Recent progress in positronium laser cooling

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N. Oshima[6], B.E. O'Rourke[6], K. Michishio[6], K. Ito[6], K. Kumagai[6], R. Suzuki[6],
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6 AIST NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)
7 GIC
8 KEK
9 JAEA

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19th International Conference on Positron Annihilation (ICPA-19)
2022.08.24 Helsinki, Finland (Online Conference)

Acknowledgement

創発的研究支援事業

Fusion Oriented REsearch for disruptive Science and Technology

Supported by

- JST FOREST Program (Grant Number JPMJFR202L),
- JSPS KAKENHI Grant Numbers JP16H04526, JP17H02820, JP17H06205, JP17J03691, JP18H03855, JP19H01923,
- MATSUO FOUNDATION,
- Mitutoyo Association for Science and Technology (MAST),
- Research Foundation for Opto-Science and Technology,
- The Mitsubishi Foundation,
- TIA Kakehashi TK17-046, TK19-016,
- MEXT Q-LEAP JPMXS0118067246.

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   - Physics target: Bose-Einstein condensate (BEC), precision spectroscopy, antimatter gravity
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2. **Development of Ps cooling laser**
   - Requirements
   - Chirped Pulse-Train Generator (CPTG)

3. **Experiment at KEK slow positron facility (SPF)**
   - Experimental setup
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   - Prospects

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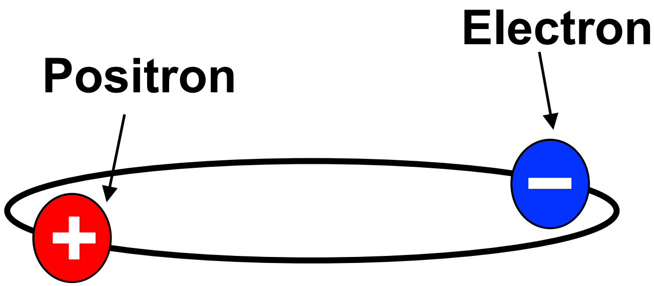
Positronium (Ps) is a good probe for fundamental physics



Bound state of an electron (e^-) and a positron (e^+)

The Lightest and Exotic Atom

- ✓ Exotic atom with antiparticle
  - ➢ Good to explore the mystery of antimatter
- ✓ Purely leptonic system
  - ➢ Experiments and theoretical calculations can be compared in high precision without uncertainties of hadronic interactions.

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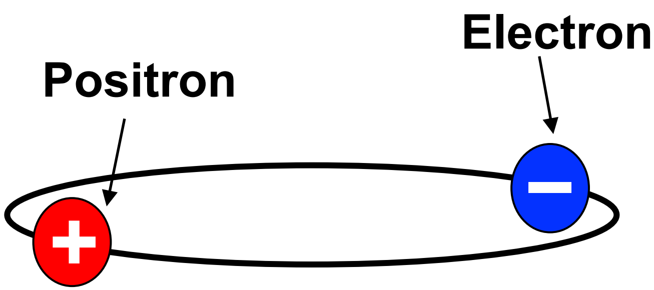

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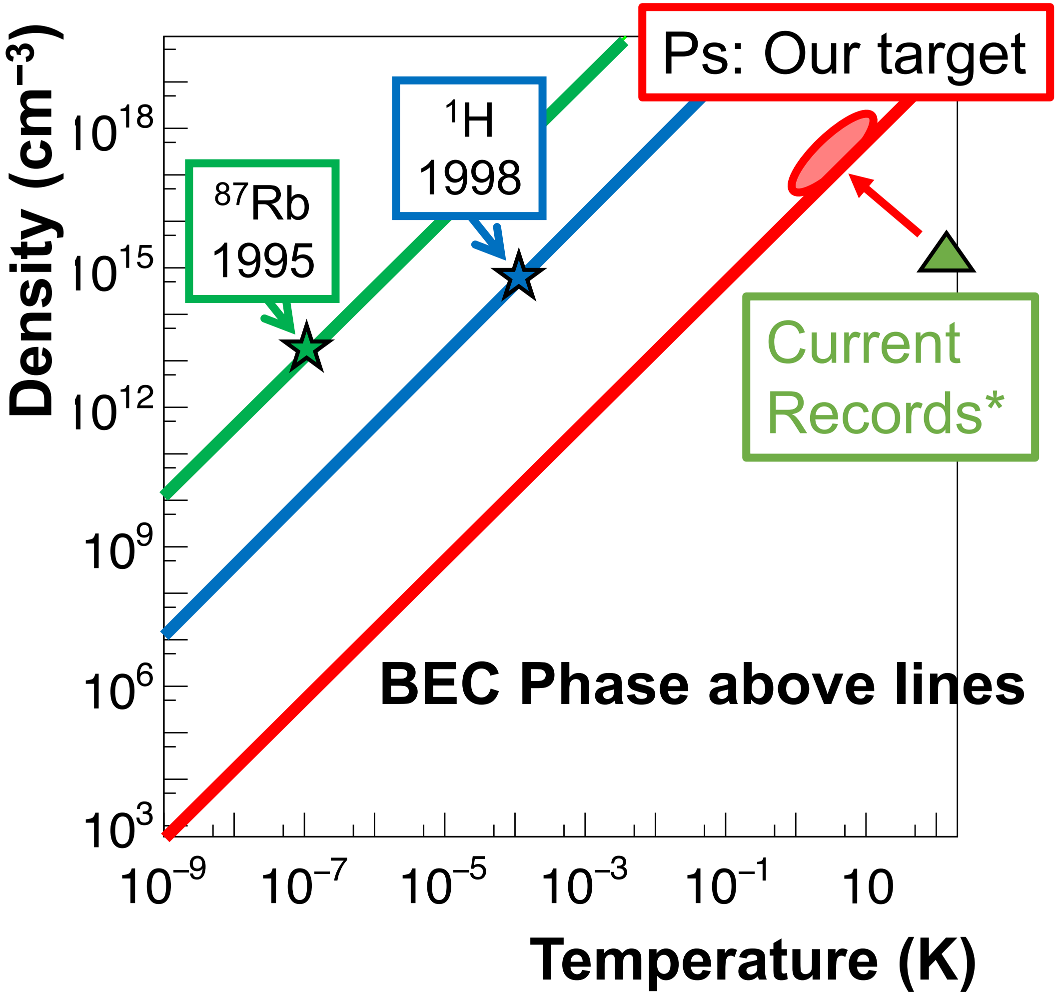
In this talk, we focus on *ortho*-positronium (*o*-Ps), the spin-triplet state with a lifetime of 142 ns.
o-Ps has much longer lifetime than the spin-singlet *para*-positronium (*p*-Ps), which has a lifetime of 125 ps.

Physics Target (1):

Positronium Bose-Einstein condensate (Ps-BEC)

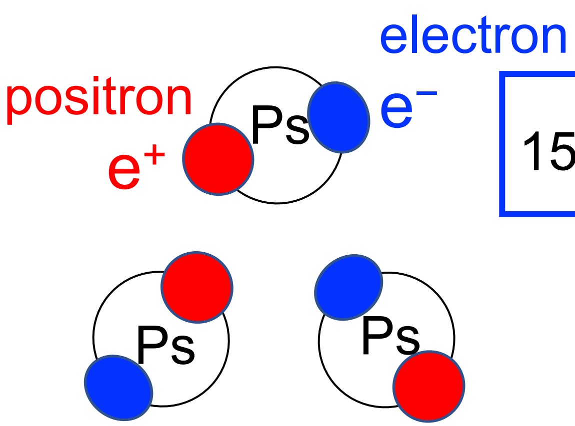


- Ps must be dense and cold
- High critical temperature because of Ps light mass (14 K at 10^{18} cm^{-3})
- One of the best candidates for the first antimatter BEC
- BEC is "Atomic laser". We would like to make the first antimatter laser and perform new experiments using the coherency of Ps-BEC.

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

Physics Target (1): Ps-BEC

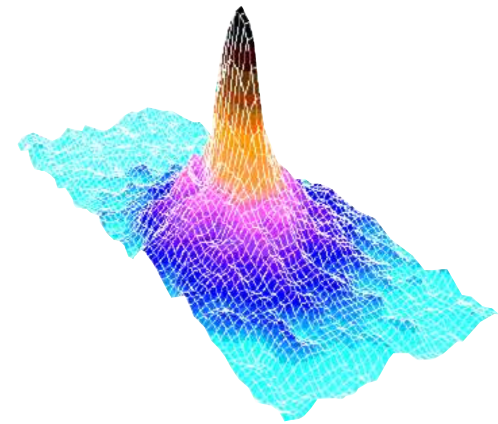
Realization of Ps-BEC at:
<u>Low temperature (10 K)</u> and
quite high density (10^{18} cm^{-3})



150 K ***Ps cooling*** 10 K

Phase transition

10^{15} cm^{-3} *High density* 10^{18} cm^{-3}



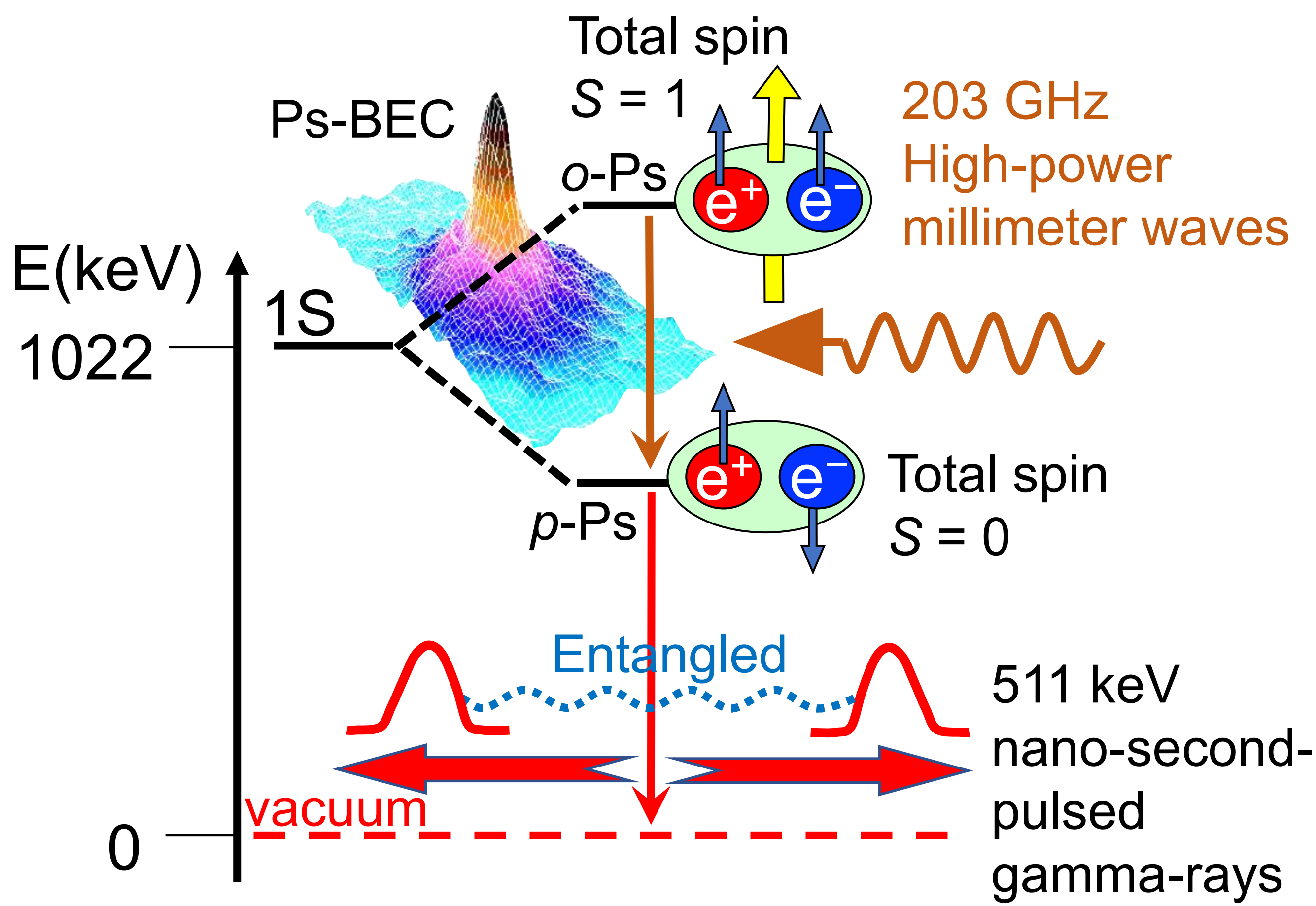
Antimatter
Positronium (Ps)
(Classical limit)

Antimatter quantum condensate
Positronium Bose-Einstein condensate
(Ps-BEC)

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

Physics Target (1): Ps-BEC

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).

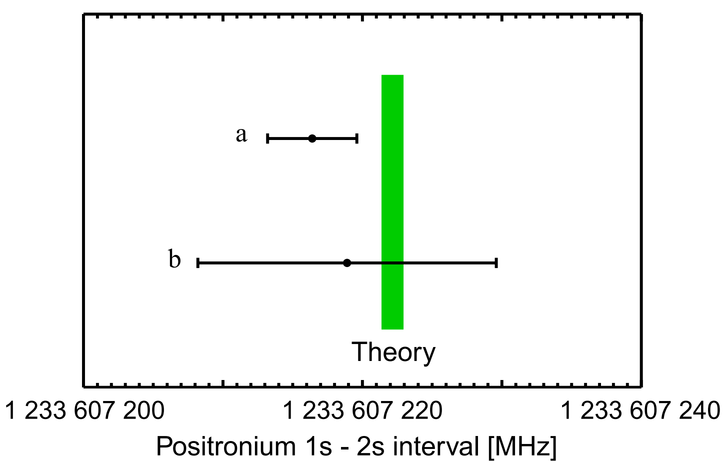
Physics Target (2):
Precision spectroscopy

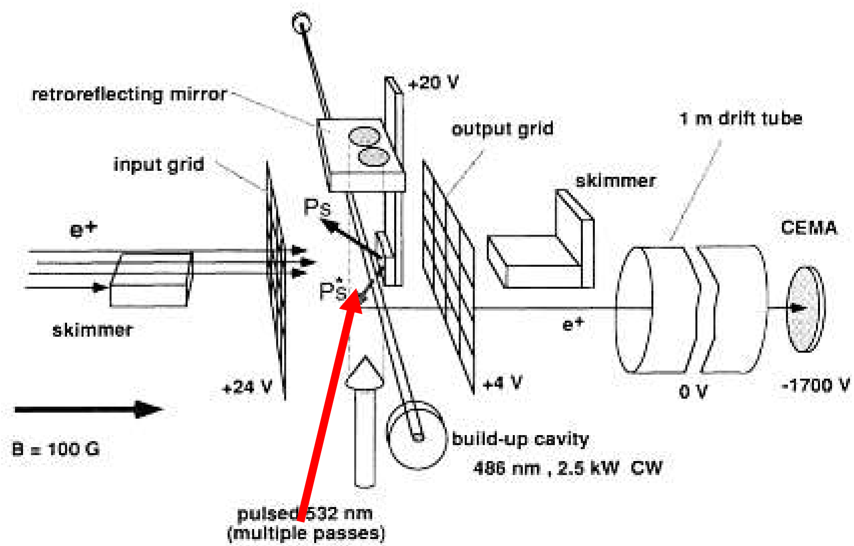
$m_{Ps} \approx 2m_e$: The lightest atom → large velocity

1*S*—2*S* precision spectroscopy: 1 233 607 216.4 ± 3.2 MHz (2.6 ppb)

Ps cooled down to 10 K can improve the precision by an order of magnitude

Savely G. Karshenboim / Physics Reports 422 (2005) 1–63





Ps at around 600 K

M.S. Fee *et al.*, Phys. Rev. Lett. **70**, 1397 (1993).

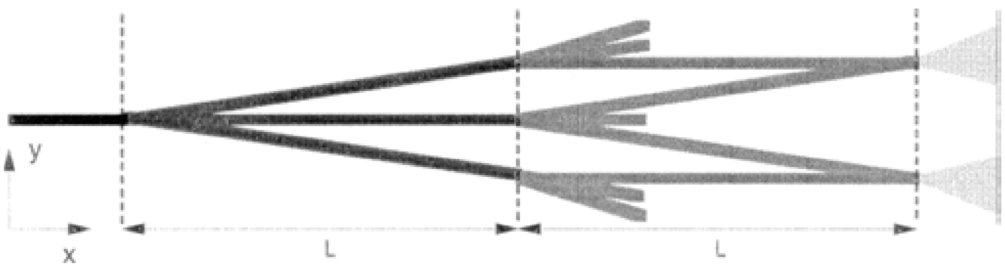
The high Ps temperature is the largest source of the uncertainty and bias.

