Positronium 1S-2S transition frequency measurement

Paolo Crivelli

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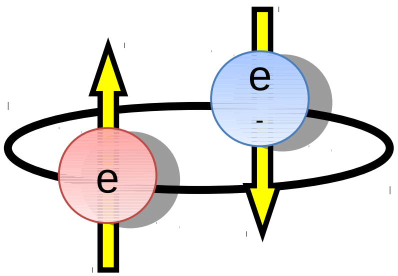
My work is supported by the Ambizione grant of the SNSF PZ00P2_132059
and ETH under the research grant ETH-47-12-1

Positronium (Ps)

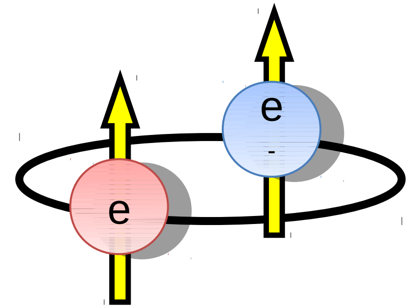
Two ground states:

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 $^3S_1$



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

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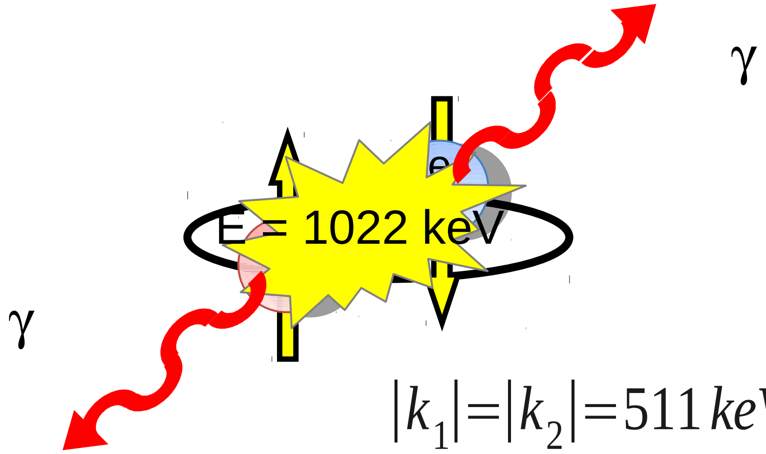

$$|k_1| = |k_2| = 511\,keV$$

.

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

Pirenne and Wheeler in 1946

Γ^{-1} = τ ≈ 125 ps (in vacuum)

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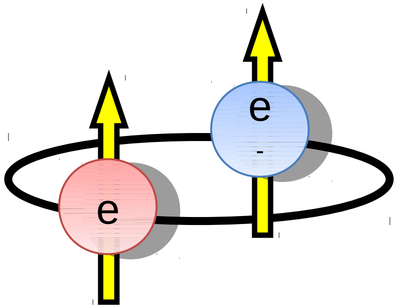

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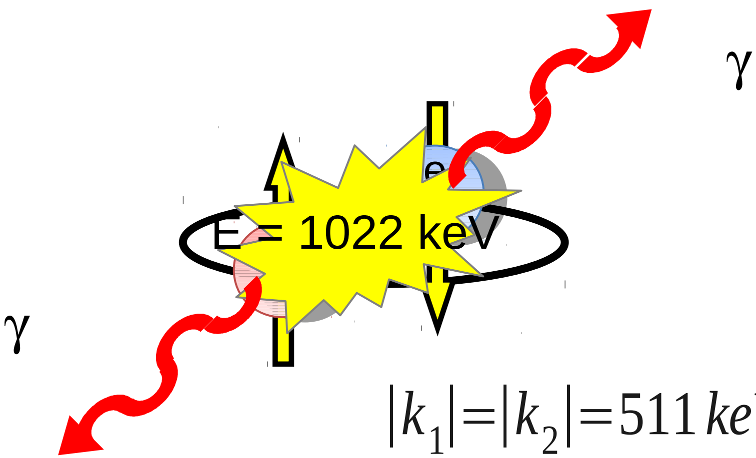

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Pirenne and Wheeler in 1946

$\Gamma^{-1} = \tau \approx$ **125 ps (in vacuum)**

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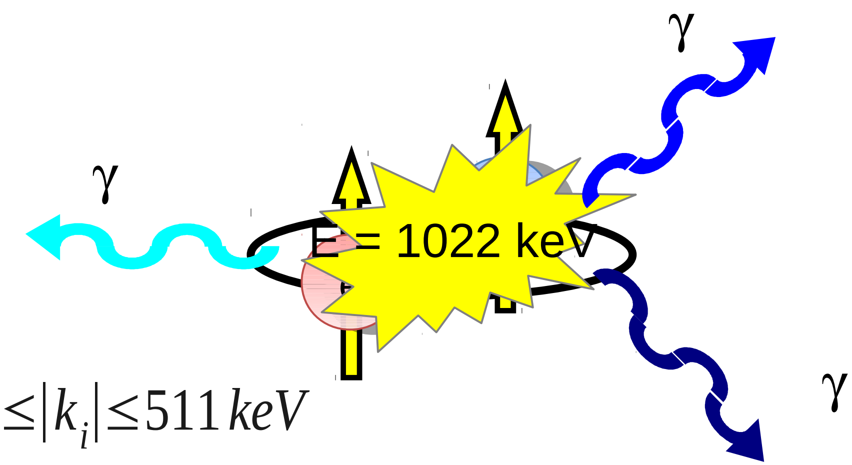


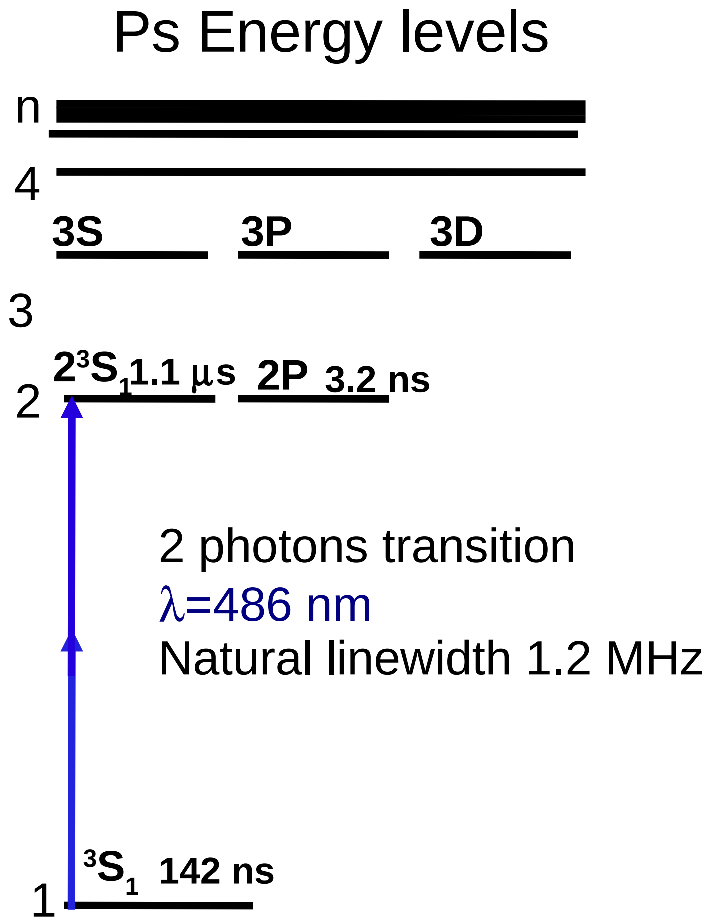
$$0 \leq |k_i| \leq 511\,keV$$

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

Ore and Powell in 1949

$\Gamma^{-1} = \tau \approx$ **142 ns (in vacuum)**

Positronium 1S-2S transition



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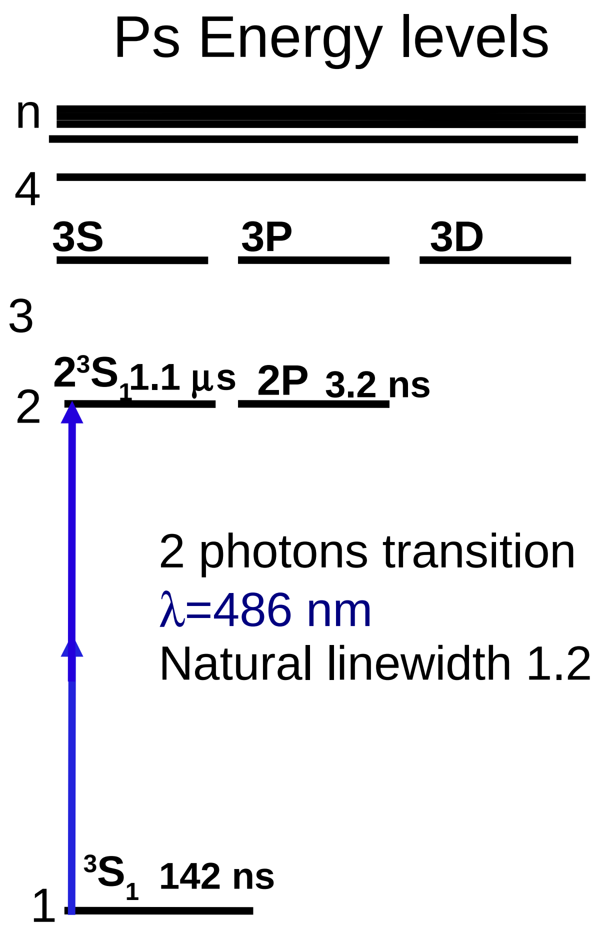
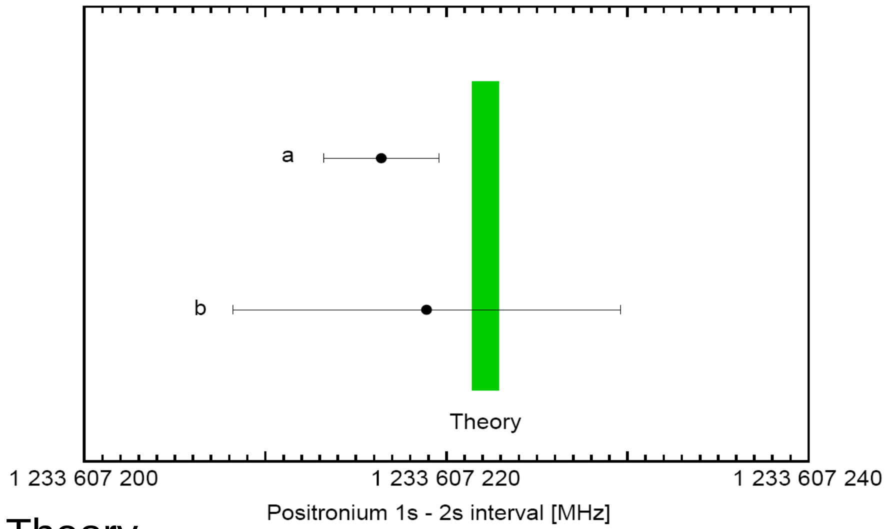


2 photons transition
λ=486 nm
Natural linewidth 1.2 MHz



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).

Experiment

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

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

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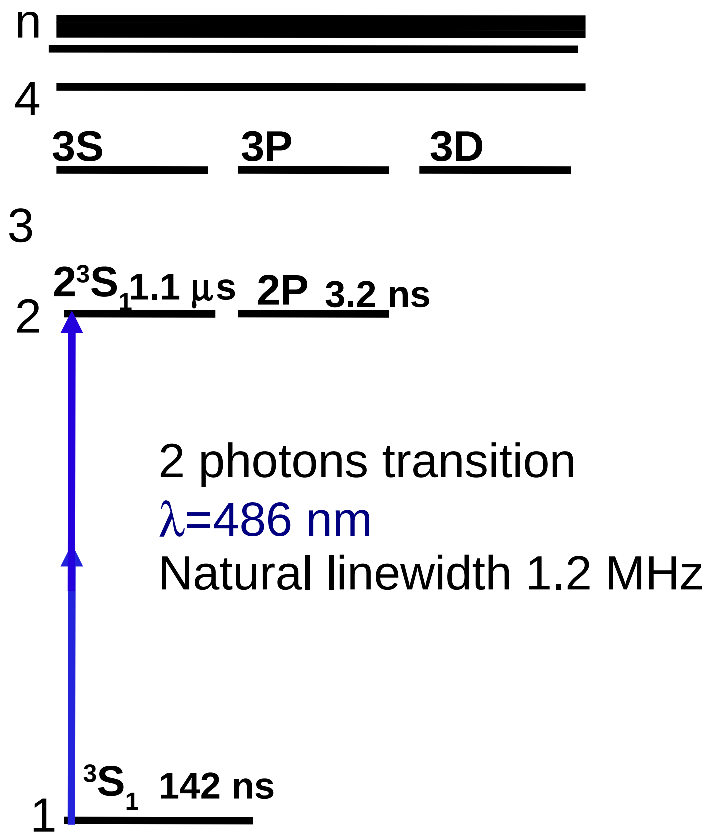

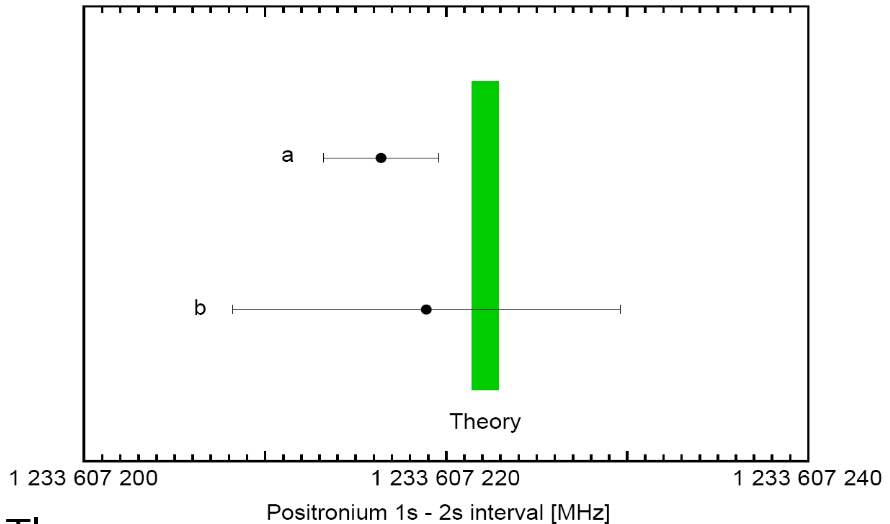

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⇒ Measurement of 1S-2S of Ps at a level about 5×10^{-10} => check QED calculations at the order $\alpha^7 m$ and provide best determination of m_{e+}/m_{e-}.

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
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• Magnetic moment (HFS)	$(Z\alpha)^2 m/M$ or $\alpha(Z\alpha)m/m_p$	α^2
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Leptonic atoms free of nuclear size effects!

Effect of gravity of antimatter -1

Attempts with charged anti-particles were not conclusive -> use neutral objects.
Recent measurement at CERN with trapped anti-H (ALPHA):
$\bar{m}_G/m_G$=(+100,-65) at 5% confidence level

NATURE COMMUNICATIONS | DOI: 10.1038/ncomms2787

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1) Gravity fall of anti-matter (anti-hydrogen at CERN): Aegis, GBar
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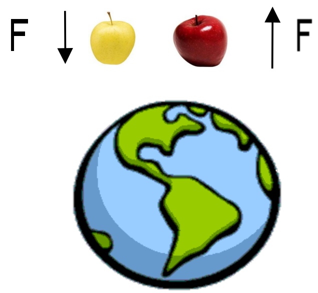
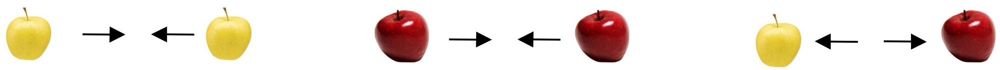
	ground state	excited state	transition frequency
h	$E = m_0c^2 + m_0gh$	$E = (m_0+\Delta m)(c^2 + gh)$	$h\nu_h = \Delta m(c^2+gh)$
	$E = m_0c^2$	$E = (m_0+\Delta m)c^2$	$h\nu_0 = \Delta mc^2$

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

Effect of gravity of antimatter -2

- Assuming antigravity:





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

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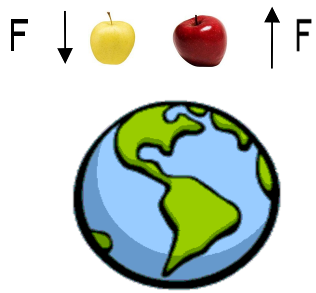

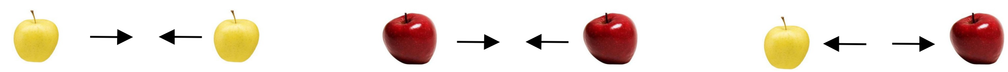

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- ΔU for different altitudes in the gravitational field of the earth is too weak for Ps

dh = 5000m ⇨ $\frac{\Delta\nu}{\nu} = 5.2 \times 10^{-13}$

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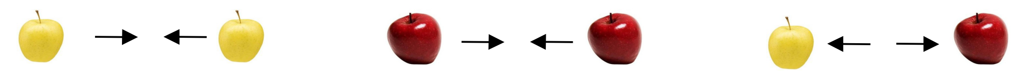

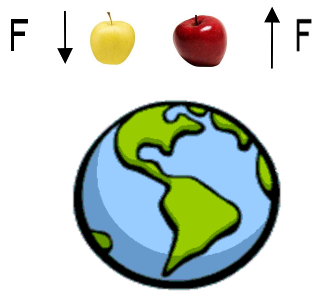

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- ΔU for different altitudes in the gravitational field of the earth is too weak for Ps

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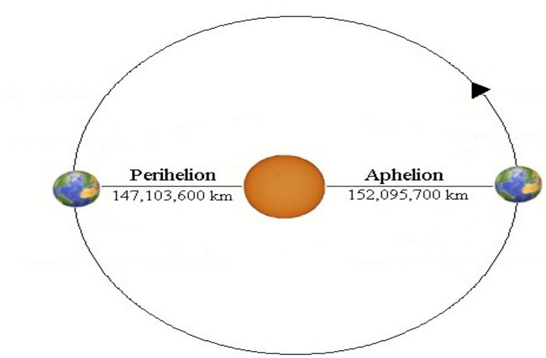
- Variation in the earth orbit around the sun : $5\text{x}10^6$ km.



