Experimental progress towards positronium Bose-Einstein condensation

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https://tabletop.icepp.s.u-tokyo.ac.jp/?page_id=365

4th Japan-China Joint Workshop on Positron Science (JWPS2019)
TIA Kakehashi Symposium: Application of Positron Beams at Major Facilities
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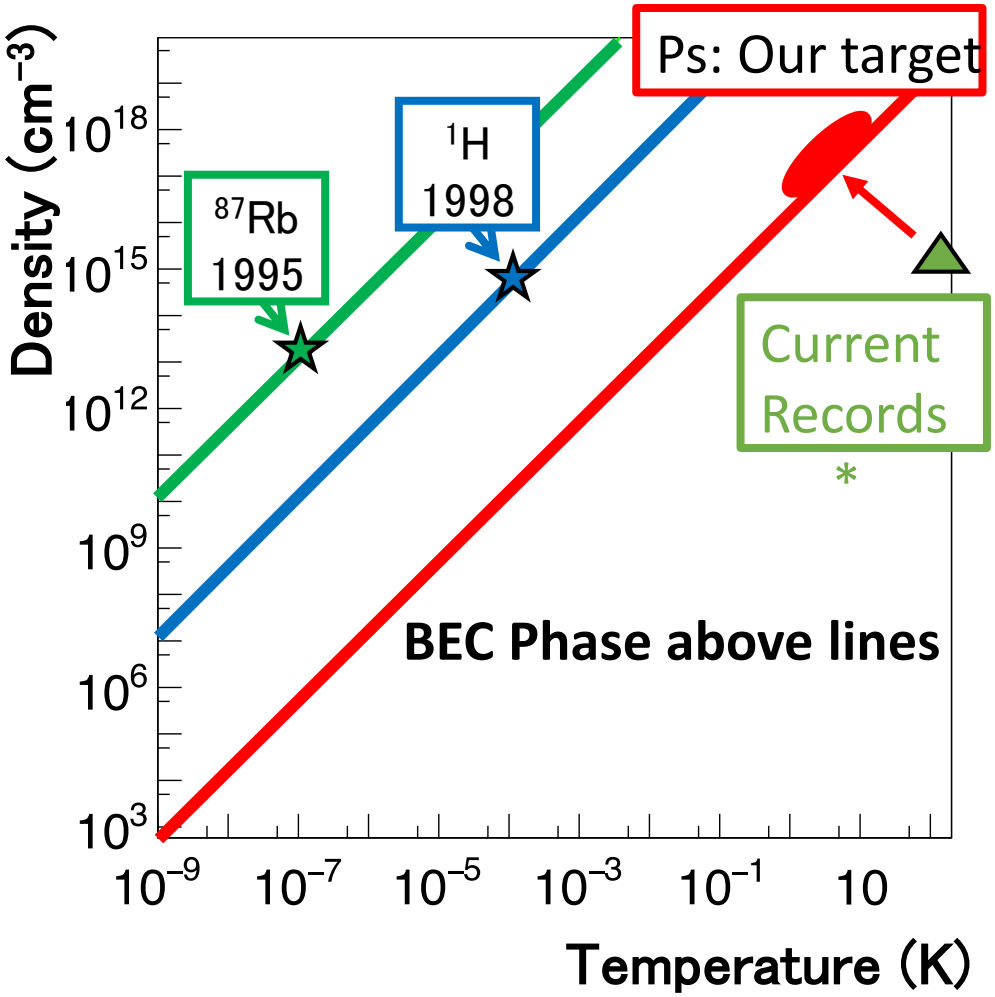
Contents

- Motivation for Ps-BEC: Good candidate for the first antimatter laser.
- Our new idea to realize Ps-BEC
  1. Positron focusing system
  2. Ps converter/condenser/cooler
  3. Ps laser cooling
- 1S-2P Ps excitation experiment by shining 243 nm UV laser

Our Target: Positronium Bose-Einstein Condensation (Ps-BEC)

- Ps must be dense and cold
- High critical temperature because of 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 the first antimatter laser and perform new experiments using the coherency of Ps-BEC.

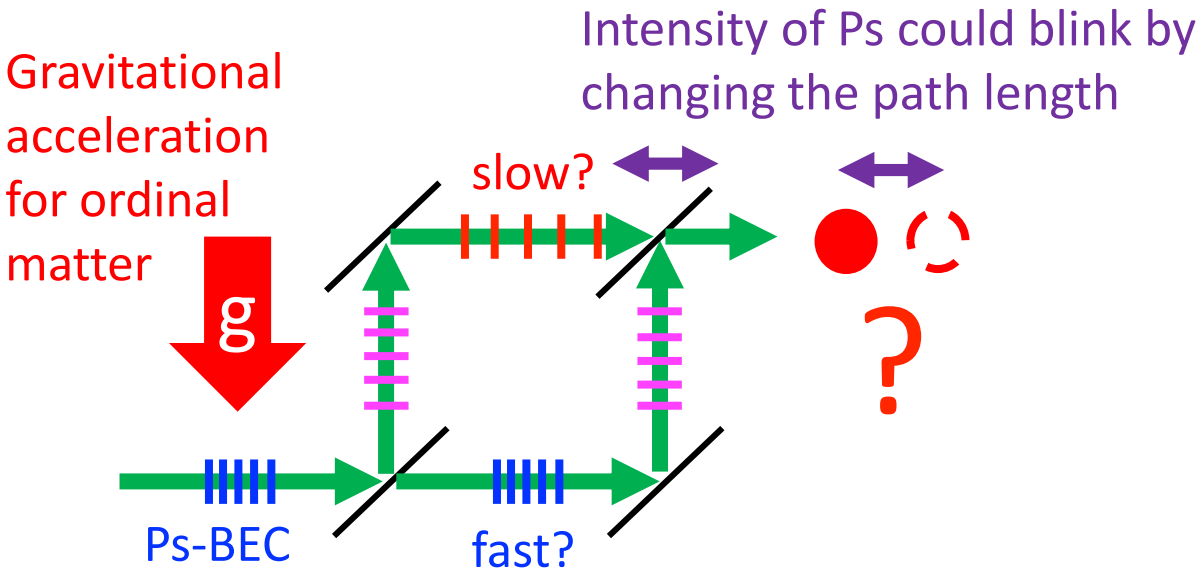


* : S. Mariazzi *et al.* Phys. Rev. Lett. 104, 243401 (2010)
* : D. Cassidy *et al.* physica status solidi 4, 3419 (2007)

Applications of Ps-BEC for fundamental physics

1. <u>Antimatter gravity:</u>

Build Ps-BEC atomic interferometer to see gravitational effect on antimatter.

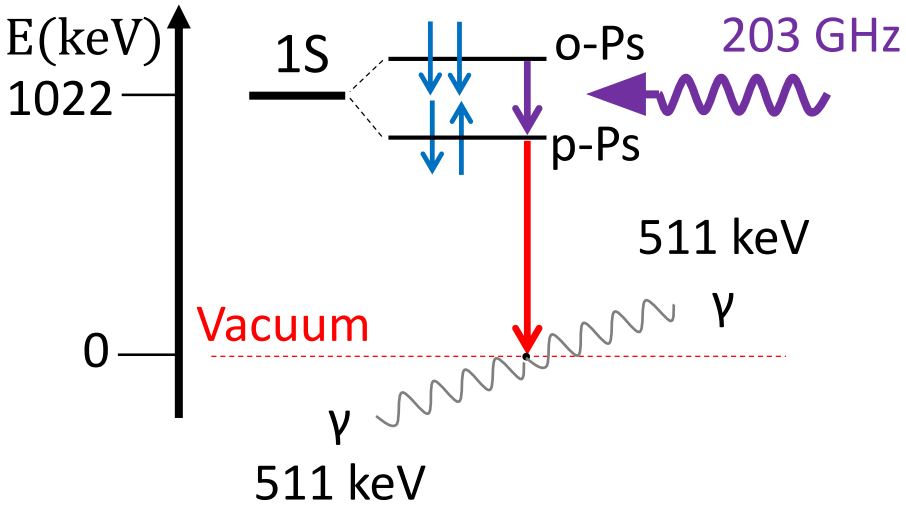


- Gravity could shift phase of Ps in different paths

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

Applications of Ps-BEC for applied physics

2. 511 keV γ-ray laser



- *o*-Ps BEC to *p*-Ps by 203 GHz RF
- *p*-Ps BEC collectively decays into coherent 511 keV gamma-rays

Phys. Rev. A 92, 023820 (2015)

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

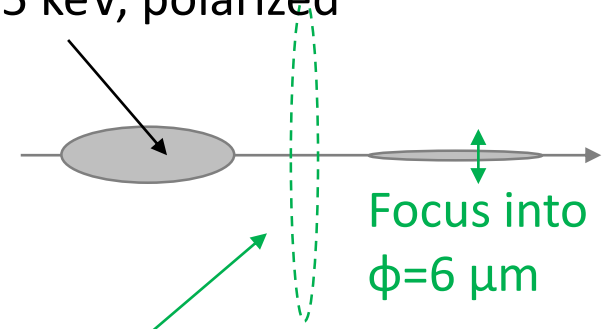
Our new idea:

3 technologies to realize Ps-BEC

Our new idea to realize Ps-BEC

1. Positron focusing system

Nanosecond positron bunch
1.5x10^8 e^+ , 5 keV, polarized



1. Many-stage
Brightness Enhancement System
Create dense positron bunch
(Hashidate, S-02)

Our new idea to realize Ps-BEC

1. Positron focusing system
2. Ps converter/condenser/cooler

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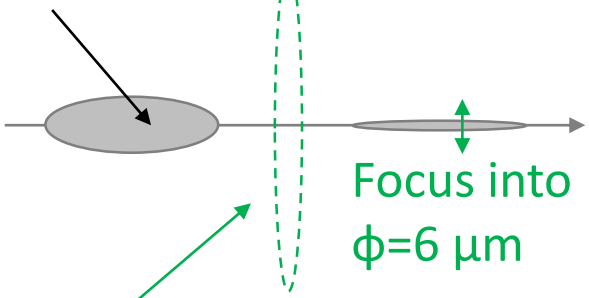
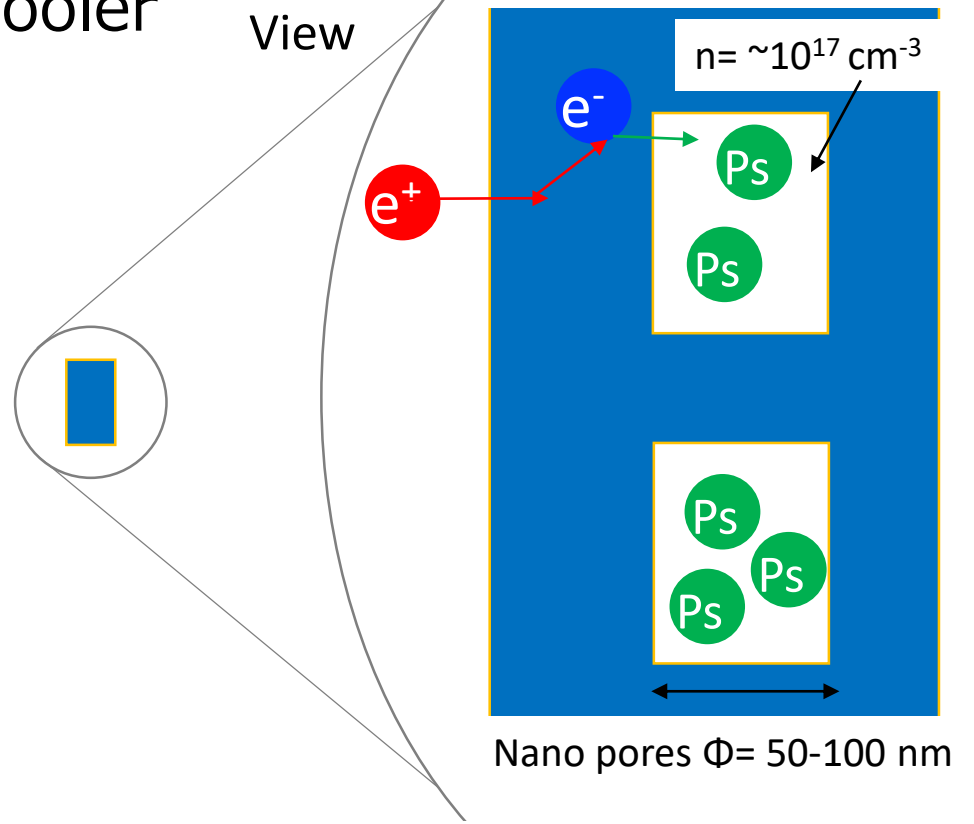


Focus into
ϕ=6 μm

1. Many-stage
Brightness Enhancement System
Create dense positron bunch
(Hashidate, S-02)

Magnified View

Cool down to 4K by cryogenic refrigerator



2. $e^+ \rightarrow$ Ps
converter/condenser/cooler
Silica (SiO_2)
(Shu, S-03)

