Recent Progress towards Positronium Bose–Einstein Condensation

K. Yamada, K. Shu, K. Hashidate, A. Ishida, T. Namba[A], S. Asai, M. Kuwata-Gonokami, Y. Tajima[B], C. Eumni[B], K. Yoshioka[B], N. Oshima[C], B E O'Rourke[C], K. Michishio[C], K. Ito[C] K. Kumagai[C], R. Suzuki[C], S. Fujino[D], T. Hyodo[E], I. Mochizuki[E], K. Wada[F]

Dept.of Phys, UTokyo, [A]ICEPP, UTokyo, [B]Photon Science Center, UTokyo, [C]AIST, [D]Kyushu Univ, [E]KEK,[F]QST

The 11th International Workshop on Fundamental Physics Using Atoms
2019.3.4 @OIST

Contents of my talk

- Ps-BEC and its application
- Challenges to realize Ps-BEC
- Three technologies to develop for Ps-BEC
    1. Positron system
    2. Ps converter
    3. Cooling laser
- Current Status
- Roadmap towards Ps-BEC

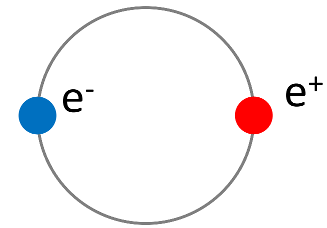
Positronium: Good probe on Fundamental Physics

Positronium (Ps)

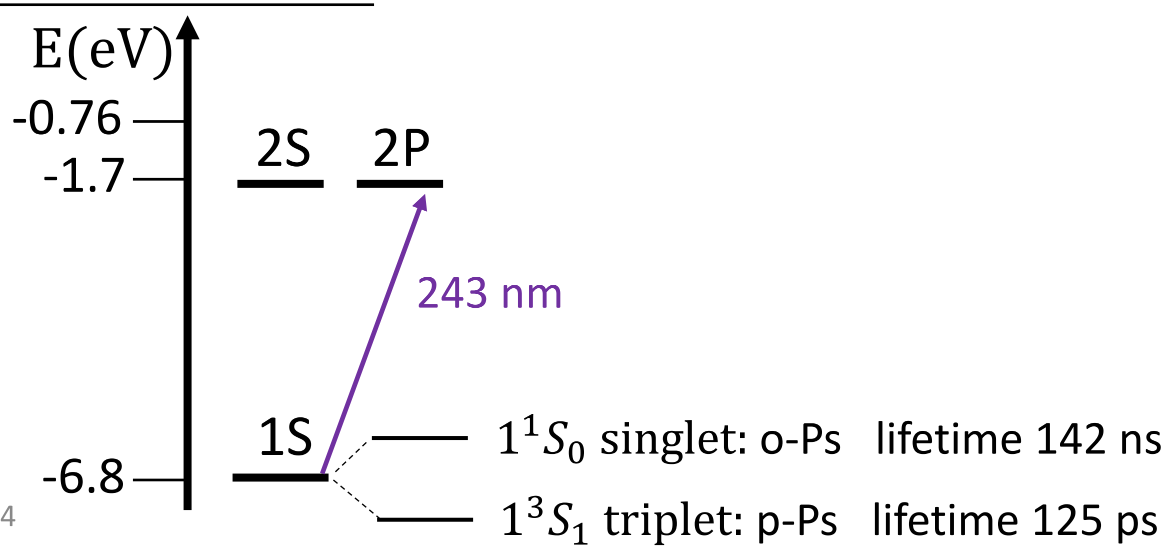
- Easiest atomic antimatter system to produce
- Exotic atom: e^- & e^+
- Hydrogen-like, simple and pure leptonic system

→Good system for precision test of bound state QED

Positronium



Energy spectrum of Positronium



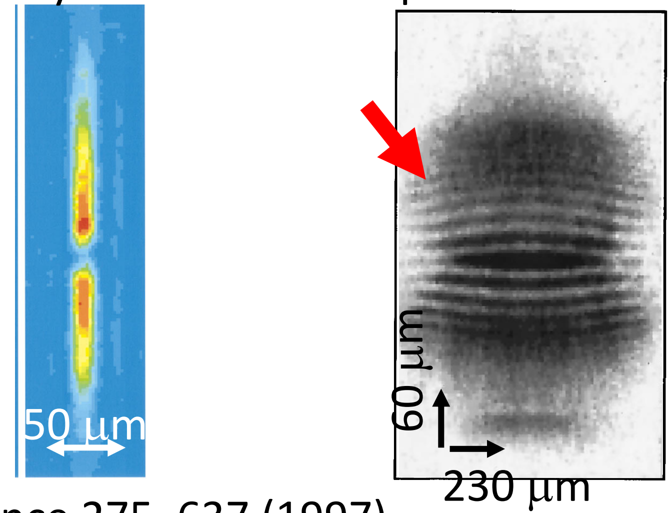
Our Target:
Positronium Bose-Einstein Condensation

- Ps must be dense and cold
- High critical temperature thanks to Ps light mass (14K at 10^{18} cm^{-3})
- One of the best candidates for the first antimatter BEC
- BEC is "Atomic laser", We would like to make first antimatter laser and perform a new experiment using the coherency BEC.

Interference frindge of BEC (Rb)

Before release trapped by double-well

After release expand to overlap

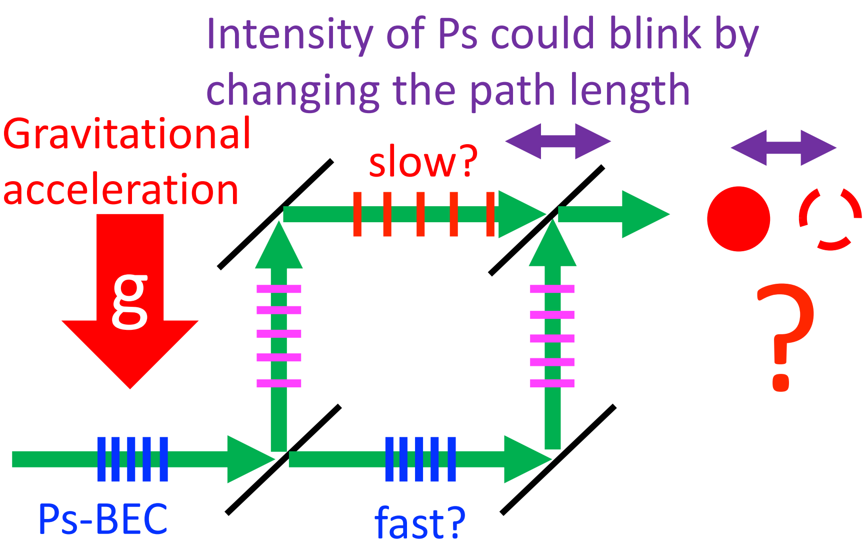


Science 275, 637 (1997)

Applications of Ps-BEC

1. Antimatter probe:

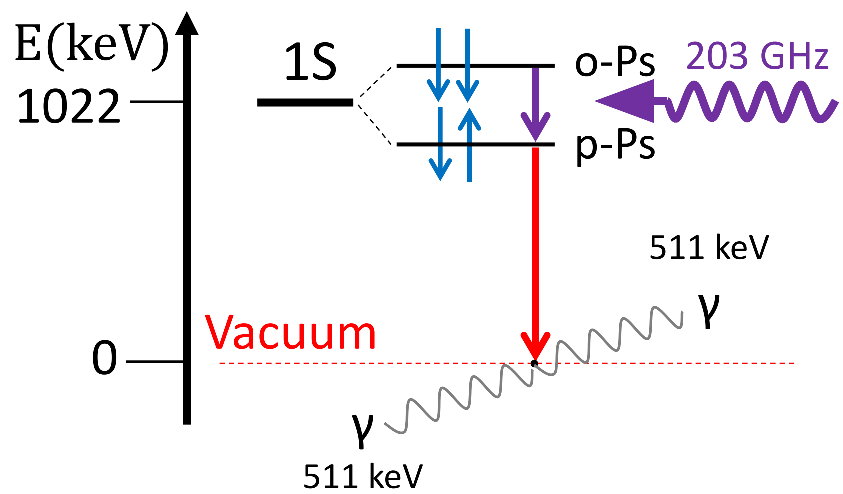
Build Ps-BEC atomic interferometer to see tiny effect on antimatter: such as gravity



- Gravity shifts phase of Ps in different paths
- Path length 20 cm to see gravity effect

Phys. stat. sol. 4, 3419 (2007)

2. 511 keV γ-ray laser



Phys. Rev. A 92, 023820 (2015)

- *o*-Ps BEC to *p*-Ps by 203 GHz RF
- *p*-Ps BEC collectively decays into coherent 511 keV gamma-rays
- 10 times finer probe than current X-rays