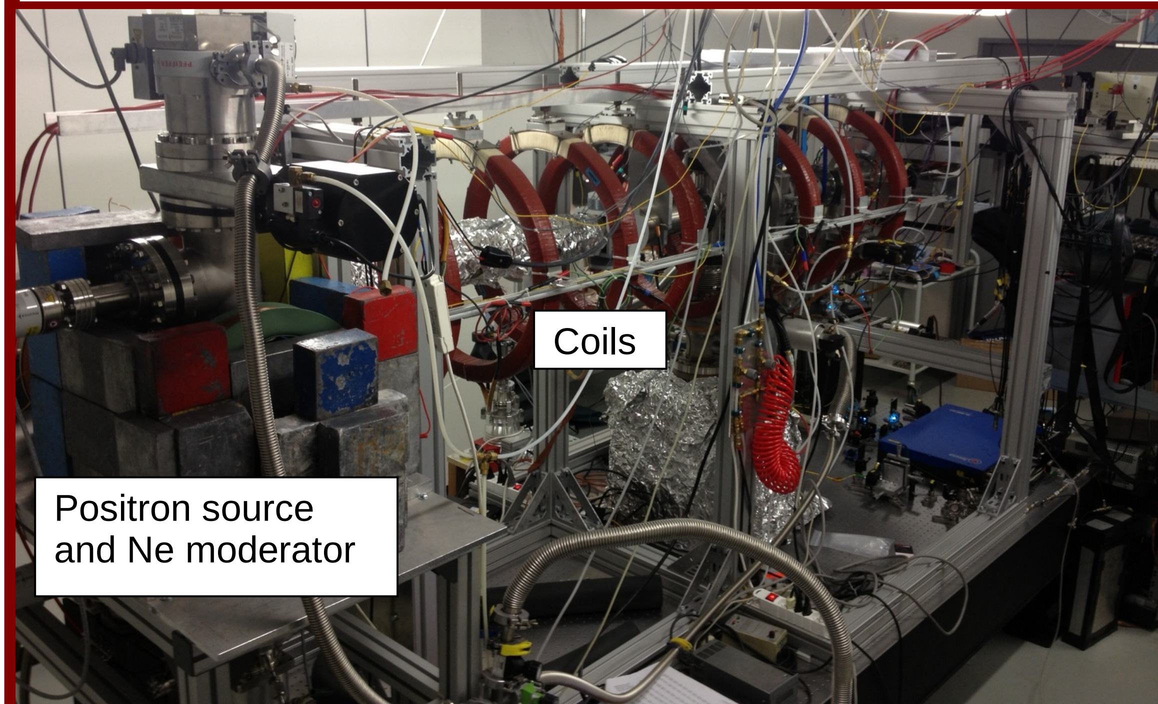
$$\frac{\Delta U(r_{\max}) - \Delta U(r_{\min})}{c^2} \simeq 3.2 \times 10^{-10}$$

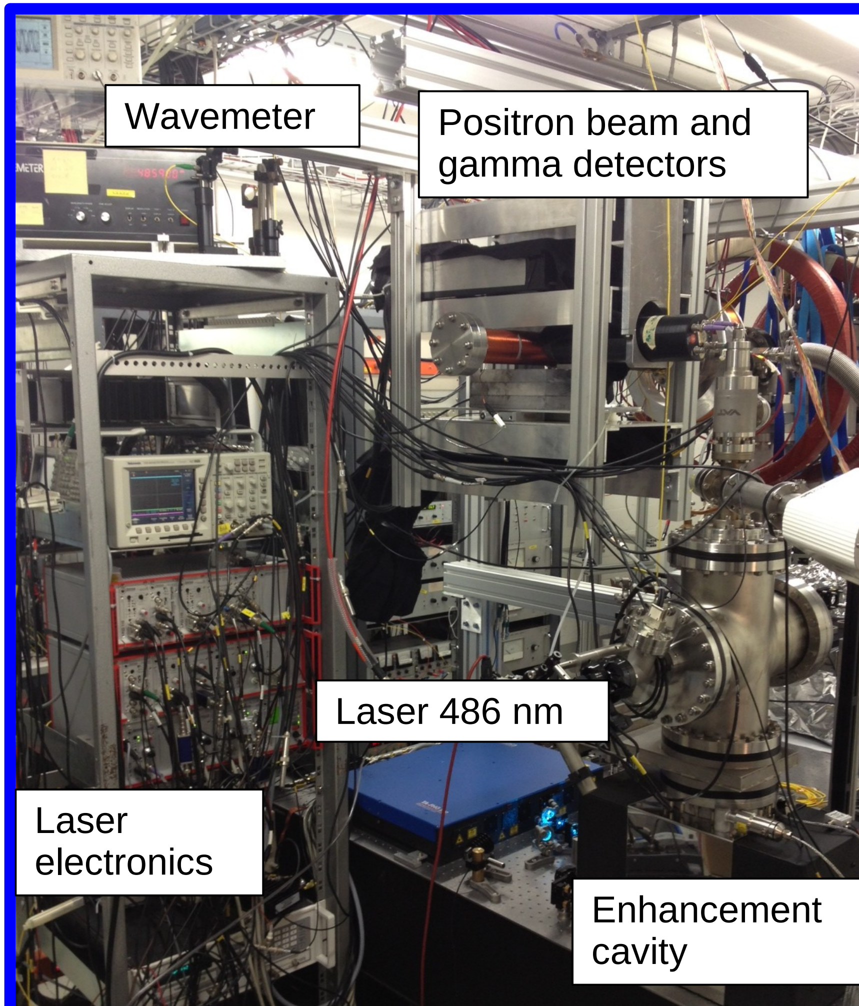
Measurement of 1S-2S Ps, Mu or HBar at a level about $1\text{x}10^{-10}$ => sensitivity to check the shift of antigravity.

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

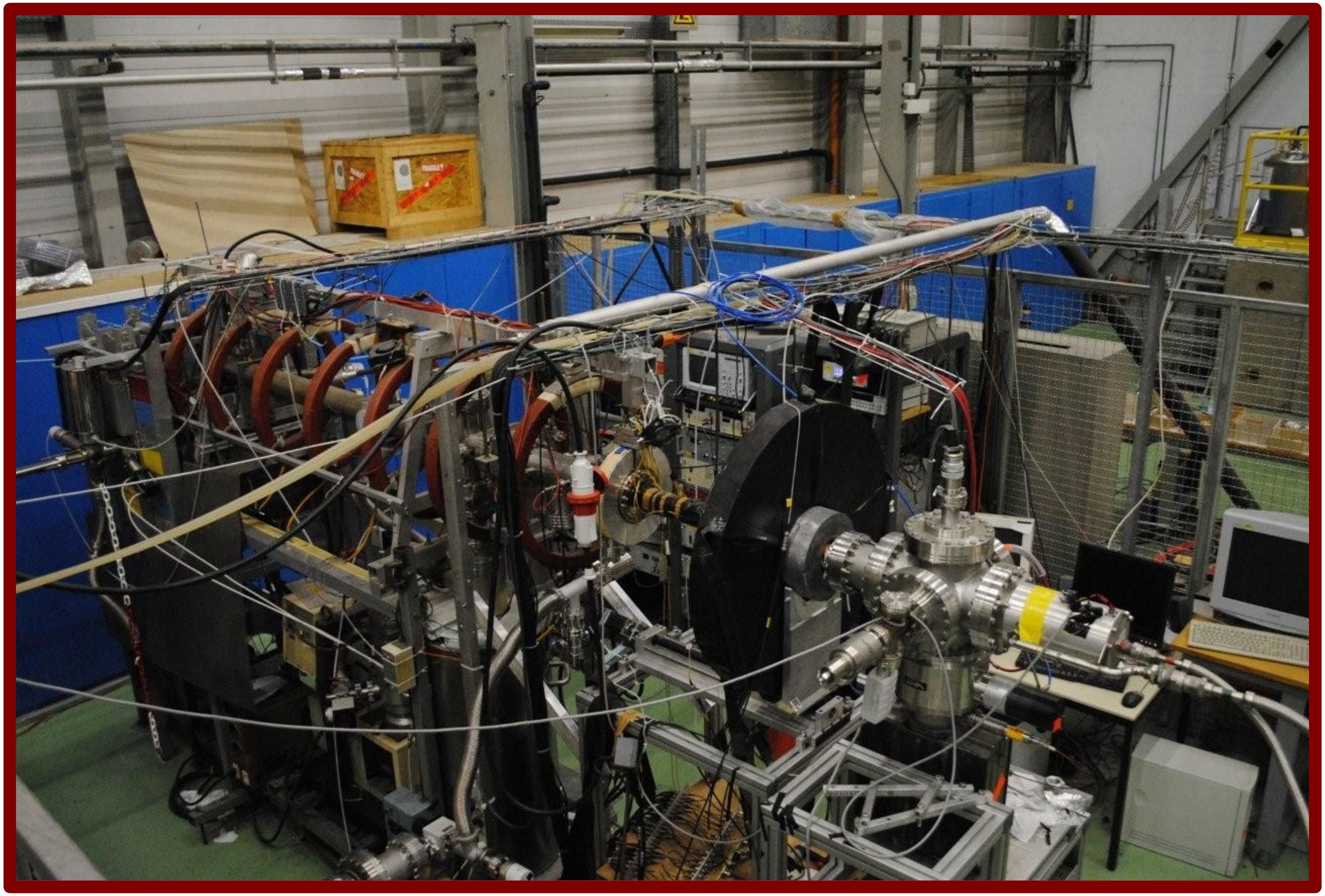




Laser system for generation of 486 nm light

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

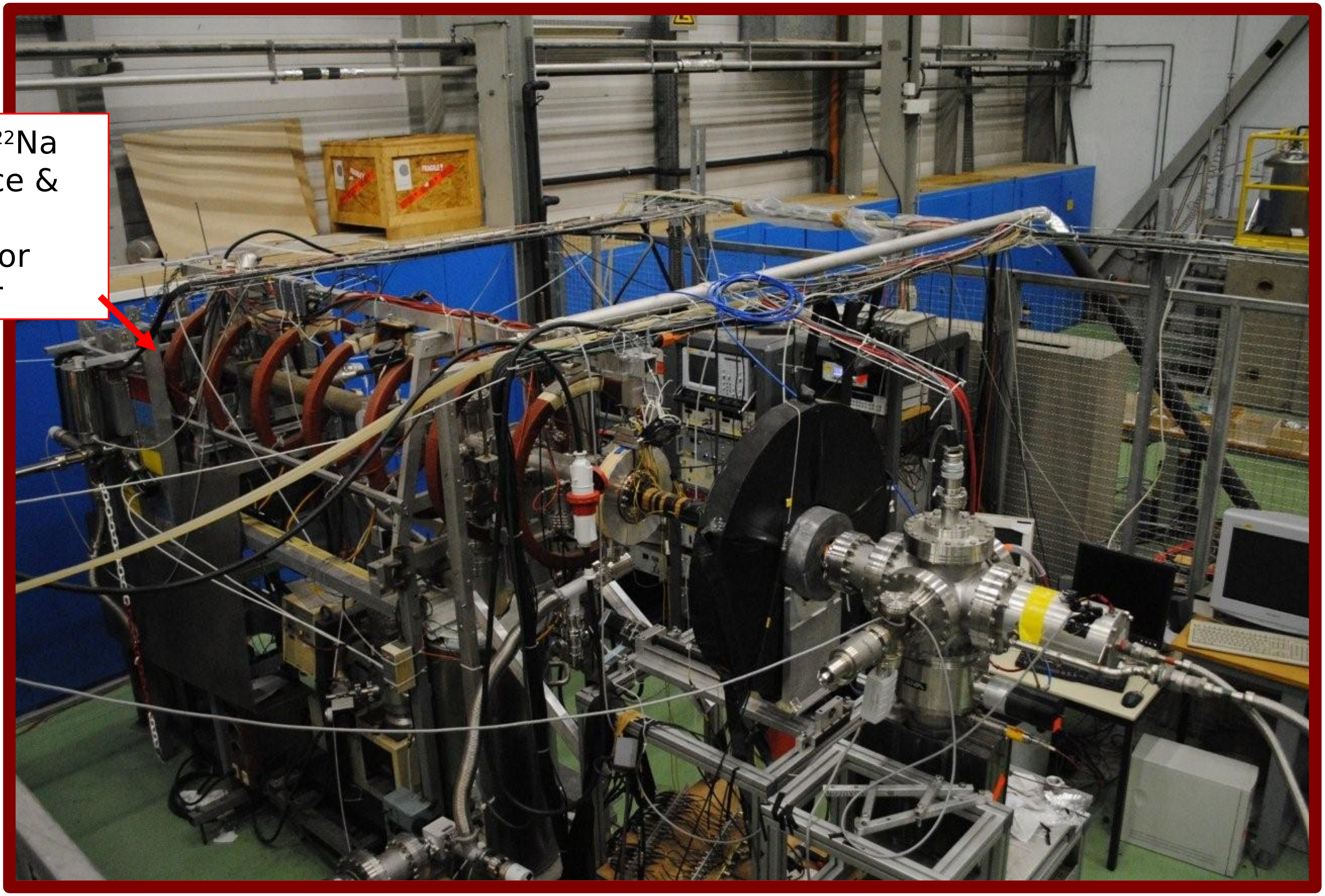
ETHZ slow positron beam



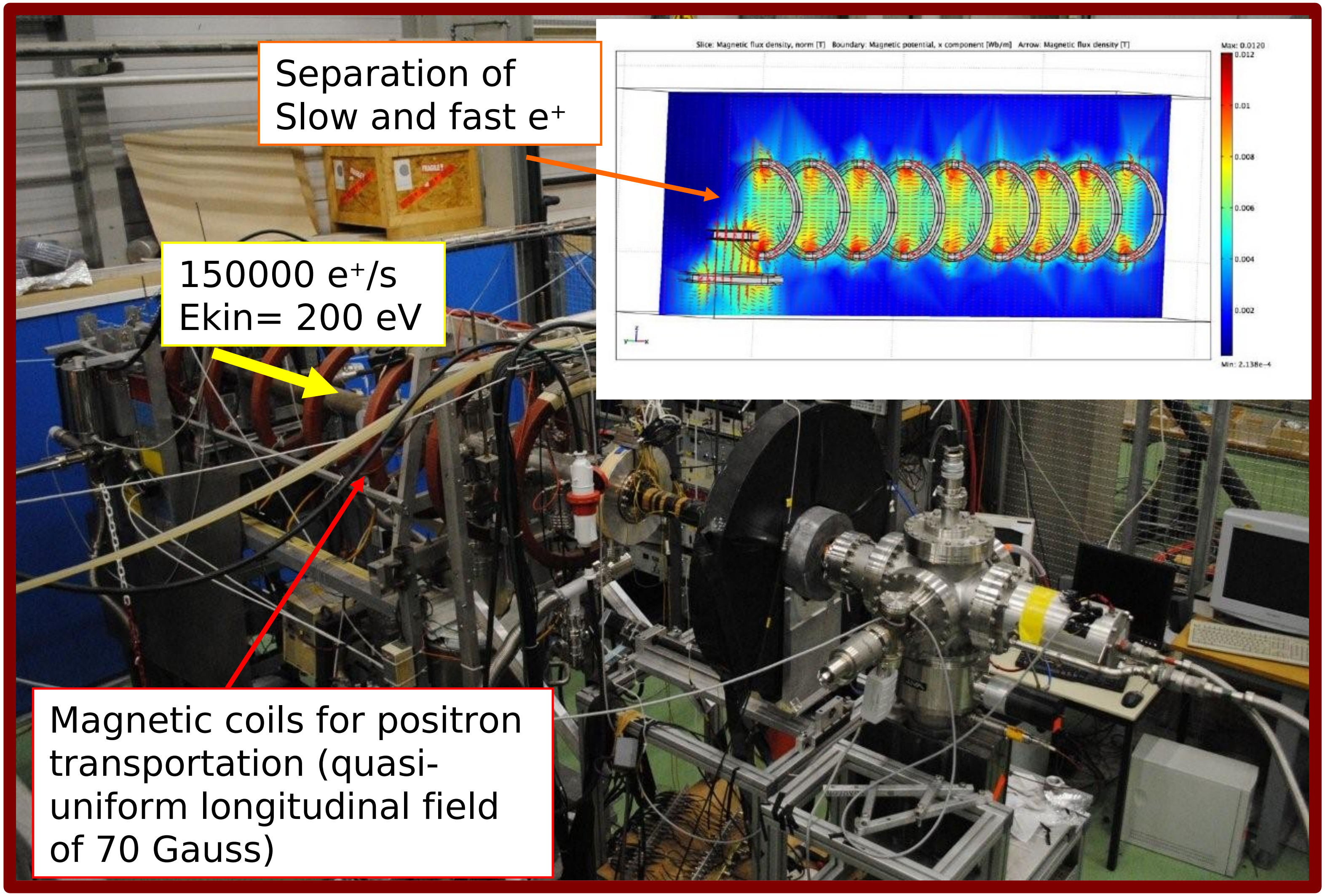
Production of positronium in vacuum requires slow positrons

The positron source

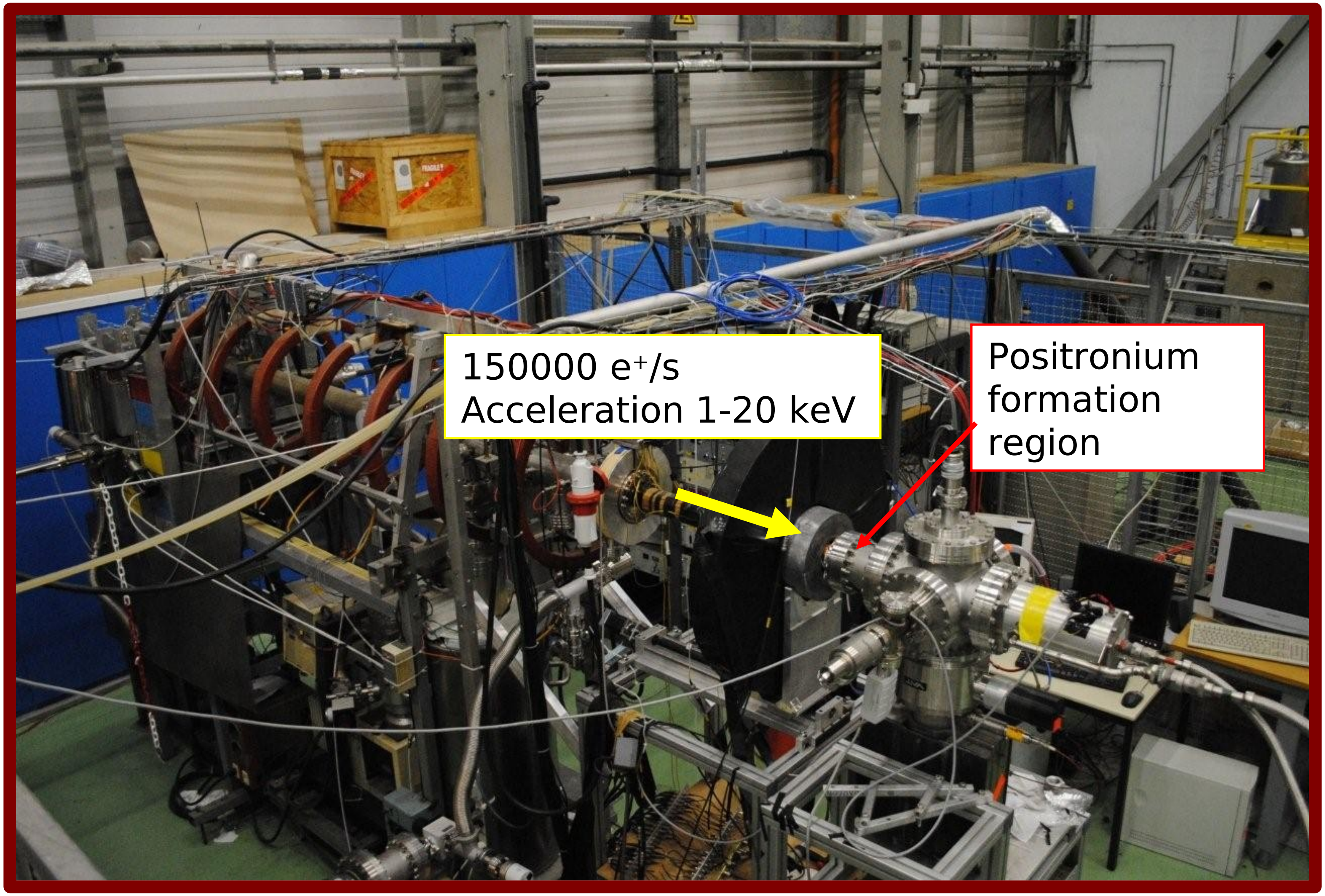
70 MBq ^{22}Na e+ source & Neon moderator chamber



