Rydberg positronium for pulsed antihydrogen production

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Galileo's Pisa leaning tower thought experiment

free-fall is independent of body masses

$$\begin{cases} \mathbf{F} = m_i \mathbf{a} \\ \mathbf{F_g} = m_g \mathbf{g} \end{cases} \xrightarrow{UFF} m_i = m_g$$

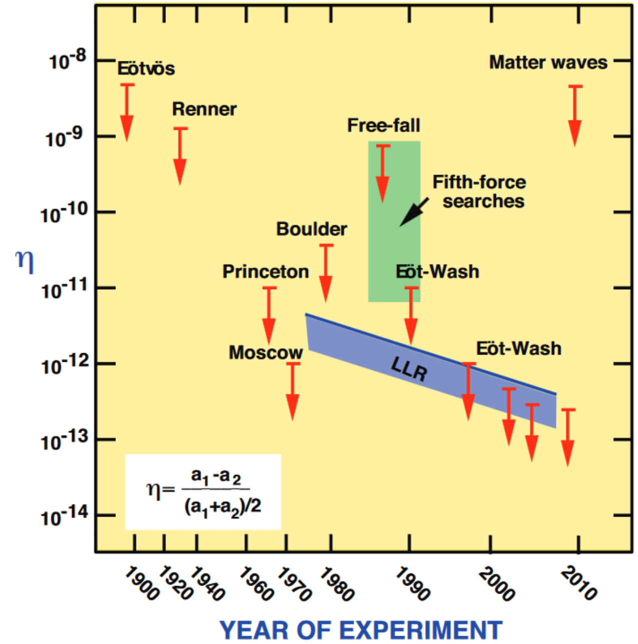
Einstein's Equivalence Principle

The result of any local non-gravitational experiment is independent from the velocity of an observer in free-fall and his position and time in the universe

EP = UFF (universality of the free fall)
+ LLI (local Lorentz invariance)
+ LPI (local position invariance)

With normal matter

- Eötvös-like torsion balances (2 part per 10^{13})
- Lunar laser ranging (3 part per 10^{4})
- Cold atoms interferometry (3 part per 10^{8})



With antimatter?

- Attempts with charged positrons ~ 1967
- Attempts with charged antiprotons ~ 1985
- Some indirect limits ~ 1987 - 2000
- Limit on antihydrogen by ALPHA collaboration, 2014

any deviation from the expected matter/antimatter equality would be an indication of new physics

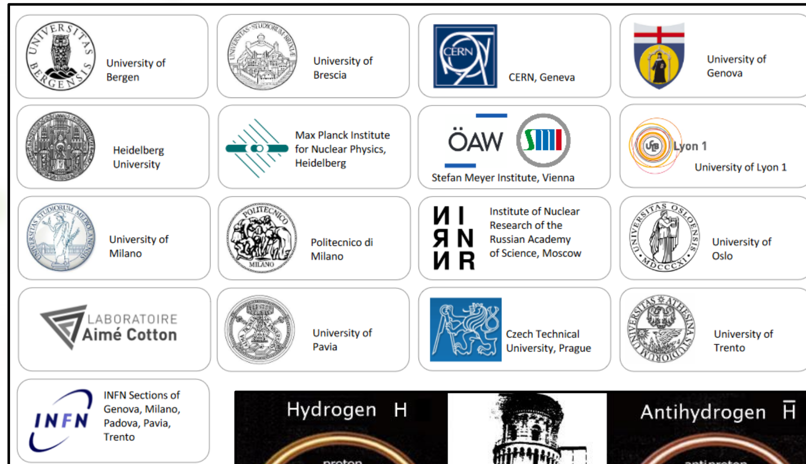
Clifford M. Will, *Theory and experiment in gravitational physics* (1993)

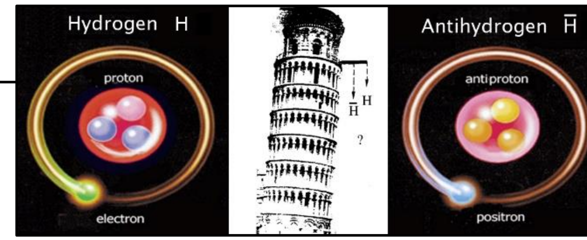
The AEgIS collaboration

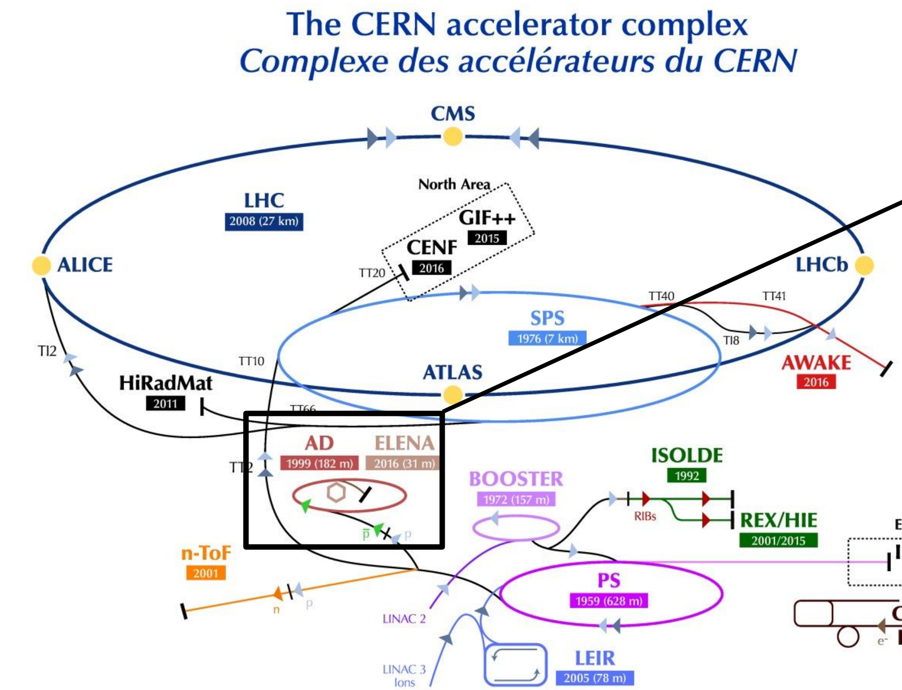
Antimatter Experiment:

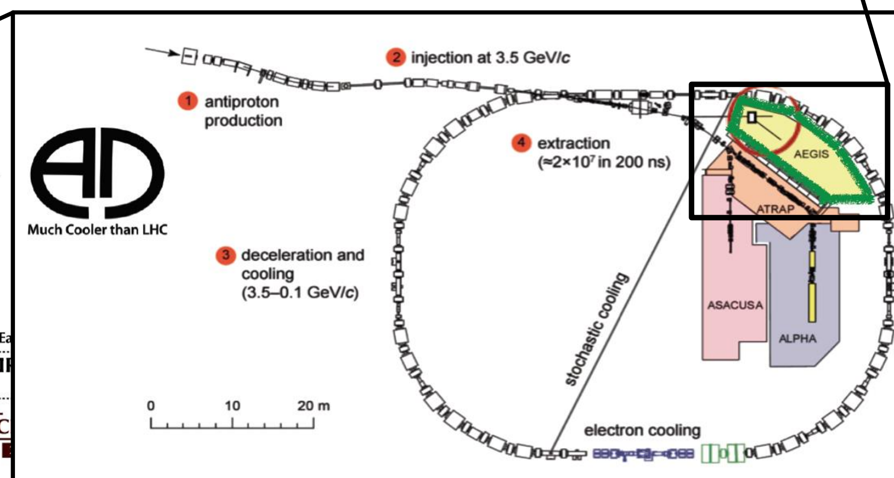
Gravity, Interferometry, Spectroscopy

- CERN-based collaboration of ~50 collaborators
  and 16 institutes
- Aims to perform the first direct free-fall measurement of gravity on antihydrogen





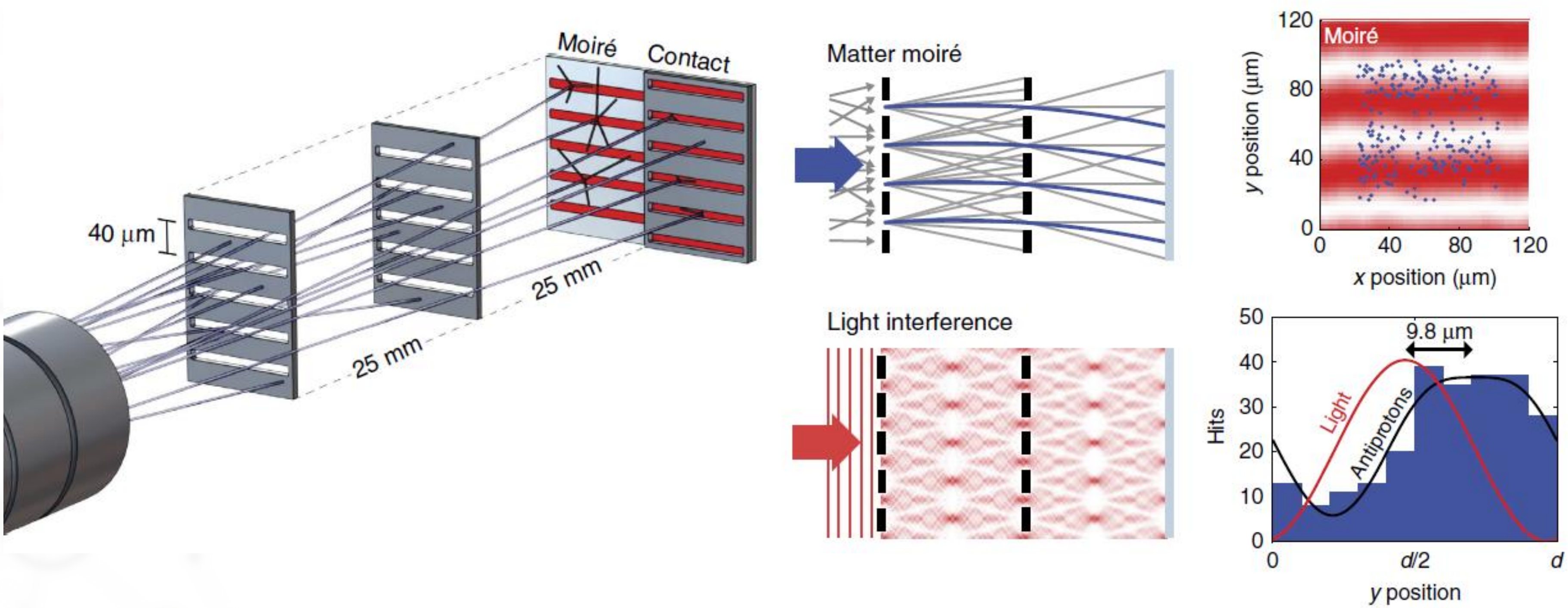




Detection method: the moiré deflectometer

ARTICLE
Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014
DOI: 10.1038/ncomms5538
OPEN

