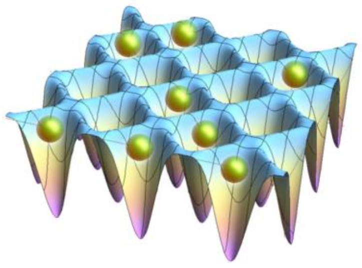
the University of Tokyo

Introduction

eEDM（permanent electric dipole moment of electron） search

Fr atoms × **Optical lattice**





Enhancement factor：R=799

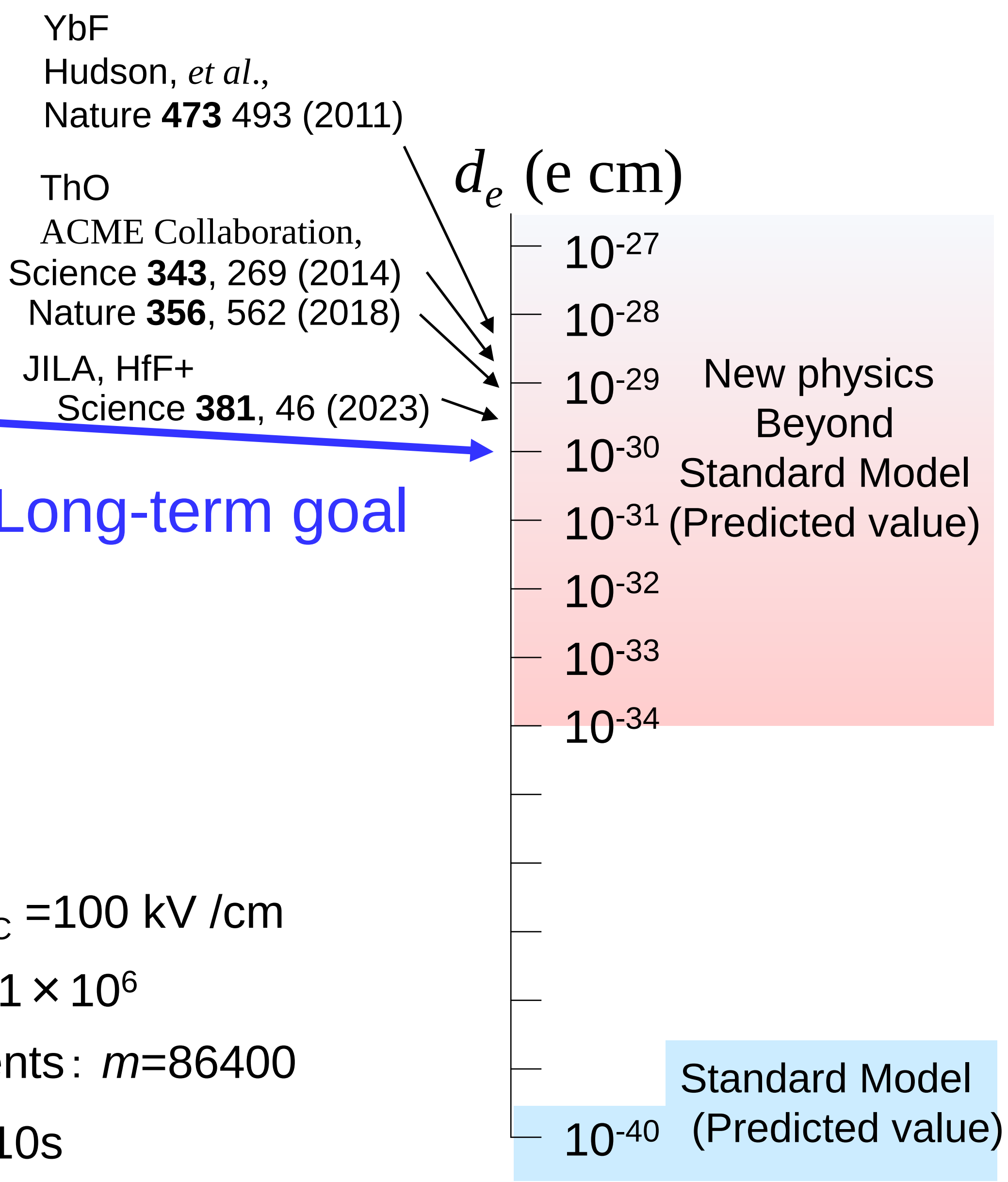
N. Shitara *et al*. *JHEP* **2021**, 124 (2021).

Large

Interaction time: T=10 s

Long

Long-term goal



Toward ultra-precise spectroscopy that can resolve

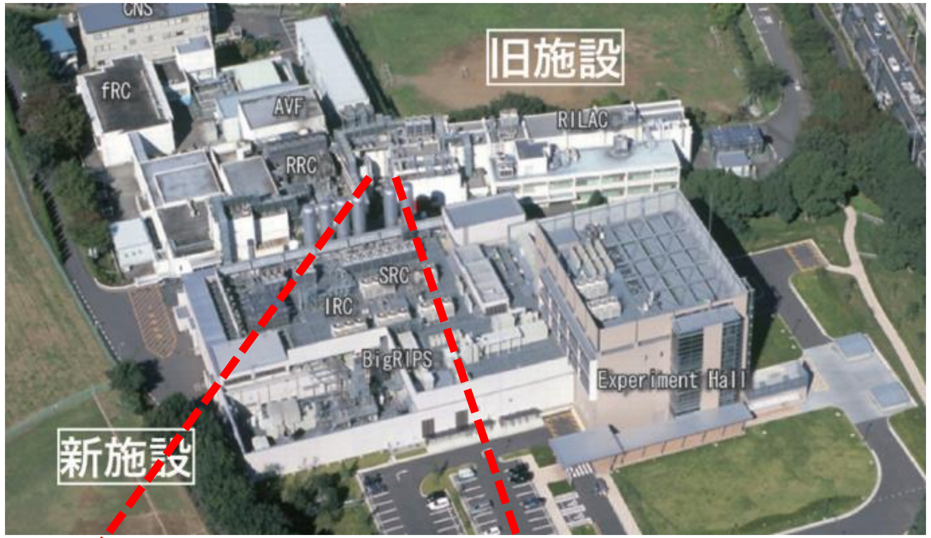
$d_e \sim 10^{-30}$

$$d_e \sim \frac{\hbar}{2 R E_{DC} V(T) T \sqrt{Nm}}$$

- Static electric field：E_{DC} =100 kV /cm
- Number of atoms：N=1×10^6
- Number of measurements：m=86400
- Visibility：$V(T)$ ~1 @T=10s

