Dense positronium formation for Bose-Einstein condensation

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N. Oshima[3], B. E. O'Rourke[3], K. Michishio[3], K. Ito[3], K. Kumagai[3], R. Suzuki[3],
S. Fujino[4], T. Hyodo[5], I. Mochizuki[5], K. Wada[5] and T. Kai[6]

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2 APSA Advanced Photon Science Alliance; UT-PSC
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4 GIC
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12.5th International Workshop on Positron and Positronium Chemistry (PPC 12.5)
2021.08.31 Internet

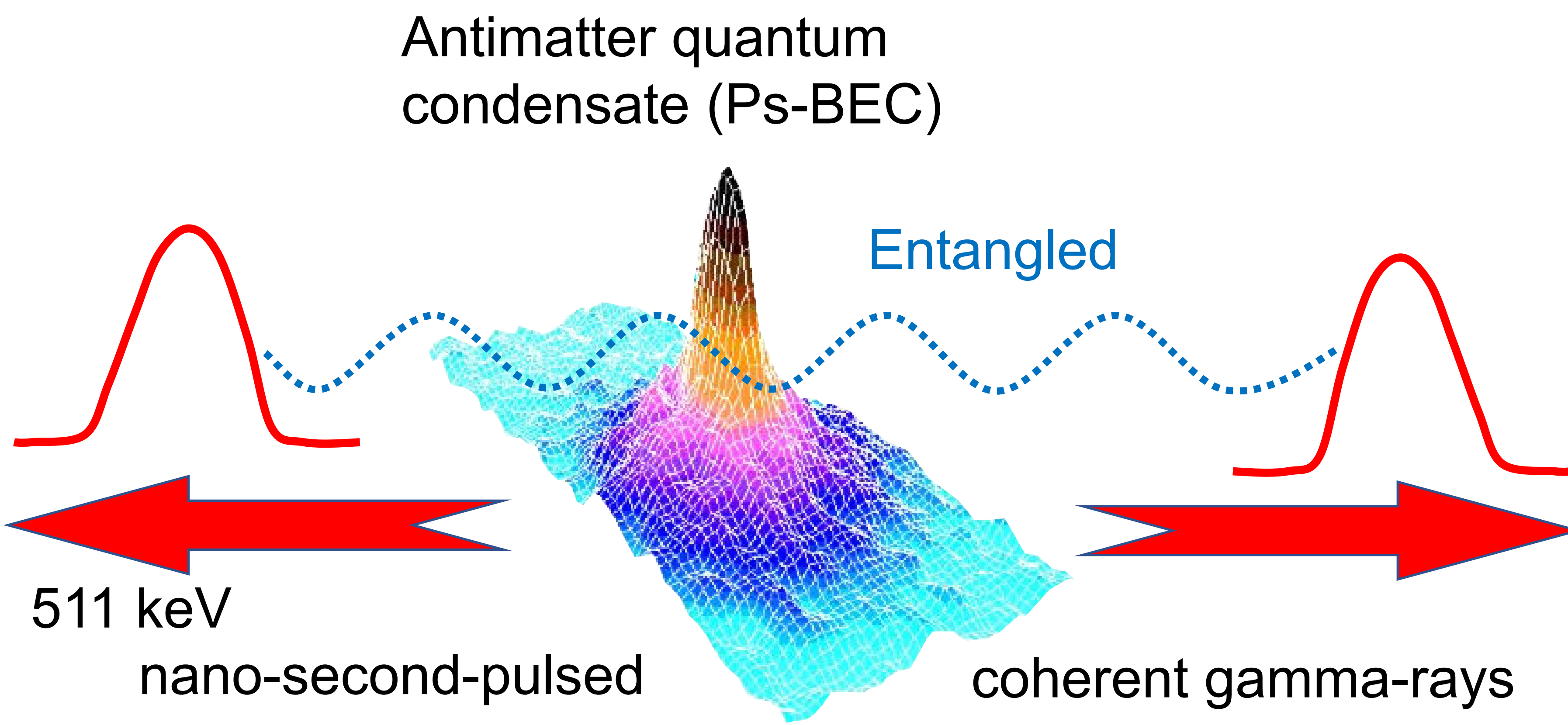
Contents

- Motivation for Ps-BEC
- Overview of our Ps-BEC project:
  1. Positron focusing system
  2. Ps generator/condenser/cooler
  3. Ps laser cooling

  (Items 1–2: This talk)

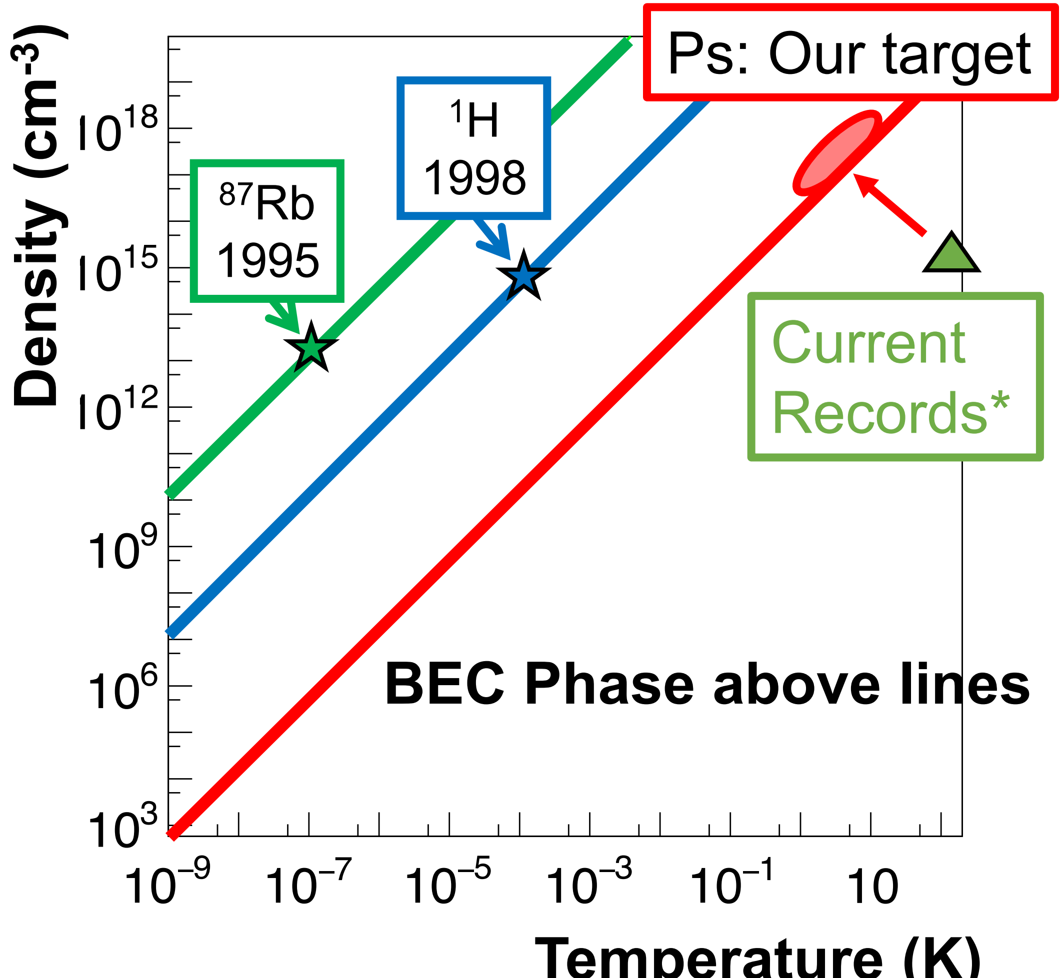
  → Details will be presented in the following talks by R. Uozumi and Y. Tajima.
  → A related talk will also be presented on September 3 (Friday) by K. Shu.

We want to realize an **antimatter quantum condensate** = positronium Bose-Einstein condensate (Ps-BEC). **Gamma-ray lasers** may be realized using Ps-BEC as a source.



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

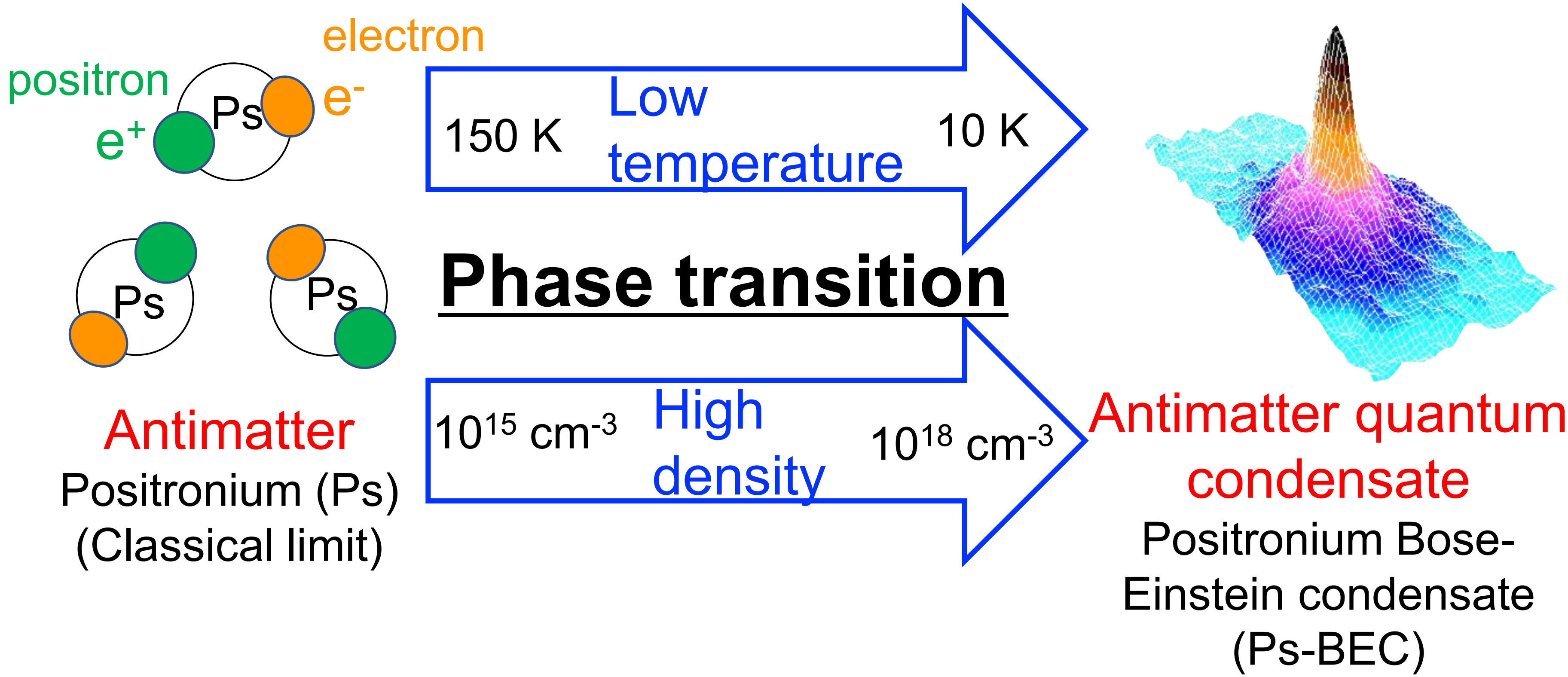
- Ps must be dense and cold
- High critical temperature because of Ps light mass (14K at 10^{18} cm^{-3})
- One of the best candidates for the first antimatter BEC
- BEC is "Atomic laser". We would like to make the first antimatter laser and perform new experiments using the coherency of Ps-BEC.



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

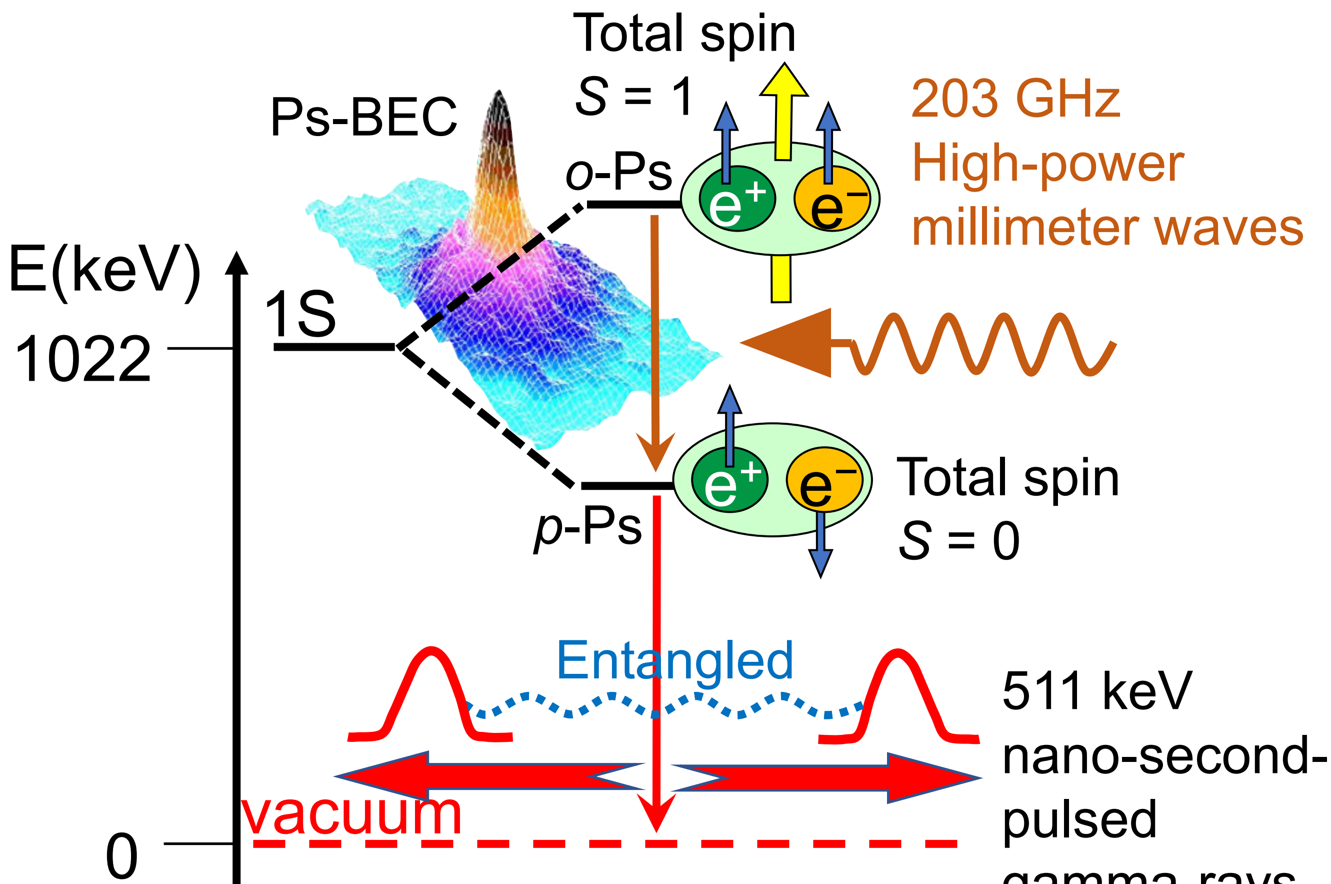
K. Shu *et al.*, J. Phys. B **49**, 104001 (2016), A. Ishida *et al.*, JJAP Conf. Proc. **7**, 011001 (2018).