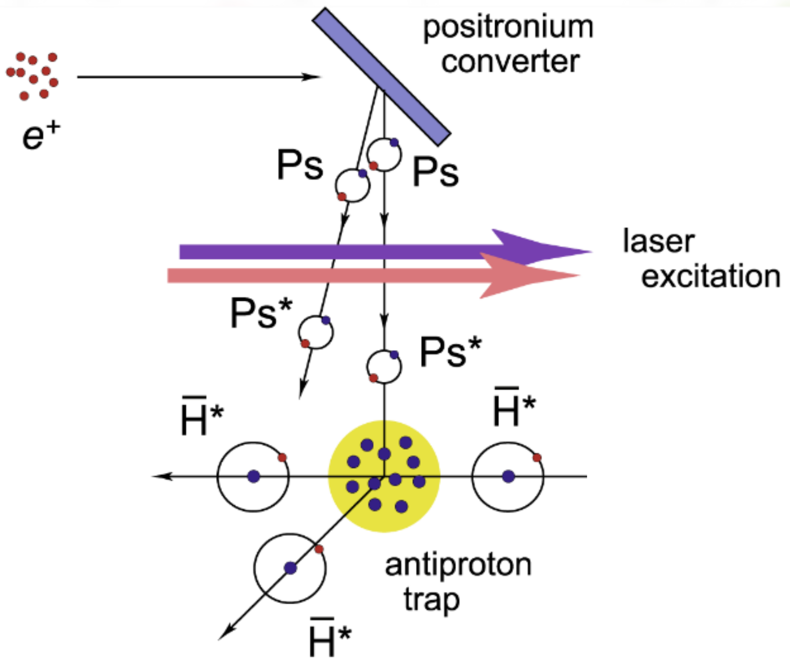
A moiré deflectometer for antimatter



- Near-field diffraction of light as a tool for gratings alignment in all three spatial directions
- Atoms' time-of-flight knowledge required

$$\Delta y = \frac{F_{\|}}{m}\tau^2 \longrightarrow F_{min} \approx 5 \cdot 10^{-16}\,\mathrm{N}$$

First milestone: pulsed antihydrogen production



Conceptual experimental scheme

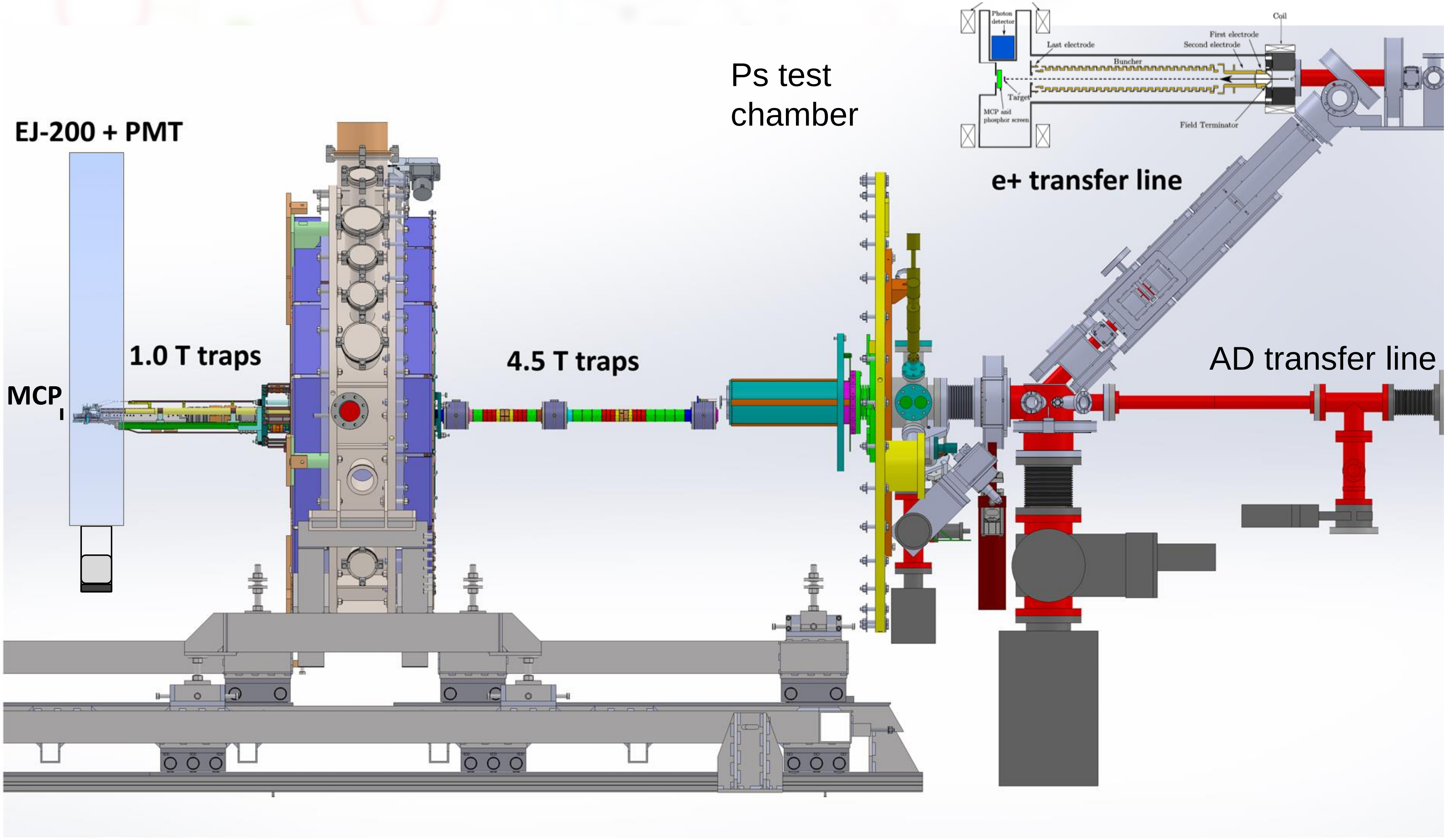
1) Preparation of a cold antiproton plasma in a Penning trap
2) Pulsed production of cold Ps from e^+ conversion in mesoporous silica
3) Two-step laser excitation of Ps to Rydberg levels
4) Charge-exchange with antiprotons

$$Ps^* + \bar{p} \longrightarrow \bar{H}^* + e^-$$

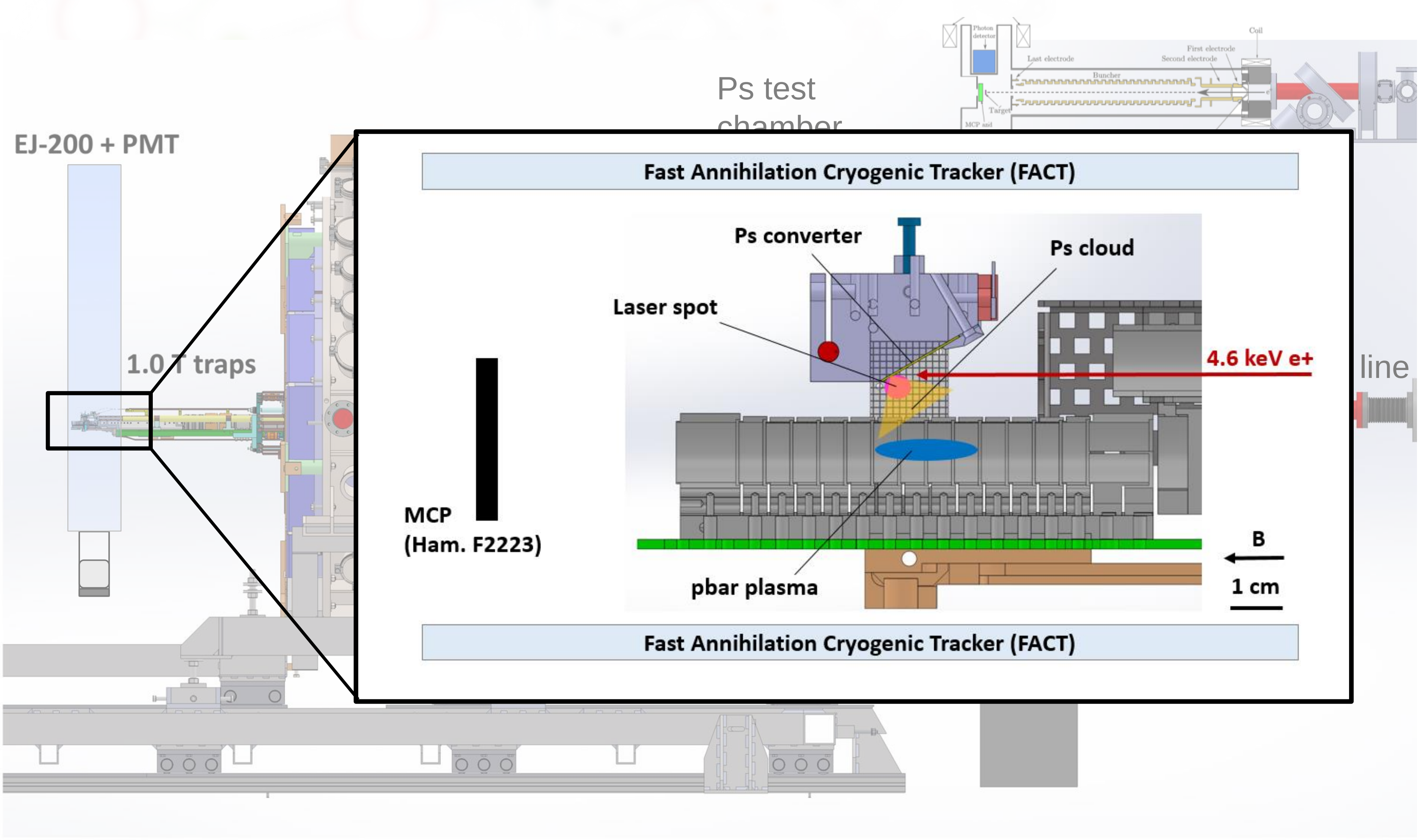
5) Detection of the annihilation products after collision with the trap walls