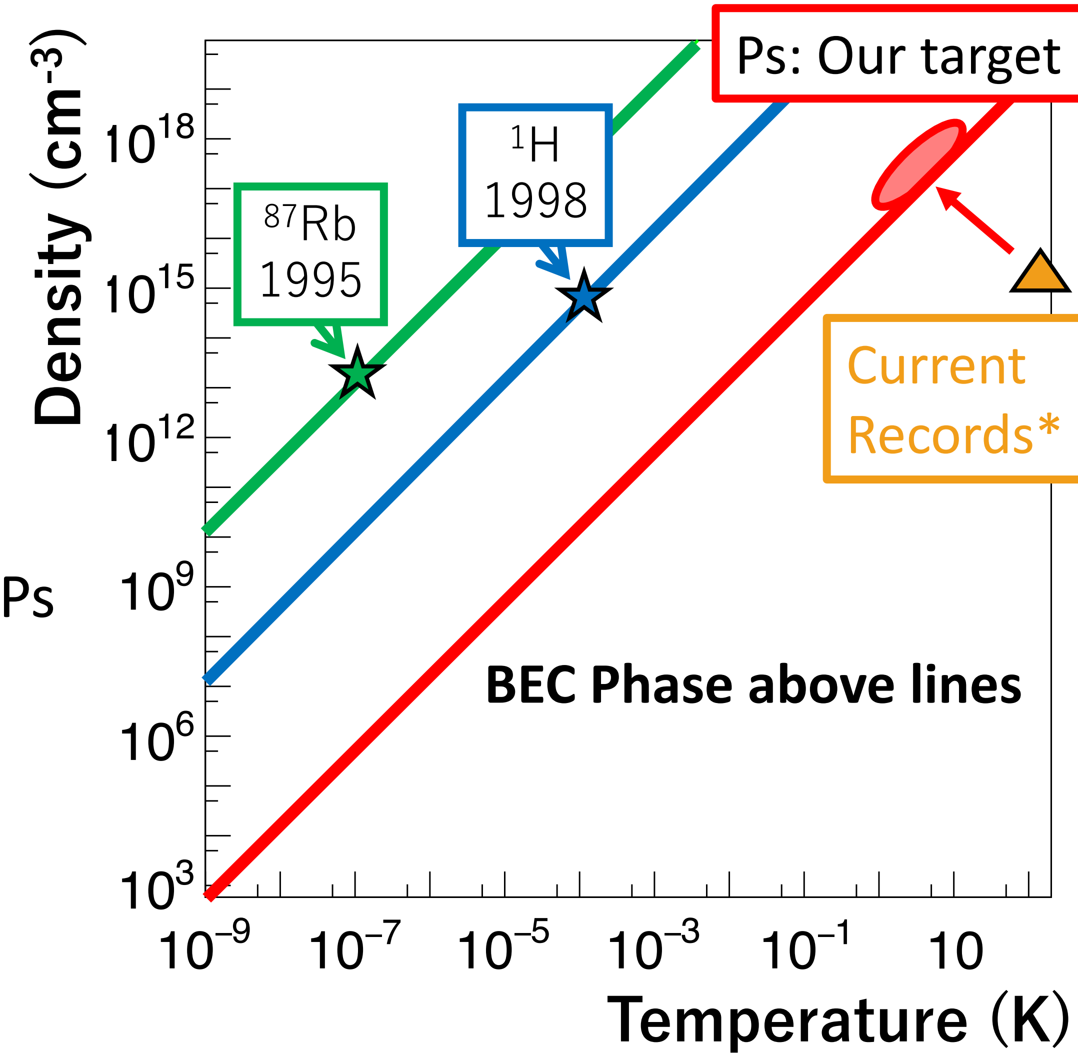
Two challenges to realize Ps-BEC

Main problem

Ps lifetime is only 142 ns

Two challenges

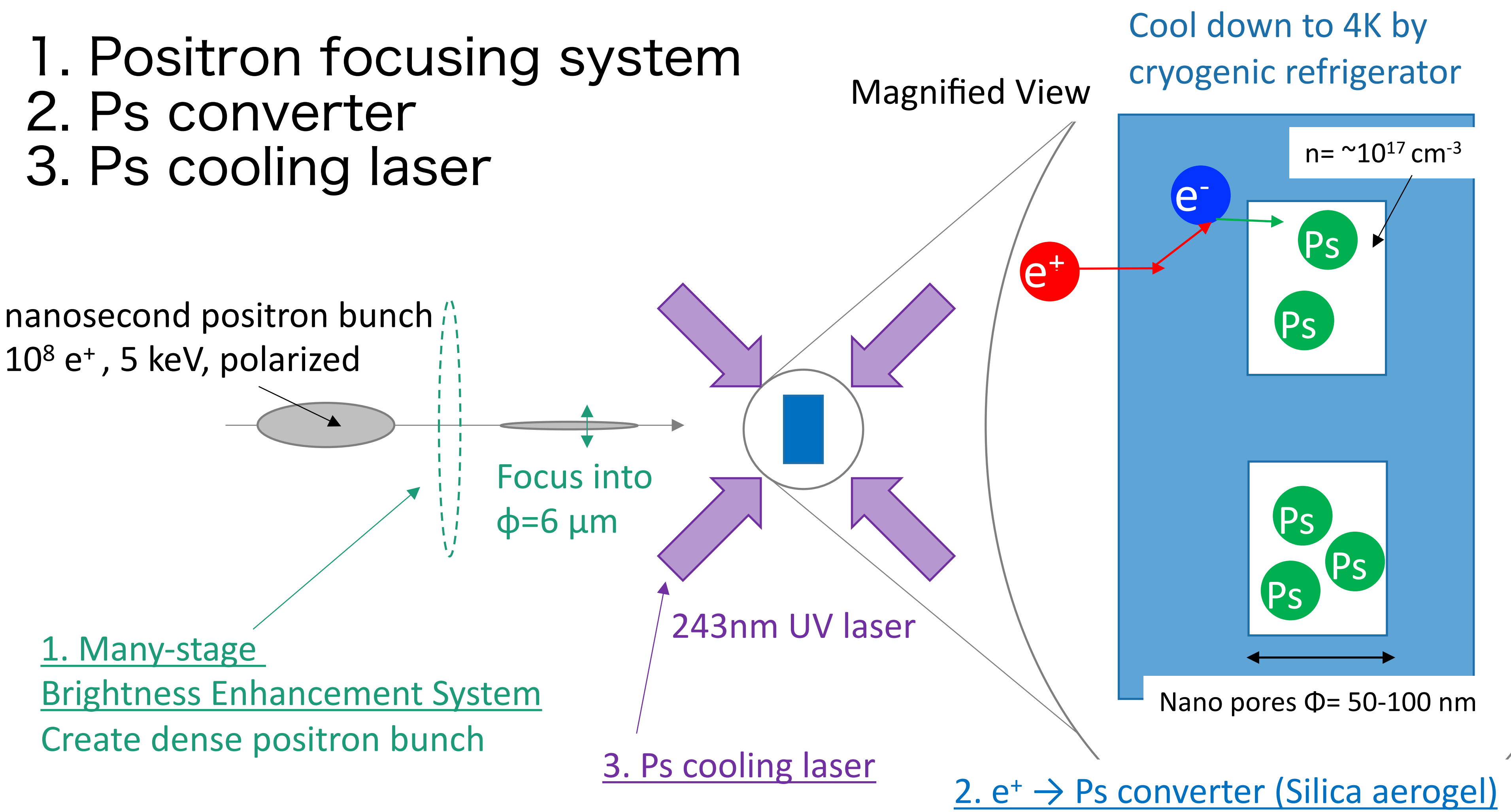
1. Instant creation of dense Ps
   $> 10^{17}$ cm^{-3} in < 50 ns
2. Rapid cooling of Ps
   < 10 K in ~300 ns



* : S. Mariazzi *et al.* Phys. Rev. Lett. 104, 243401 (2010)
* : D. Cassidy *et al.* physica status solidi 4, 3419 (2007)

Three technologies to develop for Ps-BEC

1. Positron focusing system
2. Ps converter
3. Ps cooling laser

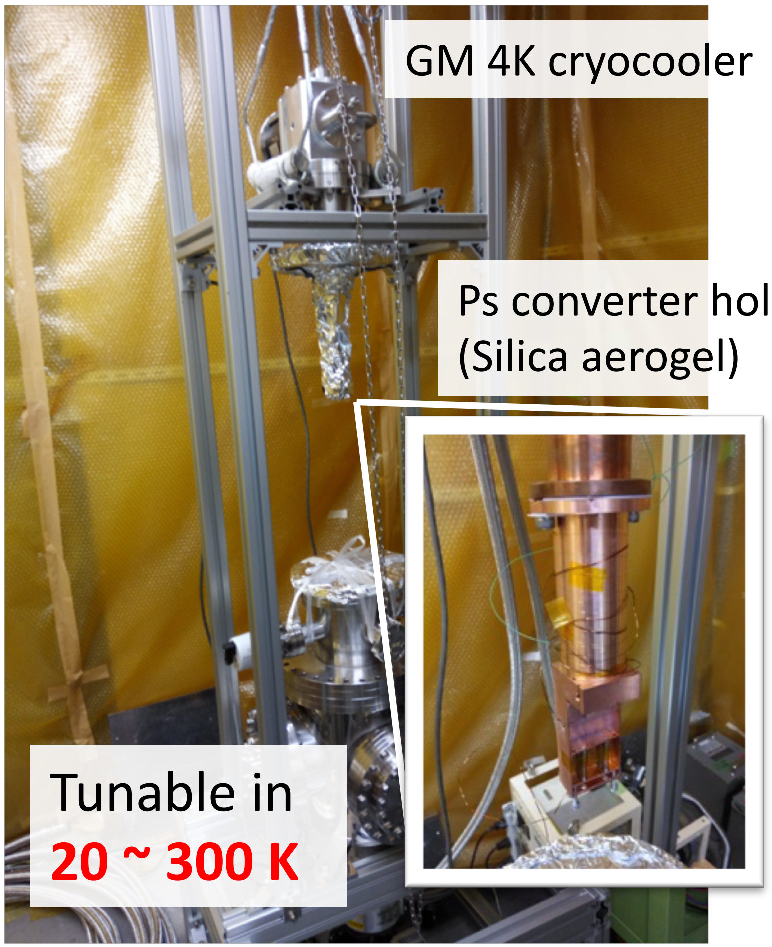


Combine thermalization and laser cooling
to cool down Ps to 10 K in 300 ns

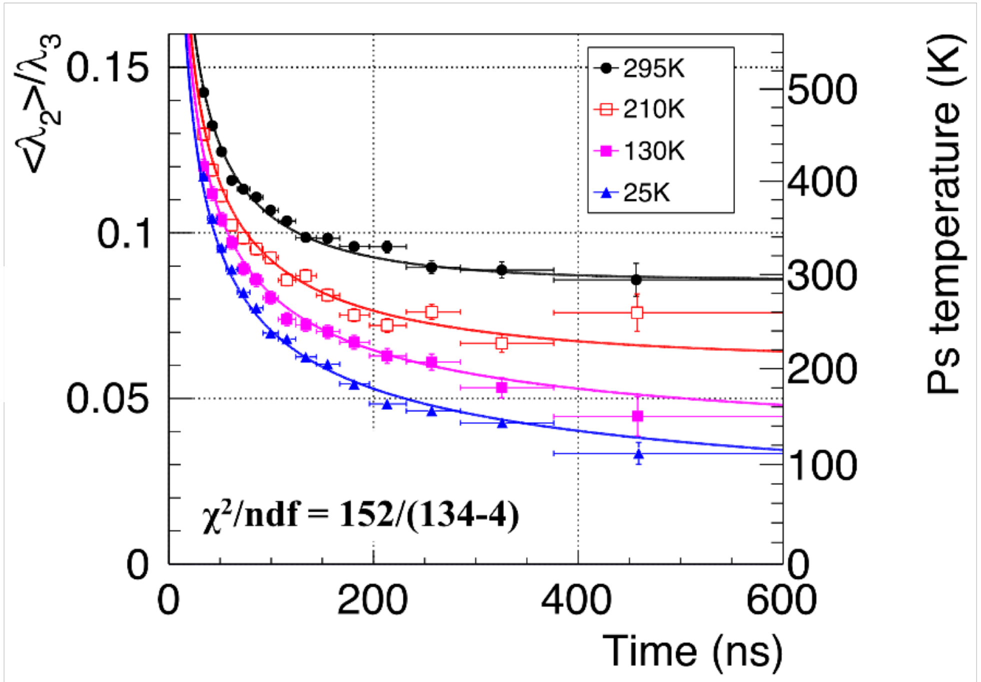
K. Shu *et al.* J. Phys. B 49, 104001 (2016)

Ps thermalization down to 100 K was observed

We confirmed if Ps can be thermalized in its short lifetime (142 ns).