Introduction

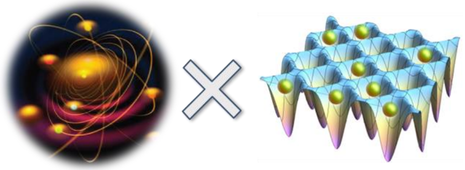
RIKEN Nishina Center for Accelerator-Based Science



Source: J. Particle Accelerator Society of Japan, Vol. **14**, No. 3, 2017

RIKEN/CNS

Fr EDM/PNC project



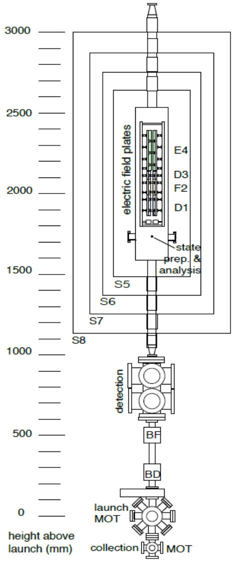
Fr production facility

Other groups

LBNL/TRIUMF

Fr EDM project

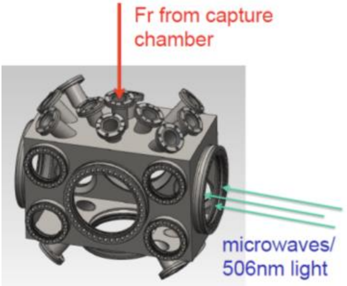
Fountain



B. Feinberg *et. al* AIP Advances **8**, 035303 (2018)

TRIUMF

Fr PNC project



Source: https://www.physics.umass.edu/acfi/sites/acfi/files/slides/u_mass_orozco_2014_0.pdf

INFN Legnaro

Fr EDM/PNC project

Source: https://www.ifj.edu.pl/msd/docs/wyklad_Calabrese.pdf

Members and Collaborators

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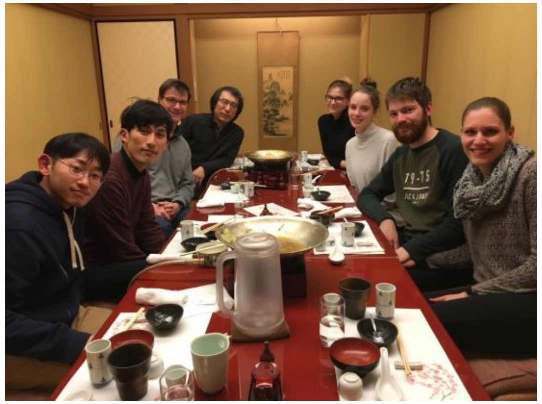
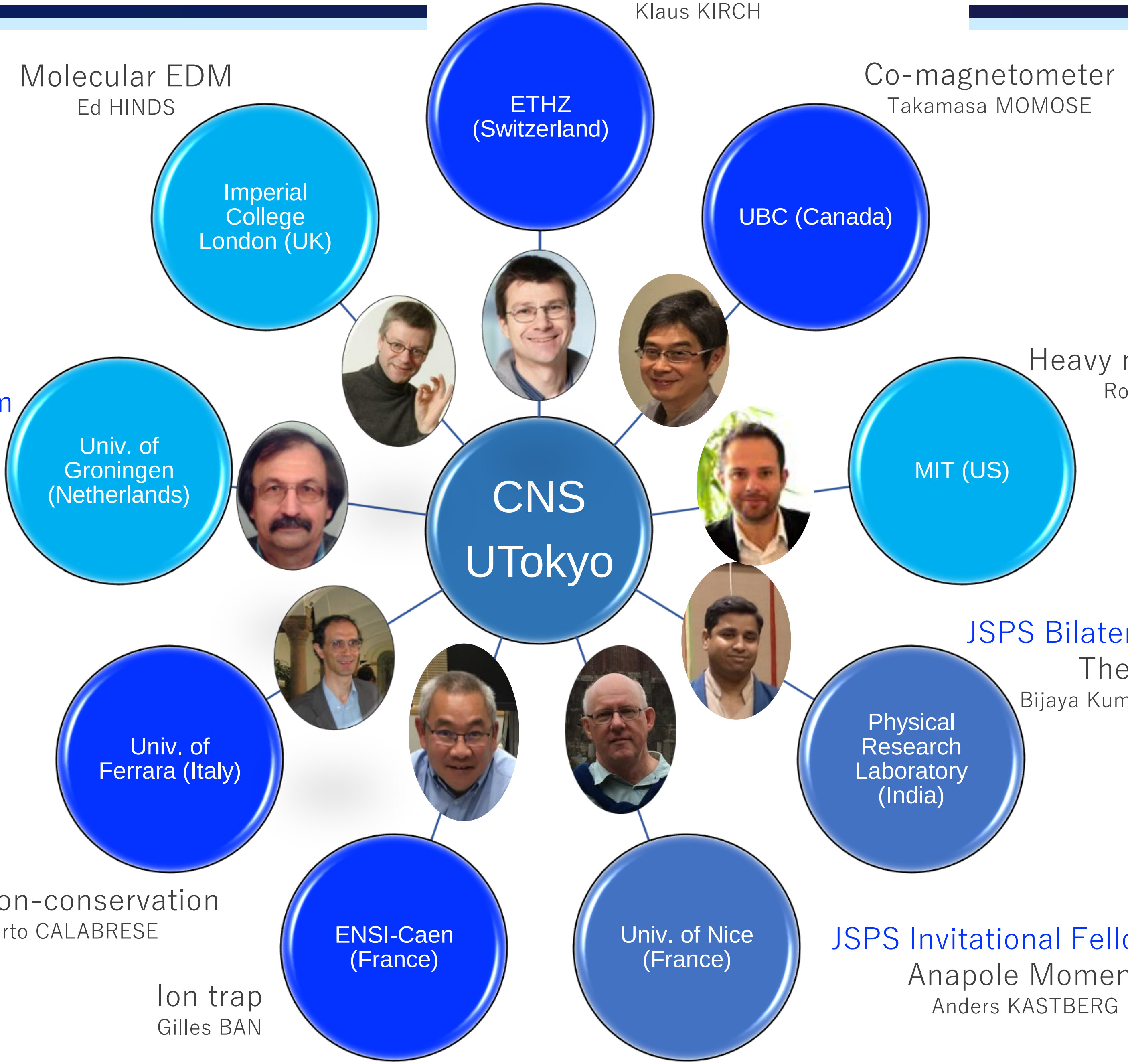
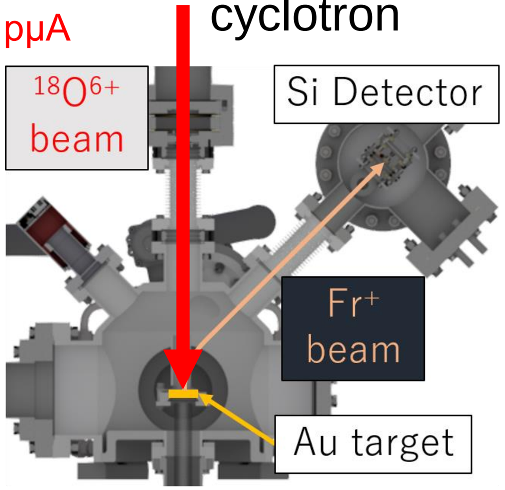




