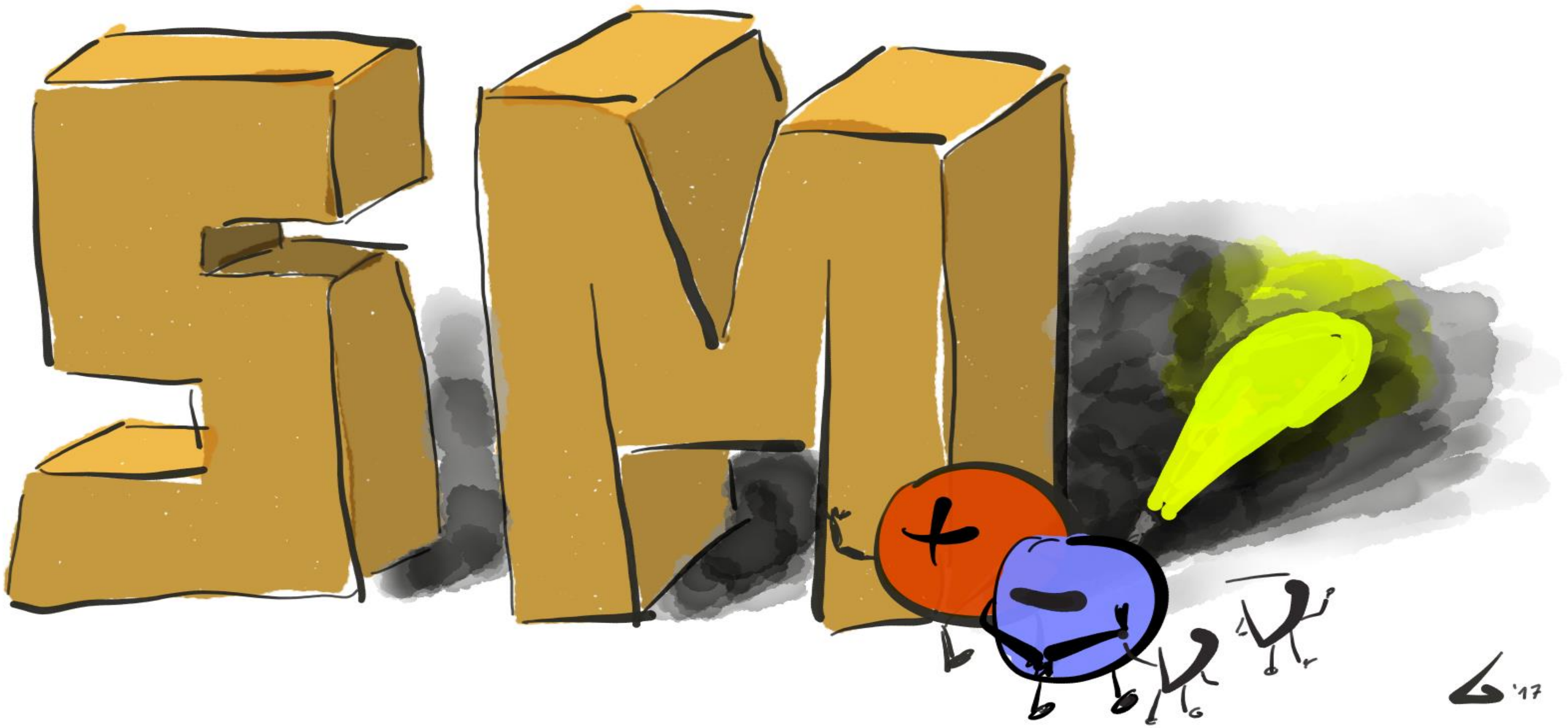

Lorentz and CPT tests with Positronium

Precision spectroscopy of the 1s-2s and excited state hyperfine transitions

CPT – Invariance

- Every quantum field theory respecting
  - Lorentz-Invariance
  - Locality
  - Unitarity

- J. Schwinger, Phys. Rev. 82 (1951) 914.
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  is invariant under the combined transformations
  - C – charge (changes sign of all charges)
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  - T – time (time reversal)

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However, can there still be CPT violations?

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CPT – Violation

- CPT can be naturally broken (e.g. in string theory)

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CPT – Violation

- CPT can be naturally broken (e.g. in string theory)
- Breaks Lorentz symmetry
- Can be well described at low energy scales as effective field theory:
  Standard Model Extension (SME)
  - built from General Relativity and the Standard Model
  - includes Lorentz- and CPT violating operators
  - up to mass dimension 4 (minimal SME) and above
  - coefficients have to be determined experimentally

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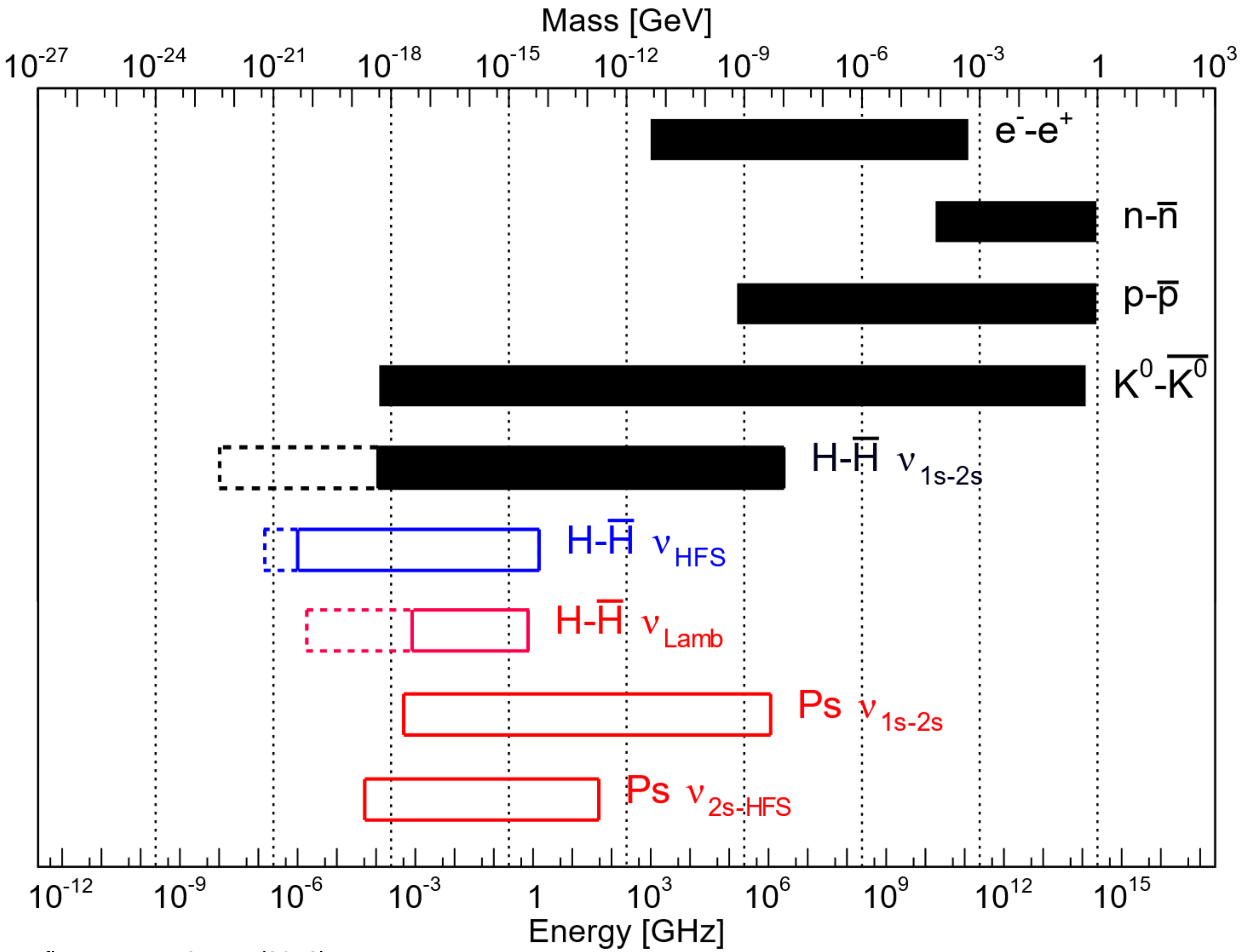
CPT tests in different systems



- Adapted from: E. Widmann et al., Hyperfine Interact. 215, 1 (2013).

Spectroscopy and the minimal SME

- Minimal SME terms can produce striking effects, e.g.

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  - Hydrogen sector
    - time dependent shifts in hydrogen spectra (e.g. annual shifts)
    - different hydrogen and anti-hydrogen spectra
  - Positronium sector
    - SM forbidden momentum-polarization correlations in Positronium decay
    - shifts in Positronium spectra from Lorentz-invariant values
      - 1s-2s transition
      - hyperfine splitting

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Positronium Spectroscopy

- Ps is purely leptonic system
- Free from
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- Ps is purely leptonic system
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- Precision test bench for
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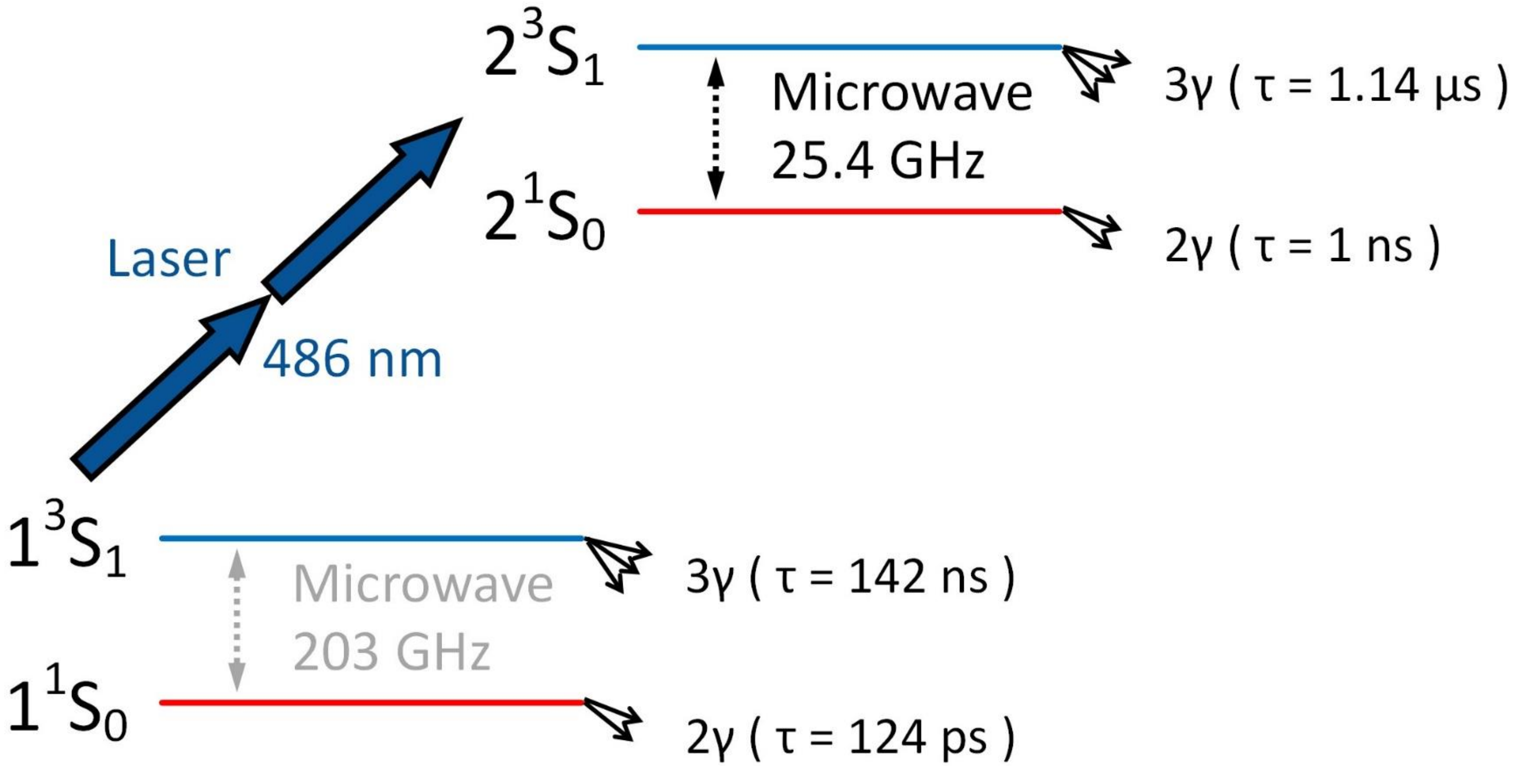
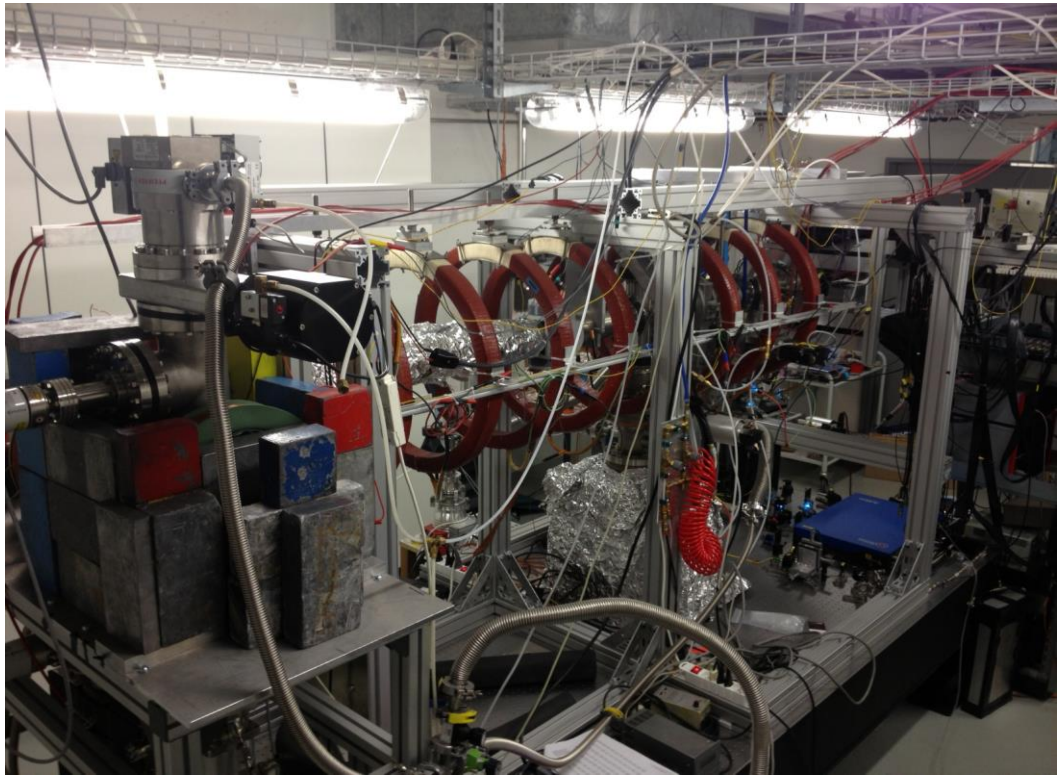
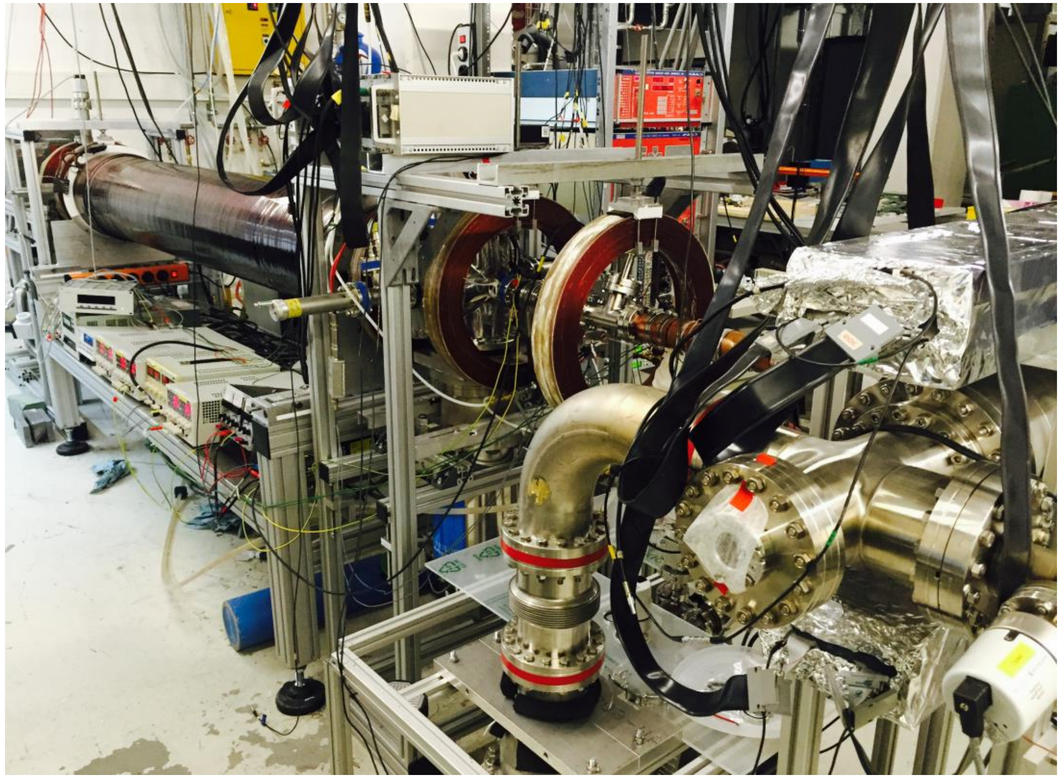


ETH slow positron beamlines

- Continous beam (since 2012)

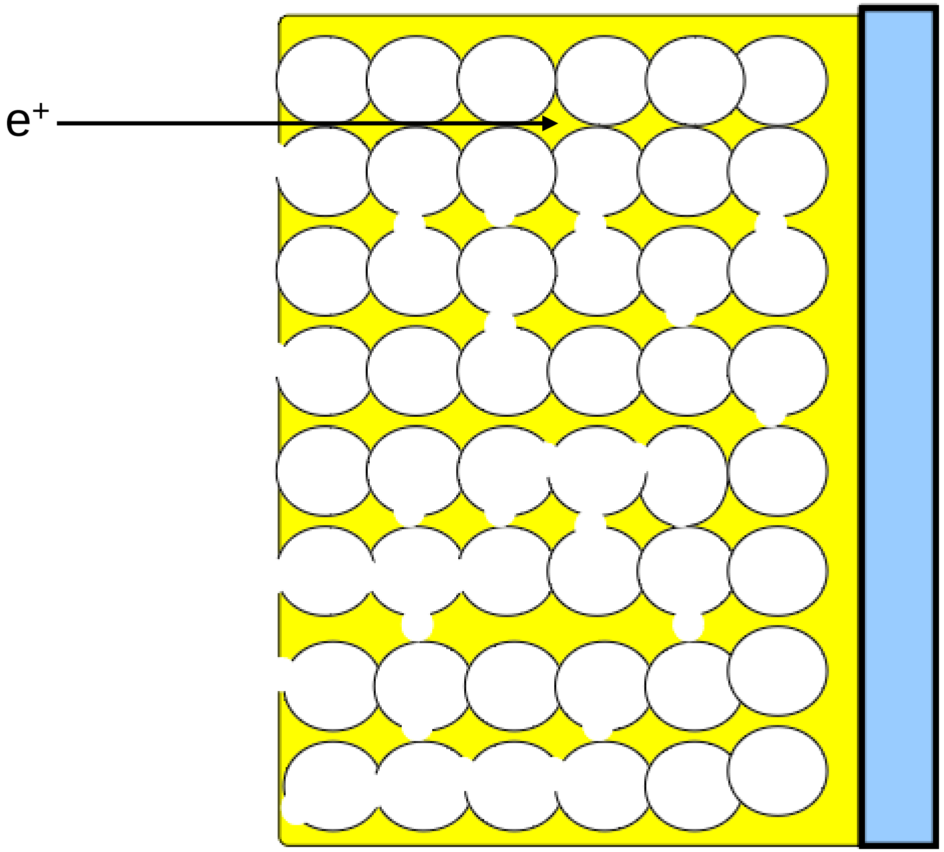


- Pulsed beam (since 2015)



Positronium formation

- Implantation in porous silica thin film
  - approx. 1 µm thick, 3-4 nm pore size
  - e^+ energy of a few keV
  - rapid thermalization



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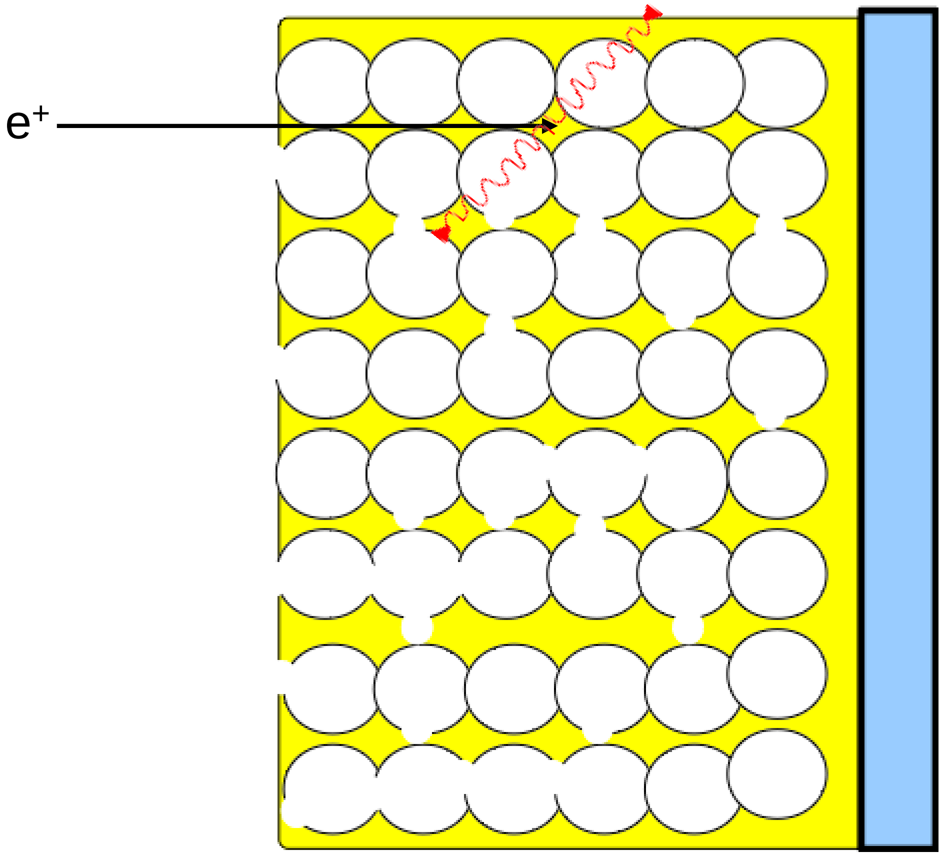