Physics Target (3):

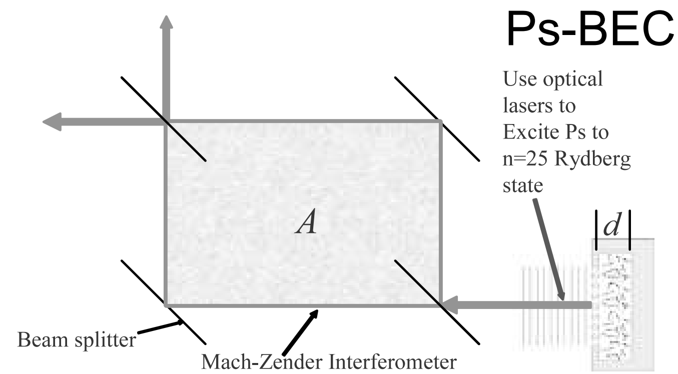
Antimatter gravity

Interferometry

coherence will be increased by cooling Ps



T. J. Phillips, Hyperfine Interactions **109**, 357 (1997).



D. B. Cassidy and A. P. Mills, Jr., phys. stat. sol. (c) **4**, 3419 (2007).

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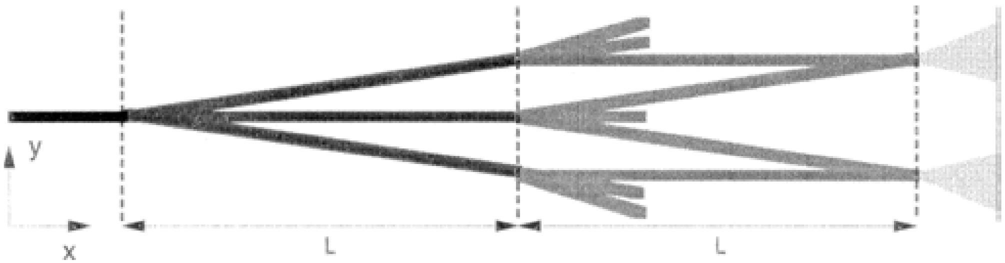
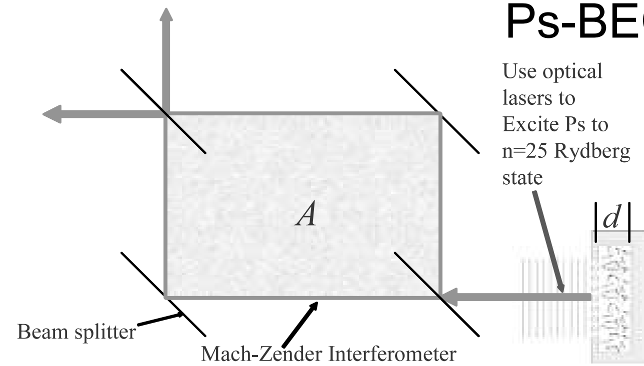


T. J. Phillips, Hyperfine Interactions **109**, 357 (1997).

Ps-BEC



D. B. Cassidy and A. P. Mills, Jr., phys. stat. sol. (c) **4**, 3419 (2007).

Spectroscopy

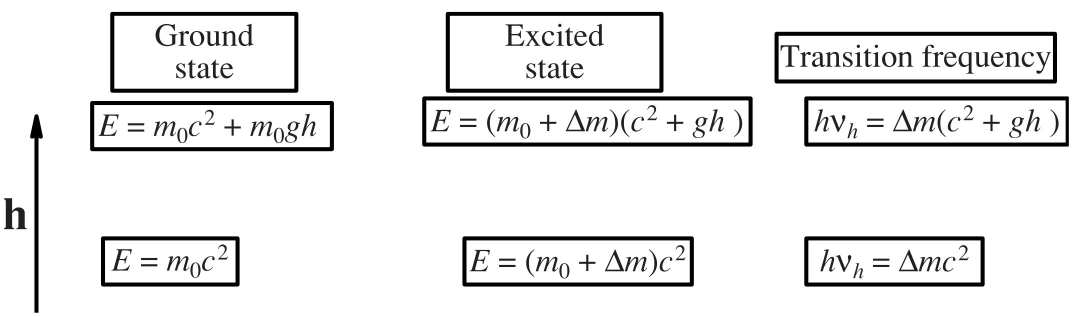


Fig. 1. Derivation of the gravitational red shift.

S. G. Karshenboim, Astron. Lett. **35**, 663 (2009).

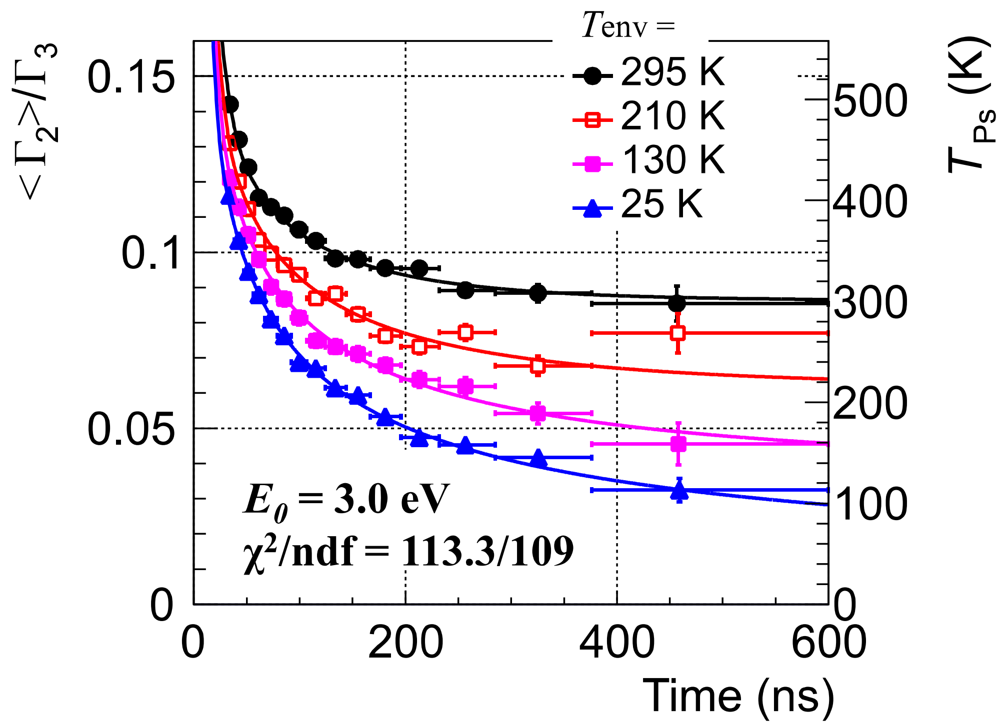
Different distance from the Sun:

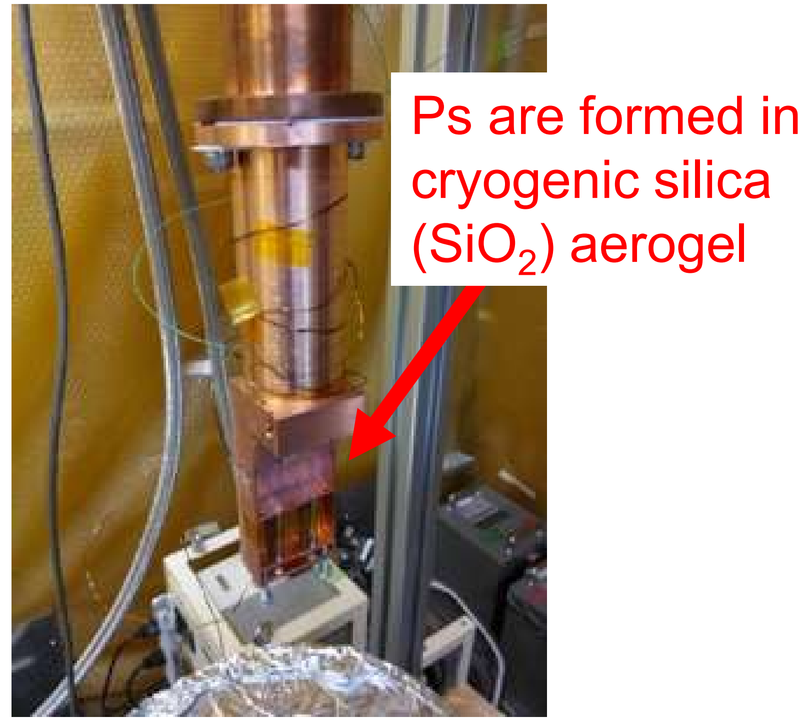
$$\frac{\Delta U(r_{\max}) - \Delta U(r_{\min})}{c^2} \simeq 3.2 \times 10^{-10}.$$

(0.32 ppb)

cf. Ps 1*S*—2*S* : 2.6 ppb

Thermalization cooling is too slow to get 10 K.
→ We need faster cooling: Ps laser cooling.





PHYSICAL REVIEW A **104**, L050801 (2021)

Letter

Observation of orthopositronium thermalization in silica aerogel at cryogenic temperatures

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Nagayasu Oshima, Brian E. O'Rourke, and Kenji Ito
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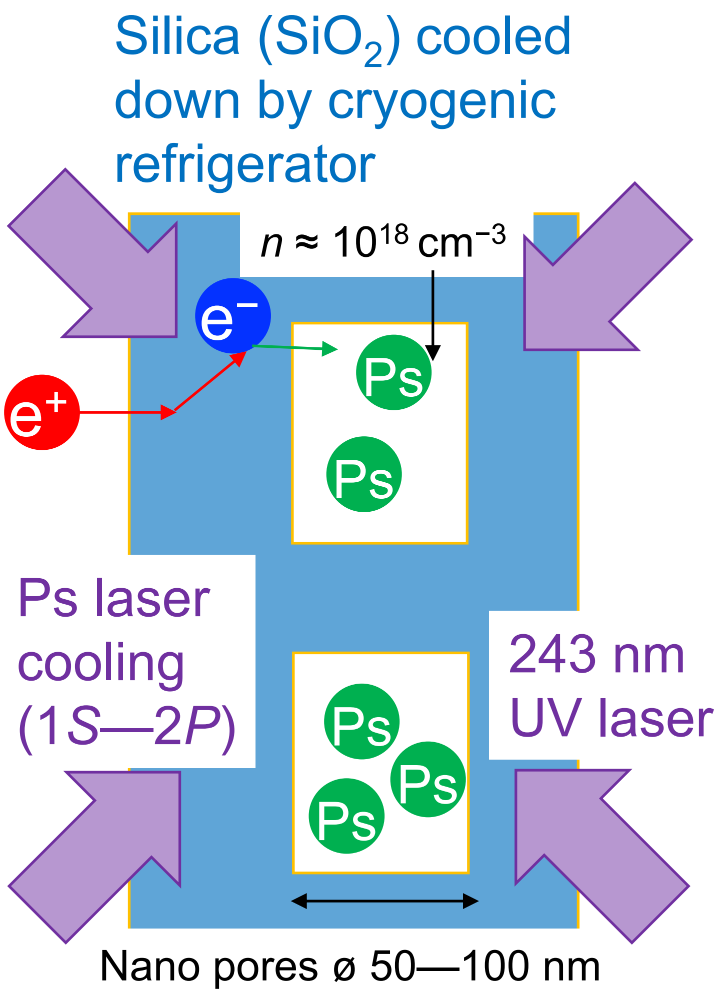
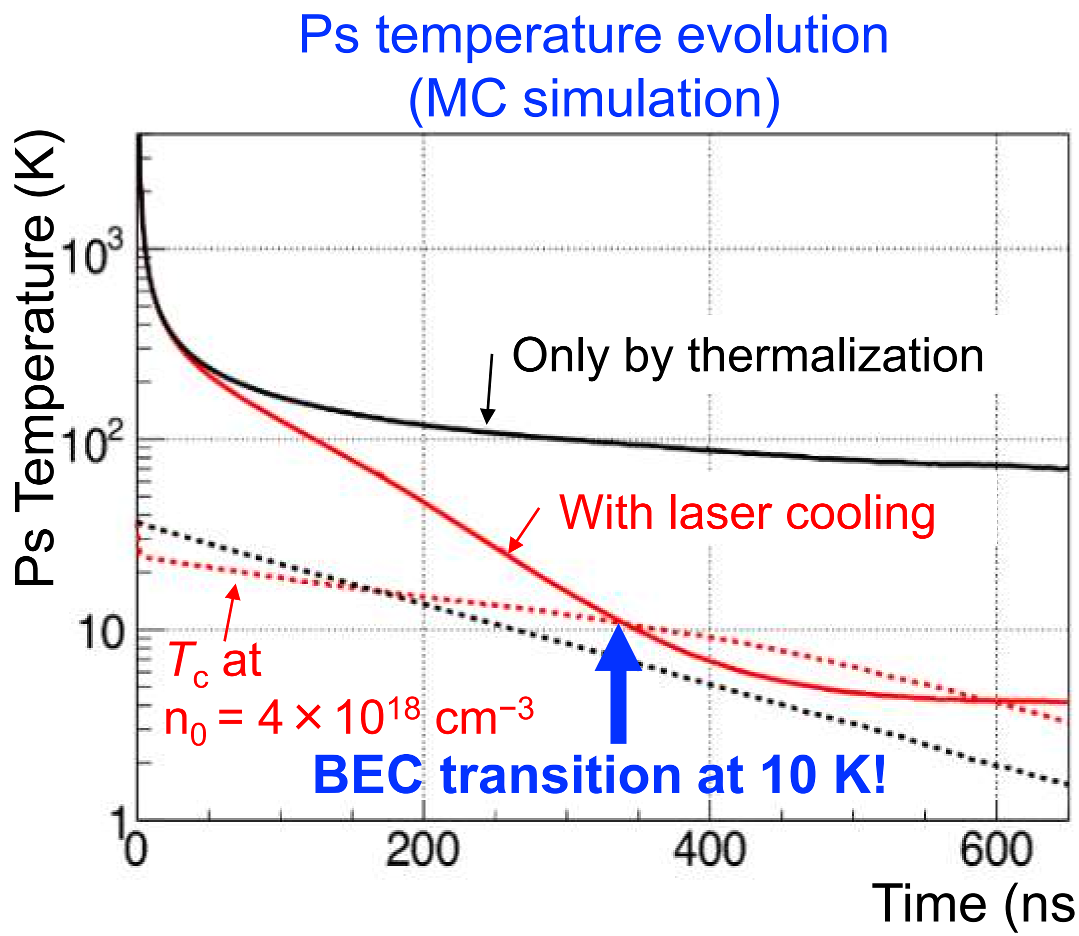
Combination of Thermalization and Laser cooling is suitable for fast Ps cooling to realize Ps-BEC.





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

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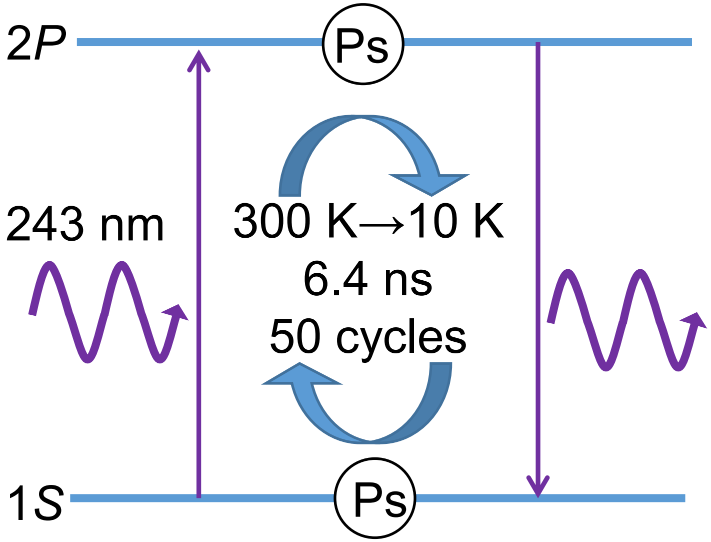
Requirements for Ps cooling laser

1. Long pulse duration and sufficient pulse energy
   ← Ps lifetime: 142 ns



- 1*S*—2*P* (243 nm)
- 6.4 ns × 50 ≈ 300 ns → Cool down Ps with 300-ns single pulse
- Pulse energy ≥ 40 μJ

Requirements for Ps cooling laser

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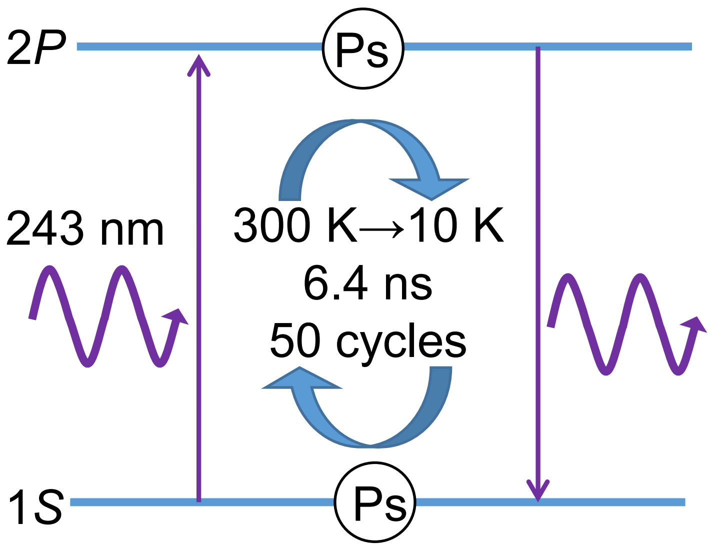
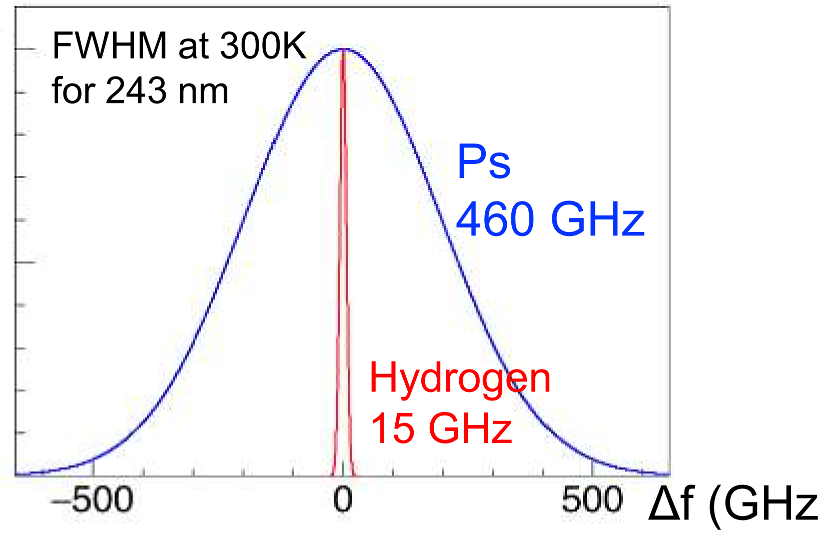