Doser M. et al., Class. Quantum Grav. 29, 184009 (2012).

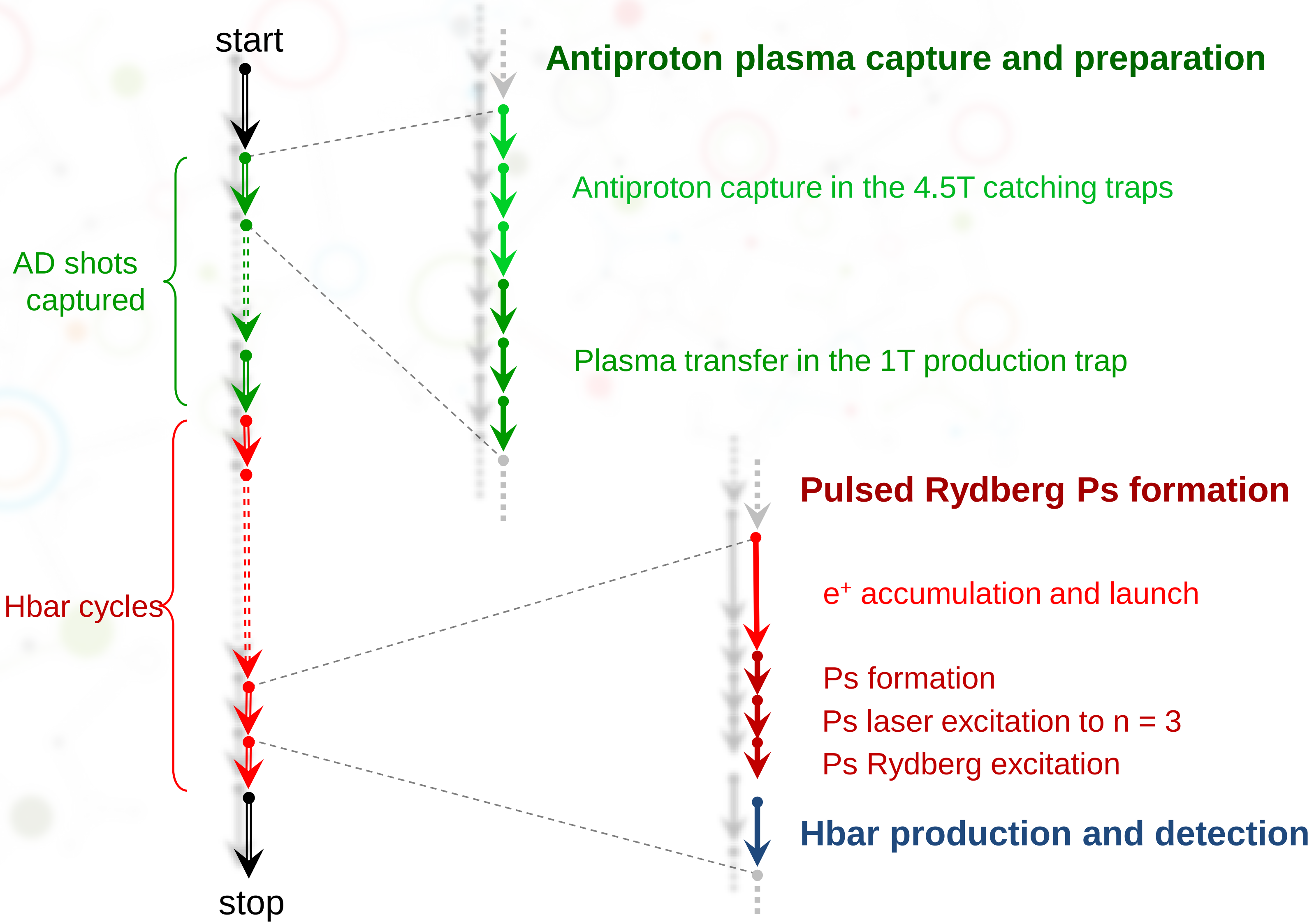
The AEgIS experimental complex



The AEgIS experimental complex

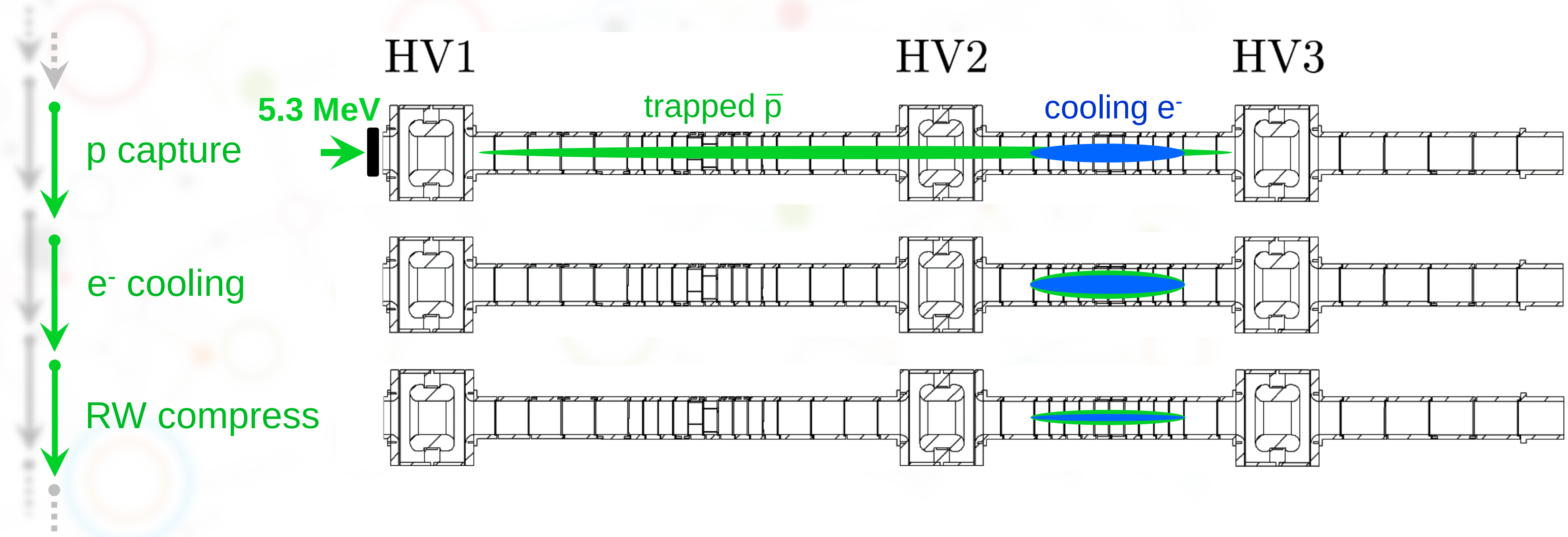


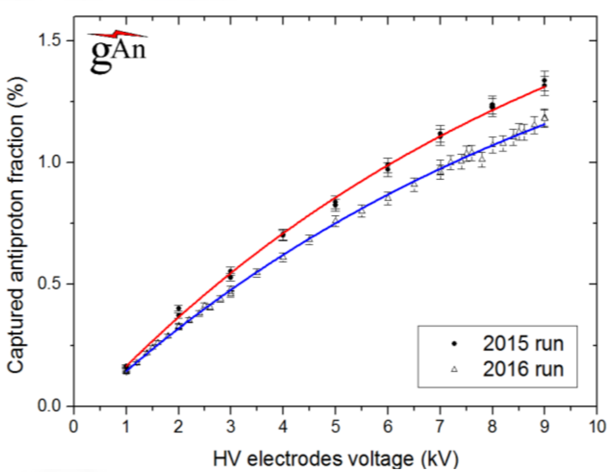
Overview of an antihydrogen production cycle

