# Development of a high-quality, energy-tunable positronium beam via photodetachment of positronium negative ions

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Akinori Igarashi

KEK

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Toshio Hyodo
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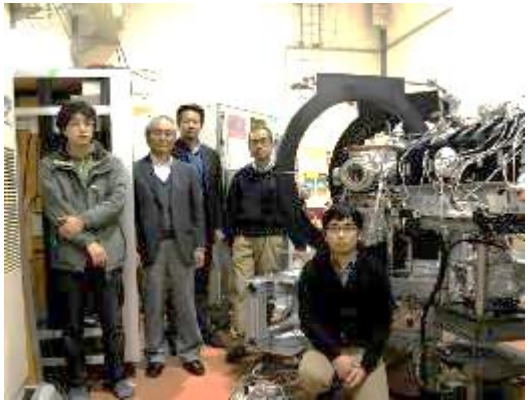

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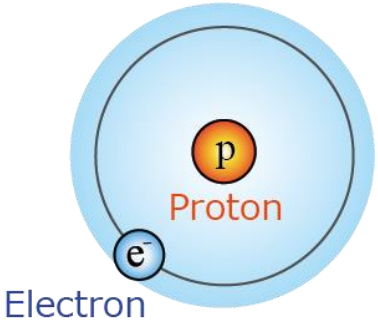
JSPS KAKENHI Grants No. JP24221006, JP21H04457, JP17H01074 and JP16K17705

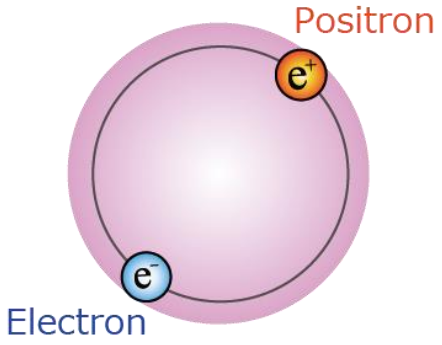
科研費 KAKENHI

# Outline

- Introduction
- Positronium beam
- Recoil momentum manipulation
- Summary

# Positronium




## Hydrogen (H)

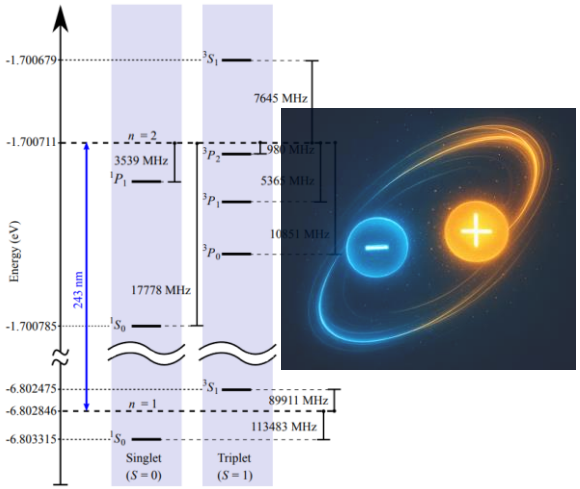
- Mass：$m_p + m_e$
- Lifetime：$\infty$

## Positronium (Ps)

- Mass：$2m_e$
- Lifetime：125 ps (spin singlet, *p*-Ps)
  142 ns (spin triplet, *o*-Ps)

# Positronium applications

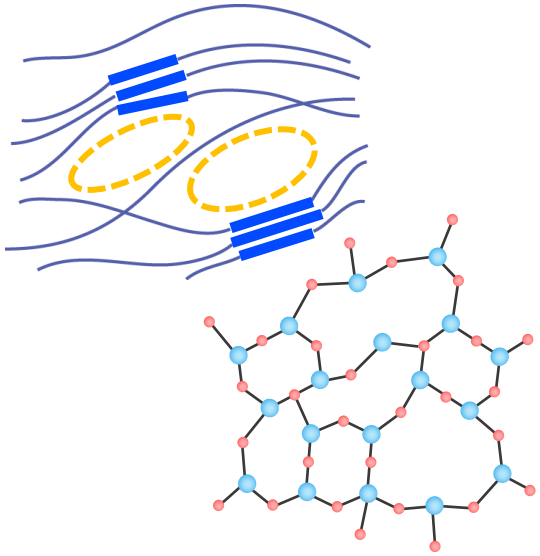
## Advanced Physics




Verification of standard model
New physics phenomena

D. B. Cassidy, Eur. Phys. J. D **72**, 53 (2018)

## Material Analysis

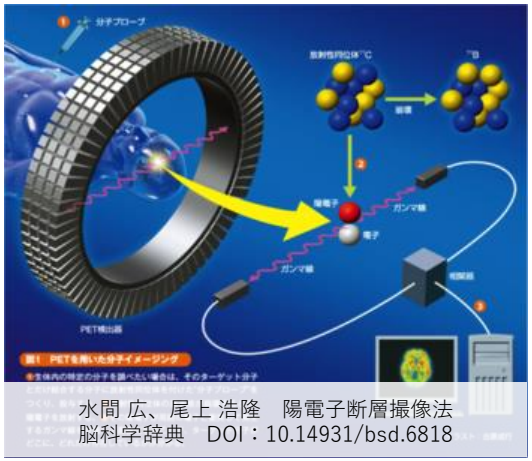


Subnanoscale pore structure

Y. C. Jean, Microchem. J. **42**, 72 (1990)

## Medical Application

Positron Emission Tomography

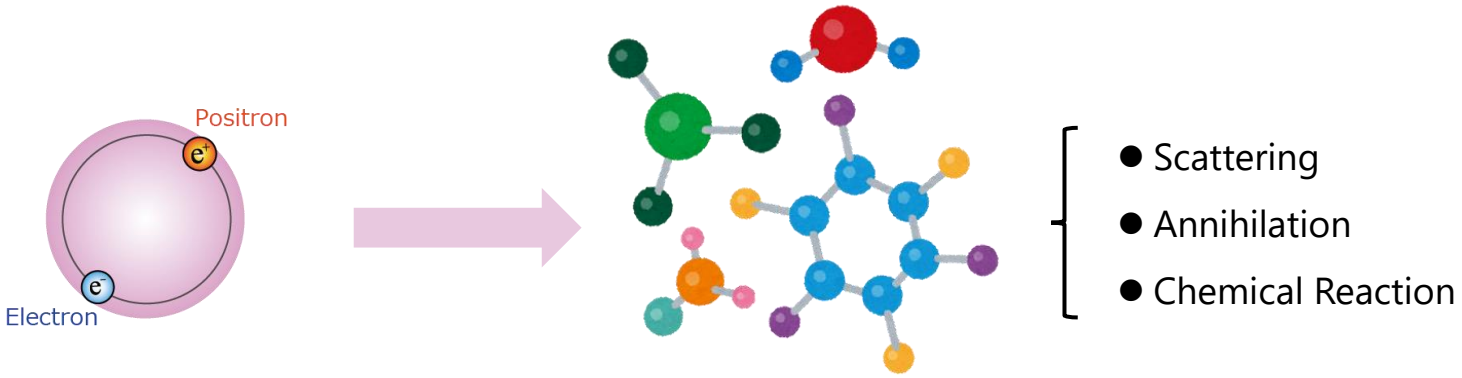



水間 広、尾上 浩隆　陽電子断層撮像法
脳科学辞典　DOI：10.14931/bsd.6818

Correlation between Ps lifetime and oxygen or radical concentrations

P. Moskal *et al.*, Sci. Adv. **10**, eadp2840 (2024)

# Positronium beam



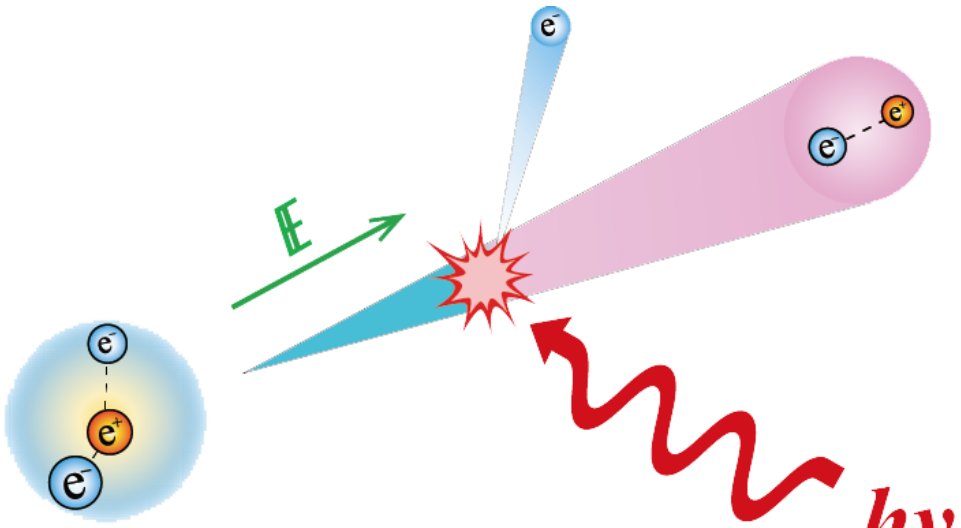

Comprehensive understanding of Ps interactions with atoms and molecules

- Thermal positronium formed in materials ： $k_B T \sim 25$ meV
- Charge exchange reactions between positrons and gaseous atoms/molecules
  $(e^+ + \mathrm{A} \rightarrow \mathrm{A}^- + \mathrm{Ps})$ ： $< 400$ eV