- 1S—2P (243 nm)
- 6.4 ns × 50 ≈ 300 ns → Cool down Ps with 300-ns single pulse
- Pulse energy ≥ 40 μJ

2. <u>Broadband and frequency-chirped</u>
   ← Ps light mass: $2m_e$



- Doppler broadening is 30 times larger than hydrogen. To follow the change in the Doppler profile by cooling (300 to 10 K in 300 ns)
  → Broadband (≥ 10 GHz) and Frequency chirp ≥ +0.2 GHz ns^{-1}

→ 243 nm sub-μs pulsed, broadband, and frequency-chirped laser

Chirped Pulse-Train Generator (CPTG)

PHYSICAL REVIEW APPLIED **16,** 014009 (2021)

Theoretical Analysis and Experimental Demonstration of a Chirped Pulse-Train Generator and its Potential for Efficient Cooling of Positronium

K. Yamada,[1] Y. Tajima,[2] T. Murayoshi,[1] X. Fan,[1,†] A. Ishida,[1] T. Namba,[3] S. Asai,[1]
M. Kuwata-Gonokami,[1] E. Chae,[2,4,5] K. Shu,[1,2,4] and K. Yoshioka[2,4,*]

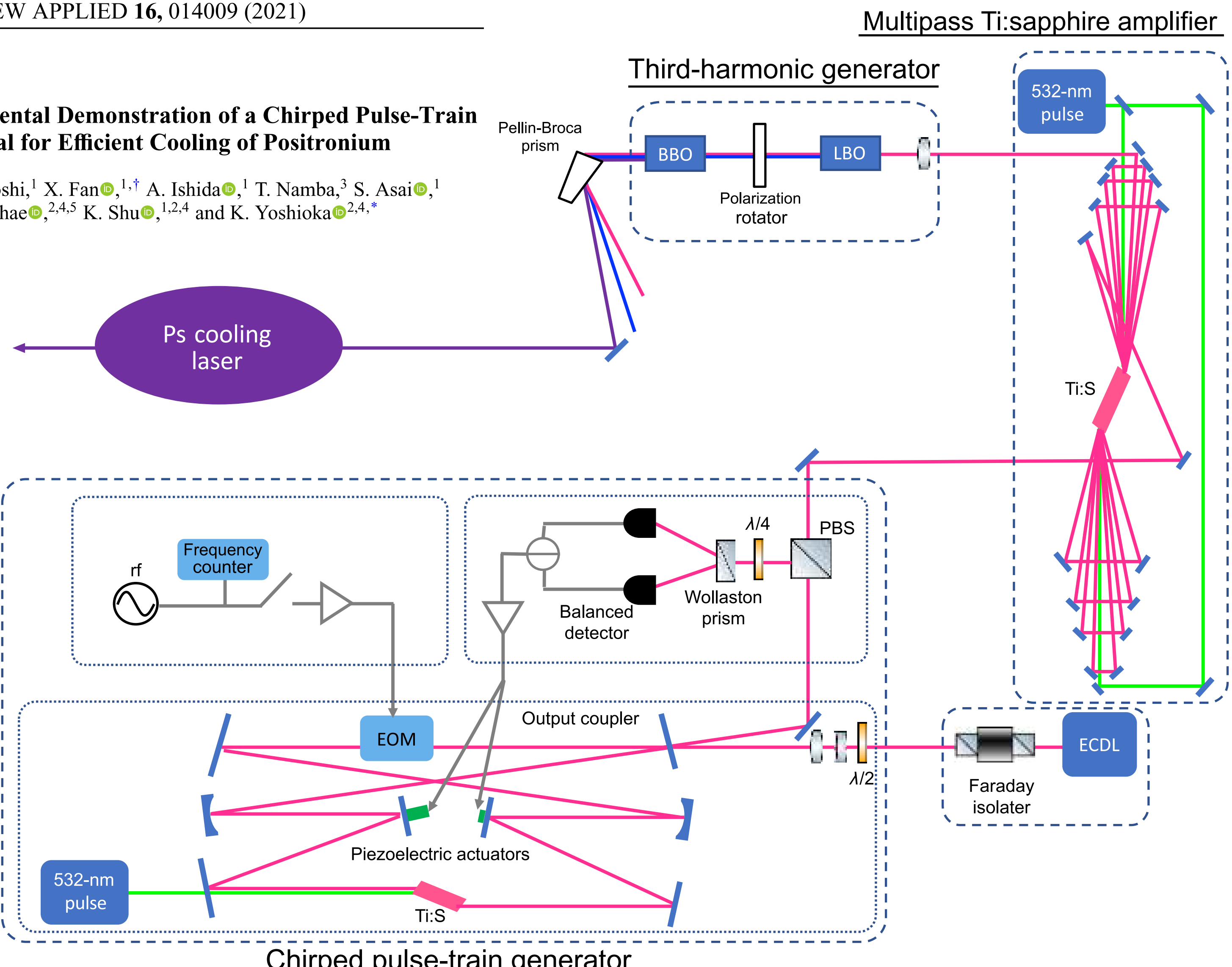
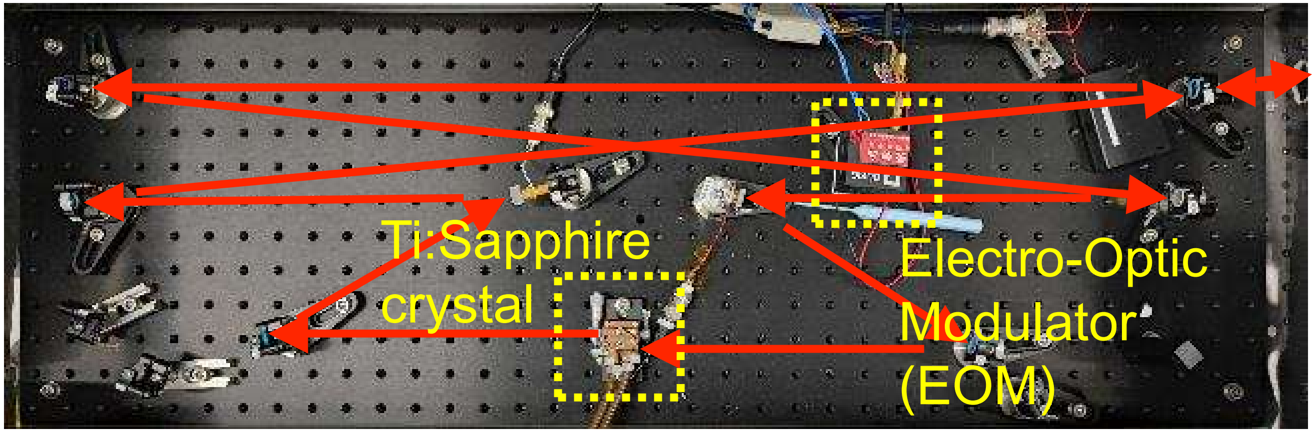
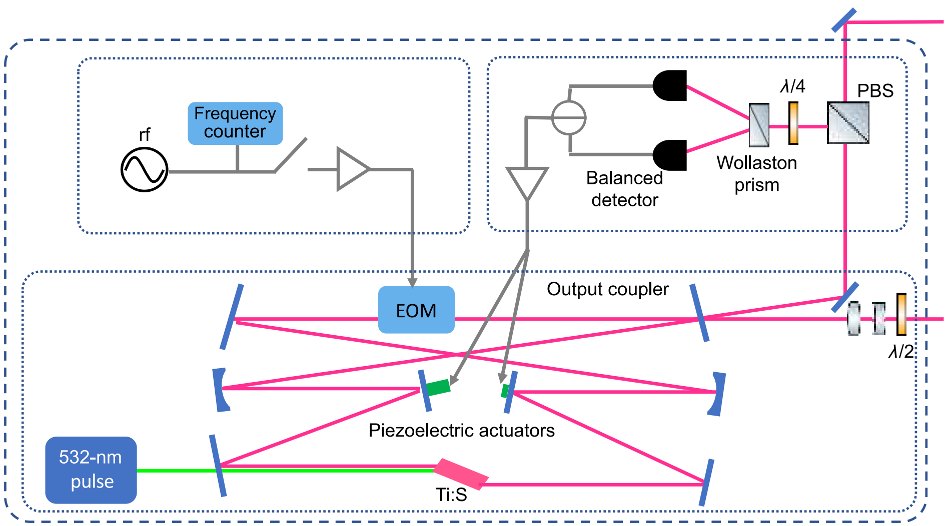


FIG. 1. Schematic of the prototypical cooling laser system. ECDL, external-cavity diode laser; $\lambda/2$, half-wave plate; $\lambda/4$, quarter-wave plate; EOM, electro-optic phase modulator; rf, driving radio frequency; Ti:S, Ti:sapphire crystal; PBS, polarizing beam splitter; LBO, lithium triborate crystal; BBO, β-barium borate crystal.

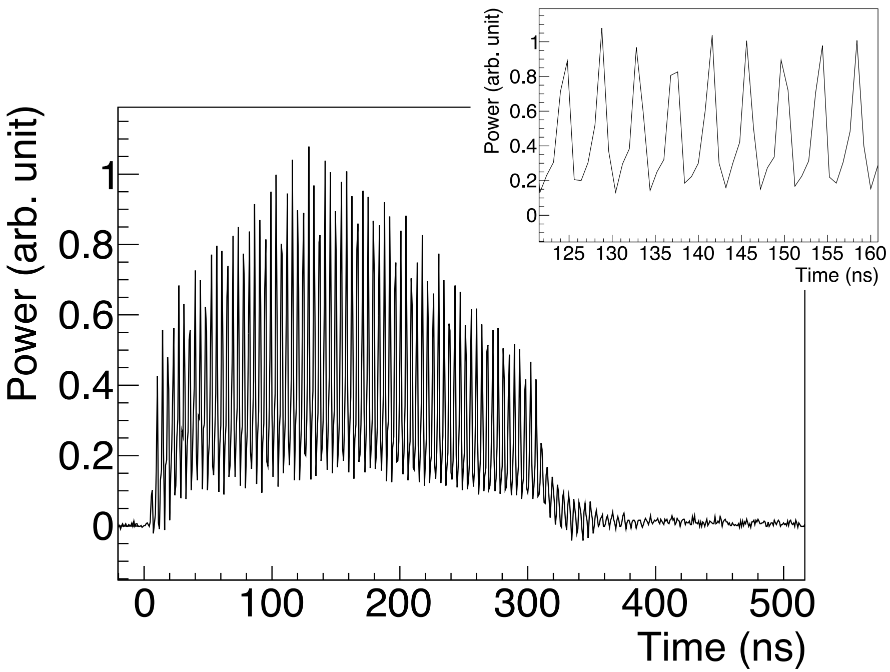
Ps cooling laser

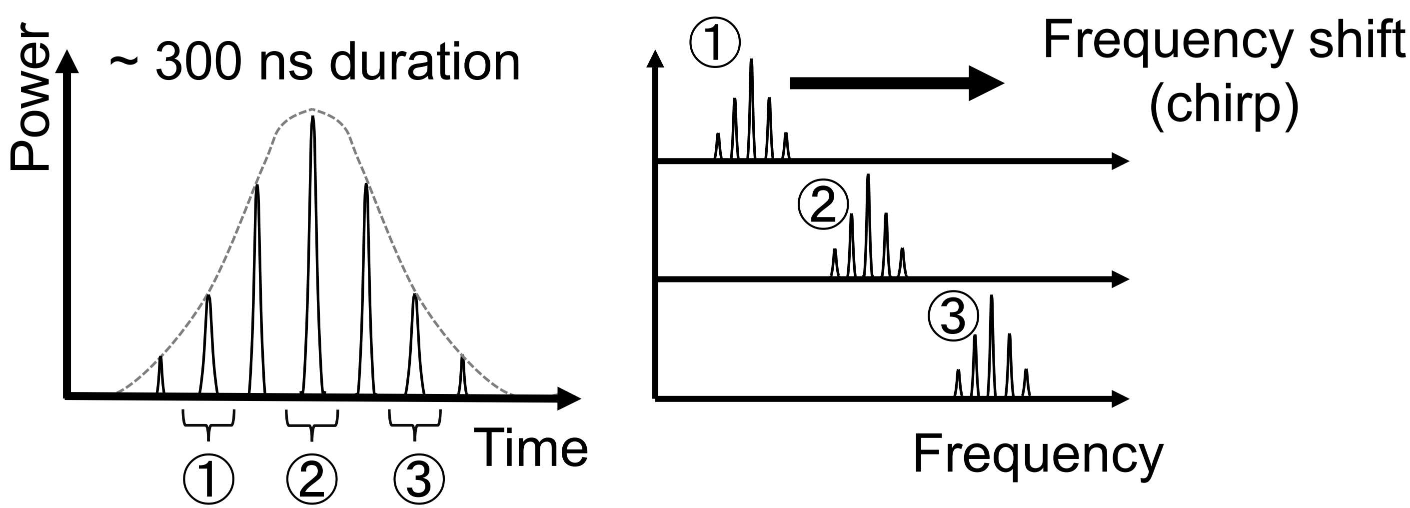




Chirped pulse-train generator

Achieved 300-ns pulse duration





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   - Experimental setup
   - Current status of proof-of-principle experiment
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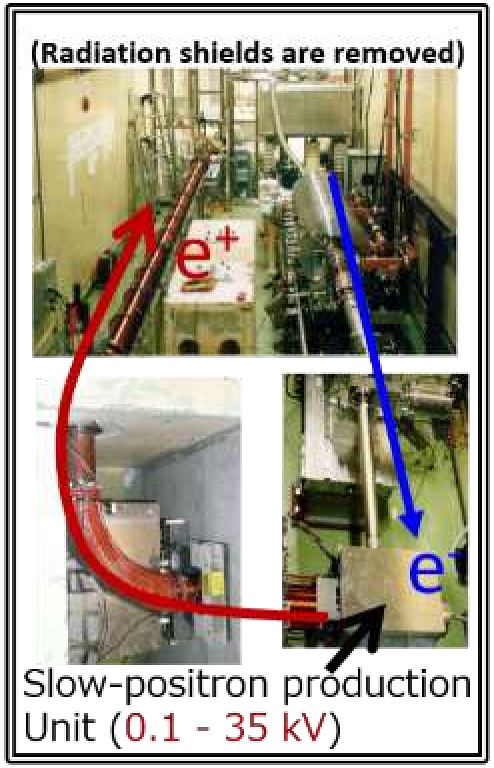
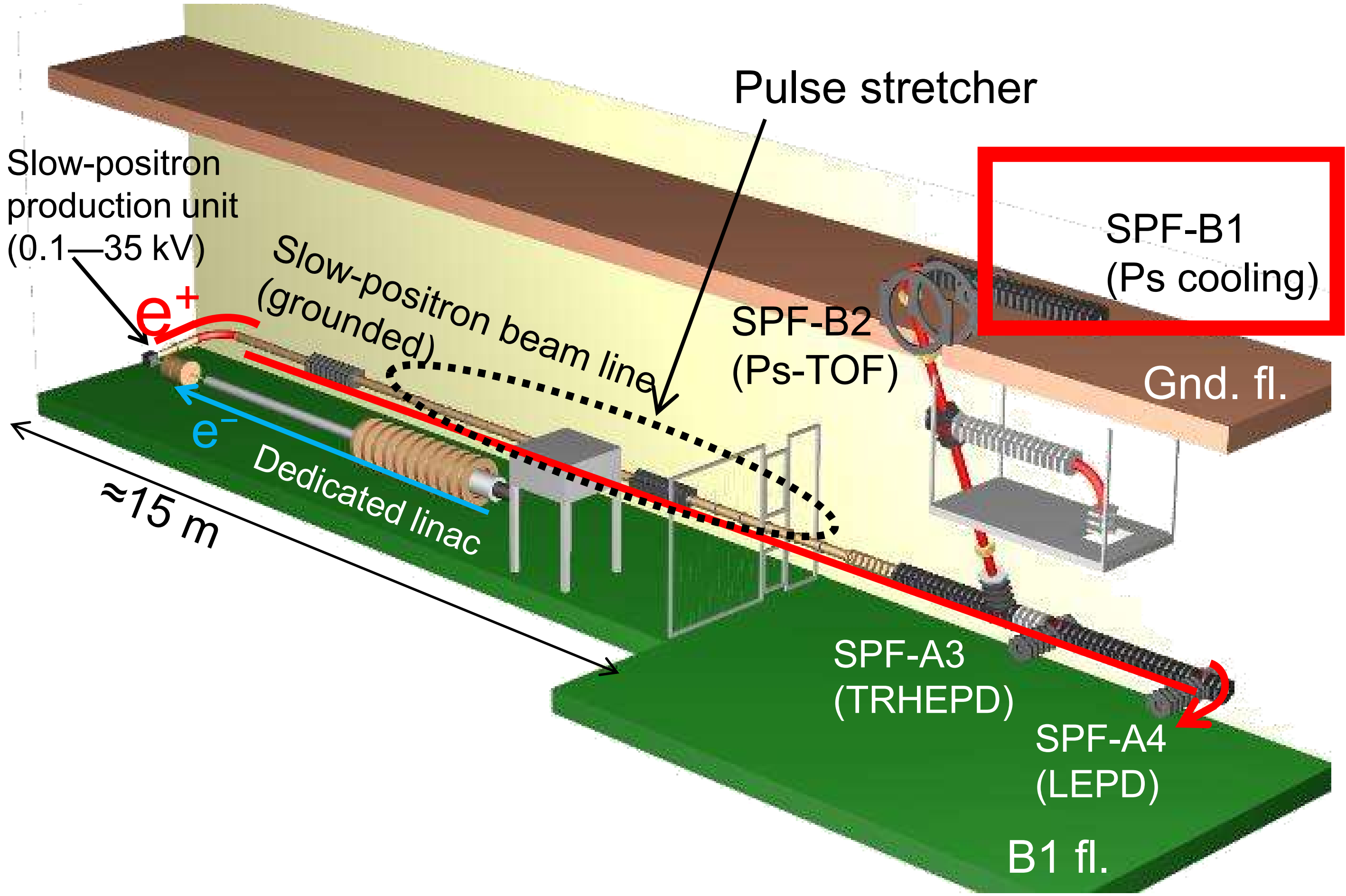
We are trying a proof-of-principle experiment to **laser-cool Ps in vacuum** at **KEK-SPF (Slow Positron Facility)**, Tsukuba, Japan.