Thermalization curves of Ps in various silica temperature



- ✓ Thermalization into cryogenic temperature was clearly observed
- ➢ Next, Laser cooling and cool Ps down to 10 K

Thermalization and Laser cooling is efficient enough to realize Ps-BEC

1.Thermalization

- Efficient at > 200 K

Initial Ps energy is 0.8 eV = 6000 K (work function of silica)

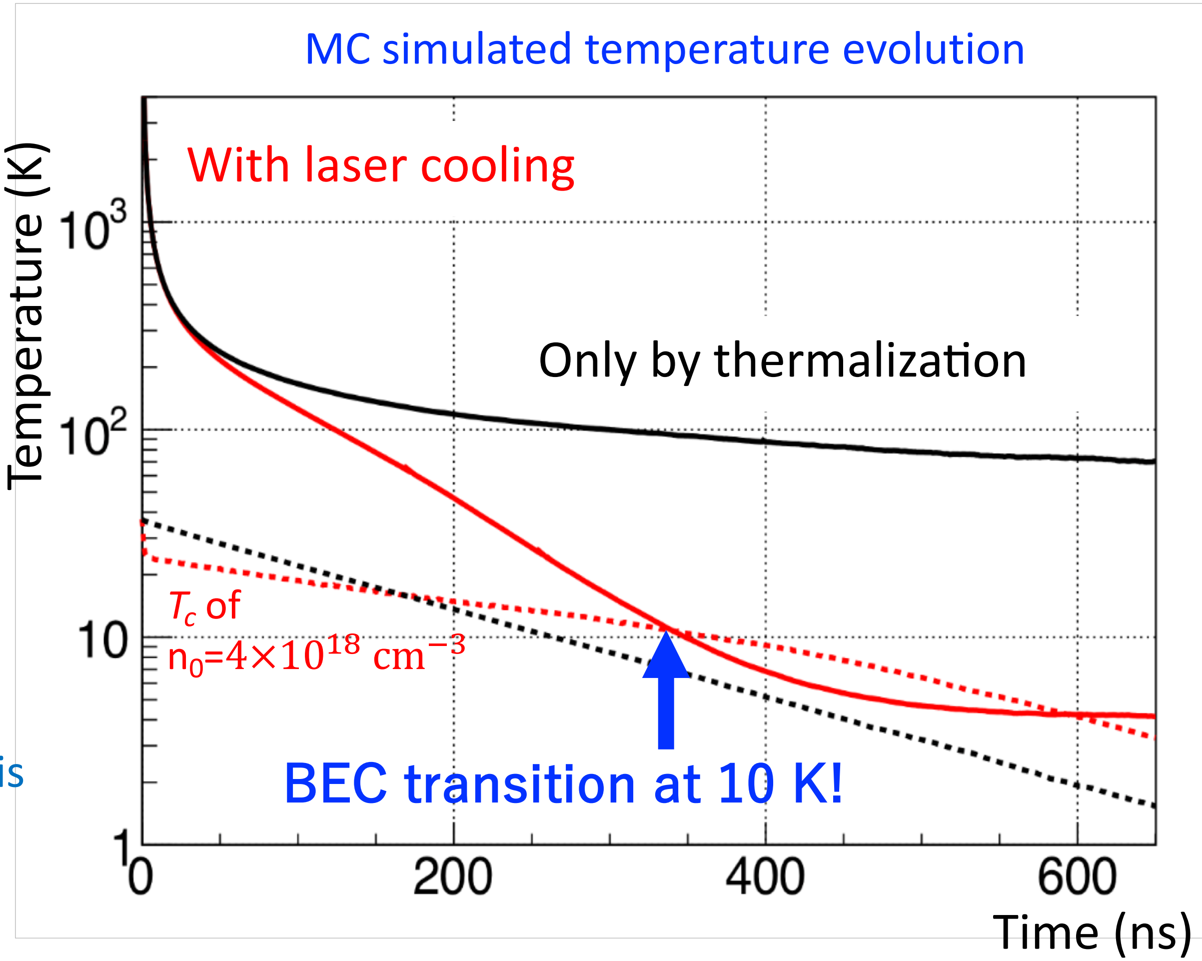
Ps collide with cold silica(< 10 K) and cool down to 100 K

2.Laser cooling

- Efficient at < 200 K

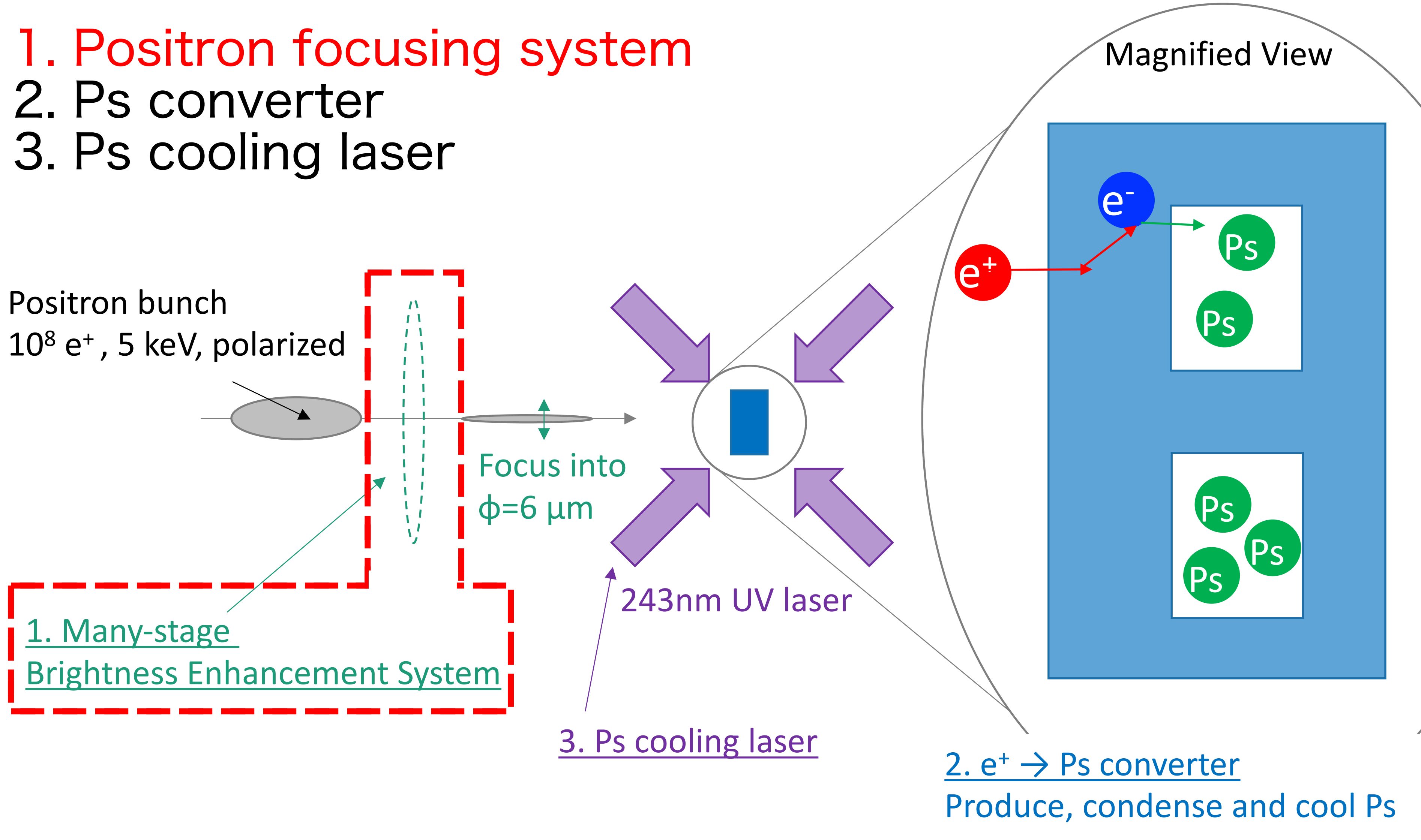
Cooling down to < 10 K is possible

✓ Combining these two methods is essentially important



Three technologies to develop for Ps-BEC

1. Positron focusing system
2. Ps converter
3. Ps cooling laser



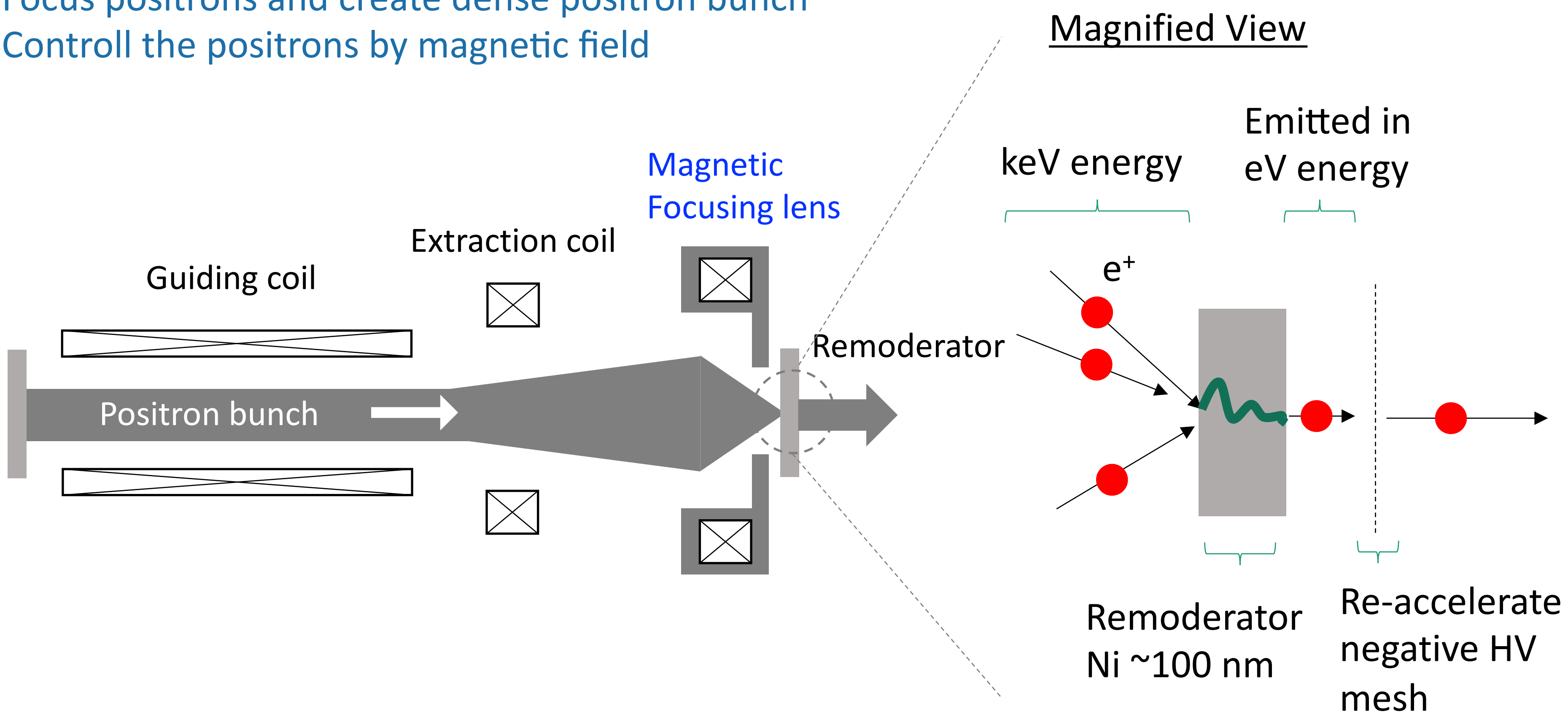
Positron Focusing

1.Positron system

Brightness Enhancement System

Focus positrons and create dense positron bunch

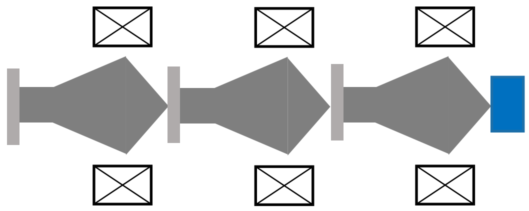
Controll the positrons by magnetic field



Narrow and low-emittance positron beam can be created

Many-Stage Brightness Enhancement System
1.Positron focusing system

Many-Stage Brightness Enhancement System



- Repeat the Brightness Enhancement multiple times and gradually focus the positrons.
- Currently focusing into 30 μm* is possible by this method so we consider improving this technique
- Now studying and designing beam optics

*N. Oshima *et al.* Materials Science Forum 607, 238(2008)