G. Laricchia *et al.*, La Rivista del Nuovo Cimento **35**, 305 (2012)

**Producing a beam of electrically neutral, short-lived Ps is extremely difficult**

# New method




Ps negative ion

New scheme：

① Generate positronium negative ions and accelerate them with an electric field

② Detach the electron with light to produce a positronium beam

K. Michishio *et al.*, Appl. Phys. Lett. **100**, 254102 (2012)

# ①Efficienct $Ps^-$ ion production

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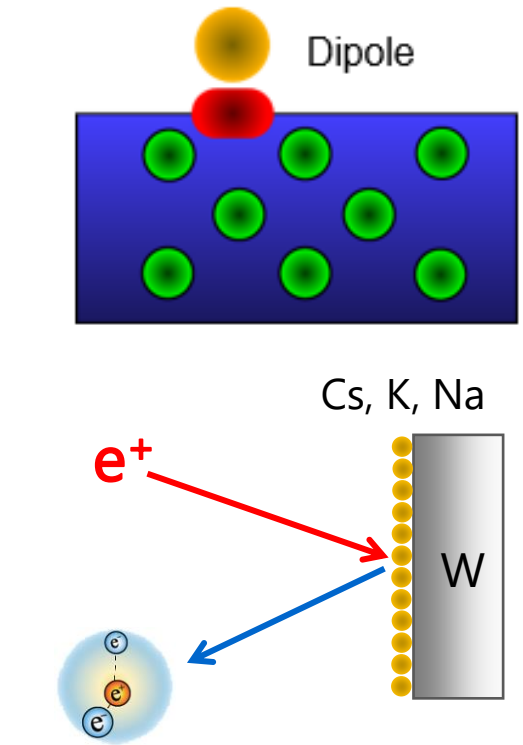
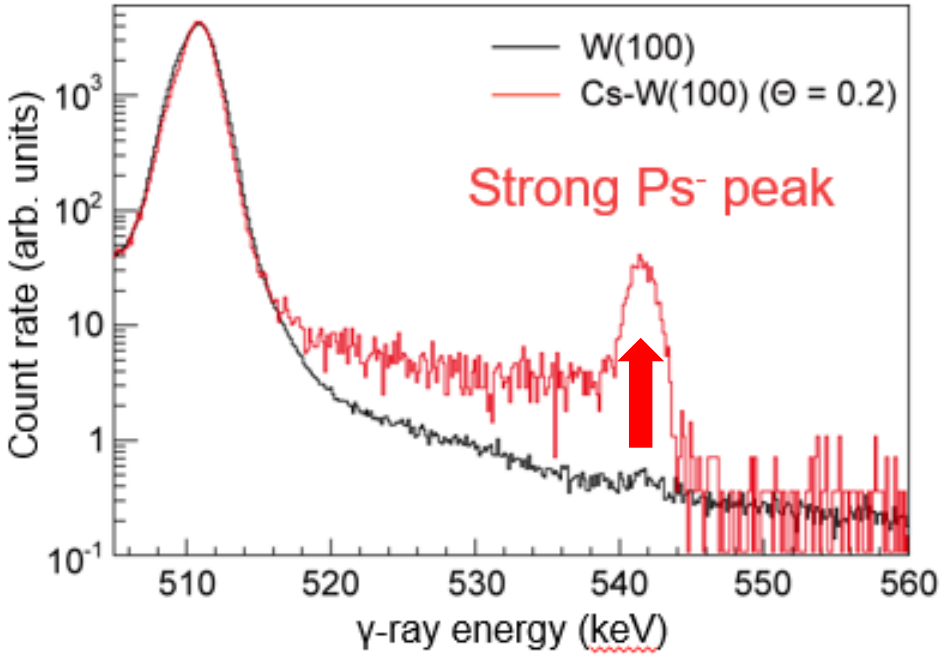



- Negative $Ps^-$ affinity for surfaces
- Low-density electron gas at the surface




$e^+$ - $Ps^-$ conversion efficiency ~2%

(Improved by a factor of 200! compared to conventional method)

Y. Nagashima, Phys. Rep. **545**, 95-123 (2014)

# ②Laser photodetachment

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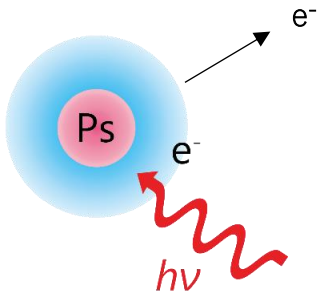
☹ **Quite short living nature : $\tau$~0.5 ns**

Cross-collision of nanosecond $Ps^-$ and high-intense pulsed laser

➡ **Both are densified in the nanosecond time domain and collided!**




Nanosecond $Ps^-$ ion beam

**KEK Slow positron facility**

Pulse width : 10 ns
Intensity : ~$10^6$ $e^+$/s

×

Nanosecond pulse laser

**Q-S.W. Nd:YAG laser**

Pulse width : 10 ns
Energy : 1 J/cm$^2$ (~100 MW/cm$^2$)

K. Michishio *et al.*, Phys. Pev. Lett. **106**, 153401 (2011)

# ②Laser photodetachment

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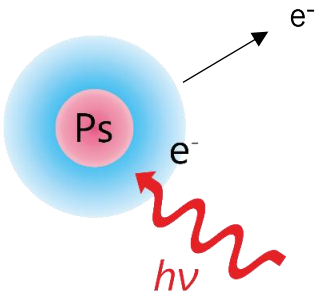
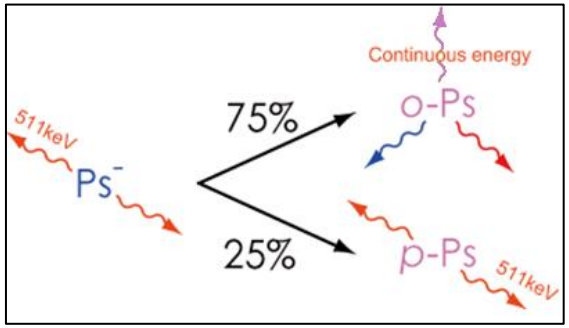
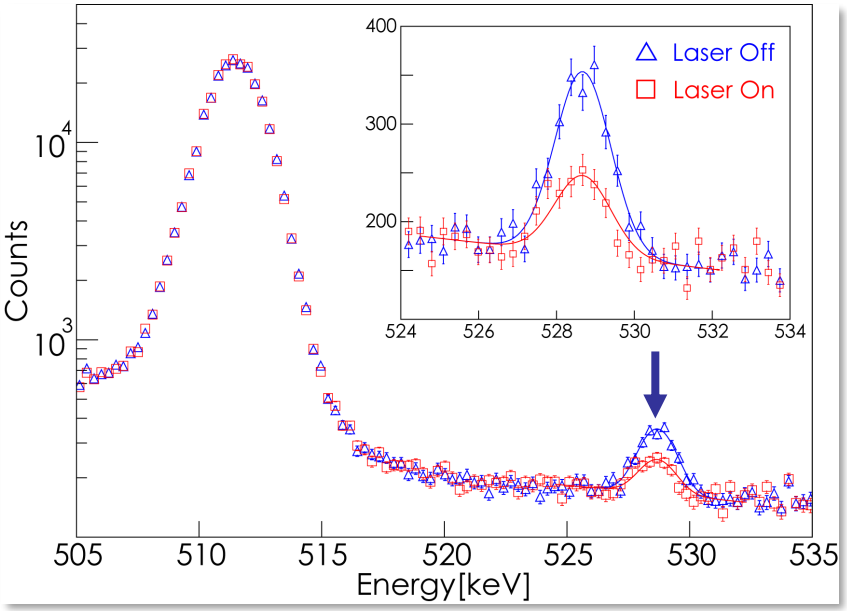