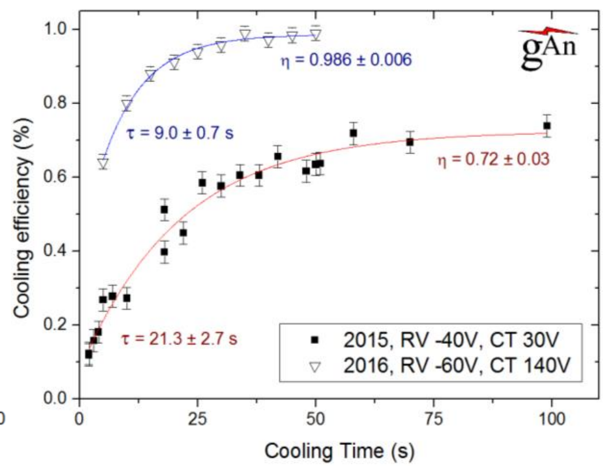


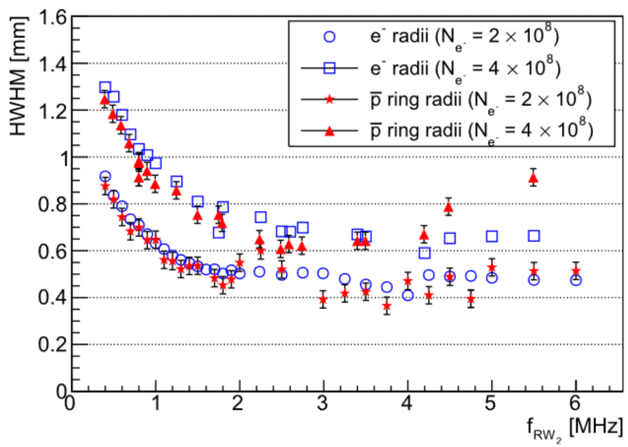
Tietje I. et al., *J. Phys.: Conf. Ser.* **1612** (2020) 012025

Antiproton capture in the 4.5T catching traps







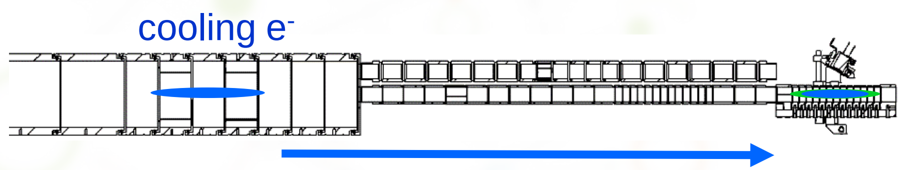


Eur. Phys. J. D (2018) 72: 76
https://doi.org/10.1140/epjd/e2018-80617-x

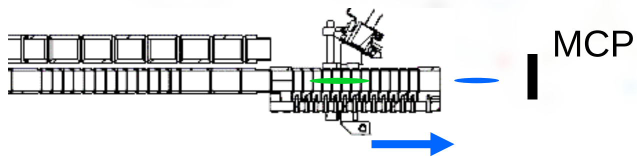
Plasma transfer in the 1T production trap

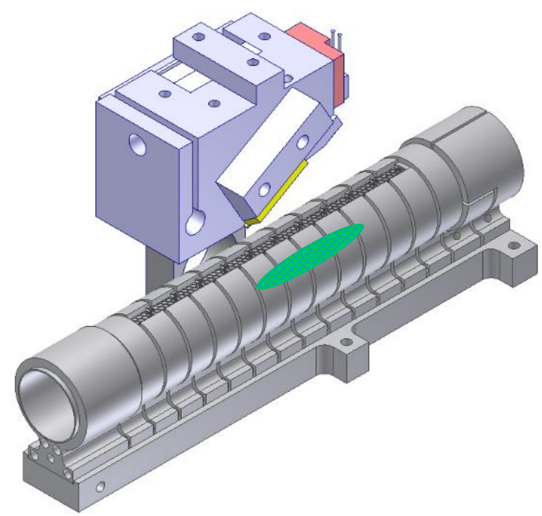
p transfer

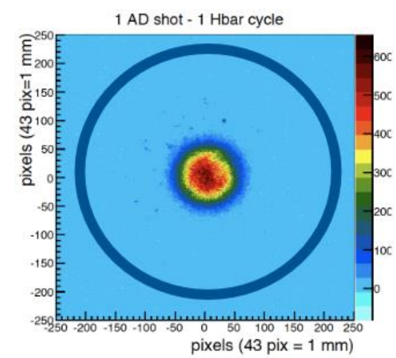
e⁻ transfer and cooling

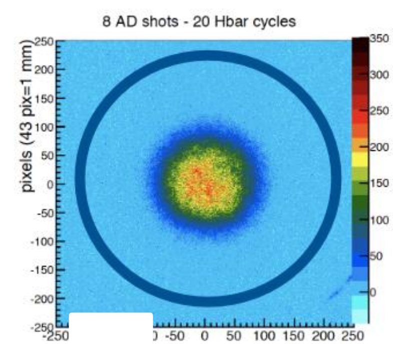


e⁻ number reduction





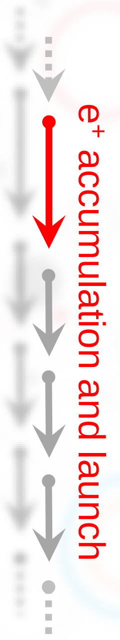


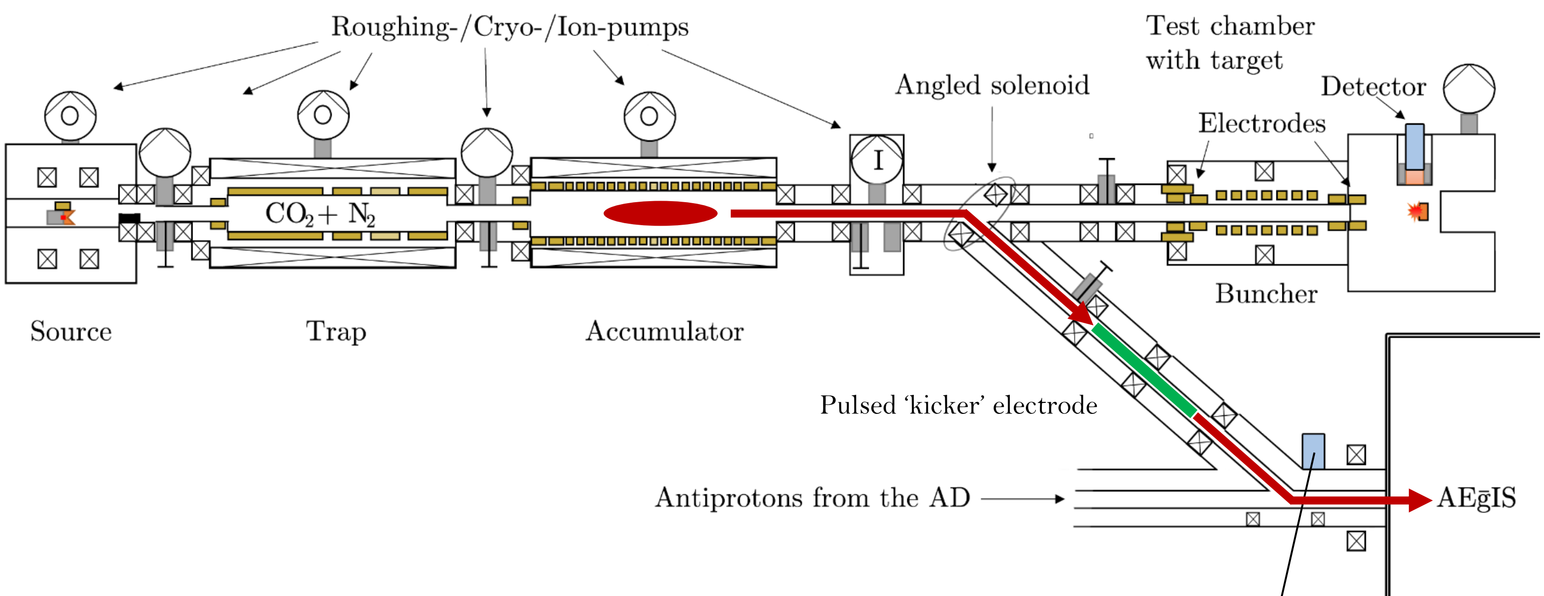


Final cryogenic plasma parameters

1) ~1.8 10^5 antiprotons loaded per cycle
2) Antiprotons lifetime >> 1 h
3) Axial pbar temperature ~ 400 K
4) Radial transport due to non-standard trap design

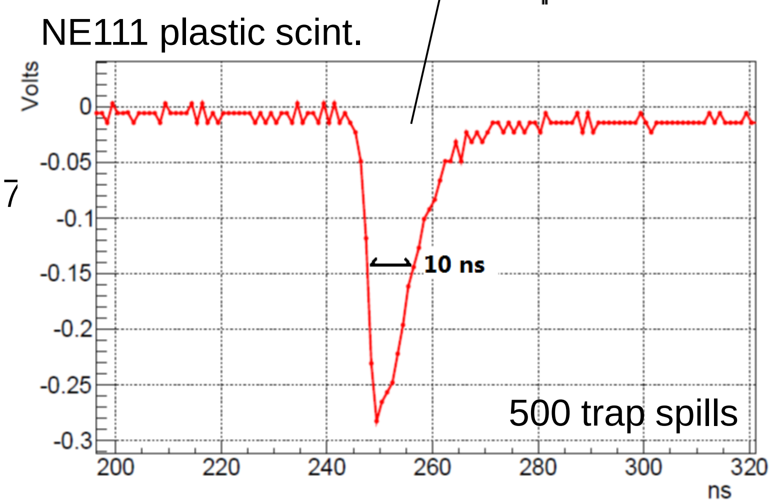
more on AEgIS non-neutral plasmas in the next talk of I. Tietje



