1S-2S Spectroscopy of Positronium

SPS-2017 Geneva, Switzerland

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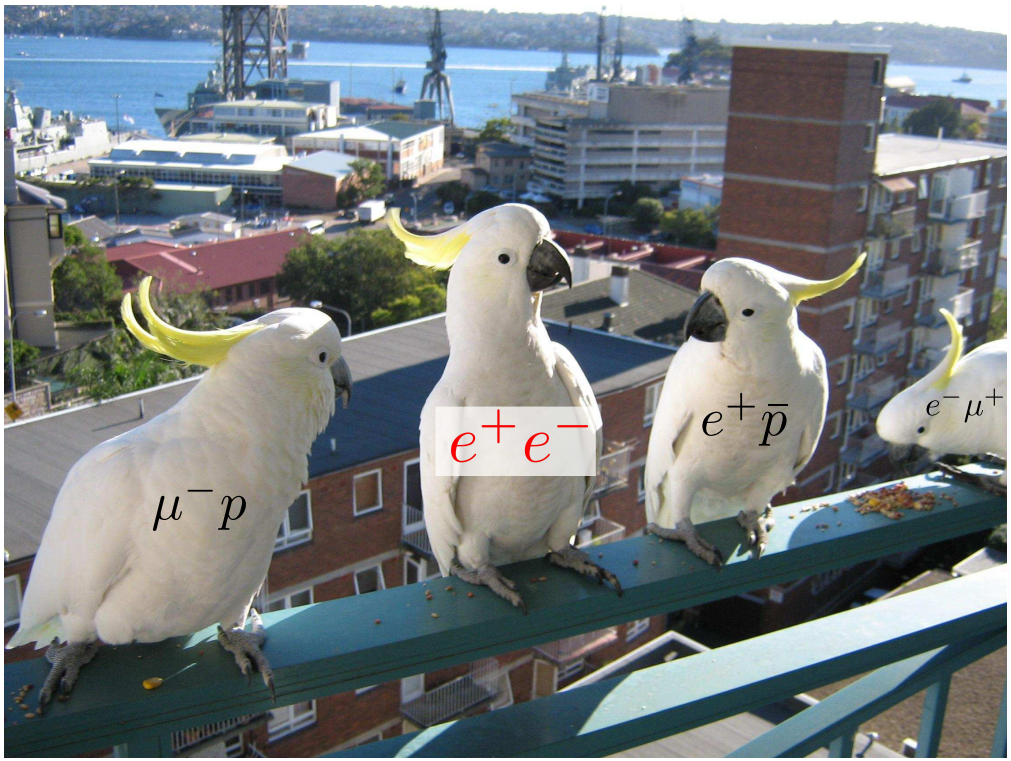
Precision Physics at Low Energy, Kirch Group
Positron and Positronium Laboratory, Rubbia Group

August 24, 2017

Exotic Atom Spectroscopy



Von S B from Sydney, Australia - Cockatoos at breakfast, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=5445640

muonic hydrogen/deuterium:

Pohl R, Antognini A, Nez F, Amaro FD, Biraben F, et al., Nature 466:213 (2010)

Pohl R, Nez F, Fernandes L M P, Amaro F D, et al., Science 669-673 (2016)

antihydrogen:

M. Ahmadi, B. X. R. Alves, C. J. Baker, W. Bertsche, E. Butler, A. Capra, C. Carruth, C. L. Cesar, M. Charlton, S. Cohen, R. Collister, S. Eriksson, A. Evans, N. Evetts, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, A. Gutierrez, J. S. Hangst, W. N. Hardy, M. E. Hayden, C. A. Isaac, A. Ishida, M. A. Johnson et al., Nature 541, 506510, 2017

muonium ($e^-\mu^+$, Mu):

V. Meyer et al., Phys Rev. Lett. 84, 1136 (2000)

positronium (e^+e^-, Ps):

M.S.Fee, A.P.Mills, Jr., S.Chu, E.D.Shaw, K.Danzmann, R.J.Chichester, and D.M.Zuckerman, Phys. Lett. 70, 1397 (1993)

Motivation

Proton radius puzzle: (due to muonic hydrogen)
Test of bound-state QED without finite nuclear size effects.

[1] e.g. Krzysztof Pachucki and Savely G. Karshenboim, PRL 80, Nr.10, 1998
[2] e.g. Adkins, Gregory S. and Kim, Minji and Parsons, Christian and Fell, Richard N., PRL 115, 233401, 2015
[3] Kostelecky and Vargas, Phys. Rev. D 92, 056002, 2015

Motivation

Proton radius puzzle: (due to muonic hydrogen)
Test of bound-state QED without finite nuclear size effects.

Precision Test of bound-state QED.

- QED calculations[1] completed to the order of $m\alpha^6$ (uncertainty ± 0.6 MHz, 9 digits).
- Ongoing work[2] for $m\alpha^7$.

Lorentz and CPT test[3]

[1] e.g. Krzysztof Pachucki and Savely G. Karshenboim, PRL 80, Nr.10, 1998
[2] e.g. Adkins, Gregory S. and Kim, Minji and Parsons, Christian and Fell, Richard N., PRL 115, 233401, 2015
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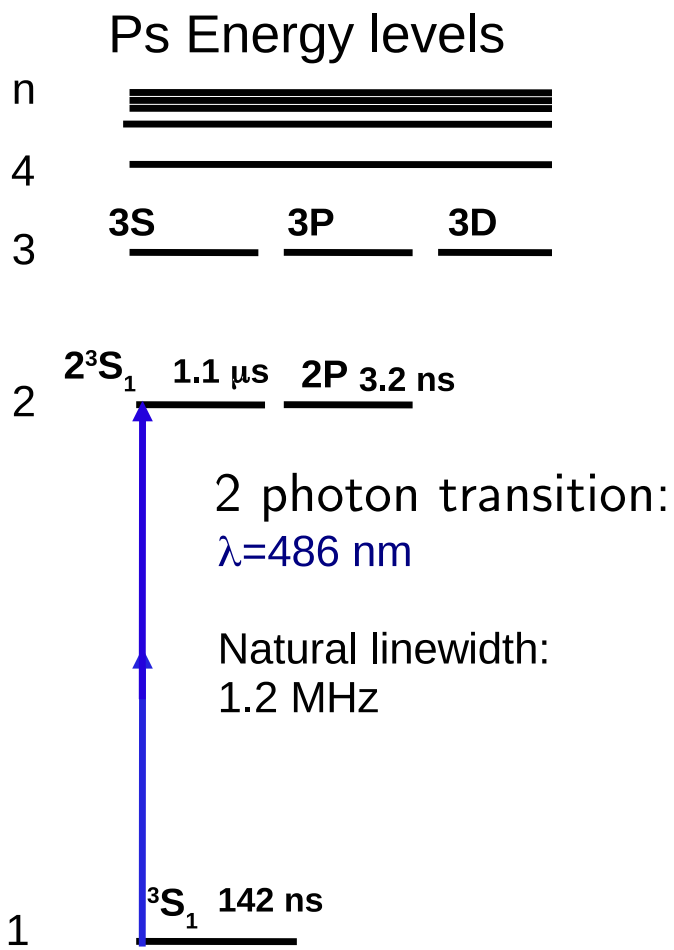
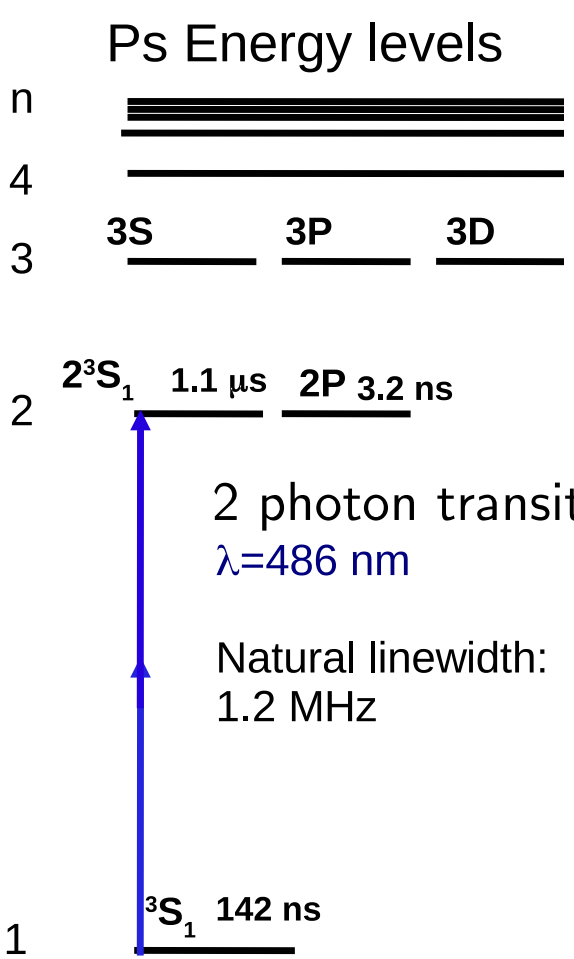
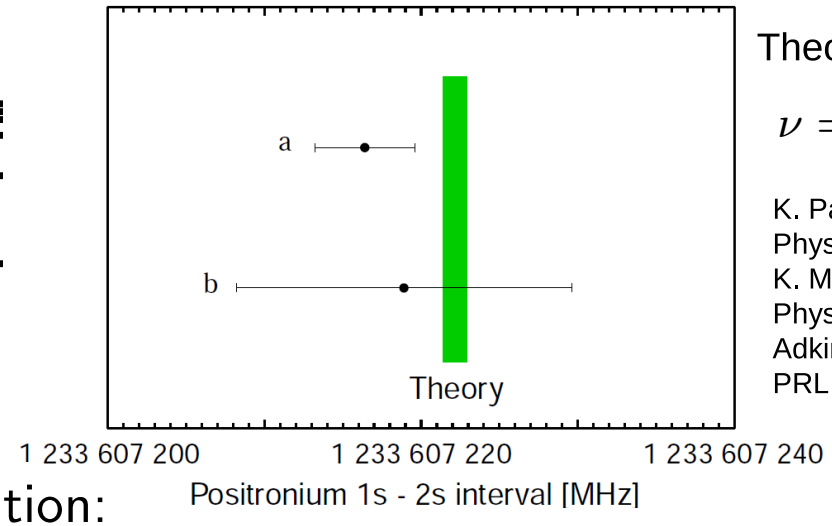

Ps Energy levels
n
4
3
3S
3P
3D
2
2^3S_1 1.1 μs
2P 3.2 ns
2 photon transition:
λ=486 nm
Natural linewidth:
1.2 MHz
$^3S_1$ 142 ns
1





Theory:

$$\nu = 1\,233\,607\,222.2(0.6)\ \mathrm{MHz}$$

K. Pachucki and S. G. Karshenboim, Phys. Rev. A60, 2792 (1999), K. Melnikov and A. Yelkhovsky, Phys. Lett. B458, 143 (1999)¨. Adkins, Kim, Parsons and Fell, PRL 115 233401 (2015)

Experiments:

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

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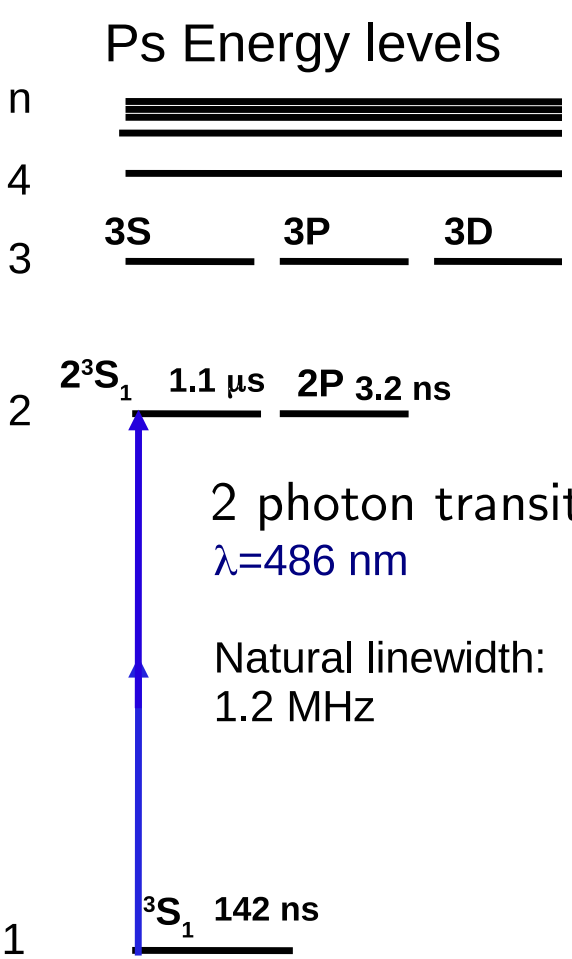
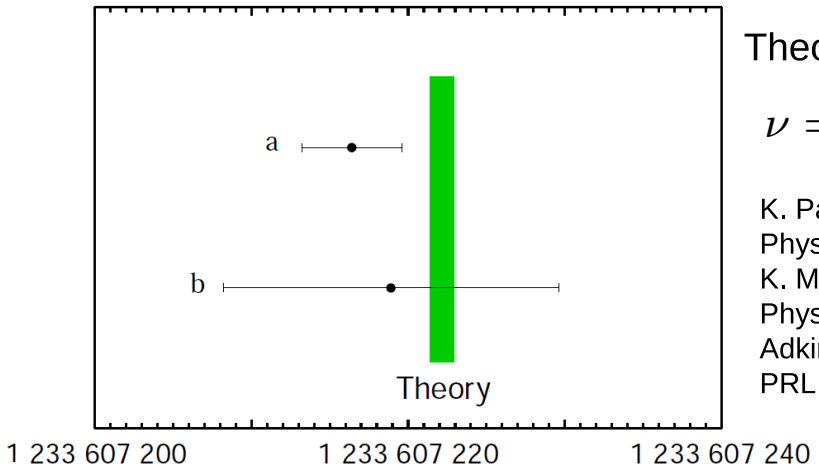
$$\nu = 1\,233\,607\,218.9(10.7)\ \mathrm{MHz}$$





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Positronium 1S-2S transition

P. Crivelli (ETHZ), D. Cooke (ETHZ), A. Rubbia (ETHZ), A. Antognini (ETHZ/PSI), K. Kirch (ETHZ/PSI), G. Wichmann (ETHZ), J. Alnis (MPQ), T. W. Haensch (MPQ), B. Brown (Marquette)

Positronium (Ps, e^+e^-)

Reduced mass $m_{\mathrm{Ps}} = m_{\mathrm{e}}/2 = 0.26\,\mathrm{MeV}/c^2$.

Bound system of matter and antimatter.

Lifetime depends on spin configuration

ortho-Ps 142 ns
para-Ps < 1 ns

Lifetime limited by annihilation
(wave function overlap of e^+ and e^-)

$\tau_{2\mathrm{S}} = 1.1\,\mu\mathrm{s}$
radiative lifetime $\tau_{2\mathrm{S}} = 244\,\mathrm{ms}$

negligible annihilation lifetime for 20P
radiative lifetime $\tau_{20\mathrm{P}} \approx 3 \quad \mu\mathrm{s}$

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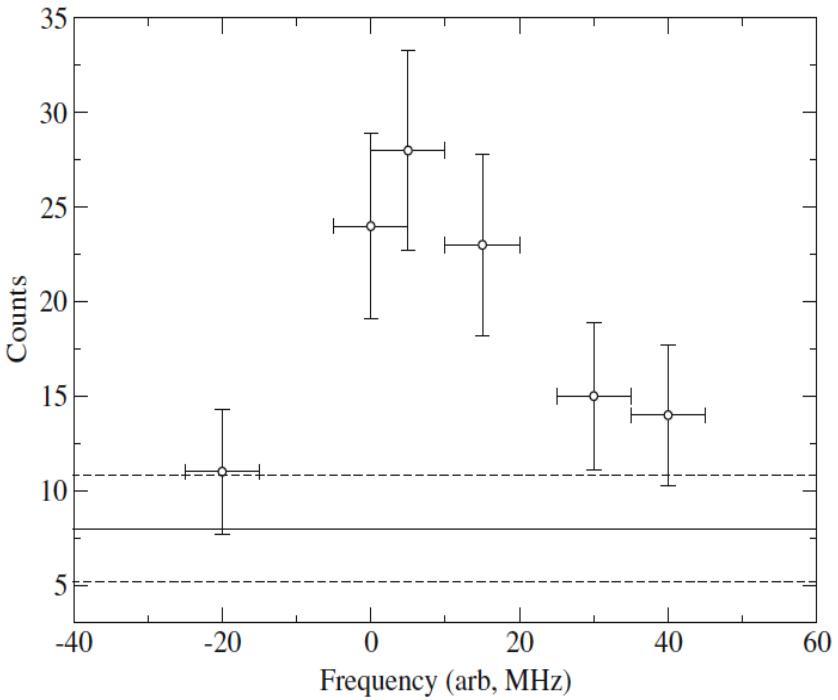
negligible annihilation lifetime for 20P
radiative lifetime $\tau_{20P} \approx 3\ \ \mu\mathrm{s}$

In this setup:

The emitted Ps velocity is around $10^5\,\mathrm{m/s}$ ($\approx 50\,\mathrm{meV}$, $\beta = v/c = 3.1 \cdot 10^{-4}$).
$\Rightarrow 10\,\mathrm{cm}$ results in an experimental time window $\leq 1\,\mu\mathrm{s}$.

Previous Experiment



Predecessor:
D.Cooke et al, Hyperfine Interact. 233 (2015)
[arXiv:1503.05755 [physics.atom-ph]]

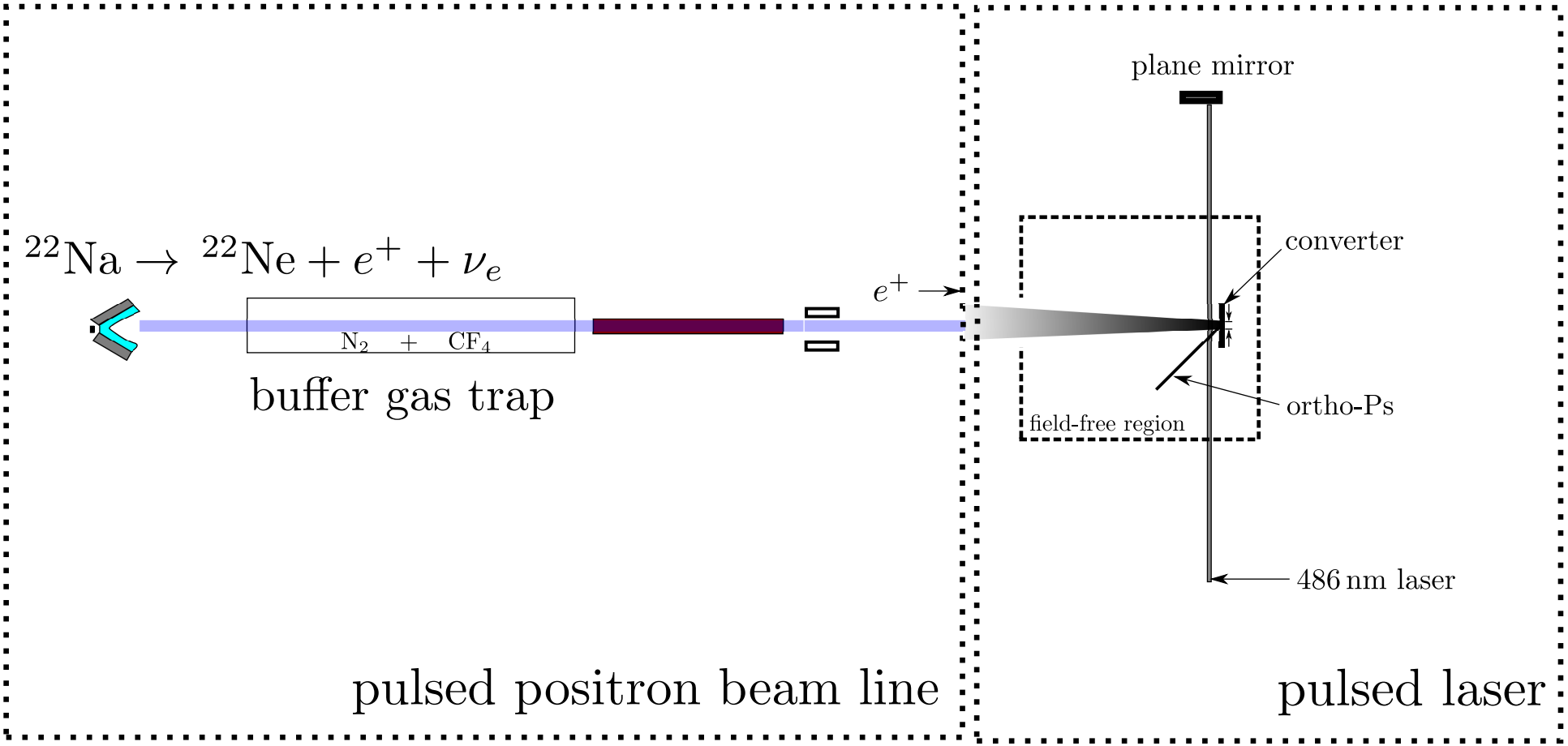
- excitation of 1S-2S with
  CW laser enhancement cavity
  demonstrated.