Positron transportation

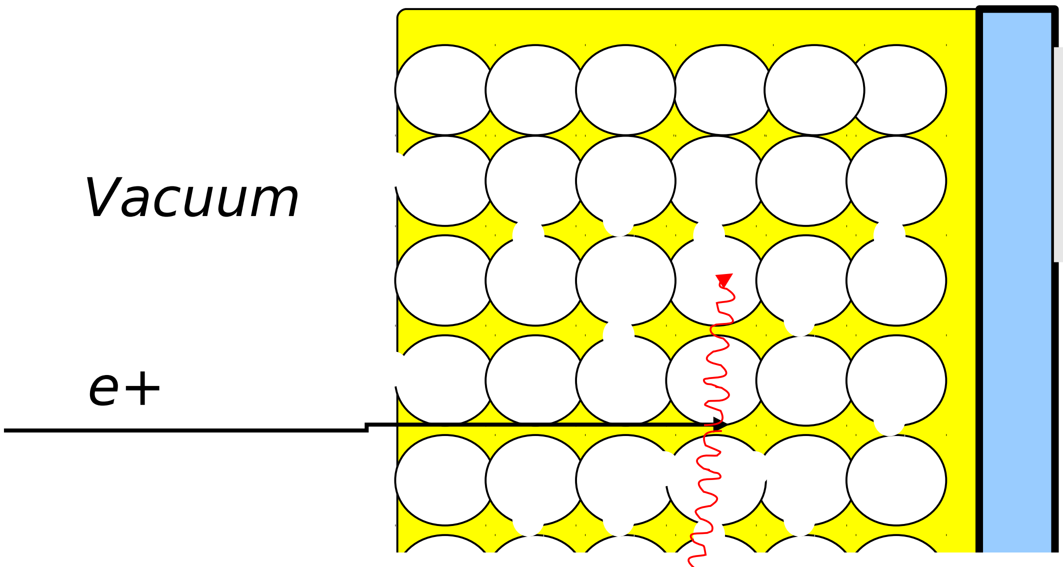


Positron-Positronium conversion target



Positron implantation

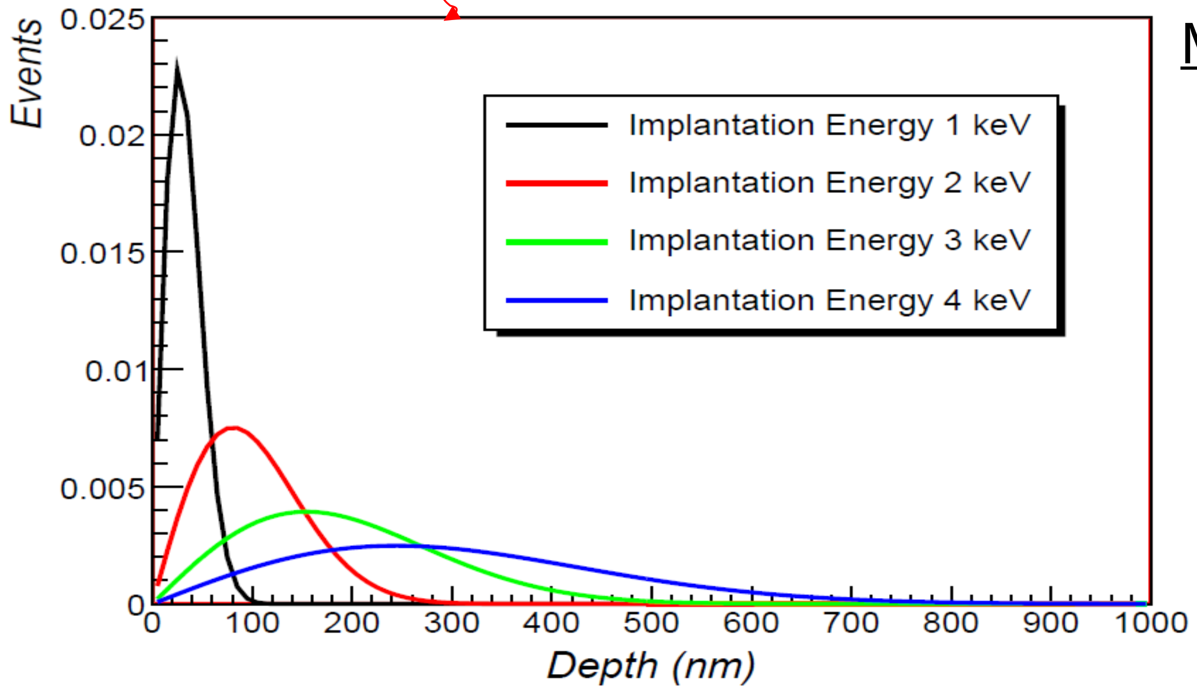
Porous Silica thin film ~1000nm 3-4 nm pore size



Positron implanted with keV energies

Rapidly thermalizes in the bulk (~ps)

A fraction undergo direct annihilation



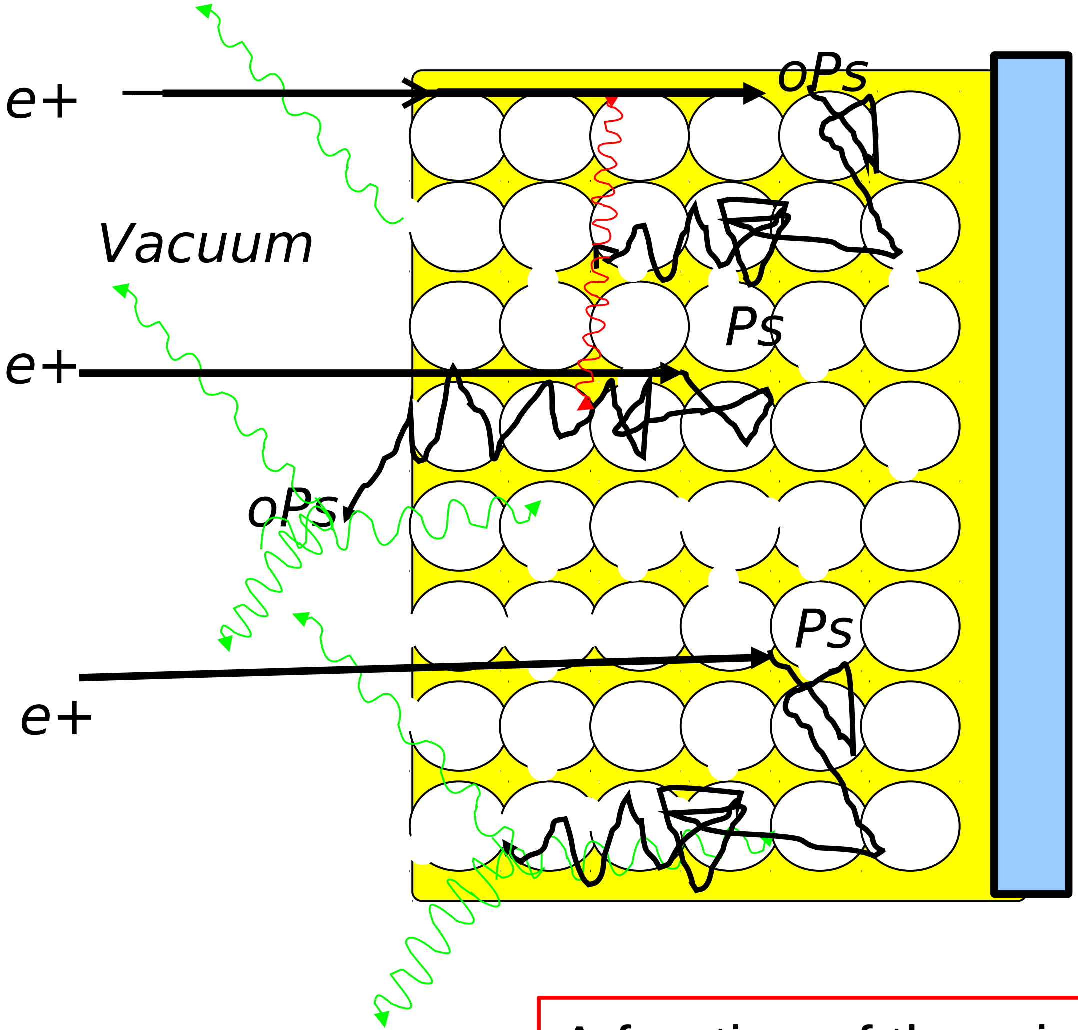
<u>Makhovian profile</u>

$$P(x,E) = \frac{m x^{m-1}}{x_0^m} e^{-(x/x_0)^m},$$

$$x_0 = \frac{x_m}{\Gamma((1/m)+1)},$$

$$x_{\mathrm{m}} = \frac{40}{\rho} E^{1.6},$$

Positronium formation



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

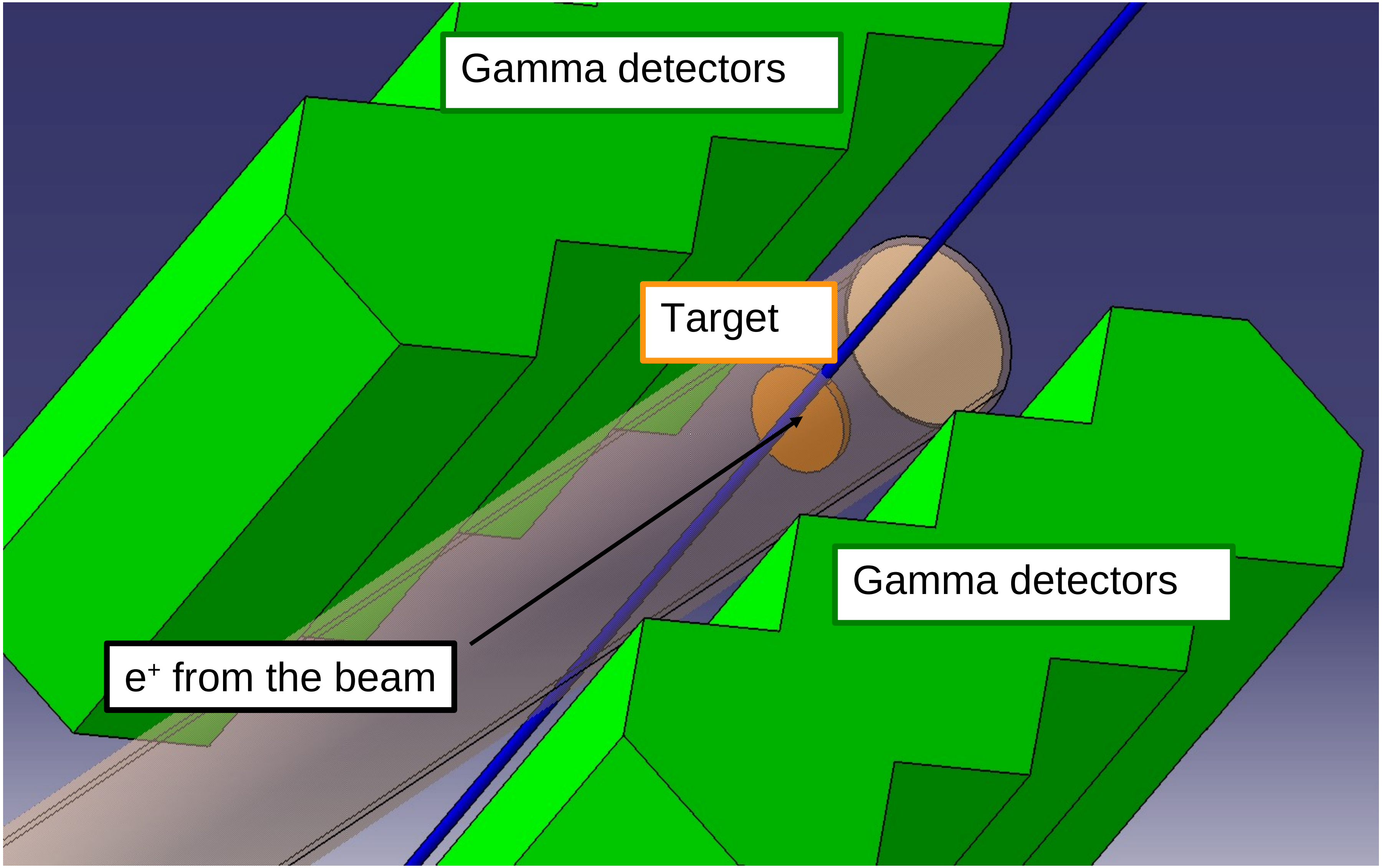
Diffusion to the pore surface and emission in the pores

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

Thermalization via collisions and diffusion in the interconnected pore network

A fraction of them is emitted into vacuum.

Ps detection



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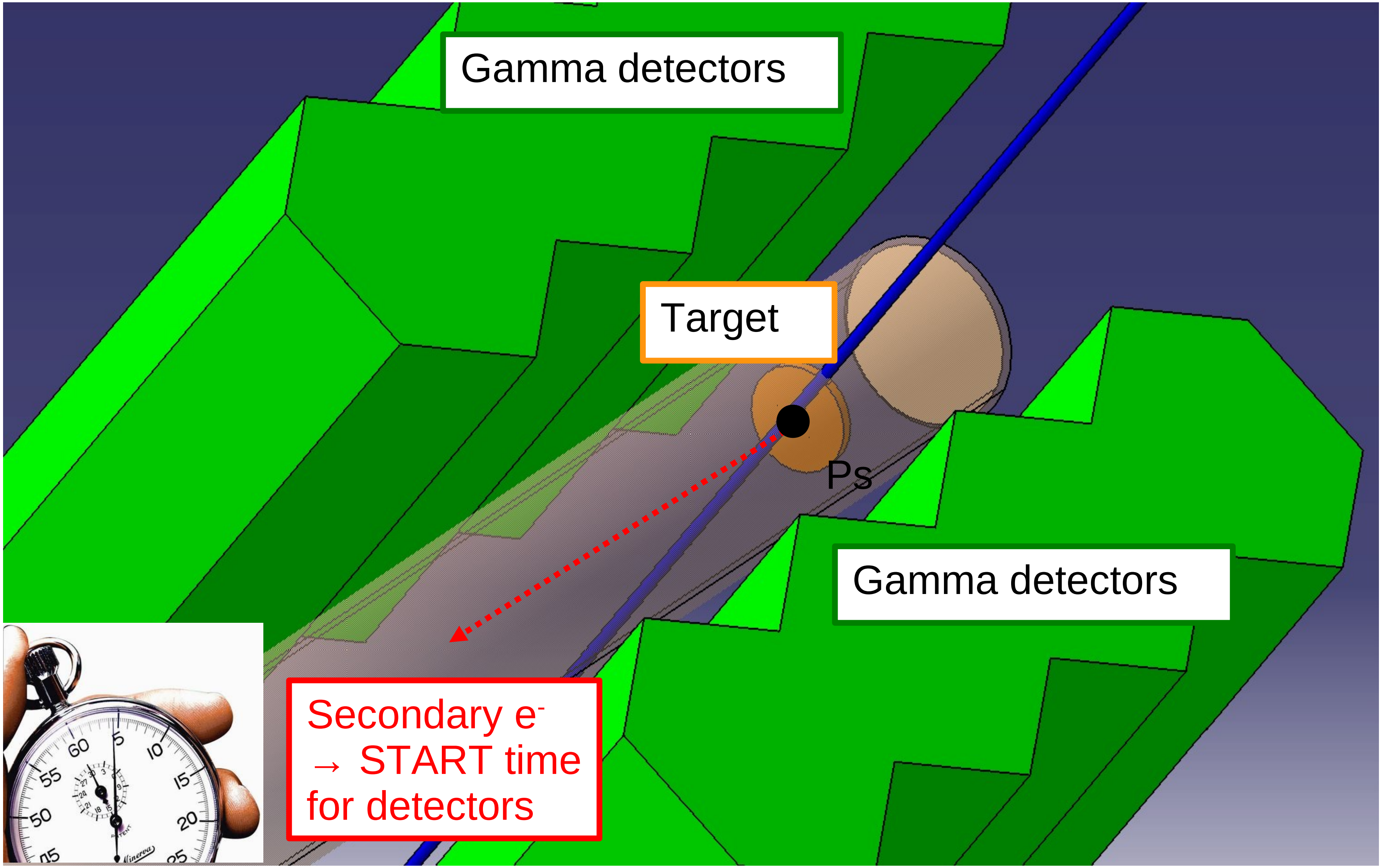