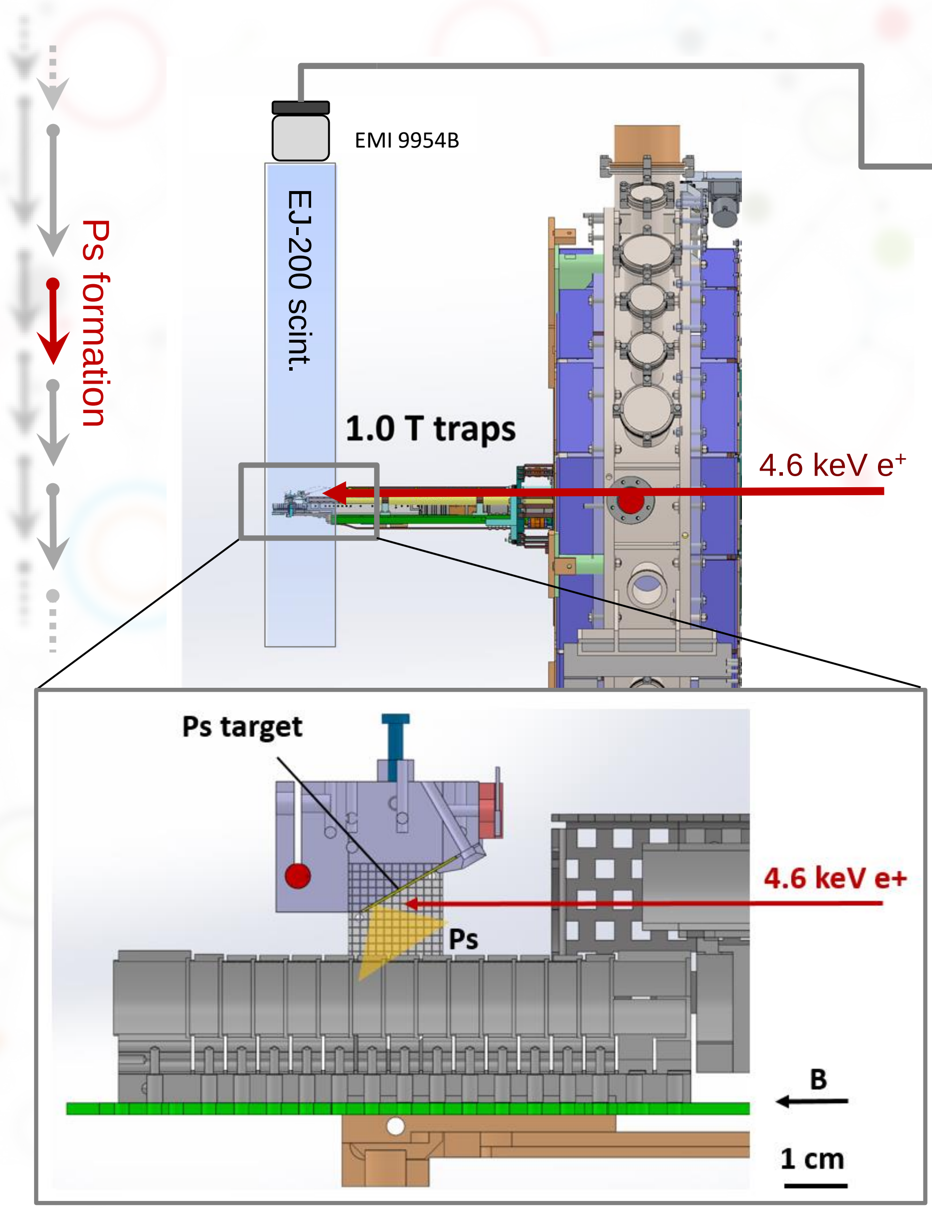


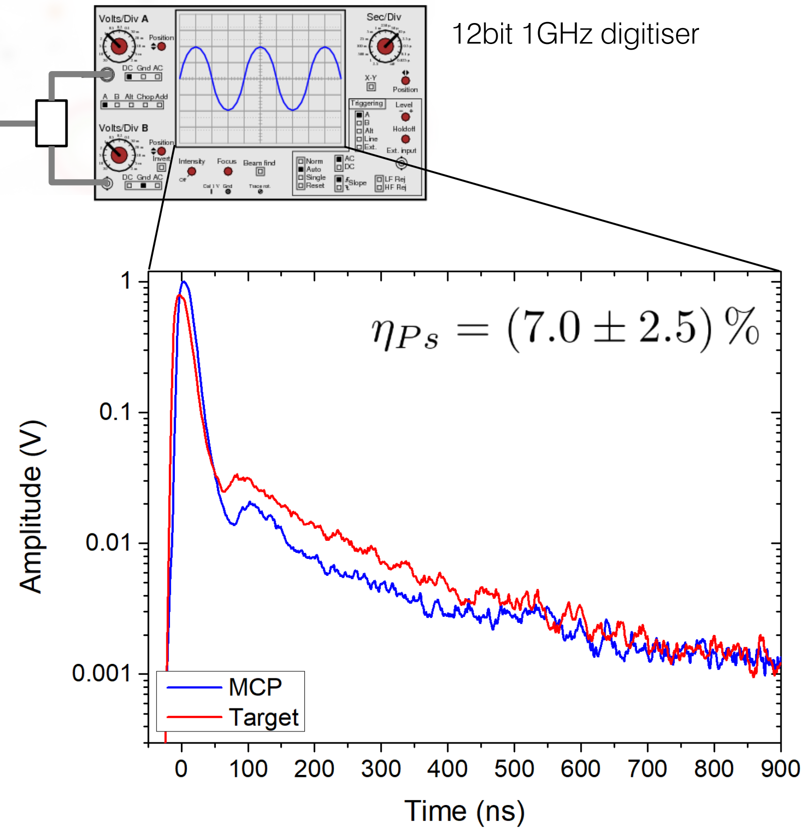
Positron bunch preparation

- Solid-neon-moderated ^{22}Na source (activity 25 mCi)
- Buffer-gas Surko-type e^+ trap (spills of $4 \cdot 10^5$ e^+ / 0.17
- Magnetic accumulator (lifetime up to 7000 spills)
- Nanosecond extraction at 300 eV with magnetic t.line
- Acceleration with pulsed 'kicker' electrode to 4.6 keV
- Steering with horizontal/vertical t.line coils



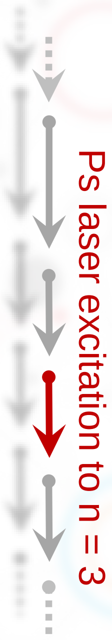
Ps formation and detection



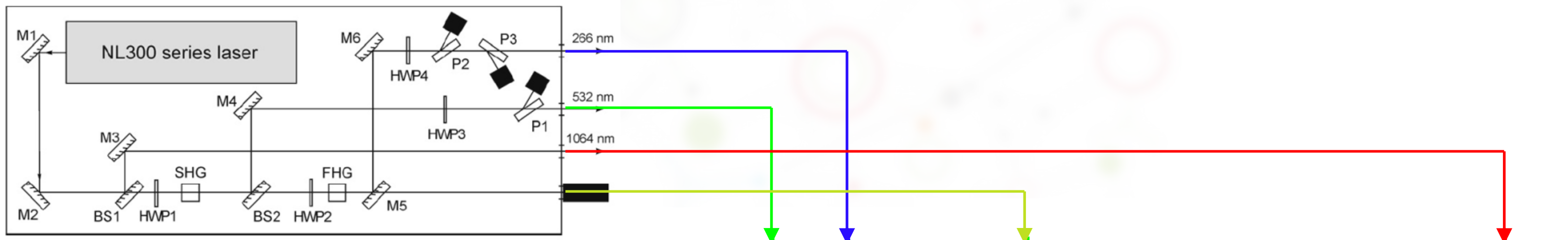


Positronium formation

- Implantation of e^+ bunch in nanoporous silica
- Detection using external plastic scintillators
- Averaging of ~200 shots w/w.o Ps formation

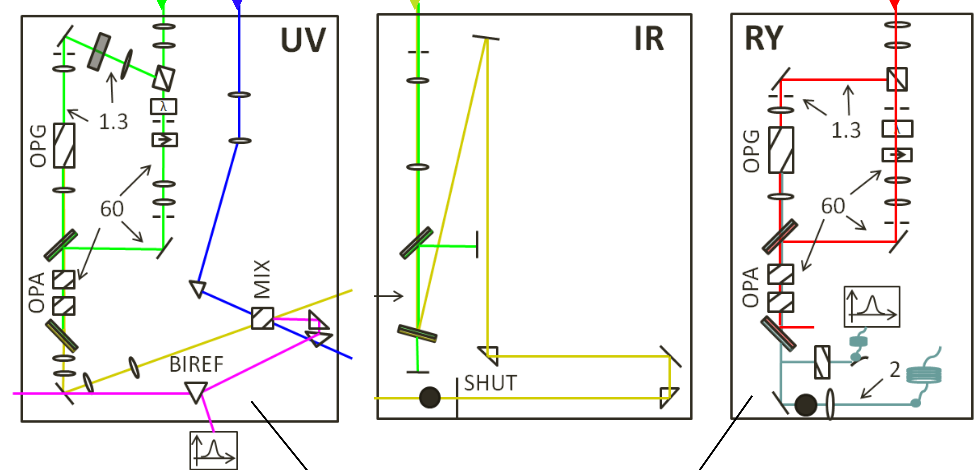


Full solid-state YAG-based custom-built system



Good variety of wavelengths

- 205 nm – Ps 1s-3p
- 532 nm – photoion. 2s, 3p
- 1064 nm – photoion. 3p
- 1312 nm – Ps 2s-3p
- 1700 nm – Ps 3p-n=17
- 2880 nm – photoion. n=17



