Towards improved 1S-2S spectroscopy of positronium

Zurich PhD seminar 2016

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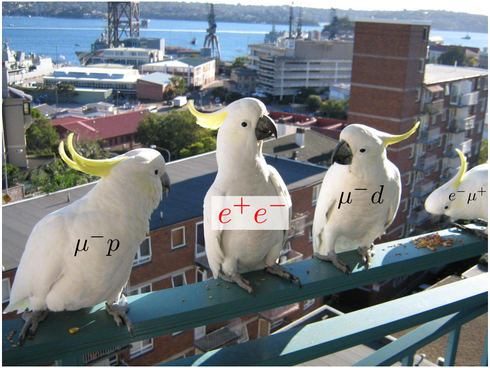
Why Positronium?

Positronium (e^+e^-, Ps): The **lightest atom** of the universe.

Energy levels known to very high precision
from theory and experiment down to 1 ppb (9 digits).

$\Rightarrow$ sensitive probe for smallest effects ($\rightarrow$ **new physics**).

Exotic Atoms



muonic hydrogen:

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

muonic deuterium:

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

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)

Why improving the error?

The 1S-2S spectroscopy sensitive to $m\alpha, m\alpha^2, m\alpha^3, \ldots$

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

Test of CPT symmetry and effect of gravity on anti-matter.

→ Lorentz and CPT tests with hydrogen, antihydrogen, and related systems
Kostelecky and Vargas, Phys. Rev. D 92, 056002 (2015)

Precision Test of bound-state QED

Testing the fine structure constant: $\alpha = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c}$

Energy levels of Ps by the Bohr Model: $\left(m = \frac{m_{e^+} \cdot m_{e^-}}{m_{e^+} + m_{e^-}} = 0.26\,\mathrm{MeV}/c^2\right)$

$$E_{1S\text{-}2S} = -\frac{me^4}{8h^2\epsilon_0^2}\left[\frac{1}{2^2} - \frac{1}{1^2}\right] = 6.802\,\mathrm{eV} \cdot \frac{3}{4} = 5.102\,\mathrm{eV} \quad (1233.7\,\mathrm{THz})$$

The best measured value is 1233.607 216 4[1] THz ± 3.2 MHz (9 digits).
A difference of 80 GHz (4 digits).

[1] 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)

Precision Test of bound-state QED

Rigorous calculations possible with derivations of the Kernel of the **Bethe-Salpeter** equation for the two-body problem.

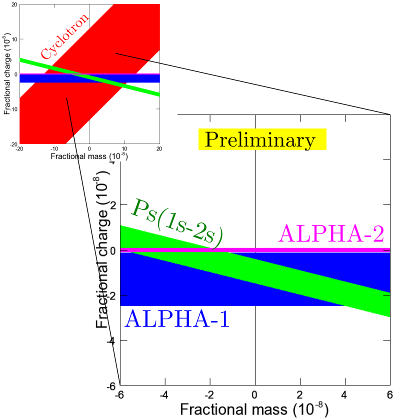
QED calculations completed to the order of $m\alpha^6$.
a systematic error level of ± 1 MHz (9 digits).

Krzysztof Pachucki and Savely G. Karshenboim, PRL 80, Nr.10, 1998

Ongoing work for $m\alpha^7$.

e.g. *Adkins, Gregory S. and Kim, Minji and Parsons, Christian and Fell, Richard N., PRL 115, 233401, 2015*

Matter / anti-matter mass and charge?



ALPHA experiment:

Charge neutrality of **antihydrogen**

Long-term goal
atomic spectra of antihydrogen

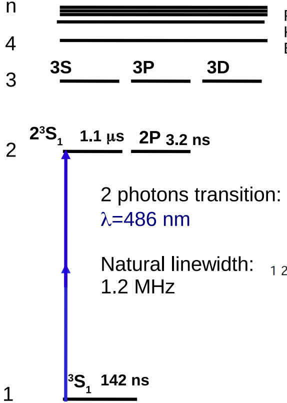
Actual crossing not at zero.