- Highest intensity (5×10^7 slow e^+ s^{-1})
- Variable energy (0.1—35 keV)

Samples and detectors are electrically grounded.

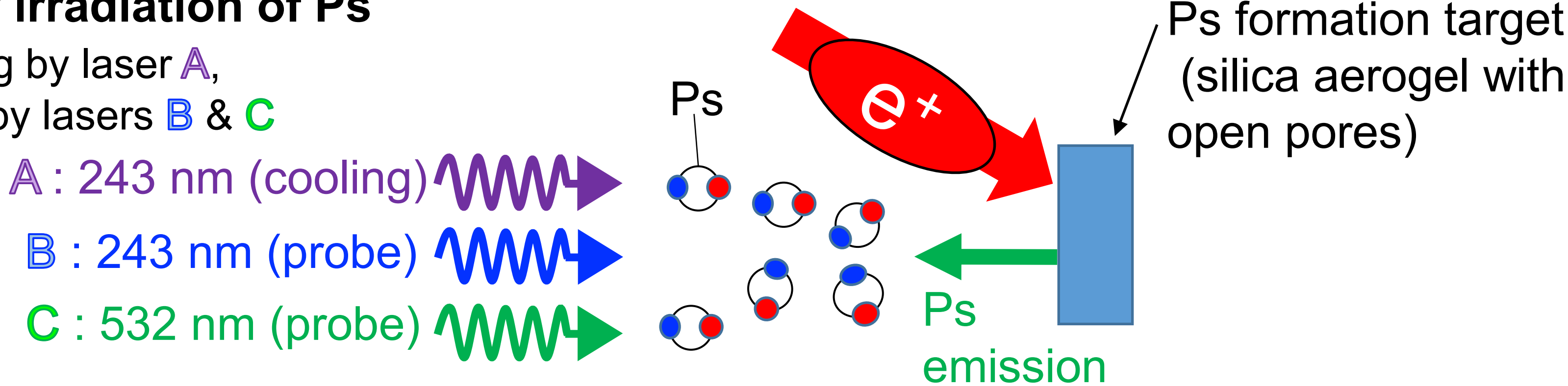




Ps Doppler cooling experiment with 3 lasers
—1 cooling (243 nm) and 2 probe (243 & 532 nm) lasers—

(a) Laser irradiation of Ps

Cooling by laser A,
Probe by lasers B & C



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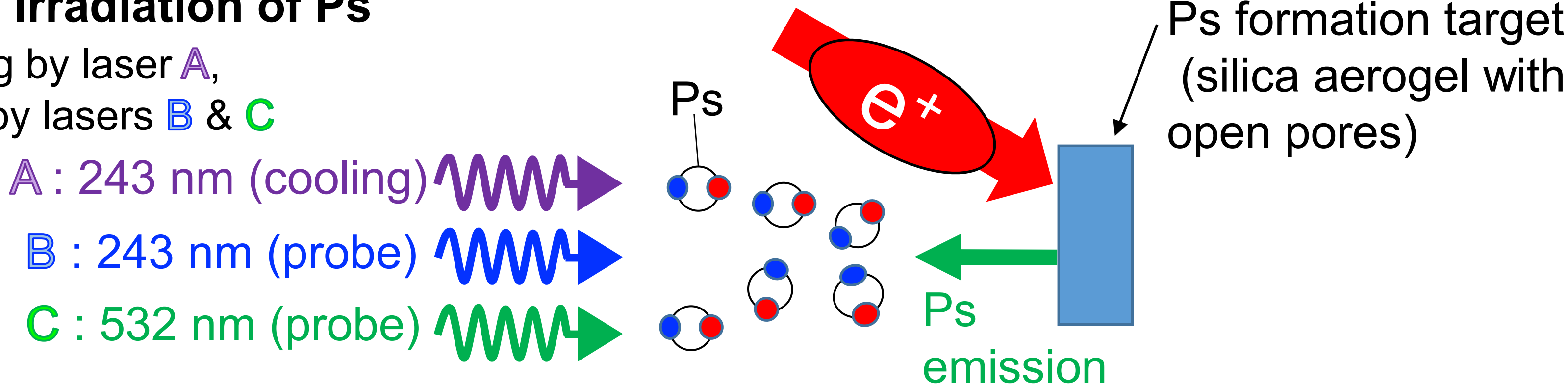
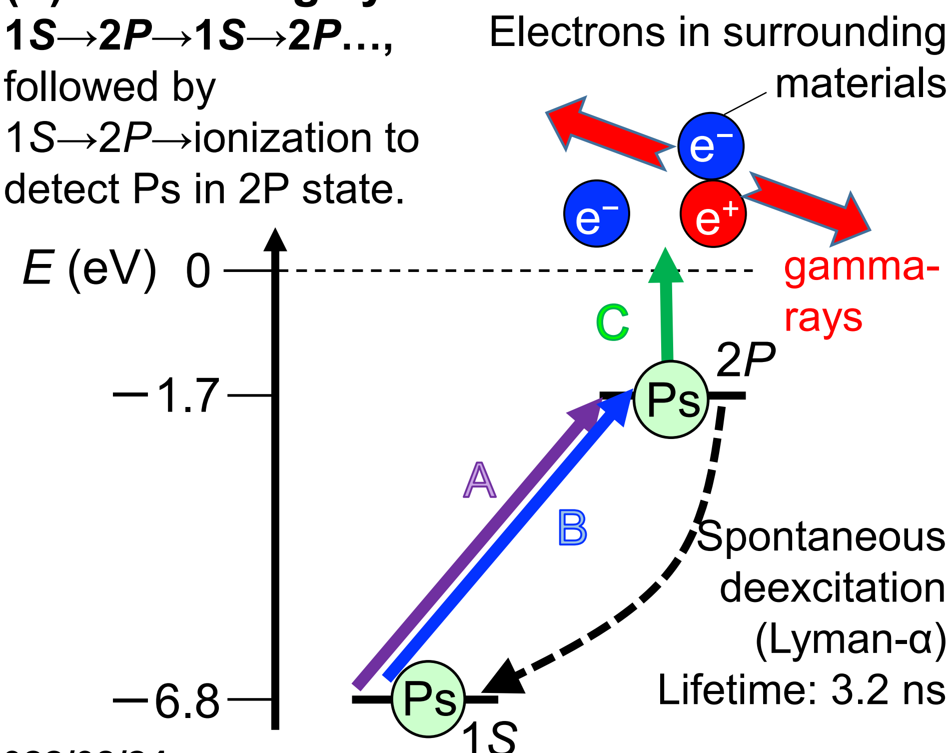


(b) Ps cooling cycle

1*S*→2*P*→1*S*→2*P*…, followed by 1*S*→2*P*→ionization to detect Ps in 2P state.



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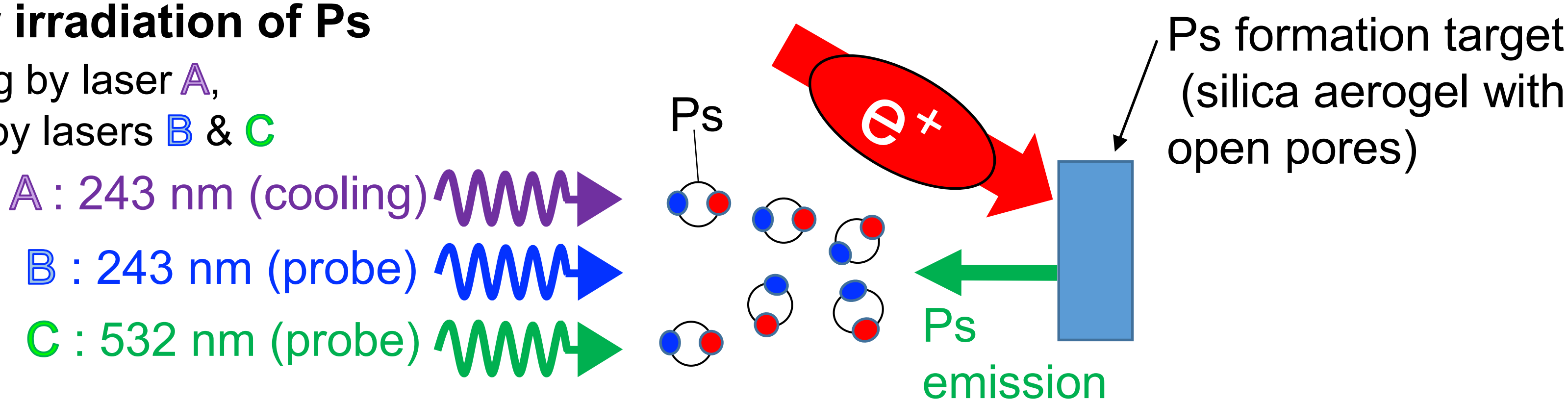

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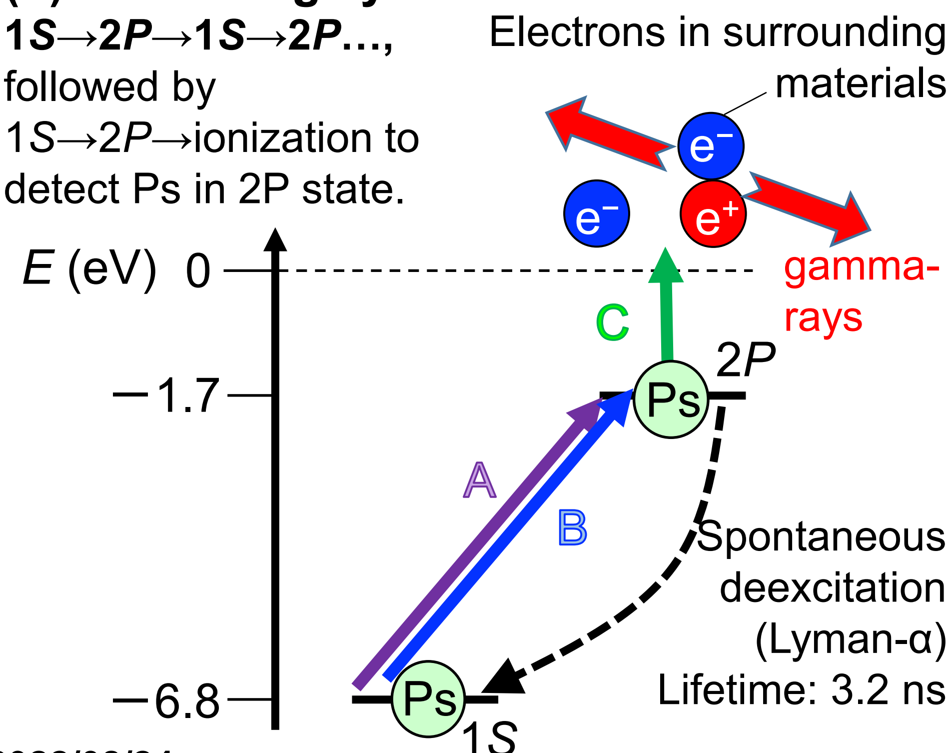
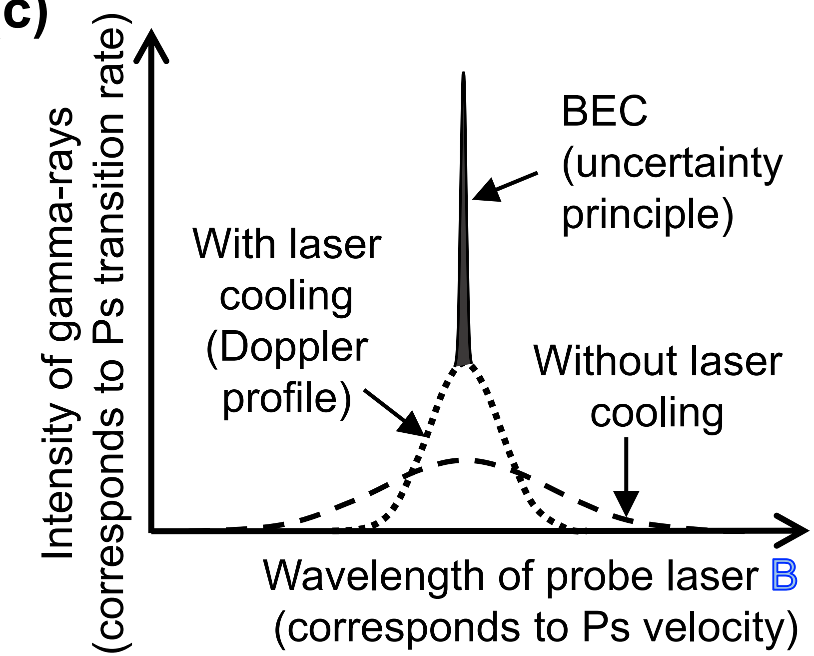
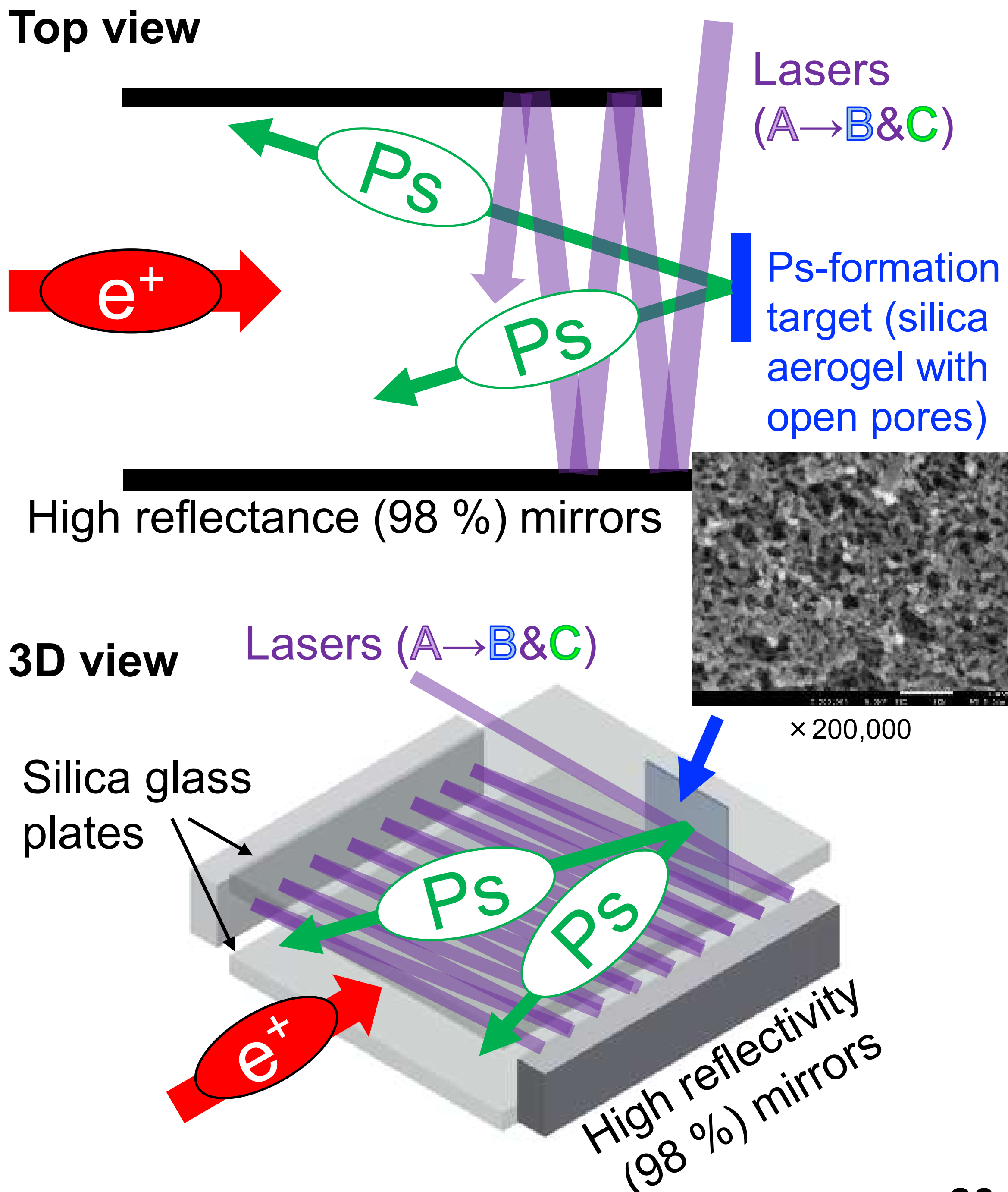