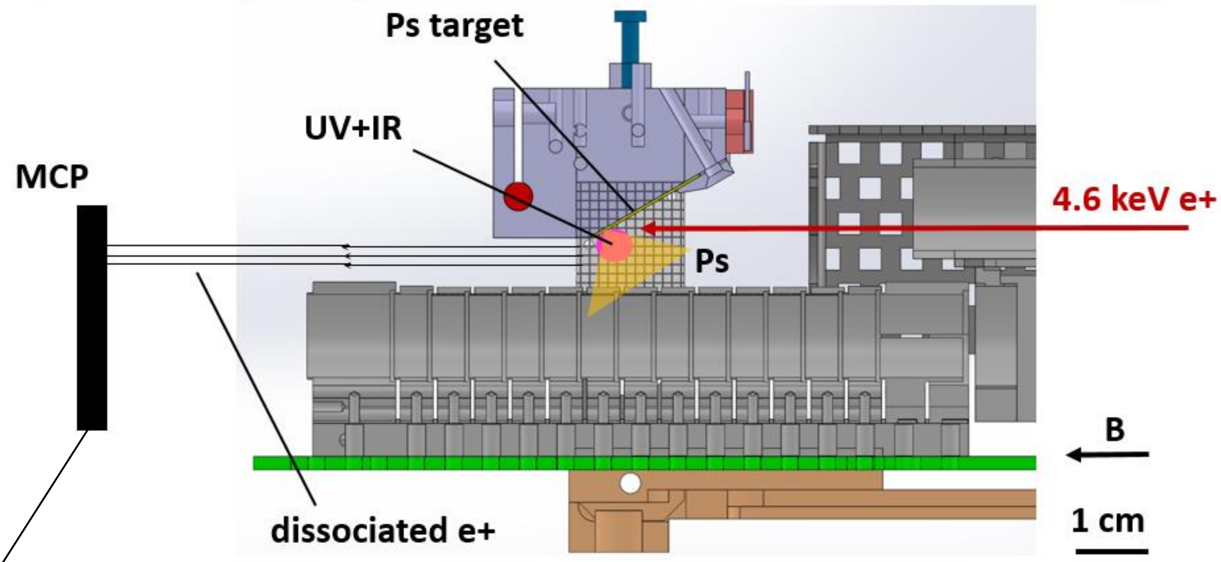
$$\begin{aligned}
532\,\mathrm{nm}_{(o)} &\longrightarrow 894\,\mathrm{nm}_{(o)} + 1314\,\mathrm{nm}_{(o)} \quad \mathrm{OPG,\ type\,II} \\
532\,\mathrm{nm}_{(e)} &\longrightarrow 894\,\mathrm{nm}_{(o)} + 1314\,\mathrm{nm}_{(o)} \quad \mathrm{OPA,\ type\,I} \\
894\,\mathrm{nm}_{(o)} + 266\,\mathrm{nm}_{(o)} &\longrightarrow 205\,\mathrm{nm}_{(e)} \quad \mathrm{SFG,\ type\,II}\ .
\end{aligned}$$

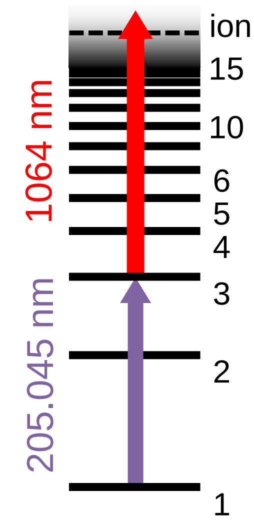
205.045 nm
60 uJ
1.5 ns (FWHM),
120 GHz

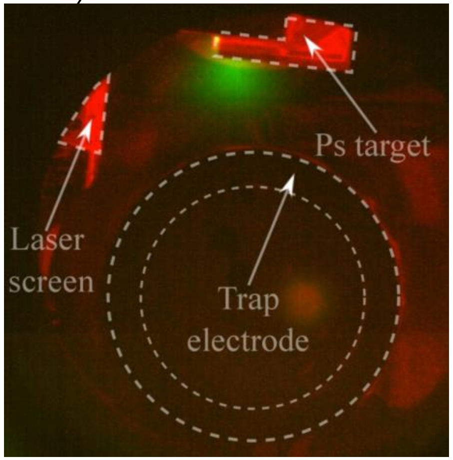
1700.0 nm
400 uJ
4.0 ns (FWHM),
300 GHz

Cialdi S. Boscolo I. Castelli F. Villa F. Ferrari G. and Giammarchi M. G., *NIM B 269 (2011) 1527-1533*
Caravita R., *Laser apparatus for exciting Positronium*

Ps excitation to n = 3: photodissociation MCP detector







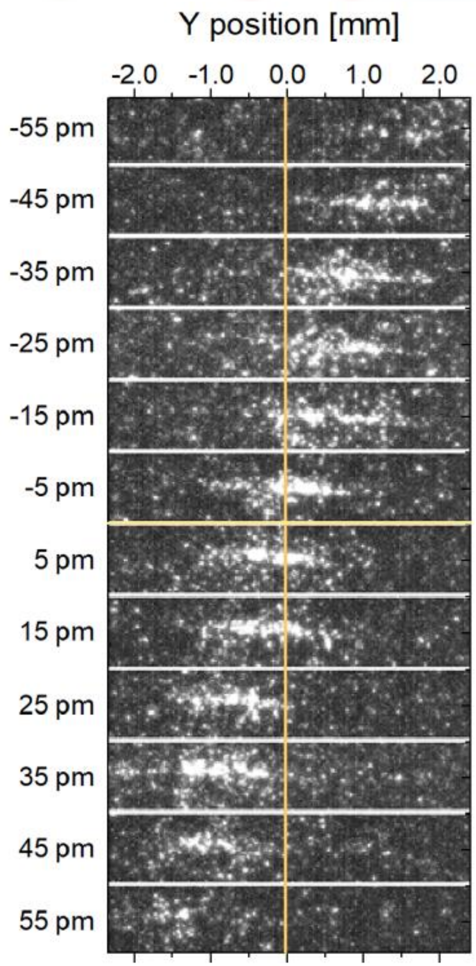
Detection of photo-e$^+$ with MCP+P47/CMOS

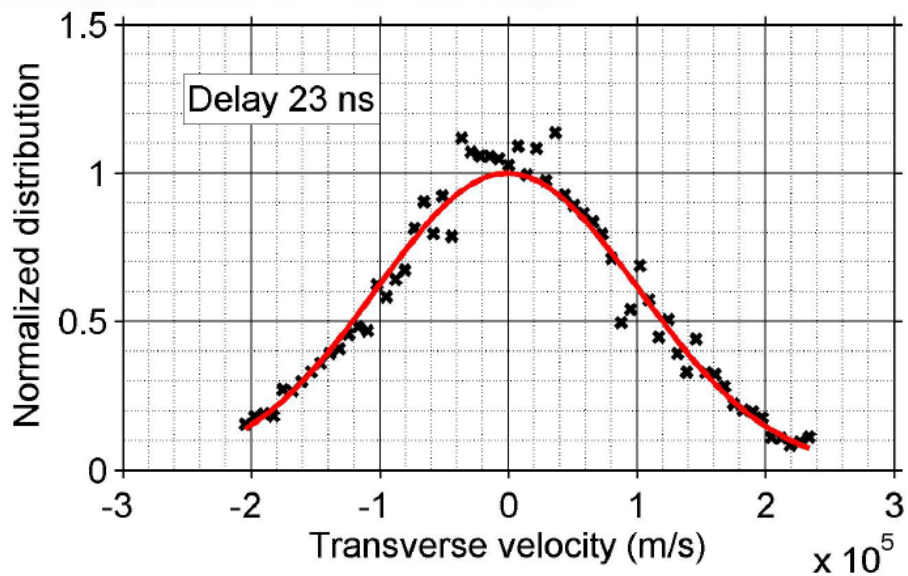
- High-res. imaging capability in the transverse plane
- Small accelerating E field below the target (20 V/cm)
- Front face bias to -180V (maximize e+ efficiency)

$$Res_{(FWHM)} = 88 \pm 5\ \mu m$$

Nuclear Inst. and Methods in Physics Research B 457 (2019) 44–48

Ps excitation to n = 3: measurement of Ps Doppler distribution





Doppler distribution in the laser propag. axis

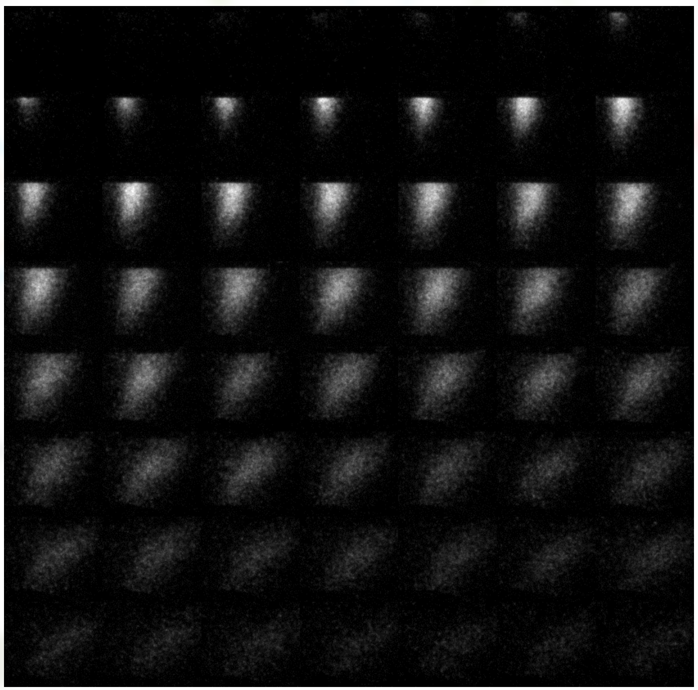
- Ps 1^3S-3^3P spectroscopy via UV wavelength scan
- Doppler selection from UV laser bandwidth (120 GHz)