Realized highly efficient laser photodetachment of $Ps^-$ :
70% - 80%




K. Michishio *et al.*, Phys. Pev. Lett. **106**, 153401 (2011)

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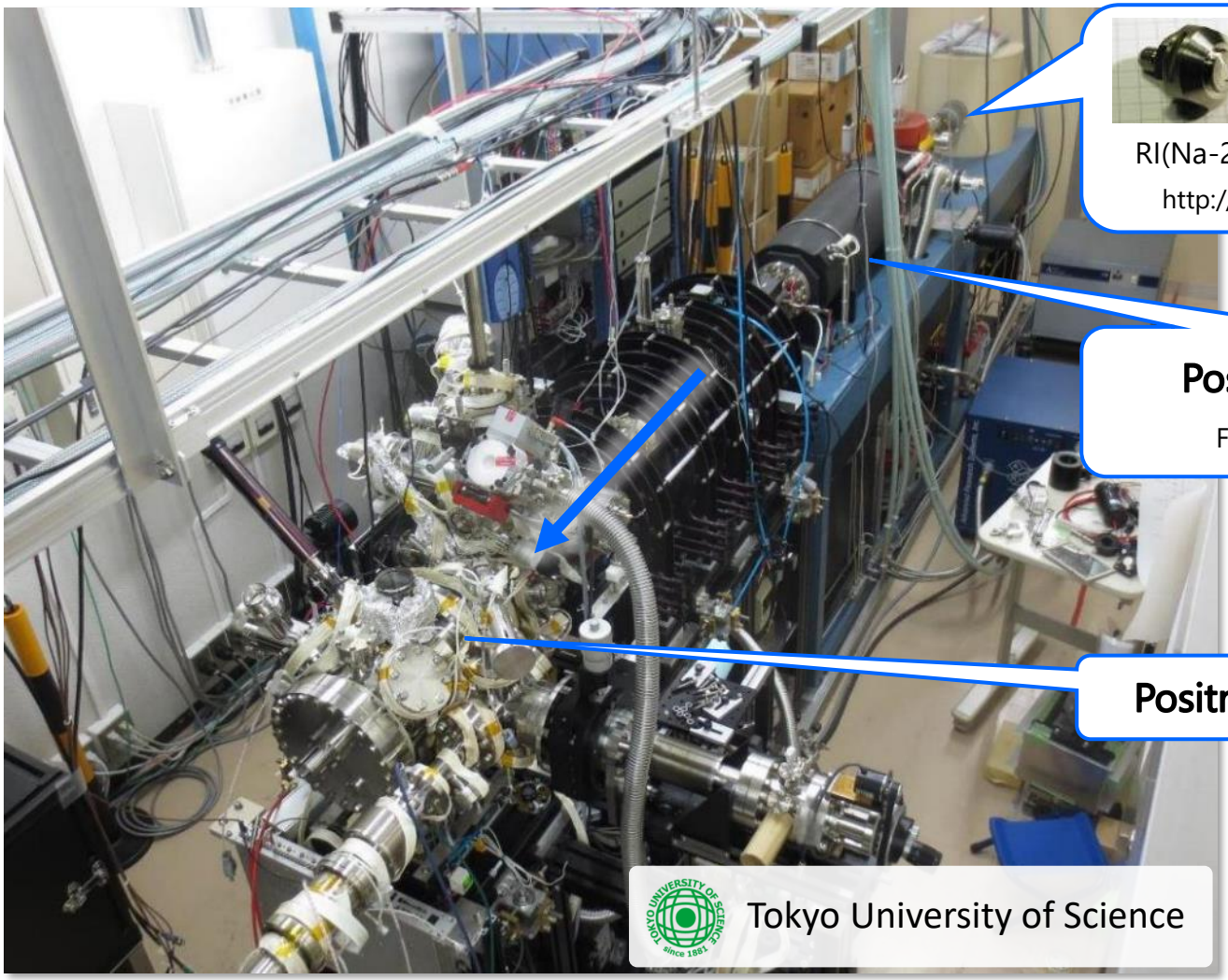
# Positronium beam system



# Pulsed positron beam system

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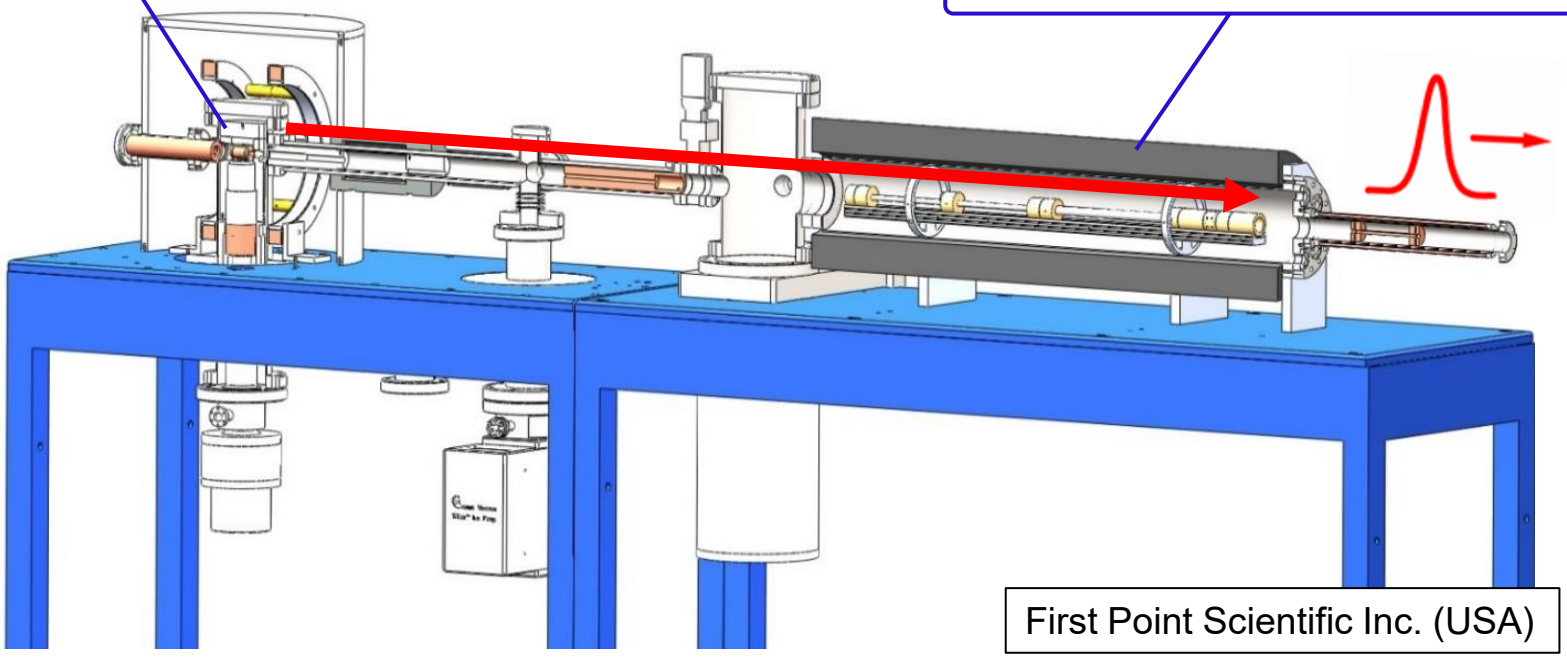
$^{22}$Na (10 mCi) + solid Ne moderator

Intensity：$2\times10^{6}$ slow $e^{+}$/s

Buffer-gas trap

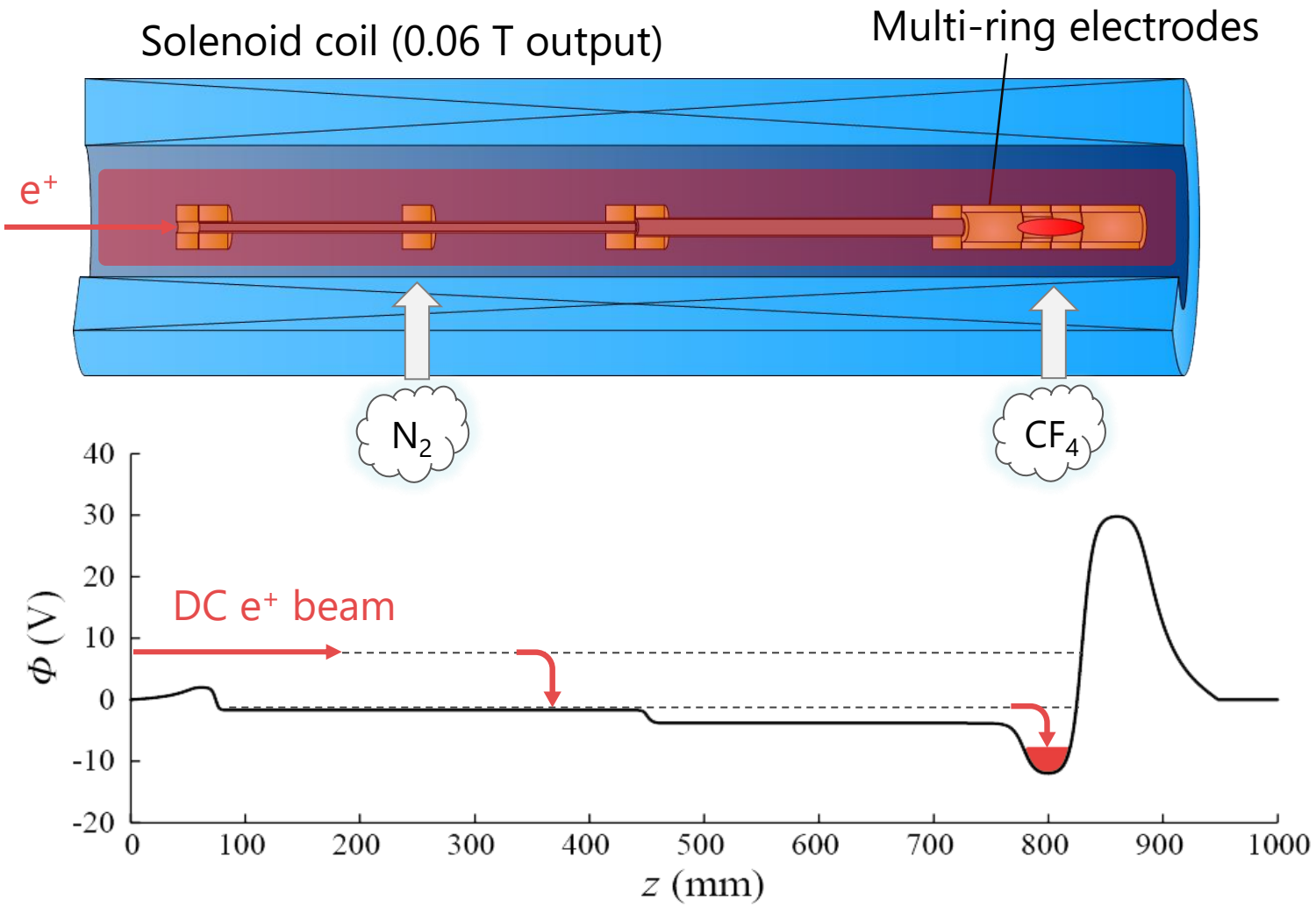
Pulse width：2 ns (FWHM)
Repetition rate：50 Hz