Our new idea to realize Ps-BEC

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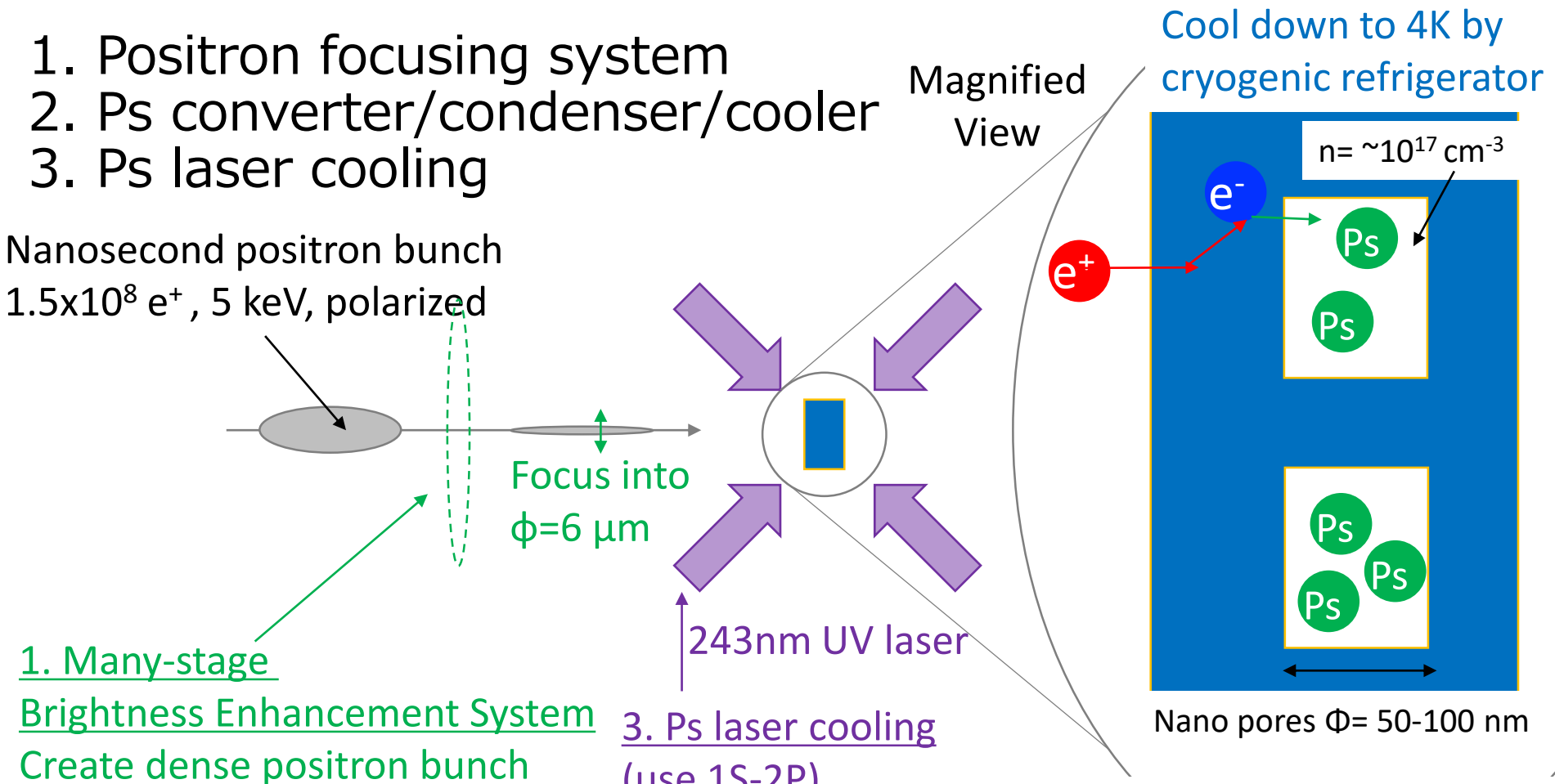
2. Ps converter/condenser/cooler
3. Ps laser cooling



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

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

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

1.Thermalization

- Efficient at > 200 K

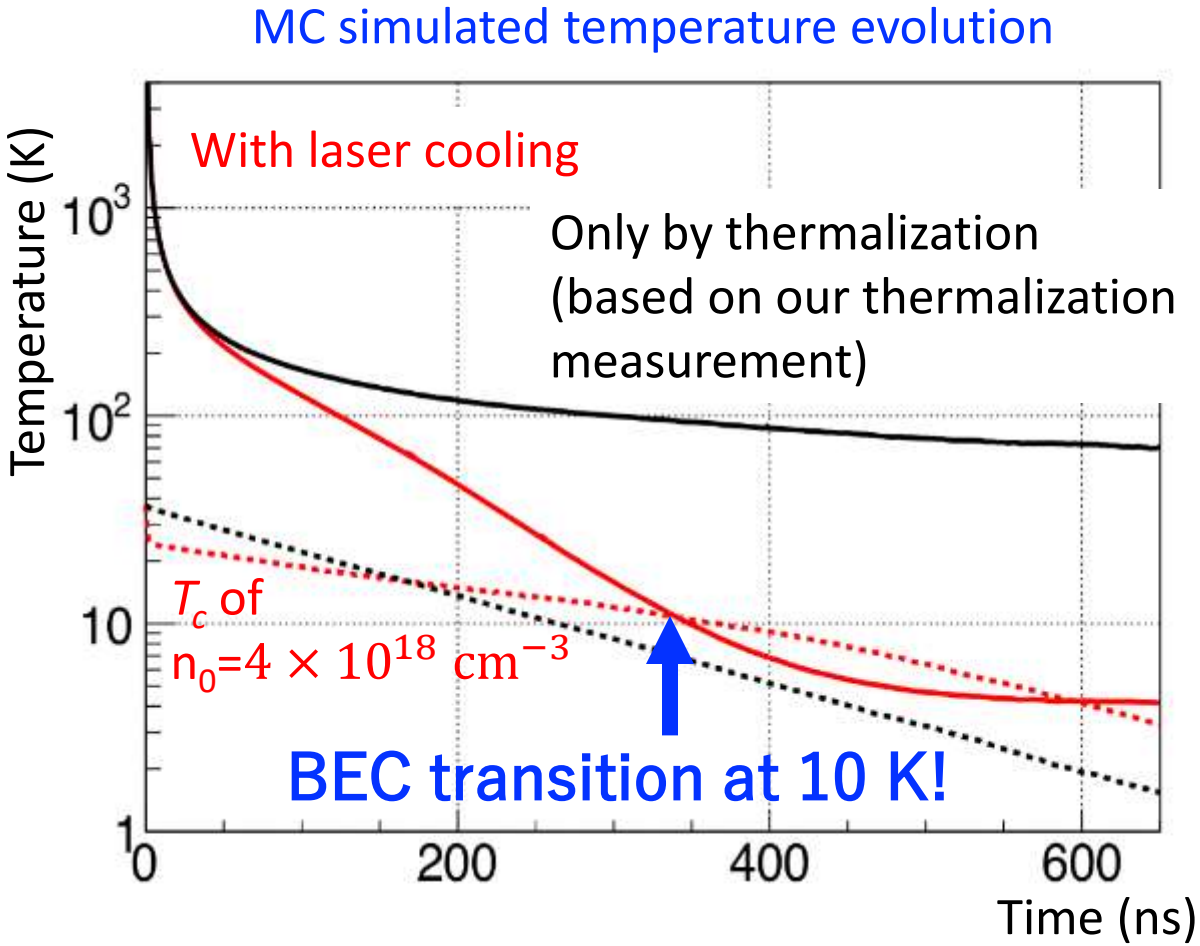
Initial Ps energy is 0.8 eV = 6000 K.
Cooling Ps down to 100 K

2.Laser cooling

- Efficient at < 200 K

Cooling Ps down to < 10 K is possible

✓ Combining these two methods is essentially important



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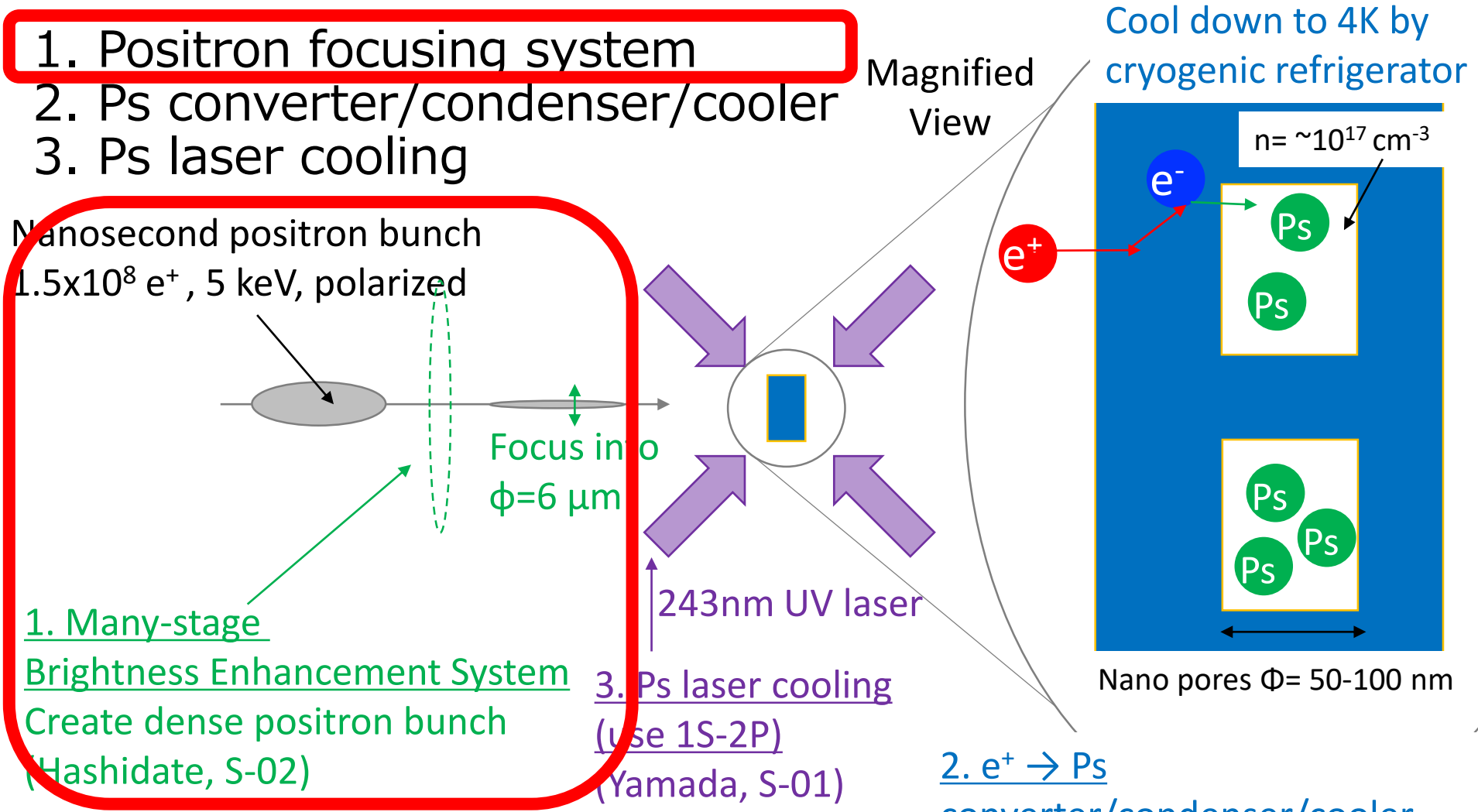
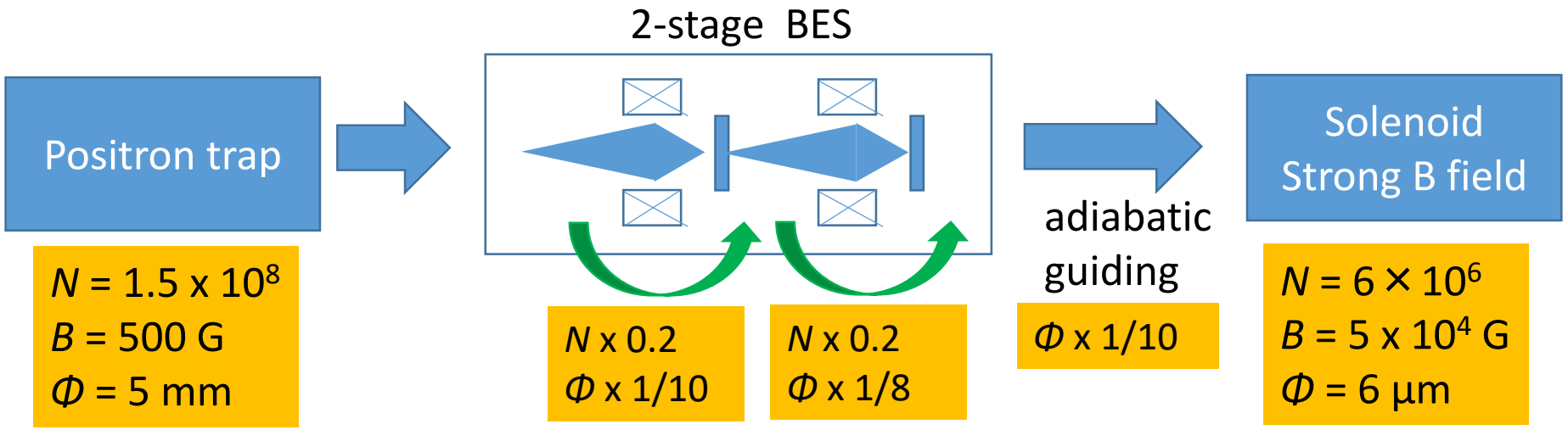


Combine thermalization and laser cooling to cool Ps down to 10 K in 300 ns

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

Our method to achieve dense enough e^+ bunch for Ps-BEC

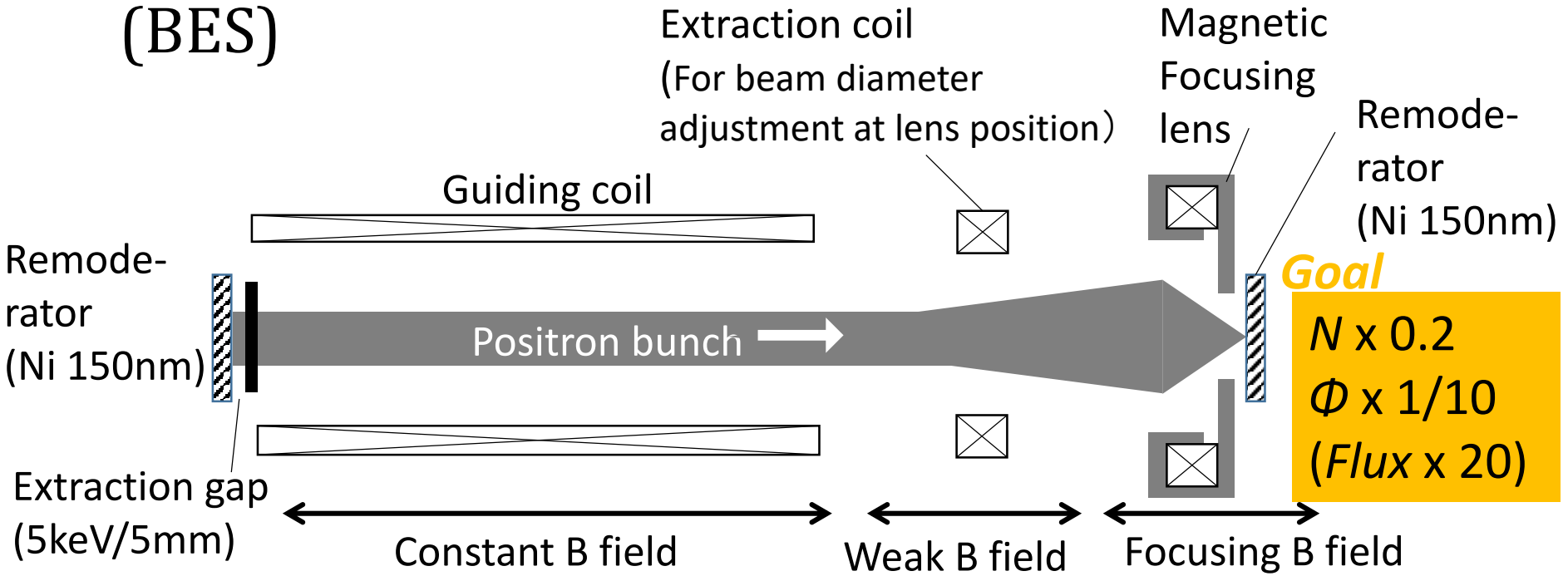
Trap → 2-Stage Brightness enhancement system (BES) → Solenoid (strong B fields)



We have shown that a high-enough density for Ps-BEC could be reached by the model.