Introduction

7 MeV/u
1 pμA

RIKEN AVF cyclotron



^{210}Fr

$^{197}Au(^{18}O, xn)\,^{215-x}Fr$

nuclear fusion-evaporation reaction

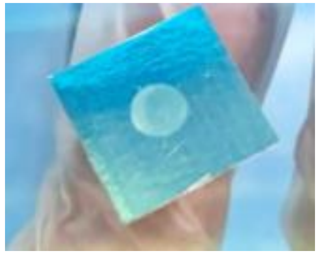
$^{210}Fr^{+}$

$\sim 5 \times 10^{6}$ /s

N. Ozawa *et al.*, Rev. Sci. Instrum. **94**, 023306 (2023).

^{221}Fr

α decay of ^{225}Ac

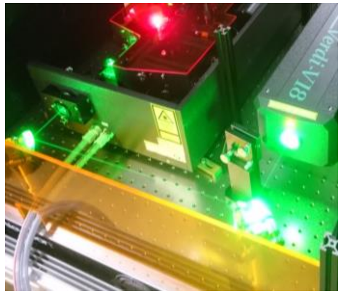


$^{221}Fr^{+}$

$\sim 1 \times 10^{7}$ /s

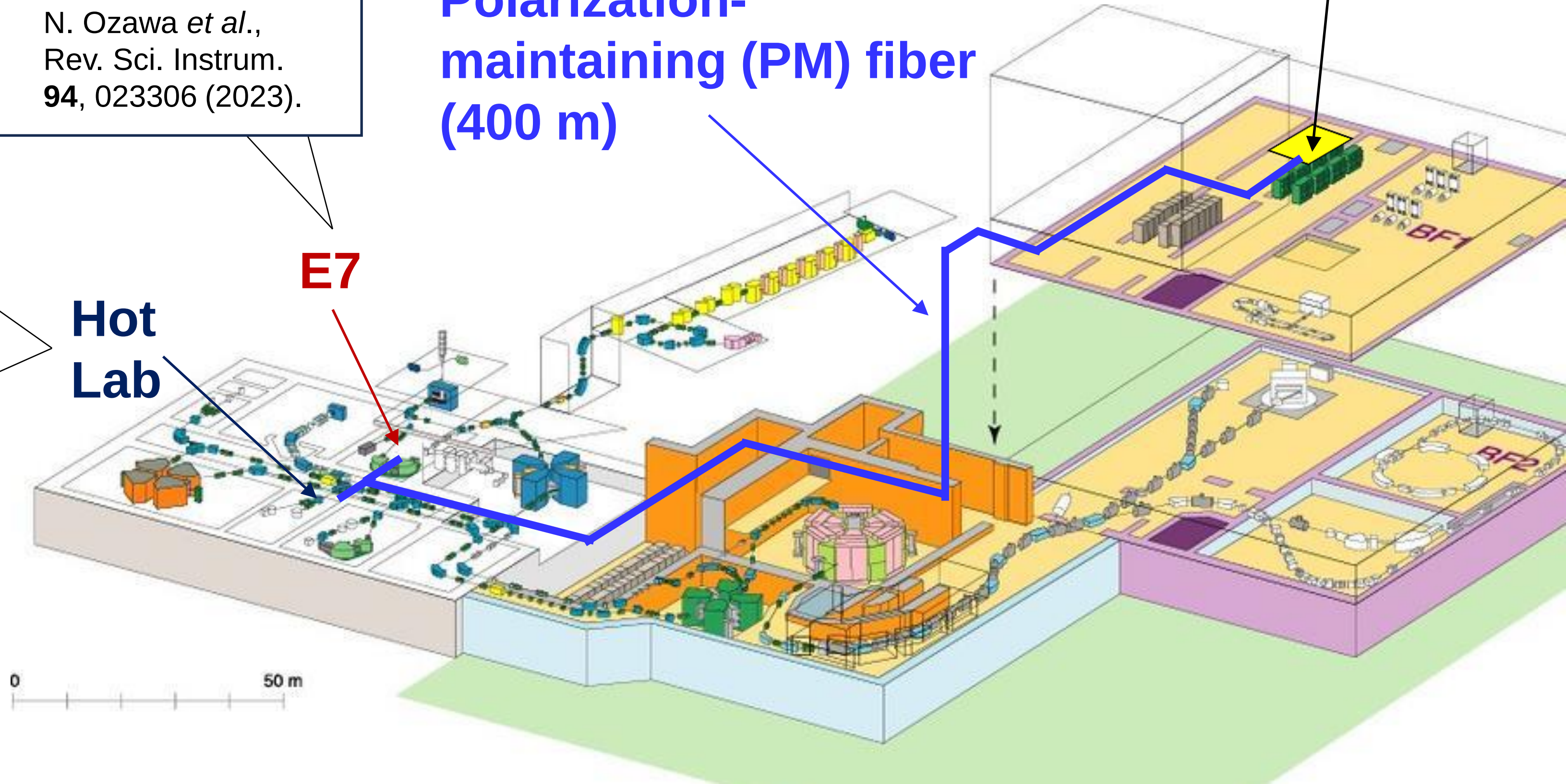
M. Sato *et al.*, RIKEN Accel. Prog. Rep. **55**, 129 (2022).