Calculation

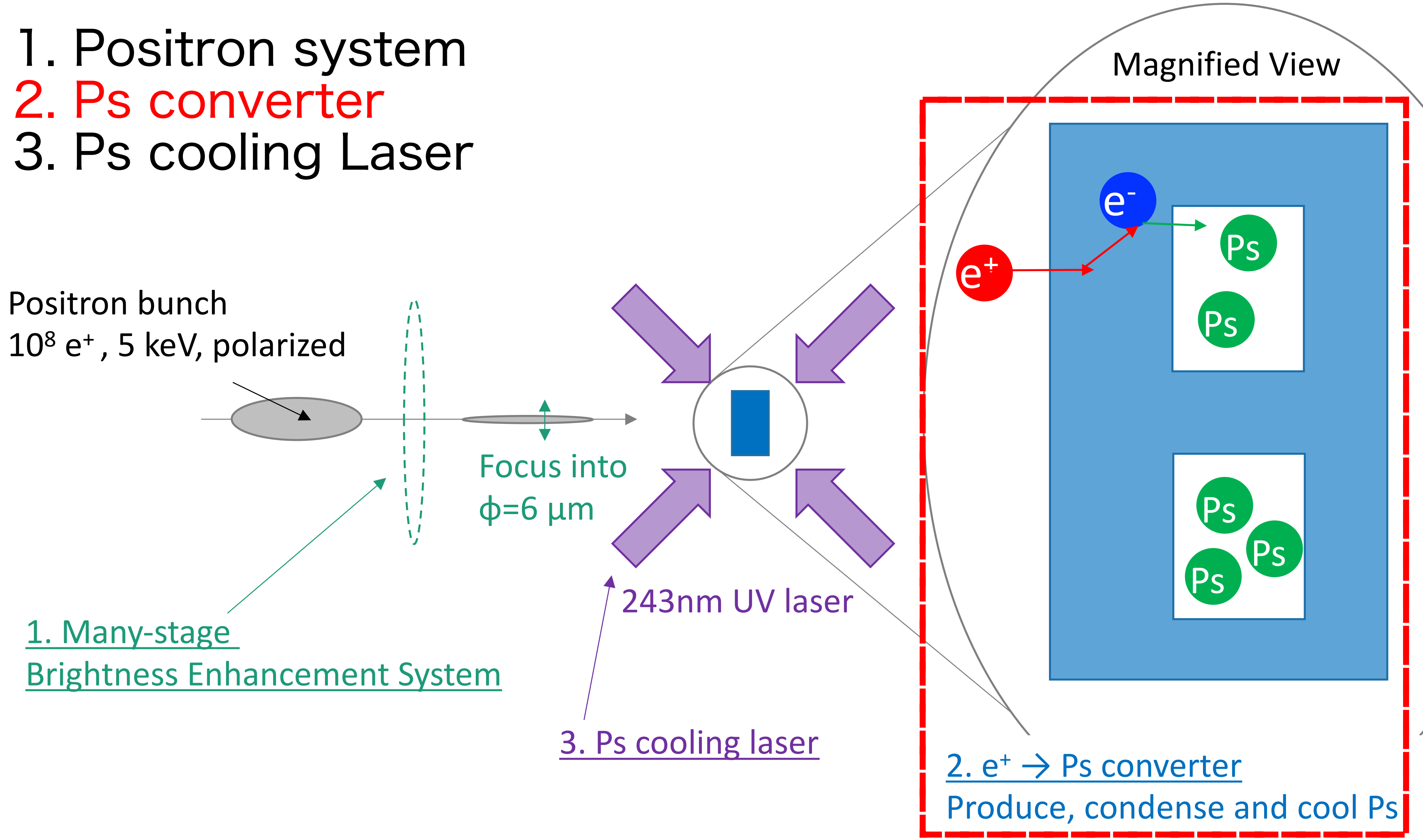
Beam Parameter	1 st	2 nd	3 rd	final
	BE →	BE →	Focus only →	
Ps Density* (cm^{-3})	2.5×10^{12}	4.9×10^{13}	6.8×10^{14}	6.8×10^{16}
Diameter	5 mm	500 μm	60 μm	6 μm
e^+ Number	1×10^{8}	2×10^{7}	4×10^{6}	4×10^{6}

Positronium density 6.8×10^{16} cm^{-3} is achievable

*Positronium Production rate 10% is assumed

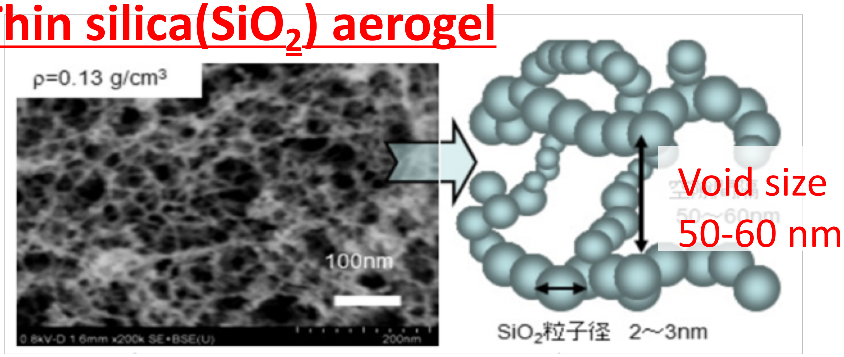
Three technologies to develop for Ps-BEC