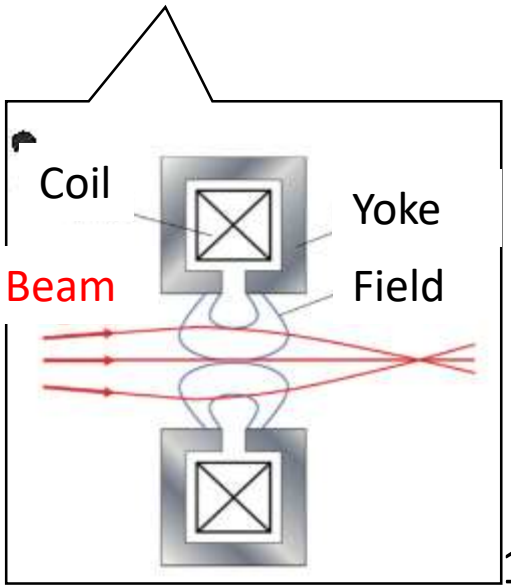
We have considered (1) space charge limited current density (Child-Langmuir law), (2) Brillouin flow, and (3) the beam envelope equation including space charge effect. (N. Oshima, ICPA-18)

Positron Brightness Enhancement System (BES)

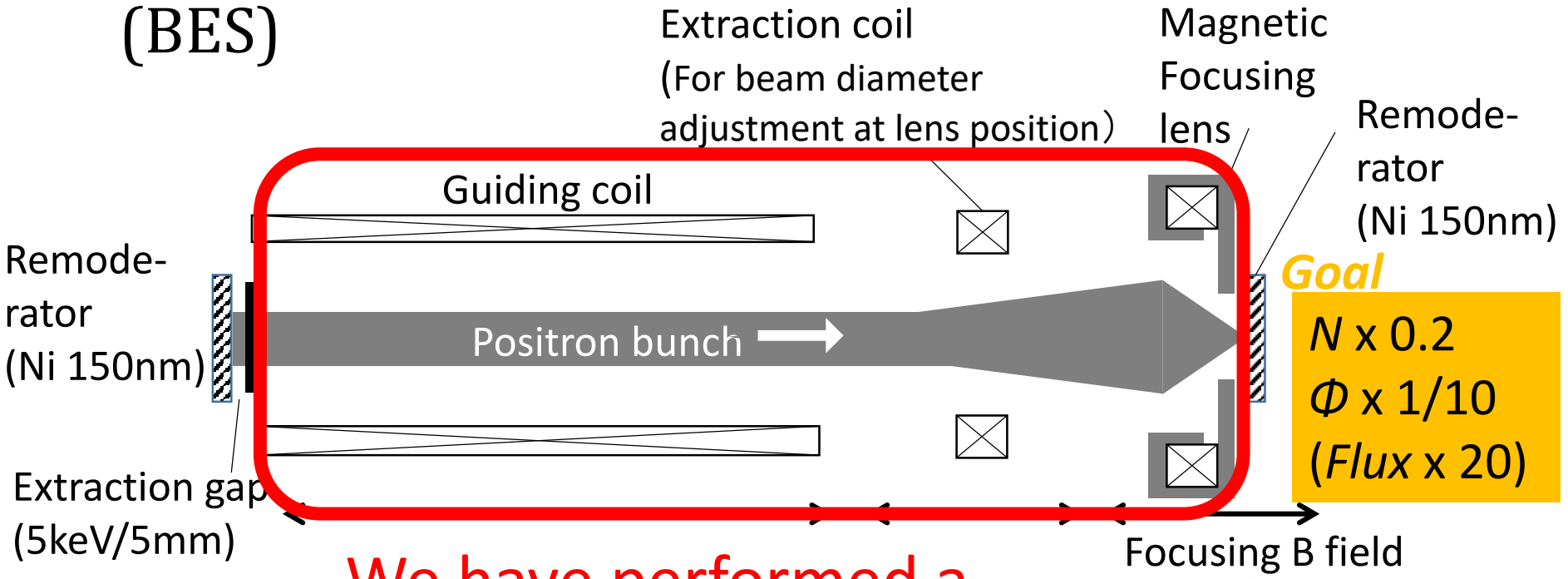


- This system consists of solenoids and a magnetic focusing lens

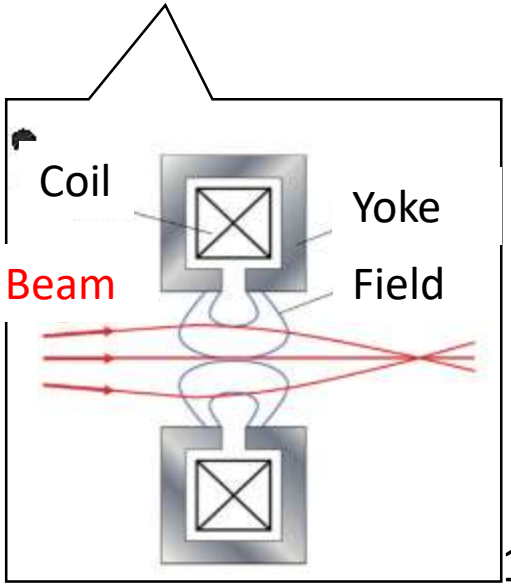
1. slow positron beam is magnetically guided with solenoids.
2. The beam is extracted from the constant B field to the weak B field
3. The beam is focused by the magnetic focusing lens



Positron Brightness Enhancement System (BES)



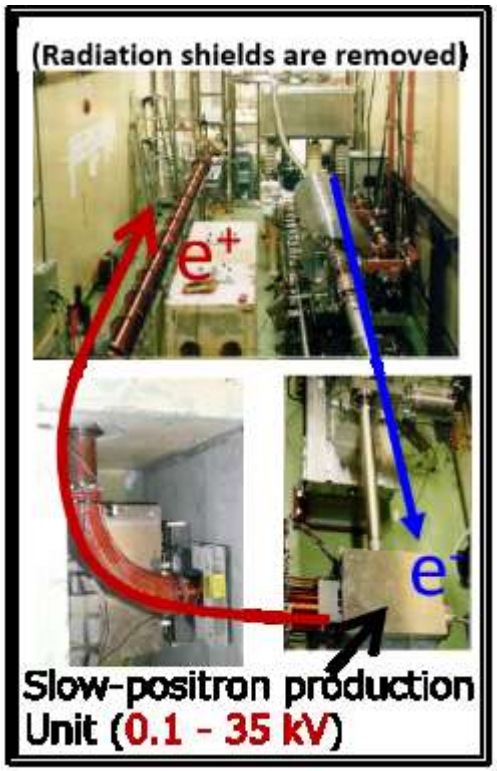
We have performed a test experiment to focus positron beams.

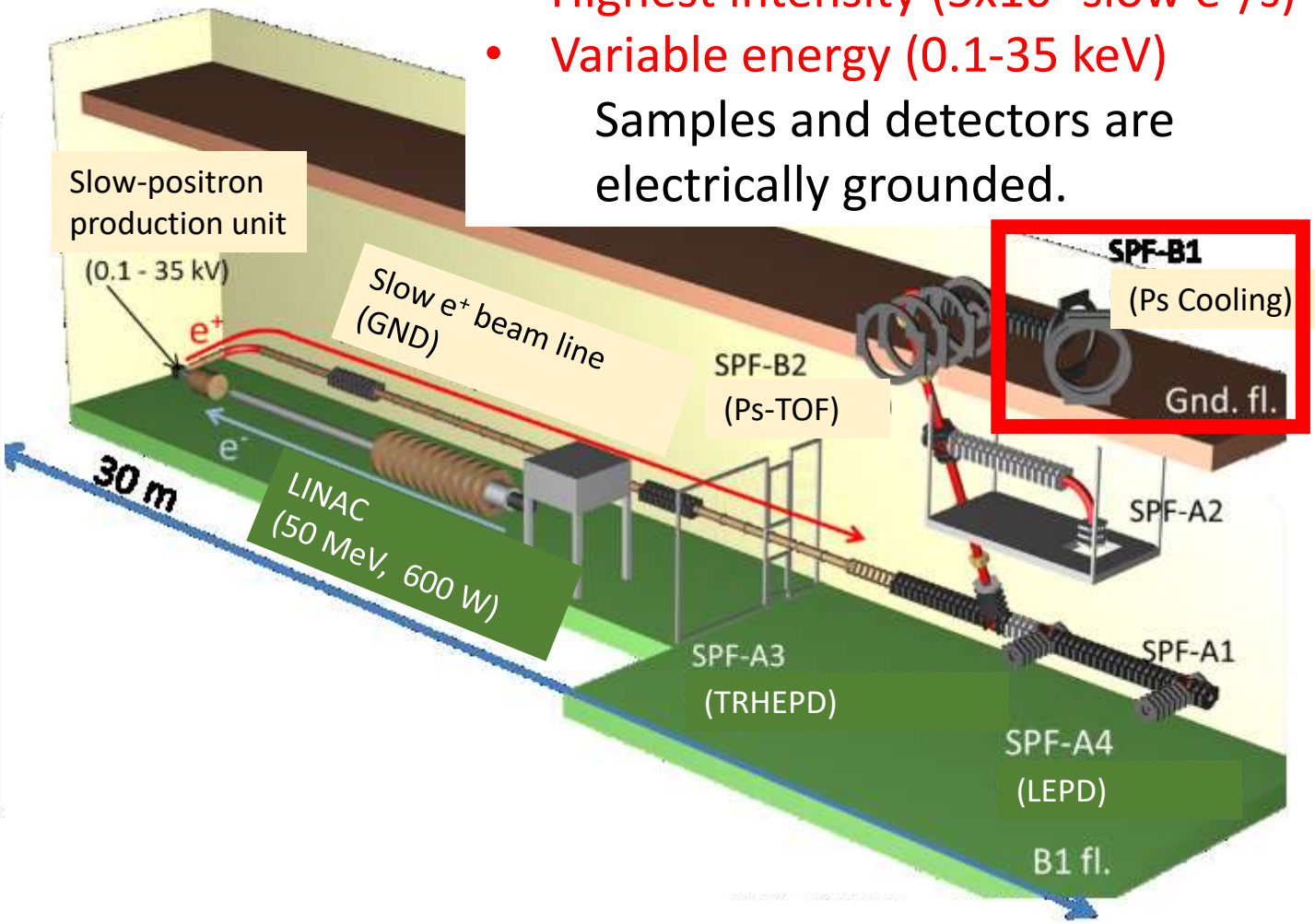


We have performed a test experiment to focus positron beams at KEK-SPF (Slow Positron Facility), Tsukuba, Japan

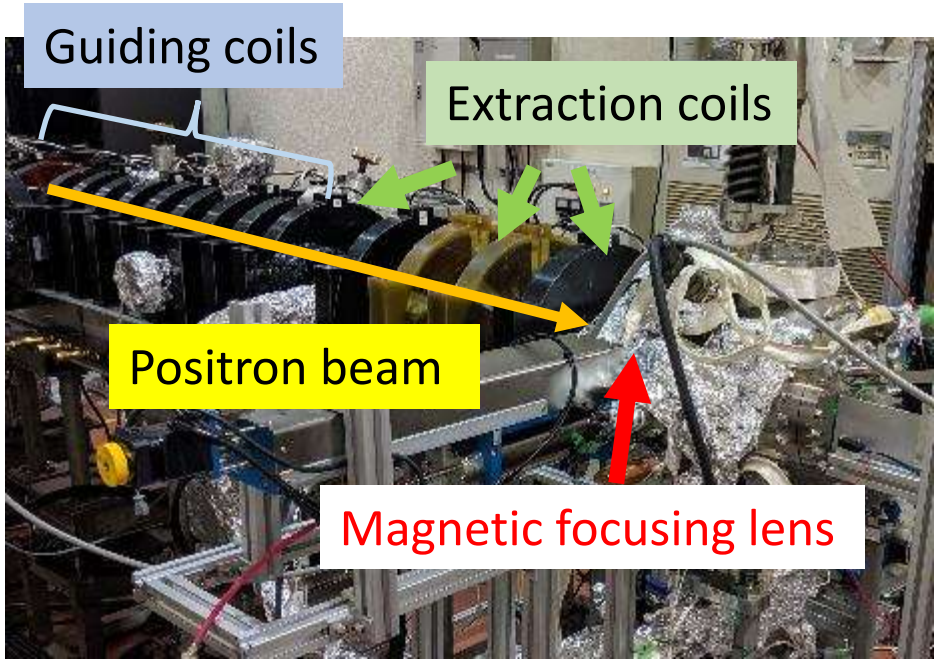
- Highest intensity (5×10^7 slow e^+/s)
- Variable energy (0.1-35 keV)

  Samples and detectors are electrically grounded.

