Testing antigravity with Positronium 1S-2S spectroscopy

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and ETH under the research grant ETH-47-12-1

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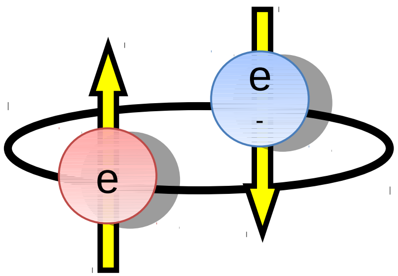
Positronium (Ps)

Two ground states:

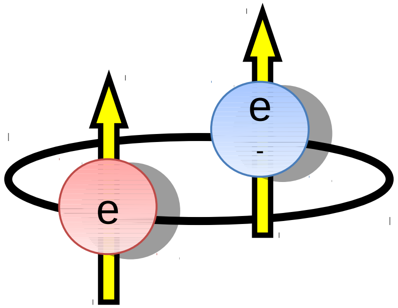
Parapositronium (p-Ps) singlet spin state $^1S_0$



.

$$|0,0\rangle = (\uparrow\downarrow - \downarrow\uparrow)/\sqrt{2} \Big\} \quad s = 0 \quad \text{(singlet)}$$

Orthopositronium (o-Ps) triplet spin state $^3S_1$



$$\left.\begin{aligned} |1,1\rangle &= \uparrow\uparrow \\ |1,0\rangle &= (\uparrow\downarrow + \downarrow\uparrow)/\sqrt{2} \\ |1,-1\rangle &= \downarrow\downarrow \end{aligned}\right\} \quad s = 1 \quad \text{(triplet)}$$

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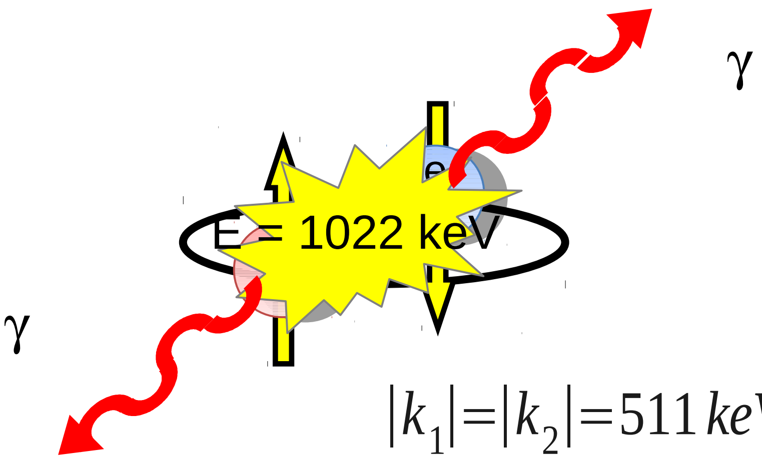

$$|k_1| = |k_2| = 511\, keV$$

.

$$\Gamma^{(0)}_{2\gamma}(n\,^1S_0) = \sigma^1_{2\gamma} v\,|\psi_n(0)|^2 = \frac{1}{2}\,\frac{m_e c^2}{\hbar}\,\frac{\alpha^5}{n^3}$$

Pirenne and Wheeler in 1946

Γ^{-1} = τ **≈ 125 ps (in vacuum)**

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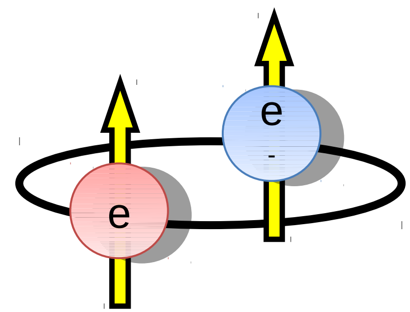

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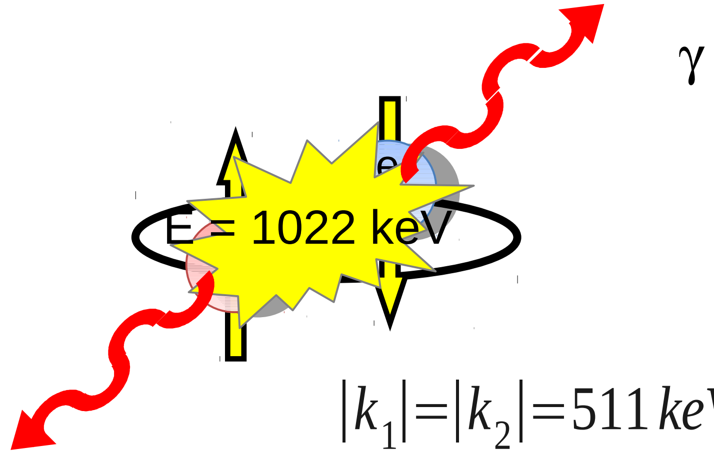

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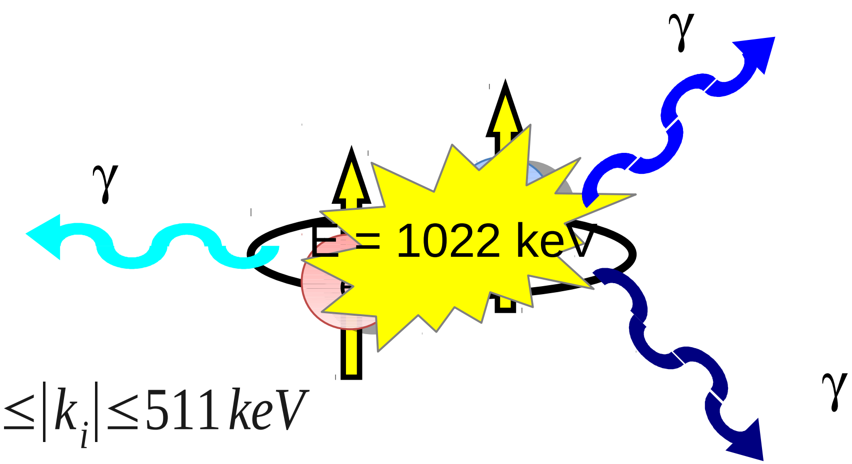


$$0 \le |k_i| \le 511\,keV$$

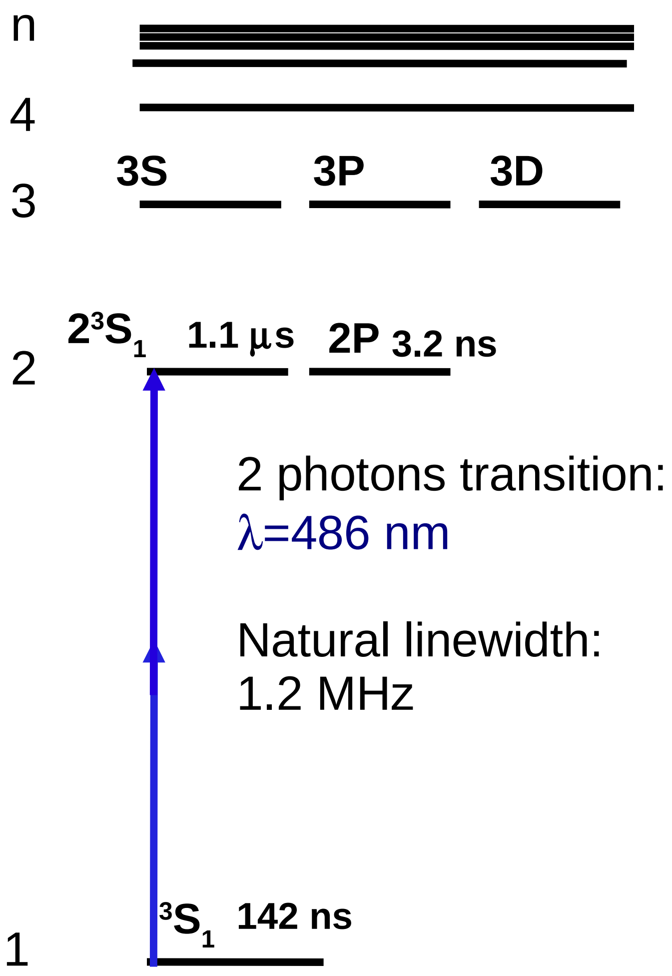
$$\Gamma^{(0)}_{3\gamma}(n\,^3S_1) = \frac{2}{9\pi}\,(\pi^2 - 9)\,\frac{m_e c^2}{\hbar}\,\frac{\alpha^6}{n^3}$$

Ore and Powell in 1949

Γ^{-1} = τ ≈ 142 ns (in vacuum)

Positronium 1S-2S transition

Ps Energy levels



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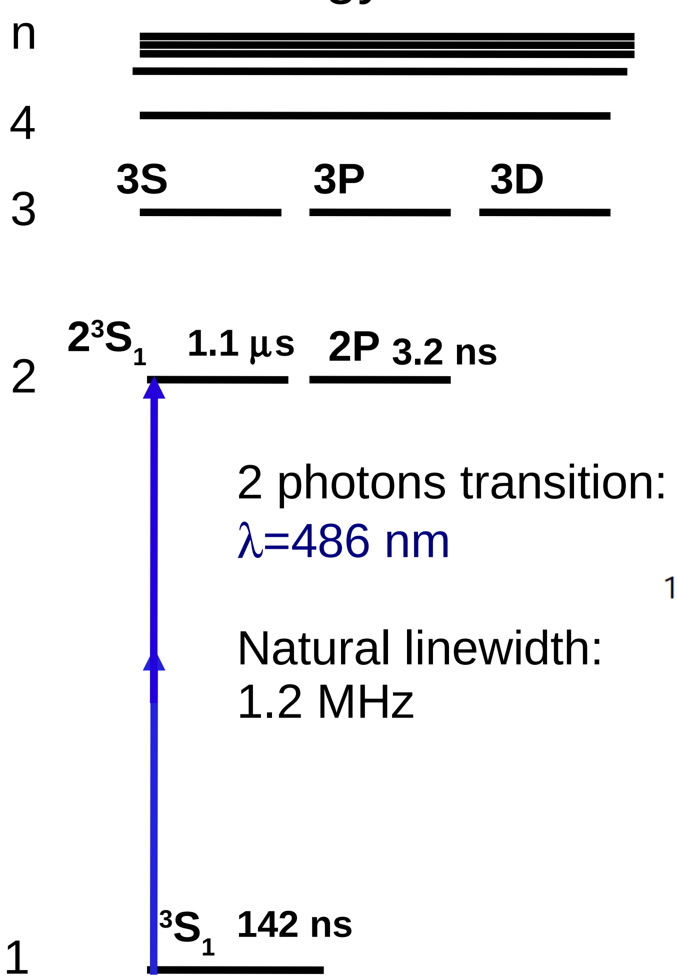

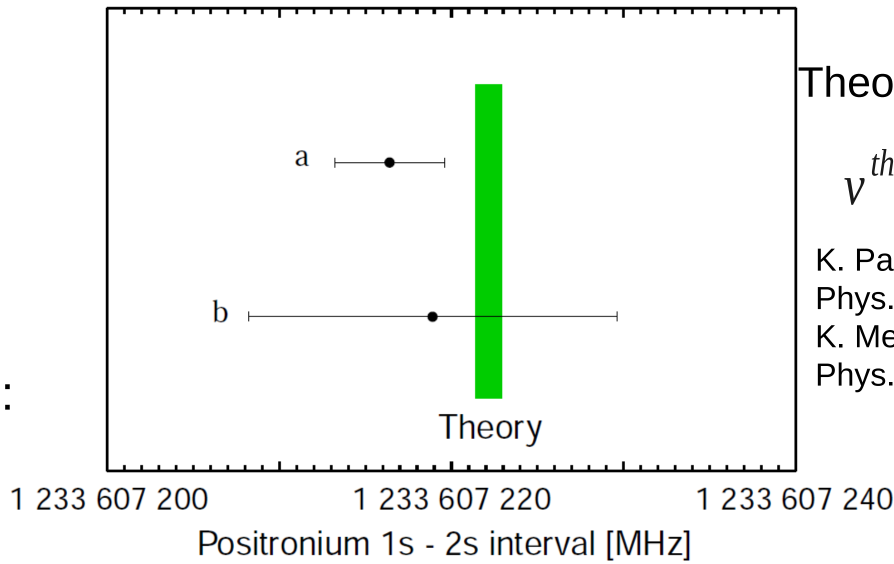

Theory:

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

K. Pachucki and S. G. Karshenboim, Phys. Rev. A60, 2792 (1999), K. Melnikov and A. Yelkhovsky, Phys. Lett. B458, 143 (1999).

Experiments:

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

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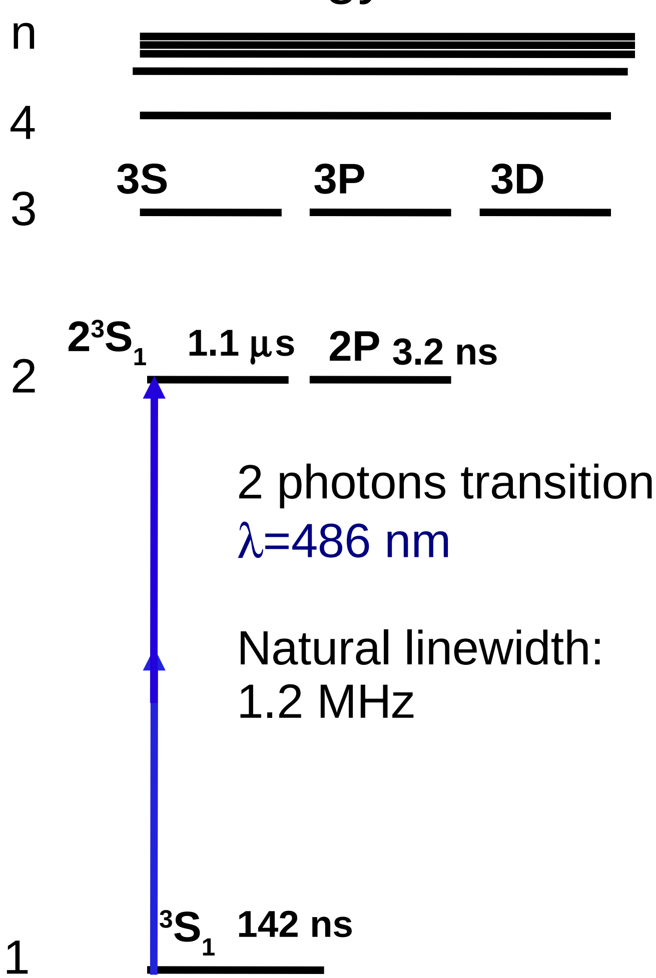
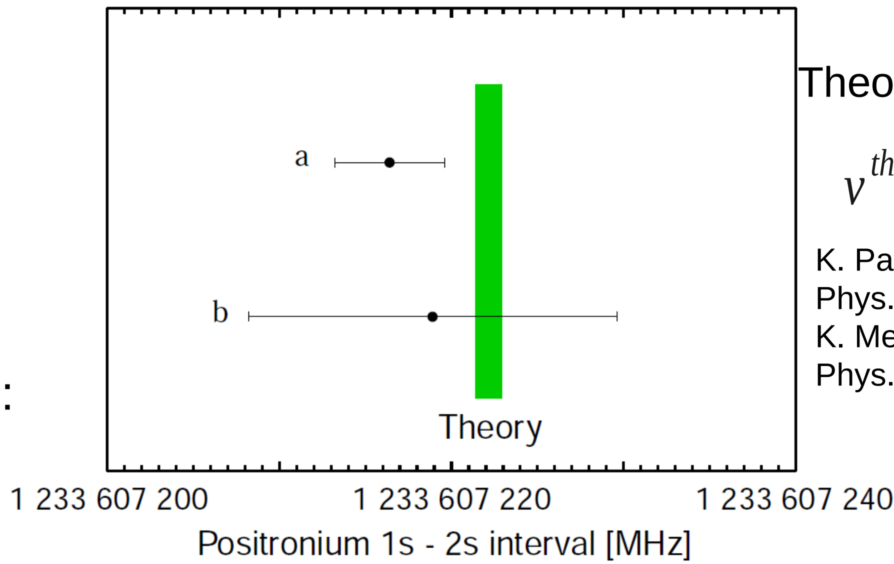


2 photons transition:
λ=486 nm

Natural linewidth:
1.2 MHz



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Measurement of 1S-2S of Ps at a level about $5\text{x}10^{-10}$ => check QED calculations at the order $\alpha^7 m$ and provide best determination of m_{e+}/m_{e-}.

Hydrogen like vs Ps

Various contributions to the energy levels

Contribution	Hydrogen-like electronic atom	Positronium
Schrödinger contributions		
• With $M = \infty$	1	1
• With m_R (correction)	m/M	1
Relativistic corrections		
• Dirac equation	$(Z\alpha)^2$	α^2
• Two-body effects	$(Z\alpha)^2 m/M$	α^2
Quantum electrodynamics		
• Self-energy	$\alpha(Z\alpha)^2 \ln(Z\alpha)$	$\alpha^3 \ln \alpha$
• Radiative width	$\alpha(Z\alpha)^2$	α^3
• Vacuum polarization	$\alpha(Z\alpha)^2$	α^3
• Annihilation		
– Virtual	—	α^2
– Real	—	α^3
Nuclear effects		
• Magnetic moment (HFS)	$(Z\alpha)^2 m/M$ or $\alpha(Z\alpha) m/m_p$	α^2
• Charge distribution	$(Z\alpha mc R_N/\hbar)^2$	—

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Leptonic atoms free of nuclear size effects!