half-life $^{210}Fr \sim 3$ min,
$^{225}Ac \sim 10$ days, $^{221}Fr \sim 5$ min



Laser room

Polarization-maintaining (PM) fiber (400 m)



Introduction

☑ Fr ion source

$^{210}Fr^{+}$ ~ 5 × 10^{6} /s

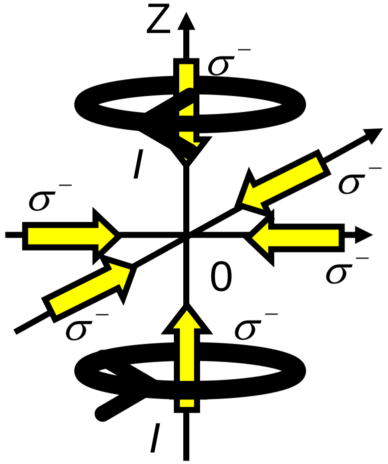
$^{221}Fr^{+}$ ~ 1 × 10^{7} /s

☐ Neutralizer

under development

Fr atoms

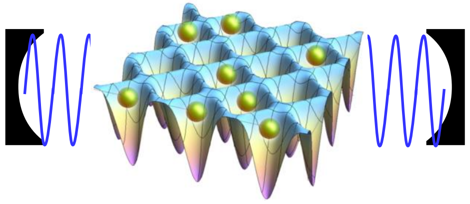
Magneto-optical trapping (MOT)



☑ Laser and optical system

laser light

Today,
I'll introduce
this section.



☐ Optical lattice

Alkali atom

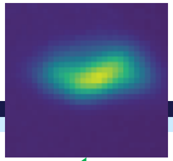
Rb
Cs
Fr

Test MOT experiments using stable Rb atoms

Similar chemical properties

Rb experiment is useful as a benchmark for future Fr experiments.

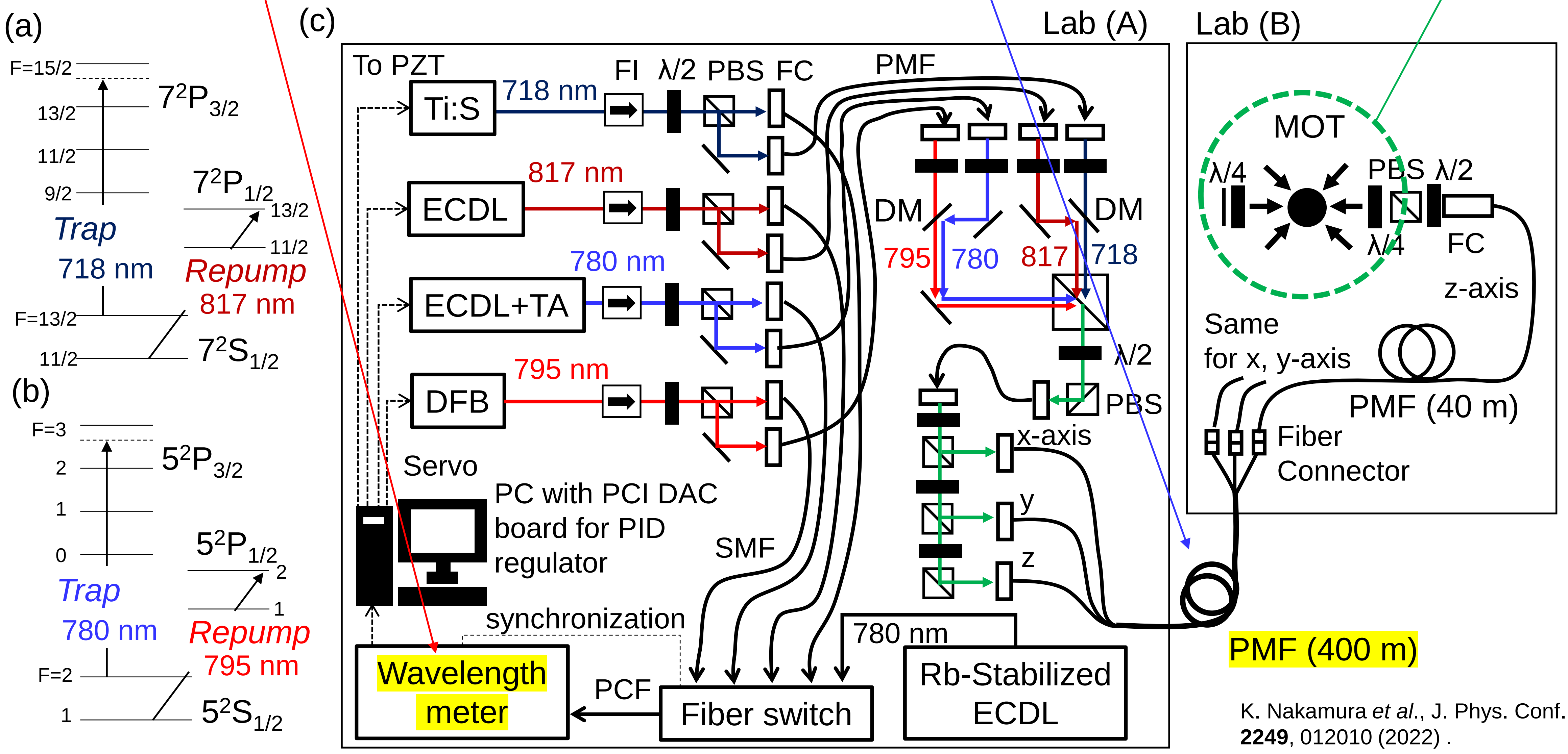
Overview of the system



Two highlighted features

①High-accuracy wavelength meter

②Optical delivery system connected by 400 m PM fibers



K. Nakamura *et al.*, J. Phys. Conf. Ser. **2249**, 012010 (2022) .

Wavelength meter

Frequency Standard

WS8-2 Standard (HighFinesse)

wavelength range：300 – 1180 nm

Feedback control of up to seven laser frequencies simultaneously

Manufacturers specifications

Absolute accuracy

2/10/30 MHz for ±2 nm/±200 nm/other wavelengths around the calibration wavelength