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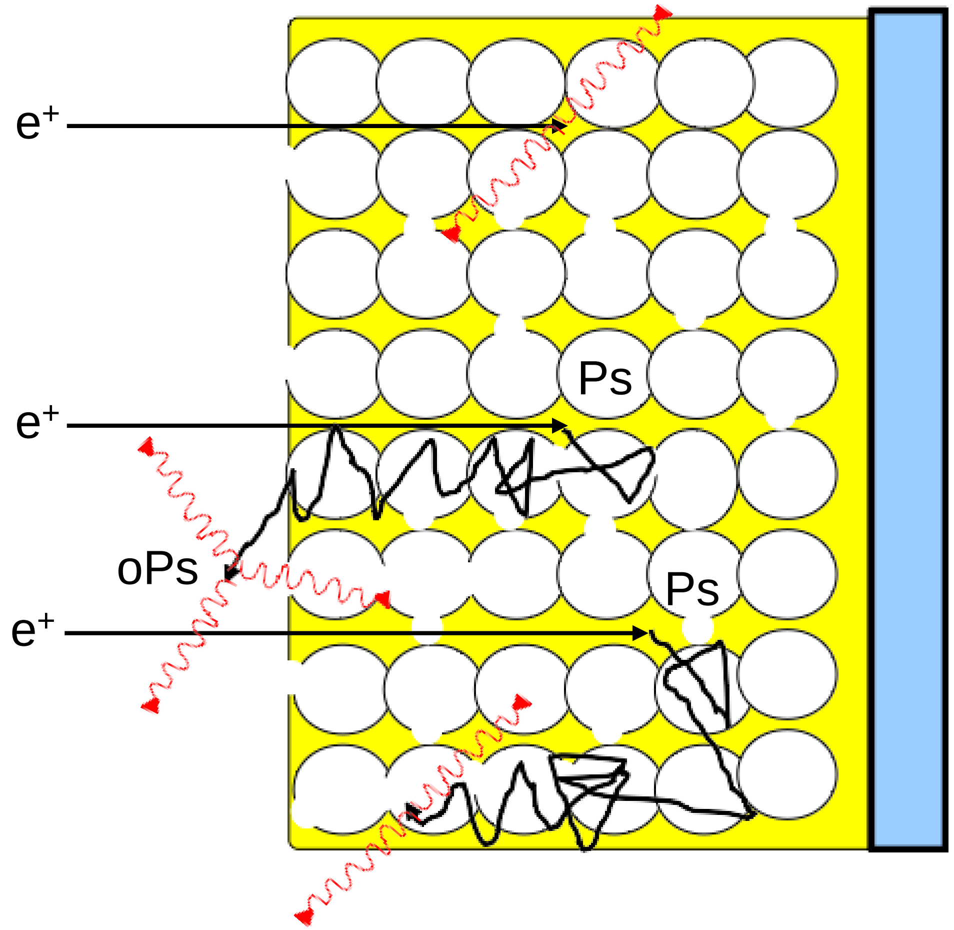
- Diffuse and annihilate
- Form Positronium by capturing e^-
  - 25% pPs and 75% oPs
  - diffusion to surface
  - emission into vacuum
    - $W_{Ps} = \mu_{Ps} + E_B - 6.8\ eV < 0\ eV$



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Positronium emission into vacuum

- Very efficient
  - ≈ 30% of incident e^+ produce oPs into vacuum
- Almost monoenergetic
  - ≈ 40 meV (≈ 10^5 m/s!)

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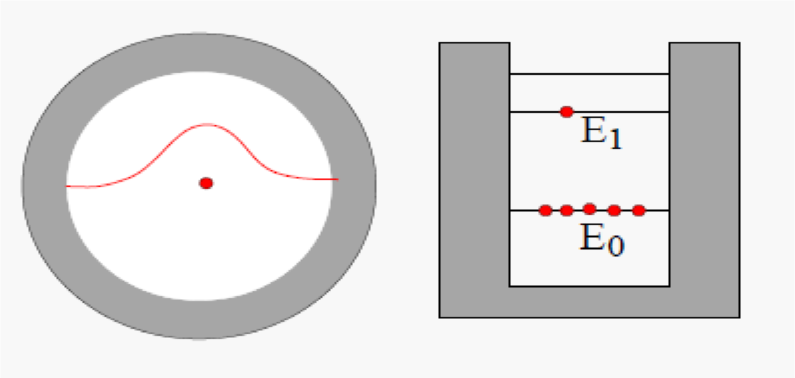
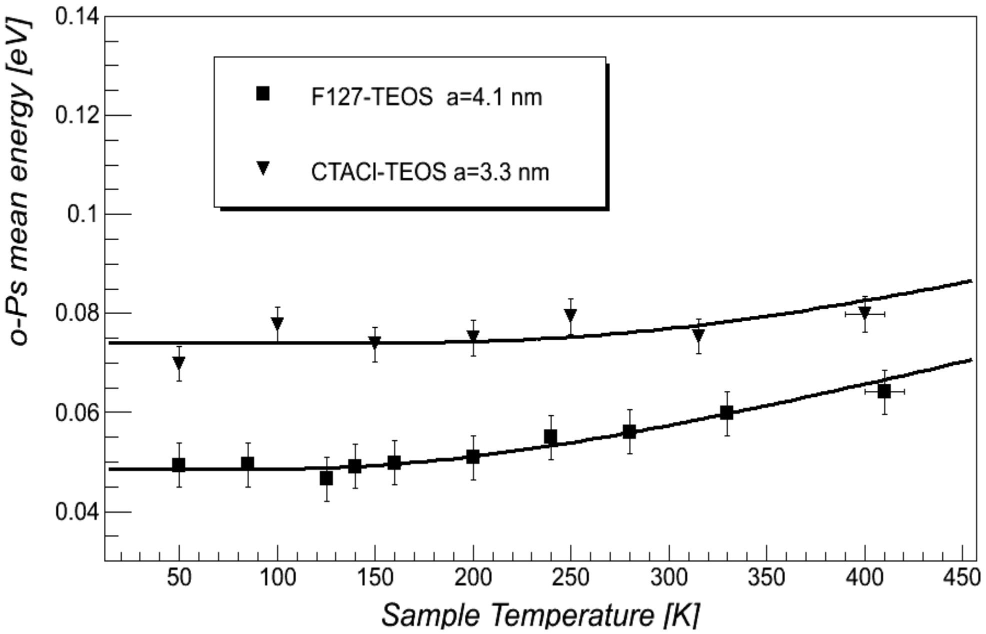
  - particle in a box
    - $E_{Ps} = \frac{h^2}{2\, m\, d^2} \approx 0.8eV \left(\frac{1nm}{d}\right)^2$





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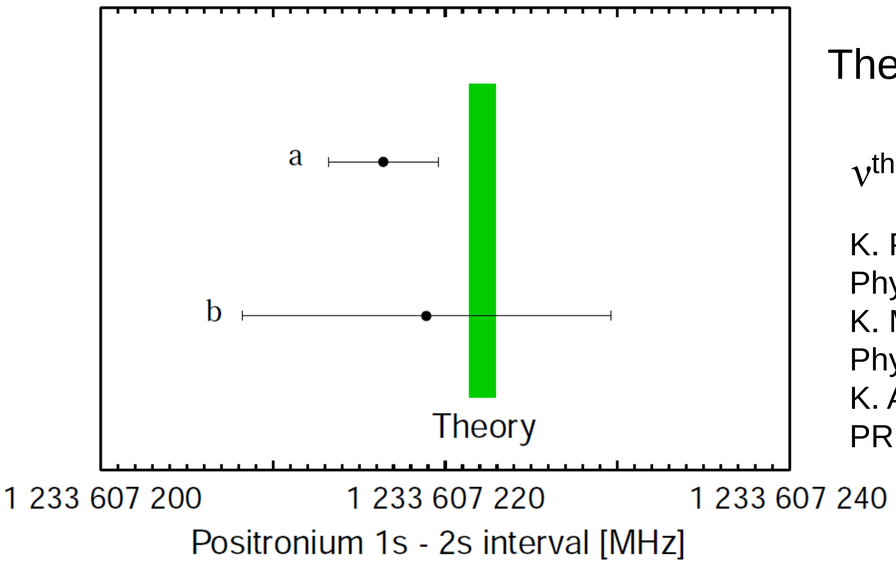
Ps 1s-2s: transition frequency



Theory:

ν^{theory} = 1233607222.2(6) MHz

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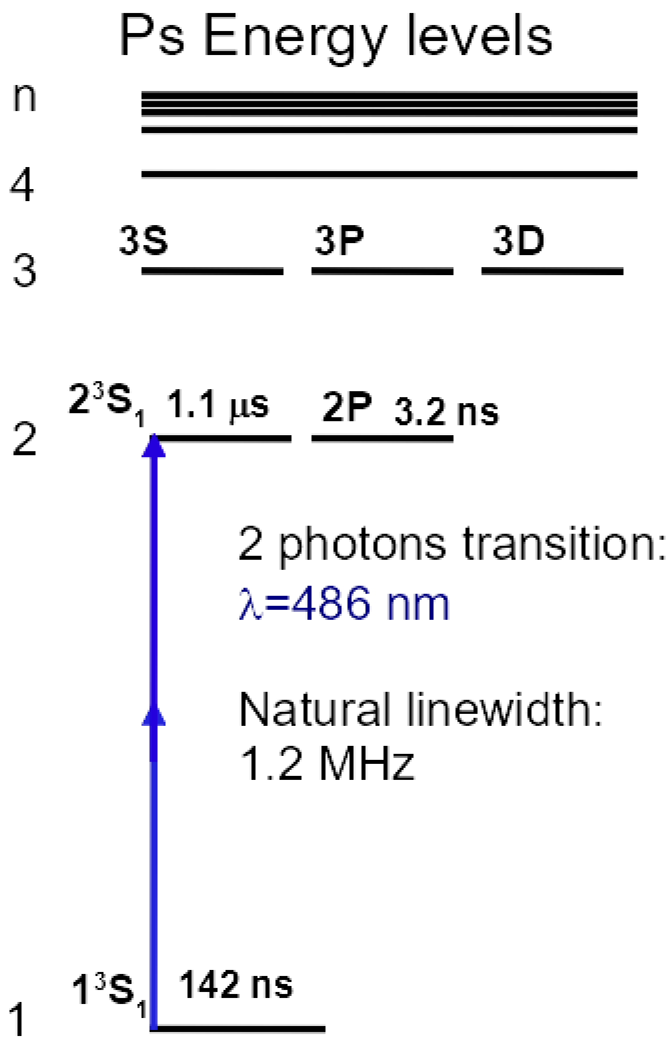

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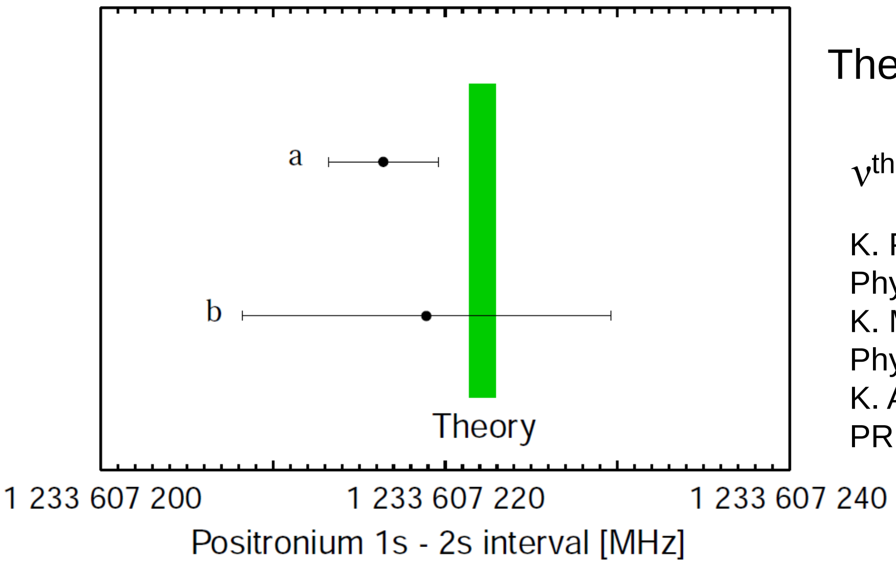

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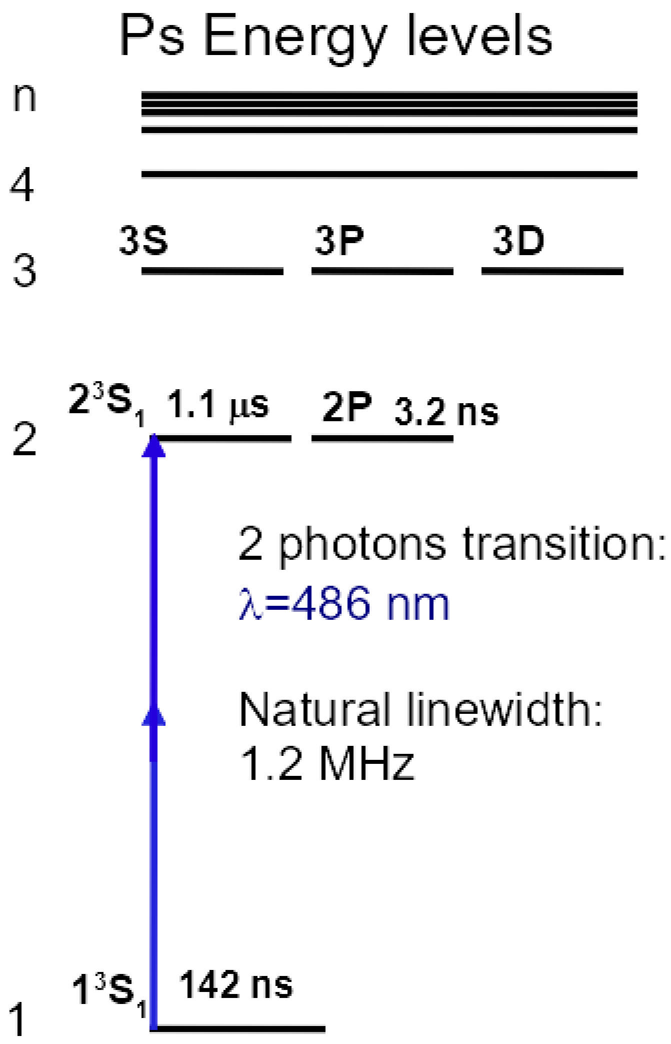

- 0.5 ppb precision ➔ check bound state QED at order $\alpha^7 m$

Ps 1s-2s: laser system

Requirements:
- High power (up to 1 kW) at 486 nm → detectable signal
- Long term stability (continuous data taking over days)
- Scanning of the laser ≈ 100 MHz

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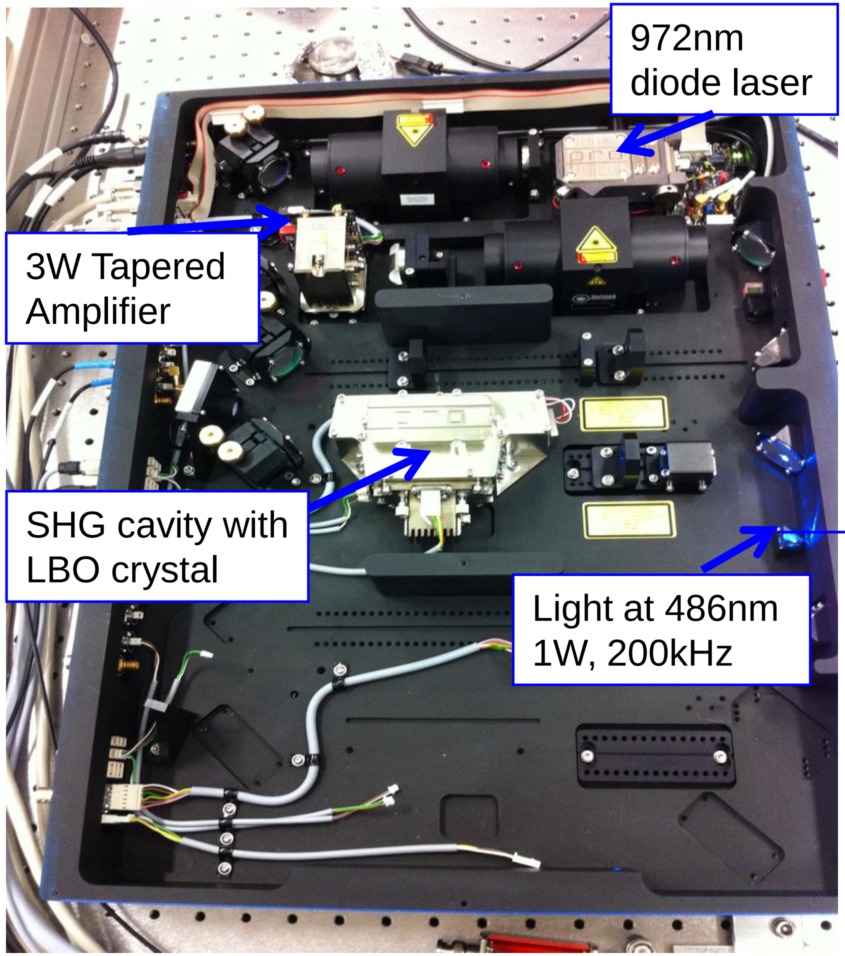

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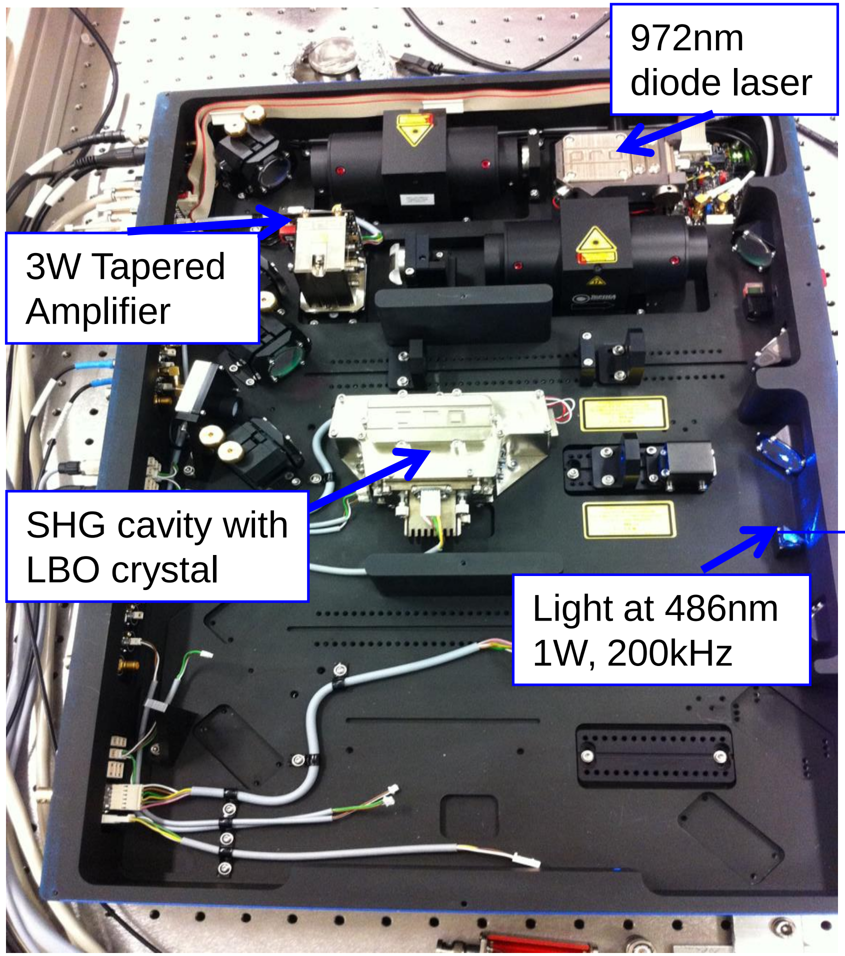

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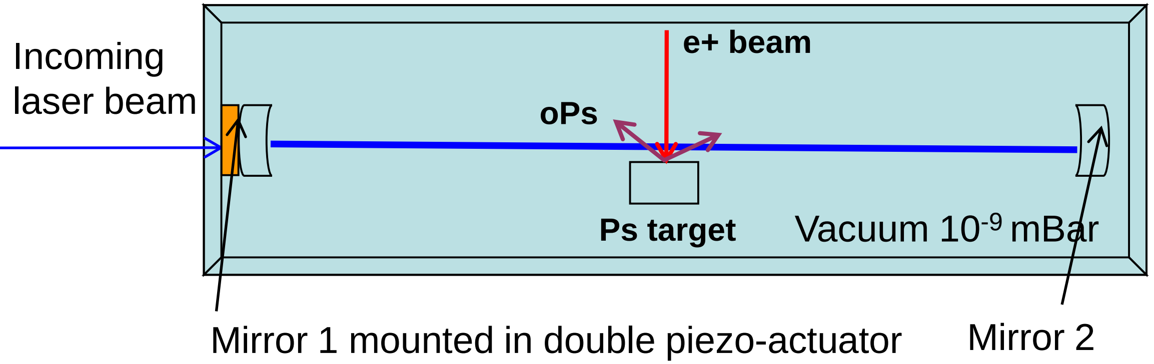
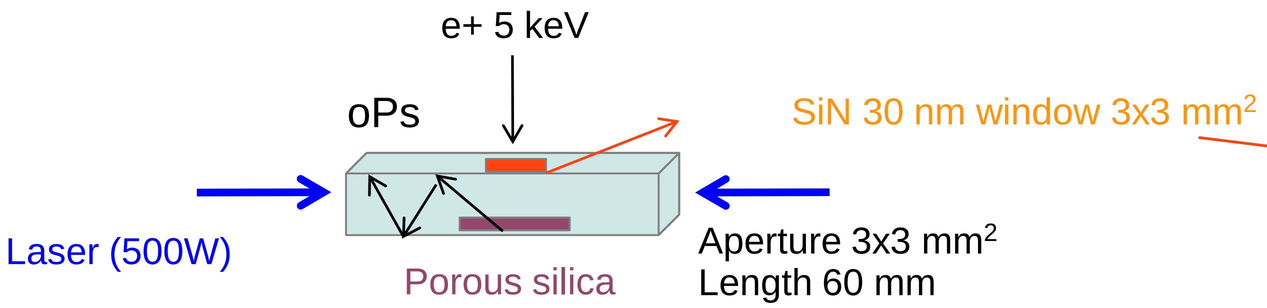
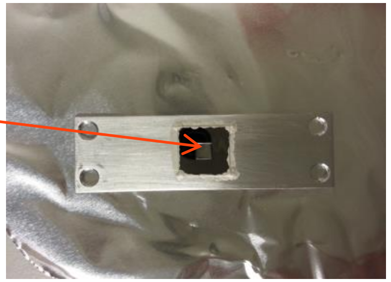