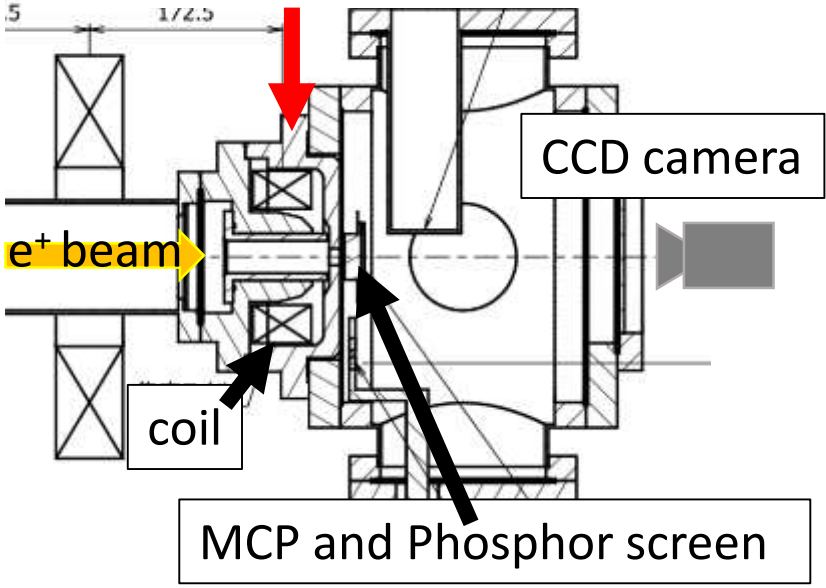




Positron focusing test experiment at KEK-SPF



Magnetic focusing lens
(prototyped by AIST)



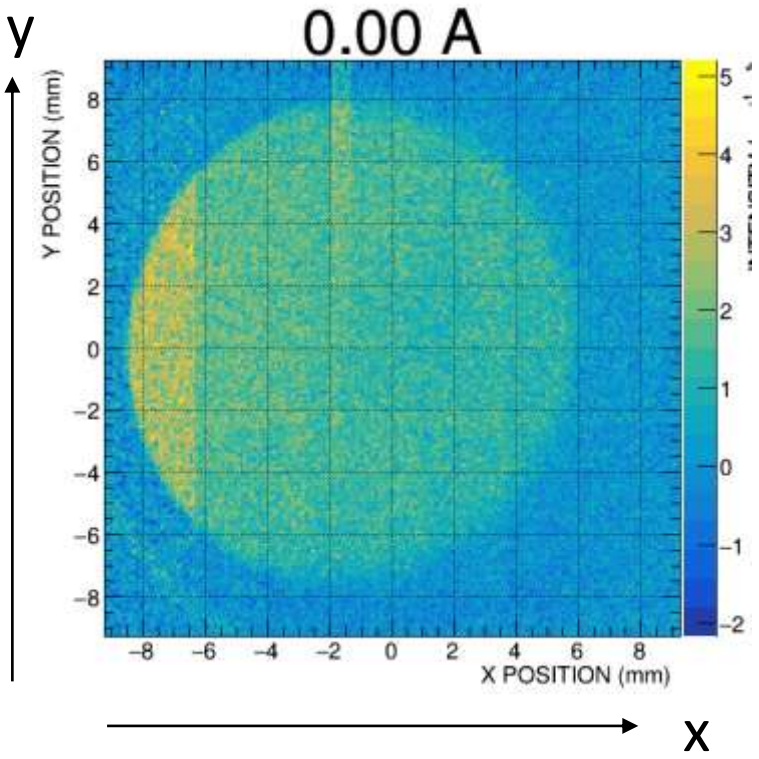
Beam profiles

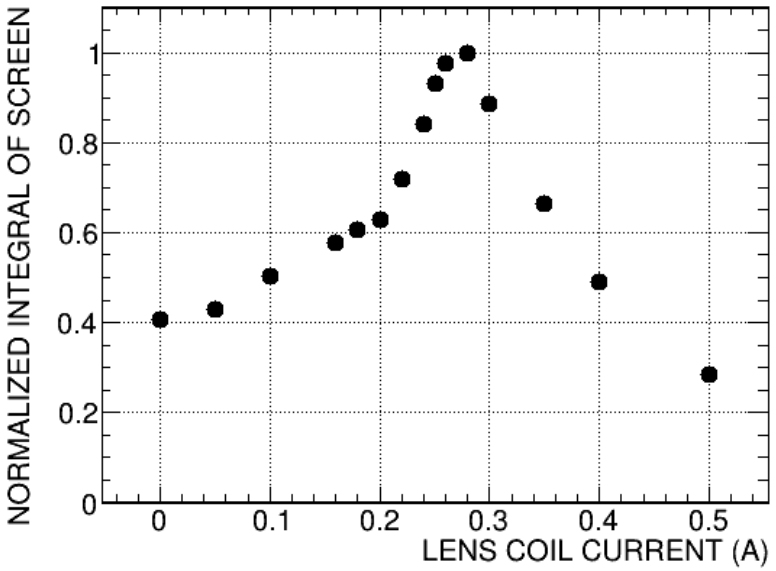
- Energy : 5 keV
- Intensity : $5 \times 10^5\ e^+/s$
- Pulse repetition : 50 Hz
- Pulse width : 16 ns

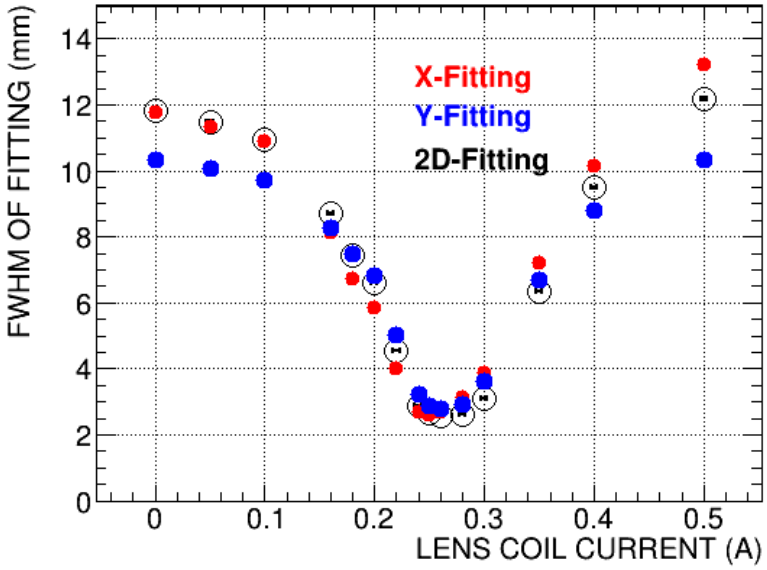
We observed the image of MCP / Phosphor screen recorded by a CCD camera.
This focusing lens will be used for Ps laser cooling experiment at the same beamline if it has a good enough performance.

The beam has been focused. Detailed analysis is ongoing.

CCD image



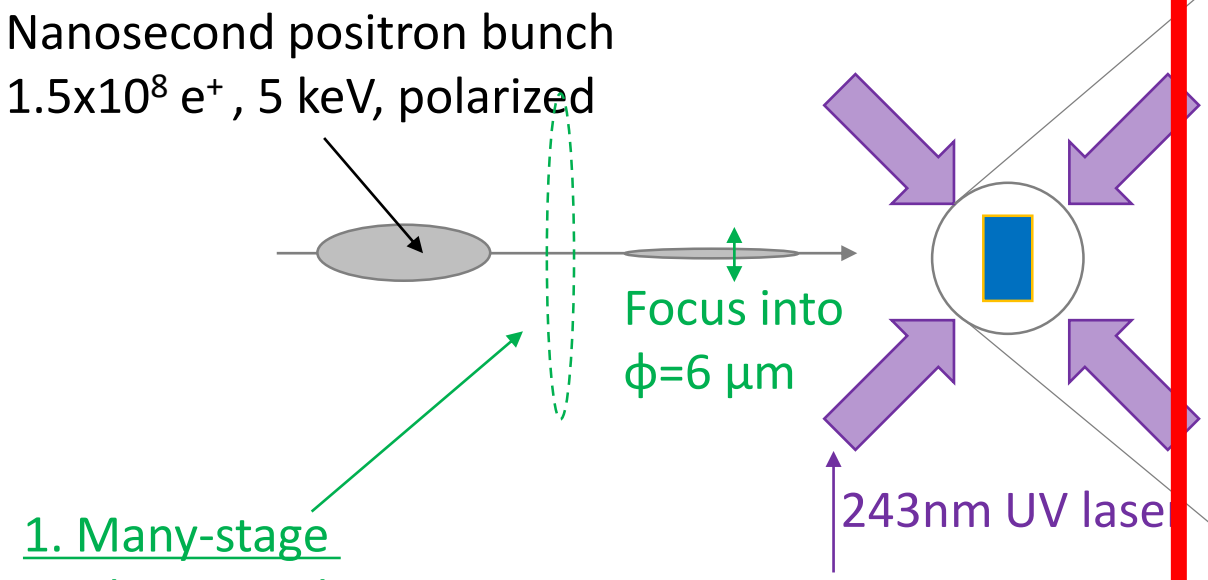




→ *K. Hashidate (Nov. 1, S-02)*

Details of each component

1. Positron focusing system
2. Ps converter/condenser/cooler
3. Ps laser cooling

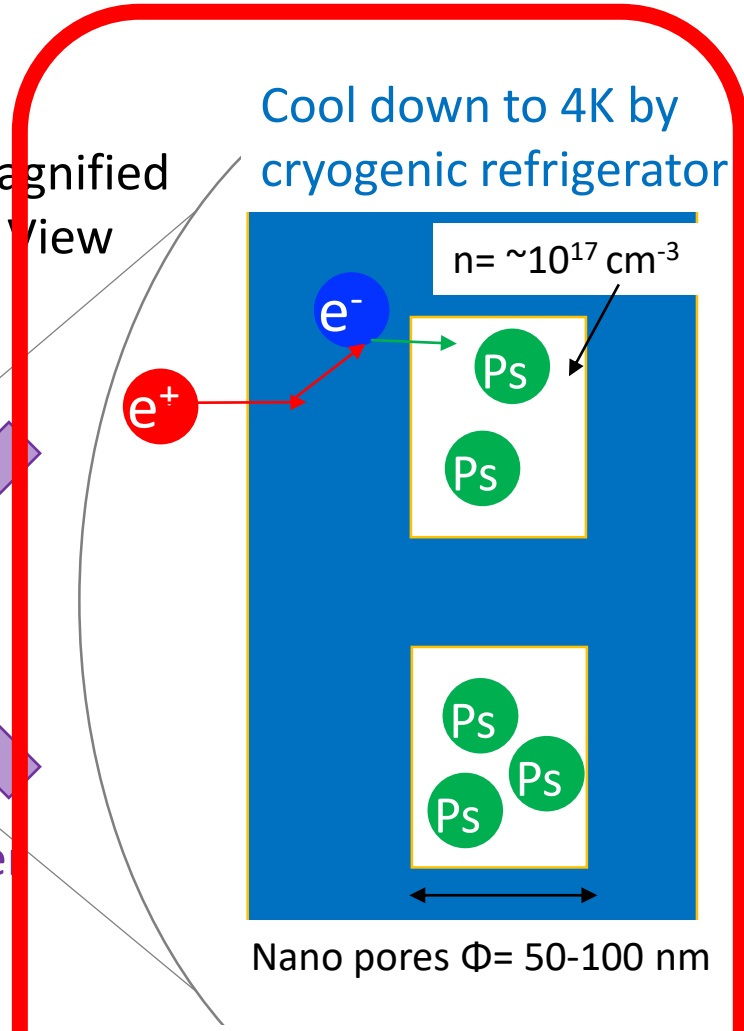


1. Many-stage Brightness Enhancement System
Create dense positron bunch
(Hashidate, S-02)

3. Ps laser cooling (use 1S-2P)
(Yamada, S-01)

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

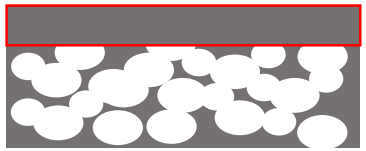
K. Shu *et al.* J. Phys. B 49, 104001 (2016)



2. e$^+$ → Ps generator/condenser/cooler
Silica (SiO_2)
(Shu, S-03)

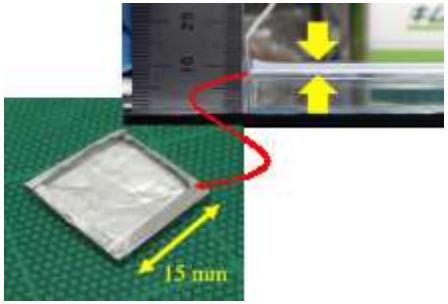
Silica (SiO_2) aerogel is a good candidate. Capped the surface of the aerogel by amorphous silica thin film using plasma CVD.