$\rightarrow$ too high noise level (accidentals).

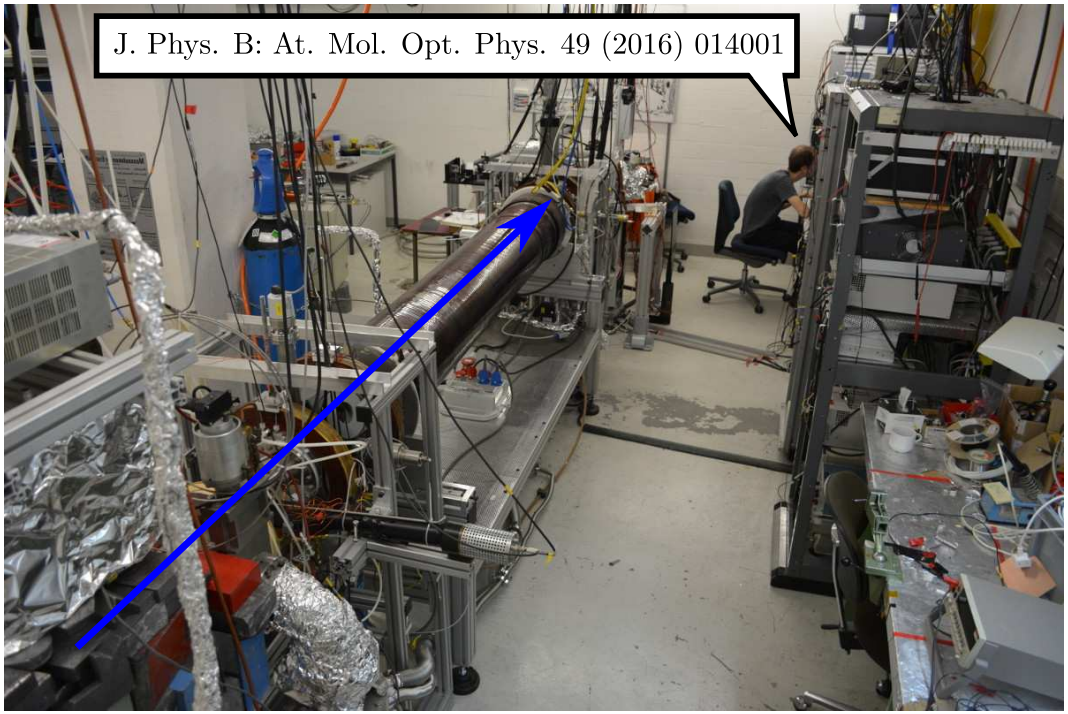
$\rightarrow$ frequency reference only by
a wavemeter (± 10 MHz).

$\Rightarrow$ e^+ in bunches would reduce noise level (shorter time window).

Overview - Current Setup



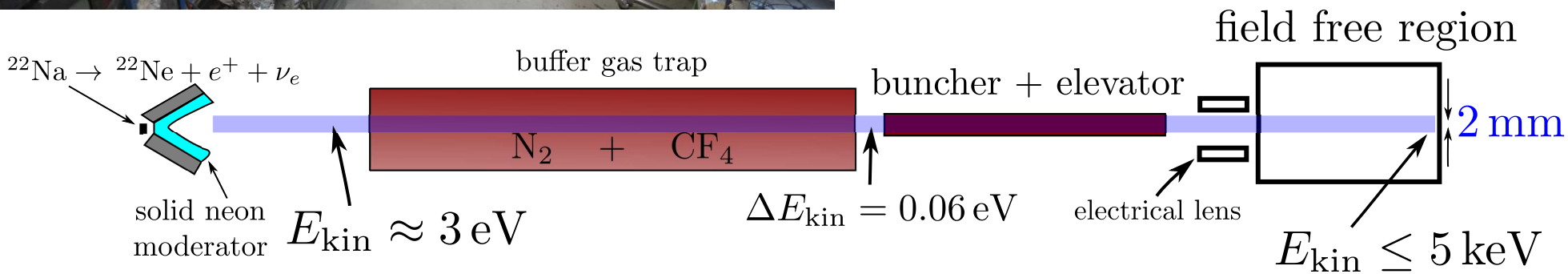
Bunched Positron Beam



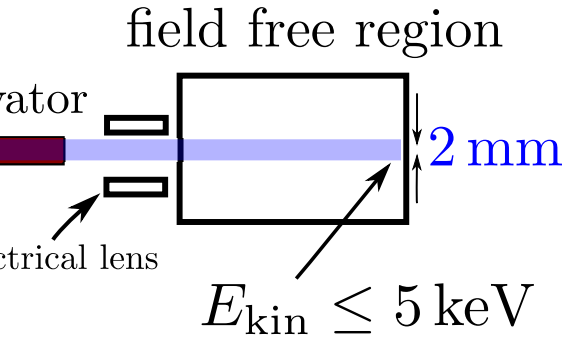
β^+ decay converted to bunches with

- 1 ns FWHM and $\sigma = 1$ mm
- 1 to 10 Hz repetition rate
- $E_{\text{kin}} = 3$ to 5 keV

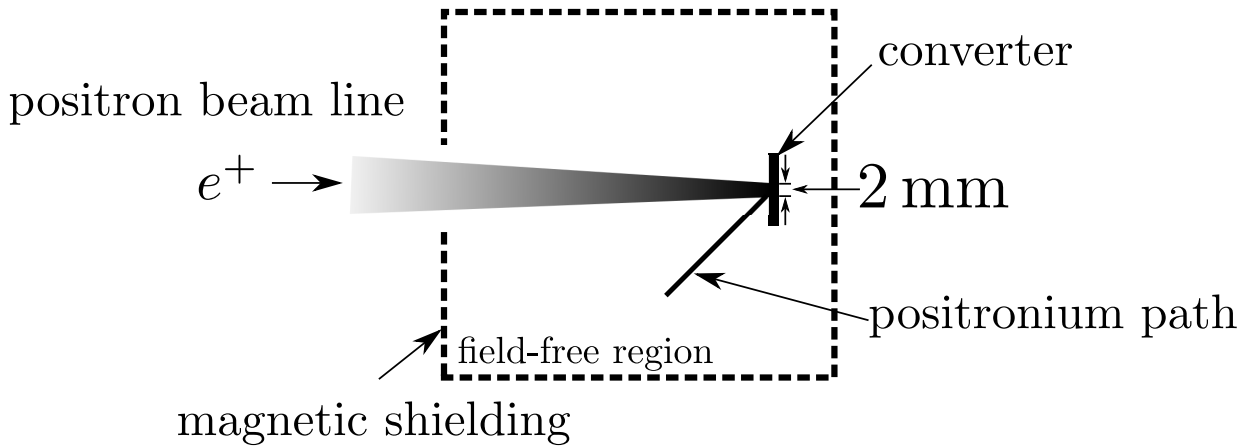
$\geq 20'000\, e^+/s$



Bunched Positron Beam



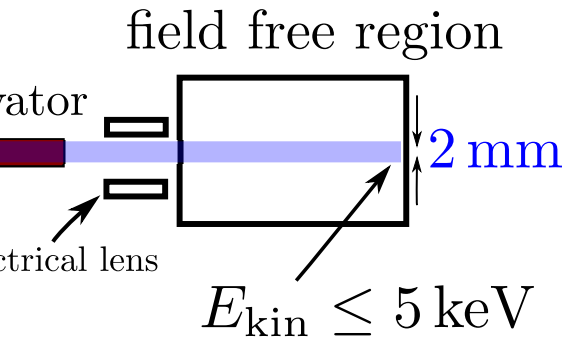
- 1 ns FWHM
- $\sigma = 1\,\text{mm}$
- 20'000 e^+ per bunch

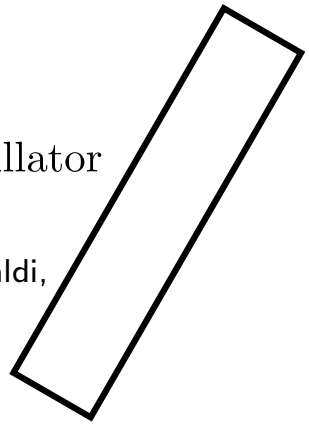


$\Rightarrow$ Noise level reduction is achieved by e^+ bunching!

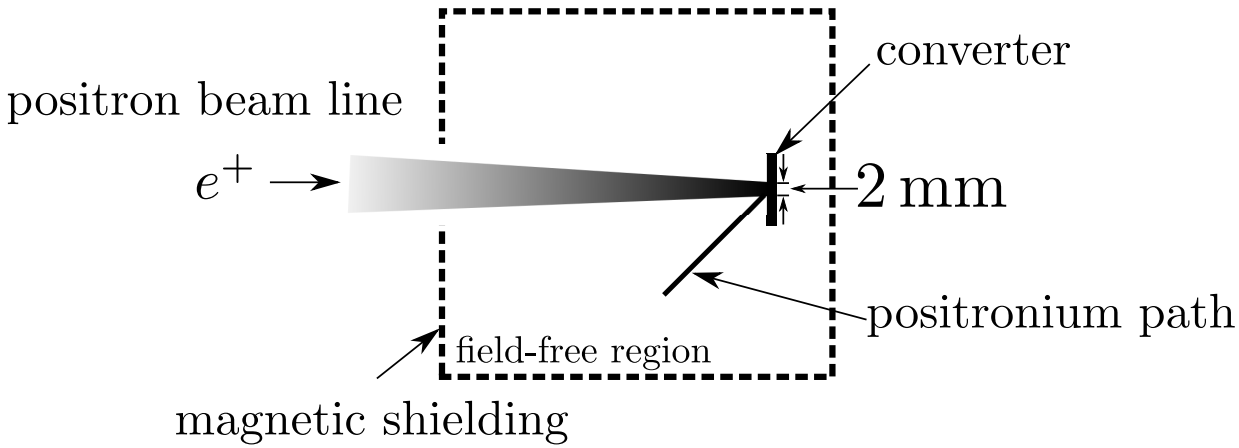
$\Rightarrow$ Time window for hitting the converter generated! (start trigger)

Positronium Generation





thanks to
Dr. Francesca Nessi-Tedaldi,
Dissertori Group ETHZ



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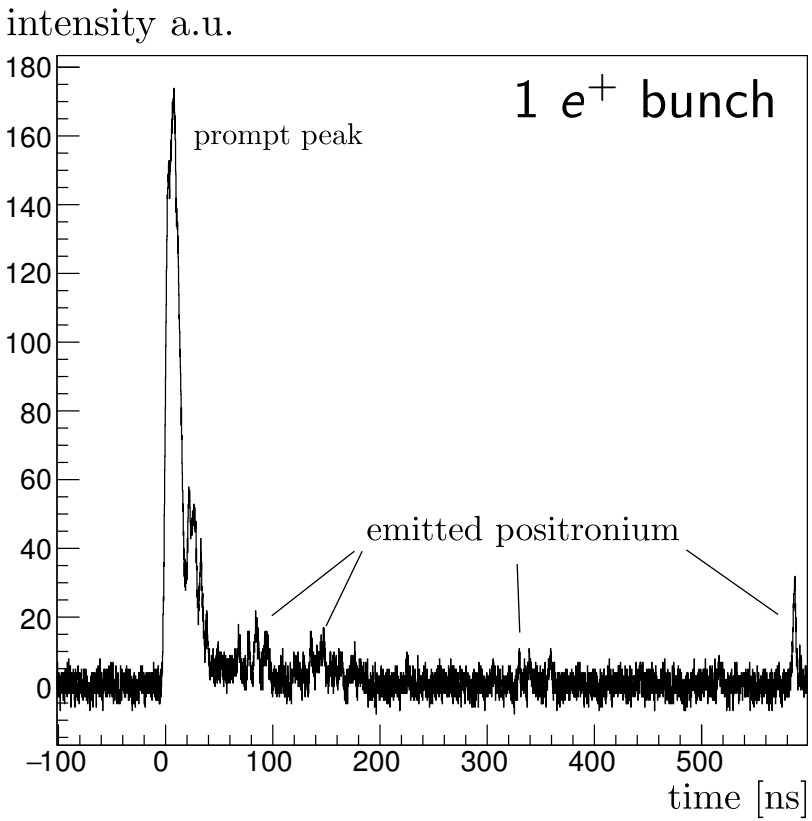

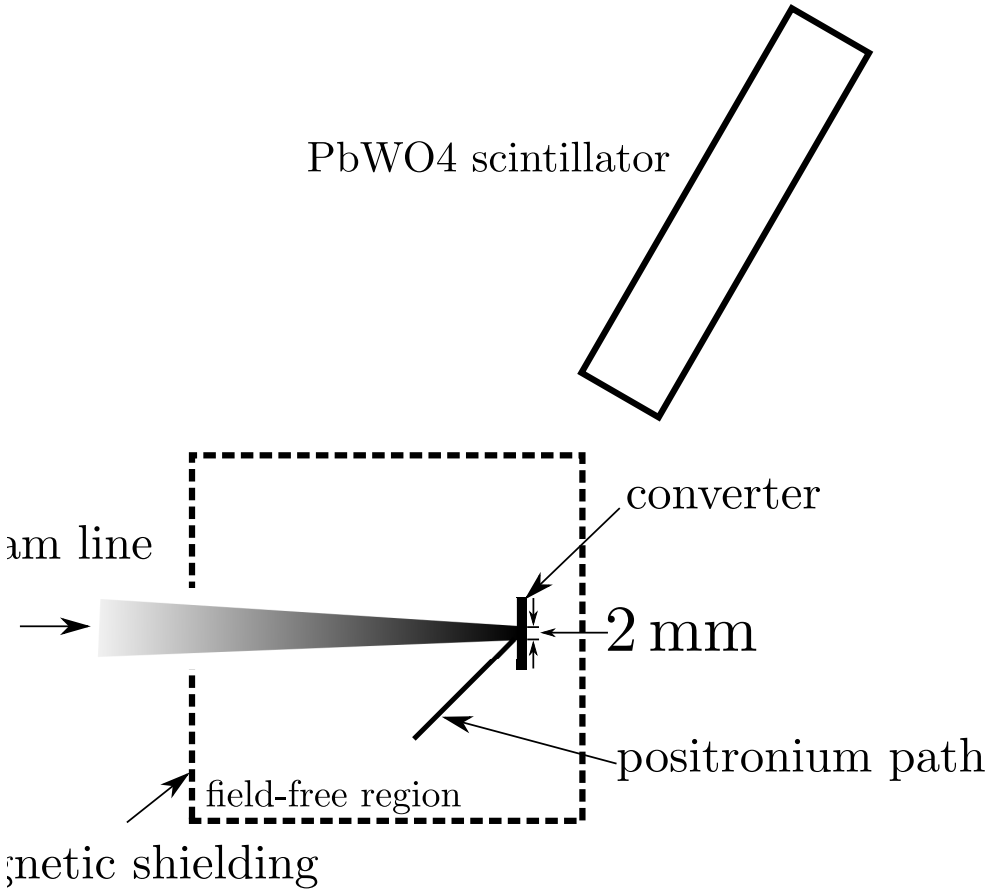

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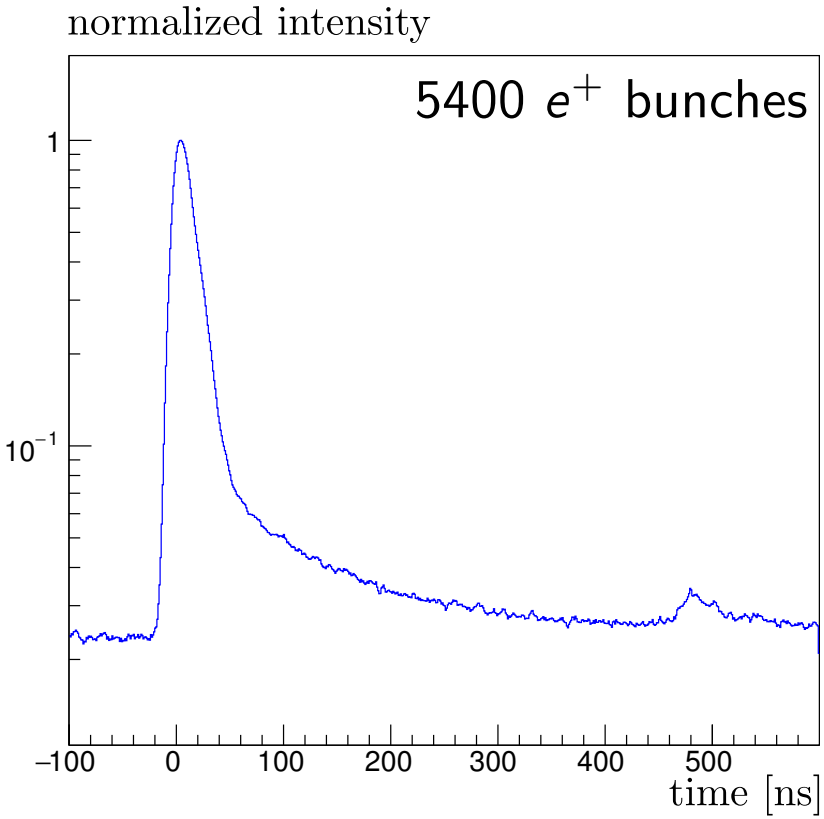

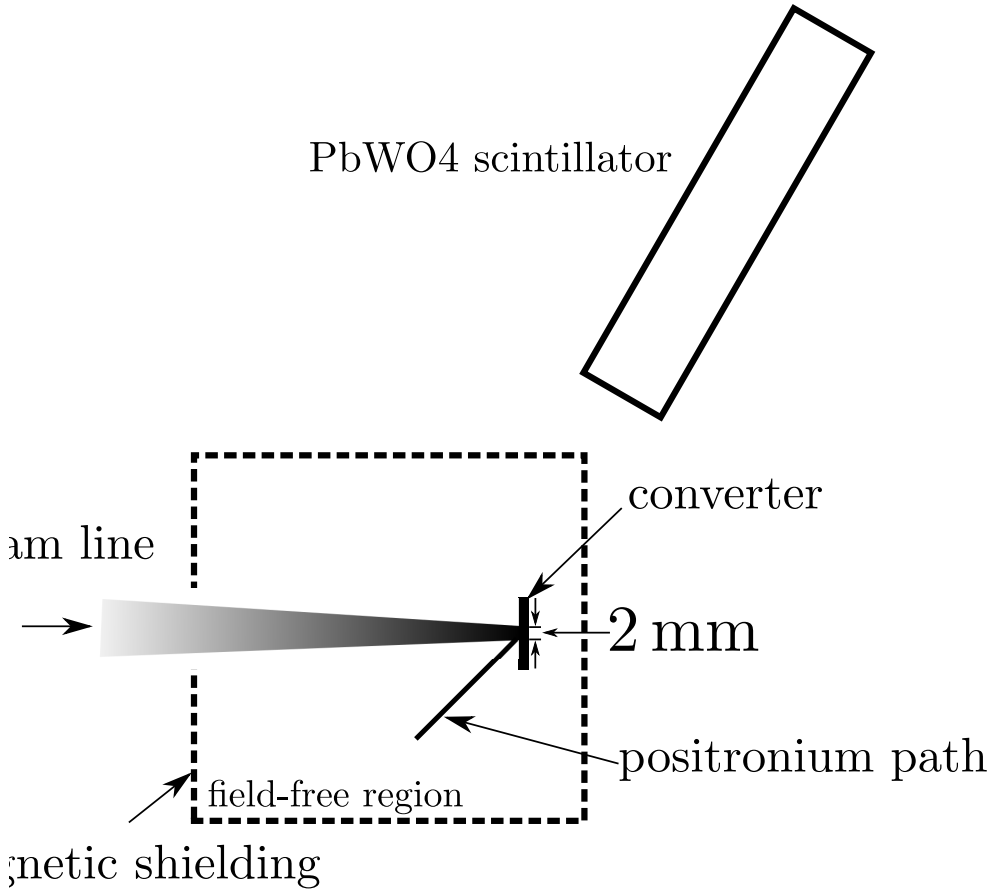

⇒ Noise level reduction is achieved by e^+ bunching!