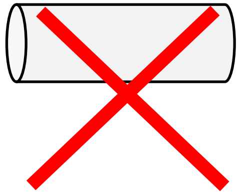
Instability

No guarantee

Natural width (D2 lines)

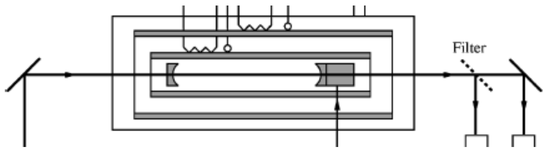
Fr: 7.6 MHz
Rb: 6.1 MHz

Fr vapor-cell



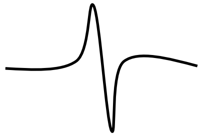
Not practical

Scanning transfer cavity



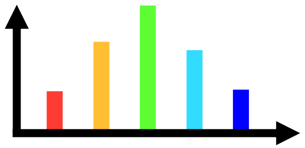
W. Z. Zhao *et al*. Rev. Sci. Instrum. **69**, 3737 (1998)

Weak iodine transition lines



K. Harada *et al*. Appl. Opt. **55** (5) 1164 (2016)

Optical frequency comb



Y. Hisai *et al*. Opt. Express **27**, 6404 (2019)

We report here the results of our evaluation of absolute accuracy and instability.

Wavelength meter (1. Absolute accuracy)

Wavelength meter (HighFinesse)

improved model

WS8-2

Photonic crystal fiber

WSU2

Single mode fiber

Input optical fiber (and internal optics corresponding to the NA of the fiber)

guess

[ ] ≤ +3.5 ± 1.5 MHz @760-900 nm

\+
± 1 MHz
(temporal fluctuations in laser room)

Estimation

≤ ±3.5 MHz @wide range

Natural width

Fr D2 line: 7.6 MHz

These specifications are useful for quickly determining the optimum optical frequency for the Fr MOT.

Oher group's study

Ti:Sa

Measurement

Wavelength meter

Frequency comb

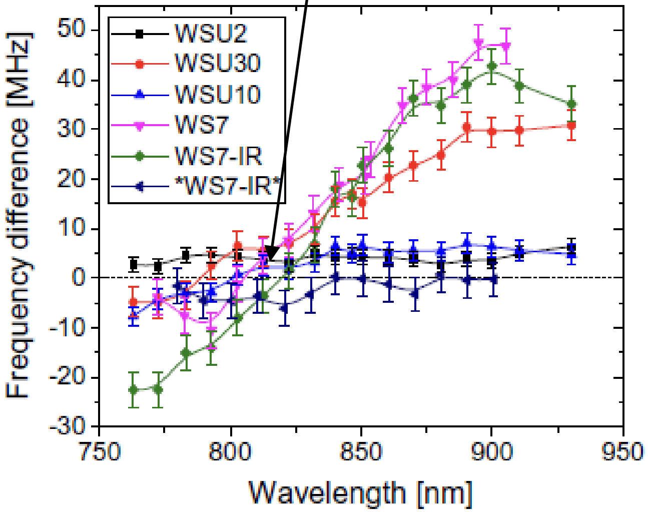
Calibration

iodine-stabilized HeNe laser (632 nm)

Temperature environment similar to ours

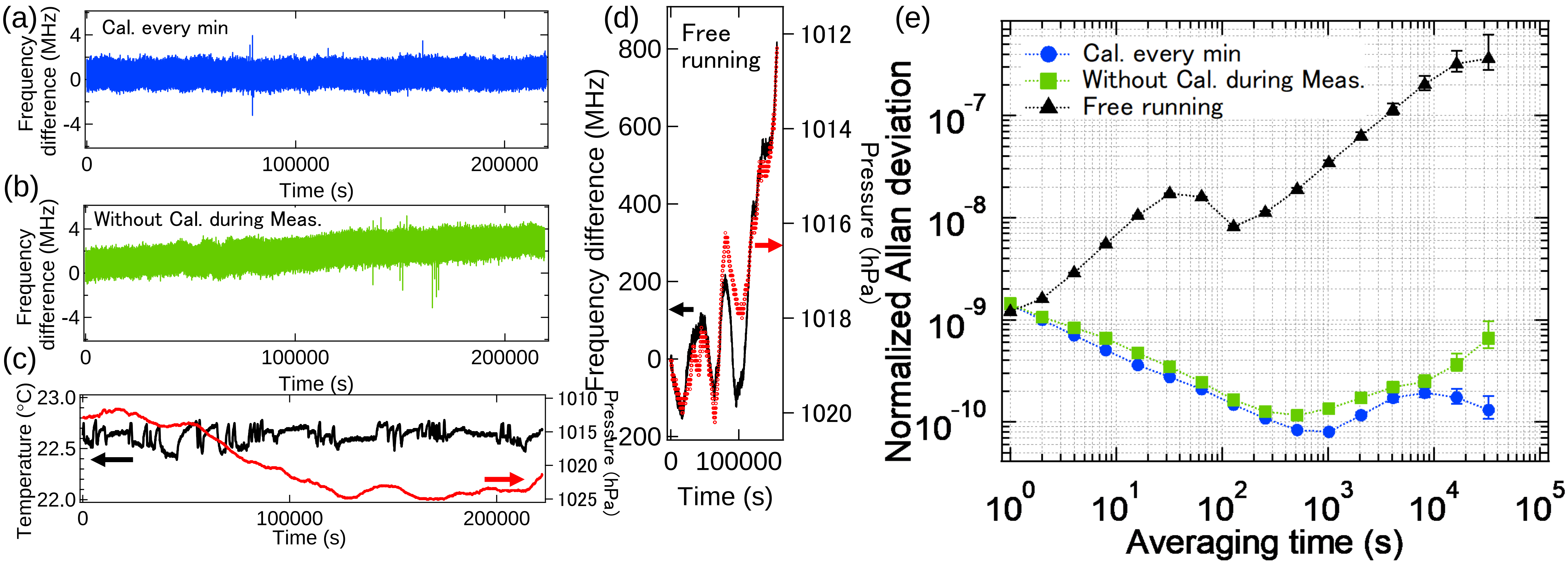
WSU2 **Absolute accuracy**

+3.5 ± 1.5 MHz @760-900 nm



K. König *et al*. Appl. Phys. B **126**, 86 (2020)

Wavelength meter (2. Instability)