1. Positron system
2. Ps converter
3. Ps cooling Laser

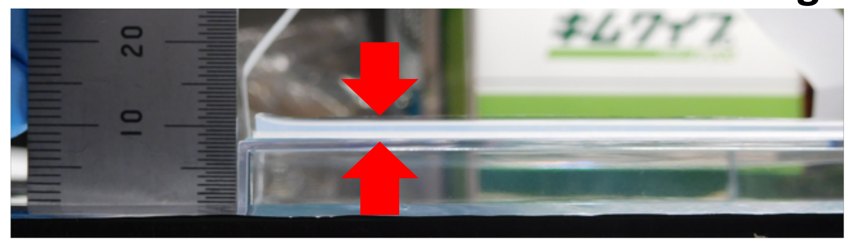


Ps converter(Silica aerogel) is ready for laser-cooling & Doppler spectroscopy

Thin silica(SiO_2) aerogel

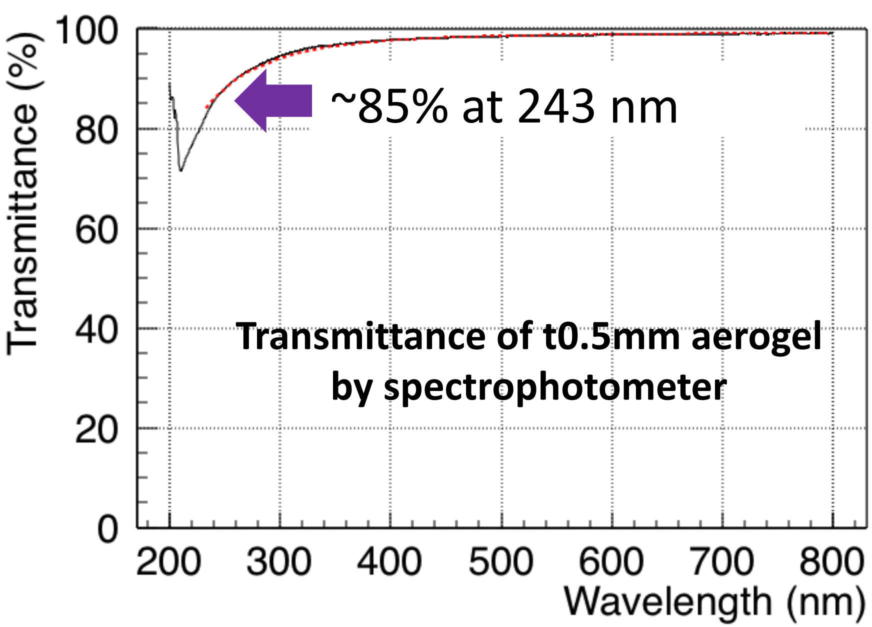


0.5 mm thick silica aerogel*

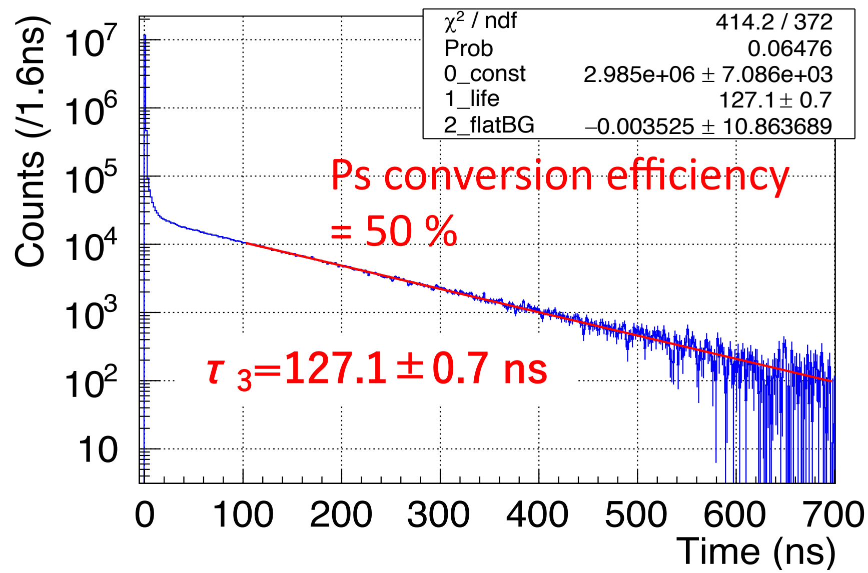


* Developed by JFCC

① High UV Transparency



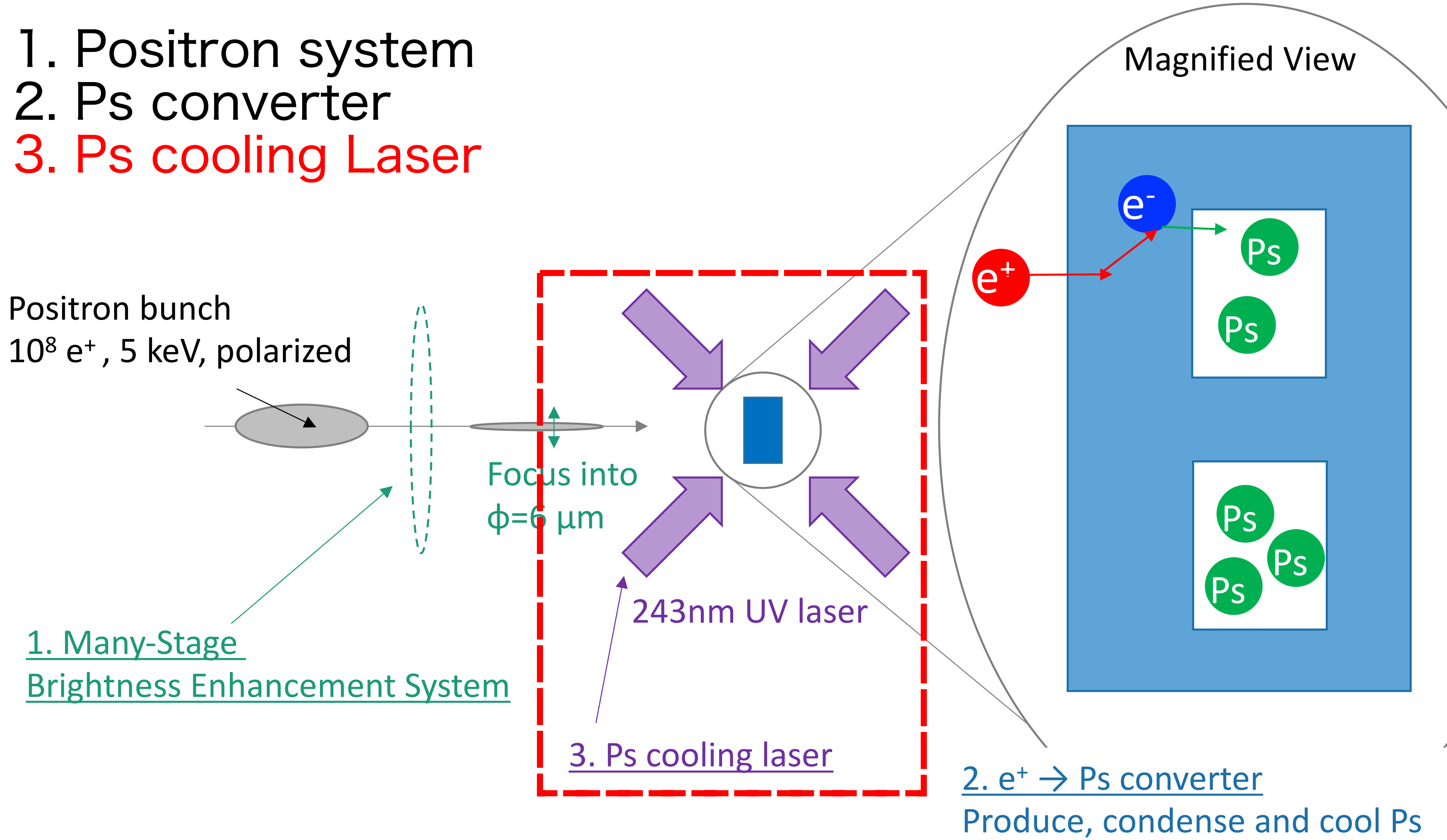
② High e⁺→Ps conversion efficiency



③ High porosity Porosity ~ 95%

Three technologies to develop for Ps-BEC

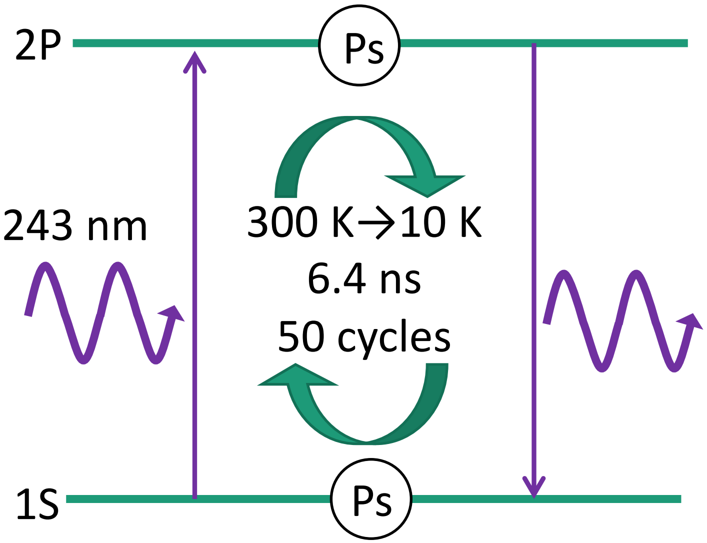
1. Positron system
2. Ps converter
3. Ps cooling Laser



Two Challenges for Ps Laser Cooling

1. Rapid cooling

∵ Short Ps lifetime: 142ns

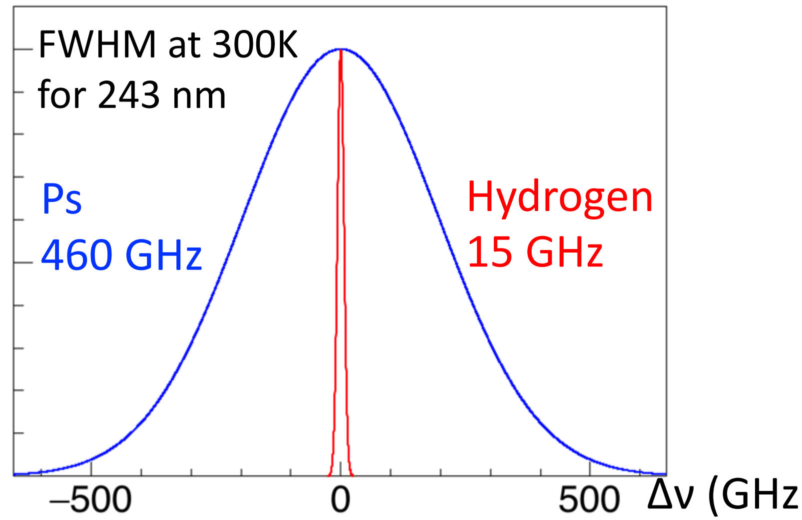


- Largest energy gap: 1S-2P (243 nm)
- 6.4 ns × 50 ~ 300 ns

→ Cool down Ps with single long pulse

2.Broadband laser

∵ Ps light mass: $2m_e$



- Doppler broadening is 30 times larger than Hydrogen

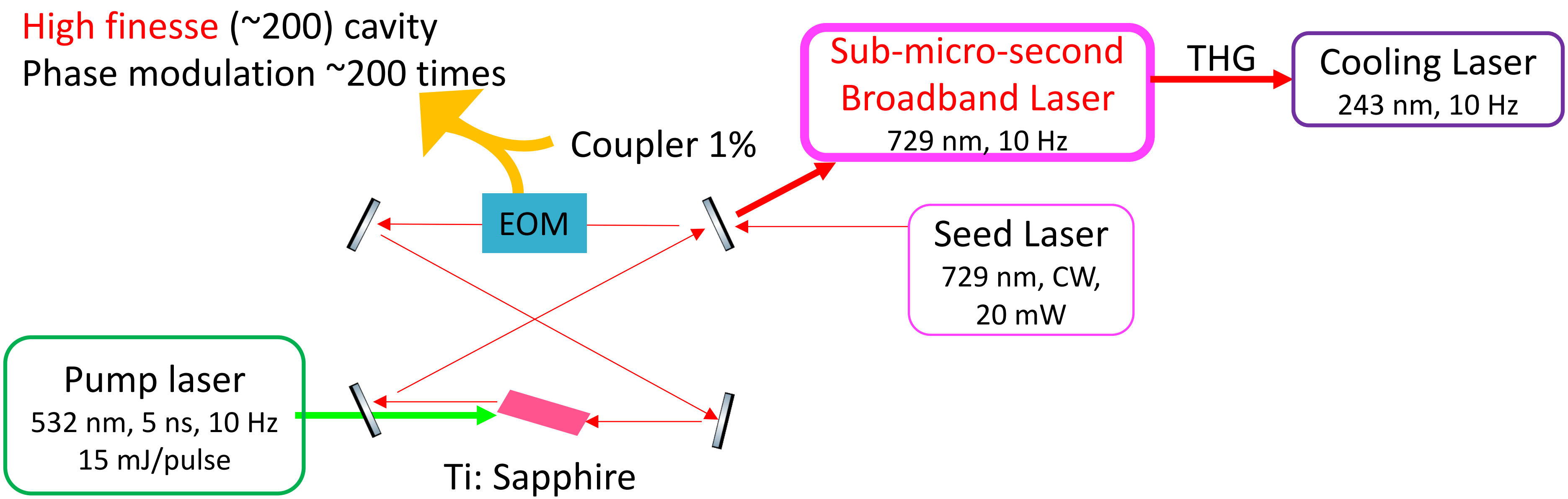
→ Broadband (150 GHz) laser is necessary to cool down all the Ps

243 nm broadband CW laser with enough power is difficult

→243 nm sub-micro-second pulsed broadband laser

Commercially unavailable → Build cooling laser system ourselves

Production of sub-micro-second pulsed broadband laser



Sub-micro-second long pulse

→long photon decay time

1. long cavity (3.8 m)
2. High finesse cavity
   loss/cycle = 1%(coupler)+0.6%

Broadening of pulsed laser

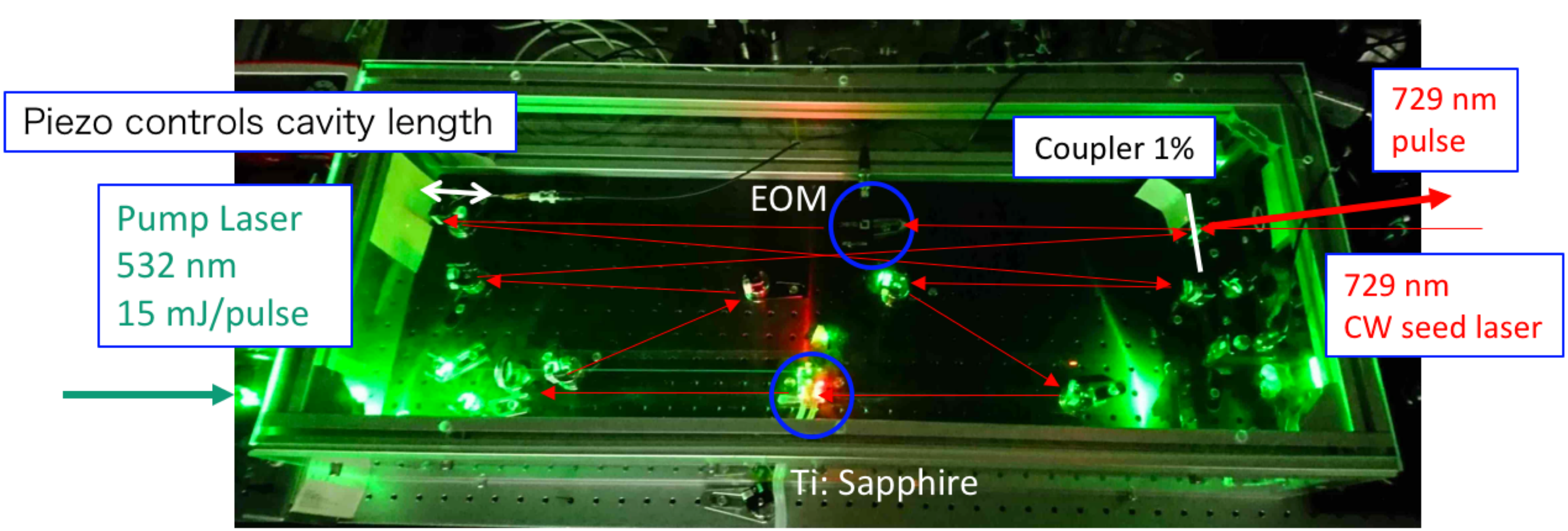
1. EOM: sideband generation
2. High finesse (~200) cavity

EOM modulates the laser ~200 times and creates sidebands up to high order .