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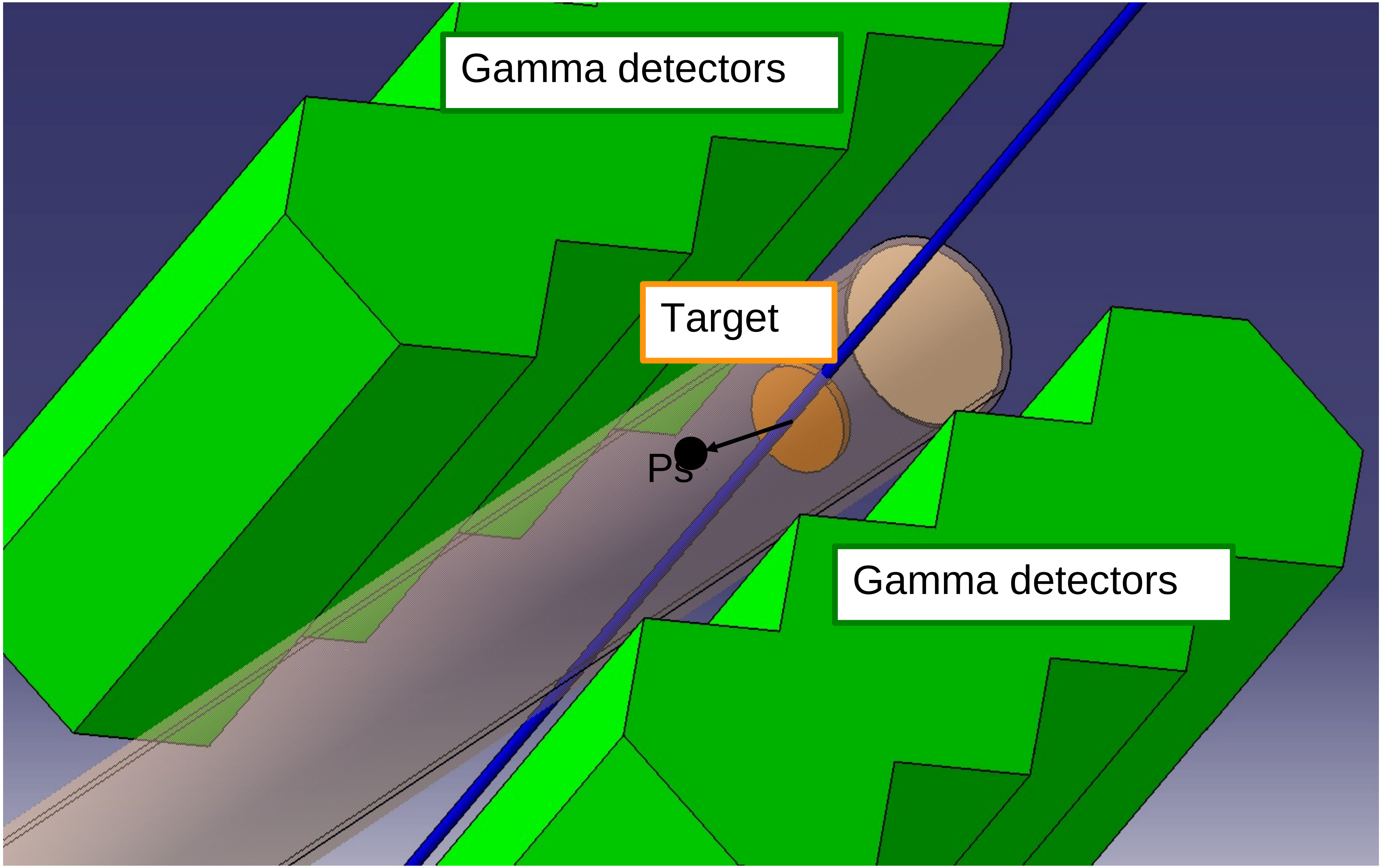

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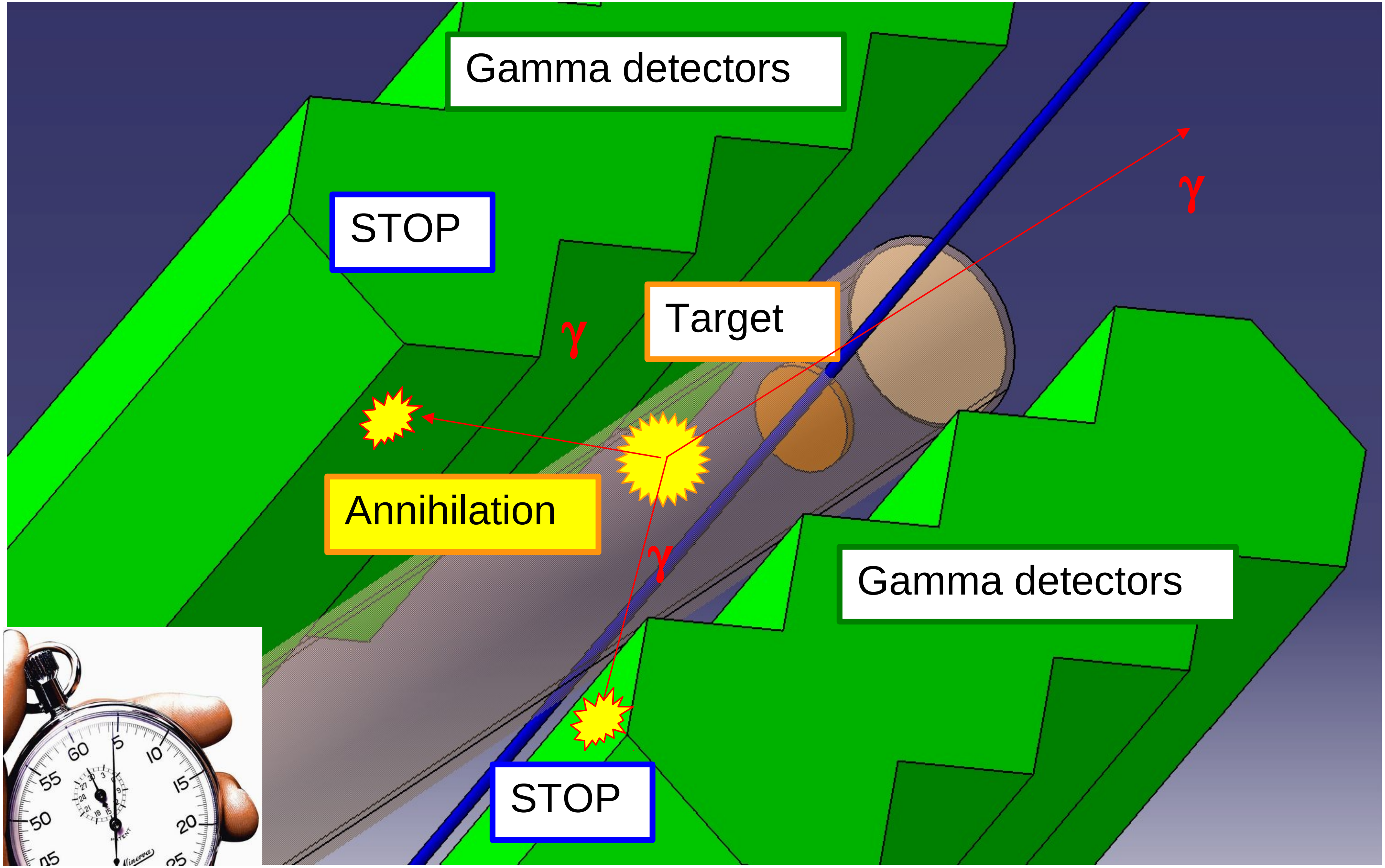
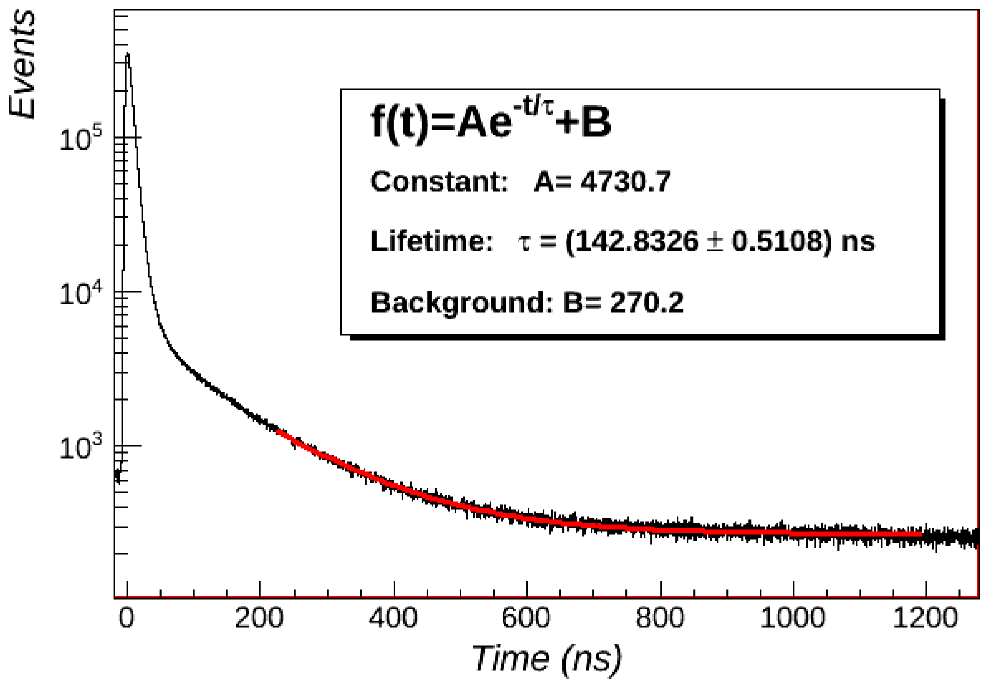
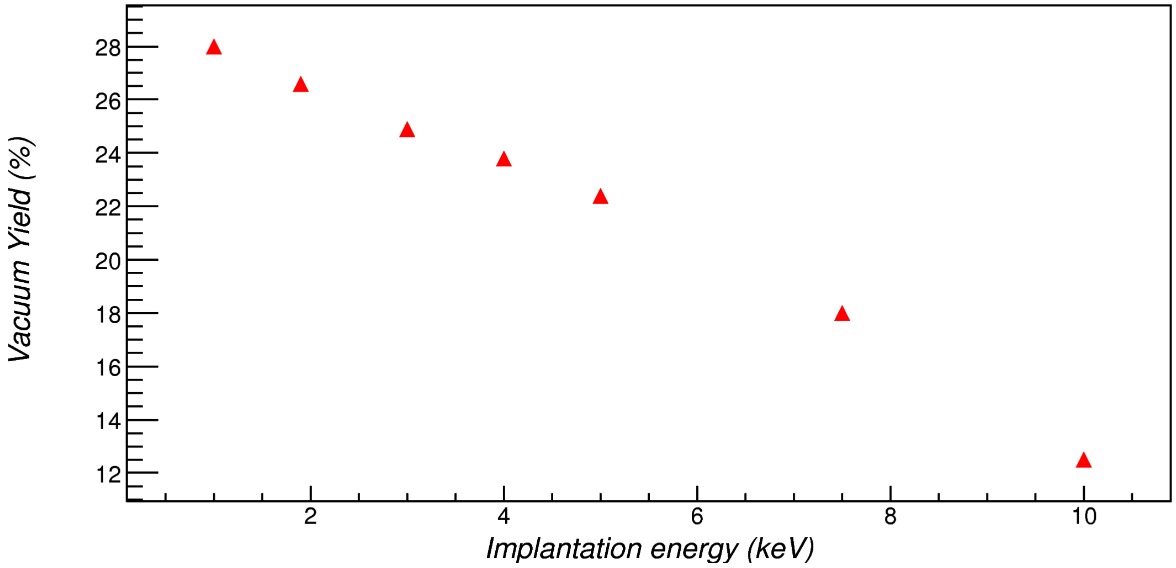


Positron annihilation lifetime spectra- PALS





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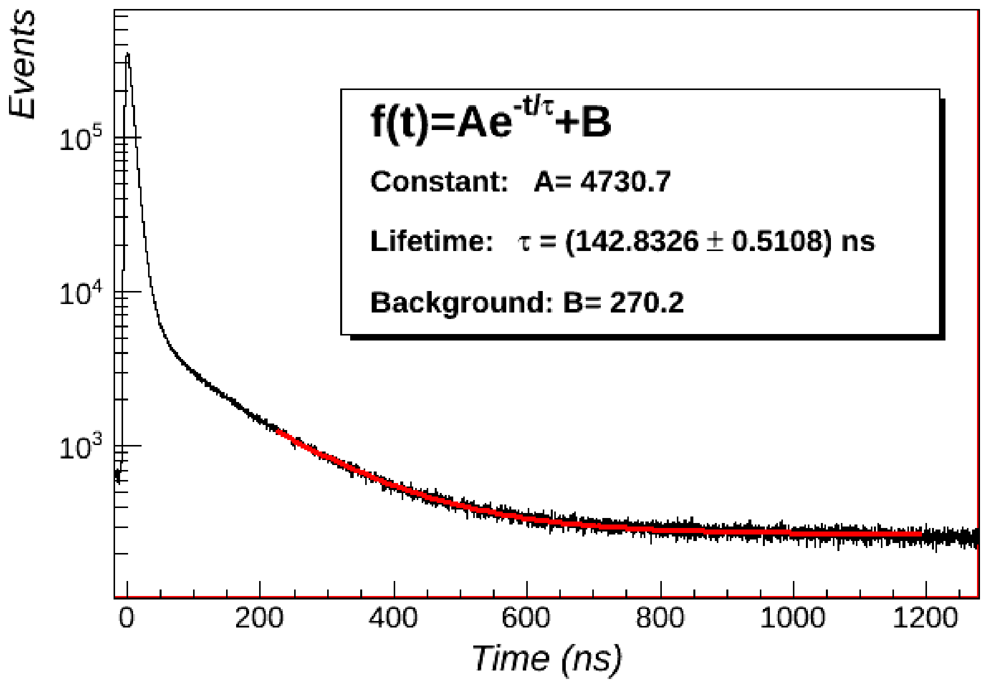
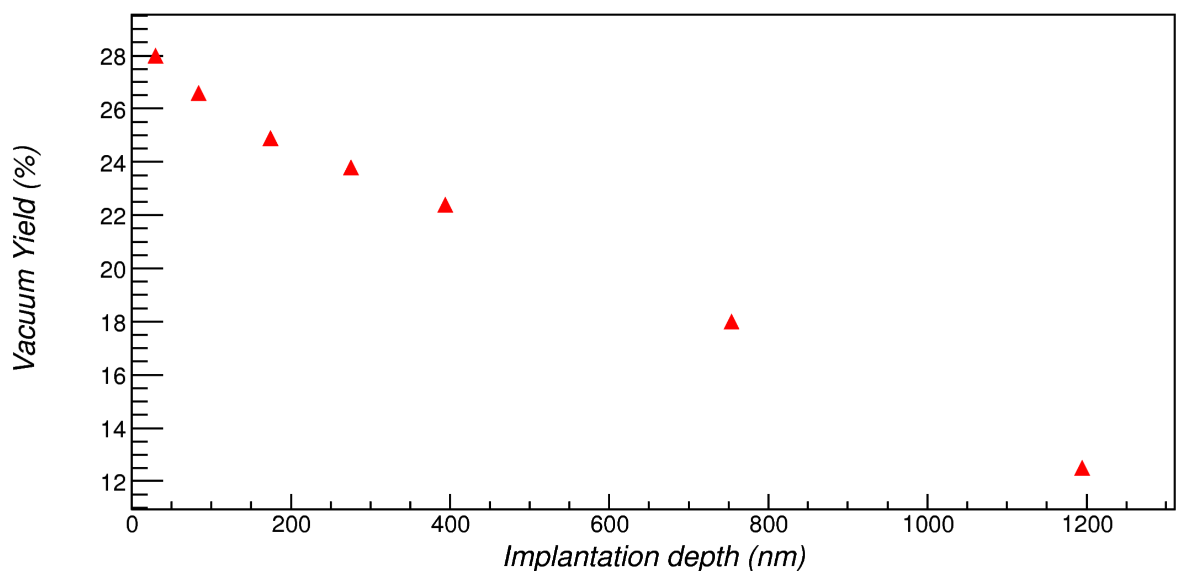
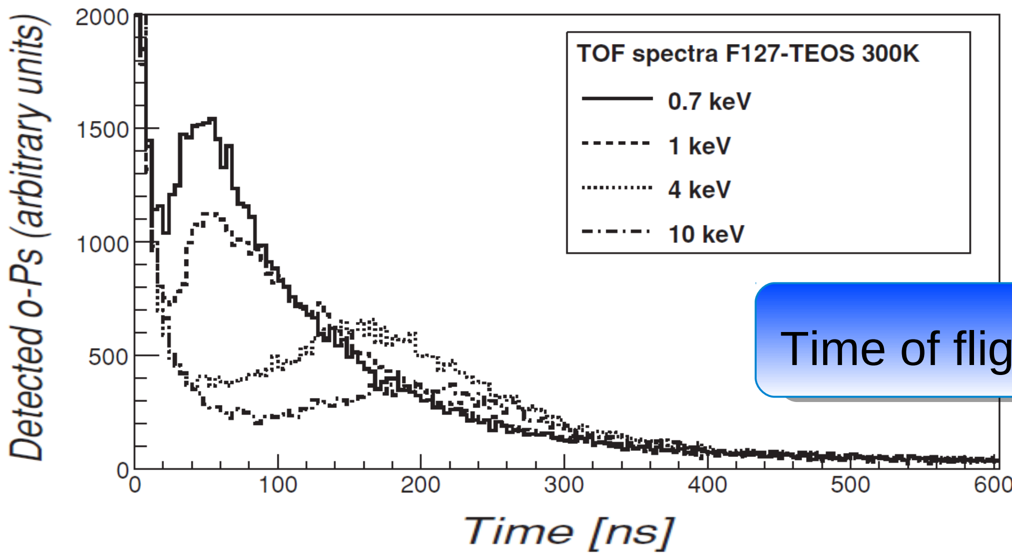
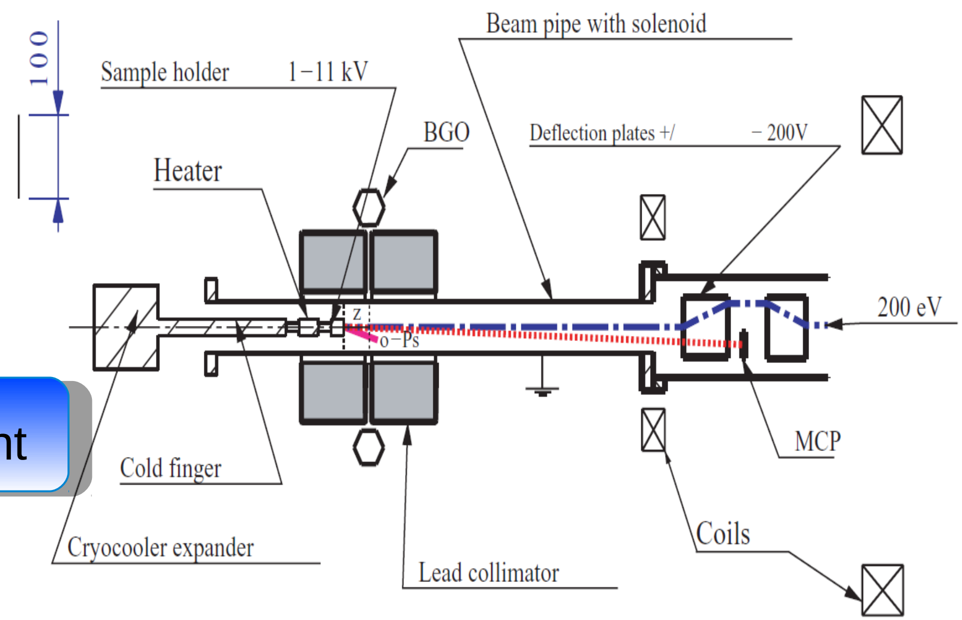