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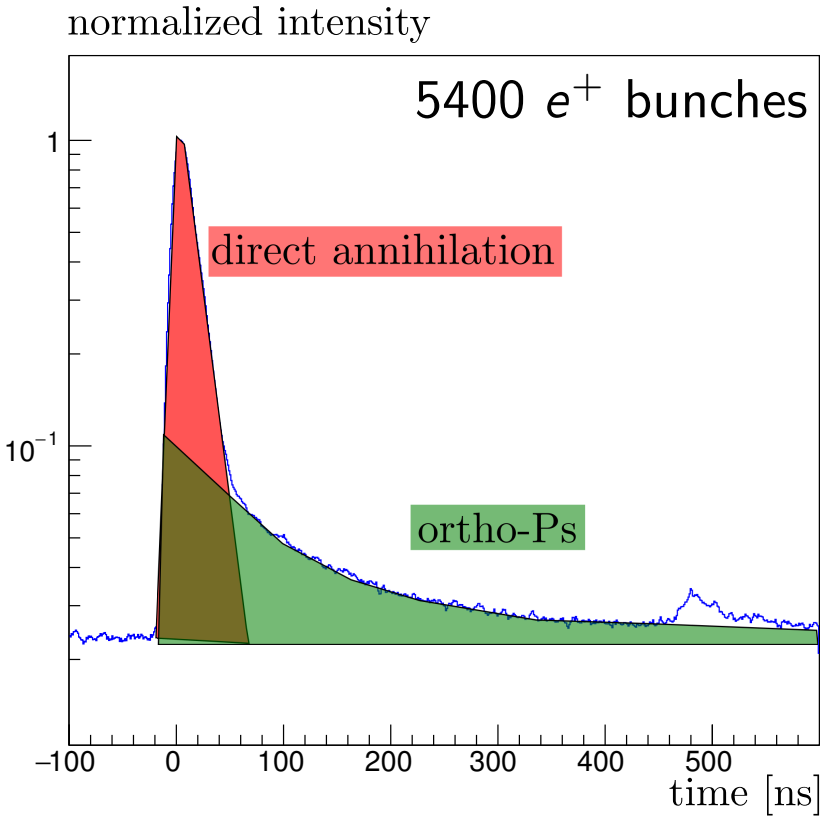

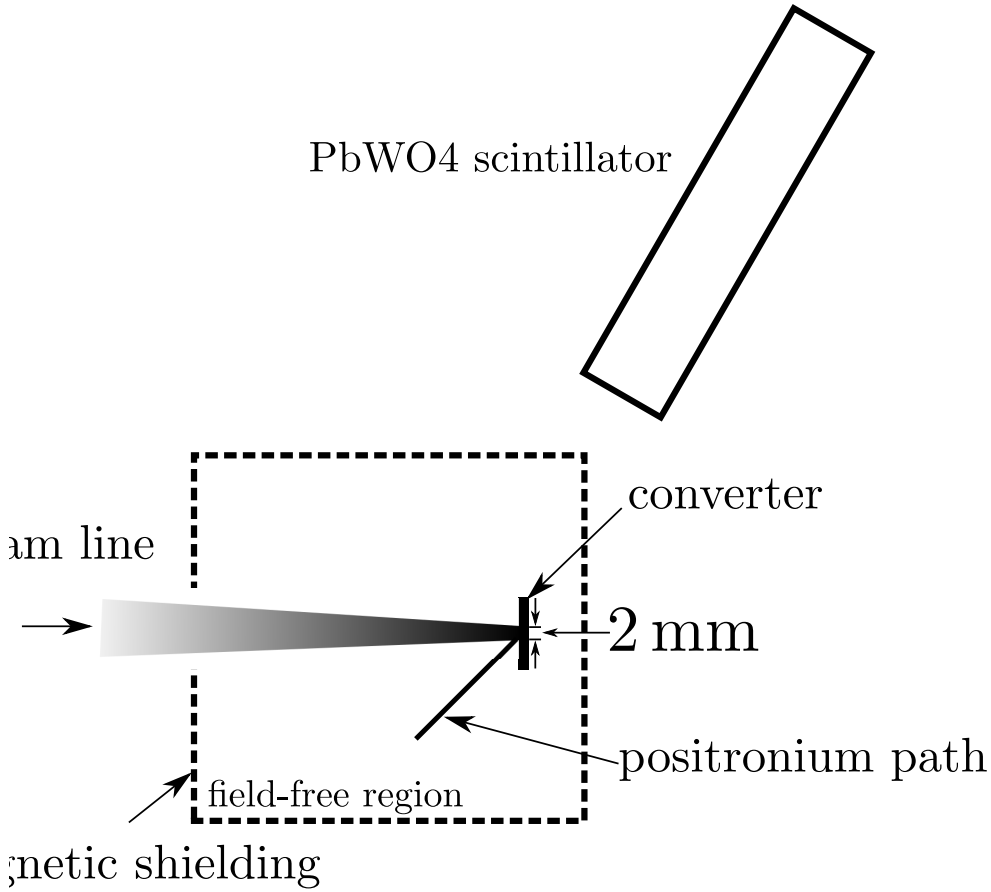

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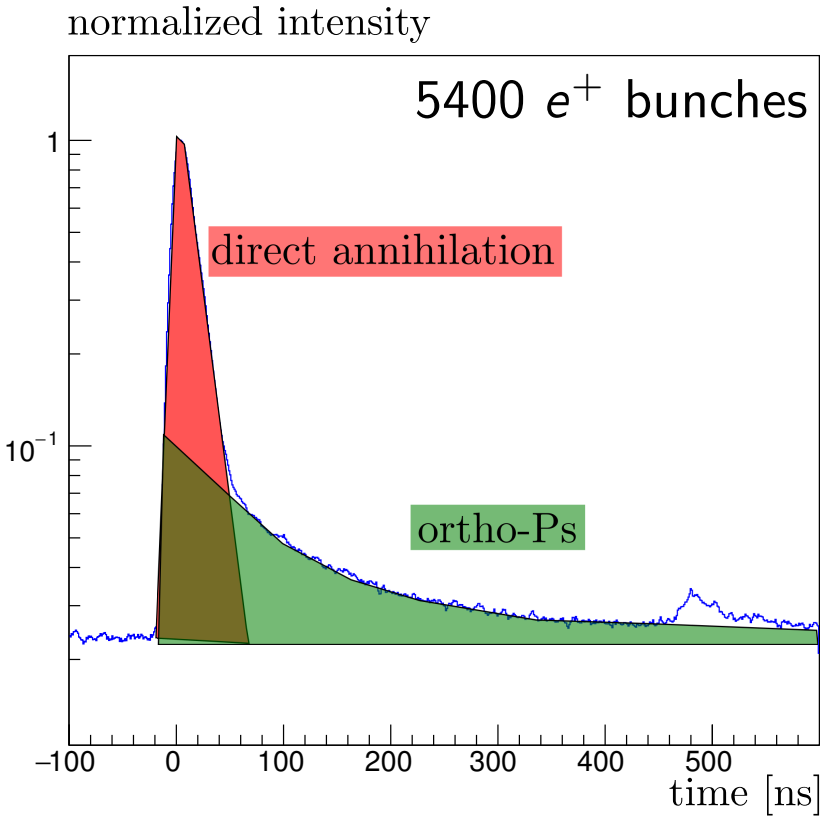
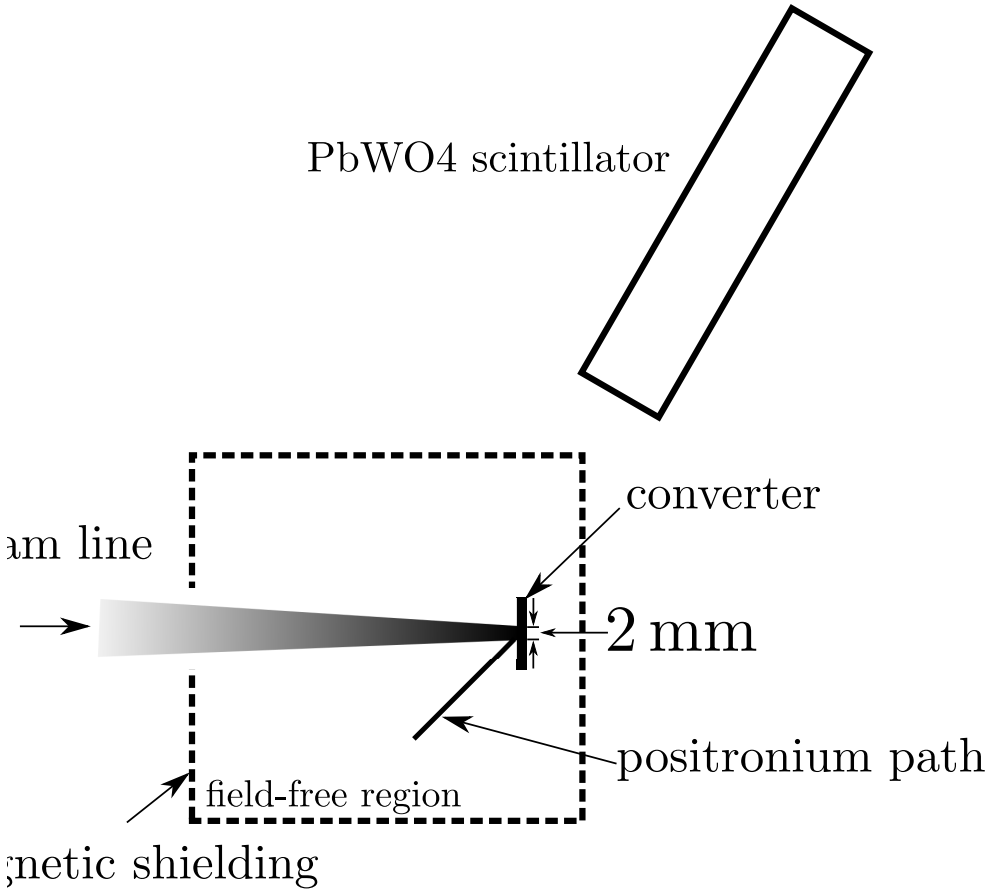
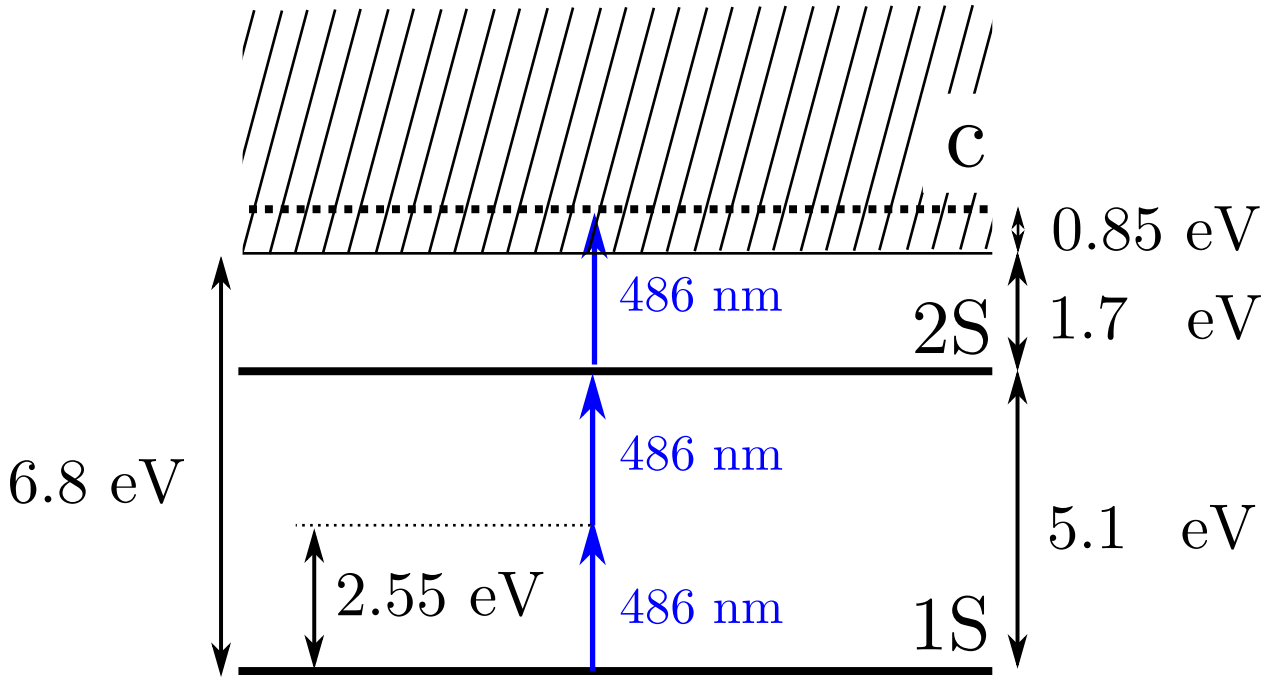




Next Step:

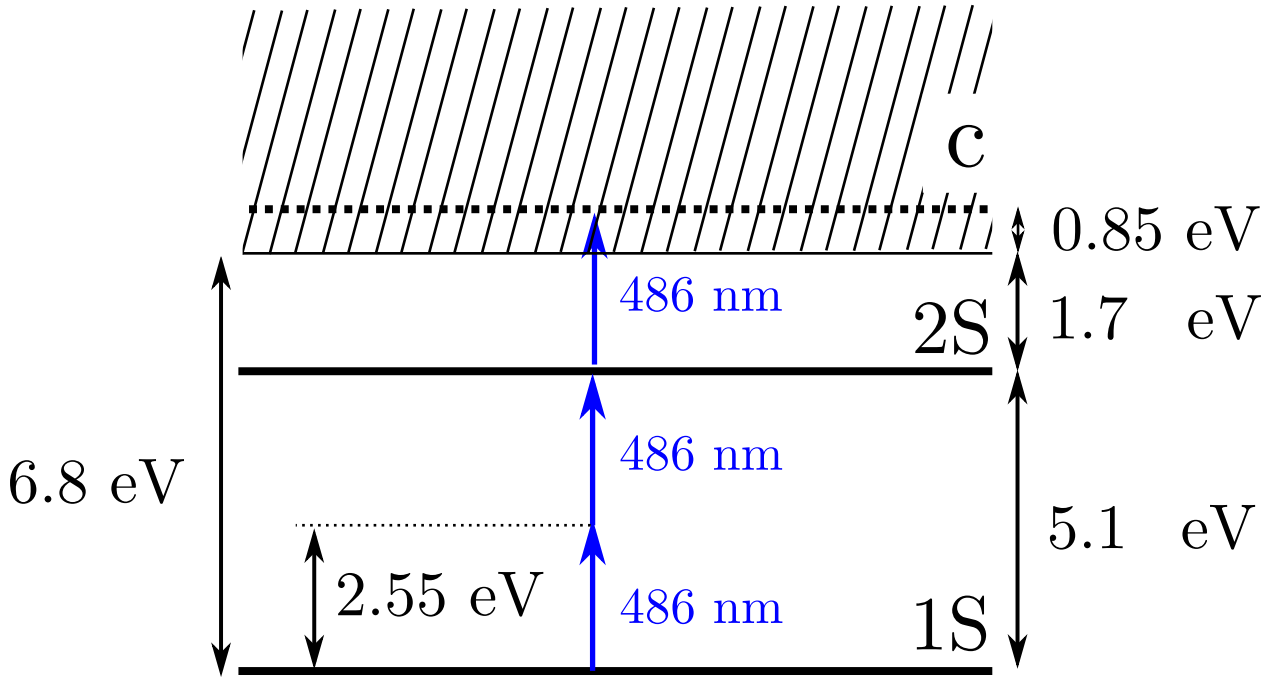
Generation of excited 2S Ps.

Resonant Multi-photon ionization of ortho-Positronium



Resonant Multi-photon ionization of ortho-Positronium

using 3 photons of 486 nm with 17 mJ, 7 ns length, waist ≈ 2 mm,
back reflected by a plane mirror with a misalignment of ≈ 0.5 mrad.