→Broaden the laser spectrum effectively

Long and high finesse cavity

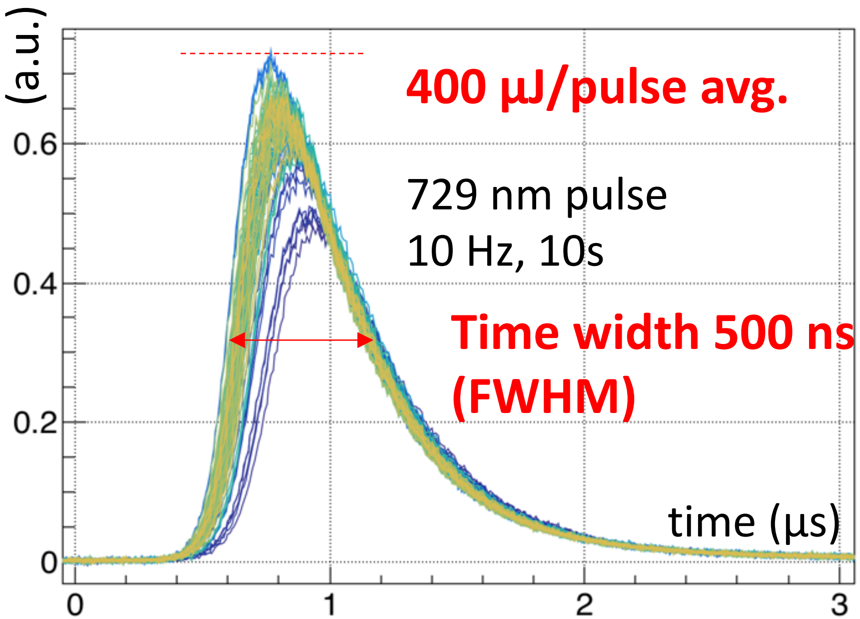
A core of the cooling laser system



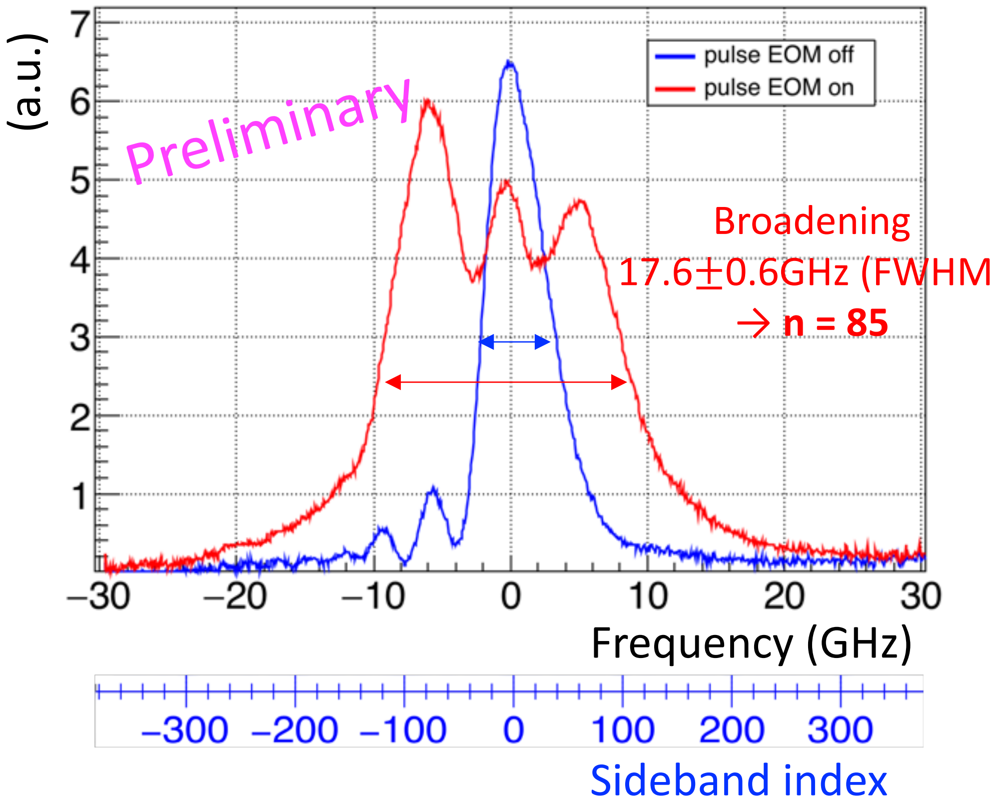
1. Long cavity (3.8 m) Folded with 8 mirrors (96 × 36 cm^2)
2. High finesse (~200)

Ps cooling laser is almost ready

Time profile of 729 nm pulse



Spectral profile of 729nm pulse



- ✓ Long pulse: 500 ns
- ✓ Enough pulse energy: 400 μJ

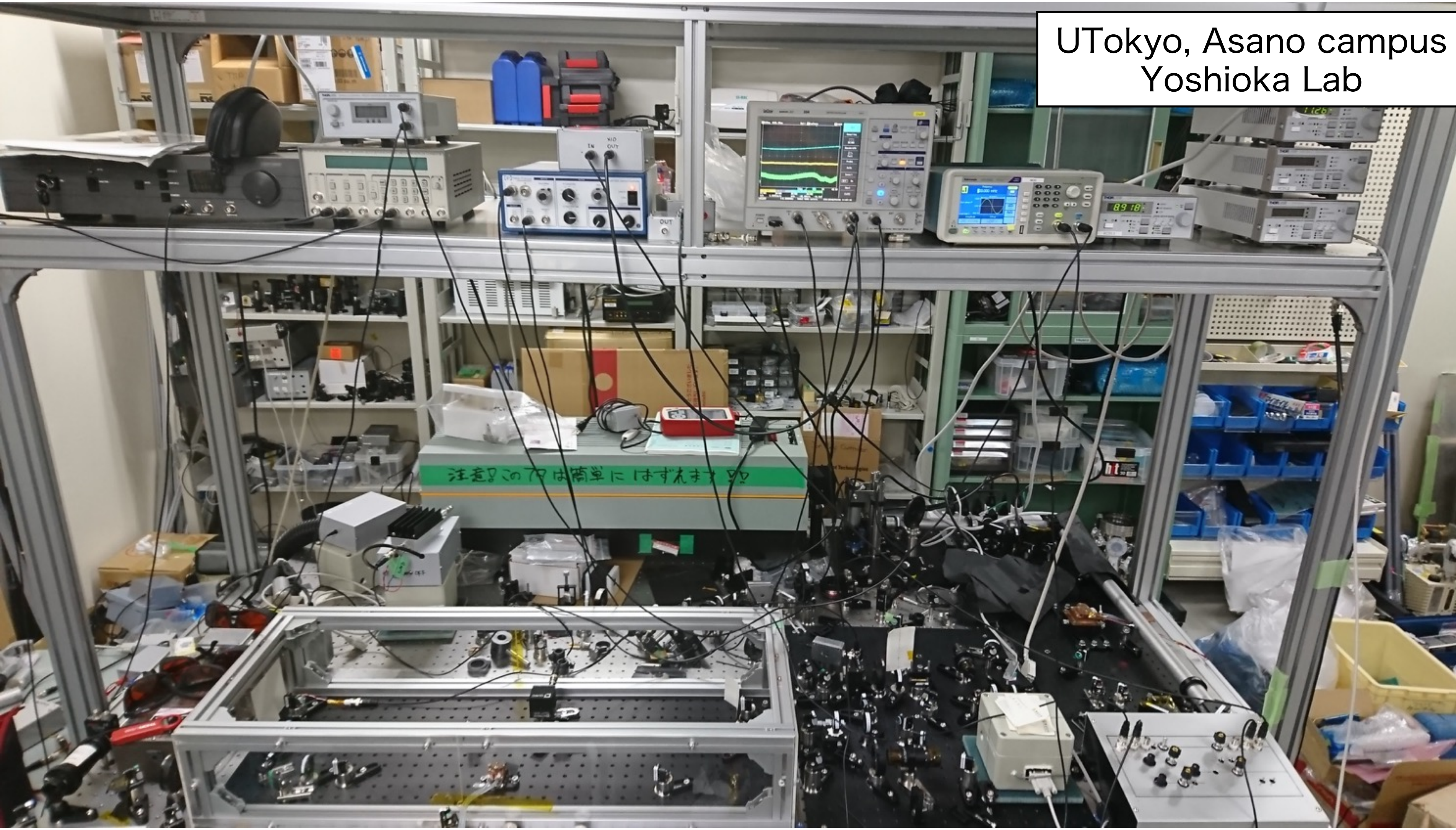
First high order sidebands generation with pulsed laser

- ✓ ±n = 85 has achieved (FWHM)

✓ Most difficult and important part of cooling laser is done. Almost ready for laser cooling.

Overview of the cooling laser system

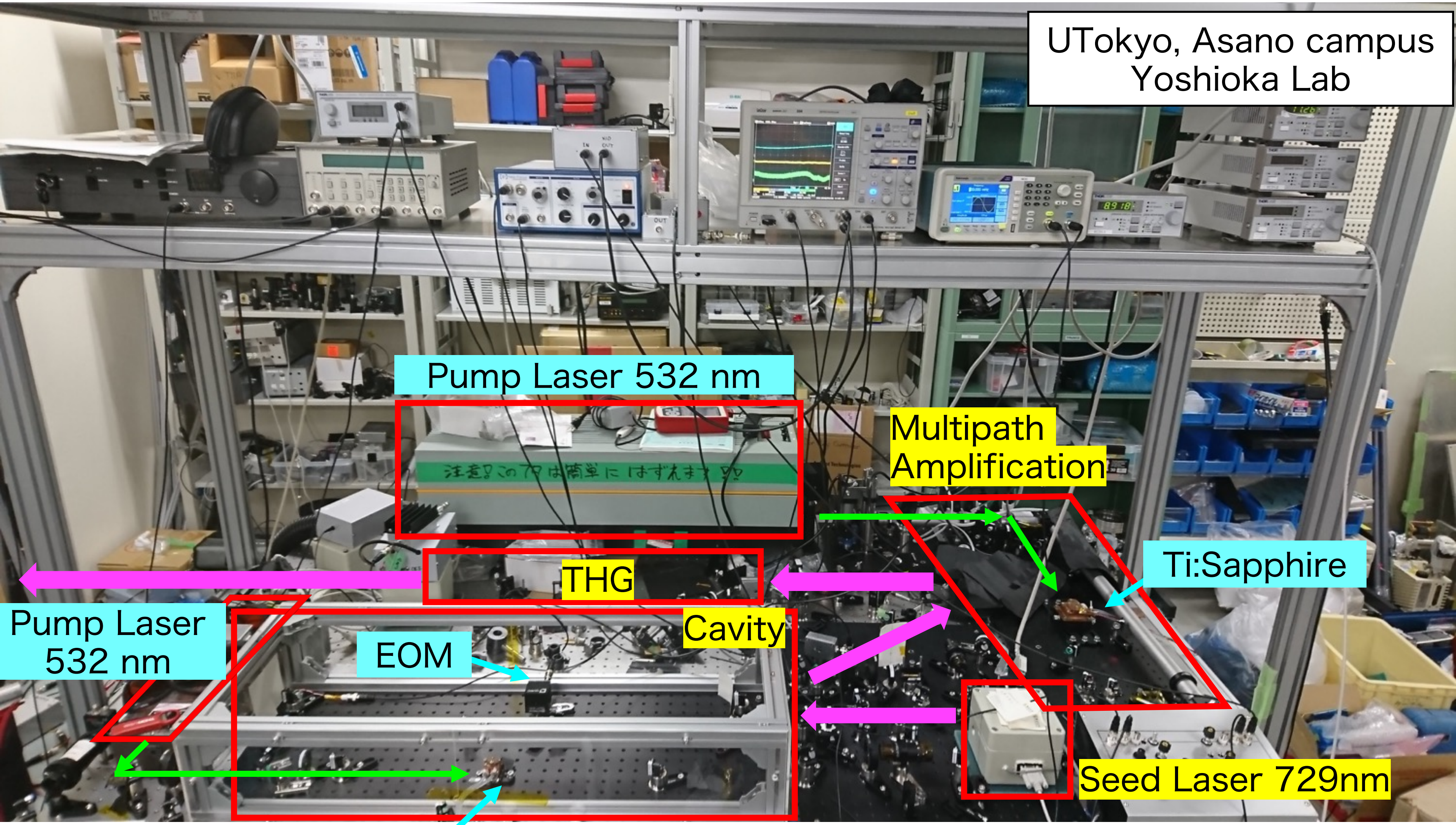
Compact system (2.0 m×1.1 m) will be moved to KEK-SPF (Slow e+ Facility)