Measurement of Ps energy

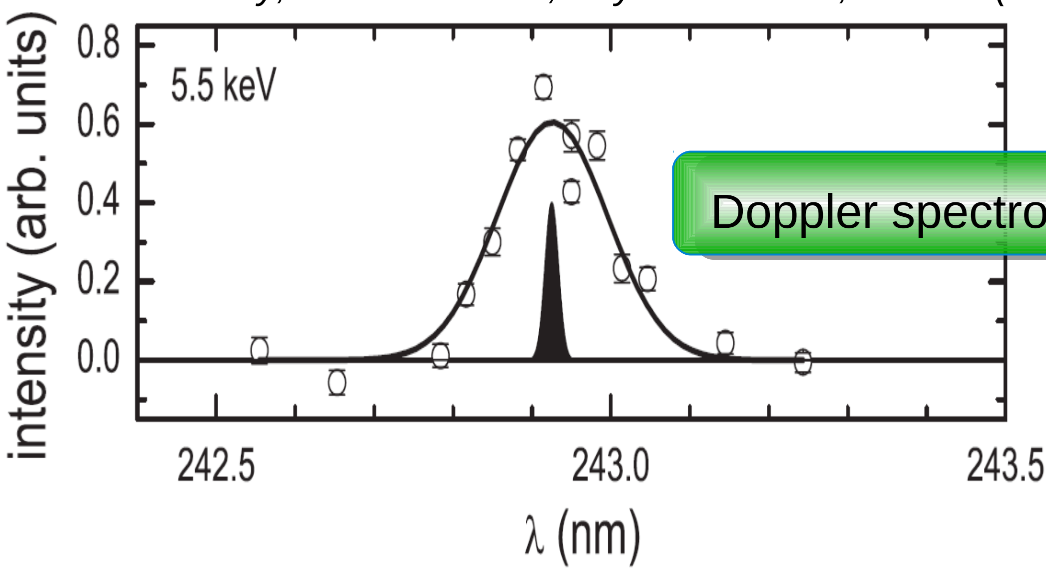
P. Crivelli et al. , Phys. Rev. A81, 052703 (2010)



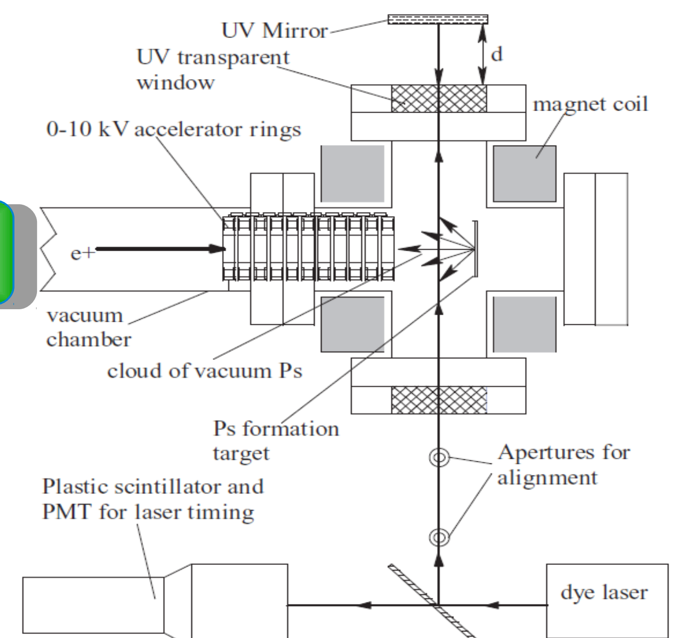


Time of flight

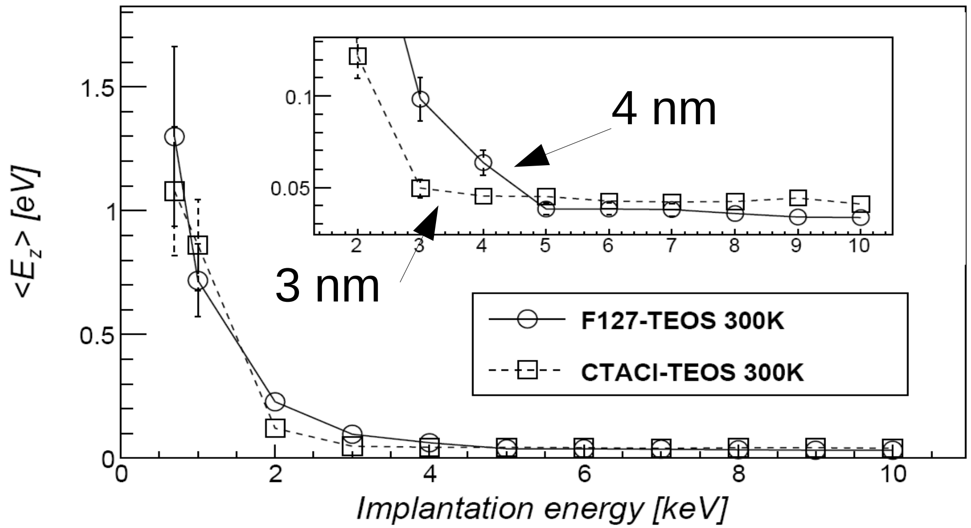
D. Cassidy, P. Crivelli et al., Phys. Rev. A 81, 012715 (2010)

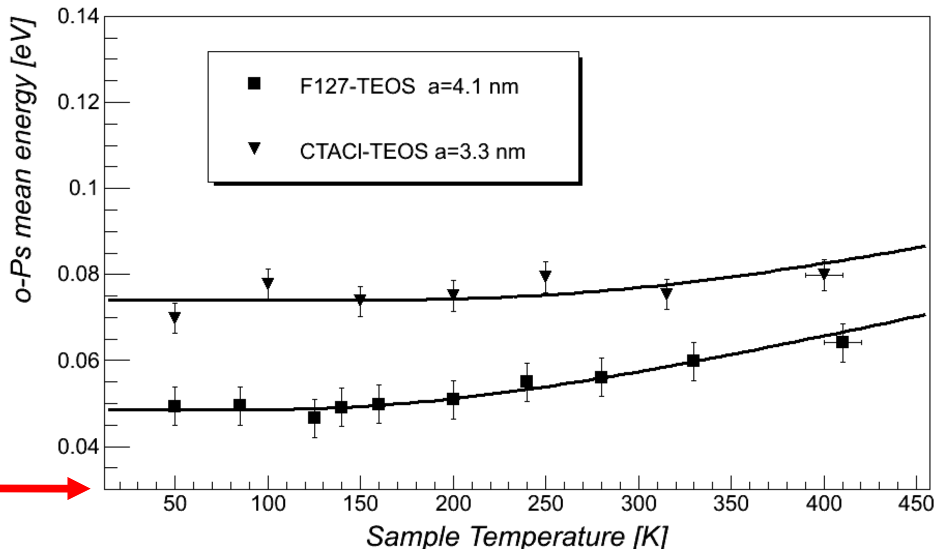


Doppler spectroscopy



Measurement of Ps energy





Thermal energy 30 meV

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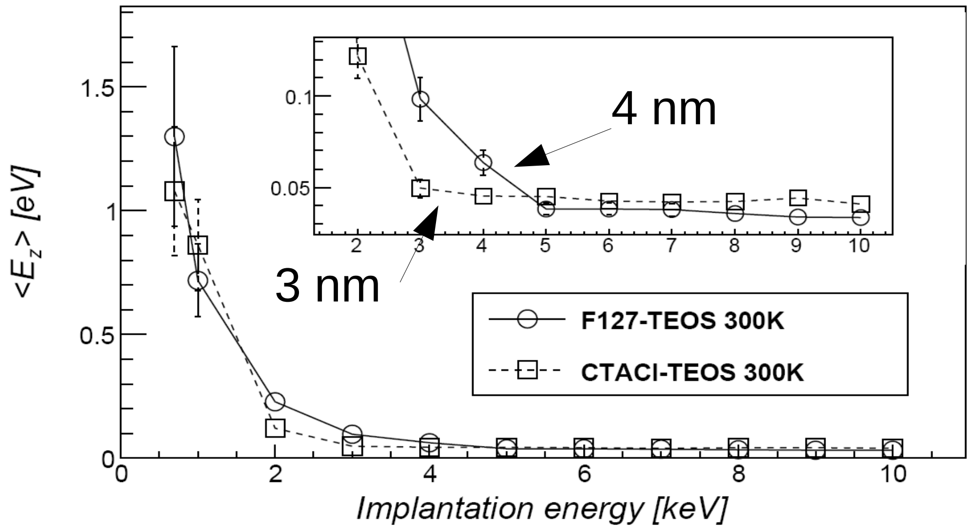


Ps de Broglie wavelength comparable to pore size -> Ps in the pores as to be treated QM

Ground state energy

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

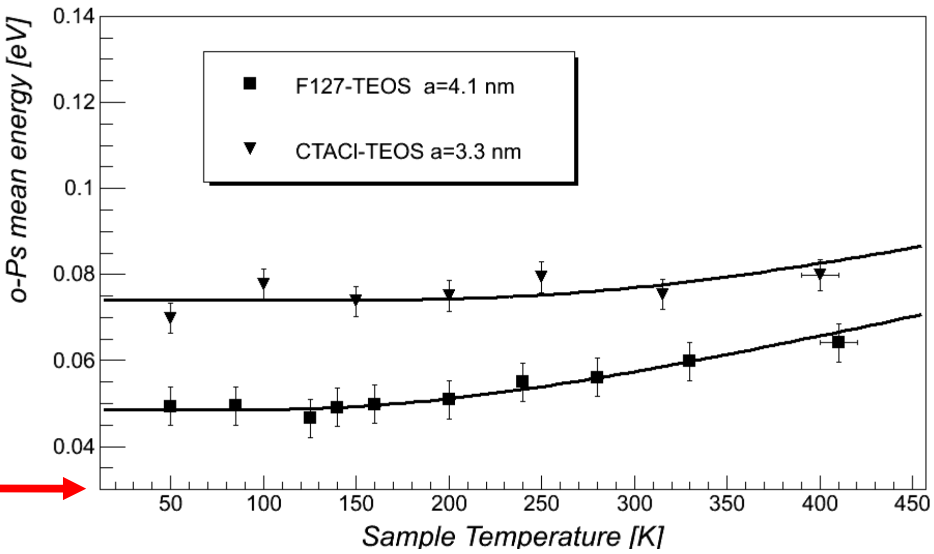
Ps as a particle in a box

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

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



Colder Ps from silica films?

In principle it should be easy: use larger pores of 8-10 nm confinement energy ~50-100K (for muonium we could reach 100 K with 4 nm since de Broglie wavelength much smaller)

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

Recently: aluminum oxide nano-channels 5-8 nm -> 7% of Ps at 150 K

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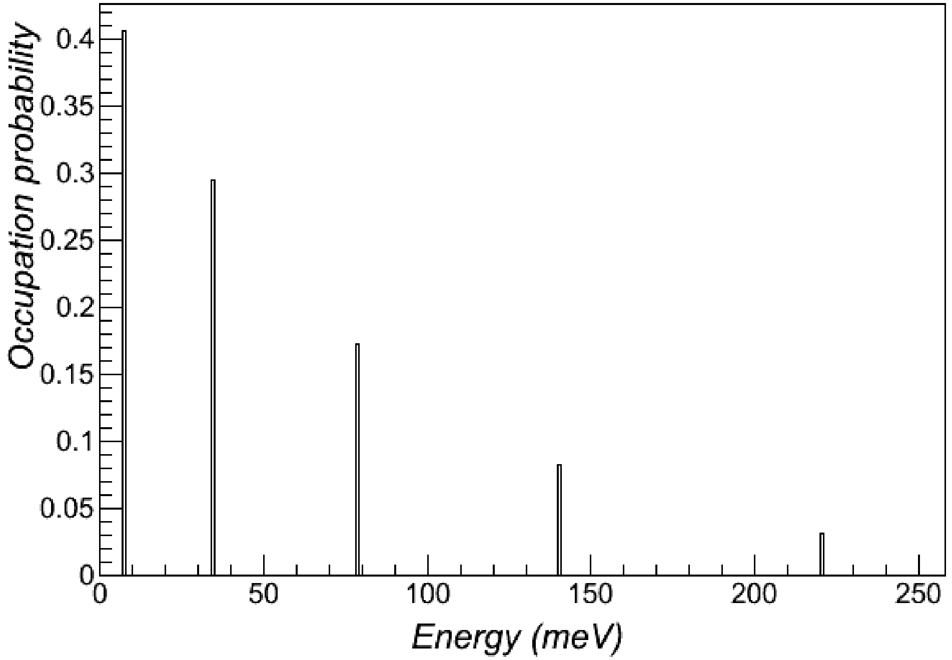
In practice: not easy to find the right recipe...work in progress (in collaboration with CEA Saclay).

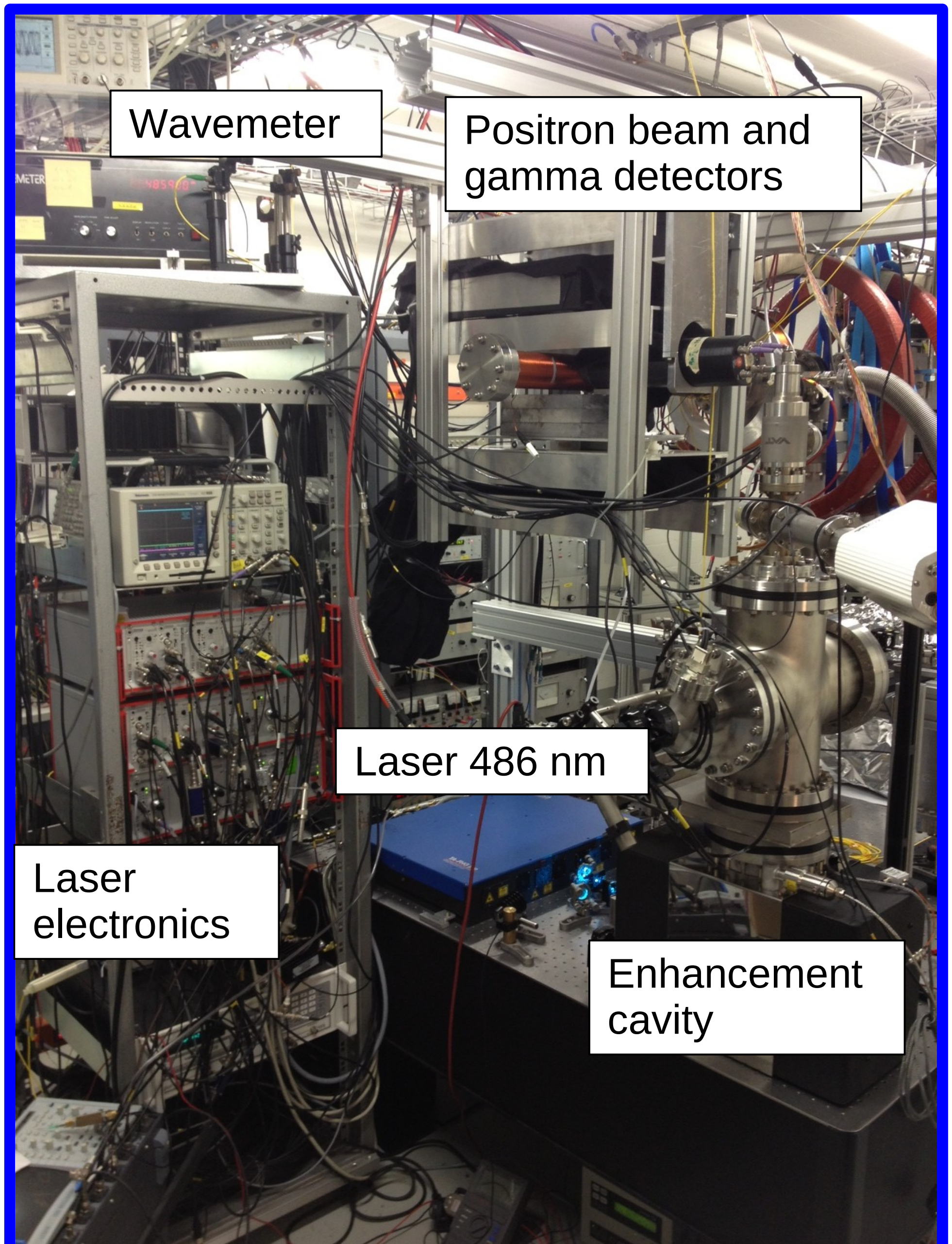
Even at room temperature Ps is very fast ~ 7×10^4 m/s

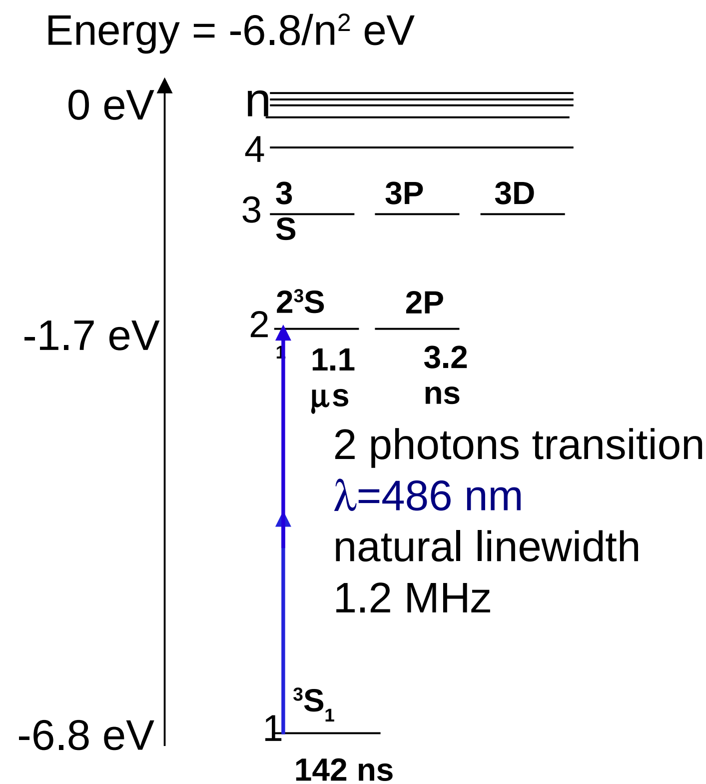
-> Second order Doppler shift ~ 30 MHz is expected to be the main systematic in our measurement.