High finesse resonator for power build up
500 mW ⇨ 1 kW

Ps 1s-2s: detection scheme





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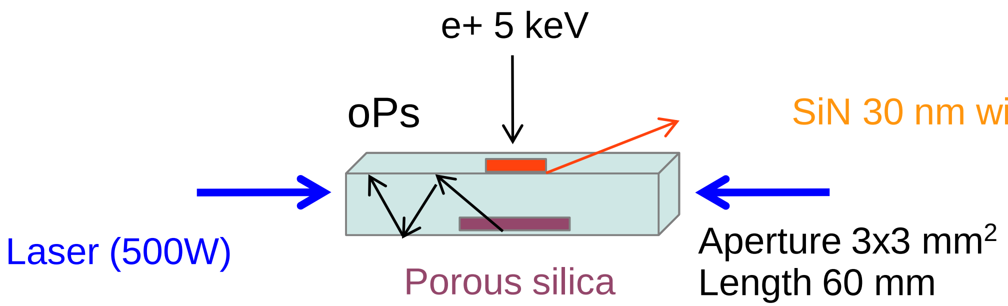
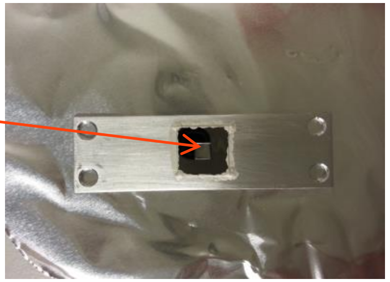
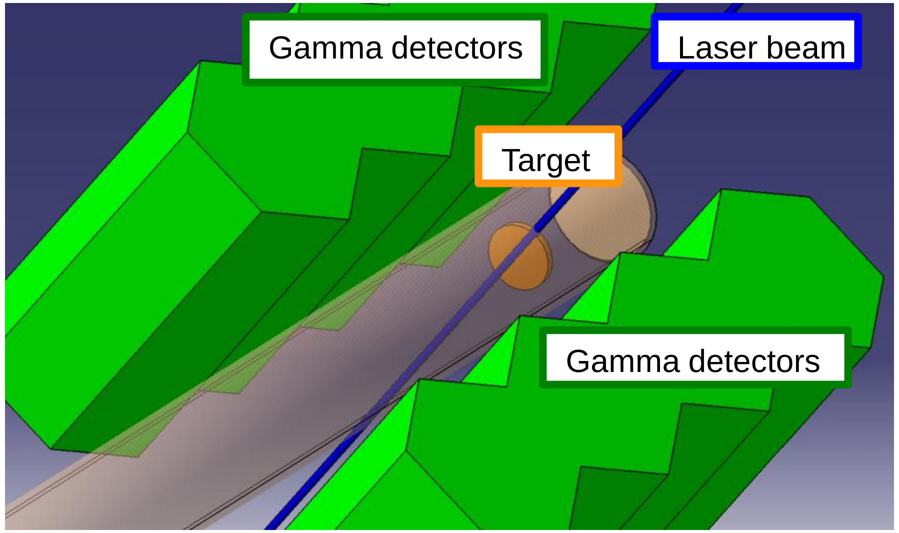


SiN 30 nm window 3x3 mm^2



$\tau_{2S} / \tau_{1S} = 8$

Detection of annihilation photons. Lifetime of excited S states ~ n^3



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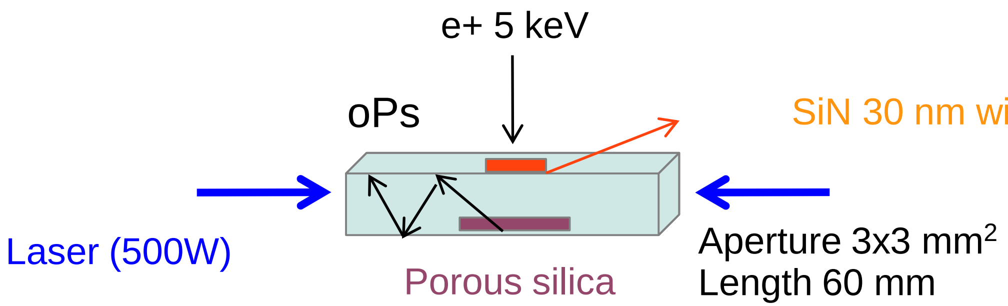

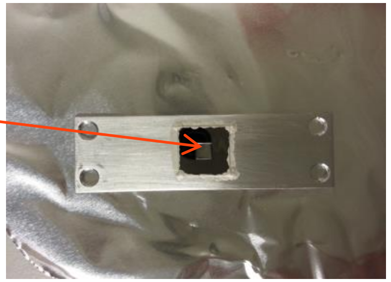

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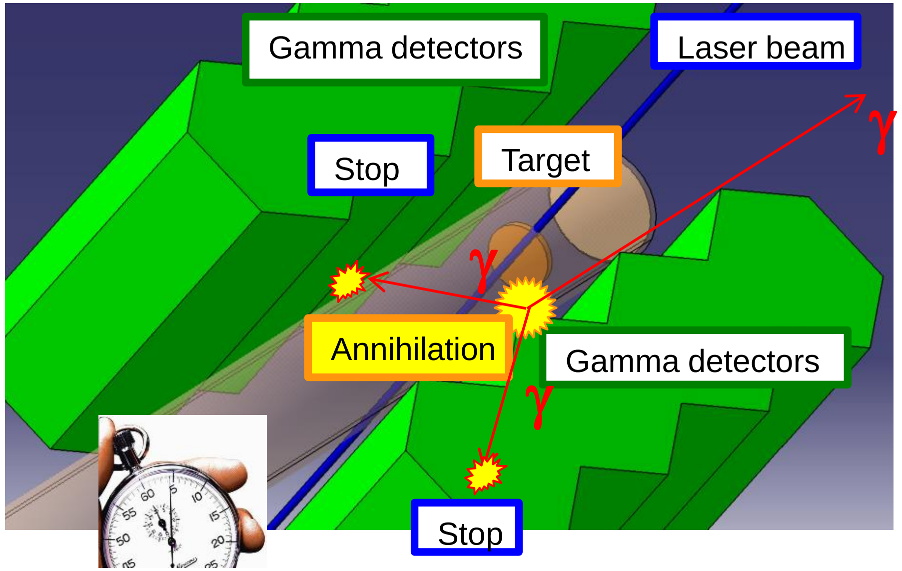
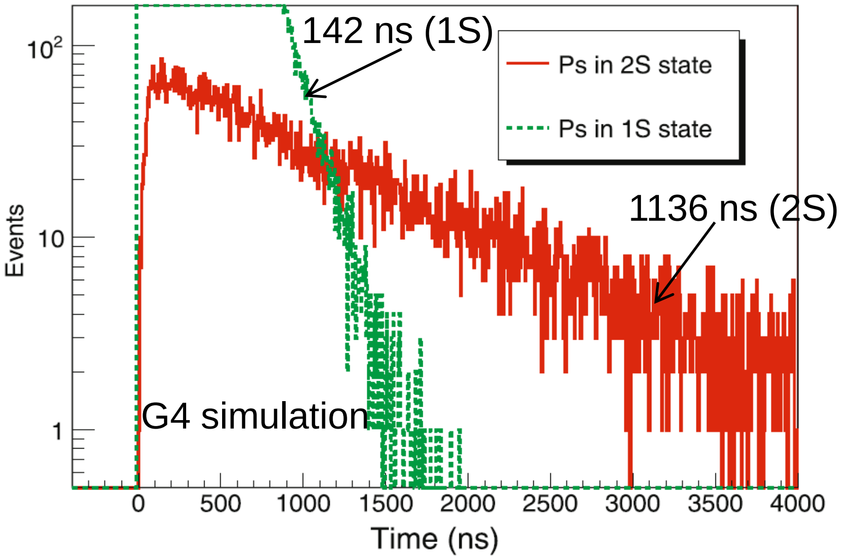
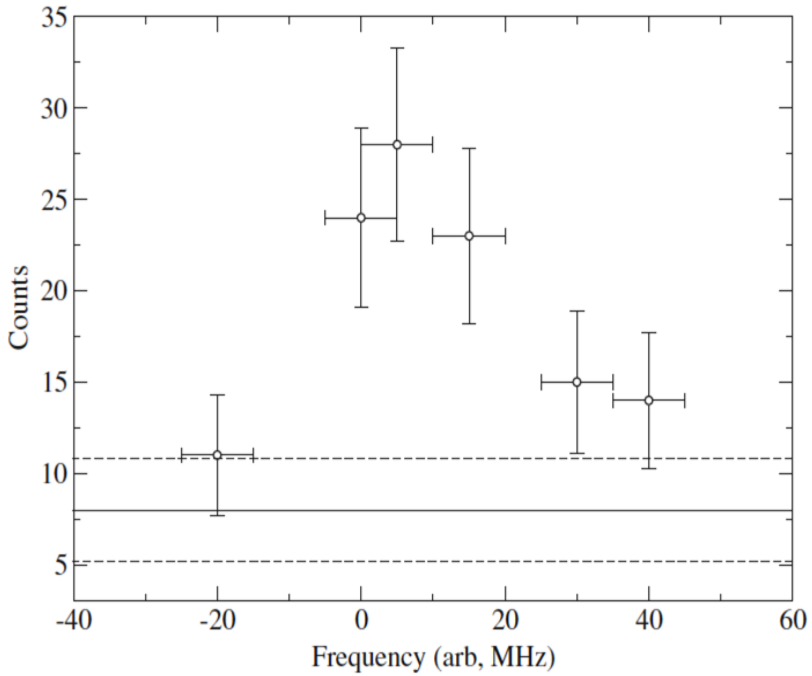




Ps 1s-2s: preliminary results (2014)



First successful scans
(about 3 hours data taking,
~ 10^6 positronium atoms/point)

→ S/N ratio should be improved.

- D.Cooke et al, Hyperfine Interact. 233 (2015) 1-3, 67.

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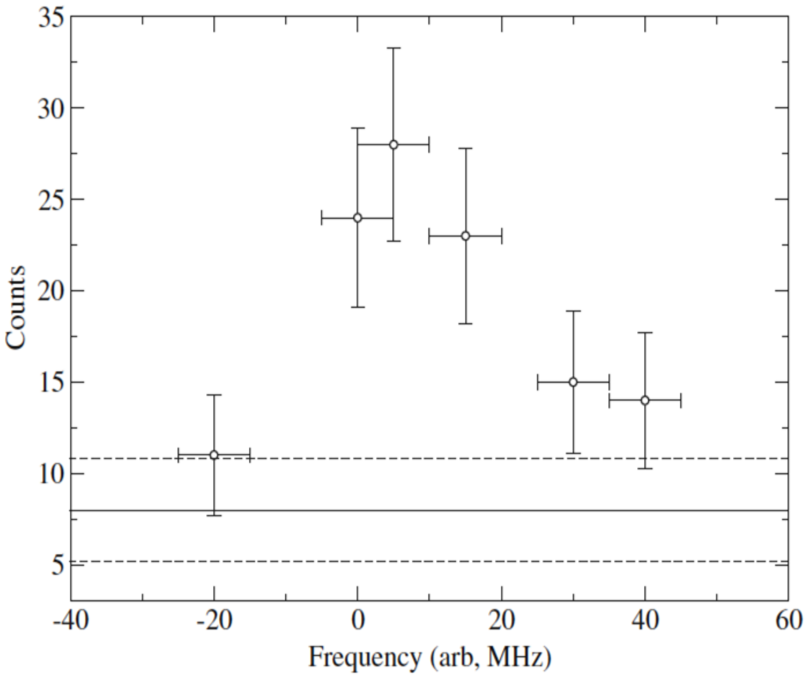

First successful scans
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S/N ratio should be improved.

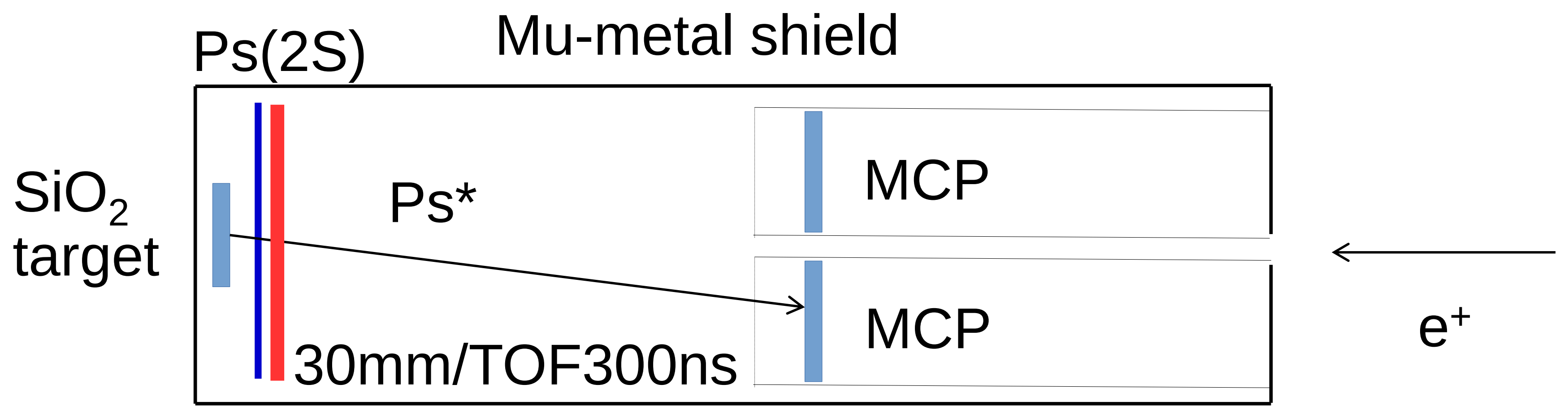
Need for a bunched beam → use buffer gas trap

→ noise from accidentals reduced by 2 orders of magnitude

→ In addition to lifetime method possibility to use pulsed lasers for systematic studies and increased signal rate

- D.Cooke et al, Hyperfine Interact. 233 (2015) 1-3, 67.

Ps 1s-2s: New detection scheme



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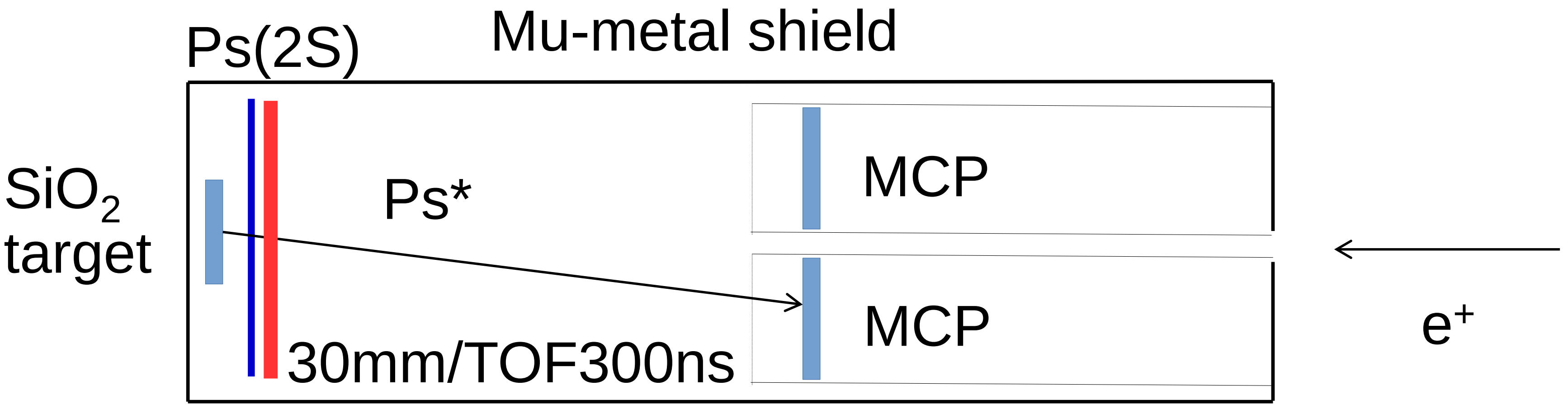

→ Excitation 2S atoms to Rydberg states (n=20) → time-of-flight measurement of 2S atoms using position sensitive MCP detector to correct for 2nd order Doppler shift.

→ Increase in the S/N ratio by two orders of magnitude.

→ Extraction to a field free e-m region → removal of systematic due to DC Stark and Zeeman (affecting m=0 triplet states) and motional Stark shift.

Ps 1s-2s: Status, outlook

- Status
  - pulsed beam operational
  - enhancement cavity installed and locked
  - new detection scheme is currently being tested with pulsed dye amplifier (486nm & 730nm)

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- Status
  - pulsed beam operational
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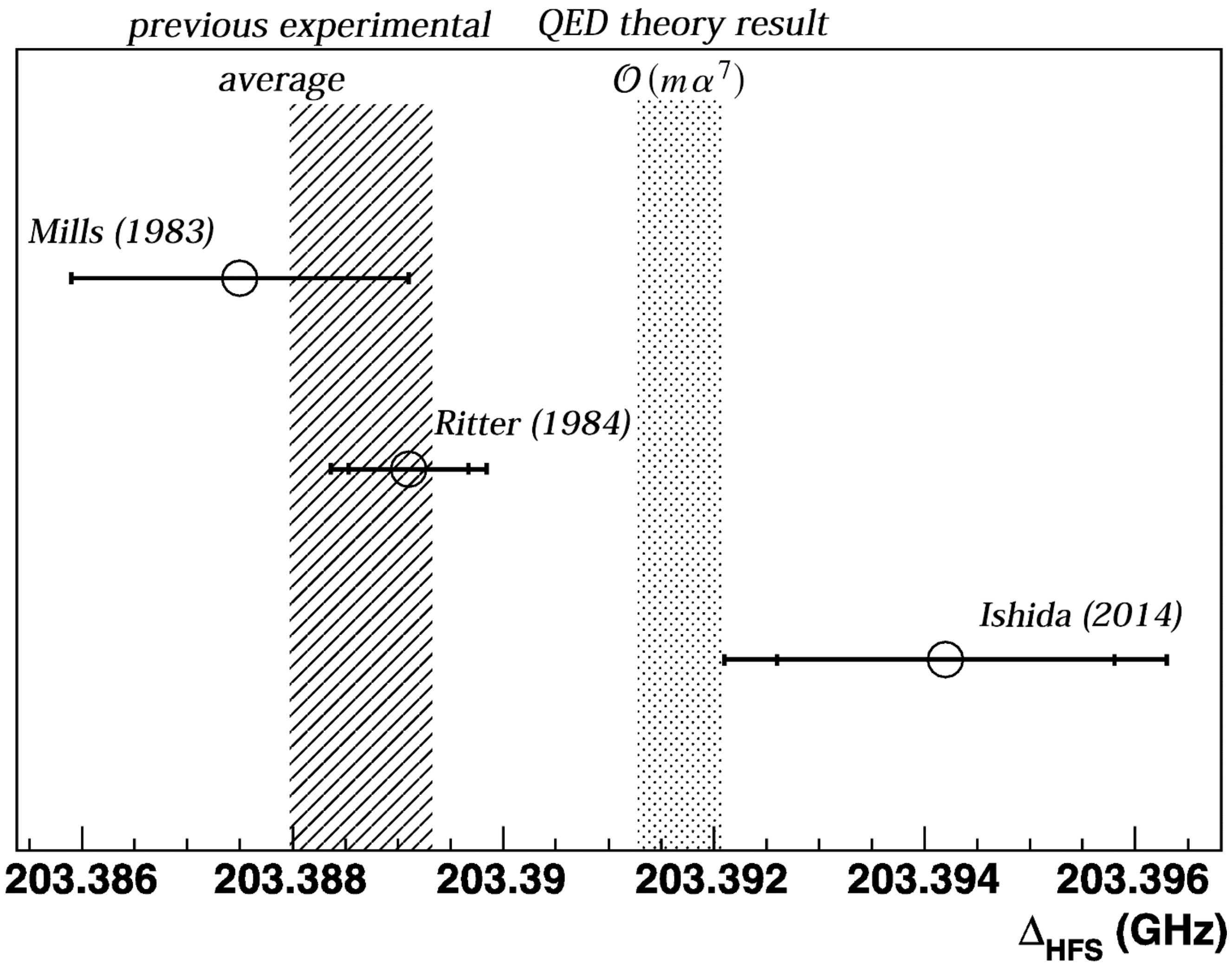
- Outlook
  - precision of 0.5 ppb seems feasible → stringent test of current QED calculations
  - more precise measurements requires cold Positronium (< 10^4 m/s)
    - time-of-flight broadening comparable to natural linewidth (1.2 MHz)
    - main systematic (2^{nd} order doppler effect) suppressed by 2 orders of magnitude
    - a few ppt precision might be in reach
    - would allow independent determination of rydberg constant

Ps HFS: Additional Motivation

- Very precise measurements in 1970s and 1980s
- Almost 4 sigma discrepancy with most recent QED result
- Two common sources of possible systematics identified:
  - indirect measurement
  - conducted in dense gases