K. Nakamura *et al*., J. Phys. Conf. Ser. **2249**, 012010 (2022)

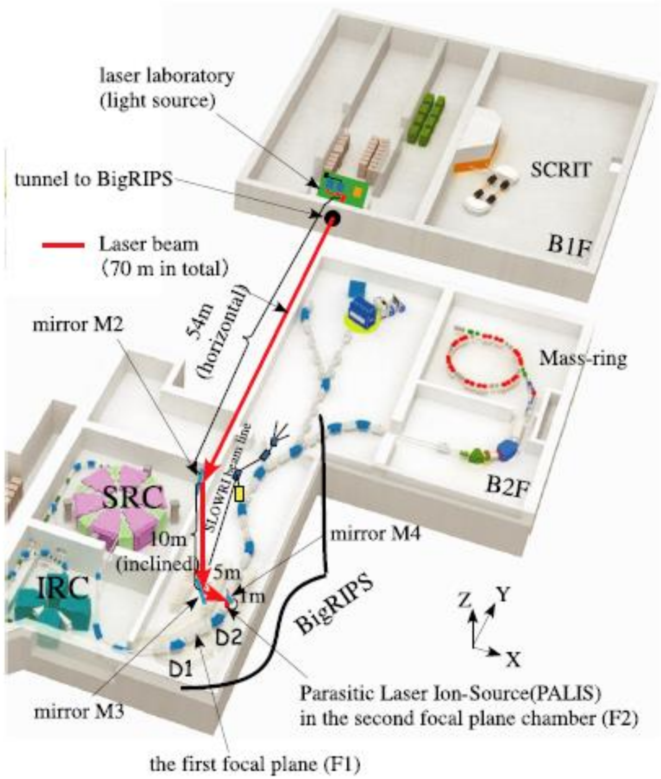
Optical delivery system

Radioactive experiments face significant spatial constraints

RIBF-PALIS experiment at RIKEN

Laser light was transmitted

70 m in free space



T. Sonoda *et al*., Nuclear Inst. and Methods in Physics Research, A **877**, 118 (2018)

Our EDM search project at RIKEN

400 m PM fiber optic delivery system

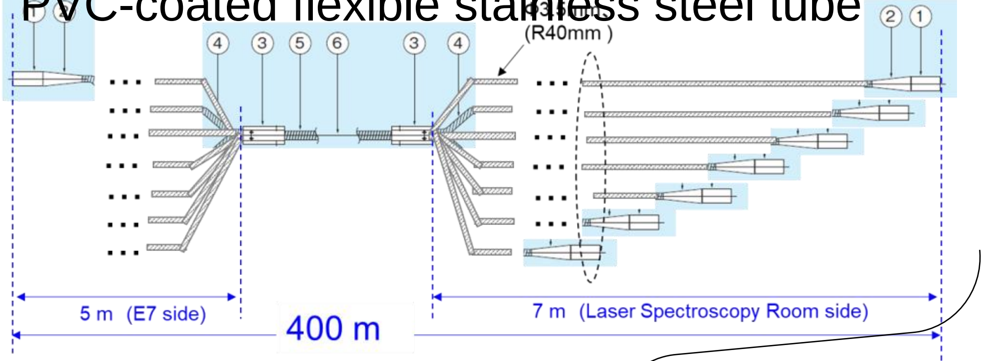
Fujikura