BUT for porous silica one would expect to see at least 3 peaks in the resonance curve
-> correction of the 2^{nd} order Doppler shift



The laser system for Ps 1S-2S





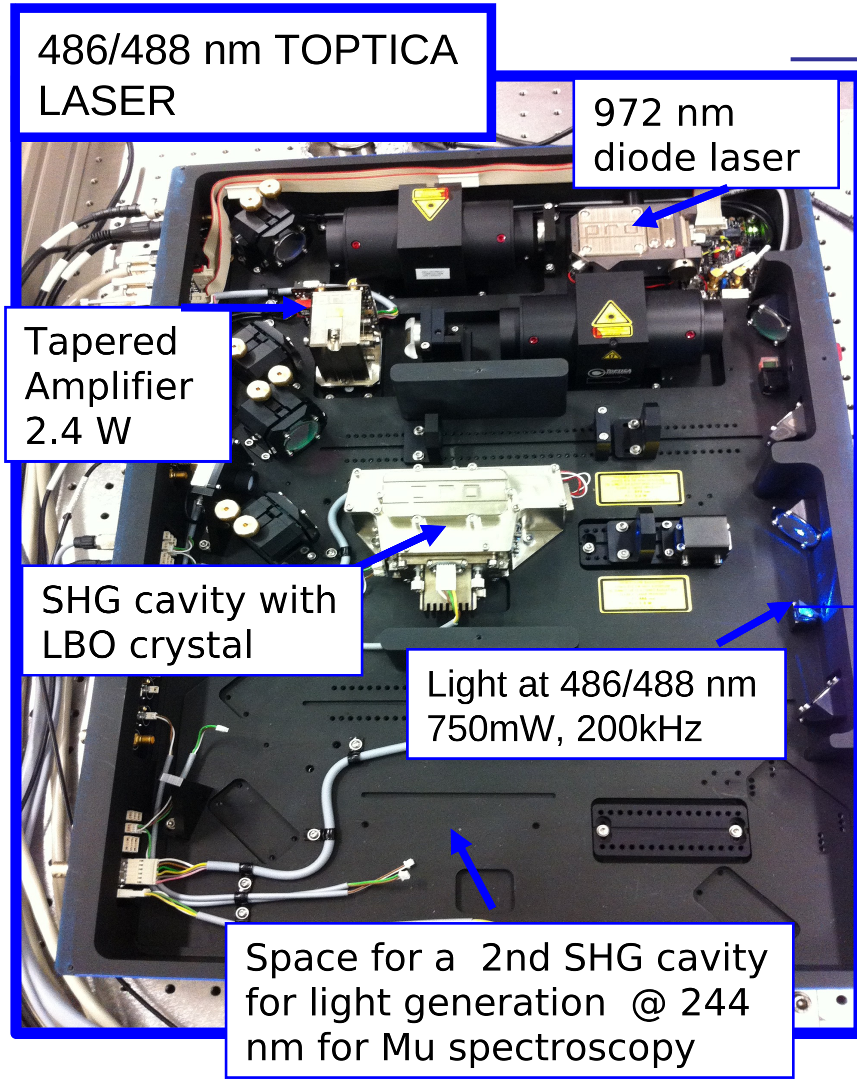
Requirements:

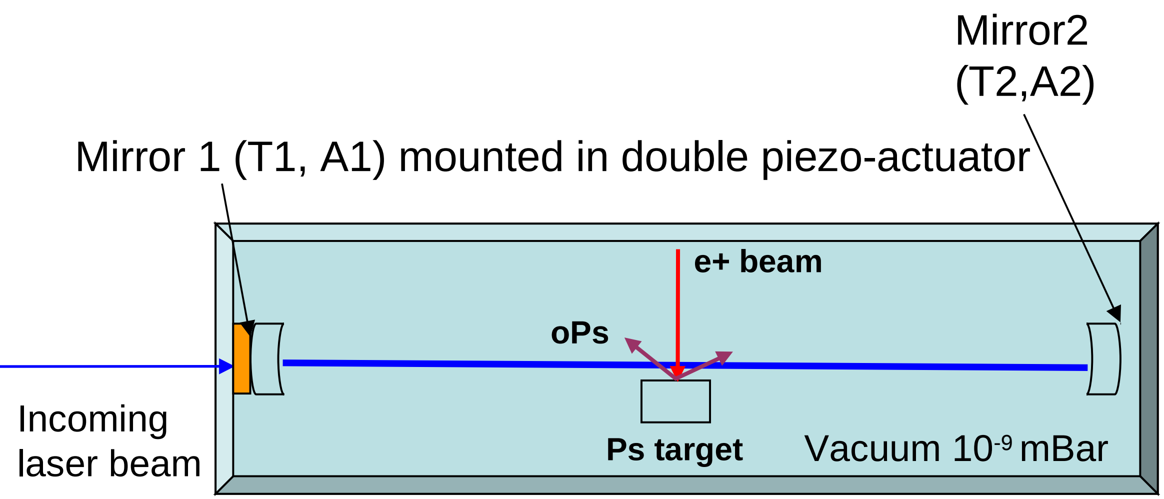
-> High power (~kW) at 486 nm to get a detectable signal

-> Long term stability (continuous data taking ~days)

-> Scanning of the laser ± 100 MHz

The laser (Ps and Mu)





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

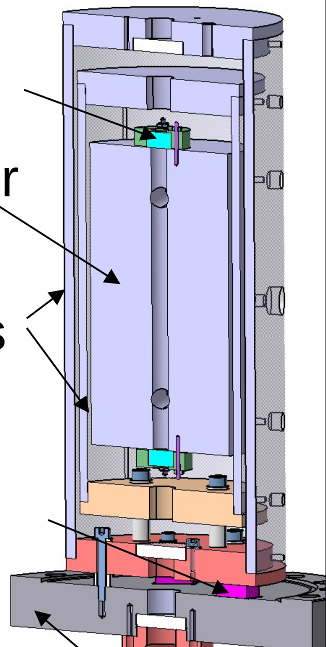
MPQ design

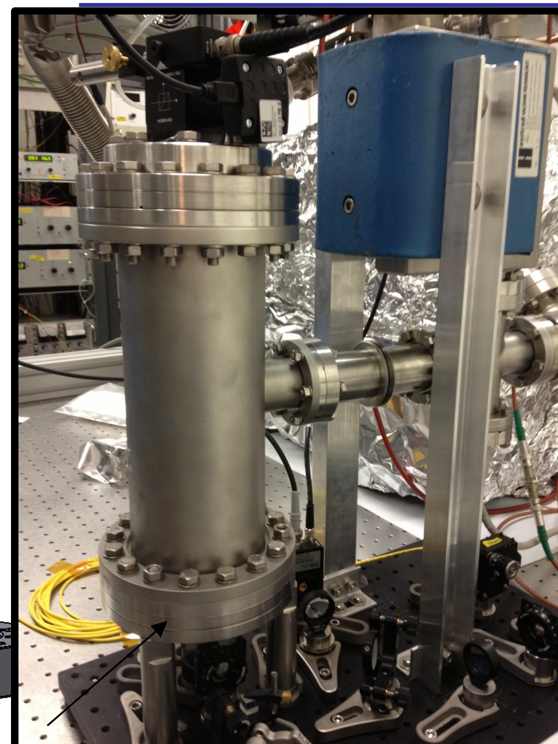
mirror

ULE spacer

Thermal shields

Peltier elements

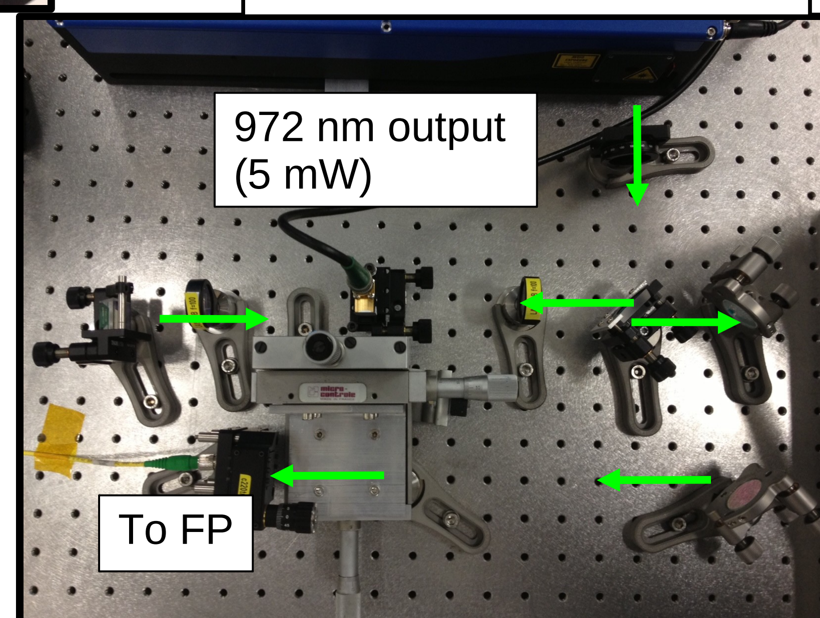




Vacuum flange

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

Double pass AOM
-> ±200 MHz @ 486 nm

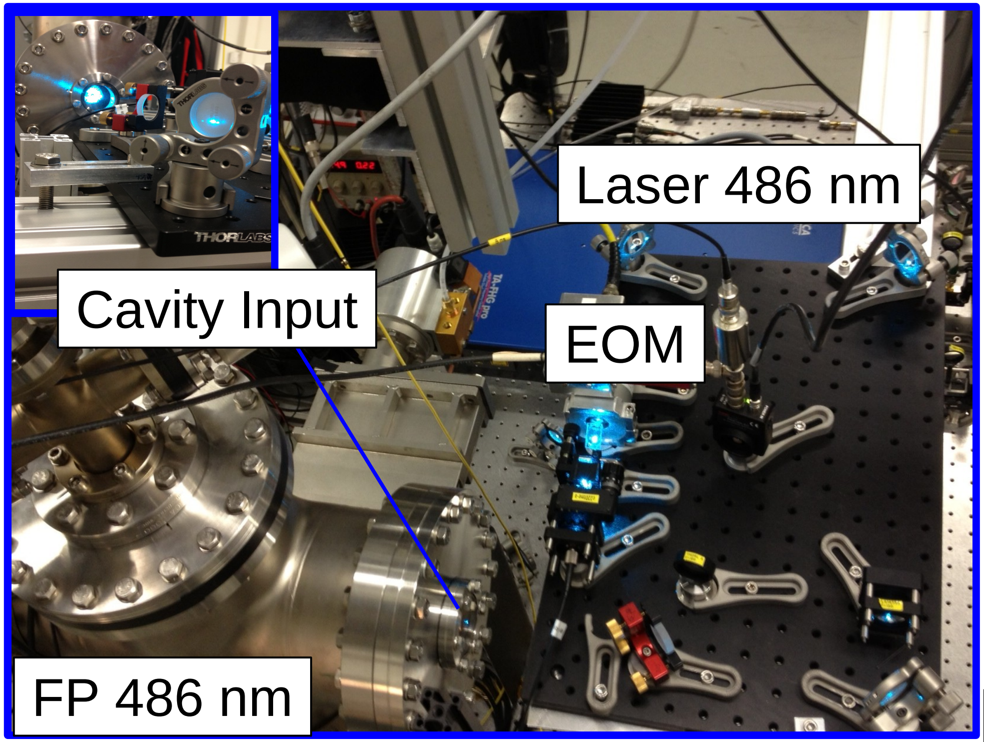


Charachterization:

- Long term drift against Te2
(T not yet optimized) <1 MHz/day

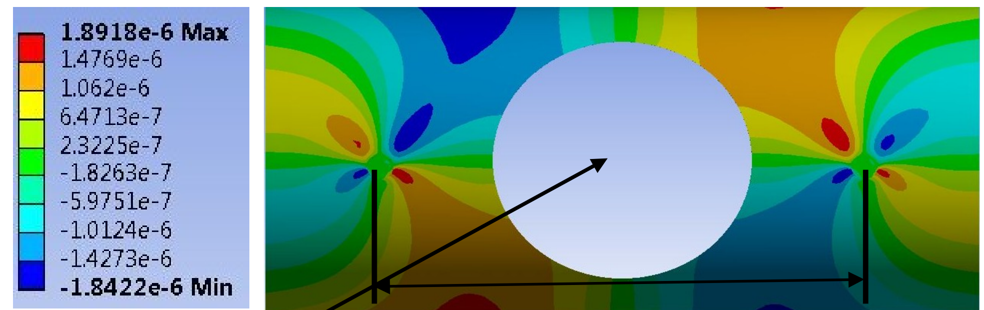
- Short term ~ kHz (efficient incoupling
to FP 486 nm)

The enhancement cavity @ 486 nm



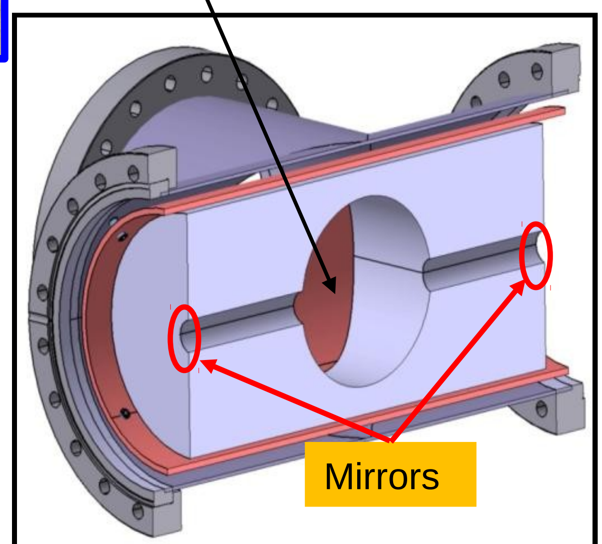
T1 = 49 ppm, T2 = 7 ppm
A1 = 12 ppm, A2=7ppm
FSR= 0.55 GHz
Linewidth = 7 kHz
Finesse ~ 80000
Incoupling 40%

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

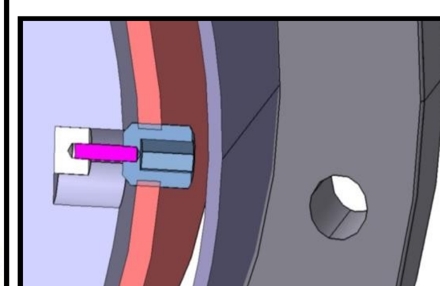


Optimized distance 186.7mm for suspending the resonator -> deformation due to gravity does not change mirror separation