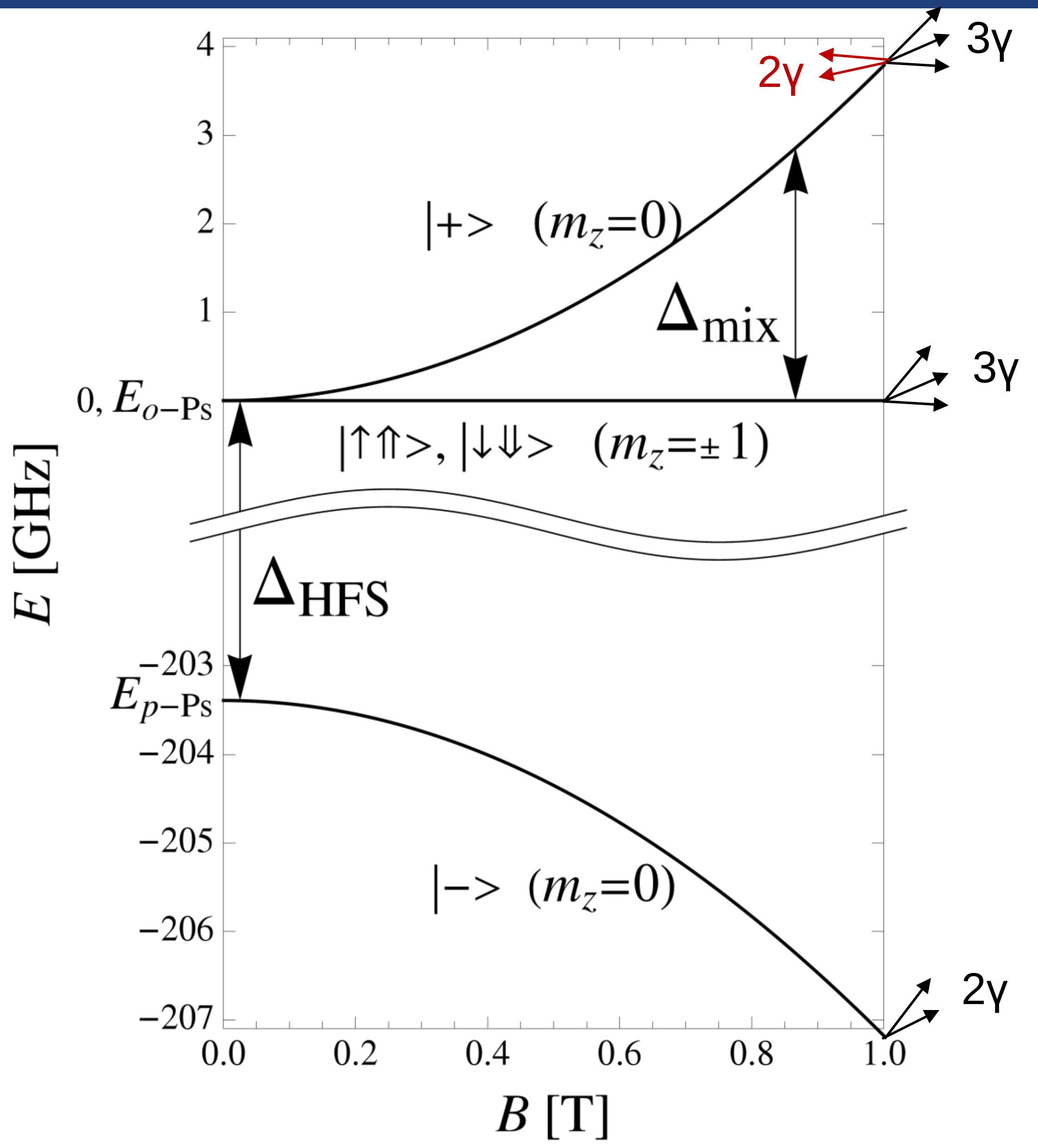


- A. Ishida et al. New Precision Measurement of Hyperfine Splitting of Positronium. *Phys. Rev. Lett. B*, 734:338–344, June 2014.

Ps HFS: Indirect measurements

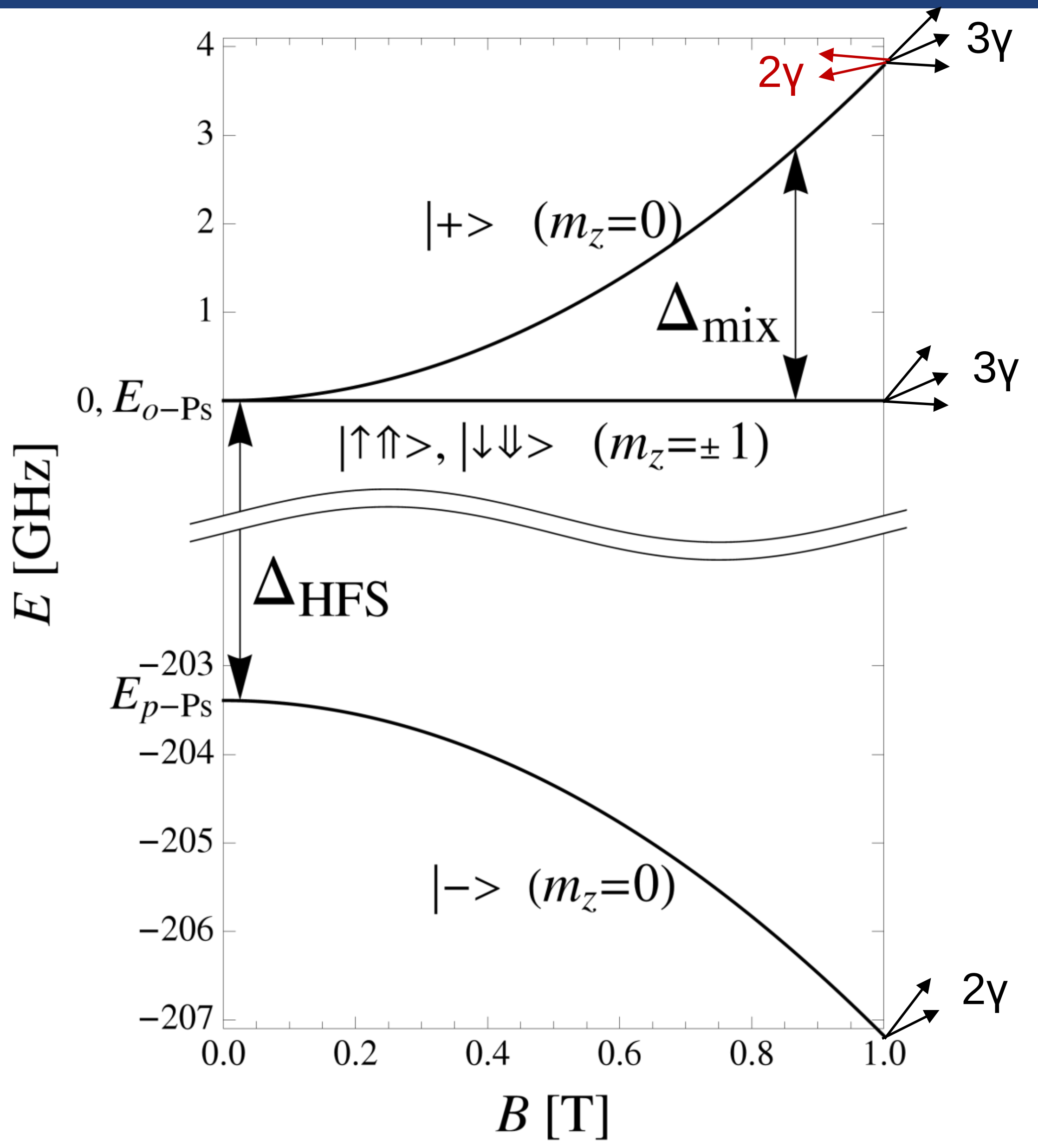
- In a static magnetic field:
  - antiparallel spin states pick up ΔE
  - The $|\,1{,}0>$ state mixes with the $|\,0{,}0>$ state
    - magnetic quenching
- One can induce transitions between different m_Z's instead of different J's
- Compare: $\Delta_{mix} \approx 4\ GHz$ (at $1\ T$)

  vs. $\Delta_{HFS} \approx 203\ GHz$



Ps HFS: Indirect measurements

- one calculates Δ_{HFS} from:
  - $\Delta_{\text{mix}} \approx 0.5 \cdot \Delta_{\text{HFS}}\left(\sqrt{1+q^2}-1\right)$
  - where: $q \propto \frac{B}{\Delta_{\text{HFS}}}$
- needs very high B-Fields ($\sim 1\ T$)
- Disadvantages
  - some theoretical uncertainty
  - inhomogeneities in the fields contribute directly to systematic errors



Ps HFS: Mesurements in dense gases

- In dense gases
  - gas acts as e^+ target
  - e^+ can ionize a gas atom
  - e^+ picks up the e^- and forms Ps
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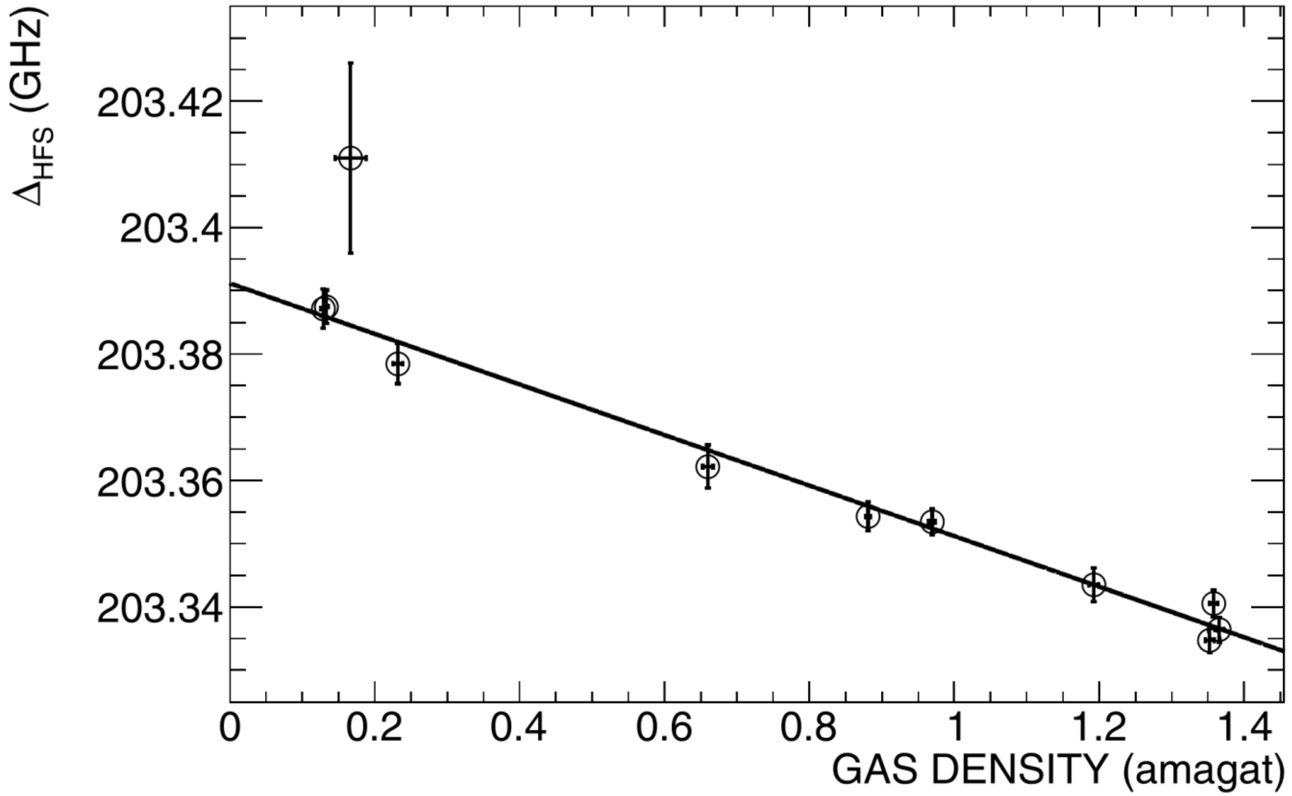
- Disadvantages:
  - E field of gas atoms → Stark effect
  - Needs extrapolation to vacuum
  - Uncertainties in the Ps thermalization
  - High MW powers can strongly interfere with Ps production in gases



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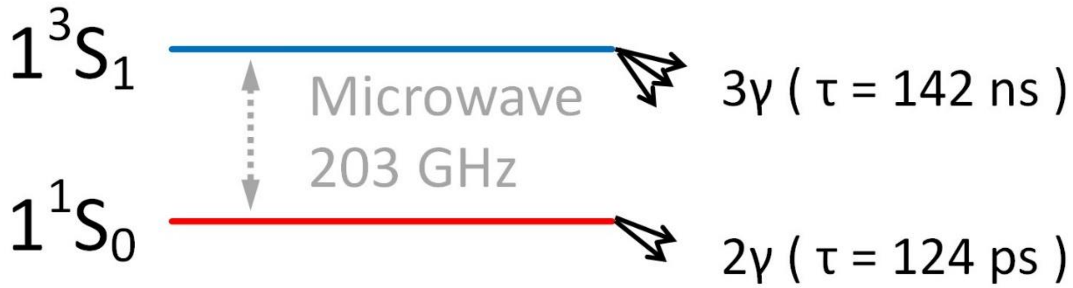
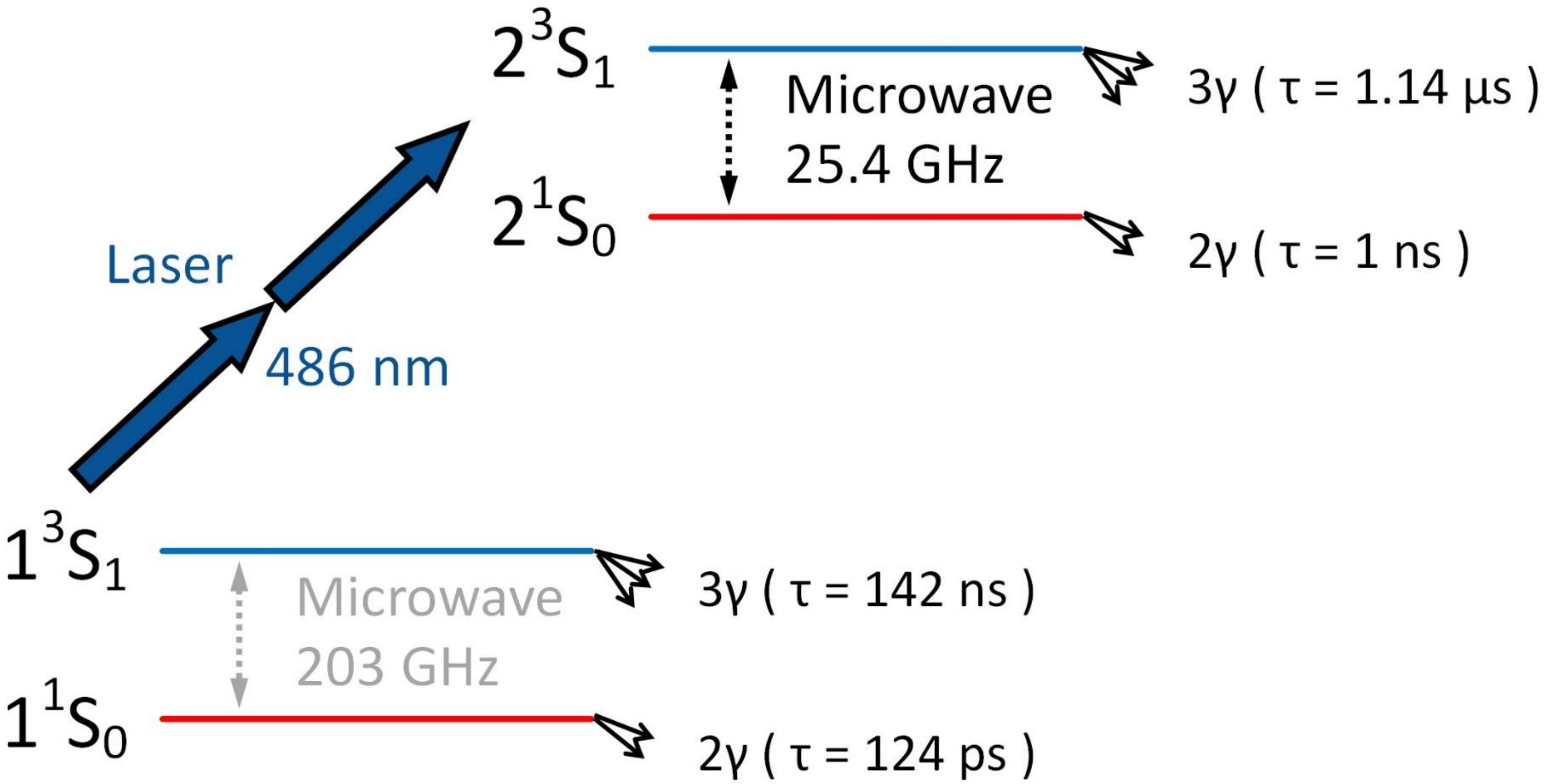
Ps HFS: New technique avoiding systematic sources

- Transition in vacuum
  - no extrapolation necessary
  - need a beam
  - need different converter



Ps HFS: New technique avoiding systematic sources

- Transition in vacuum
  - no extrapolation necessary
  - need a beam
  - need different converter
- Direct transition
  - no theoretical uncertainty
  - needs no static B field
  - need 486nm laser
- Commercially available
  - Signal Generators: 200mW
  - TWT Amplifiers: 100’s of W



Ps HFS: Schematic overview of the experiment

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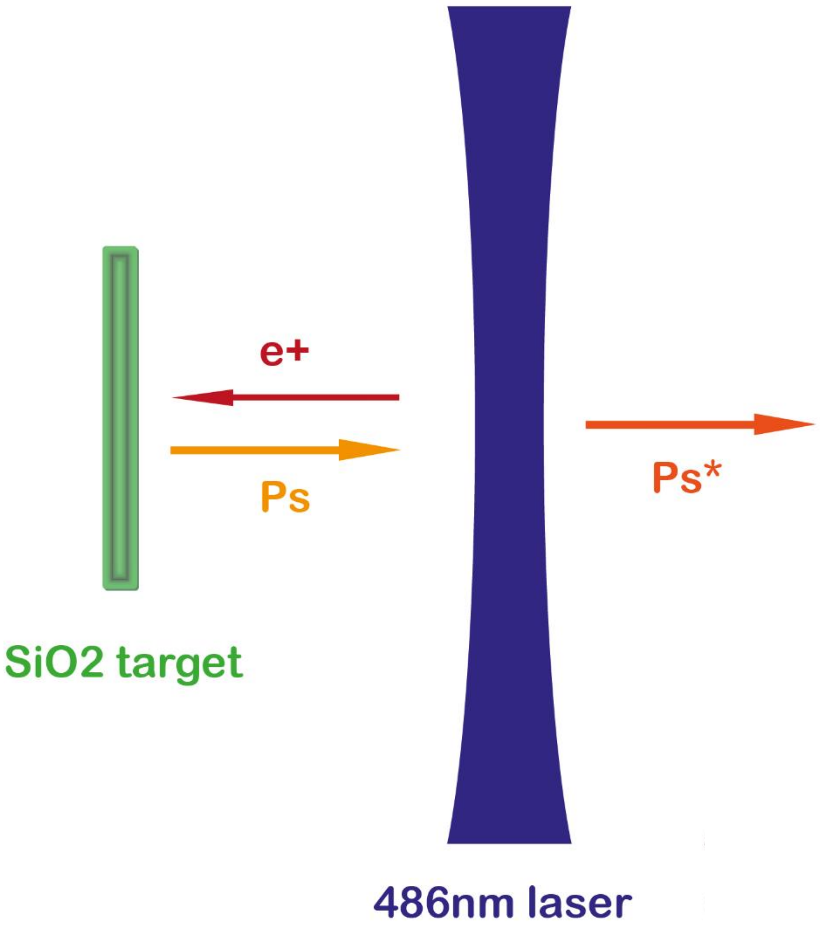