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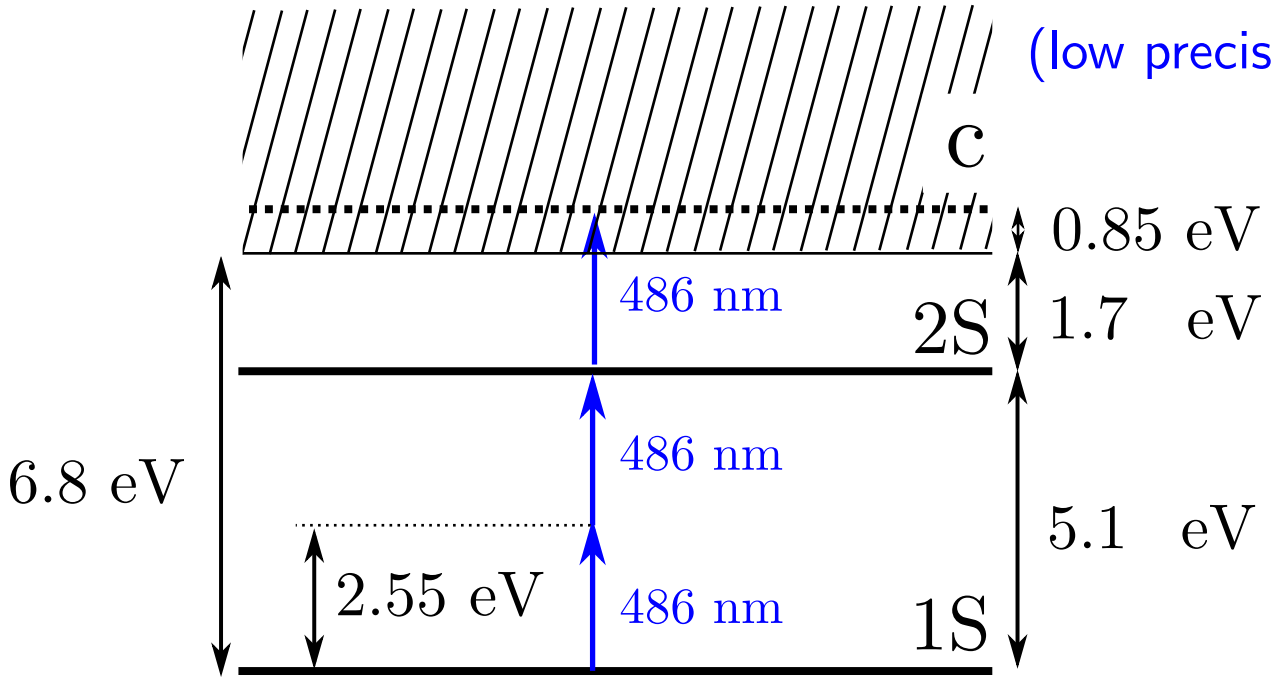
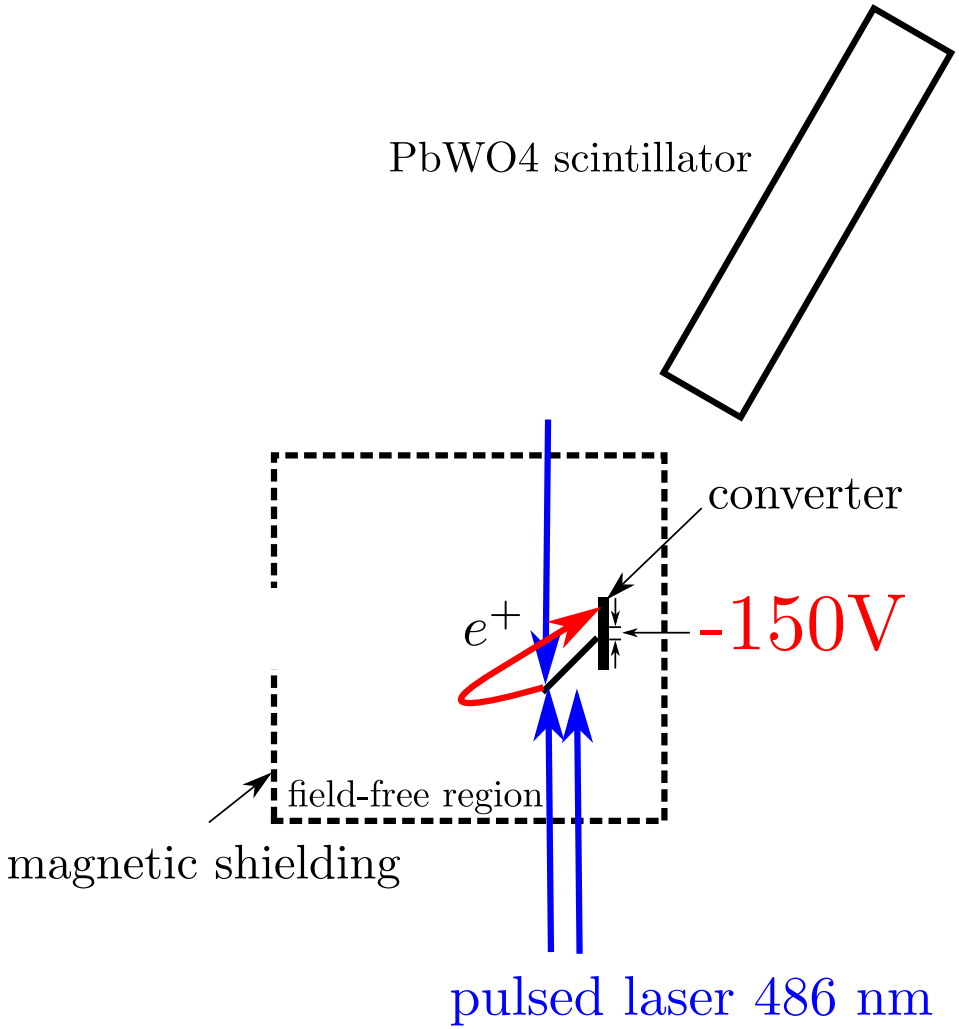


Large fraction ($\approx 10\%$) of ortho-Ps excited for probing new detection scheme.

Expected broadening of around 150 MHz from 7 ns long pulse and around 100 MHz from residual first order Doppler broadening.

Measurement with Pulsed Laser



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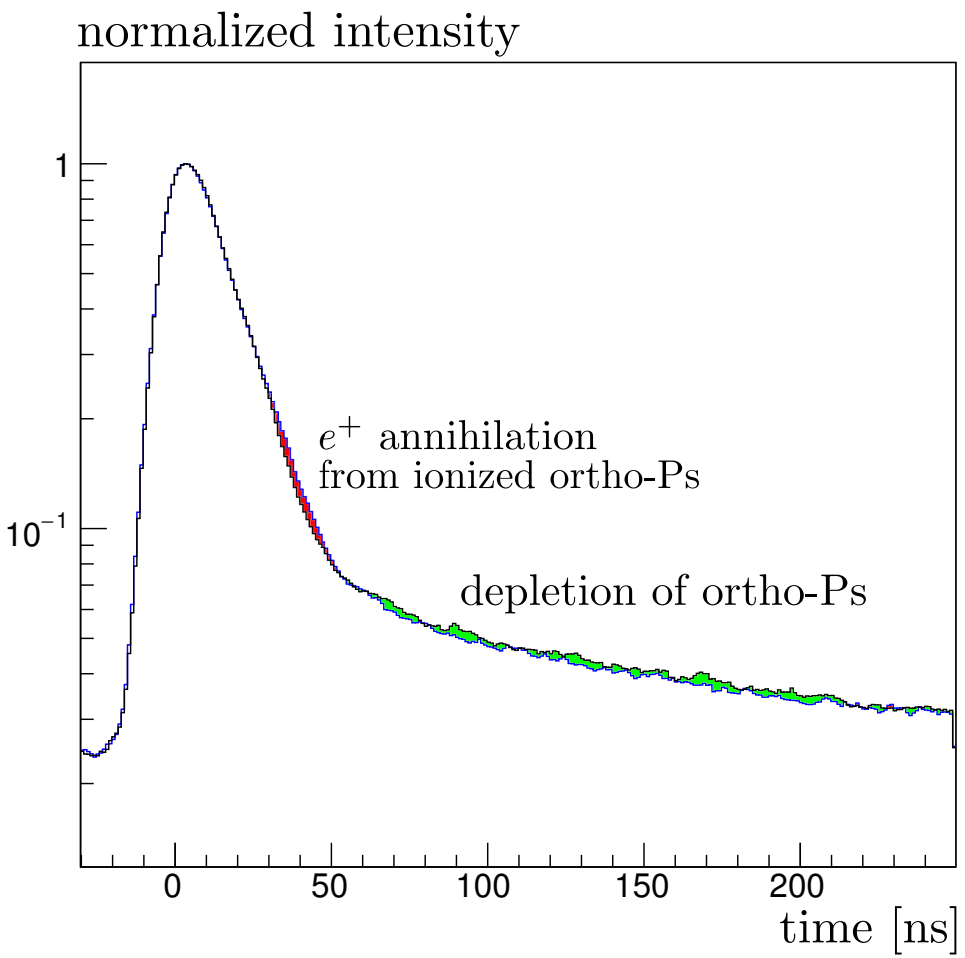
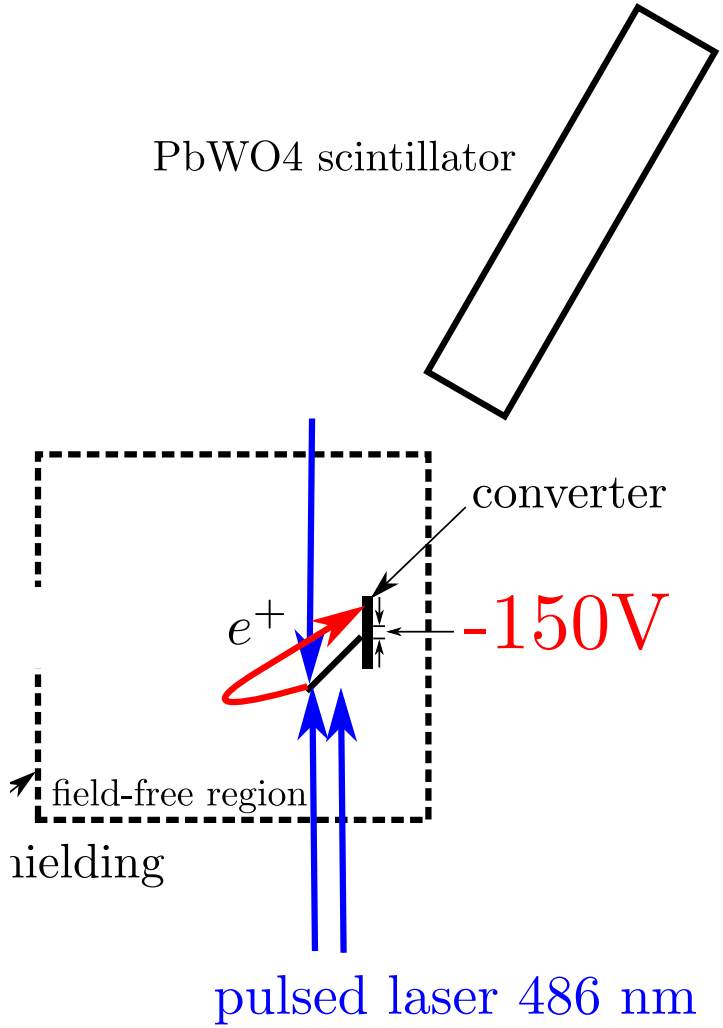
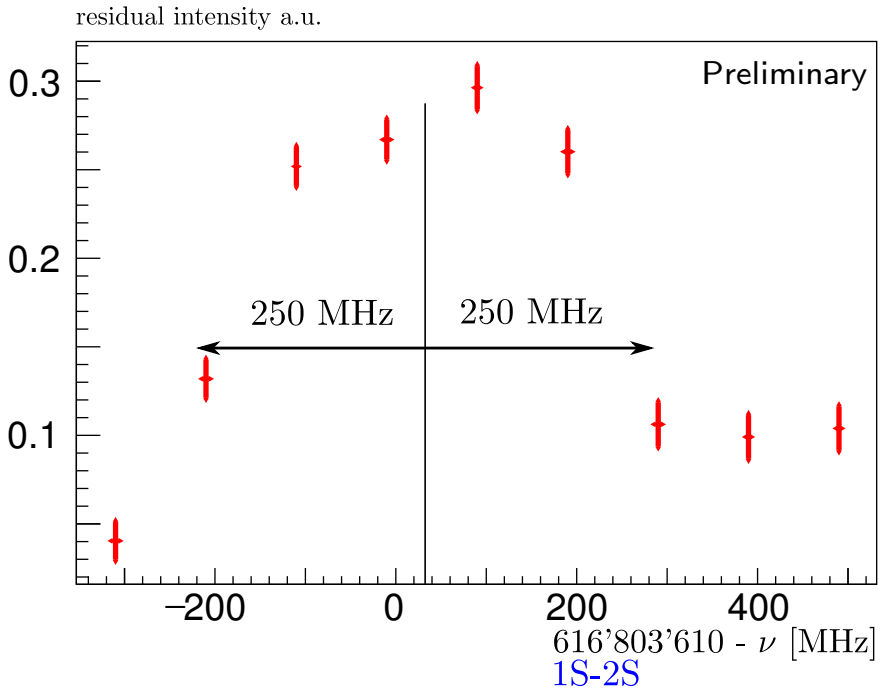
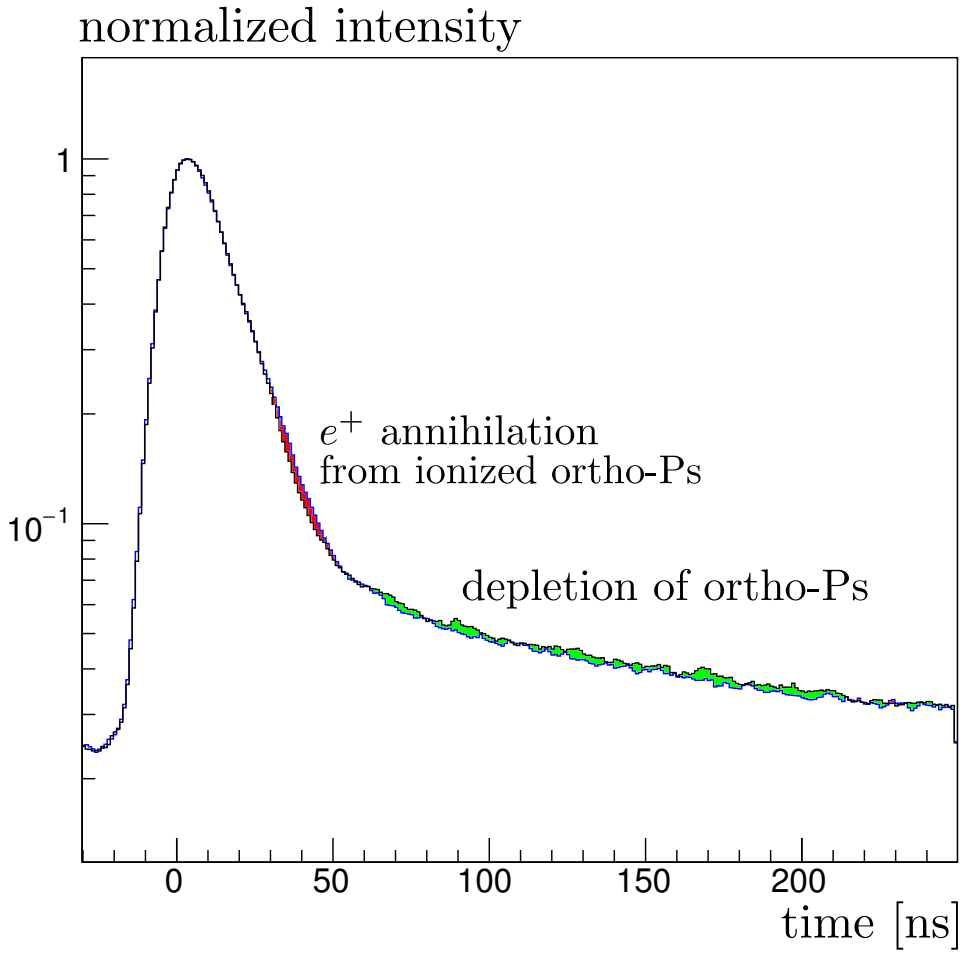




Measurement with Pulsed Laser

Annihilation signal of ionized Ps





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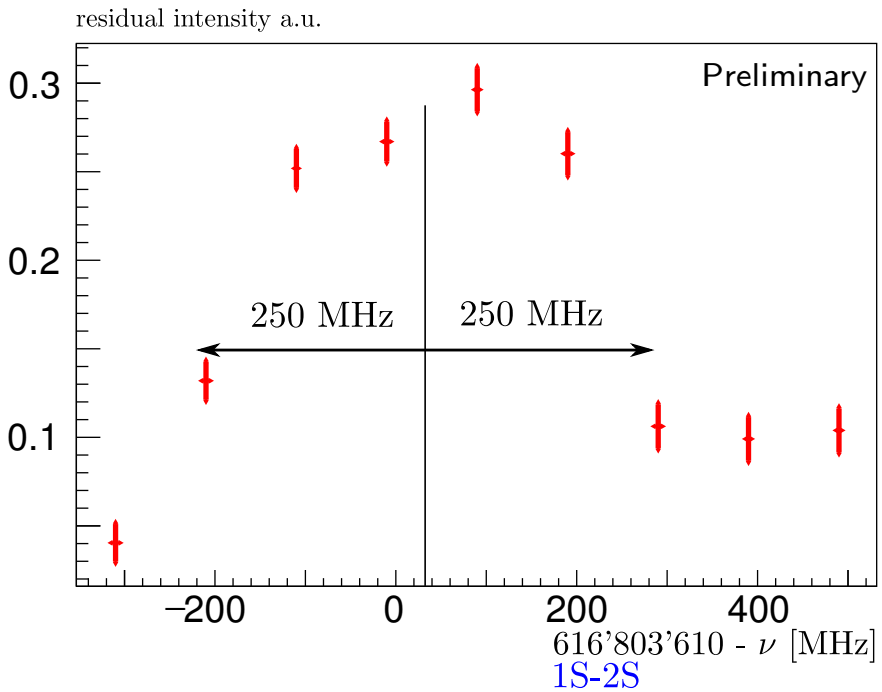
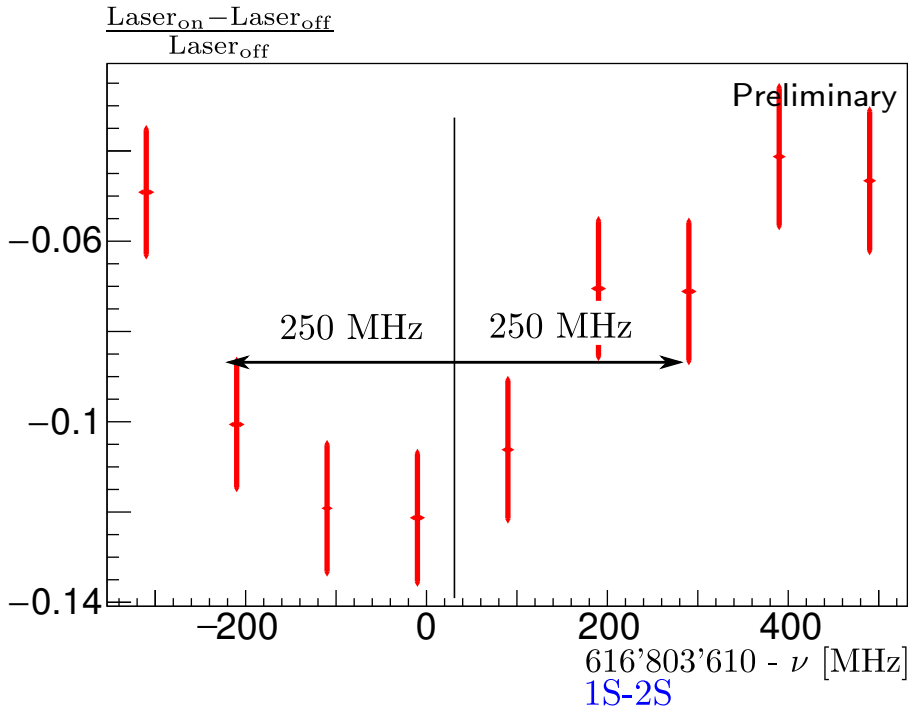


Depletion of 1S

Measurement from 10.08.2017



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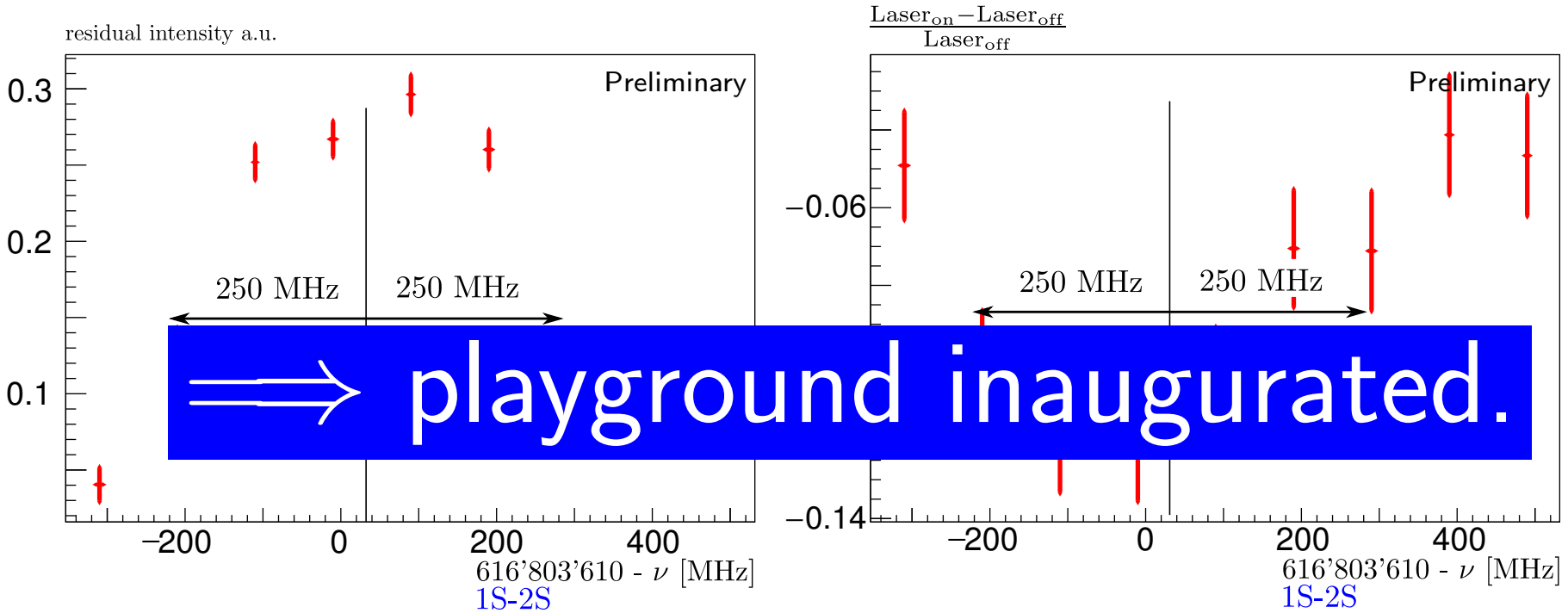

$\Longrightarrow$ playground inaugurated.