(c)



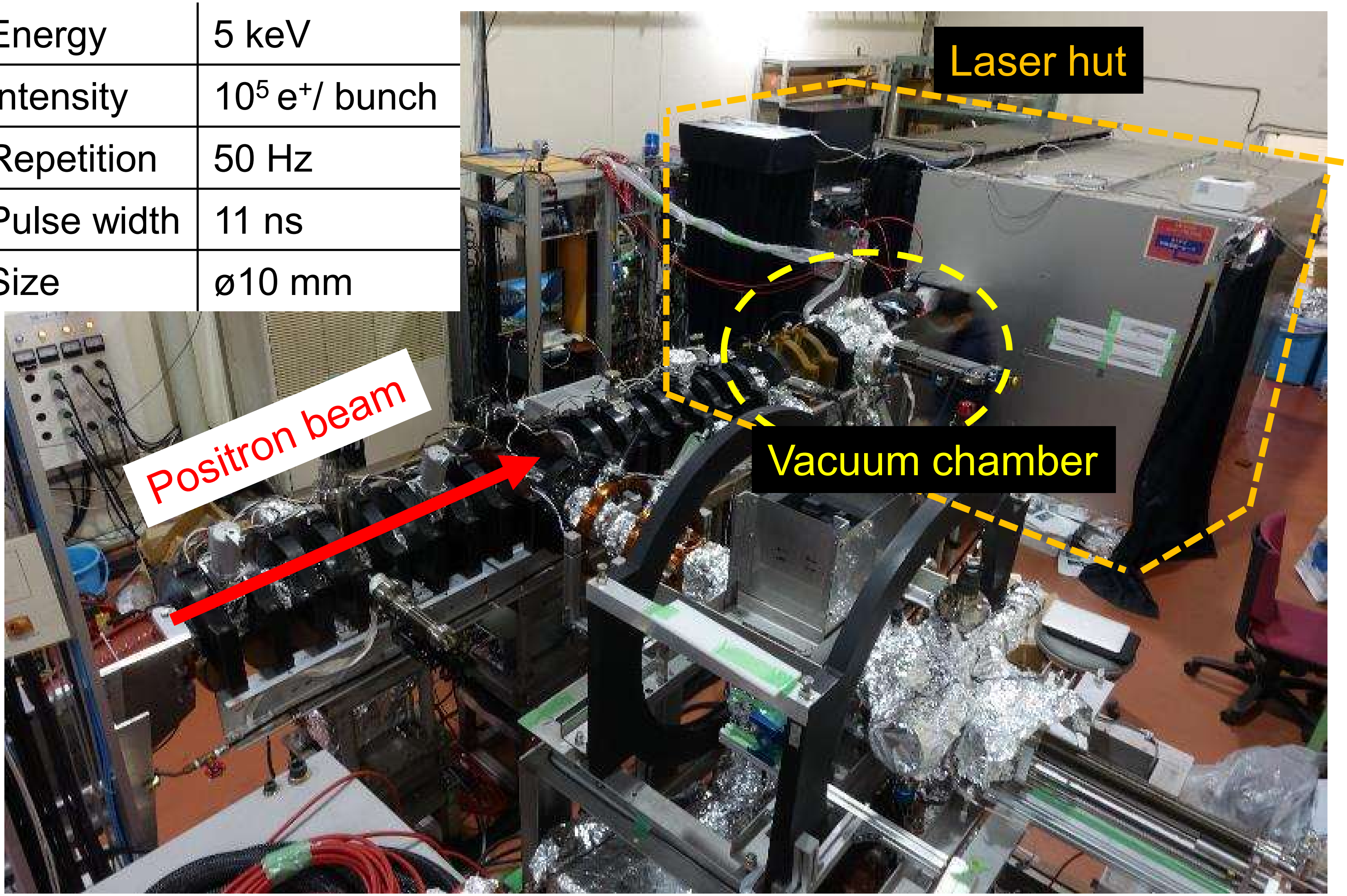
1D laser cooling of Ps in vacuum.

- 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 reflectivity mirrors to obtain the interaction area between the laser and Ps.
- Confine Ps with two silica glass plates.



Experimental setup at KEK-SPF

Energy	5 keV
Intensity	10^5 e^+/ bunch
Repetition	50 Hz
Pulse width	11 ns
Size	ø10 mm



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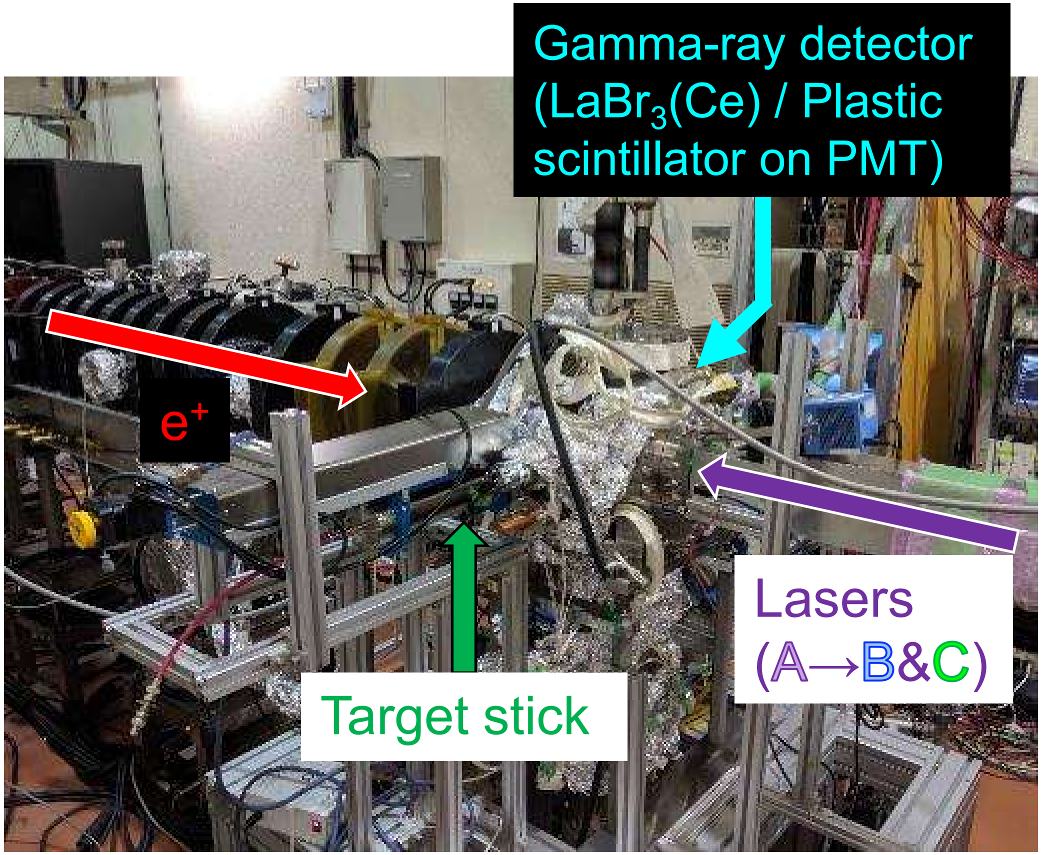

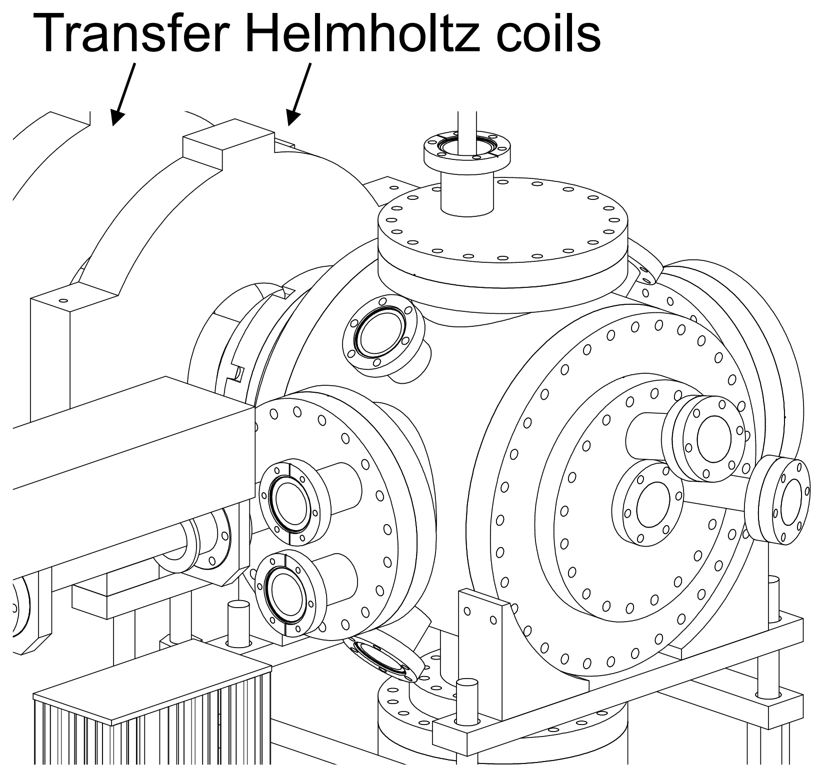

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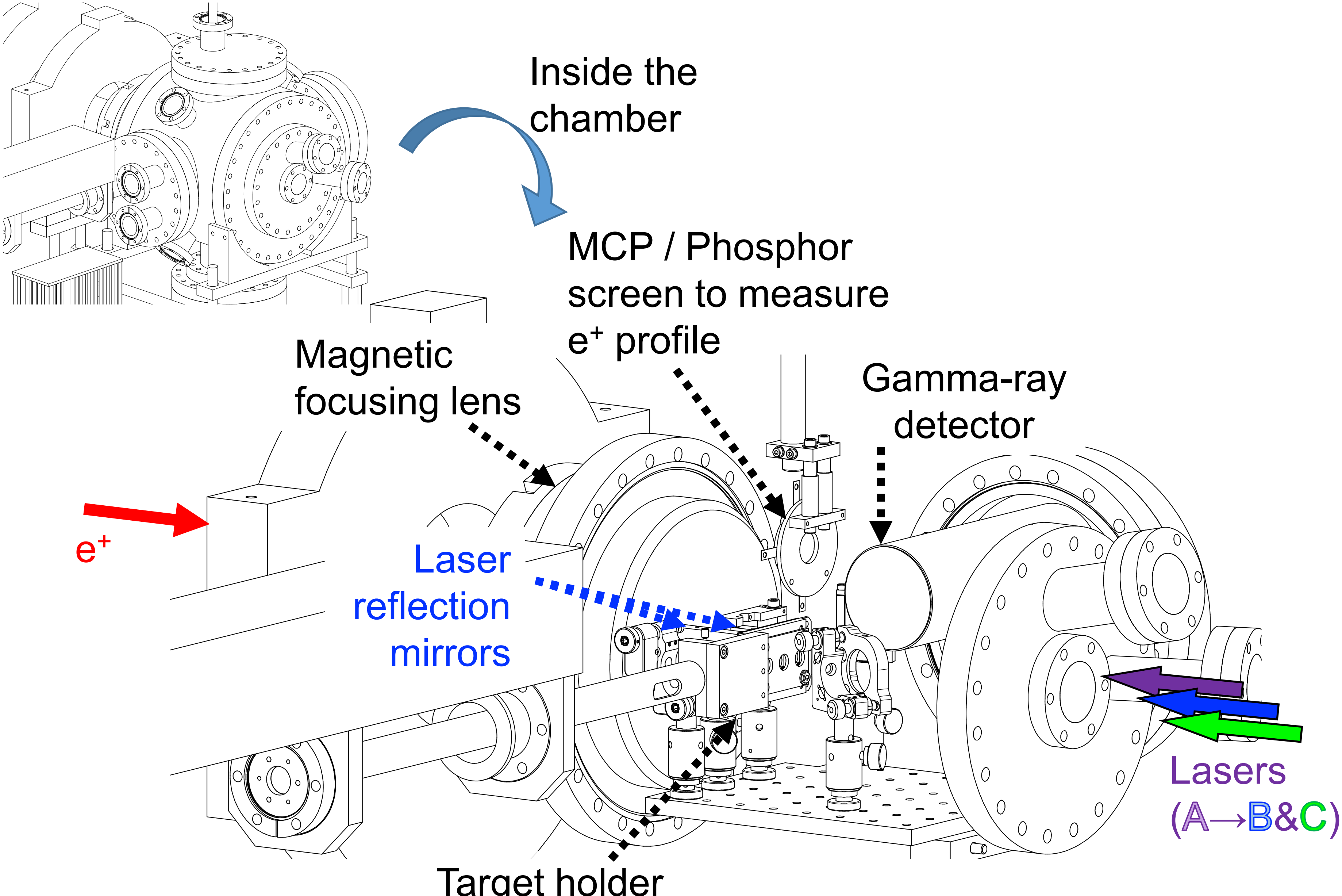

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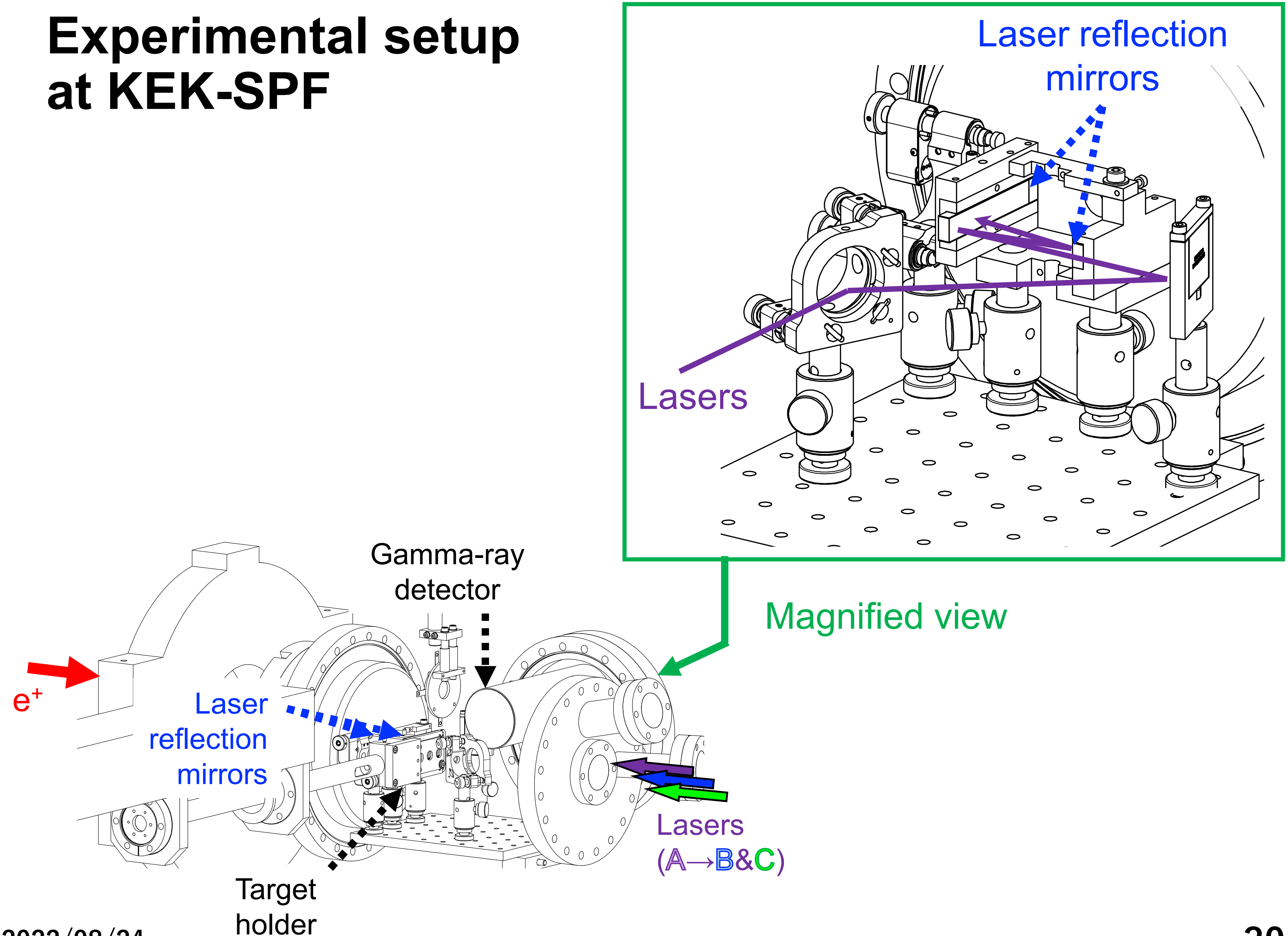