First Point Scientific Inc. (USA)

To photodetach short-lived $Ps^{-}$ ions,
nano-second positron bursts were used for synchronization with pulsed laser

# Pulsed positron beam system



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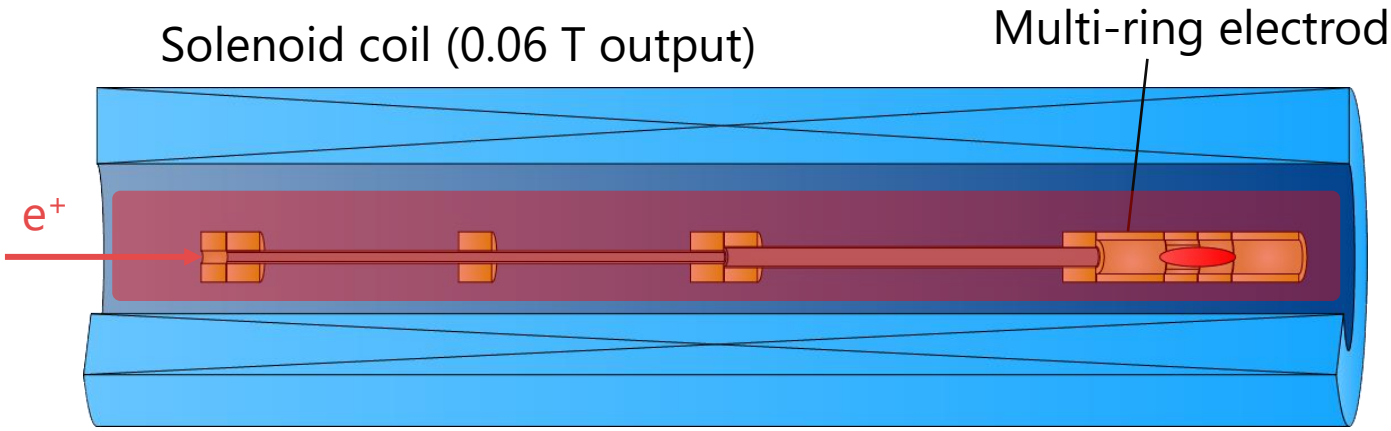
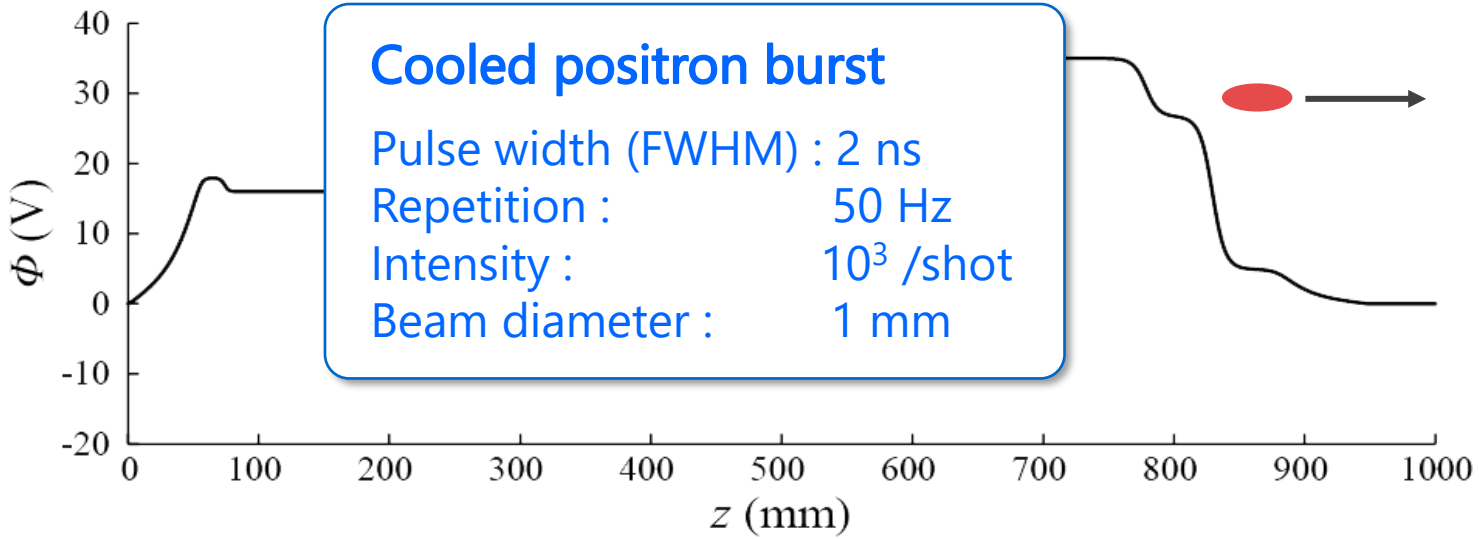
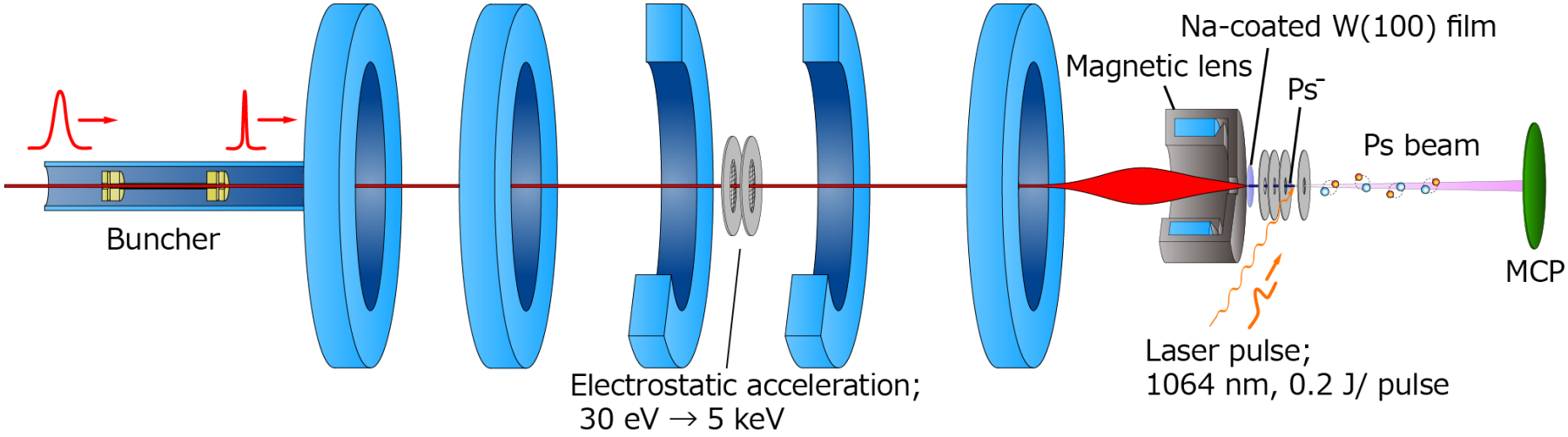



## Cooled positron burst

Pulse width (FWHM) : 2 ns
Repetition : 50 Hz
Intensity : $10^3$ /shot
Beam diameter : 1 mm