Measurement with Pulsed Laser

Annihilation signal of ionized Ps

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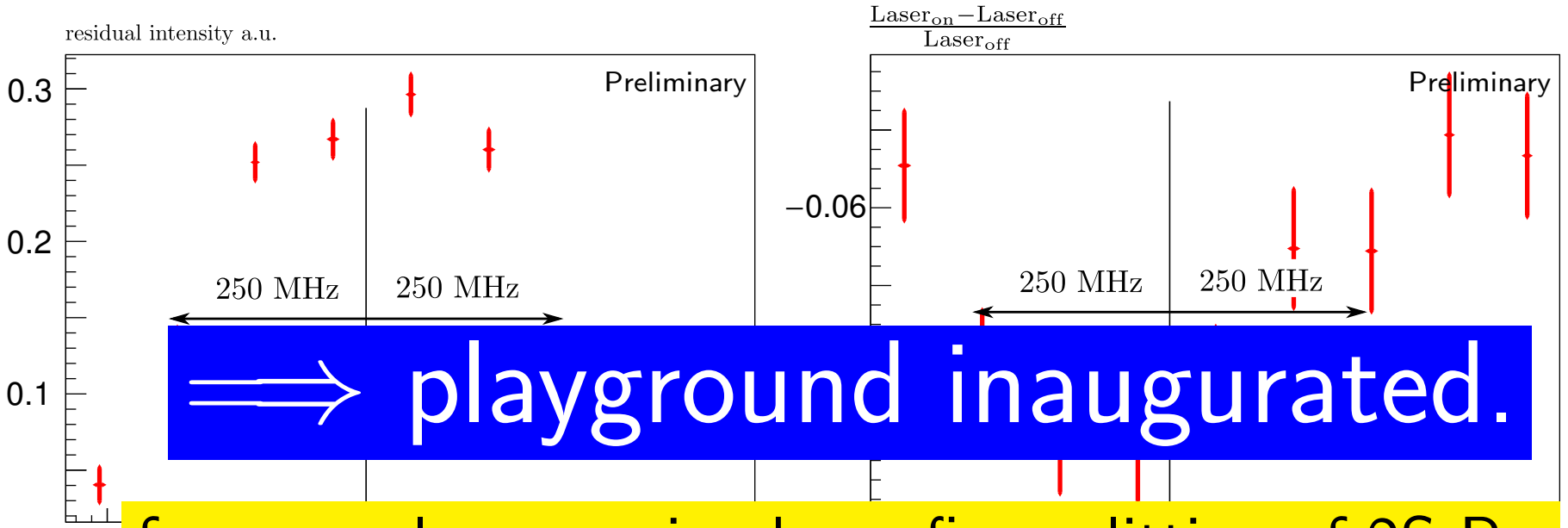
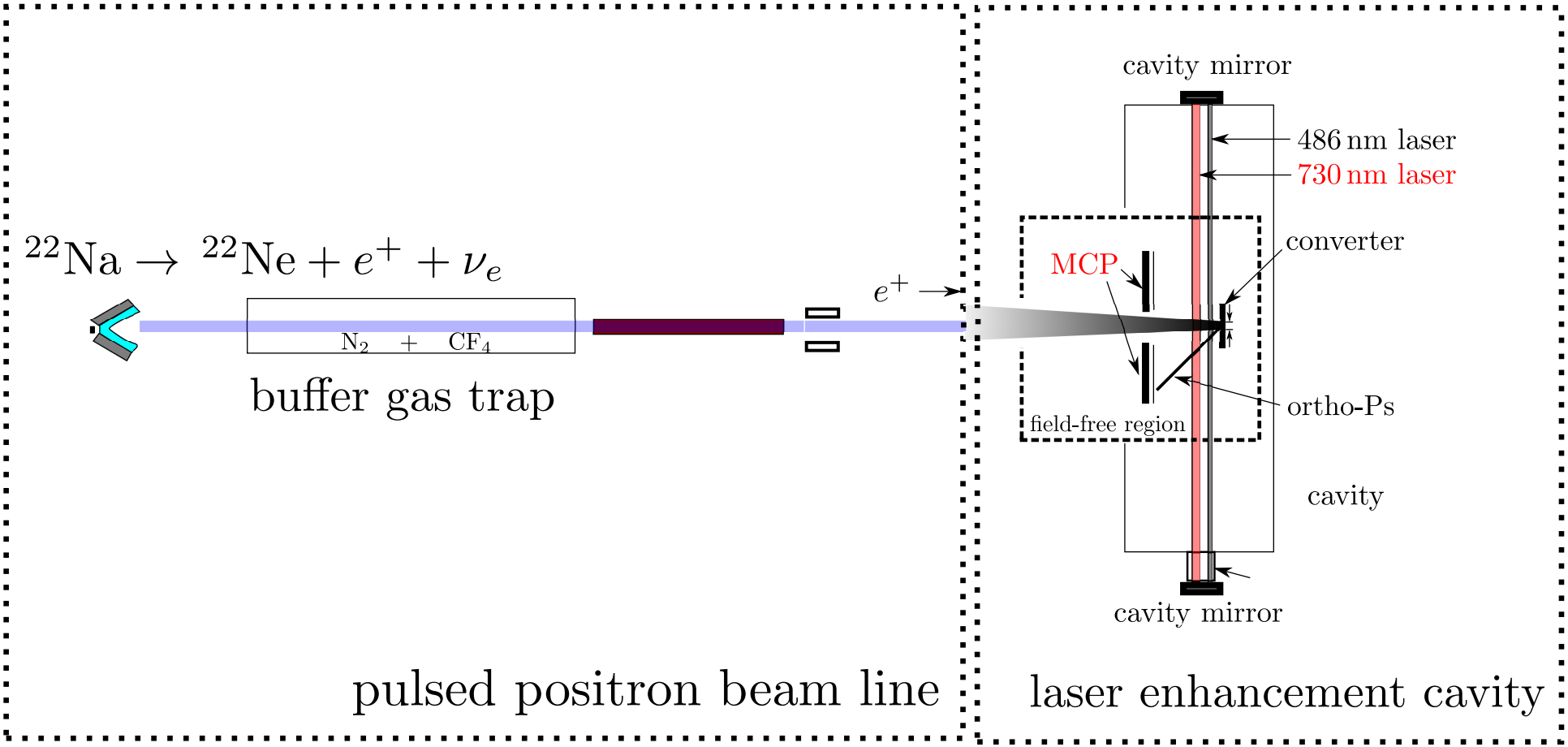


$\Longrightarrow$ playground inaugurated.

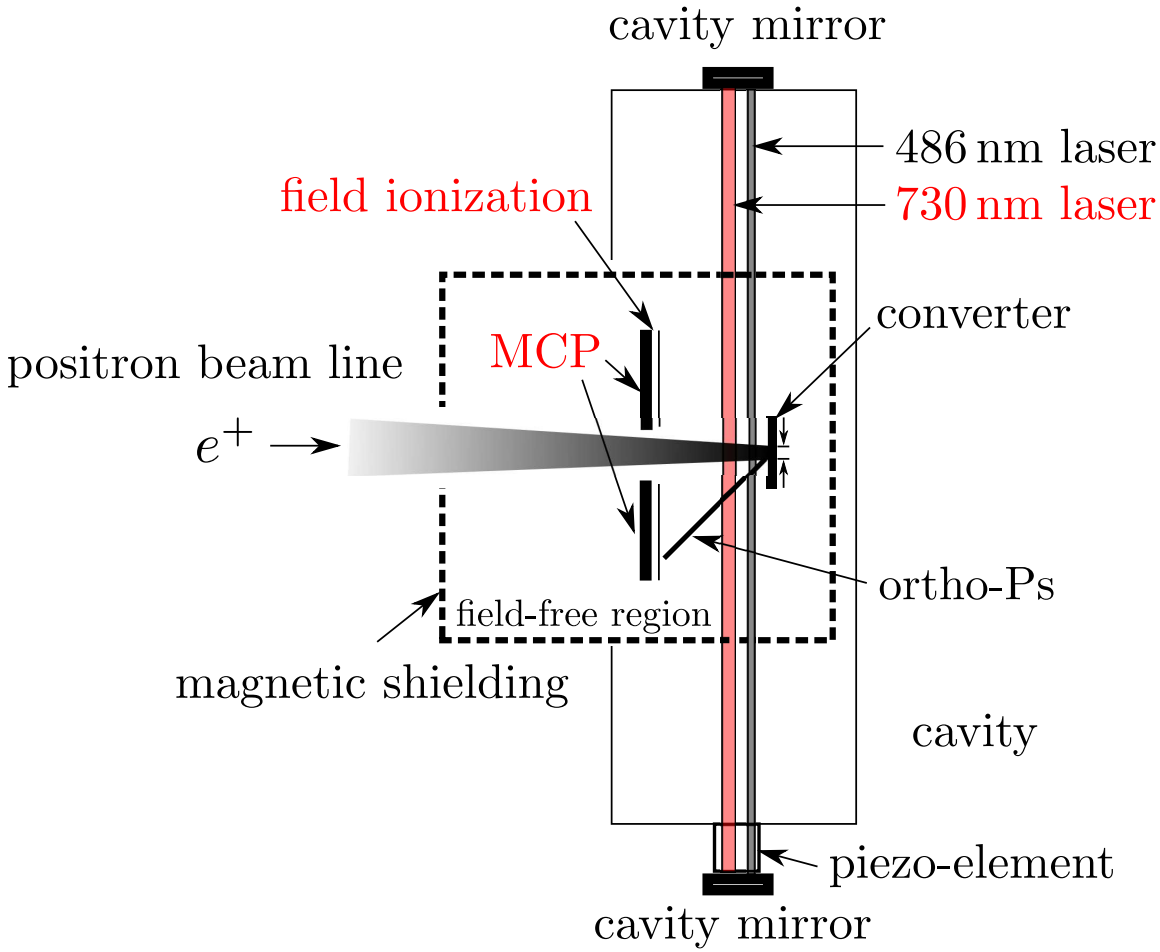
for example upcoming hyperfine splitting of 2S Ps.

(presented by M.Heiss this Friday, CICG Room 5)

Setup with Cavity - 1S-2S CW Spectroscopy



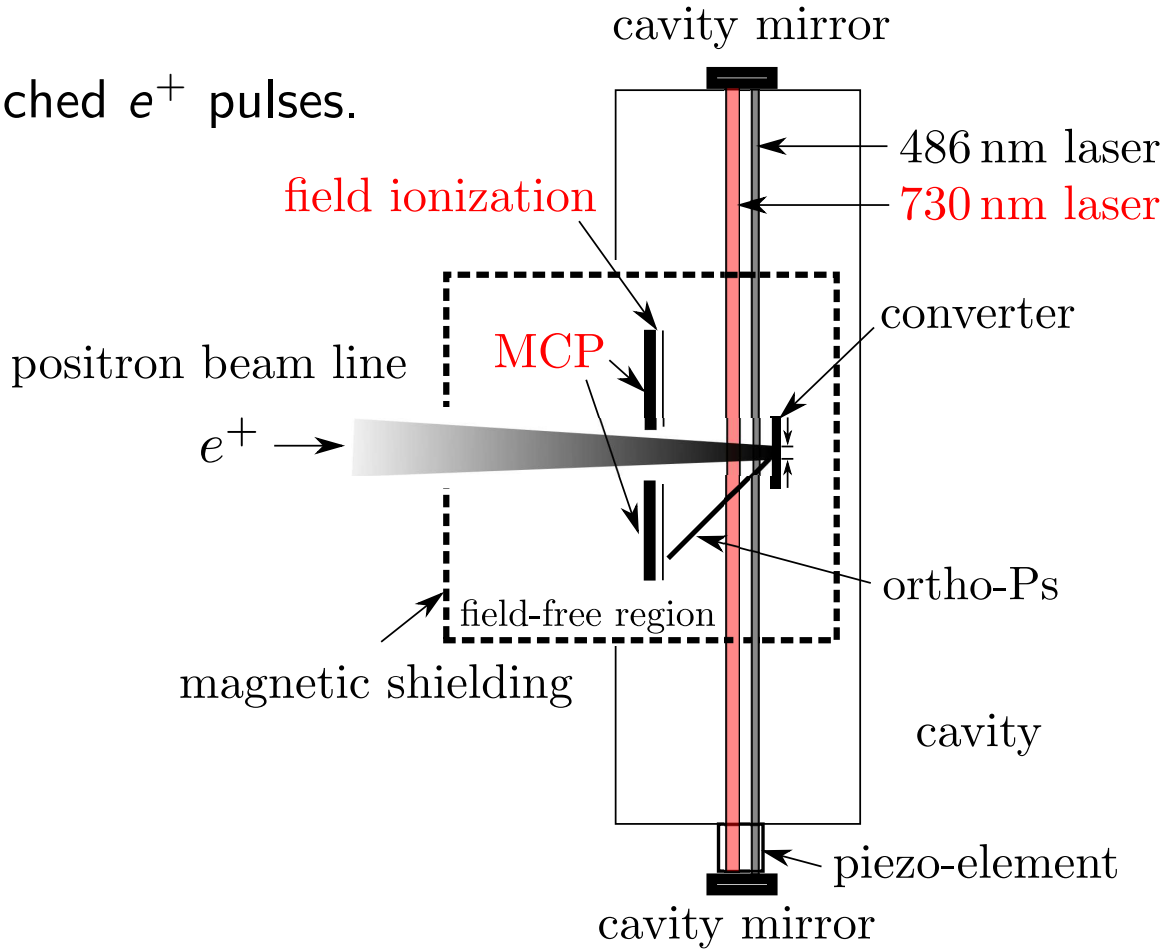
Overview - Excitation Scheme



laser enhancement cavity

Overview - Excitation Scheme

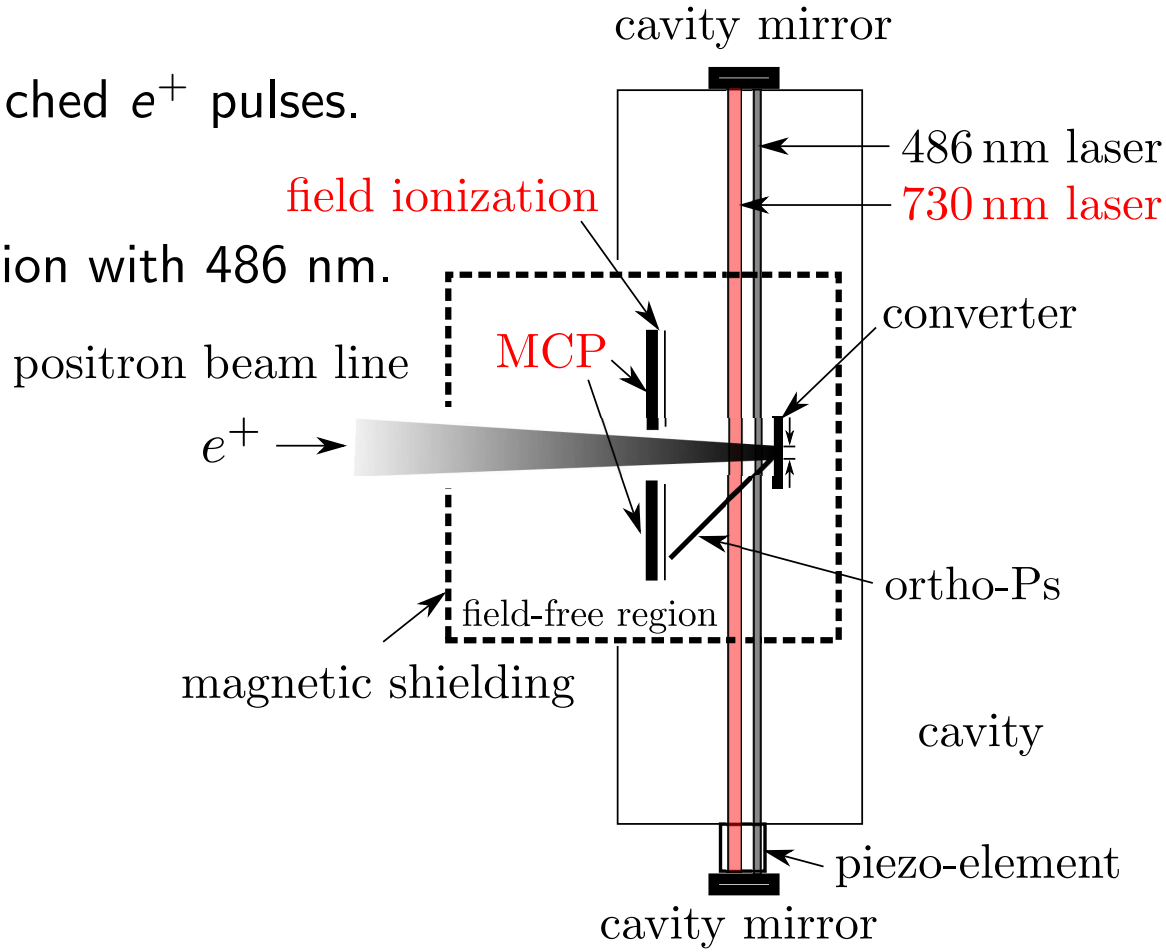
1. incoming bunched e^+ pulses.