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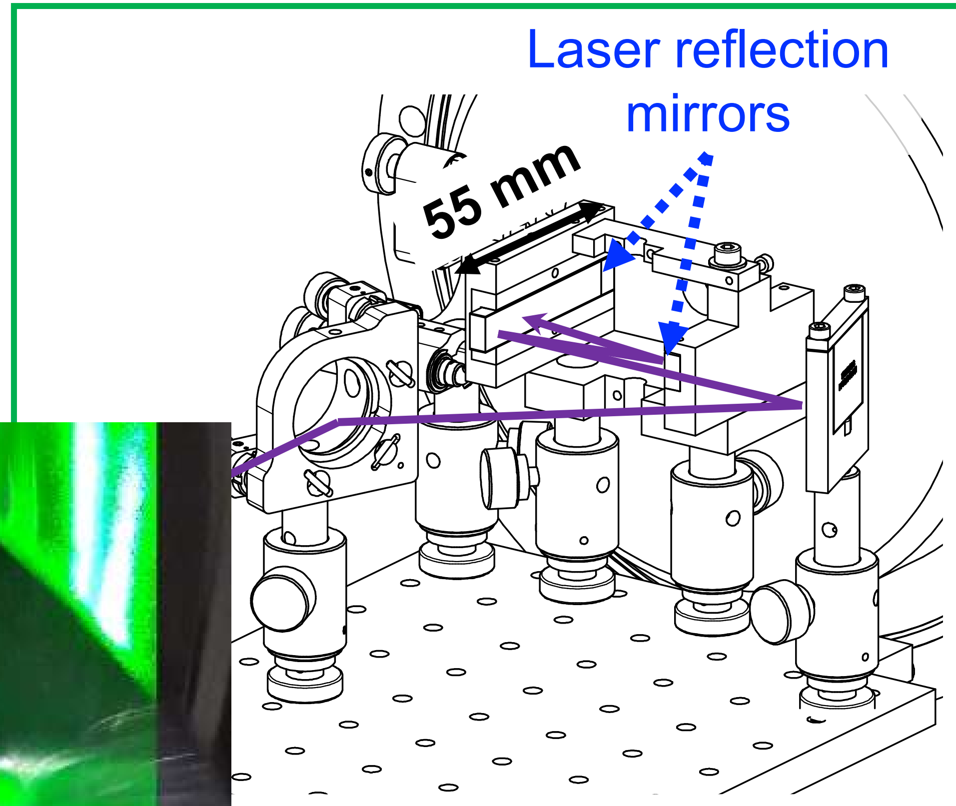
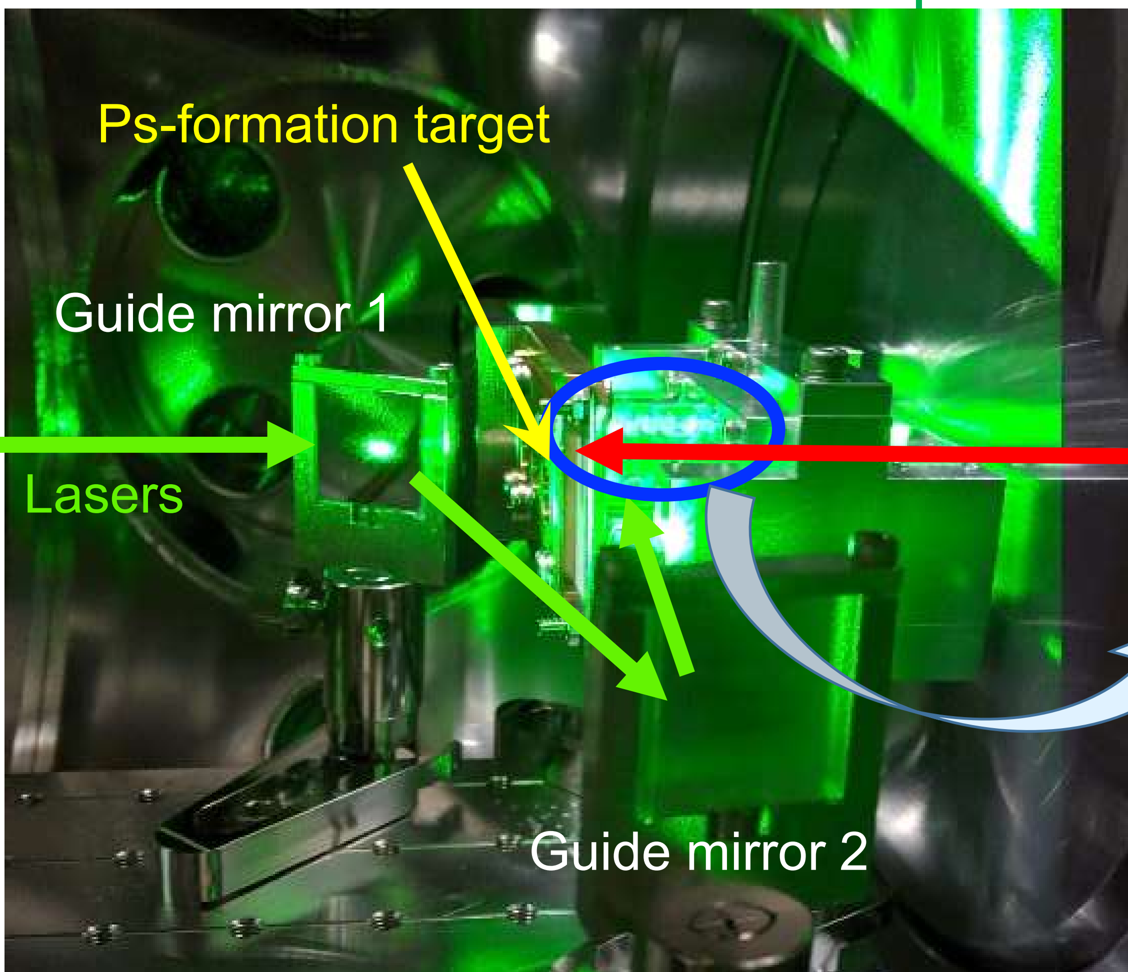
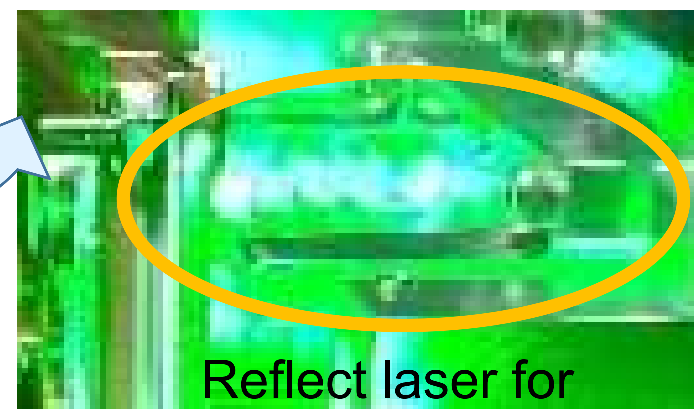
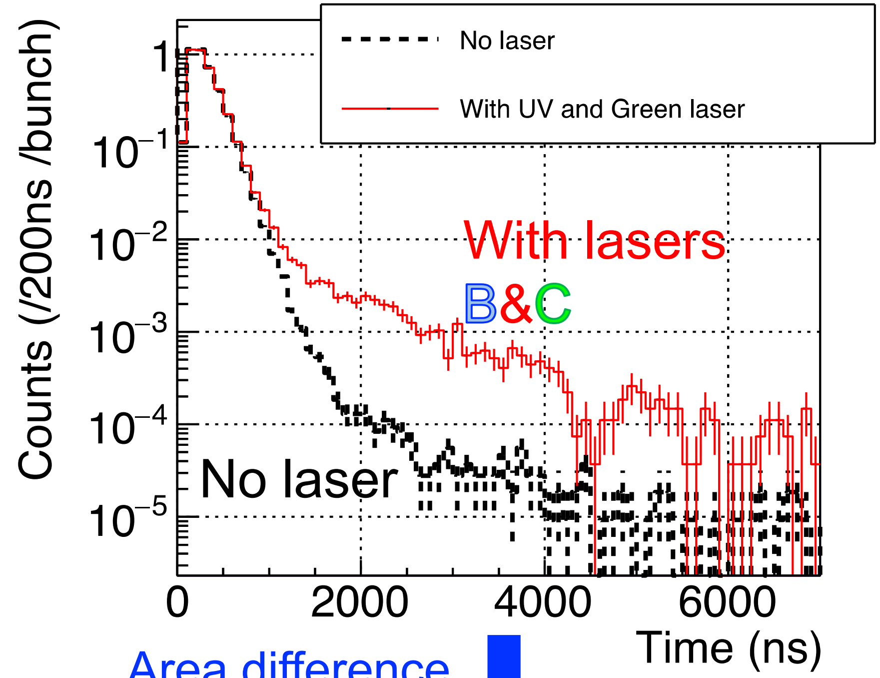


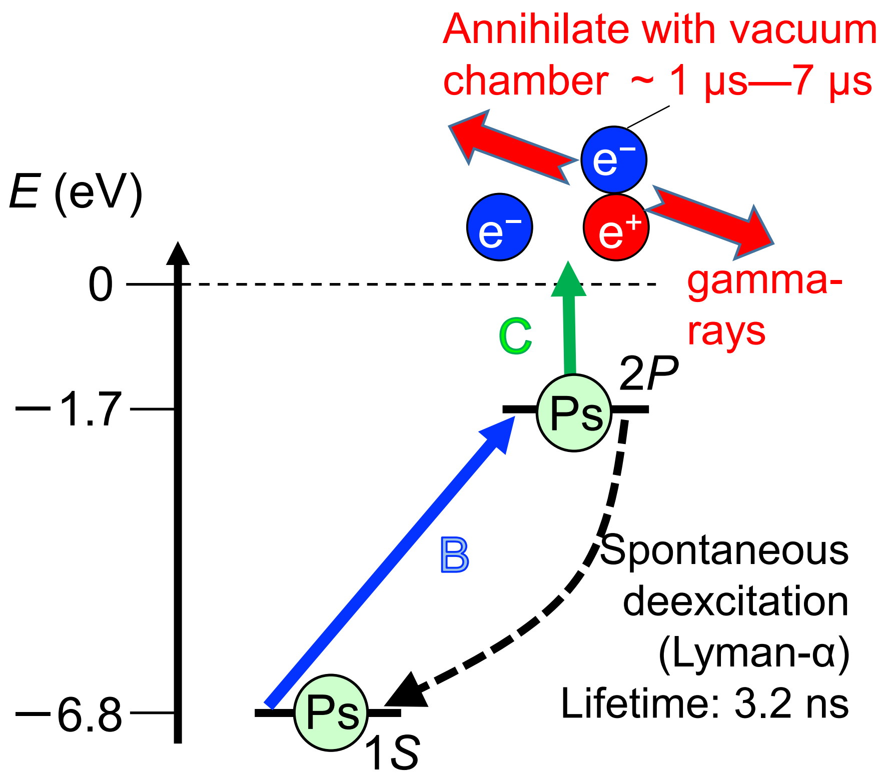




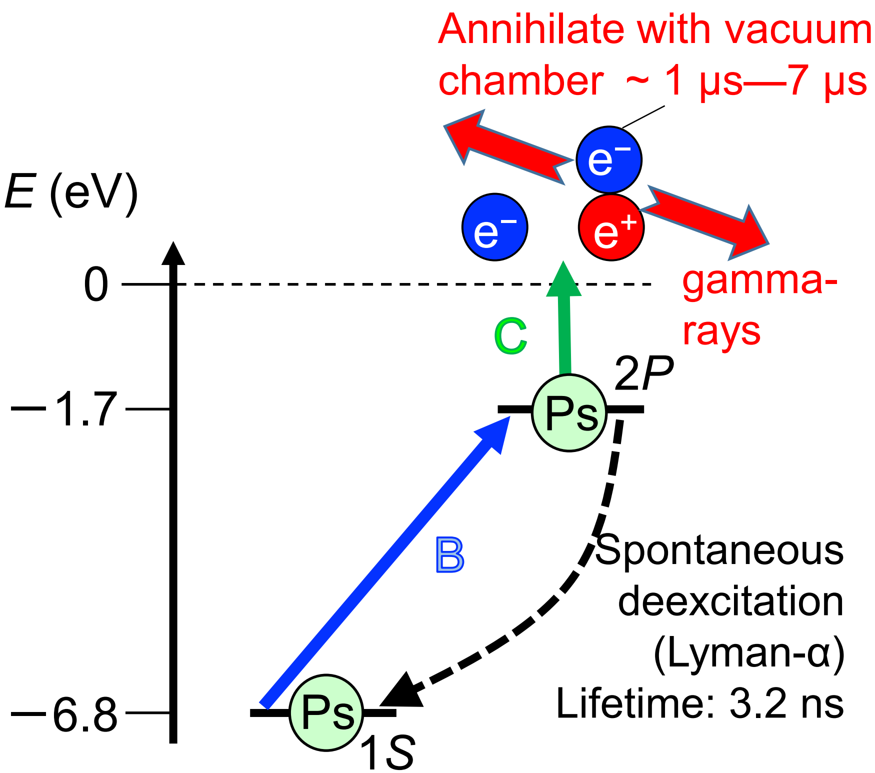
Without shining the cooling laser A, we confirmed stimulations of 1*S*→2*P* transition of Ps with probe lasers B&C.

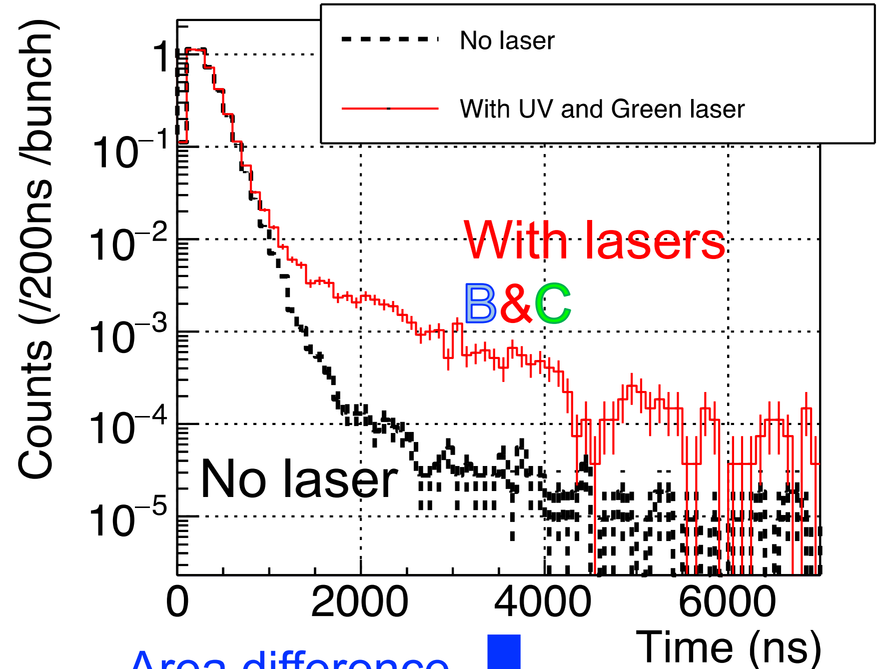


Area difference in 1 μs—7 μs



Without shining the cooling laser A, we confirmed stimulations of 1*S*→2*P* transition of Ps with probe lasers B&C.





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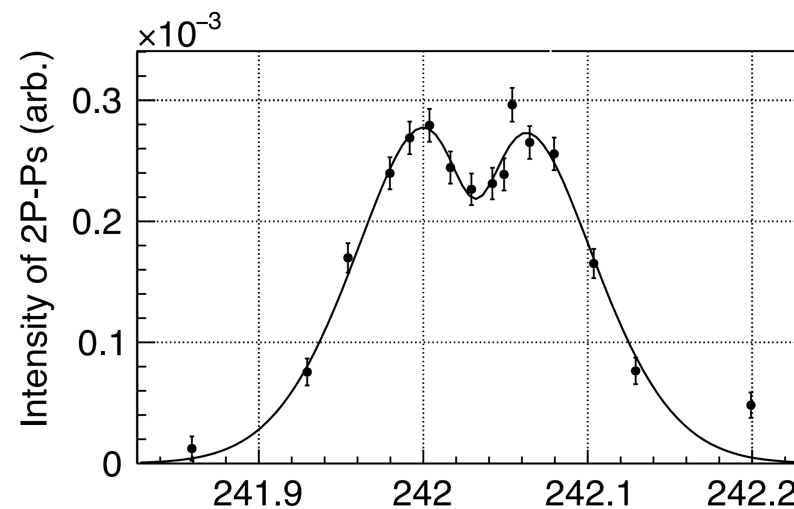
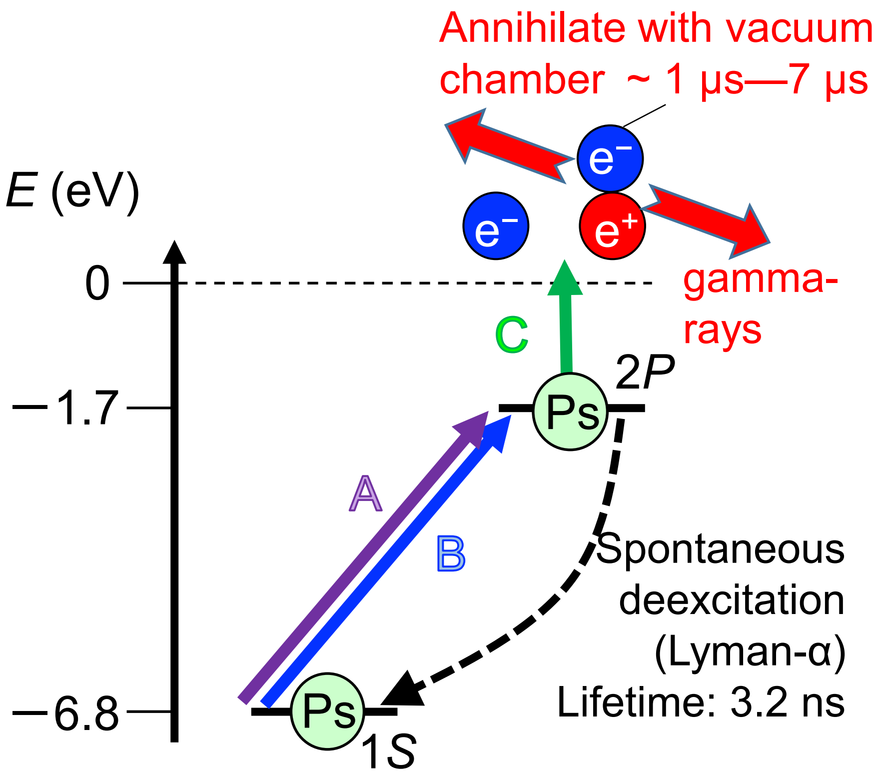