Construction of Cooling laser system will be finished this summer

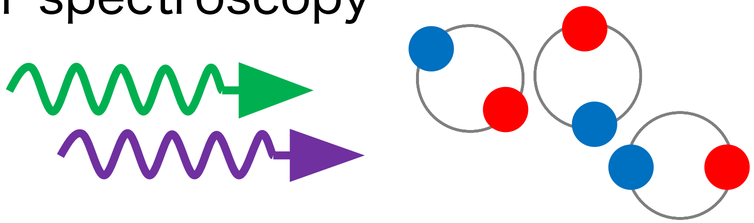
Overview of the cooling laser system

Compact system (2.0 m×1.1 m) will be moved to KEK-SPF (Slow e^+ Facility)

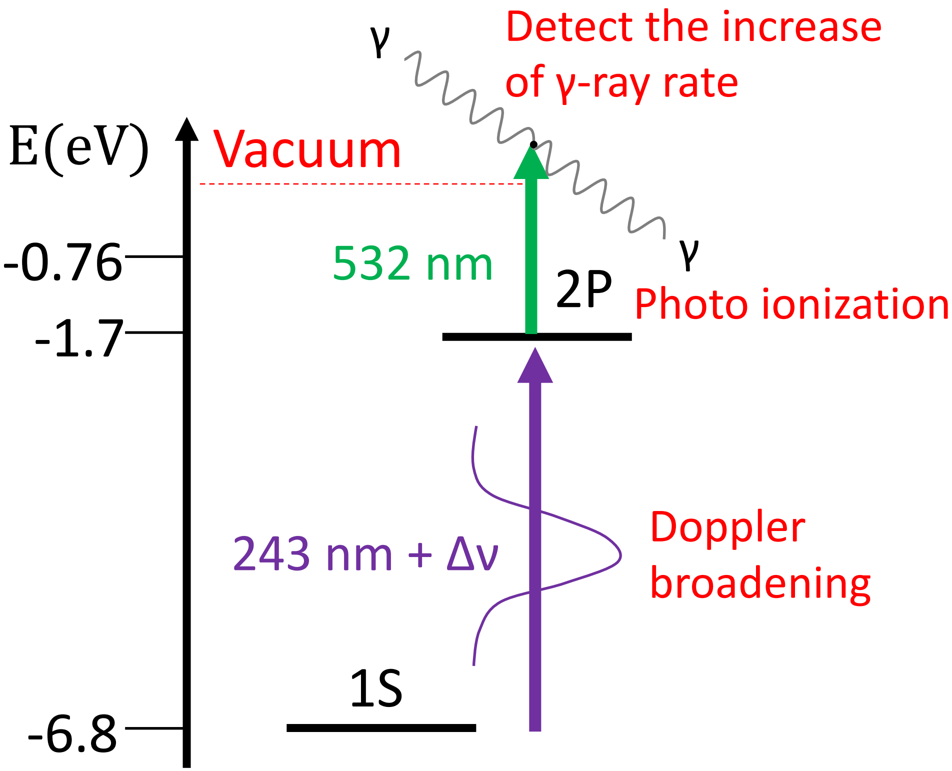


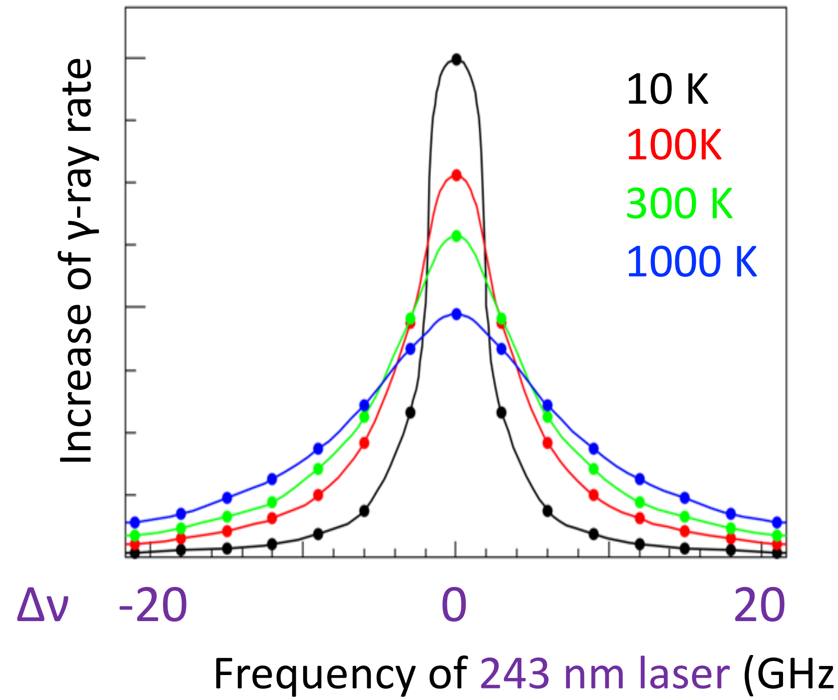
Next Step:
Ps temperature measurement (this March)

Doppler spectroscopy



243 & 532 nm nano-second pulsed laser





Expected resonance curve for 10 K Ps
with 10^7 Ps in total, at t=300 ns

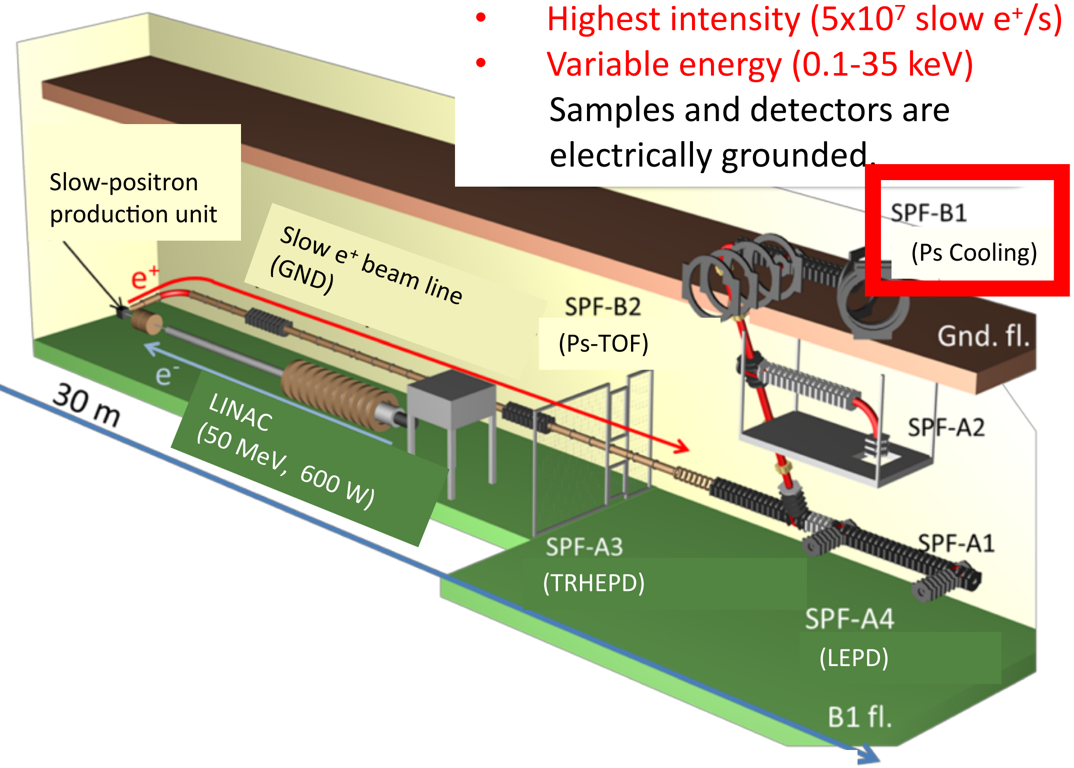
Positron Beam Line (KEK-SPF-B1)

Positron Beam Parameters

Energy	0.1–35 keV
Highest Intensity	10^6 e^+/ pulse
Repetition	50 Hz
Time width	16 ns
Size	Φ = 5 mm

- Highest intensity (5×10^7 slow e^+/s)
- Variable energy (0.1-35 keV)

Samples and detectors are electrically grounded.

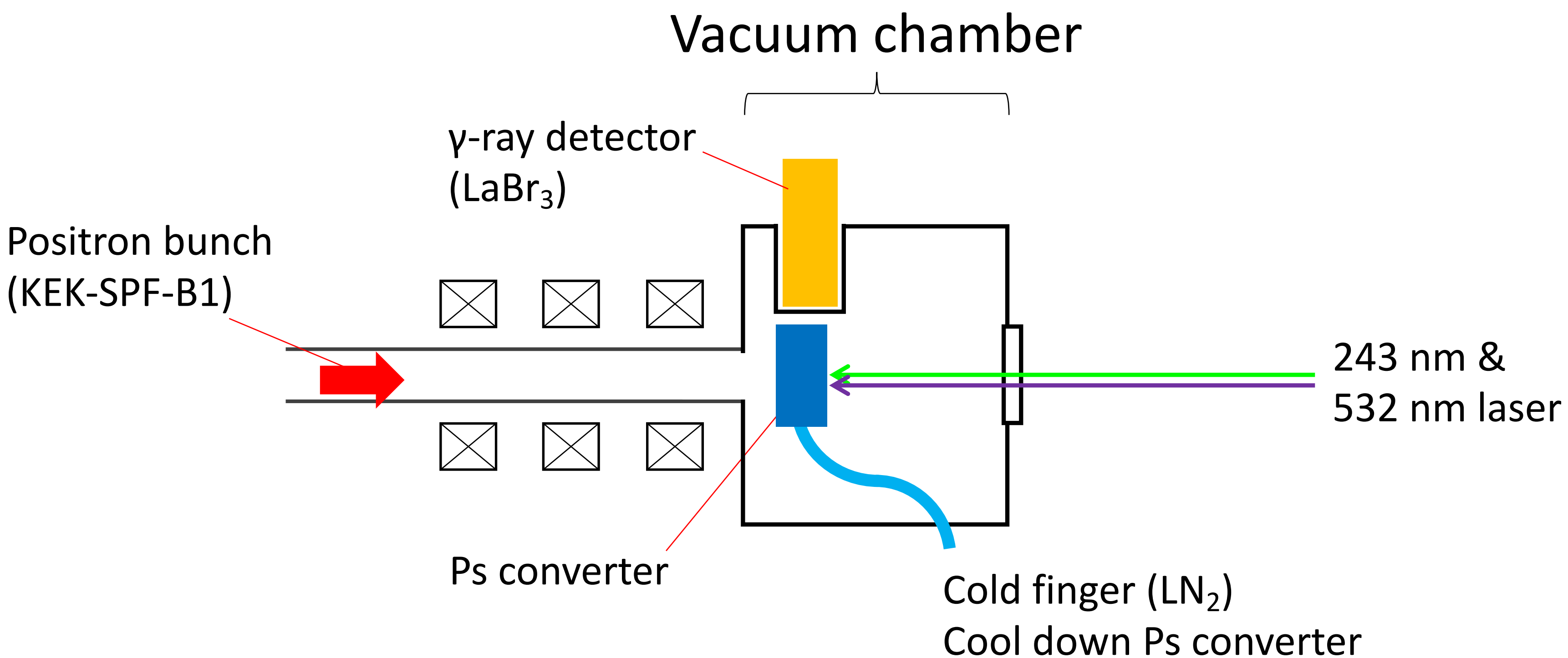


We have been preparing the e^+ beamline for about a year for the first Ps laser cooling