Silica aerogel 0.1 g cm^{-3}
50 nm pores

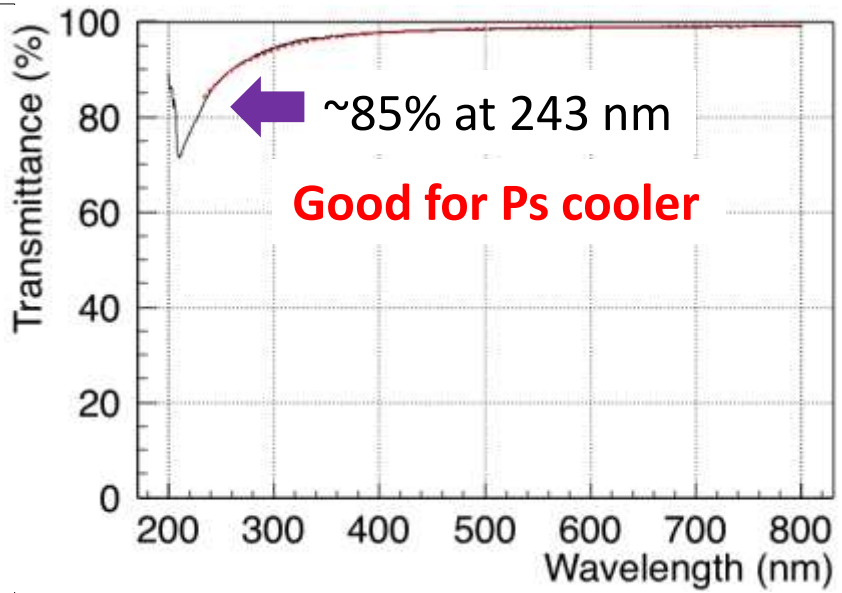


CVD 75 nm

Silica aerogel 0.5 mm



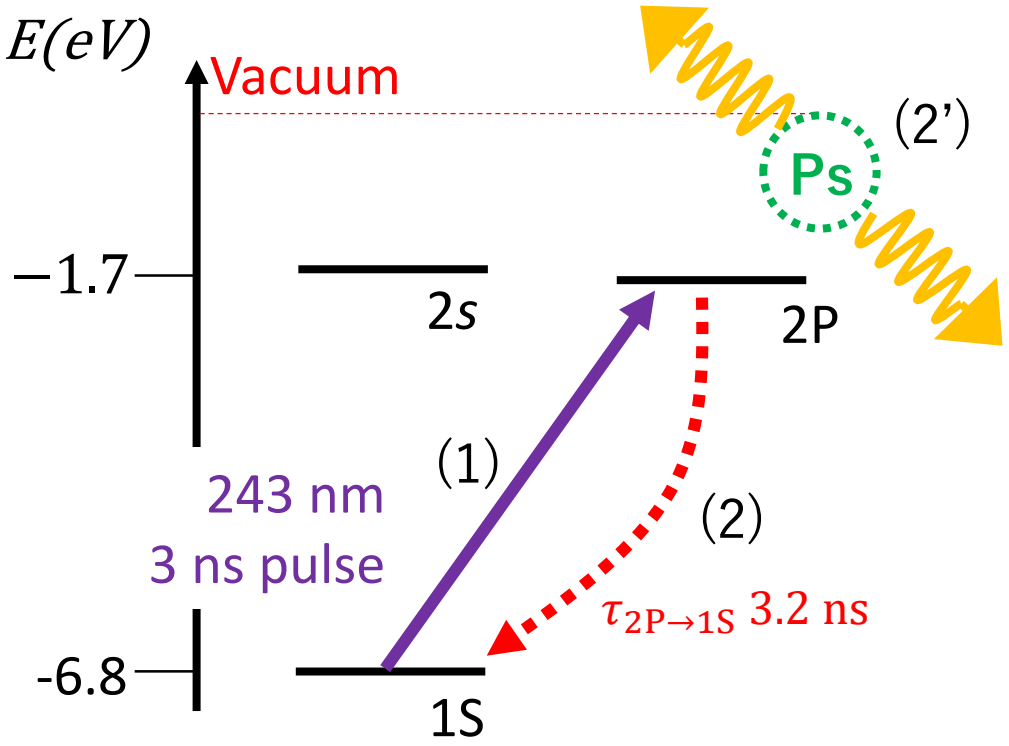
$\tau = 129.9 \pm 1.1$ ns
I = 13%
Good for Ps generator/condenser



Parallel light transmittance measured by spectrophotometer with t0.5mm silica aerogel

Timing spectrum of bulk-PALS measurement using ^{22}Na with t=1 mm silica aerogel

Test experiment to Excite Ps inside the silica aerogel pores to 2P state by shining 243 nm, 3 ns pulsed UV laser.



Ps energy levels

Core process of the Ps laser cooling

(1) Excite Ps to 2P state by shining 243 nm UV laser.

(2) If nothing special happens...

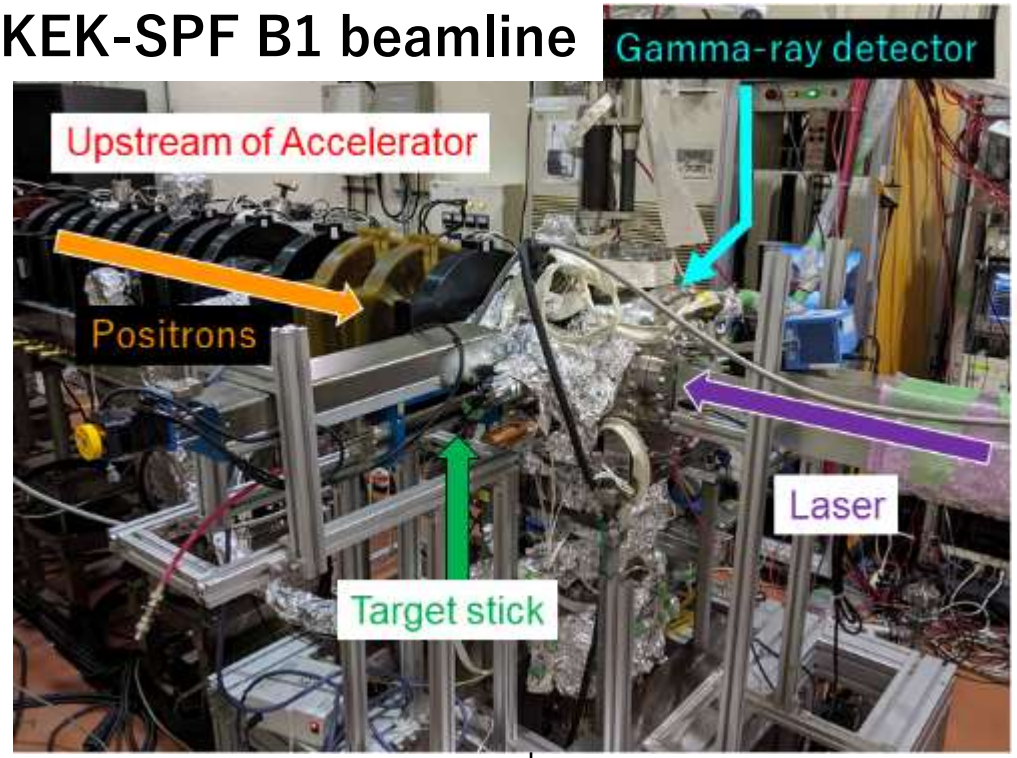
- Ps is de-excited to 1S state with lifetime of 3.2 ns (Lyman-alpha).
  →Good for laser cooling

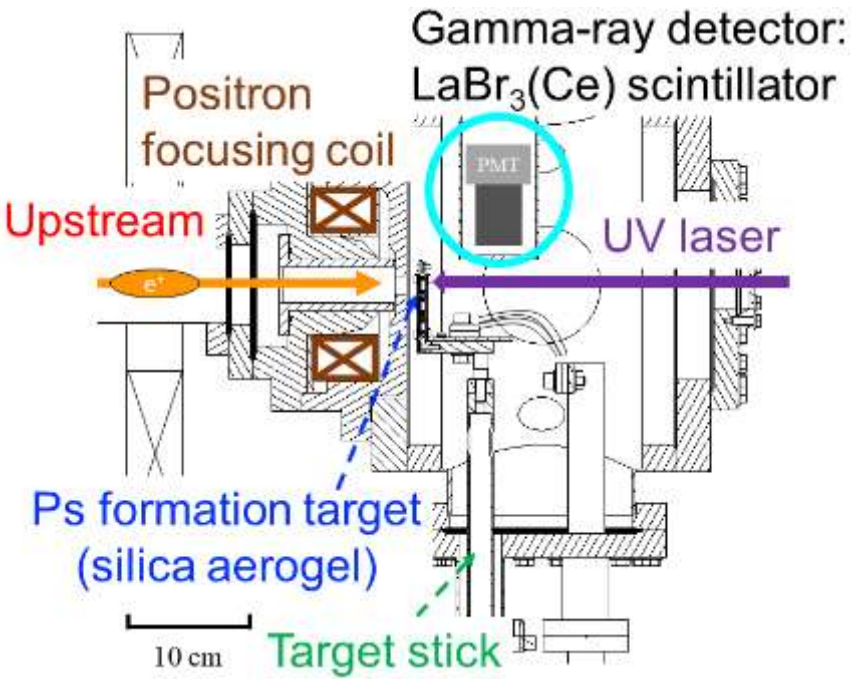
(2') If lifetime of 2P-Ps inside pores is short as reported in B. S. Cooper et al. PRB 97, 205302 (2018)....

- Annihilation rate to gamma-rays is increased.
  →Bad for laser cooling

Experimental setup at KEK slow positron facility (KEK-SPF) in Tsukuba, Japan

KEK-SPF B1 beamline



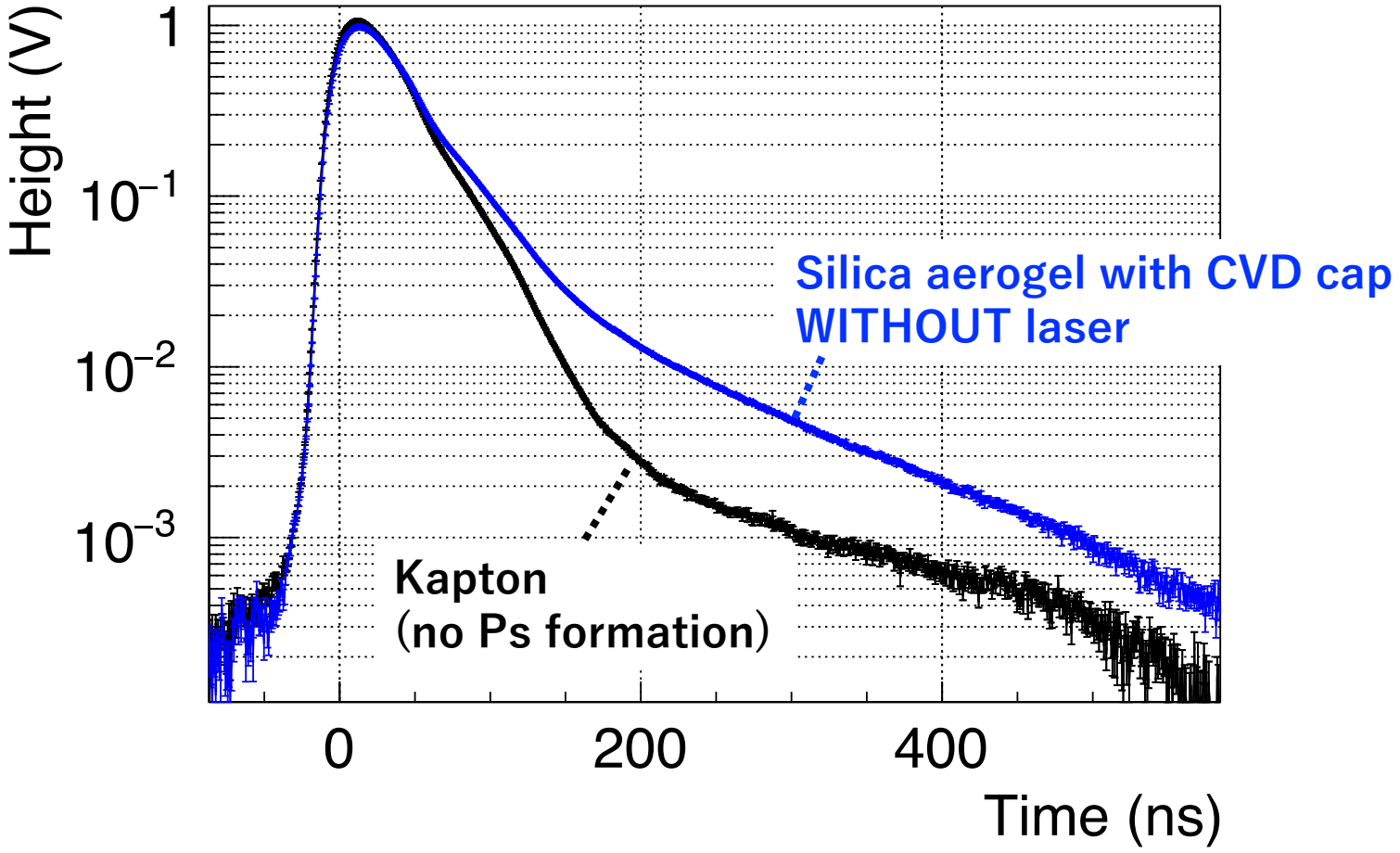


Energy	5 keV
Intensity	～10^4 e^+/ pulse
Repetition	50 Hz
Pulse width	16 ns
Size	Φ ～10 mm