A. Ishida *et al.*, Photon Factory Activity Report **37**(2020)201 (Japanese).

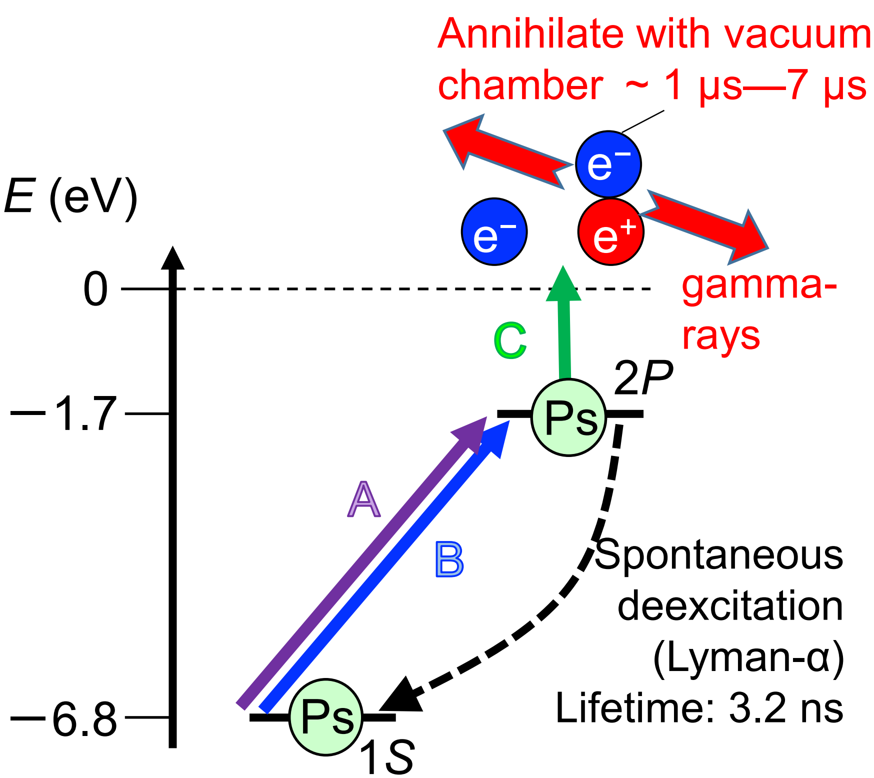
The Ps 1*S*—2*P* transition signal was nearly **doubled at all wavelengths of probe laser** B when we did the **first trial to shine a prototyped Ps cooling laser** A before shining lasers B&C.

→ We still need further detailed analysis and consolidations, but so far it turned out that there was **a huge systematic effect caused by shining UV lasers to the apparatus**, especially to the laser reflection mirrors.



To investigate possible systematic effects caused by shining UV lasers to the apparatus, **we removed the cooling laser A**.

We split the probe UV laser B to two paths and used one of them as a *mock* cooling laser A' while using the other as a probe laser B'. Then we performed a *mock* cooling experiment to check systematic effects.



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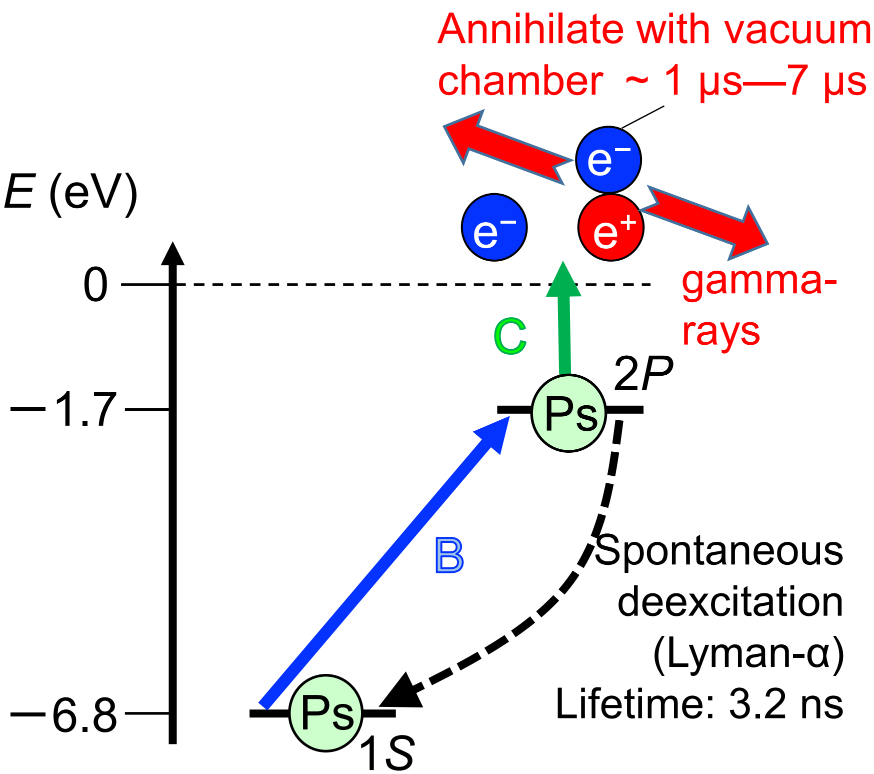

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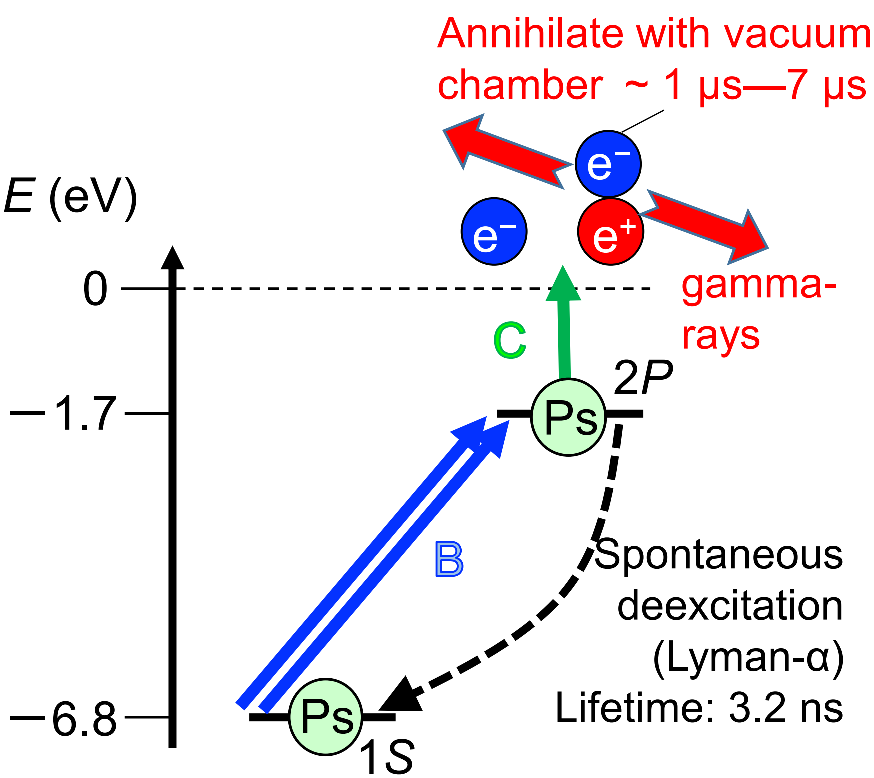

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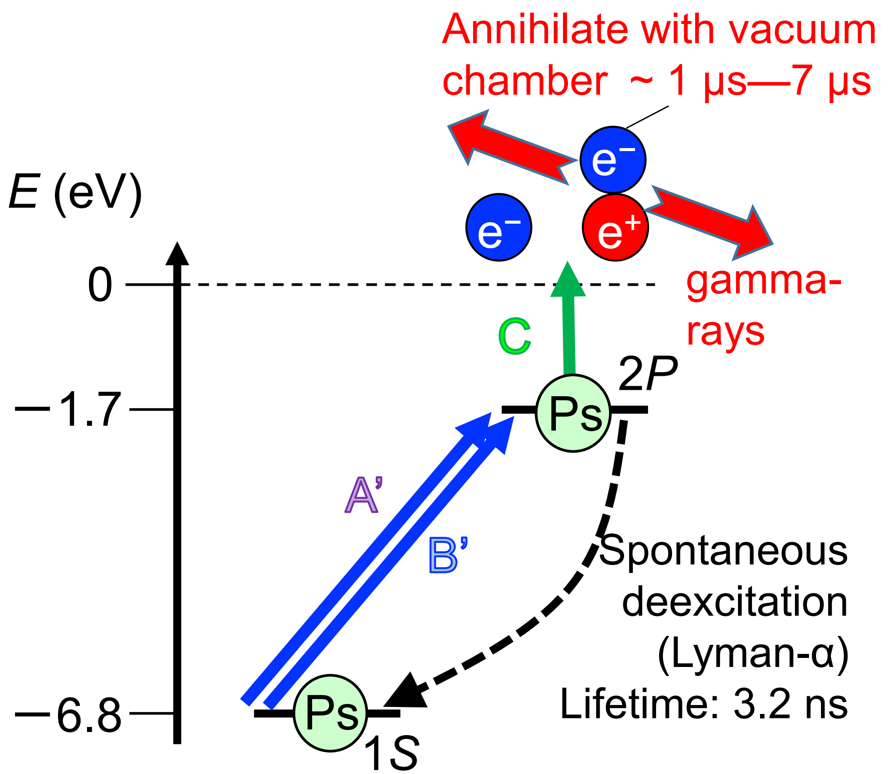

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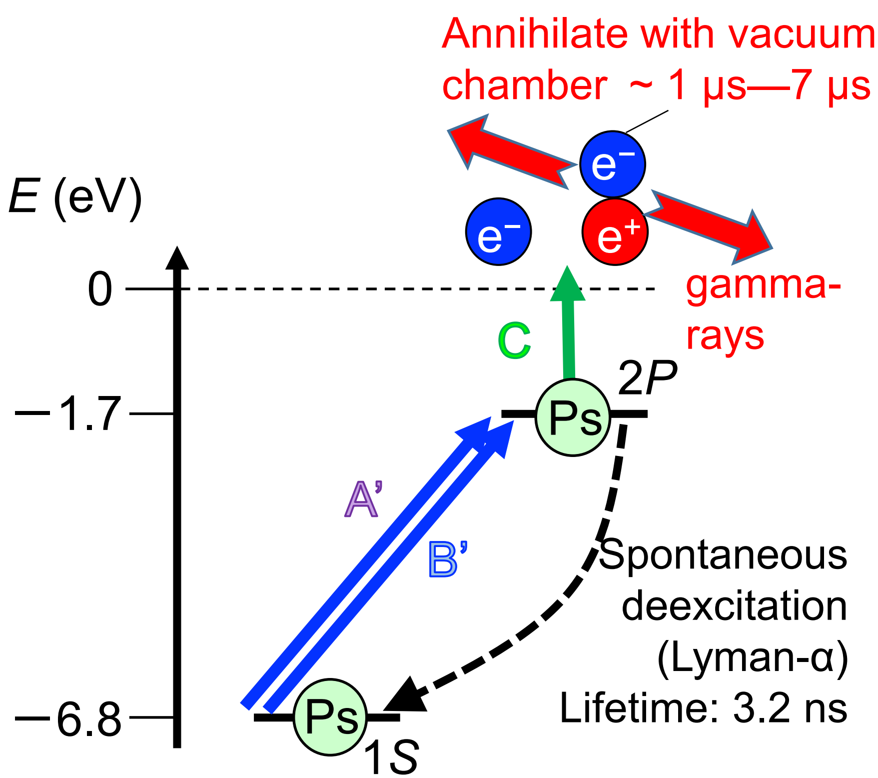
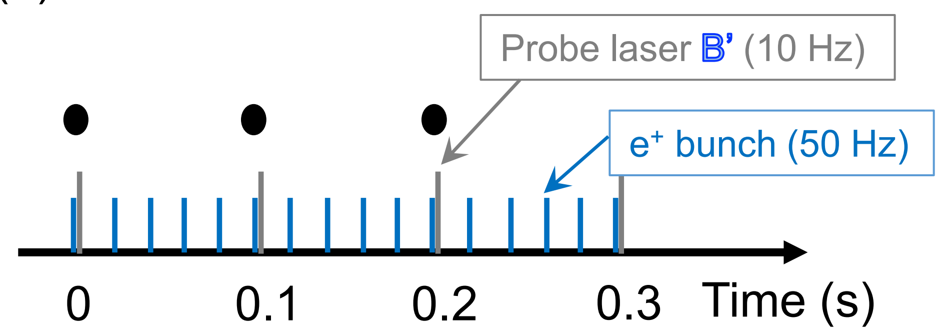


(a) Without *mock* laser A'



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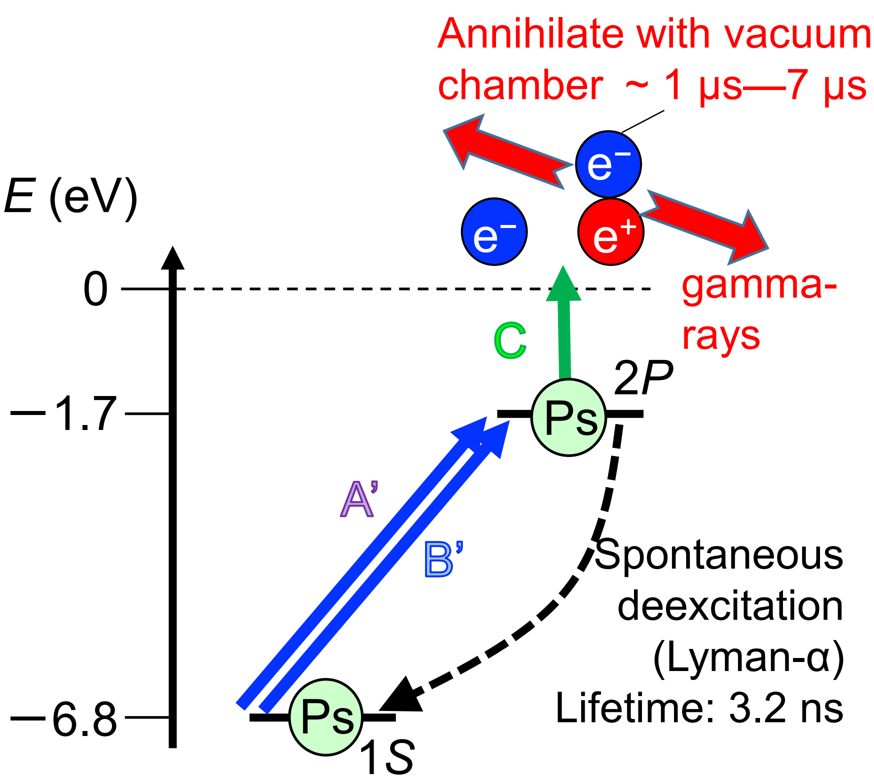