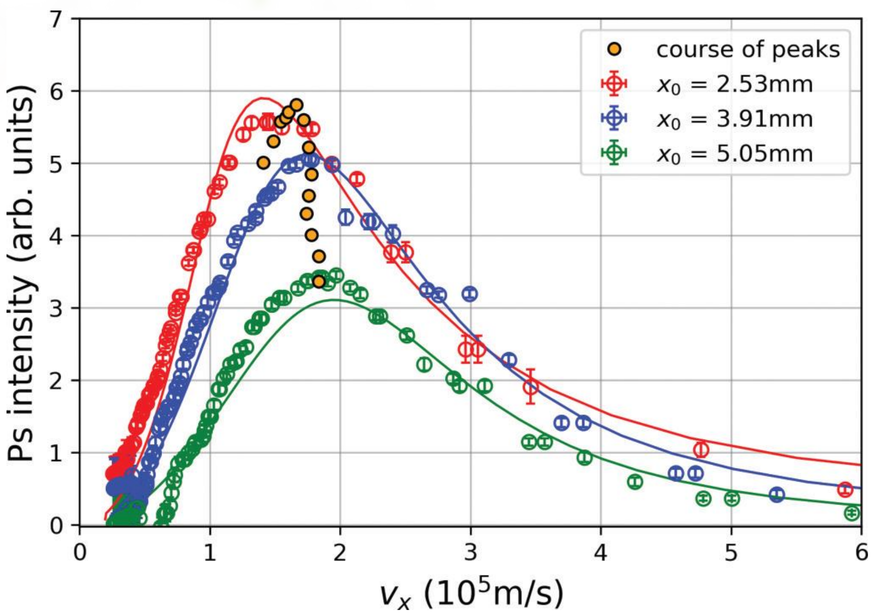
$$\sigma_D = (10.3 \pm 0.3) \cdot 10^4 \quad m\ s^{-1}$$

Antonello M. et al., Phys. Rev. A **102** (2020) 013101

Velocity distribution in the target normal direction (TOF with light)

- UV laser set at constant wavelength (205.045 nm)
- Ps cloud evolution varying the UV laser pulse delay time in steps of 1 ns

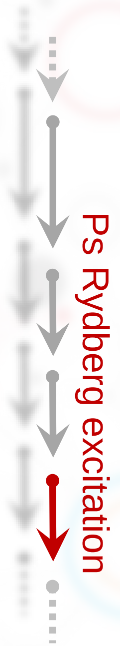




$$v_{max} = (18.0 \pm 2.5) \cdot 10^4 \quad m\ s^{-1}$$

Mariazzi S. et al., Phys. Rev. Lett. **104** (2010) 243401
Antonello M. et al., Phys. Rev. A **102** (2020) 013101

Ps Rydberg excitation: self-ionization disappearance detection

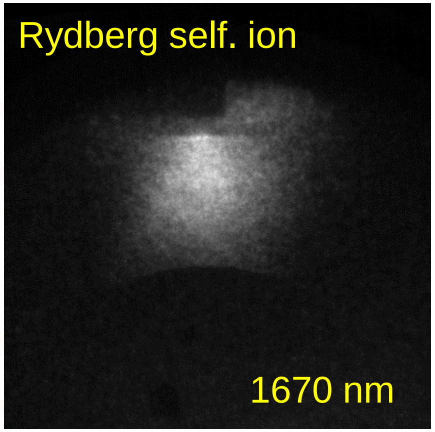


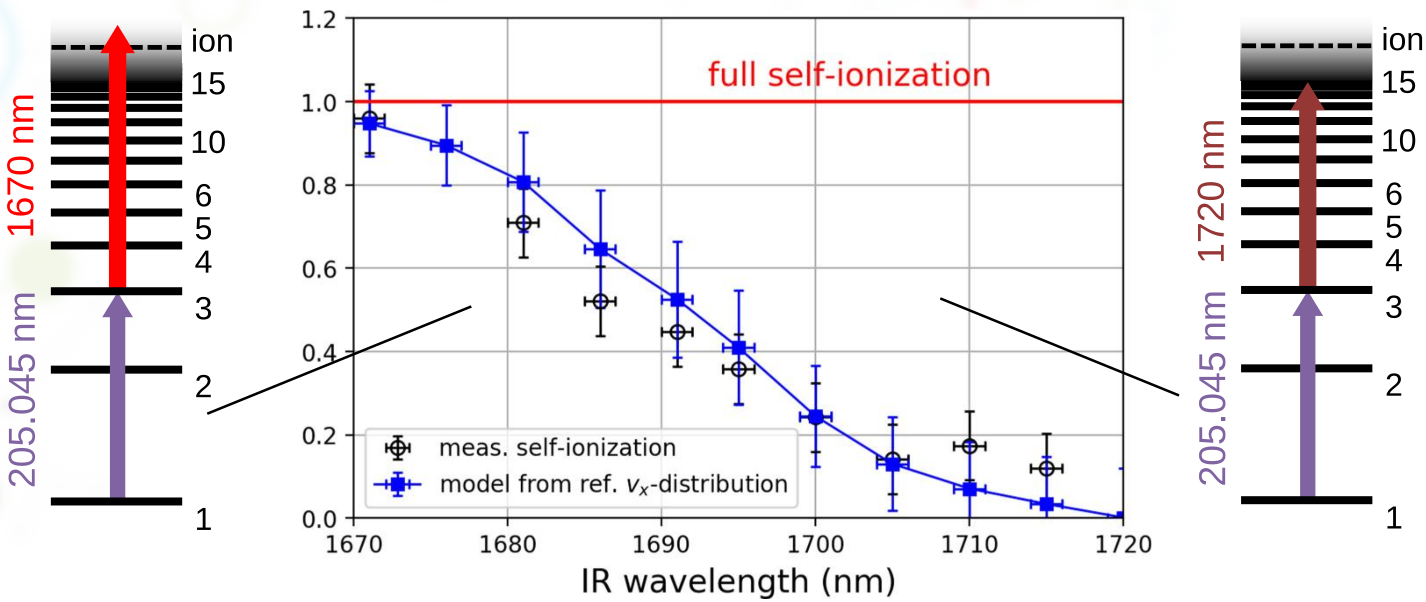
Rydberg Ps partly ionizes in strong B field

- Motional Stark electric field ~ classical ionization limit

$$F = vB\sin\theta \qquad F^{*}_{\text{class}} = 1.3\cdot 10^{6}\,\frac{1}{9n^{4}}\,\text{kV cm}^{-1}$$

- Free e^{+} from spontaneous dissociation of Rydberg Ps
- Disappearance diagnostics: ion. signal vs. IR





Antonello M. et al., Phys. Rev. A **102** (2020) 013101

~70% (surviving) Ps conveyed to n = 17

Hbar detection

Typical experimental parameters

- Stored plasma average density

$$n_{\bar{p}} \approx 10^{13}\,\mathrm{m}^{-3}$$

talk of I. Tietje

- Rydberg Ps entering the antiproton trap

$$N_{Ps^*} \approx 10^3\ \mathrm{cycle}^{-1}$$

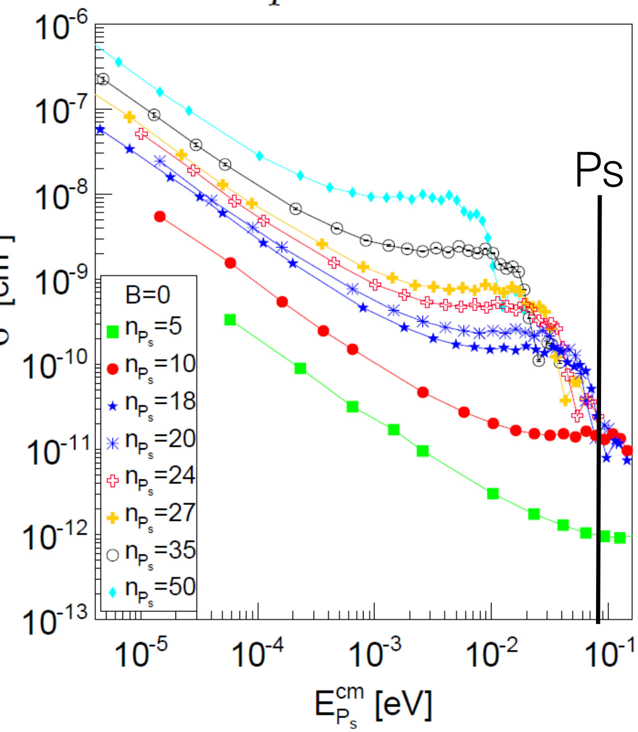
- Cross-section from CTMC calculation

$$\sigma(n = 17, E_{cm} = 0.1\,\mathrm{eV}) \approx 10^{-11}\,\mathrm{cm}^2$$

- Average Ps trajectories angle $\theta_{Ps} \approx \pi/3$

$$N_{\bar{H}} = \int \sigma\, n_{\bar{p}}\, N_{Ps}\, v_{rel}\, dt \approx 10^{-2}\ \mathrm{cycle}^{-1}$$