Realization of Ps-BEC at:
Low temperature (10 K) and quite high density (10^{18} cm^{-3})



K. Shu *et al.,* J. Phys. B **49**, 104001 (2016), A. Ishida *et al.*, JJAP Conf. Proc. **7**, 011001 (2018).

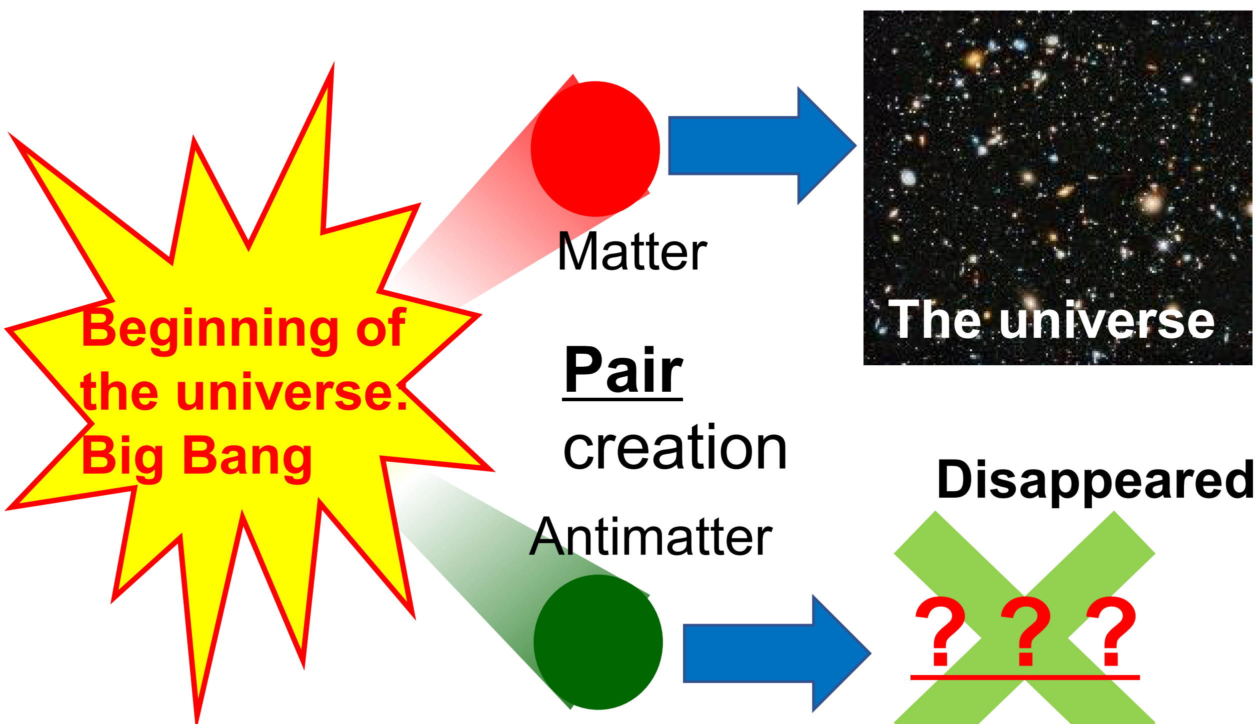
Self-annihilations of Ps-BEC can generate 2 coherent and entangled gamma-rays: Realization of gamma-ray lasers

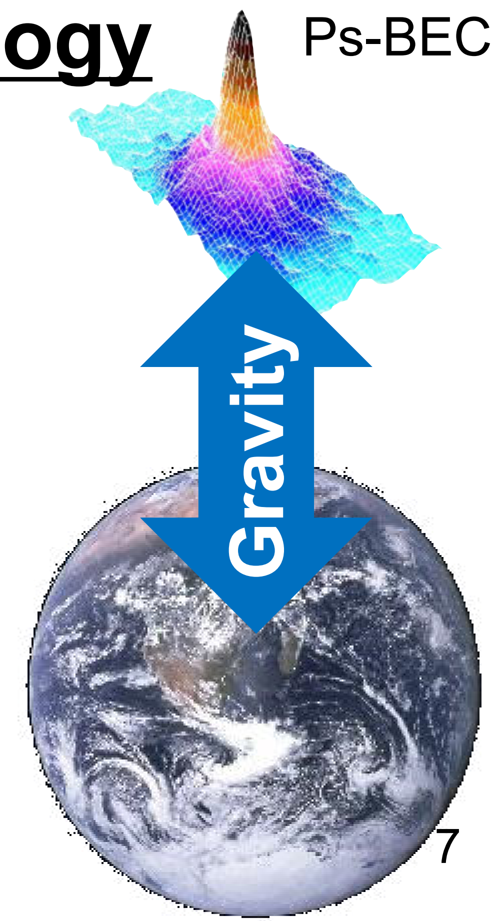


H. K. Avetissian *et al.*, Phys. Rev. A **92**, 023820 (2015).

Motivation 1.
Answering the big question:
“Why is there far more matter than antimatter in the universe?”

Game change in particle physics, atomic physics, and cosmology

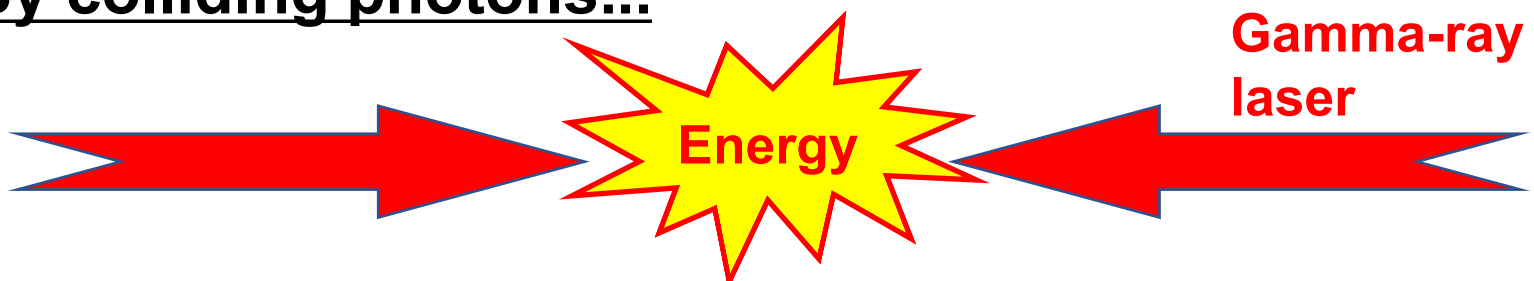




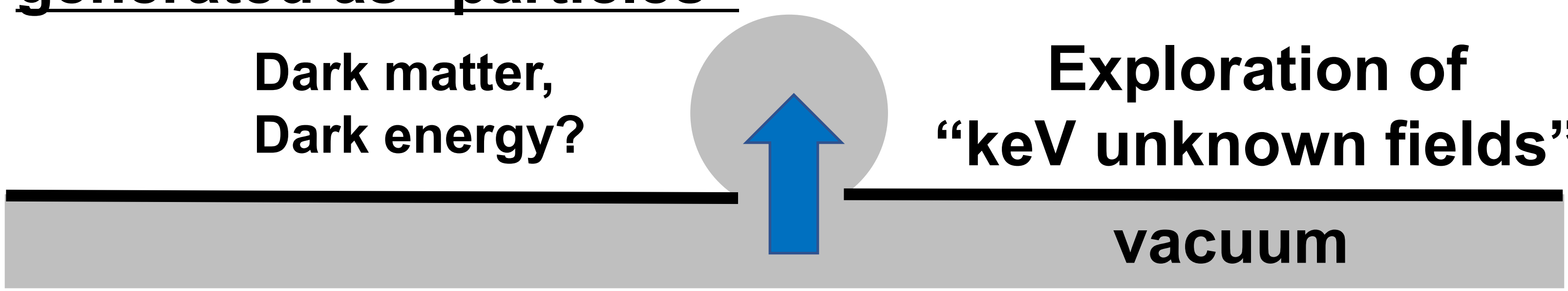
Motivation 2.
Revealing hidden rich structures in vacuum and space-time

Game change in particle physics

By colliding photons...



Hidden fields in vacuum will be excited and generated as "particles"

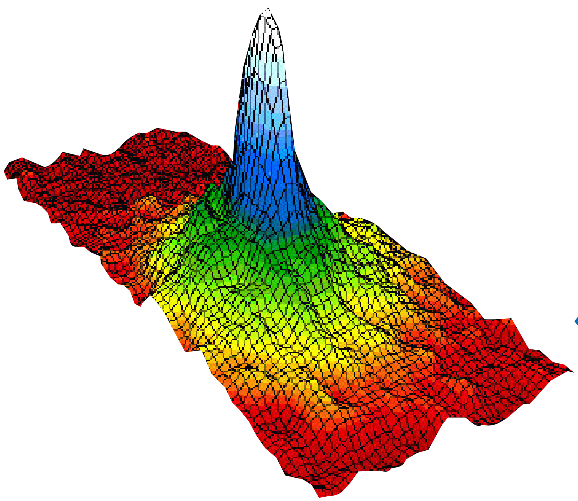


Motivation 3.
Pioneering new field of science: macroscopic quantum phenomena of antimatter

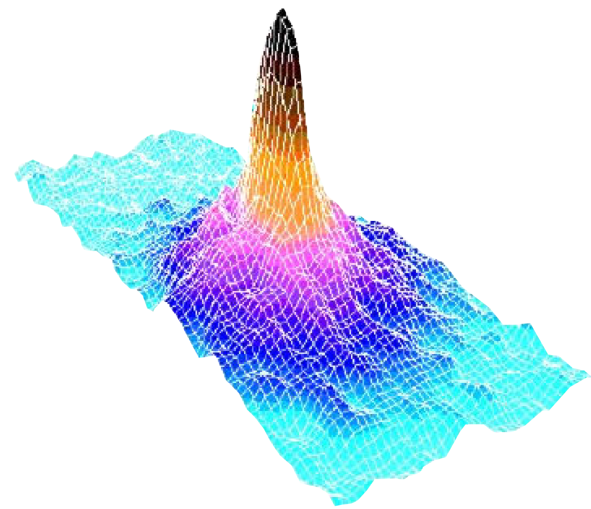
<u>Creation of new academic field</u>

Normal BEC

Antimatter BEC



Opposite charge



Macroscopic quantum phenomena

Superconductivity,
Superfluidity

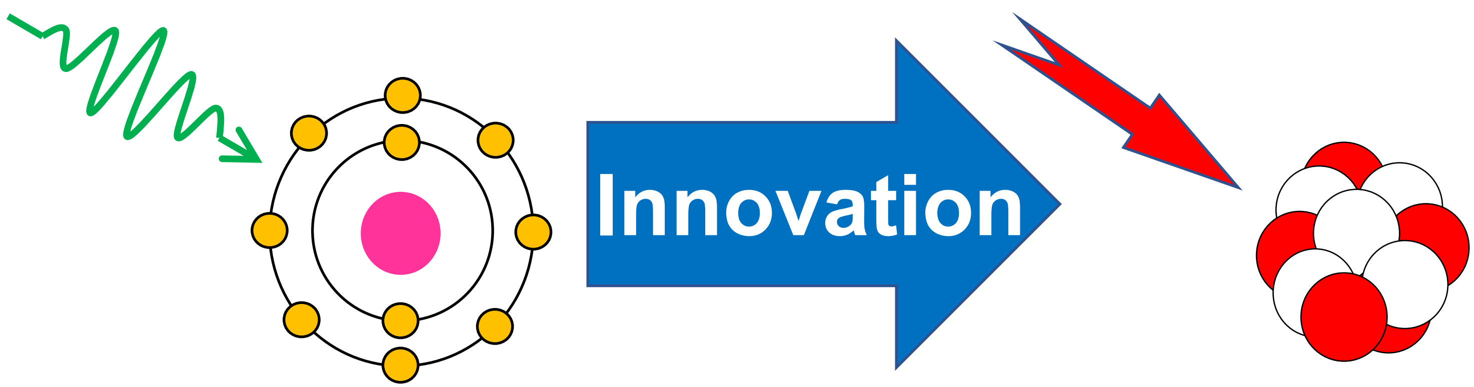
Macroscopic quantum phenomena

<u>？？？</u>

Motivation 4.
Exploration of unknown energy regions in all quantum optics research

Game change in the fields of optics, atomic physics, and nuclear physics

Visible laser & **atom** **Gamma-ray laser** & **nucleus**



Two challenges to realize Ps-BEC

Main problem

Ps lifetime is only 142 ns

Two challenges

1. Instant creation of dense Ps
   $> 10^{18}$ cm^{-3} in < 50 ns
2. Rapid cooling of Ps
   < 10 K in ~300 ns

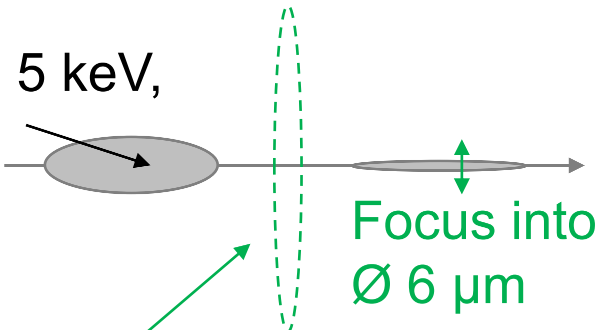
Our new idea:

3 technologies to realize Ps-BEC

Our idea to realize Ps-BEC

1. Positron focusing system

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

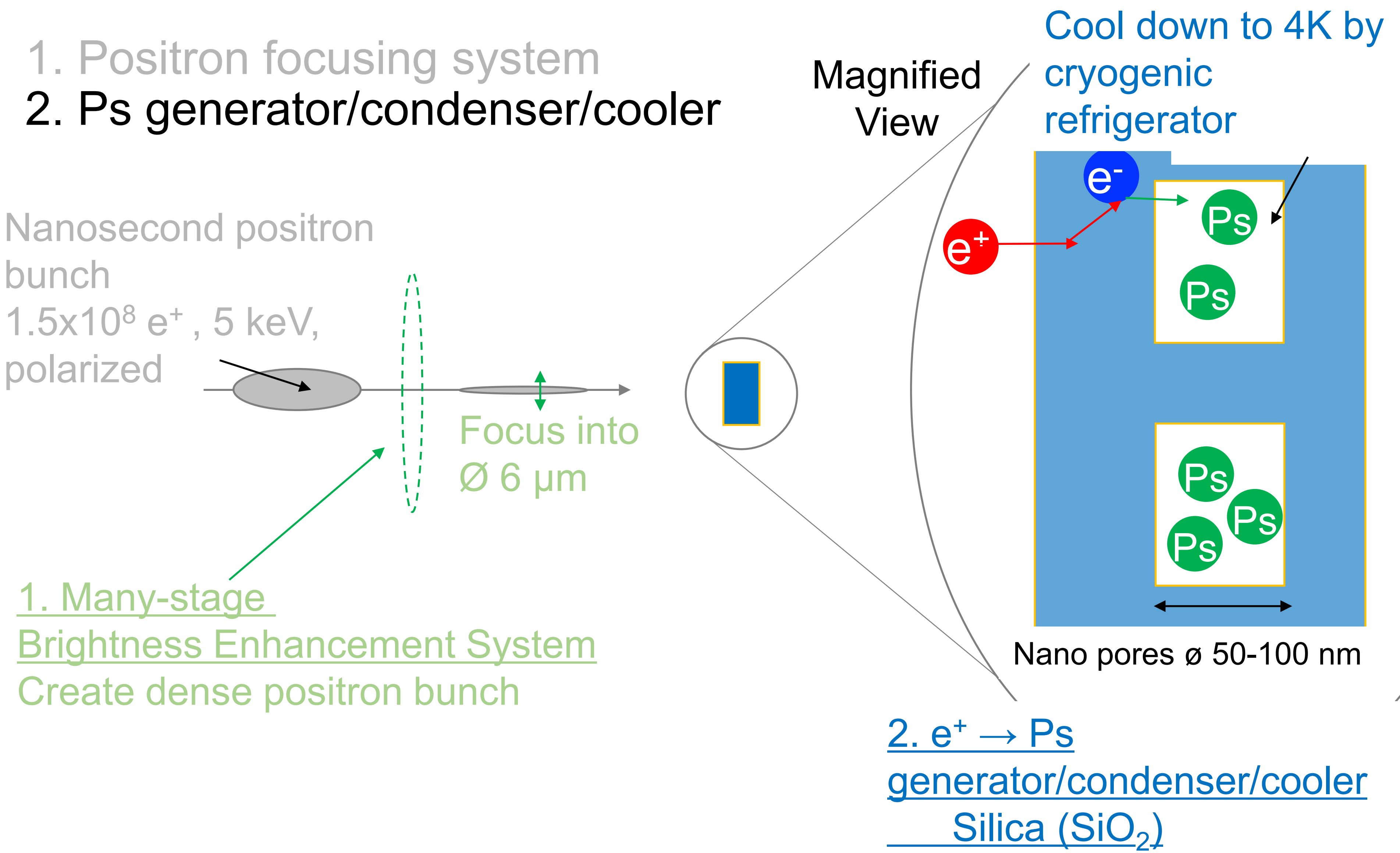


Focus into
Ø 6 μm

1. Many-stage
Brightness Enhancement System
Create dense positron bunch

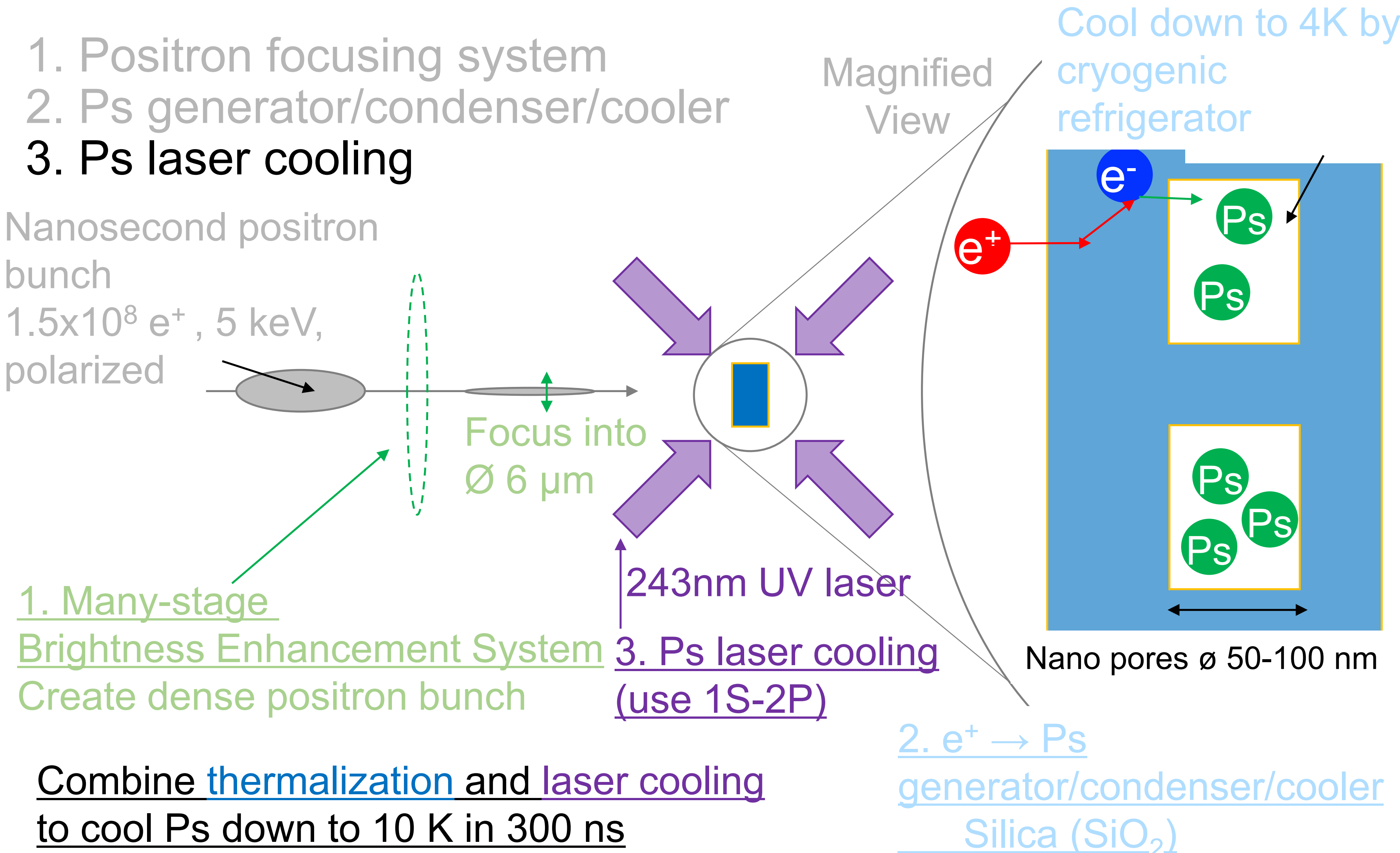
Our idea to realize Ps-BEC

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



Our idea to realize Ps-BEC

1. Positron focusing system
2. Ps generator/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

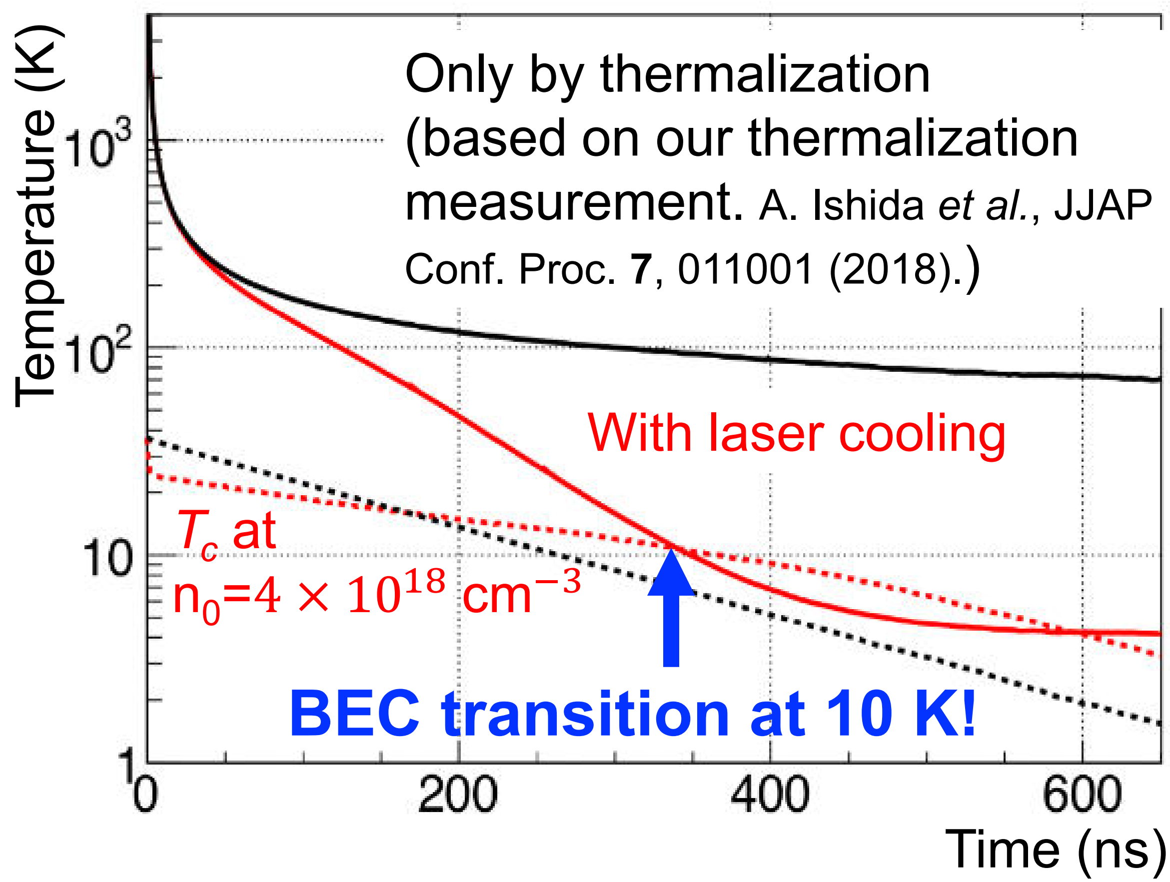
2.Laser cooling

- Efficient at < 200 K

Cooling Ps down to < 10 K is possible

✓ Combining these two methods is essentially important

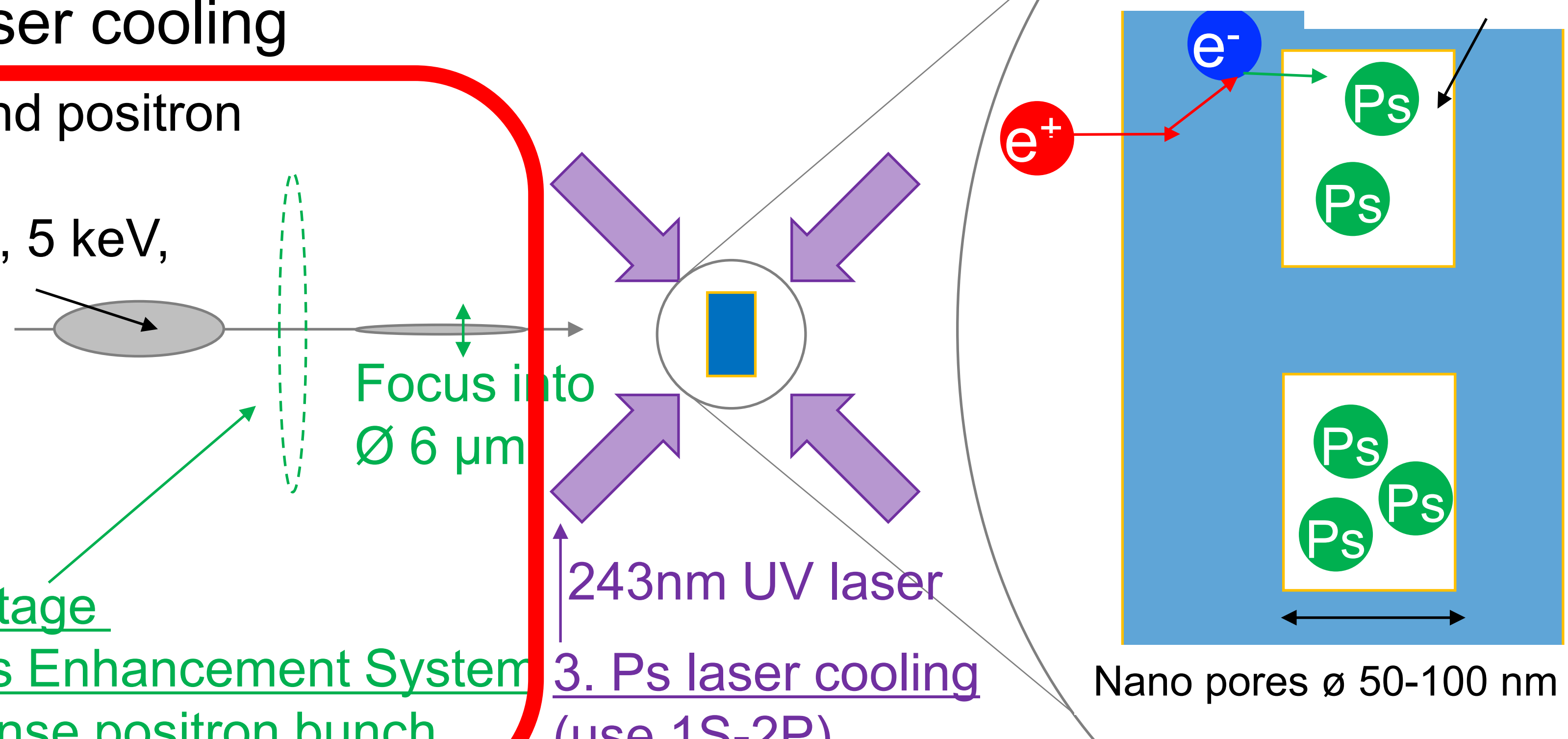
MC simulated temperature evolution



Details of each component

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

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



1. Many-stage Brightness Enhancement System
Create dense positron bunch

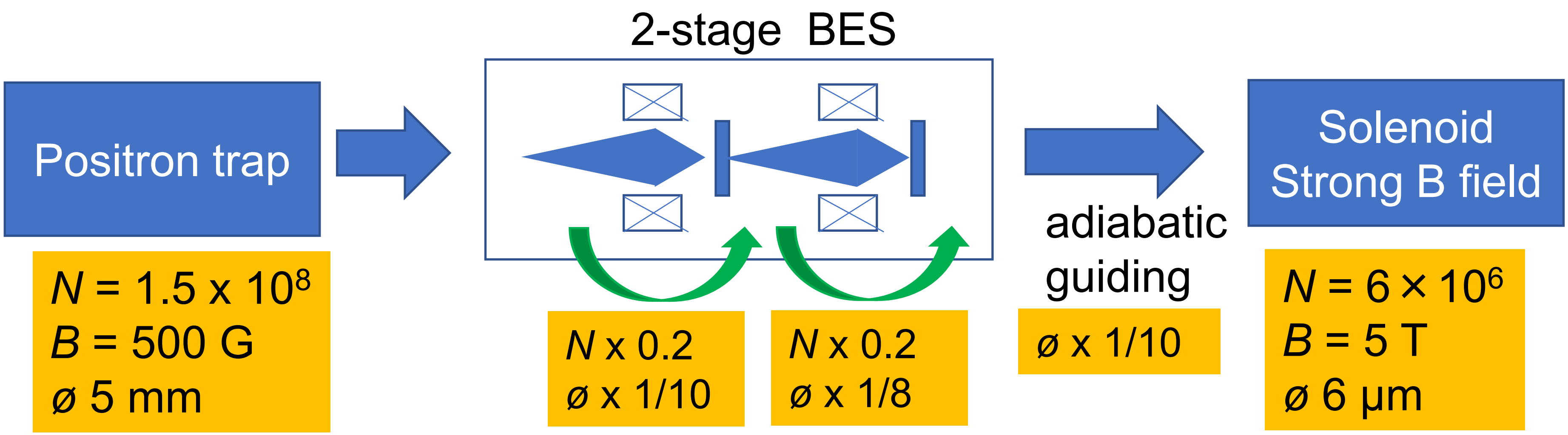
2. $e^+ \rightarrow$ Ps generator/condenser/cooler
Silica (SiO_2)

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)