Vacuum chamber

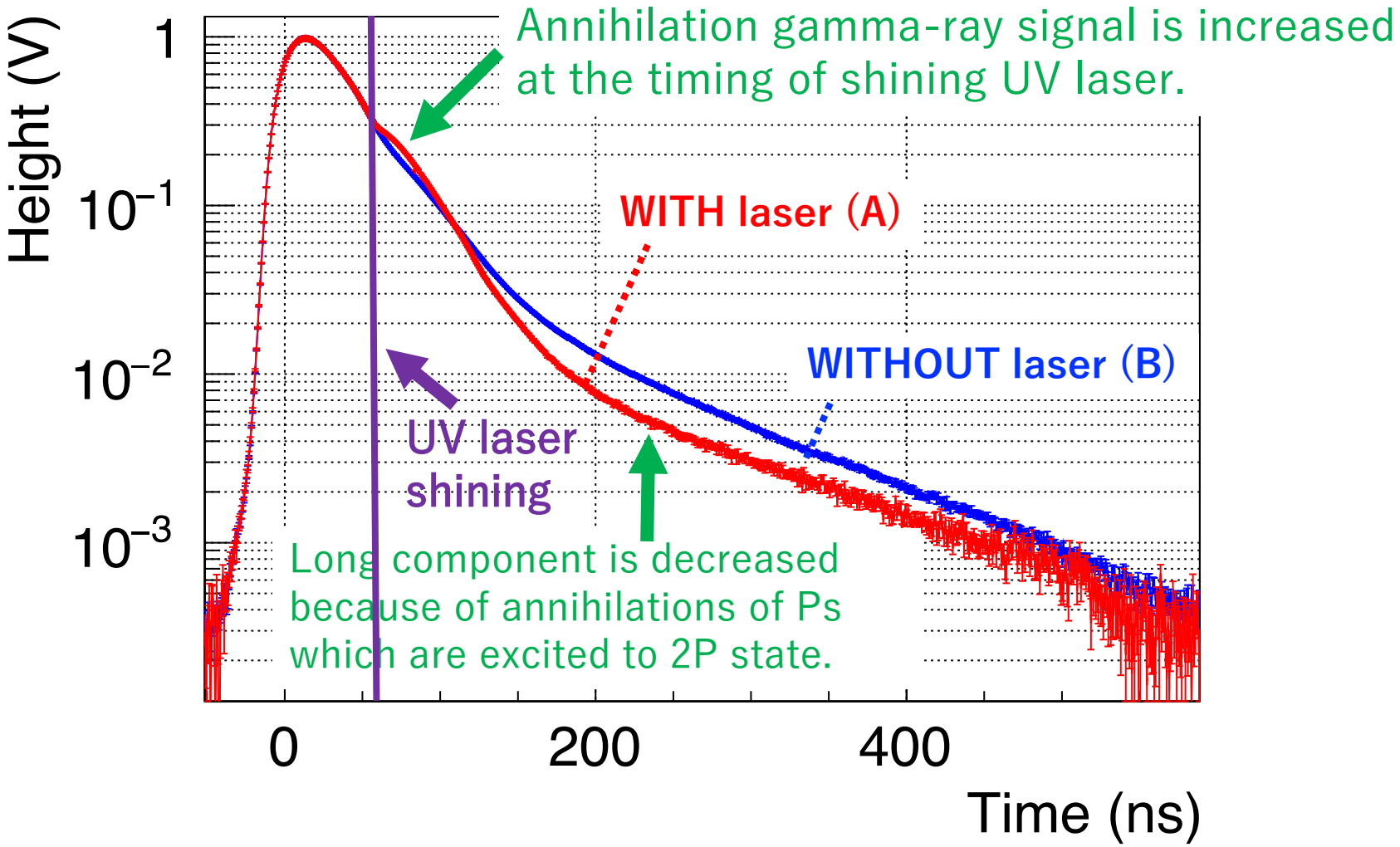
Positrons are focused to 3 mm so that it matches the laser size.

Slow component of o-Ps annihilations is observed in silica-aerogel timing spectrum without shining UV laser.



PMT signals made by annihilation gamma-rays detected by $LaBr_3(Ce)$ scintillator (absolute signal height)

2P-Ps annihilates into gamma-rays immediately in silica aerogel.



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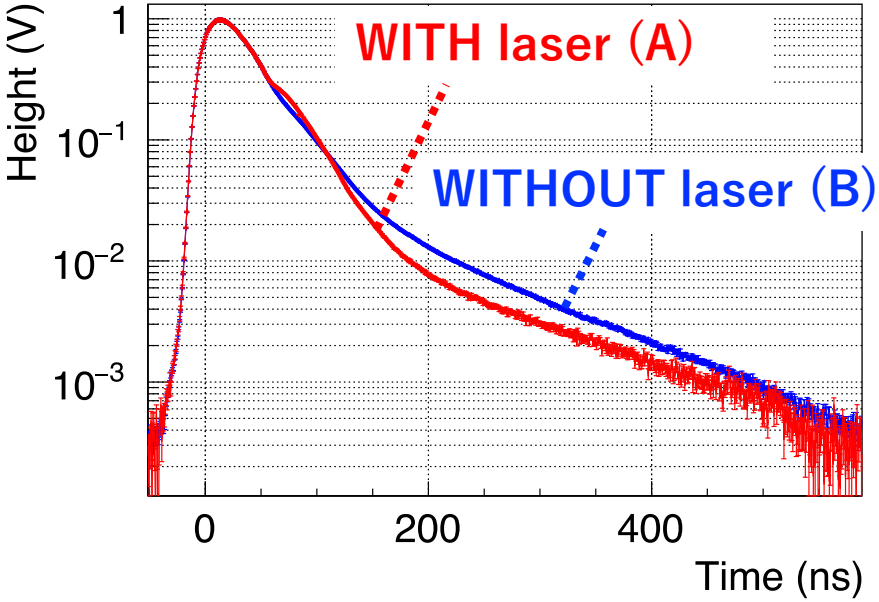

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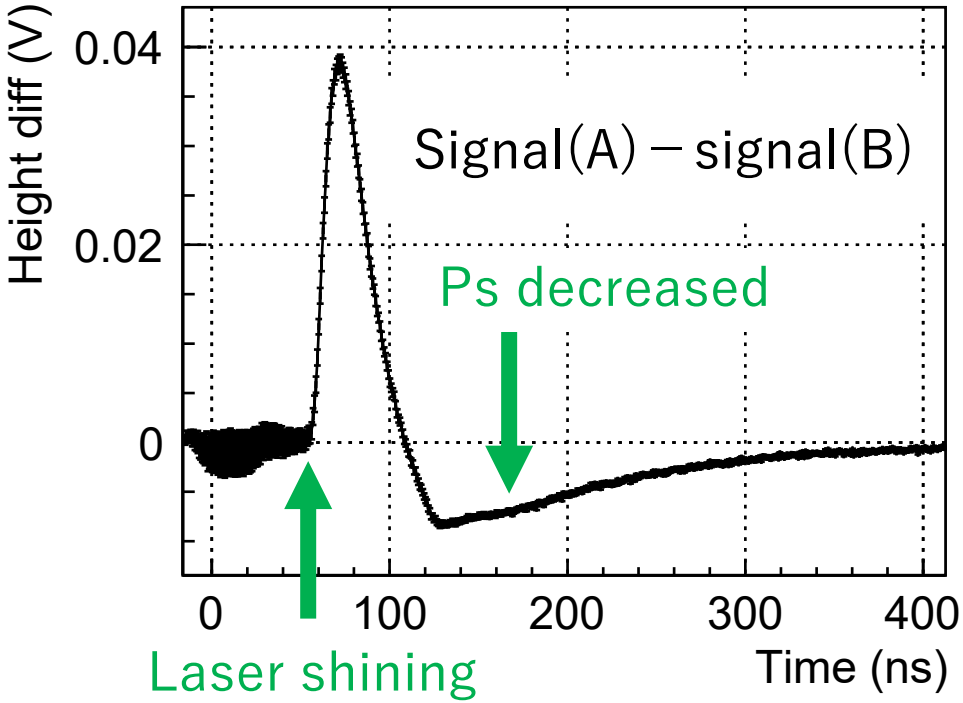


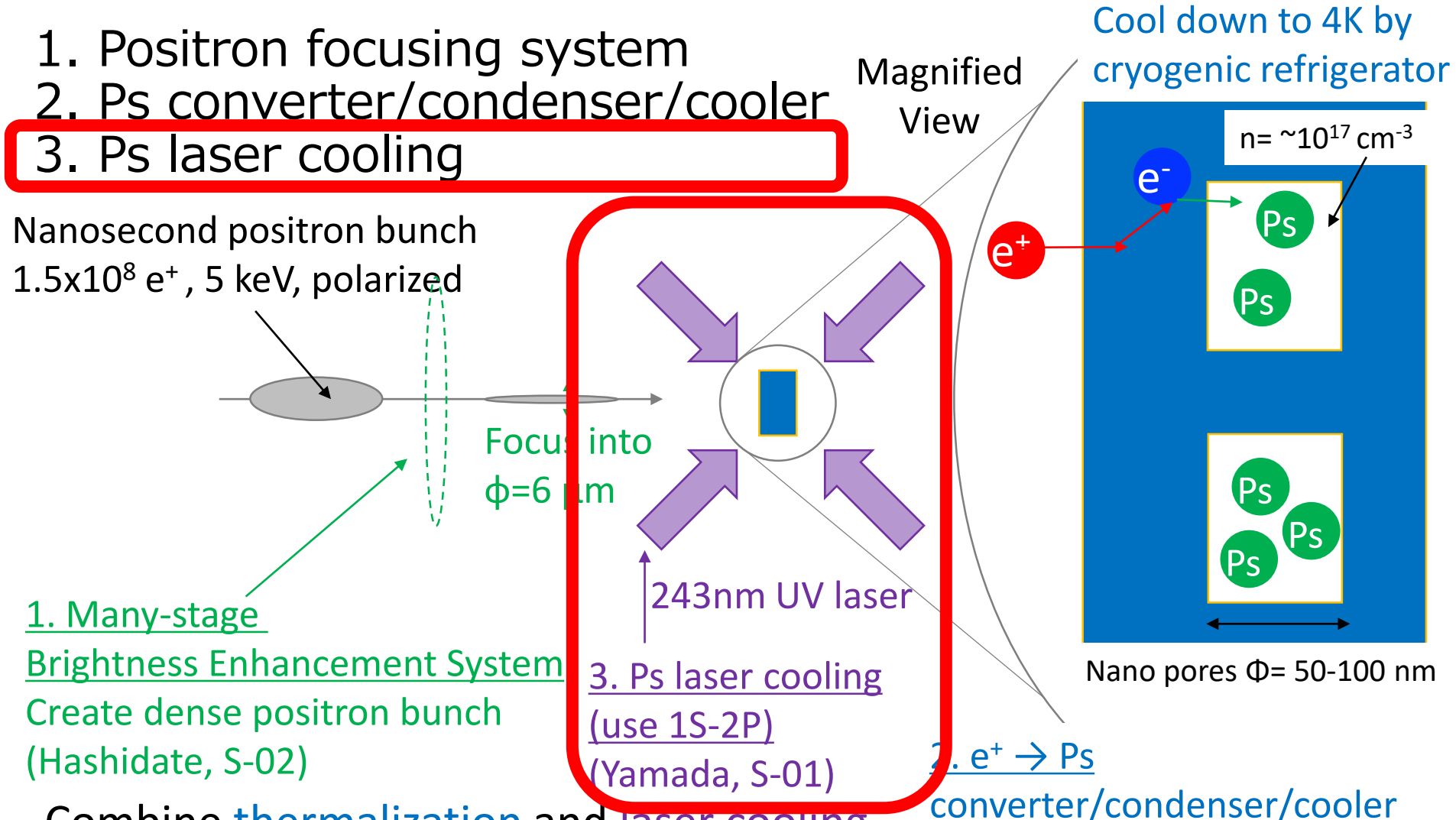
Signal difference caused by shining UV laser

Only UV laser of 300 μJ pulse caused Ps annihilations to gamma-rays. Lifetime of 2P-Ps is short in silica aerogel. This means **Ps laser cooling inside the silica aerogel pores is very difficult. Next step: Ps laser cooling in vacuum**

→ K. Shu (Nov. 1, S-03)

Details of each component

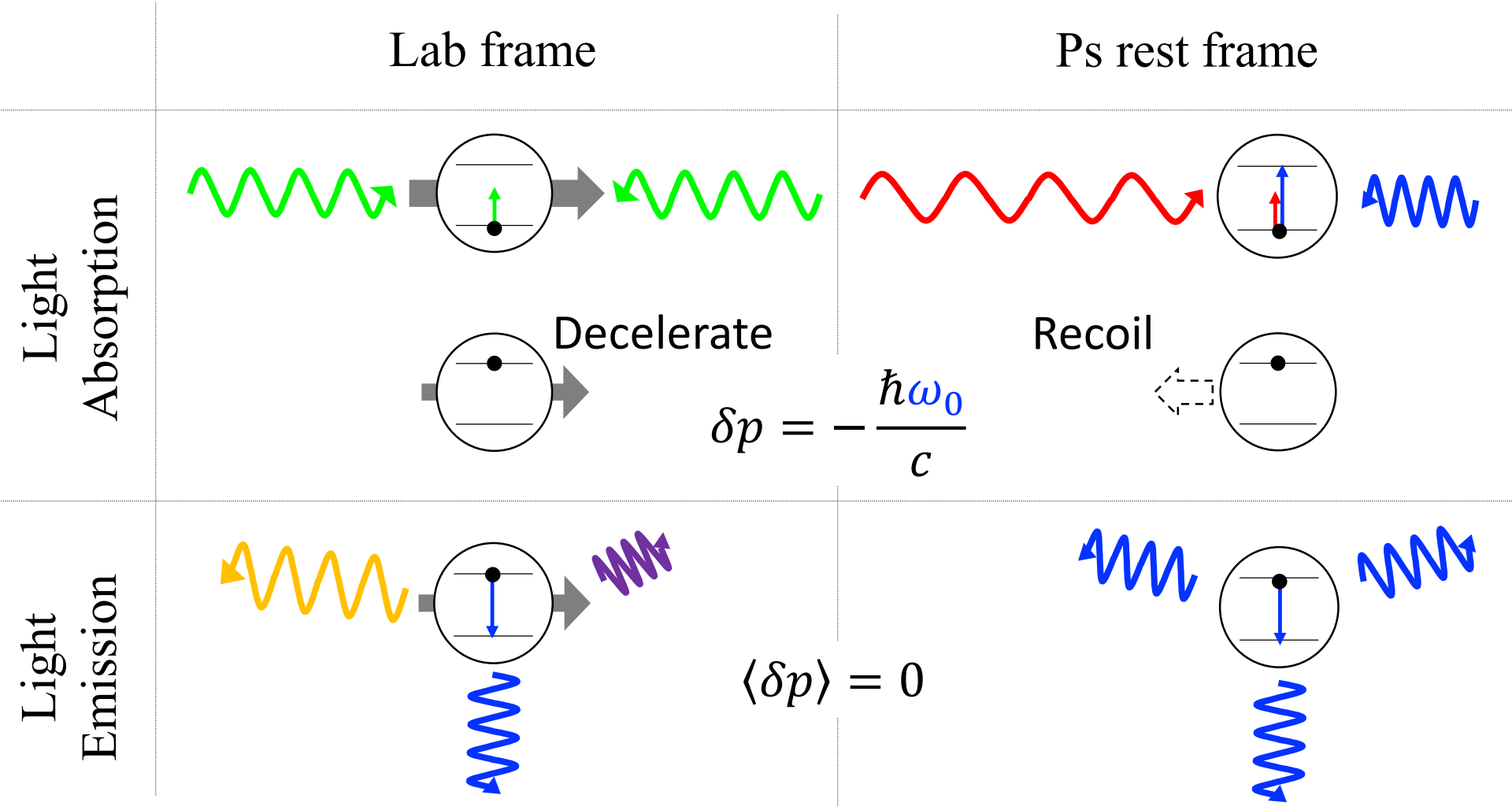
1. Positron focusing system
2. Ps converter/condenser/cooler
3. Ps laser cooling