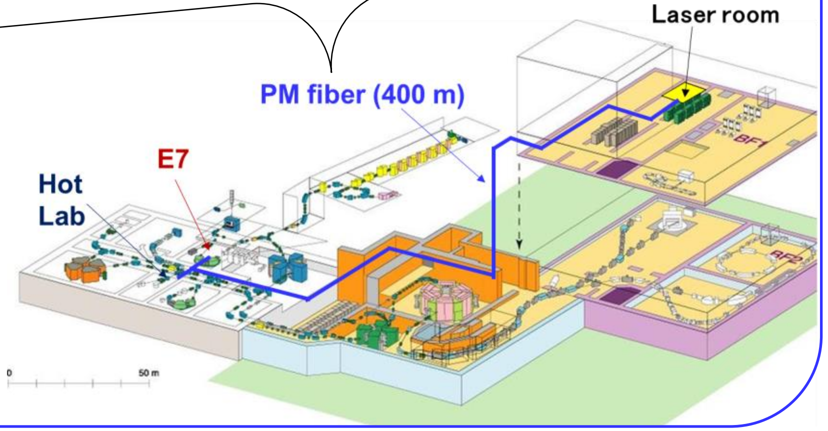
Housing bare
7 PANDA fibers

NIPPON STEEL WELDING & ENGINEERING

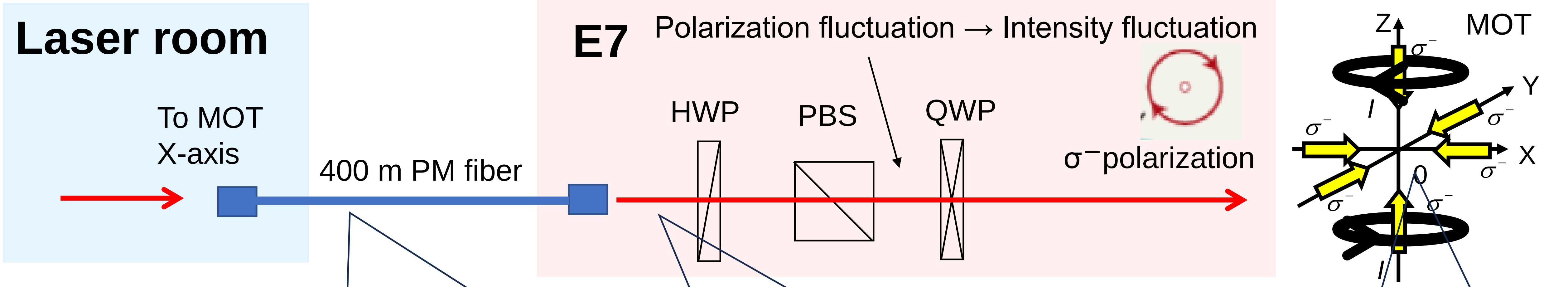
PICOFLEC®/PLJ

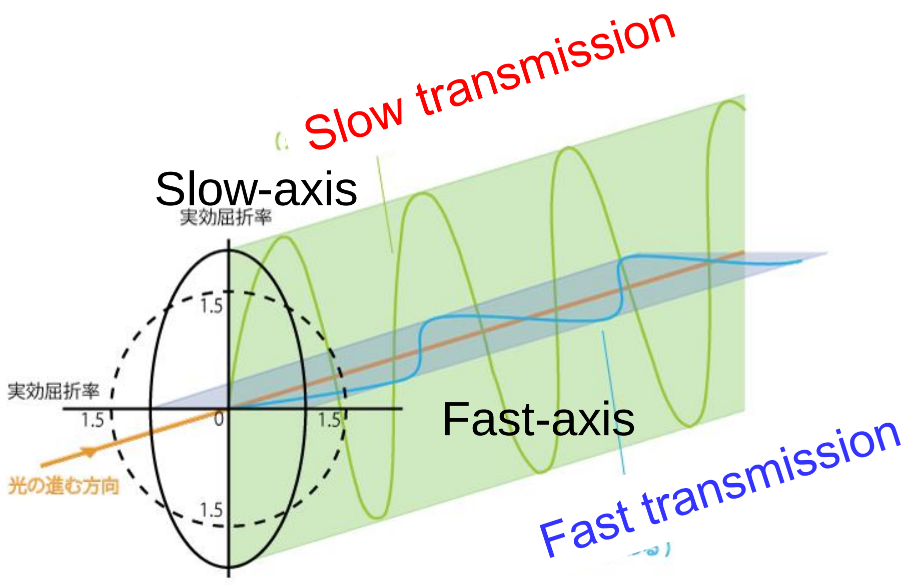
PVC-coated flexible stainless steel tube





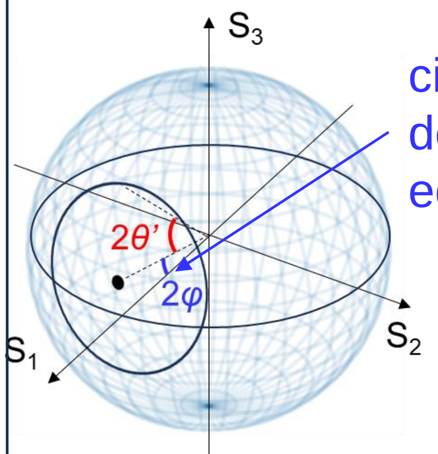
Optical delivery system





Source: https://www.fiberlabs.co.jp/tech-explan/about-pmfiber/

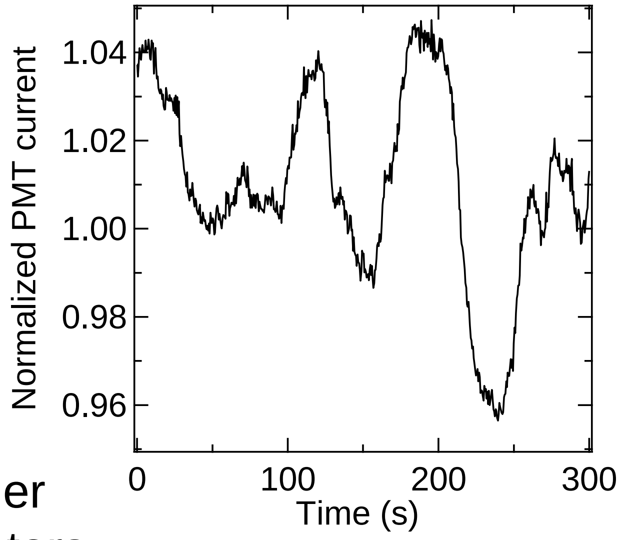
"State of polarization (SOP)" plotted on **Poincaré sphere**