From talk of M.Fujiwara at the PSI2016 conference

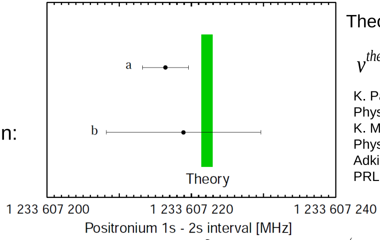
The Experiment

Positronium 1S-2S transition

Ps Energy levels



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)



Theory:

$$\nu^{theory} = 1233607222.2(6) \text{ MHz}$$

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:

$$\nu^{a} = 1233607216.4(3.2) \text{ MHz}$$

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

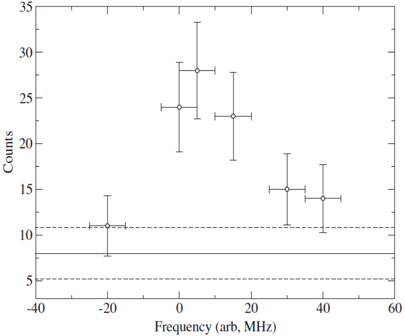
$$\nu^{b} = 1233607218.9(10.7) \text{ MHz}$$

S. Chu, A. P. Mills, Jr. and J. Hall, Phys. Rev. Lett. 52, 1689 (1984)

From talk of P.Crivelli at the PSI2016 conference

Positronium and Muonium 1S-2S Laser Spectroscopy as a Probe for the SME
P. Crivelli, G. Wichmann, arXiv:1607.06398, 21 Jul 2016

The Experiment



Predecessor:

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

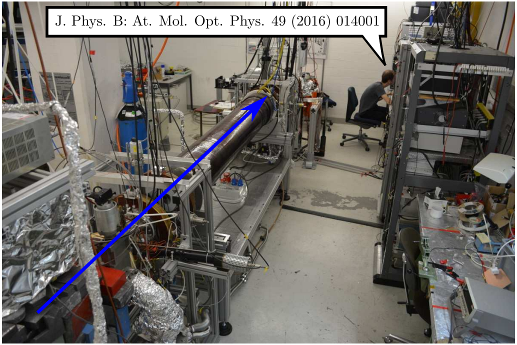
→ too high noise level.

→ frequency reference only by a wavemeter (±10 MHz).

⇒ e^+ in bunches would reduce noise level.

⇒ frequency reference should be improved.

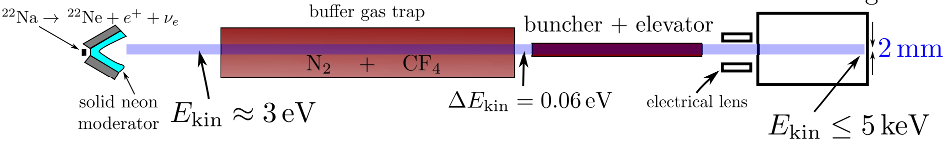
Bunched Positron Beam



β^+ decay converted to bunches of $\approx 100\, e^+$ with

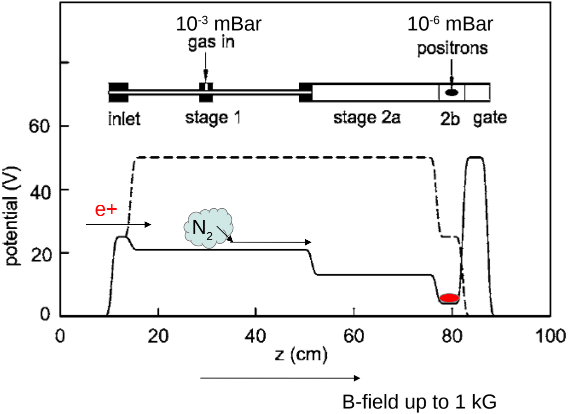
- 1 ns FWHM and 2 mm waist
- 10 Hz repetition rate
- $E_{\text{kin}} = 3$ to 5 keV