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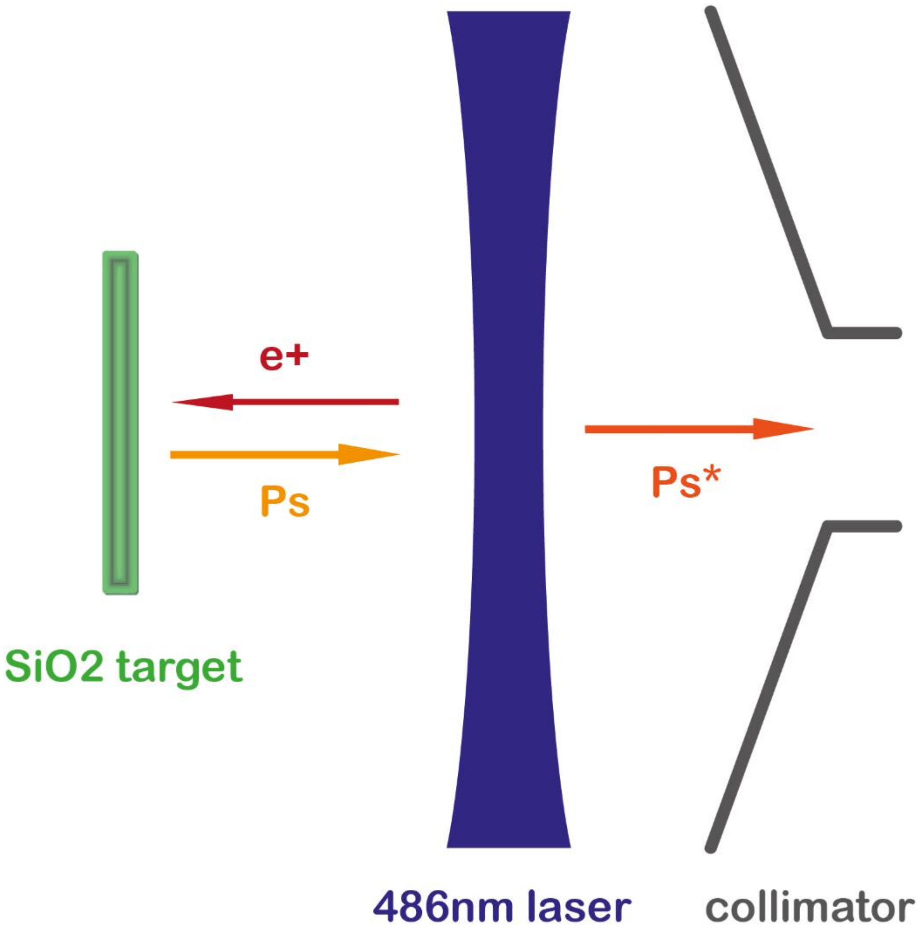
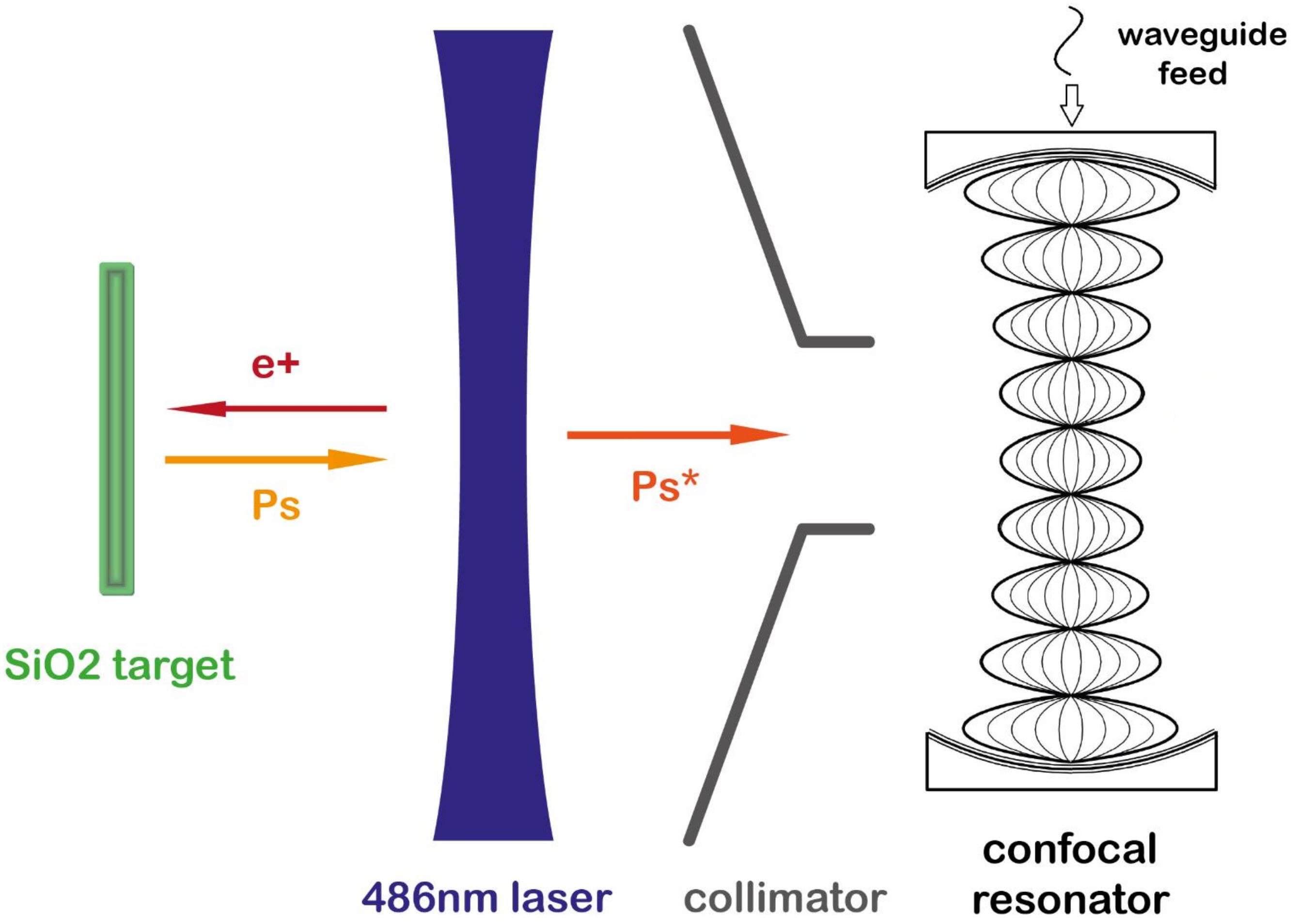


Ps HFS: Schematic overview of the experiment



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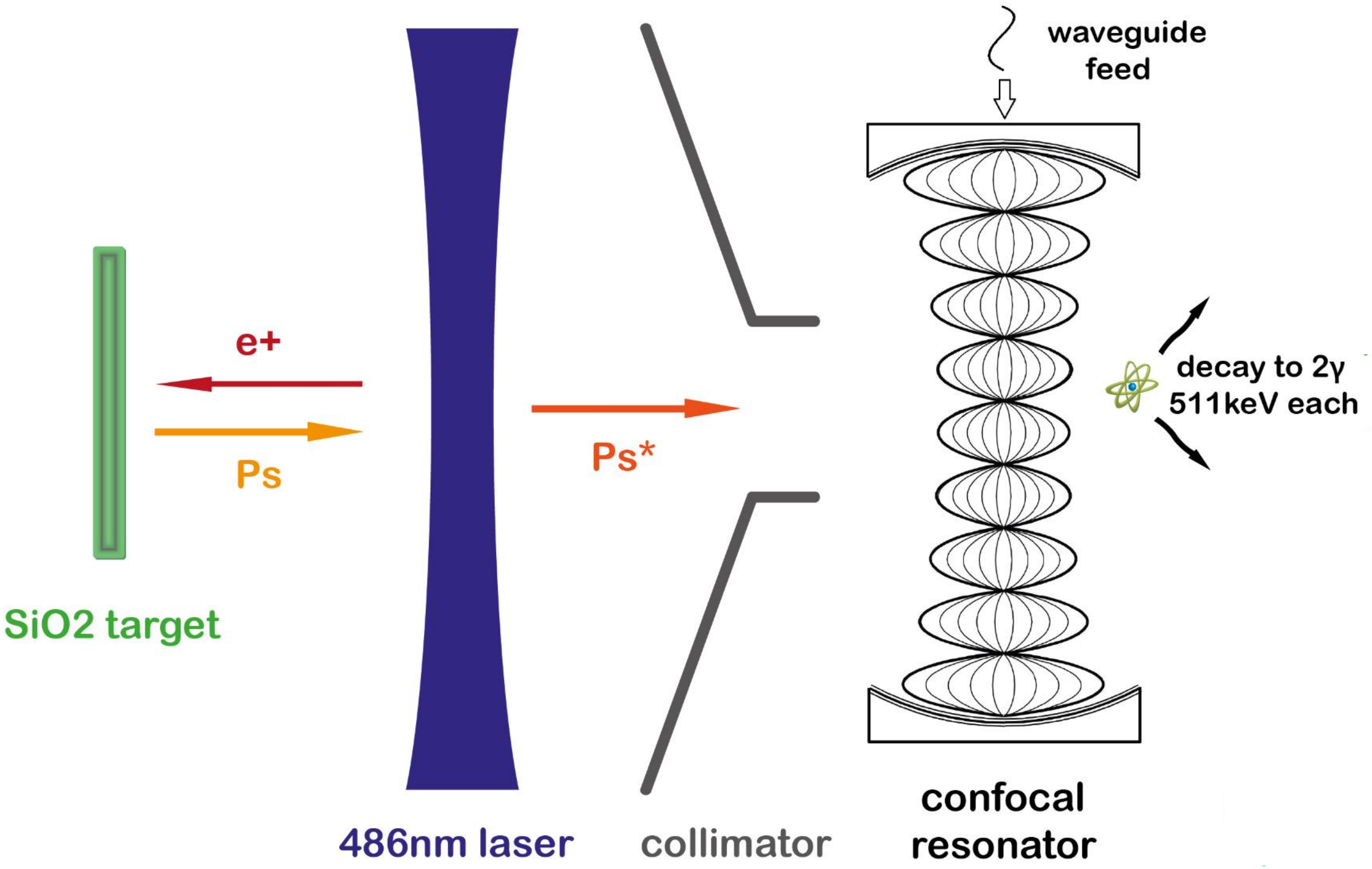

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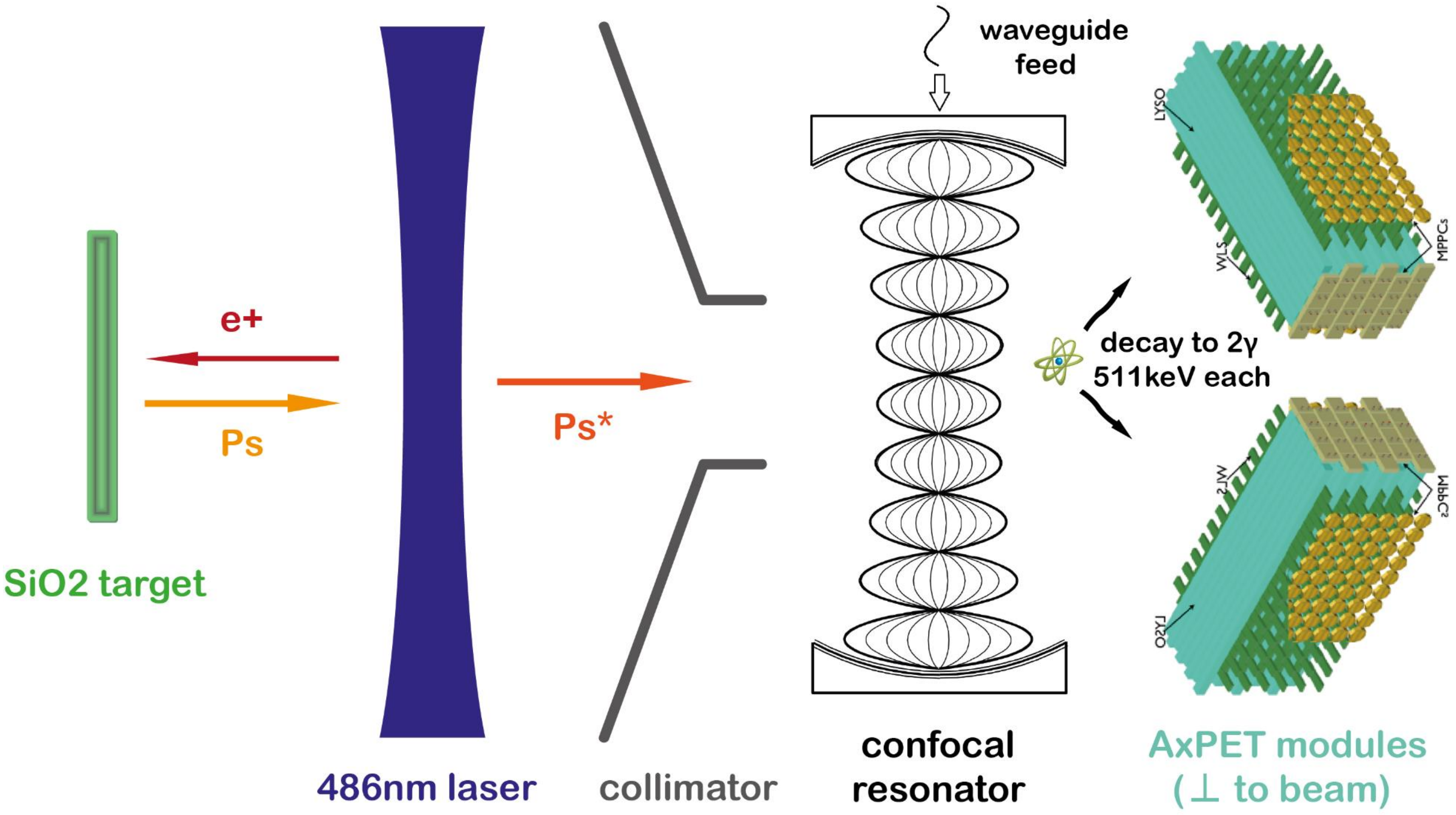
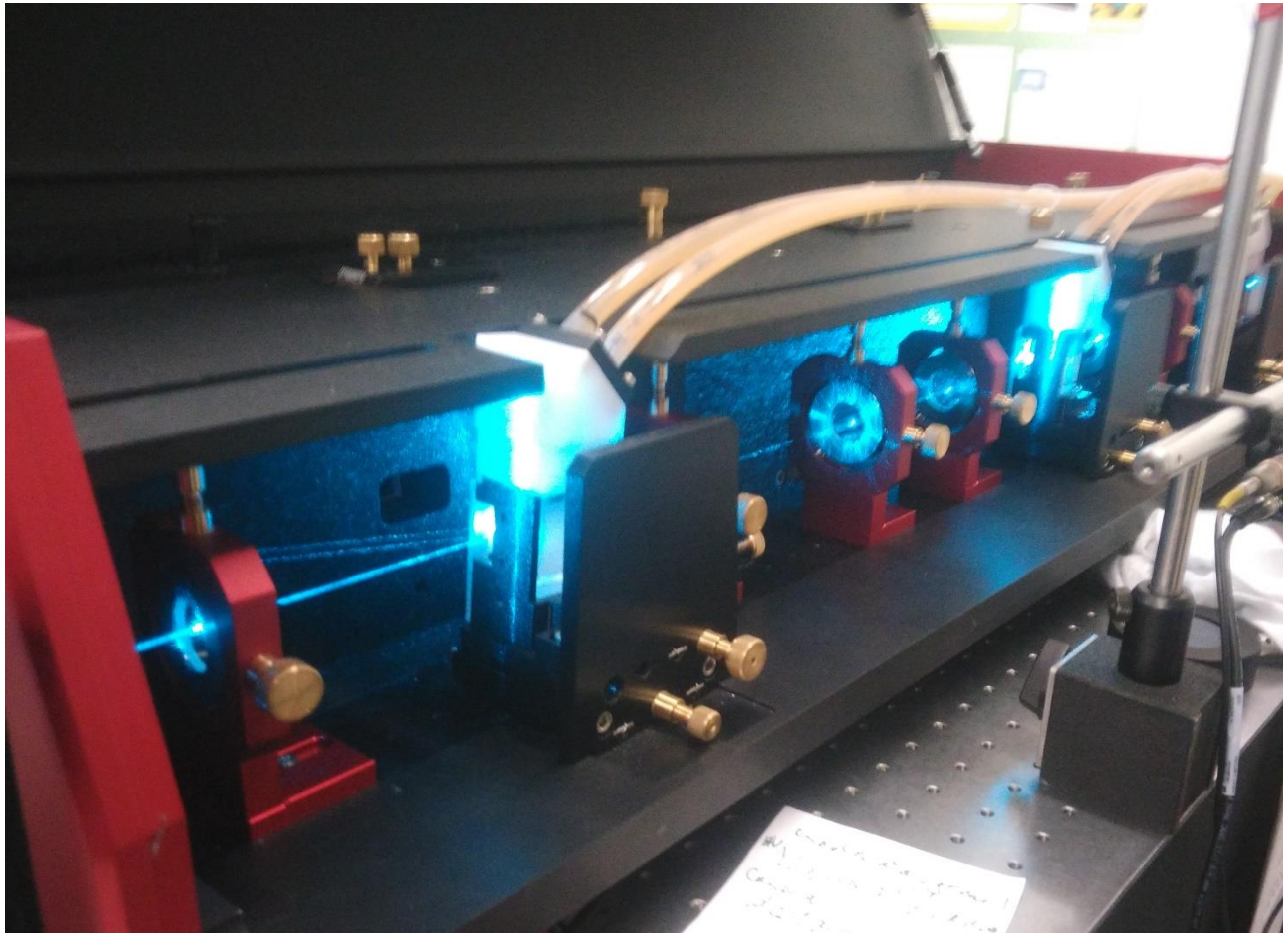


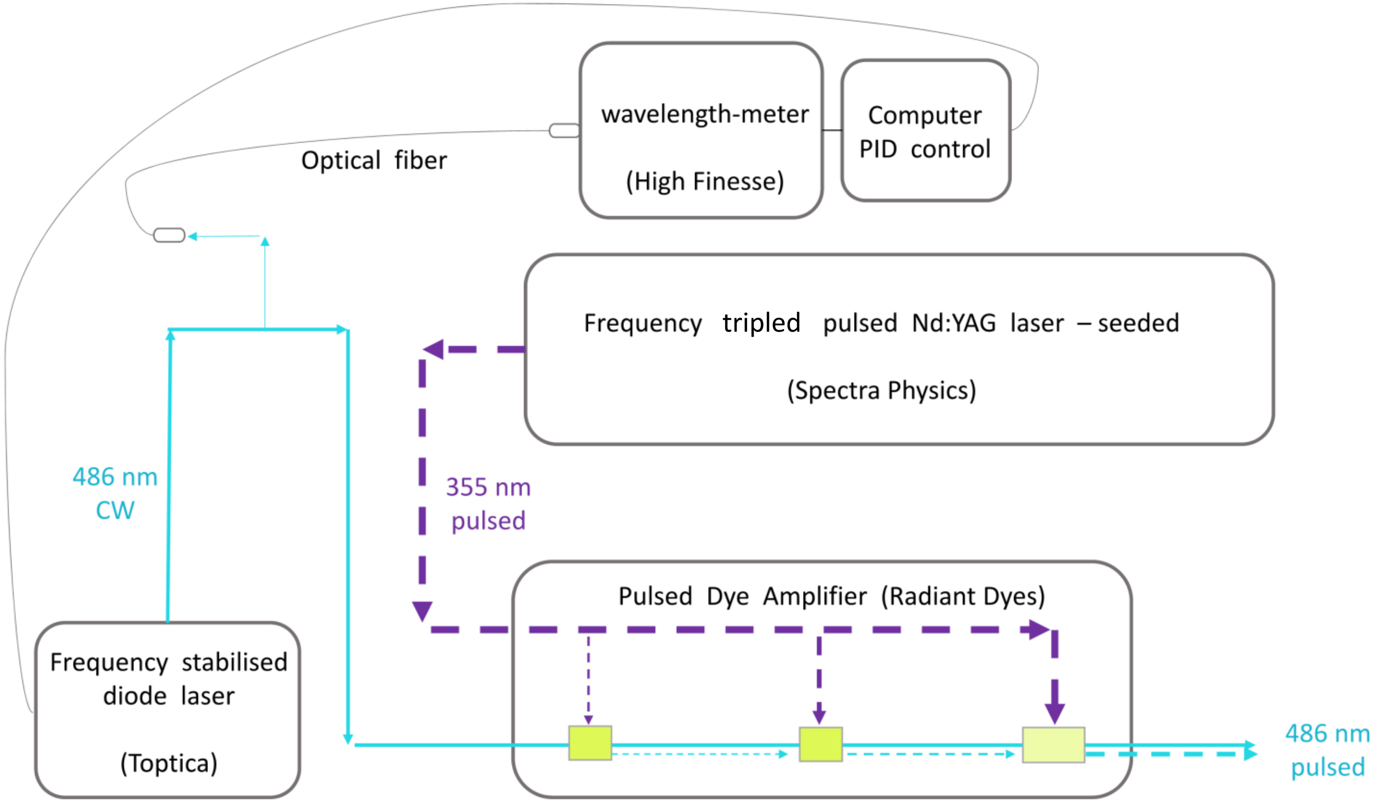
Ps HFS: 2s Laser excitation

- Pulsed laser setup



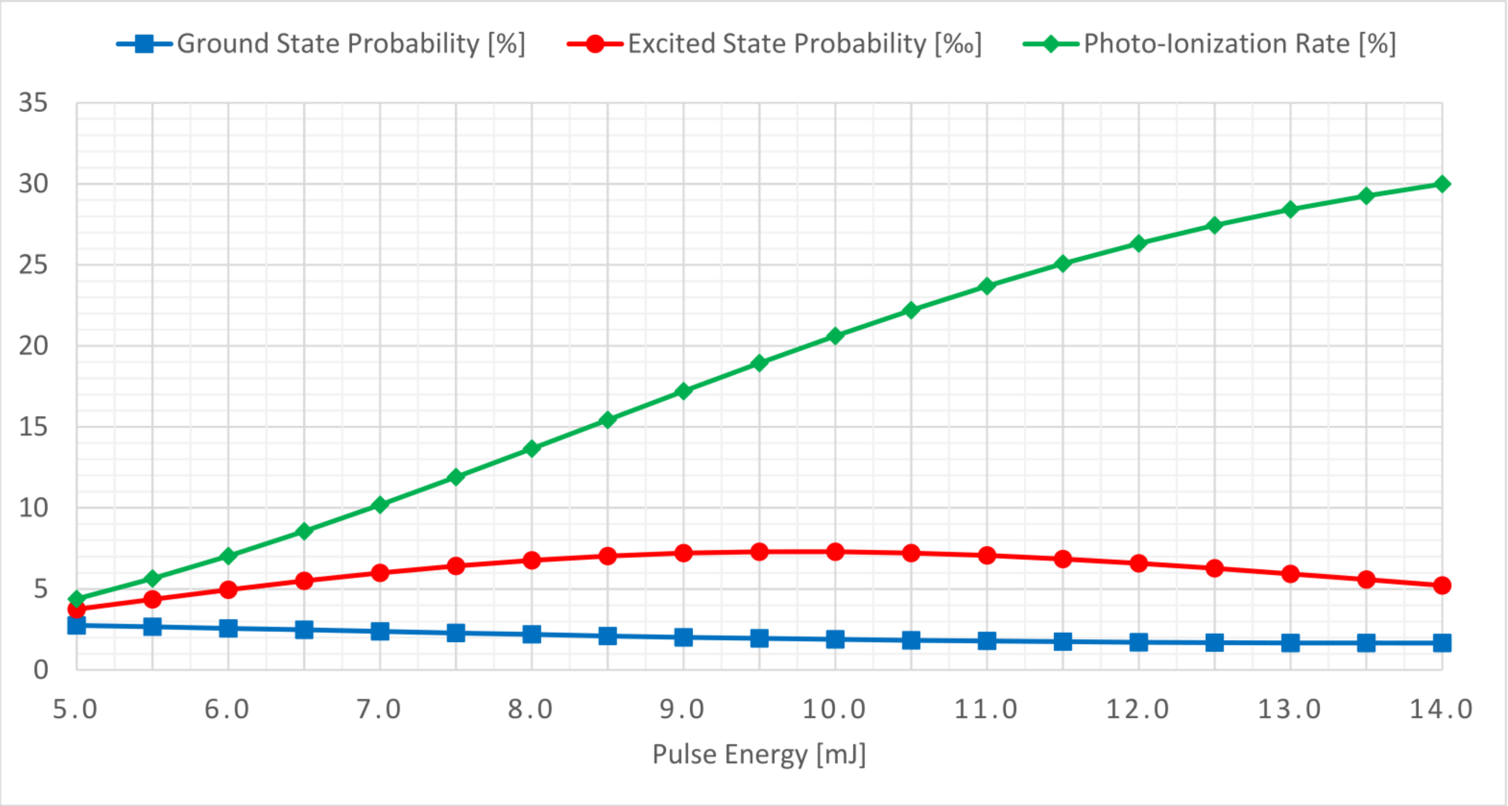
Ps HFS: 2s Laser excitation

- Pulsed laser setup
- Multi-purpose system
  - HFS spectroscopy
  - 1s-2s spectroscopy
  - Rydberg excitation