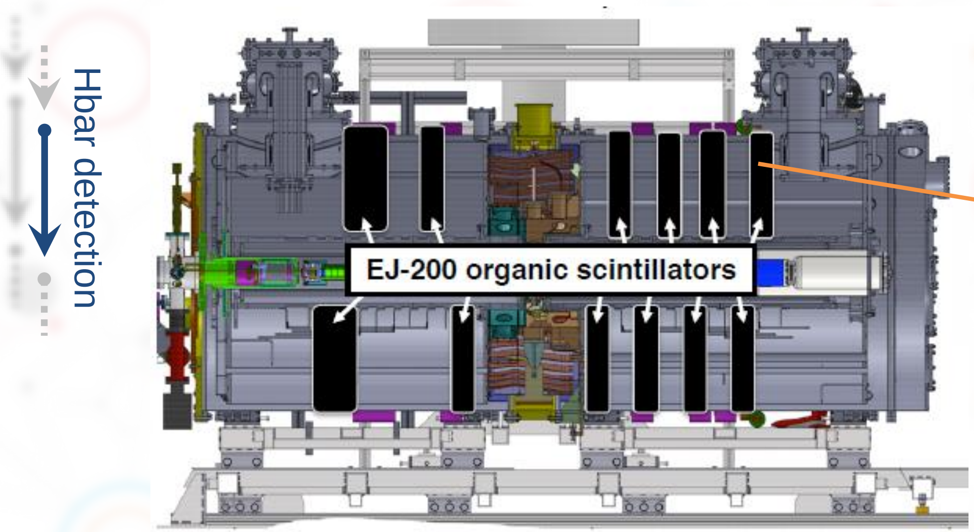
$$Ps^* + \bar{p} \longrightarrow \bar{H}^* + e^-$$

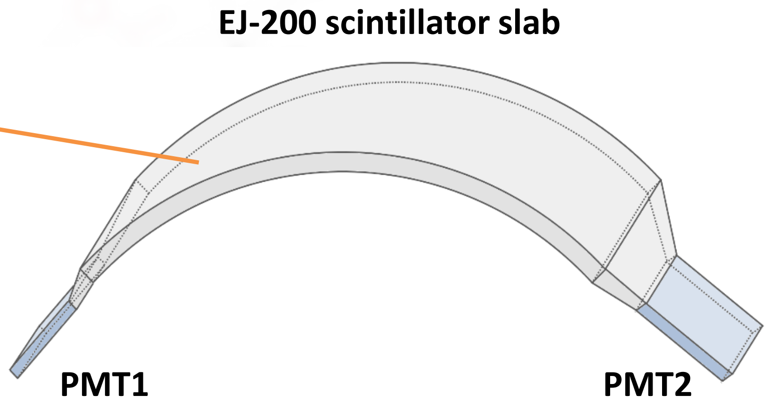


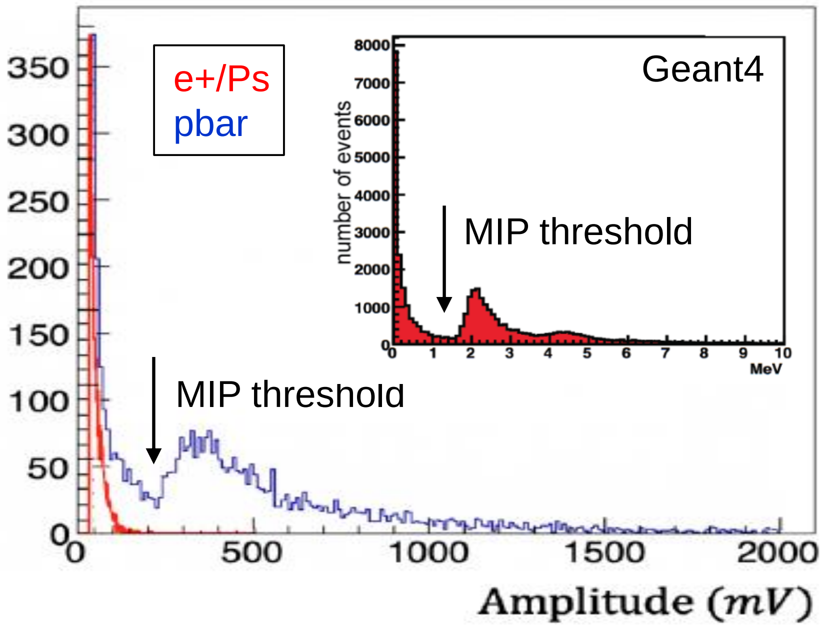
search for rare annihilation events!

Krasnicky D., Caravita R., Canali C., Testera G., PRA **94** (2016) 022714
Caravita R., Ph. D. thesis, Università degli Studi di Genova (2017)

Antihydrogen detection – scintillator array for MIP detection







Scintillator array for MIP detection

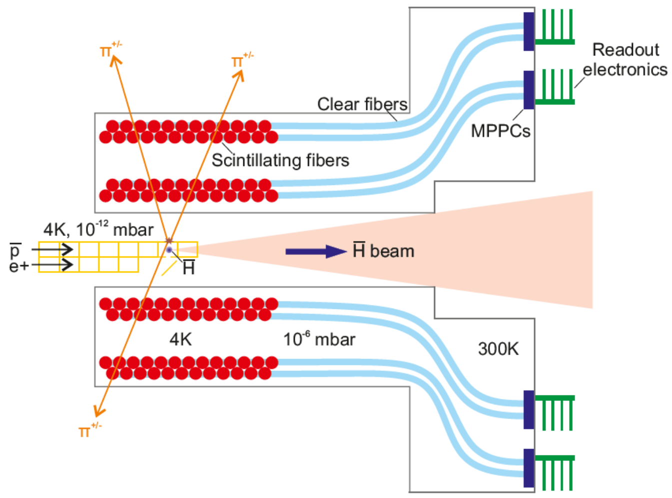
- 8 x EJ-200 scintillator slabs
- Scintillators are read at both ends with photomultipliers
- Each PMT is digitized at 250 MHz
- software **coincidence** between the signals is performed

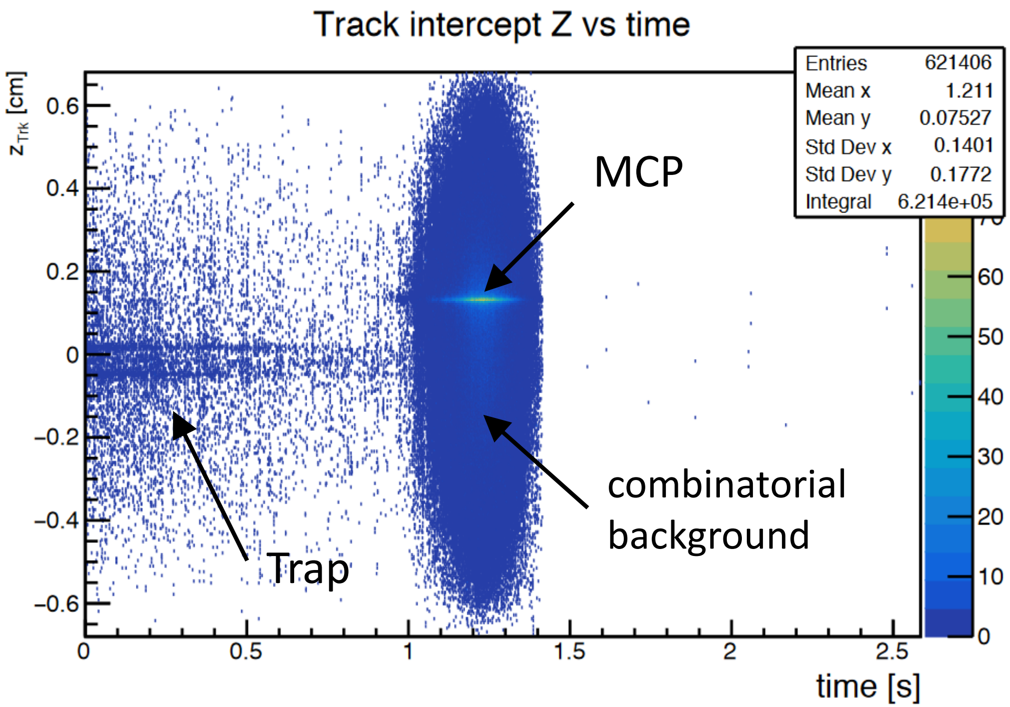
Antihydrogen detection – SciFi tracker

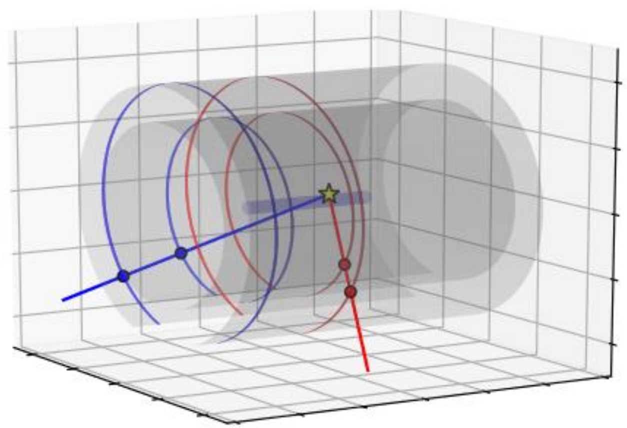
Hbar detection

Scintillating fiber tracker (FACT)

- Charged particle tracker operating at 4K
- 800 Kuraray SCF78 scintillating fibers
- Readout by MPPC + fast distriminator
- Discriminated and readout by FPGA







tracking capability (res ~ mm) in the z direction

Conclusions

AEgIS: probing the weak equivalence principle with antimatter

1. Proof-of-concept pulsed antihydrogen source
2. Pulsed beam of antihydrogen
3. First free-fall tests using a moiré deflectometer

Achievements

- Development of antiproton and positron sources
- Demonstration of all individual steps necessary the first pulsed Hbar source
- <u>Results of the first proof-of-concept experiments are under review.</u>

BACKUP

Antihydrogen detection – analysis strategy