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

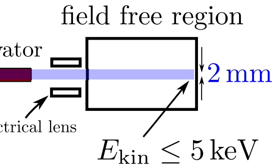


→ see talk of L.Gerchow

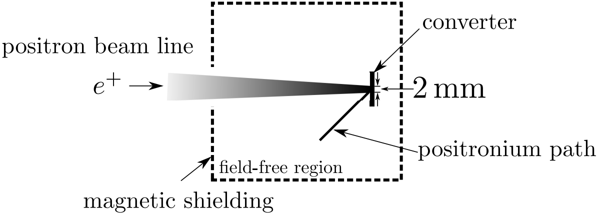
Buffer Gas Trap



Positronium Generation



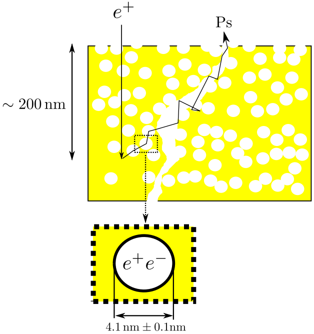
- $1\,\mathrm{ns}$ FWHM
- $2\,\mathrm{mm}$ waist
- 10'000 e^+ per bunch



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

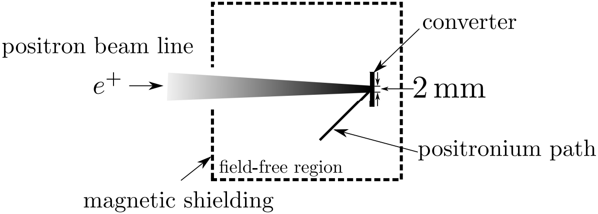
⇒ Time window for hitting the converter generated! (start trigger)

Converter - Porous Silica



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

→ see also talks of C.Vigo, L.Gerchow, M.Heiss



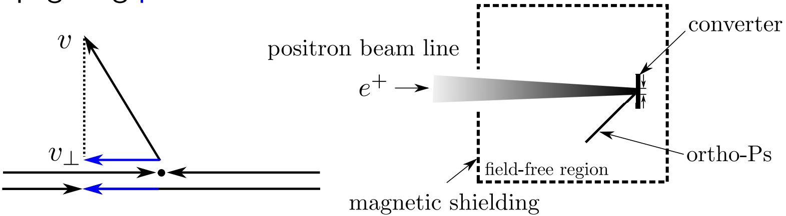
- para-Ps (1^1S_0, anti-parallel spins) with a lifetime of 0.125 ns and ortho-Ps (1^3S_1, parallel spins) with a lifetime of 142.05 ns is produced.
- para-Ps decays into ≥ 2 photons, ortho-Ps into ≥ 3 photons.
- Mean Ps emission time is in the range of ns.

⇒ Only ortho-Ps can exit the converter before annihilation.

⇒ Monochromatic emission velocity: $v_{Ps} \approx 10^5\ m/s \pm 2\%$.

1S-2S transition

- The 1S2S transition corresponds to 1234 THz or 243 nm.
- Direct excitation from S-state to S-state with two counter propagating photons of 486 nm.

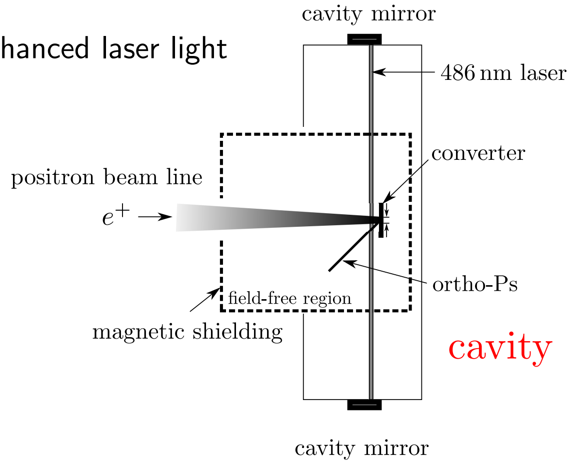


⇒ No first order Doppler shift.

⇒ High laser intensity needed.