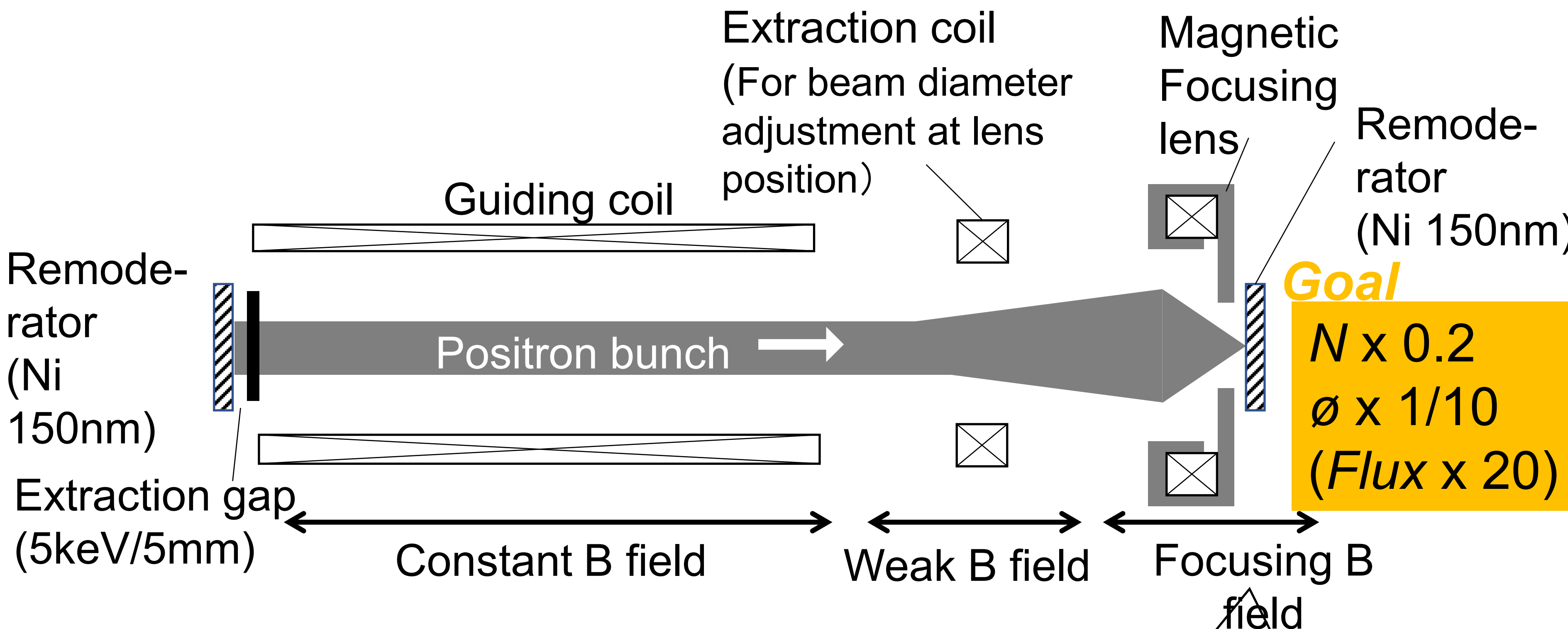
Our method to achieve dense enough e^+ bunch for Ps-BEC

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



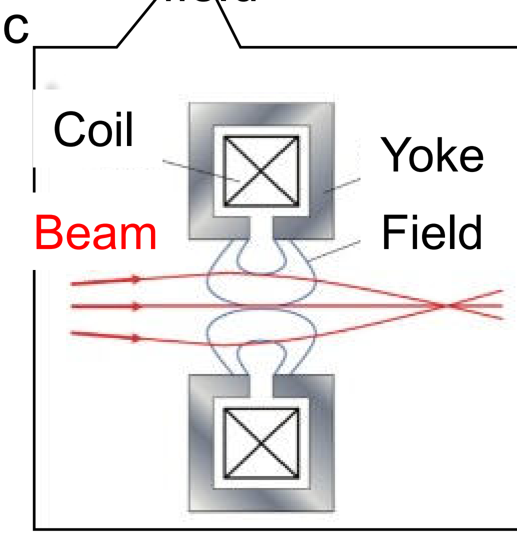
We have shown that a high-enough density for Ps-BEC could be reached by the model.
We have considered (1) space charge limited current density (Child-Langmuir law), (2) Brillouin flow, and (3) the beam envelope equation including space charge effect. (N. Oshima, ICPA-18)

Positron Brightness Enhancement System (BES)

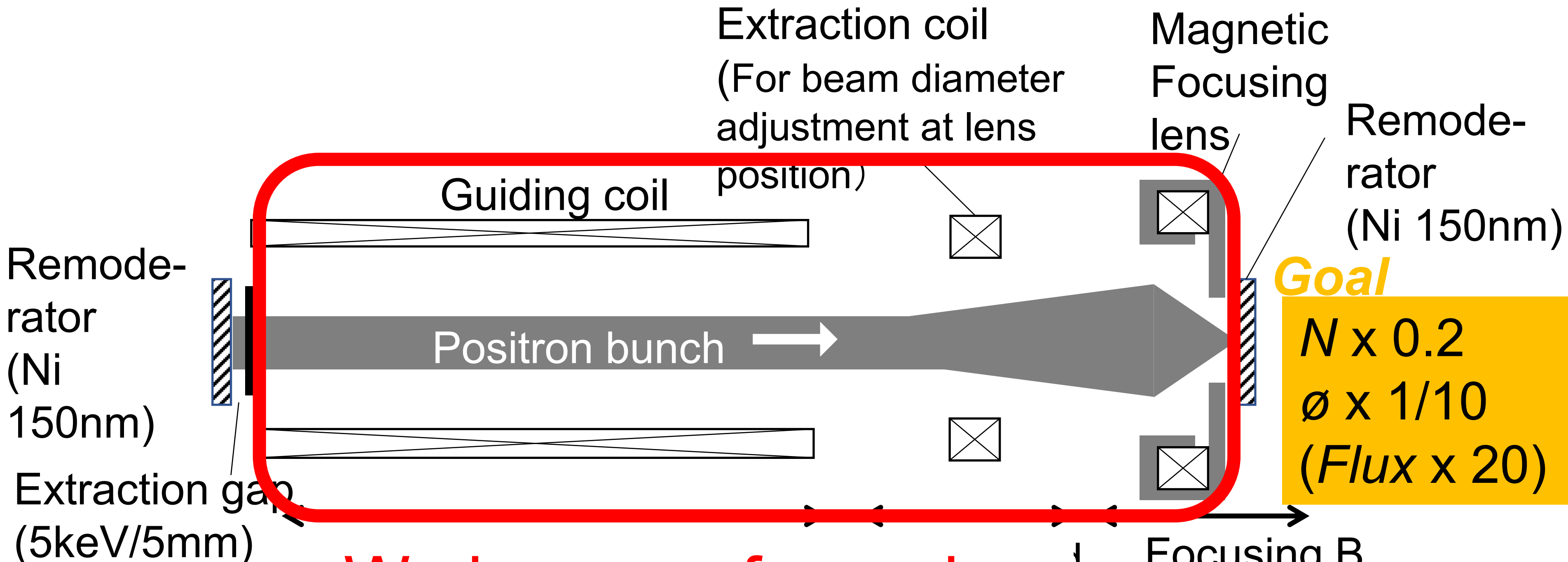


- This system consists of solenoids and a magnetic focusing lens

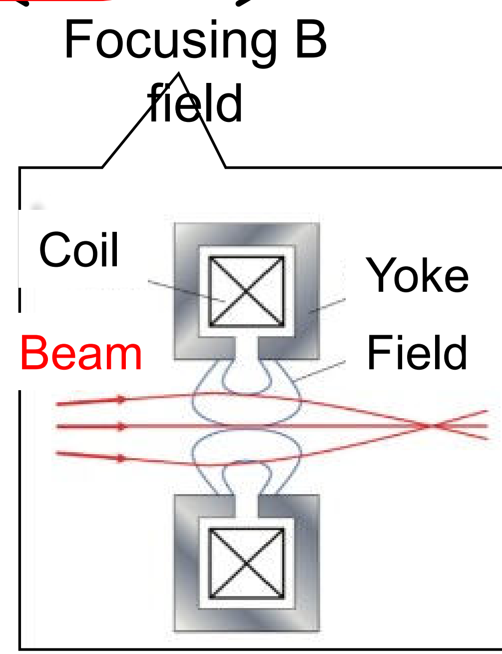
1. slow positron beam is magnetically guided with solenoids.
2. The beam is extracted from the constant B field to the weak B field
3. The beam is focused by the magnetic focusing lens



Positron Brightness Enhancement System (BES)



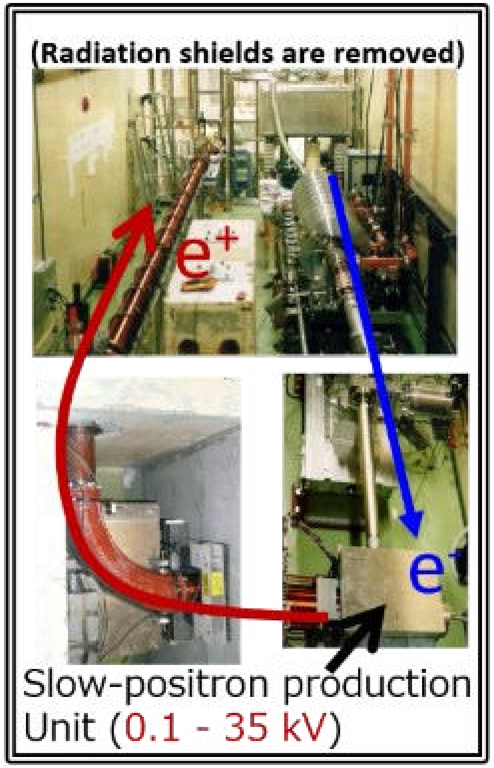
We have performed a test experiment to focus positron beams.

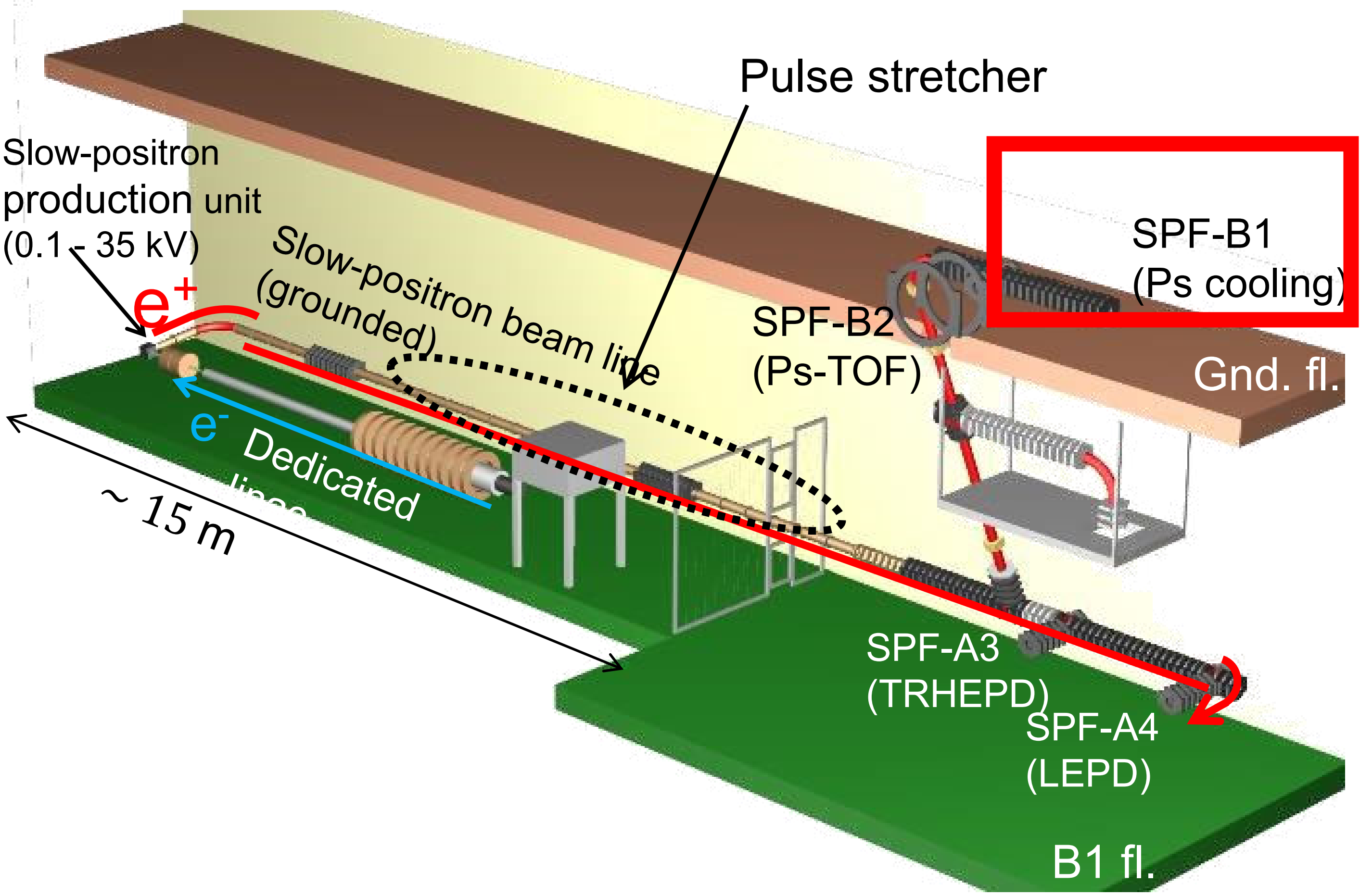


We have performed a test experiment to focus positron beams at KEK-SPF (Slow Positron Facility), Tsukuba, Japan.