Hole for positron beam

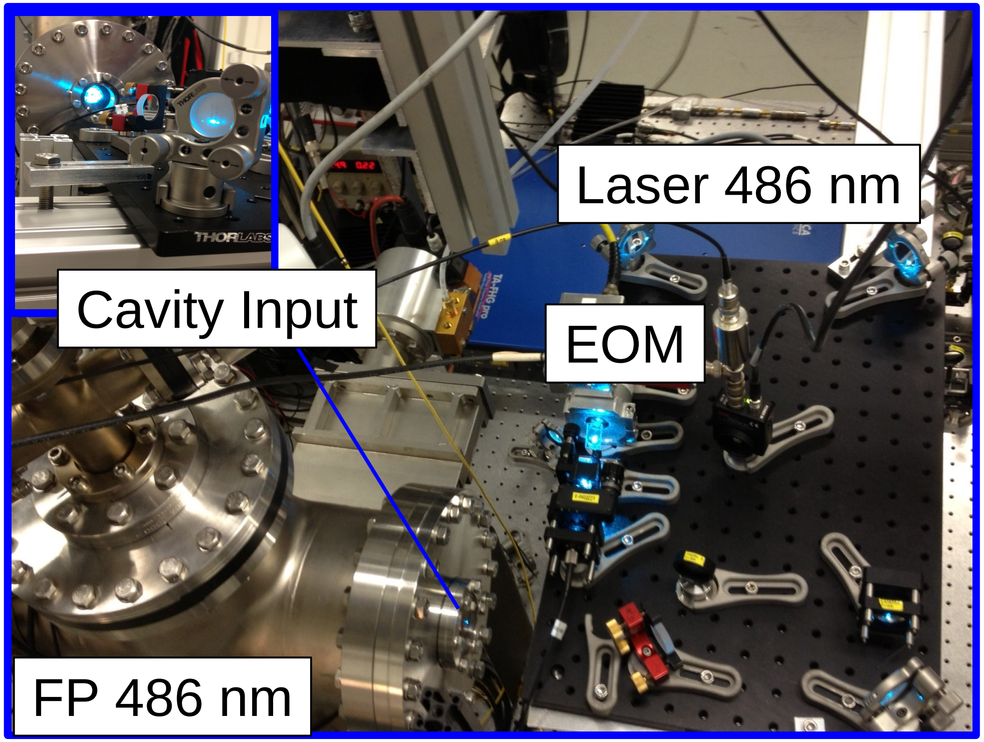


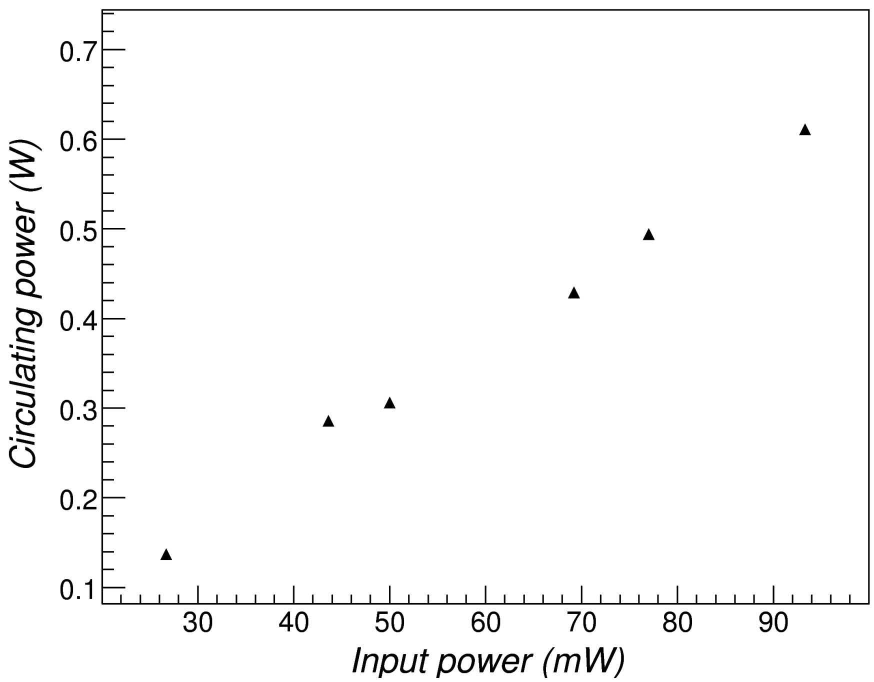
Suspension System



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

The enhancement cavity @ 486 nm





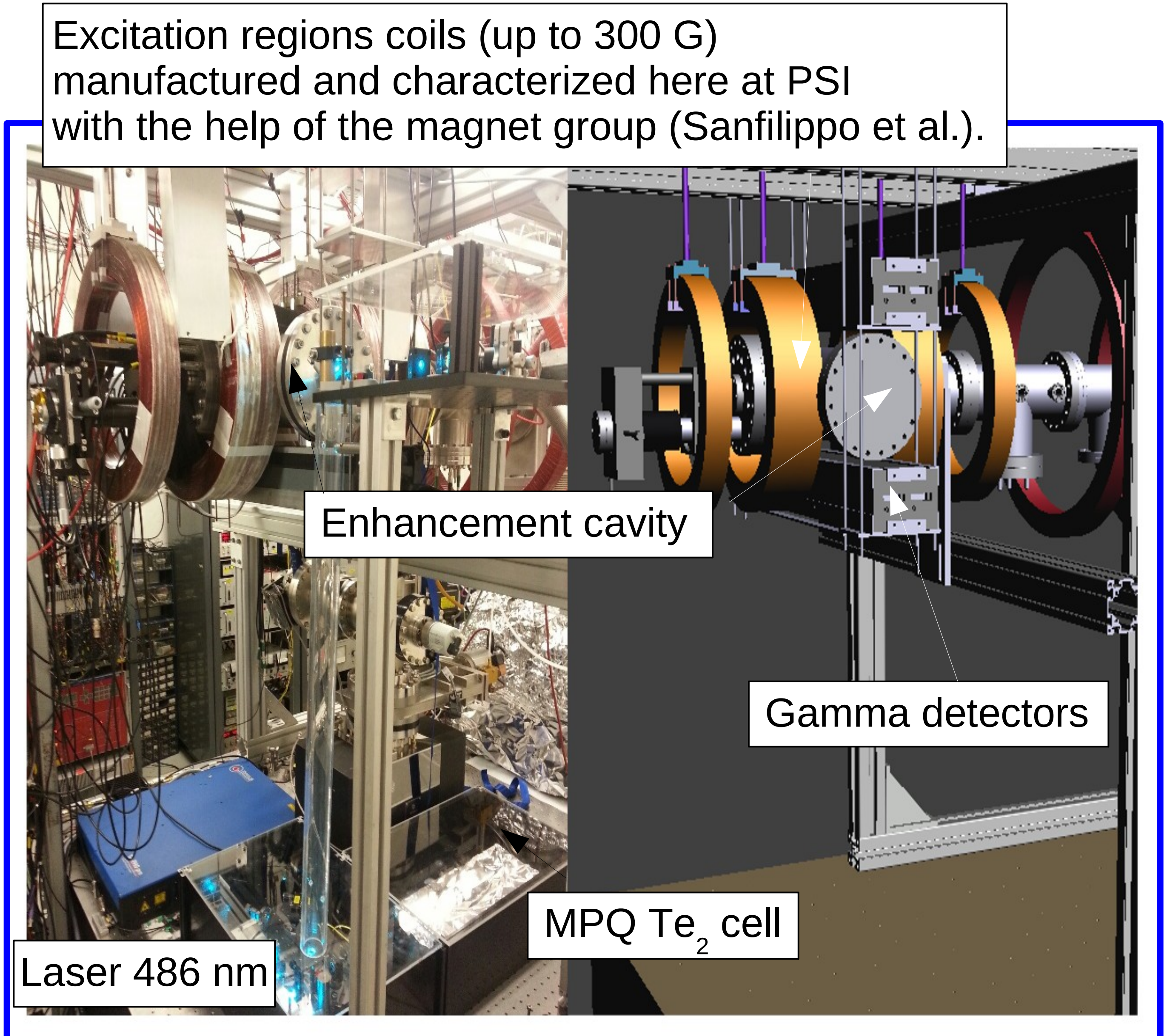
T1 = 49 ppm, T2 = 7 ppm
A1 = 12 ppm, A2=7ppm
FSR= 0.55 GHz
Linewidth = 7 kHz
Finesse ~ 80000
Incoupling 40%

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}

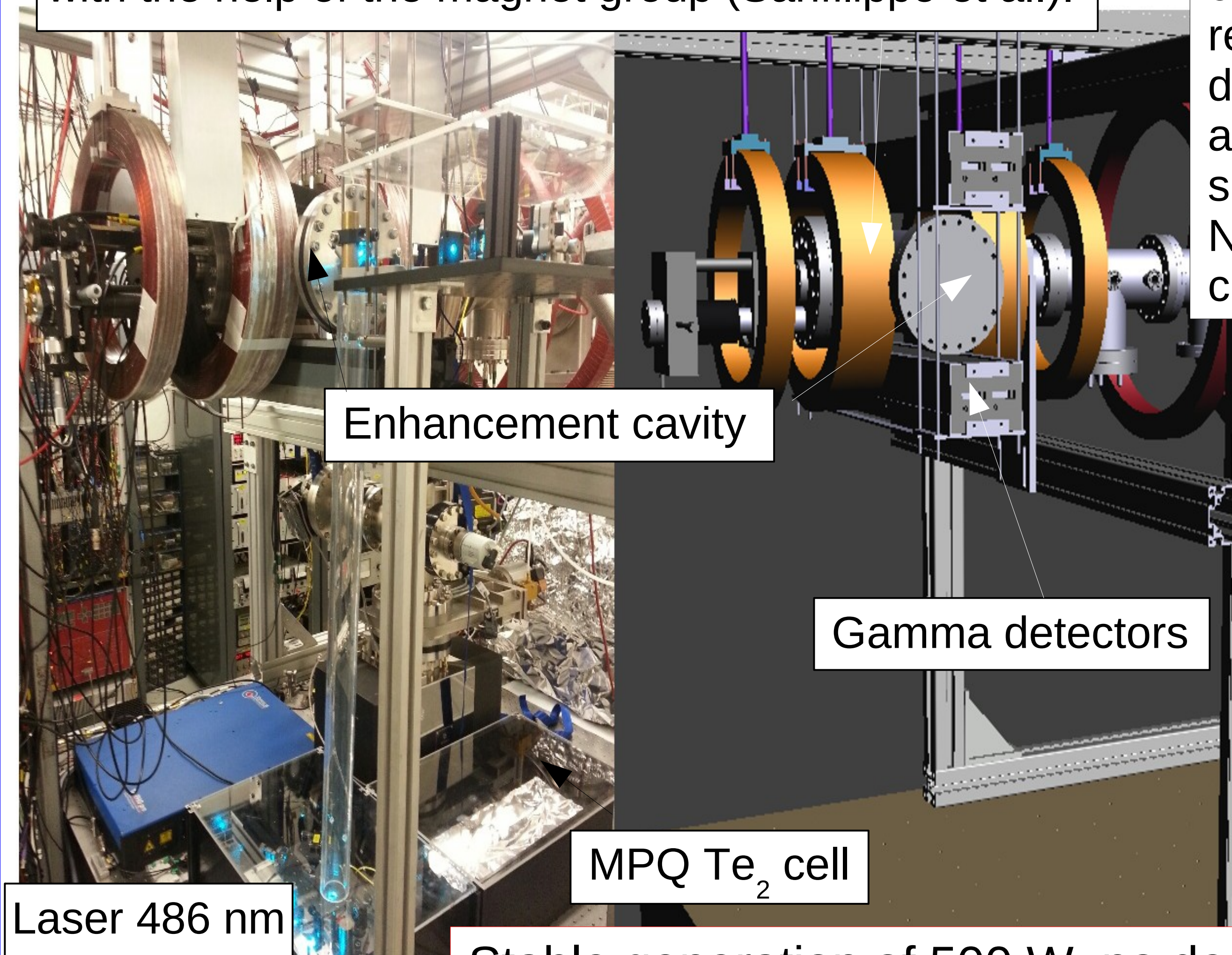
*Ultra-low-loss mirrors from ATFilms (https://www.atflims.com)

The enhancement cavity @ 486 nm



The enhancement cavity @ 486 nm

Excitation regions coils (up to 300 G) manufactured and characterized here at PSI with the help of the magnet group (Sanfilippo et al.).



Problem: after mounting the cavity on beam line could not reproduce the same results, degradation occurred already at 500W ...Suspected input mirror since its transmission changed. Now both mirrors from the same coating run.

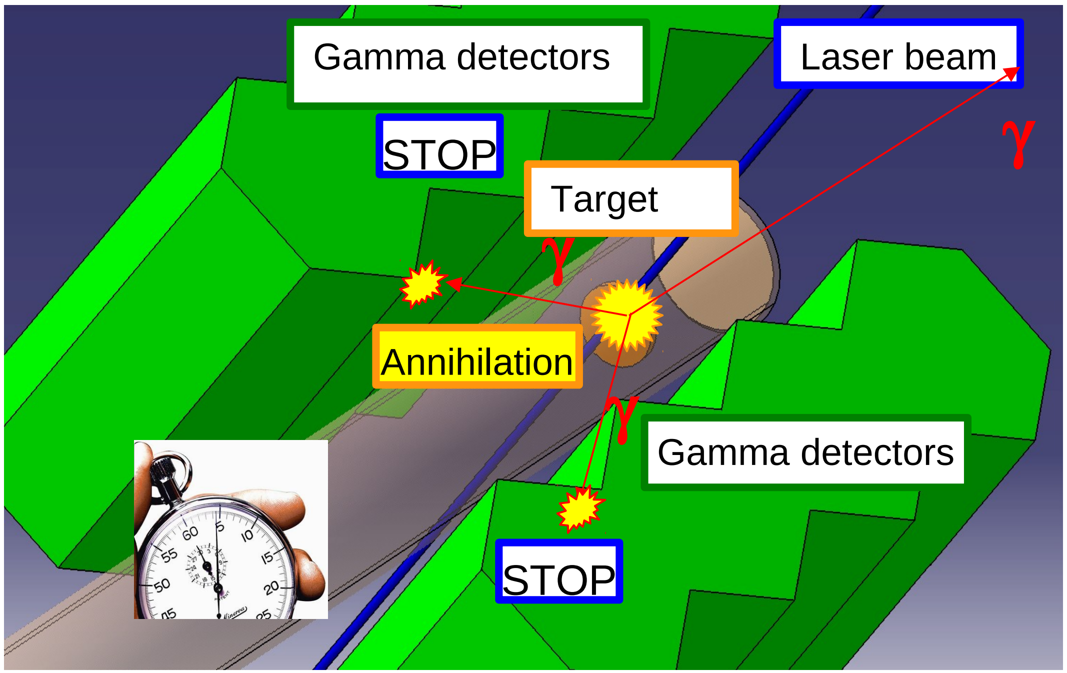
T1 = T2 = 7 ppm
A1 = A2 = 7 ppm
FSR= 0.55 GHz
Linewidth = 2.5 kHz
Finesse ~ 225000
Incoupling 24%

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

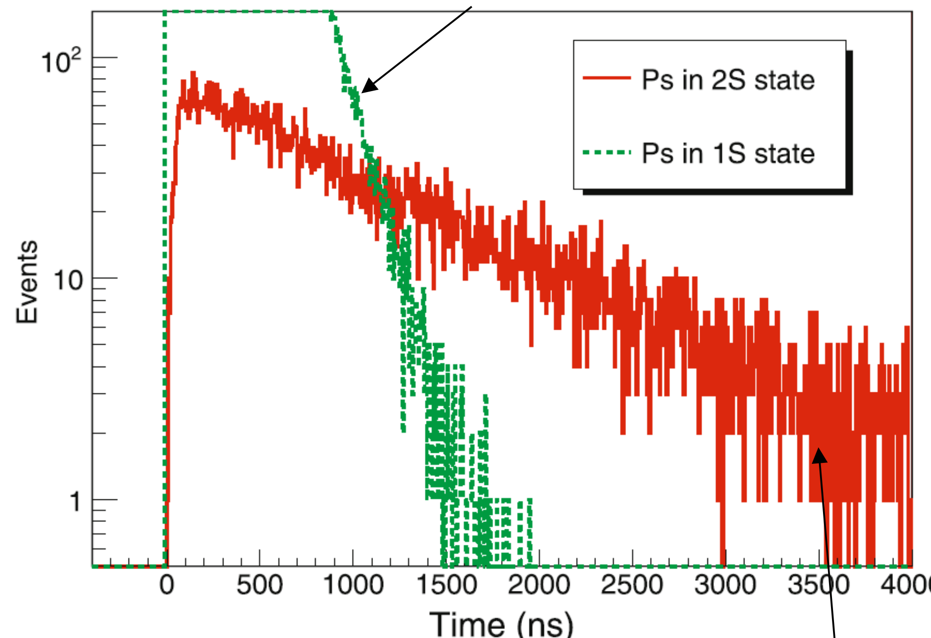
1) Detection of Ps 1S-2S – Lifetime method

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

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



3x10[7] triggers =10 minutes, P_c = 0.5 kW

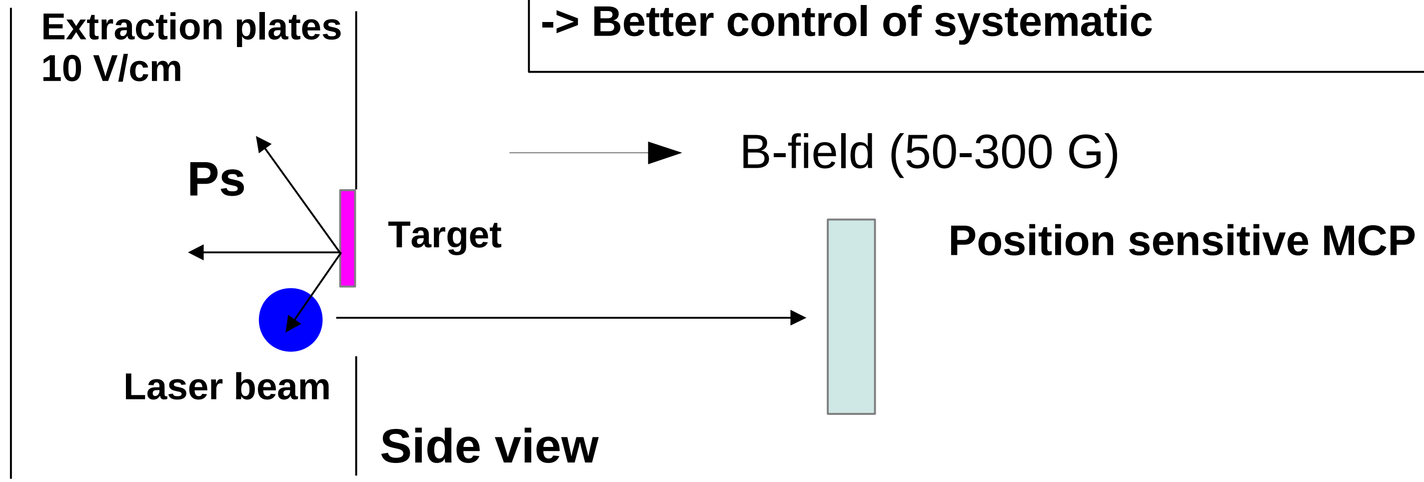


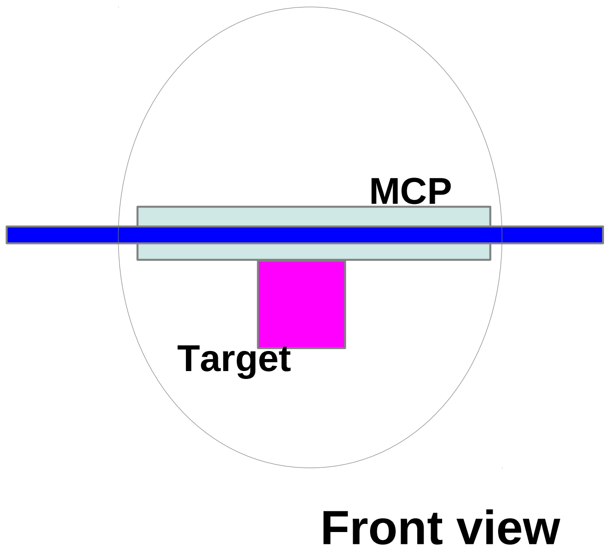
	Events	1 BGO (2-4µs)	2 BGO (2-4µs)	ΔT ±10 ns
2S Ps	4 x 10^3	342	129	127
1S	9.8 x 10^6	4	2	2
Accidentals	-	4950	42	4

On resonance:
1250 events
in 2 hours run

2) Detection of Ps 1S-2S - PI positrons

Detect photo-ionized positrons (3 photons resonant ionization)
PI prob = 0.1 Exc prob but detection efficiency higher
-> Expected signal rate factor 4 smaller than lifetime method
-> Better control of systematic





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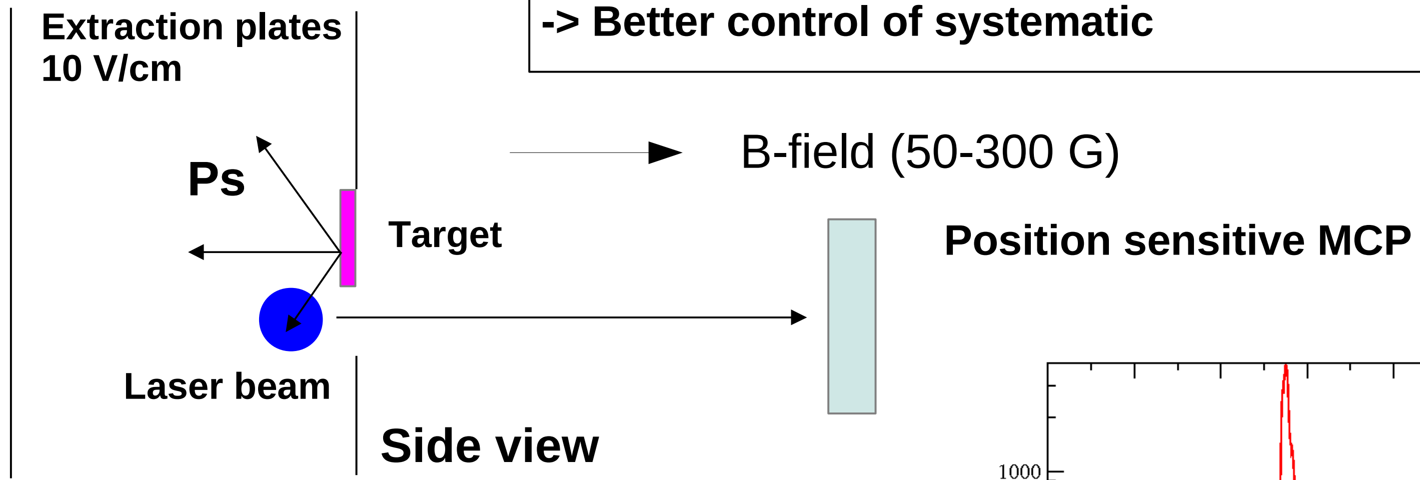