Gravitational Redshift

h

ground state	excited state	transition frequency
$E = m_0c^2 + m_0gh$	$E = (m_0+\Delta m)\,(c^2 + gh)$	$h\nu_h = \Delta m(c^2+gh)$
$E = m_0c^2$	$E = (m_0+\Delta m)c^2$	$h\nu_0 = \Delta mc^2$

S. G. Karshenboim, Astr. Lett. 35, 663 (2009).

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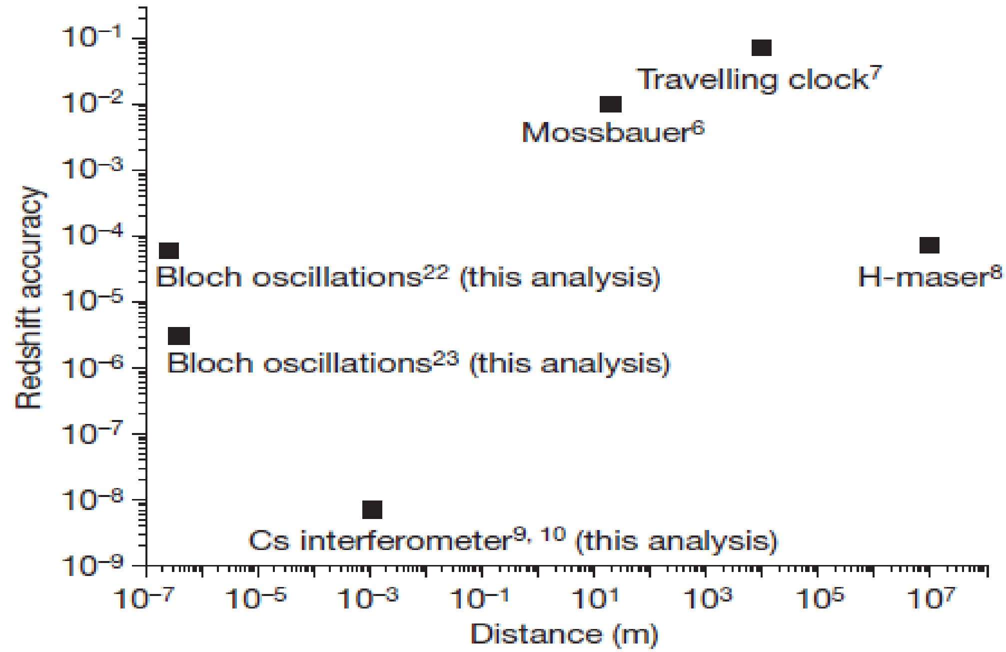
$$\frac{\Delta\nu}{\nu_0} = \frac{\Delta U}{c^2}$$



Muller, Peters, Chu, Nature 463, 08776 (2010)

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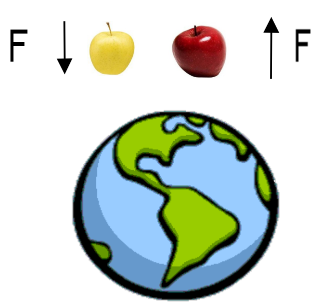
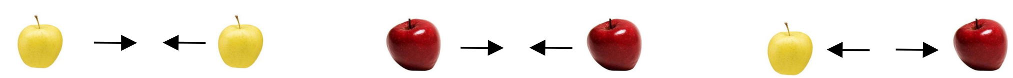
- Assuming antigravity:





$$\nu(r) = \nu_0 \times \begin{cases} \left(1 + \frac{U(r)-U(\infty)}{c^2}\right) & \text{for H} \\ 1 & \text{for Ps} \\ \left(1 - \frac{U(r)-U(\infty)}{c^2}\right) & \text{for } \overline{H} \end{cases}$$ *or Mu*

Gravitational Redshift

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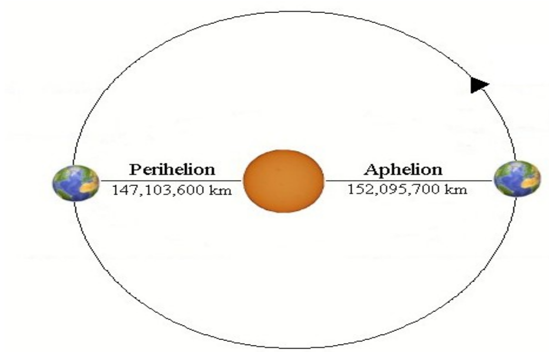
- Variation in the earth orbit around the sun : 5×10^6 km.



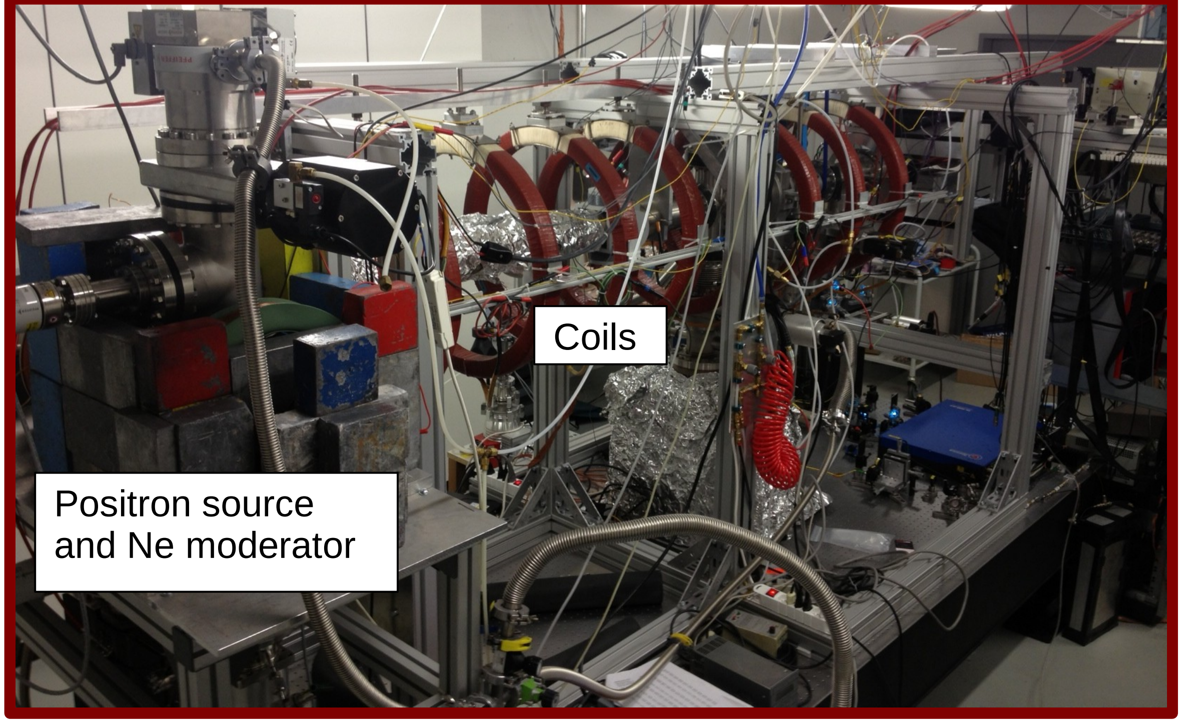
$$\frac{\Delta U(r_{\max}) - \Delta U(r_{\min})}{c^2} \simeq 3.2\times10^{-10}$$

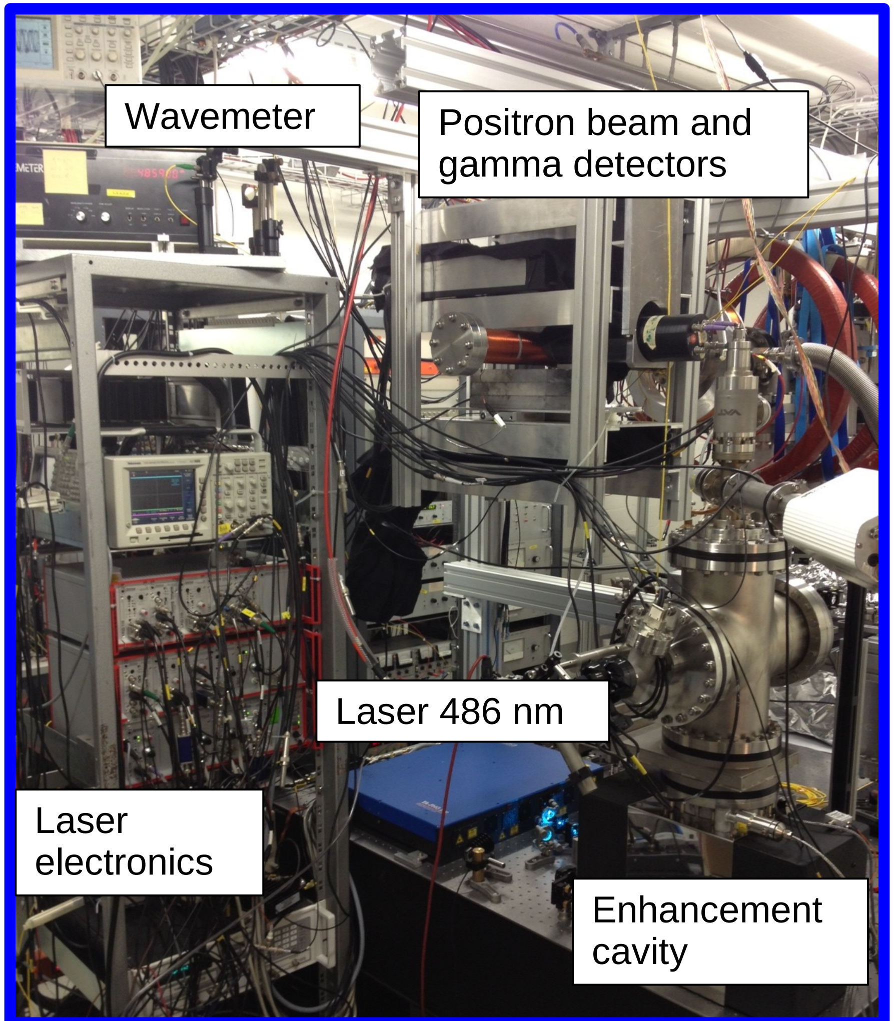
Measurement of 1S-2S Ps, Mu or HBar at a level about 1×10^{-10} => sensitivity to check the shift of antigravity.

New measurement ongoing @ ETH

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

new lab (01/2012) @ ETHZ

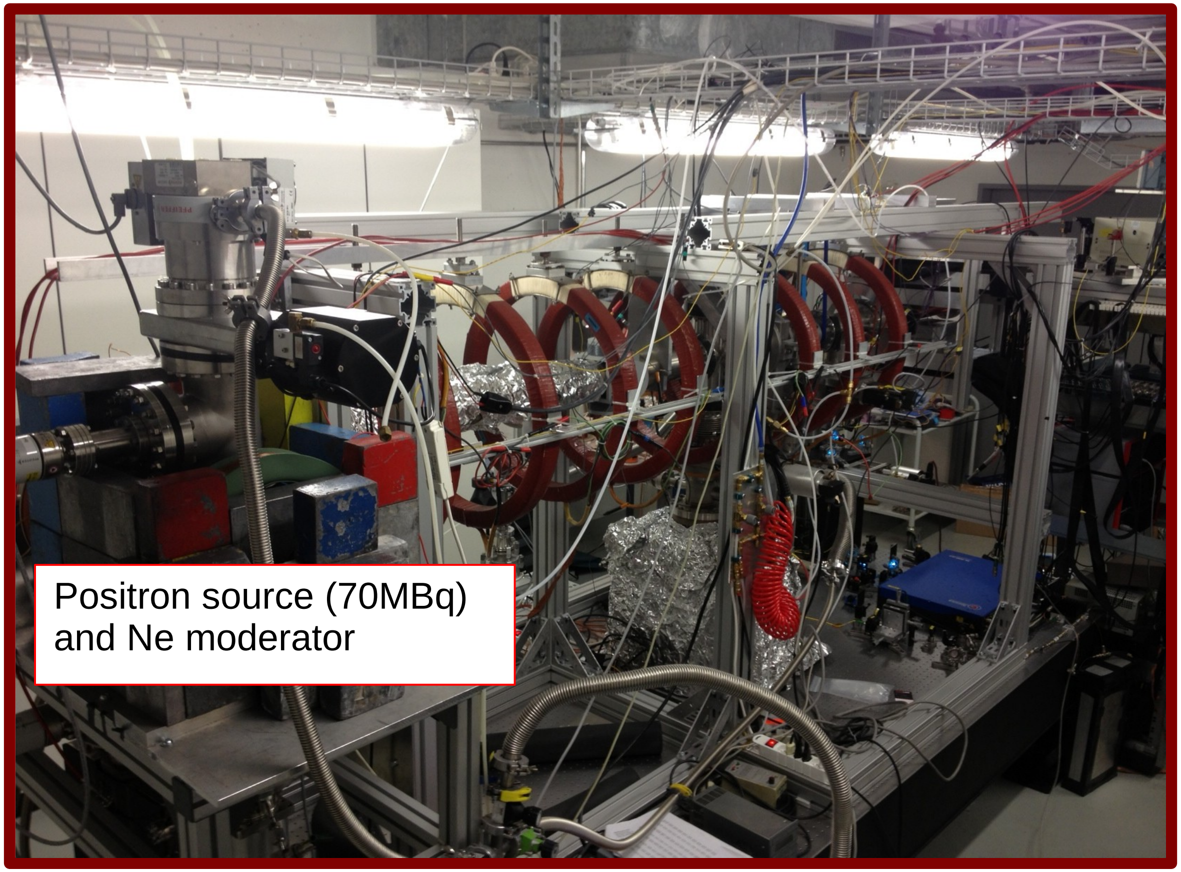




Laser system for generation of 486 nm light

Project supported by the SNSF Ambizione grant (PZ00P2_132059) and by ETH (Research Grant ETH-47 12-1)

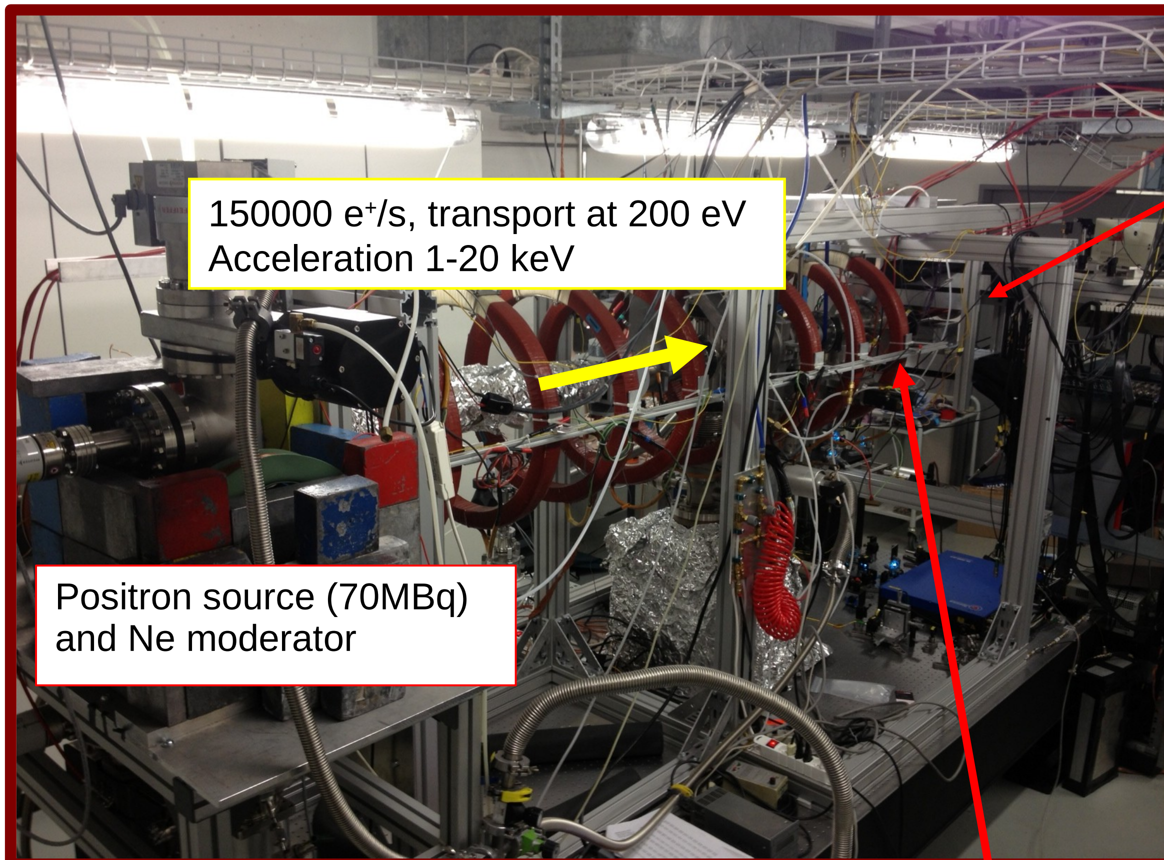
ETHZ slow positron beam



Positron source (70MBq)
and Ne moderator

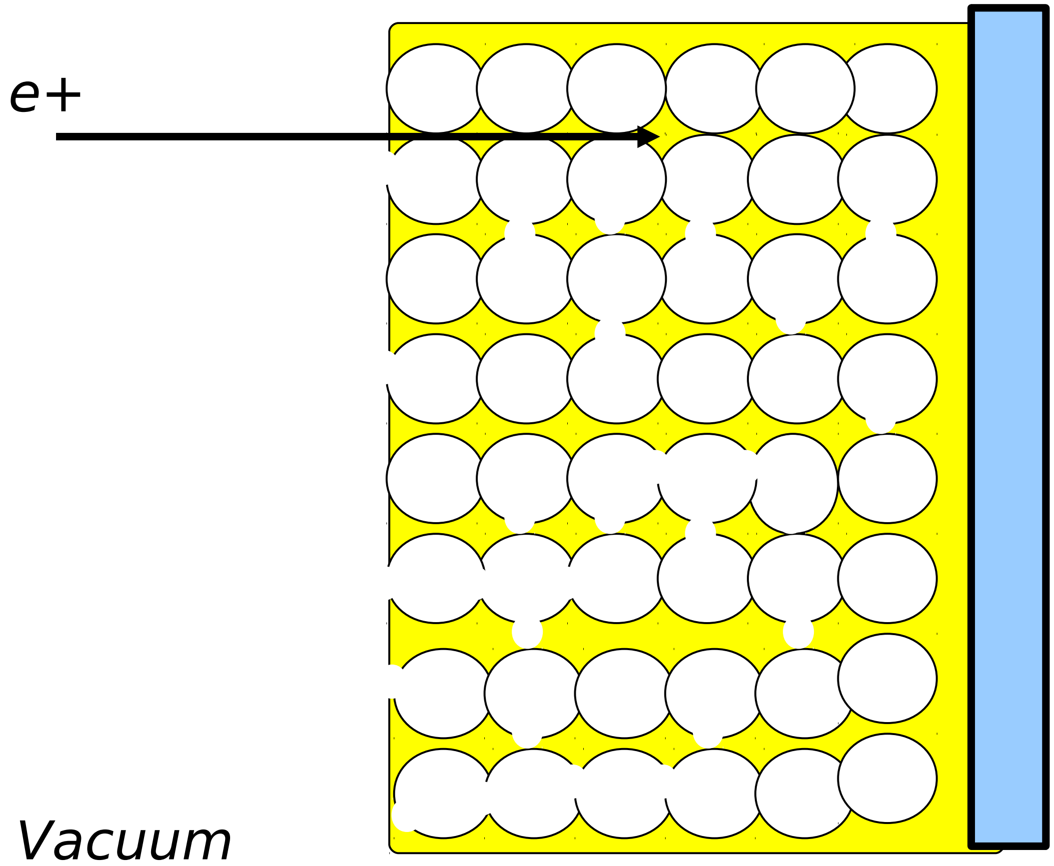
Production of positronium in vacuum requires slow positrons

Definition of t0 (positron on target)