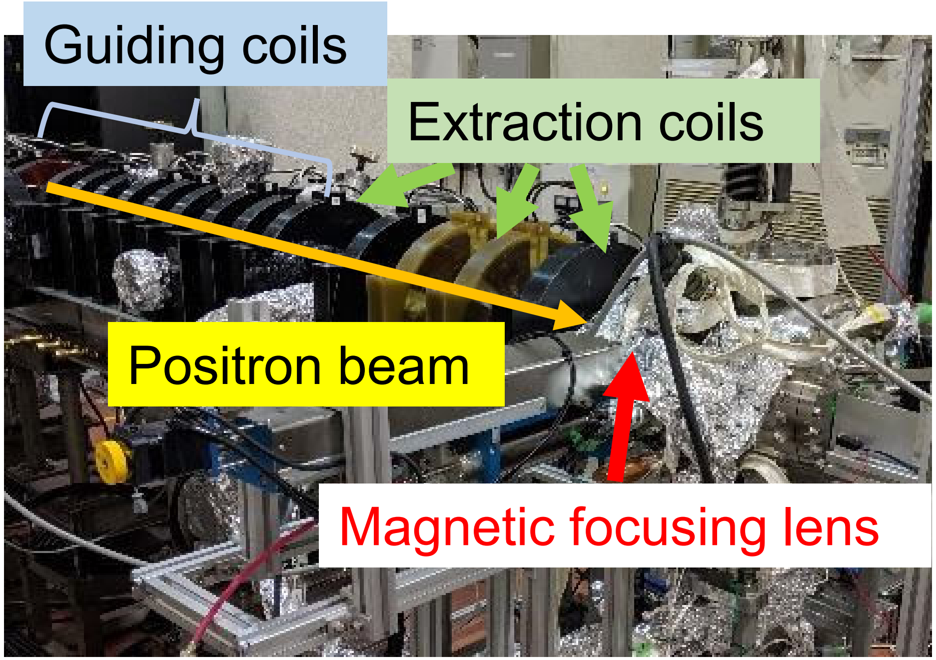
- Highest intensity (5×10^7 slow e^+/s)
- Variable energy (0.1-35 keV)

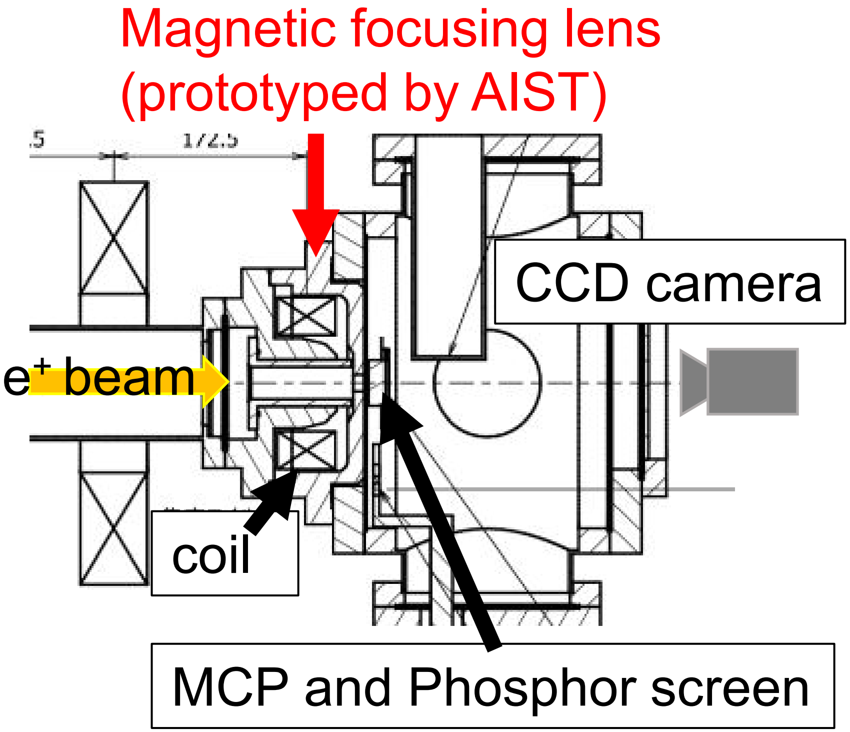
Samples and detectors are electrically grounded.





Positron focusing test experiment at KEK-SPF



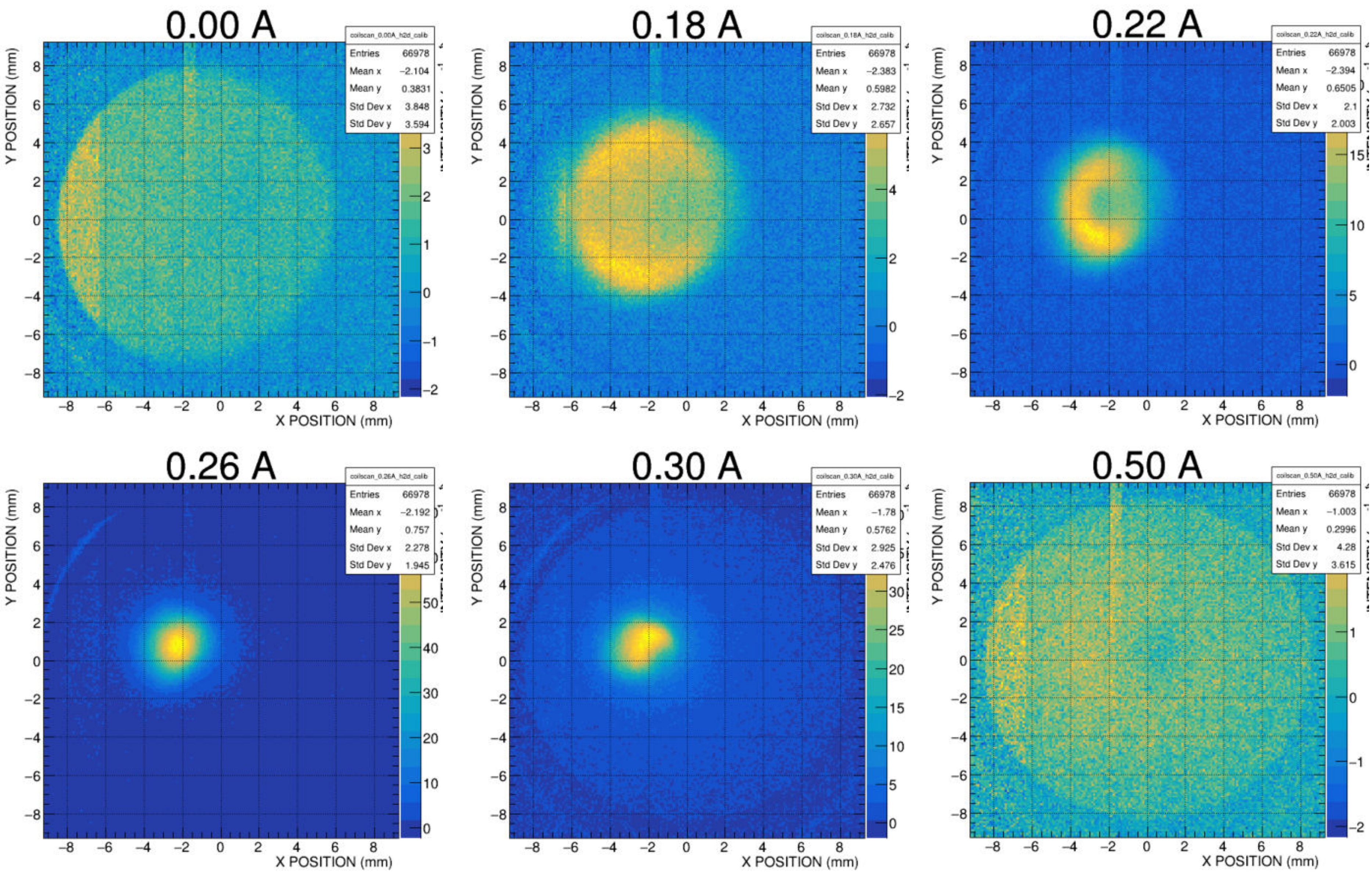


Beam profiles

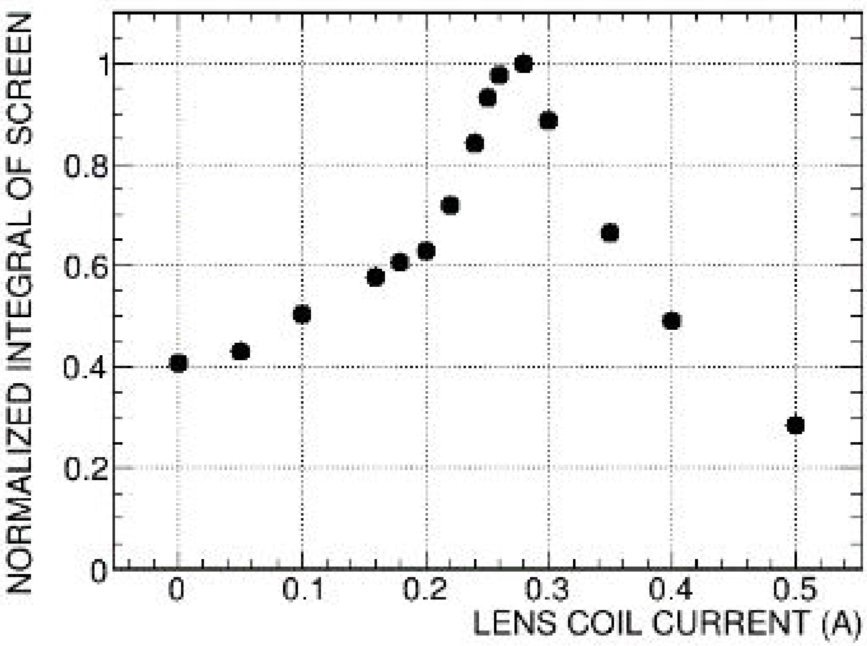
- Energy : 5 keV
- Intensity : $5 \times 10^5\ e^+/s$
- Pulse repetition : 50 Hz
- Pulse width : 16 ns

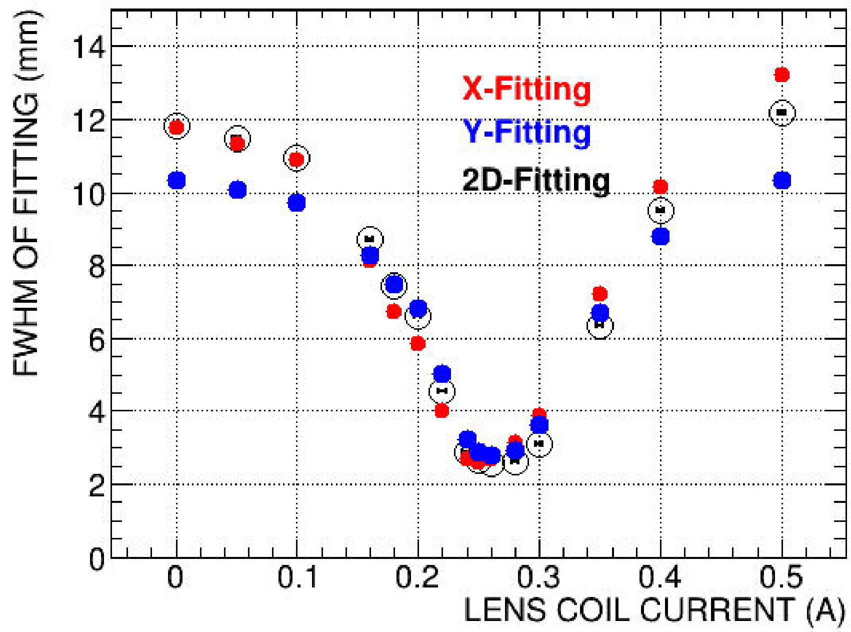
We observed the image of MCP / Phosphor screen recorded by a CCD camera.
This focusing lens will be used for Ps laser cooling experiment at the same beamline if it has a good enough performance.

MCP images at various currents of the lens coil.



The KEK beam has been focused by the prototype lens.
Detailed analysis and comparison with simulations is ongoing to design and develop a dedicated positron focusing system for Ps-BEC.