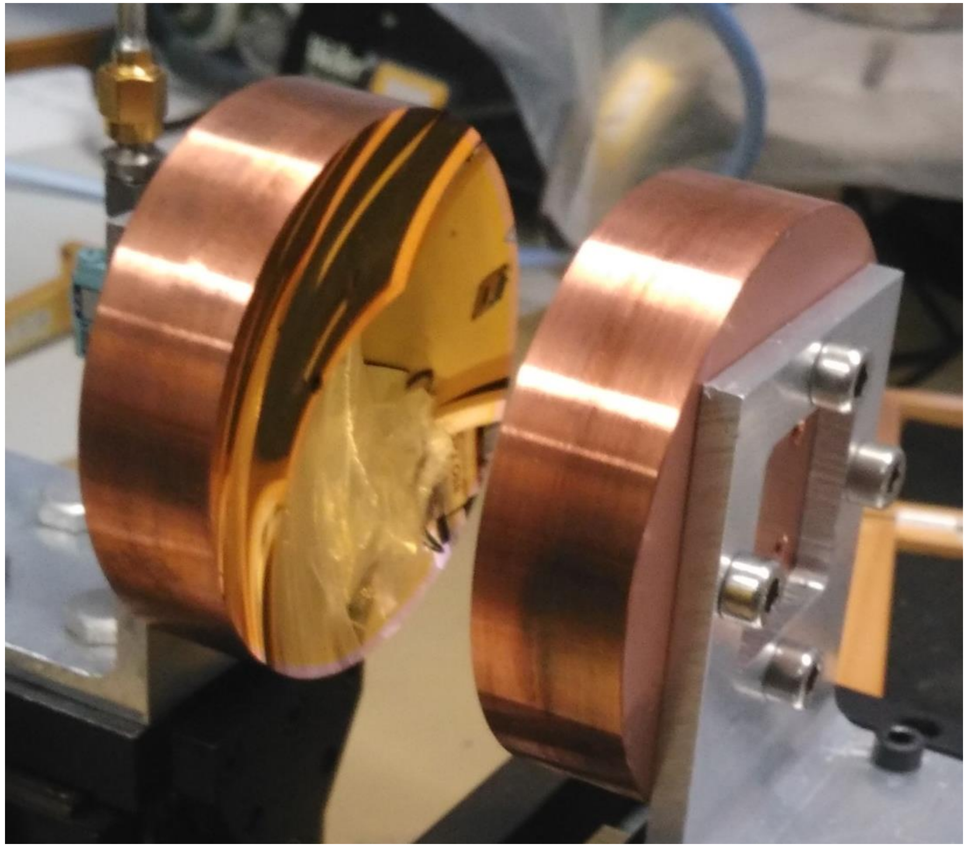
Ps HFS: 2s Laser excitation

- Pulsed laser setup
- Multi-purpose system
  - HFS spectroscopy
  - 1s-2s spectroscopy
  - Rydberg excitation
- Simulation
  - ≈ 1% of Ps available for HFS
  - limited by
    - photoionization
    - oscillation back to ground state



Ps HFS: Microwave system

- Confocal resonator @ 25.4 GHz
  - two spherical mirrors
  - impedence matched coupling hole
  - waveguide signal feed (TWT amplified)



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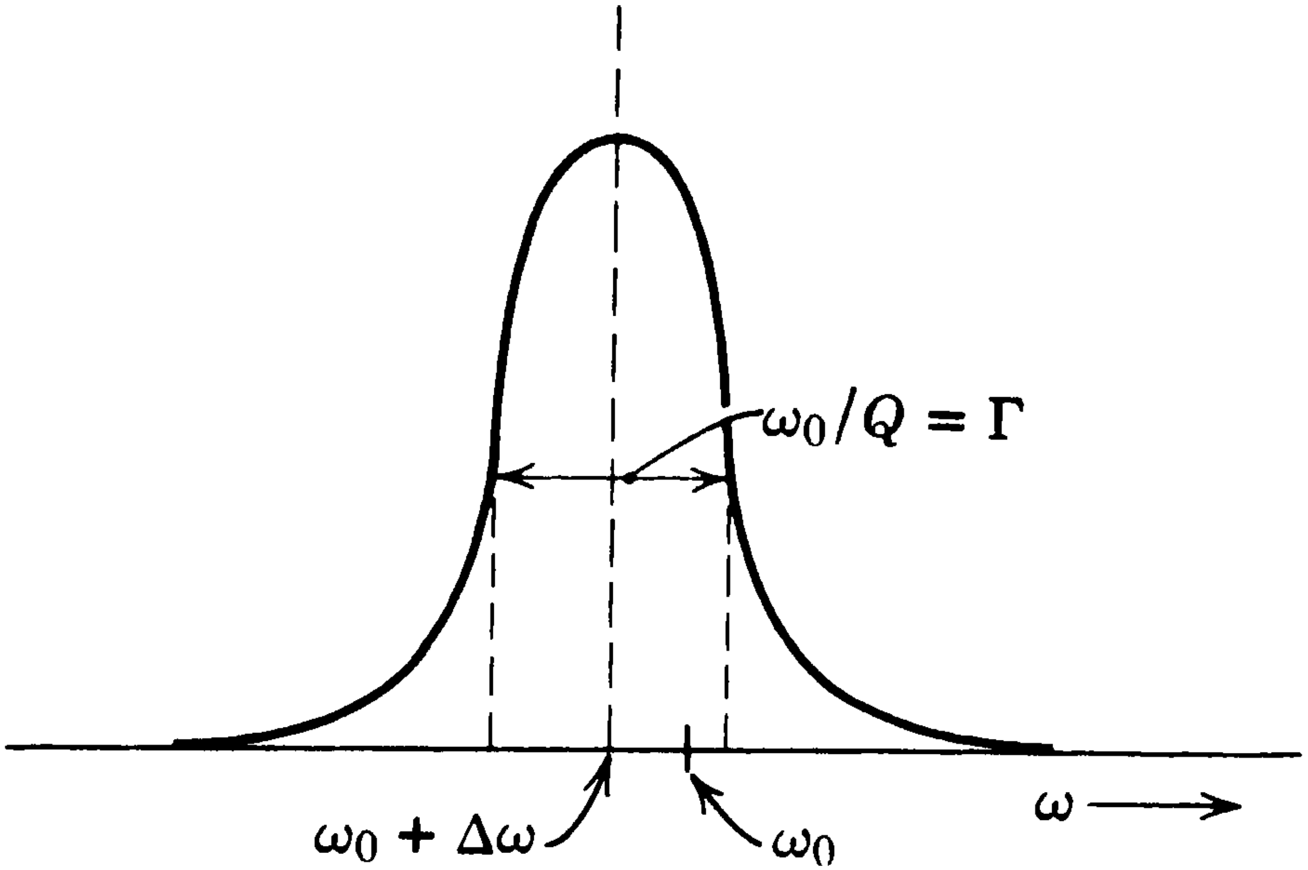
- Quality factor: $Q \approx 50000$
  - $Q = \frac{\nu_0}{\Delta\nu}$
  - $Q = 2\pi \frac{energy\ stored}{energy\ lost\ by\ cycle}$



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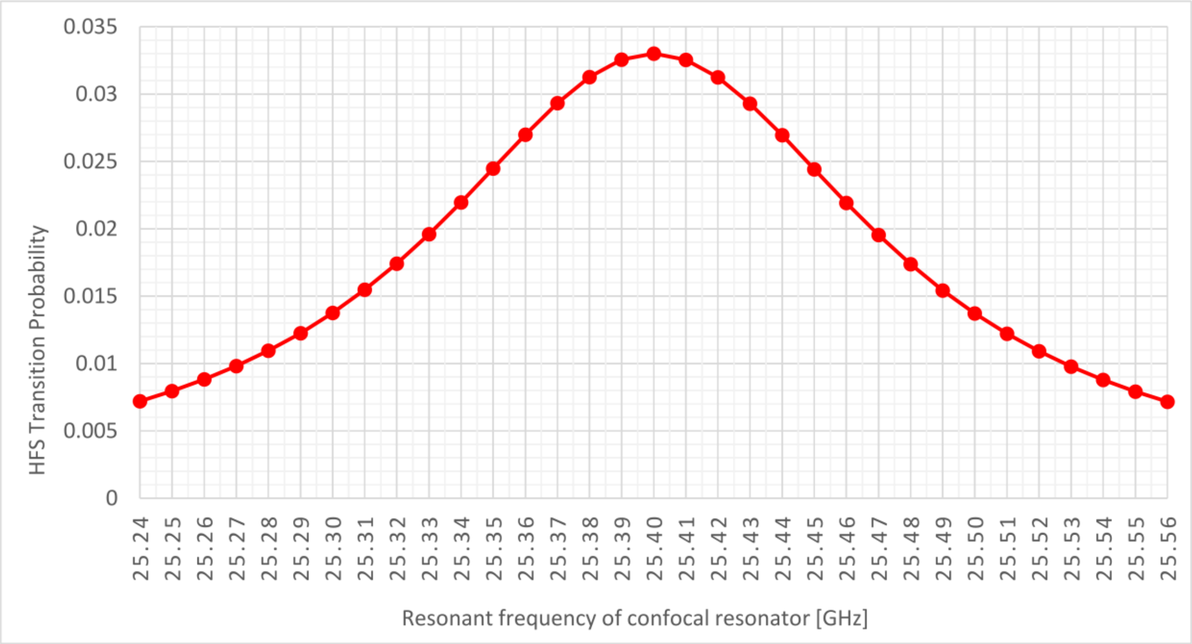
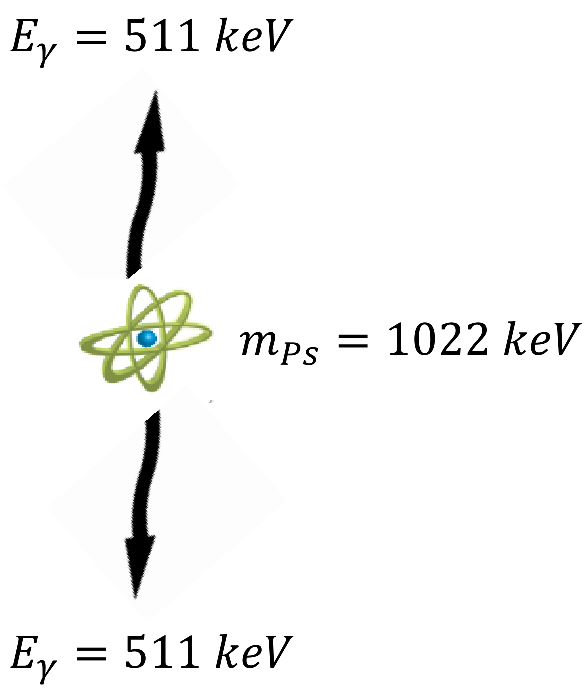
- Simulation
  - HFS transition probability ≈ 3.5%



Ps HFS: Event signature

- Experimental signature (pPs decay)
  - 2 matching back-to-back 511 keV photons
    - temporal coincidence in opposite detector modules
    - intersection of connecting line with target region
    - energy cut



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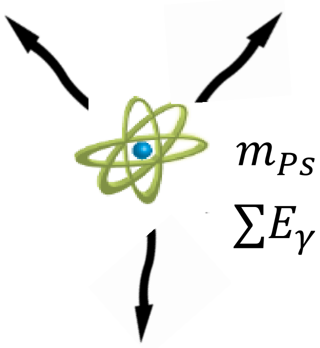

$$m_{Ps} = 1022\ keV$$

$$\sum E_{\gamma} = 1022\ keV$$

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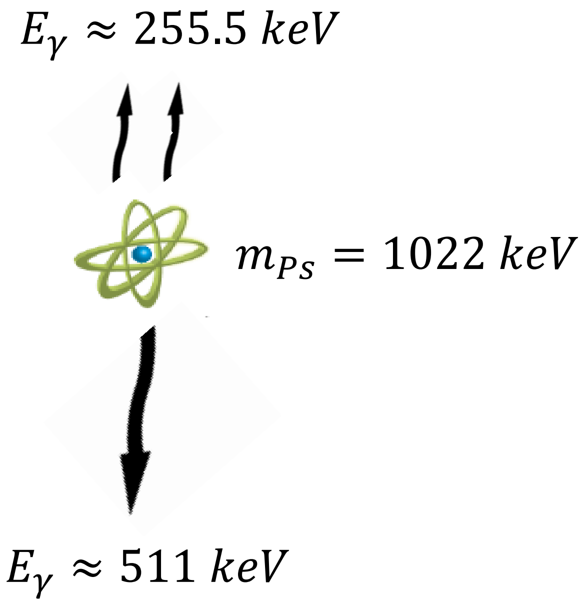

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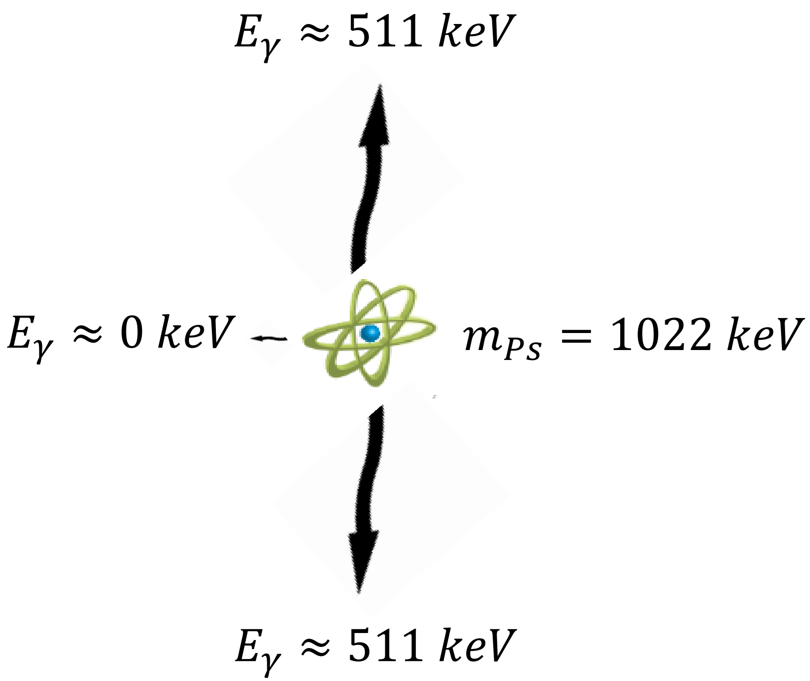

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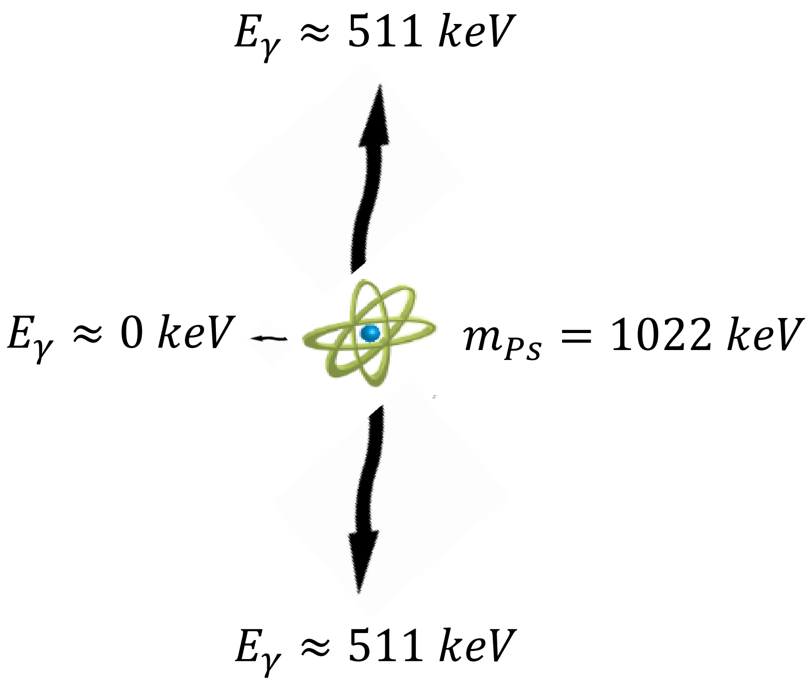
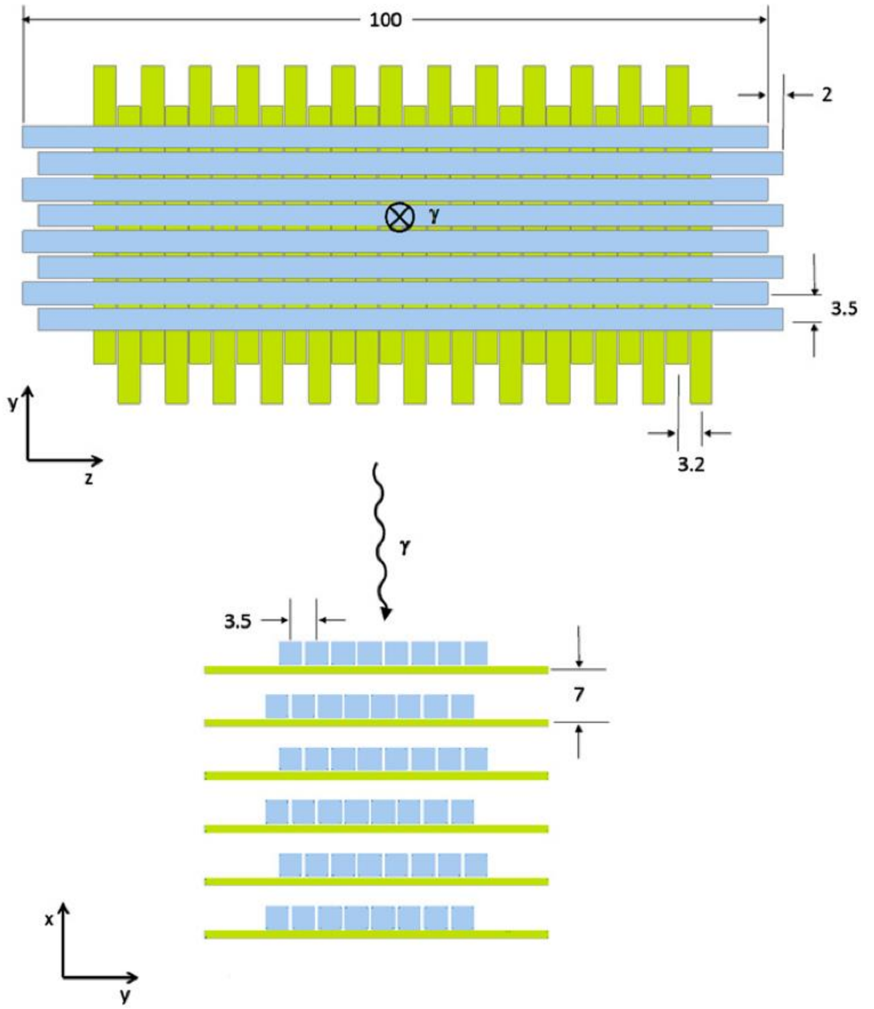
  - misidentification of 3 photon decays as 2 photon decays
    - very small angle between 2 of the 3 photons
    - one photon very soft
- Ground state positronium
  - removed by time of flight (separation of converter and cavity)



Ps HFS: Detector – AxPET

- AxPET demonstrator
  - provided by ETH group of Prof. Dissertori
  - very good temporal and spatial resolution
  - 6 layers per module
  - 8 LYSO crystals
  - 26 wavelength shifters
  - 204 MPPC & bias voltage supply channels
- Reinstrumentation necessary
  - noise reduction
  - new DAQ
    - PETsys TOFPET2



- Beltrame et al., The AX-PET demonstrator – Design, construction and characterization. 2011.