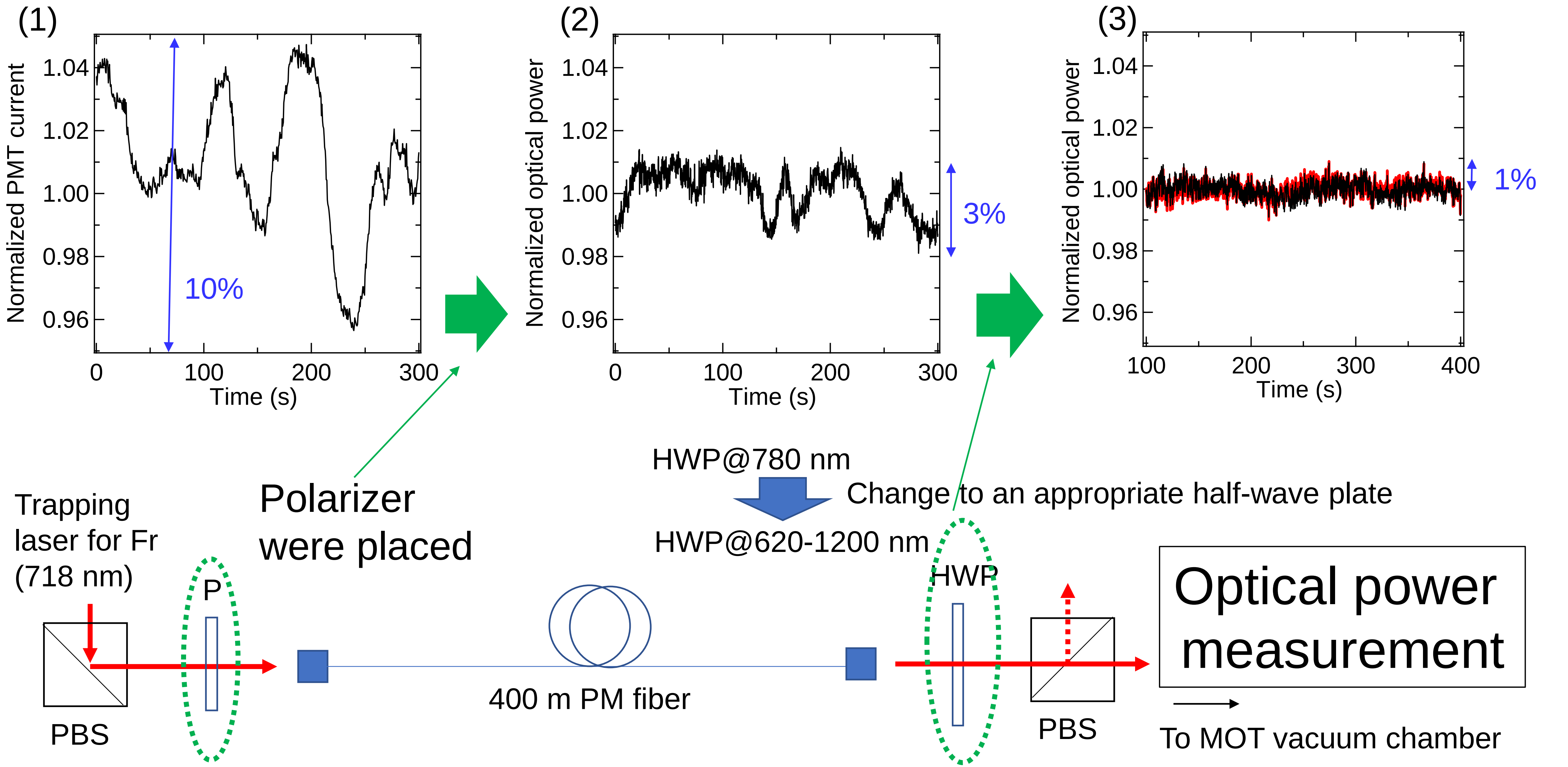
circle's center deviates from the equatorial plane

stress-induced birefringence and/or other polarization changes due to the connectors.

Background noise in MOT fluorescence measurements



Optical delivery system



K. Nakamura *et al.*, Proceedings of the 2022 Conference on Lasers and Electro-Optics Pacific Rim, CTuP7C-03, pp.1-2, (2022)

Estimate towards Fr MOT

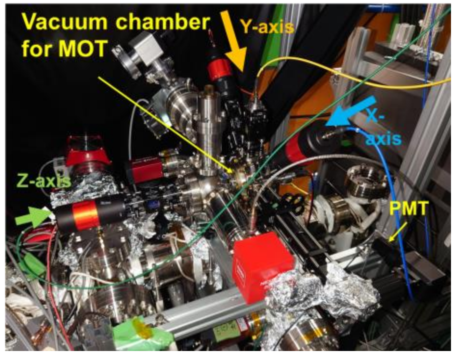
S. Aubin *et al*. Rev. Sci. Instrum.,**74**, 4342 (2003)

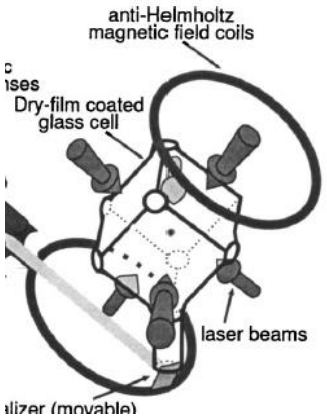
Fr MOT
~ 2.8 x 10^5 /pulse

$N = R\tau$		K. Lindquist *et al*., Phys. Rev. A **46**, 4082 (1992). K. Lindquist *et al*., Opt. Lett. **38**, 661 (2013).
$R \propto L^{3.6}$	constant intensity, $L > 2.3$ mm	
$R \propto I/I_s$	$(I/I_s < 4)$	K. E. Gibble *et al*., Opt. Lett. **17**, 526 (1992).
$R \propto \log_e(I/I_s) - 0.0775$	$(I/I_s \geq 4)$	
$\tau \sim (2\times10^{-6}\ [\mathrm{s}])/p[\mathrm{Pa}]$		J. E. Bjorkholm *et al*., Phys. Rev. A **38**, 1599 (1988).

Estimation

Fr MOT
~ 2 x 10^8 /pulse





Diameter of laser beam L = 30 mm → (Efficiency for MOT, x 6) → L = 50 mm

Optical power 127 mW /axis → (x 1/15) → Optical power 14 mW /axis

Degree of vacuum p ~ 7 x 10^{-6} Pa → (x 70) → p ~ 1 x 10^{-7} Pa (target value)

Cell coating quality
~ Difficult to evaluate

Diameter of laser beam L = 16 mm

In the future, we plan to replace

L = 50 mm

Neutralizer

Neutralizer

If we can successfully develop a neutralizer with the same efficiency

$^{210}Fr^+$ ~ 3.6 x 10^5 /s → (x 27) → $^{221}Fr^+$ ~ 1 × 10^7 /s

Conclusion

We have succeeded in developing a laser and optical system for Fr MOT under difficult conditions.

Funding.

This work was supported by JSPS KAKENHI Grant Numbers JP19H05601, JP20K14482, JP22K18273.

Acknowledgments.

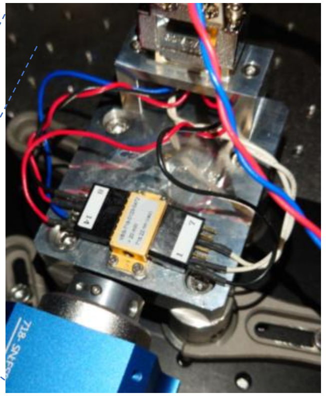
This experiment was performed at RI Beam Factory operated by RIKEN Nishina Center and CNS, The University of Tokyo.

Thank you for your attention.

Outlook ~ Toward the development of Unit 2 ~

Portable laser and optical system

Fr trapping laser source (718 nm)



20 mW
free space output

VHG-based ECDL
(Sacher)