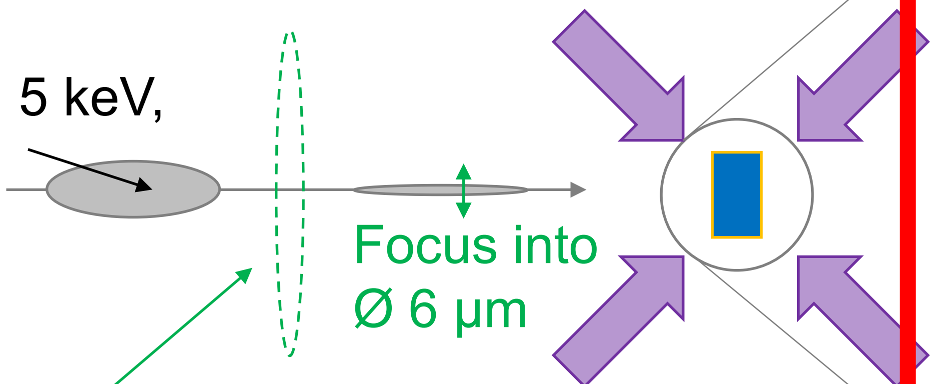




Details of each component

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

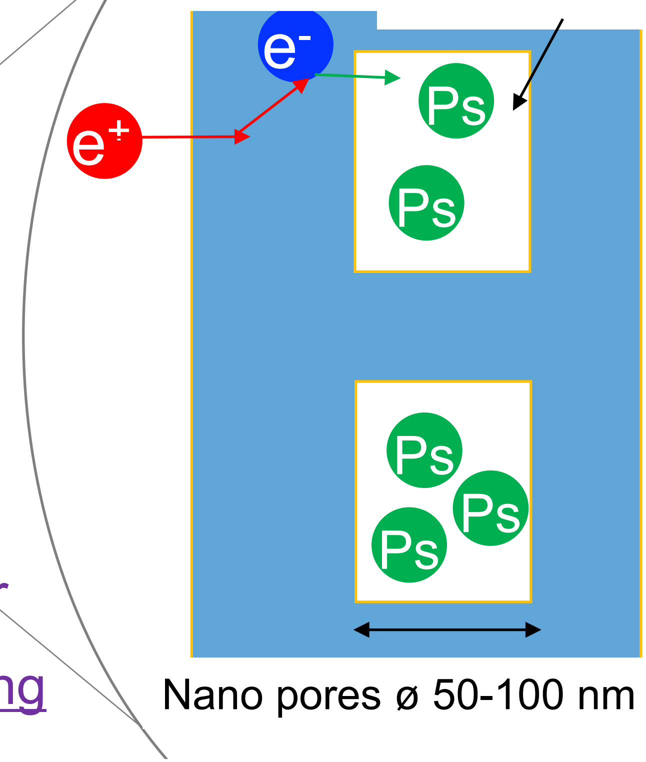
Nanosecond positron bunch
1.5×10^8 e^+, 5 keV, polarized



Focus into Ø 6 μm

Magnified View

Cool down to 4K by cryogenic refrigerator



Nano pores ø 50-100 nm

1. Many-stage Brightness Enhancement System
Create dense positron bunch

243nm UV laser

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

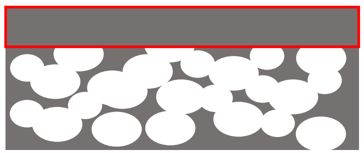
2. $e^+ \rightarrow$ Ps generator/condenser/cooler
Silica (SiO_2)

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

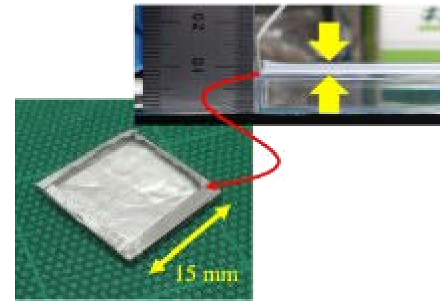
K. Shu *et al.* J. Phys. B 49, 104001 (2016)

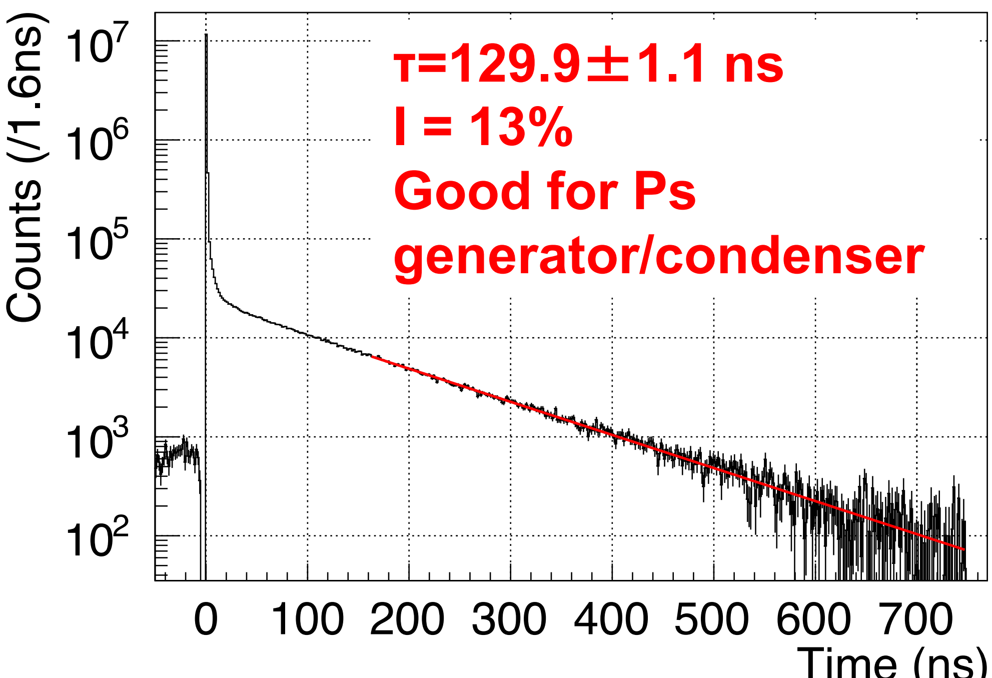
Silica (SiO_2) aerogel was thought to be a good candidate. Capped the surface of the aerogel by amorphous silica thin film using plasma CVD.

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

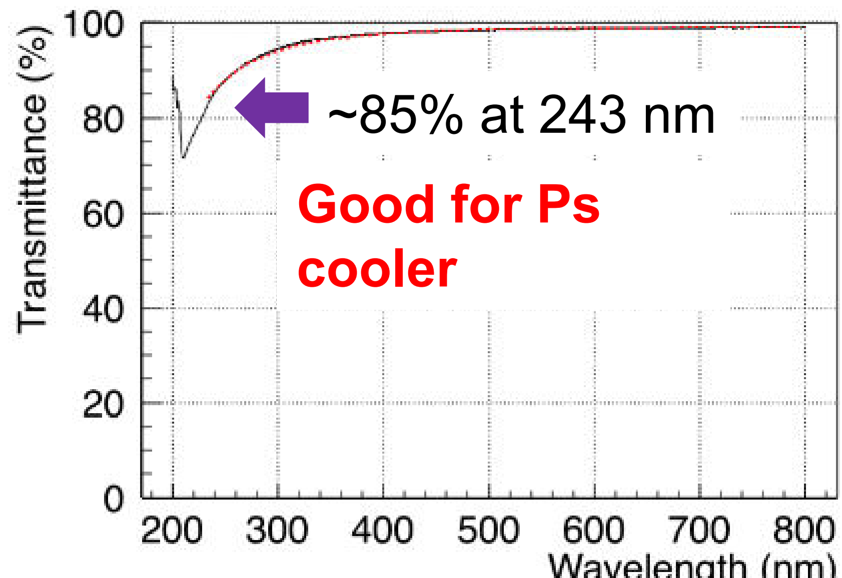


CVD 75 nm
Silica aerogel 0.5 mm



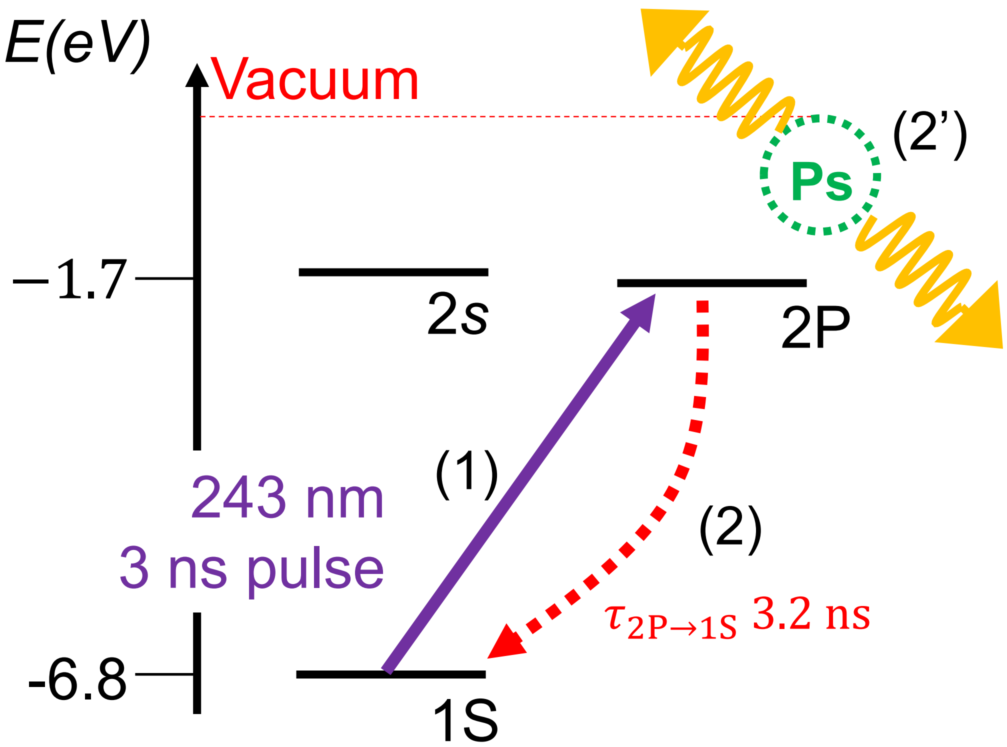


Timing spectrum of bulk-PALS measurement using ^{22}Na with t=1 mm silica aerogel



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

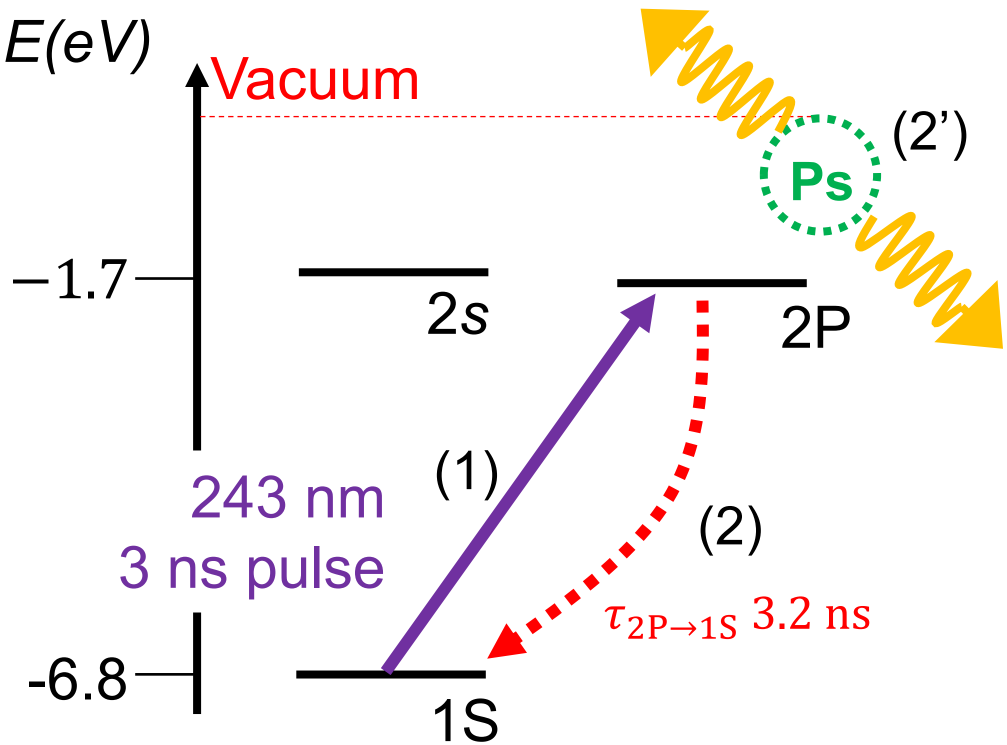
(2) If nothing special happens...

- 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

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

R&D of Ps generator/condenser/cooler other than silica aerogel is also ongoing.

Unfortunately, (2') was the case.

Details will be presented on September 3 by K. Shu.

Ps laser cooling inside the silica aerogel pores is very difficult. Next step: Ps laser cooling in vacuum

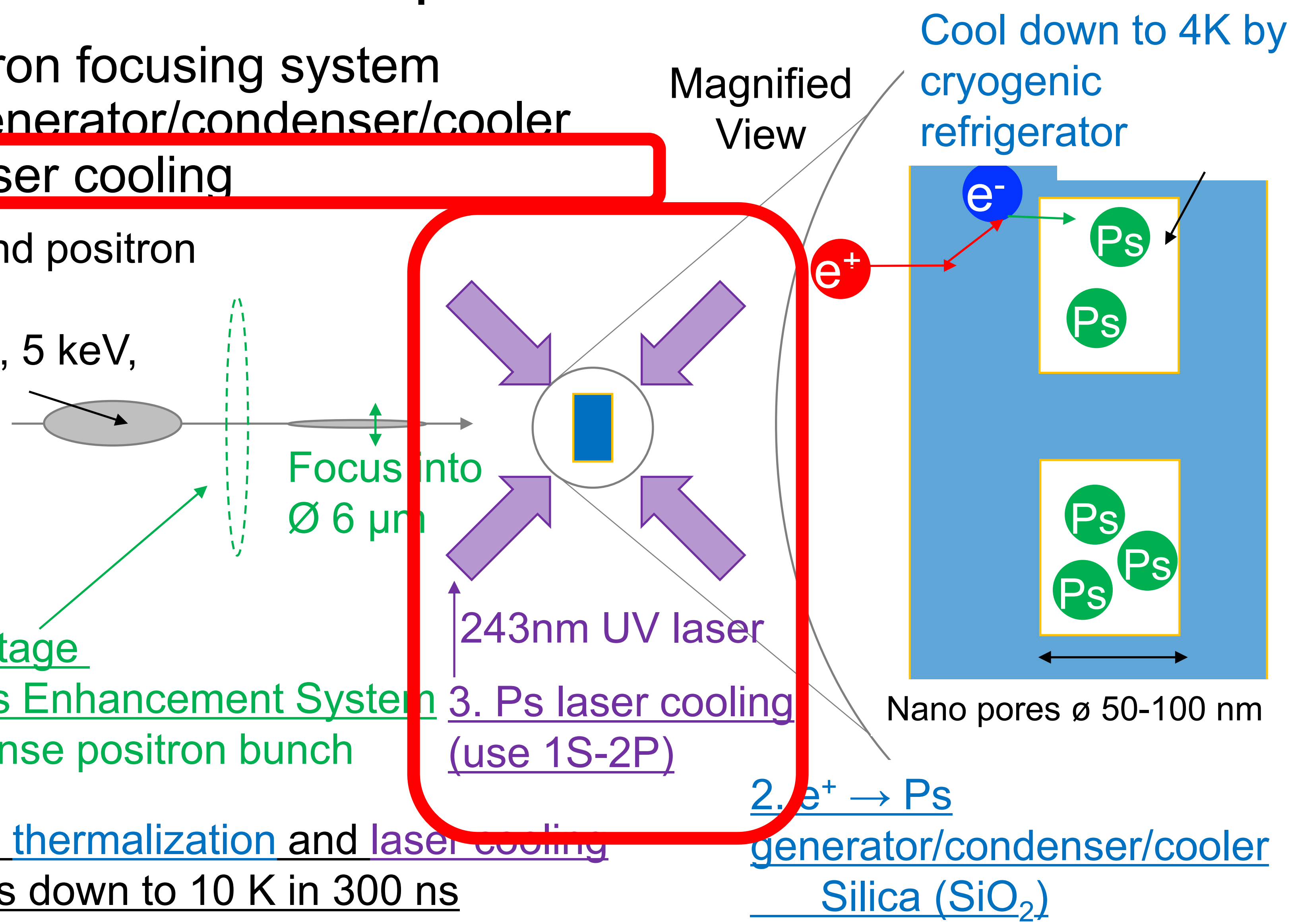
(2') If lifetime of 2P-Ps inside pores is short as reported in B. S. Cooper et al. PRB 97, 205302 (2018)....