Ps HFS: Simulation results

- Simulation
  - average rate of 4×10^5 e^+/s
  - 30% Ps conversion efficiency
- optimization for S/N
  - ~3% detection efficiency
  - 1 misidentified oPs event for ~40 signal events

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- optimization for S/N
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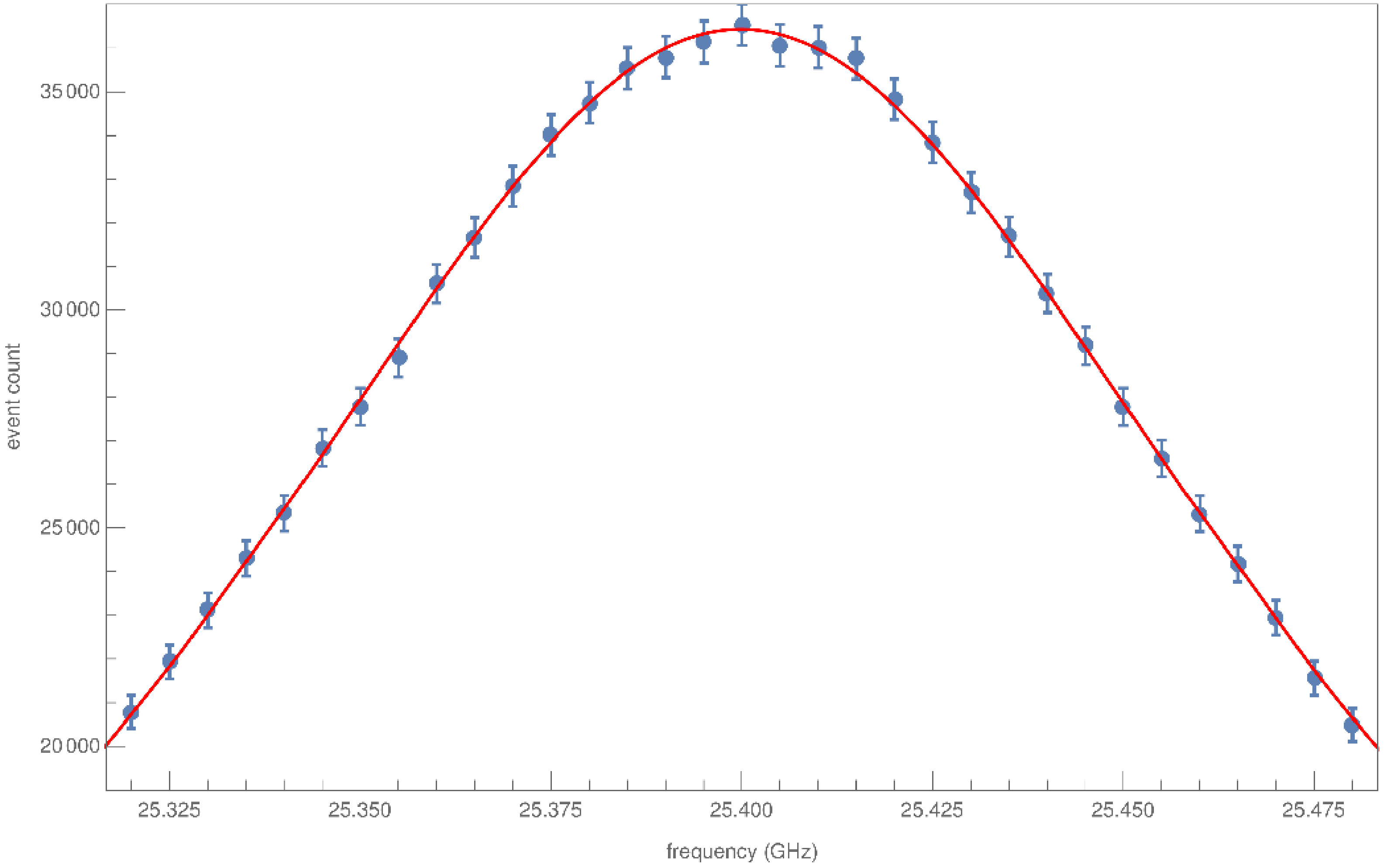
  - 1 misidentified oPs event for ~40 signal events
- projected sensitivity:
  - ± 5 ppm (stat)
  - ppm level systematics



Ps HFS: Status, outlook

- Status
  - 2s excitation is currently being tested with pulsed dye amplifier
  - microwave cavity succesfully tested
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- Status
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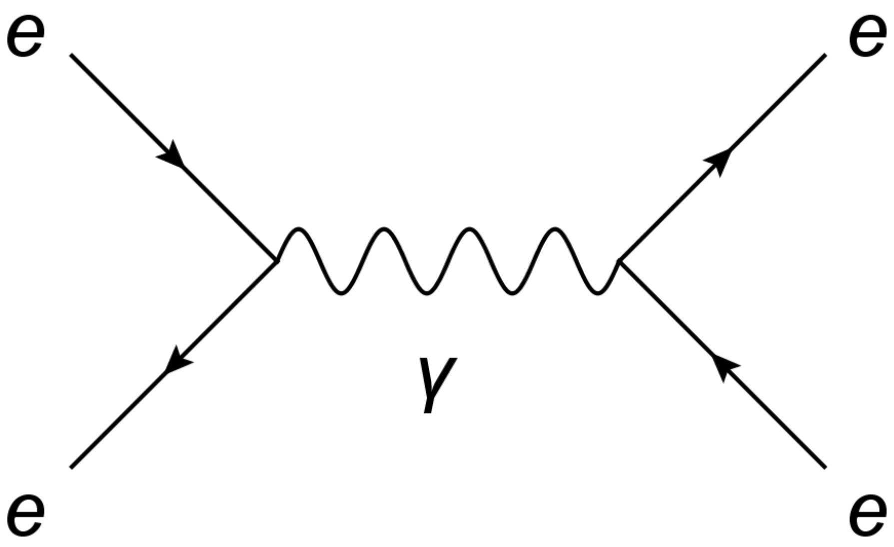
- Outlook
  - precision of a few ppm should be achievable → resolve discrepancy with bound state QED
  - more precise measurements feasible
    - LN2 cooling of resonator (increase Q factor significantly)
    - increase MW power (TWT amplifier)
    - improved event analysis (pattern recognition, e.g. neural net)
    - limited by systematic uncertainties

Thank you for your attention

Backup Slides

Positronium Spectroscopy

- Ps is purely leptonic system
- Free from (well, almost)
  - QCD effects
  - weak force effects
- Precision test bench for
  - bound state QED



$$Vertex \sim \frac{1}{137}$$

$$Propagator \sim \frac{1}{1\ MeV^2}$$

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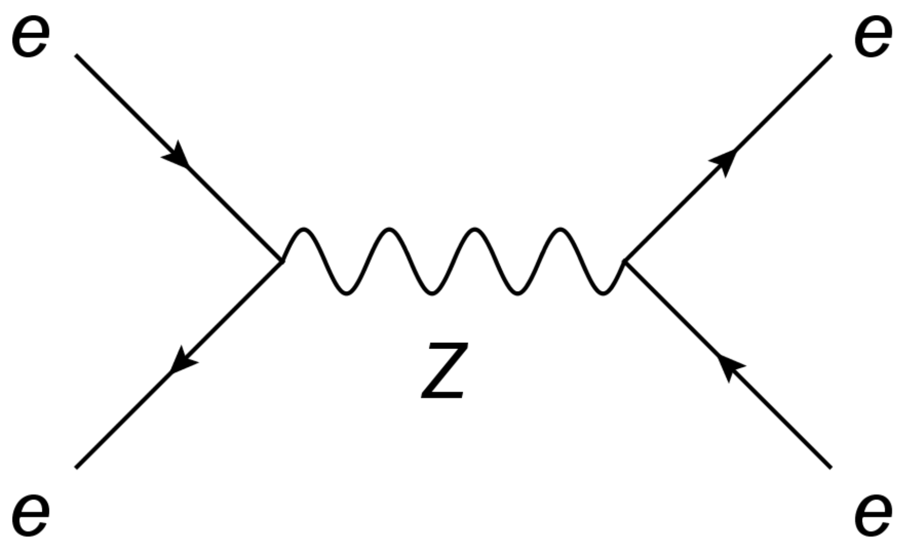

$$Vertex \sim \frac{1}{137} \cdot 2$$

$$Propagator \sim \frac{1}{1\,MeV^2 - 10^{10} MeV^2}$$

Positronium Spectroscopy

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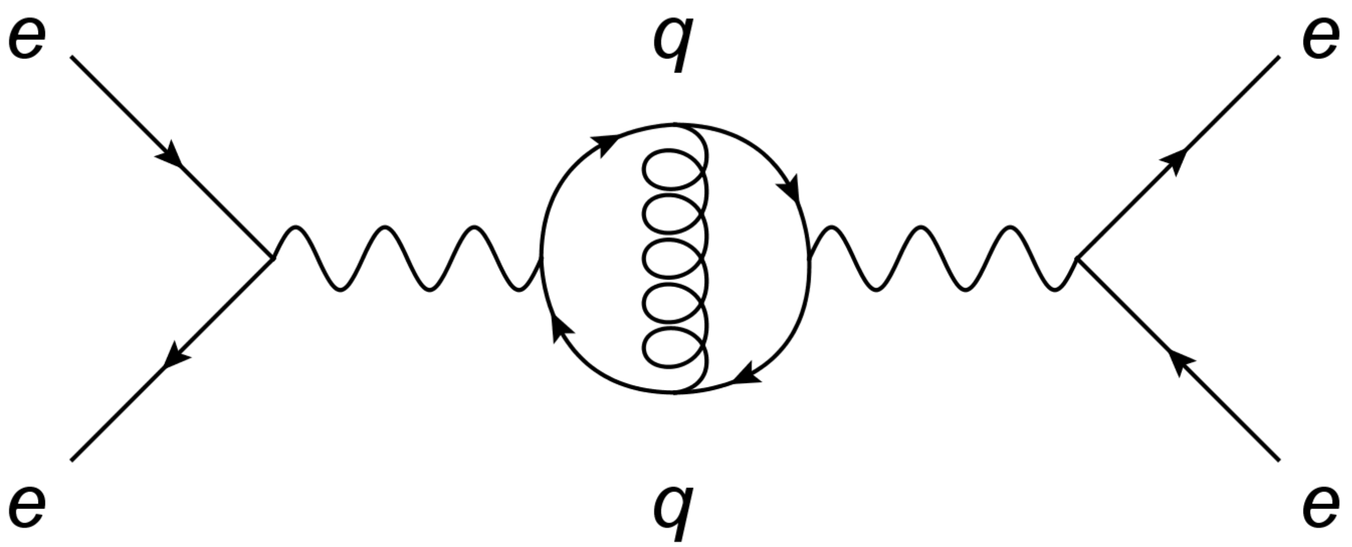
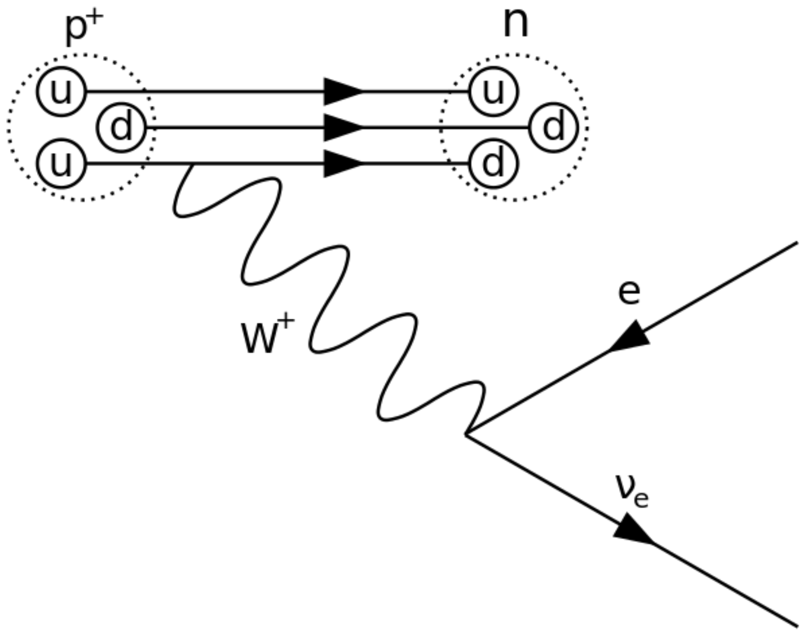


$$Vertex \sim \frac{1}{137} \cdot \frac{1}{137} \cdot \frac{\alpha_S}{16\pi^2} \sim \frac{1}{137} \cdot \frac{2}{10^5}$$

Positron production

- Positrons produced in β^+ decay of ^{22}Na
  - $^{22}Na \rightarrow {}^{22}Ne^* + \nu_e + e^+$
    - continous spectrum: 0 – 543 keV
    - moderate half-life: $\tau_{1/2}$ = 2.6a
  - $^{22}Ne^* \rightarrow {}^{22}Ne + \gamma$
    - discrete energy: 1.27 MeV
    - almost immediate process: 3.7 ps delay
    - can be used to tag β^+ decay of ^{22}Na
- Need for moderate rate sources
  - CW beam: 300 MBq
  - Pulsed beam: 350 MBq



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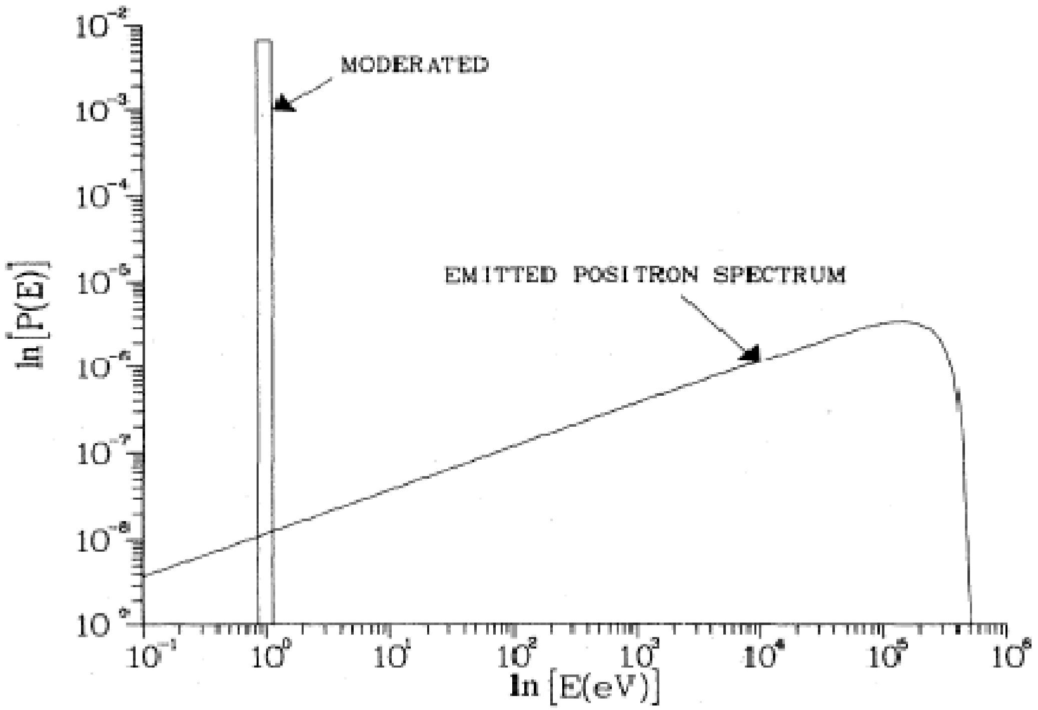
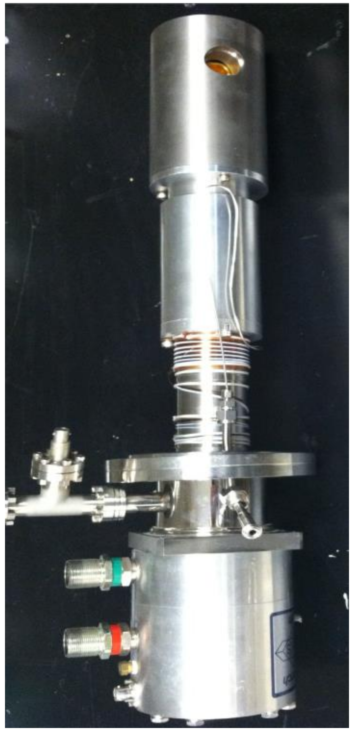
- Need moderation: solid rare gas moderator



Positron moderation

- Large energy spread: use moderation
- Solid rare gas moderation
  - 4K cold head
  - tungsten allow shield



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  - ^{22}Na in capsule with
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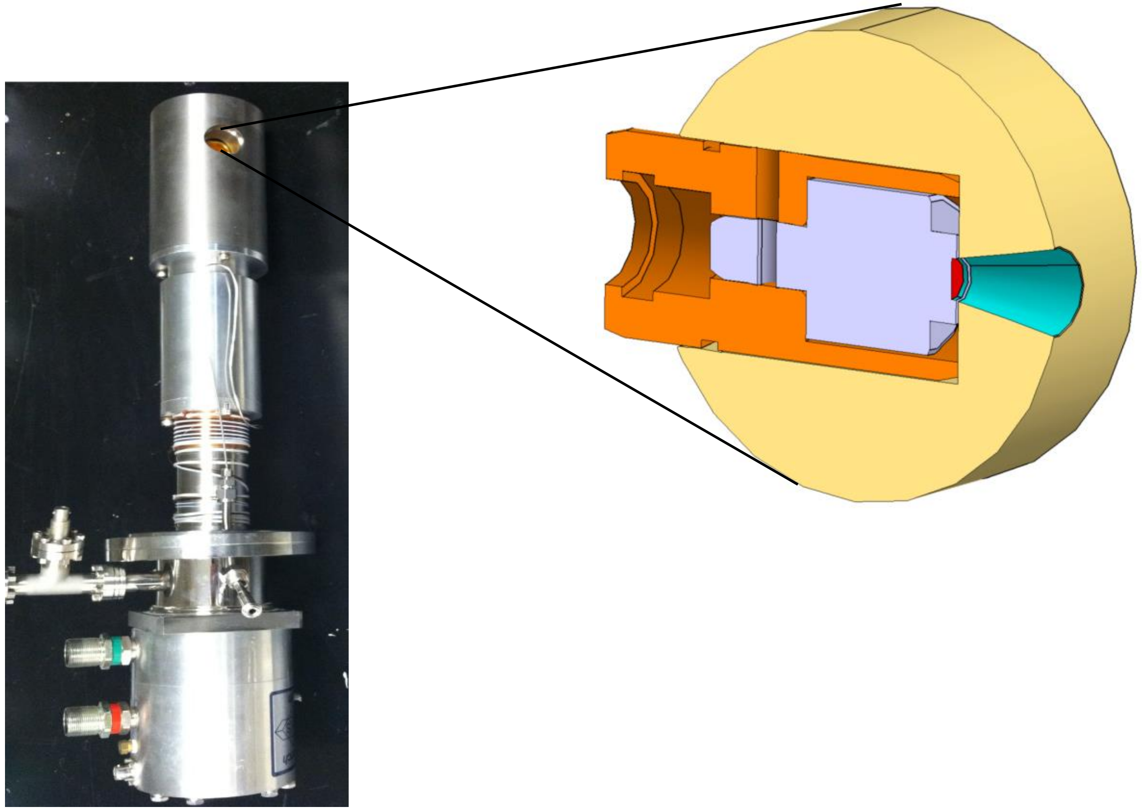
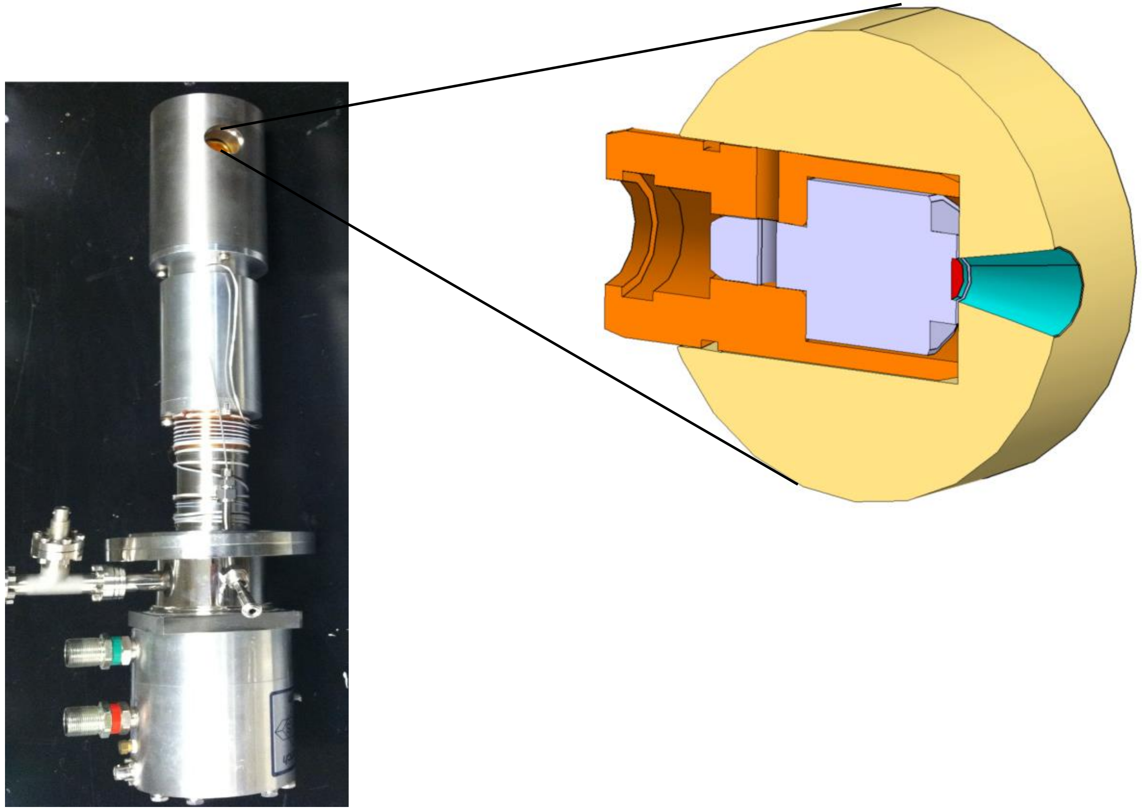