laser enhancement cavity

Overview - Excitation Scheme

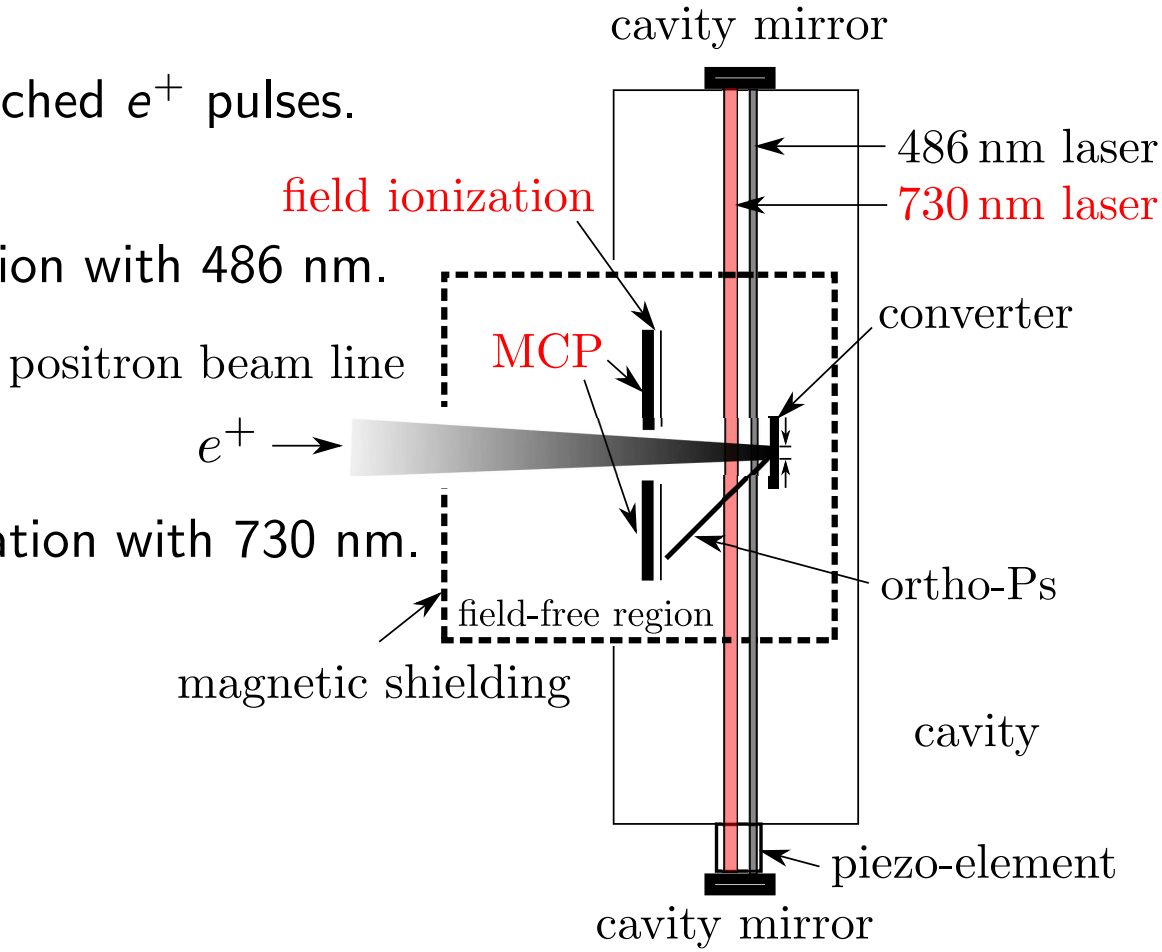
1. incoming bunched e^+ pulses.
2. 1S-2S excitation with 486 nm.



laser enhancement cavity

Overview - Excitation Scheme

1. incoming bunched e^+ pulses.
2. 1S-2S excitation with 486 nm.
3. 2S-20P excitation with 730 nm.



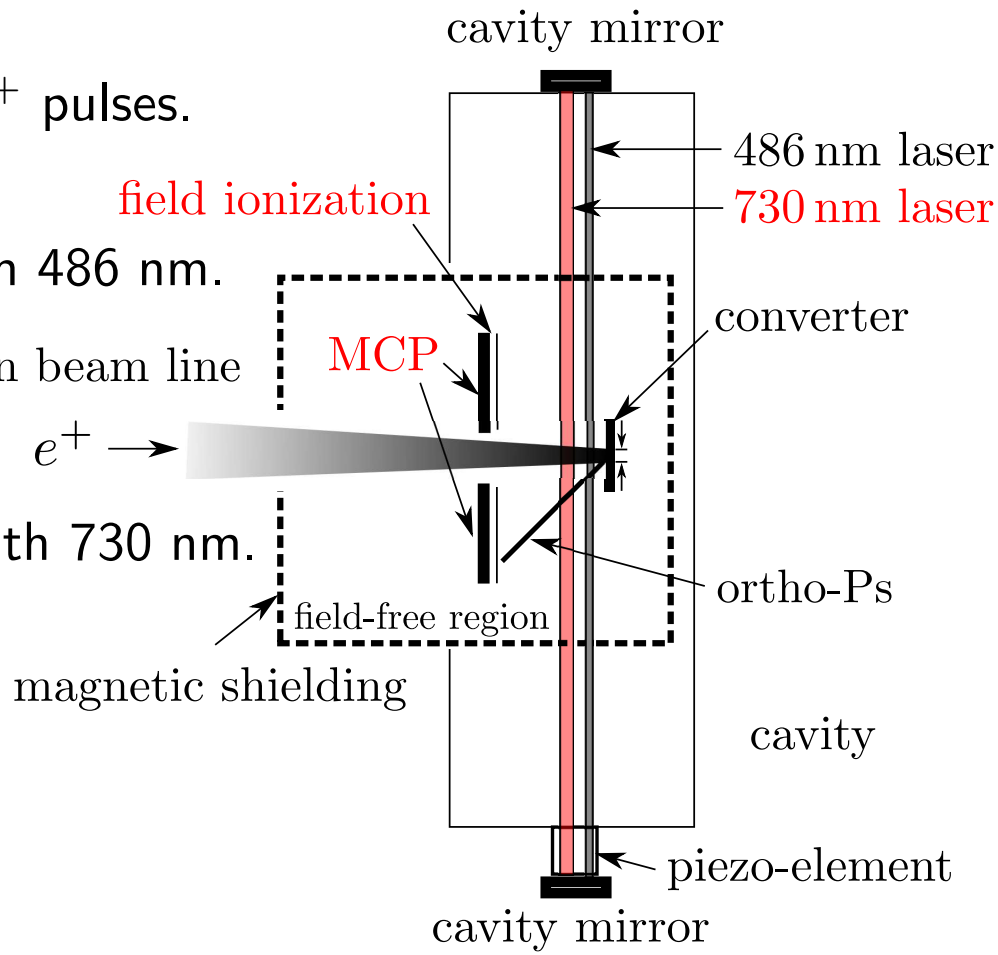
laser enhancement cavity

Overview - Excitation Scheme

1. incoming bunched e^+ pulses.
2. 1S-2S excitation with 486 nm.
3. 2S-20P excitation with 730 nm.
4. Detection on MCP.

   1S Ps $\rightarrow 3\gamma$

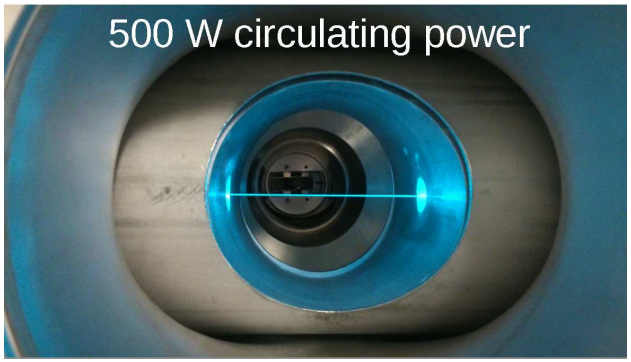
   20P Ps $\rightarrow e^+, e^-$

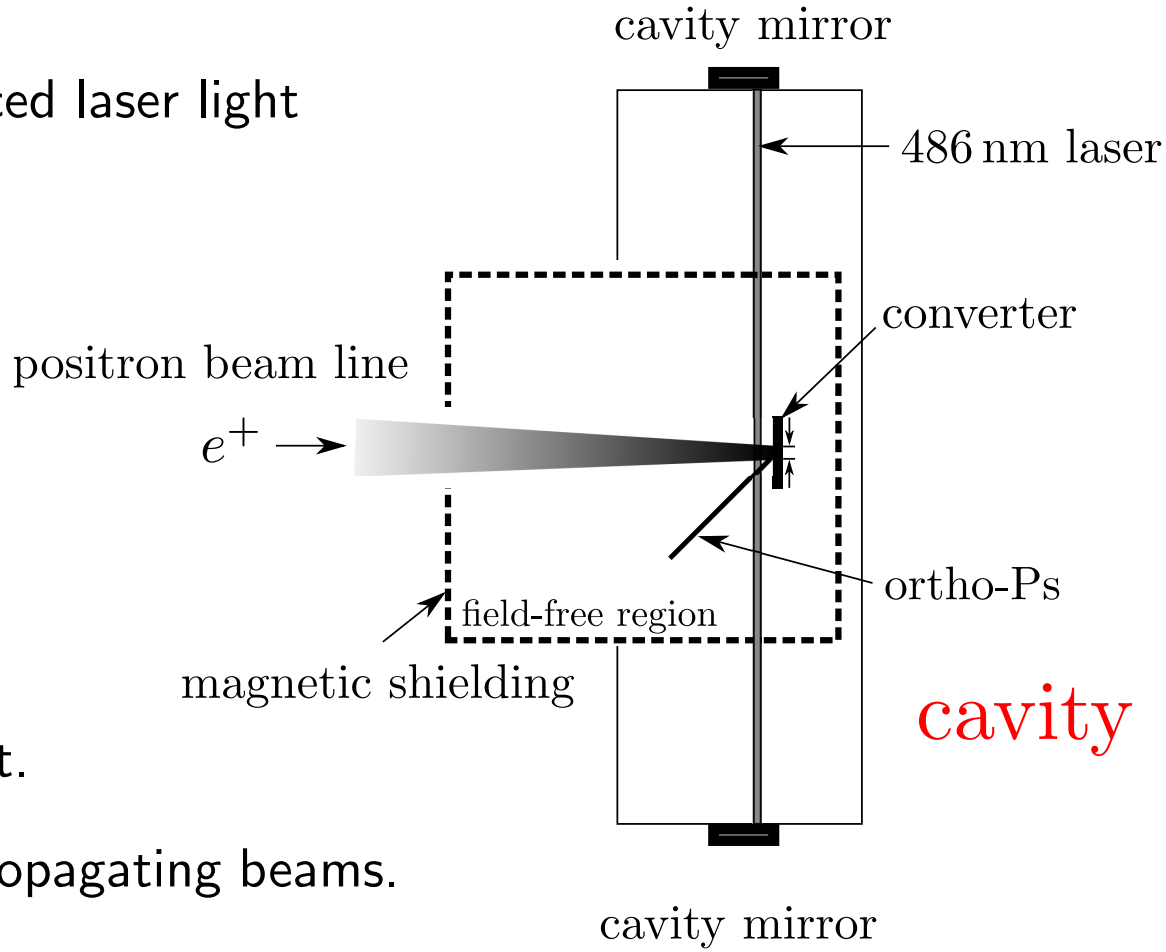


laser enhancement cavity

Laser Cavity

ortho-Ps transits the enhanced laser light in the cavity:

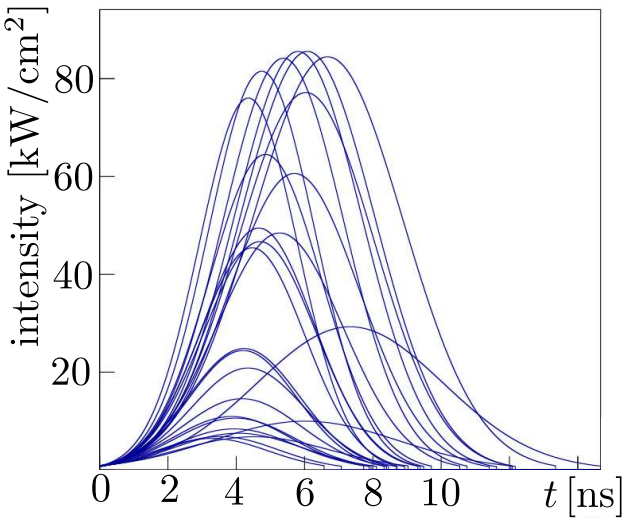


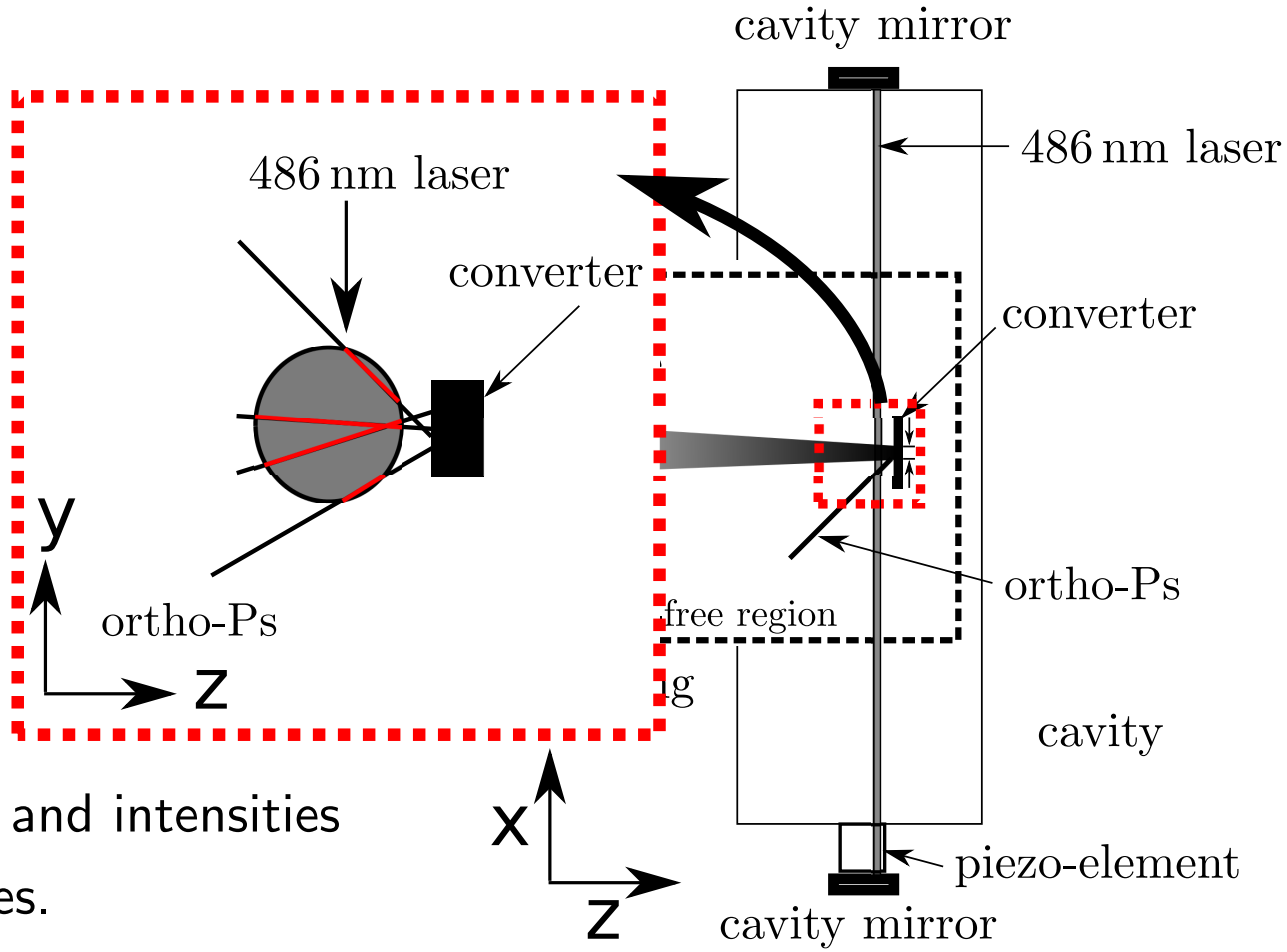


- No first order Doppler shift.
- Highly collinear counter propagating beams.
- Ultra high finesse cavity.

  (enhancement factor > 5000)

Laser excitation

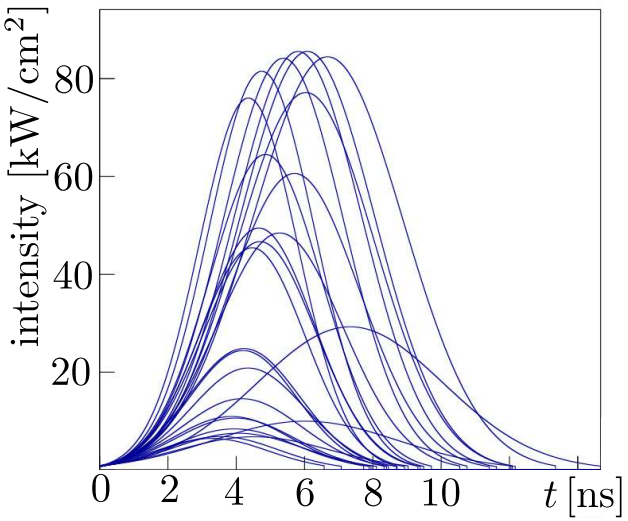




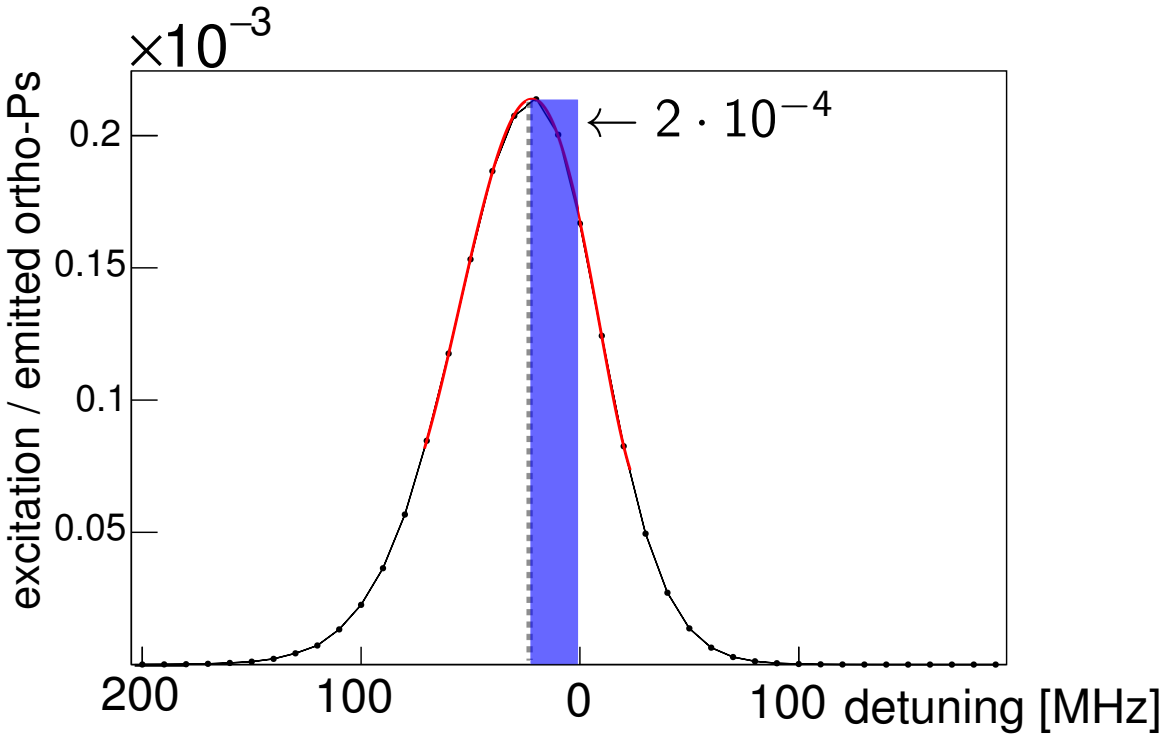
- Different interaction times and intensities for different emission angles.