- Annihilation rate to gamma-rays is increased.

  →Bad for laser cooling

Details of each component

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



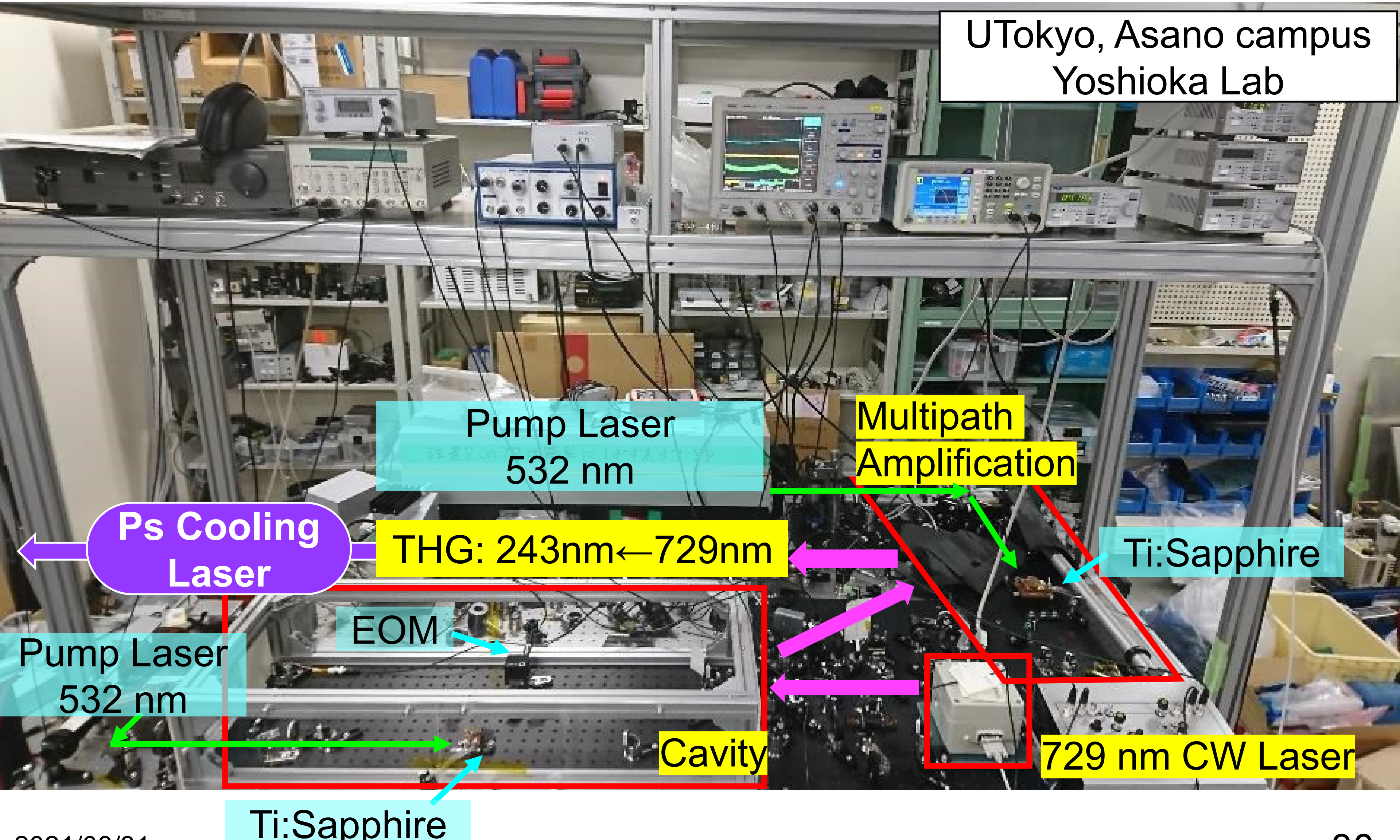
Combine thermalization and laser cooling to cool Ps down to 10 K in 300 ns

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

We have developed a prototype laser for cooling Ps. Compact system (2.0 m × 1.1 m)

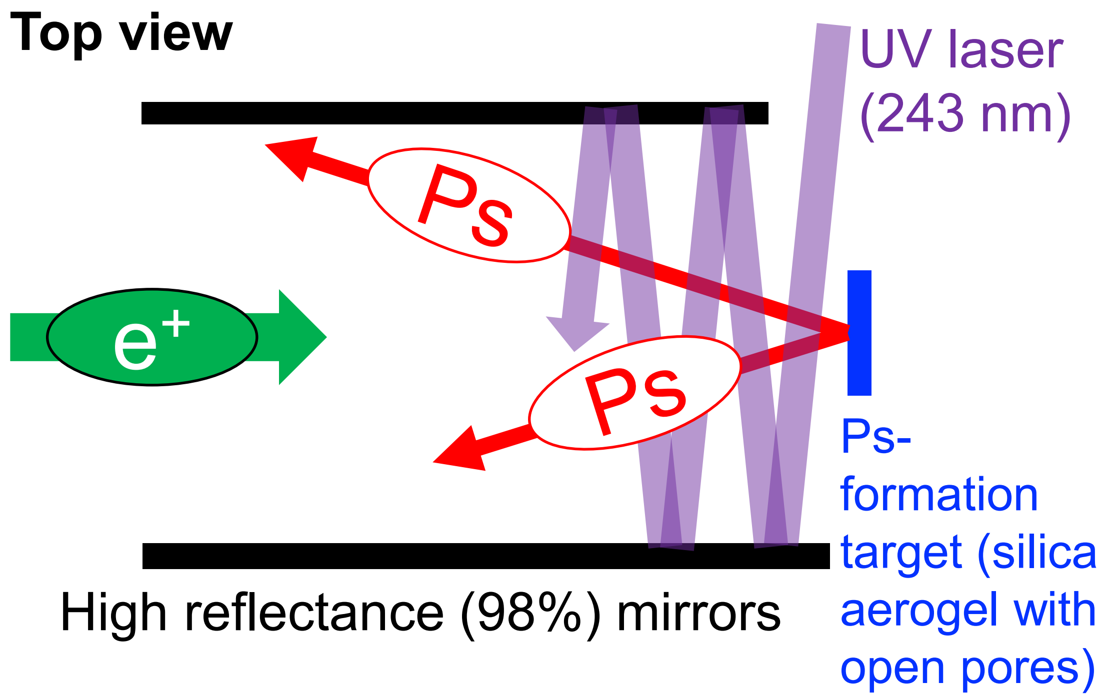
Details will be presented in the following talks by R. Uozumi and Y. Tajima.

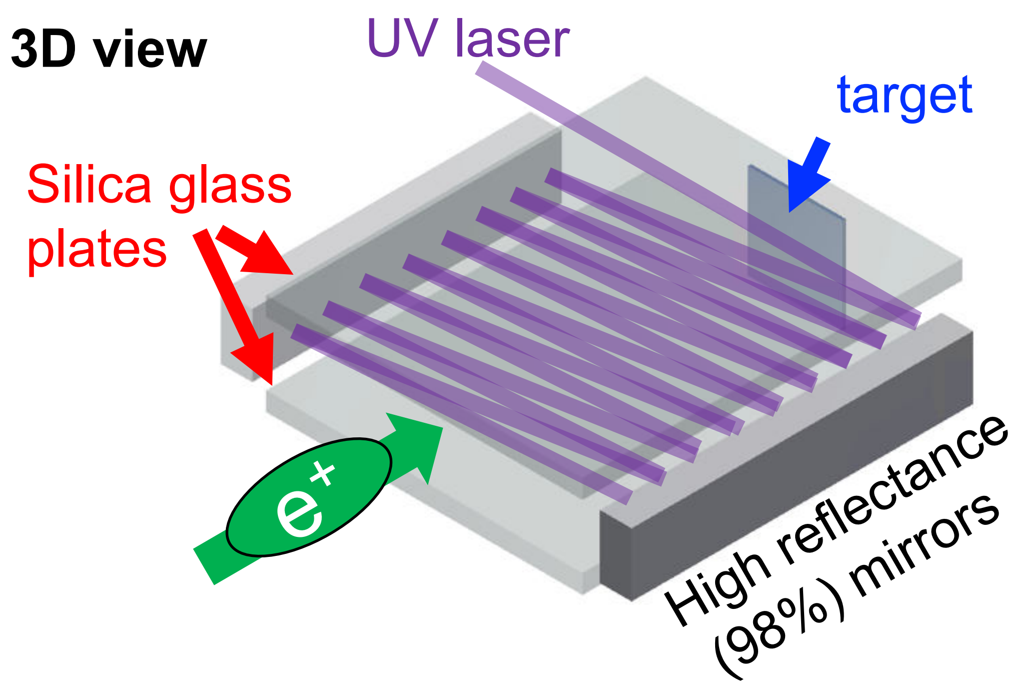
Reference: K. Yamada *et al.*, Phys. Rev. Applied **16**, 014009 (2021).



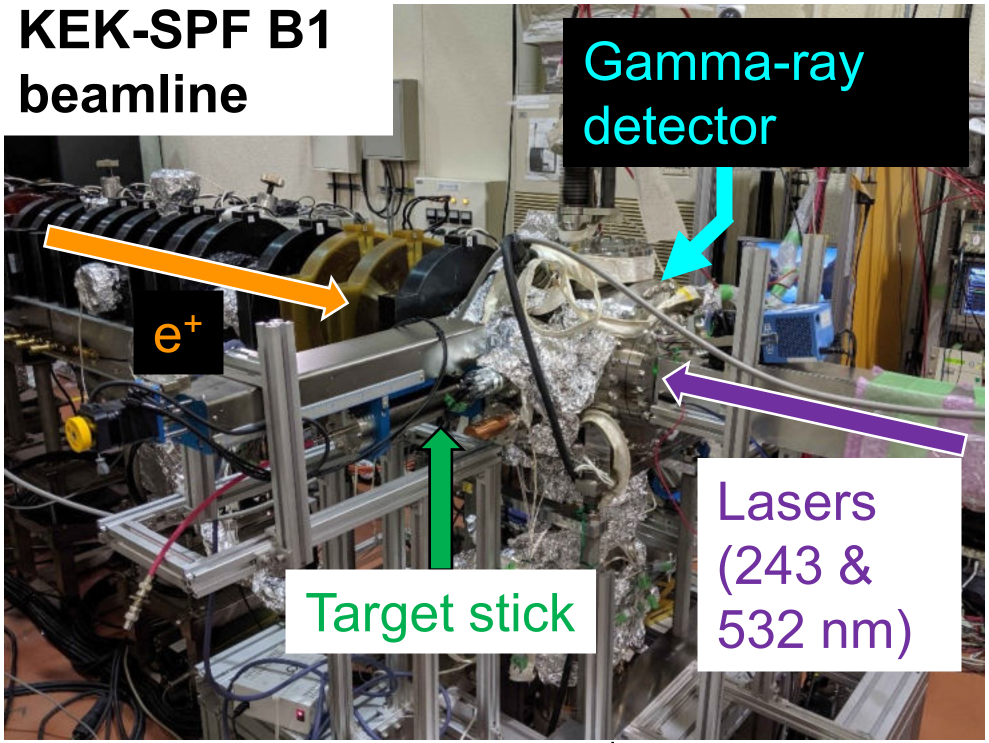
We are trying a proof-of-principle experiment to laser-cool Ps in vacuum.