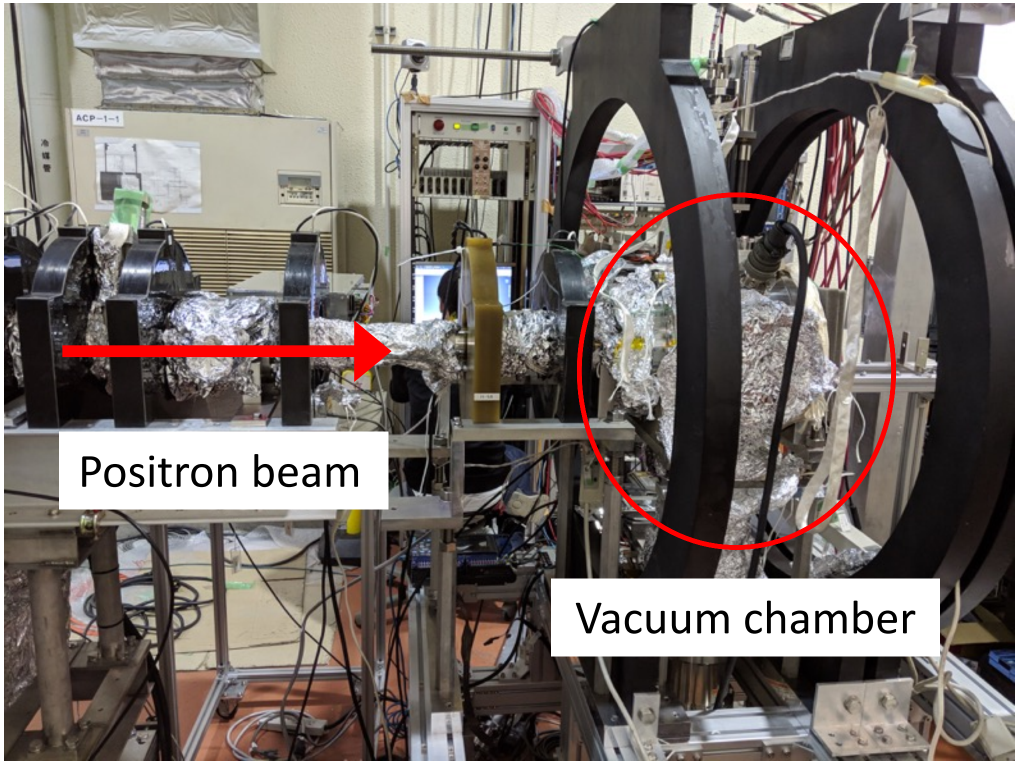
- Measured the instant Ps production in Ps converter (Silica aerogel)
- Improved the time resolution of e^+ bunch
- Test of e^+ bunch focusing

Setup of Ps temperature measurement

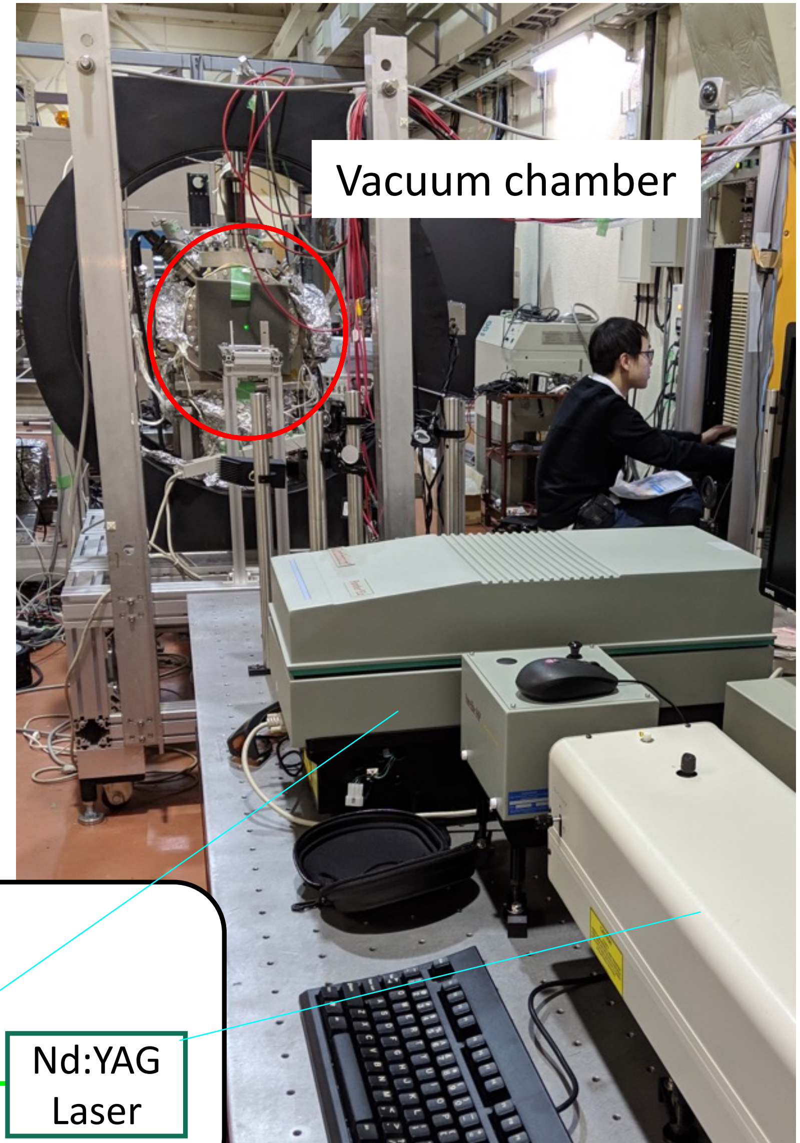
Top view

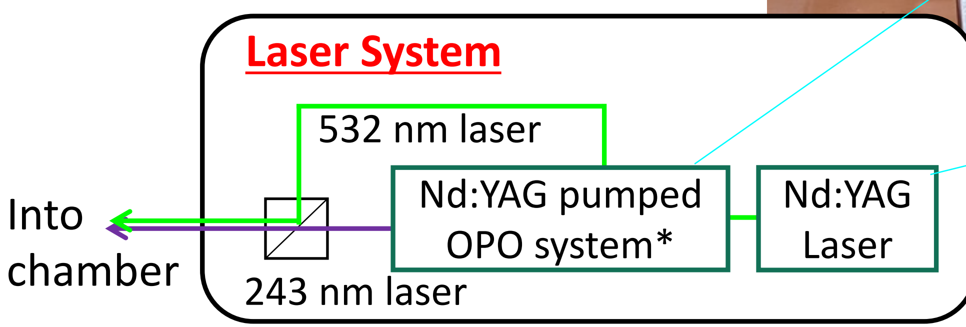


Side view:
Positron beamline and Vacuum chamber



The view from downstream:
Vacuum chamber and Laser system





*Thanks Prof. K. Yoshimura, Okayama Univ.

Roadmap towards Ps-BEC

Doppler spectroscopy
& First laser cooling of Ps
In 2019 at KEK-SPF

Ps-BEC In ~ 5 years

Doppler spectroscopy of Ps(March 2019)

Measure the temperature of Ps by Doppler spectroscopy

- ✓ Positron system and Ps converter are ready

First Ps Laser-Cooling (in 2019)

- ✓ Essential part of cooling laser is done: long pulse and broadening
- ➢ Pulse amplification & THG

Positron system

- ➢ Many-stage Brightness Enhancement
- ➢ Spin-polarized positron buncher

Ps converter

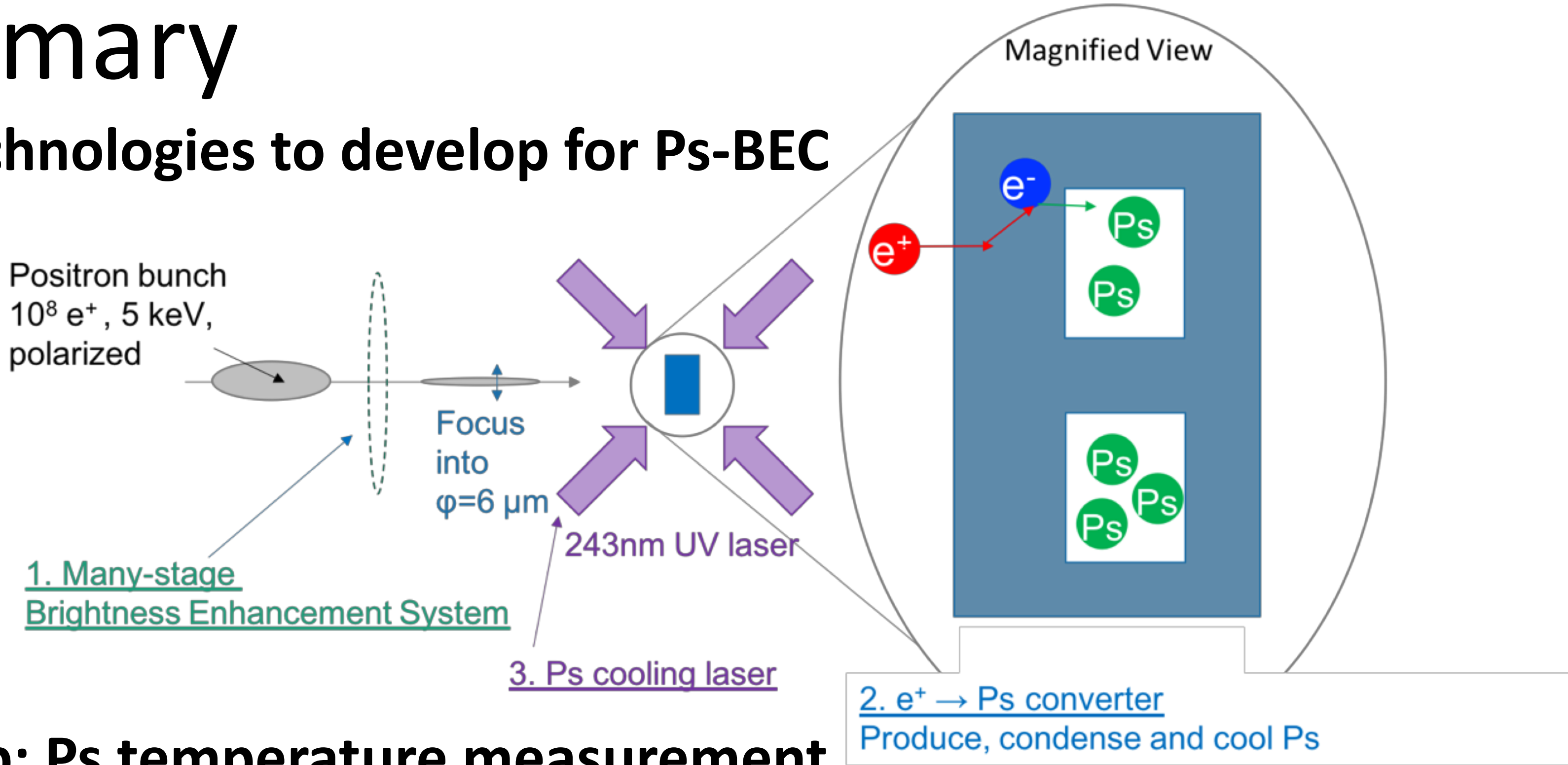
- ➢ Heat and charge up problem by dense positron

Cooling laser

- ➢ Further optimization (rapid chirping) is necessary to achieve Ps-BEC

Summary

1. Three technologies to develop for Ps-BEC



2. Next Step: Ps temperature measurement