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

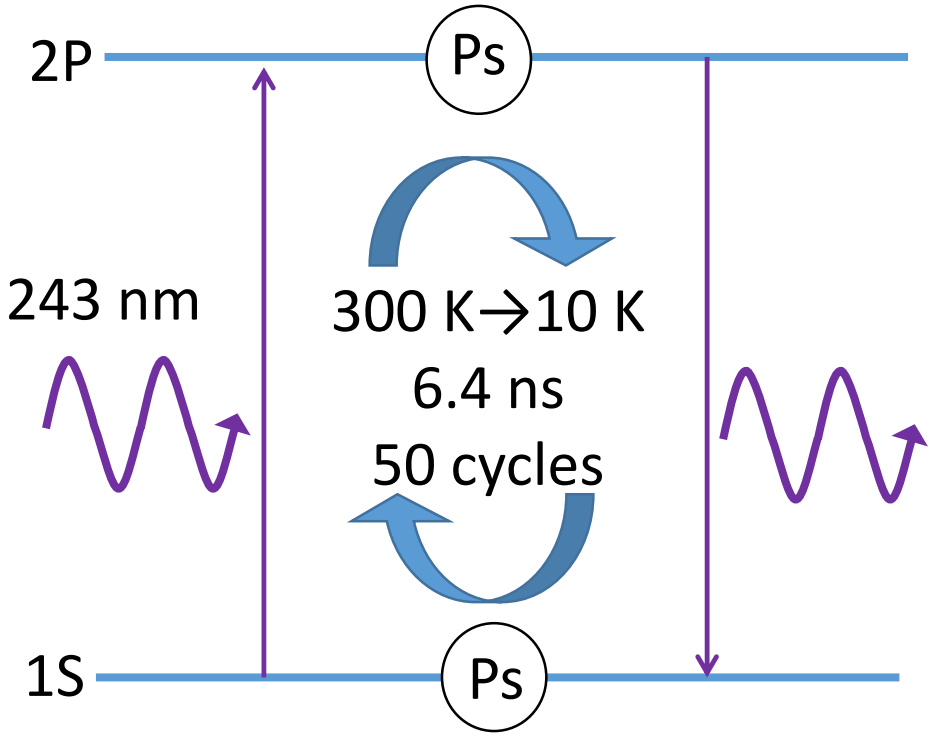
K. Shu *et al.* J. Phys. B 49, 104001 (2016)

Principle of Laser Cooling
(Doppler cooling)



Two Requirements for Ps Laser Cooling

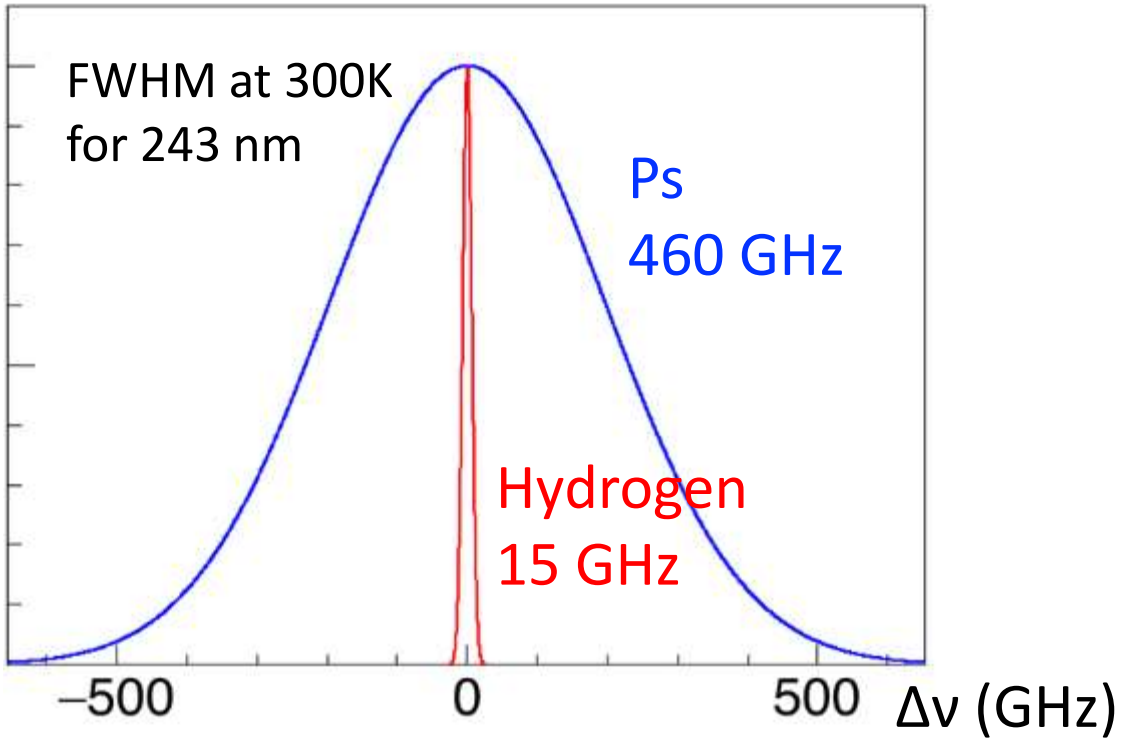
1. Long-pulsed laser



- 6.4 ns × 50 ~ 300 ns
- Complete the laser cooling within a single 300 ns long pulse (~ Ps lifetime 142 ns)

Two Requirements for Ps Laser Cooling

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.

Overview of the cooling laser system

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

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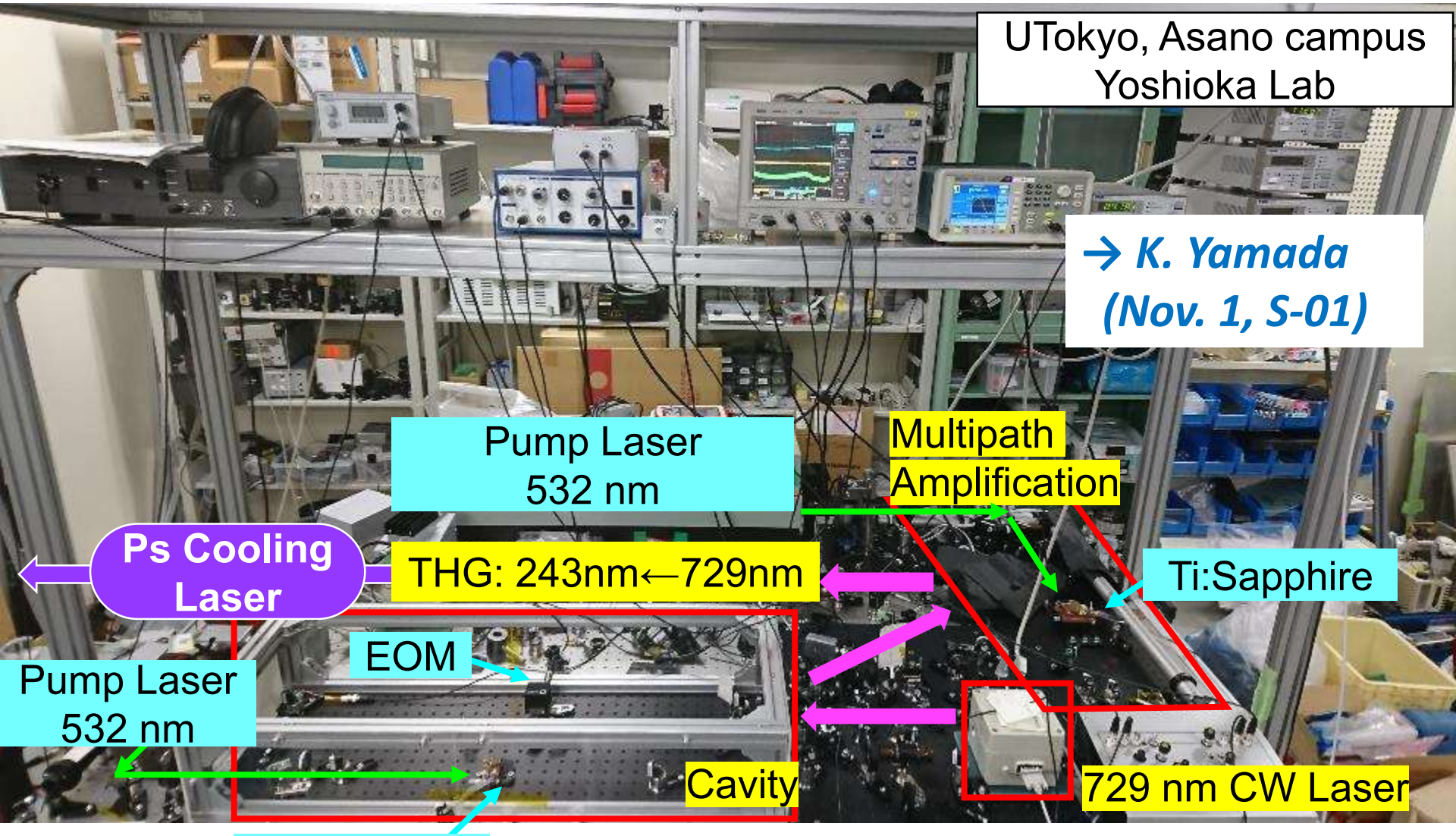
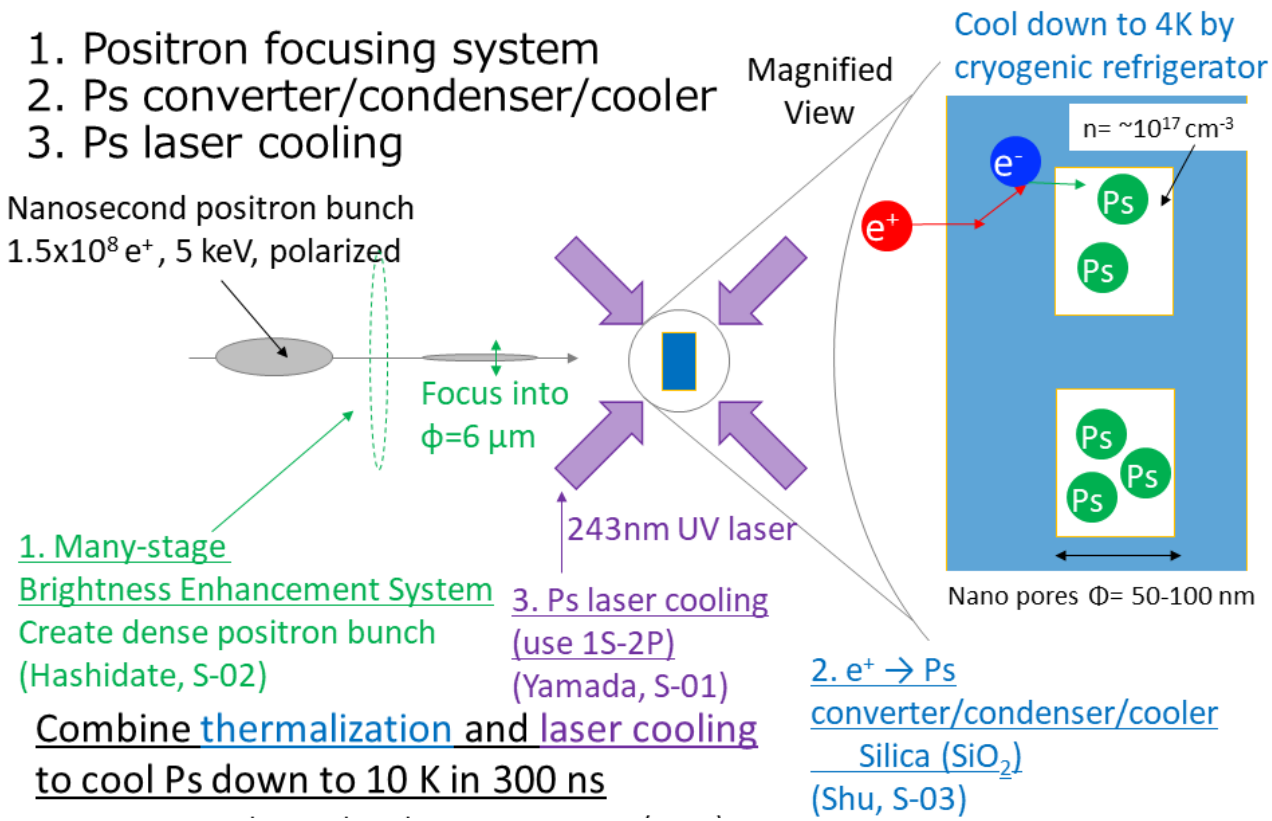


Our beamline (KEK-SPF-B1) has been upgraded to be laser-safe.