# High-quality Ps beam



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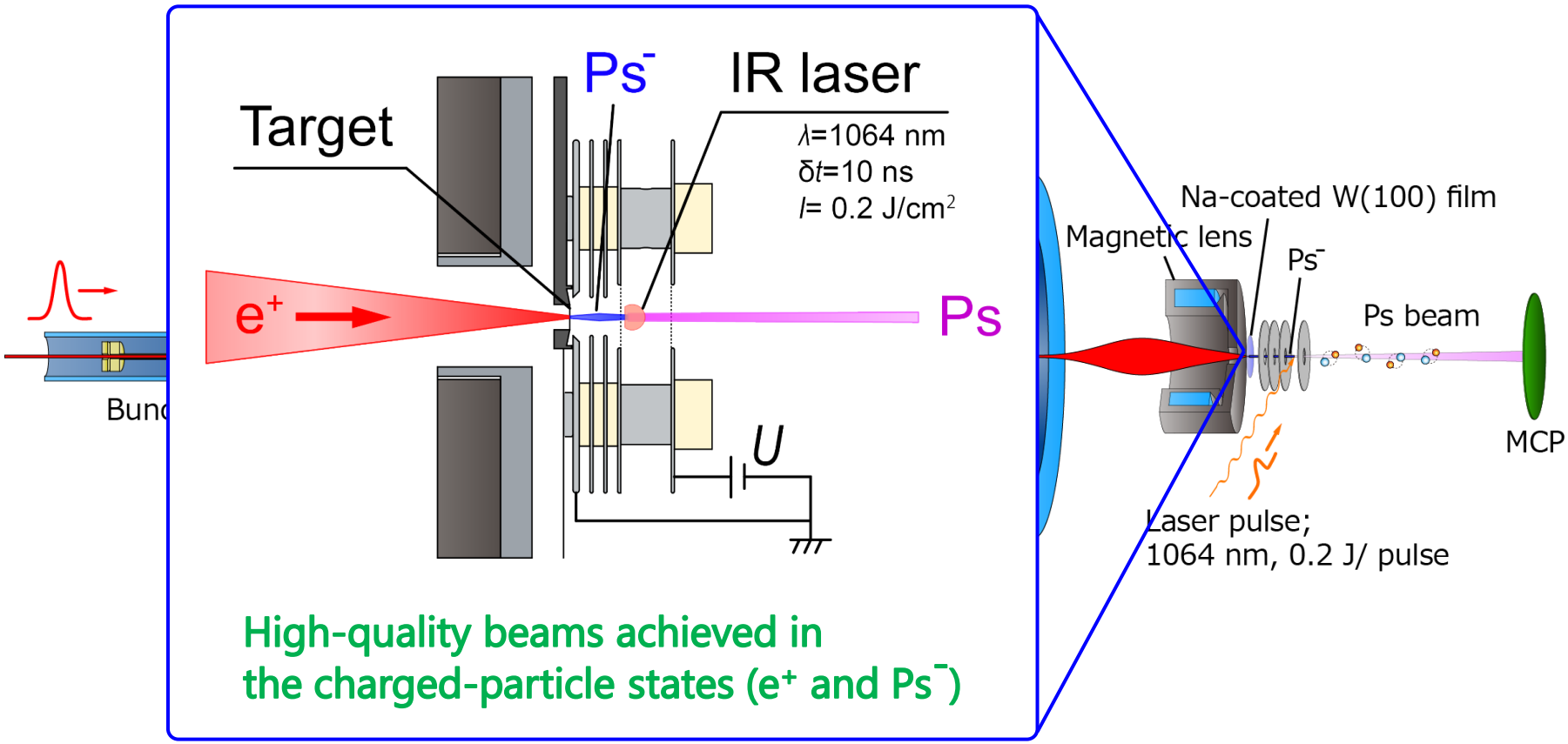

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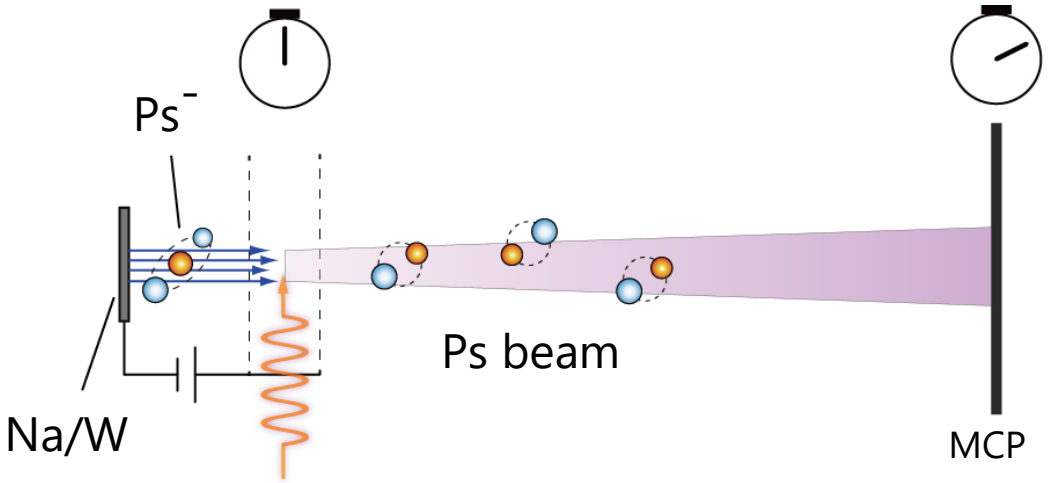