Laser Cavity

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



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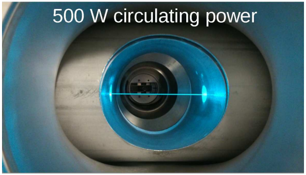

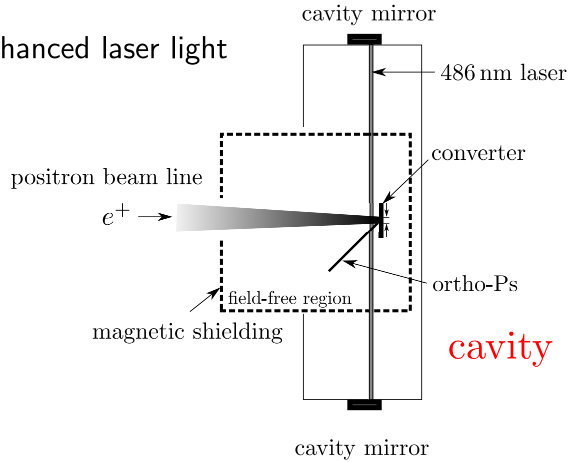

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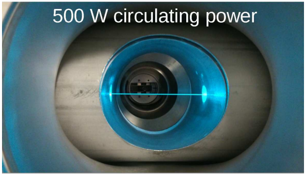
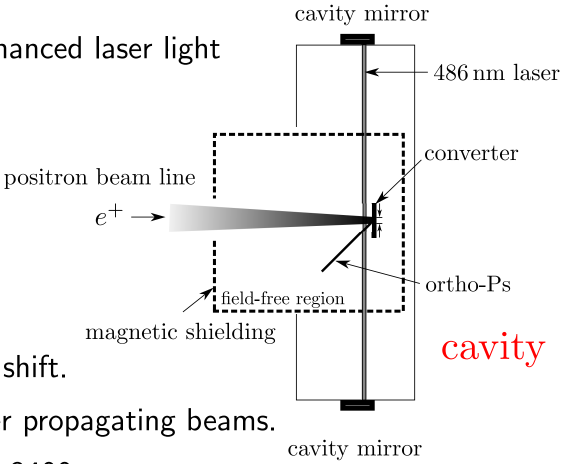




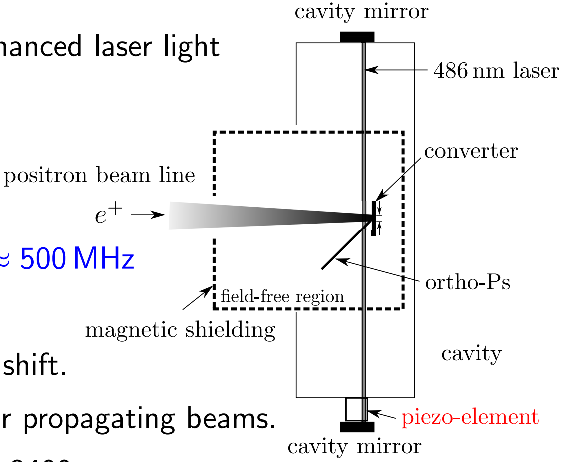
- No first order Doppler shift.
- Highly collinear counter propagating beams.
- Enhancement factor > 3400.

(Ultra high finesse cavity, $F \approx 75'000$)

Laser Cavity

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

$L \approx 0.3\,\text{m}$:
$\nu = n \cdot c / [2(L + \Delta L)] \approx 500\,\text{MHz}$



- No first order Doppler shift.
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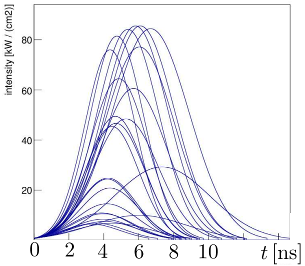
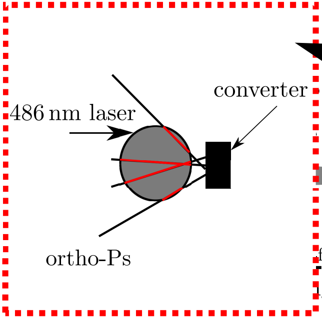
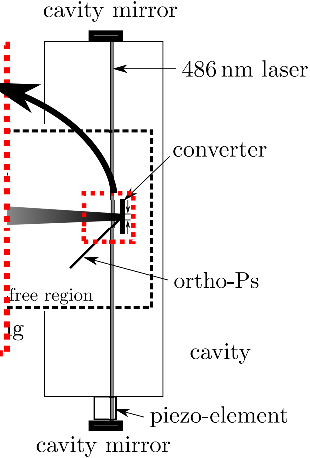
Laser excitation