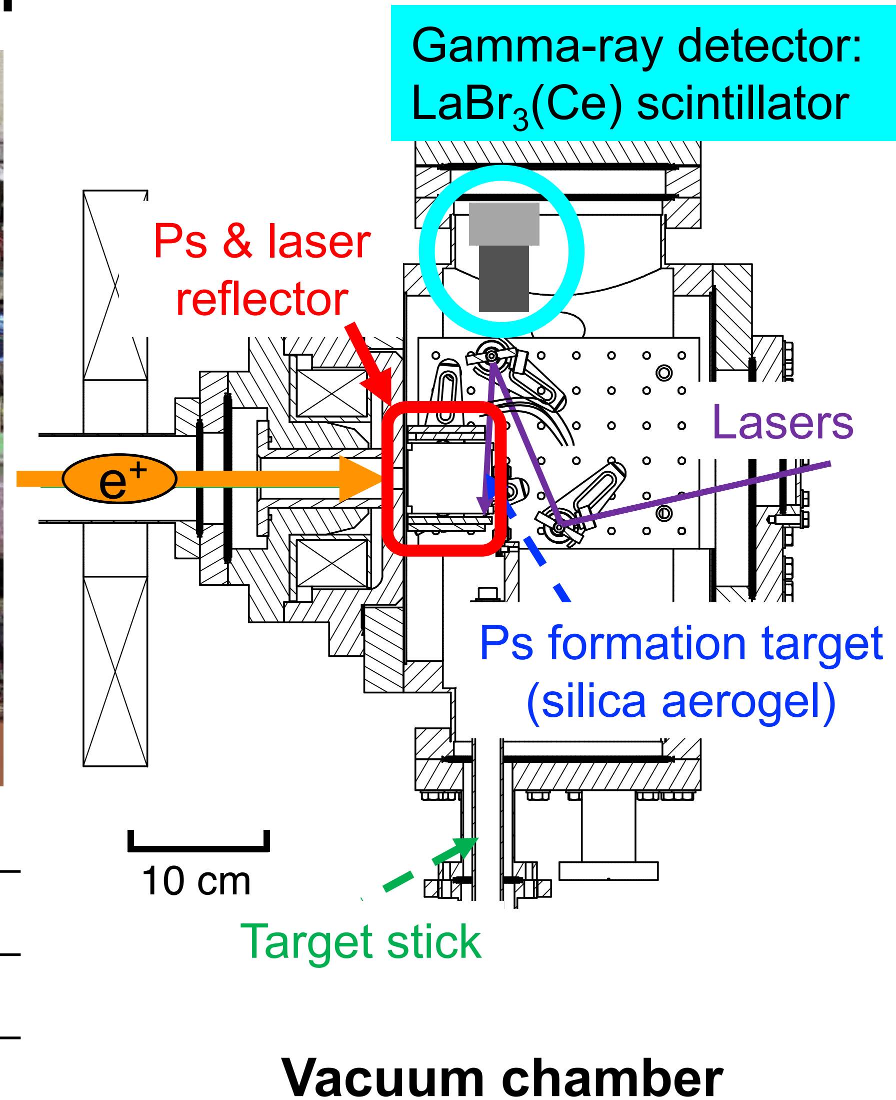
- Create Ps by irradiating a Ps-formation target (silica aerogel with open pores) with positron beam.
- Irradiate Ps emitted from the target with 243 nm UV laser.
- Reflect lasers for multiple times by high reflectance mirrors to obtain the interaction area between the laser and Ps.
- Confine Ps with two silica glass plates.





Experimental setup of Ps laser cooling at KEK-SPF

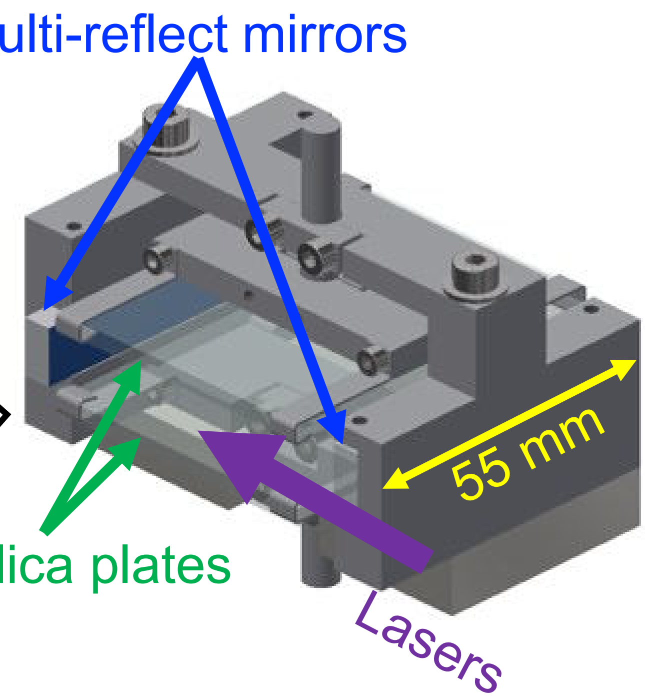




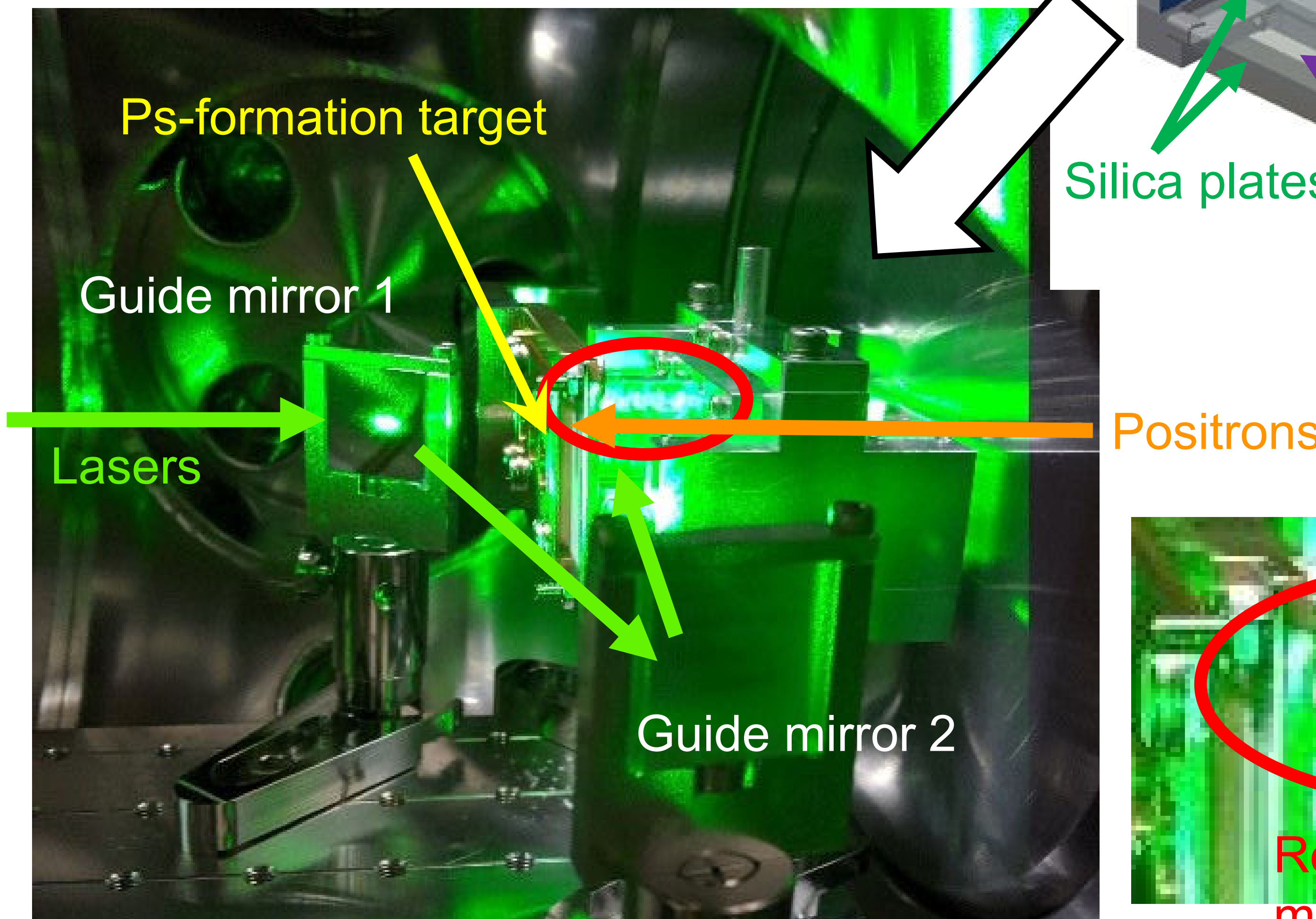
Energy	5 keV
Intensity	$\sim 10^6$ e^+/ s
Repetition	50 Hz
Pulse width	11 ns FWHM
Size	Ø ~10 mm

Photographs of the experimental setup at KEK-SPF

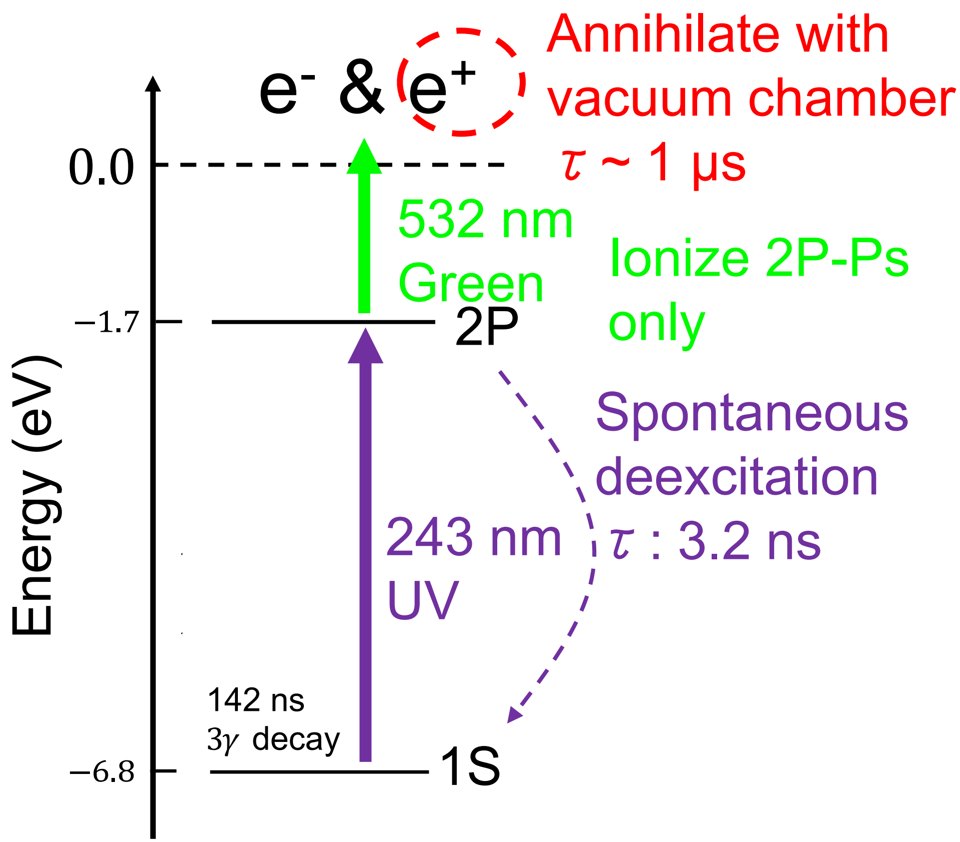
Ps & laser reflector



Inside the vacuum chamber

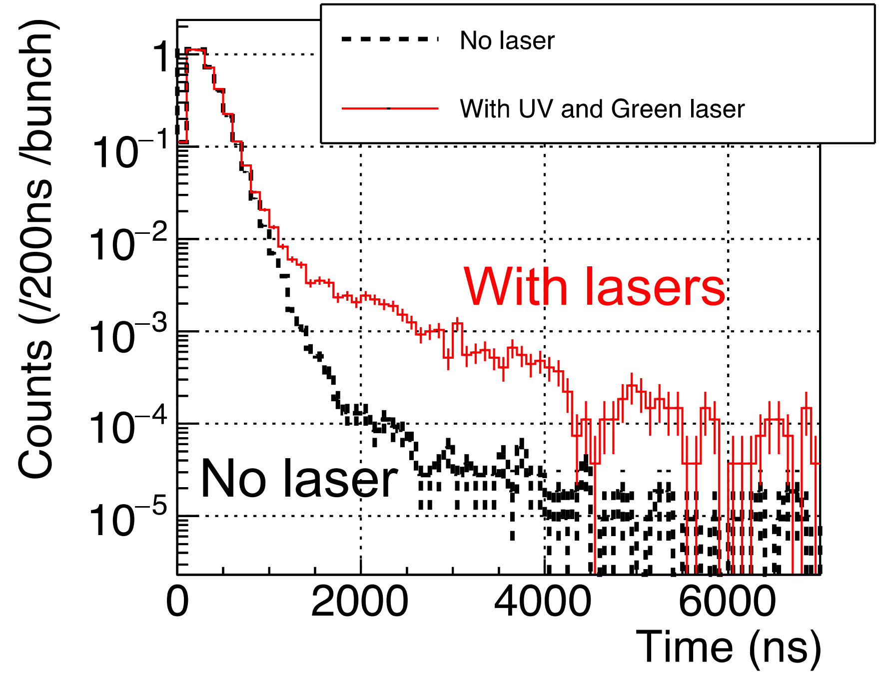


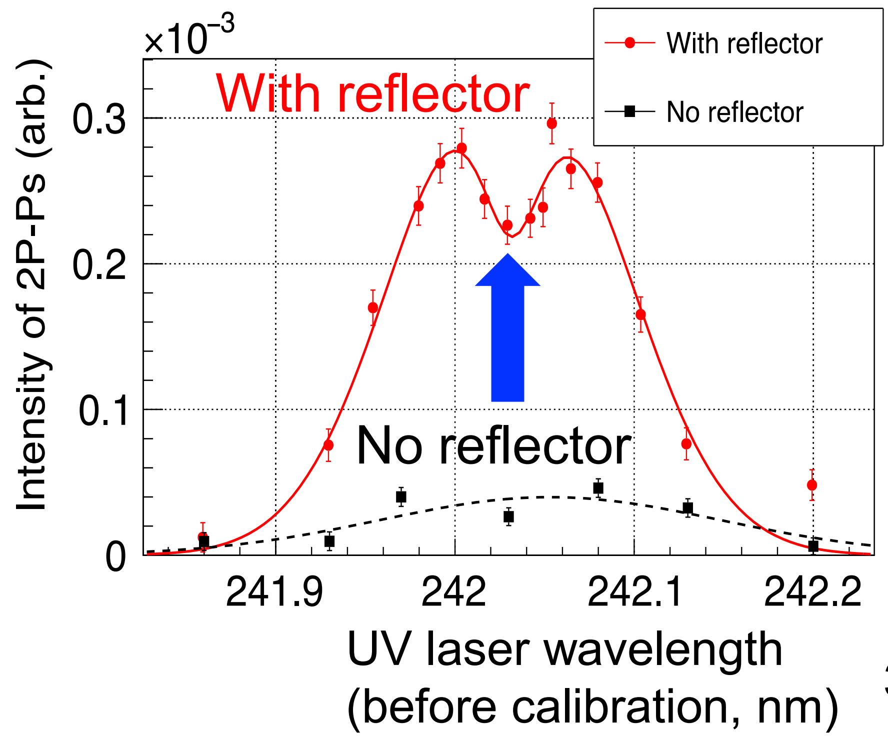
Successfully stimulated 1S→2P transition of Ps at KEK-SPF.
We expect a proof-of-principle experiment of Ps laser cooling within a year.



Total spin 1
o-Ps

A. Ishida *et al.*, Photon Factory Activity Report **37**(2020)201 (Japanese).





Summary

We want to realize an **antimatter quantum condensate** = positronium Bose-Einstein condensate (Ps-BEC).
Gamma-ray lasers may be realized using Ps-BEC as a source.

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

} This talk

3. Ps laser cooling → following talks