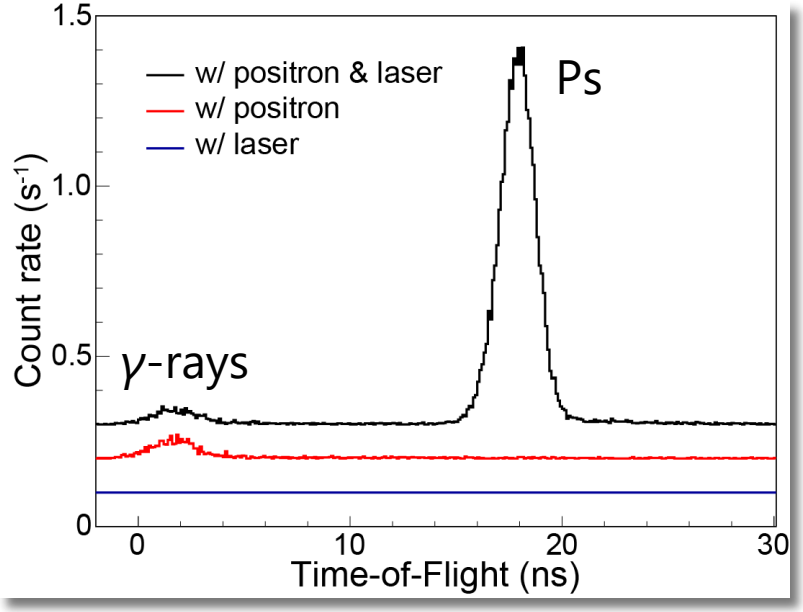

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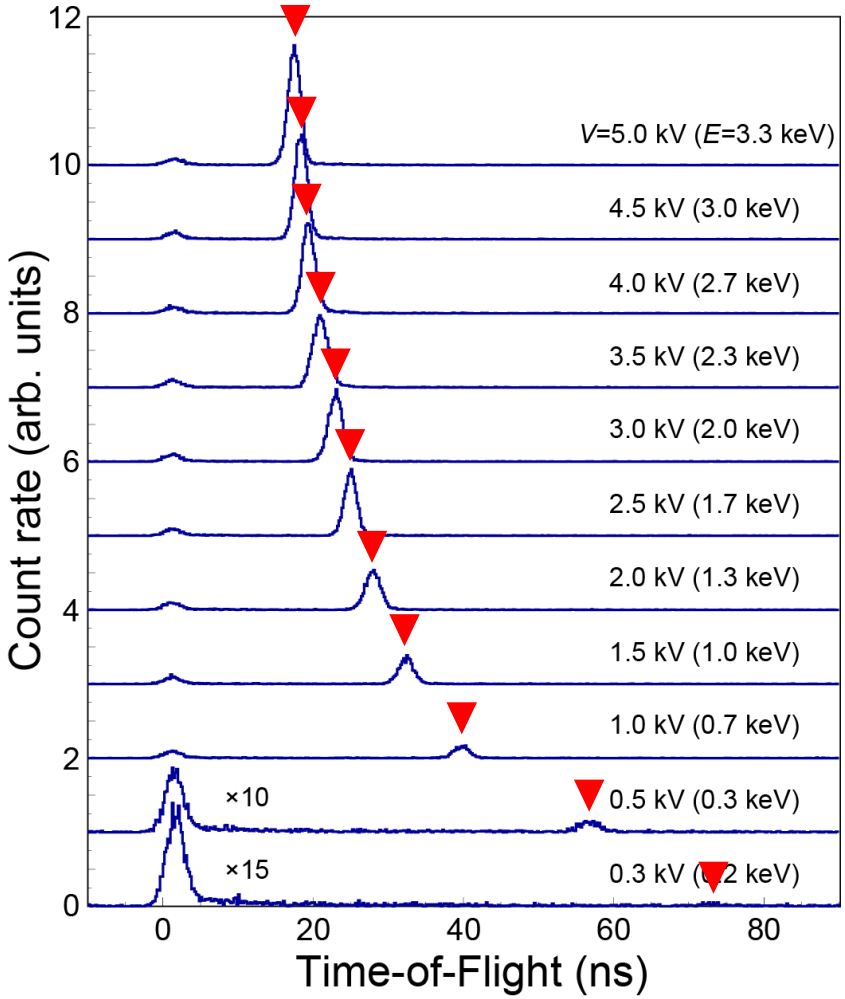
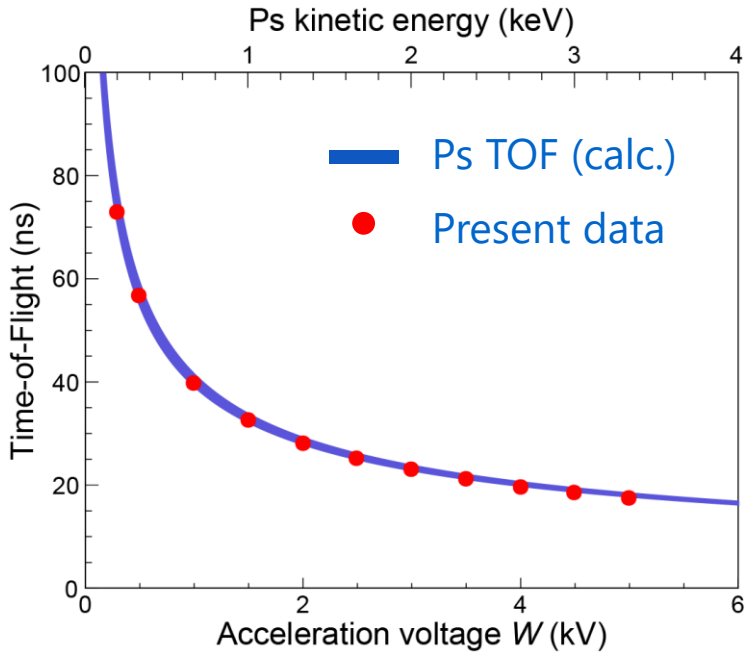
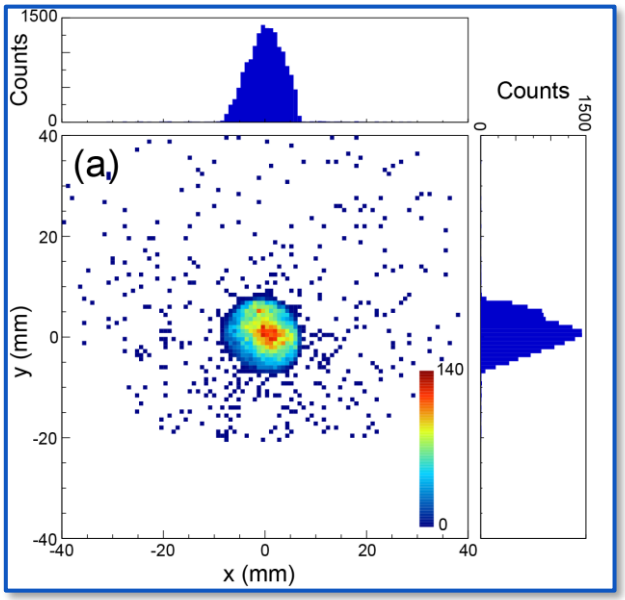


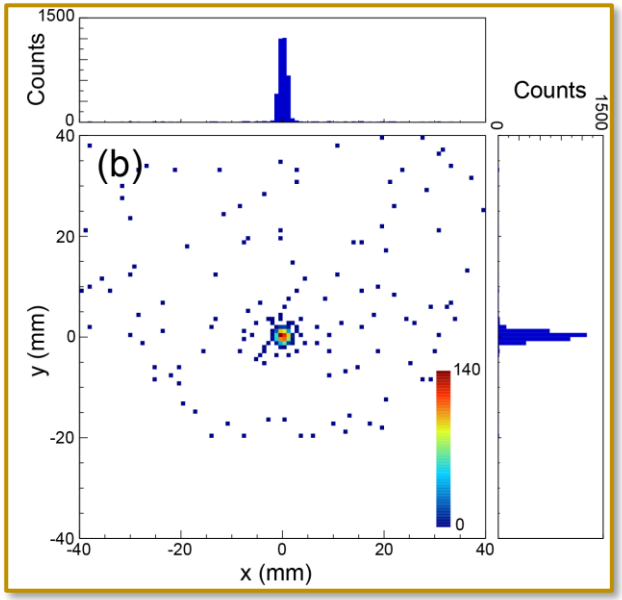




- Energy-tunable：0.2 keV – 3.3 keV
- Ps beam rate：20 cps (S/B : 300)

K. Michishio *et al.*, *Rev. Sci. Inst.* **90**, 023305 (2019)
Front cover of *Rev. Sci. Inst.* & AIP highlight

# High-quality Ps beam




- Spatial size：~Φ 9 mm
  Φ 1 mm, angular deviation < 0.1° (with collimator)
- Energy resolution : <1 %

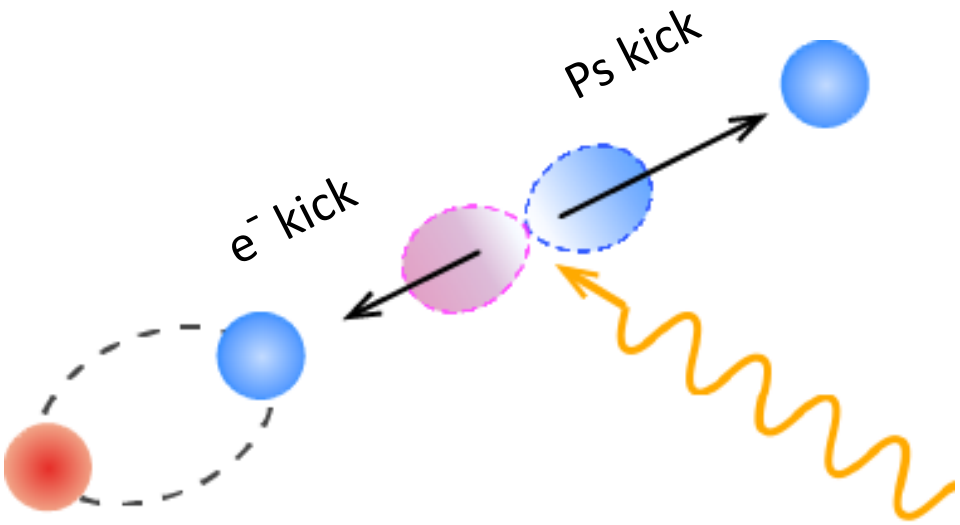
➡ **Coherent Ps beam with interference capability**

K. Michishio *et al.*, *Rev. Sci. Inst.* **90**, 023305 (2019)
Front cover of *Rev. Sci. Inst.* & AIP highlight

# Outline

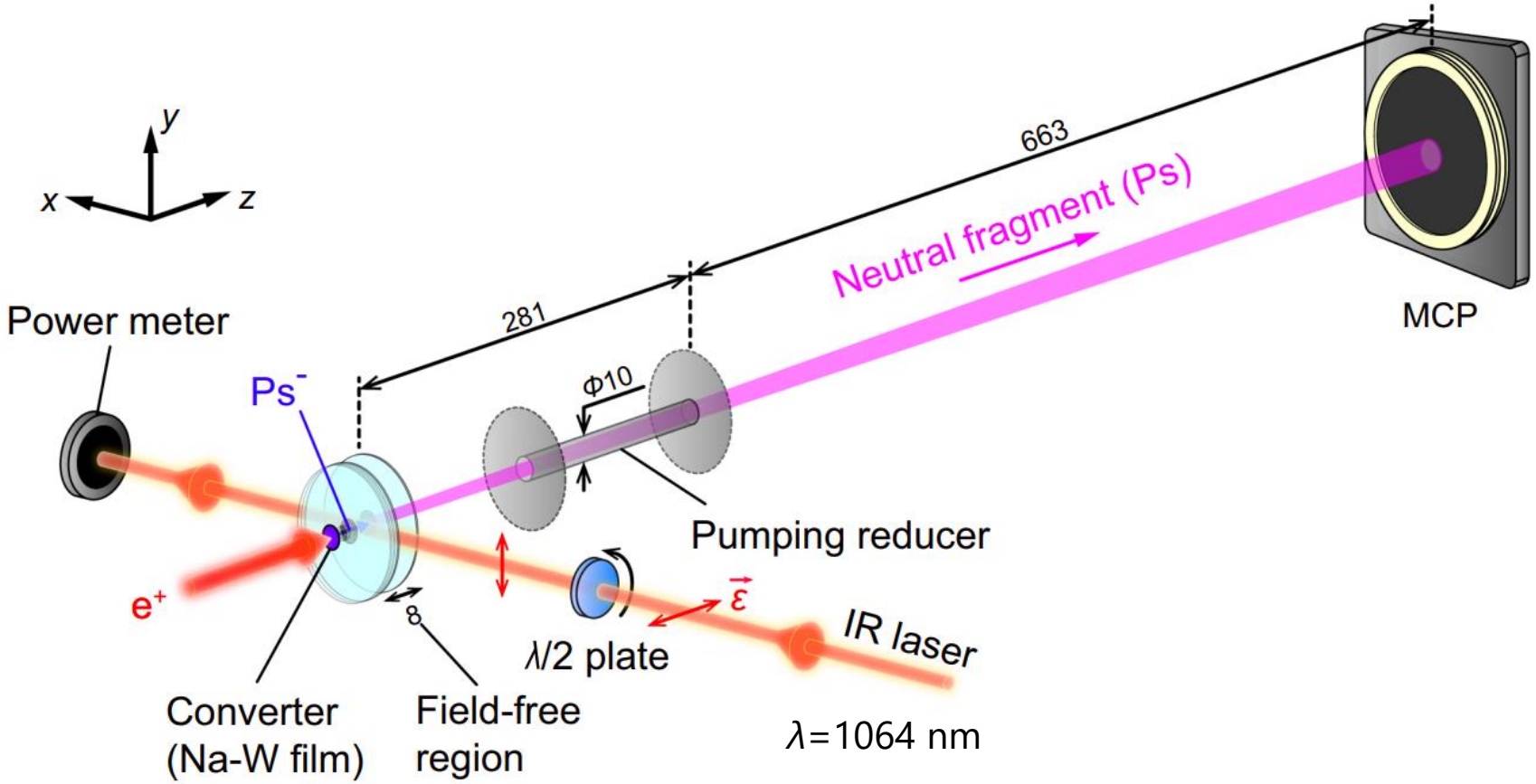
- Introduction
- Positronium beam
- **Recoil momentum manipulation**
- Summary