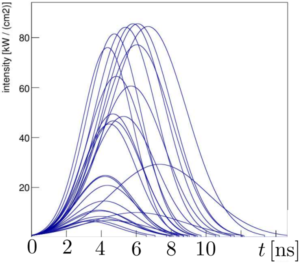




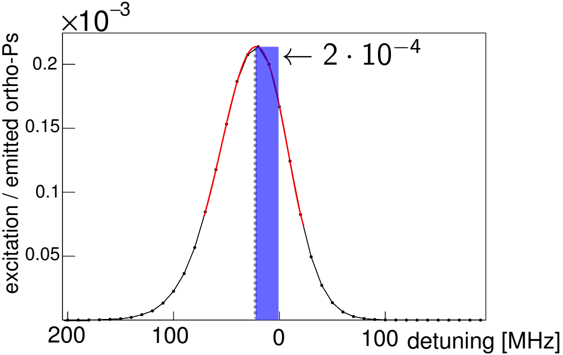


- Different interaction times and intensities for different emission angles.
- Laser intensity limited by the incident laser power. and the damage threshold of the laser mirrors (minimal waist).

Laser excitation



$\Rightarrow$



Natural linewidth 2S: 1.2 MHz

Laser Power 500 W, beam waist 0.3 mm

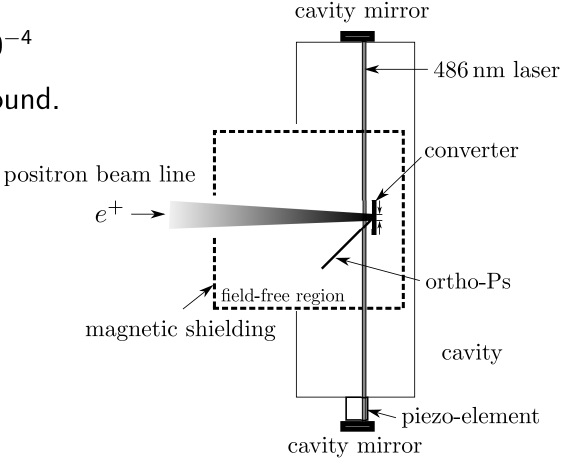
Optical Bloch equation with second order Doppler shift: ($\approx$ 60 MHz shift)

$$f_\Sigma = f_\beta + f_{-\beta} = f_0 \cdot \left(\sqrt{\frac{1+\beta}{1-\beta}} + \sqrt{\frac{1-\beta}{1+\beta}} \right) \approx 2 f_0 \cdot \left(1 + \frac{\beta^2}{2} \right)$$

2S Ps detection

- excitation rate of $\approx 10^{-4}$

$\Rightarrow$ Need for low background.



2S Ps detection

- excitation rate of $\approx 10^{-4}$

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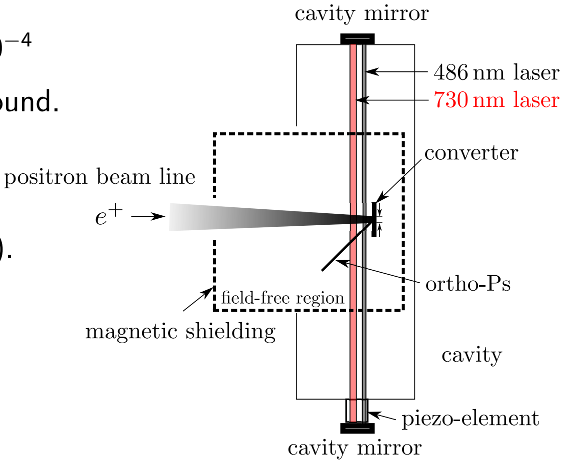
- Excitation of 2S Ps to Rydberg states (n=20).