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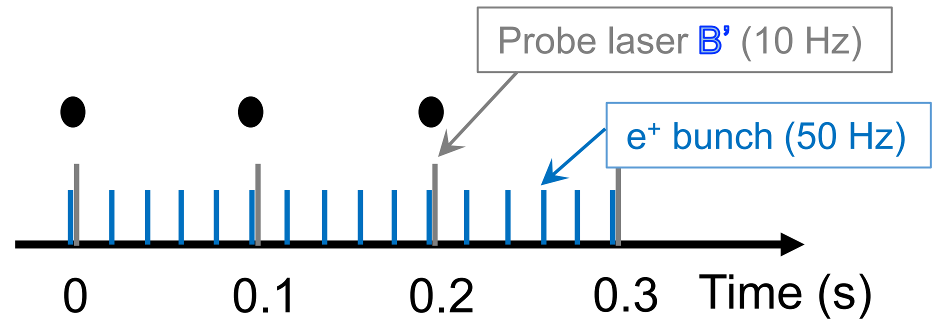
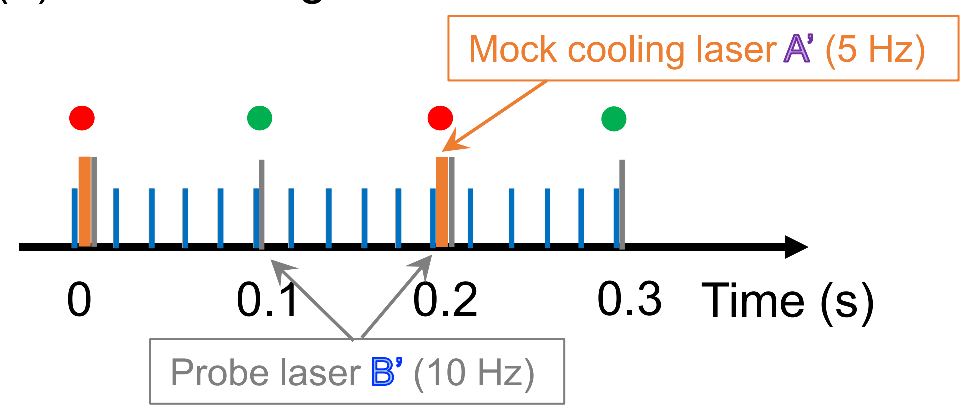
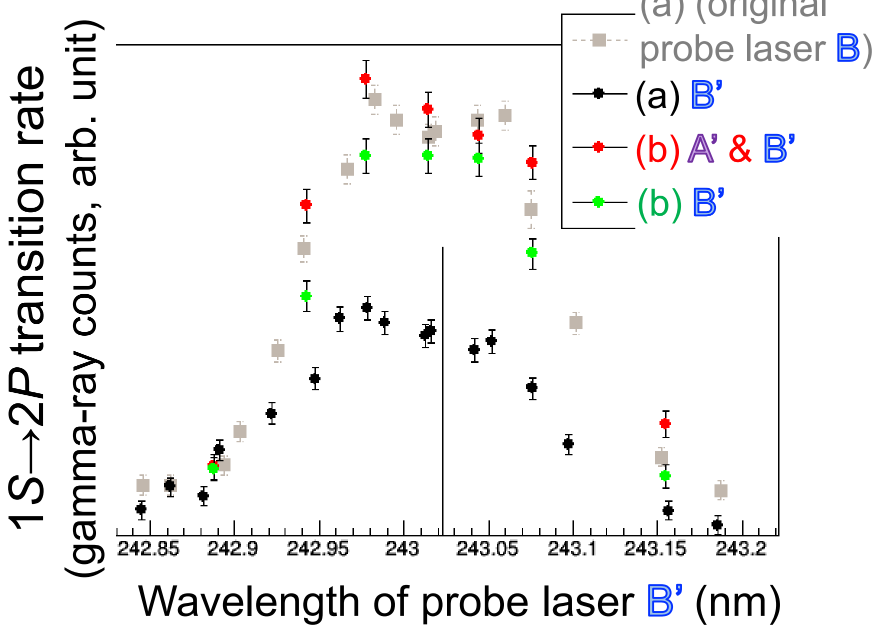


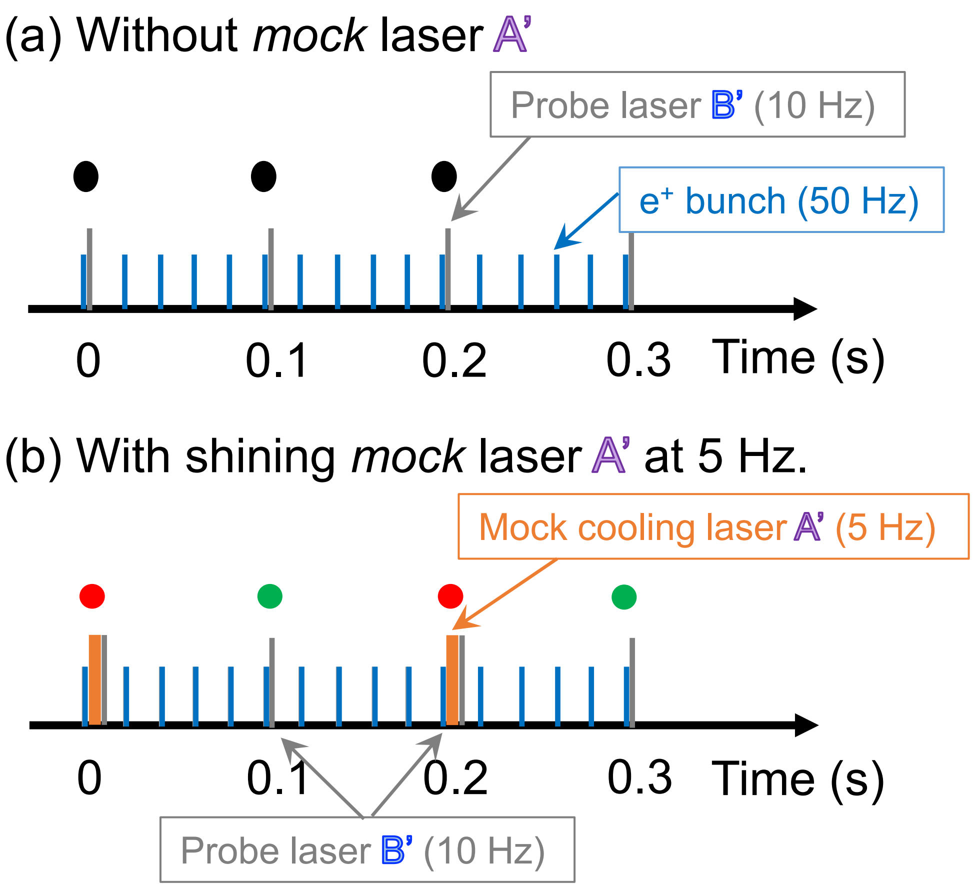
(b) With shining *mock* laser A' at 5 Hz.



We observed a **signal increase by the *mock* cooling experiment**.
The systematic effect by shining the *mock* laser A' could be seen **even at the timings when the mock laser A' was not shined**.
The decay constant of the effect was found to be ~ 5 minutes.

(2021/11/10—13 @KEK-SPF)





The transition rates are high for both conditions in experiment (b).

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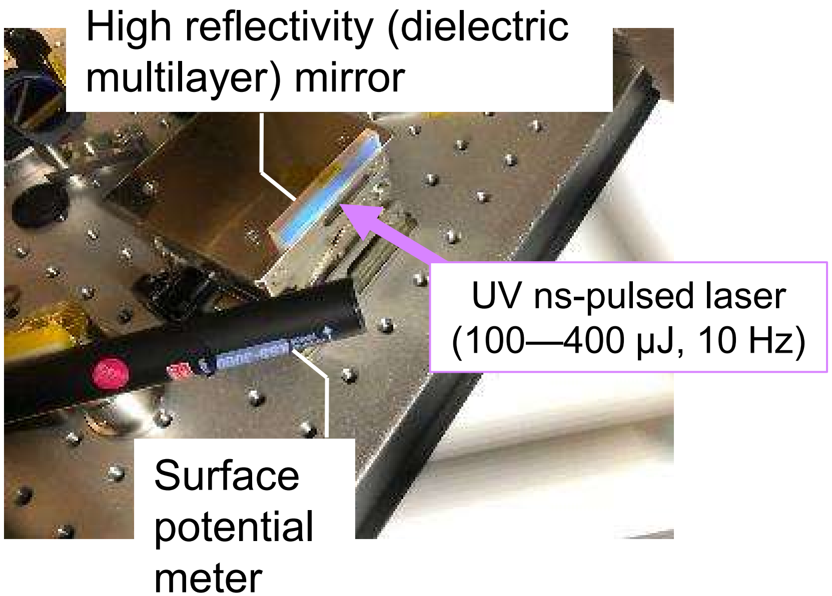
We found that **the laser reflection mirrors were negatively charged by UV lasers**, which caused a huge systematic bias on the measurement of Ps transition rate.

Electric potential measurement in atmosphere.



<u>The mirror was negatively charged.</u>
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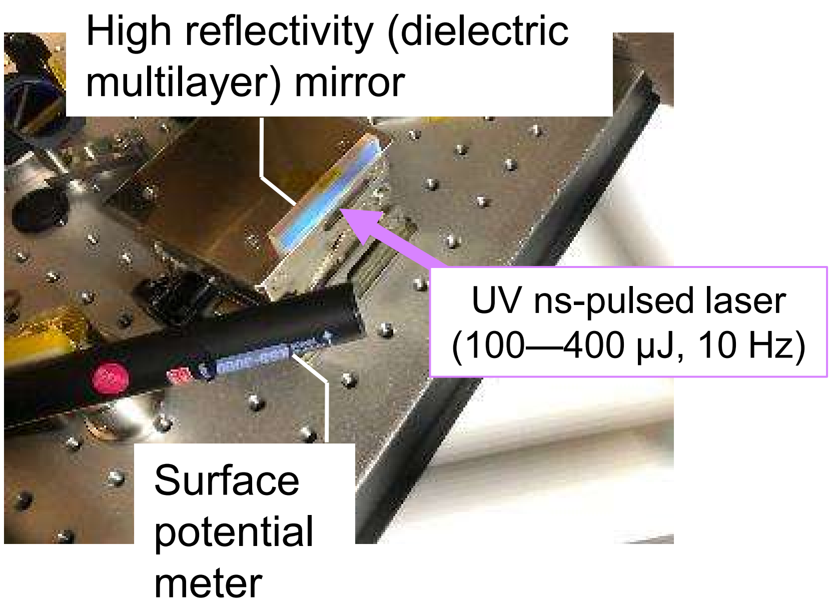

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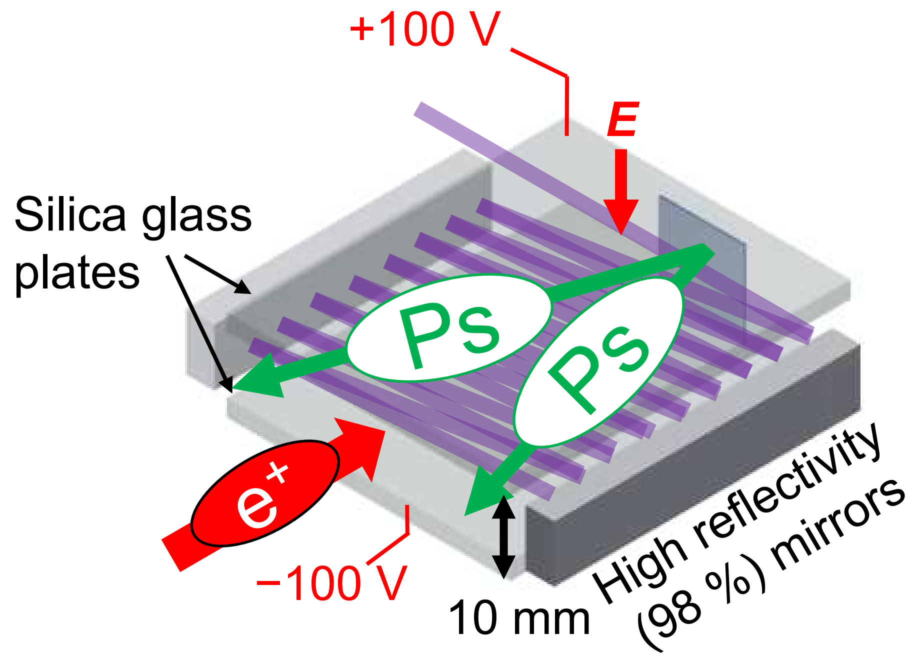
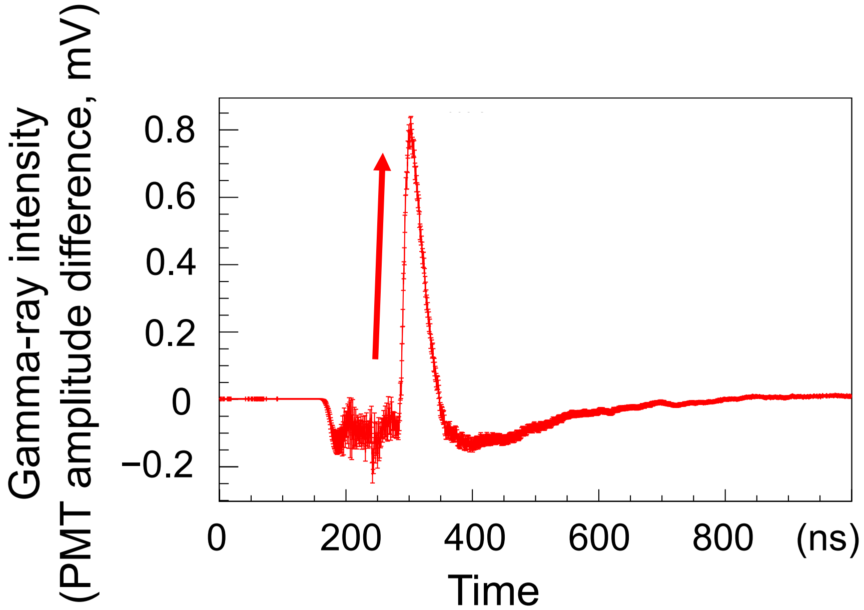
Our solution:



We attached tungsten (W) meshes (93 % open area) to form an electric field. → Control the trajectories of ionized positrons.

We observed a **sharp increase of the gamma-ray counts** at the timing of laser irradiation.



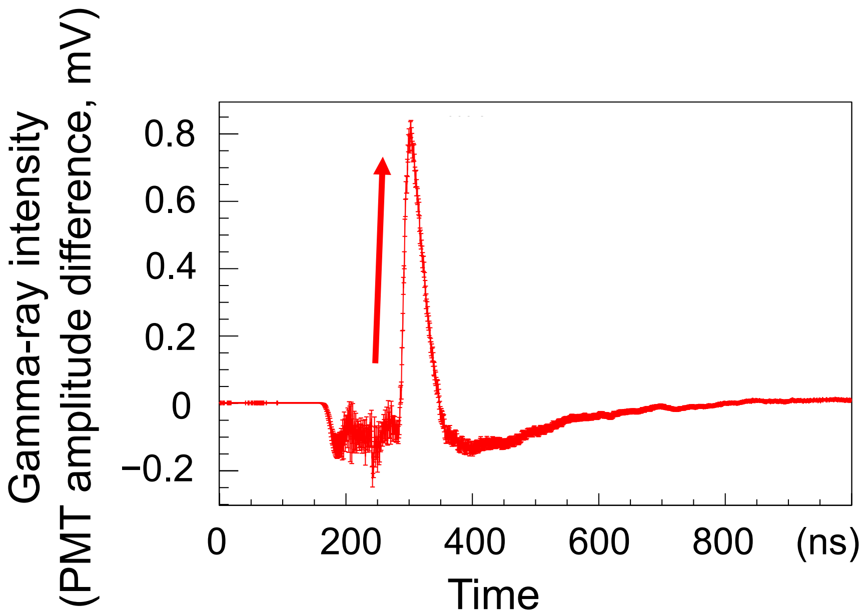
Forced positrons to annihilate immediately after Ps ionization so that we obtain $1S \to 2P$ transition rate with a timing window which is as narrow as a few ns.

A. Ishida *et al.*, Photon Factory Activity Report **39**(2022)183 (Japanese).

We observed a **sharp increase of the gamma-ray counts** at the timing of laser irradiation.

We **succeeded in removing the systematic effect** caused by the mirror charged by the UV lasers.

We expect a proof-of-principle experiment of Ps laser cooling within a year.



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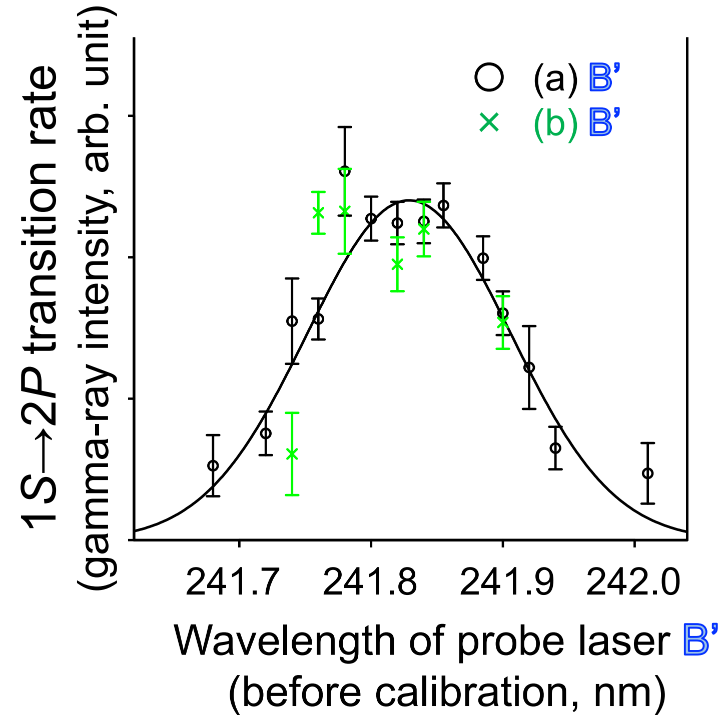

Checked by another mock cooling experiment.
No difference was observed.

A. Ishida *et al.*, Photon Factory Activity Report **39**(2022)183 (Japanese).

Summary

We want to **cool Ps down to 10 K** for various physics interests.

1. Combination of Ps thermalization cooling and laser cooling will be efficient enough to realize Ps-BEC.
2. We have developed a dedicated laser system for Ps cooling, Chirped Pulse-Train Generator (CPTG), with 300-ns pulse duration and 0.4 GHz ns^{-1} frequency chirp.
3. We are trying a proof-of-principle experiment to laser-cool Ps in vacuum at KEK-SPF. We succeeded in removing the systematic effect caused by the mirror charged by the UV lasers.
4. We expect a proof-of-principle experiment of Ps laser cooling within a year.

K. Shu, X. Fan, T. Yamazaki *et al.*, J. Phys. B: At. Mol. Opt. Phys., **49**, 104001 (2016).
A. Ishida, K. Shu, T. Murayoshi *et al.*, JJAP Conf. Proc., **7**, 011001 (2018).
K. Shu, A. Ishida, T. Namba *et al.*, Phys. Rev. A, **104**, L050801 (2021).
K. Yamada, Y. Tajima, T. Murayoshi *et al.*, Phys. Rev. Applied, **16**, 014009 (2021).
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