# Recoil momentum control

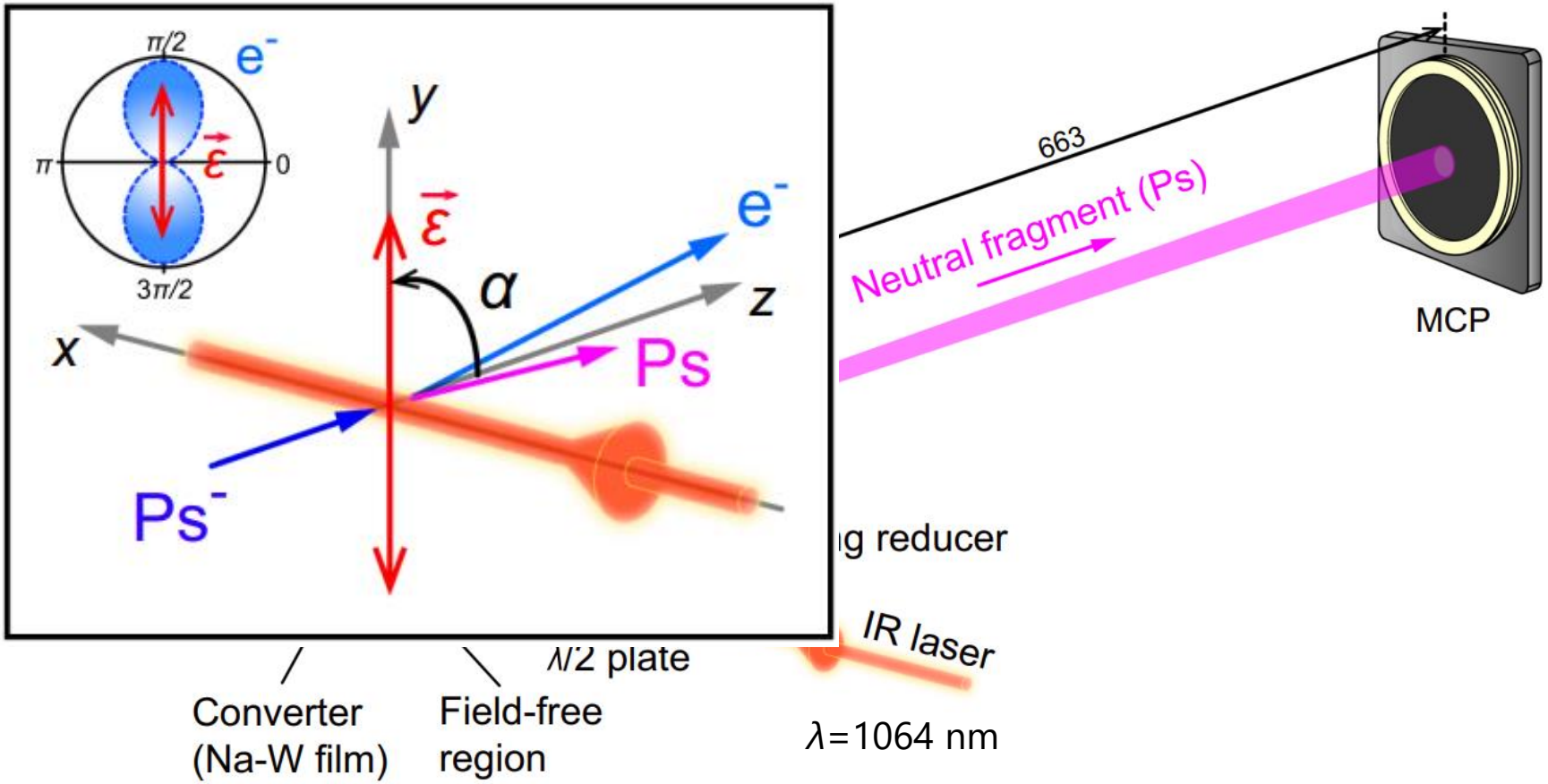



- Ps undergoes recoil kick from photoelectron
  ➡ energy and momentum spread
- Photoelectron emission direction controlled by polarization

# Recoil momentum control



# Recoil momentum control



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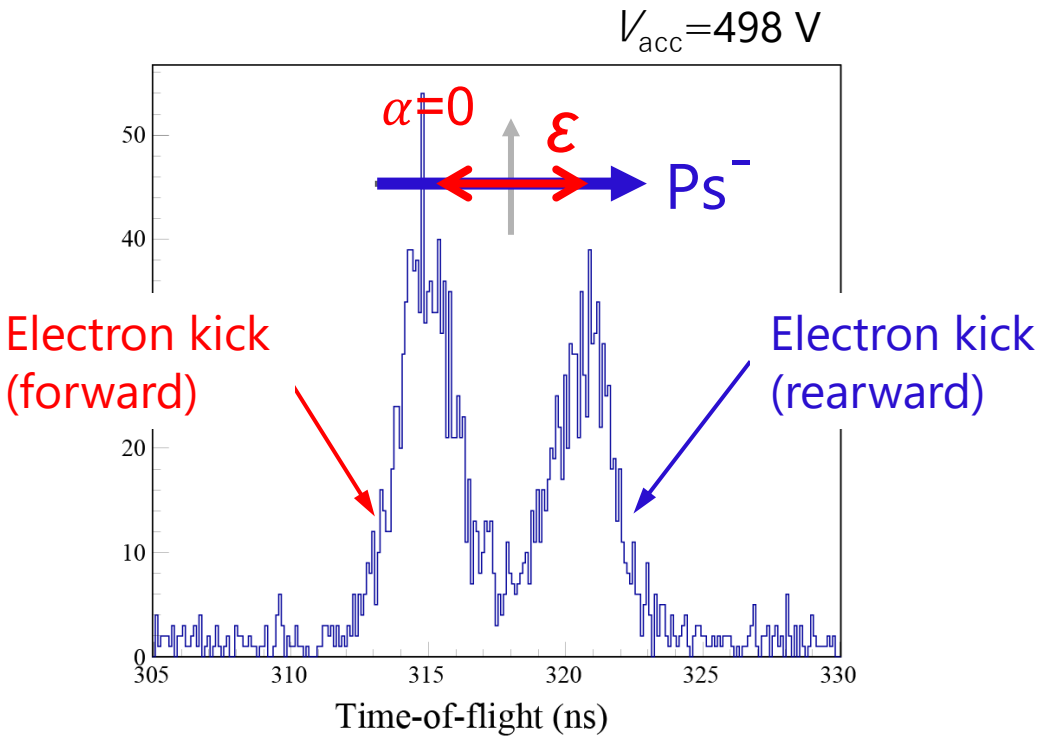
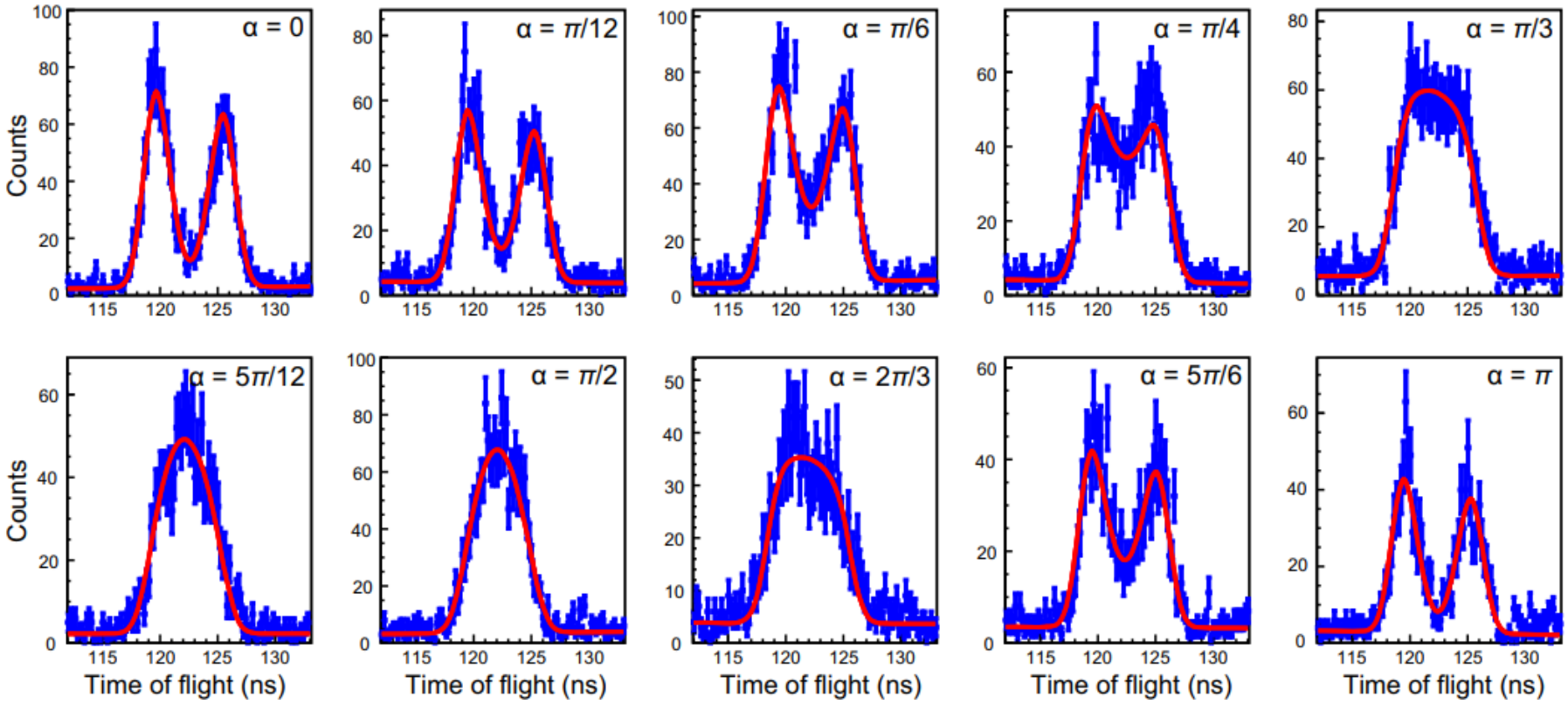