2S Ps detection

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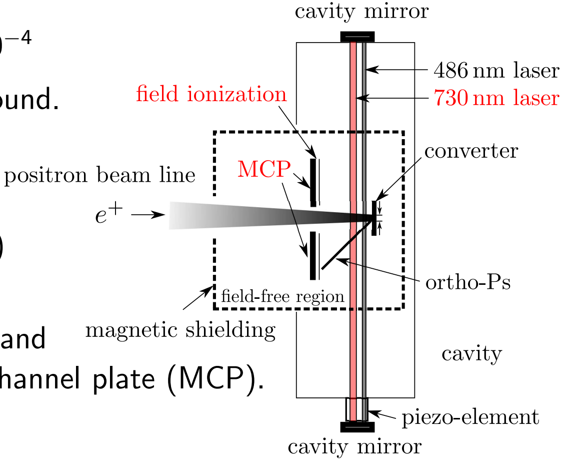
- Excitation of 2S Ps to Rydberg states (n=20)

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



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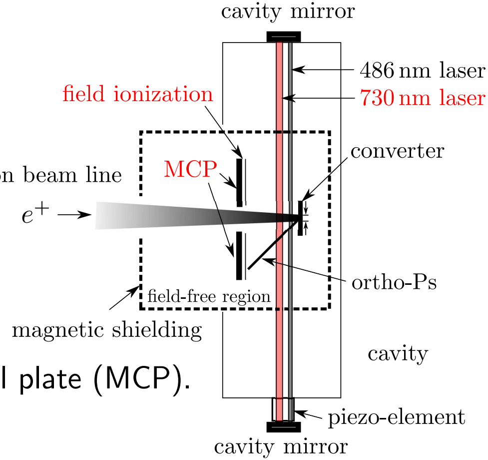
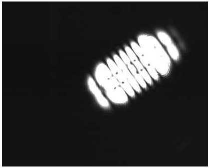


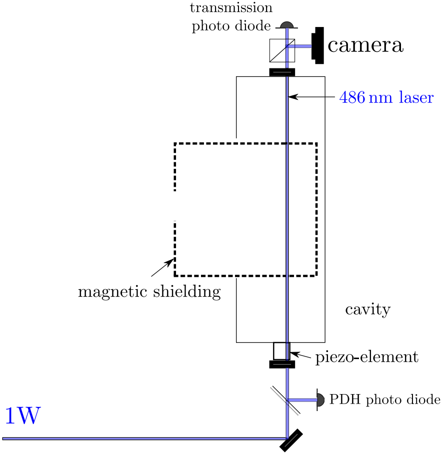
- Excitation of 2S Ps to Rydberg states (n=20)

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

- time-of-flight measurement of the 2S atoms from incident e^+ bunch to MCP signal. Reconstruction of $\beta \Rightarrow$ Correcting second order Doppler shift!

The Laser System





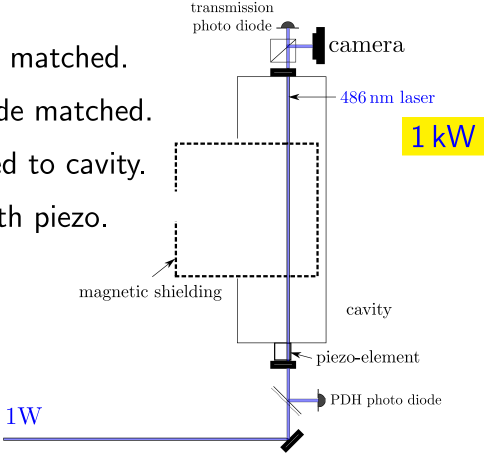
The Laser System and Cavity

- Mirrors impedance matched.
- Incident beam mode matched.
- 972 nm laser locked to cavity.
- Frequency scan with piezo.

planned:

compare laser to frequency comb

$\Rightarrow \pm 200\,\text{kHz}$



Conclusion

- pulsed e^+ beam working.

- MCP detector and cavity installed.

$\rightarrow$ Test of detection scheme by
pulsed laser excitation with 486 nm and 730 nm laser.
(see also talk of M.Heiss)

Beginning of next year:

$\rightarrow$ change to CW laser for spectroscopy.

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

Acknowledgment

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

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

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