- Laser intensity limited by the damage threshold of the laser mirrors.

Laser Excitation



$\Rightarrow$



Natural linewidth 2S: 1.2 MHz

Laser Power 500 W, beam waist 0.3 mm

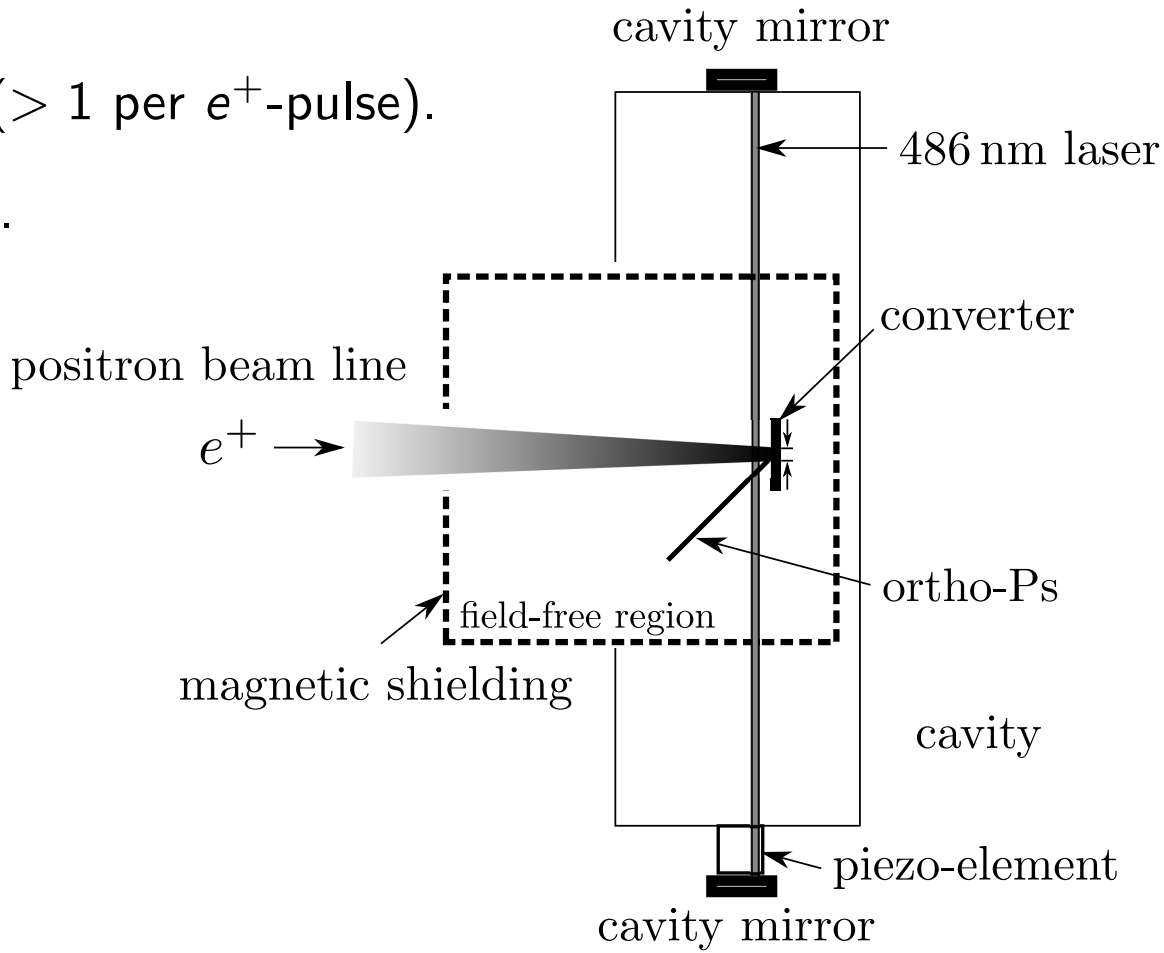
Optical Bloch equation with second order Doppler shift and AC Stark shift.

(expected FWHM around 60 MHz)

2S Ps Detection

- excitation rate of $\approx 10^{-4}$ (> 1 per e^+-pulse).

$\Rightarrow$ Need for low background.

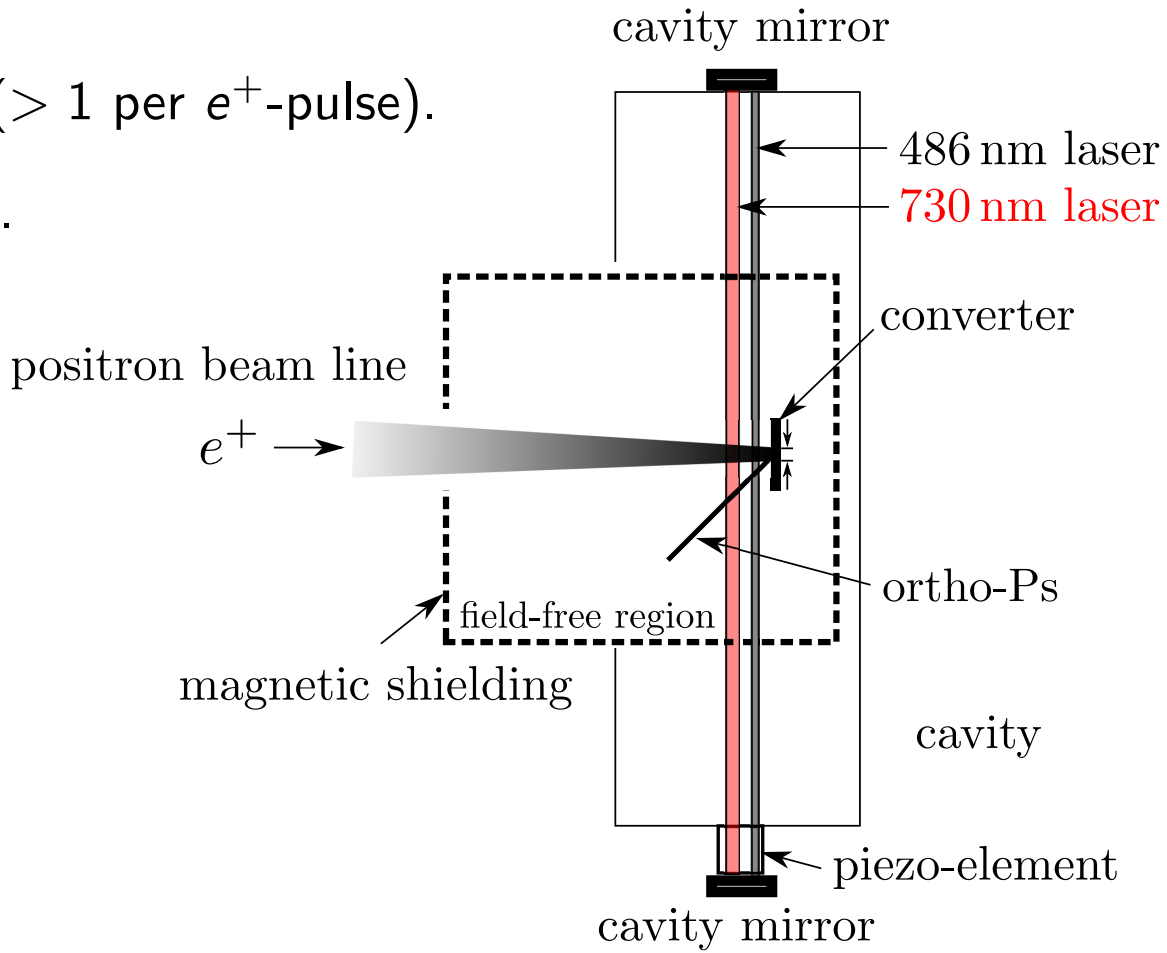


2S Ps Detection

- excitation rate of $\approx 10^{-4}$ (> 1 per e^+-pulse).

$\Rightarrow$ Need for low background.

- Excitation of 2S Ps to Rydberg states (n=20).



2S Ps Detection

- excitation rate of $\approx 10^{-4}$ (> 1 per e^+-pulse).

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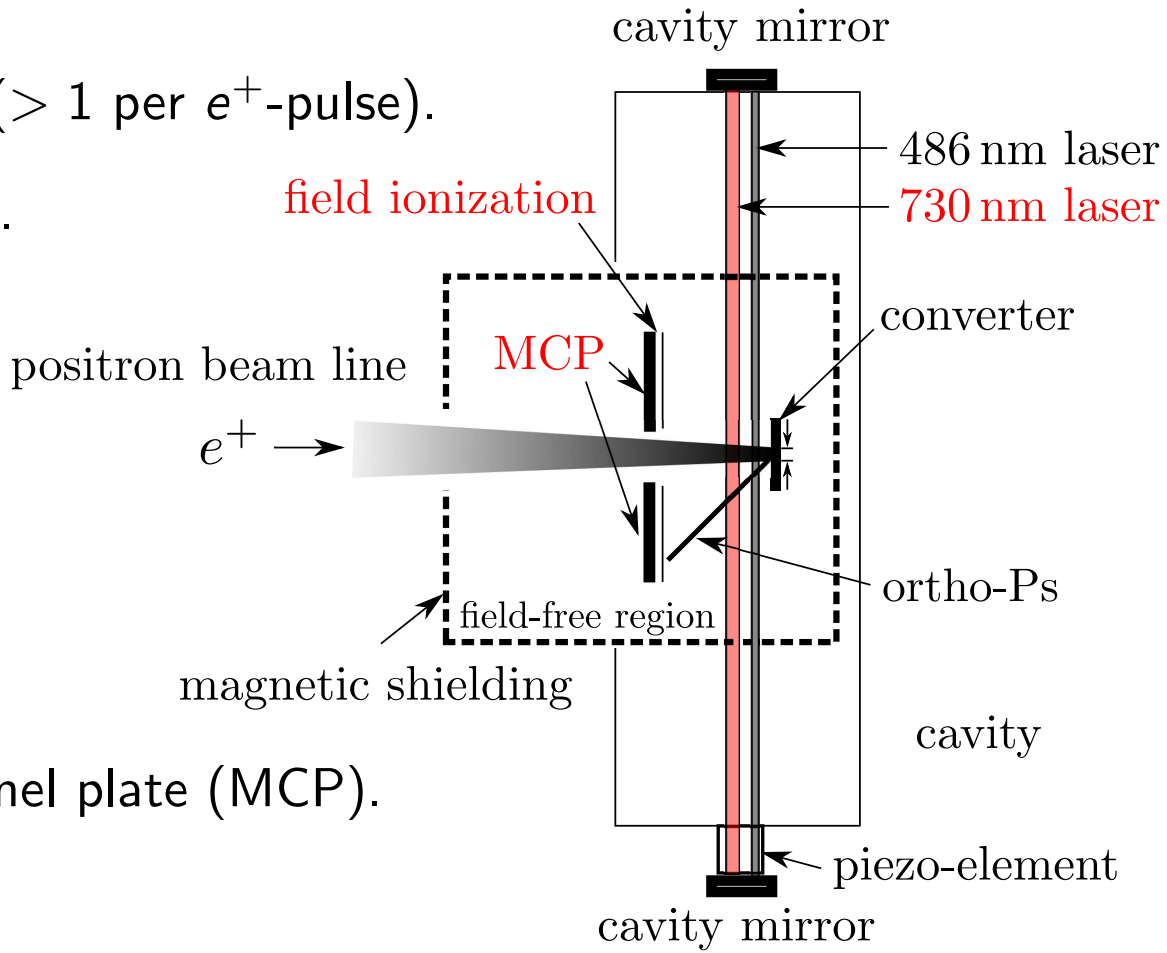
- Excitation of 2S Ps to Rydberg states (n=20).

- Subsequent ionization and detection by a micro channel plate (MCP).



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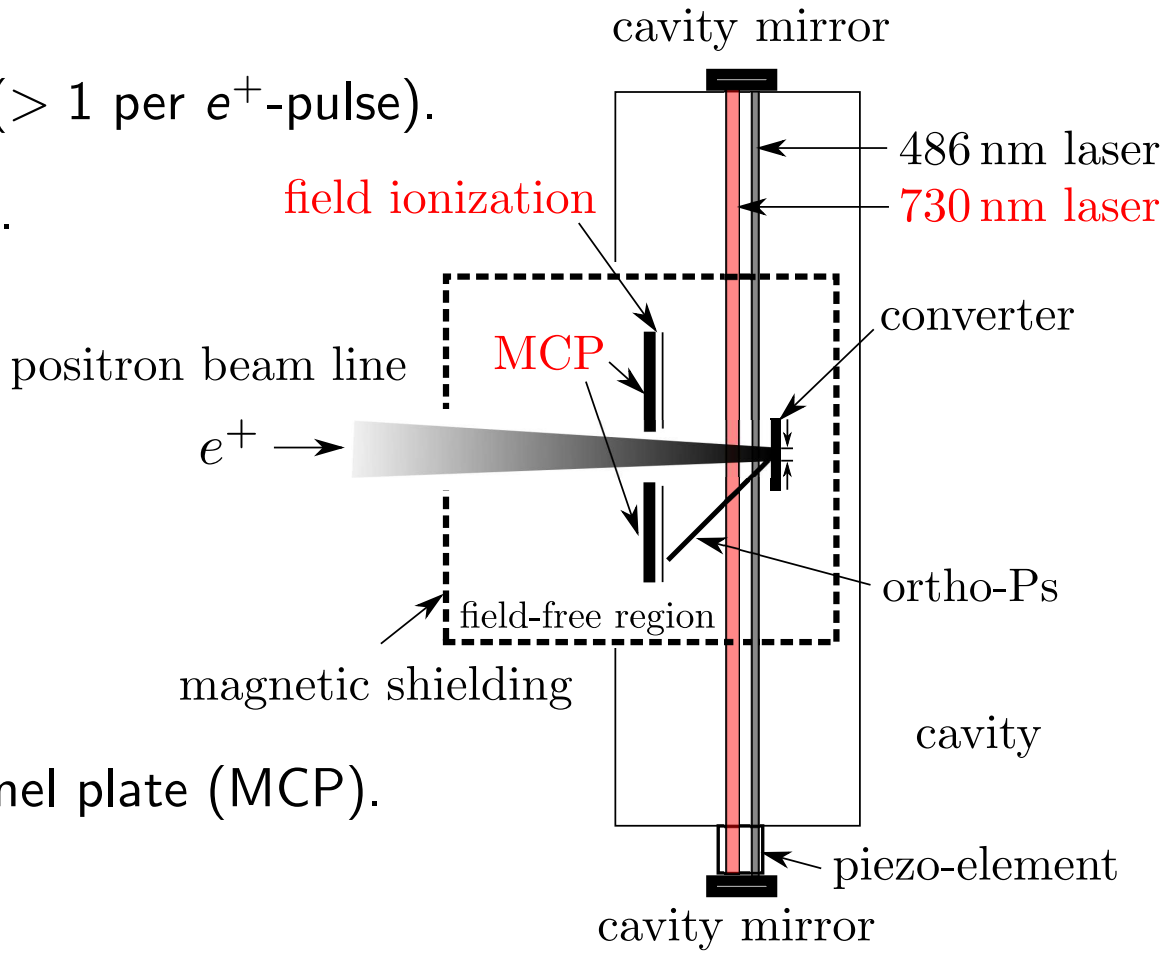
- Major systematic:

  second order Doppler shift and **AC Stark shift**



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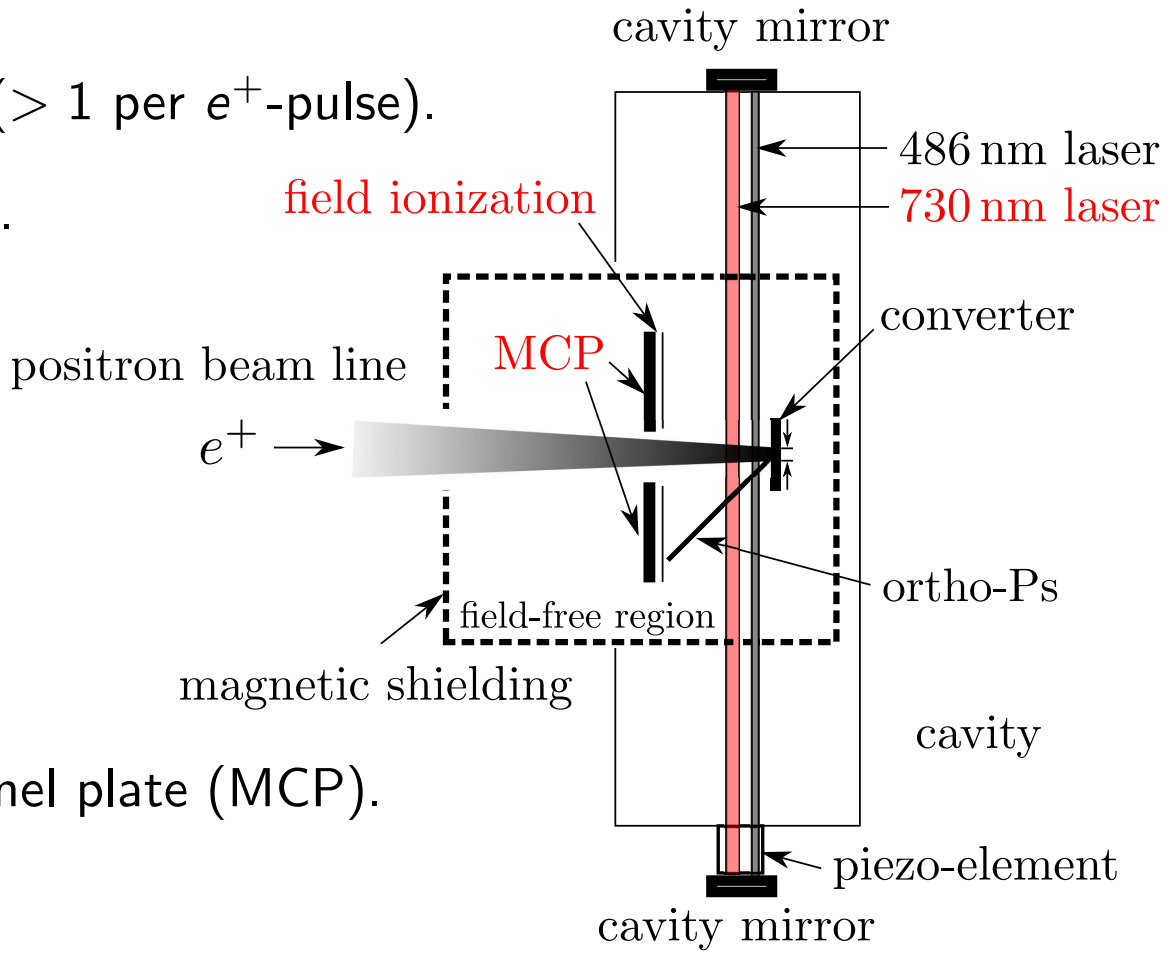
- Subsequent ionization and detection by a micro channel plate (MCP).