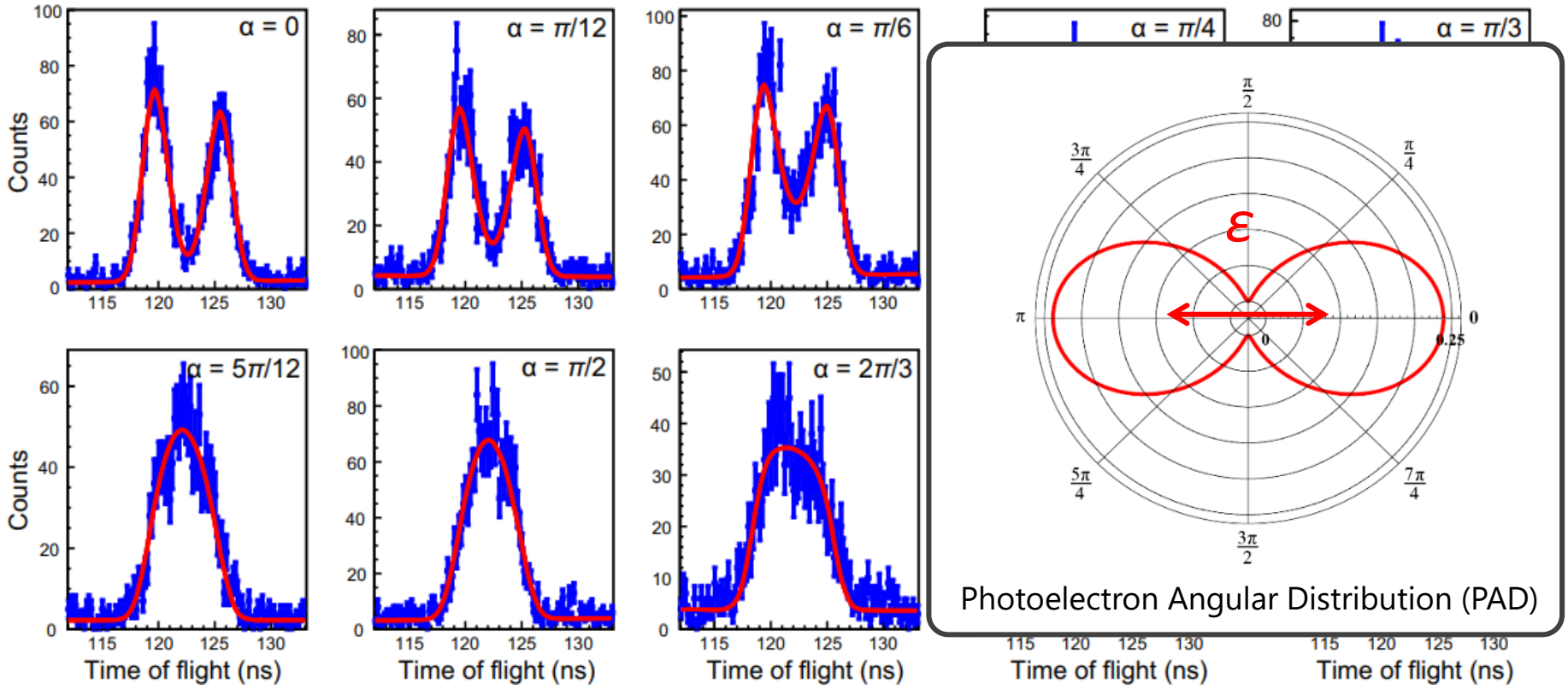

- Observation of photoelectron recoil to Ps atoms
- Photoelectron Angular Distribution (PAD) is anisotropic

# Recoil momentum control




K. Michishio *et al.*, *Phys. Rev. Lett.* **132**, 203001 (2024)

# Recoil momentum control




- Clarified correlation between PAD and polarization vectors
- Demonstrated polarization-controlled translational momentum distribution of Ps beam

K. Michishio *et al.*, *Phys. Rev. Lett.* **132**, 203001 (2024)

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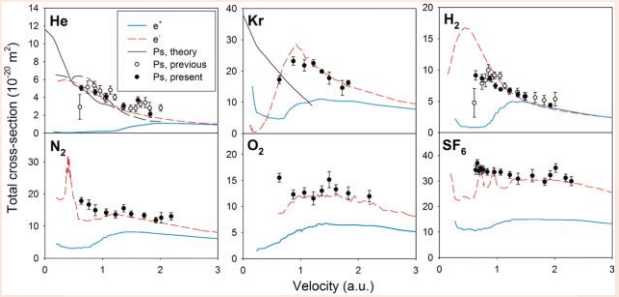
# Future prospects

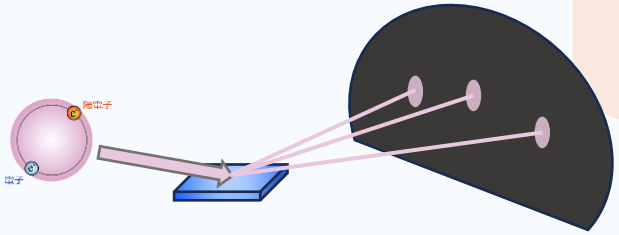
## Fundamental data




S. J. Brawley *et al.*, Science **330**, 789 (2010)

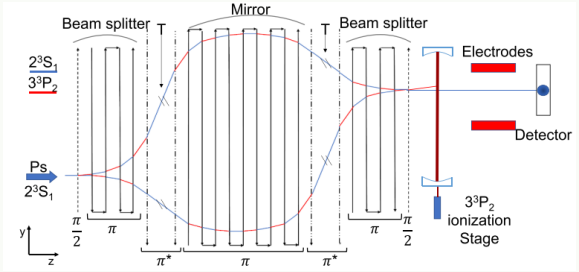
**Ps - matter interactions**
across wide energy ranges

## Materials analysis



**Ps atomic diffraction**
(Ferroelectrics, ferromagnets, and EM field environments)

## Advanced physics




G Vinelli *et al.*, Class. Quant. Grav. **40**, 205024 (2023)

**Ps - "field" interactions**

**Applied research using a novel quantum beam of Ps**

# Summary

- Realization of a high-quality and energy-tunable Ps beam by the photodetachment of $Ps^-$ ions

➡ *state-of-art performance, high intensity, low-background detection, wide energy range, and ultra-high-vacuum compatibility*

- Photoelectron recoil control of Ps beam by light polarization

➡ Manipulate recoil momentum distribution of Ps atoms

Thank you for your attention