Summary

Three technologies to develop for Ps-BEC

1. Positron focusing system
2. Ps converter/condenser/cooler
3. Ps laser cooling



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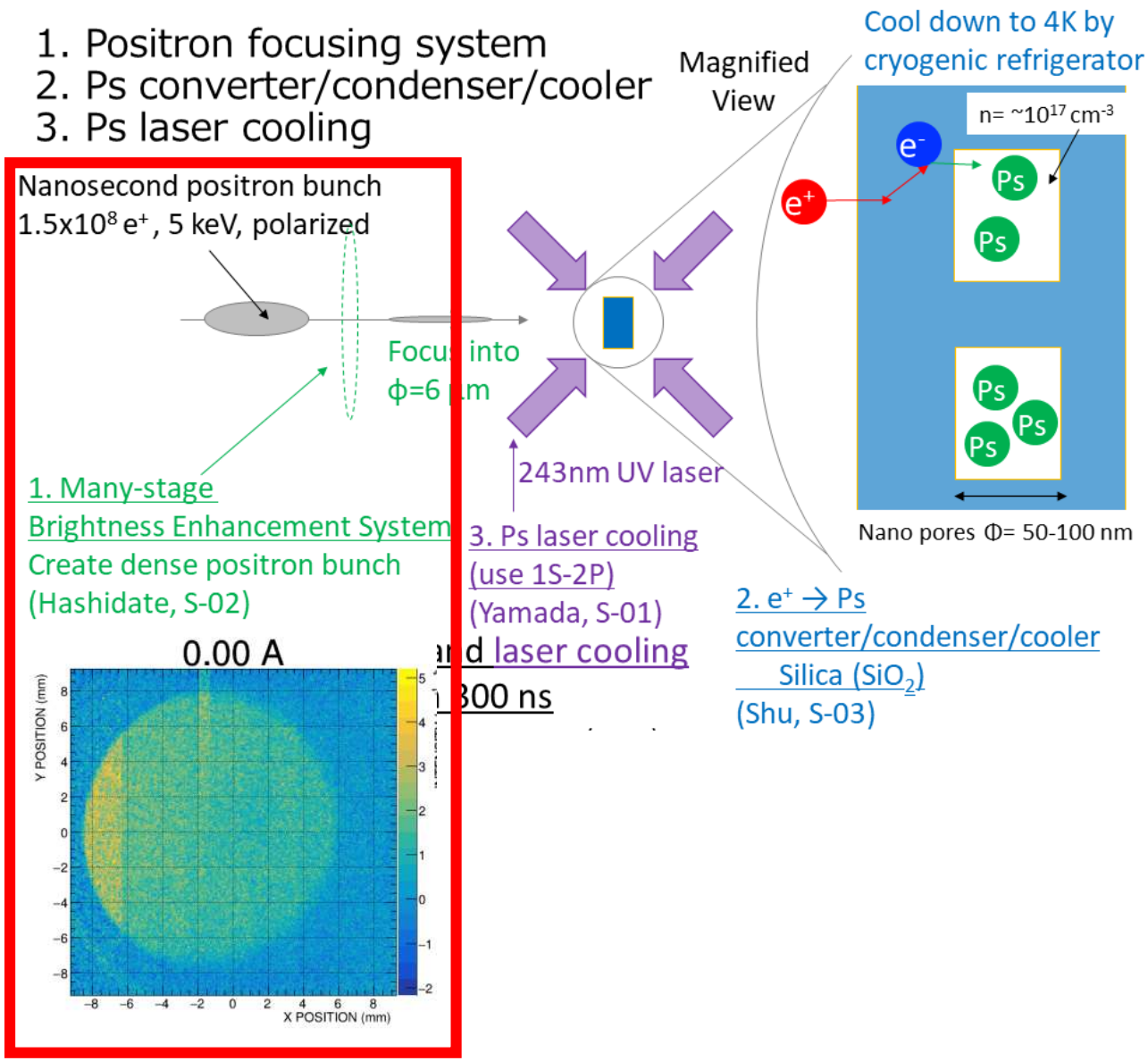
2. Ps converter/condenser/cooler
3. Ps laser cooling



Summary

Three technologies to develop for Ps-BEC

1. Positron focusing system
2. Ps converter/condenser/cooler
3. Ps laser cooling

Nanosecond positron bunch
1.5×10^8 e^+, 5 keV, polarized

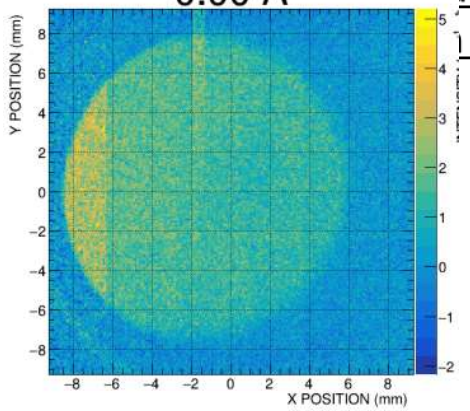
Focus into
ϕ=6 μm

1. Many-stage
Brightness Enhancement System
Create dense positron bunch
(Hashidate, S-02)

243nm UV laser

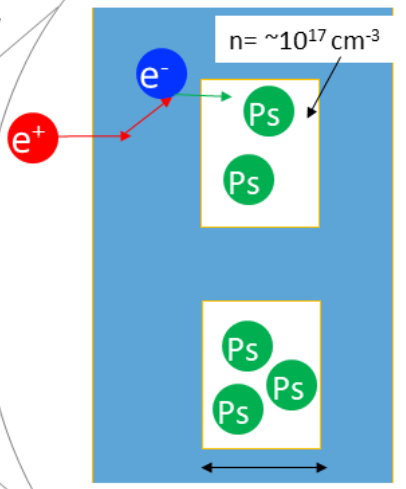
3. Ps laser cooling
(use 1S-2P)
(Yamada, S-01)

d laser cooling
300 ns



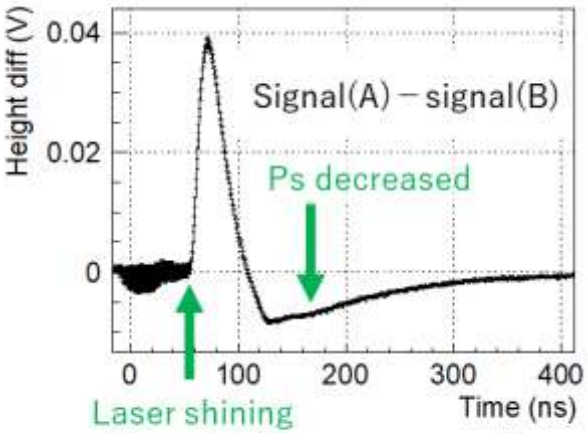
Magnified View

Cool down to 4K by
cryogenic refrigerator



Nano pores Φ= 50-100 nm

2. $e^+ \rightarrow$ Ps
converter/condenser/cooler
Silica (SiO_2)
(Shu, S-03)



Signal difference caused by
shining UV laser

Summary

Three technologies to develop for Ps-BEC

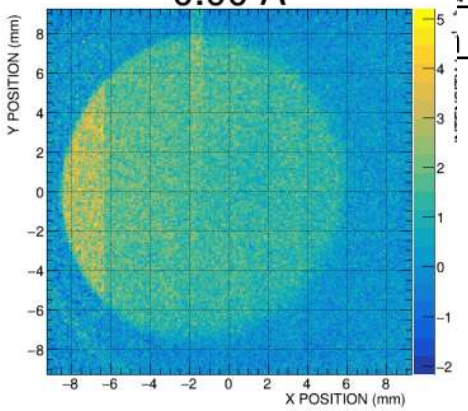
1. Positron focusing system
2. Ps converter/condenser/cooler
3. Ps laser cooling

Nanosecond positron bunch
1.5×10^8 e^+, 5 keV, polarized

Focus into
ϕ=6 mm

1. Many-stage
Brightness Enhancement System
Create dense positron bunch
(Hashidate, S-02)

0.00 A

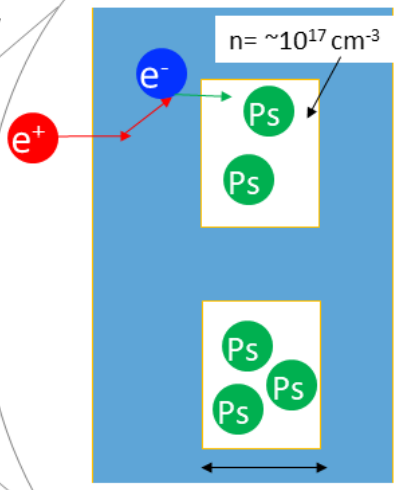


243nm UV laser

3. Ps laser cooling
(use 1S-2P)
(Yamada, S-01)
Pulsed laser cooling
300 ns

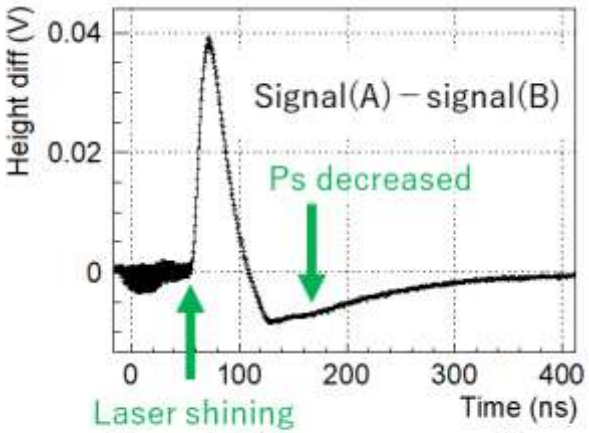
Magnified View

Cool down to 4K by
cryogenic refrigerator

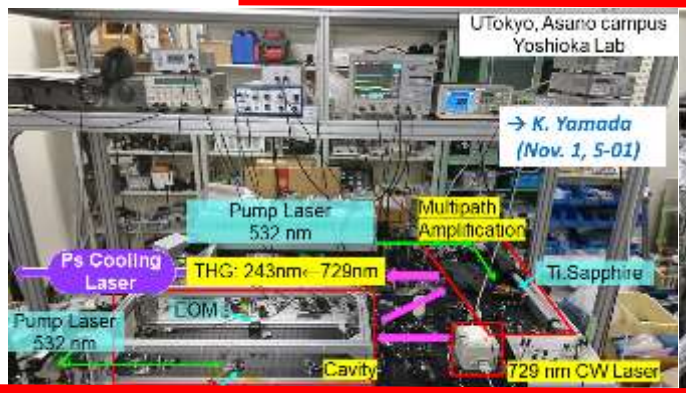


Nano pores Φ= 50-100 nm

2. $e^+ \rightarrow$ Ps
converter/condenser/cooler
Silica (SiO_2)
(Shu, S-03)



Signal difference caused by shining UV laser



Summary

https://tabletop.icepp.s.u-tokyo.ac.jp/?page_id=365

Three technologies to develop for Ps-BEC

Stay tuned!

1. Positron focusing system
2. Ps converter/condenser/cooler
3. Ps laser cooling

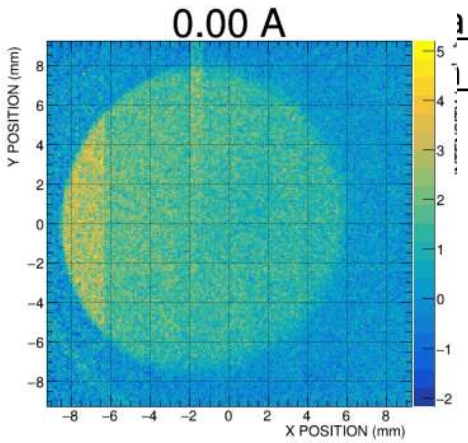
Nanosecond positron bunch
1.5×10^8 e^+, 5 keV, polarized

Focus into
ϕ=6 mm

243nm UV laser

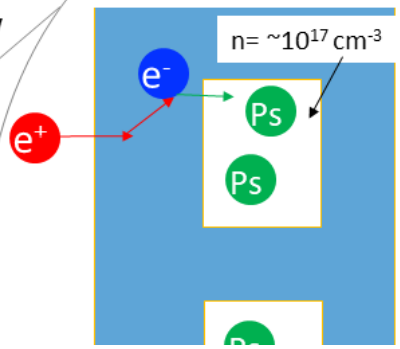
→ *K. Hashidate (Nov. 1, S-03)*

3. Ps laser cooling
(use 1S-2P)
(Yamada, S-01)
laser cooling
300 ns

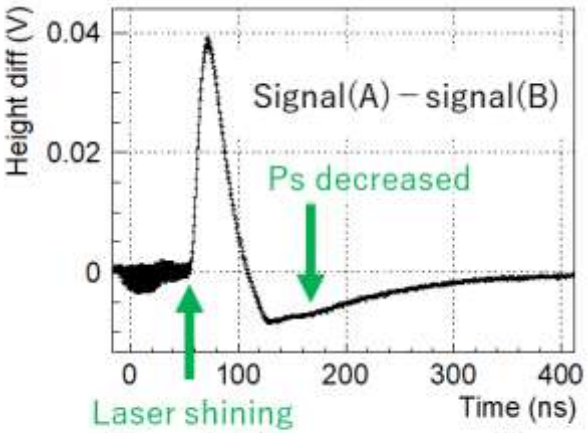


Cool down to 4K by cryogenic refrigerator

Magnified View



→ *K. Shu (Nov. 1, S-02)*



Signal difference caused by shining UV laser

2. $e^+ \rightarrow$ Ps converter/condenser/cooler
Silica (SiO_2)
(Shu, S-03)

→ *K. Yamada (Nov. 1, S-01)*