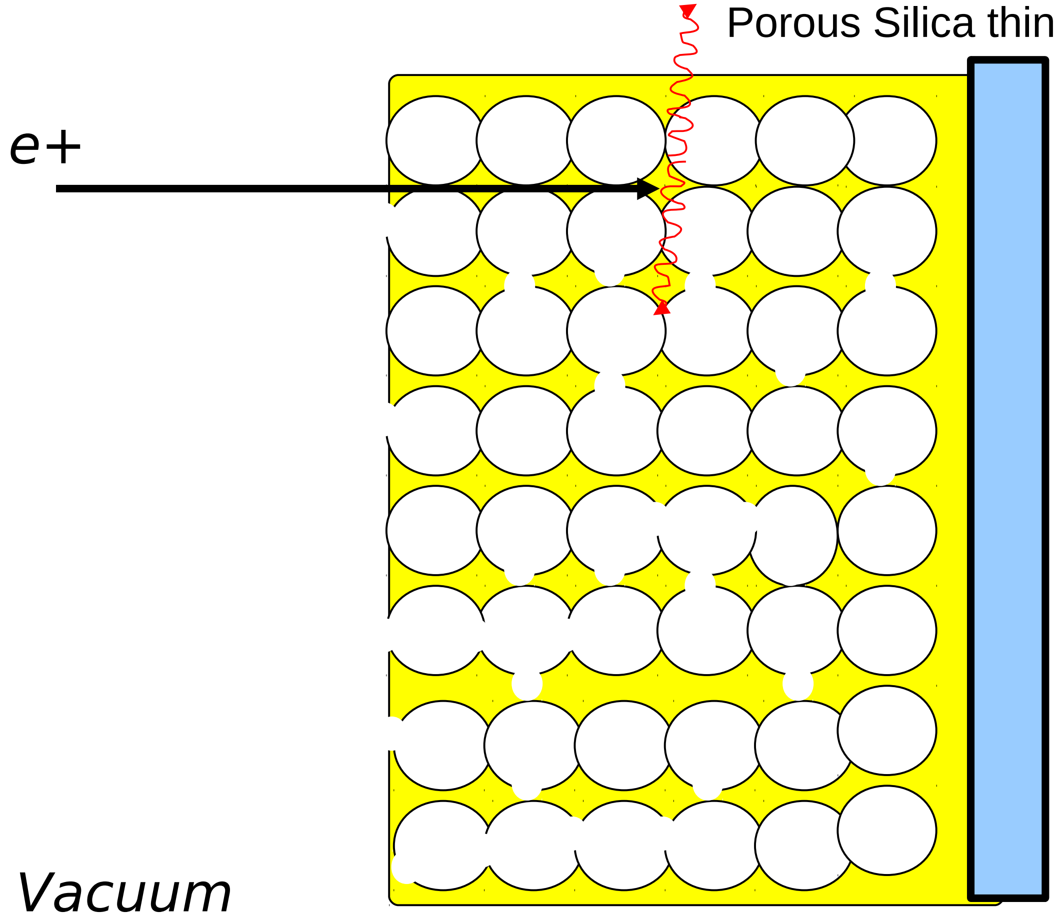
Positronium formation

Porous Silica thin film ~1000nm 3-4 nm pore size



Positron implanted with keV energies
Rapidly thermalizes in the bulk (~ps)

Positronium formation



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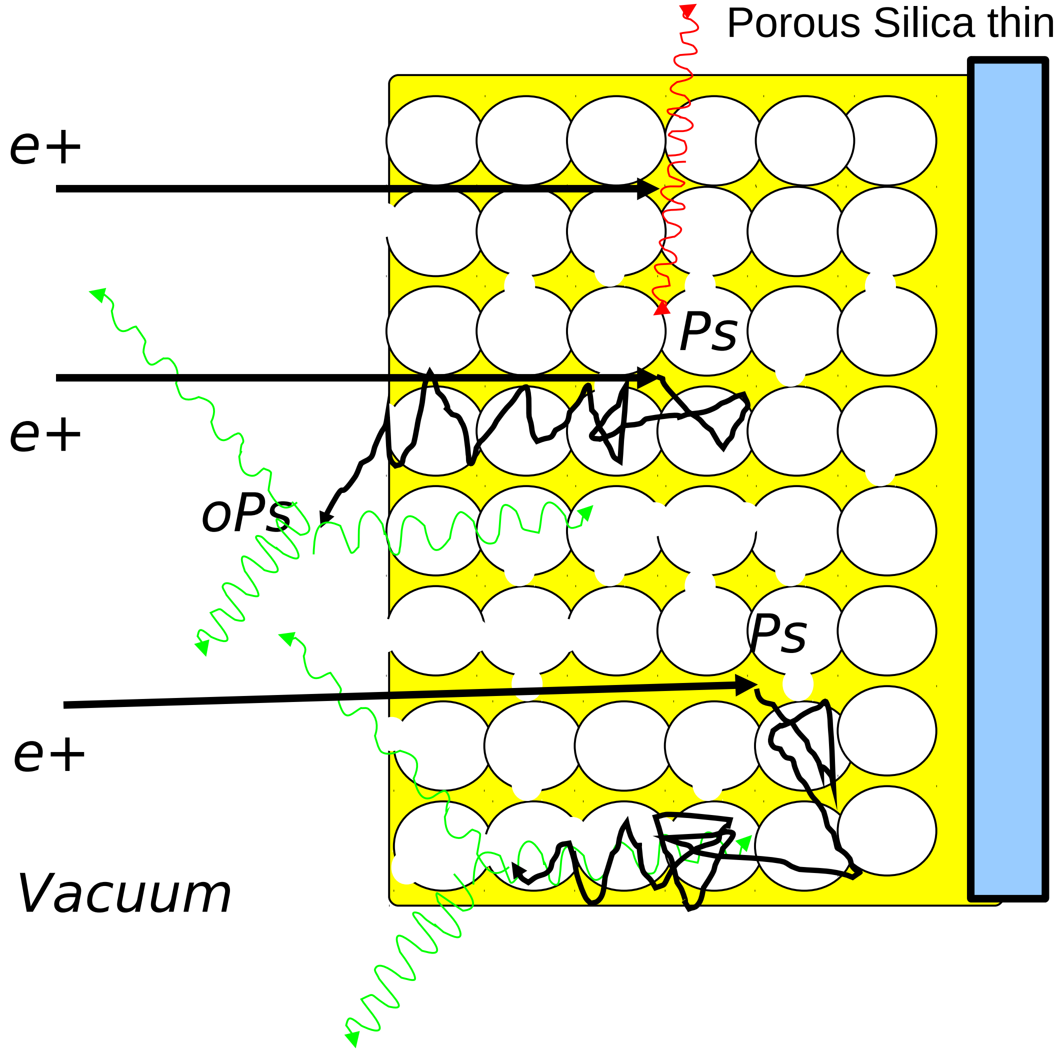
Positron diffusion and annihilation

Positronium formation



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Positron diffusion and annihilation

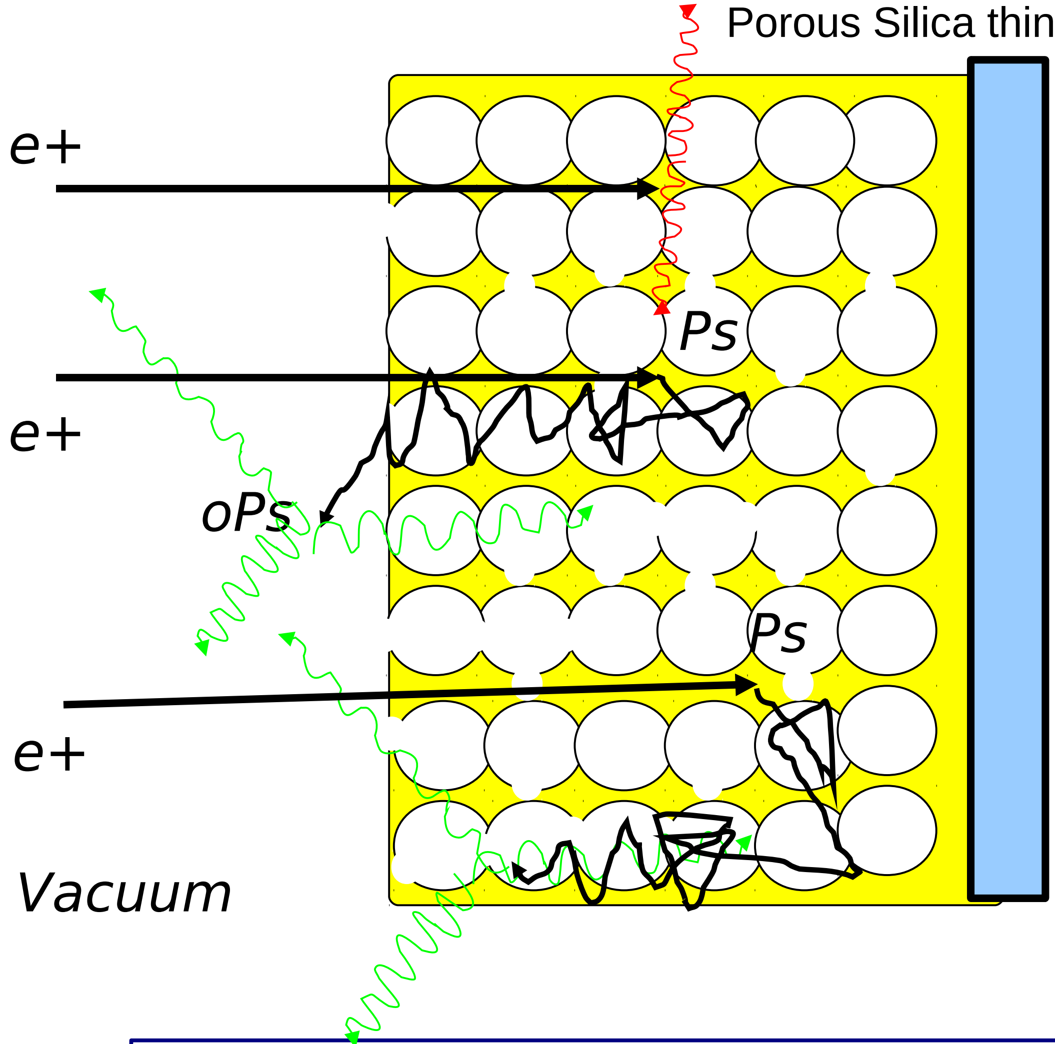
Positronium formation (1/4 pPs, 3/4 oPs) in SiO_2 by capturing 1 ionized electron

Diffusion to the pore surface and emission in the pores:

$W_{Ps}=\mu_{Ps} + E_B - 6.8\ eV=-1\ eV$

Thermalization via collisions and diffusion in interconnected pore network

Positronium formation



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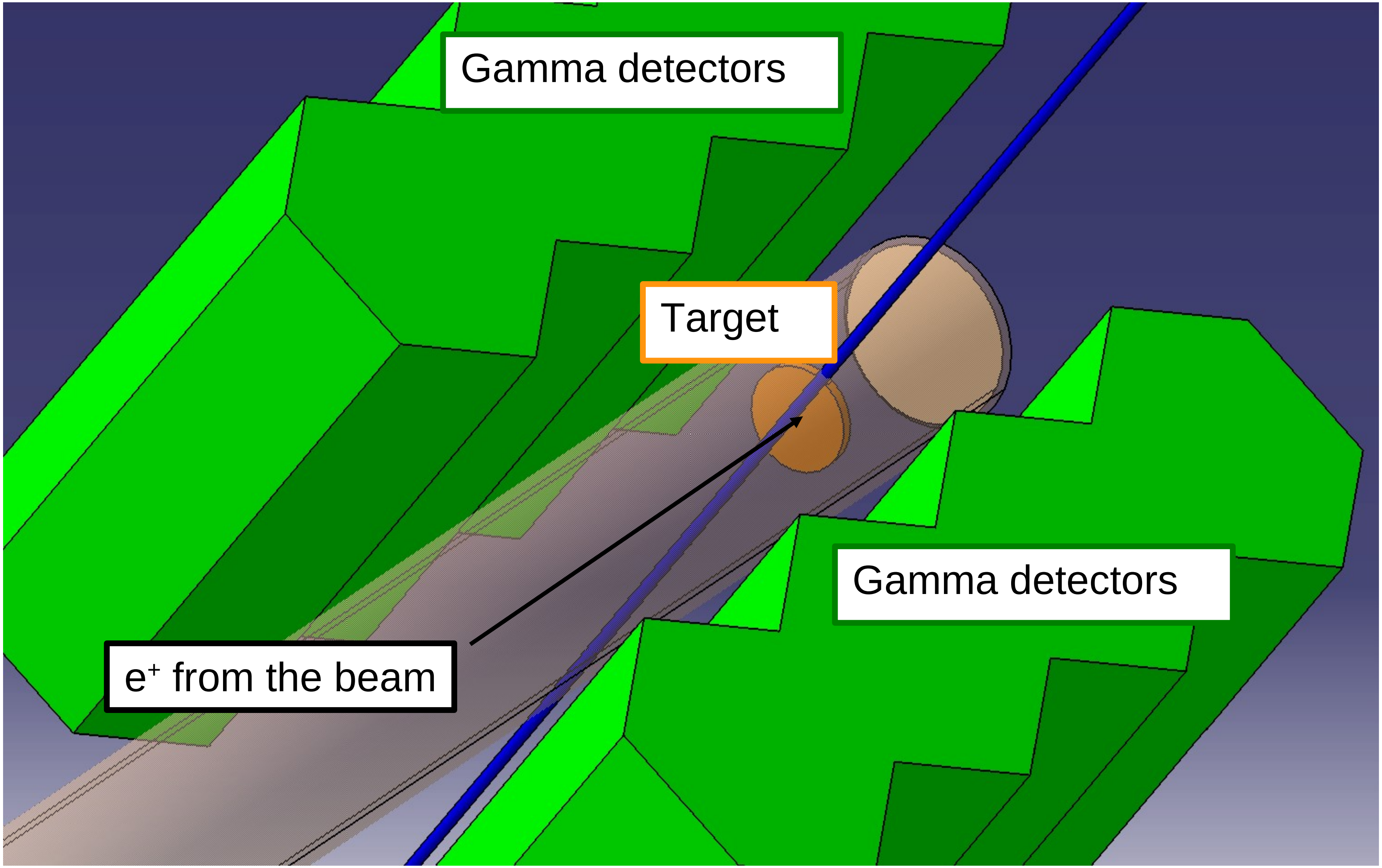
30% of the incident positrons are converted in positronium emitted into vacuum with 40 meV.

P. Crivelli et al., Phys. Rev. A. 81, 052703 (2010)

Ps detection



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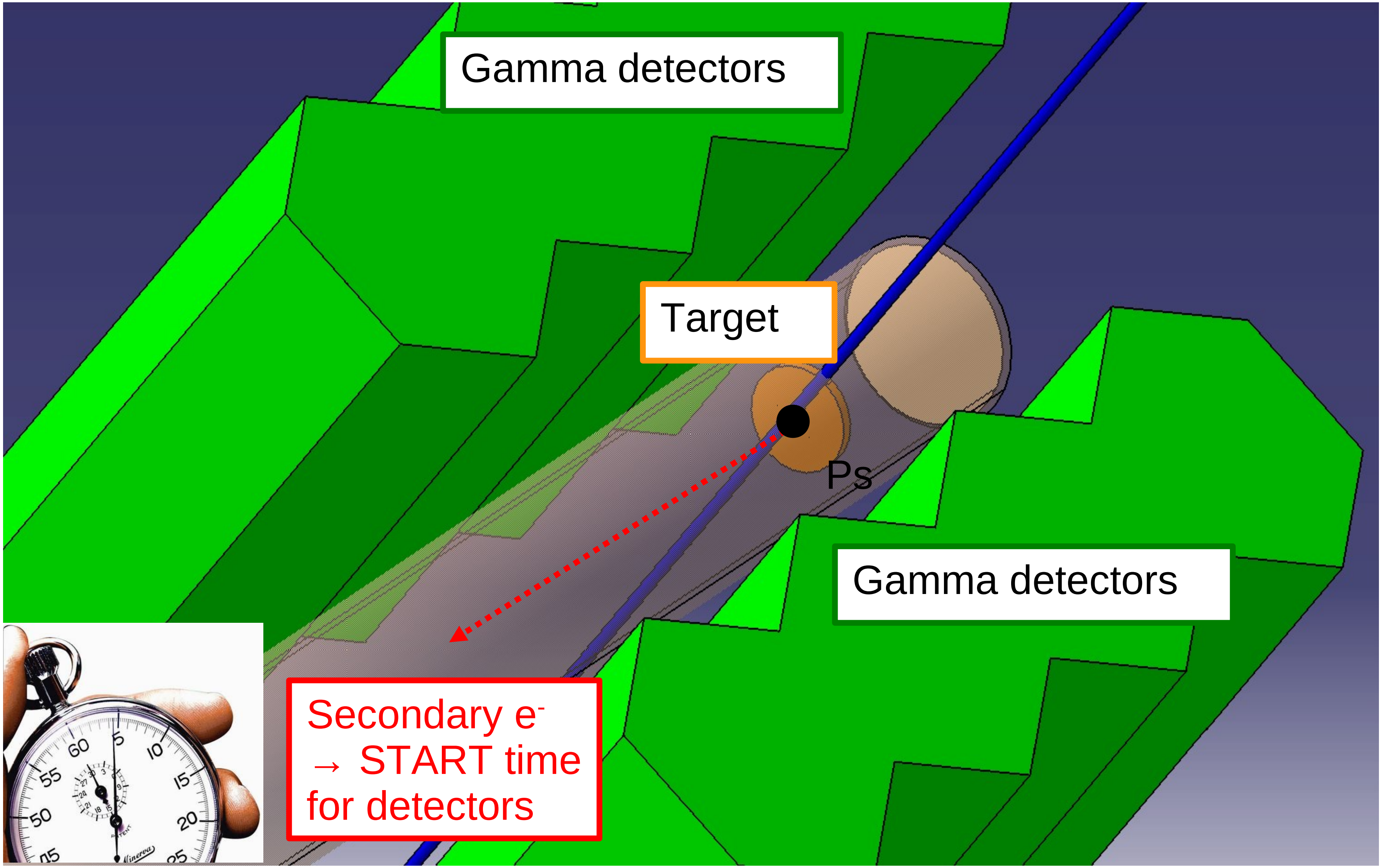

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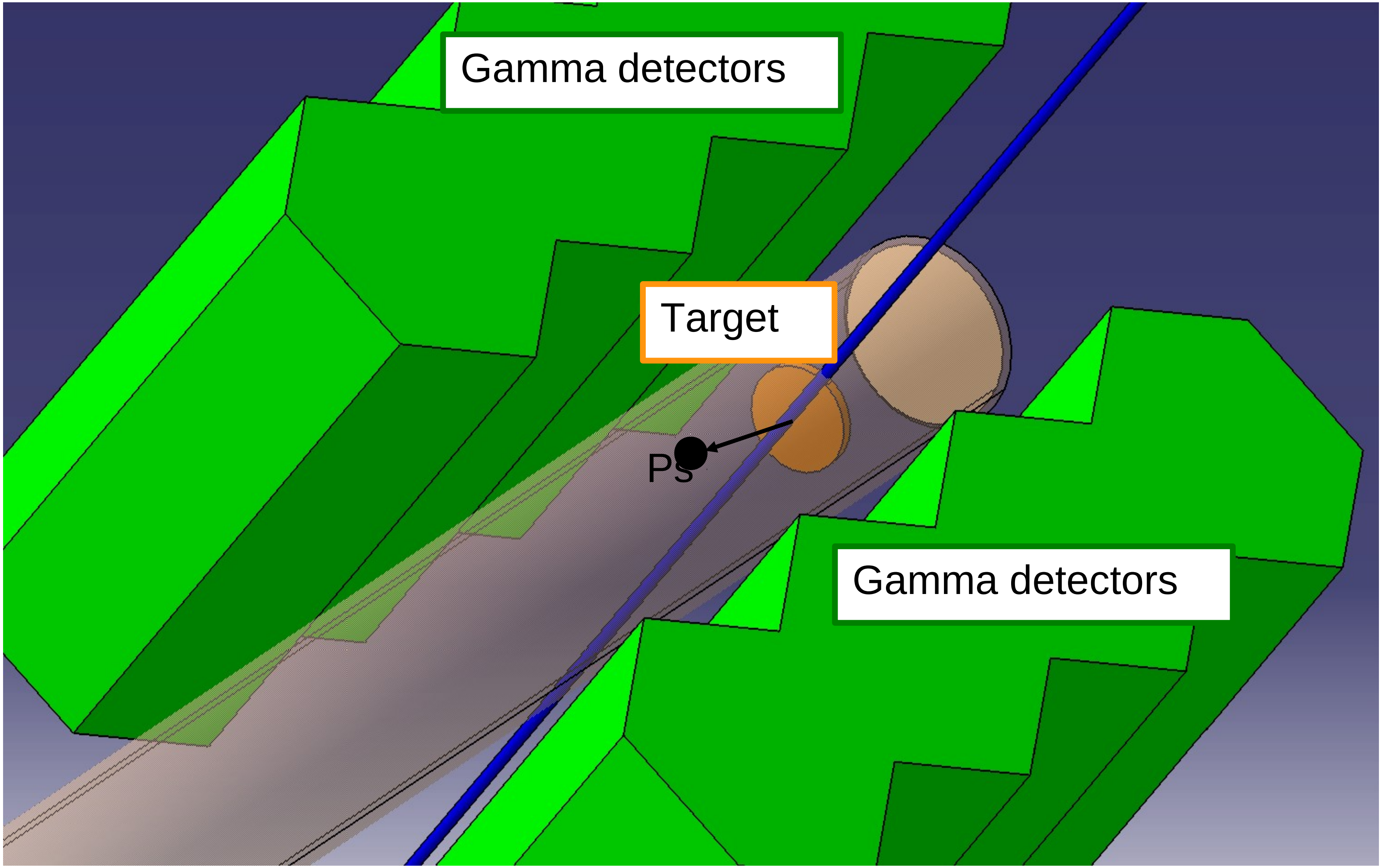

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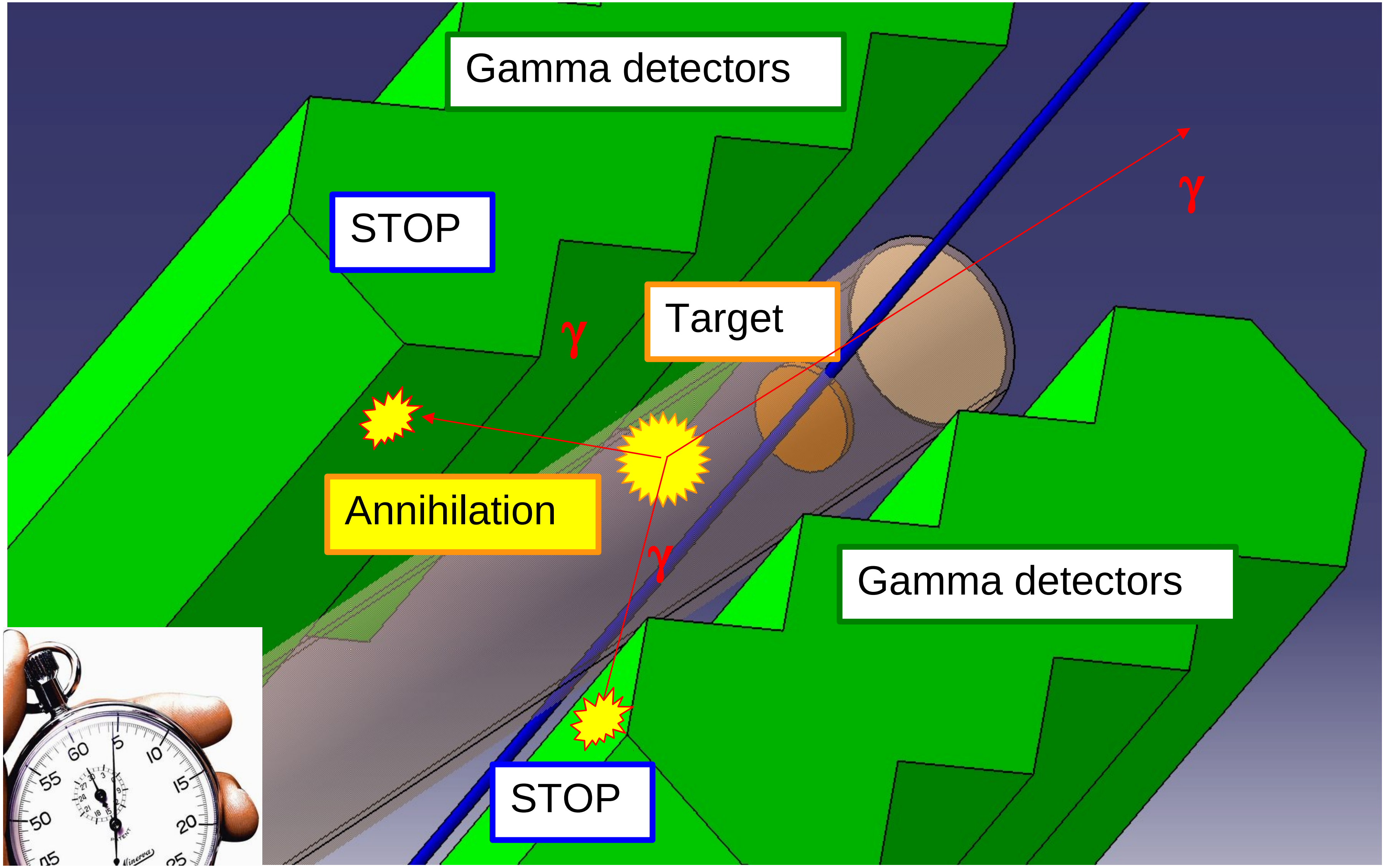
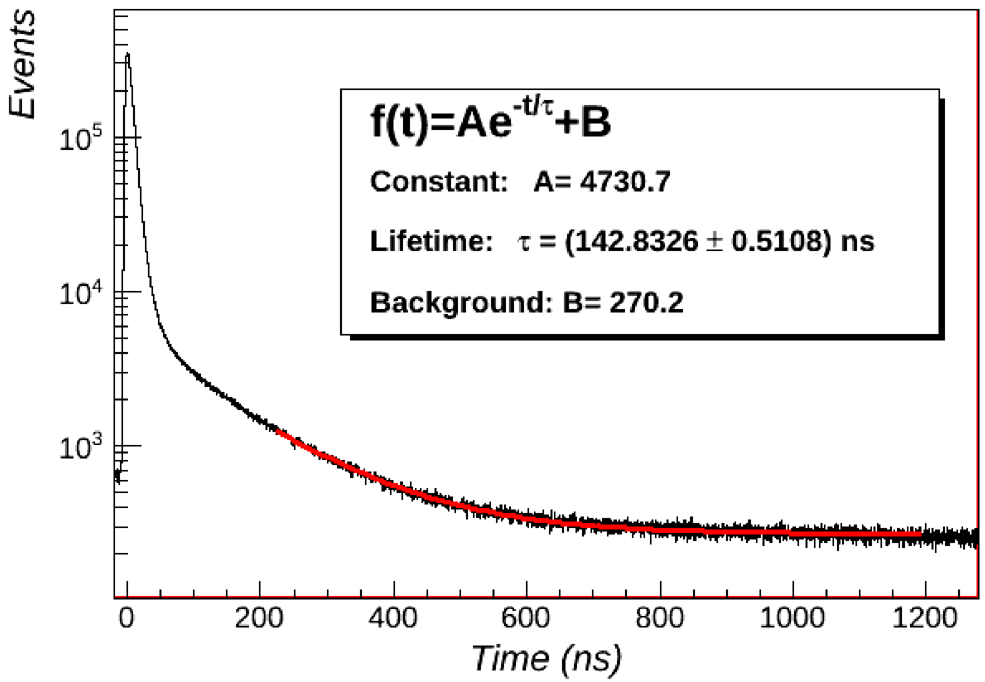
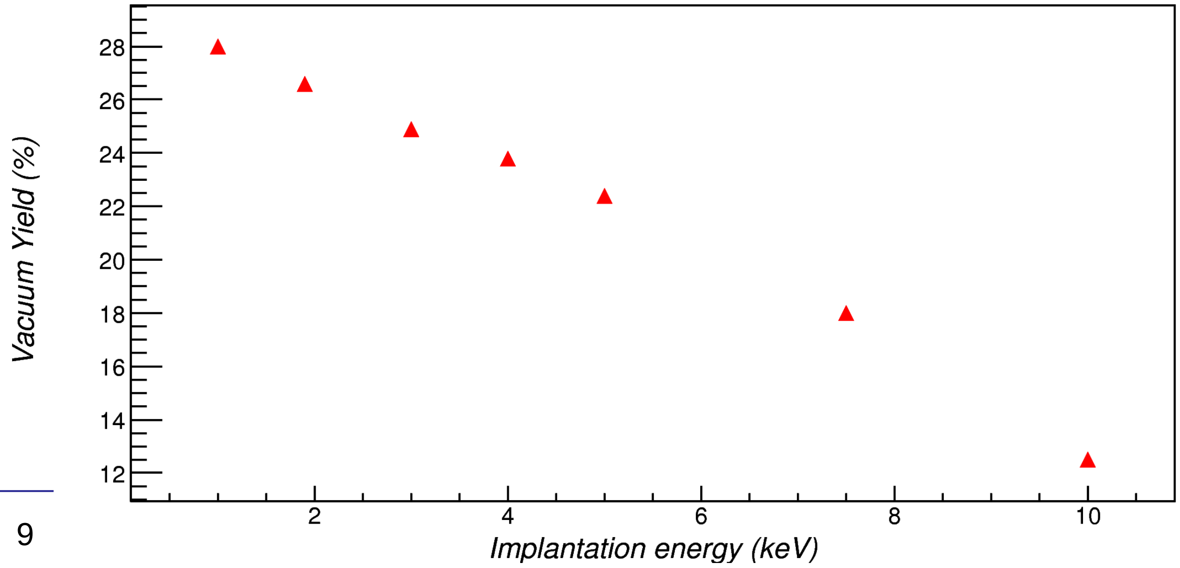


Positron annihilation lifetime spectra- PALS





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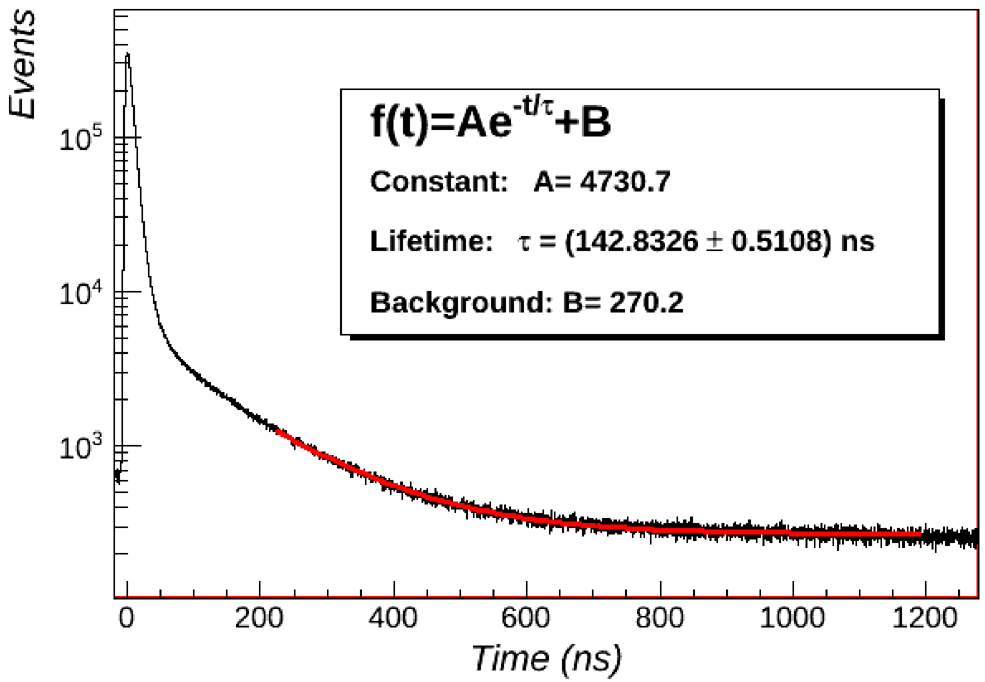
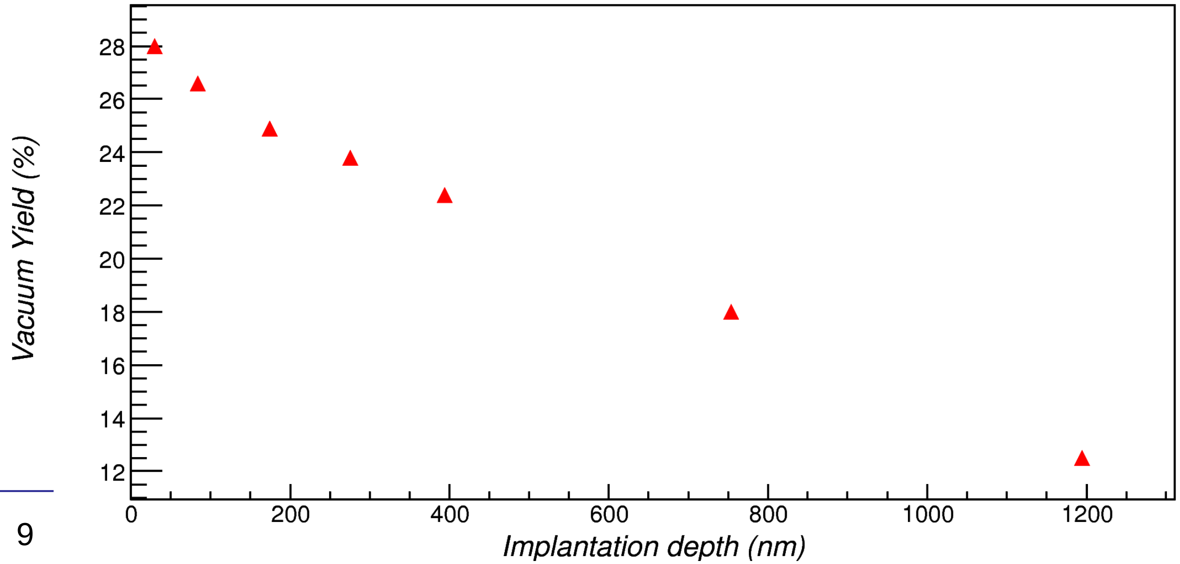
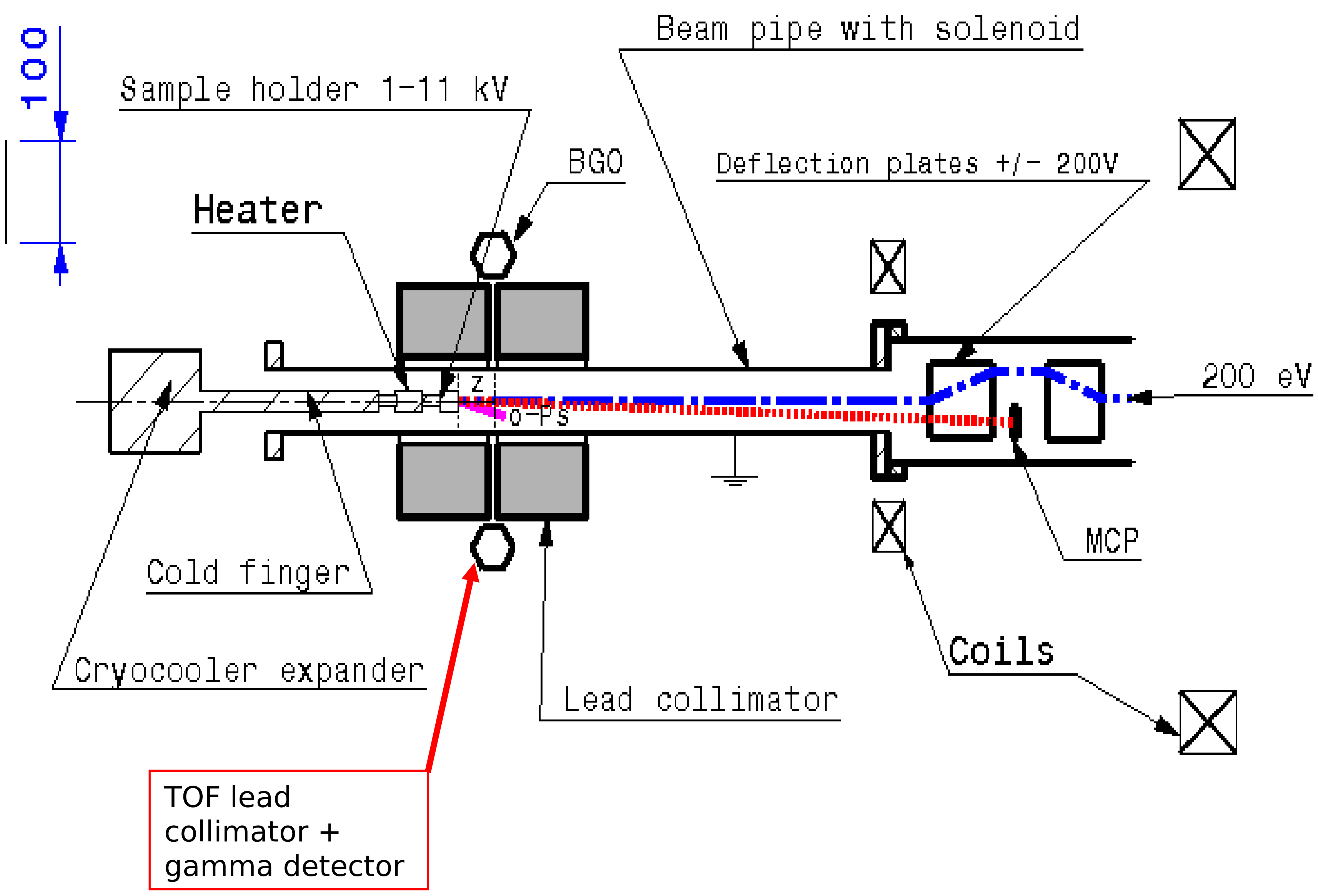




TOF measurement of Ps energy



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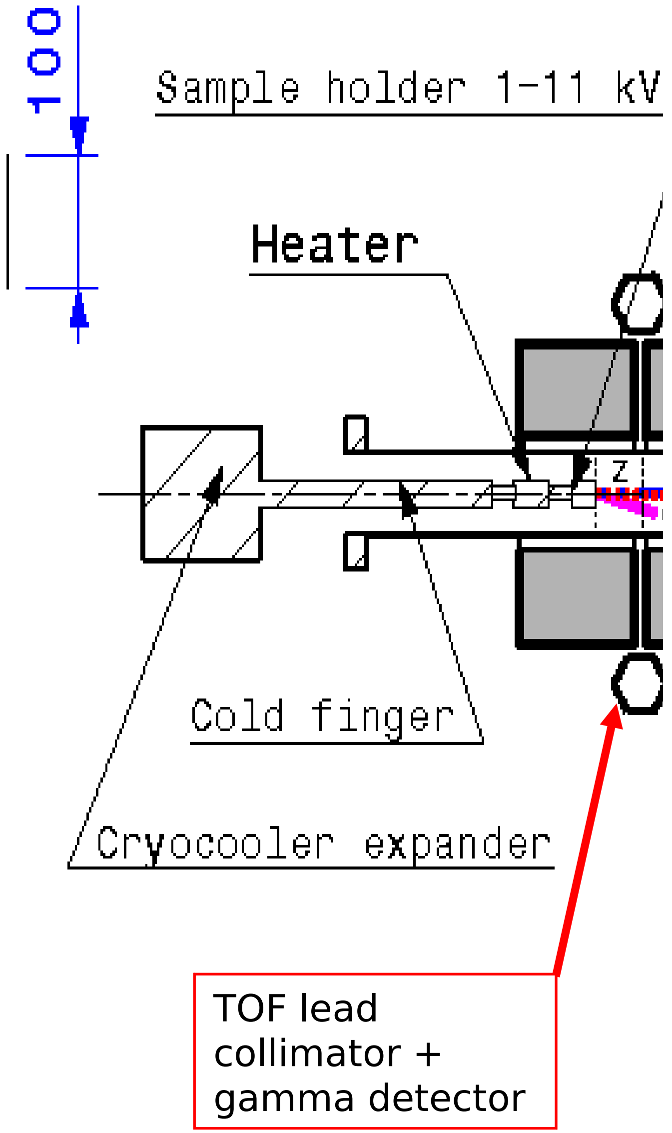

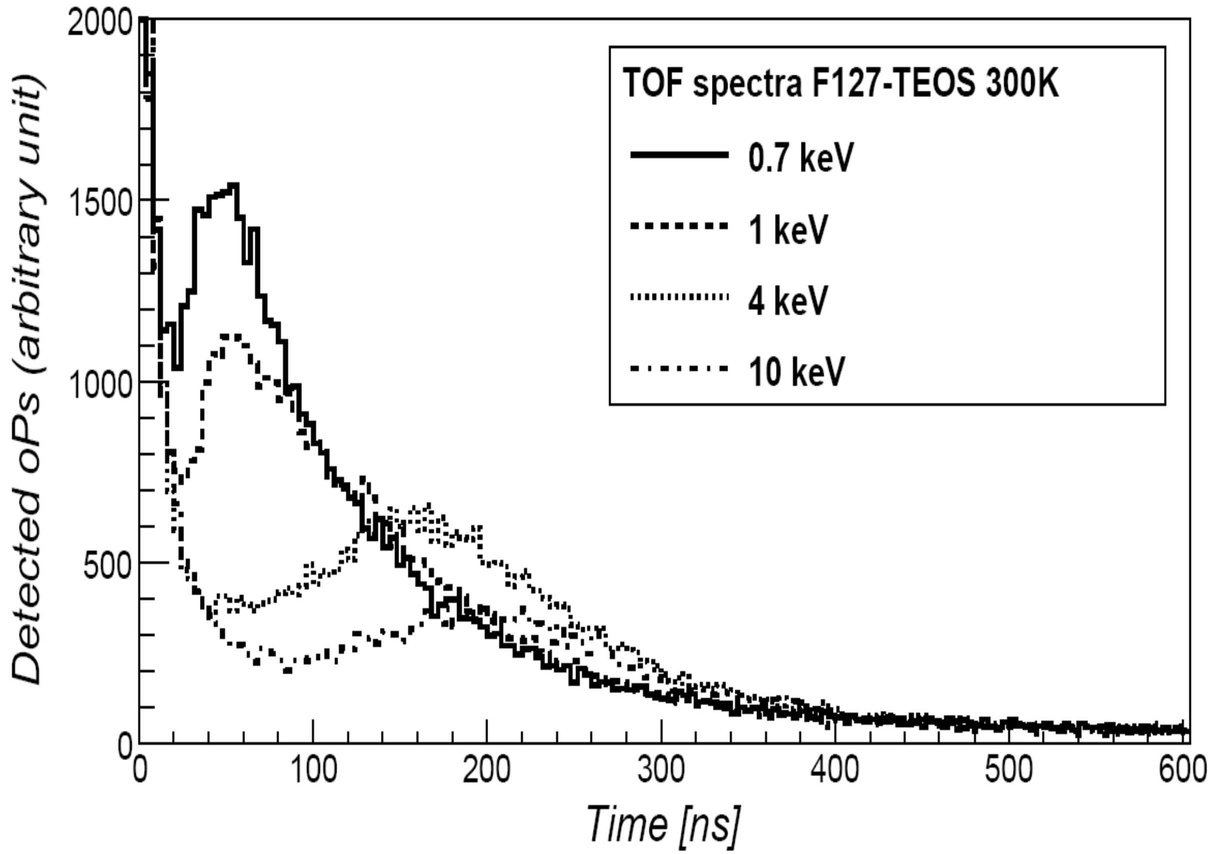

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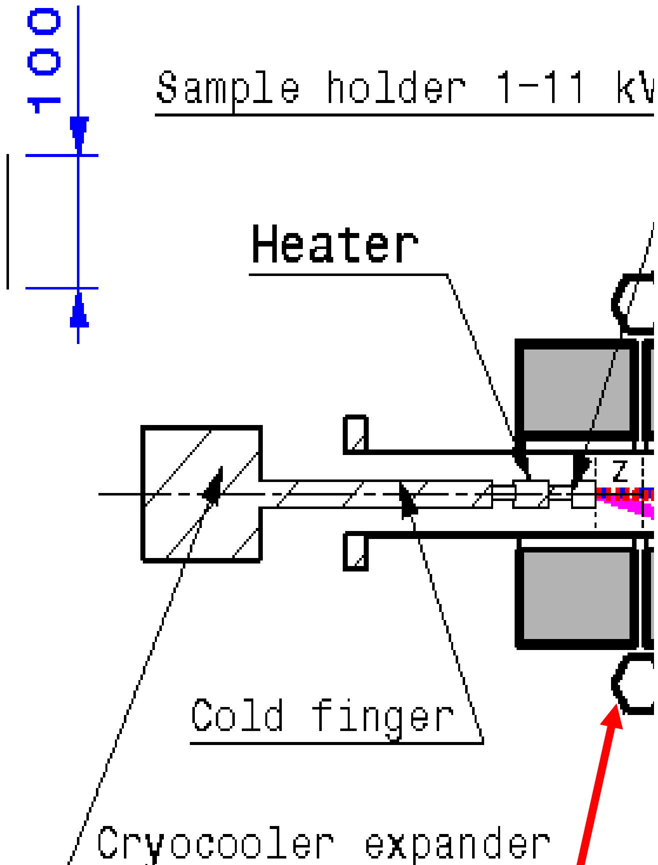
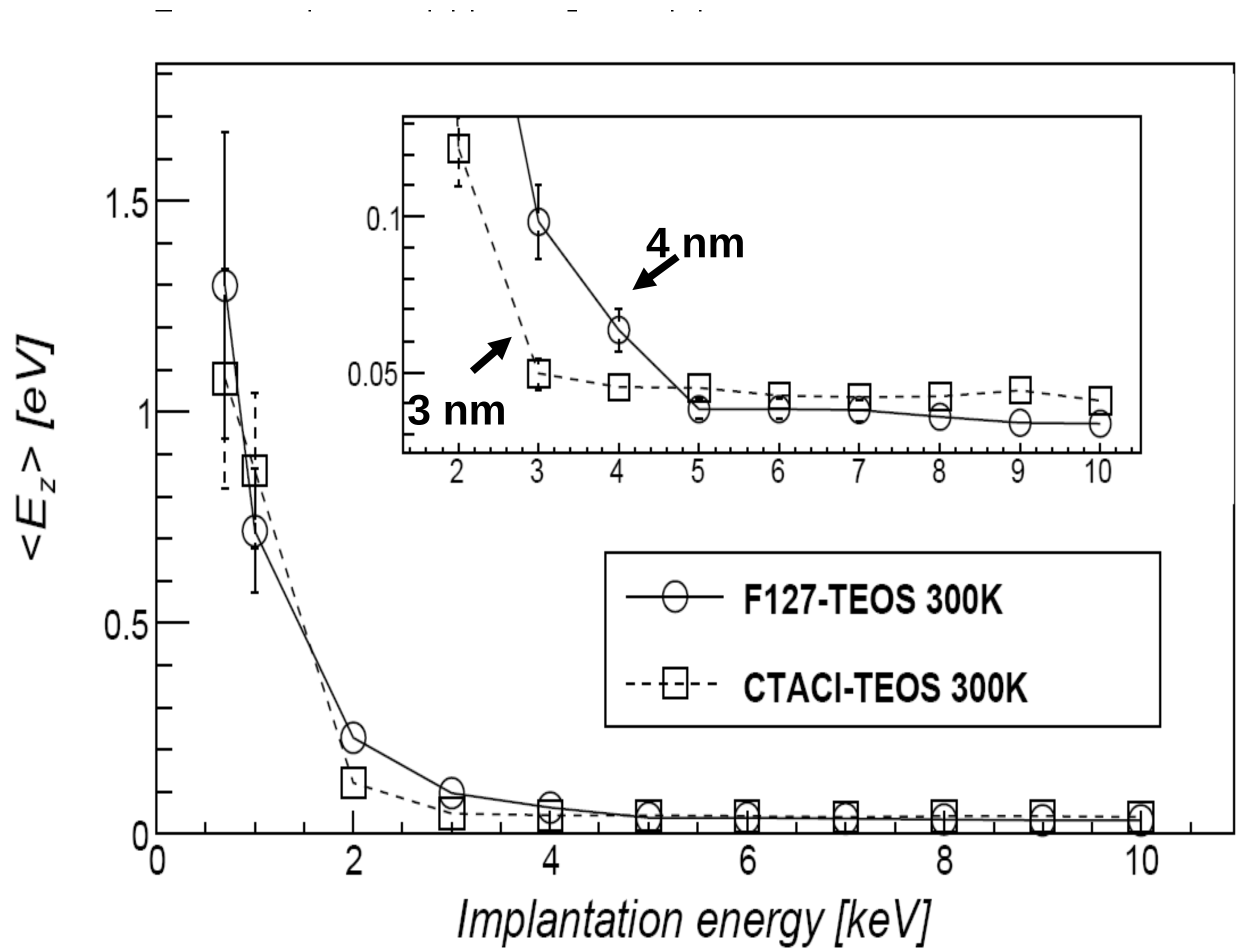


TOF lead collimator + gamma detector



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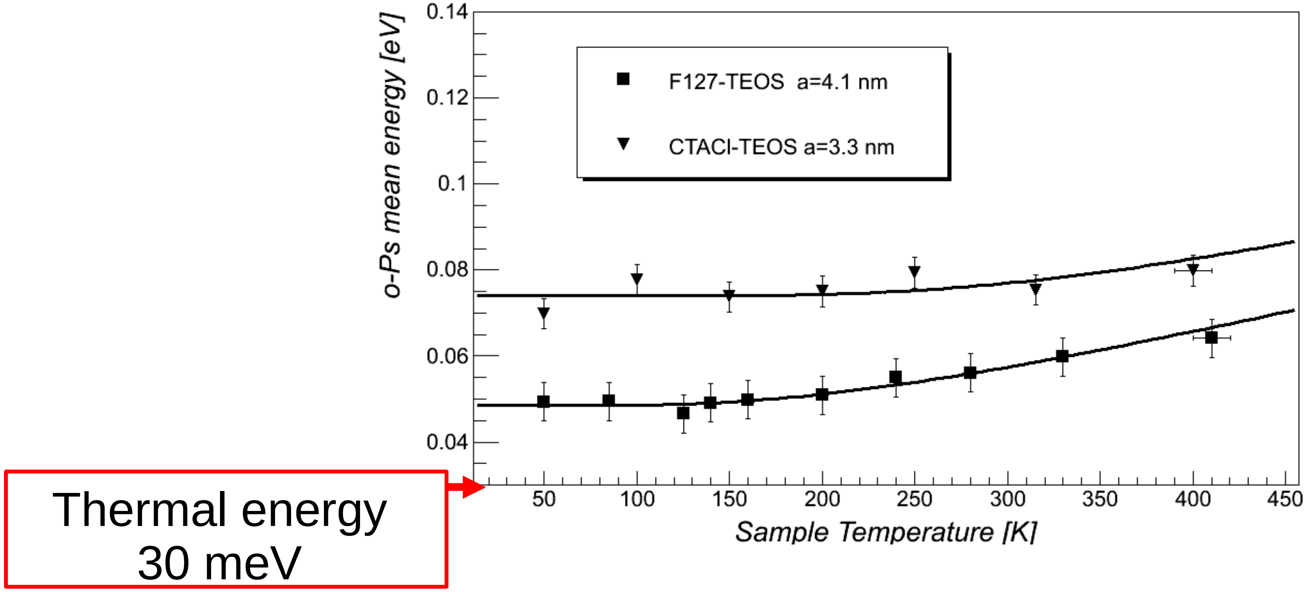
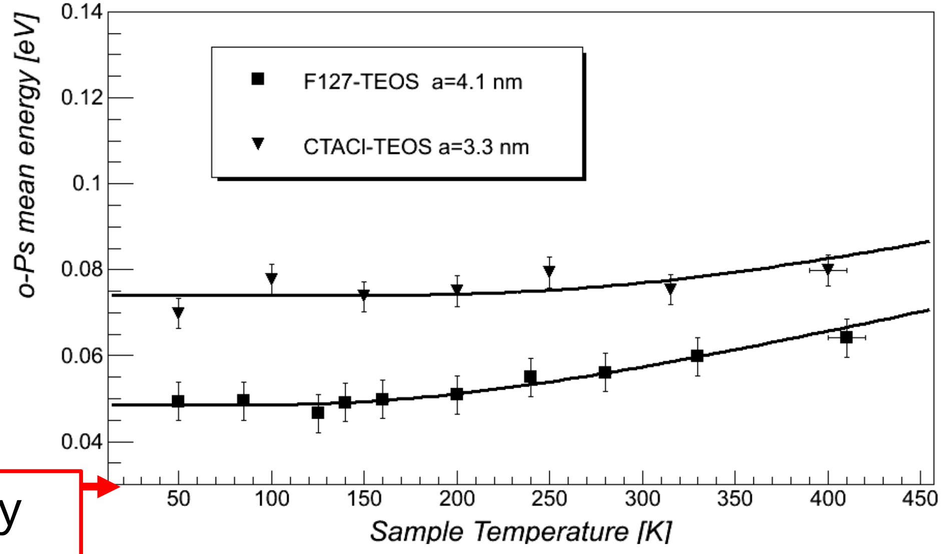


Measurement of Ps energy

- Ps de Broglie wavelength ~ pore size
-> Ps in the pores has to be treated QM



- Ps as a particle in a box

$$\langle H \rangle = kT^2 \left(\frac{1}{Z(a)} \frac{dZ(a)}{dT} + \frac{1}{Z(b)} \frac{dZ(b)}{dT} + \frac{1}{Z(c)} \frac{dZ(c)}{dT} \right)$$

Z is the partition function defined as

$$Z(a) = \sum_{n=1}^{\infty} e^{-\frac{h^2 n^2}{8ma^2}/kT},$$

Thermal energy
30 meV

- Ground state energy

$$E_{\mathrm{Ps}} = \frac{h^2}{2m\,d^2} \approx 0.8\,\mathrm{eV}(1\,\mathrm{nm}/d)^2$$

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- Ps as a particle in a box

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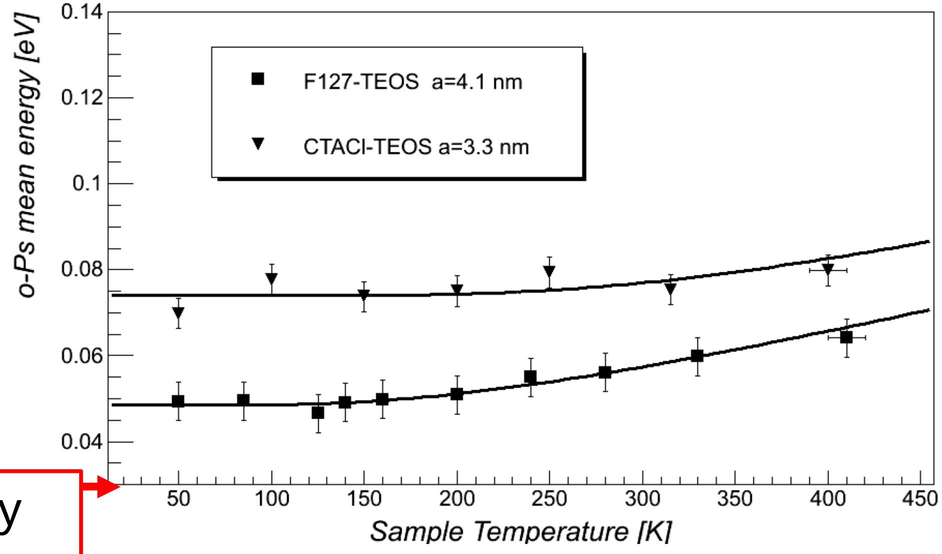

Thermal energy
30 meV

- Ground state energy

$$E_{\mathrm{Ps}} = \frac{h^2}{2m\,d^2} \approx 0.8\,\mathrm{eV}(1\,\mathrm{nm}/d)^2$$

Colder Ps from silica?

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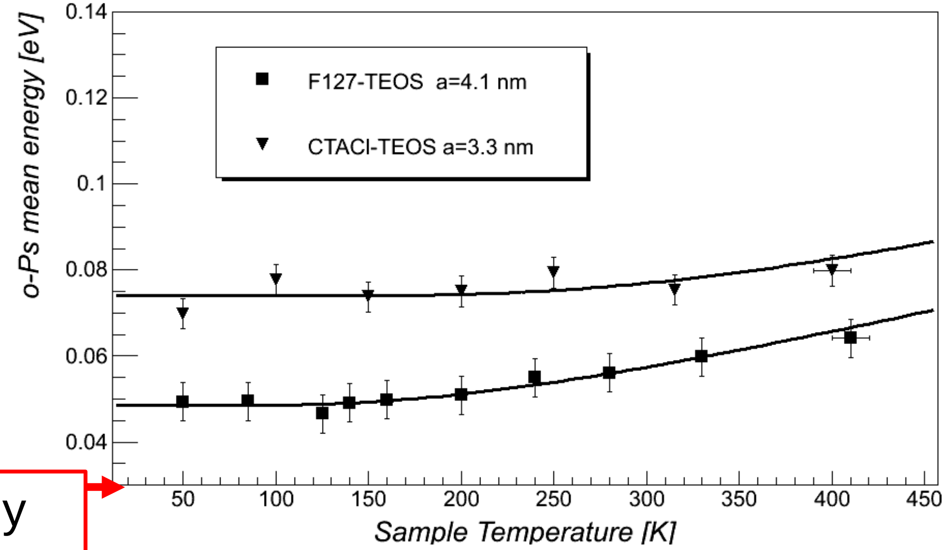

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(for muonium we could get aoms at 100 K with 4 nm pores since $\lambda_{deBroglie}$ is much smaller)

A. Antognini et al., PRL 108, 143401 (2010)

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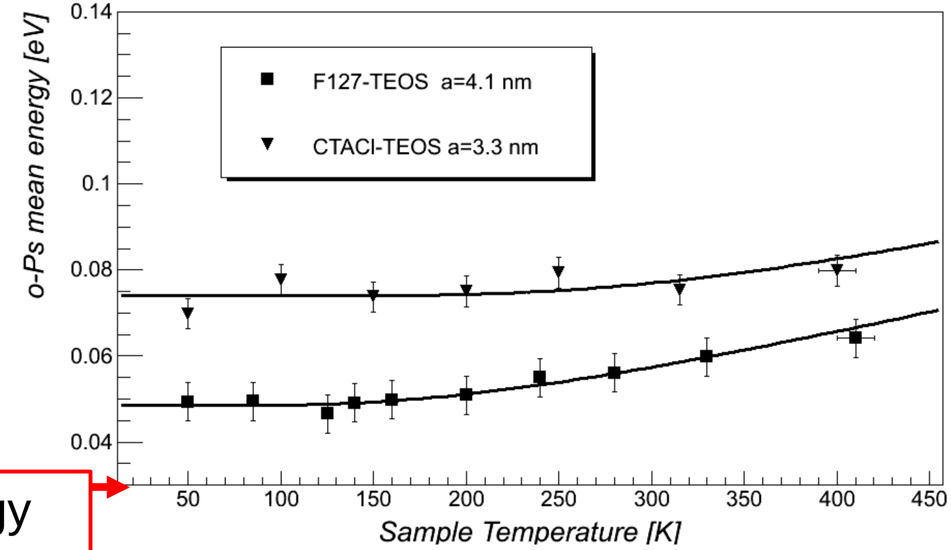

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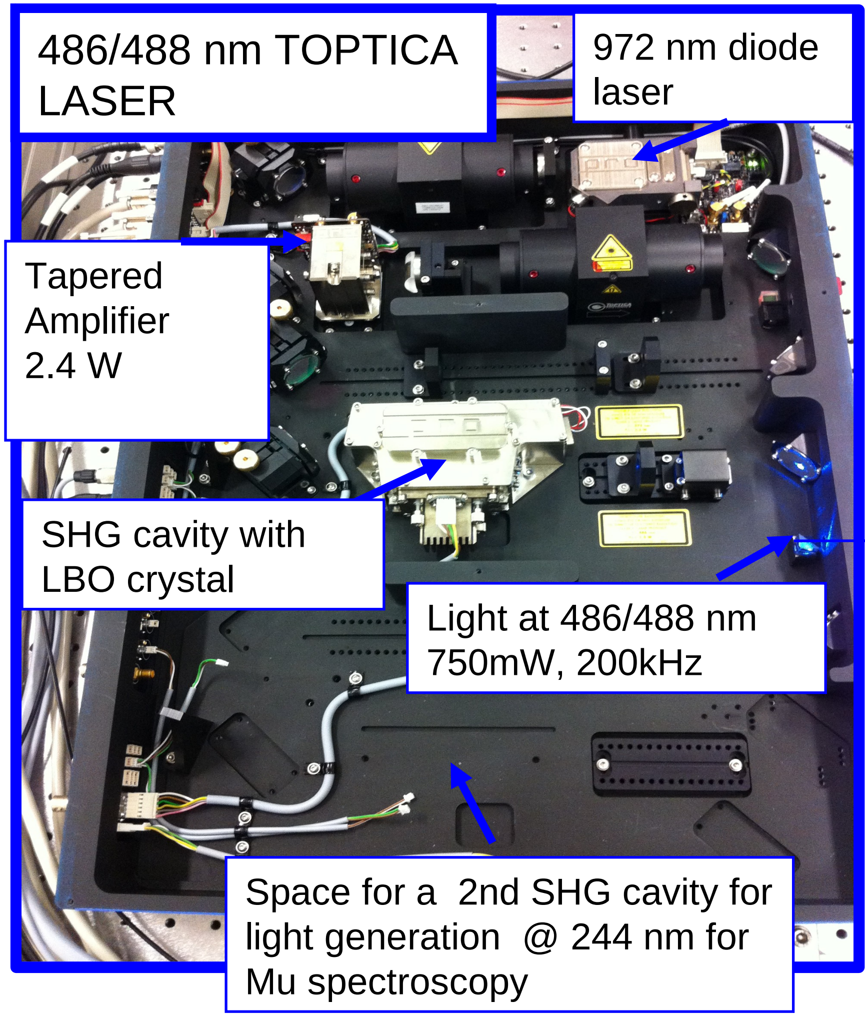
- In practice: not easy to find the right recipe...work in progress.

The laser system

<u>Requirements</u>:
High power (~kW) at 486 nm -> detectable signal
Long term stability (continuous data taking ~days)
Scanning of the laser ± 100 MHz

The laser system



Incoming laser beam

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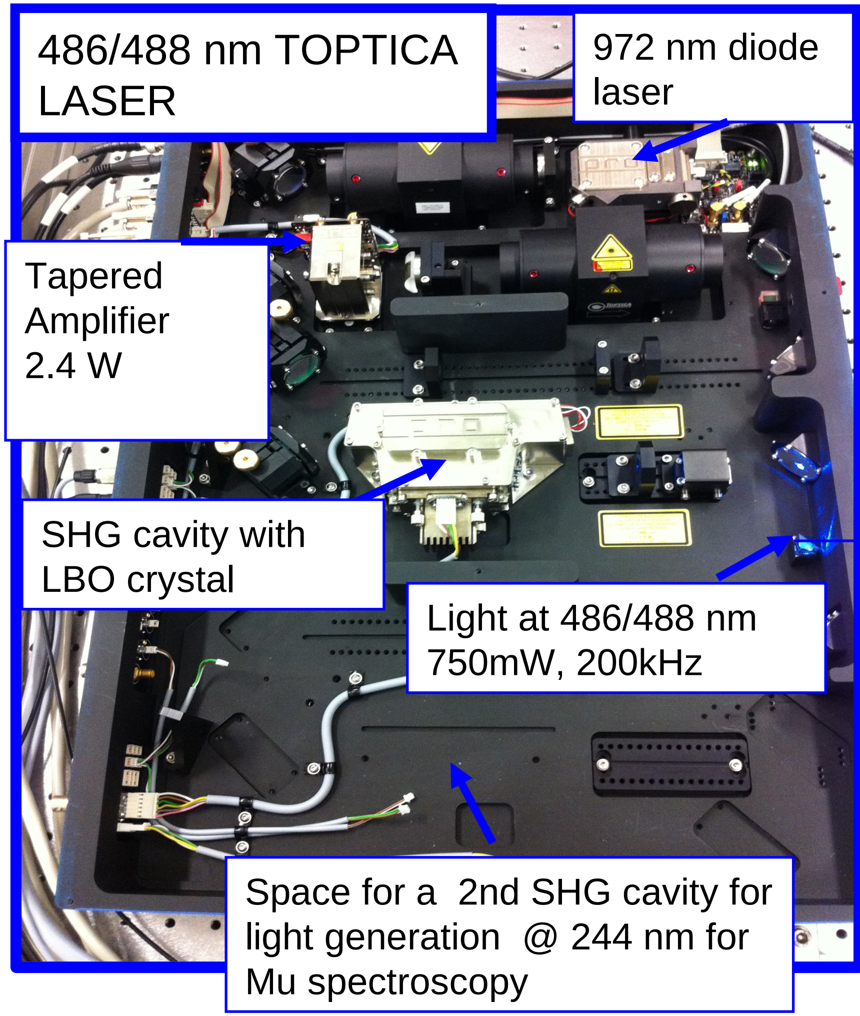

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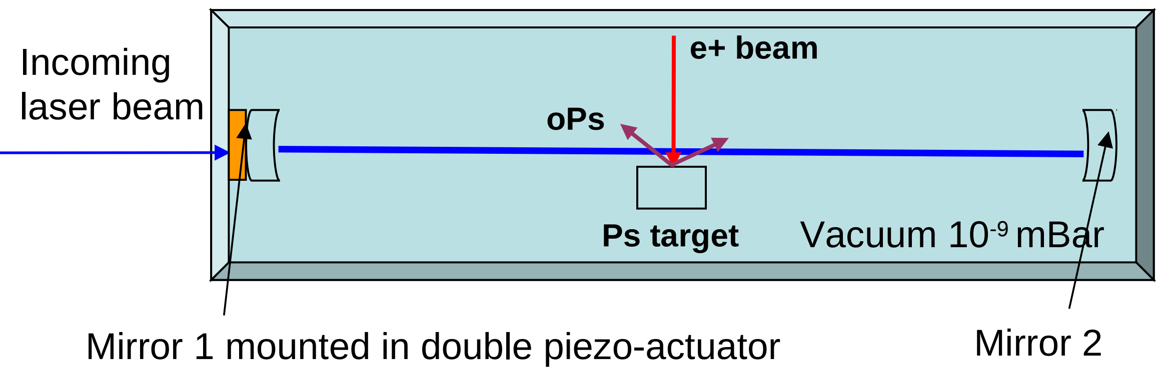
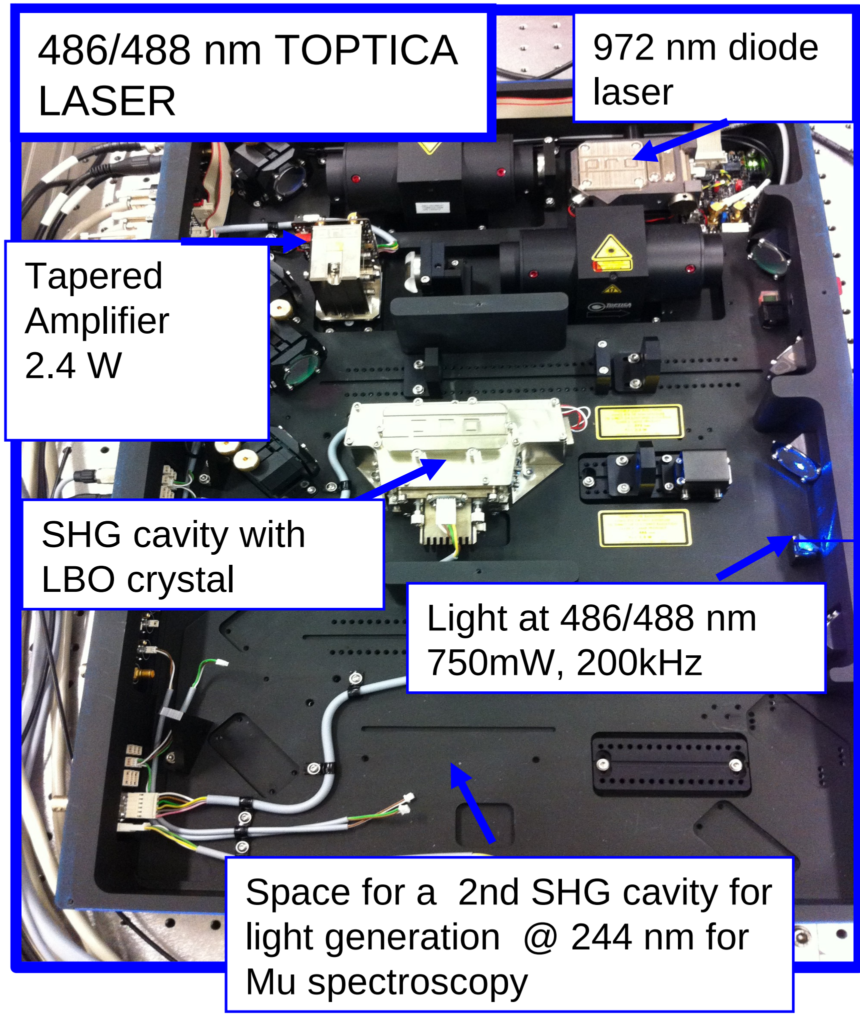


High finesse resonator for power build up
400 mW ⇨ 0.5 kW

The laser system



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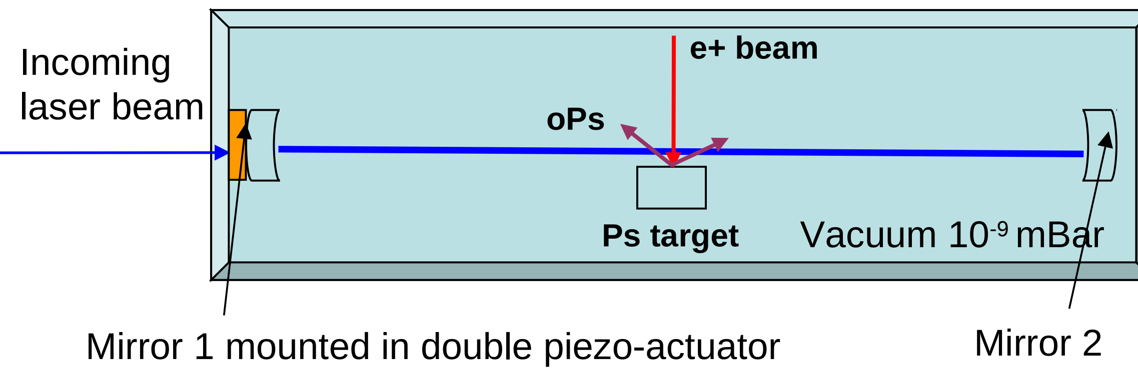
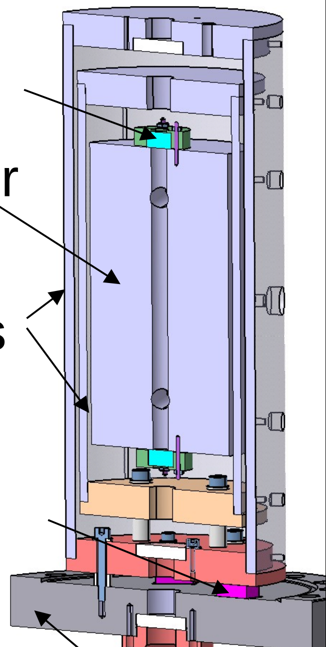


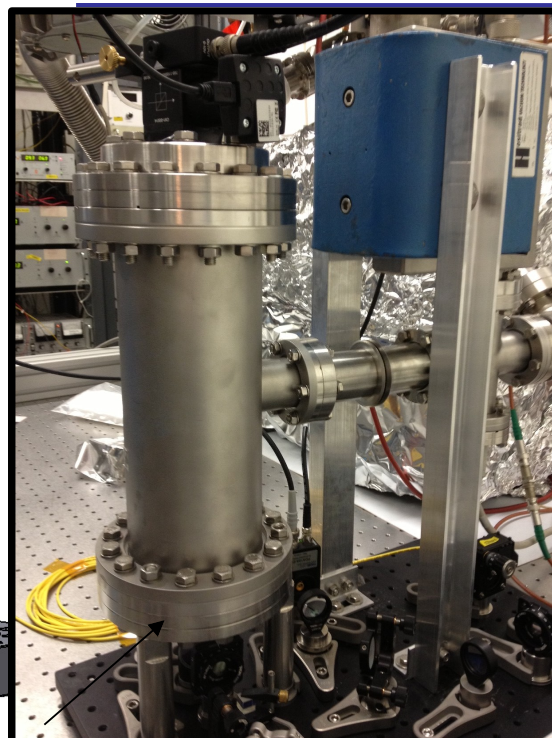
High finesse resonator for power build up
400 mW ⇨ 0.5 kW

⇨ Cavity linewidth few kHz -> laser need to be stabilized to the same level.

Stabilization - the 972 nm FP

Built at ETHZ in collaboration with MPQ (group Prof. T. Haesch)

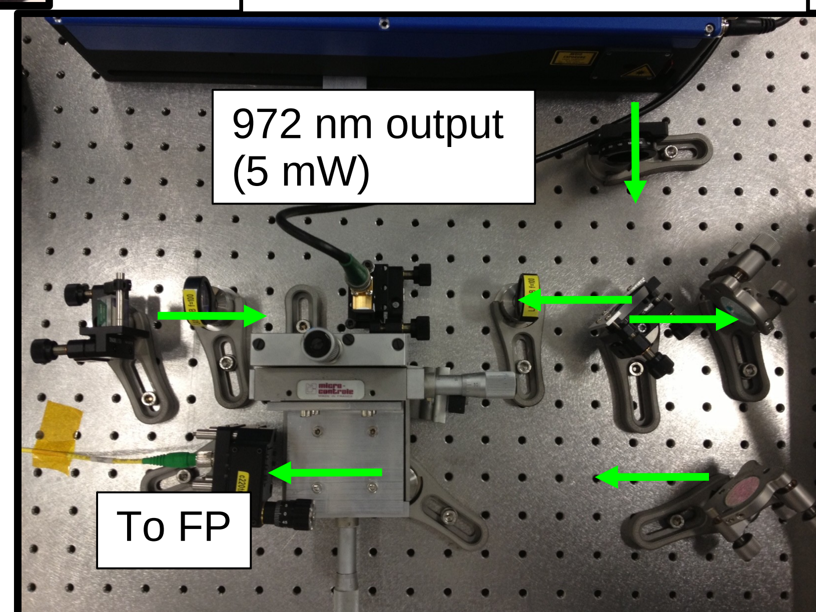




Vacuum flange

R 99.99% (Layertec)
F = 31000
FSR = 1.5 GHz
Linewidth 48 kHz

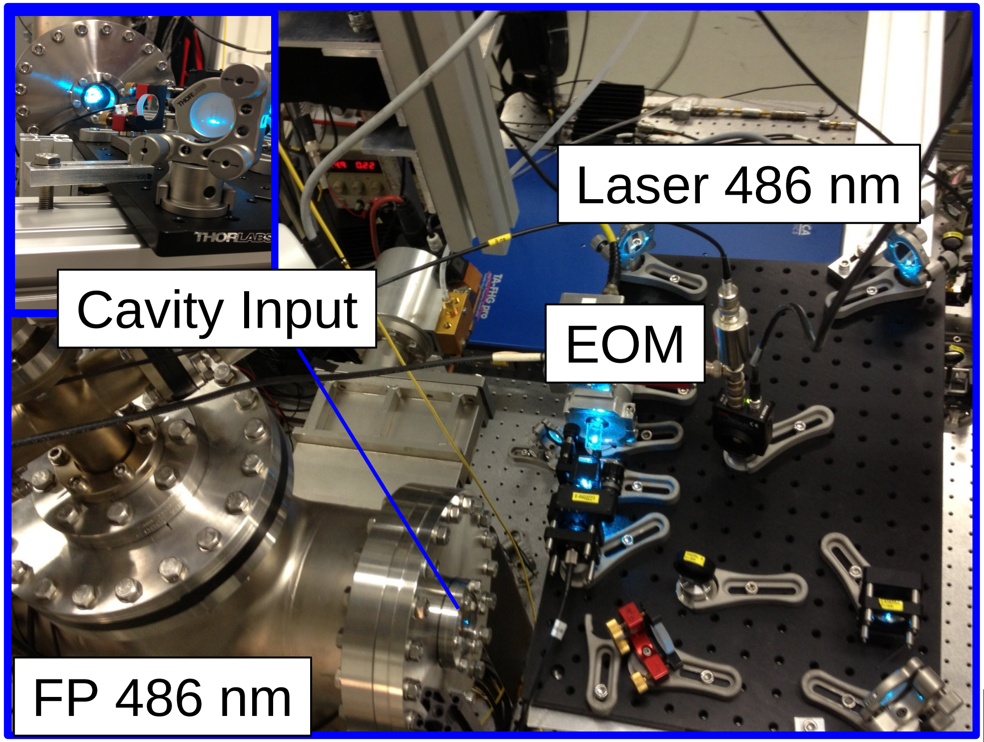
Double pass AOM
-> ±200 MHz @ 486 nm



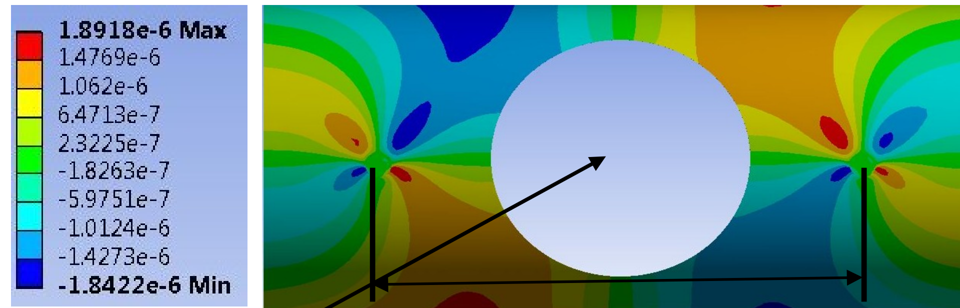
<u>Charachterization:</u>

- **Long term drift against Te2 (T not yet optimized) <1 MHz/day**
- **Short term ~ kHz (efficient incoupling to FP 486 nm)**

The enhancement cavity @ 486 nm

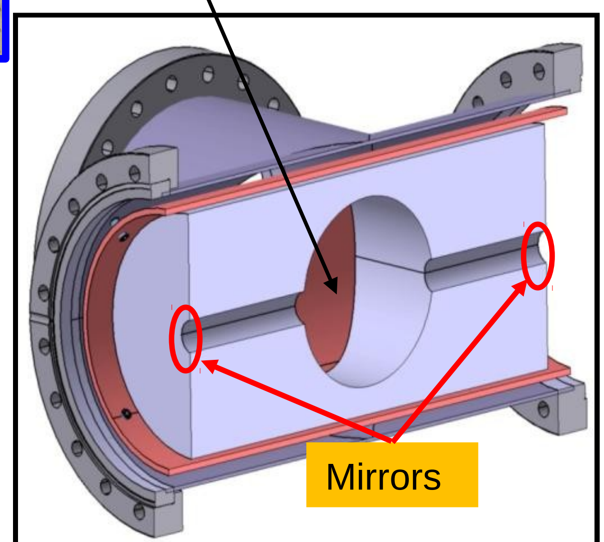


Static structural directional deformation analysis (ANSYS) along the X axis (units: mm)

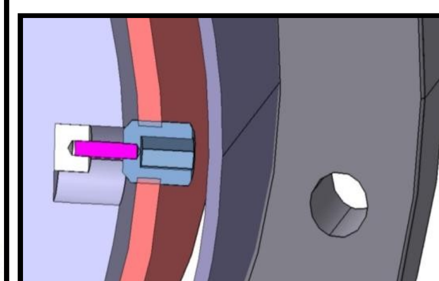


Hole for positron beam

Optimized distance 186.7mm for suspending the resonator -> deformation due to gravity does not change mirror separation



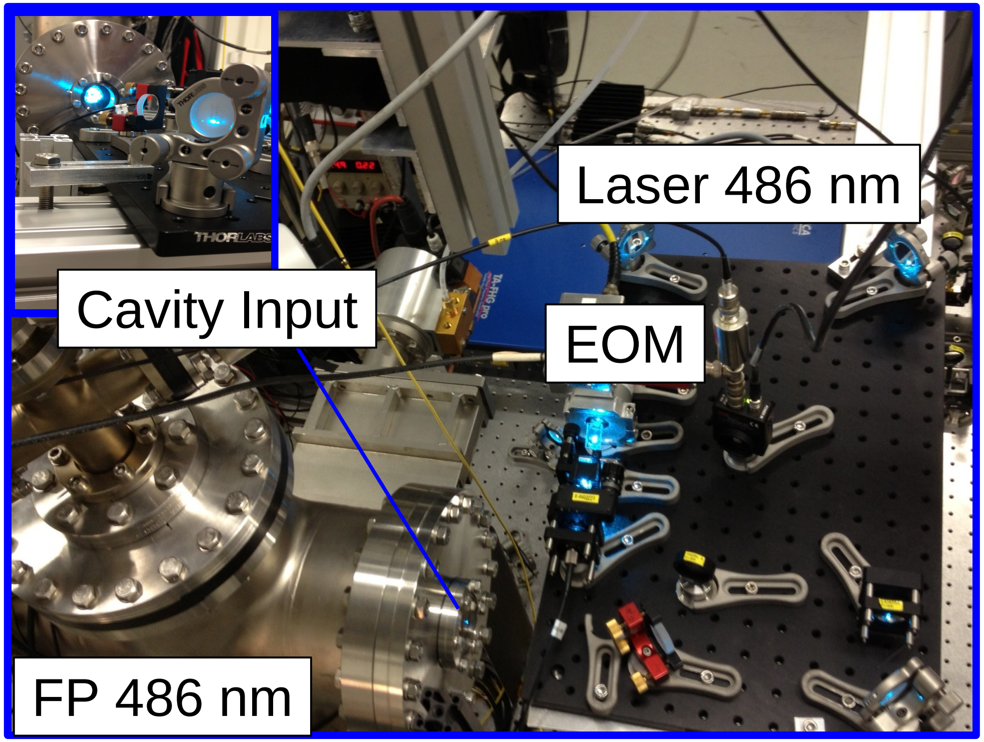
Suspension System

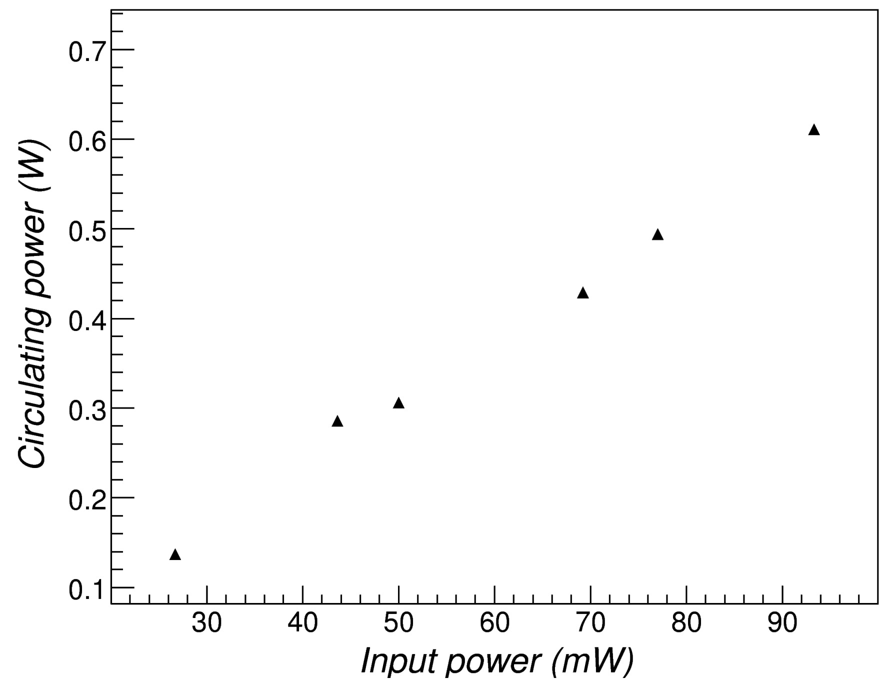


T1 = T2 = 7 ppm
A1 = A2 = 7 ppm
FSR= 0.55 GHz
Linewidth = 2.5 kHz
Finesse ~ 225000
Incoupling 24%

*Ultra-low-loss mirrors from ATFilms (https://www.atflims.com)

The enhancement cavity @ 486 nm





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Incoupling 24%

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

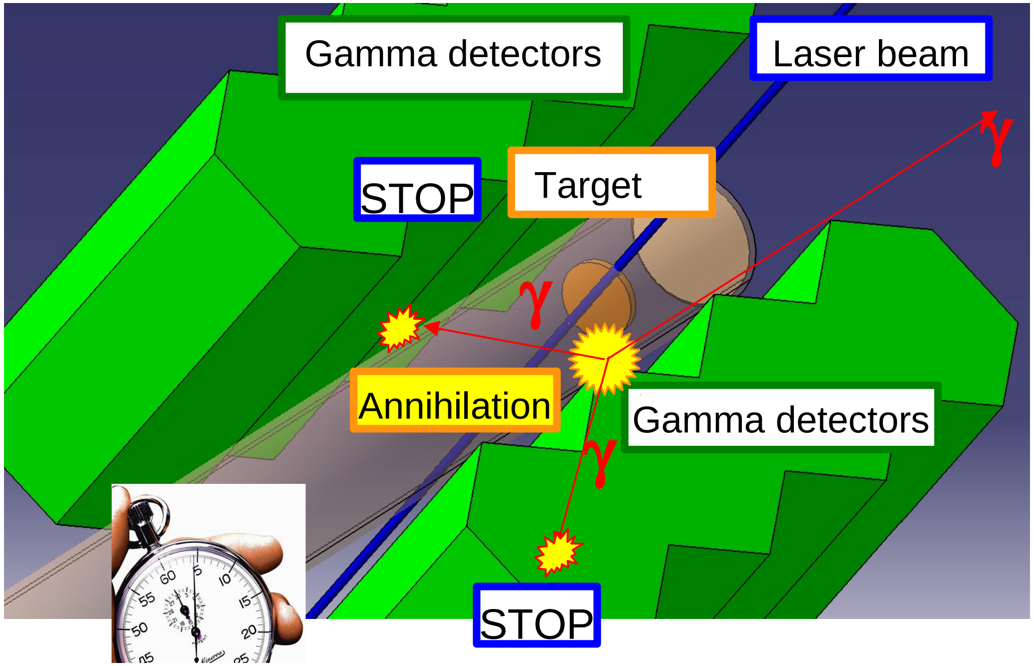
Run @ 0.5 kW:
-> Excitation prob ~ $4x10^{-4}$
-> Resonant 3γ PI ~ $4x10^{-5}$

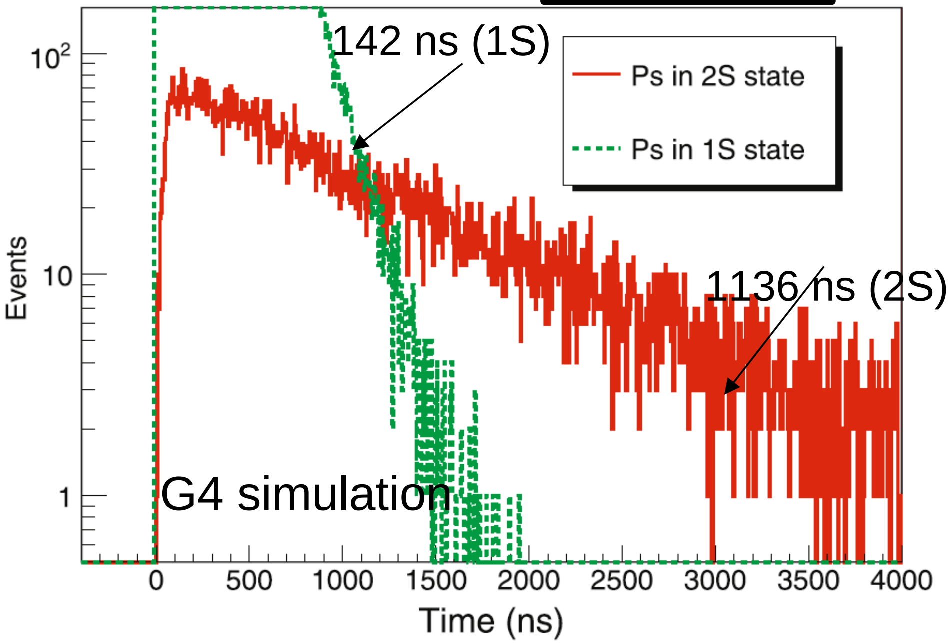
Stable generation of 500 W, no degradation over hours of continuous operation.

Detection of Ps 1S-2S

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

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





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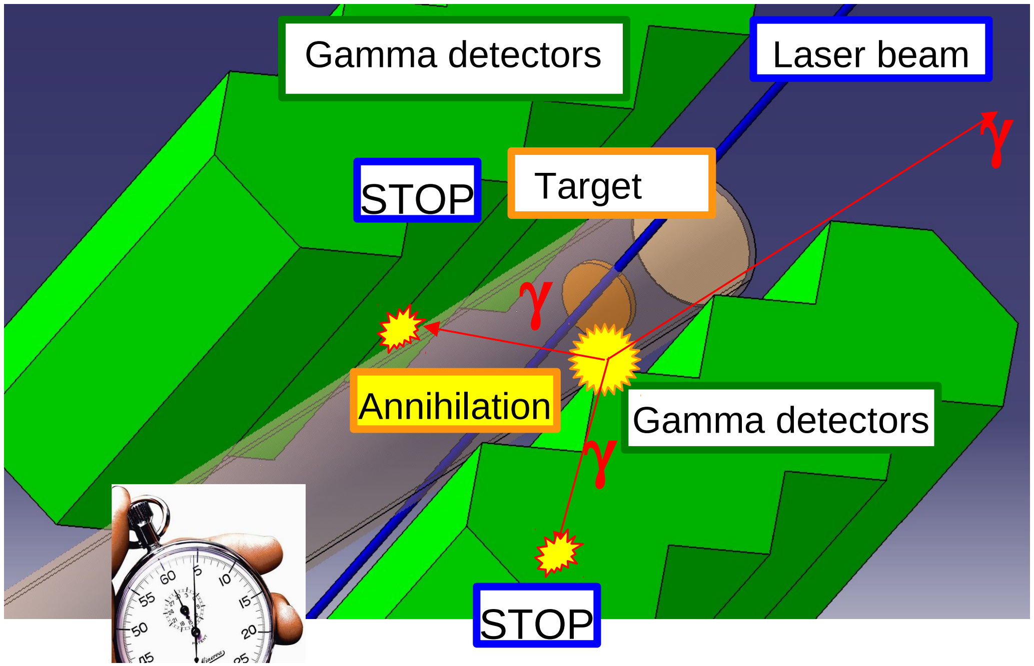

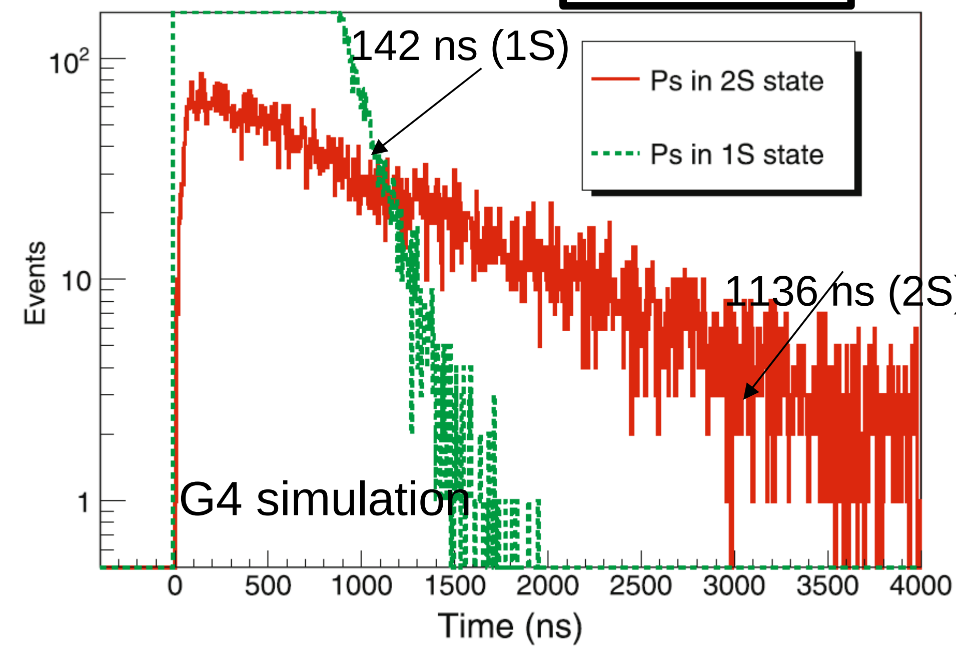

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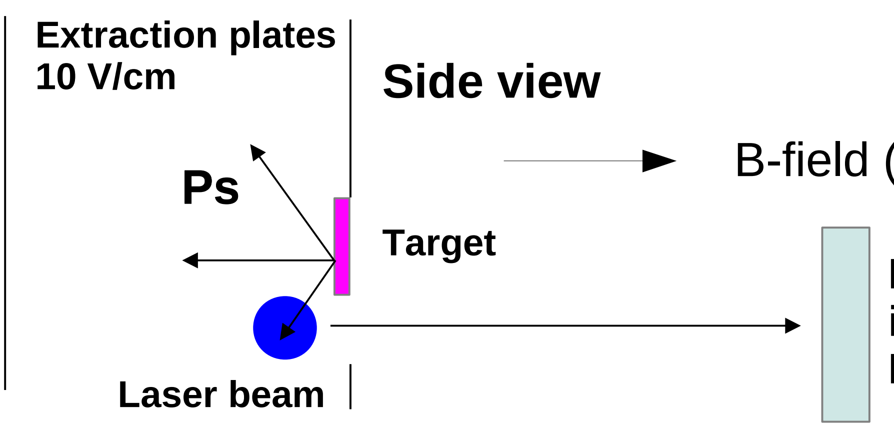

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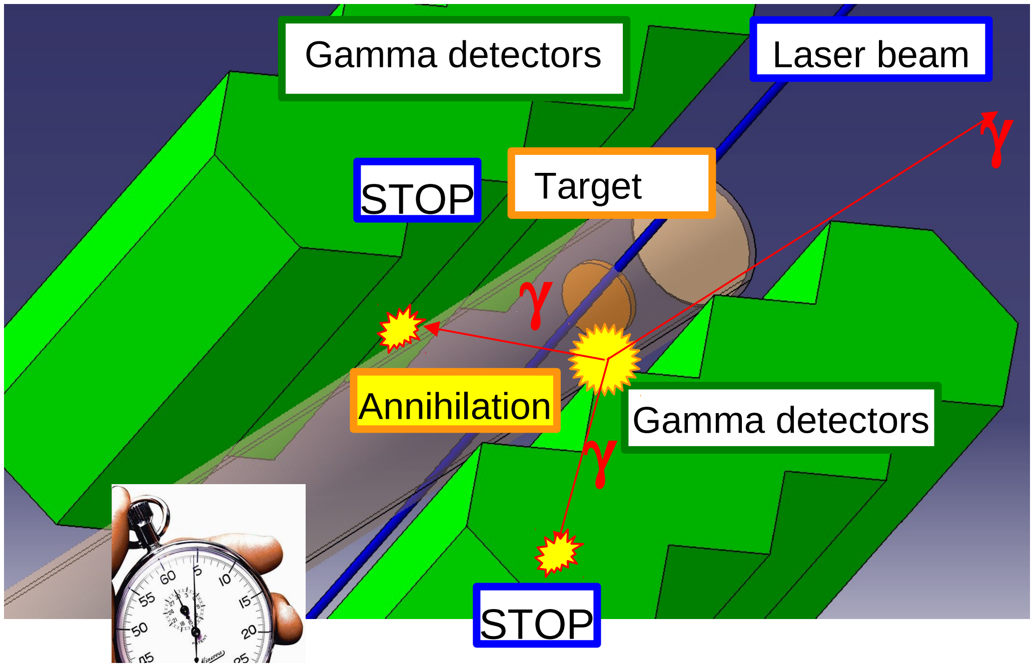

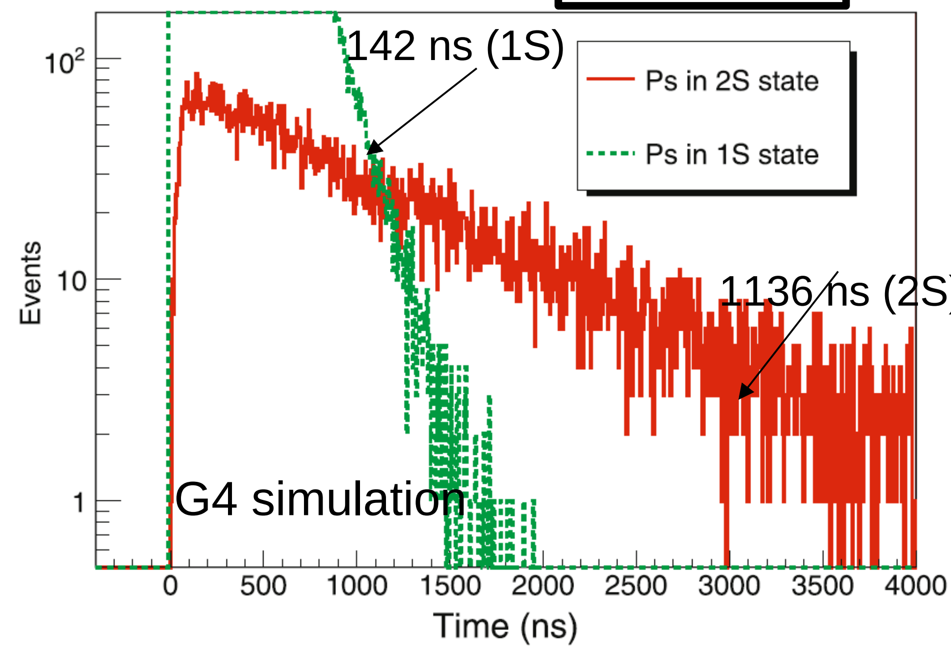

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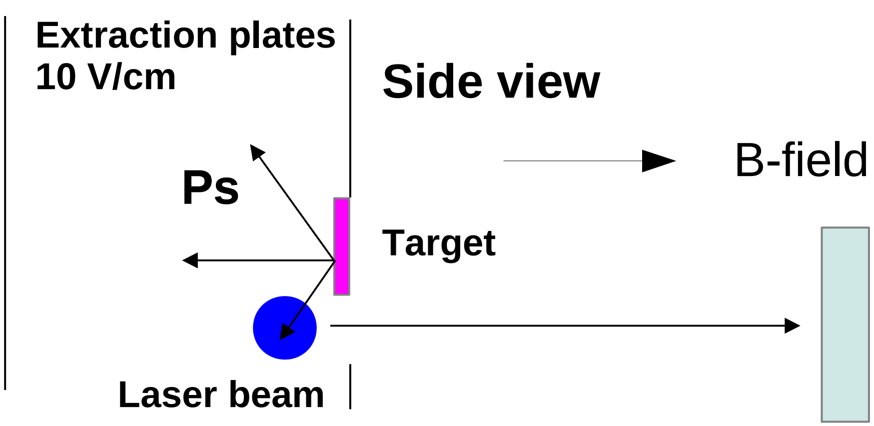

Study of systematic varying the magnetic field (characterized at PSI to better than 1%)
Motional Stark effect ~v^2 (same dependence as 2^{nd} order Doppler as was done for H at LKB by Biraben et al .)

Status of 1S-2S experiment

<u>Positron beam</u>

Upgraded with solid neon moderator (factor 20 more positrons)

Construction of the excitation chamber.

New coils built and charachterized at PSI.

Efficient and stable positronium production.

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Laser system

Stabilization to 1 kHz (short term), 1 MHz/day (drift)

Stable generation of 500 W circulating power (no degradation over hours).

Reference: saturated spectroscopy of molecular tellurium (line 55 MHz from Ps)

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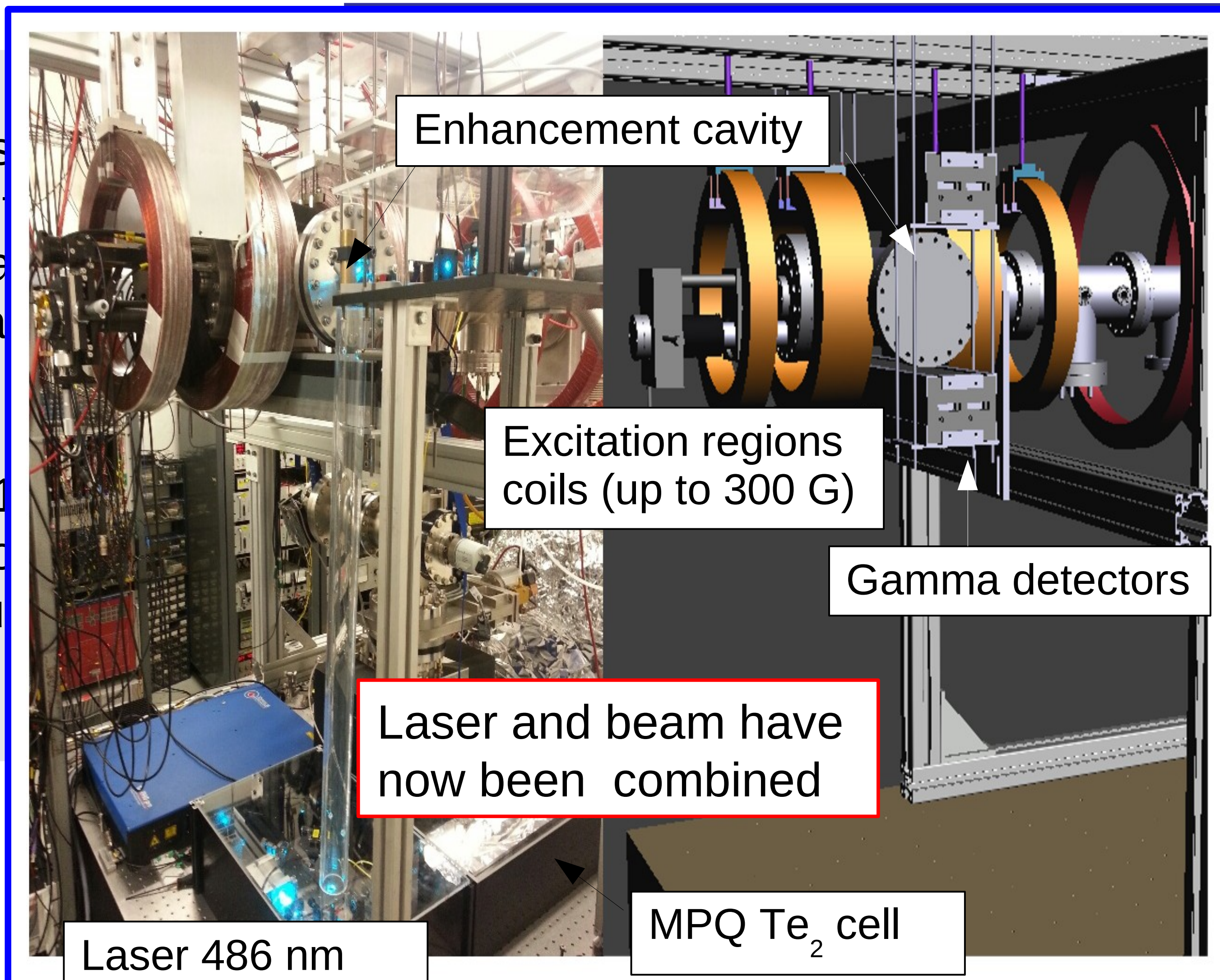

Work in progress to reduce background (shielding + beam bunching), improve stability of the system and maintenance of cryocooler will be required.

Ps Target- “Tube” geometry

To enhance Ps interaction time with laser (as proposed by P. Perez for Gbar) we installed (last week) a new target in a “tube” geometry.

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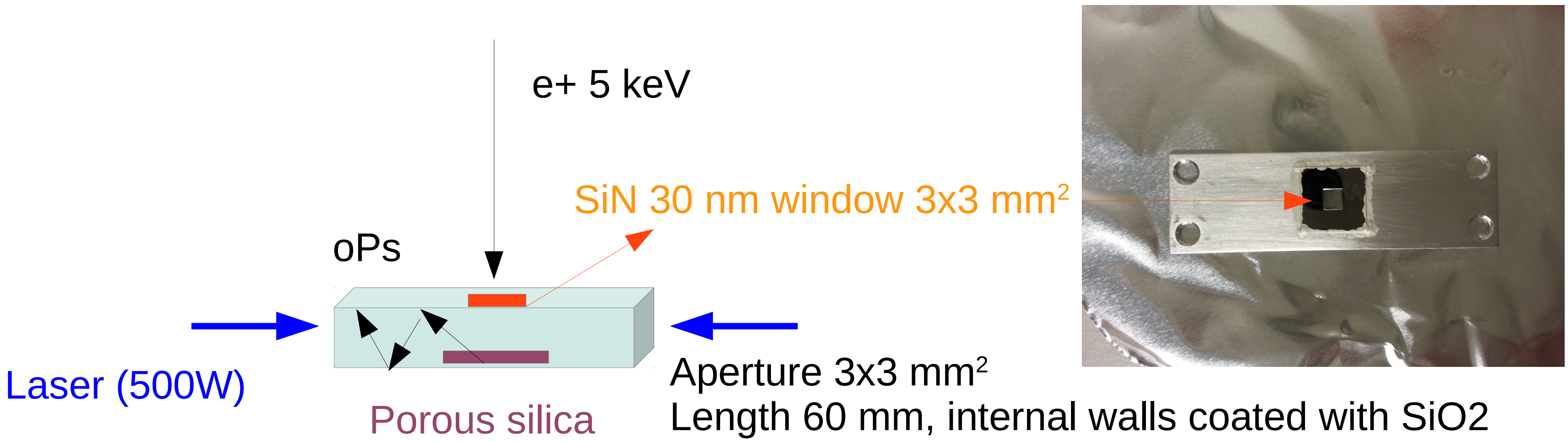

SiN transmission @ 5 keV close to 100%, Measured Ps fraction into vacuum of 22% (tube geometry -> about 5% reduction).

Data taking in progress...

Expected accuracy

With available source of Ps:
- Porous silica films: 30% @ 40 meV mono-energetic, isotropic emission

1) Uncertainty from statistics 1.8 MHz -> 0.35 MHz.
- Better positron beam (1 mm), higher detection efficiency,
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Further improvement at a level of 1×10^{-10} to test gravitational Redshift
only possible with cryogenic Ps.

Cryogenic Ps

- Aluminum oxide nano-channels 5-8 nm -> 7% of Ps at 150 K Brusa et al., PRL 104, 243401 (2010)

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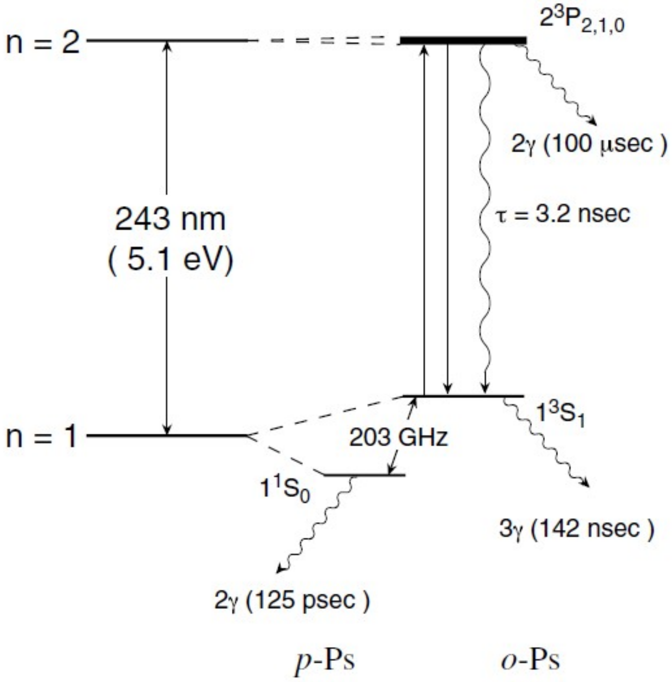
- Laser cooling?

1D Laser cooling 1S->2P (243 nm)
- Recoil limit: 0.2 K (v = 1500 m/s)
- Doppler limit 7.5 mK

- $I_{saturation}$=0.5 W/cm^2
- In saturation lifetime of Ps -> 280 ns

From RT to recoil limit -> 50 cycles (~Ps lifetime)



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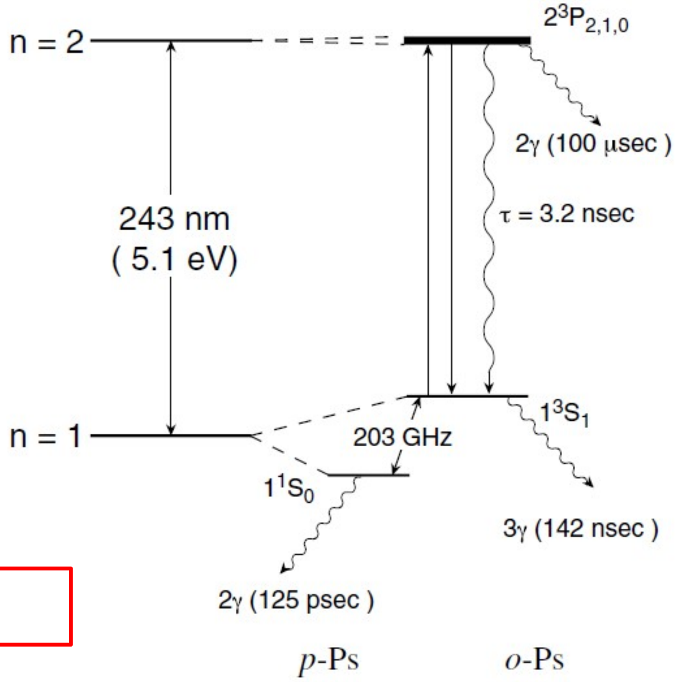

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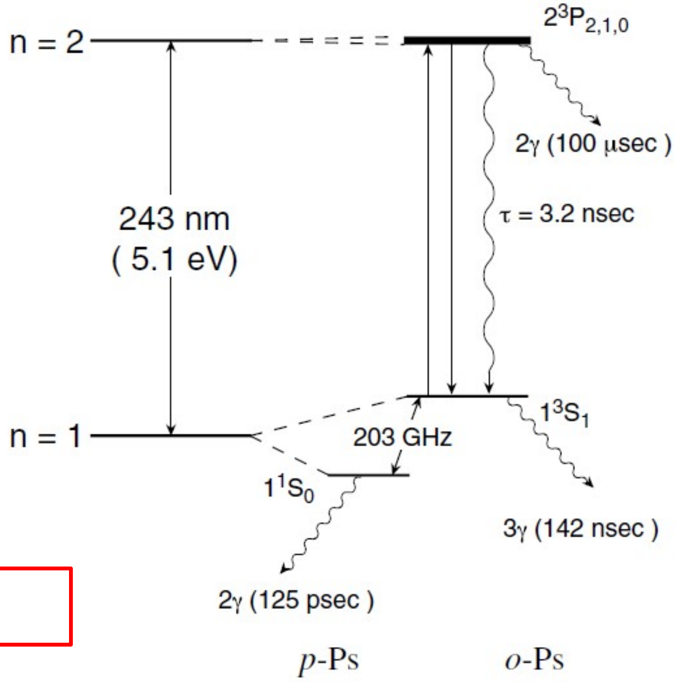

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Possible solution: use a mode locked laser at 80 MHz
(as proposed by F. Biraben for excitation of Ps in the 2P for the Gbar experiment).
Preliminary simulation is promising.

For Cd+ ions B. Blinov, J. Opt. Soc. Am. B/Vol. 23, No. 6/June 2006, 1170
For Na atoms P. Strohmeier, Z. Phys. D - Atoms, Molecules and Clusters 21,215-219 (1991)

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Thank you for your attention ☺