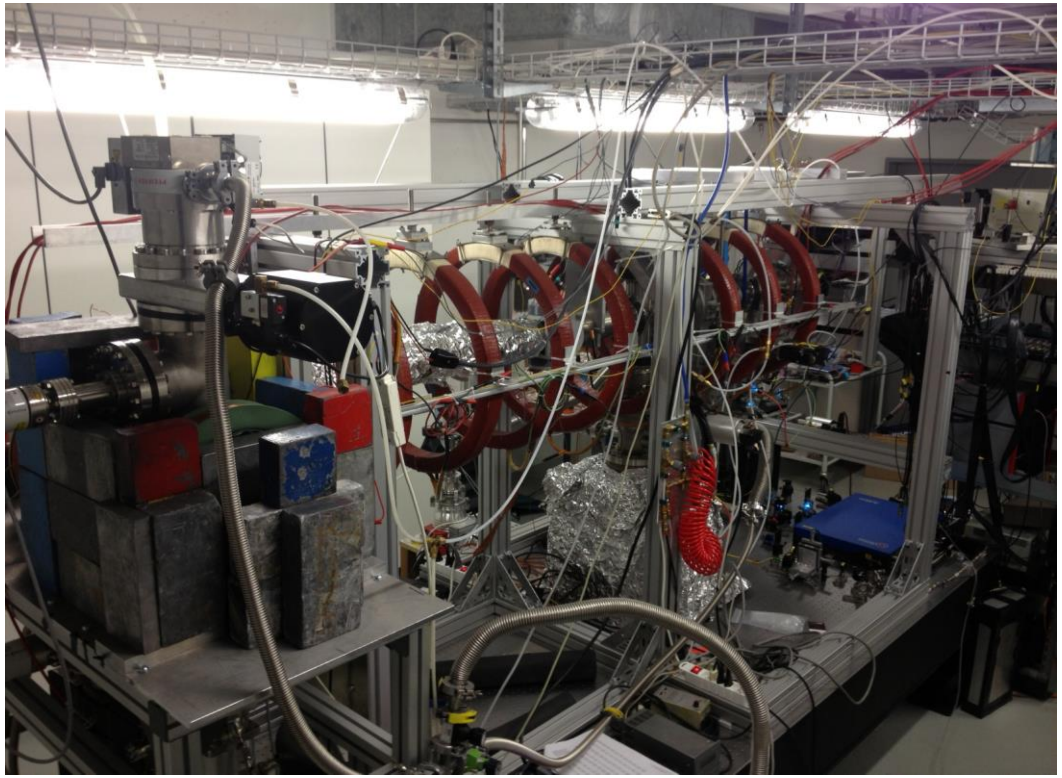
Positron moderation

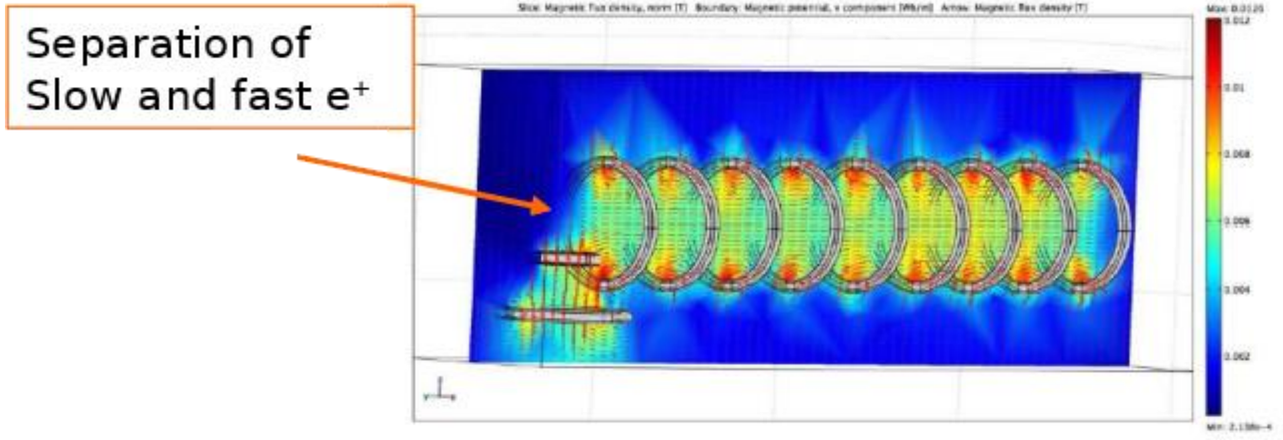
- Large energy spread: use moderation
- Solid rare gas moderation
  - 4K cold head
  - tungsten allow shield
  - ^{22}Na in capsule with 5µm titanium window
  - solid neon film is grown
    - e^+ loses energy only inefficiently below band gap (≈20eV)
    - large fraction of e^+ is emitted into vacuum with epithermal energies



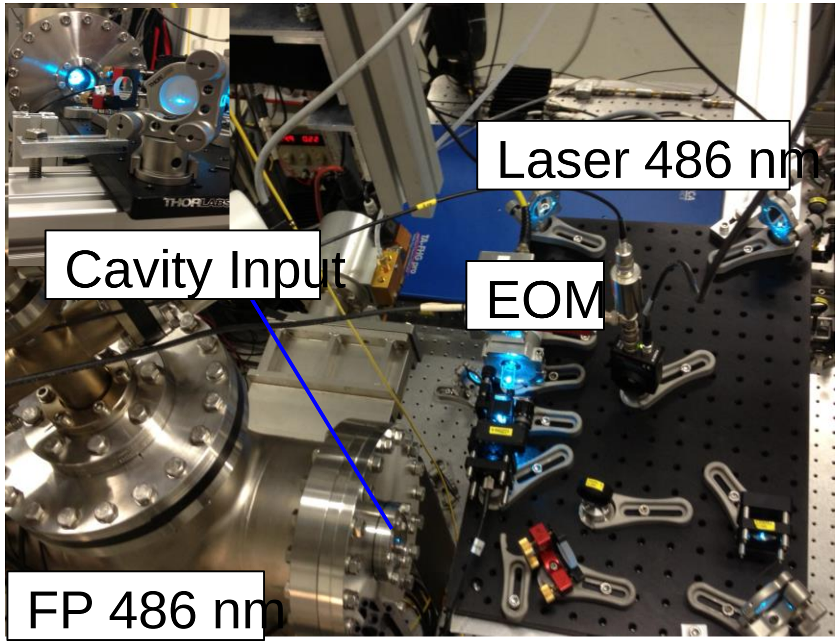
Transportation of slow positrons

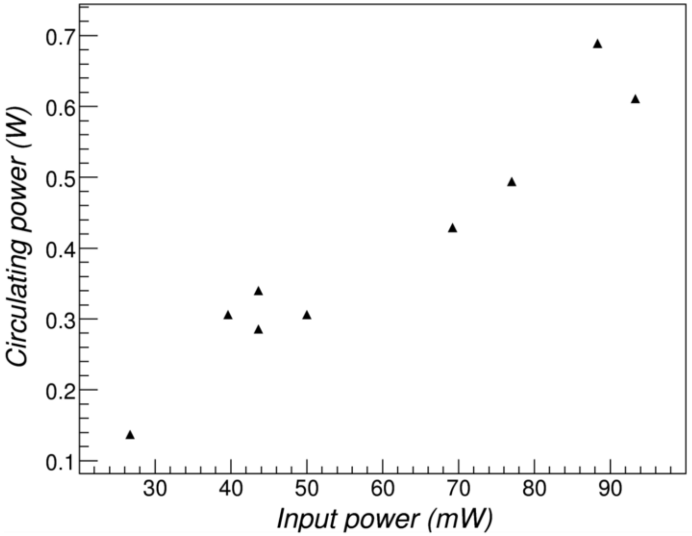
- Positrons follow magnetic field lines
- quasi-uniform longitudinal field of 70 Gauss

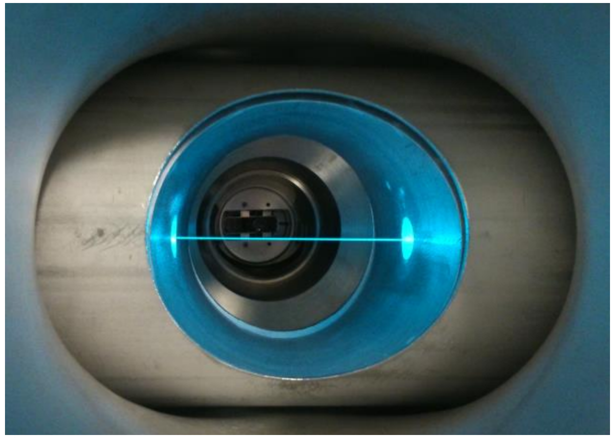




Ps 1s-2s: enhancement cavity







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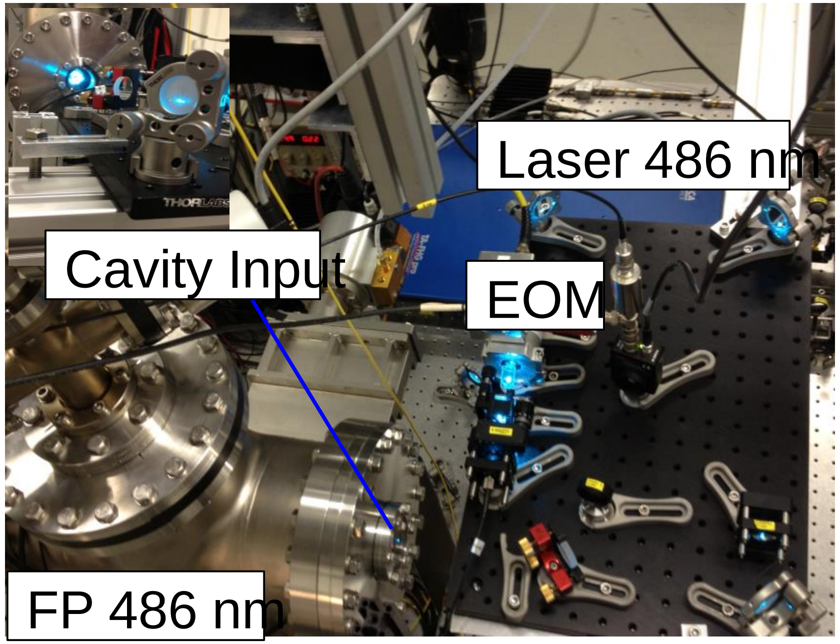
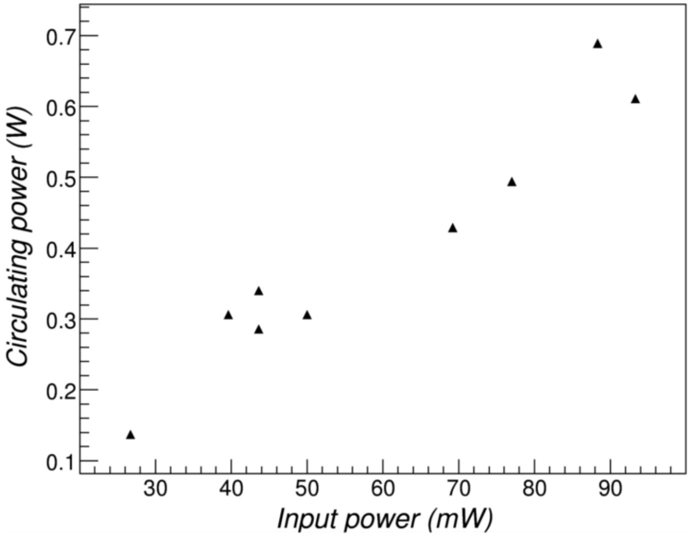
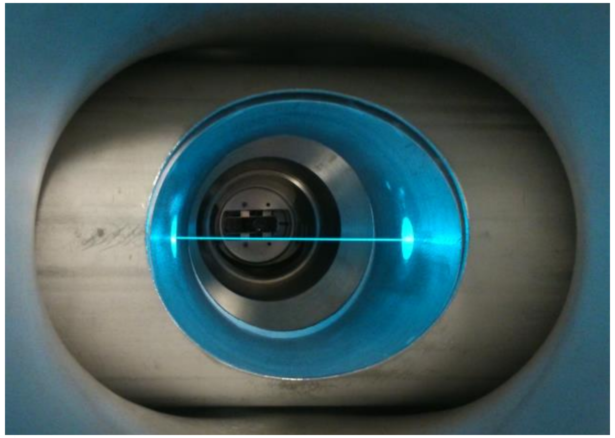




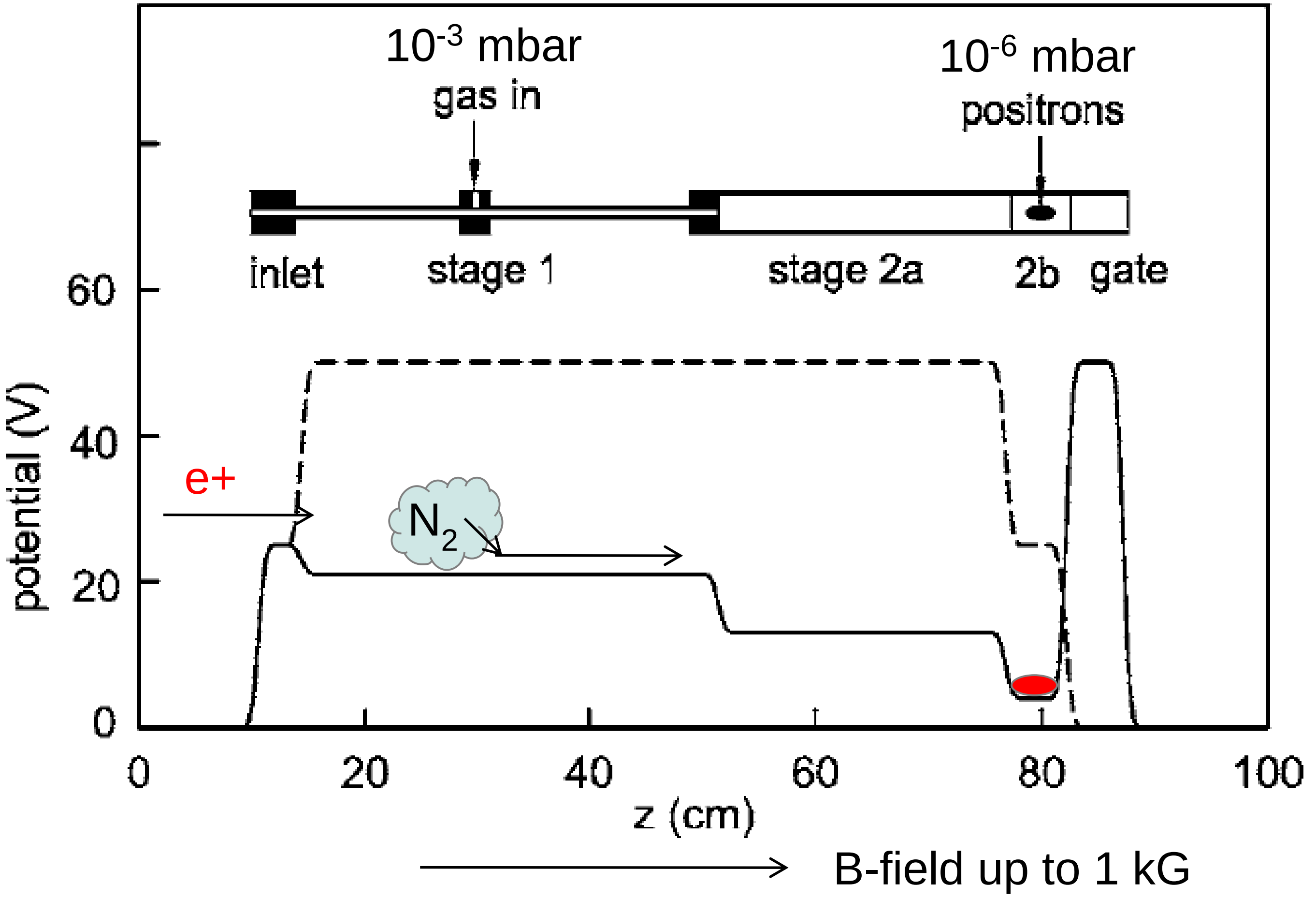


At 0.4 MW/cm^2 (0.7 kW circulating power) mirror degradation observed.

Run @ 0.4-0.5 kW:
-> Excitation prob ~ 1x10^{-4}
-> Resonant 3γ PI ~ 1x10^{-5}

Generation of 500 W, no degradation over hours of continuous operation.

Ps 1s-2s: buffer gas trap



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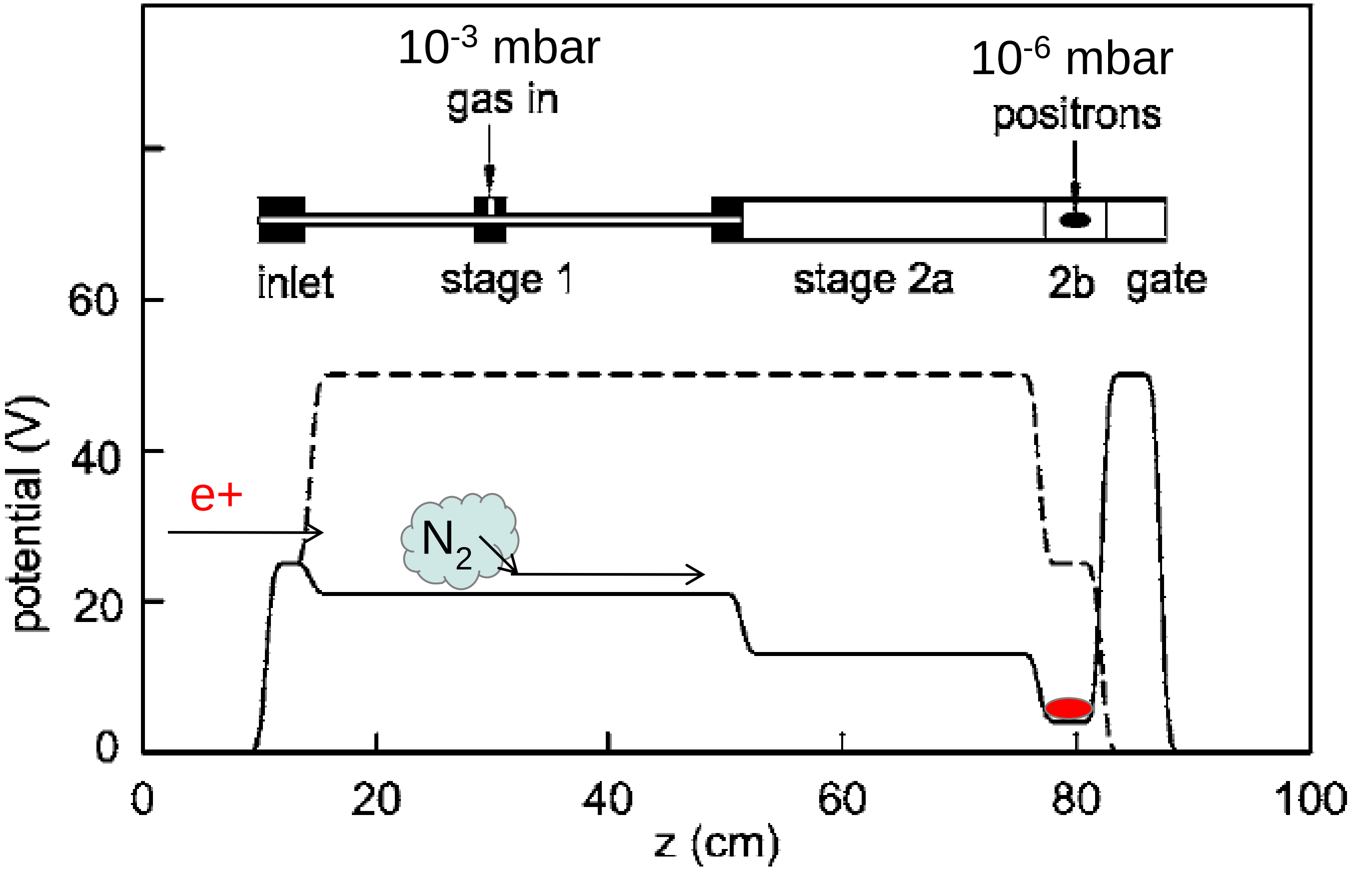
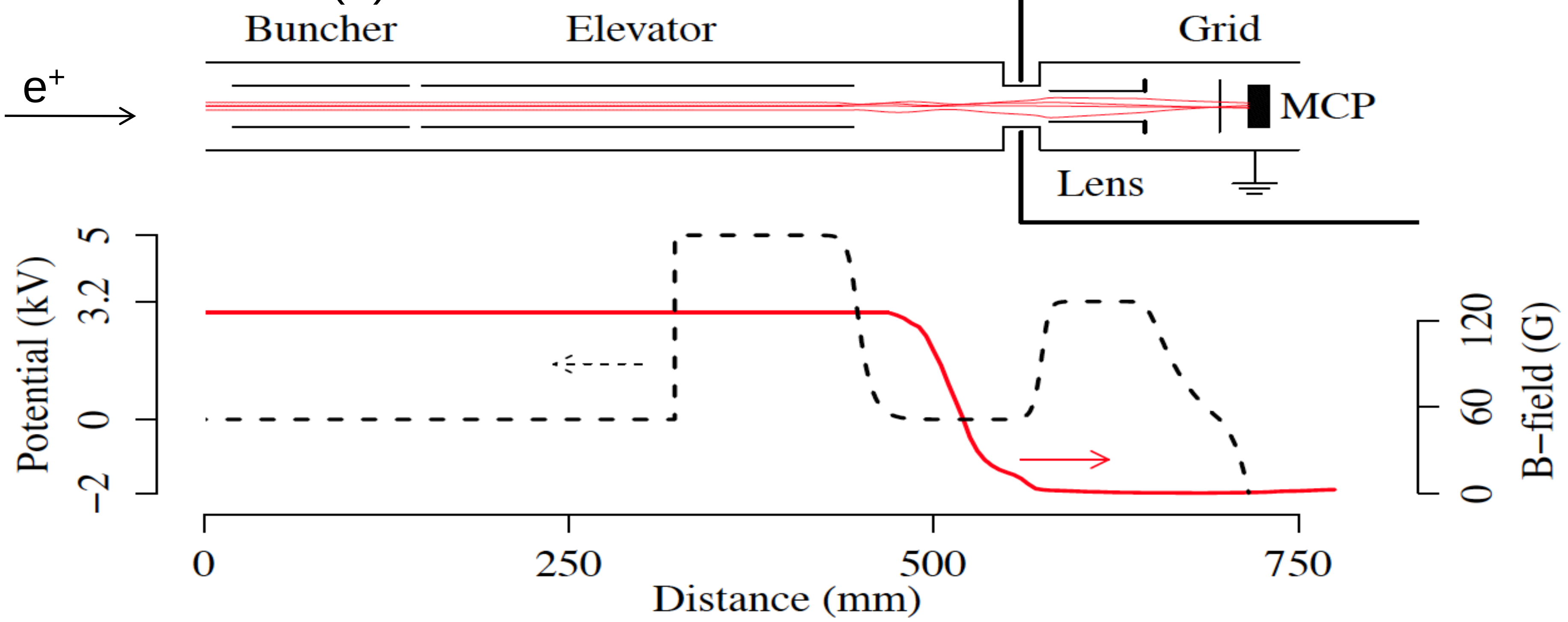


B-field up to 1 kG

Positrons in few eVs
bunches (50 ns)
At 10 Hz rep rate

Ps 1s-2s: positron bunching and extraction

Positron (7 eV) bunches from the trap
50 ns and 1 mm (σ) in 120 G



On target (kept at ground): positron bunches of 1 ns with a beam spot of 1 mm extracted to the field free e-m region with 90 % efficiency.

- D. A. Cooke G., Barandun, S Vergani,, B Brown, A Rubbia and P Crivelli, J. Phys. B: At. Mol. Opt. Phys. 49 014001 (2016).

Ps HFS: Review - First direct measurement

- Notoriously difficult ($\Delta\nu = 203\ GHz$)
  - no off-the-shelf sources
  - no off-the-shelf resonators
  - behavior somewhat between microwave and light
- Multiple resonators required
  - need to be changed for every frequency point
- Needs very high MW power
  - very rudimentary power estimation
    - measured the heat absorbed by water

Parameter
$\Delta^{\mathrm{Ps}}_{\mathrm{HFS}}$ [GHz]
Theory
203.391 69(16)
Direct Measurement
$203.39^{+0.15}_{-0.14} \pm 0.11$

- A. Miyazaki et al. First millimeter-wave spectroscopy of ground-state positronium. *Progress of Theoretical and Experimental Physics*, 2015(1), 2015.