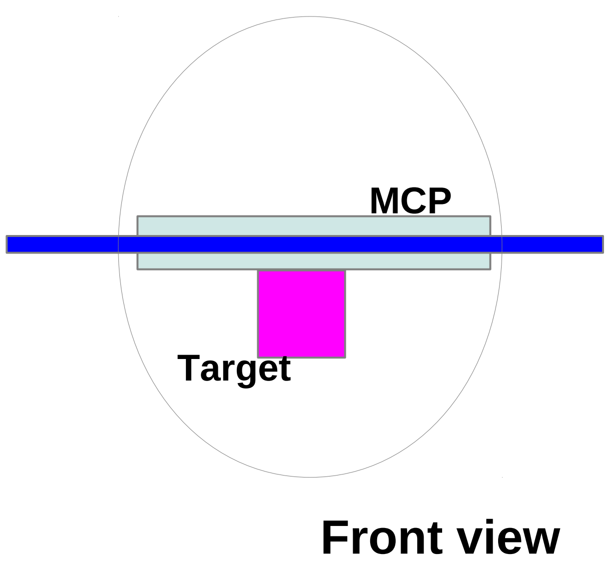

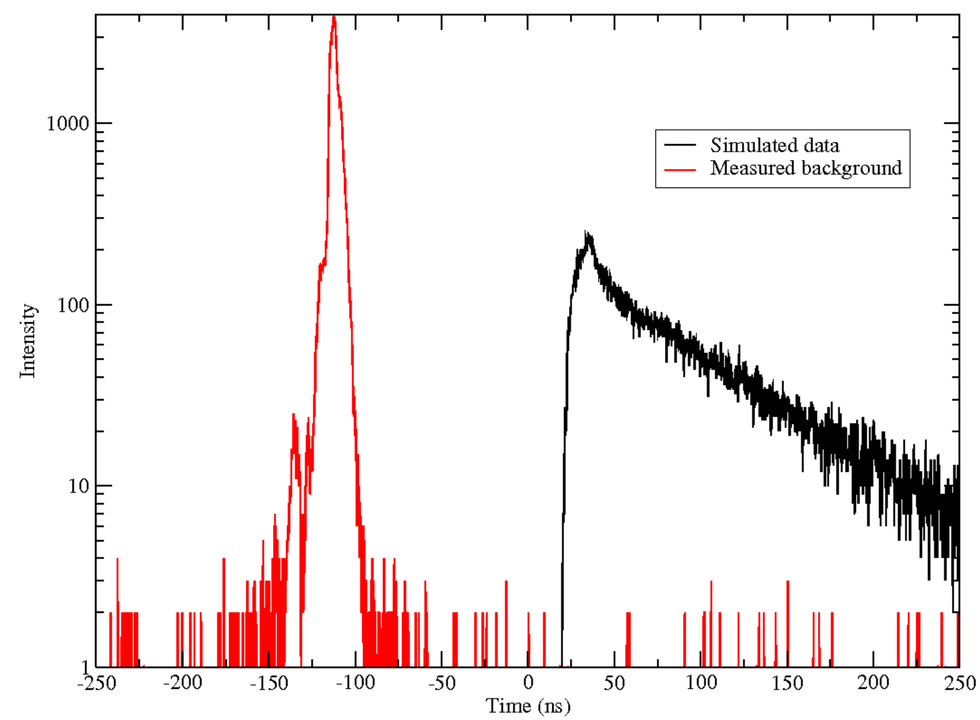

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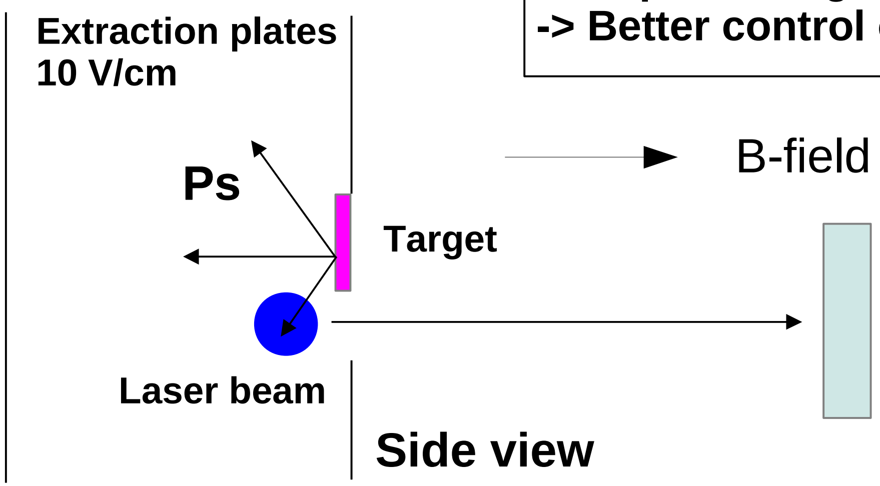
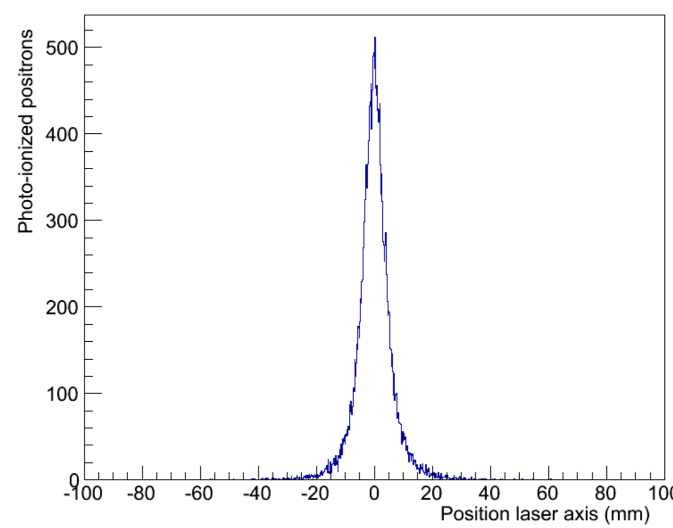
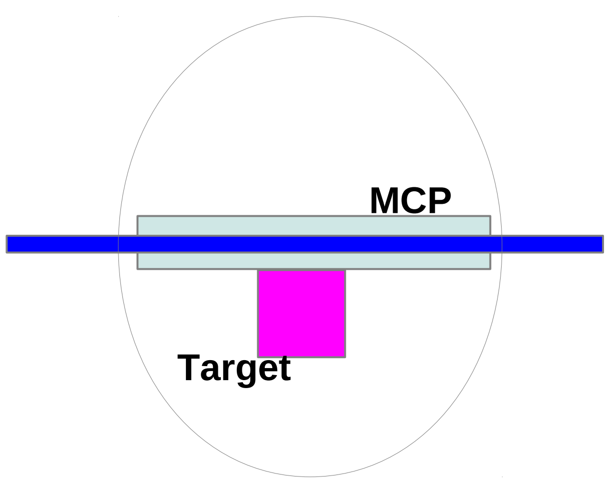


B-field (50-300 G)

Position sensitive MCP :
imaging of the positron photo-ionization point





Front view

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

Expected accuracy

<u>With available source of Ps:</u>
- 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,
no restriction of beam time (careful systematic study), stable Ps formation

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- Main contribution of 1993 exp. unknown parameters
in pulsed photoionization laser -> proposed methods free of this systematic.
- Systematic dominated by 2nd order Dopplershift

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Measurement of 1S-2S of Ps at a level about 5×10^{-10} seems feasible
=> check QED

Outlook

- Laser system and positron beam are combined

- In July: problems with enhancemement cavity and arcing now solved
-> stable generation of 500 W and new desing for the electrodes in the excitation chamber
- Last week cryocooler to grow Ne moderator started to have problems.
The temperature of 7K cannot be kept constant...some maintenance needed (involve handling the radioactive source)...
Use Ar instead that is providing 30% of Ne efficiency...we will go ahead with that for the moment...

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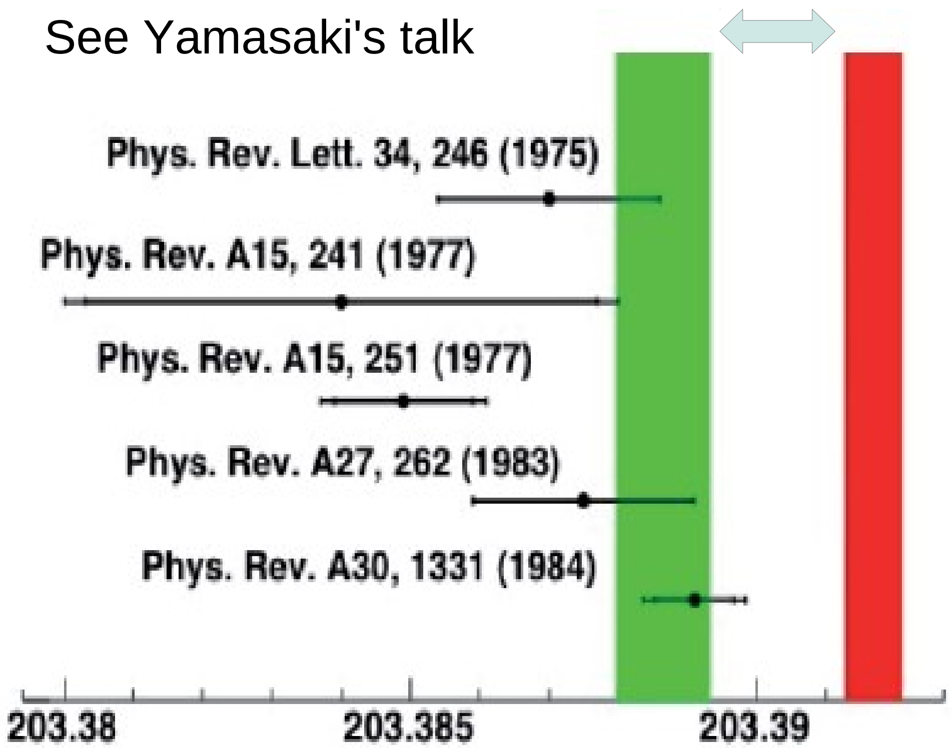
Efforts to reduce the Ps velocity (~100 K should be achievable with porous films):
-> new porous films being tested (in collaboration with CEA Saclay) and hierachical zeolites (in collaboration with Prof. J. Perez, ETHZ Chemistry department).

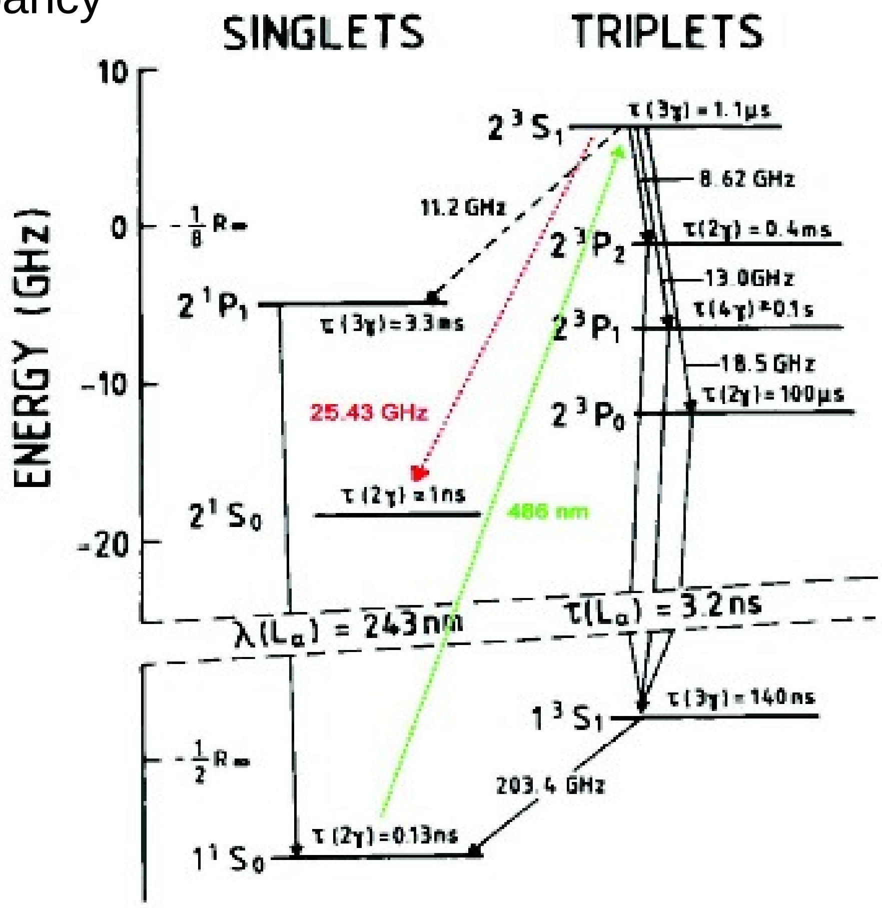
2S hyperfine splitting

GROUND STATE HFS 15 ppm (3.5 σ) discrepancy

See Yamasaki's talk



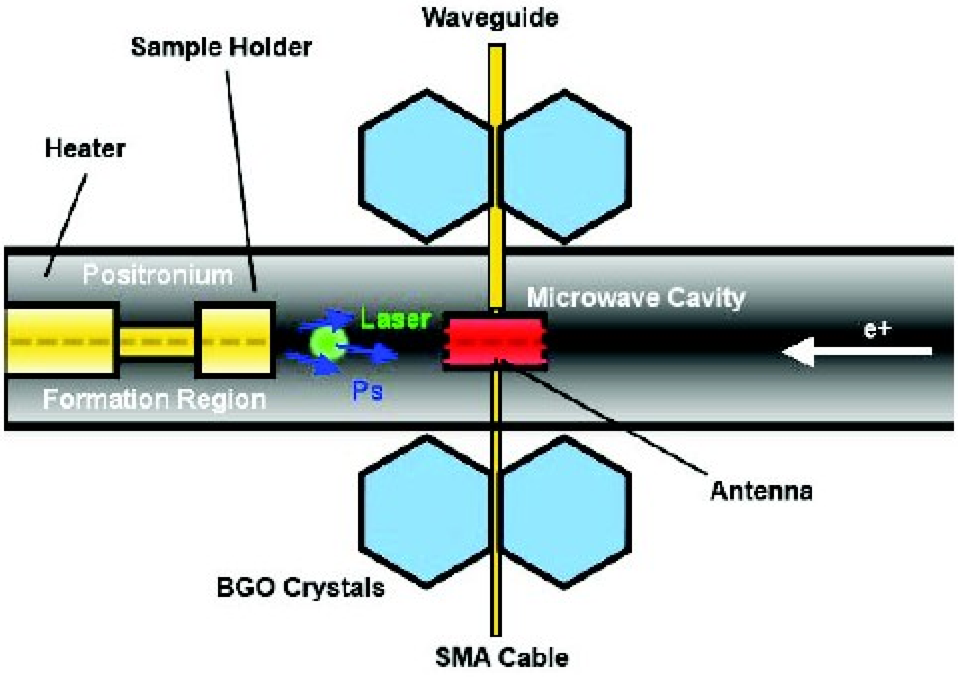
Theory



K. Melnikov, A. Yelkhovsky,Phys. Rev. Lett. 86, p. 1498{1501 (2001).
R. J. Phys. Rev. Lett. 86, p. 3280 (2001).
K. Pachucki, Phys. Rev. A 56, 297 (1997).
A. Czarnecki, K. Melnikov, A. Yelkhovsky, Phys. Rev. Lett. 82, p. 311{314 (1999).

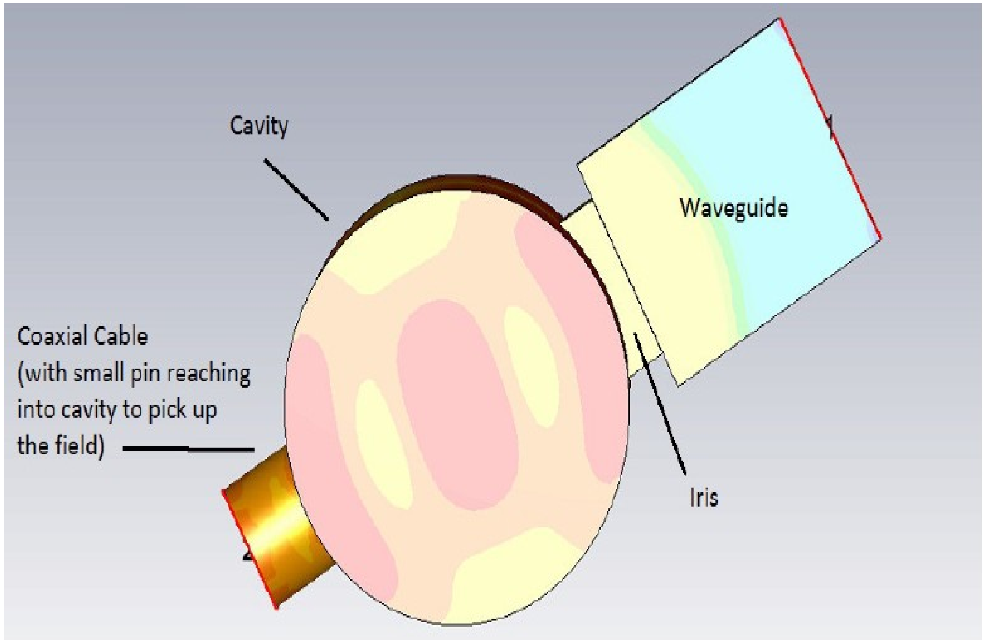
Origin? Experimental problem (linear extrapolation to zero density), theory, new physics?

2S hyperfine splitting



Advantages: Different experimental method than measurements in ground state
- no need for extrapolation to zero density since Ps in vacuum
- no need for challenging level control on magnetic field.
- Required power at 25.43 GHz is commercially available.

Goal:
- observe this transition for the first time (a level of 50 ppm seems feasible)
- long term reach accuracy comparable with the one of the ground state, using high granularity detector for background suppression and 10 times stronger positron Source. Colder Ps would be of great help.



Design in progress (Dr. Friedreich)

Thank you for your attention ☺