- Major systematic:

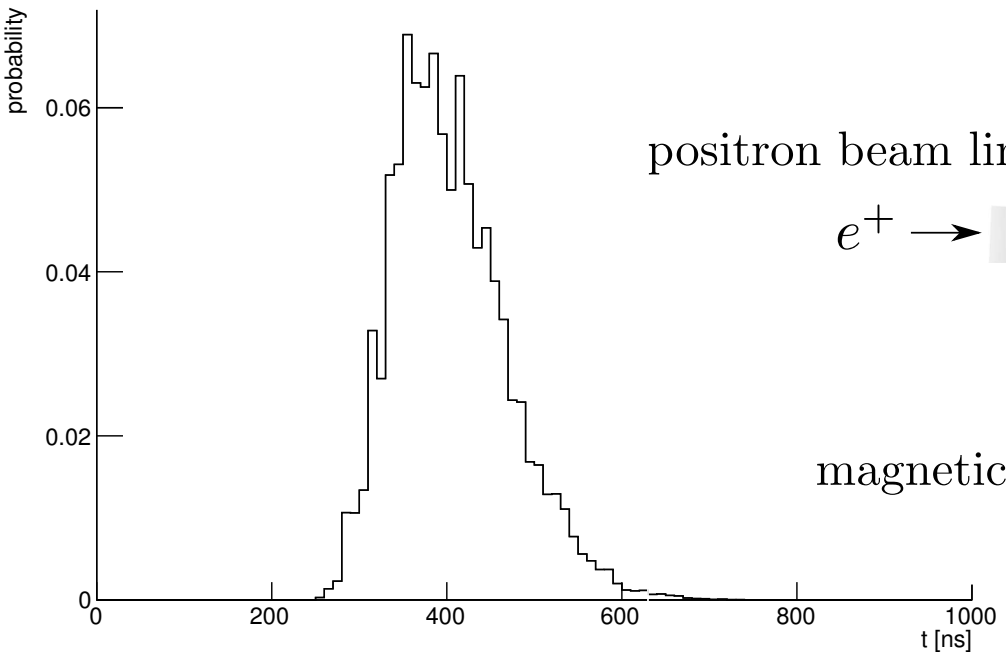
  second order Doppler shift and **AC Stark shift**

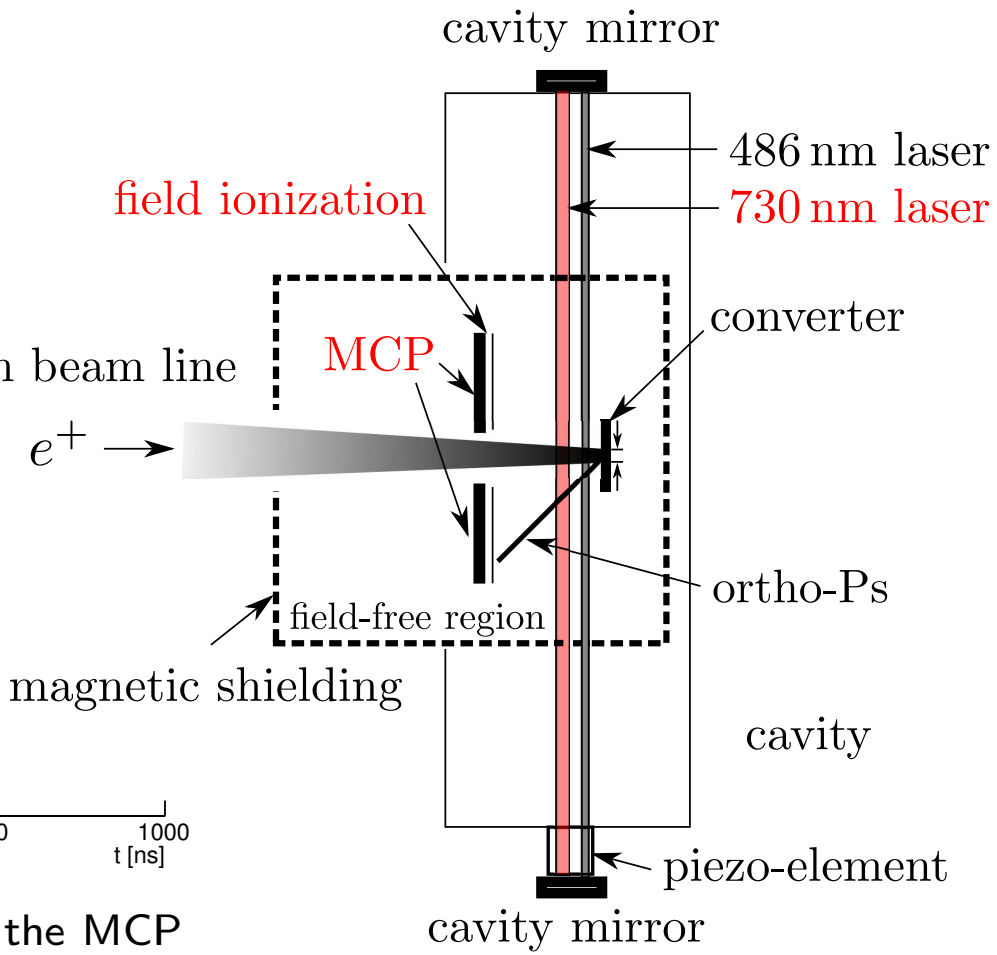
- compared to our previous setup:

  $\rightarrow$ no DC Stark shift, Zeeman shift or motional Stark shift.



Ps Velocity and Angular Distribution





Expected time spectra for excited Ps on the MCP in 40 mm distance to the converter.

$\Rightarrow$ extraction of the mean emission velocity to $\approx 4\%$

Status

- pulsed e^+ beam working.

Status

- pulsed e^+ beam working.

- depletion of ortho-Ps (generation of 2S) with pulsed laser working.

Status

- pulsed e^+ beam working.
- depletion of ortho-Ps (generation of 2S) with pulsed laser working.
- MCP detector and cavity prepared.

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Next:
$\rightarrow$ Installation of the MCP detector.
$\rightarrow$ Ps excitation to Rydberg states and recording of time spectra.

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- pulsed e^+ beam working.

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Next:
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$\rightarrow$ Ps excitation to Rydberg states and recording of time spectra.

$\rightarrow$ change to CW laser with enhancement cavity for spectroscopy.

Status

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- depletion of ortho-Ps (generation of 2S) with pulsed laser working.

- MCP detector and cavity prepared.

Next:
$\rightarrow$ Installation of the MCP detector.
$\rightarrow$ Ps excitation to Rydberg states and recording of time spectra.

$\rightarrow$ change to CW laser with enhancement cavity for spectroscopy.

$\Rightarrow$ Precision in sub-MHz range, seeking order of $m\alpha^7$.

Acknowledgment

P. Crivelli, D. Cooke, P. Comini, L. Gerchow, M. Heiss, C. Vigo

K. Kirch, A. Antognini, K. Schuhmann, D. Taqqu, M. Rawlik

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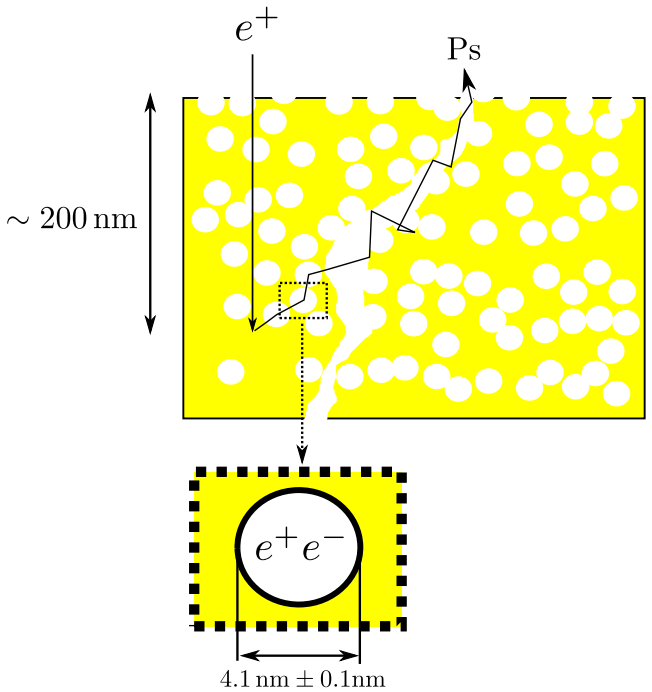
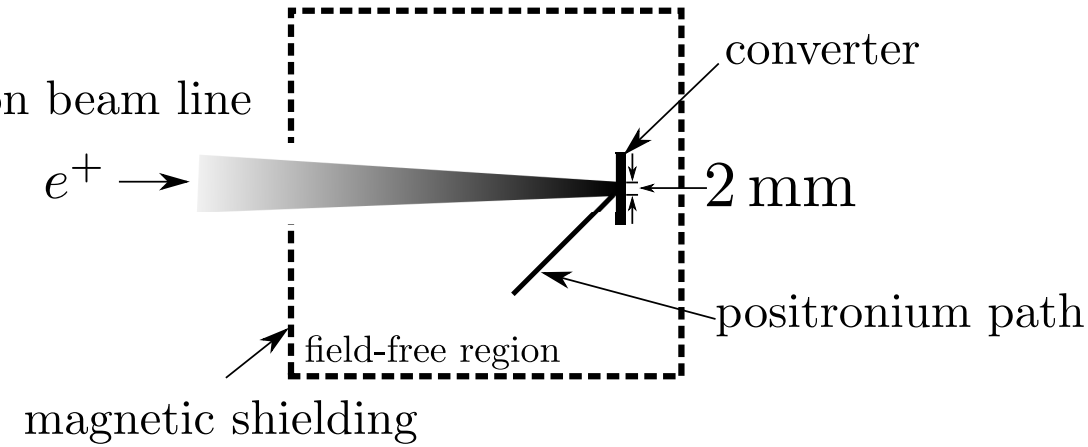
Backup Slides: Converter - Porous Silica



P. Crivelli et al. , Phys. Rev. A81, 052703 (2010)



- para-Ps lifetime: 0.125 ns (1^1S_0, anti-parallel spins, decays into ≥ 2 photons)
- ortho-Ps lifetime: 142.05 ns (1^3S_1, parallel spins, decays into ≥ 3 photons)
- Mean Ps emission time[4] is in the range of a few ns.

$\Rightarrow$ Only ortho-Ps can exit the converter before annihilation.

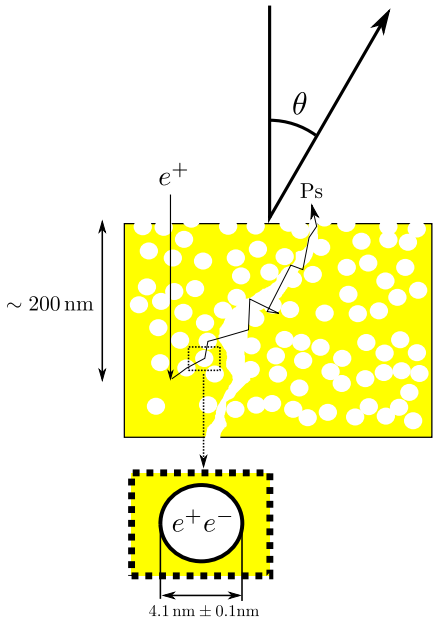
$\Rightarrow$ Monochromatic emission velocity. $v_{Ps} \approx 10^5\ m/s \pm 2\%$ (particle in a box of 4.1 nm).

[4] D. B. Cassidy, T. H. Hisakado, V. E. Meligne, H. W. K. Tom, A. P. J. Mills, Delayed emission of cold positronium from mesoporous materials, Physical Review. A 82, 2010

Backup Slides: Second order Doppler shift and AC Stark shift

- Numerically solving Maxwell-Bloch equations.[5]

- Determination of the Ps velocity.



Assumptions:

Spatial emission Lamberts cosine law[6]:

$$\rho(\theta)\,\mathrm{d}\theta = \frac{1}{2}\cos\theta\,\mathrm{d}\theta$$

Monochromatic emission velocity:

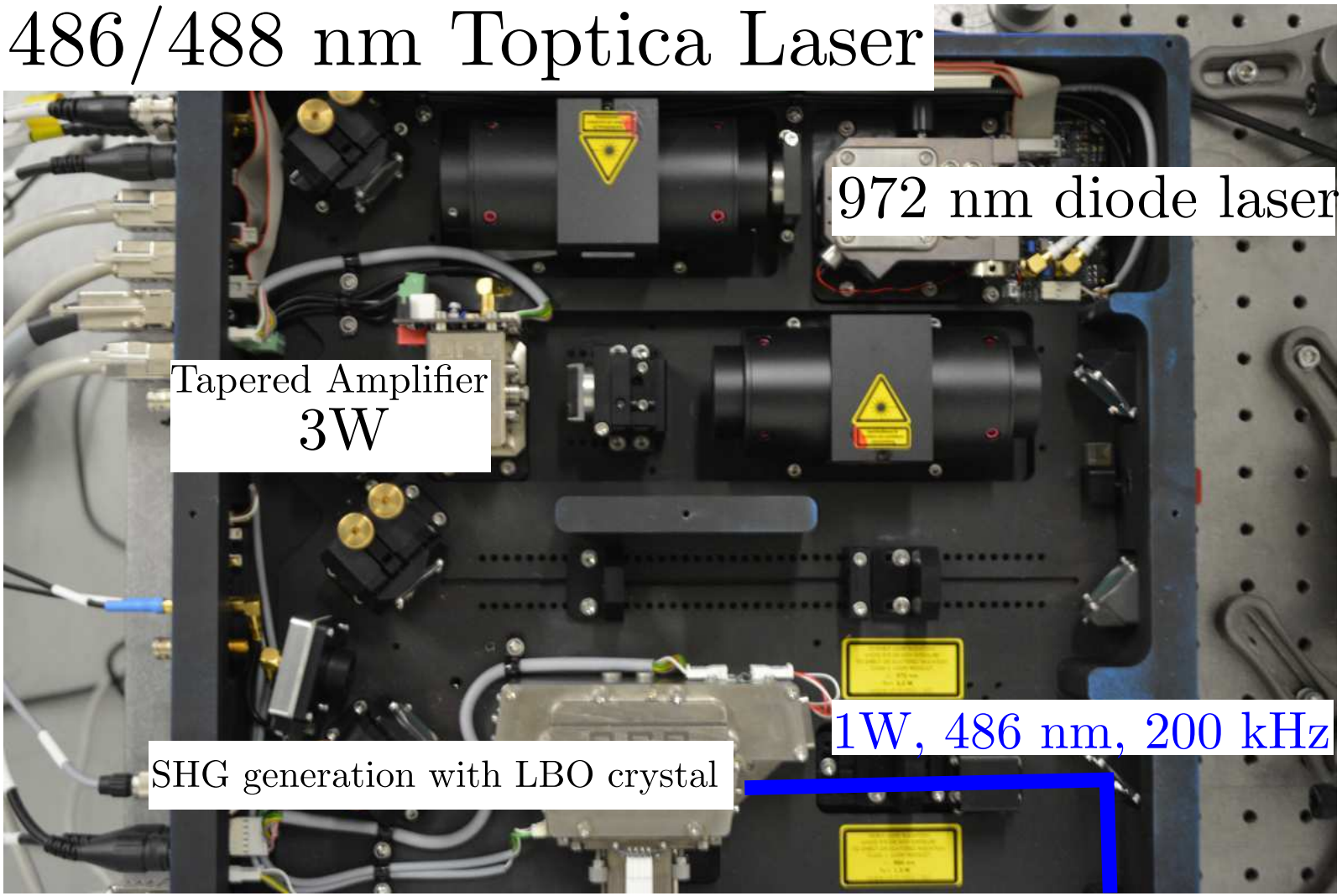
$v_{Ps} \approx 10^5\ m/s \pm 2\%$.

[5] M. Haas, U. D. Jentschura, C. H. Keitel, N. Kolachevsky, M. Herrmann, P. Fendel, M. Fischer, T. Udem, R. Holzwarth, T. W. Haensch, et al., Two-photon excitation dynamics in bound two-body coulomb systems including ac stark shift and ionization, Physical Review. A 73 (5). doi:10.1103/PHYSREVA.73.0.

[6] D. B. Cassidy, P. Crivelli, T. H. Hisakado, L. Liszkay, V. E. Meligne, P. Perez, H. W. K. Tom, and A. P. Mills, Jr., Phys. Rev. A 81, 012715 Published 29 January 2010; Erratum Phys. Rev. A 81, 039904 (2010)

Backup Slides:

486/488 nm Toptica Laser



Backup Slides:

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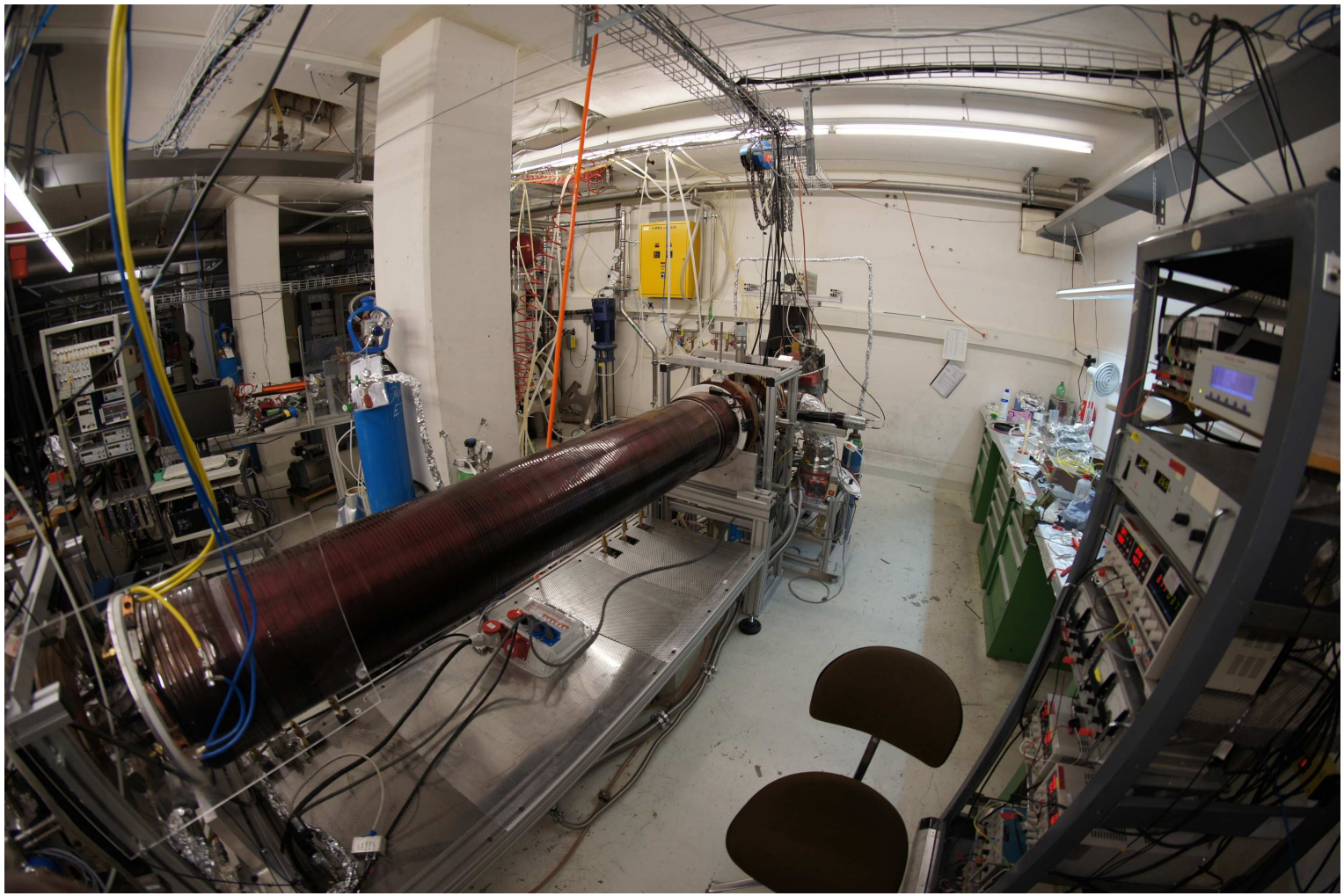

Backup Slides: